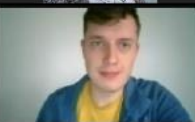
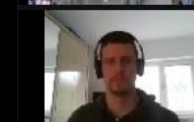
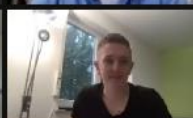
			
				
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2020

CBM Progress Report 2020

Imprint

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Published 2021 by GSI Helmholtzzentrum für Schwerionenforschung GmbH, Darmstadt, Germany
(<http://www.gsi.de>)
GSI is member of the Helmholtz association of national research centers (<http://www.helmholtz.de>)

ISBN 978-3-9815227-9-2

DOI:10.15120/GSI-2021-00421 (<https://dx.doi.org/10.15120/GSI-2021-00421>)

Printed in Darmstadt by GSI

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The activities within the CBM project are supported by:
the National Natural Science Foundation of China under grants no. 11927901, 11420101004, 11735009, U1832118,
the Ministry of Science and Technology of China under grants no. 2018YFE0205200, 2016YFA0400100, FAIR-CZ-OP (CZ.02.1.01/0.0/0.0/16 013/0001677) and FAIR-CZ (LM2018112), Czech Republic,
the European Union's Horizon 2020 research and innovation programme under grant agreement No. 871072 (CREMLINplus),
Bundesministerium für Bildung und Forschung, Germany, under grants 05P15VHFC1, 05P19PMFC1, 05P19PXFCA, 05P19RFFC1 and 05P19RGFCA,
Deutsche Forschungsgemeinschaft, Germany, under grant 405580046,
GSI Helmholtzzentrum für Schwerionenforschung, Germany,
Helmholtz International Centre for FAIR, Germany,
Helmholtz Graduate School HGS-HIRe,
Helmholtz Forschungsakademie Hessen für FAIR, Germany,
Frankfurt Institute for Advances Studies, Germany,
Variable Energy Cyclotron Centre Kolkata, India (EHEP&A Group),
University of North Bengal, India,
IDUB-POB-FWEiTE-1 project granted by Warsaw University of Technology, Poland, under the program Excellence Initiative: Research University (ID-UB),
Romanian Ministry of Research, Innovation and Digitization NUCLEU Project Contract PN 19060103 and RO-FAIR Project FAIR-03/16.11.2020,
Ministry of Science and Higher Education of the Russian Federation, Project "Fundamental properties of elementary particles and cosmolog" No 0723-2020-0041,
the Russian Foundation for Basic Research (RFBR) funding within the research project no. 18-02-40086,
the Russian Science Foundation grant 17-72-20234,
the National Research Nuclear University MEPhI in the framework of the Russian Academic Excellence Project (contract no. 02.a03.21.0005, 27.08.2013),

Preface

2020 was a very difficult year for all of us. The pandemic and the various counteractive measures dramatically changed our way of life, and, consequently, also our daily work. The restrictions at universities and in the institutes complicated and delayed our activities in the laboratory. Many of us had to stay in home office, missing the discussions with colleagues. Travelling was practically impossible, preventing the international participation in beam times and meetings.

Against these odds, important milestones have been reached on the way towards the realization of the CBM experiment: the Technical Design Report for the MVD has been submitted, the Engineering Design Review for the module and ladder assembly of the STS has been passed, important reviews of mechanical parts incl. the absorbers of the MUCH and of the camera for the RICH have been completed, the Production Readiness Review for the outer modules of the TRD has been passed, successful beam tests of TOF modules have been performed in mCBM, and the Final Design Reviews of the yoke and the power supplies of the magnet have been completed. Important steps towards the verification of the triggerless-streaming DAQ system of CBM have been achieved with the mCBM setup, where time and spatial correlations between detector subsystems have been observed with a high intensity particle beam. A particular highlight was the delivery of the first big part of equipment, the support structure of the PSD, as illustrated in the left figure below.

Substantial progress was made also in cave construction and the development of the infrastructure. A photo of the CBM cave is shown below, the shell construction will be finished in 2021 by closing the cave with a ceiling. The first infrastructure components to be installed in the cave will be the rail system carrying the large detector systems downstream the magnet, and the upstream platform, where the CBM magnet and the HADES experiment will be sitting. Both for the rail system and the platform concepts and specifications have been worked out. A task force has been established to design and realize the target chamber and downstream beam pipe with high priority. An important step towards the funding of the Cave infrastructure was the successful launch of the Construction Memorandum of Understanding (C-MoU), which meanwhile has been signed by many CBM member institutions.

Since the beginning of 2020, substantial aid for the funding of manpower is provided by the European Union program CREMLINplus, which promotes the scientific cooperation between European research infrastructures and Russian mega science projects. Joint activities between CBM and NICA are supported by 5.8 M Euro, financing more than 30 positions over 4 years mainly in Germany and Russia, but also in Poland, Hungary, Czech Republic, Ukraine, and France.

In 2021, we hopefully will overcome the pandemic, and return to normal life and working conditions.

Darmstadt, February 2021

Peter Senger



The support structure of the PSD at GSI



The CBM cave (September 2020)

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Several of the contributions to this volume also appear in the GSI Scientific Report 2020.

Executive summary: Status of the CBM Experiment

N. Herrmann

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The CBM experiment is designed for the exploration of the QCD phase diagram in the region of high baryon densities with high precision due to an unprecedented rate capability of the experiment. In the year 2020, significant progress towards the realization of this goal was made.

In 2020 the FAIR project implemented the so-called intermediate objective (IO) targeted for project completion until 2027. As part of the IO the shell construction of the CBM building is making rapid progress with a projected completion date in 2021 allowing for an earlier installation of the CBM detector. In the framework of the IO also other subsystems like especially the SIS100 synchrotron could be brought to initial operation earlier than 2027. In order to be ready for using the first beams delivered by SIS100 the preparations of the CBM experiment follow the time line shown in Fig. 1. According to the planning the cave infrastructure like the rail system for the downstream detectors has to be installed already in 2022. The proposal to finance necessary common infrastructural items by common funds was accepted by the funding agencies as part of the CBM construction MoU after the cost had been scrutinized by the ECE and ECSG committees in several meetings. Concerning funds CBM is thus well prepared to execute the demanding timeline aiming at constructing and setting up the so called day-1 version of CBM until 2025.

This version of the full setup was described in detail already in the Progress Report 2019 [1].

The collaboration is focussing now on preparing for series production of the detector elements. A prerequisite is the verification and qualification of pre-series components under realistic close to final operating conditions. Despite the difficult working conditions imposed by the pandemic these activities are pursued in dedicated test beams and in the ongoing CBM FAIR Phase-0 experiments:

- operation of mCBM,
- participation in the HADES experiment with the RICH photo detectors,
- participation in STAR with hardware (eTOF) and software (KFParticle),
- participation in BM@N with PSD and STS modules.

Highlights from these activities that address specifically system level aspects and for which details are contained in this report are:

mCBM:

In a major commissioning run with heavy-ion beams synchronous operation of all subsystems (STS, MUCH, TRD,

TOF, RICH and PSD) was successfully demonstrated employing a common data transport via FLES to the GreenITCube with high bandwidth. The offline analysis of the data was pushed to the track level where the correlation of detector hits in space and time was established for particle tracks.

HADES:

The full potential of the RICH system making use of the enhanced number of photo electrons to more than 12 per ring was exploited in the analysis of the di-lepton spectra where signal-to-background ratios of 1 and 3 could be demonstrated for the invariant mass region below and at the ω - meson mass, respectively.

STAR:

With the replacement of front-end electronics in 2019 data taking with eTOF in 2020 (Run20) was very successful. The system participated in Run20 with full acceptance over a period of 7 months and contributed significantly to the fixed target data set. For each of the center-of-mass energies $\sqrt{s_{NN}} = 5.75, 7.3, 9.8, 13.5, 19.5, 32.2$ GeV 10^8 Au + Au collision events were recorded. On the analysis side the KFParticle software package was integrated into the STAR software framework and successfully applied to the reconstruction of hyperons and light hypernuclei. First results became available for STAR fixed target data demonstrating the universality of the approach.

BM@N:

20 CBM PSD modules have been included in the FHCAL of BM@N. The readout was integrated into the DAQ system and the modules are being commissioned.

Detector subsystems

The progress in the various subsystems towards production readiness is impressive and documented in detail in the body of this report. Many reviews with internal and external experts have been prepared on different levels like Conceptual Design Review (CDR), Engineering Design Review (EDR) and Production Readiness Review (PRR) and were successfully passed.

- CBM building (Cave)

Shell construction of the CBM building has progressed according to plans, the CBM building is almost complete and roofing is expected in Q2 2021. The procurement of the rail system for the downstream systems got started as well as the engineering design of the upstream platform. Significant progress

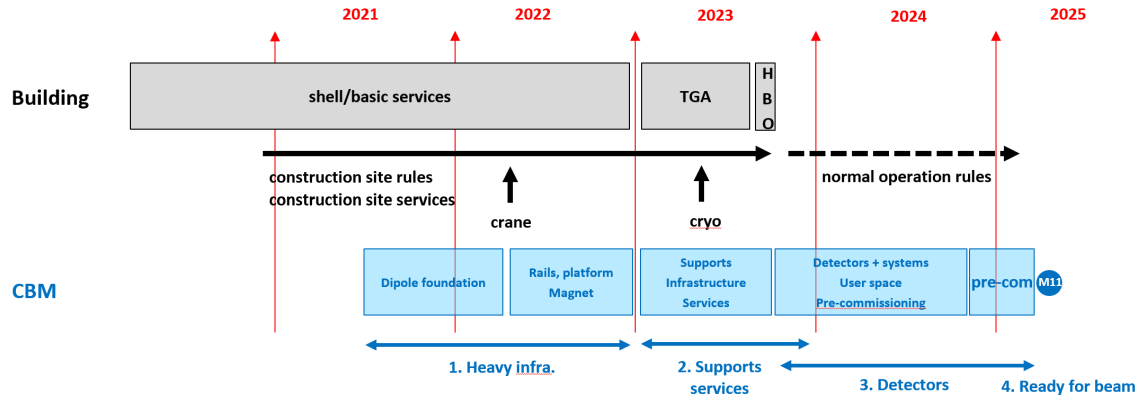


Figure 1: Construction schedule of the CBM experiment.

was made in the routing of service lines from the service stations to the consumers.

As a part of the experiment integration designing of the beam pipe including the target chamber gained in intensity. Design solutions considering segmented targets on a target ladder or wheel as well as for a joint accommodating the deflection of the primary beam by the dipole field are under investigation.

The planning of the installation procedure has matured and supports the feasibility of the overall timeline presented in Fig. 1.

- **BMON**

This project was newly established and separated from the TOF subsystem focusing on the development of the Start and HALO detectors. The Day-1 configuration will be based on the well established pcCVD diamond technology. A readout concept with two independent readout chains is foreseen for the T0 - measurement and for beam monitoring. In additions R&D has been started for a novel technology, based on LGAD sensors, that will be tested for applicability for heavy ion beams in the upcoming mCBM campaigns.

- **Magnet**

Although delays caused by the pandemic situation limited the production of mockup modules of the superconducting coil the project is advancing well and successfully prepared the PRR for the yoke and the power supplies. The overall timeline is compatible with the general plans aiming to deliver the magnet in 2023 to FAIR.

- **MVD**

In 2020 the first full sized MIMOSIS-1 detector became available and got prepared for further systematic tests. Detector integration activities progressed to the use of a new coolant (NOVEC-649TM). Together

with performance studies the project team succeeded to prepare the TDR for internal review and thus passed an important milestone.

- **STS**

The Silicon Tracking System (STS) project reached a major goal by passing successfully the EDR for module production. The project entered a pre-production phase where module production will exercise the well developed QA procedures and documentation. Participation in the mCBM campaign resulted in new insights in the operating conditions of the subsystem that resulted in improved shielding of the housing box against electromagnetic pick-up noise.

- **MUCH**

The MUCH subsystem advanced in all relevant directions. The CDR of the mechanical structure was accepted and the understanding of the GEM chamber performance during the mCBM campaign is progressing well. An instability of the readout could be cured by a redesign of the front-end electronics board. Correlations in space and time could be established with respect to mTOF tracks and yield first estimates of the matching efficiency. The instrumentation of the 3rd and 4th station with RPC counters advanced with the design of a pad readout structure that delivers promising results in terms of cluster size and efficiency.

- **RICH**

The design of the RICH detector was finalized in terms of the mirror tilt angle and the layout of the shielding box that protects the photo sensors against the magnetic field. The CDR for the mechanics including a tunnel interface to the beampipe was successfully prepared and accepted. In addition the camera design including cabling and cooling was accepted on the EDR level pushing the project now towards the readiness for production. The readout concept was verified by integrating the mRICH in the mCBM

setup where the separation power of the RICH concept could be demonstrated by suppressing matched TOF tracks significantly for particle velocities smaller than speed-of-light.

- **TRD**

The TRD project is well on track with its baseline design that successfully passed the module PRR although the development of the front-end electronics is not yet completed. However, the functionality could be demonstrated in test beams and most notably in the mCBM run in 2020 where temporal and spatial spatial correlations with the mCBM timing detectors were observed and evaluated. Progress was also made in the design of the main frame and confirmed by a corresponding CDR. The overall layout foresees the integration of high spatial resolution chambers in the inner region close to the beampipe. The design of these chambers and their readout chain is well advancing, however, due to travel restrictions caused by the covid-19 pandemic the necessary performance test had to be postponed to 2021.

- **TOF**

The main focus of the TOF project was to achieve production readiness for the inner and outer wall. Prototypes of the MRPC counters are successfully operated in STAR and in mCBM where superb values for efficiency and timing resolutions could be demonstrated. Major steps were undertaken to demonstrate the rate capability of the MRPC counters and to assure that the counters will be operational under the harsh conditions throughout the lifetime of the CBM experiment. Correspondingly, aging tests were performed at the IRASM facility in Bucharest and modifications in the MRPC counter design to achieve an optimal counting gas exchange are under consideration.

- **PSD**

Since the production of the PSD modules is already completed the major steps in 2020 were the successful integration of one module into the mCBM readout chain and the preparation of the FAIR-Phase-0 experiments with BM@N and NA61/SHINE. From those experiments as well as from advanced simulations employing Machine Learning techniques an optimization of the layout of the PSD will emerge. The upper part of the support structure of the PSD allowing for lateral and vertical movement as well as for rotations needed for proper placement with regard to the deflected beam was already delivered to FAIR as the first part of the CBM experiment underlining the advanced status of this subproject.

- **DAQ/FLES**

While the mCBM campaign in 2020 was successfully executed with a data aggregation layer based on two

FPGA boards (AFCK and FLIB), the DAQ project changed hardware technology and proceeds with a single FPGA board called Common Readout Interface (CRI) that will be placed in the entry node computers and is accessible to the CPU through the PCI bus. This change in architecture implies severe changes in the communication and control protocols and was addressed in a coherent effort by a large number of CBM member experts.

Computing

The success of CBM will depend to a large extent on the availability of well tested high-performance software that will be running on a many core compute farm. Realizing that only a very limited number of people is currently available within CBM to cope with the challenging demands the effort was focused on the most urgent and indispensable tasks. In the reporting period the computing effort was structured in the following subprojects: Simulation (SIM), Experiment & Detector Control (EDC), Online Data Management (ODM), Data Processing Framework (DPF), Algorithm (ALG), Offline Analysis Environment (OAE), Software Infrastructure (INF), Parameter Database (PDB). Of these SIM and OAE remained without project leaders at the end of the reporting period since the attention concentrated on developing a data processing model that allows to address the challenges specific to real-time systems and that is necessary for operating mCBM as a demonstrator for future CBM.

Nevertheless several important milestones have been reached:

- the whole CBM software was migrated from the code management system *svn* to *git* allowing for a more efficient collaboration of different developers (INF),
- the FLES software package served as data taking backbone in the 2020 mCBM campaign and demonstrated the efficient distribution and monitoring of time slices (ODM),
- experiment control was inaugurated as an human interface project with multilayered Finite State Engines (FSE) communicating with the underlying hardware (EDC),
- time based tracking based on the Cellular Automaton (CA) Ansatz was re-established for full CBM and is being extended as tracking concept for mCBM (ALG),
- the FAIRMQ framework was chosen as a promising environment to utilize the multi core architecture of modern computers for heterogeneous tasks (DPF),
- first steps are undertaken towards a common database model based on TGenBase serving the needs among others for tracking detector components, setup parameters, event selection parameters and conditions, and physics analysis parameters and tags (PDB).

Physics performance analysis

Physics performance analyses by means of Monte Carlo simulations are an essential step to validate the layout of the experiment and the performance of the reconstruction and analysis software. The physics analysis effort is currently structured in working groups addressing common issues like geometry definition, centrality selection, event generation or efficient data processing (PWG-COM), hadronic observables (PWG-HAD), observable from di-leptons (PWG-DIL) and correlation, flow and fluctuations (PWG-C2F). As documented in the body of this report the activities extended notably by an increased effort in collaborating institutes.

Highlights of the achievements are

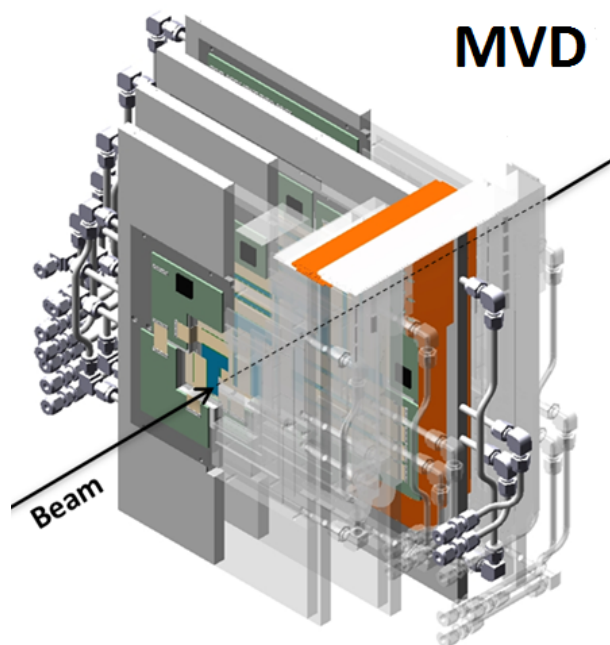
- the geometrical description of the possible experimental setups in the simulation environment was made consistent with the engineering drawings (CAD models),
- development of a slim physics analysis environment (datatree) for efficient processing,
- application of machine learning techniques to improve hyperon reconstruction efficiencies,
- dependence of the reconstruction efficiency on the magnetic field strength,
- evaluation of the expected yields for strange hadrons with different models and reconstruction strategies,
- accuracy of directed flow measurements for protons, Λ - baryons and charged kaons,
- feasibility of J/Ψ measurements at SIS100,
- background studies of di-lepton measurements employing MVD information,
- feasibility of femtoscopic measurements.

In summary, the CBM collaboration is actively preparing on all fronts for a timely start of SIS100 operation and eagerly awaits its first commissioning run in 2025 with a well understood day-1 setup.

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Micro-Vertex Detector



Micro Vertex Detector - Summary

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Abstract:

In 2020 we have received the first dedicated and full-size pixel sensor MIMOSIS-1, passing first studies at IPHC Strasbourg on noise characterization. Further systematic test beam campaigns are mandatory to design and submit the follow-up sensors MIMOSIS-2 end of 2021. Integration studies with the MIMOSA-26-based prototype of a larger module (TPG carrier) have been continued, further consolidating 24/7 runs in vacuum, incorporating EPICS-based experiment control at both of our vacuum test stands. Studies focused on employing the new coolant NOVEC-649TM and confirming the concept of electrical feedthroughs. Last but not least, we very busy with reporting, resulting in a CBM Technical note on CAD geometry models, two Computing Notes on the digitizer and simulation geometries, respectively, and finalizing and submitting the Technical Design Report to the internal review of CBM.

Sensor:

In 2020, MIMOSIS-1 has been submitted and received back from foundry, comprising 18 wafers with six different variants of doping profiles have been fabricated, aiming at identifying the optimum w.r.t. radiation hardness, signal charge collection and spatial precision as well as the in-pixel circuitry employed. The introducing "smoke tests" and subsequent noise studies conducted at IPHC Strasbourg revealed the expected performance and recommend the chip for systematic, and mandatory, characterization with test beams in 2021 with a focus on radiation hardness and single event effects. Simulation studies on the requirements w.r.t. the tolerance of the sensors to ions and nuclear fragments were carried out to guide those tests.

Sensor integration activities

Long-term test runs with the MVD module prototype PRESTO, equipped with MIMOSA-26 sensors on both sides of the carrier, were continued. Special attention was put on further optimizing the cooling by employing NOVEC-649TM as mono-phase and highly volatile coolant for <0° C operation. To do so, a new chiller (JULABOTM) providing a closed coolant system was installed. First systematic studies with a PRESTO heat sink (latest generation) and a pCVD diamond carrier clamped to it have been conducted in a dedicated test stand. The results confirm the outstanding properties of NOVEC-649 regarding operation (e.g. less pressure drop due to lower viscosity) and hence better cooling performance compared to Glycol-water mixtures. We are considering this coolant for future operation, and continue systematic tests to scrutinize the decision. Starting from a first prototype of

electrical feedthroughs used for the long-term operation, we have changed the concept to meet the required signal density while improving on connectivity and handling. Dedicated PCBs glued in narrow slits of a vacuum flange feed the signals through, provide dedicated connectors to receive the cables (inside vacuum) and hold FEE boards (outside). This concept provides an inexpensive, robust and safe, w.r.t. vacuum tightness and connectivity, solution to meet the requirements. Four of such feedthrough flanges will be mounted on the large target box flange, providing about 900 signal lines for read-out, controls and monitoring purposes.

Operation and Simulation

Operation: While in the previous year the focus was on long-term commissioning runs to establish in-vacuum operation, this year shorter test runs of PRESTO were conducted to study various aspects of detector controls. This activity was mainly motivated by concluding measurements for a PhD thesis on this subject.

Simulation: Motivated by the request to perform realistic simulations mainly on increased background from conversion for the dielectron physics program with the MVD in place, we have updated the MVD geometry w.r.t. an updated station layout based on the MIMOSIS dimension, and on a more realistic material budget. In addition, we provide a version with an artificially increased material budget to allow for conservative studies on the background caused by conversion. CBM Computing Notes document all technical details, both on the MVD geometry modifications as well as on the MVD digitizer currently implemented in CbmRoot. We have also updated the CAD layout of the MVD accordingly, also described in a (Technical) Note. This is important to identify and resolve open questions related to the interface volume, and installation sequence, between MVD and the CBM target and the STS beam pipe, respectively.

All of these activities have been considered in the **Technical Design Report** of the MVD, which has been finalized in December and filed to a CBM Internal Review Panel.

First full scale CMOS sensor prototype for the CBM vertex detector

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The Micro-Vertex Detector (MVD) of the CBM experiment requires very light detector stations equipped with highly granular and thin pixel sensors adapted to hostile running conditions. A specific monolithic CMOS pixel sensor, called MIMOSIS, is being developed for this purpose. Inspired by the ALPIDE sensor equipping the recently upgraded ALICE-ITS, its design focuses on the more demanding specifications of the MVD in terms of hit rate and radiation tolerance. The first full scale prototype of MIMOSIS was fabricated in 2020, followed by extensive functional tests and preliminary electronic noise estimations.

In the first semester of 2020, 18 wafers of the first full size prototype MIMOSIS-1 (see characteristics in Table 1) were fabricated with 6 different variants of doping profiles (3 wafers of each). Besides the usual, fully p-doped, epitaxial layer adopted for the ALPIDE sensor [1], 5 variants were introduced, which feature a thin n+ layer underneath the sensing nodes, on top of the epitaxial layer. For 3 of these variants, an extra p+ implant was introduced in between the sensing nodes. Its purpose is to further extend the depletion field and minimize the risk of leaving corners in the epitaxial layer with poor drift field. These modifications enhance the sensor tolerance to non-ionising radiation and accelerate the signal charge collection, possibly at the expense of the spatial resolution.

Parameter	Value
Technology	TowerJazz CIS 180 nm
Epi layer thickness	~ 25 μm
Epi layer resistivity	> 1 k Ωcm
Sensor thickness	~ 50 μm
Pixel size	26.9 $\times$ 30.2 μm^2
Pixel array	1024 $\times$ 504 pixels
Sensitive area	$\approx$ 4.2 cm^2
Sensor dimensions	3.1 $\times$ 1.7 cm^2
Matrix readout time	5 μs
Power consumption	< 100 mW/cm^2

Table 1: MIMOSIS-1 characteristics.

Each wafer hosts 27 MIMOSIS-1 sensors (see Figure 1) and several test structures primarily devoted to the exploration of alternative in-pixel circuit designs. The run was organized in partnership with CERN, where the epitaxial layer modifications mentioned above were designed, motivated by CERN's own applications. They focus in par-

ticular on designs where fast signal charge collection governs the sensor requirements. The wafer reticle hosting MIMOSIS-1 incorporated therefore as well prototypes specific to CERN's R&D program.



Figure 1: MIMOSIS-1 sensor.

Figure 2 shows a block-diagram of the in-pixel circuitry, where the sensing part consisting of a PIN diode is connected to a shaping and discrimination circuit with tunable threshold. Two depletion modes can be applied to the epitaxial layer: one from usual back-bias and the other by connecting the sensing element to a voltage source.

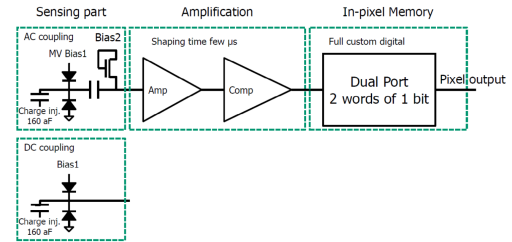


Figure 2: Block-diagram of the MIMOSIS-1 in-pixel circuitry. The sensing part is displayed in its two alternative variants: DC- and AC-coupled.

Each sensor prototype incorporates 4 different variants of the in-pixel circuitry, each populating a sub-array of the sensor. They are labeled respectively MATRIX A, B, C and D (see Fig. 3). The first two sub-arrays (MATRIX A and B) host pixels with a sensing part DC-coupled to the pre-amplifier, similar to the pixels composing the ALPIDE sensor. The remaining sub-arrays (MATRIX C and D) host pixels with a sensing part AC-coupled to the pre-amplifier and the shaping circuit. In the case of an AC-coupled sensing part, the voltage source connected to the PIN diode is decoupled from the in-pixel signal processing circuitry thanks to a capacitor. This will enable the diode input voltage to be raised up to several tens of volts, resulting in an extended depletion of the epitaxial layer.

* Now at IJLab, Orsay.

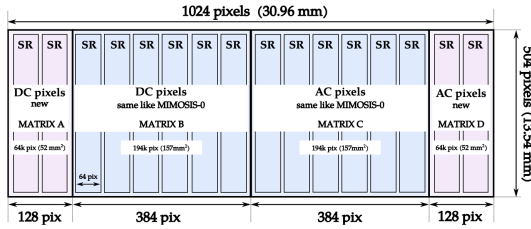


Figure 3: MIMOSIS-1 sub-arrays' layout.

The pixel read-out is performed with a data driven priority encoder common to pairs of columns, each pair featuring 2×504 pixels. The information delivered by the pixel array is processed through a sparse data scan micro-circuit integrated on the sensor edge, common to the whole sensor. The processed data are transmitted to an elastic buffer foreseen to accumulate several consecutive read-out frames in order to flatten out the data flow induced by the beam current fluctuations.

The sensor may deliver up to 2.4 Gbits/s of data, read out according to the GBTX standard. In order to mitigate the impact of SEE, crucial components of the signal processing circuitry include a triple vote logic. The sensor periphery hosts also microcircuits allowing to test the sensor in a programmable way with the I2C standard.

Laboratory tests have started for sensors with the usual, unmodified epitaxial layer. The sensors under tests were diced and thinned down to 300 μm . To save time, the calibration of the charge-to-voltage conversion factor was provisionally taken from the previous, small size, prototype MIMOSIS-0 [2], which featured 16 column pairs of the pixels composing MATRIX B. Compared to MIMOSIS-0, MIMOSIS-1 includes a redesign of the digital part, including elastic buffers and hardening of single event upset by triple modular redundancy.

The laboratory tests addressed primarily the Temporal (pixel) Noise (TN) and the dispersion of the discriminator thresholds among the pixels, expressed by the Fixed Pattern Noise (FPN). The latter results essentially from the tolerances on the fabrication mask associated to the process. All measurements were performed at a temperature of about 15°C. A first set of 3 sensors were tested.

The preliminary results shown hereafter were obtained with the 384×504 pixels composing MATRIX B. The sensors were tested with a variable charge injection emulated via the test circuitry integrated on the sensor edge. The amplitude of the charge injected was varied within a range encompassing a fixed value of the in-pixel threshold value, corresponding typically to about $500 e^-$.

Figure 4 represents the so-called S-Curve, which indicates the fraction of pixels where the charge injected passes the threshold. The pixel noise distribution derived from the S-Curve is also displayed. It exhibits a value of $\approx 5 e^- ENC$. Similar values were found with the two other sensors tested.

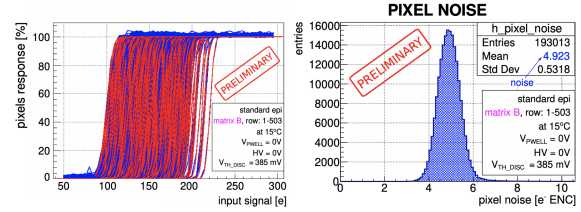
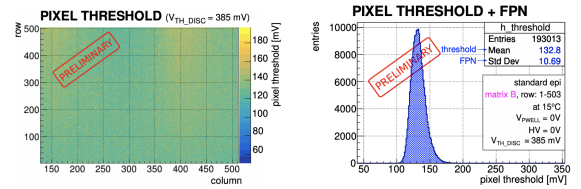


Figure 4: Left: Pixels' responses with respect to the injected charge. Right: Temporal pixel noise distribution.

Figure 5 displays a map of the pixel threshold values calibrated with charge injection. It also shows the corresponding distribution of thresholds over the pixel array, resulting in a Fixed Pattern Noise of $\approx 11 e^- ENC$ for the sensor tested. Minor local trends appear, which depart from a uniform distribution in a well affordable way.

Figure 5: Left: 2D map of the pixel threshold. Right: Pixel threshold distribution showing a FPN of $\approx 11 e^- ENC$.

The plans for 2021 address an extensive program of tests and characterisations. They include in particular a comparative study of the pros and cons of the different epitaxial layer variants, as a function of the depletion approach, for various levels of irradiation. SEE will be investigated with particular attention, the risk of latch-up being a concern. As for the detection efficiency and spatial resolution, they will be evaluated with particle beams for each epitaxial layer variant and in-pixel circuitry option. The outcome of these studies, which will also include fabrication yield estimates, will serve as input to the design of the next prototype (MIMOSIS-2), foreseen to be sent for fabrication toward the end of the year.

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Heavy ions hits at the CBM-MVD

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Being located in direct vicinity to the target, the CBM Micro Vertex Detector (MVD) will be exposed to a high radiation doses caused by various collision products. A particular threat for a save device operation might be caused by nuclear fragments knocked out from the target. We provide first simulation results on the energy, charge and spatial distribution of those fragments as impinging the MVD during runs with Au+Au collision systems in the SIS-100 energy regime.

Heavy ions may damage the CMOS Monolithic Active Pixel sensors (CPS) used in the MVD through integrated radiation damage and single event effects (SEE). A prominent SEE is the so-called latch-up, a reversible short circuit that occurs in vulnerable CMOS structures once numerous minority charge carriers are created for example by a heavy ion hit. Latch-ups were observed once exposing elder CPS to particles creating a linear energy transfer (LET) $>3 \text{ MeV cm}^2/\text{mg}$ [1]. If not quenched rapidly by means of a power-cycle, they may destroy thermally the affected device. E.g., the STAR-PXL detector lost 14% of its sensors due to latch-up before the activation threshold of the circuits performing this power cycle could be correctly adjusted [2]. To prevent a similar scenario, the MIMOSIS-sensor being developed for featuring the best possible immunity to latch-up and will moreover be protected by improved power-cycling circuits [3]. The LET of ions scales with Z^2 and low momentum ions of a given charge Z show a substantially higher LET than relativistic beam ions of similar charge. Heavy and slow target fragments may thus generate a higher LET and such introduce higher requirements to the latch-up tolerance of the technology than the relativistic beam ions considered so far. However, it was so far not studied if such ions would reach the MVD.

Two independent strategies were tested, which were (i) shooting beam ions generated with the FairIonGenerator on the target, which turns into a fragment production by GEANT4, and (ii) the simulation of heavy ion collisions with the so-called DCM-QGSM-SMM model, which also simulates collision fragments, and transporting those fragments with GEANT. The simulations were performed CBMRoot for the VX (Vertex) and TR(acking) detector geometry for Au+Au collisions of 3.5 A GeV with 30% magnetic field, and 12 A GeV with 100% magnetic field.

Fig.1 shows energy and charge of fragments hitting the MVD stations. They were produced with 10^6 DCM-QGSM-SMM events, starting their track in the middle of a $25 \mu\text{m}$ Au-target assuming a 12 A GeV Au beam and the

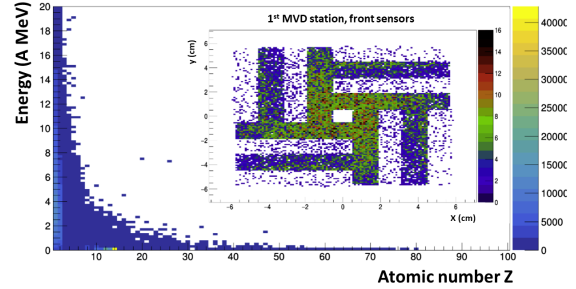


Figure 1: Kinetic energy of nuclear fragments created by the 12 A GeV Au-beam in the CBM target vs. the ion charge Z . Inlay: Spatial distribution of ion hits on the sensors of the first MVD station (TR geometry) per 10^6 minimum bias collisions.

TR(racking) geometry of the MVD. The simulations indicate that the MVD is hit by a variety of ions up to the Z of Au. Still, the energy of the heavier fragments appears limited to $<1 \text{ A MeV}$, which limits their range in Si to few $10 \mu\text{m}$. The inlay of Fig. 1 shows the spatial distribution of the ion hits on the first MVD station (TR detector geometry). All sensors of the station are hit. However, the sensors mounted on the downstream side of the carrier are less exposed as most of the low energy ions are stopped by the $\sim 300 \mu\text{m}$ thick, carbon based cooling support of the station. The more downstream stations (not shown) are exposed to substantially less ions. The simulations relying on the FairIonGenerator and GEANT4 yield similar results.

One observes the MVD to be exposed to slow and heavy target fragments. According to first SRIM [4] simulations, highest Z fragments are too slow to reach the vulnerable structures located behind an anticipated $10 \mu\text{m}$ thick passive layer (SiO_2 and metal lines) covering the sensors. Still, some fragments create a substantially higher LET than beam ions. After being scrutinized, this finding will guide the scheduled test on the heavy ion tolerance of the MIMOSIS-1 sensor prototype.

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CBM-MVD: vacuum-tight, PCB-based electrical feedthrough

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This report will summarize the activity towards dedicated, PCB-based electrical feedthroughs for the CBM-MVD operating in vacuum of the target chamber of CBM. Space restrictions and harsh working conditions w.r.t. radiation call for passive FEE placed in close vicinity to the MVD sensors. The read-out concept calls for 900 data and clock links between the GBTx ASICs (outside) and FEB boards (inside the vacuum). In addition, lines for power, detector control (via GBT-SCA) and dedicated sensors (e.g. temperature monitoring), remote positioning and grounding have to be provided. To feed the desired amount of interconnections between the FEE and R/O electronics placed in immediate vicinity on the target chamber flange outside the vacuum, commercial feedthroughs are not available.

A PCB-based electrical feedthrough concept was selected to provide the required signal density. To do so, dedicated PCBs are glued in narrow slits of the vacuum flanges. Four of those flanges will be employed later. Hence, in a first step, vacuum tightness has to be demonstrated. Figure 1 left shows the corresponding CAD design, providing connectivity for flex cables (top side, vacuum), and space for GBTx functionality. To realize the task, we needed to produce the elements shown in Fig. 1, right. First, the dummy PCBs (Fig.1(1)) were inserted in the slits of the 3D-printed holder (Fig.1(3)). Then, the 3D printed element called glue-stop (Fig.1(2)) was placed such that it was in the direct contact with the holder. In the least step the CNC machined feedthrough plate (Fig.1(5)) was positioned inside the holder. Then the slits inside the feedthrough plate were filled with low amount of TorrLabTM vacuum compatible adhesive. This particular adhesive was used since its (not too low) viscosity allows for controlled application and curing. When the gaps between the PCBs and the feedthrough plate were preliminarily sealed, EpoTecTM 301 was used to fill the rest of remaining space. Both adhesives were out-gassed to remove bubbles before use. After the steps of applying the adhesives, the constructed object was kept at 70°C for a short time to lower the viscosity of adhesives, and therefore, allow them to penetrate accurately the targeted areas. Then, the curing was performed at room temperature to eliminate any thermal expansion problems that might occur when curing is done at temperatures different than a targeted working temperature of the object. After curing the feedthrough plate, now holding the PCBs, was dis-attached from the holder. This operation was rather sophisticated due to the tight tolerances between elements

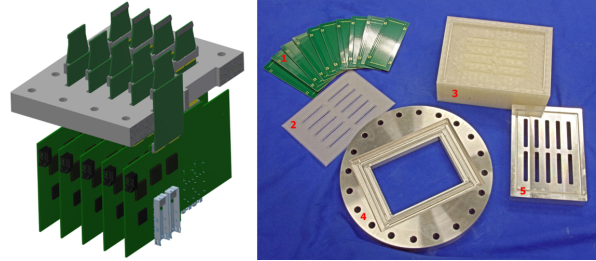


Figure 1: Left: CAD design of the electrical feedthrough, and elements used to build its first prototype (right).

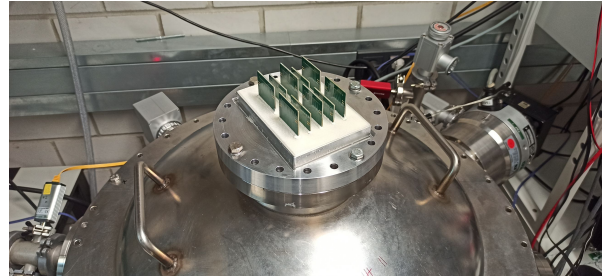


Figure 2: Feedthrough connected to the UFO test stand.

and the fact that the glue-stop demonstrated not to be 100% efficient, calling for further optimization to ease the process and most likely improve the yield. In the last step, the feedthrough plate with PCBs was glued to the CNC-machined CF160 flange (Fig.1(4)). Also in this case, both already mentioned adhesives and the same procedure have been employed.

The final device, depicted in Fig. 2, was mounted to the UFO [1] vacuum chamber and tested. In a first round of tests about 20 pressure cycles between the atmospheric pressure and 10^{-3} mbar were applied. No obvious mechanical damage was noticed. Prototyping and testing will continue to further optimize the production procedures and to demonstrate long-term vacuum operation to qualify the device for deploying in the CBM (vacuum) target chamber.

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CBM-MVD: First experiences with NOVEC-649TM mono-phase cooling

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We report on first experiences with the new MVD mono-phase cooling employing NOVEC-649TM from 3MTM [1] as coolant. The UFO [2] test stand, dedicated to the thermal characterization of MVD components, has been recently upgraded with a novel mono-phase, closed-circuit cooling system JULABOTM PRESTO A40. The need for this upgrade was motivated by the wish to switch from standard coolants like glycol-water or silicone-based mixtures to most modern dedicated coolants, optimized for the MVD operation temperature range of -20 to 0°C, e.g. the NOVEC line from 3M, becoming a standard at CERN experiments [3]. The CBM-STs has also abandoned two-phase cooling towards mono-phase cooling with 3M NOVEC-649. The custom STS cooling system will have enough power and interconnection to provide cooling for the MVD systems, a consolidation reducing costs and concentrating expertise.

The JULABO PRESTO A40 was ordered as a CERN-recommended small-scale closed-circuit system, ideal for basic tests with NOVEC-based refrigerants, i.e., adapting the MVD cooling concept, characterize heat-sinks and optimizing operation parameters such as flow. First, the JULABO chiller was filled with several liters of NOVEC-649 and its input and output were shorted for test purposes. After eliminating all leaks we connected the cooling system to the UFO test-stand equipped with Swagelok stainless steel pipes and fittings providing a refrigerant to a device under test inside the vacuum chamber. Although, no leaks were reported while running the UFO stand with glycol-water cooling liquids in the past, we observed a significant fading of the coolant in the order of 1 l/week. The NOVEC-649 is known as a highly-evaporating, and therefore, more demanding liquid in terms of a cooling system hermeticity. We are currently working on detecting and eliminating the leaks by using a dedicated leak-detector (Testo 316-4 [4]) to allow for 24/7 operation as a next step.

The observed leaks did not hampered us from testing the heat-sink and pCVD diamond based DUT described in [2]. Figure 2 depicts, as example, the pressure drop over a MVD heat sink prototype comparing a Glycol-water (1:1) mixture and NOVEC-649 as coolant. The lower value especially at high flows and low temperature (-10°C) indicated the beneficial impact of the significantly lower dynamical viscosity of NOVEC-649 (1.02 cP at -10°C) compared to the Glycol mixture (15.2 cP at -10°C), and it recommends NOVEC-649 for the envisaged MVD operation temperature range.



Figure 1: JULABOTM PRESTO A40 cooling system.

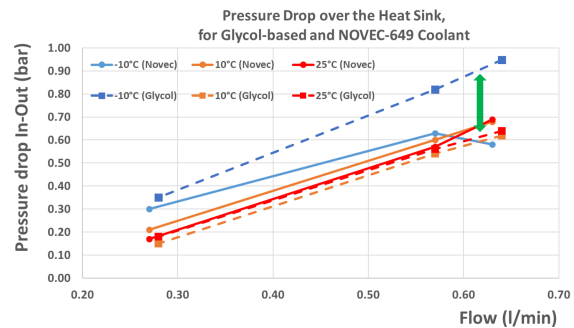


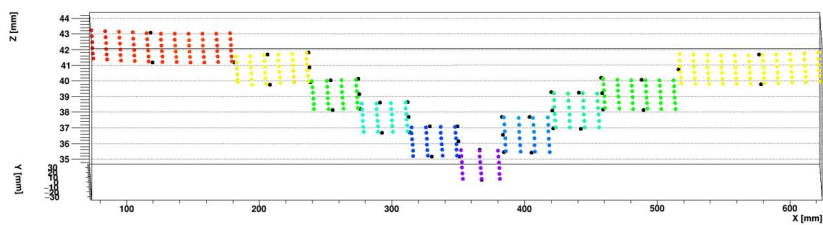
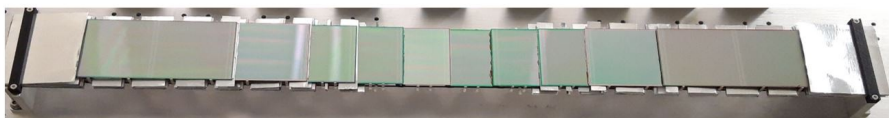
Figure 2: Measured pressure drops over a MVD heat sink (latest CTX version) vs. the flow of the coolant, comparing NOVEC-649 and a Glycol-based mixture (Glycol:water=1:1). The green arrow flags the difference in performance of the coolants under study at low temperatures and high flow.

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Silicon Tracking System



Silicon Tracking System – Summary

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In the course of the year 2020, the Silicon Tracking System project achieved essential progress towards starting detector assembly in 2021. Two major events took place on the central topic of module and ladder assembly, the most labour intensive and delicate work aspect of the STS construction effort.

Project Retreat, Engineering Design Review on module and ladder assembly

From 17 to 18 February 2020, about 40 members from the STS project teams [1] met in the Odenwald country side, about an hour away from GSI, and discussed in topical sessions the different aspects and status of module and ladder assembly [2]. The work relates closely to EU-Horizon2020 project *CREMLINplus* [3], whose work package 2 entitles “Development of instrumentation for NICA and FAIR/CBM”, and served as its first deliverable. A hundred page document [4] resulted as a written account of the development status of components, tools and handling procedures including quality control and logistics. Open issues were named and a task list assigned to follow-up their resolution. This was largely achieved over the year, together with the demonstration of functional modules on partly completed half-ladders.

This led the base for carrying out on 16 December 2020 the Engineering Design Review (EDR) of module and ladders [5], with 5 external reviewers – this time fully remotely via video conference due to the pandemic imposed restrictions. Questions that came up during, or after, the review for further clarification or summary of a given issue, have been received and are - at the time of writing this report - close to completion and resubmission to the reviewing board. A central statement at the review was to structure the beginning of detector construction with a clear pre-production phase, resulting in a small number of fully assembled full-size ladders, and to allow for sufficient time to thoroughly test the objects under the anticipated operation conditions, i.e. at the targeted temperatures of cooling fluids and gas, and cycles of the operation conditions, before production readiness can be declared. Those activities, including the outfitting of the STS assembly lab towards the production configuration, are now ongoing. This includes an outside container hosting a “baby” cooling plant, the power supplies and data taking servers, along with realizing the necessary cable connections and piping into the laboratory room.

Progress made in the related activity fields is briefly summarized hereafter; selected aspects are further outlined in the individual contributions to this chapter.

Module components, assembly, performance

The series production of silicon sensors was completed in 2020. Nearly 1200 sensors have been delivered. At GSI, a thorough and work-intensive quality control took place, extending the factory inspection at vendor Hamamatsu Photonics to their performance at higher operating voltages, important for placing the sensors in high-radiation regions of the detector, and going also to advanced optical inspection beyond the manufacturer’s procedures. Good sensor material is available and the final grading ahead for the start of the module assembly.

Microcables are already produced at the Ukrainian vendor LTU Ltd; high-precision mask sets for around half of of the modules have been procured and sent to the processing site, and a good quarter of cable sets has already been produced.

The read-out ASIC STS-XYTER has been fabricated, after its EDR in 2019, as version 2.2 in its pilot production. The about 2500 ASICs allow their application for numerous prototype modules to drive-in their pre-production assembly. Also the power regulating ASIC LDO was produced in its two variants (1.2 and 1.8 V) as well. Both are installed on the circuit of the front-end board FEB-8 which has been adapted in its design to fit the new electronics. Production Readiness Reviews of STS-XYTER ASICs and FEBs are scheduled for March 2021. The availability of the first-of-series FEBs sets the date for the start of pre-series module and ladder assembly, expected to be in May 2021. The module assembly procedure has been fully established, materials (e.g. protective glues and thermally conducting glue to attach FEBs to cooling fins) have been chosen. A significant number of modules has been assembled which allows assessing the yield during the different assembly steps, and for completed objects. The modules recently assembled showed full functionality.

Ladder components, assembly, performance

The carbon fiber frames for the bulk amount of the ladders were produced already in 2019. In the reporting year, the central ladders were addressed, featuring a cut-out to fit with the beam pipe reaching through the STS detector volume. An engineering study yielded finite-element calculation results on the stability to be expected in a particularly low-mass solution. This was confirmed with prototypes produced. A further iteration is required to achieve higher mechanical stability, which is an ongoing activity. L-legs have been produced in full amount in industry, after the

model of the prototypes manufactured at JINR. The bearings for the attachment of the ladders to the detector units have been developed and verified to achieve the required mechanical precision also under thermal cycling. They can be readily ordered in industry.

The ladder assembly tools have been designed and are available in full ladder length. They can be copied to later parallelize ladder assembly. The photo on the title page of this chapter shows a mechanical demonstrator of a fully assembled ladder, carrying 10 silicon sensors attached with L-legs to the carbon fiber frame, and mock-up microcables stretching to the ladder's ends. The sensor positions, shown in the graph, and their mounting precision have been checked on a metrology stand at GSI.

A half-ladder populated with three modules was assembled and integrated on mSTS unit 3, installed in the COSY box serving as test system in the laboratory. The system in its realistic configuration with power boards, low and high-voltage supplies and filtering, as well as prototype read-out boards demonstrated full functionality of the modules and the integration procedure, an important achievement for the module/ladder EDR.

System design, integration, services

The detector construction advanced on many issues. The detector units are being further details in terms of module arrangement on the ladders, leading to detailed charts of module and ladder variants, e.g. with respect to the required microcable specifications and ladder assembly tools. Fitting the electronics boxes of modules facing each other on adjacent units led to a change request of STS geometry, introducing 5 mm more space between its units and thus a 40 mm longer STS, to be extended beam-upstream and thus requiring to move the target/target vacuum with MVD detector by that amount. The routing of cables, cooling lines and other services in the design is ongoing. A task force group has been created to address the thermal enclosure and the panels on the front wall to host the connector arrays for low and high voltage supply, as well as cooling fluid pipes. The specifications for power supplies are established to have a sub-set of all devices available for pre-series production, system tests, and to start tendering of the full amount of devices later in 2021. A thermal demonstrator has been set up to verify various issues regarding electronics and sensor cooling, as well as thermal insulation, and temperature and humidity monitoring and control. A full-size mechanical demonstrator is emerging to study the different mechanical aspects, e.g. unit mounting, insertion of C-frames, and the installation of the STS beam pipe section. The pipe, after a first prototype produced years back, is now being taken up, together with the GSI construction department and the new CBM beam pipe coordination project, in terms of engineering design, a new prototype, and supporting technical and physics simulations.

mSTS completion

The demonstrator system mSTS has been operated in the mCBM experiment's run in 2020. It comprised one of its in total four units and had one detector ladder with two modules installed. Both modules were operational and allowed for a number of studies, in particular of the front-end electronics configuration and its long-term stability. The system performance in terms of noise was suffering from a longer-standing, supposedly external electromagnetic impact from the mCBM environment, which was neither present in the STS assembly laboratory nor during the beam-test carried out in 2019 at COSY. In a dedicated study, this was finally identified as coming from the nearby vacuum pump for the target chamber and the beam pipe as a wave guide that brought the signals close to the modules. The "cut-out" structure in the mSTS enclosure, necessary to achieve the spatial configuration of the systems in the confined area of the mCBM target region, was identified as the weak spot, not shielding sufficiently against the electromagnetic impact. A new 3D-printed mechanical structure was produced, made from power-dissipating plastic material and coated with copper foil, thus realizing a good Faraday cage. The noise is now at the laboratory level close to the theoretically expected value. This allows now completing the mSTS units with the remaining modules and ladders for the coming mCBM data taking campaigns.

STS construction: teams and timeline

The module assembly work will be shared by the teams at GSI, KIT and JINR. Ladder assembly will be done exclusively at GSI, as well as the system assembly with support from the STS project teams. The timeline drawn in the STS project plan schedules the start of module and ladder pre-production in May 2021, followed by a Production Readiness Review in October 2021 and the series detector production until December 2023. System integration and fractional commissioning is carried out as made-to-order detector components arrive, going in hand with unit by unit assembly, and stretches from mid 2022 to March 2024. Full commissioning of the STS in the lab is to be achieved by August 2024, with the detector being made ready for installation into the CBM cave by October 2024.

References

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- [3] EU-H2020 project CREMLINplus under grant agreement no. 871072, <https://cordis.europa.eu/project/id/871072>
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Basic electrical inspection of silicon microstrip sensors for the STS

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In 2020, Hamamatsu Photonics as vendor of the STS silicon microstrip sensors, has completed delivery of the series production sensors, altogether 1191 devices in four form factors. They all fulfil the agreed key specifications:

- full depletion voltage: 40 – 150 V;
- breakdown voltage: > 200 V;
- leakage current: < 1.5 / 3 / 4.5 / 9 μA at 200 V (for sensors 6.2 cm by 2.2/4.2/6.2/12.4 cm);
- bias resistance: 0.5/1/2 M Ω ;
- number of defect strips (short in AC coupling insulation, Aluminum opening, and Aluminum short to neighbor strips): max. 15 per side.

Basic electrical inspection as a part of the sensors' quality control (QC) aims to define the quality grade of each sensor in order to determine the best position of the sensors in the final setup.

Quality inspection

At the GSI Detector Laboratory's clean room all received sensors were tested on custom-specific probe stations for their current-voltage and capacitance-voltage characteristics. First of all, a comparison of measurement data with vendor data was done to exclude possible damage of sensors during transportation. Exemplarily, Fig. 1 shows the measured detector current and full capacitance for the sensors of variant 6.2 by 4.2 cm in comparison of vendor data and acceptance inspection at GSI - which was extended to higher bias voltage up to 500 V, important for sensor deployment in high-radiation regions of the STS detector.

Radiation regions

As it is illustrated on the example for one station in the Fig. 2, the sensors will - at the end of their life time, - have accumulated different amount of the non-ionizing energy loss dose, depending on their positioning. This requires that some sensors, due to radiation damage with time, will be operated at the much higher bias voltage than 200 V, the maximum possible testing value at the vendor. All 1191 sensors have been tested electrically to check which maximal reverse bias voltage (up to 500 V) can be applied - this is shown in Fig. 3.

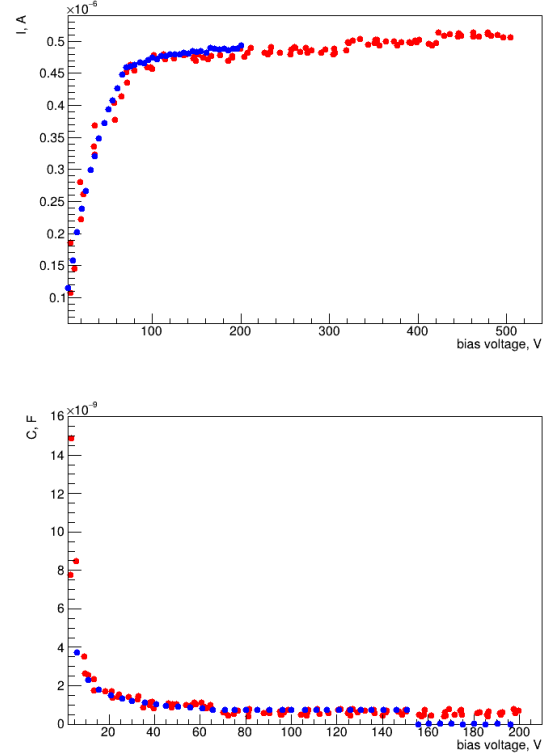


Figure 1: Current-voltage and capacitance-voltage measurements from Hamamatsu and CBM comparing a 6.2 by 4.2 cm sensor. Vendor data corresponds to blue points, measurement to extended bias at GSI to red points. Both current measurements are normalized to the same temperature 20°C.

Quality grading

Based on our studies of irradiated sensors [1], three (still preliminary) sensors quality grade have been defined as listed in Table 1. The resulting required amount of sensors of each quality grade, to match the radiation distribution in the STS detector, is summarized in Table 2.

In order to grade the received sensors, a scheme has been conceived [2] based on the ratios (1) of the sensor currents at the four distinct reverse bias 150 V, 250 V, 350 V and 500 V. The obtained values are then used for a simplified sensors radiation tolerance classification applying the cuts as of Table 3. Initially done for the first batches [2], this has now been adapted to the full amount of sensors.

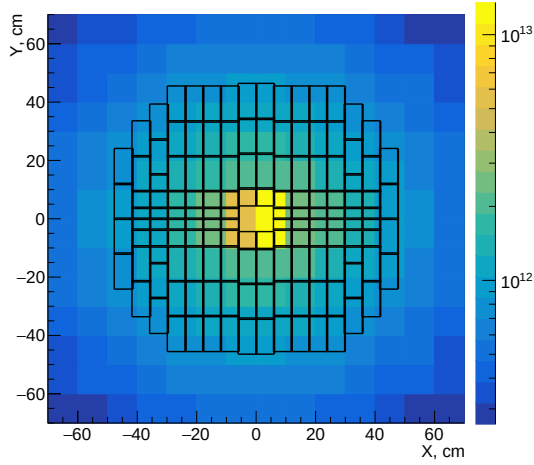


Figure 2: Non-ionizing radiation dose [$1 \text{ MeV n}_{\text{eq}}\text{cm}^{-2}$] in a foreseen operation scenario at the most downstream STS station.

Table 1: Definition of quality grades for sensors with different expected radiation load.

QC grade	Non-ionising dose $1 \text{ MeV n}_{\text{eq}}\text{cm}^{-2}$	Maximal operational voltage
Grade A	up to $1 \cdot 10^{14}$	500 V
Grade B	up to $5 \cdot 10^{13}$	350 V
Grade C	up to $1 \cdot 10^{13}$	250 V

Table 2: Estimated number of the sensors of each quality grade based on simulation and the latest geometry layout.

Sensor height	total	Grade A	Grade B	Grade C
22 mm	80	30	46	4
42 mm	272	90	150	32
62 mm	204	46	106	52
124 mm	320	6	220	94

$$\begin{aligned}
 R1 &= \frac{I(250V)}{I(150V)} \\
 R2 &= \frac{I(350V)}{I(150V)} \\
 R3 &= \frac{I(500V)}{I(150V)}
 \end{aligned} \quad (1)$$

Despite of the fact that for a fraction of the sensors a increase of the leakage current w.r.t. the vendor data and vice versa was observed (which is under further study [3]), a corresponding preliminary estimation of the number of sensors in each quality grade was done which is summarized in Table 4.

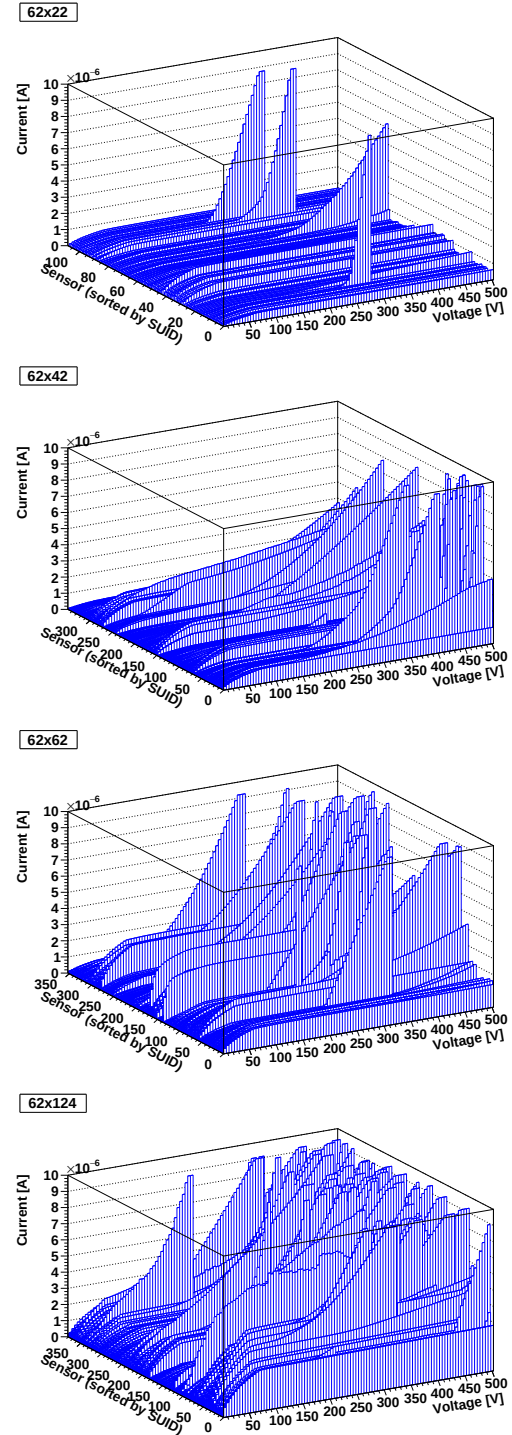


Figure 3: Current-voltage characteristic for all 1191 sensors received, extracted from the data base. The sensors with observed charge-up [3] characteristics prior to their further treatment are also included here. Each panel corresponds to one of the four sensor variants.

Table 3: Cuts applied for quality grades determination.

Current ratio	Grade A	Grade B	Grade C
R1	-	-	[1.0; 2.0]
R2	-	[1.0; 1.13]	-
R3	[1.0; 1.15]	-	-

Table 4: Preliminary extended basic electrical QC results.

Sensor height	total	A	B	C	fail
22 mm	108	98	2	7	1
42 mm	349	260	17	66	6
62 mm	353	247	15	79	12
124 mm	381	214	26	117	24

Conclusion

An overall quality grade will be calculated from all available information: optical inspection, basic electrical inspection, strip test and vendor data. Also the curing of sensors with larger currents will become effective beneficially on the grading. The preliminary inspections results allow us though already now to conclude that we received sufficient sensors of good quality to deploy them in the STS detector.

References

- [1] Ievgeniia Momot, *Characterization and radiation hardness studies of the silicon microstrip sensors for the CBM experiment*, PhD thesis, Goethe Universität, Frankfurt (2019).
- [2] J. M. Heuser et al., *Start of STS microstrip sensor series production and testing*, CBM Progress Report 2019, 16 - 19
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Stabilization of sensor current characteristics prior to module assembly

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Observed unstable sensor bias current characteristics during sensor QC

The determination of the sensor bias current characteristics is one part of the electrical quality control (QC) for the silicon strip sensors of the STS. The measured parameters will be used for grading the sensors so that they may be allocated along their level of radiation tolerance. During the measurements, several sensors with unusual bias current behavior were identified. Similar bias current measurements are performed on vendor site prior to shipment. The effect observed at GSI can also be recognized in the vendors' data for some sensors. It can be explained as some kind of charge-up of the corresponding device. A more detailed investigation of the affected sensors was done to elaborate an appropriate 'stabilization procedure' for the bias current of the corresponding sensors prior to their assembly as a part of a module. Without external intervention(s), the observed time constants, in which the sensor bias current becomes stable and stays so for several weeks, cover the broad range between a few days/weeks and several months. In total approximately 200 sensors of different sizes were identified that they need to be treated and stabilized in the coming months.

Evaluation of stabilization procedure

The procedure to be chosen as candidate for the sensor bias current stabilization has to fulfill the following requirements:

- Duration time as short as possible, which practically means
- Applicability to a large amount of sensors simultaneously,
- No influence on the device performance or other characteristics,
- Long term stability of the device bias current, which implies
- Avoidance of possible re-charge up of the device during further handling.

Until now three different types of unstable behavior could be identified. Among them two subtypes were observed. Discussions with the vendor lead to the attempt of discharging the sensors through a bakeout treatment up to 200°C for several hours.

In Fig. 1 one example for such unusual bias current characteristics as well as the same characteristics after different attempts had been made and procedures followed to reliably stabilize the bias current are shown.

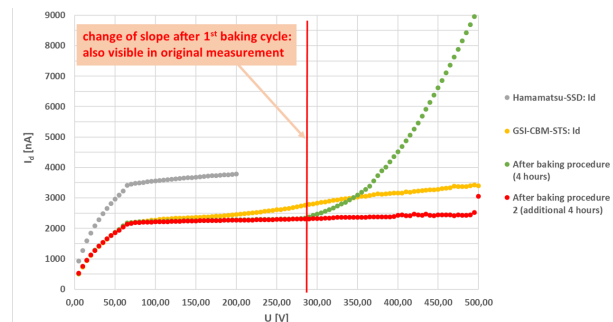


Figure 1: Bias current characteristics of one designated sensor before and after application of stabilization procedures.

In Figs. 2 and 3 some results of the applied stabilization procedure are shown for a sample of sensors showing the same designated type of charge-up before treatment.

Conclusion

Even though the investigations to identify the origin of the observed charge-ups is still ongoing and the physical effects resulting in such bias current characteristics are still to be identified in detail, an appropriate stabilization procedure was found for most of the sensors affected [1]. Reproducibility as well as longterm stability (> one month) of the bias current of the devices treated accordingly were tested with positive result (cf. Fig. 3). Fine-tuning of the bakeout procedure to be applied on the remaining sensors showing different types of charge-up is work in progress.

References

- [1] A. Wilms, *Discharge procedure on STS sensors - envisaged bakeout procedures and their charge-up type dependencies*, STS Coordination meeting, November 2020

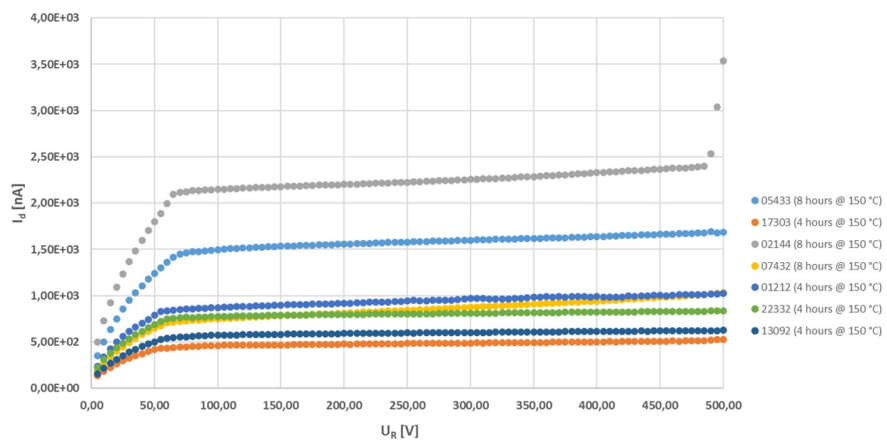


Figure 2: Characteristics of some sensors a few days after bakeout.

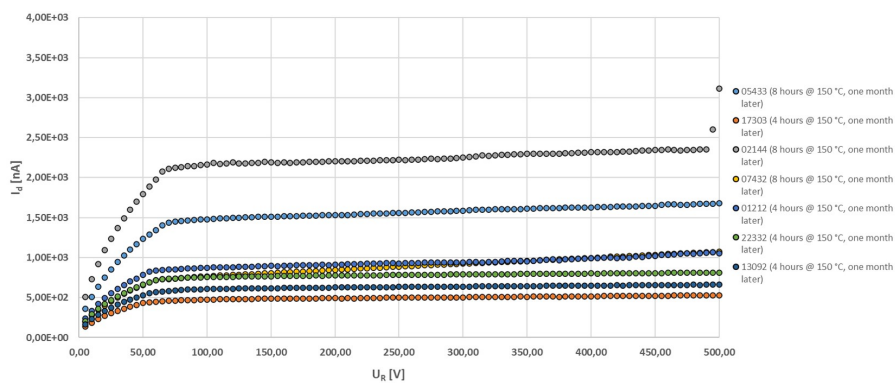


Figure 3: Characteristics of the same sensors as shown in Fig. 2, one additional month of storage later.

Electrical inspection of strips

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The CBM Silicon Tracking System will employ 876 double-sided micro-strip sensors. Optical and basic electrical inspection of the sensors was carried out during the whole last year. Every sensor has 1024 strips per side placed with 58 μm pitch. They collect charge produced by particles from beam-target interactions and thus their integrity is of high importance. Electrical inspection of strips focuses on two aspects: Integrity and compliance of parameters with the CBM specifications [1].

The goal of the integrity tests is to identify defective strips. There are three important defect classes to distinguish: “pinholes”, strip breaks and shorts. Pinholes in the coupling dielectric layer compromise AC readout and are the only defect type that is potentially dangerous for the readout ASIC, if a too large current flow or voltage occurs. Strip breaks and shorts only affect signal read out. As an example, false multi-strip hits can be observed in case of a short of two or more neighboring metal strips.

Three parameters, namely dielectric current, strip capacitance and resistance are measured as a part of the standard integrity test procedure. They are used for defect analysis and, at the same time, provide essential information about coupling capacitance and polysilicon resistance. Measurements of these parameters are performed on the dedicated custom-built probe station that was developed at University of Tübingen. We already reported on its installation in the GSI Detector laboratory in [2] where also a description of the setup can be found.

Electrical inspection of strips is currently in progress. Figure 1 shows an example of the inspection data for a $2 \times 6 \text{ cm}^2$ sensor where identified defective strips on both of the sensor sides are highlighted. After advanced analysis is applied, a defect class is assigned for each strip with irregular parameters. Correlation with visible defects identified in optical inspection has been established, as well as pinhole data provided by vendor has been verified for inspected sensors. After one full batch has been tested, strip electrical inspection can be narrowed to one sensor per production batch in order to control strip parameters. Suspects from optical inspection are an additional subject for electrical inspection.

References

- [1] J. M. Heuser et al., *Description of the STS microstrip sensors for series production*, CBM-TN-19005, 2019
- [2] I. Panasenکو et al., *A Custom Probe Station for Testing of CBM Silicon Strip Detectors*, CBM Progress Report 2019, 20

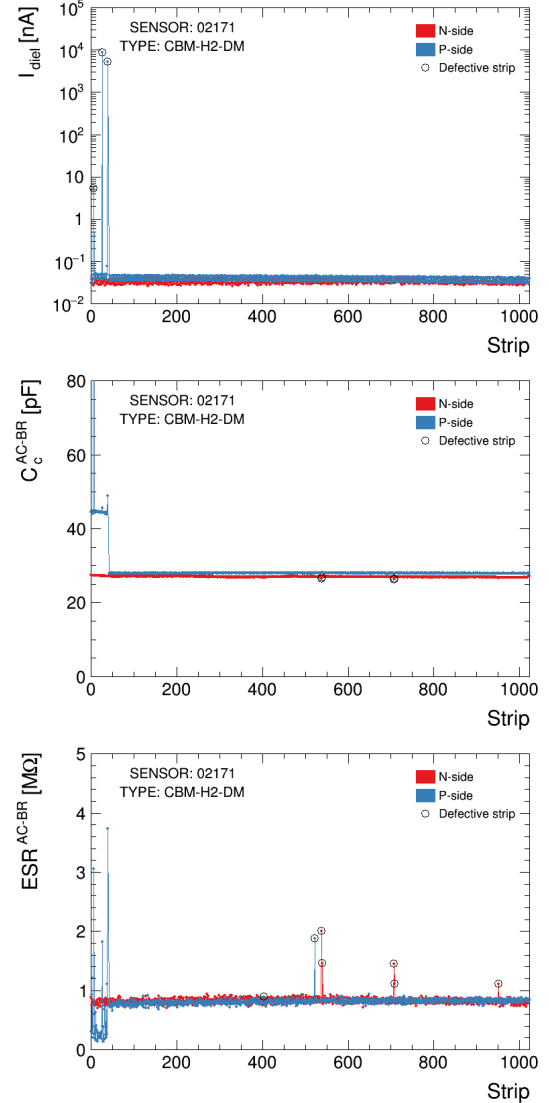


Figure 1: Electrical inspection data comprises three parameters: Dielectric current I_{diel} , strip capacitance $C_c^{\text{AC-BR}}$ and equivalent series resistance $\text{ESR}^{\text{AC-BR}}$. In the plots, identified defective strips on both of the sensor sides are highlight with a small circle.

Results of the series optical inspection of STS silicon micro-strips sensors

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Introduction

The Silicon Tracking System (STS) is the key detector of the Compressed Baryonic Matter (CBM) Experiment to determine primary/secondary track and momentum information of the particles that are passing through the CBM physics aperture (polar angles $2.5^\circ - 25^\circ$). The STS comprises 8 tracking stations and is located inside the 1 Tm dipole magnetic field. The tracking stations are built from 106 carbon fibre supporting ladders on which 876 silicon sensor modules will be placed with the support of L-shape legs. Double-sided silicon micro-strip sensors of 4 different sizes – $6.2 \times 2.2 \text{ cm}^2$, $6.2 \times 4.2 \text{ cm}^2$, $6.2 \times 6.2 \text{ cm}^2$ and $6.2 \times 12.4 \text{ cm}^2$ - will be used to build detector modules. The sensors are $320 \pm 15 \text{ }\mu\text{m}$ thick. The strip pitch of $58 \text{ }\mu\text{m}$ results in a single-strip spatial resolution of about $16 \text{ }\mu\text{m}$. The strips on the p-side of the sensor are inclined w.r.t. n-side strips by an angle of 7.5° to reduce the amount of ghost hit events. Each sensors has 1024 strips on both p and n side, with their read-out at one sensor edge.

Optical inspection of the sensors

In total 1191 sensors (see Table 1) were received from fabrication at Hamamatsu Photonics and underwent quality control at GSI.

Table 1: Total amount of the sensors expected to be used in the STS detector.

Sensor size (cm^2)	No. of sensors	Fraction (%)
6×2	108	9.07
6×4	349	29.30
6×6	353	29.64
6×12	381	31.99
Total	1191	100

In order to assure the quality of the sensors different inbound quality control checks are performed. The first step is the optical inspection of their surface. Per agreed specifications with the vendor, the silicon sensors allowed to have up to 30 defective strips. However, there might be more defects that could worsen the sensor's overall quality and performance, if they are present in substantial numbers or in clusters. We can identify a number of sensor surface defects, or apparent irregularities: implant breaks, p-stop breaks, double metal layer defects, dust grains, aluminium opens, aluminium shorts, scratches, passivation layer open-

ings and resistor defects etc, which can not all be addressed by the vendor's control. The defect detection technique is described in depth in [1]. In this work, a custom made setup for automated sensor QA was built at University of Tübingen. It was then moved to the detector laboratory at GSI for sensor series production inbound quality control.

A variety of defects and also their clusters were detected on the surface of different sensor size using the Convolutional Neural Network (CNN) object detection approach. Based on the total amount of defect observed on the sen-

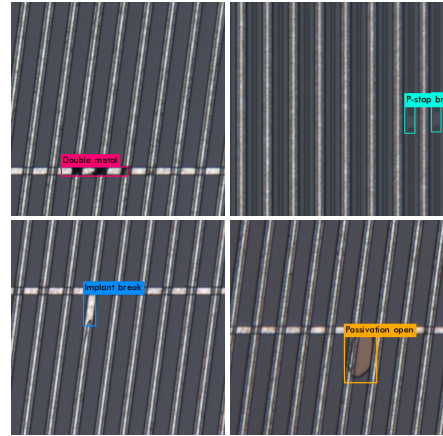


Figure 1: Different defects on the surface of silicon sensors identified with the neural network after training.

sor's surface while evaluating the data, a quality grade was assigned to each sensor so that the best sensors with the minimum amount of surface defects can be chosen for their use in the module assembly for the STS. Figure 1 shows detected double metal layer, p-stop break, implant break and passivation open defects using CNN. The efficiency of the neural network to find the defects of a particular class was found to be 91.52% with an error about 8.48%.

Overview of the results

In this section, the results of the total number of defective strips, quality grade and quality score is discussed. Also, presence of defective strips clusters were seen on the sensor's surface. The result of defective strips map and mapping of the defects is also presented here.

Total number of defective strips

Figure 2 shows the total number of defective strips, accounting for implant break, p-stop break, aluminium open, aluminium short, for p and n-sides of the sensors of all types. Some sensors comprise more than 30 defective strips. Among these there was one sensor observed with 126 defective strips.

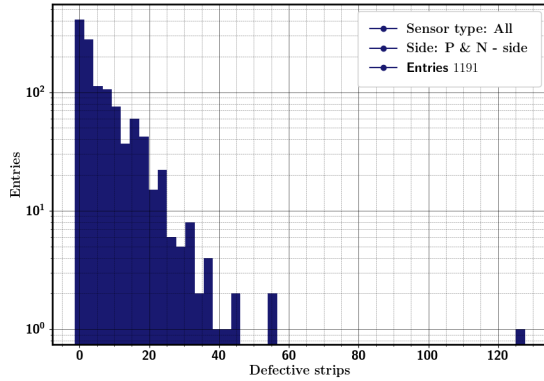


Figure 2: Total number of defective strips per sensor, for the entire set of sensors received.

Quality grade

For the analysis of the sensor's quality grade, only the defects like implant break, p-stop break, aluminium open and aluminium shorts were taken into account. The quality grade scheme is categorized into four classes. The number of flawed strips considered in each grade is listed in Table 2. A summary of the assigned grade to the sensors of all four type is shown in Table 3. The majority of the sensors, 1021 specimen, have received grade A. On the other hand, 147 and 19 sensors were found to be in grade B and C, respectively. Only 4 sensors were assigned a grade D.

Table 2: Quality grade definition with the amount of defective strips considered.

Grade	A	B	C	D
Defects	≤ 15	≤ 30	≤ 45	> 45

Table 3: Summary of the resulting sensor quality grades.

Sensor size (cm ²)	Grade	A	B	C	D
6×2		106	2	0	0
6×4		346	3	0	0
6×6		330	19	4	0
6×12		239	123	15	4
Total		1021	147	19	4

Quality score

The quality score of the sensor was estimated by assigning a certain penalty factor to all type of observable defects, or irregularities. The total number of individual defects found on the sensor's surface was then counted. A penalty factor was applied to the defects of each class to determine the quality score between 0 and 1. Figure 3 represents the quality scores for all sensors. The mean value, after a Gaussian fit, is about 75%. So far, the quality score has not yet been applied towards the sensor grading.

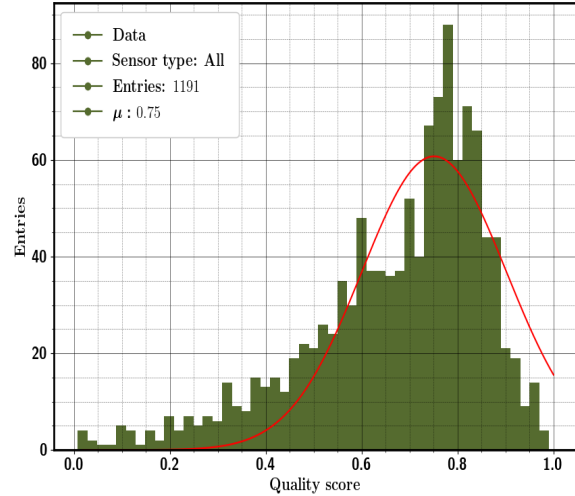


Figure 3: Quality scores for the full set of optically inspected sensors.

Defective strip map

There are 1024 micro-strips on each side of the sensors. The defect types implant break, p-stop break, aluminium open and aluminium shorts were used to create a defective strips mapping.

Figure 4 shows defective strips from all sensors combined, separately for the p and n sides of the sensors. These histograms might identify the tendencies of a certain strip regions to be defective. From the figure it is seen that the n-side of the sensors has more defects compared to p-side. However the distribution is quite uniform, without regions of increased amount of defects.

Defective strips clusters

An algorithm was implemented that can find consecutive strips (clusters) having a defect, for the classes of implant break, p-stop break, aluminium open, and aluminium shorts. As can be seen from Fig. 5, most of the sensors have single-strip detects. Larger clusters occur with less and less numbers. Few sensors have larger clusters of aluminium open and aluminium shorts defects. With larger cluster sizes, e.g. five strips in a row, the defect types implant break and p-stop break occur.

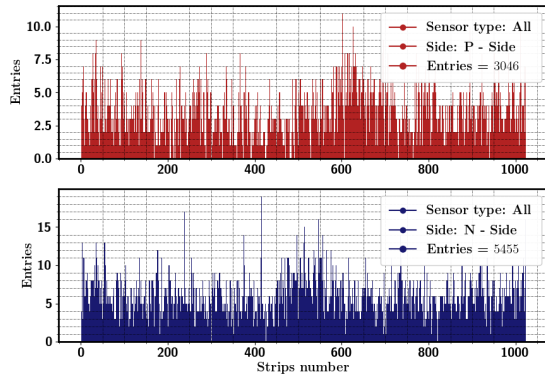


Figure 4: Maps of defective strips for all sensors, separately for p and n sides.

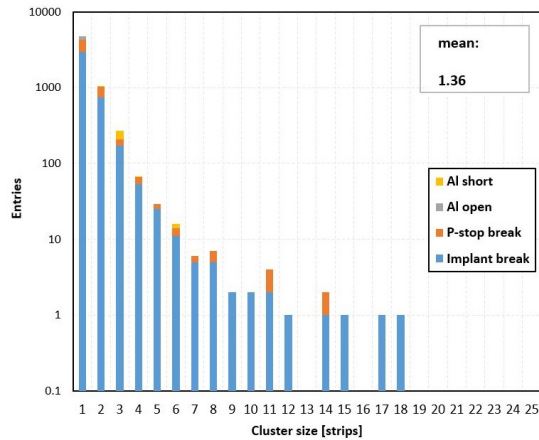


Figure 5: Cluster size distribution of defects, for all sensors. The mean cluster size is 1.36 strips.

2D maps of defects

A two-dimensional map of the defects was created based on the position of a particular defect on the sensor's surface. The local coordinate values during the scanning were converted into the sensor coordinates. Figure 6 shows the mapping of 381 sensors of size $6 \times 12 \text{ cm}^2$, without dust defects. It is noticeable that quite many defects of implant break, p-stop break, scratch, double metal, and passivation open defects were found while very few defects of aluminium open, aluminium shorts and resistor were observed. Moreover, due to the use of the vacuum tool during the sensor's production at Hamamatsu Photonics (confirmed by the vendor), some of the defects or their clusters have emerged in a circular pattern shape.

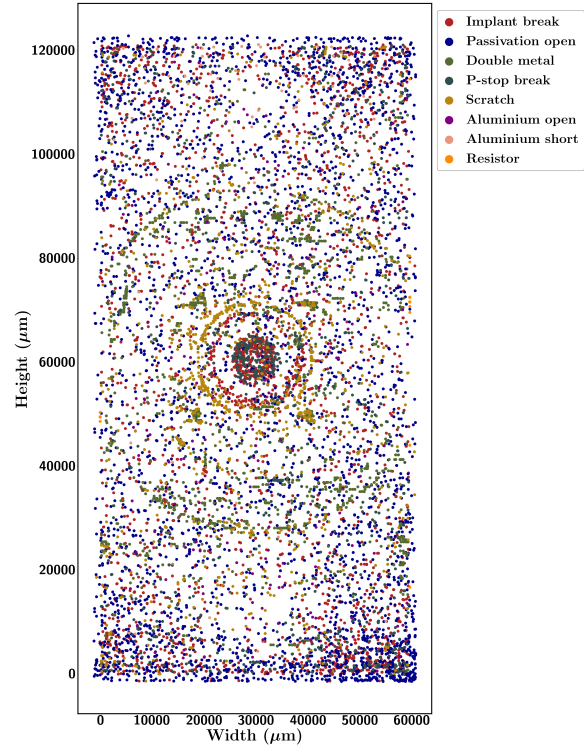


Figure 6: Two-dimensional defect map for the sensor size $6 \times 12 \text{ cm}^2$, p and n sides.

Summary

Optical inspection of all delivered 1191 silicon microstrip sensors has been carried out. It allowed spotting defect types beyond the vendor's capabilities, e.g. such interpreted as strip implant breaks. Most of the sensors were assigned grade A. However, to confirm whether the defects observed by optical inspection are really affecting the performance of the sensors or not, and are correlated with the vendor's final inspection data, requires a dedicated study with a specially assembled detector module. This is ongoing effort. The information obtained about the strip defects will be used for the module assembly and sensor arrangement among the tracking stations.

References

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STS sensor ID verification using Computer Vision

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Introduction

Image processing using Open Computer Vision (OpenCV) [1] has found wide application in machine learning and object detection methods. An image is a two-dimensional matrix of pixels. In an image, every single pixel is represented by a particular value and further categorized in three different colour channels called Red, Green and Blue. For example, a 8-bit RGB image has 256 pixel values between 0 and 255. The colour channels are used to extract the information from an image. However, it depends on the application and how a particular object is illuminated in an image. More on, a kernel is also used widely in image processing. A kernel (2-dimensional convolutional matrix) of different sizes (3×3 , 5×5 , etc.) is used to remove noise, highlight features, and many more. In our case, the application of image processing was used to extract the sensor's unique id information from an image discussed in the following section.

Bit code id verification

The bit code is a sensor's unique identification (ID) number encoded as scratch marks on dedicated pads placed along the inactive rim on the P-side of the sensor. The bit code provides us with information about the production lot number, the wafer number in the production lot, and the sensor number on the wafer. As can be seen from Fig. 1 the bit code is divided, due to its size, into two images of the dimensions $2448 \times 2048 \mu\text{m}^2$.

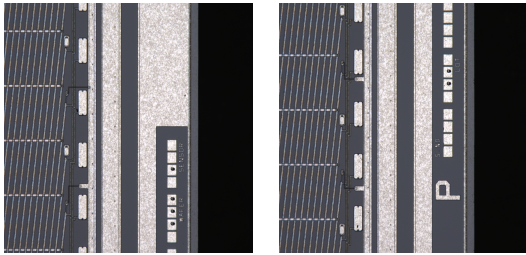


Figure 1: Raw images of bit code information taken with the optical inspection set-up.

A contour finding technique was used to extract the information. The Region of Interest (ROI) was taken out after the process of `np.concatenate()` (to merge two images) and a Gaussian blur filter applied (to remove noise). Figure 2 shows the isolated ID pattern with its five different pad groups of which four contain scratch marks.



Figure 2: Bit code information on the p-side of an image after the concatenating process.

After that step, the RGB colour image (see Fig. 2) was converted to a grey-scale image and then to a binary image for the further morphological process, e.g. *CLOSE*, as depicted in Fig. 3.

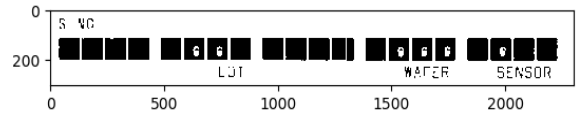


Figure 3: Gray scale ROI converted to binary image.

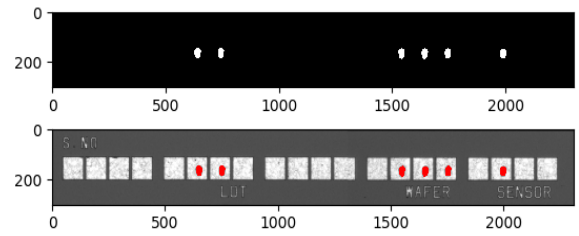


Figure 4: The extracted information of an internal contours (top) and marked with red colour (bottom).

The internal contour information was taken out from their external contour and highlighted by red colour as shown in Fig. 4. Further details are accessible from [2].

Outlook

Finding a contour using OpenCV is a promising technique for verifying sensor's unique id from an image. However, it has a few limitations. The technique would not work when the internal contour is not closed because the outer contour/s can not differentiate. Also, there should not be any other object(s) like dust on the pad.

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Verification of the STS-XYTERv2.1 energy calibration using a ^{241}Am source

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The energy calibration of the STS-XYTERv2.1 is a procedure based on the functionalities of the built-in internal pulse generator [1]. The ADC absolute threshold is established through a dedicated digital-to-analog converter (DAC), the $V_{\text{Ref_T}}$. This 6-bit DAC value allows to adjust the position of the signal baseline level relative to the set of ADC discriminator levels, i.e. setting the effective threshold without the need to modify the ADC transfer function or the trim values [2]. This provides a convenient degree of freedom that can be exploited during calibration or in case of noise saturation. Therefore, for a correct operation of the ASIC in the detector readout, a proper understanding of the $V_{\text{Ref_T}}$ DAC and its transfer function is essential.

Although the $V_{\text{Ref_T}}$ functionality was re-designed in the v2.1 of the ASIC in order to operate in four possible ranges [3], this work targets the largest range, which is typically used during the module operation. To assess the DAC response and to evaluate its linearity, a reference signal from a ^{241}Am gamma source was measured at different $V_{\text{Ref_T}}$ values.

The tests were performed with the module 03Tl.3, produced for the mSTS project. The module was built using a $6.2 \times 6.2 \text{ cm}^2$ silicon sensor interconnected with two FEB-8 via 42 cm long microcables. The testing setup consists of a light-tight aluminum box, which also provides shielding against electromagnetic interference. The box is equipped with a water cooling system for the FEB-8, and it integrates a holder for accurately positioning of a radioactive source.

During the measurements, the sensor was biased symmetrically at 150 V and analog signals were read out from all 1024 channels on each side. The overall noise performance was evaluated for both polarities. The ENC distribution across all channels is illustrated in Fig. 1. Moreover, to have a better energy resolution, the module was calibrated for a reduced, small ADC range ($\sim 3.4 \text{ fC}$) with the settings shown in Table 1.

Table 1: Average results from the ADC calibration of the module 03Tl.3.

Parameter	<i>n</i> - side	<i>p</i> - side
ADC gain [fC/LSB]	0.113 ± 0.007	0.103 ± 0.002
Thres. spread [e^-]	330	230

Results

The tests were carried out using as a reference the 59.5 keV gamma line from a non-collimated ^{241}Am source with an activity of 37 MBq. The values of the $V_{\text{Ref_T}}$ DAC

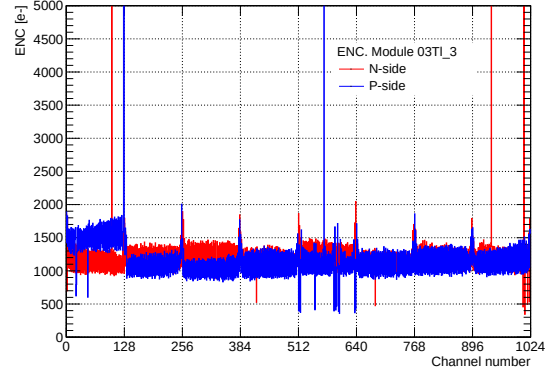


Figure 1: ENC distribution for module 03Tl.3.

were scanned between 51 to 58 LSB, with steps of 1 LSB unit. At each register value, a source and a corresponding background measurements were recorded. The calibration of the ADC with a fine resolution brought the possibility to reconstruct the source spectra in each case, where the gamma photopeak could be identified. Figure 2 shows an exemplary spectrum acquired at a $V_{\text{Ref_T}} = 56 \text{ LSB}$, where only 1-strip cluster signals were considered. The low energy peaks in the gamma spectrum such as 13.6 keV and 26.3 keV were not observed due to the high threshold value. The data was fitted with a Gaussian function in order to extract the peak centroid. The procedure was repeated for all ASICs on both p- and n-sides.

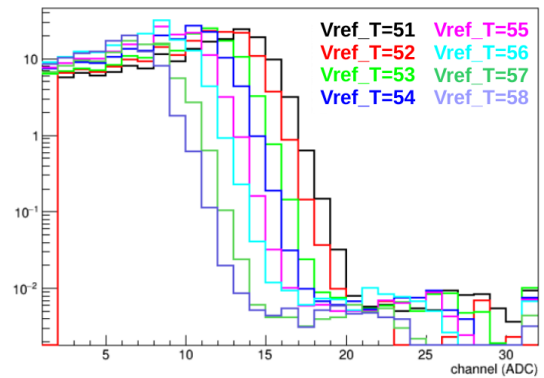


Figure 2: Gamma spectrum of an ^{241}Am source measured with the module 03Tl.3 for different $V_{\text{Ref_T}}$ threshold values.

From the peak position at different $VRef_T$ values, shown in Fig. 3, it is possible to check the register linearity in this range, and assess the equivalent of 1 LSB in electrons or as a function of amp_cal LSBs. The last one, is a measurement of the ASIC pulse generator. Figure 3 shows the measured linearity for the change in $VRef_T$ values.

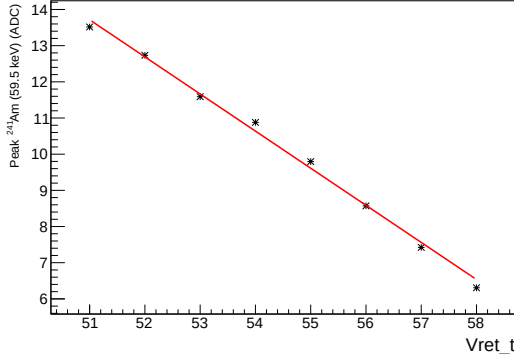


Figure 3: Linearity check of the $VRef_T$ DAC using the 59.5 keV gamma line of an ^{241}Am source.

The measured slopes show deviations from unity of few percent, up to 5%, and some differences in the different ASICs.

Using the transfer function, and recalculating the offset for each value of $VRef_T$, the deposited energy can be calculated as $E = \text{gain} * \text{peak} * fC/e + \text{offset}$, where $peak$ is the mean of the gaussian fit. Using an average of the peak value over all the $VRef_T$ measurements, we obtained 14592 (15877) e^- for the n (p) side.

Using the corresponding noise measurements of 1193 (1121) e^- for the n (p) side, we have calculated a signal-to-noise ratio of 12 (14).

In order to get an estimate the charge collection efficiency, the measured charge has to be compared to the estimated value for the 59.5 keV gamma line of the ^{241}Am source.

However the collected and the measured charge are slightly different, because the input capacitance of the electronics is not infinitely large compared to the detector one. So, in order to determine which fraction of the total charge collected by the sensor is really sampled by the electronics, we must consider, in a first approximation, the total capacitance in the signal path. This can be estimated using an open-loop gain assumption for the amplifier.

We assume that all the charge is collected on the sensor which is fully depleted and not irradiated. Therefore we expect $59 \text{ keV}/3.6 \text{ eV} \sim 16400 e^-$.

This value has to be corrected by $1/(1 + C_{\text{det}}/C_{\text{inp}})$, where C_{inp} is the dynamic input capacitance of the CSA, and C_{det} is the capacitance of the whole detector system. The detector capacitance is given by the sum of the capacitance of the sensor and the microcables, i.e. $C_{\text{det}} = C_{\text{mic}} + C_{\text{sensor}} = 22.16 \text{ pF}$. The dynamic input capaci-

tance can be estimated using the open-loop gain relationship, $C_{\text{inp}} = A \cdot C_{\text{feedback}}$, where $A \sim 4.8 \text{ kV/V}$, as it was in the STS-XYTERv2.0, and not modified in the v2.1; $C_{\text{feedback}} = 100 \text{ fF}$, established for the STS mode chip. Therefore we can estimate $C_{\text{inp}} \sim 480 \text{ pF}$.

We can then determine the fraction of charge that is sampled by the electronics: $Q_{\text{meas}}/Q_{\text{coll}} = 16400 \cdot 1/(1 + C_{\text{det}}/C_{\text{inp}}) \sim 16400 \cdot 1/(1 + 22/480) = 16400 \cdot 95.6\% \sim 15700$.

This value, compared to the signal we have measured, using an average of the measurements on the p and n-side, would correspond to a charge collection efficiency of approximately 96%.

Summary

In summary, we have developed an energy calibration procedure based on the functionalities of the built-in internal pulse generator which, together with a dedicated digital-to-analog converter, provides the ADC absolute threshold. The response was tested with a reference signal from the 59.5 keV gamma line of a non-collimated ^{241}Am source, measured at different $VRef_T$ values. The peak position of the source spectra was obtained with a gaussian fit, and shows a good linearity with respect to the change in $VRef_T$ in the tested range, with deviations of few percent, and small differences among ASICs. Using the transfer function, and the corresponding noise measurements, we have calculated a signal-to-noise ratio of 12 (14) for the p (n) side, respectively, and a charge collection efficiency of $\sim 96\%$.

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- [3] W. Zubrzycka, K. Kasinski, and R. Szczygiel, “STS-XYTER2.1, a revised prototype readout ASIC for the STS and MUCH detectors”, CBM Report 2018, 14

New and final ASIC STS-XYTER Version 2.2

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The new and final version of the readout chip for CBM-STs as well as CBM-MUCH has been submitted and produced during 2020. STS-XYTERv2.2 is a version with only slight modifications compared to the previous version 2.1. The engineering run which this time was exclusively dedicated to the STS-XYTER chip was signed off in December 2019 through a submission readiness review by CBM-internal experts.

The aim of the submission was to realize certain modifications with a clear aim at minimizing risk of spoiling the proper function of the chip, which would otherwise imply an immediate full year delay. So no fundamental modifications were actually accepted. The following facts about the STS-XYTER were in consequence acknowledged:

- The LVDS common mode capture range was identified through simulation to the range 0.5 V to 1.6 V.
- The thermal behavior was found OK. The STS-XYTERv2.1 had been shown to operate and not break at $T > 200^\circ\text{C}$ without glob top. This appears clearly satisfactory. Operation at 40°C resulted in extra noise of about 50 ENC. The chip also operates below -20°C .
- No changes on the front-end amplifiers were to be realized. Even though the biasing resistance of the sensor strips with 0.9 MOhm is lower than the desired ~ 10 MOhm resistance, the resulting noise from these resistors will only be dominating until 20% end-of-life fluence (EOL). After this point, leakage current caused by radiation damage will dominate noise performance.
- No change of assignment of the bits for DICED cells was done.
- The almost full flag was decided to be left unaltered at word 6 of the fifo.

The following modifications were agreed upon and consequently realized in this production run:

- Bond pads were enlarged in various places and finalized as demanded by the bonding experts.
- Some electrical traces very close to bond pads for digital power were buried deeper into the chip so as to avoid shorts while bonding.
- The STS-XYTERv2.1 proved that the diode-version of ESD protection avoids differential leakage that

would cause offset drift. It protects the chip for pulses up to 105 nC within ~ 50 ns. This is 4000 times more than a Au-Ion could generate in the sensor. It was decided to double the ESD-diode nevertheless and add it to each channel input to forfeit the consequences of an accidental sensor short through an excusing beam which would additionally be protected by the punch through circuit on the sensor. Only with doubled diodes could the expected 500 nC charge pulse be supported without damage.

- Fix to the bug on the readout of one particular global register that could not be read back. Tune of the fast reset timing circuitry such that fast reset would start 150 ns after an incoming pulse and then discharge the pre-amp during a period of 100 ns.
- One unnecessary command cycle in resetting the fifo-full state was identified and it was decided to be removed from the circuit to speed up throttling turnaround.
- The ESD protective diodes of the clock and data inputs as well as the output pads were decided to be doubled as to achieve 400 nC ESD hardness.

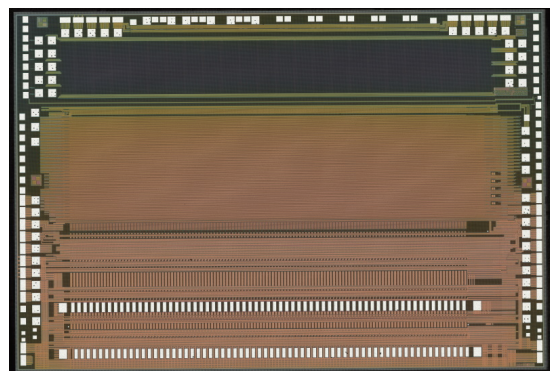


Figure 1: The new STS-XYTERv2.2 ASIC is available.

From this submission 6 full wafers were delivered with roughly 2500 dies which were thinned to 200 μm and diced by laser stealth dicing at Disco Europe. The chip is now being characterized towards the final production readiness review before the full amount of 100 wafers will be ordered.

Quality Assurance (QA) and Quality Control (QC) tools for the CBM-STS

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The QA and QC tools of the silicon tracking system of CBM currently in use, cover the spectrum from single component delivery, over needed logistics up to the assembly and testing of the assembled carbon fiber ladders. Existing tools are continuously optimized and further tools to be developed inside this framework will accompany the production up to its final version. Up to now the production of the STS at the three assembly sites (GSI, JINR, KIT) is foreseen to be coordinated, streamlined and documented using the following main groups of tools:

- Redmine
- elog
- Data logistic tools
- Component Database

Redmine

The STS-Assembly project as part of the CBM redmine system [1] enables the participating sub-workgroups to coordinate workflows, to handover action items between different sub-groups and to ensure adequate information management related to detector assembly. An overview of the internal group structure of the redmine project is given in the QA-Wiki of the STS [2]. The project mainly consists out of sub-repositories dealing with general information regarding the CBM-STS assembly, the assembly of modules and the assembly of ladders. Also groups correlated to data-management and -logistics, as well as to related software are existing. Additionally a logistics group is defined to distribute logistic-information such as e.g. actual shipping status of compounds and components. This coordination tool eases the execution and supervision of QA/QC- and assembly processes within the STS-Assembly project. Sub-group members can allocate tasks to members of their own work-group and others, who can report on the corresponding outcome to keep everybody informed.

elog

The elog of the STS currently provides approx. 50 different electronic logbooks [3]. For each component of the STS, for their testing, for possible R&D projects and for component assembly and created compounds, like chipcables, individual logbooks with adopted parameters exist. For assembly documentation purposes interactive workflow checklists were set up, which are a main tool for the QA of the assembly as well as for the QA of the different assembly procedures. The workflow sheets contain each single step of the assembly procedure to be documented and commented if necessary. As an assembly process can take several hours and, thus stretches over more than just

one login session, the corresponding workflow checklist is saved as an elog attachment to the corresponding 'Assembly Checklists' elog entry. These attachments are also used as status record of the compound production, namely of a designated module or ladder.

Data-logistic tools

To ensure persistence for data collection of QA/QC-processes related to the CBM-STS-Assembly a generalized dataflow was conceived:

- As a start, data measured in QA- or QC-processes are saved locally in .csv or .txt files together with possibly existing configuration files*.
- Available vendor data are extracted via Python scripts into the same format like the data measured.
- All data are transferred to a central storage system using nomenclature and consistency checking gatekeepers. The directory structure of this storage reflects the class structure of the corresponding database instance [4].
- Data from central storage are imported into the corresponding database sections by using a generalized parser. This tool will be usable for all components or compounds with already existing database instances and is currently in the test phase. It is written in Python and is also used for checking parameter name consistencies between database parameters and the corresponding parameters of input files.
- In case of vendor feedback is envisaged, e.g. for the STS-sensors, microcables, etc., VBA tools were set up, to provide the needed data in the format preferred by the corresponding vendors.

QA and QC protocols, as well as manuals for performing measurements and for usage of available software tools are documented in QA-Notes, which are available in the QA-Wiki of the STS [2]. This documentation activity is continuously work in progress due to optimization and elaboration of procedures and tools.

References

- [1] <https://redmine.cbm.gsi.de/projects/sts-assembly>
- [2] <https://cbm-wiki.gsi.de/foswiki/bin/view/STS/STS-QA>
- [3] <https://elog.gsi.de/cbm-sts/>
- [4] <https://cbm-wiki.gsi.de/foswiki/bin/view/STS/STSTComponentsDatabase>

*The filename nomenclatures are generalized up to a certain level to ensure the highest possible degree of automation of the subsequent dataflow.

STS sensor cooling: concept, calculations and CFD simulations

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Given the end-of-lifetime (EOL) NIEL¹ damage ($10^{14.1}$ MeV_{neq}/cm²) seen by the inner STS sensors close to the beam pipe, active sensor cooling will be required to remove the expected power dissipation of ~ 6 mW/cm² (at -10°C) [1] to avoid thermal runaway and reverse annealing. This will be achieved by using forced gas cooling to ensure that minimal extra material budget is introduced inside the detector's physics aperture.

Based on the NIEL damage projections [2], only the innermost sensors of the inner detector ladders ($\Delta x, y = \pm 10$ cm) of every station dissipate substantial power (≥ 3 mW/cm² at -10°C , EOL). Thus, only these sensors require active cooling and the rest of the sensors could be cooled by natural convection (provided that the ambient temperature is approximately -10°C). This report describes the working hypothesis and ongoing R&D on sensor cooling.

Thermal Runaway Calculations

The sensor leakage current and consequently the power dissipation are strongly dependent on the sensor temperature. Therefore, the cooling power must always be greater than the heating power in order to avoid this self-feeding system to go into 'Thermal Runaway'.

Heating Power in a silicon sensor is calculated as [3]:

$$P_{\text{Sensor}} = V_{\text{Bias}} \cdot I_{\text{Leakage}}$$

$$P_{\text{Sensor}} \propto V_{\text{Bias}} \cdot T_{\text{Sensor}}^2 \cdot e^{-\frac{E_{\text{gap}}}{2 \cdot T_{\text{Sensor}} \cdot k_B}}$$

Cooling Power is theoretically calculated by assuming that the cold gas flows parallel to the innermost silicon sensor's surface, with the detailed formalism described in [4].

Figure 1 shows that a gas flow of 3 m/s at -10°C is sufficient to remove the nominal EOL power dissipation of the sensors. This would result in a stable operating temperature of -7°C and a critical thermal runaway temperature of 17.4°C , thereby ensuring sufficient margin from the stable temperature.

CFD Simulations with SolidWorks

A 'toy model' was designed² to carrying out Computational Fluid Dynamics simulations and to test the potential

¹Non Ionizing Energy Loss

²<https://www.solidworks.com/>

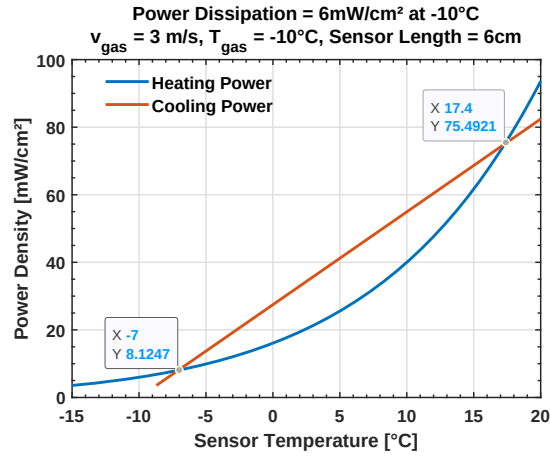


Figure 1: Comparison of the nominal heating power and the required cooling power to avoid thermal runaway.

air cooling concept with two dummy stations resembling the STS stations no. 1 and 8 in an enclosure. Only the active volume of the detector (i.e., sensors staggered on ladders, and the beampipe) was modelled in order to include the most crucial components for simulating air flow and also to reduce computation times.

A Perforated Carbon-Fibre (CF) Tube (outer diameter 2.4 mm, wall thickness 200 μm) is located 10 mm in front of all four inner ladders to blow cold air directly on the innermost sensors. Based on the material properties of CF tubes [5], it's expected to introduce an additional average material budget of $x/X_0^{\text{av}} = 0.016\%$ to the one of the silicon sensors themselves ($x/X_0 = 0.34\%$), therefore adding only marginally to the total material budget.

Each CF tube carries 20 l/min at -10°C of air flow. The resulting flow velocity distribution (of ≥ 3 m/s) on the innermost silicon sensors in the 'toy-model' is shown in Fig. 2. The corresponding sensor temperature profile is shown in Fig. 3 with the maximum sensor temperature of -4.9°C .

The same design of the perforated CF-tubes works for both stations, thereby ensuring redundancy and simplification of the eventual detector integration procedure. Please note that also studies on ladder vibrations under air flow, and the subsequent effects on tracking performance are ongoing.

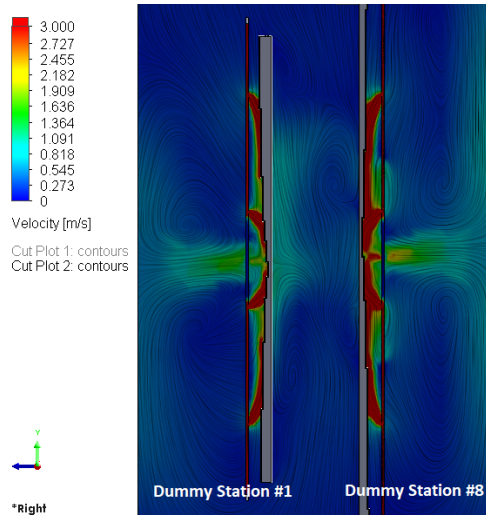


Figure 2: Cross-sectional flow profile.

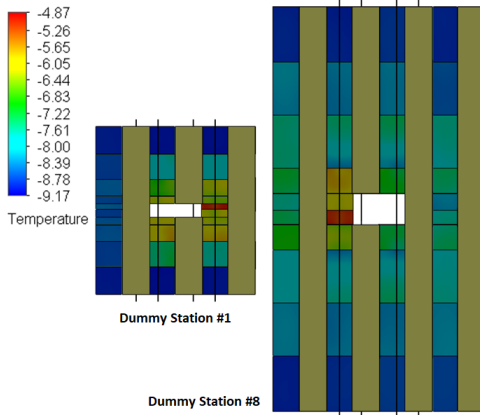


Figure 3: Sensor temperature distribution.

Manufacturing and Testing of CF Tubes

Based on the design obtained from the CFD simulations, one metre long CF tubes were successfully manufactured by ICM Composites³, thereby establishing the commercial manufacturability of tubes with such thin shell thickness (200 μm) and holes along the tube length (Fig. 4).

A CF tube's lateral displacement or bending at the centre was studied under the ladder metrology setup [5] (Fig. 5) to check its mechanical stability under air flow. Please note that the displacement (marked as Δy in Fig. 6) is expectedly observed in the opposite direction of air flow (shown as blue arrows in Fig. 6). At the nominal flow of 20 l/min, the tube displacement is 350 μm and tube vibration observed visually with the metrology table's camera is less than 50 μm (shown as error bars).

³ICM Composites, Weiterstadt, Germany, www.icm-composites.de

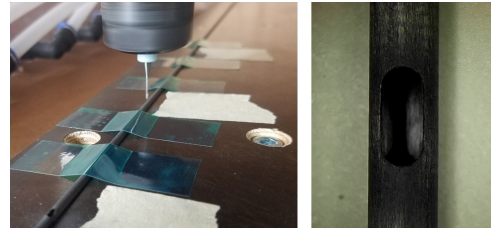


Figure 4: CF tube manufacturing process.

So their cooling performance will be tested experimentally in a dedicated thermal demonstrator [6].

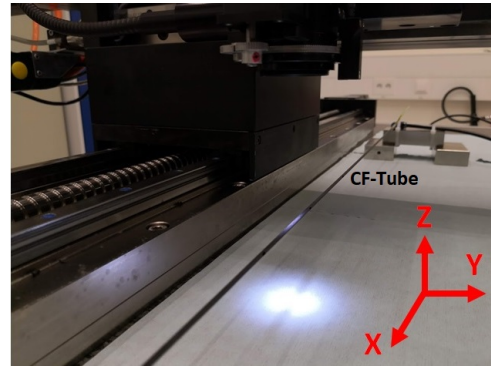


Figure 5: A CF tube under mechanical tests.

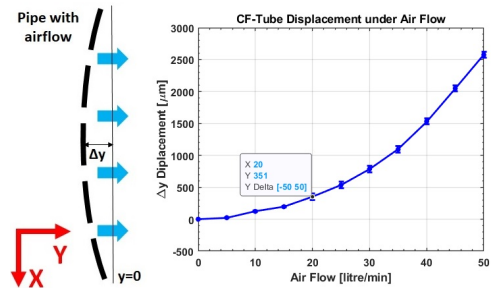


Figure 6: CF tube displacement under air flow.

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Status of STS module assembly at GSI

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Through the assembly of 25 STS-modules for mCBM we encountered and resolved several problems in the assembly that are related to the ASICs, the glob top, the micro-cables, quality control (QC) measurements as well as handling steps. We have optimized the order of assembly steps, changed the Globtop and dedicated tools were designed.

Assembly workflow

In principle, the workflow (laid out in Fig. 1) consists of five main steps that are subdivided in more detailed working instructions. The aim is to reduce handling steps to a minimum to avoid damages. Electrical QC measurements should be possible after wire- and TAB-bonding and finally the order of steps should generate a good yield.

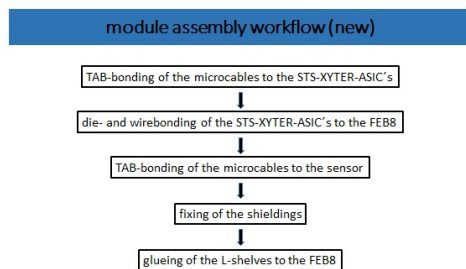


Figure 1: Workflow for the STS-module-assembly.

At first, the microcables are TAB-bonded to the STS-XYTER ASICs. After having been tested successfully these chipcables are die- and wirebonded to the two types of the front-end-board for a module. After wirebonding the ASIC-rows are tested, then protected with globtop. The third step is the TAB-bonding of the microcables to the sensor. This stage of module assembly is shown in Fig. 2. Next after the connectivity test is the fixing of the shieldings to both sides of the module. Finally the FEB8s are glued to the cooling fins of the FEB-box with thermally conductive but electrically insulating glue. This order of steps allows to reject and replace defect components like chipcables and front-end-boards with problematic ASICs.

Assembly fixtures

Due to the sensitive and thin micro-cables and the manageable amount of modules automated procedures are not a feasible option. To ease and accelerate the assembly procedures, dedicated fixtures have been developed.



Figure 2: STS-module with largest sensor.

The bottom part of the universal TAB-bonding-fixture (Fig. 3) serves as a vacuum holder for the ASICs and sensors. The upper part fixes the micro-cable with vacuum and allows their fine-alignment with micro-positioners.

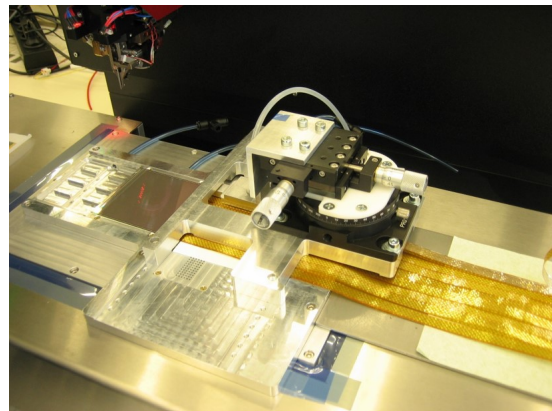


Figure 3: TAB-bonding fixture.

The fixture for ASIC diebonding (Fig. 4) holds the ASICs for one row with vacuum and places them accurately with micropositioners. A testfan cutting tool shall help to remove the testfan at the sensor side of the micro-cable precisely without damaging outer traces and the bonding area.

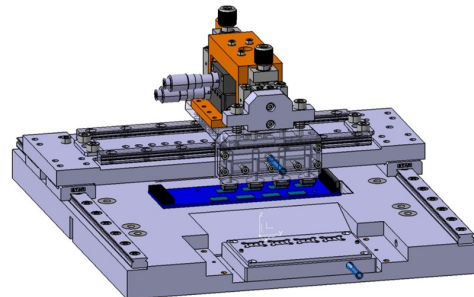


Figure 4: Fixture for ASIC diebonding.

Status of STS module assembly at JINR

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Module assembly is the most time consuming and delicate procedure of the STS detector construction. It comprises TAB-, die- and wire-bonding procedures, as well as alignment, gluing and QA control. In this section, the progress achieved for the assembly workflow and QA developments at JINR assembly site is reported ¹.

The STS detector-grade module is defined as a module, which has less than 1.5% of non-operating channels. The loss of channels during the assembly may be caused by two main reasons. The first one is a bad quality of the bonding, the second is an electrostatic discharge (ESD) which may destroy the input channel of the ASIC. Bonding parameters strongly depend on the width of rgw bonding pads of the micro-cables. The optical inspection of the bonding zone of each micro-cable is performed to guarantee that the variation of the bonding pad width does not exceed the limits. Cleanliness of the die surface also plays important role for the bonding quality. That is why a cleansing of the ASICs was introduced before the TAB-bonding of micro-cables to the STS-XYTER ASICs. Ultrasonic cleansing is performed in two steps: First in 71IPA engineered fluid and then in deionized water. The bonding parameters depend also on the temperature and humidity of the environment. Therefore, the environmental parameters should be stable during the whole assembly workflow. Before the wire and TAB-bonding procedures are carried out, QA tests are performed with the help of a pull test machine (Fig. 1). Bonding parameters are set based on the pull tests results.

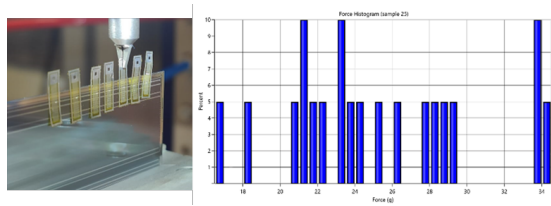


Figure 1: Pull test of TAB-bonds. Tests are performed on the test zones of the micro-cables, bonded to a dummy sensor (left); Measured pull-off force for samples with different bonding parameters (right).

After the attachment of ASICs to micro-cables, the test zone on the micro-cable is cut off. This operation is performed manually with a scalpel and is potentially dangerous in terms of ESD. After the assembly of first modules, up to 10% of channels were destroyed at that step. To overcome this issue, one should avoid using of triboelectric ma-

terials, such as teflon substrates during the operation. Special attention should be also paid to the ESD protection of the personnel.

After each step of the assembly, dedicated quality assurance tests are performed and the test results are stored. Special software was developed to store the bonding quality data [1]. Tests performed with a Pogo-pin test circuit are based on the noise-per-channel measurements after each step of the assembly. In case of good bond, the channel noise increases due to higher inter-channel capacitance. If the channel is destroyed, the program shows zero noise level which reflects absence of the signal from that particular channel. A graphical user interface (GUI) of the test software is shown in Fig. 2.

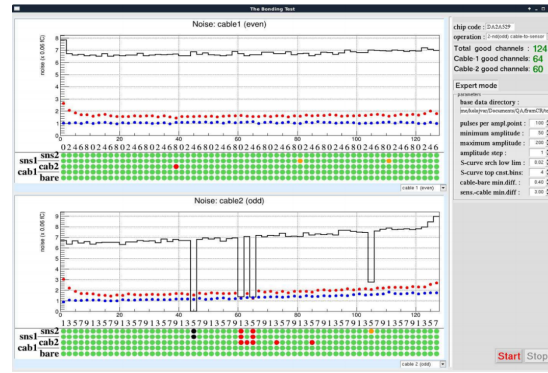


Figure 2: GUI: bonding of a microcable to a $62 \times 22 \text{ mm}^2$ sensor. The red dots in the noise histogram stand for noise values of the cable bonded only to an ASIC, the blue dots correspond to noise of a “bare” ASIC.

The most recent three modules assembled at JINR have 0.5-1% of randomly distributed not operable channels per side. The developed workflow allows to assemble the detector-grade modules. However, yields and production capacity still to be estimated.

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¹Work supported by RFBR grants 18-02-40047 and 18-02-40113.

Setting up STS module production at KIT

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The Karlsruhe Institute of Technology (KIT) is one of the production centers for the STS detector modules for the CBM experiment. KIT is supposed to assemble about one-third of the modules for the detector, summing up to about 500 modules comprising 500 sensors, 1000 front-end read-out boards, 4000 STS-XYTER read-out chips, and 8000 aluminum micro-cables. The sensors and the dies will be tab-bonded to the micro-cables. The front-end boards (FEB) will be mounted to cooling support structures and the micro-cables covered with a specific noise shielding material. During the detector production phase within a period lasting from May 2021 to about December 2023. After the R&D development phase for an alternative copper cable module [1] in the mid of 2020, KIT started with the set-up of the production steps for the STS detector modules with aluminum cables by the production of five mechanical dummy modules. This paper describes the current preparation status for the module production for the STS detector.

Assembly of Al-cable modules

The development of the assembly sequence for the modules built up with aluminum micro-cables was optimized in the year 2020. The production starts with the provision of known-good material to KIT by GSI. KIT starts with the cleaning of the FEBs and the die and wire-bonding of the LDOs to the FEB. After an initial electrical test, the wire-bonds of the LDOs are protected with a glob-top material. In parallel, the STS-XYTER chips are tab-bonded to two aluminum micro-cables. The tab-bond process is sequentially executed: After bonding and testing the first cable, its tab-bonds are protected by a polymer. The process is repeated for the second cable and results in a complete chip-cable. The test-fans, which are used to contact the pogo-pin tester, are cut-off with a newly designed test-fan cutter. The cutting process requires the positioning of three blades with an accuracy of less than 15 micro-meters concerning the cutting-position in the micro-meter range. Hence, the test-fan location can be adjusted relative to the blades by an X-Y- Θ micro-meter stage (see Fig. 1).

Four of these chip-cables are attached in parallel to the FEB by a specifically developed “Chip-Cable to FEB Mounter” (CC2FM), as depicted in Fig. 2. The STS-XYTER chips are precisely positioned on a mechanical tray defining the position on the FEB. They are picked up, the FEB with the pre-applied conductive glue is placed on the mechanical jig and the dies are lowered onto the FEB. The CC2FM is placed on a heater, which is used to cure the conductive glue. The enlarged image on the lower right of

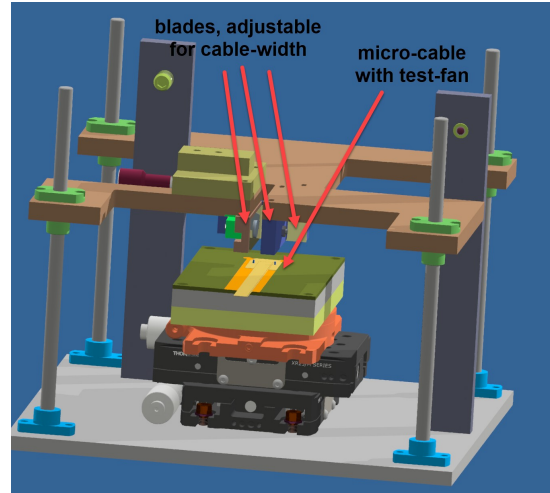


Figure 1: Construction of the test-fan cutter.

Fig. 2 shows a detailed view of the chip-cables before the placement on the FEB. The STS-XYTER wire-bond connections to the FEB are established and protected by glob top. This production step is repeated for the second row of chip cables and the second FEB of the module’s n-side. Additionally, a first shielding layer protecting the first row of STS-XYTER chips is attached to the FEBs.

In the next assembly step the loose cable-ends are bonded to the n- and p-side of the sensor. The electrical connectivity is checked once again before the tab-bonds are protected by epoxy glue.

Towards start of production

KIT built up five test modules to practice the production steps and to identify gaps in the production flow. Next to some missing test equipment, a further wire bonder machine needs to be installed. Additionally, new modules with the new versions of the STS-XYTER and LDOs will be built up to train the people and ramp up the production figures until the start of production in May 2021.

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- [1] P. Pfister et al., *Development and Characterization of a novel high-density interconnection technology for the CBM Silicon Tracking System at Fair*, Helmholtz Program “Matter and Technologies”, Annual Meeting, 1-3 February 2021, <https://indico.desy.de/event/28053/>

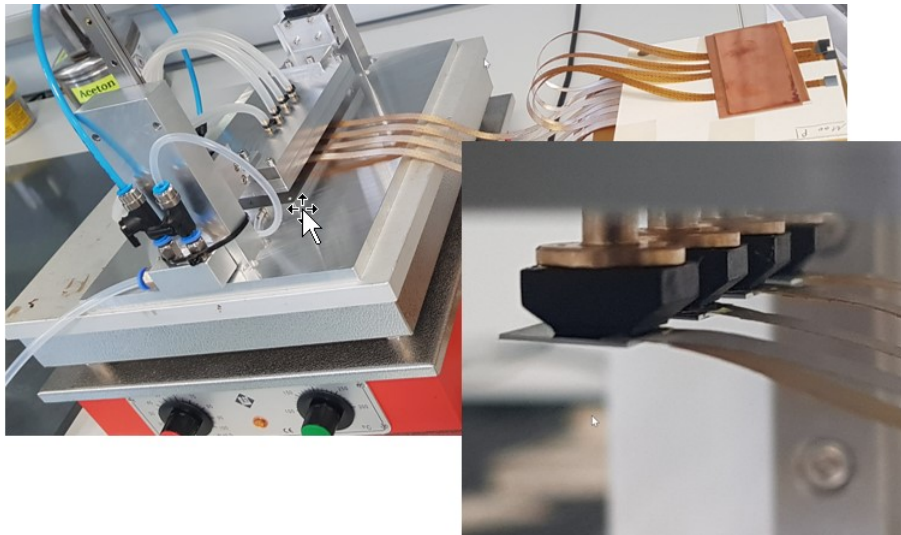


Figure 2: Chip-Cable to FEB Mounter.

Test and characterization of fully assembled STS modules

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The assembly of the detector modules is a crucial step towards the realization of the STS. Before installation in the ladder, a set of tests to evaluate the modules performance is carried out. The tests include to check the ASIC calibration in terms of ADC gain and threshold uniformity, as well to evaluate the noise performance and to check the number of broken channels [1]. Over the last year, a total of 11 modules were tested and characterized in the STS lab. From the total, 9 of them were produced by GSI detector lab, using sensors with different sizes and some of the longest micro-cables (larger than 40 cm). Further details on the tests and characterization of the modules are given below.

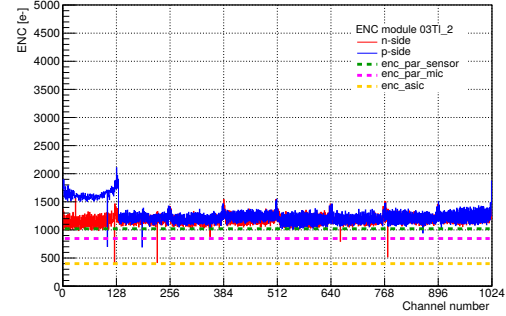


Figure 1: ENC distribution for module 03TL2.

Module test setup

A dedicated setup has been assembled to carry out the module tests with a fully biased sensor. It consists of a light-tight aluminum box, which also acts as shield from the electromagnetic environment in the laboratory. In addition, the box is equipped with a water cooling system to remove the heat dissipated by the FEB-8. The FEBs are connected with flexible flat cables to a common readout board (C-ROB), where data are aggregated and transported via a high-speed optical link to the data processing board, implemented in an FPGA based (AFCK) board.

In the modules performance, not only a low noise is required, but also homogeneity in channels response. The ADC gain and the threshold spread are among the parameters that indicate a good homogeneity. Their distributions across all the channels for the module 03TL2 are shown in Fig. 2.

Modules performance

For every module, operating parameters such as writing/reading configuration values, current consumption and overall system noise are investigated. During operation, the sensor is biased symmetrically at 150 V and analog signals are read out from 1024 channels on each side. A dedicated calibration procedure [2] is then carried out in order to improve the linearity of the ADC and to reduce the dispersion among the channels response in the module. The overall noise performance is evaluated for both sides in each module. An example of the distribution across all channels for the module 03TL2 is illustrated in Fig. 1. The measured ENC noise should be compared to the green dashed line which represents the simulated noise for the full module.

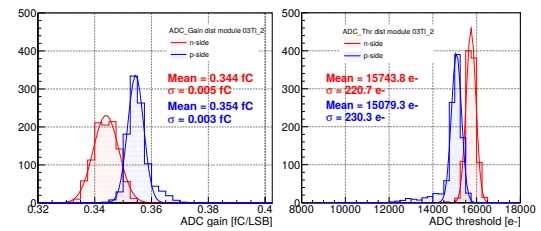


Figure 2: ADC gain (left) and threshold distribution (right) across all the channels for module 03TL2.

For operation over long periods of time, a reliable detector performance at different operational voltages, together with its stability in time are considered important parameters. Figure 3 shows the results of a bias voltage scan performed for several ASICs of the module 03TL2.

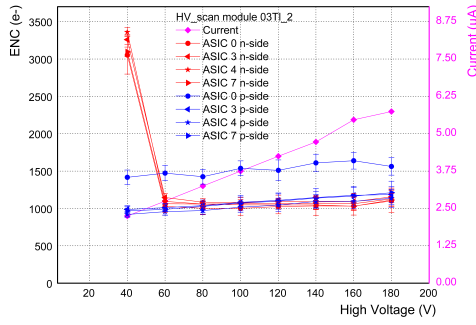


Figure 3: Noise as a function of the high voltage for different ASICs in module 03T1.2.

It can be noticed the low values of the noise for the P-side ASICs starting at low operational voltages as expected. On the contrary, the N-side show large noise values below the full depletion voltage, which can be estimated around 60 volts.

Long term stability test studies the noise over time for the ASICs and contributes to identify sources of problems that could be difficult to find during short running periods. An example for one of the ASICs of module 03T1.2 is shown in Fig. 4. Noise measurements were taken in each ASIC every 40 minutes during 5 continuous days.

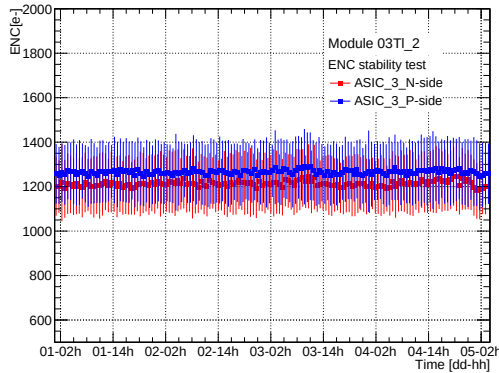


Figure 4: Overall noise results measured for one ASIC of the module 03T1.2 in a long term stability test.

Statistics and test experiences

Module assembly and testing provides invaluable experience in handling and operating modules. The iterative development of QA procedures for the testing is an important step in order to improve the modules assembly. Table 1 summarizes some of the most important parameters that help to characterize the modules in terms of performance. For each module side the noise was calculated as the average amount all channels, the errors correspond to

the standard deviation. The high amount of broken channels, present in some modules, is mostly related to non operational ASICs.

The broken channels statistics are a strong argument to compare the production yield. A full comparison of the amount of broken channels for N and P side, and for odd and even channels is shown in Fig. 5.

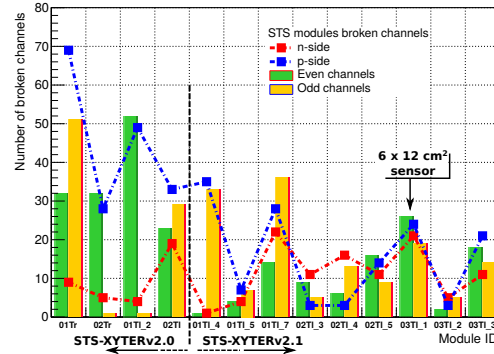


Figure 5: Broken channels distribution for all tested modules.

Significant improvements in the yield of broken channels can be observed towards the most recently produces modules. By comparing the absolute noise level measured in every channel, it is also possible to identify the component where problem occurred. From the overall statistics, 13% of the broken channels can be related to bonding issues on the ASIC side, while a 30% shows no analog response and the rest is associated with problems on the traces of the microcables or the bonding at the sensor side.

References

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- [2] A. Rodriguez Rodriguez and J. Lehnert, *STS-XYTERv2 ASIC calibration procedures for ADC and FAST discriminator*, CBM Progress Report 2017, 27

Table 1: Statistics on module performance.

Module	Side	Sensor length (cm)	Microcable length (cm)	ENC (e^-)	Gain (fC/LSB)	Threshold spread (e^-)	Broken channels
01Tl_4	n	6.2	49	1750 ± 169	0.33	220	1
	p			1690 ± 187	0.35	292	65
01Tl_5	n	6.2	49	1333 ± 152	0.34	223	132
	p			1360 ± 161	0.35	234	6
01Tl_7	n	6.2	49	1476 ± 512	0.34	778	33
	p			1455 ± 559	0.31	304	28
02Tl_3	n	6.2	45	1647 ± 199	0.33	290	7
	p			1622 ± 415	0.35	215	3
02Tl_4	n	6.2	45	1584 ± 327	0.32	281	19
	p			1547 ± 412	0.30	1074	4
02Tl_5	n	6.2	45	1212 ± 119	0.33	417	11
	p			1181 ± 142	0.31	337	14
03Tl_1	n	12.4	42	1627 ± 160	0.34	273	21
	p			1689 ± 212	0.35	348	26
03Tl_2	n	6.2	42	1183 ± 79	0.34	221	18
	p			1217 ± 93	0.35	230	8
03Tl_3	n	6.2	42	1161 ± 94	0.34	225	11
	p			1070 ± 90	0.30	265	21

Characterization of the thermal interface between front-end electronics boards and cooling fins of STS modules

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In the assembly of a STS module, the final step of module building is the attachment of front-end electronics boards (FEBs) to T-shaped aluminium cooling fins before transferring the module onto the detector ladder. There are various possibilities to choose the thermal interface materials (TIMs) between the FEBs and the fins: Thermally conductive ones like thermal pads, glues, tapes etc. Since the nominal power dissipation per FEB is up to 7 W, optimising the interface material as per the requirements is very important.

To be accepted as a possible candidate, there are certain specifications for the TIMs as per the requirements of the STS module. There should be a permanent joint between the FEBs and fins with thickness not more than 150 μm . It should have good thermal conductivity ($> 1 \text{ W/m}\cdot\text{K}$) with high dielectric strength ($> 5 \text{ kV/mm}$). One of the crucial parameters for TIM is that it should be able to compensate for any thermal stresses that might occur due to the mismatch in the thermal expansion coefficients between FEBs and T-fins (copper–aluminum). Also, the radiation hardness should be up to 1 MRad.

On the basis of above mentioned requirements and learnings from other experiments [1], three different glue candidates were shortlisted: Stycast 2850FT (with 23 LV Catalyst) [2], Dowsil SE4445 [3], and Bergquist EA1805 [4]. The main goal is to choose the best amongst them which could be used as the baseline solution for the last step of the STS module assembly. Various properties of the glue candidates are listed in Table 1. In this report, the results of thermal and mechanical properties for the glue candidates are summarised along with the gluing applications.

Table 1: Properties of different glues to be tested for TIMs between the FEBs and T-fins.

Product	Thermal Cond. [W/m.K]	Dielectric Strength [kV/mm]	Oper. Temp. [°C]	Viscosity [Pa.s]	Curing @ 25°C [hrs]	Hardness [Shore-D]	Thermal Exp. [ppm]	Radiation Hardness
Stycast 2850FT (+23LV)	1.02	14.8	-65 ... 105	5.6	16 – 24	92	39.4	$8 \times 10^{15} \text{ n}_{\text{eq}}/\text{cm}^2$
Dowsil SE4445	1.34	5.0	-45 ... 150	15.0	24+	N/A	N/A	10 MGy
Bergquist EA1805	1.80	10.0	-40 ... 125	60.0	10	90	N/A	N/A

Thermal stress

The targeted operating temperature for STS front end electronics is -10°C and it is important to test the interface at this temperature to ensure that it is able to tolerate the mismatch between the FEB back plane (copper) and T-fins (aluminium) at nominal power dissipation of 7 W per FEB. The mismatch in CTE could lead to different failure scenarios: large mechanical stresses could deteriorate the functioning of the ASICs which could result in low shear strengths or overheating of ASICs.

The long-term weakening of glue joints caused by repeated temperature changes was investigated in a home made climate chamber. The performance of the selected candidates was tested thermally, different samples were prepared using thermal dummy FEBs which were glued on the T-fins (Fig. 1). These T-fins were screwed on the cooling plate in which circulated a coolant fluid to regulate the temperature of the FEBs during the cycling. Each sample was subjected to thermal cycling and 25 of such cycles were performed with 6 hours duration per cycle between $T = -15^\circ\text{C}$ to $+40^\circ\text{C}$, under conditions of controlled relative humidity. The temperature was kept constant at the extreme temperatures for 2 hours.

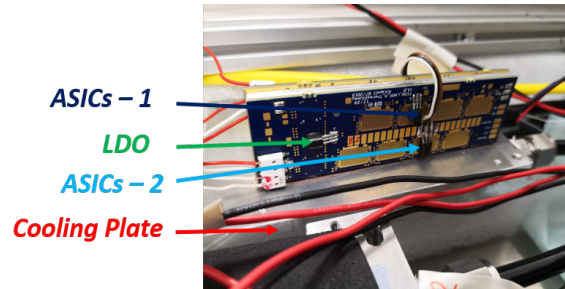


Figure 1: Thermal dummy FEBs glued to the T-shaped aluminium fins.

The observables were the maximum temperature differences in the ASICs and LDO regulators with respect to the cooling plate, and whether thermal stresses deteriorated the glue joint over the multiple cycles. Since power density for LDOs is much higher than that of the STS-XYTER ASICs, the temperature difference between the LDOs and the cooling plate for each FEB was considered at the maximum and minimum temperature as the observables (Fig. 2).

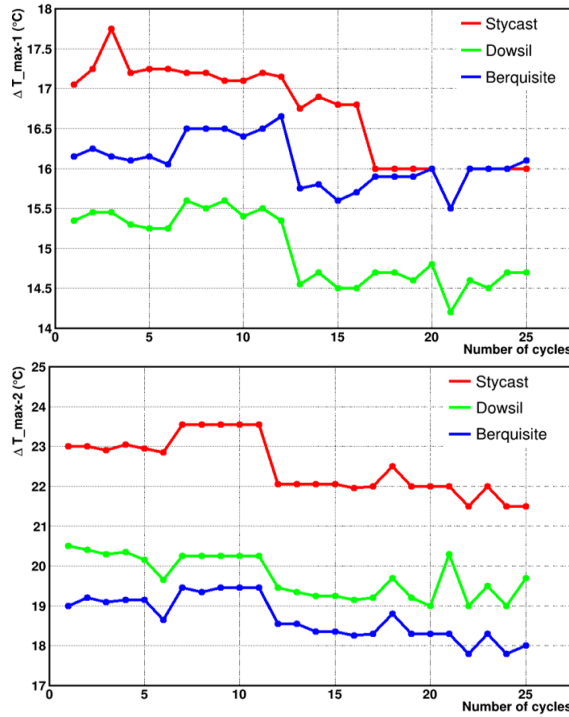


Figure 2: Temperature difference between LDOs and cooling plate at $\Delta T_{max-1} = 40^\circ\text{C}$ and at $\Delta T_{max-2} = -15^\circ\text{C}$ for 25 cycles.

The temperature difference for the extreme temperatures over 25 cycles is shown in Fig. 2. From the plots, it is evident that no deterioration in any of the samples was observed after 25 cycles. This indicates that all the glues are suitable to be used as TIMs when it comes to the thermal properties.

Lap shear stress

In order to measure the mechanical properties of different glues, a shear test was performed using a Instron pull tester [5]. The samples were prepared separately and a lap joint was made between copper clad FR4 sheets and aluminium for the different glue candidates. The shear stress was applied to the sample in such a way that the bottom part was held fixed and the other part was allowed to move under the influence of the external force.

For each glue, 8 samples were prepared, out of which 4 were kept in a climate chamber to undergo cycling from -40 to $+40^\circ\text{C}$ by keeping the samples at each extremes for one hour. Lap shear test were performed before and after the thermal cycling in order to determine possible impacts of the thermal cycling on the glue joints.

The main concern to perform the shear test was to experimentally observe the extension and how much load is required to acquire certain extension. Table 2 summarises the load for 0.1 mm extension and the minimum load to break off the glue joints, before and after the thermal cy-

Table 2: Results of lap shear test for the glue candidates before and after the thermal cycling.

Product	Before Thermal Cycling		After Thermal Cycling	
	Load for 0.1 mm Extension [kPa]	Break-Off Load [kPa]	Load for 0.1 mm Extension [kPa]	Break-Off Load [kPa]
Stycast 2850FT (+23LV)	14.80	577.60	10.08	519.20
Dowsil SE4445	7.20	23.00	4.62	19.36
Bergquist EA1805	18.10	517.80	12.42	472.45

cling of the glue samples. When it comes to the comparison between the three glues with respect to lap shear strength, Stycast and Bergquisite performs better than Dowsil. For Dowsil being a soft silicon glue, the force needed to pull the samples apart is much lower as compared to the other two.

Glue applications

After testing the glue candidates thermally and mechanically, other important factor to check is how to apply the glue on the surface in such a way that there are no air bubbles trapped and it covers the maximum area under the FEB. Also, since the viscosities of all the three glues are different, the technique how to apply the glues has to be optimised accordingly keeping the thickness constant (not more than $150\ \mu\text{m}$) and without applying any extra force.

In order to get the maximum surface coverage with minimum oozing, a well defined pattern needs to be optimised with a good hold over the volume dispensed. To meet this requirement, a specialised glue dispenser was used which can control the volume. Depending on the area of the FEB, a customised pattern was designed. The first trial was made with glass sheets and Fig. 4 shows the time lapse of how the glue deposition takes place. It is clearly visible in Fig. 3

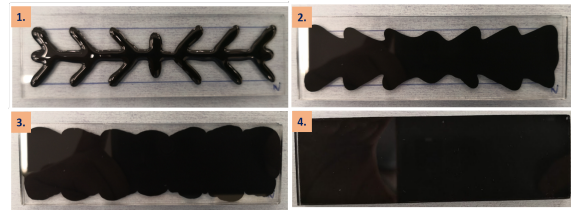


Figure 3: Time lapse for the glue deposition for stycast over 24 hours.

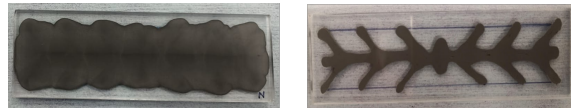


Figure 4: Glue deposition for Dowsil and Bergquisite after 24 hours.

that capillary action works nicely for Stycast because of its low viscosity and almost the whole surface is covered. On

the contrary because of higher viscosities of Dowsil and Bergquisite, capillary action did not work nicely and for Bergquisite some external force is needed to get the full coverage of the surface as shown in Fig. 4.

After obtaining good results with the glueing pattern on the glass sheets, the pattern was tried on real modules to understand the pros and cons while handling the modules. Figure 5 shows the different glueing steps involved while glueing FEBs to the fins. After 24 hours, minor oozing was observed on the surfaces but that is not crucial as it ensures that almost the whole surface was covered with glue. Since this process is to be repeated for numerous number of times, a glueing tool is under production to reduce the human errors and semi-automatise the process.

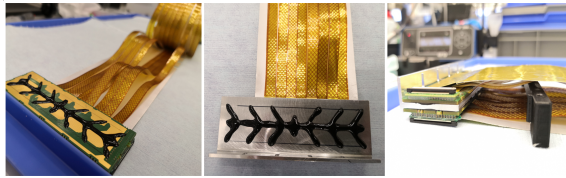


Figure 5: Steps showing glue deposition on the FEBs and t-fins with the STS module.

Conclusion

Given that the nominal power dissipation per FEB is up to 7 W over an area of $10.3 \times 3.06 \text{ cm}^2$, to optimise the thermal interface between FEBs and T-fins is crucial. From the tests performed so far, Stycast came out best as it stands for the thermal and mechanical properties of the glue. Low viscosity of Stycast makes the capillary action to work nicely over the surface without applying any external force which might be harmful for the electronics on FEB. Further study for Stycast is still ongoing like electrical and radiation hardness tests to make sure that it is the suitable candidate to be used as the last step of the module assembly.

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Integration of mSTS Unit 3 and evaluation of ladder operation performance

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Mini-STs (mSTS) is a part of the project mCBM at SIS-18 [1]. Two detector layers consisting of silicon microstrip sensor modules will measure the reaction products from the interaction of a heavy-ion beam (Ag) with a target (Au), at intensities up to 10^8 ions/s and collision rates up to 10 MHz. The detector stations are arranged in four mechanical units (“C-frames”) that carry the detector ladders, including front-end electronics, as well as readout boards, power boards and cooling infrastructure (Fig. 1). The commissioning of the first unit has validated the assembly concept and yielded detailed information on the detector performance [2].

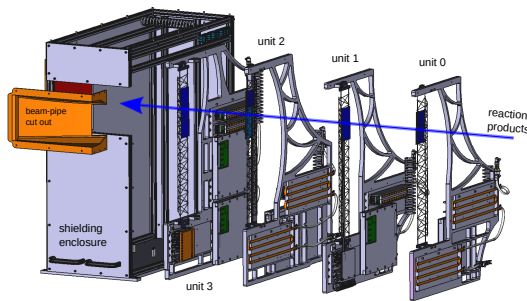


Figure 1: Composition of the mSTS setup. Four mechanical units make up two detector layers.

A ladder with three modules, each featuring a $6 \times 6 \text{ cm}^2$ microstrip sensor, has been assembled as a step towards completion of the mSTS detector. The shielding layers of these modules have been made wider than the sensor and its microcable stack in an attempt to improve noise performance for the outer channels. Additionally, a complementary ladder with narrow shields has been assembled. Exchanging the two ladders will enable the comparison in terms of noise and possible effect of parallel operation of the neighbouring modules within a ladder.

The integration steps for the U3 unit are shown in Fig. 3. They include mounting of the readout boards (cROBs) in shielded enclosures, high and low voltage cabling for the front-end electronics, installation of the circuit to provide a signal return path for every detector module and routing of the data cables between the front-end boards and cROBs. The low voltage lines were made using flat cables with 0.3 mm^2 cross section of individual strands. High voltage has been provided over shielded coaxial cables whereas cable shields have been connected to the enclosure (detector ground). In order to provide the return path for the signal,

FEB grounds on the p - and n -sides have been connected with two capacitors in series and with their center tap connected to the detector ground. To protect the sensitive analog lines from transients in the digital electronics, the data cables have been routed far away from the LV/HV lines and shielded. Their shields have been referenced to the ground of the cROBs.

The noise performance of module 03TI-2 is shown in Fig. 2. Uniform response over 1024 channels on both sensor sides at the level of 1 ke has been achieved, matching the expected model value. The elevated noise level in the first 134 channels of the p -side is related to the “zig-zag” strips connected via second metallization layer that effectively increases the strip length and consequently the capacitive load presented to the input of the front-end electronics.

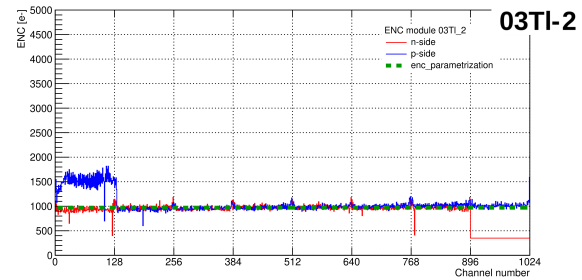


Figure 2: Noise performance of the detector module 03TI-2 after the assembly of the U3 C-frame.

The setup showed mostly satisfying performance and provided valuable experience with integration techniques needed for further detector production.

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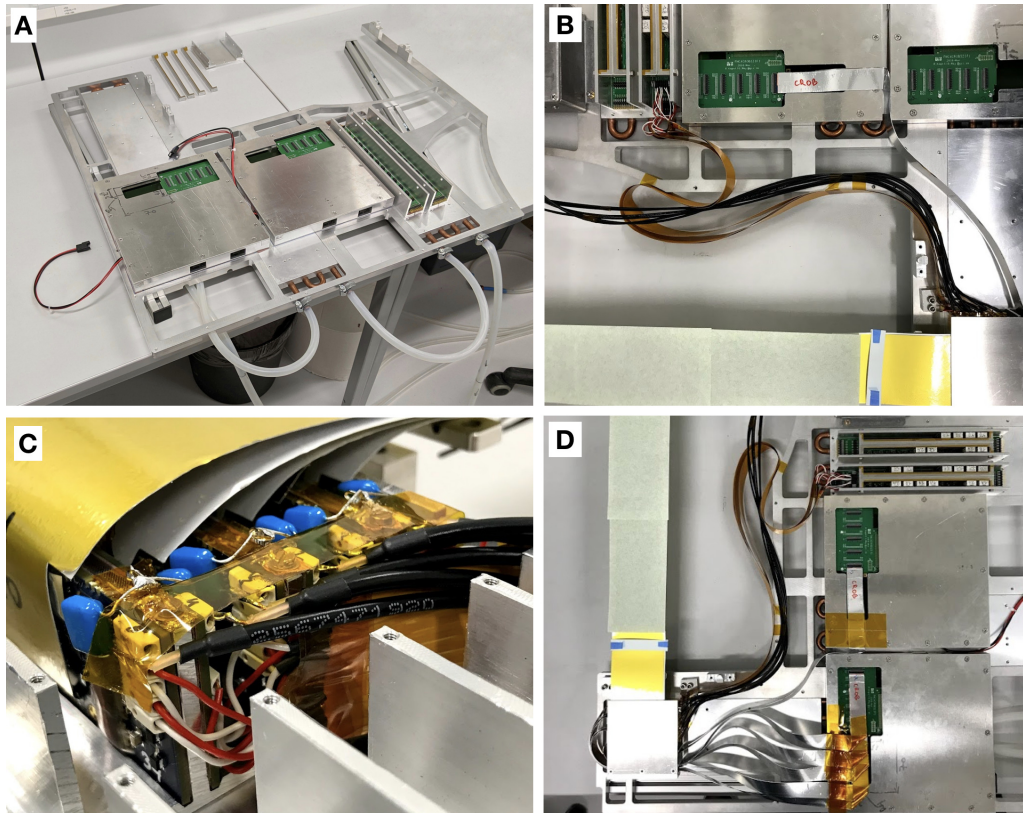


Figure 3: Integration steps of the U3 C-frame: (A) mounting of cROBs onto the C-frame, (B) HV/LV cabling, (C) connection of services and return path circuit, (D) arrangement of the data cables between FEBs and readout boards.

Performance studies of prototype STS modules

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In this contribution we report on the operation and functional validation of a prototype detector module for the CBM Silicon Tracking System, fully integrated and equipped with the complete front-end electronics to read out all sensor channels, based on various laboratory and beam tests carried out with high-intensity proton beams at COSY, Research Center Jülich, in November 2019, which was already discussed in [1], as well as in the mCBM setup operational since 2018 at SIS18. The results shown below contributed to concluding the Engineering Design Review in December 2020 and will give important input to the CBM module series production readiness procedure.

Operation of single modules

The procedure to bring a single module in operation starts with the test of each fully assembled module before integrating it into a ladder. This is done in the so-called *Module Test Box*, a precursor for the module QA setup, which comprises of a shielded enclosure as well as all services: LV, HV, readout, FEB cooling-module, where the module is mounted in *close-to-final* positioning. The setup can flexibly adapt to all module sizes. It also has a window which can be used for measurements with sources.

During the test, different aspects of the module operation are evaluated, including: FEE functional verification, signal path connectivity, sensor HV biasing, charge calibration, module noise performance, signal processing and calibration, sensor response, sensor I-V characteristics.

Operational Performance

The most challenging scenario to test the operational performance of the STS modules is the heavy ion beam-time with miniCBM. The “miniCBM” (mCBM) demonstrator experiment is operational at GSI/SIS-18 since 2018. It mimics CBM operation conditions with beam intensities up to 10^8 heavy ions/s and collision rates up to 10 MHz.

Two mCBM beam campaigns took place, the first one started in November/December 2018 and continued in March 2019 with ^{108}Ag at 1.2 and 1.58 AGeV; the second one started in November 2019 and continued in the period March-May 2020 with ^{40}Ar at 1.7 AGeV and ^{206}Pb at 1.06 and 1.075 AGeV. We used two different Au targets of 1% and 10% interaction probability.

The mCBM setup does not include a magnetic field. The setup comprises of various other detector components, small-size prototypes of the final CBM detectors, including a T0 diamond reference detector.

The mSTS system operated in the 2019-2020 campaign comprised of 2 sensors equipped with 4 FEBs (2 x FEB8-1 v. A2, 2 x FEB8-1 v. B1), with all 32 ASICs operational. We achieved a reliable long term operation, with the systems switched on continuously 47 days: LV and HV bias continuously on after the start-up phase, and synchronous data transfer permanently active. Over this period we alternated few shifts with beam and frequent test runs with the detector in stable operation: e.g. no resynchronization was needed for 136 h.

The achieved STS data rates were up to 800 MB/s, which corresponds to an average of 6.25 Mhits/ASIC/s (close to the limit of 10 Mhits/s/ASIC in the available FEB8-1 readout). We note that this rate is dominated by delta electrons, whose contribution is very strong in the proximity of the target region and not suppressed by any magnetic field.

Module noise behavior

The system noise level is estimated with a *S-curve* scan: the discriminator response to a signal amplitude applied from an internal test pulser is scanned, the width of the signal distribution is an effective measurement of the overall noise. Figure 1 shows the results for all channels in both p- and n-side of one module. The targeted system noise of around 1000 e^- ENC, in agreement with an estimation based on the total detector capacitance, was measured both during detector commissioning in the assembly laboratory at GSI and in the COSY beam environment. Few unconnected channels (typically less than 1%) are recognized by a significant reduction in the noise level compared to connected ones. Some differences in the noise level between odd and even channels is also visible, as well as an increase in the ASIC edges. The significantly larger values observed in the first channels of the p-side are due to the larger capacitance of the edge strips interconnect lines on the second metallization layer.

Detector response

For the evaluation of the performance, in terms of signal-to-noise and charge collection efficiency, various tests of the prototype STS detector modules were performed.

Measurements with ^{241}Am source

The signal response of the module was studied in laboratory tests reading out the signal of a gamma emitter, specifically a non-collimated ^{241}Am gamma source, placed outside of the sensor window of the test box, which allows to

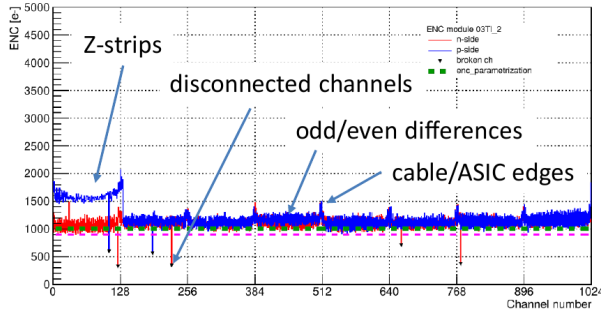


Figure 1: ENC as a function of channels for an entire module given in units of electron charge.

illuminate different locations on the sensor.

Figure 2 shows the hit rate for all the channels of the module when the source is placed centrally over the sensor. The different colours in the picture correspond to different requirements in the charge of the hits. Requiring a deposited charge larger than 2 ADC units removes most of the differences between odd and even channels, except in the edge ASICs of the p-side.

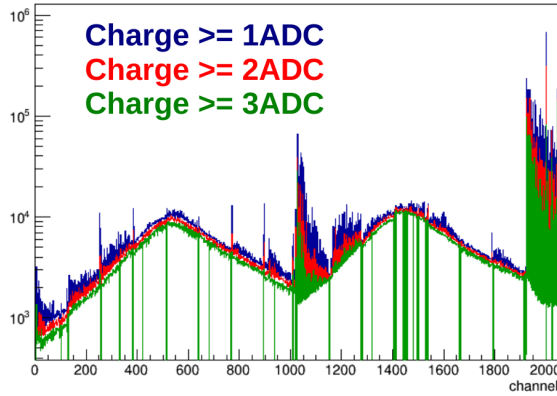


Figure 2: Hit rate for all the channels of the module(n-side: channels 0-1023, p-side:channels 1024-2047).

The resulting charge spectrum in ADC units is shown in Figure 3, where only 1 strip-cluster signals are considered. The background contribution, concentrated in the first 1-2 ADC units, is removed subtracting from the raw charge spectrum the spectrum measured in runs collected without the source. The peak corresponding to a gamma energy of 59.5 keV is visible. Different measurements were taken, varying the thresholds, which correspond to the different background-subtracted spectra, shown in the figure.

The peak position is determined by a Gaussian fit, yielding an ADC value which ranges around 10 LSB, depending upon threshold. According to the ADC transfer function for the high resolution calibration, as described in details in [2] the deposited energy can be calculated as 14592 (15877) e^- for the n (p) side.

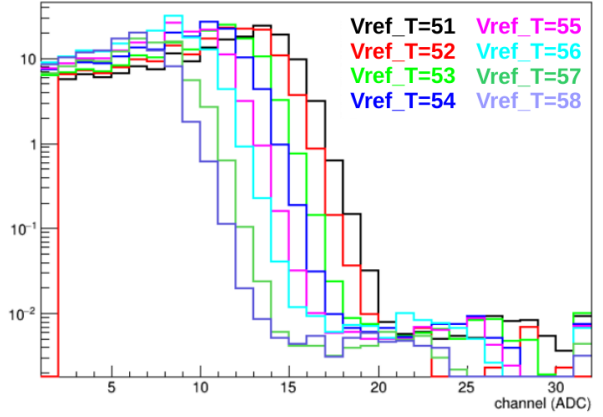


Figure 3: Gamma spectrum of a ^{241}Am source. The different curves correspond to different thresholds.

Measurements with a p-beam at COSY

We studied the system response to a p-beam with energy and momentum of $E_{\text{kin}} = 1.92 \text{ GeV}$, $p = 2.7 \text{ GeV}/c$ in a test carried out in the JESSICA cave at COSY in November 2019, under different detector configurations.

Figure 4 shows the charge spectrum in ADC units, for 1 strip-cluster signals only, for different thresholds. The background contribution is concentrated in the first 1-3 ADC units and negligible elsewhere, and it is well separated from the signal. The position of the peak corresponding to the monoenergetic proton, well visible around 7-8 LSB, is extracted fitting a Landau distribution. According to the ADC transfer function, the deposited energy can be calculated as 22282 (24829) e^- for the n (p) side.

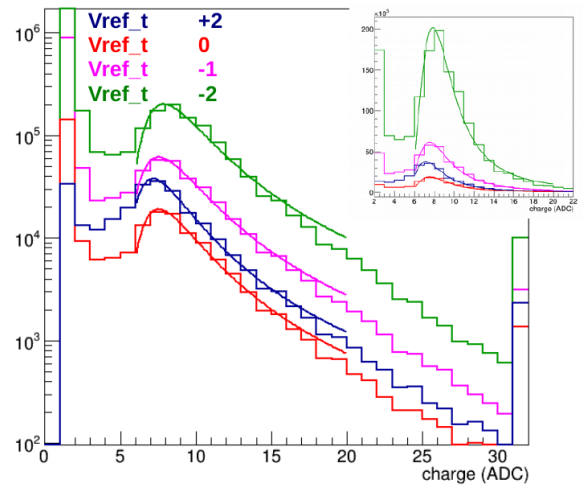


Figure 4: Charge spectrum in ADC units. Different curves correspond to different thresholds. Insert at linear scale.

Using the corresponding noise measurements, we have calculated a signal-to-noise ratio above 20 for the p-beam measurements at COSY, and around 14 for the Am-source.

In order to evaluate the charge collection efficiency, we compare the measured charge with the expected, keeping into account that the capacitance of the whole system, including sensor and microcables, effectively reduces the collected charge to $\sim 96\%$.

For a 59.5 KeV gamma emitted by the Am-source we expect $59 \text{ keV} / 3.6 \text{ eV} \sim 16400 \text{ e}^-$.

The typical signal charge for a proton of $p = 2.7 \text{ GeV}$ traversing $300 \text{ } \mu\text{m}$ of Si (density = 2.33 g/cm^3) is $1.63 \text{ MeV/g/cm}^2 \cdot 2.33 \text{ g/cm}^3 \cdot 300 \text{ } \mu\text{m} = 3.8 \text{ MeV/cm} \cdot 300 \text{ } \mu\text{m} = 380 \text{ keV/mm} \cdot 300 \text{ } \mu\text{m} = 113 \text{ keV}$. With an average energy of 3.6 eV required to create an electron-hole pair for silicon, this result in a mean number or 31,000 electrons produced and the most probable value of 22,000 electrons in the Landau distribution.

Therefore, using an average of the measurements on the p and n-side, corrected for the system capacitance, and finally compared to the expectation, we would obtain a charge collection efficiency of $\sim 96\%$ (generally higher on the p-side).

Time resolution

Time resolution is studied by correlating the signal measured by the STS with the one measured by the T0 diamond detector in mCBM. Figure 5 shows the time difference between the STS signal and the T0 signal as a function of the STS signal amplitude. An expected delay of approximately 20 ns can be seen for low amplitude signals (below 5 ADC units) compared to larger ones, in good agreement with the measured time-walk of the ASIC. For large amplitude signals, the measured sigma ($\approx 3.4 \text{ ns}$) obtained from a Gaussian fit, indicates a good time resolution achieved by the detectors. Since T0 time resolution is in the order of tens of ps, the overall resolution is dominated by the STS contribution.

Clusters are reconstructed by correlating signals from neighbouring strips. Hits are finally derived from the correlation of clusters in the p- and n-side. Figure 6 shows the time difference of signals in 2-strip cluster signals, separately for the p- and the n-side. Considering that walk correction to the signal time has not yet been applied, the plot demonstrates an excellent time resolution of few ns, in agreement with what observed above.

Space resolution

The setup used in the COSY experiment includes also two stations of a scintillating fiber hodoscope, with 64 channels per station, read-out and reconstructed together with the silicon detector. The hits from the STS module and the two hodoscope stations reconstructed in space are presented in Figure 7.

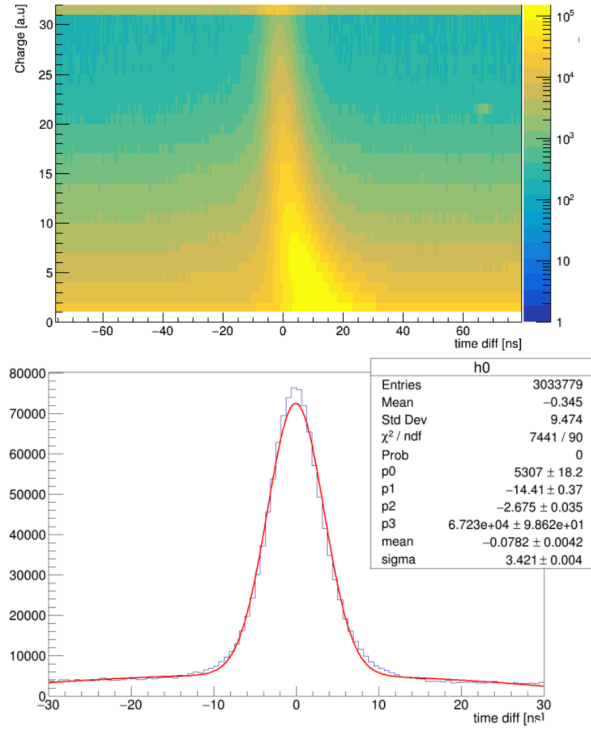


Figure 5: top: Time difference between STS signal and T0 signal as a function of the amplitude of the STS signal; bottom: Time difference between STS signal and T0 signal for amplitude larger than 20 ADC units.

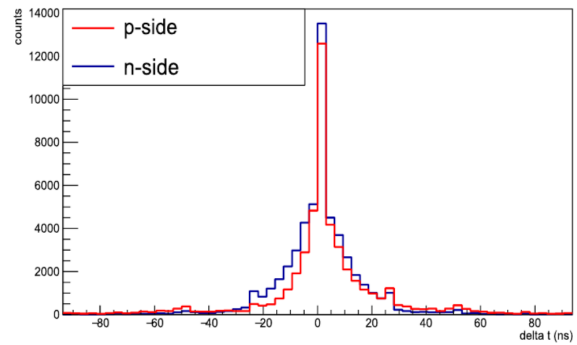


Figure 6: Time difference between two STS signals that form a cluster.

To understand the space resolution performance of the STS sensor, the coincidence with the hodoscope system has been studied, using the best time-coincidence of the correlation between the forward and the backward hodoscopes as reference, to extrapolate the expected hit position.

Figure 8 shows the position difference in X and Y between the extrapolated hit and the hit measured by the STS sensor: A sharp peak is visible on top of a broad background. The mean value is not centered at zero, since the STS sensor was not aligned with respect to the hodoscopes system. The resolution in X ($\approx 0.07 \text{ cm}$), Y ($\approx 0.03 \text{ cm}$) is

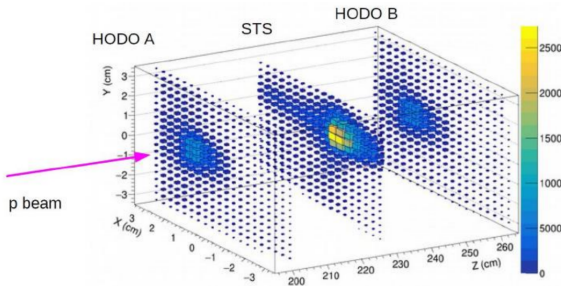


Figure 7: Reconstructed hit maps of the beam particles in the detector test system. No transverse alignment corrections have been applied yet.

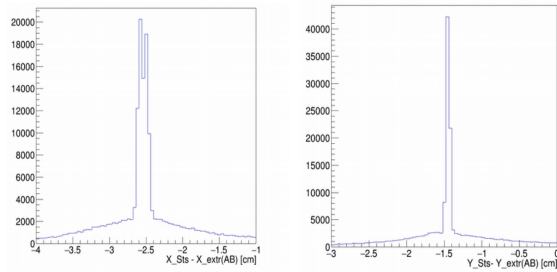


Figure 8: Residuals in space (X and Y coordinates) of straight-line tracks extrapolated from the hodoscope two-dimensional hits at the silicon detector.

narrow as expected. It is however important to note that the precision of the extrapolated signal is significantly lower than that of the sensor.

Summary

With module operation in beamtime campaigns, we have gained some experienced of the performance of the detector. Reliable long-term operation in heavy-ion test-beam was achieved. The targeted STS system noise of around $1000 e^-$ was achieved, in agreement with theoretical expectations. With only a few unconnected channels (typically less than 1%), some differences among odd/even channels are attributed to the routing of microcables and are subject to ongoing optimizations. The charge distributions show clear separation between noise and proton signal peak, obtaining a S/N ratio larger 20, and a charge collection efficiency around 96%. The beam spot reconstruction was achieved successfully. An excellent time resolution (3.4 ns) was demonstrated. The position resolution is also in line with expectations.

References

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- [2] A. Rodriguez Rodriguez, et. al, “*Verification of the STS-XYTERv2.1 energy calibration using a ^{241}Am source*”, CBM Progress Report 2020

STS ladder vibration study

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Full-length carbon fiber support structures of STS detector ladders have been prepared for a vibration study, being carried out in co-operation with G. Viehhauser, Physics Department of the University of Oxford, Great Britain, within the EU project AIDA2020 [1]. At the Physics Department, a vibration test stand had been developed for LHC experiments' tracking detector development and was made available to further interested groups (see e.g. [2]) within the above mentioned EU project.

In a first step, one of the carbon fiber structures, described in [3, 4], was fitted at its ends with bearings [5], the attaching blocks to the STS detector mechanical half-units' C-frames, and sent to Oxford (Fig. 1). There it was installed on the table of a vibration test stand as shown in the photo of Fig. 2. Visible are two capacitive probes which enable displacement measurements of selected surface regions as a result of mechanically exciting frequencies.

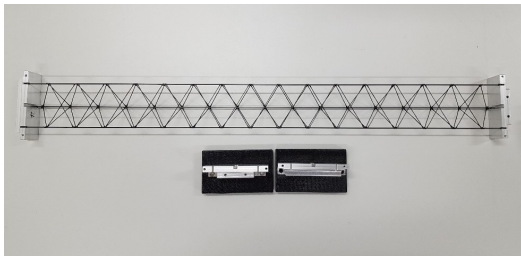


Figure 1: Carbon-fiber ladder with bearings attached, and matching counter parts.

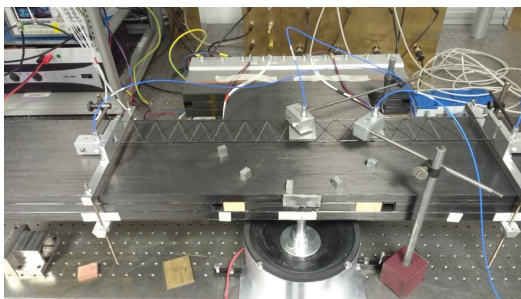


Figure 2: Ladder mounted on vibration test stand at Oxford University, fitted with capacitive probes (Photo: G. Viehhauser).

First results

First results have been obtained and are illustrated in Fig. 3 showing two main Eigenfrequencies of the ladder for the front-face and side movements.

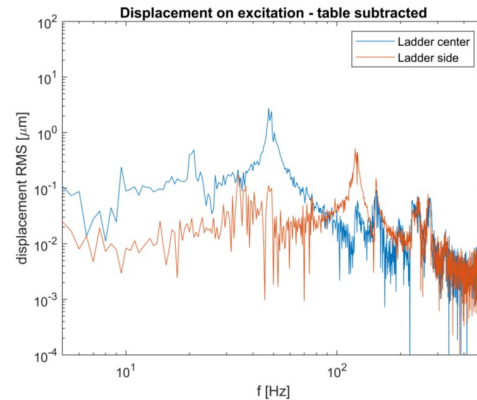


Figure 3: Excitation curves for front and side of the ladder (Measurements: G. Viehhauser).

Outlook

A further ladder, now equipped with 10 dummy modules, has been assembled and transported to Oxford where it is currently being installed on the test stand. The ladder is shown on the STS chapter's title page along with results of its components' positions in 3D space after optical metrology. The silicon sensors are real ones from the prototyping phase, fitted out with dummy microcables stretching towards the ladders' ends. The sensors, glued with L-legs to the carbon fiber frame, and the microcables will alter the stiffness of the object, which is to be studied. Yet a further ladder is being prepared, this time equipped with a low-mass perforated carbon fiber tube for blowing cooling gas onto the sensors. The resulting effect on the vibration behaviour will be also studied in 2021 with the same set-up at Oxford.

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Towards humidity and temperature monitoring of the STS

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This contribution describes the ongoing efforts related to Fibre Bragg Grating humidity and temperature sensors suitable for conditions in the STS detector. Furthermore, the aim was to establish effective methods for further calibration and testing of such sensors.

Motivation

Environmental sensors for high energy physics detector systems, especially for the application in the STS, need to meet the following requirements:

- radiation resilience at least up to 12 kGy,
- insensitivity to the magnetic field,
- repetitive and correct readout below -10°C ,
- low mass and small dimensions (few mm size),
- response to the full range of relative humidity (RH),
- long term stability.

Conventional humidity sensors do not fulfil these requirements, but Fibre Bragg Grating (FBG) or Long Period Grating (LPG) sensors are suitable for such applications [1]. Apart from the above mentioned features fibre optic sensors (FOS) can be multiplexed, and furthermore there is no additional electronic circuitry involved (apart from a readout device - optical interrogator).

Brief introduction to the FBG technology

A FBG based fibre optic sensor is formed by photoinduced modulation of the refractive index in the core of a single-mode optical fiber. Such structure in the core of the fibre acts as a wavelength selective filter, which reflects the incoming light at a certain wavelength (Bragg wavelength λ_B) [2].

$$\lambda_B = 2 n_{\text{eff}} \Lambda \quad (1)$$

The Bragg wavelength is dependent both on the refractive index n and the grating pitch Λ . The latter one can be affected by both temperature and strain, making it suitable for strain and temperature sensing applications. Thanks to the sensitivity to strain it is also possible to measure the humidity by applying a thin layer of polyimide coating ($\approx 10 \mu\text{m}$) on the cladding, what can be seen in Fig. 1 [3].

According to the literature [4] the response behavior of a polymer-coated FBG can be described as a linear superposition of relative humidity and temperature. This relation can be expressed as:

$$\frac{\Delta\lambda_B}{\lambda_B} = S_{\text{RH}}\Delta T + S_T\Delta\text{RH} \quad (2)$$

S_T and S_{RH} are the sensitivity coefficients for temperature and relative humidity respectively.

The characteristic Bragg wavelength for the sensors used in this study was $\sim 1540 \text{ nm}$ for the temperature sensor and $\sim 1527 \text{ nm}$ for the humidity sensor. As the sensors were located at $\sim 2 \text{ cm}$ from each other, the effect of cross-sensitivity of the temperature and relative humidity can be neglected.

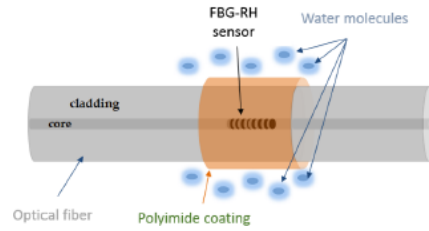


Figure 1: Structure of the FBG-coated relative humidity sensor [1].

Experimental setup

An experimental setup, which consists of climate chamber, specific humidity and/or temperature calibration standards and/or reference sensors is required to characterize and calibrate fibre optic sensors. In the second half of 2020, substantial efforts were made to establish an effective and accurate way for these studies. The sensors being the subject of this study can be seen in Fig. 2.



Figure 2: RH and T sensors in a dedicated packaging (dimensions: length 14 cm, outer diameter 1.6 mm).

To perform first measurements, a home-made climate chamber was prepared. This chamber was equipped with a Michell S8000 Precise Dewpointmeter (chilled mirror for dew point and PT1000 sensor for temperature measurements), 2 SHT85 sensors, 3 PT100 sensors, a FBG-coated humidity sensor and a FBG temperature sensor (together with optical interrogator for readout). Furthermore, to control temperature, effectively in the range of $0 - 35^\circ\text{C}$,

a Lauda Chiller was connected to the chamber. A wide range of humidity (0-75%) was achieved by using saturated sodium chloride solution and a controlled flow of nitrogen (with usage of a flow meter).

Data acquisition and control of the chiller were implemented within EPICS Input/Output Controllers [5]. As a next step all information was stored in a Redis database and monitored using Control System Studio (Phoebe).

First measurements and results

To establish the performance of a FBG-coated humidity sensor, first a humidity scan at a stable temperature of 25°C was performed. Due to the inhomogeneities of conditions inside the chamber the closest SHT85 sensor (accuracy: $RH = \pm 1.5\%$, $T = \pm 0.1^\circ\text{C}$) was chosen to compare the results. To compare absolute values, the relative humidity was converted into dew point using the Magnus Formula [6]:

$$Dp(T, RH) = \frac{\lambda \left(\ln\left(\frac{RH}{100}\right) + \frac{\beta T}{\lambda + T} \right)}{\beta - \left(\ln\left(\frac{RH}{100}\right) + \frac{\beta T}{\lambda + T} \right)} \quad (3)$$

For the temperature range -45°C to 60°C , Magnus parameters are: $\alpha = 6.112$ hPa, $\beta = 17.62$ and $\lambda = 243.12^\circ\text{C}$. This approximation leads to an error of 0.35°C [6].

Figure 3 depicts the response time and overall performance of the humidity FOS in comparison to the SHT85 sensor. These measurements show that, for example, in the range from $\sim 8^\circ\text{C}$ down to $\sim 4^\circ\text{C}$, the SHT85 sensor has response time of 78 min to reach stable readouts and for humidity FOS it is 156 min. This effect might be related to the packaging of the sensor seen in the Figure 1 or to the thickness of the coating. Nevertheless, the humidity FOS follows the readouts of the SHT85 in the entire range at 25°C .

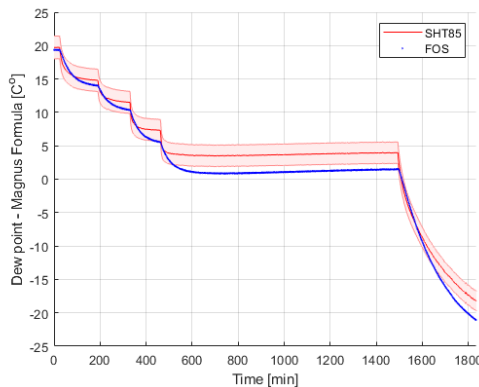


Figure 3: Comparison of dew point for the humidity FOS and SHT85 sensor at 25°C .

To establish the sensitivity of the sensor on humidity changes, measurements of the shift in Bragg wavelength in a wide humidity range at stable temperatures were performed. These results can be seen in Fig. 4. The sensor shows linear response with changing humidity at each of the chosen temperature values.

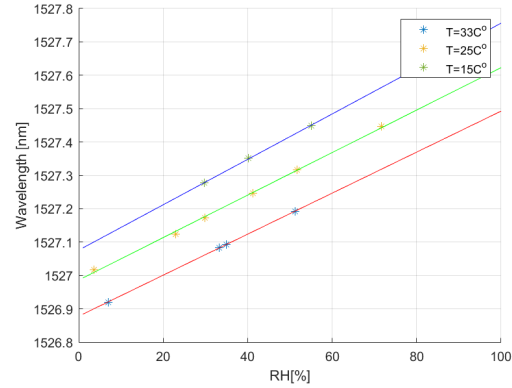


Figure 4: Characteristic curves of the humidity FOS at the three considered temperatures

Conclusions

First studies with FBG-based sensors were performed, showing correct behavior in a wide humidity range ($\sim 1\%$ to $\sim 75\%$) for different temperature values (15°C , 25°C , 33°C). These measurements featuring the in-house prepared box indicated that to achieve a homogeneous distribution of temperature and humidity, the next step is to redesign the experimental setup with the usage of an industrial climate chamber and several saturated salt solutions (LiBr , MgCl_2). Furthermore, more measurements and larger statistics (several sensors) are needed to establish the performance of such sensors down to -40°C . To address the response of the sensor, prototyping the packaging of sensors is planned. The upcoming studies should focus also on checking the sensitivity to temperature and the performance after irradiation.

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Studies of data rates in the STS detector

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For assessing the detector needs in terms of read-out and network transfer components, it is of fundamental importance the estimation of the data rates expected in various possible running scenarios. This contribution extends previous studies [1] of this subject with the aim to investigate the impact of the delta electrons originating from interactions of the beam with the target in case of reduced magnetic field.

Three major contributions to the total data rate were considered: data from nuclear collision events, background signals from delta electrons not correlated to the nuclear collision events and the detector noise. These are estimated with CBMROOT transport and digitization simulations. The rates are calculated for a scenario of an instantaneous beam rate of $10^9/s$, and a 1% interaction probability, i.e. and event rate of 10^7 for the p+Au or Au+Au interactions. We have simulated a statistics equivalent to 10 ms of the detector operation time for Au+Au and about 10 times more for p+Au, scaled up to 1 second and added together. This results in 10^5 UrQMD events and 10^7 Au ions transported through the target, and about 10 more for the p+Au case.

Simulations setup and parameters

Delta electrons are secondary electrons knocked out of atoms by charged particles or ions. They can originate from beam-target, beam-pipe interactions and elsewhere in the detector system. The first two effects are event-uncorrelated since they are produced at all times, even when no heavy-ion collisions are happening. When low energetic enough, delta electrons of this kind can spiral in the magnetic field for some time, possibly overlapping with the next particles produced in a heavy-ion collision event, introducing some background. In our work, delta electrons were generated with Geant 3 simulation engine. This has a standard delta electron cut of 1 MeV.

As in [1], particle tracks are considered delta electrons if the Monte Carlo information fulfills the following criteria: $PID_{PDG} = 11$, $ID_{Mother} = 0$, $E > 10$ keV, $|X_0| < 1.5$ cm, $|Y_0| < 1.5$ cm, $|Z_0| < 0.1$ cm.

The amount of detector noise produced during the digitization procedure was kept to a level of $1500 e^-$ and 4σ digitization threshold, corresponding to $6000 e^-$. The parameters used in the digitization procedure are the following: Dynamic Range $75000 e^-$, Number of ADC levels: 32, Time resolution: 10 ns, Dead time: 500 ns, fraction of dead channels: 0%, Zero noise rate: $3.9789 \cdot 10^{-3}$, Use of Lorenz shift: Yes, Use of charge diffusion model: Yes,

Use of cross-talk model: Yes, Energy loss model: Fluctuations.

The impact of passive material in the STS geometry is very important as it shields off the majority of delta electrons spiraling from outside of detector. We have used the STS geometry v19a implemented in CBMROOT, which includes all active and passive elements within the detector aperture of $2.5^\circ < \theta < 25^\circ$.

STS data rates

The scenarios we have studied are: Au+Au at 12 AGeV with 1 and 0.7 T field, Au+Au at 4 AGeV with 0.7, 0.5, 0.3 T field, and p+Au at 28.3 GeV with 1 T field.

The data rate on the detector is calculated from the amount of digis produced by the detector multiplied by the transport message size of 32 bits.

Figure 1 shows the particle density of delta electrons in X and Y in the 8 STS stations for the worst scenario, namely 4 AGeV at 0.3 T. The magnetic field deviates particle towards the left, therefore the particle density is reduced going from the first to the last station. The relative impact to the total expected rates is shown in Fig. 2 which shows the particle density in the 8 detector stations, summed for all contributions of signal, delta electrons and noise. It is well concentrated in a slice of the detector, well visible up to the last station.

Figure 3 shows a comparison of the particle density in the first (top) and in the fourth (bottom) station for different magnetic field scenarios, namely 0.3, 0.5 and 0.7 T. The increasing strength of the magnetic field deviates more and more electrons towards the left and reduces significantly the particle density. We also note some yield of delta electrons on the right side of the picture, rising from electrons emitted out of the detector acceptance and bent in by the magnetic field. On the other hand the contribution on the 4th station is still large with 0.3 T field, while with a stronger field of 0.7 T it is essentially negligible.

Table 1 shows the integral data rate from all the contributions summed over all chips and detector stations for all the different considered scenarios.

Summary

Complementing the studies in [1], the data rate contributions from nuclear collisions, delta electrons from beam-target interactions and detector noise were studied within the CBMROOT experiment simulation and analysis framework for various scenarios of beam energy and magnetic field were studied. The impact of delta electrons to the

Table 1: Integral data rate from all the contributions for all the different considered scenarios. The beam intensity is assumed to be $10^9/s$, and the event rate $10^7/s$ (10 MHz). For p+Au the noise contribution was not included.

	Au+Au 12 AGeV		Au+Au 4 AGeV			p+Au 2.83 GeV
	1 T	0.7 T	0.7 T	0.5 T	0.3 T	1 T
Total	178	194	164	211	363	11
Signal	159	148	118	115	116	11
Delta	14	42	42	91	242	0.009
Noise	5	5	5	5	5	-

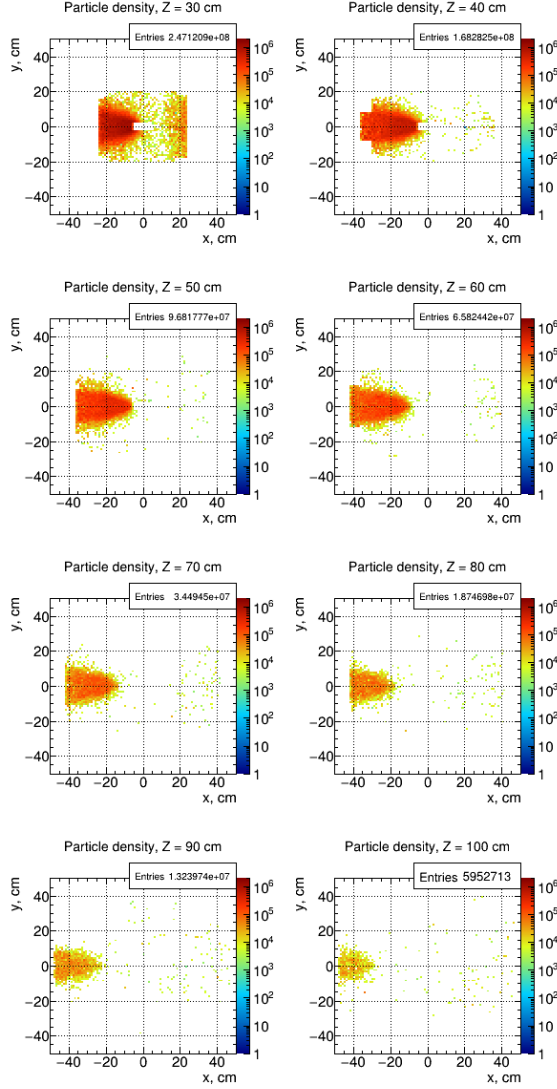


Figure 1: Particle density of delta electrons produced in beam-target interactions, in Au+Au collisions at 4 AGeV with 0.3 T field. The density is shown as a function of X and Y for the 8 STS stations.

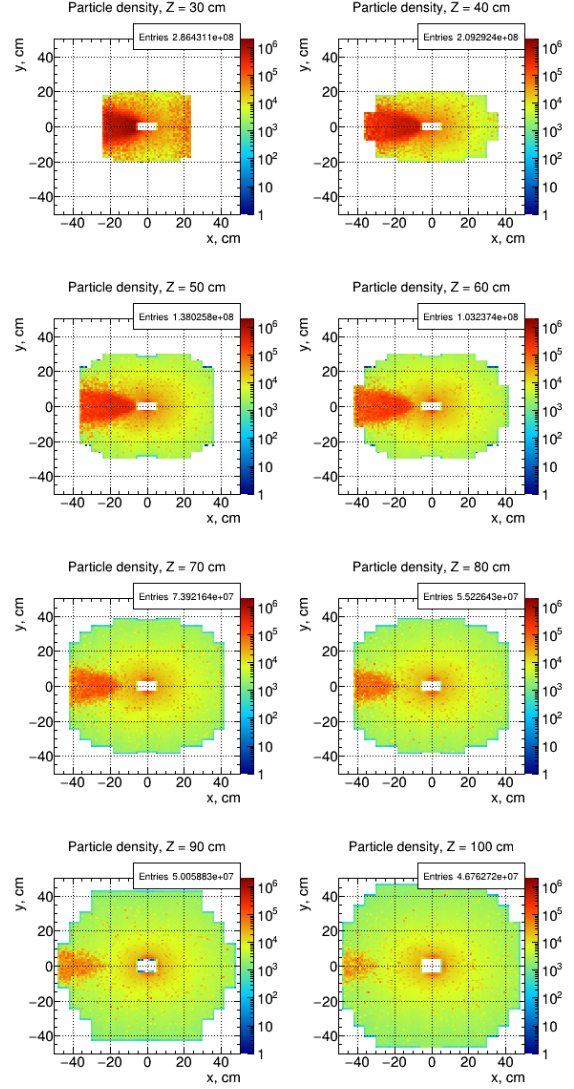


Figure 2: Particle density summed for all contributions of nuclear collisions, delta electrons, and noise produced in Au+Au collisions at 4 AGeV with 0.3 T field. The density is shown as a function of X and Y for the 8 STS stations.

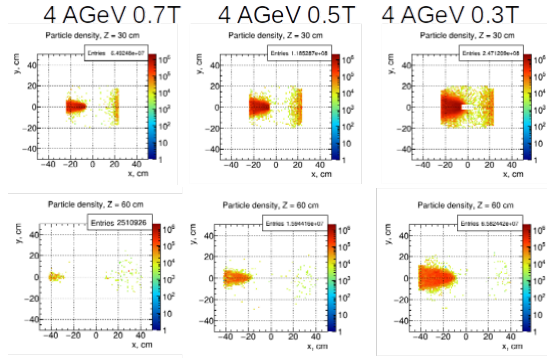


Figure 3: Top: Particle density of delta electrons produced in beam-target interactions, in Au+Au collisions at 4 AGeV with 0.3, 0.5 and 0.7 T field. The density is shown as a function of X and Y for the first STS station. Bottom: Same for the fourth station.

total STS rates is significant and has to be carefully evaluated. The beam energy does not have a significant impact on the rates, neither from nuclear collisions, nor to delta electrons. In contrast, the reduction of the magnetic field brings a large increase in the rates of delta electrons.

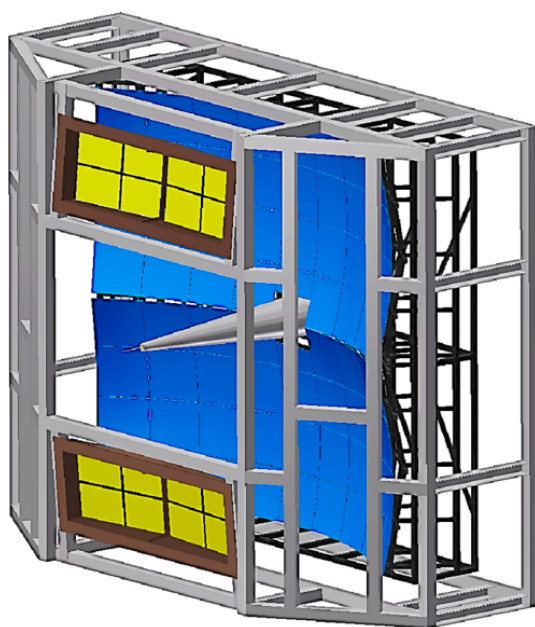
The critical region is only a *slice of cake* on one side around the horizontal axis which corresponds to approximately 1/8 or 1/6 of the detector acceptance. All other regions are not affected by delta electrons in neither of the various scenarios. Therefore in those the worst case scenario for the rates is the Au+Au at 12 AGeV with the nominal 1 T magnetic field. In the region affected by delta electrons however, the worst possible case is the 4 AGeV with 0.3 T field. In this case some ASICs reach a hit rate of 100 Mhits/ASIC/s and channel rate of 780 khits/ch/s which significantly exceeds the maximum ASIC readout rate of 50 Mhits/s, for all ASICs in the triangular region the 0.3 T delta electron contribution leads to a significant increase in data rate compared to the 12 AGeV and 1 T reference case.

The consequence of trying to increase the readout bandwidth in **just this region** to cope to the largest possible extend (i.e. the max. ASIC readout rate) with the delta rate at 0.3 T magnetic field would be a significant increase of resources in the full readout and DAQ chain: the number of FEB8-5, i.e. frontend boards where the full ASIC readout bandwidth is used, would increase by a factor > 6 , the overall number of readout boards (STS-ROB) and of DAQ-CRI boards, and thus the overall cost of the STS readout, would increase by more than 70%. An overall data rate which can be handled and which is compatible to the 12 AGeV and 1 T scenario for the case of a 0.3 T field can only be reached by reducing the interaction rate by a factor of approximately 10, or by accepting significant data losses in the *slice of cake* region.

References

- [1] E. Lavrik et. al, *Assessment of STS data rates*, CBM Technical Note, to be released

Ring-Imaging Cherenkov Detector



RICH summary

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The CBM RICH project has made substantial progress in various fields in 2020 as will be presented in this CBM Progress Report.

The mechanical layout and design of the RICH detector has seen a huge improvement. The geometry was finally fixed to a mirror tilt angle of 12° leaving more space towards the dipole magnet and moving a bit outwards of the stray field. A final design of the shielding box has been developed and simulated using three different software packages (COMSOL, ANSYS Maxwell, OPERA). Together with slightly released requirements on the maximum strayfield in the photon-detector camera due to the better performance of the H12700 MAPMT compared to the H8500, this design now fulfills all requirements. Fixing the shielding box design, a concept for the mechanical integration of the photon-detector camera has been proposed. The pillar structure of the mirror wall has been decided to be built from aluminum as no significant benefit was found in simulations when using carbon fiber structures. The open issue with the beampipe has been relaxed as the RICH layout now foresees a tunnel as border for the gas volume through which the beampipe will be guided. This concept minimizes heavy material budget, such as would be introduced by flanges, and allows for a lightweight connection to the STS beampipe. With these improvements, a CDR of the RICH mechanics has successfully been prepared and accepted.

The layout of the photodetector camera has been developed in further detail and a CDR has successfully been presented and accepted. This CDR includes a concept for cooling, cabling, and the above mentioned concept of mechanical integration into the RICH gas box. The development of the cooling concept did advance considerably with a prototype that has been built and successfully used for first measurements.

Overall, with this progress the RICH group comes close towards a final, complete mechanical design which would be the start of construction.

The 12 mirror prototypes delivered in 2019 have been tested in detail in 2020 and integrated in the mirror wall prototype. As all remaining issues have been investigated, a mirror CDR is in preparation.

The mRICH detector in mCBM has been completed with a second aerogel block and the full photon detector plane comprising 36 MAPMTs in six 2×3 arrangements on backplanes. The detector could be run reliably during the complete beamtime period although run remotely due to the Covid Pandemia. The mRICH analysis successfully could prepare a first measured β -spectrum of mCBM. Currently, work is ongoing to port the firmware to the new CRI boards in order to be ready for the next beamtime 2021. For the RICH detector the CRI platform will be the final DAQ platform in CBM.

The RICH upgrade of HADES has shown a phantastic performance of the RICH as reported last year. In 2020 many detailed studies of the RICH performance have been done and the full RICH potential was exploited for the dilepton spectra leading to a signal-to-background ratio of about 1 for masses below the ω -meson and of about 3 at the mass of the ω -meson.

The CBM RICH software has continuously been improved. RICH simulations by now can also successfully be performed with GEANT4. Dilepton simulations show a clear influence of the additional material budget of the STS but no drop in the performance of the dilepton measurements yet.

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CBM RICH detector conceptual design

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The largest component of the RICH detector (Fig. 1) is the radiator gas vessel (2), carrying the focusing mirror system. The radiator gas vessel is filled with radiator gas (CO₂). The focusing mirror system is located inside the vessel. It is based on a mirror support structure (3), to which mirror tiles are mounted using special mirror mounts and intermediate small frames. The vessel is installed on the RICH support frame – a base support platform with adjustable hinged (articulated) supports (1), which in turn are mounted on the common RICH/MuCh foundation matching the beam line height of approximately 6 m above floor level of the CBM cave. The two photon detectors are installed above and below the beam pipe on the front side of the gas vessel. They are contained in massive magnetic shielding boxes (4) to protect the photon sensors from the stray field of the nearby dipole magnet. The radiator vessel has thin input (6) and output (7) windows at the front and back sides, respectively, to minimize the material budget for detectors further downstream. A special reflective mesh will be placed in the area of the entrance window to control the orientation of the mirror tiles during detector operation (CLAM method). A special plastic (or carbon fiber) tunnel (5) for the beam pipe is located in the center of the gas vessel.

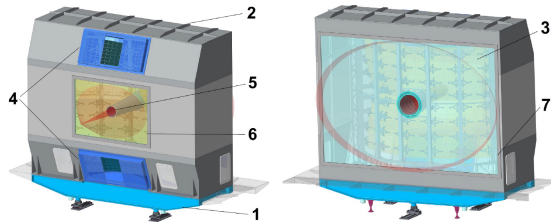


Figure 1: General layout of the CBM RICH detector mechanical structures, (1) – RICH support frame with adjustable hinged (articulated) supports, (2) – radiator gas vessel, (3) – mirror supporting structure, (4) – magnetic shielding boxes, (5) – tunnel for the beam pipe, (6) – input window, (7) – output window.

The RICH support frame (support platform) ensures the stability of the installation of the entire detector in the operation position, and also provides the possibility of detector position alignment on the beam axis in the cave of the CBM experiment. Alignment of the detector is carried out using adjustable hinged supports, which are pre-installed on the RICH/MuCh foundation. To reduce the effects of various mechanical stresses on the mirror system, which is tuned with high accuracy, the support frame is designed as

a rigid structure and provides the basis for the rest of the RICH detector. Displacement of the detector is done by crane lifting the frame using special lifting beam. The support frame is mounted on three adjustable hinged supports, each of which is designed to carry the static load of 6000 kg. Two (or more) additional safety supports will probably be used to provide additional stability of the structure. The plate which provides the basis for the radiator gas vessel and mirror support structure mounting is fixed to the top of an I-beams frame. Hemispherical support elements are fixed to the bottom of the support frame for installation on adjustable hinged supports.

The design of the adjustable hinged supports allows to move the detector in vertical direction (y -axis) within 15 mm, 100 mm in horizontal direction (x -axis, across the beam), and 580 mm along the beam axis (z -axis). With this, the design ensures accurate positioning of the detector along the beam axis. Increased displacement along the beam axis (z -axis) allows to have access to the section of the beam pipe located between the RICH and the dipole magnet, as well as to make safer crane lifting of the detector when moving it from its operation and parking positions.

Two types of adjustable hinged supports are used to adjust the position of the support frame. The design of the supports is shown in Fig. 2. The support of the first type regulates the movements in transverse and vertical directions, and it has free movement in longitudinal direction and all rotational degrees of freedom. The support of the second type regulates the movements in longitudinal and vertical directions, and it has free movement in transverse direction and all rotational degrees of freedom.

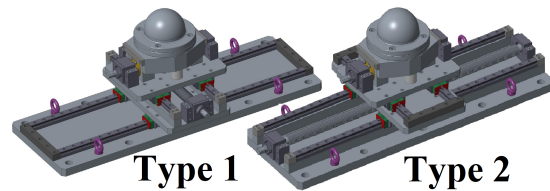


Figure 2: Design of the adjustable hinged supports.

There is a hemisphere that provides rotational degrees of freedom at the top of supports. The lead screws and linear guides provide the movement of the hinged supports. The rotation of the screws is carried out manually. Special sliding wedges provide vertical movements. In case of insufficient adjustment in vertical direction (y -axis), special spacer pads can be used. The installation diagram of the adjustable hinged supports is shown in Fig. 3 (bottom

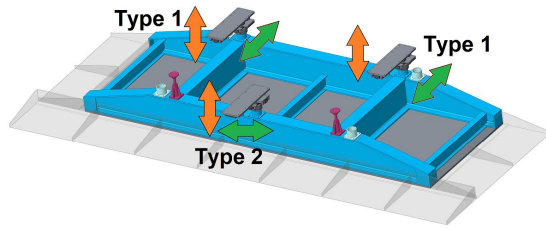


Figure 3: Installation diagram of supports for adjusting the position of the support frame (bottom view). The arrows show the operation direction of the adjusting screws for different types of supports.

view).

The mirror support structure (mirror support frame) will ensure the mechanical stability of the focusing mirror system with focusing mirror tiles. The focusing mirror system is split into two halves one of which is located above and other below the beam pipe. The spherical mirror surface will be made up of single trapezoidal tiles of four different types with different sizes. Each mirror tile is individually orientated towards the photon detectors and is a part of a sphere with radius of 3 m. The design of the mirror support structure should ensure the long term global positioning of the mirrors with accuracy better than 1 mrad. In addition, the parts of the mirror support structure should pose as little material budget in the CBM acceptance as possible.

The option of the mirror support structure with thin-walled aluminum pillars is proposed for construction (see Fig. 4) as a result of intensive studies carried out to date [1]. Each pillar carries two vertical rows of mirror tiles. Mirror tiles are mounted on a special small transition frame and are attached to the pillar through special consoles. Preliminary analysis showed that such design can provide the required strength and stiffness, while ensuring a minimum of material budget in the acceptance of the detector.

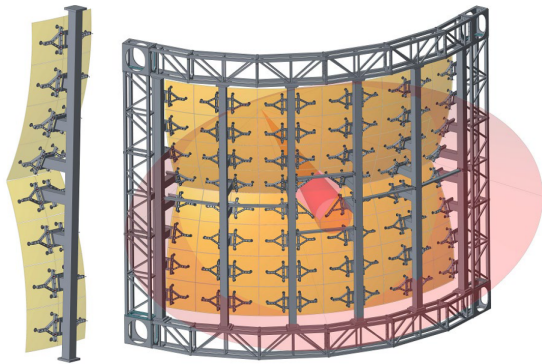


Figure 4: Pillar with two vertical rows of mirror tiles installed (left), structure of the mirror support structure and the mirror system assembled with pillars (right).

The design of the small frame for fixing mirror tiles and mirror mounts is shown in Fig. 5. The frame is as-

sembled from aluminum parts and has mounting seats for mirror mounts. The mirror tiles are attached to the frame with three adjustable mounts which allow aligning the mirror tiles independently of each other to achieve satisfactory convergence and focusing of the entire focusing mirror system [2]. The adjustment of the position of the mirror tiles is done manually by rotating a regulating screw of the mount using removable handles.

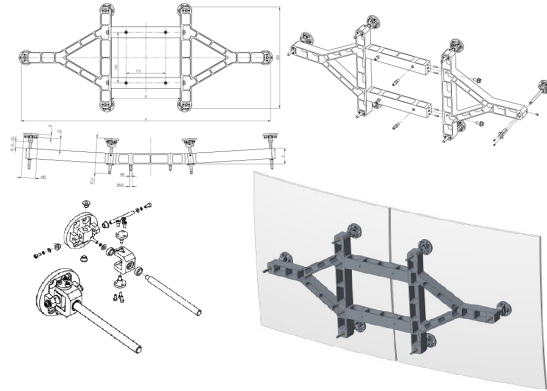


Figure 5: Design of the thin-walled frame for fixing mirror tiles (small frame, top), mirror mount (bottom left), small frame, mounts and mirror tiles assembled (bottom right).

The radiator gas vessel is installed on a stiff platform (RICH support frame) which can be aligned to the beam position and direction (see Fig. 1). The vessel provides a gas- and light-tight enclosed volume for the gas radiator and provides the mounting of the magnetic shielding boxes of two photon detectors. The dimensions of the vessel are about 2.2 m in length, more than 5 m in height and about 6 m in width. The parts of the front and rear cover lying within the CBM acceptance region must provide a material budget as low as possible. For example, the front window can be made of Kapton foil or similar, the rear window can be made from thin plastic sheets. The vessel is expected to be assembled from several aluminum parts for easy transportation and production. The mirror support structure is not mechanically coupled with the vessel to reduce such impact.

A tunnel for the beam pipe is located in the center of the detector (see Fig. 1). It will be made of plastic or carbon fiber and will be fixed on special extensions in the area of the input and output windows. Entrances located at the front and lateral sides of the detector will be made to provide access to the inside of the radiator vessel.

This mechanical design concept reaches all requirements and has been approved by the collaboration.

References

- [1] D.Ivanichshev *et al.*, CBM Progress report 2018, Darmstadt 2019, p. 40
- [2] D.Ivanichshev *et al.*, CBM Progress report 2019, Darmstadt 2020, p. 47

Update on the magnetic shielding box design and simulations

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Further progress has been made with respect to the design of the magnetic shielding boxes for the RICH photon detectors. These iron shielding boxes are integral parts of the RICH radiator vessel, and will house the camera modules. Recent calculations of the expected stray field including the effect of a laminated magnet yoke done by the CBM magnet group predicted a further increase of the total magnetic stray field in the relevant RICH PMT region of up to $\sim 25\%$ in a worst case scenario (see [1] for details).

Another effect not considered so far (but now taken into account in our most recent simulations) is the effect of the significant amount of KOVAR alloy in the MAPMT housings (~ 42 kg) which could potentially draw additional field lines into the region of the photon detectors. KOVAR is an alloy (54% iron, 29% nickel and 17% cobalt) with relatively large magnetic permeability μ_r in the range of 1000 - 5000. Finally, the camera position was slightly adapted in accordance with the latest RICH geometry, and also the shielding box size was slightly increased to match latest mechanical design considerations. This shift of -50 mm upstream (towards the magnet), and 75 mm outwards in vertical direction (away from the beam), provides some additional space between acceptance cone and camera and allows for further optimization of the shape of the shielding box.

A sketch of the final shielding box, together with the magnet, is shown in Fig. 1. It also includes an optional iron shielding plate (green) between magnet and shielding

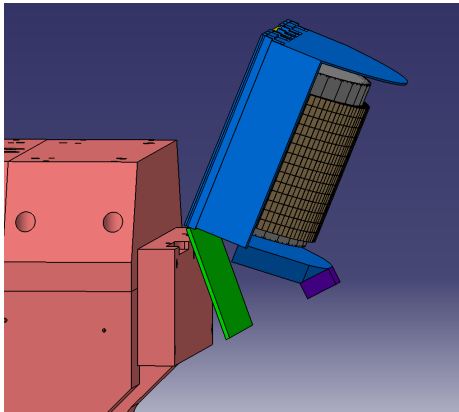


Figure 1: Magnetic shielding geometry for the photon detection camera. Red colored: magnet, blue colored: shielding box, purple colored: enlarged wing, green colored: extra shielding plate.

box. This would, according to simulations, provide additional suppression of the stray field within the camera volume and could be added later in case of unexpectedly high stray field. The design of the RICH- and the magnet would not be affected by such an addition.

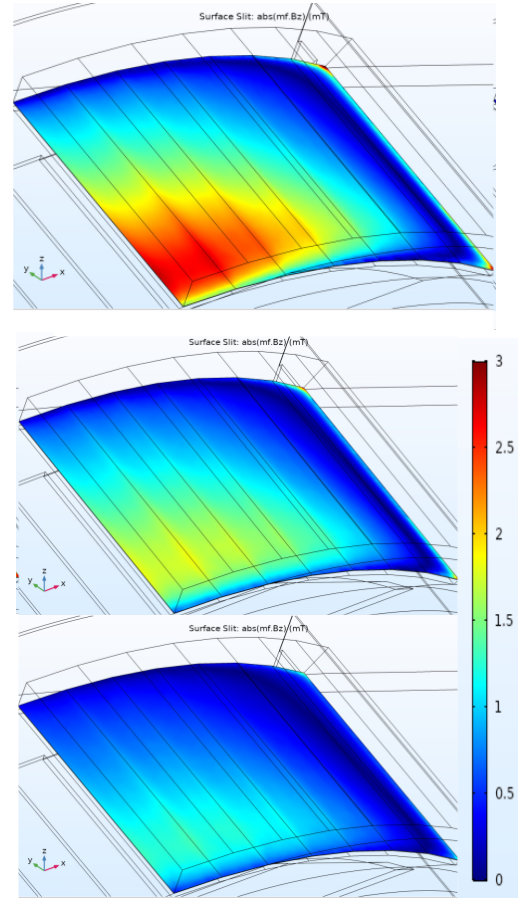


Figure 2: Comparison of total magnetic stray field for: shielding box + KOVAR alloy + original wing design (top), with optimized wing design (middle), with optimized wing plus extra shielding plate (bottom). Field values in mT using the same color scale for all plots.

The field calculations shown Fig. 2 have been performed using the COMSOL Multiphysics software package including the AC/DC module for magnetic fields. The main goal of this study was to further optimize the design of the shielding box and inner wing structure for optimum detector performance.

Adding additional iron (~ 70 kg per shielding box) to the inner wing structure, together with an optimization of its shape, reduces the magnetic stray field by $\sim 35\%$ (Fig. 2 top vs center plot). Adding the extra shielding plate (width: 2000 mm, height: 600 mm, thickness: 20 mm, total weight: ~ 200 kg) located outside the gas radiator vessel between the field clamp of the dipole magnet and camera shielding box reduces the field by another $\sim 30\%$. Combining both wing modification and shielding plate results in a reduction of the maximum total field by more than 50% (c.f. Fig. 2 bottom).

Thus, the suit of simulations suggests that the main requirement of reducing the stray field in the area of the MAPMTs down to values of 2 - 3 mT can be fulfilled. However, it should be noted that the simulations do not yet include the effect of magnet yoke lamination which could increase the stray field by up to 25%. The additional shielding plate between magnet and camera box can thus be considered as additional optional measure in case the results of later field measurements show slightly higher stray fields than expected. However, the safety margin is not very large and only in the order of 1 mT.

The results of these simulations and the final shielding box design are presently being cross checked by ANSYS Maxwell calculations carried out by the CBM magnet group.

References

- [1] P. Senger et al., The superconducting dipole magnet of the CBM experiment, CBM Progress Report 2019, p.146

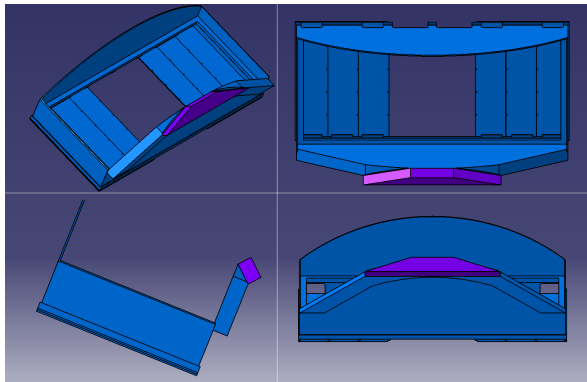


Figure 3: Latest design of the magnetic camera shielding box

This design of the shielding box, which we now consider as final, is depicted in Fig. 3. An important aspect is that it will become an integral part of the radiator vessel and will provide a gas-tight interface to the photon camera by a surrounding flange. The photon camera will be mounted from the backside into the shielding box like a drawer. Because of these requirements, the shielding box will be a complex structure requiring precise manufacturing using materials of appropriate magnetic properties. It was found that substituting the originally foreseen soft iron by steel 1010 will have only minor effects on shielding capabilities but would provide much better mechanical handling properties.

Conceptual design of the CBM RICH photon detector

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In 2020, the conceptual design of the CBM RICH detector has been finalized and has passed a critical Conceptual Design Review (CDR) in November 2020. This design is now further worked out towards a full engineering design before starting the construction of the RICH detector. Of particular interest here are the modular design of the RICH photon detection cameras and their surrounding iron magnetic shielding boxes. A concept has been worked out how the photon detectors interface with the main RICH vessel, and how the cooling of the readout electronics inside these detectors will be achieved.

Mechanical design concept

Figure 1 shows a sketch of the latest design of the CBM RICH detector. The two photon cameras are positioned inside the iron shielding boxes above- and below the beampipe. Parts of the backward cover plates of the photon camera boxes are shown in grey. A large central patch board (placed on the lower right of the detector) provides the interface to all electrical and optical connections. Cables from patchboard to the cameras will be fixed to the vessel, allowing for easy mounting and unmounting of the cameras themselves as explained below.

The camera module and the surrounding shielding box are two distinct entities, where the heavy shielding box (see

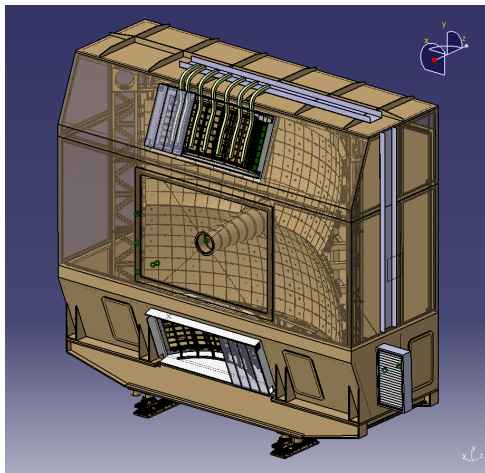


Figure 1: Schematic drawing of the RICH detector with both photon cameras installed. All electrical and fiber interconnects will be routed via the central patch panel on the lower right side of the detector.

[1, 2]) will be fixed as integral part of the RICH gas vessel. The backward enclosure of the shielding box (outer parts: iron slabs, central part: non-magnetic) can be removed to allow insertion of the photon camera from the backside, as sketched in Fig. 2 (camera module: blue, shielding box: grey).

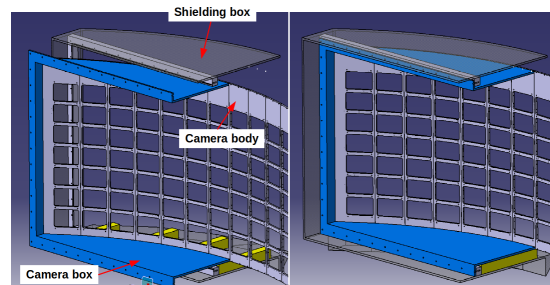


Figure 2: The RICH photon detector frame is slid into the magnetic shielding box, and fixed only via the (gas-tight) backward mounting flange. Plastic glider wedges (yellow) help during the installation procedure.

Removing the shielding box back cover will also allow maintenance access to the readout electronics from outside (when the RICH is placed in its maintenance position) without removing the photon detectors. Special plastic / Teflon guides (shown in yellow) help to guide the camera module into its final position before it gets fixed to the shielding box via the large rectangular flange at the back. The flange provides a gas-tight seal, and is the only contact area between camera and shielding box once flange screws are fixed. This protects the camera with its sensitive photon sensors (placed on the outside radius of the cylindrical detection plane) of any possible deformation of the heavy shielding box.

The photon camera module itself consists of a cylindrical shaped front part made of 14 CNC-milled aluminum elements (each $157 \times 901 \text{ mm}^2$, 10 mm thick), each carrying 7 readout modules with each $3 \times 2 = 6$ MAPMTs on the front, and $7 \times (12 + 2)$ DIRICH readout modules on the back. The individual aluminum elements will be screwed and glued together in order to ensure gas tightness. Precise shape and stability of the cylindrical front face is maintained by the top and bottom aluminum plates (each 15 mm thick) of the camera box. Further stability is achieved by the large rectangular mounting flange, which also serves for crane lifting the whole camera during installation.

Sufficient stability of this design (total weight of each

camera is estimated 425 kg, including 250 kg for read-out electronics, photon sensors, and internal structures) was studied in FEM simulations, where in these simulations the camera was supported only via the rectangular flange. Results (see Fig. 3) show very little deformation of the whole structure by maximum ~ 0.16 mm only, proving sufficient stability of the overall design.

Arrangement and fixture of the readout modules is sketched in Fig. 4.

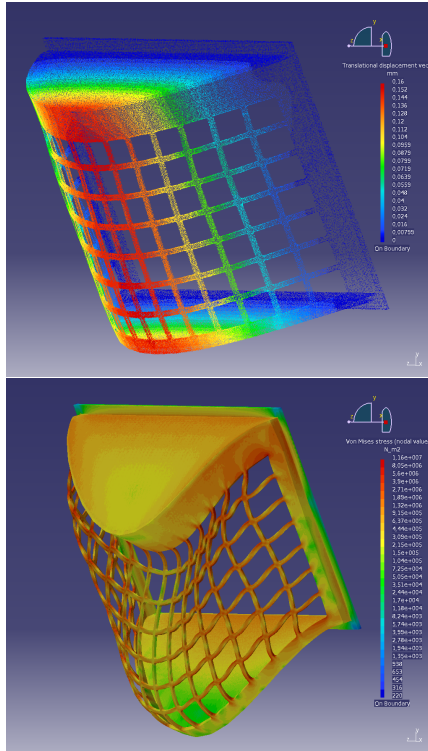


Figure 3: FEM stability calculations of the camera module frame. The frame (Eigen-weight: 175 kg, plus additional 250 kg acting on the cylindrical front) is supported via the mounting flange only. Maximum displacement (upper plot) is ~ 0.16 mm only, maximum von-Mises stress is $\approx 10^7$ N/m² (lower figure, distortion exaggerated for visualization purpose only).

As described in [1], the front-end modules are supported by 3d-printed plastic "masks", which not only provide mechanical stability to each module, but also incorporate cooling air distribution channels. Cooling air ($\leq 18^\circ\text{C}$) is injected into each module column from top and bottom, distributed via the interconnected support "masks", and leaves close to the connector side of each electronic module, providing optimal air cooling for each module and backplane PCB (with the temperature sensitive PMTs mounted on their opposite inner side).

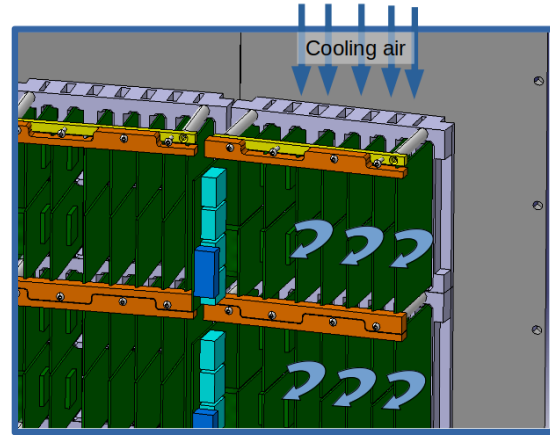


Figure 4: Mounting structure for the readout electronic modules using special air distribution masks supporting the modules mechanically. Cooling air, injected from top and bottom of each column, is distributed via these masks.

Camera installation procedure

The installation procedure of a complete camera module into its corresponding shielding box is done in several steps as sketched in Fig. 5. A special crane tool attached to the mounting frame of the camera module will be used for installation of the camera, balancing the camera module in the correct tilt angle of 22° downwards (upwards for the lower camera) for installation. Guiding pins on the flange will help to position the camera for insertion. Once the camera module is fixed inside the shielding box via the mounting flange, in the next step all cable- and fiber connections are connected directly to the DIRICH-Combiner and DIRICH-Power frontend modules. The cables will be arranged in several individual cable arms permanently fixed to the RICH vessel, allowing for easier removal of the camera module. Finally, also the cooling air supply hoses are connected, and the back cover of the shielding box is re-installed.

An important aspect in the camera installation procedure is the question whether it will be safe enough to install the camera modules with all photomultipliers already in place, fairly unprotected at the front face of the camera, or if the PMTs have to be installed after camera installation, from inside the radiator vessel. Installation of photon sensors after camera installation is difficult in particular for the upper camera module, where later excess from inside the radiator vessel is very difficult due to height (approx. 4 m above radiator floor level) and the tight space constraints and proximity of the fragile RICH mirror inside the gas box. PMTs on the lower camera box will probably be fairly well accessible also from inside the radiator according to the latest design (providing access doors to the radiator vessel). However, access from inside will require full removal of the radiator gas (CO_2) first, and is posing the risk of polluting the radiator and mirror.

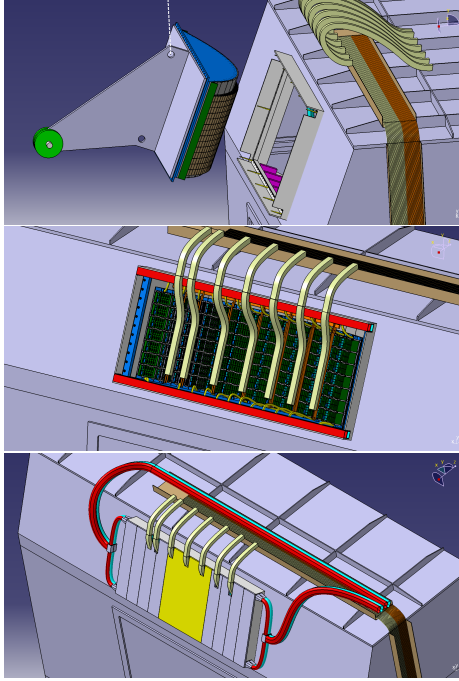


Figure 5: The Photon camera is mounted into the shielding box from outside using a dedicated crane tool, afterwards all electrical and air supply lines get connected. Finally, the backward shielding box wall is closed with iron slabs.

Camera cooling

The total heat dissipation of all readout frontend electronic inside both photon detectors will be in the order of $2 \times 3 = 6$ kW, and will be extracted via a closed loop air circulation system. Inside the photon detectors, cool air will be distributed via the PCB masks covering each module backplane PCB as sketched above.

The circulation system consists of a large air blower, capable of delivering up to $10 \text{ m}^3/\text{min}$ of air at ~ 100 mbar over-pressure. This blower is extracting the warm air from both photon detector modules and recirculating it via a large water-cooled heat exchanger close to the blower. The cooled air is then routed back to the detector. The heat exchanger will be connected to the cave cooling water circuit (water-temperature $\sim 10\text{--}12^\circ\text{C}$), providing cooling air of $\sim 16\text{--}18^\circ\text{C}$ at the detector inlet. A filter and cyclone water separator behind the heat exchanger will safely remove any condensing water from the cooling air. This place inside the heat exchanger unit is the only place where condensation can happen. Close temperature monitoring of all detector parts will eliminate the risk of water condensation anywhere else inside the detectors. Recirculating the air will limit the total amount of condensing water, and will also help to avoid dust and dirt accumulating inside the readout electronics. Special spring loaded over/under pressure air flaps in the shielding box enclosure will protect the photon cameras from any dangerous over- or under-

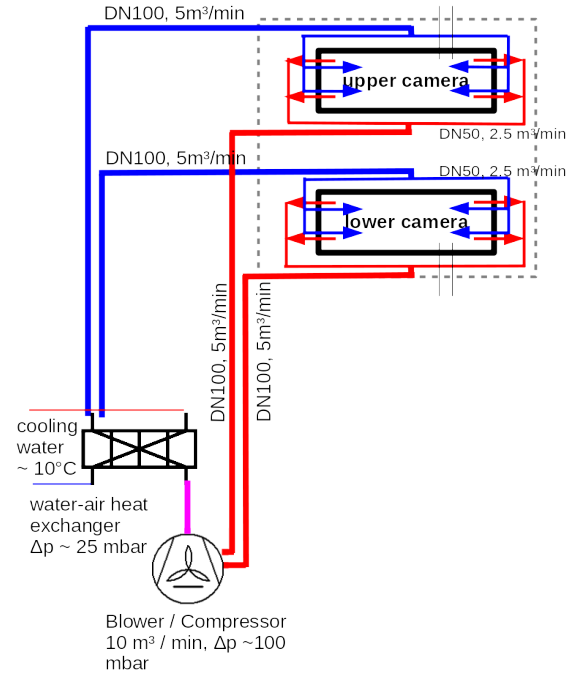


Figure 6: Sketch of the cooling air circulation loop consisting of blower, heat exchanger, and the two photon camera modules.

pressure in case of faults (e.g. broken hoses) in the circulation system. A sketch of the circulation loop, with rough estimates on required air flow and minimum tubing cross sections is shown in Fig. 6.

The cooling system components (blower and heat exchanger) will be placed in the cave, not too far from the detector working position. An isolating enclosure of the blower will limit the sound emission into the cave. Fixed air channels, probably installed along the MUCH foundation below the detectors, will guide the cooling air to and back from the RICH measurement position.

Outlook

The concept for the photon detectors and cooling system is far advanced. We have started to construct a full size demonstrator of one camera module in order to test and optimize the manufacturing procedures. Together with the first readout electronic components hopefully available by end of 2021 we also plan to test the cooling concept under nominal load with this demonstrator.

References

- [1] D. Pfeifer et al., Magnetic field simulation, construction and cooling of the CBM RICH camera, CBM Progress Report 2019, p.50.
- [2] D. Pfeifer et al., Update on the magnetic shielding box [...], this report.

Camera cooling prototype - first measurements

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A sophisticated air cooling system is being developed for the photon cameras of the CBM RICH detector. The main requirement is to provide cooling of the readout electronics and to keep the temperature of the backplane PCBs, to which the readout modules are mounted, at temperatures in the order of $\approx 30^\circ\text{C}$. This low temperature of the backplane PCBs is important as they are in turn also in close thermal contact to the photon sensors, whose noise floor depends sensitively on the operation temperature (see [1] for details.)

In order to understand the requirements in terms of cooling air-flow rate and -temperature, a prototype model of a single readout column (1/14 of the full camera) has been built at Wuppertal University. This prototype consists of a fully equipped camera column comprising 7 MAPMT backplanes, 84 DiRICH-frontend modules, and 7 Power- and Concentrator modules. Total heat dissipation of the electronics is in the order of 170 W (1/14 of a fully equipped camera). The prototype is enclosed in a thermally insulating box to minimize conductive cooling. For first tests, conventional compressed air has been used as cooling air. The air flow is measured using flow sensors (Sensirion, SFM 3000) and regulated by an automated valve. The temperature of the cooling air is regulated using a water cooled heat exchanger, precise control of air-temperature and -flow are achieved by applying PID regulators implemented inside the EPICS control system. Automated parameter scans of cooling temperature and flow rates were carried out while all relevant parameters, including temperatures of all DIRICH modules and backplanes (using digital sensors DS18B20 from Dallas Semiconductors), cooling air flow, and cooling temperature were constantly logged for subsequent analysis. Figure 1 shows first results of the measurements in terms of backplane temperature as function of cooling air flow and air temperature. The following observations were made:

- (i) Operating the read out electronic without any cooling heats up the backplane PCBs very rapidly. Temperatures of the PMTs rise up to well beyond 50°C , far outside the acceptable range.
- (ii) Applying sufficient air cooling, the temperatures are significantly reduced. The minimum temperature of the cooling air needs to be above about 16°C in order to safely prevent formation of condensing water. At this minimum allowed cooling air temperature, a flow rate of $\gtrsim 350 - 400\text{ l/min}$ is required for the prototype in order to provide sufficient cooling. Scaling up these numbers to a complete camera module results in a flow rate requirement of $\sim 5\text{ m}^3/\text{min}$ per camera ($\sim 10\text{ m}^3/\text{min}$ for full

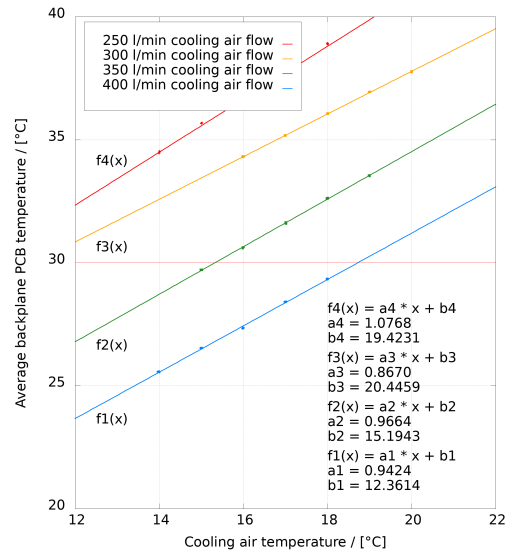


Figure 1: Measured mean temperatures of the backplane PCBs as a function of cooling air temperature for four different flow rates.

detector) in order to keep the MAPMT temperature below $\sim 30^\circ\text{C}$ at all times.

- (iii) The temperature gradient along the vertically staggered backplanes in a camera column is kept below $\pm 2\text{ K}$ from the mean value.

Next steps: At present, the compressed cooling air is injected only on the upper and lower end of the readout column and is then distributed vertically in each column via the interconnected cooling masks. By using different masks with varying air nozzle sizes in dependence of the vertical position of the masks we hope to further equalize the temperature profile. The next step is the construction of a full camera module demonstrator including a full size cooling system (consisting of an air blower and large water heat exchanger) in order to qualify the cooling concept for final production. Construction of this full size demonstrator has started beginning 2021.

References

- [1] D. Pfeifer et al., Magnetic field simulation, construction and cooling of the CBM RICH camera, CBM Progress Report 2019, p.50

Material for the RICH mirror support structure: aluminum vs. carbon

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The type of material to be used for the RICH mirror support structure is still undecided. Presently, two options are considered: aluminum and carbon. Both materials have advantages and disadvantages. The aluminum option is much cheaper and easier in production and maintenance, but adds material inside the acceptance of the experiment. On the other hand, the carbon option is more expensive and it requires more expertise in production, but it reduces the material budget by a factor of two in comparison to aluminum. In this report, we compare the two material options by performing corresponding simulations.

Figure 1 shows the main components of the mirror support structure, namely, 6 pillars and 80 belts as they are implemented in the *cbmroot* framework. In order to study the effect of material for pillars and belts independently, 4 RICH geometries were prepared for the simulations: 1) Aluminum-Aluminum (A-A), 2) Carbon-Carbon (C-C), 3) Aluminum-Carbon (A-C), 4) Carbon-Aluminum (C-A). The first material in the name defines the pillar material, the second one defines the belt material. All geometries are based on the *v17a.1e* version of the RICH geometry. The *STSBorCarbonFibre* material from *media.geo* was used as a carbon material.

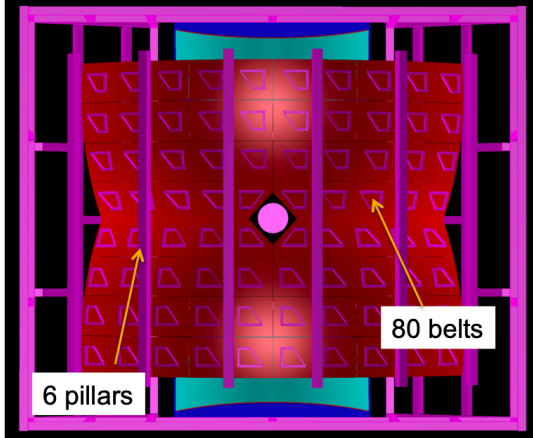


Figure 1: The RICH geometry *v17a.1e* in the simulation. The mirror support structure consists of 6 pillars and 80 belts.

Figure 2 shows the radiation thickness of the RICH detector for parallel tracks. One can clearly see the difference between aluminum and carbon materials. The aluminum pillars and belts (left plot) are more pronounced than the carbon ones (right plot), however, the difference

is not big. Taking into account the material budget in front of the RICH from the STS detector, the difference becomes even smaller.

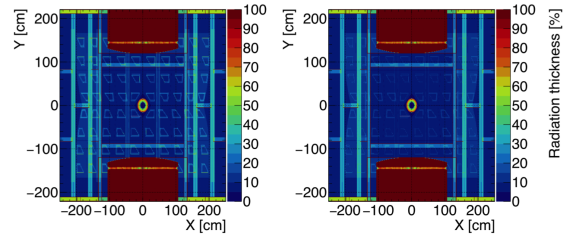


Figure 2: Radiation thickness of the RICH detector for parallel tracks. Left: A-A geometry. Right: C-C geometry. Maximum is set to 100% for a better view of the pillars and belts.

The reconstruction performance was studied with 100K UrQMD central Au+Au collisions at 8 AGeV and 12 AGeV beam energies, 10 additional $e^\pm$ were embedded in each event in order to investigate the electron performance.

Table 1: Number of MC points, digis and hits in the TRD and TOF detectors.

Number/event	A-A	C-C	A-C	C-A
UrQMD Au-Au central at 8 AGeV				
TRD MC points	1703	1686	1694	1696
TRD digis	5191	5133	5161	5167
TRD hits	1447	1432	1439	1441
TOF MC points	6180	6139	6157	6162
TOF hits	740	735	737	738
UrQMD Au-Au central at 12 AGeV				
TRD MC points	2287	2263	2273	2276
TRD digis	6962	6880	6915	6923
TRD hits	1946	1924	1934	1936
TOF MC points	8465	8405	8429	8437
TOF hits	1004	997	1000	1001

The first thing to check is how much background the additional material adds for the upstream detectors. Good indicators for this are the number of MC points, digis and hits in the TRD and TOF detectors. Summary results are presented in Table 1. No big differences are observed between different material variants. The simulation with the

A-A RICH geometry shows 1% more TRD MC points in comparison to the C-C version. Approximately half of the additional background is caused by the pillars, another half by the belts. For the TOF detector the difference between A-A and C-C versions is even less pronounced. Simulations for 12 AGeV beam energy show similar results.

Figure 3 shows the global tracking performance results for primary $e^\pm$. The mean efficiency for 8 AGeV beam energy is 79.9% for the A-A geometry and 80.4% for C-C. The corresponding numbers for 12 AGeV beam energy are 77.4% and 77.9%, respectively. The gain of the usage of a fully carbon mirror support structure is 0.5%. Again, half of the gain is caused by the pillars, the other half by the belts.

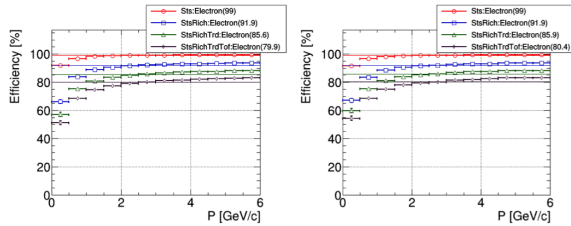


Figure 3: Global tracking performance for primary $e^\pm$. Left: A-A geometry. Right: C-C geometry. UrQMD central Au+Au collisions at 8 AGeV.

Figure 4 shows the electron identification efficiency and pion suppression for primary $e^\pm$. The mean numbers for 8 AGeV beam energy are 78.9% and 36.9K for the A-A geometry; 79.3% and 35.6K for C-C. The corresponding numbers for 12 AGeV beam energy are 76.3% and 19.6K; 76.8% and 19.7, respectively.

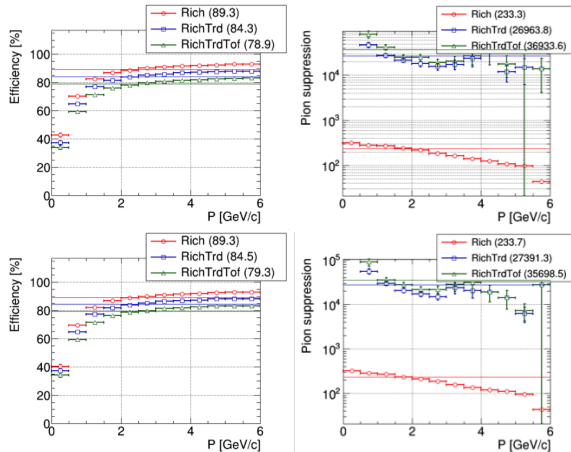


Figure 4: Electron identification efficiency (left) and pion suppression (right). Top: A-A geometry. Bottom: C-C geometry. UrQMD central Au+Au collisions at 8 AGeV.

A summary of the reconstruction results for 8 AGeV and 12 AGeV beam energies is presented in Table 2.

Table 2: Summary table of results from the reconstruction performance. The efficiencies are shown for primary $e^\pm$. All numbers are calculated for a momentum range [0 – 6] GeV/c.

Efficiency [%]	A-A	C-C	A-C	C-A
UrQMD Au-Au central at 8 AGeV				
TRD tracking	90.5	90.8	90.6	90.6
TOF matching	93.3	93.4	93.4	93.4
Global efficiency	79.9	80.4	80.1	80.1
El. id. efficiency	78.9	79.3	79.0	79.1
Pion supp.	36.9k	35.6k	33.9k	34.5k
UrQMD Au-Au central at 12 AGeV				
TRD tracking	89.9	90.2	90.1	90.1
TOF matching	93.1	93.3	93.3	93.2
Global efficiency	77.4	77.9	77.7	77.6
El. id. efficiency	76.3	76.8	76.6	76.6
Pion supp.	19.6k	19.7k	19.5	20.2

Summary. Four different variants of the RICH geometries with aluminum and carbon mirror support structure were tested. Overall, the difference in results for all geometries is at the 1% level. The contribution of the pillar and belt materials is approximately the same. Thus, in absence of a clear argument for carbon pillars, the RICH mirror support structure will be built from aluminum.

RICH mirror distortion from holding structure gluing process

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In previous reports, results from QA tests were presented to characterize the CBM RICH mirror quality [1]. Latest studies showed inhomogeneous distortions at those positions, which were glued to the aluminium plate of the mounting structure [2]. For mounting the mirror with low material budget, three aluminium plates of 40 mm diameter and 2 mm thickness are used for each mirror to attach the mirror to the holding structure thus fixing its position.

These distortions have been studied and characterized with D0 measurements which are usually used to measure the homogeneity of the full mirror tile.

For the D0 measurement a point like laser is reflected by the mirror to a camera. D0 is defined as the diameter where 95 % of the integrated light intensity is reflected to. This method provides the radius of curvature of the full mirror tile, or can be used to determine the radius of curvature of a certain local area, while the rest of the reflecting area is covered by a mask. We compared the silicon based RTV157 glue with the epoxy resin Araldite2012 by performing systematic studies in terms of the amount of glue, the pressure while curing, the curing time, and the shape of the holding structure aluminium plate. As result of these measurements, we find that the extent of distortion can be minimized by using silicon based glue instead of epoxy resin. In addition, it is important to reduce the amount of glue to a minimum, which in our case is ≈ 0.3 g per aluminium plate. The time of curing under pressure and the weight used for curing do not effect the strength of the distortion.

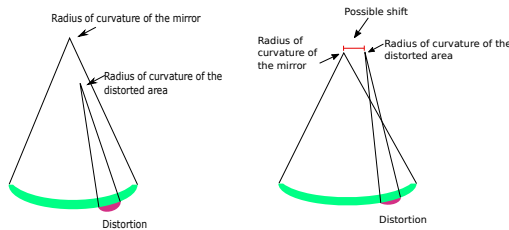


Figure 1: Left: distortion which changes the radius of curvature of the distorted area, Right: distortion which shifts the focus of the distorted area

In figure 1 two different kinds of distortions are shown schematically, which might influence the quality of the ring reconstruction. The results of measurement of the radius of curvature (r_0) of a full mirror tile and of a slightly distorted area is shown in figure 2. Comparing the two minima of the distributions, we clearly see a 10 mm difference in r_0 towards smaller values for the distorted area. The glued alu-

minium plate obviously contracts the glass slightly. For a stronger distorted area these values reach up to 25 mm. Deviations of this magnitude have indirectly been simulated in context with the optimization of the RICH geometry [3] and the influence in ring quality is rather small.

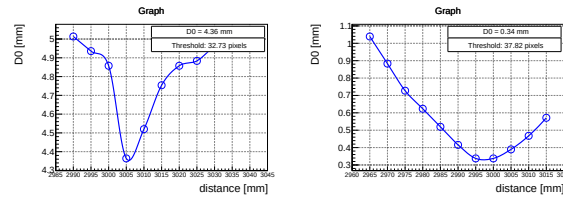


Figure 2: Results of the D0 measurement for the whole mirror on the left, and for a slightly distorted area on the right (0.5 g epoxy glue, 0.7 kg weight)

In addition to characterizing the radius of curvature of the distorted area we also measured a possible shift of the focus which is schematically shown in figure 1 on the right. Therefore, we repeated the D0 measurements and focused on the center of gravity of the light intensity.

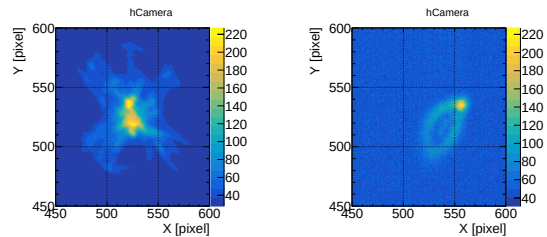


Figure 3: Spatial distribution of the light intensity, left for the whole mirror, right for the distorted area which we investigated

The measurement shows a shift of the center of curvature which is in the order of 0.33 mm. Compared to the size of a single CBM RICH MAPMT pixel of $6 \times 6 \text{ mm}^2$ this is neglectable.

This, the resulting distortions which have been investigated are rather small and will not harm the quality of the RICH.

References

- [1] J. Bendarouach et al., CBM Progress Report 2019, p.57
- [2] D. Ivanishchev et al., CBM Progress Report 2019, p.47
- [3] S. Lebedev et al., CBM Progress Report 2019, p.55

Comparison of the reflectivity for HfO_2 and MgF_2 coatings of RICH mirror prototypes

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In 2019 12 new mirror prototypes have been delivered. They differed in size but also in the protective coating of the reflective Al layer. Eight prototypes were delivered to PNPI for implementation in the mirror wall prototypes, 4 remained at University Giessen for further tests, see [1].

The reflectivity and its long-term behaviour of the hafnium (HfO_2) coated mirrors has been measured in order to investigate a possible influence of air humidity and higher temperatures. Therefore, the mirrors were placed in a climate chamber for altogether 60 days. For the first half of this period, the ambient conditions were $T = 30^\circ\text{C}$ and $H = 50\%$. For the second half, they were increased to $T = 40^\circ\text{C}$ and $H = 70\%$. In between, reflectivity measurements were done every 7-10 days.

As shown in Fig. 1, no effect to the integrated reflectivity can be found. The fluctuations are well within measurement errors.

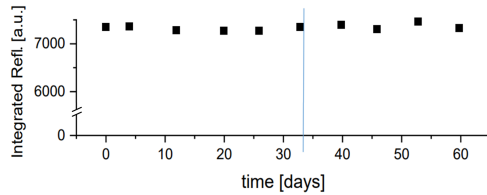


Figure 1: Integrated reflectivity of the HfO_2 coated mirror as a function of time spent in the climate chamber.

Next, the resistance of the hafnium coating to dirt, fingerprints, etc. had been tested. Marks with a nitrile glove, a cotton glove and a finger were made on the surface. In contrary to the others, a clean cotton glove leaves almost no marks. Afterwards each mark was cleaned with a cloth. The prints vanished almost completely, however no cross-check of reflectivity was done so far.

A comparison of the reflectivity spectrum of three HfO_2 and a MgF_2 coated mirror as well as our very first test mirror (MgF_2) is shown in Fig. 2. In general Hf coated mirrors have a higher reflectivity in the UV, however there are quite large differences between the mirrors.

In addition, the MgF_2 coating was also tested for mechanical stability by adding fingerprints. Unlike for the HfO_2 coating it was by far not possible to remove the fingerprints, in fact, additionally the surface was scratched by the cloth.

Finally, a qualitative Ronchi test was applied to the hafnium and magnesium coated mirrors. It showed slightly more uniform grid lines on the hafnium coated mirrors thus

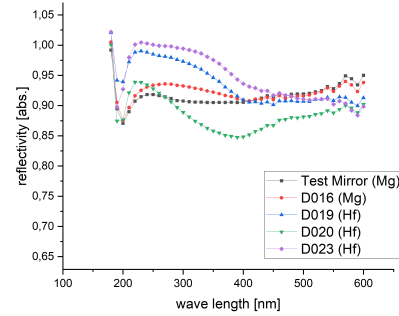


Figure 2: Wavelength dependent reflectivity of the hafnium and magnesium coated mirrors. The correction factor due to the spherical surface is not yet considered and will decrease the values by a few percent.

a more uniform surface there, although both are very good (see Fig. 3).

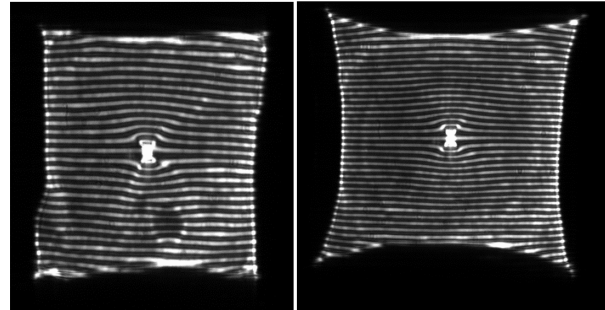


Figure 3: Ronchigrams of the magnesium coated mirror (left) and one of the hafnium coated mirrors (right).

References

- [1] M. Becker et al., this CBM Progress Report.

mRICH status and results of the mCBM beamtime 2020

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Status of the mRICH detector

The mRICH detector is a small size prototype of the future CBM RICH detector which is operated in the mCBM experiment to serve primarily as a test for the newly developed TRB based free streaming detector readout. The detector follows the concept of a proximity focussing Cherenkov detector with two $20 \times 20 \times 3 \text{ cm}^3$ aerogel radiator blocks ($n = 1.05$). The produced Cherenkov photons are detected 10 cm further downstream by 36 MultiAnode PhotoMultiplier Tubes (MAPMTs), arranged on 2×3 front-end backplanes (see Fig. 1). Each backplane is equipped with a combiner board, twelve DiRICH boards and a power module. The DiRICH detector readout is based on Trb-Net and connects to the free streaming data acquisition of mCBM via the AFCK board in mCBM phase-I [1].

The mCBM beamtime in spring 2020 was the first test of the AFCK readout with the fully equipped mRICH detector. During the beamtime only a few DiRICH boards were inactive to provide an extremely stable condition for the full mCBM experiment.

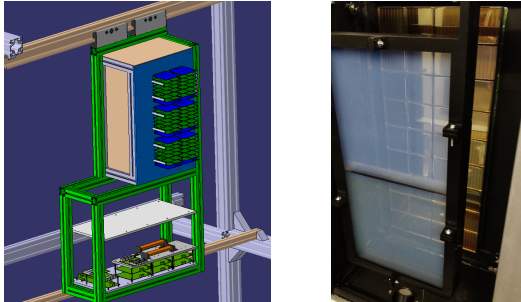


Figure 1: Left: CAD drawing of the full mRICH detector with support equipment below the detector box. Right: View inside the detector with the two aerogel blocks in front and the MAPMT readout plane behind.

Performance of the mRICH

The mRICH detector showed a very reliable performance during the 2020 beamtime campaign. Besides the stable performance of the detector, the analysis of the collected data show very clear correlations to the reference detector mTOF (as well as mT0) both in time as well as in localization of the hits. The analysis and the corresponding correlations will be presented in the following.

The analysis of the data is performed with a fork of cbm-

root, available at https://git.cbm.gsi.de/a.weber/cbmroot/-/tree/phD_Thesis_analysis, commit 40986898.

The analysis relies on *run 831* using a ^{208}Pb beam at 1.06 AGeV impinging on a 0.25 mm gold target foil. The standard trigger windows of the sub-detectors are chosen. *Events* are selected by requiring a minimum number of digis in the various subdetectors: 1 digi in T0, 10 in mTOF and 5 digis in mRICH. In order to decouple timing corrections in the mRICH from the analyzed data, a time correction in between mRICH channels (inner channel delay (ICD)) is derived on run 836 and applied to run 831.

Figure 2 shows the time difference between the mRICH and the T0 detector after a constant time offset correction of -310 ns was applied. A clear correlation between both detectors is seen. The time is shifted to a positive value to improve the event building capabilities. The visible correlation is investigated in all analysed runs and is found to be constant. A time-slice wise analysis of the correlation confirms that no jumps in time between T0 and mRICH are found.

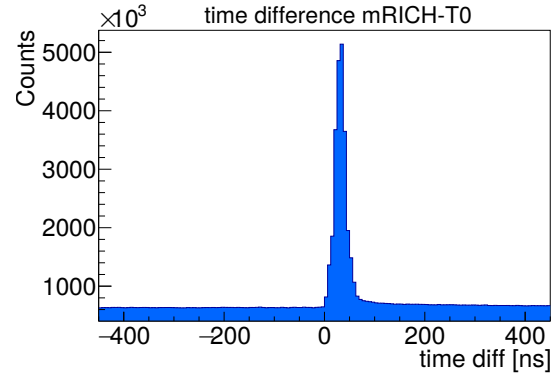


Figure 2: Time difference between mRICH and T0 digis after time offset correction. The time correlation stays constant over all recorded runs.

The event building is applied on the basis of the time-slice data. A cut on the time over threshold of the mRICH hits between 23.7 and 30 ns is applied. The resulting distribution of the hits in the mRICH detection plane is shown in Fig. 3, left. A fairly homogeneous hit distribution in the upper as well as the lower half is visible. The difference in the total amount of hits between the upper and lower half is most likely related to the aerogel radiator block. The block in the lower half of the mRICH is one year older and less transparent. This difference is also slightly visible in

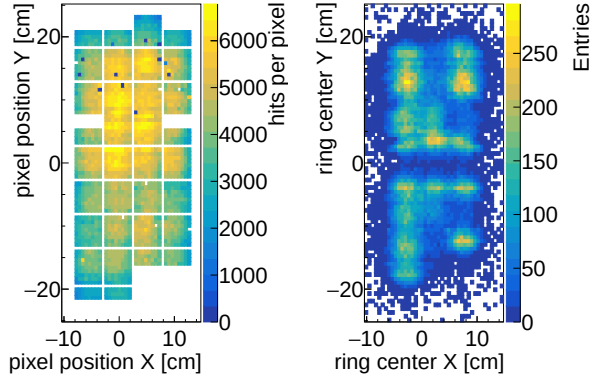


Figure 3: Left: distribution of reconstructed mRICH hits in the detection plane after the application of a ToT cut in reconstructed CBM events. Right: Positions of the centers of the reconstructed rings. It seems as the ring finder prefers a position of the ring center in between two MAPMTs.

Fig. 1, right. Nevertheless the overall distribution reflects the expectation. Moreover, the individual missing DiRICH boards are visible in the edges of backplanes.

The distribution in the r.h.s. of Fig. 3 shows the centers of rings as reconstructed by the ring finder algorithm. The distribution shows perfectly the separation between the lower and upper half with a small block of plastic separating the two aerogel blocks. The positions of the ring center are most likely in between two MAPMTs and finally lead to the inhomogeneous accumulation seen in the plane. The overall position of the enhanced regions matches the results from previous beamtimes, but is still not understood [2].

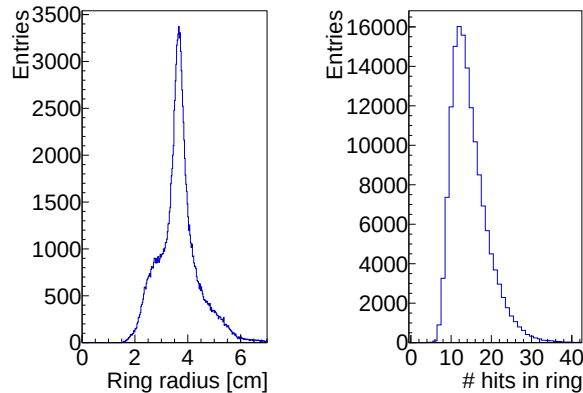


Figure 4: Left: Radii of reconstructed rings in the mRICH detector after event building and ToT-cut. Right: Number of hits per reconstructed mRICH ring.

The two main parameters of a ring are the number of hits in a ring and the radius of the ring. Both are shown in Fig. 4. The ring radius, after the application of the ToT cut and the event building, peaks at a value of 3.6 cm. An additional small tail down to a radius of 2 cm is visible. The number of hits per ring peaks around 12 hits. Both distribu-

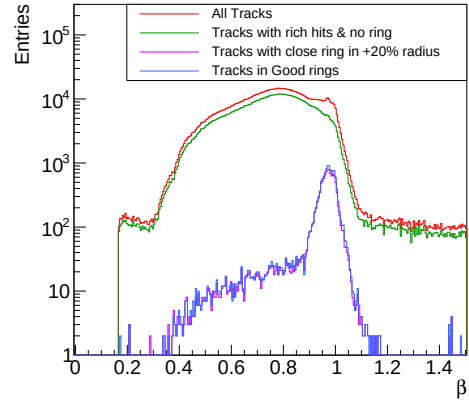


Figure 5: Distribution of reconstructed relativistic velocities β of mTOF tracks in different conditions. Red: all tracks. Green: Tracks, with hits in the mRICH, but no found ring. Violet: Tracks with a distance to a close ring smaller 120% of the radius of the ring. Blue: Rings with a radius between 2.0 and 4.2 cm and a track in a distance smaller 120% of the radius.

tions agree with expectations and confirm the results from previous beamtimes (see [2]).

Next to the analysis of mRICH parameters, the mTOF detector is used for the analysis of spatial correlations. The use of mTOF tracklets and their extrapolated position in the mRICH detection plane are part of the spatial correlation analysis. Fig. 5 shows the distribution of the relativistic velocity β of the tracks under different conditions. The existence of a ring near the mTOF track leads to an enhancement in the β -spectrum between 0.9 and 1.1. In the low β -region, only a small fraction of the tracks are assigned to a ring, demonstrating the strong hadron suppression capability of the mRICH detector.

A cut in the β -distribution can now be used to improve the spatial correlations. First, we show in Fig. 6 the correlation between mTOF hits and mRICH hits in X - and

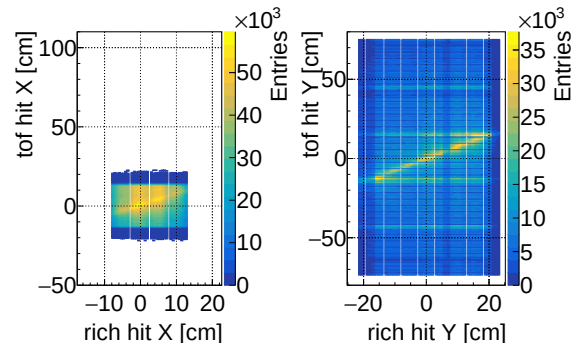


Figure 6: Spatial correlation between the mTOF and mRICH hits in X - and Y -direction. Both directions show a clear correlation. In the X -direction, an additional background increasing towards the main beamline is visible.

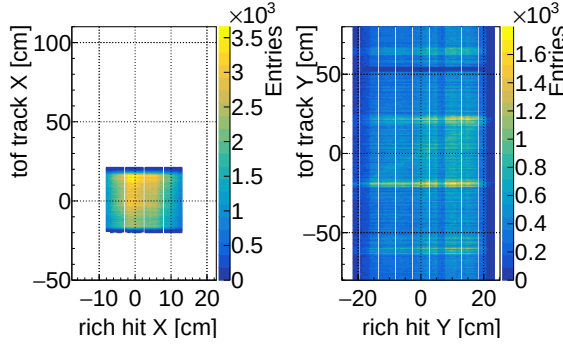


Figure 7: Spatial correlation between mTOF tracks and mRICH hits in X- and Y-direction. The mTOF tracks have a $\beta < 0.9$ respectively $\beta > 1.1$. Only a very tiny correlation in Y is left.

Y-direction with only a ToT-cut applied. Even in this very raw distribution, a correlation is clearly visible. In the X-direction an additional background increasing towards the beamline is found. In Y-directions the overlapping regions between individual mTOF modules are also visible.

Figure 7 shows the same distribution with mTOF tracks instead of hits and with an additional cut on the β -value of the tracks. Only tracks with $\beta < 0.9$ and $\beta > 1.1$ are accepted. The resulting distribution shows, that only a very small correlation in Y survives the cut on the velocity and consequently most of the mRICH hits are correlated to a track of the mTOF with a β range close to 1. Moreover, Fig. 7 shows that most of the background in X-direction is related to the selected beta range.

Finally, Fig. 8 presents the correlation between mTOF tracks and mRICH ring centers. The mTOF tracks are selected to be in the velocity range $0.9 < \beta < 1.1$ with 3 or 4 hits per track and with a ring reconstructed in mRICH. The rings are required to have a radius between 2.0 and

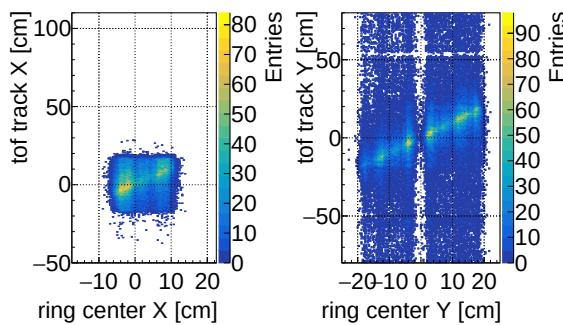


Figure 8: Spatial correlation between mTOF tracks and mRICH ring centers. Only tracks with β close to 1 and with 3 or 4 hits assigned are shown and with reconstructed mRICH radii between 2.0 and 4.2 cm. A clean correlation between tracks and rings is seen with enhancements in the region of preferred ring centers.

4.2 cm. A clean correlation is seen in this higher level of correlation between tracks and rings. The inhomogeneous distribution is related to the clustering of rings center in between MAPMTs and still a matter of investigation.

Next to the investigation of spatial correlations and basic detector parameters like ring radii, the timing precision of the detector has been investigated. As introduced in the beginning, a correction in between the individual channels (ICD correction) of the mRICH has been performed. After five iterations of ICD corrections, the distribution of the time of hits on a ring relative to the mean ring time is constant. The resulting time resolution in run 831 is found to be $\sigma = 496$ ps. This value is worse as compared to previous measurements, but is influenced by the performance of the ring finder and the distortions in this process due to the hits in the center of a ring.

The mRICH detector showed a very reliable performance over the full beamtime. Nevertheless an increase of the rates in mCBM pushed the mRICH phase-I readout to its limits. In runs with a thick target and with beam intensities beyond $2 \cdot 10^7$ ions/spill, the buffers on the FEE reached their limits. The limitations of the mRICH detector are mostly due to the readout intervals and the limited data size of UDP packages. A change to the phase-II readout with new features in the data readout and no limitation by UDP packet sizes will open new capabilities in higher rates. A test with a changed setup in phase-I already confirmed the potential improvement. Nevertheless, the main limitation of the mRICH detector is the increased radiation with higher interaction rates. The FEE suffers from the operation in acceptance with rates above approx. $1 \cdot 10^8$ ions/spill.

The analysis of the mRICH data of the mCBM beamtime in 2020 with the phase-I readout concept and a fully equipped mRICH detector shows a great performance of the detector. The velocity distribution demonstrates for the first time the strong hadron suppression capabilities of the RICH detector. Also, the time and spatial correlations on different levels of the detector data confirm the functionality of the readout concept and pave the way towards a CRI based detector readout in mCBM phase-II.

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A new lab setup for studying DiRICH and PMT properties

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A new DIRICH test setup has been prepared in the Wuppertal lab to complete the characterization and performance study of the DIRICH frontend readout electronics in further detail with special emphasis on high count rate conditions. The setup is based on the former COSY prototype box [1] and allows to read out several MAPMTs simultaneously using a fully equipped DIRICH readout module with up to 6 MAPMTs and up to 12 DIRICH frontend cards. A low-current DC powered LED is used to illuminate the MAPMTs homogeneously and to simulate large background rates, where at the same time a pico-second pulsed laser will be used to project a ring-shaped pattern of photons onto the MAPMTs (very similar to a Cherenkov ring) with adjustable photon yield (0-30 photons/pulse). This will eventually allow to study the ring reconstruction performance as function of PMT occupancy and overall data rate, and to tune the optimal readout parameters.

In a first commissioning measurement, this setup was used to re-evaluate the neighbouring-channel charge-sharing cross talk of the H12700 MAPMTs (8×8 pixels) in comparison to its predecessor H8500. This cross talk is caused by parts of the electron avalanche leaking into neighbouring pixels and causing a signal above threshold. A similar study has been done already in the past [2] using CERN testbeam data, but using different (nXYter based) readout electronics and slow signal shaping. The new results presented here are based on the exact same DIRICH readout as used in the later CBM RICH detector and allow now to quantify the amount of cross talk (to be included in Monte Carlo simulations), and to study the influence of DIRICH-specific readout parameters, as for example the applied threshold value.

Measurement principle

The measurement presented here is based on the illumination of the MAPMT with short pulses (~ 5 ns) of 2-4 detected photons on the MAPMT per pulse. A reference signal from the pulse generator is fed into the data and used to select “good” hits based on a time cut around the prompt peak. The charge sharing cross talk into a neighboring channel is then estimated as follows:

- Only events with two simultaneous “good” hits on the MAPMT are selected (characterized by a relative time difference between reference pulse and PMT signal of less than 10 ns, and a ToT (Time over Threshold) ≥ 3 ns).

- The distance between the positions of the two hits (counted in number of pixel) is histogrammed.
- The obtained 1D distance distribution is compared to a simple Monte Carlo simulation where two hits are randomly thrown on the MAPMT.
- In the simulation, each pair-event is weighted according to the product of the total number of detected hits of both participating pixels in the measurement in order to correct for efficiency variations or a non-uniform illumination of the MAPMT which might distort the statistical distribution of measured distances in data.
- The simulated distance distribution is scaled to the measurement such that optimal agreement for all distances $d \geq 2$ is achieved. Any excess yield of measured distances $d = 1$ can now be contributed to the charge-sharing cross talk.
- Finally, the relative cross talk contribution is quantified using the following formula:

$$F_{cross\ talk} = \frac{N_{data,d=1} - N_{sim,d=1}}{N_{sim,all}} \times 100\% \quad (1)$$

Where $N_{data,d=1}$ and $N_{sim,d=1}$ are the number of entries in data and simulation histograms corresponding to distance $d = 1$. $N_{sim,all}$ is the total number of simulated pair events.

- The same procedure is repeated for four different PMTs and for five different threshold values.

Results and Discussions

The preliminary results of the first measurement are shown in Fig. 1.

The measured distance distribution matches very well the simulation results, with the only sizable difference being observed in the first bin corresponding to the cross talk into neighbouring channels. The H8500 MAPMT (Fig. 1 top) shows a sizable amount of cross talk which is much reduced in case of the H12700 MAPMT (Fig. 1 bottom).

Results for measurements on 4 different MAPMTs (2x H8500 and 2x H12700) are summarized in Fig. 2, with relative cross talk being plotted as function of DIRICH threshold value (threshold after pre-amplification).

The observed cross talk for H8500 MAPMTs is in the order of 10-15 %, which is in good agreement with the earlier

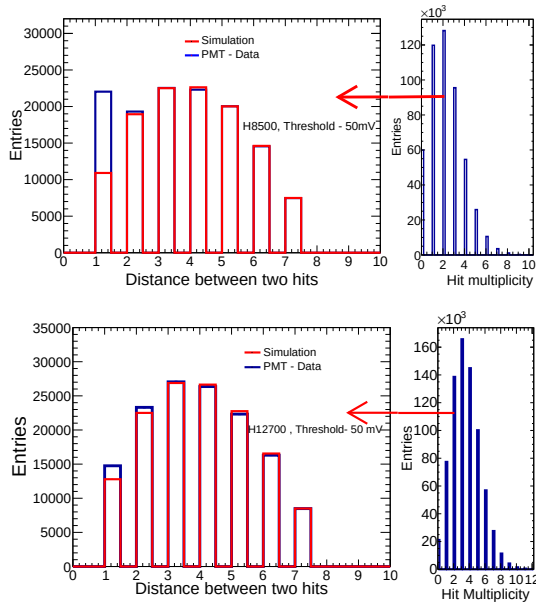


Figure 1: Left: Measured distance between two hits for data (blue) and simulation (red). Right: Hit Multiplicity of detected photons per event, for a H8500 MAPMT (upper plot), and a H12700 MAPMT (lower plot). Threshold: 50 mV (after preamplification).

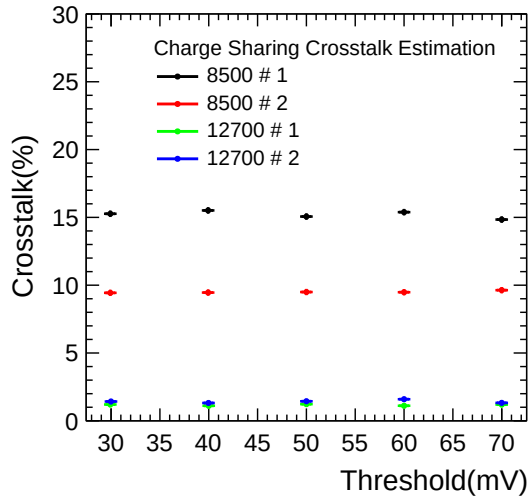


Figure 2: Estimation of neighboring channel charge sharing cross talk

measurements. In contrast, the cross talk for both H12700 MAPMTs is only in the order of 1-2%. This has already been expected based on the MAPMT series testing results, but could now be confirmed with the full DIRICH readout chain.

As a second interesting result, the cross talk contribution seems not to depend on the applied readout threshold. This comes as bit of a surprise, since the total amount

of charge generated by a photon is fixed, and sharing this charge over two channels should result in a reduced signal amplitude and thus reduced charge sharing contribution at higher threshold values. However, the range of threshold values covered in this study resembles realistic threshold values as would be used in the real experiment. All studied thresholds are still well below the average single photon signal, in the order of 10 % to 20 % of the typical single photon charge. The expected reduction of charge sharing would probably be observed at much higher threshold values only.

Outlook

The new lab setup has been taken into operation and now allows for different dedicated test measurements in particular on the high rate behavior of MAPMT and DIRICH readout, complementing the ongoing performance study of the DIRICH readout chain in the HADES RICH detector which already proved the large potential of the new readout electronics.

We will now continue with commissioning the laser-based ring image source. This will allow to study quantitatively in addition the effect of cross talk caused by capacitive coupling between common last dynode and anode pads on the MAPMT, which only occurs for large MAPMT hit occupancies.

These measurements will be essential for the upcoming production readiness review of the CBM RICH DIRICH readout electronics scheduled for Mai 2021.

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RICH simulations using GEANT3 and GEANT4

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In this report, results of RICH simulations using GEANT3 and GEANT4 as transport engines are compared. The first simulation results using GEANT4 showed that the RICH detector simulation has problems, no photons were registered on the PMT planes. It was found that the current implementation of the mirror optical properties, namely, mirror reflectivity, works only for GEANT3 but not for GEANT4. Therefore, photons were not reflected properly by the mirrors. Several approaches of the mirror reflectivity implementation were implemented and tested. The finally selected one uses the GEANT4 mechanisms of the setting of optical properties. It consists of 3 main steps: 1) definition of the optical surface, 2) setting the reflectivity for this optical surface, 3) setting the skin surface for the mirror volume. The mirror reflectivity in dependence on photon energy (see left plot of Figure 1) is defined inside the *CbmRich* class, whereas for the old GEANT3 implementation it was done in the *media.geo* file. The new implementation works only for GEANT4 and does not work for GEANT3, thus one has to keep the old implementation as well for backward compatibility. In the *CbmRich* class one of the implementations is chosen based on the used transport engine.

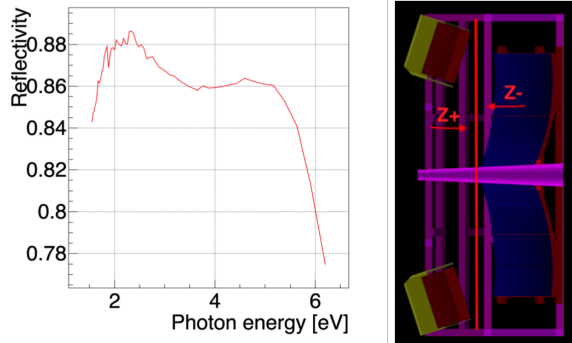


Figure 1: Mirror reflectivity in dependence on photon energy as it is implemented in *cbmroot*.

After fixing this, a new problem was observed. The number of MC points in RICH were comparable for GEANT3 and GEANT4 simulations but the number of RICH hits were 40% less for the GEANT4 simulation. It was found that a kind of a boundary problem exists: some coordinates of MC RICH points are not registered inside the deepest *pmt.pixel* node but several levels higher in the hierarchy. The reason of such GEANT4 behavior is not clear but it was fixed using a small shift of the *z*-coordinate.

Results of the comparison are presented in Figure 2. The

main observation is that the photon energy distributions after photon reflection from the mirrors are different for GEANT3 and GEANT4 simulations but they are almost the same before reflection. The photon energy distribution after photon reflection for the GEANT4 simulation matches the reflectivity curve (Figure 1, left) which indicates that the reflectivity values are properly taken into account. However, for the GEANT3 simulation the photon energy spectra were constantly increasing and it could indicate that there are problems with the mirror reflectivity implementation in GEANT3.

Comparing the number of MC points and hits per electron ring in the RICH, one observes the following: The mean number of MC points for GEANT3 is 229, for GEANT4 it equals to 230. The mean number of hits are 32.5 and 32.9 for GEANT3 and GEANT4, respectively.

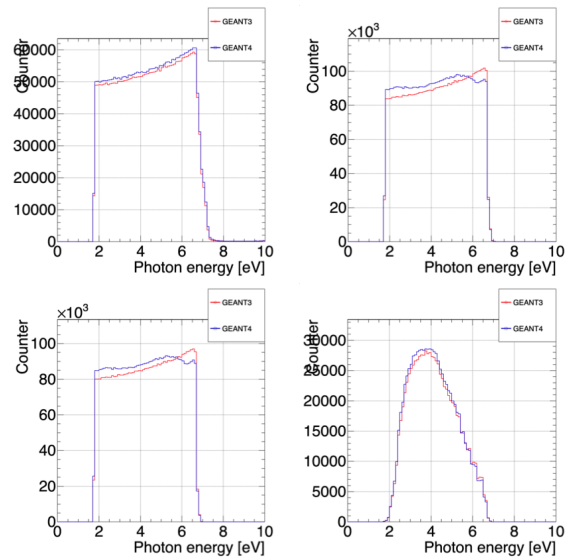


Figure 2: Photon energy spectra at different steps in the simulation. Top-left: Sensitive plane, before photon reflection (Z+). Top-right: sensitive plane, after photon reflection (Z-). Bottom-left: MC RICH points on PMT plane. Bottom-right: RICH hits. See also right plot of Figure 1.

Summary. The simulation of the RICH detector works with GEANT4. The results of simulations using GEANT3 and GEANT4 showed similar number of points and hits in RICH but different photon energy spectra.

Investigation on impact of higher material budget in STS on LMVM

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During the development of the STS detector its material budget was significantly increased by taking into account holding structures, electronics, cooling, and more. This increase in material budget lead to large increase of secondary electrons in the RICH detector. For illustration, Fig. 1 shows the vertices of photon conversions comparing the STS versions v16g and v19a. In general, about 35% more hits are seen in the RICH detector due to the increased STS material budget.

To investigate if and how much this change affects the LMVM studies, two full chain simulations with 5 million events each were performed with the STS versions v16g and v19a. The sis100.electron geometry had been used here with a Au+Au collision energy of 8 AGeV (detector versions: MVD v17a_tr; RICH v17a_1e; TRD v17n_1e; ToF v16e_1e).

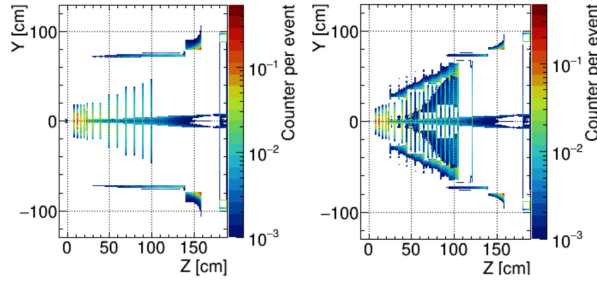


Figure 1: Vertices of photon conversions in the STS for both the v16g (left) and v19a STS versions (right), shown in the y-z-plane.

Tracking efficiency and electron identification efficiency are more or less unaffected, however the pion suppression decreases in the RICH by 30%. This is because the additional secondary electrons usually do not have a reconstructed track and thus can by chance be matched to the frequent pion tracks. As shown in Fig. 2, the electron identification efficiency decreased from 70.7 % to 69 %, with STS, RICH, TRD and ToF included. However, the pion suppression decreases by approximately 18 % considering the RICH, the TRD and the ToF detector.

Fig. 3 shows the final invariant mass spectra. Still, the signal-to-background ratio did not yet deteriorate a lot due to the high combined pion suppression power of RICH and TRD. However, at some point this will break down, so that every additional material budget in STS has to be chosen carefully.

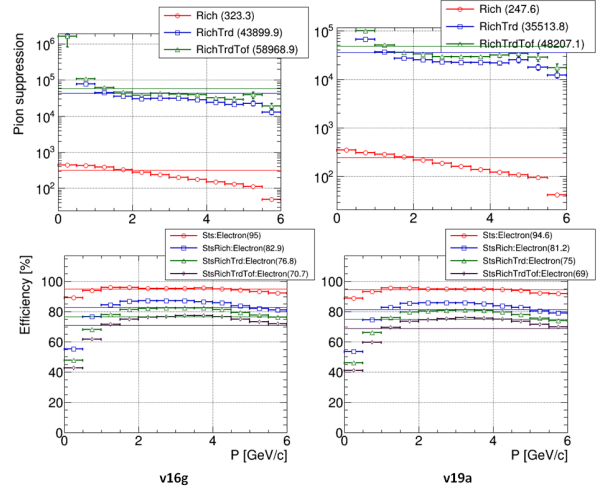


Figure 2: Pion suppression (top) and electron identification efficiency (bottom) for the STS v16g (left) and v19a (right) versions.

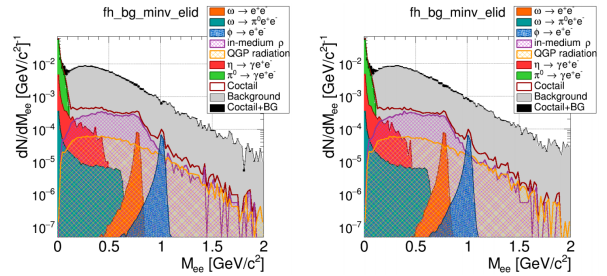


Figure 3: Invariant mass spectra of 5 M events after electron identification for the STS version v16g (left) and v19a (right), central Au+Au collisions at 8 AGeV beam energy.

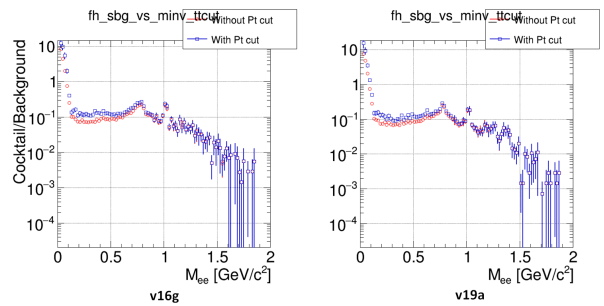
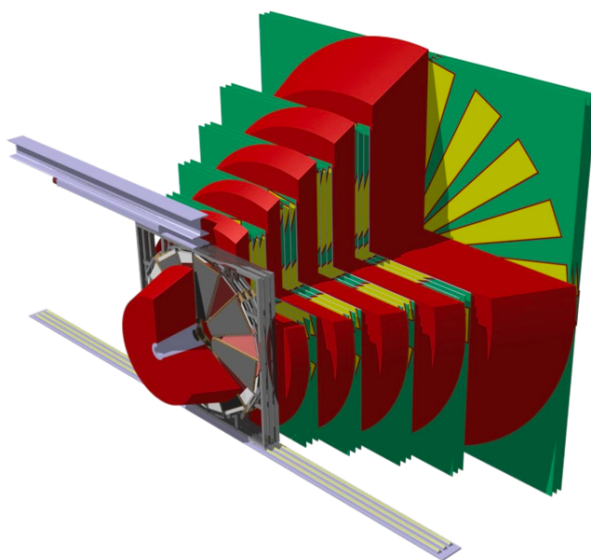


Figure 4: Signal-to-background ratio with and without additional pt-cut for the LMVM spectra for the STS versions v16g (left) and v19a (right).

Muon Detection System



Muon Chambers (MuCh) for the Compressed Baryonic Matter (CBM) experiment at FAIR: a status report

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The development activities of various subsystems of the Muon Chamber (MuCh) system of CBM are in very crucial phases and continued in full swing even during the pandemic period. During this year major emphases were on (a) mini-MUCH data taking and analysis (b) review of the CDR of the Low Voltage distribution system and (c) review of the CDR of the MUCH mechanical system mainly on the system related to the superstructure and concepts on absorber, platform among others (d) development of production infrastructure like a dedicated clean-room at VECC for production of GEM chambers (e) fabrication of the 1st chamber of the 2nd GEM station (f) detailed simulation on the effects of tolerances and of the realistic material profiles and properties of the mechanical structure (g) completion of the fabrication of the LDOs for CBM and (h) elaborate R&D on the RPC detector. Some details of the activities are given below in addition to the contributions in the MUCH section of this report.

- The PNPI and VECC teams have participated in an extensive review of the CDR on MUCH superstructure in presence of several experts. The superstructure, layout and steps of fabrication of different absorbers and the movement system of the platform were presented. There were discussions on various safety aspects including the possible effect of earthquake on the structure. The discussions led to a major modifications in both the 1st absorber layout and the orientation of the cryostat of the CBM magnet. The platform has been divided into two parts, the short platform contains the 1st to 4th absorbers and arrangements for mounting of the detectors in the stations. The 1st absorber will consist of a combination of low-density graphite and concrete blocks and rest of the absorbers are made of iron. The 5th absorber of 1 m thickness will sit on a separate platform with a separate transport arrangements. The movement of the platform during RICH and MUCH modes of operations will be performed using a hydraulic system. An extensive discussion took place on the service (HV, LV, gas, water, fibre) arrangements. Subsequently, the team at VECC has prepared the first draft of the service lines as will be taken from the MUCH-RICH platform to the top of the superstructure. Similar reviews will take place soon on the gas system of MUCH detectors.
- During the period, two real-size GEM chambers have taken data in mCBM during May-June 2020, i.e. during the lockdown period. Indian team joined the data

taking remotely and analysed the data towards extraction of efficiency and correlation with other detectors like TOF, T0. One issue that came up for mMUCH during data taking is the disconnection of link of the FEBs with AFCK during high rate data taking at high voltage. Extensive investigations have since been done in the lab to understand the reason for such a link break. Investigations in the lab reveals that the possible cause is the shorter than required physical gap between opto-couplers used in the high voltage circuit. It is planned to test the observations in the next mMUCH campaign. In the analysis, it has been shown that the TOF tracks projected on the GEM planes can be used to find efficiency in detection of cosmic muons of the GEM chambers. The variation of the response with the available high intensity data have also been analysed.

- After the initial understanding of the response of the RPC detector at the GIF++ muon beams in presence of photon flux, we have procured two chambers of size suitable for the 3rd station and changes in the electrode and chamber parameters have been made for the chamber to be suitable towards high rate operation. One chamber has been tested with cosmic rays and have been found to give > 90% efficiency. This chamber is planned to be installed in the mCBM in the next run for testing at high rate.
- Several major milestones have been reached on the readout electronics front like (a) LDOs have been fabricated by SCL-Chandigarh, India and shipped to GSI for use in the readout boards of STS and MUCH (b) design of the FEB board has been completed and the first few boards have been fabricated and under tests now (c) the CDR of the Low Voltage Distribution Board (LVDB) has been completed for a system with FPGA-based control (d) extensive tests have been done on optimization of the calibration time of the STS-XYTER ASIC.

During the year 2021-22, several MUCH reviews are in line on GEM, RPC, gas and HV systems and we hope that we will end up with a robust MUCH detector system suitable for production.

Implementation and performance simulation of realistic design of the GEM chambers for the first two stations of MuCh

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Gas Electron Multiplier (GEM) detectors are placed in the 1st two stations of Muon Chamber (MuCh) detector system due to the foreseen high particle densities. Based on detector R&D it has been decided that these GEM chambers will be operated with Ar/CO₂ gas mixture in 70:30 volume ratio. The drift gap of the chambers will be of 3 mm thickness, the transfer and induction gaps will be of 2 mm thick. In MuCh simulations performed within conventional CbmRoot framework, [1, 2], the Aluminium cooling plate of 1 cm thickness, 35 μ m Copper for drift and readout plane, G-10 plane of thickness 3 mm for readout PCB and only the 3 mm drift gap is implemented as a part of the active volume filled with pure Ar gas as the active medium for registering the spatial location of the energy deposition by the incident ionizing radiation inside the active gas volume. The subsequent generation of primary electrons and their amplification is implemented in the digitization of the Monte Carlo (MC) MuCh points. To make the simulation more realistic with minimal change in the existing framework, passive volumes (of 6 mm thickness) are implemented in the simulation and the gas mixture is changed from Ar to Ar/CO₂ in 70:30 volume ratio. The effect of PCB and drift planes are investigated earlier and reported in ref [1]. In Fig. 1, the detail configuration of a GEM chamber is shown. In order to check the efficacy of our existing model of detector simulation, these finer aspects of chamber design have been implemented in our simulation and the effects of each modification are investigated independently, on di-muon detection.

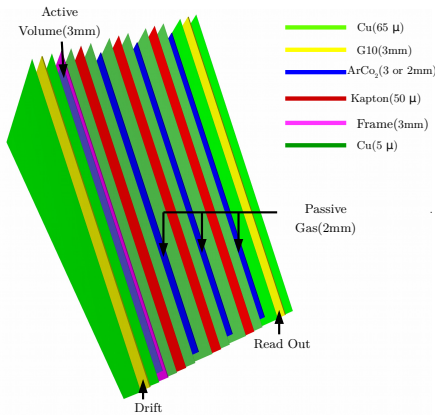


Figure 1: Schematic view the layers of a GEM module. The materials used in the geometry is listed in the legend.

The implementation of Ar/CO₂ gas mixture in 70:30 vol-

ume ratio is done by changing the media definition accordingly. The gas mixture can be implemented by considering the proportion of the weight (ncomp>0) of each material in the mixture or by considering the number of atoms (ncomp<0) of each kind in the mixture. With the ncomp> 0 mixing configuration since Argon has a lower density than CO₂, hence 70% volume of Ar will only account for about 67.8% of the mass. For the remaining 32.2%, though the ratio of the number of atoms is (O:C) 2:1 but as Oxygen atoms are heavier, they account for 72.8% of the mass of the CO₂, 27.2% of the mass of the Carbon and the proportion becomes Ar:C:O $\equiv$ 0.678:0.088:0.234. With the ncomp<0 mixing configuration, the proportion becomes Ar:C:O $\equiv$ 7:3:6. The radial distribution of the MuCh points with different gas mixture configurations for the first two stations are shown in Fig. 2. As evident, there is no significant change in point density as compared to pure Argon gas. Also, no significant change is observed in the reconstruction performance with the change of the gas from Ar to Ar/CO₂ mixture.

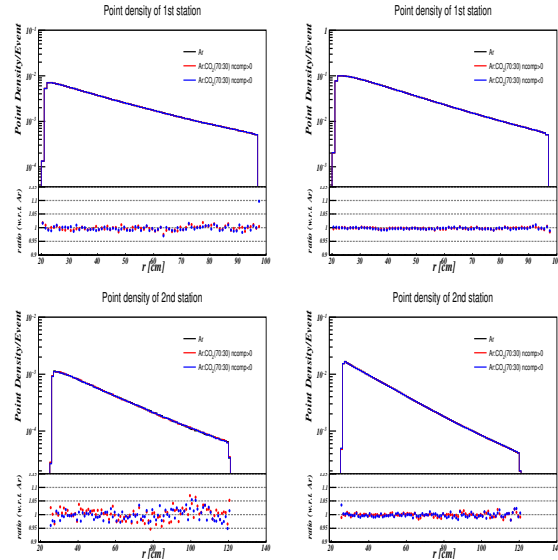


Figure 2: Radial distribution of point density for primary (left) and secondary (right) particles at the first station (top panel) and the second station (bottom panel) with different gas mixtures and gas mixture configurations.

As stated earlier, only the drift volume of the GEM was implemented as an active medium of thickness 3 mm but the actual triple GEM configuration will consist of two

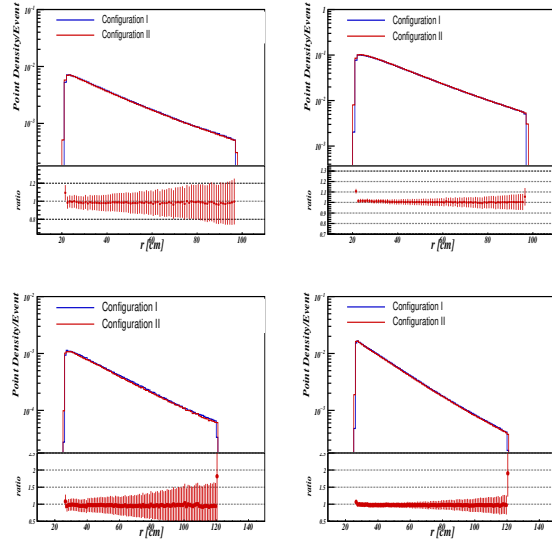


Figure 3: Radial distribution of point density for primary (left) and secondary (right) particles at the first station (top panel) and the second station (bottom panel) for two different GEM geometry configurations.

2 mm thick transfer gaps and one 2 mm thick induction gap. Therefore to make the GEM configuration more realistic, three 2 mm passive gas volumes are implemented in the chamber design. The configuration without pas-

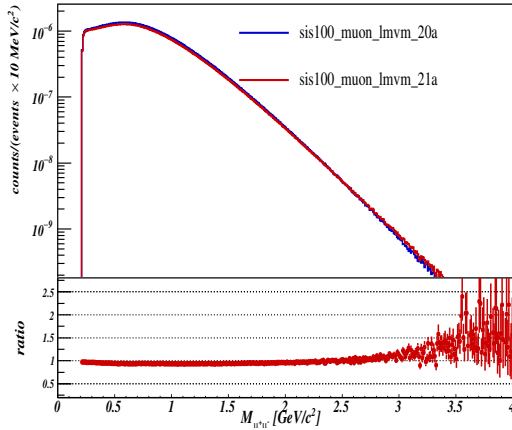


Figure 4: Invariant mass spectra for the combinatorial background for the two different GEM configurations.

sive volume and with only Ar gas is labelled as Configuration I. The other configuration with the passive volumes and Ar/CO₂ gas mixtures is labelled as Configuration II. After the implementation of 6 mm passive gas volumes and Ar/CO₂ gas mixture, the MC point density is calculated and compared with the previous version (without the

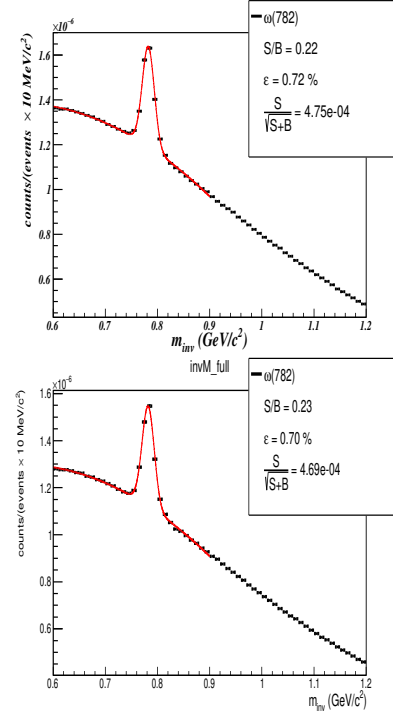


Figure 5: Invariant mass spectra for reconstructed ω meson in central Au+Au collision at 8A GeV for *Configuration I* (Top panel) and *Configuration II* (Bottom panel)

passive volume and only with Ar gas). The comparison of point densities at the first two stations of MuCh is shown in Fig. 3. No significant change in the MC points is observed. To check the effect of passive volume and gas mixture on reconstruction and resulting physics performance, the invariant mass distribution is calculated for the detection of ω mesons in 8 AGeV central Au+Au collisions. The invariant mass distribution for the combinatorial background is shown in Fig. 4 and in Fig. 5, the invariant mass distribution of ω meson is shown. No significant change in the ω reconstruction efficiency and signal to background ratio is observed after the implementation of passive volume of thickness 6 mm and Ar/CO₂ gas mixture in 70/30 ratio.

An internal note containing a more detailed description of this work is under review and will be communicated shortly.

Acknowledgements

The authors would like to thank A. M. Ahrens of University of Münster for his useful suggestions in the course of this study.

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Detailed crosstalk study of a prototype Bakelite RPC for the 3rd and 4th stations of CBM-MuCh

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Introduction

A prototype single gap (gap size 2 mm) Resistive plate chamber (RPC) has been tested at the GIF++ test beam for the 3rd and 4th stations of CBM-MuCh. The chamber is made of bakelite plates (area 30 x 30 cm²) of bulk resistivity ($3.5 \times 10^{10} \Omega\text{-cm}$) and inside of those plates are double-layered linseed oil-coated. The detector has shown promising results at the GIF++ test beam using a front-end readout electronics MuCh-XYTER 2.0 [1]. GIF++ results indicated larger cluster size i.e., higher crosstalk between strips. Large cluster size could be the result from two sources, i.e., large avalanche size or crosstalk between readout strips/pads [2]. Our main aim in this report is to determine the reason of large cluster size values. This work is in the continuation of the crosstalk results reported in the last CBM progress report. On the last reported results, we have seen that higher the percentage of SF₆, larger is the crosstalk because of the high applied voltage. Also, preliminary results have shown the cluster size doesn't depend on the size of the readout strips/pads on the PCB, rather the total number of read out strips/pads remain constant for the same gas mixture ratio as well as the same application high voltage [2]. In this study, we have decreased the SF₆ percentage and repeated the study with two different percentages of SF₆. Also, we have studied the cluster size with three different sizes of readout units like the old report.

Experiential Setup

A cosmic ray bench (Fig.1) has been setup to test the detector. Three scintillator detectors have been used as 3F-coincidence for triggering purpose. The dimensions of the scintillators are 3.0 cm × 3.0 cm, 7.0 cm × 1.5 cm and, 1.5 cm × 1.0 cm. The trigger area has been confined to a small area to accurately determine the number of pads getting hit due to crosstalk. A mixture of gases with two different ratios, Gas I : R134a: iC₄H₁₀ : SF₆ :: 95.0 : 4.5 : 0.5 and, Gas II : R134a: iC₄H₁₀ : SF₆ :: 94.0 : 5.0 : 1.0 have been used for testing the detector. Three readout PCBs have been used individually for signal processing.

PCB P1: A 10 cm × 10 cm readout panel with no ground plane consisting of pads of dimensions 4 mm × 4 mm.

PCB P2: A 30 cm × 30 cm PCB with a pad size (2.8 cm × 2.8 cm) with no ground plane,

PCB P3: A strip readout PCB of 30 cm × 30 cm size covered by 2 mm wide long strips [2].



Figure 1: Setup of RPC with the finger scintillator and PCB P1.

To reduce the system noise and accquing data via MuCh-XYTER 2.1 at a lower threshold, several precautions have been adopted, like the introduction of a low pass filter between the HV module and RPC, placement of the detector inside a copper box, a common grounding scheme between the PCB, electronics, shielding box, HV connection[2]. A dedicated number of FEBs have been used for data taking from RPC, and the trigger scintillator. The data were acquired at a MuCh-XYTER threshold of 12 fC in a controlled lab environment.

Experimental Results

Results with Gas I (0.5 % SF₆)

We have obtained a time correlation peak between the scintillator trigger and the RPC detector at 9.8 kV with PCB P1 shown in Fig. 2. We have calculated that the cosmic muon detection efficiency of the prototype is ~ 88 % at 9.8 kV from the time correlation spectra. At this voltage, the cluster size of RPC is ~ 12, i.e., 12 pads have been hit when a cosmic muon falls on the detector. The projection of the pad distribution in a single axis shows a cluster size of ~ 3.8 (# of pads), i.e., ~ 1.6 cm in one direction. We can conclude that the cluster size is confined within a maximum of 2.0 cm × 2.0 cm region. This result is in proper agreement with the ALICE results where the cluster size (in terms of cm) with 1 cm strip size was 2.0 cm [3].

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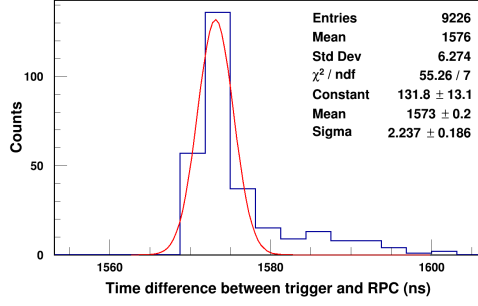


Figure 2: Time correlation spectra between the scintillator trigger and the RPC data at 9.8 kV with PCB P1.

The prototype RPC alongwith PCB 2 has also shown promising results. Fig. 3 shows the two-dimensional representation of pads. The pad corresponding to the yellow region refers to the triggered area. Unfortunately the pads pinpointed as 'D' mark are dead MuCh-XYTER channels.

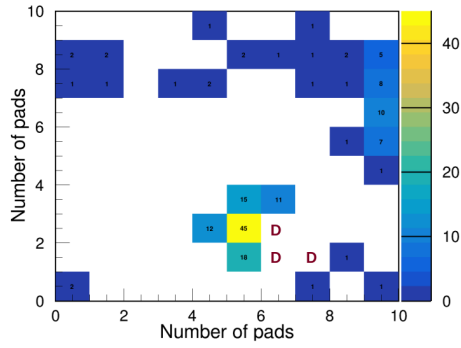


Figure 3: Distribution of Pads in PCB 2 at 9.8 kV.

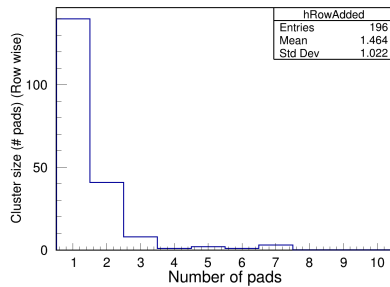


Figure 4: Cluster size distribution along row-wise in RPC in PCB 2 at 9.8 kV.

The cluster size distribution along row-wise and column-wise have been shown in Fig. 4 and Fig. 5 respectively. The measured cluster size with 2.8 cm x 2.8 cm pad is 6.0 cm which is in close agreement with the ALICE RPC cluster size result, i.e. 4.8 cm of 4.0 cm strip width [3]. The comparison of cluster sizes have been presented in a tabular form in Fig. 6.

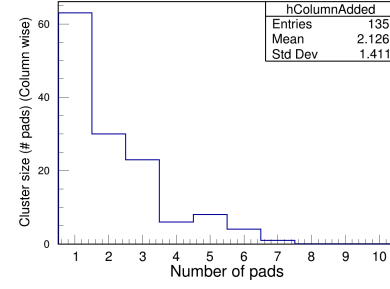


Figure 5: Cluster size distribution along column-wise in RPC in PCB 2 at 9.8 kV.

Our Prototype RPC Results				ALICE RPC Results	
4 mm x 4 mm Pad		2.8 cm x 2.8 cm Pad		1.0 cm strip	4.0 cm strip
2-D Cluster Size	1-D Cluster Size	2-D Cluster Size	1-D Cluster Size	2.0 cm	4.8 cm
2.0 cm x 2.0 cm	~1.6 cm	8.4 cm x 8.4 cm	~6.0 cm		

Figure 6: Comparison of cluster size results. Our data were taken at 9.8 kV with $\sim 88\%$ efficiency without the dead area correction.

We have achieved 85 % efficiency for the detector with PCB P3 at 10 kV with an average cluster size 9. Crosstalk has been confined to a 1.8 cm area horizontally.

Results with Gas II (1.0 % SF₆)

The detector has been operated with a gas mixture containing 1 % SF₆ with PCB P1 and P3. The threshold values at MuCh-XYTER have been kept 12 fC and 16 fC respectively for P1 and P3. The detector achieved 92 % efficiency at 9.9 kV with PCB P1, with a cluster size 16 (# of pads). For P3, it has achieved 86.8 % efficiency at 10.1 kV with a cluster size 8.5. In both the cases, horizontal spread of the cluster size is almost the same, ~ 1.8 cm.

Conclusions

The present results show that the cluster size is in good agreement with the ALICE results. By comparing the results with pad PCBs with 0.5 % of SF₆, we can see that cluster size is dependent upon the size of the pads. For bigger pad size, cluster size is less, and for smaller pad size, cluster size is high. The strip result doesn't quite match with the statement though. We need to further investigate the results.

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Development of front-end chip with interpolation technique for signal peak detection

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The prototype front-end ASIC for MUCH GEM detectors is under development at NRNU MEPhI. ASIC contains 8 analog channels, each followed by ADC, an interpolator and high speed SLVS interface. The analog channels work with both signal polarities and have a 100 fC dynamic range. ENC equals to 1000 el. at 50 pF detector capacitance. ADC has a 10-bit resolution at 25 MHz sampling rate. Both analog channels and ADCs have differential structure. The key feature of the ASIC is a built-in interpolator, which determines a signal peak value and timestamp.

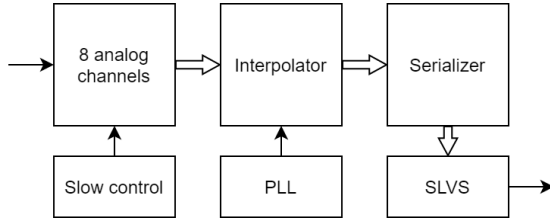


Figure 1: ASIC structure

The interpolator uses the 6-th order Lagrange interpolation polynomial. The data coming from the ADC to the interpolator are synchronized and written to a 6-word ring buffer. If the data matches the signal amplitude ratio pattern: $PTS[0] < PTS[1] < PTS[2] \geq PTS[3] > PTS[4] > PTS[5]$, where $PTS[i]$ is the ADC counts, the interpolator calculates the values at intermediate points, between samples $PTS[1]$ and $PTS[3]$. The values are calculated at three additional intermediate points between adjacent samples. This increases the actual sampling rate of the ADC by 4 times. The values at intermediate points are calculated in the cycle. The calculated value is compared with the previous maximum, and in case the current value is less than the previous one, the maximum is fixed, and the interpolator working cycle is stopped. Figure 2 shows the output of the shaper of the analog channel (ADC input). Interpolated values are depicted by red filled circles between the ADC samples. The errors of peak detection for digital peak detector (conventional approach) and interpolator versus the delay between ADC maximum sample and peak time are shown on Figure 3 [1-2].

In the designed ASIC the interpolator improves the resolution of the system from 10 bit of ADC to 12 bit. An additional function of the interpolator is to determine the time stamp of the signal maximum. The power consumption of the interpolator is 4 mW (32 mW for all 8 channels), the analog channels plus ADCs is within 40 mW, 10 SLVS

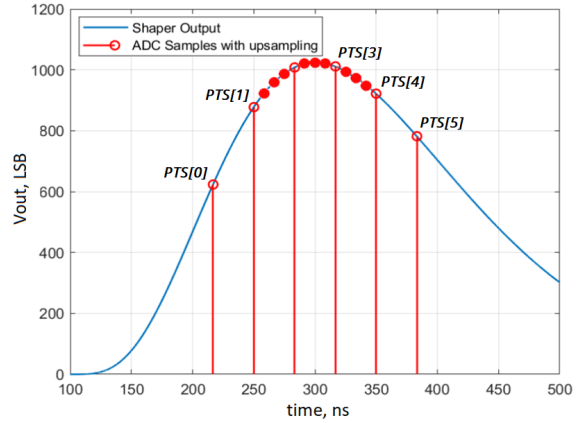


Figure 2: Sampling points

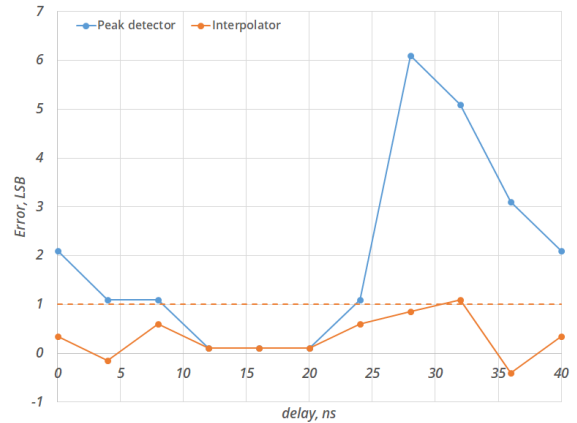


Figure 3: Errors vs signal delay

transmitters add 42 mW. Front-end ASIC has been prototyped in UMC 180 MMRF process in the mid of 2020. Currently the prototyped chips are under tests at lab conditions.

This work was supported by Grant No. 18-79-10259 of the Russian Science Foundation.

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Dynamic range scanning of STS/MUCH-XYTER v2.1 for use with MUCH detector systems

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Introduction

As reported earlier, STS/MUCH-XYTER ASIC is a dual gain ASIC designed to be used for CBM-STS as well as CBM-MUCH detector systems. The CBM-MUCH detector system consists of four stations and out of these four stations, first two stations will be using the Gas Electron Multiplier (GEM) detector while last two detector will be using low resistivity bakelite Resistive Plate Chamber (RPC) detectors. These two detectors have different characteristics in terms of gain as well as design. Due to this, the dynamic range requirement also varies along with other tuning parameters. Initially the ASIC was designed considering the GEM detectors only which requires the dynamic range of 60 fC but after introduction of RPC, the requirement of the dynamic range increased 3 fold to contain the Minimum Ionizing Particle(MIP) energy range of the detector at its operating gain mode. To achieve this requirement, a detailed scanning of the bias parameters has been done at VECC which is presented here.

Test Bench setup

To perform the study, a setup was prepared at VECC using STS/MUCH-XYTER 2.1 Front End Board (FEB). The picture of the setup can be seen in Figure 1. All the channels of the FEB were injected using a charge injector driven by a pulse generator. The charge injector is a specially designed circuit which consists of a 64 number of 1 pf capacitors, a lemo connector for the voltage input and 68-pin 1.27mm pitch dual row ERNI connector which is mating to the FEB connector. This connector is used to inject charge to the 64 channels of the FEB. Two such charge injectors are required to inject the charge to all 128 channels of FEB. The 50 ohm terminator is used at the end of the line of the two connectors to avoid the reflections in the voltage input. The picture of the charge injector can be seen in figure 2. For the pulse generation, Keysight 33600A waveform generator was used. This device was controlled with the python scripts so as to incorporate the flexibility of tuning the parameters within the bias scanning python scripts of the main code. This waveform generator can be tuned in steps as low as 1 mV which converts to 1 fC charge injection with a 1 pf capacitor.

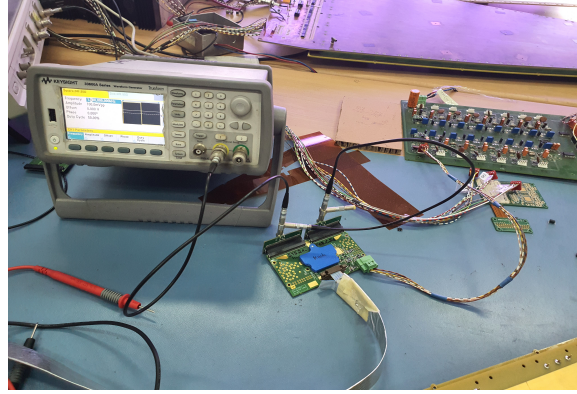


Figure 1: Bias scanning setup of STS/MUCH-XYTER 2.1 Front End Electronics Board at VECC

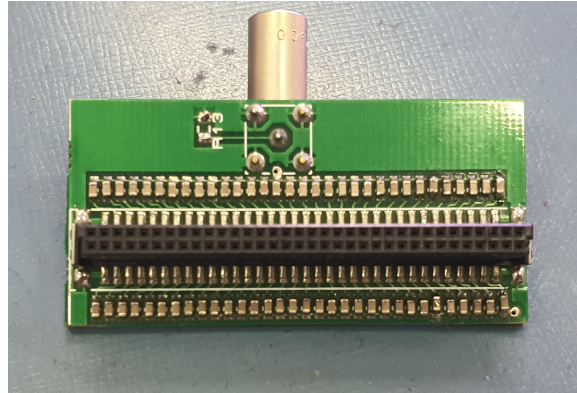


Figure 2: Charge injector designed for CBM-MUCH Front End Board

VrefN and VrefP bias scanning for dynamic range

The MUCH mode which is the low gain mode of the ASIC was used for scanning the ASIC for use with the bias parameter VrefN and VrefP which control the dynamic range of the flash ADC. With these parameters, the dynamic range of the ADC can either be increased or decreased depending on the requirement. VrefN as well as VrefP are controlled by a 6-bit Digital to Analog converter (DAC) circuitry. Thus there are about 4096 possible combination possible to be verified for at least first and last discriminator of a particular channel of the FEB. There are 128 channels in the FEB and as the channels also have dif-

ference in their characteristics among each other, this will be a lot of effort to complete the task. Thus for the first hand study to get the basic idea, only two good working channels of the FEB were selected for this scanning purpose. To start the scan, VrefN was set to 0 and VrefP was scanned from 0-63 in step. In each step, fixed number of pulses were injected via charge injector circuitry and charge was increased in the steps. The changing point where we see less number of pulse at lower step of pulse height and full number of pulses in higher height is considered as transition point for the given bias VrefP and VrefN settings. This is done for lowest and highest discriminator of the ADC channel. The trim values also play a role in the threshold setting. These observations were repeated for lower trim value, a mid trim value as well as higher trim settings for both the discriminator. After one set of scanning of VrefP is completed at VrefN = 0 setting, VrefN is increased to 1 and the scanning is repeated. The process continues till the full scanning of both VrefN and VrefP at three settings of the trim values for both lowest and highest discriminator of the ADC. The process took about 6 hours to finish one scan of the two channels. The final scanning plot can be seen in figure 3 where six layers represent six setting values namely 1) lowest discriminator with trim value 20, 2) lowest discriminator with trim value 120, 3) lowest discriminator with trim value 200, 4) highest discriminator with trim value 20, 5) highest discriminator with trim value 120 and finally 6) highest discriminator with trim value 200.

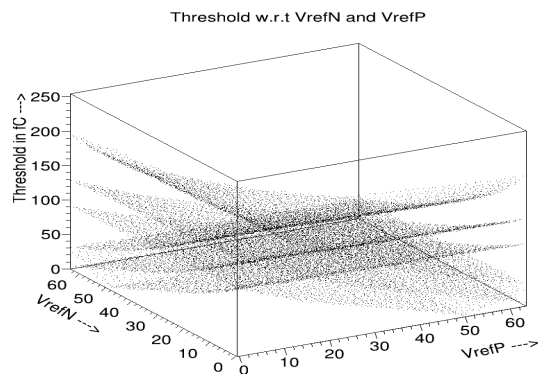


Figure 3: VrefN and VrefP scan with respect to the threshold of lowest and highest discriminator of the flash ADC

Conclusion and future plans

With the above scan data it was observed that the ASIC can be tuned for the dynamic range of as low as 12 fC to as high as 200 fC. With this dynamic range, the same ASIC can be used for the RPC detector for its several test conditions. A more detailed systematic study will be performed further to see the linearity of the tuning and analysis of the effect on other channels with the setting derived from two channels. Later on the study will be used to generalize the

bias parameter to achieve a particular range.

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Gas Parameters Monitor for GEM Detector

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It is very important to look into the gas parameter monitoring when it comes to GEM detectors. Gain parameters and performance of the gas detectors depends heavily on the gas parameters [1]. In this sense, the present paper describes the technical characteristics, test results, and a concluding application for gas parameter monitoring and leak detection. The paper presents a FPGA based system for gas parameter monitoring and leak detection.

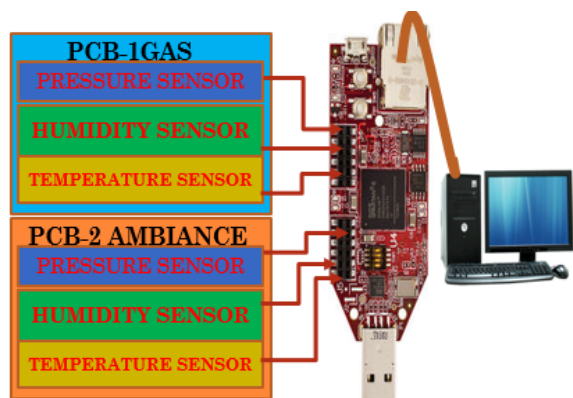


Figure 1: Layout of Sensors

As shown in figure 1 total six sensors were mounted on two different PCBs. PCB1 has been dedicated for Gas parameter sensing and PCB2 is for ambience parameter. Humidity, Pressure and Temperature sensors are mounted on these PCBs.

ADC digitized the real time signal from the sensors and fetch that data to the FPGA board, with the preliminary processing and data segregation. The FPGA then sends that data to the computer via Ethernet link. Python based scripts were written to log and plot the data.

As shown in figure 2 PCB-1 was sealed inside the 10 cm $\times$ 10 cm air tight gas chamber for gas parameter sensing. PCB-2 for ambience parameter monitoring was placed on the top of the chamber. Outlet of the detector is connected to the gas parameter monitoring system via fairly long tygon tube in order to prevent backflow.

Python based socket programs were written followed by data analysis and plotting script. The ratio of temperature and pressure (T/P) will give us fair idea about the detector gain. Leaks can be detected by analyzing the differential pattern of humidity sensors (Hambiance - Hgas).

As shown in figure 3 so far more than 95 hours data has been taken without detector in the circuit. Temporary

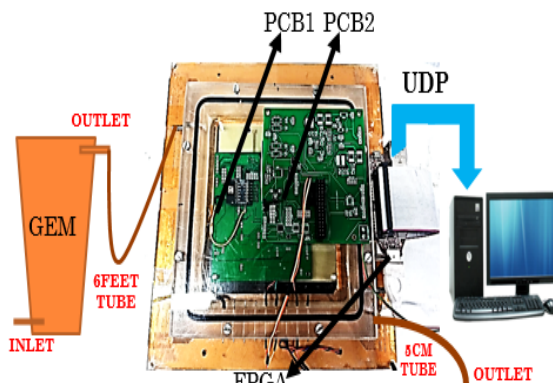


Figure 2: Lab Set up

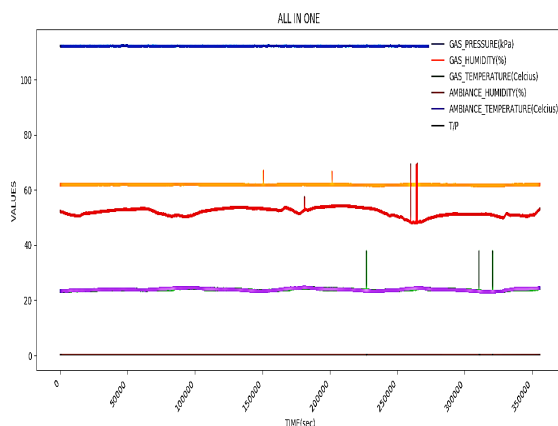


Figure 3: Plots

spikes are nothings but power hiccups in our lab.

The above scheme has the technical and functional characteristics for monitoring gas parameters and detecting the hints for the leaks in detector over the substantial period of time. Nevertheless before exploiting this system for MUCH we need to test it rigorously with the detector.

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Update on mCBM data analysis of November/December 2019 beamtime

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The large area triple GEM chambers (mMuCh) was first commissioned in the mCBM experiment in December 2018 beamtime. The results from these tests were reported earlier[1]. Two mMuCh modules were tested in November/December 2019 beamtime with Ar+Au collision at 1.7AGeV beam energy[2]. In this report, we present an update on the results from November/December 2019 data.

The time difference of the GEM signal with the TOF Digi shows a time-walk behavior as shown in the 2-D distribution of Figure 1(left). We performed time-walk correction to the GEM signals. The mean of the time-difference distribution for each ADC channel was calculated by fitting the projected distribution with Gaussian, and its variation with ADC is shown in the middle panel of the same figure. The polynomial fitting has been done for extracting the walk correction parameters, and the time-walk corrected 2D distribution of ADC with time difference is shown in the right of Figure 1.

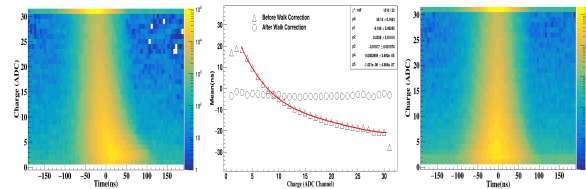


Figure 1: Time walk correction of GEM signals. Left: Time difference between GEM1 digis with TOF digis (MRPC Super Module 0) Vs. ADC channel of GEM1. Middle: Mean position of each y-bin with ADC channel. Polynomial fitting for walk-correction. Right: Time difference between GEM1 digis with TOF digis Vs. ADC channel of GEM1 after time-walk correction.

Time resolution for each channel/pad of GEM1 was measured, and 1-D distribution before and after time-walk correction is shown on the left side of Figure 2. We observed an improvement of 6-7 ns in σ after walk correction. A 2-D map showing uniformity of time resolution of GEM1 detector is shown in Figure 2 (right). The distribution is observed to be uniform with a variation of 4-5 ns.

The clustering and local hit reconstruction of GEM signals were performed after implementing time-walk correction in the data. The time resolution of the GEM1 hits was then calculated w.r.t TOF Digi. The distribution of the time difference of GEM1 hits with TOF Digi is shown in Figure 3 (left). We found a time resolution of ~ 16 ns at GEM1 volt-

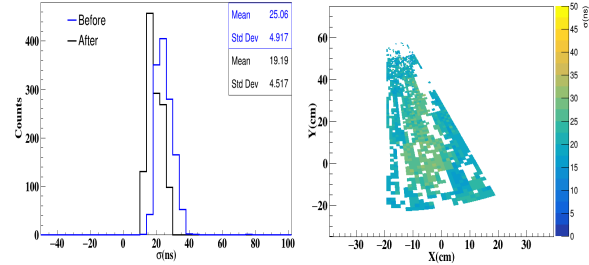


Figure 2: Left: Time resolution distribution for each channel (pad) of GEM1 before and after walk correction. Improvement of 6-7 ns in time resolution. Right: 2-D time resolution map for GEM1. The distribution is relatively uniform with a maximum variation in sigma of ~ 5 ns.

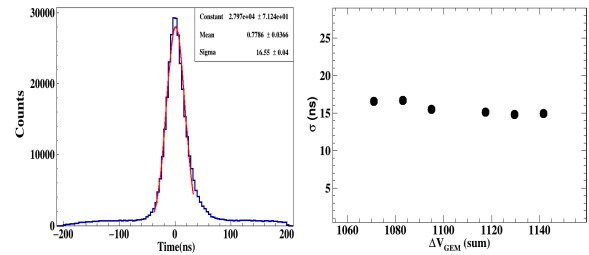


Figure 3: Left: Time difference spectra between GEM1 hits with TOF digis after walk correction at GEM voltage of ~ 1072 V. Right: Variation of time resolution with GEM voltage. The saturated value is about 15 ns.

age of ~ 1072 V. Its variation with GEM voltage is shown on the right side of the same figure. The time resolution varies only marginally with voltage in our study range, and it saturates at ~ 15 ns.

Event building was carried out by combining all digis in a fixed time interval of 200 ns with selection criteria of having a minimum of 1 T0 and 6 TOF counts. The number of reconstructed events in a TS depends on the T0 Digi, which is related to the beam intensity. The variation of the number of T0 Digi vs. TS number is shown at the bottom of Figure 4 (left). The ratio of the number of reconstructed events with the number of T0 Digi in TS will provide information about the average number of collisions. This is shown on the top of the same figure. The 1-D projection of the ratio plot is shown on the right side of Figure 4. The mean of this distribution, extracted from the Gaussian fitting, comes out to be ~ 0.08 . The theoretically calculated nuclear interaction length for Au target of thickness 2.5 mm is ~ 31.8 mm. The cross-section (σ) was obtained by running UrQMD for Ar+Au at 1.7 AGeV. The percentage interaction is equal to

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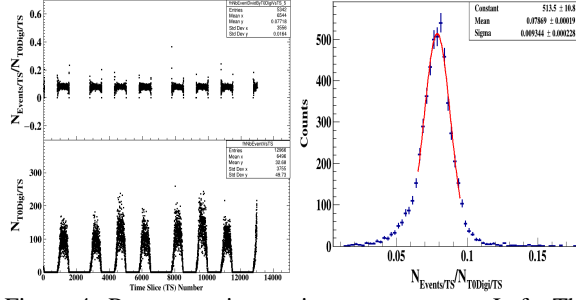


Figure 4: Percentage interaction measurement. Left: The variation of T0 digis/TS with TS (bottom) and the ratio of the number of events/TS with number T0 digis/TS (top). Right: The projection of ratio plot. The mean of this ratio tells about the percentage interaction.

$(2.5/31.8) \times 100.0 = 7.8 \%$. The theoretical value matches very well with that measured from the data.

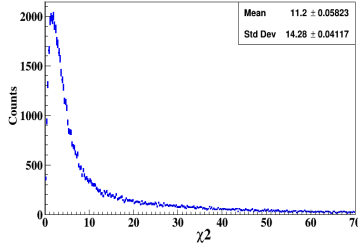


Figure 5: χ^2 distribution for tracks constructed using triple stack TOF and GEM1

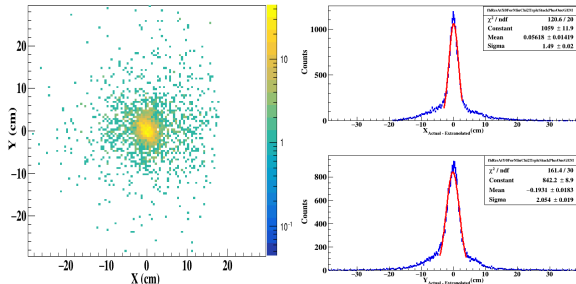


Figure 6: Tracks reconstructed using triple stack TOF and GEM1. Left: Extrapolated X-Y coordinates at the vertex. Right: Residual distribution in X (cm) and Y (cm) at vertex.

Using the hits registered on the different detector planes within the reconstructed events, we investigate the spatial correlation and track reconstruction. The spatial correlation between GEMs and between GEM-TOF is described in [2]. A straight line track-fitting has been carried out using hits on the TOF planes and on the GEM detectors. First, we construct a track using hits in the three planes of TOF and extrapolate it to the $z=0$ plane (vertex). The distribution of the extrapolated coordinates in X and Y at the origin showed shifts from (0,0), indicating the detectors' misalignment. A shift of ~ 8 cm in X and ~ 1.5 cm in Y were observed. Similarly, we reconstructed tracks using the three TOF planes and the origin and extrapolated

these to the GEM planes. We observed a shift of ~ 2.9 cm in X and ~ 6 cm in Y for the GEM detectors. Plugging in these spatial offset values, we implement corresponding translations in TOF and GEM hit coordinates and redo the tracking. The χ^2 distribution of the tracks using TOF and GEM1 after misalignment implementation is shown in Figure 5. The extrapolated X-Y distribution at $z=0$ plane, centering at (0,0), thus validating the offset correction procedure, shown in Figure 6 (left). The residuals in X (cm) and Y (cm) at $z=0$ plane with $\sigma_x = \sim 1.5$ cm and $\sigma_y = \sim 2$ cm is shown in Figure 6 (right).

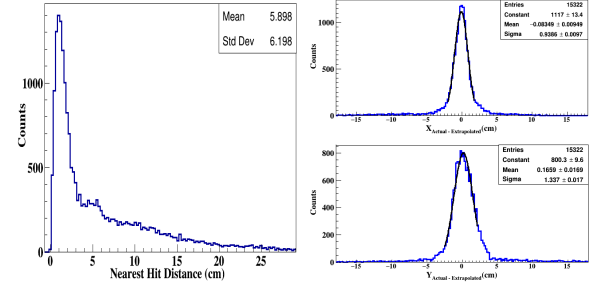


Figure 7: Tracks reconstructed using triple stack TOF and vertex ($z=0$). Left: Distribution of shortest distance between actual hits with extrapolated hits. Right: Track residual distribution in X (cm) and Y (cm) at GEM1.

After this misalignment exercise, the tracks were then constructed using TOF planes and vertex ($z=0$) to measure the track resolution at the GEM plane. The distance between extrapolated hits with the nearest hits on the GEM plane is calculated, and the distribution is shown in Figure 7 (left). Most of the hits are separated by less than ~ 5 cm. The residuals or the distribution of the difference between the extrapolated coordinates and the actual hit-coordinates in X (cm) and Y (cm) on the GEM1 plane, is shown in Figure 7 (right). The distribution peaks around zero as expected and have a sigma of 0.92 cm and 1.3 cm in X and Y, respectively, thus giving us an estimate of the detector's overall average spatial resolution. Since the granularity changes from small to large, we divided the entire area into three different regions, indicated as “small” (pad size ~ 9.9 mm to ~ 12.9 mm), “medium” (pad size ~ 12.9 mm to ~ 15.3 mm) and “large” (pad size ~ 15.0 mm to ~ 17.0 mm), and from the residual distributions thus obtained for these three regions separately, we observe a sigma of 0.8 cm, 0.78 cm, 0.98 cm, in X and 0.86 cm, 0.81 cm, 1.5 cm in Y, respectively.

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Response of the GEM chambers to varying intensity in mCBM data 2020

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Large area triple GEM chambers (mMuCh) have been commissioned in the mCBM experiment [1]. Two modules of mMuCh were tested in Mar-May 2020 beamtime with Pb+Au collisions at 1.2 AGeV beam energy. In this report, we present results from the modules for data taken at different intensities. A first response of the chambers at high and low intensities was reported in [1] and more detailed results are being presented. Data at two different voltages for a target thickness of 0.25 mm have been analysed. The average number of Digis per Time Slice (TS) have been obtained for both the modules, GEM1 and GEM2 for all these runs and have been plotted against beam intensity. While GEM1 was positioned at about 90 cm from the vertex, GEM2 was placed at about 25 cms downstream to it.

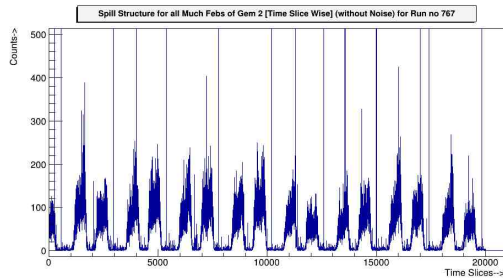


Figure 1: Spill structure for GEM2 at $2 \times 10^6/9s$ spill

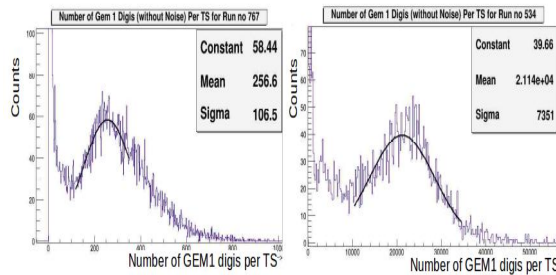


Figure 2: distribution of ndigis per TS for GEM1 for $2 \times 10^6/spill$ (left) and $8 \times 10^8/spill$ (right)

Fig.1 shows the spill structure in GEM2, for Run 767 in terms of total Digi counts as a function of the TS number, at beam intensity of 2×10^6 ions for 9 s. As we can observe that there are noisy areas and spikes in this spill. Several normalizations have been performed in this data involving intensity per spill and detector acceptances. Now the results are at the same footing and hence comparable. Some intensity values were quoted for 9 s while others for 10 s in e-logbook. All have been normalised to 9 s. Areas having link breaks have been removed. Total number

of pads and their positions have been carefully maintained to be the same throughout the period for both GEM 1 and GEM 2. As a result, the net acceptance is identical everywhere. A common pool of noisy pads was created for all runs and then all of them were masked. The intermittent spikes show no effect in the number of Digis per TS plot and fitting. Two of these distributions with two different intensities, for GEM1, are shown in Fig 2. As the final step, we have also subtracted the off-spill counts from each of the on-spill data point.

The results for GEM1 and GEM2 are shown in Fig 3 and Fig 4 respectively. The graph has been fitted by a straight line for each of the two voltages. As expected the lower slope is for lower voltage (4500 V) and higher slope for higher voltage (4600 V). The statistical error bar is within marker size. The fitted graph also passes through a point close to (0, 0) showing the robustness of our noise removal algorithm.

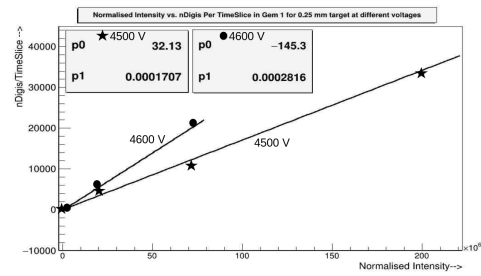


Figure 3: nDigis per TS vs Intensity per spill for GEM1

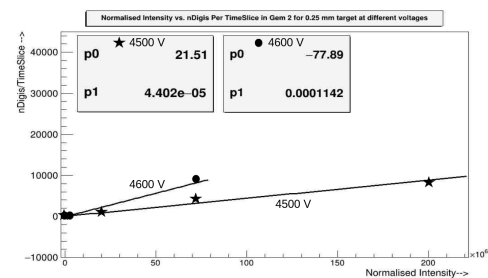


Figure 4: nDigis/TS vs Intensity per spill for GEM2

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An approach to estimate efficiency of a GEM chamber in the mCBM setup

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The primary objective of the miniCBM @ SIS18 is to examine the readiness and coherent working of different detectors systems, electronics components and DAQ under a realistic interaction rates of the CBM setup (~ 10 MHz). This also provides an excellent opportunity to test detector performances under realistic working conditions. In this work, our main focus is to determine and report the preliminary results on the extraction of efficiency of a GEM detector in the mini-MUCH system.

We have performed this work on the data collected during March-May 2020 in the mCBM experiment at SIS18 in GSI, Germany with a setup for each sub detector ; mSTS, mMUCH, mTRD, mTOF, mRICH and mPSD. For the first time data taking was managed remotely due to ongoing pandemic situation. This analysis is done with low intensity (2×10^6 /spill) Pb+Au collision at 1.06 AGeV with thick Au target of 2.5 mm thickness.

Figure 1 shows a the mCBM setup including all the sub-detectors. All detector systems are aligned at 25° relative to the beam axis. For mMUCH, two real size triple-GEM modules are used.

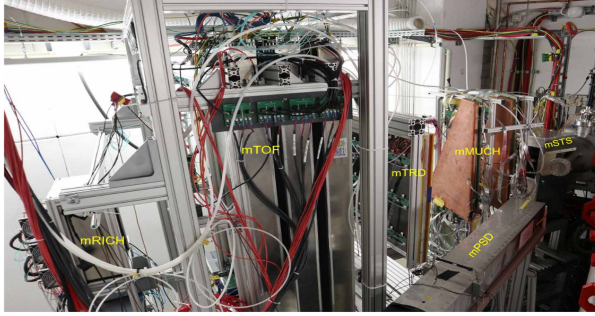


Figure 1: Photograph of the mCBM(2020) setup including all the sub detectors

For this analysis, we follow a time based event reconstruction technique using a Fixed Time Window algorithm of 200 ns width. In this algorithm, the raw data are first sorted in time stamp and then grouped together taking a time interval of 200 ns. All the information (digis from all the detectors) that are registered in this 200 ns is collectively called an event. Some additional constraints are also imposed for the event reconstruction, such as, an event must have at least 1 T0 digi and 10 TOF digis.

As a first conceptual verification of the free-streaming DAQ system of CBM and usefulness of GEM chambers as a tracking detector we have plotted the spatial correla-

tions between mMUCH and mTOF detectors using reconstructed mMUCH hits and mTOF tracks projected at GEM-1 plane [2]. The XX and YY correlations are shown in Fig. 2 which shows a clear correlation between GEM and TOF. We therefore proceed further to calculate efficiency of a GEM chamber taking mTOF tracks as a reference.

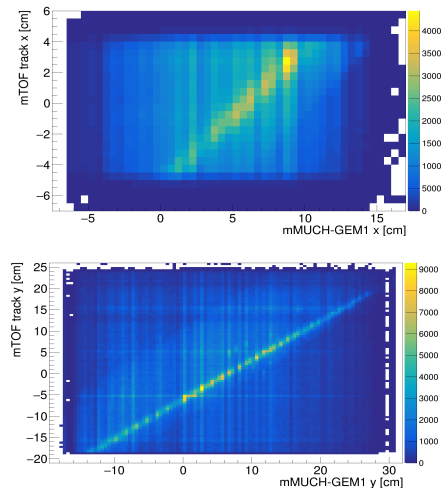


Figure 2: Spatial correlations (XX and YY) between mMUCH and mTOF detectors using reconstructed mMUCH hits and mTOF tracks.

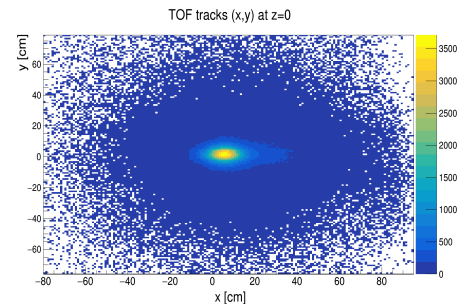


Figure 3: Projection (XY distribution) of mTOF tracks at the target plane at $z=0$

The mTOF tracking is done using latest TOF-20f geometry and the corresponding TOF calibration. In order to have good quality mTOF tracks and reduce the number of fake tracks we only consider those mTOF tracks that are constructed from atleast 3 mTOF hits. As a first check, we have projected the mTOF tracks at the target plane, i.e.,

$z=0$ as shown in Fig. 3 . We note that the peaks of both the X and Y distributions are slightly offset from the origin (0,0) by ~ 5 cm and ~ 1 cm, respectively and we select only those tracks which are within 5 cm radial distance w.r.to the this peak X,Y position. Also to mention, this tracking exclude the hits from the Diamond T0 detector. Next we have projected the mTOF tracks at the first GEM plane situated at 84 cm downstream of the target. We find that there is a misalignment between mTOF and mMUCH planes which we correct by shifting GEM-1 hits(X and Y) in the line of mTOF tracks.

After correcting for the misalignment, we have shown the common acceptance between GEM1 and the projected mTOF tracks, which is shown in Fig. 4. For efficiency calculation we use only those mTOF tracks that fall within this common acceptance (highlighted in blue color in Fig. 4). Our definition for GEM1 efficiency with respect to mTOF tracks is as follows:

$$\text{Eff} = \frac{\text{No. of GEM1 hits (around mTOF tracks projected at GEM1)}}{\text{No. of projected TOF tracks in common acceptance}}$$

For the numerator we have taken only those GEM1 hits which are within 3σ spatial window of residual X and residual Y mean position as shown in Fig. 5. Here we have plotted the residual X and Y distributions taking the spatially closest GEM1 hit w.r.to the projected mTOF tracks.

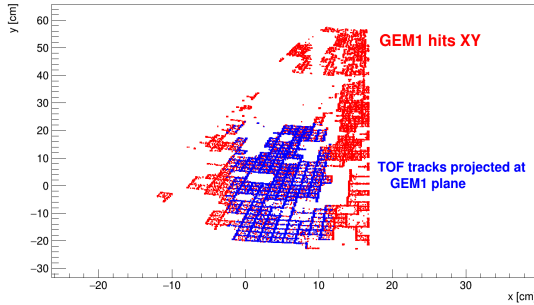


Figure 4: The common acceptance between GEM1 hits XY and the projected mTOF tracks at the GEM1 plane

We have calculated efficiency for three conditions of mTOF multiplicity, i.e, a) events with single mTOF track (mTOF track = 1), b) events that have upto 5 mTOF tracks (mTOF track ≤ 5) and c) events that have at least 1 mTOF track (mTOF track ≥ 1). The overall mTOF track distribution is shown in Fig. 6.

Table -1

	Efficiency (%)	Error(statistical)
Single track	67.1	$\pm 1.60\%$
All Tracks	72.2	$\pm 0.66\%$
mTOF mult ≤ 5	71.8	$\pm 0.67\%$

Preliminary results on efficiency value as obtained from data are shown in Table 1 for the total GEM HV of

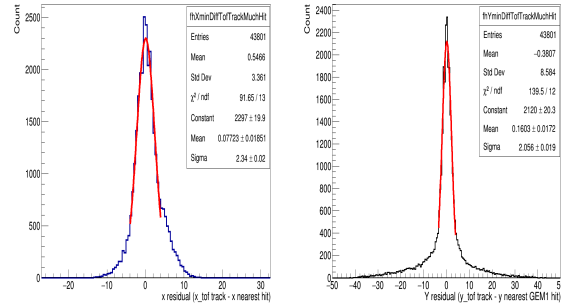


Figure 5: Residual X and Y distribution taking the nearest GEM1 hit distance w.r.t projected TOF track

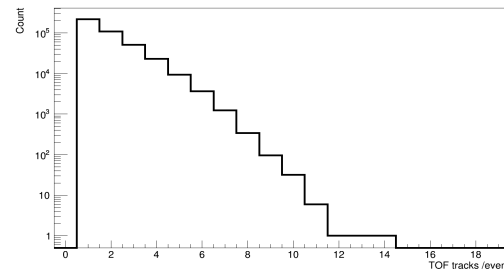


Figure 6: Total mTOF track multiplicity distributions per event

4700V. We can see that the single track efficiency is $67.1\% \pm 1.60\%$. These events are cleaner compared to the other cases as the background is comparatively less. Whereas in case of all mTOF tracks the efficiency number is high compared to single track case, as there are possibilities of background from nearest tracks, higher chances of fake hits or fake tracks which relatively less in case of single track. With mTOF multiplicity < 5 , the efficiency is similar to all track case. However these efficiency numbers are without considering the dead area or acceptance effect. An effort is going on for dead area calculation. After correcting for the acceptance loss effect the efficiency number as a whole would increase.

References

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Reconstruction of low mass vector mesons by MUCH at 8 AGeV energy

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The CBM muon detection system is aimed to measure muon pairs from the decay of low mass vector mesons and charmonium (J/ψ) produced in heavy-ion collisions at FAIR energies. We demonstrate the performance of the CBM muon detection system for low mass vector mesons (η , ω , ρ , ϕ) at 8 AGeV. The latest geometries of different modules have been used in our work. Standard SIS100 Muon Chamber (MuCh) detector system geometry have been used, which consists of 4 absorbers and 4 stations with first absorber made of 28cm low-density graphite and 30cm concrete, and subsequent three iron absorbers with thickness 20cm, 20cm, and 30 cm. Behind each absorber, there is a detector station in triplet layers. Gas Electron Multiplier (GEM) detector have been used in the first two stations of the MuCh system. Resistive Plate Chamber (RPC) detectors have been used in the last two stations.

UrQMD event generator has been used for simulating

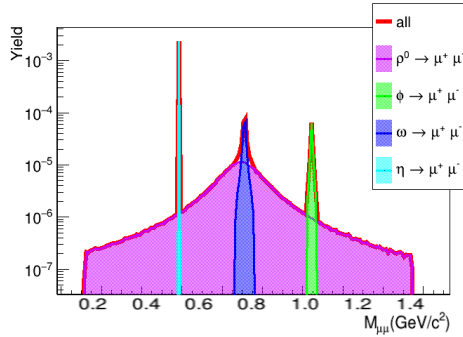


Figure 1: Different low mass vector meson sources used from Pluto event generator at 8 AGeV energy.

background. The momentum distributions of the vector mesons and of their decay products are calculated using the thermal source generator PLUTO. For proper normalisation of the signal, particle multiplicities are used from HSD and branching ratio from PDG Database. Figure 1 shows input cocktail of lvm sources used in our work. Muon pairs from signal sources are embedded into UrQMD events and are transported through the detector setup using the GEANT3 transport code. Primary track finding and reconstruction is carried at STS using cellular automaton method and MUCH detector propagates these tracks through the detector in which track and vertex fitting makes use of a Kalman Filter. The combinatorial background is calculated from UrQMD events using the superevent tech-

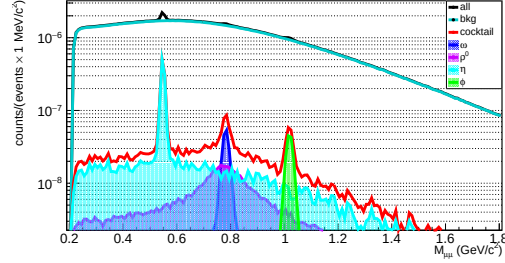


Figure 2: Invariant dimuon mass spectra calculated for central Au+Au collisions at 8 AGeV beam energy of η , ω , ρ , ϕ .

nique to increase the statistics. In order to reduce the background, conditions on the quality of the number of hits in STS, MUCH and TRD, on the quality of the primary vertex, and on the quality of the tracks in the MUCH were required in the analysis (sts hits ≥ 7 , much hits ≥ 11 , χ^2 vertex ≤ 3.0 , χ^2 much ≤ 2.0 , χ^2 STS ≤ 2.0 , TRD cut of 1 and ToF cut of 2.0). In Fig.2, the invariant mass distribution of the reconstructed muon pairs from low-mass vector mesons is shown together with the combinatorial background. The reconstructed efficiencies are 0.37, 2.02, 0.67

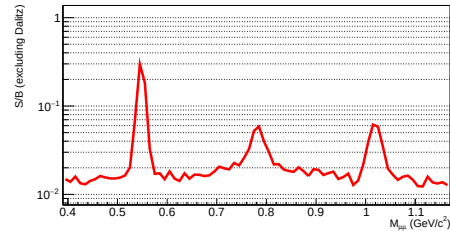


Figure 3: S/B ratio between cocktail of 4 lvm sources and background for central Au+Au collision at a beam energy of 8 AGeV.

and 1.67 respectively for η , ρ^0 , ω , and ϕ respectively. Finally Figure 3 gives the S/B ratio between cocktail of these 4 sources and background.

It can be seen that MUCH can reconstruct all lvm sources fairly well even at low SIS100 energies.

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Studying effect of digitization parameters on omega (ω) reconstruction

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The Muon Chamber (MuCh) system aims to reconstruct di-muon originating from low mass vector meson (LMVM) and charmonium, such as ρ , ω , ϕ , and J/ψ . The optimized design of the MuCh system at SIS100 energies consists of four absorbers and four tracking stations. The first absorber is made of 30 cm low-density graphite ($\rho = 1.7 \text{ g/cm}^3$) and 30 cm concrete, and the rest three made of iron (Fe) with thickness 20, 20, and 30 cm, respectively. A triplet of tracking detectors will be placed behind each absorbers layer. A Gas Electron Multiplier (GEM) detector will be used in the first two stations, and the Resistive Plate Chamber (RPC) detectors will be used for 3rd and 4th stations of the MuCh. Accordingly, simulations have been performed with GEM-like detectors in stations 1 and 2 and RPC-like detectors in stations 3 and 4[1]. The detector modules in each layer are trapezoidal for both detector types. A one-degree segmentation in phi has been implemented for the first two stations, and for the 3rd and 4th stations, five and six-degree segmentation were used due to low particle rate. The active volume consists of 3 mm Argon/CO₂ (70:30) gas for GEM-like detectors and 2 mm RPCgas[1] for RPC-like detectors. Also, 1 cm thick aluminum plates were used as a support structure and also to cool the electronics[2]. The MuCh geometry version of v20c has been used.

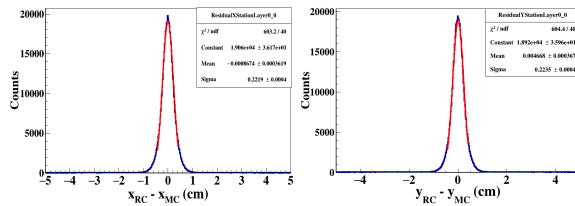


Figure 1: Distribution of residual in x (cm) and y (cm)

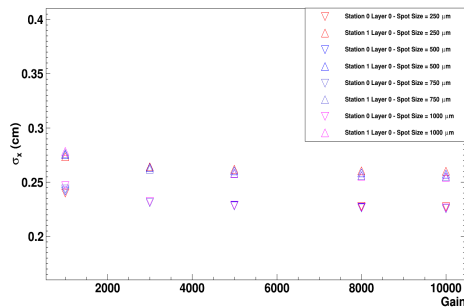


Figure 2: Distribution of residual in x (cm)

The simulation chain consists of the following steps:

- Particle generation using event generators like URQMD for background events and PLUTO for signal events.
- Transport of particles through the detector setup using GEANT3 transport engine.
- Digitization of points (generated by incident particles on the detector) to form digitized signal.
- Clustering and local hit reconstruction.
- Di-muon reconstruction.

In the third step, we provide the detector parameters, such as spot size and gas gain, for studying realistic performance. The standard value used for spot size is $500 \mu\text{m}$ and gas gain is 5×10^3 . In this report, we have studied the effect of these parameters on omega reconstruction and track residuals. The UrQMD event generator was used background events for central Au+Au collision at 8 AGeV beam energy, while the signal of ω meson was generated using the PLUTO event generator. One ω signal was embedded per event into the background. CBMROOT release version of APR20 has been used for the simulation.

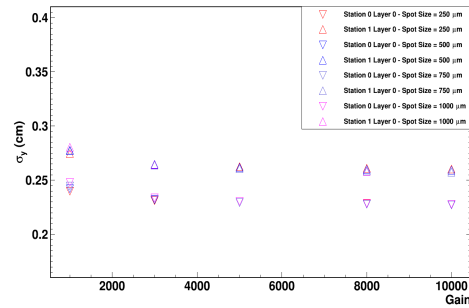


Figure 3: Distribution of residual in y (cm)

The residual distribution or the difference between reconstructed hit coordinates and Monte Carlo hit coordinates in x & y is shown in Figure 1. The sigma of this distribution is related to the track resolution, which can vary by changing the digitization parameters. The variation of σ_x with detector gain for different spot size is shown in Figure 2. The resolution improves slightly by increasing gain and saturates after 3.5 k. At any particular gain, the effect of spot size is insignificant on track resolution. This means that the change in spot size from 250-1000 μm does not affect track resolution much. It can also be seen from the same figure that the 1st station has a smaller value compared to 2nd station. The relative increase at the second

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station is attributed to the multiple scattering of charged particles inside the second absorber. The same observation can also be seen in σ_y , shown in Figure 3.

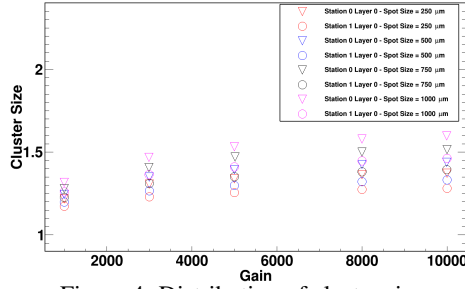


Figure 4: Distribution of cluster size

The variation of cluster size (number of the fired pad/hit) with gain for different spot size setting is shown in Figure 4. It slightly increases (at the level of 12-15% by increasing gain.

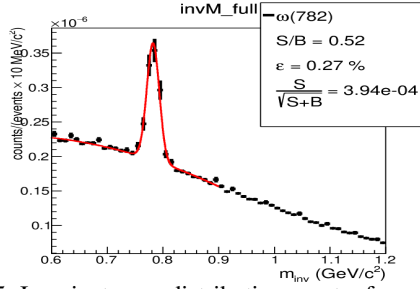


Figure 5: Invariant mass distribution spectra for omega meson

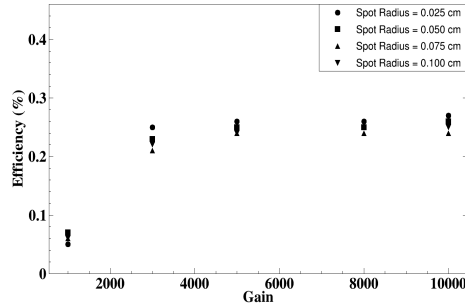


Figure 6: Variation of omega reconstruction efficiency with gain for various spot size settings

The invariant mass spectra is obtained for all the digitization parameter settings after a full simulation and reconstruction. A set of single track quality cuts are applied to the reconstructed global tracks to identify the muon track candidates. Reconstructed global tracks satisfying the condition of STS hits ≥ 7 , MUCH hits ≥ 11 , TRD hits ≥ 1 , $\chi^2_{Vertex} \leq 2.0$, $\chi^2_{STS} \leq 2.0$ and $\chi^2_{MUCH} \leq 2.0$ are selected as valid muon track candidates. The contribution of non-muonic tracks can be further reduced by applying a 2σ cut on the reconstructed TOF mass. The signal is extracted from the embedded set of events by selecting oppositely

charged muon candidate tracks on an event by event basis. The background is calculated using the super event (SE) technique, where one muon candidate track is combined with all the other oppositely charged muon candidate tracks. The invariant mass distribution for omega meson at the default setting of digitization parameter is shown in Figure 5.

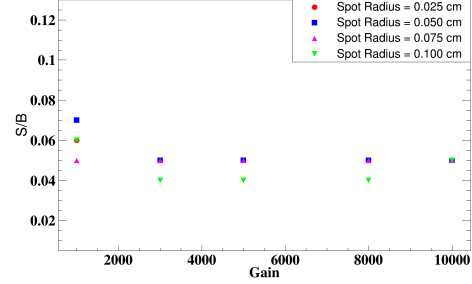


Figure 7: Variation of S/N with gain for various spot size settings

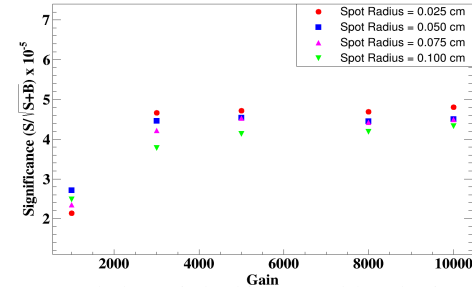


Figure 8: Variation of significance with gain for various spot size settings

The variation of reconstructed efficiency with gain at various spot-size setting is shown in Figure 6. It is low at a lower gain and jumps up to saturation value at gain > 3500 . At any particular gain, the effect of spot size on the efficiency is observed to be insignificant and remains constant. The detector gain is expected to directly influence the reconstruction efficiency. But at a gain > 3.5 k, it is observed that it becomes independent of gain. The signal to background ratio (S/B) ratio for each of these settings has been calculated and shown in Figure 7. We do not observe a significant change in the S/B ratio. One more variable tells the quality of the reconstruction, i.e., significance ($S/\sqrt{S+B}$). The variation of significance with a gain is shown in Figure 8. The trend is entirely similar to what we saw in the efficiency plot.

In summary, we conclude that omega reconstruction efficiency reaches its maximum value for a detector gain of 3.5 k. The effect of spot size on efficiency is insignificant.

I want to thank O. Singh and S. Chatterjee for the help.

References

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- [2] O. Singh, et al., CBM Progress Report 2018

Investigation of pile-up effects in the CBM-MUCH using time-based simulations*

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³GSI, Darmstadt, Germany

In order to assess effects of time resolution or dead time, a realistic simulation of the trigger-less, free-streaming data acquisition of CBM is needed. Consequently, efforts in the previous years were devoted to the development of a corresponding time-based simulation framework, going beyond traditional event-by-event simulations. In this context, a time-based digitizer for MUCH has been developed [1], which provides time-stamped digis to the *CbmDaq* emulating the data acquisition and building time slices as data containers similar to the real experiment. The underlying detectors in the MUCH setup are GEM in the first two stations and RPC for last two stations. The digitizer describes the behaviour of both the detectors and the read-out ASIC. For the latter, the STS-MUCH-XYTER (SMX) chip [2] will be used, which features a significant dead time. During this dead time, signal interference may occur on each pad/channel for tracks from a single event, but also for tracks from different events if they are close in time. The current implementation in such cases merges the two signals into one hit, which receives the time stamp of the first signal and the accumulated charge of the two signals. Thus, the second signal is effectively lost. It should be noted that this is but an approximate description of the SMX response to close-in-time signals, which, however, is already suitable to study data losses arising from finite dead time.

This report investigates the effect of this dead time using simulated central and minimum-bias Au+Au collisions at 10A GeV. Note that the time-based simulation of central collisions does not correspond to a real physics scenario; it is performed to cross-check the implemented software since it magnifies the effects resulting from the timing behaviour of the detectors. The realistic case is described by minimum-bias events.

To quantify timing effects, we study the timing inefficiency (pile-up effect) and the hit density (detector occupancy) for each channel. Pile-up is defined as the number of hits arriving within the dead-time interval of the previous hit, divided by the total number of hits in a particular channel. Occupancy is conventionally defined as the fraction of fired pads to the total number of readout pads in an event. In our free-streaming mode, we re-define this as the fraction of fired pads to total number of readout pads in a time slice divided by the number of simulated events (we perform the simulation such that data from all events are contained in a single time slice).

Fig. 1 shows the influence of the dead time on the oc-

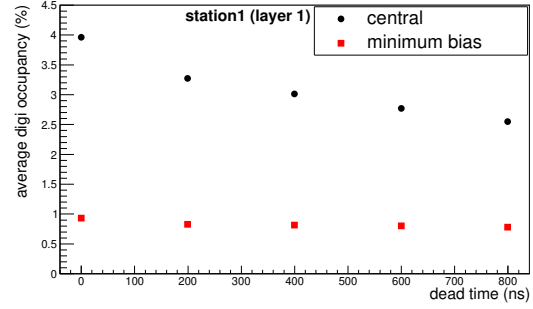


Figure 1: Average digi occupancy for the first layer of the first station as function of dead time at an interaction rate of $10^7/s$

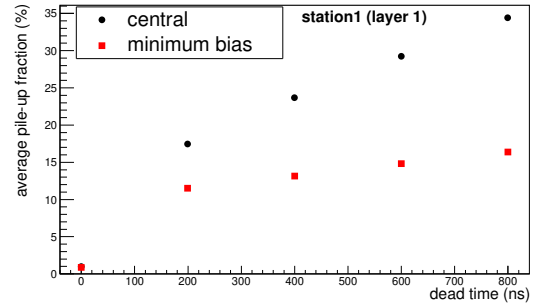


Figure 2: Average pile-up fraction for the first layer of the first station as function of dead time at an interaction rate of $10^7/s$

cupancy for an interaction rate of $10^7/s$, averaged over the first layer of the first MUCH station. As expected, a higher dead time leads to increasing hit losses and thus a decreasing occupancy. The effect for minimum-bias collisions is moderate, though. The fraction of pile-up hits is shown in Fig. 2. The losses arising from hits arriving within the dead time of a previous hit increases with the dead time as expected. For dead time of 400 ns, as expected from the latest design of the SMX (2.2), they amount to about 13 %. For our further investigations, we thus assume the dead time to be 400 ns.

The rate dependence of the pile-up fraction is visible in fig. 3 (top), where it is shown for each sector of the first layer in station 1. Up to an interaction rate of about

* Work supported by DST and DAE (Govt. of India).

$10^5/s$, there is little variation; the losses are determined by the (irreducible) double hits within one event. Above a rate of $10^5/s$, the increasing losses arising from double hits from different events become noticeable; at 10^7 events per second, the pile-up fraction is increased by about 50 % compared to the low-rate case for minimum-bias collisions. The effect is more clearly visible for central events (fig. 3 bottom), which, as mentioned before, do not correspond to the real experimental situation.

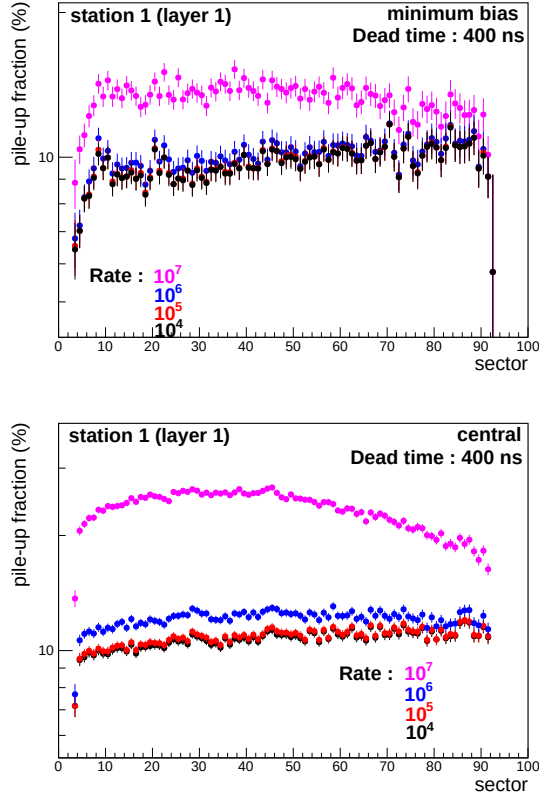


Figure 3: Pile-up fraction in each sector of the first layer of the first station for different interaction rates. The dead time is assumed to be 400 ns. The top panel shows the results for minimum-bias collisions, the bottom panel the artificial case of central collisions only.

The situation in the other three MUCH stations is similar to the one in the first station. Figure 4 shows the average pile-up fraction for the first layer in each station, respectively. A significant increase in pile-up losses is visible for interaction rates above $10^6/s$ in all stations. Note that for constructional reasons, the pad segmentation of station 2 is identical to the one in station 1, irrespective of the absorber between the two stations decreasing the particle flux. Thus, the occupancy in this station is lower by about a factor of two compared to station 1. The pad segmentation in stations 3 and 4 is adjusted to the reduced particle flux such

that the occupancy and pile-up fraction is comparable to station 1.

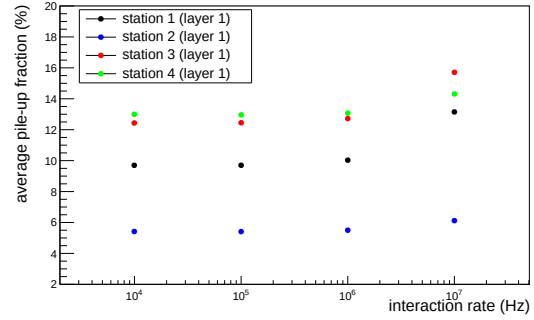


Figure 4: Average pile-up fraction as function of interaction rate for minimum bias Au+Au collisions at 10A GeV for the respective first layer of the four stations of the MuCh setup. The dead time is assumed to be 400 ns.

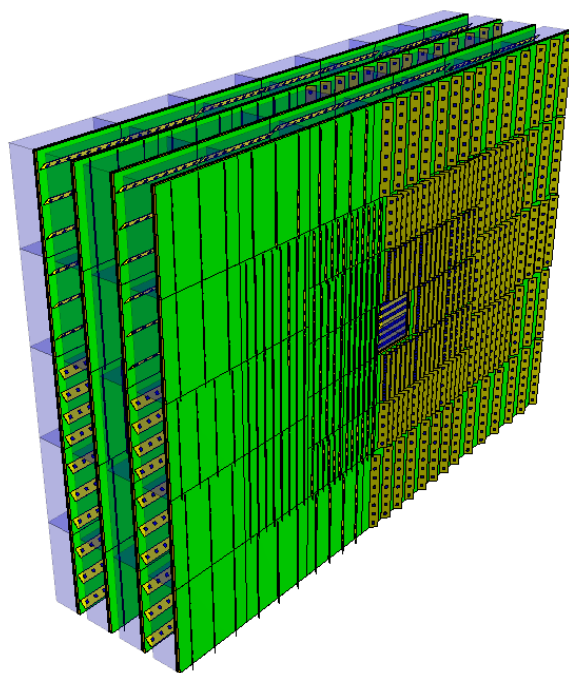
To judge the impact of the dead-time related data losses on the physics performance of the MUCH detector, we studied the origin of the involved particles using MC truth information. We find that 95% of all pile-up cases happen for two secondary tracks, presumably created in a shower in the absorber material. 5% of pile-ups occur for a primary and a secondary track; interactions between primary tracks are negligible. This suggests that the performance impact is minute, which, however, has yet to be substantiated by corresponding simulation studies.

To summarize, we have studied the effect of finite electronics dead time for the MUCH detector, employing time-based simulations as possible within the cbmroot framework. The findings in terms of data losses as function of dead time and as function of interaction rate are in qualitative agreement with our expectations, which to some extent verifies the software implementation. Quantitatively, we find significant losses above the irreducible in-event pile-up for rates above $10^6/s$. The effects of these losses on physics observables will be the subject of future studies. The significance of the rate-dependent losses at high interaction rates also motivates to work on a more realistic software description of pile-up hits in accordance with the response behaviour of the SMX read-out ASIC.

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Transition Radiation Detector



Summary on the TRD project

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Introduction

The main task of the Transition Radiation Detector (TRD) is to identify electrons above momenta of 1 GeV/c and thus to extend the electron identification capabilities of the CBM experiment into momentum regions above $p \sim 5$ GeV/c. For high momenta the TRD should provide a pion suppression factor in the range of 10 – 20 at an electron efficiency of 90 %, in order to allow for a high quality measurement of dielectrons in the mass range from below the ρ and ω masses to beyond the J/ψ mass. Due to its capability to identify charged particles via their specific energy loss, the TRD in addition will provide valuable information for the measurement of fragments and thus be also decisive for the hypernuclei program of CBM.

These requirements can be fulfilled with a Xe/CO₂ based Multi-Wire Proportional Counter (MWPC) detector in combination with an adequate radiator. The default MWPC design is composed of a symmetric amplification area of $3.5 + 3.5$ mm thickness, complemented by a 5 mm drift region to enhance the TR-photon absorption probability in the active gas volume. This geometry provides also efficient and fast signal creation, as well as readout, with timescales below 250 ns per charged particle track. The performance of the detector is maximized by reducing the material budget between radiator and gas volume to a minimum.

The baseline design for the TRD at SIS100 will consist of one station, composed of four detector layers. It will be positioned between the Ring Imaging Cherenkov (RICH) and the Time-Of-Flight (TOF) detector and thus will help to reduce the background in the TOF resulting from track mismatches by providing additional position information between RICH and TOF. The TRD will also be used as tracking station behind the last absorber of the MUCH detector in the muon configuration of CBM.

Project milestones

Several important milestones were reached in the course of the last year. Most important was the successful data taking with a TRD module during the mCBM beamtime in spring 2020. This achievement was an essential prerequisite for the Production Readiness Review (PRR) of the outer TRD modules, which was taking place on Oct. 1. at GSI. No major issues were identified during the review and it was conditionally accepted, provided further studies and improvements on the signal-to-noise-ratio were performed. It is foreseen to now build five pre-series modules of type-

5 in Frankfurt and Münster, which will then be thoroughly tested. The results of these tests will be the basis of a concluding review in May/June 2020, after which mass production can start. In addition, also ageing studies on several materials to be used in contact with the counting gas have been started (see [1] for first results).

Type 5: BMBF 19–21
Type 3 (partially): BMBF 21–24
Type 1: Romania

		3	3	3	3		
7	7	3	3	3	3	7	7
7	5	3	3	3	3	5	7
		1	1	1	1		
5	5	1			1	5	5
		1	1	1	1		
7	5	3	3	3	3	5	7
7	7	3	3	3	3	7	7
		3	3	3	3		

Figure 1: Depiction of the different module types. The day-1 setup is denoted by the colored areas.

In the context of the BMBF-applications by the involved German groups in 2020, a strategy for an optimal day-1 setup for the TRD was developed which should ensure a maximal physics output with the funding available until 2024 (see Fig. 1). A study of the physics performance with this setup was done for dielectron measurements, indicating no dramatic loss in pair statistics with respect to a complete TRD [3]. It is foreseen to add the missing outer modules (depicted as gray in Fig. 1) after 2024, provided the corresponding funding will be granted.

Also on Oct. 1. the Conceptual Design Review (CDR) of the TRD mainframe was held [2]. Here several points were identified which will need further study (e.g. the larger layer spacing imposed by the support structure and the alternative use of welded steel components) before one could conclude on a final design. Also the integration of services still needs to be addressed in detail.

On the addendum of the Technical Design Report (TDR) for the inner region of the TRD a lot of progress has also been made. Apart from many developments on the hardware side, the improvements in the global track reconstruc-

tion achievable with the 2D-position reconstruction of the proposed inner module design have been investigated in detail [4]. It is planned to schedule an internal review of the TDR addendum by the end of February 2021 and to subsequently submit it to the FAIR-ECE.

The overall status of the TRD-project was discussed on a retreat meeting on Aug. 19. – 21., 2020, in Münster (see <https://indico.gsi.de/event/11003/overview> for the agenda).

Front-end electronics and readout

The SPADIC chip, developed at the ZITI in Heidelberg, will be used for the readout of the outer TRD modules. During 2020 the version 2.2 was extensively tested and also used during the mCBM data taking campaign. While the ASIC did generally provide the required functionality, it turned out that this version, on one side, exhibited problems in the analogue part in many channels, and on the other side was suffering from a relatively high noise level. As these issues would make the application of the ASIC in the final experiment quite cumbersome, it was decided to rather introduce an intermediate development version 2.3. This version provides, in addition to modifications supposed to solve the above mentioned problems, also several minor bug fixes (e.g. configurable number of pre-samples and proper read-back of the analogue shift register) and other new features (e.g. charge injection on all channels). A first submission of SPADIC 2.3 was made in Dec. 2020. It is planned to test the new version until May 2021 and then to decide on a submission of the production version 2.4, to be used in the final experiment.

A lot of progress has been made in the development of the firmware for the SPADIC based readout [5]. While a first version was already successfully used during the mCBM data taking, the firmware has meanwhile been completely reworked in order to be able to properly handle high load situations. It has also been prepared for the transition to the CRI-based readout in 2021, as foreseen for mCBM in 2021.

For the innermost modules the readout is supposed to use the Fast Analog Signal Processor (FASP) chip, developed for high data rates at the IFIN-HH in Bucharest. It will be operated on the newly designed FASPRO-FEB, which also provides the ADC. The I/O part will be handled by the additional Generic Event Time-stamping Streamer (GETS) board and will be implemented on radiation tolerant PolarFire FPGAs by MicroSemi. This readout chain has been tested in laboratory tests in Bucharest and is being prepared for its operation in the mCBM DAQ chain at GSI.

Software and reconstruction

A general framework for the analysis of simulated and real TRD data has been developed in the recent year [6]. It is being used for the reconstruction of the DESY testbeam data from 2019 and the mCBM data from 2020. One of the main aims of the DESY testbeam was the evaluation

of radiators of different thicknesses. A systematic study of the achievable pion suppression factors has been performed [7], showing that even for a thickness of 31.5 cm no saturation of the pion suppression can be observed yet.

Another important topic being addressed is the revision of the geometry representation in GEANT. The main aspect here is the real description of the support structures and services. As these components of the TRD project are currently under development [2], an iterative verification of the design via simulations is crucial. In particular, the question whether the increased layer spacing, as required by the current support structure design, can be tolerated in terms of physics performance. A first study indicates that this might indeed cause a deterioration of the particle identification capabilities, such that another revision of the geometry would be required.

mCBM participation

The TRD successfully participated in the mCBM data taking with one installed module. The analysis of the collected data allowed to identify many problems, which, however, were subsequently solved [8]. As a result a clear time- and space-wise correlation of the TRD signals with the ones from the TOF detector was seen.

For 2021 it is planned to extend the mCBM setup by a second large module (in type similar to the one foreseen for the outer TRD region) and one additional module of the inner region. The latter will include the 2D-readout, as proposed in the TDR addendum, and will be read out by the FLES-based electronics developed by the Bucharest group.

References

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Updates on mainframe construction (after CDR)

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On October 1st, 2020, the Conceptual Design Review (CDR) for the TRD mainframe took place at GSI. While the process is documented and the basic concept was positively evaluated, this text shall briefly report on the evolution in consequence to and after the review.

Mainframe review

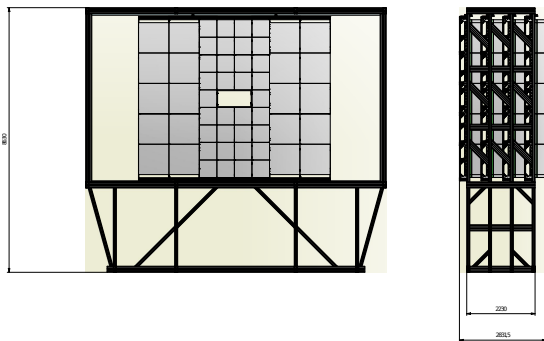


Figure 1: TRD frame as presented in the review. The four inner layers are foreseen to be moveable along x to enable installation and maintenance access to each TRD module.

The concept of the TRD support structure was presented already in [1]. It is planned to consist of a fixed outer frame and the four actual detector-carrying inner layers. The inner layers are foreseen to be built from rather lightweight aluminum structures (industrial profiles and self-designed parts). Those inner layers will be individually moveable along x direction. The inner layers are currently designed “standing”, to transport their weight load directly into the bottom part of the outer structure. A “hanging” construction was discussed, but would entail significant strengthening of the outer frame, potentially with solid carriage within CBM acceptance. Besides that, following a CDR recommendation, a cross-check with the outer frame/lower part built as welded steel construction was started.

Further evaluation: physics performance

With improved completeness of the TRD mainframe design, the necessary layer spacing in z dimension increased to 710 mm (front to front). This spacing has been included now in the CbmRoot geometries v20b_* – with particular thanks to P. Raisig and D. Emschermann – and studies of the effect on the physics performance have already

been started. For the electron setup the TRD starting position of 4100 mm behind the target will remain unchanged ($z_{\text{end}} = 6980$ mm) and a TRD acceptance, i.e. here “hit in all four layers“, of $\pm 25.4^\circ$ in x dimension and $\pm 21.4^\circ$ in y dimension is calculated. Discussions were triggered during the CDR whether a decrease of layer spacing in z dimension can still be achieved: i.e. a reduction of radiator thickness, leading to a tradeoff in electron identification performance, but to an acceptance improvement. More sophisticated options like a further integration of the radiator into the support structure have to be investigated with respect to realistic maintenance and cooling concepts, these comparisons are ongoing. In the muon setup, a z starting position of 4900 mm was agreed upon.

Deformation studies and measurements

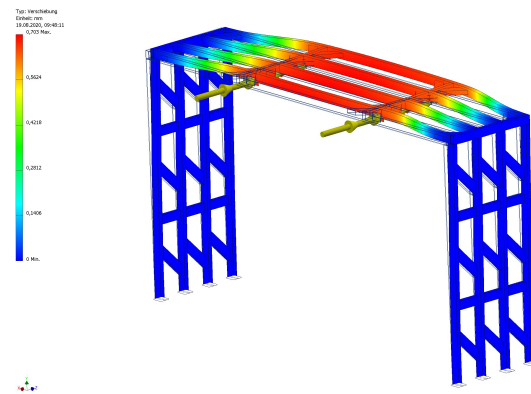


Figure 2: Simulation of TRD mainframe deformation with the load of the fully installed detector system. Calculated with finite-element methods (*Autodesk Inventor*).

Deformation studies with the foreseen frame design were presented, like e.g. the expected z deformation of the outer frame with fully installed TRD, as shown in Fig. 2. Checks of the calculations have been suggested, and a real deformation measurement under mechanical load is currently being prepared to be carried out with the support structure test segment in Münster.

References

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Ageing test of new materials used in the TRD

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In the high-rate heavy-ion experiment CBM, gaseous detectors like the TRD encounter big challenges in terms of degradation of their performance due to a phenomenon called ageing. It is caused by impurities of the detector gas from out-gassing materials. The materials for the construction of the TRD detector chambers have to be carefully selected, either they have been proven to work in other experiments under similar conditions or new materials have to be tested. We expect an accumulated charge of up to 70 mC/cm on the anode wire in the inner region of the detector. A validation of the materials is planned for at least 100 mC/cm. A setup, dedicated to the investigation of ageing properties of materials for gaseous detectors constructed and commissioned at the GSI detector laboratory [1,2] has been used to investigate new materials for the TRD.

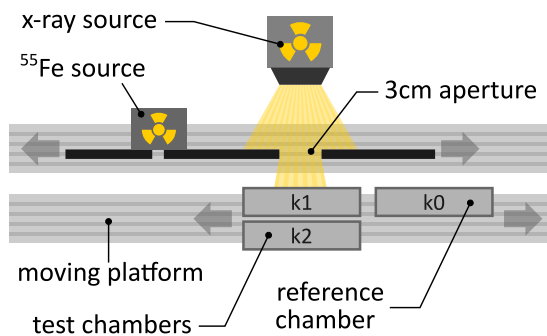


Figure 1: Schematic representation of the test setup.

New materials in the TRD

In the TRD, the composite material EPC GC 203 is expected to be used for the ledges and Tecasint or Vespel (for the gas seal). Data is not yet available for these materials. Although the pad-plane will be made of common FR4 material, this may vary from manufacturer to manufacturer. We have therefore decided to test the PCB material as well.

Test setup at GSI

The setup consists of three identical Multi Wire Proportional Chambers (MWPCs) mounted onto a moving platform, an x-ray generator to produce ionizing radiation and a ⁵⁵Fe source for gain diagnostics (Fig. 1). A second moving platform holds an aluminum collimator plate. The

setup has been equipped with a data acquisition and control system enabling fully automated measurements during long term tests. The material samples are placed in two outgassing-boxes in the gas supply lines to the detectors. Any contamination caused by the material samples is transferred into their respective detector chambers. The setup is operated with premixed ArCO₂(80/20) gas. A third chamber serves as a reference. During the operation of the chambers the onset of ageing is detected by a loss of the energy resolution and a decrease of the gas gain.

First results

First ageing tests for the TRD materials have been carried out with two samples (k1: EPC GC 203, k2: Tecasint and Vespel) over 51 days. Figure 2 shows in the two upper graphs the resolution for the two samples. Over the measurement period, both chambers showed no degradation in energy resolution and thus no sign of ageing. The lower plots show the p/T corrected gain and the gain ratio to the non-irradiated areas for the two samples. The determination of the gas amplification has to be corrected for temperature and pressure changes. Small changes in gas composition and humidity can affect the gain factor. In Fig. 2 three events are highlighted: the first change of the gas cylinder (1), the resumption of operation after the Christmas break (2) and the second change of the gas cylinder (3). While the first cylinder change had no significant effect, the second cylinder change and the restart after the Christmas break led to major changes in the measured gas gain. Obviously, these abrupt changes cannot be explained by sudden ageing. The crucial parameter for determining the ageing is the change of the gain factor at the irradiated area in relation to the non-irradiated area shown in red. Since the change of the relative gas gain for both chambers did not exceed 1 % during the whole measuring period, everything speaks for the fact that the tested materials will have no critical influence on the ageing of the detector.

References

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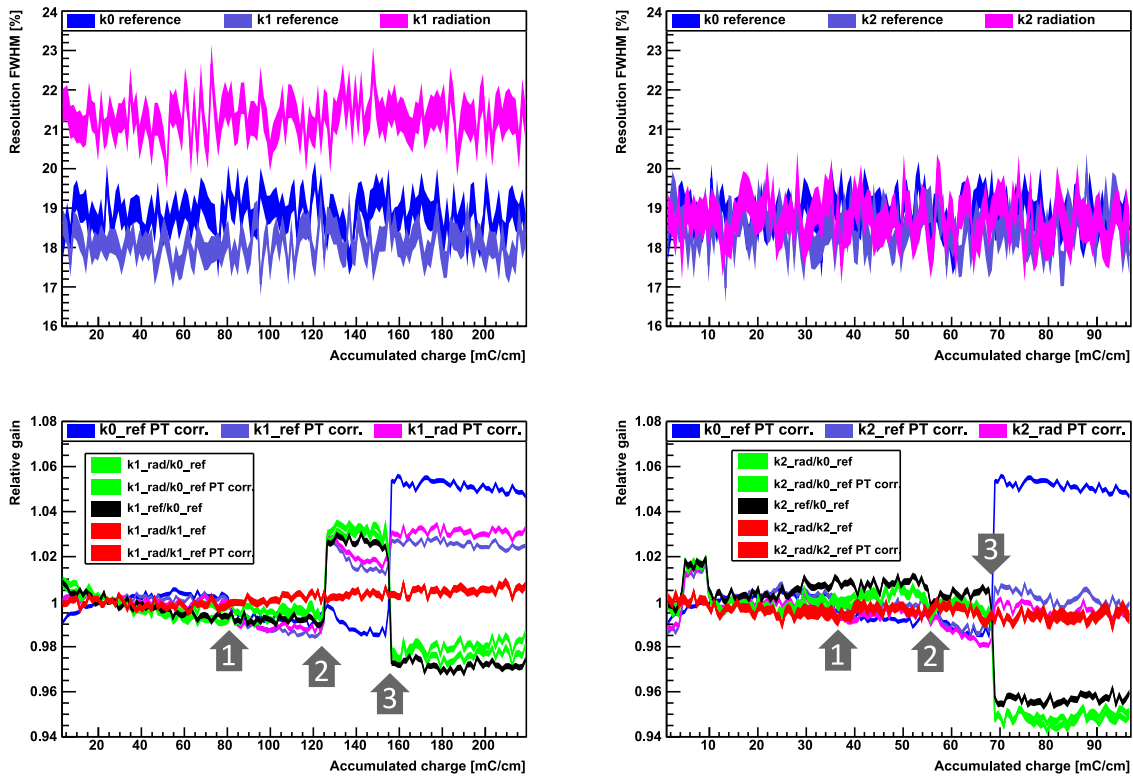


Figure 2: Data of the measurement of the first two material samples. The upper plots show the energy resolution and the lower ones show the relative gas gain as a function of the accumulated charge. The left plots refer to the first test chamber (k1, composite material EPC GC 203) and the right plots to the second test chamber (k2, Vespel and Terasint). The active measurement time was 51 days.

Status update: SPADIC TRD firmware

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Introduction

The mCBM 2020 campaign as well as the transition to the CRI showed that the firmware for the SPADIC TRD needed a thorough rework. During the mCBM campaign it became clear that the firmware was not well equipped to handle high load situations. This resulted in undocumented lost data and loss in time synchronization. Additionally, while planning the transition to the CRI, the requirement to lower the resource usage per link prompted a complete rework of the data aggregation tree. Therefore, the newly developed firmware vastly improves on stability in high load situations, documentation whenever data had to be discarded, as well as resource usage. Furthermore, the firmware employs several building blocks that were written with Vivado High-Level-Synthesis (HLS).

The Concept

One of the goals of the firmware rework is to develop a maintainable and upgradeable code base. Therefore, all functional blocks in the new data aggregation scheme use the AXI4-Stream protocol [1]. This allows for an easy integration of new modules regardless if they are written in HDL (Hardware Description Language) or HLS. Additionally, the communication between modules of variable latency can be implemented elegantly with the protocol, which further simplifies the usage of HLS where one does not have complete control over the processing processing latency. Furthermore, the FLIM interface is based on the AXI4-Stream protocol, which made the protocol the obvious choice. In the microslice specifications the TLAST flag is used to mark the end of a microslice. The new firmware borrows this concept and asserts TLAST at the end of each epoch, i.e. the TS_MSB frames are marked as TLAST. As these TLAST frames are used to stay synchronous in time, they must not get lost under any circumstances. Using the TLAST flag as an indicator for the most important frames allows for a common handling of buffer overflow conditions, so that they can be recovered and marked with a flag to indicate that data had to be discarded. For the SPADIC the four LSB of the TS_MSB frame are empty and can be used as flags.

The Data Aggregation Tree

Figure 1 shows the data aggregation tree for the new firmware. For each elink there is one timeout monitor mod-

ule, which monitors the incoming TS_MSB frames. Upon a reset of the data handling, a counter is started and if this counter reaches six epoch periods ($96\mu s$) without a TS_MSB frame the elink is set to a timeout state. When this elink is first set into the timeout state one TS_MSB frame with flag 0b1000 is generated. Following that, one TS_MSB frame with flag 0b0001 is generated each $16\mu s$. In the timeout state no message is forwarded to the data handling. The elink will remain in timeout as long as no new TS_MSB frame reaches the timeout monitor.

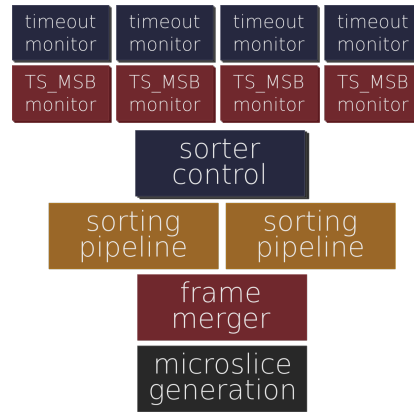


Figure 1: Schematic depiction of the SPADIC TRD data aggregation tree.

The TS_MSB monitor is another module that is instantiated for each elink. The module is responsible for generating any missed TS_MSB frame. This is accomplished by calculating the difference between the timestamp of current TS_MSB frame and the previous TS_MSB frame. If the difference is larger than one and smaller than six the module will generate TS_MSB frames with flag 0b0010 according to the difference. If the difference is larger than six (or zero), then the TS_MSB frame is discarded. Additionally, the module recognizes the first timeout TS_MSB frame and generates five additional TS_MSB frames with flag 0b0001 to regain synchronization.

The next block is the sorter buffer control module. This module controls the data flow to the sorting pipeline. The raw SPADIC frames in between two TS_MSB frames (one epoch) are buffered for each connected link. When each buffer received data from one epoch the data from this epoch is sent to one of the two sorting pipelines, where the data is serialized and sorted.

To keep track of the incoming and outgoing TS_MSB

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frames there is one register for each elink on the input (received_epochs_i) and on the output (received_epochs_o) side of the FIFO. On the incoming side the register is 4 bits large and the register is increased by one whenever a TS_MSB frame arrives. On the outgoing side the register is 1 bit in size and is set to one when the TS_MSB frame is received from the FIFO. This also stops the data flow from the FIFO to the sorting pipeline. Once the register on the incoming side is larger than zero on all elinks, the pending_epochs register is increased by one and each received_epochs_i register is decreased by one. Whenever the pending_epochs register is not zero and the sorting pipeline is not busy, the data of one epoch can be fed into the sorting pipeline. Once all TS_MSB frames are received by the sorting pipeline the pending_epochs register is decreased by one and the received_epochs_o is set to zero for each elink. The sorting pipeline is set to busy as long as there is data inside the pipeline.

The frame merger block is responsible to merge the data stream from the two sorting pipelines into one 64 bit frame as well as assigning the TLAST flag for the microslice generation module. This is accomplished, by counting the incoming TS_MSB frames. For each processed epoch there need to be as many TS_MSB frames as connected elinks. When all TS_MSB frames have arrived the processed epoch counter is increased by one and if this counter reaches n the microslice frame is set as TLAST, where $n = \frac{\text{microslice length}}{16\mu s}$.

Inside the microslice generation module the current microslice index is generated from the TLAST flag of the input stream, the data is flow controlled according to the microslice index window and proper backpressure handling is ensured.

Buffer Overflow Handling

In the current iteration of the firmware there are two FIFO buffers where buffer overflow conditions are a concern. These are the sorter control buffers and the output FIFO to the FLIM module. As the sorter control buffers hold the data for the serialization they can become full if there is too much data to be serialized. At the moment the data is serialized at 160 MHz. As the firmware buffers data of one epoch period (16 μs), the maximum number of frame that can be serialized without the buffers filling up is 2560.

If the number of frames is above this value for several epochs, the buffers will begin to fill up. In order to not lose time synchronization, the TS_MSB frames must not get lost when the buffers are full. Therefore, whenever a TS_MSB frame had to be discarded due to a buffer overflow, a pending TS_MSB is incremented. And as soon as the buffer frees up the pending TS_MSB frames are generated. They carry the flag 0b0100 and the number of frames that had to be discarded due to the buffer being full.

The output FIFO to FLIM module can become full due to backpressure from the FLES. If this happens, the TLAST

words must not get lost. As the TS_MSB frames also carry the TLAST flag, the same mechanism is used to recover the TLAST frames. If data had to be discarded this way, the microslice is marked with the FLIM user flag.

Vivado HLS

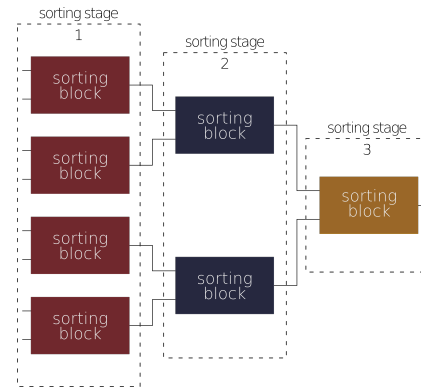


Figure 2: Schematic depiction of the blocks inside the sorting pipeline. In this example eight elinks are connected to the sorting pipeline.

In this firmware some of the modules were written with Vivado HLS. Vivado HLS allows C++ code to be synthesized into HDL. This significantly improves development time at the cost of suboptimal resource usage. While HLS is not suited for every module, especially if it is latency sensitive, but it produces good results for dataflow applications, where there is not much feedback required.

One examples where HLS was used in this firmware is the sorting pipeline. The sorting pipeline employs the dataflow pragma [2]. Figure 2 depicts the inner working of the sorting pipeline. In the C++ code the module is logically split into sorting stages and sorting blocks. As the incoming elink streams are already sorted in time individually, the sorting algorithm is simple. Each sorting block compares two values and queues the smaller one for the next sorting block. The other port is kept and no new value can be read into that port. If one port frees up a new message can be read in. This is replicated until there is only one sorting block in the last stage. This module has an initiation interval of one and a latency equal to the number of sorting stages.

References

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First calculation of pion efficiencies from DESY 2019 testbeam data

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Introduction

As reported in [1], the TRD group performed testbeam measurements at DESY in Hamburg in 2019 using a pure electron beam at fixed momenta and radiator prototypes of various widths ranging from 1.5 to 31.5 cm. Even though a successful energy calibration could not be achieved yet, first reconstructed energy loss spectra showed a promising similarity with simulations, especially concerning the scaling with radiator thickness [1]. On the basis of these spectra, a first calculation of the resulting electron and pion efficiencies has been carried out. The pion efficiency is defined here in accordance to [2] as the fraction of pions wrongly identified as electrons at a given electron efficiency using the likelihood method.

Pion spectrum approximation

Since no pion beam is available at DESY, the pion spectrum had to be approximated by scaling the spectrum measured for electrons in the setup without any radiator accordingly. For this scaling the factor of $r = 1.35$ was used, obtained by modified GEANT3 calculations and measurements in [3]. The reconstructed spectra for the different

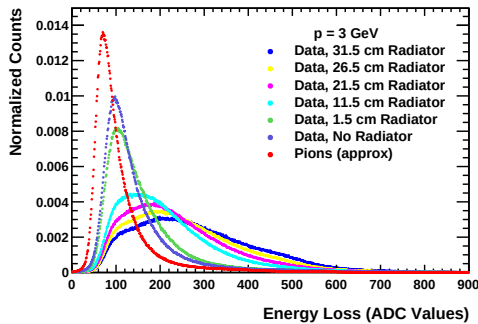


Figure 1: Measured energy loss spectra of electrons for different radiator configurations at an electron momentum of 3 GeV as well as the approximated pion spectrum. Each spectrum has been normalised by its area.

radiator setups as well as the approximated pion spectrum are shown in Fig. 1.

Likelihoods

The electron and pion likelihoods L_e and L_π were defined as [2]

$$L_e = \frac{P_e}{P_e + P_\pi}, \quad L_\pi = \frac{P_\pi}{P_e + P_\pi} \quad (1)$$

with

$$P_e = \prod_{i=1}^N P(E_i|e) \quad (2)$$

$$P_\pi = \prod_{i=1}^N P(E_i|\pi). \quad (3)$$

The products in Eqs. 2 and 3 run over the number of detector layers. In the data taken at DESY, only one TRD layer was read out. To calculate the likelihoods for more than one layer the assumption was made that all layers measure the same spectrum. The distributions of the likelihoods were then calculated by randomly¹ sampling the respective spectra once per detector layer and calculating the likelihood 2×10^6 times. The resulting likelihood distributions for the case of four detector layers with 31.5 cm thick radiators can be seen in Fig. 2.

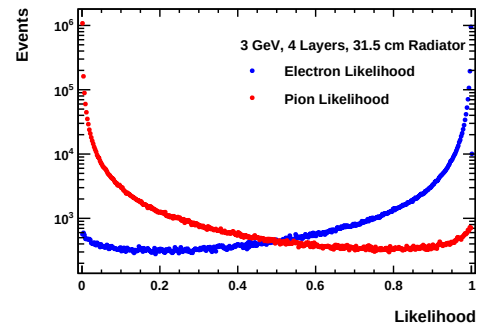


Figure 2: Likelihood distributions for pions and electrons at a momentum of 3 GeV for a setup with four detector layers and a radiator width of 31.5 cm.

Results

The pion efficiencies at an electron/pion momentum of 3 GeV and a required electron efficiency of 90 % are shown

¹Note: Randomly according to the histogram bin contents, not at fully random x-positions

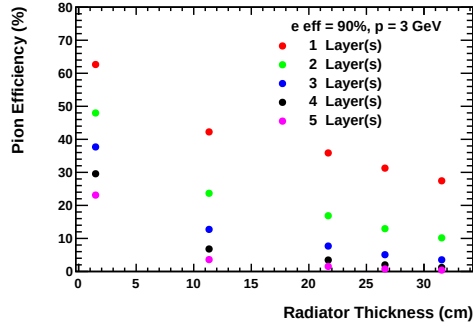


Figure 3: Pion efficiency depending on radiator width and number of detector layers for an electron/pion momentum of 3 GeV and a required electron efficiency of 90 %, shown with linear y-axis.

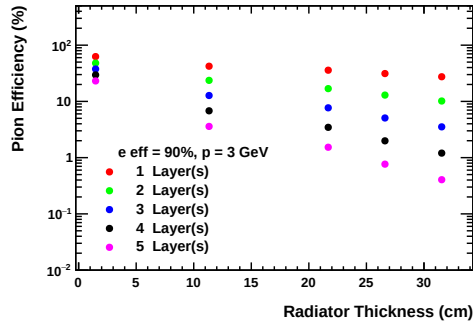


Figure 4: Pion efficiency depending on radiator width and number of detector layers for an electron/pion momentum of 3 GeV and a required electron efficiency of 90 %, shown with logarithmic y-axis.

in Fig. 3 and Fig. 4 with linear and logarithmic scaling, respectively. As expected, the pion efficiency decreases with an increase of detector layers or radiator width.

Discussion and outlook

This analysis successfully quantified the visible difference of the reconstructed energy loss spectra in terms of parameters relevant for the detector performance. As the shown pion efficiencies were calculated on the basis of data without a proper energy calibration, their absolute values should be taken cautiously. However, the general trend of decreasing pion efficiency with increasing radiator width is clearly visible and subsists even above a width of 25 cm, reaffirming the foreseen choice of 31.5 cm thick radiators for the CBM-TRD. This analysis may be repeated for the DESY19 data once a successful energy calibration has been achieved, or for comparative testbeam measurements.

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Analysis of TRD data from mCBM 2020

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During the 2020 mCBM data taking campaign the TRD successfully recorded data, allowing temporal as well as spatial correlation analyses of the measured signals of all mCBM detectors. The installed TRD setup consists of one module, with an active area of $92 \times 92 \text{ cm}^2$, divided into $0.72 \times 15 \text{ cm}^2$ ($x \times y$) sized readout-pads, which are connected in groups of 32 to SPADIC 2.2 ASICs. The detector was operated with Ar/CO₂ 80:20 at an anode voltage of 1750 V and a nominal drift field of 100 V/mm (design value). Further details of the TRD setup in mCBM 2020 can be found in [1].

With this setup more than 20 runs were recorded. A summary of the campaign can be found in [2]. Used for the presented analysis is run 831, which is agreed to serve as reference run for first mCBM analyses and contains roughly 10 minutes of data taking. The primary aim of the ongoing work is the analysis of the TRD data quality, with the final intention to ensure the usability of the data for the foreseen mCBM benchmarks. The confirmation of parameter sets for detector operation and providing input for the ongoing development of TRD firmware blocks are further goals.

Data reconstruction and calibration

The TRD data reconstruction consists of three steps. It begins with the “unpacking” of the incoming raw messages (SPADIC 2.2 and subsequent DPB layer message blocks) into so-called digis, which contain the information on the channel that registered the signal and the charge equivalent value of the signal [1]. Afterwards, the digis from adjacent pads and within a time window of one SPADIC 2.2 clock-cycle (62.5 ns) are grouped into charge clusters. From those clusters, the actual *hit* in the chamber created by the traversing particle is reconstructed. An early integrity check for data from the subsystems produced by the free-streaming mCBM DAQ is the proof of temporal correlations between the detector streams. Due to its low noise and clear signal correlation with beam–target interactions, the T0 detector is a natural choice for a reference detector [2].

During first quality assurance tests of the data in May 2020, time shifts of the correlation peak between the TRD and T0 time were found. The observed shifts occur in multiples of the microslice length (1.28 ms). In the top panel of Fig. 1, an example of a shifted correlation peak is given. Instead of appearing in the region of $\Delta t = 0 \text{ ns}$ it is shifted to larger values ($\Delta t \approx 7 \cdot t_{\text{microslice}}$). The

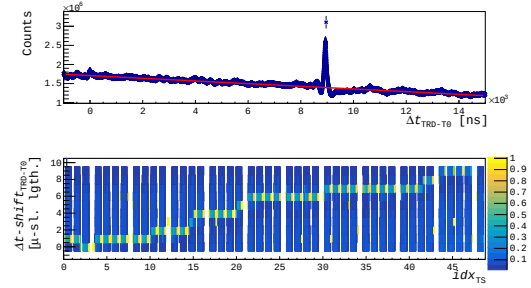


Figure 1: Top: time difference between TRD and T0 hits in a 3 s long interval of run 831. Bottom: multiples of microslice lengths by which the correlation of TRD and T0 digis is shifted as function of the timeslice index.

multiple of the microslice length by which the correlations are shifted as function of the timeslice index is depicted in the bottom panel of Fig. 1. Based on the observed shifts calibration parameters have been extracted, for the common data analysis. In parallel, a correction scheme which is more elaborate, but also requires more manual intervention, was developed for a first spatial correlation analysis between reconstructed TRD hits and TOF tracks, see below. Meanwhile, a potential reason for the observed time shifts in the TRD data was identified and solved in hardware. Additionally, a more robust implementation of the timing algorithm was developed for the corresponding TRD firmware [3].

Hit and track reconstruction

The unpacked data were at first corrected for the aforementioned discrete time shifts, which is assumed to result in an exact recovery of the real values. The resulting TRD digis were then resorted into their proper timeslices to ensure time overlap in the time-slice-based correlation analysis with TOF tracks. Based on precise manual measurements of the relative detector positions a setup geometry was created and used as reference for the hit position reconstruction. Eventbuilding was done with a common algorithm that splits the data stream into events whenever the time difference of two consecutive digis exceeds 250 ns. For the TOF hit reconstruction the latest calibration was applied. The diamond detector was included as a station in the tracking algorithm, assuming each track emerges from target position ($x = y = z = 0$).

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Temporal correlation with T0 and TOF

To probe temporal correlations between TRD, TOF and T0 the time differences of TRD and TOF hits ($\Delta t_{\text{TRD-T0}}$, $\Delta t_{\text{TOF-T0}}$) within an interval of ± 2000 ns around each T0 hit were calculated. The resulting values are shown in Fig. 2. Time correlations between T0, TRD and TOF are confirmed by the main diagonal. Most of the TRD hits are found after the correlated TOF and T0 hits. The sharp horizontal line indicates the naturally much better time resolution of TOF. In future the time resolution of the TRD will be improved by more sophisticated time reconstruction algorithms.

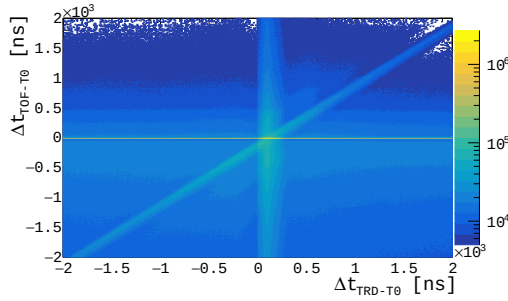


Figure 2: All possible combinations of pairs of TRD and TOF hit time differences to the T0 detector within 2000 ns.

Spatial correlations with TOF tracks

To investigate spatial correlations of TRD and TOF the tracks provided from the TOF detector were correlated with TRD hits. The study is limited to the x positions, as one TRD layer only resolves one dimension which is the x direction in this specific case. For each extrapolated track crossing the TRD acceptance all TRD hits within a time window of ± 400 ns are checked for matches. The resulting $x_{\text{TOF-Track}} - x_{\text{TRD-Hit}}$ -pairs are plotted in Fig. 3. This plot clearly shows an angle bisector which signals that TRD and TOF are not only temporally but also spatially correlated.

To take a closer look at these correlation pairs also their x distance $\Delta x_{\text{TRD-TOF}}$ and temporal differences $\Delta t_{\text{TRD-TOF}}$ were filled into the histogram in Fig. 4. At $\Delta x_{\text{TRD-TOF}} \approx 0.8$ cm a strong accumulation is seen, meaning that the TRD has an offset of about 0.8 cm to the TOF detector which can be used as offset correction in further analyses. The track matching resolution in x direction is in the range of some mm and therefore not yet satisfying. Room for improvements is seen with new versions of the mCBM geometry files, which is an ongoing joint effort in mCBM. One option for future mCBM measurements could be the implementation of track alignment routines, e.g. by using muon tracks. We note that also the still high noise level might deteriorate the apparent TRD position resolution.

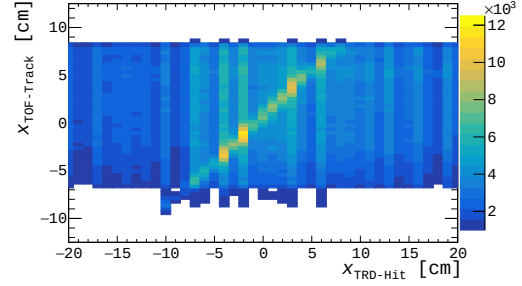


Figure 3: x positions of extrapolated TOF tracks and TRD hits within TRD acceptance and a time window of 400 ns.

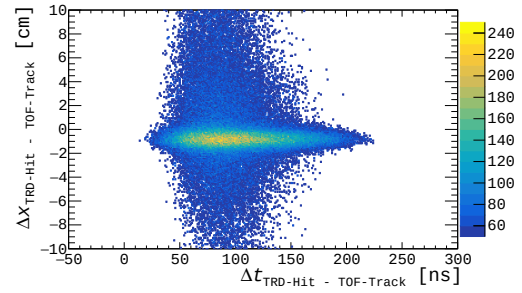


Figure 4: Differences in x and t between TOF tracks and TRD hits within the TRD acceptance.

Outlook

We still expect significant improvements of the TRD hit time resolution by evaluating the transmitted ADC samples from the raw messages in order to determine the precise hit time within a time bin. A codebase developed with simulated data exists and is to be applied to the mCBM data. The usage of other mCBM detectors as TOF and T0 as time reference is of particular value for the tuning of the methods with real data. A detailed TRD hit efficiency analysis is ongoing to further evaluate trigger settings and TRD readout. Furthermore, an analysis of the TRD HV currents with respect to the mCBM rates is expected to deliver valuable input for planning of the TRD HV system in CBM.

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Motivation for an efficient tracking device for the inner zone of the TRD wall

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The challenge the CBM experiment at FAIR will be facing is the 10 MHz top interaction rate at which it will operate. Using mixed detector techniques to reconstruct particle yields in a high rate environment, the DAQ has to run freely in order to accommodate various processing times in the system. As a fixed target device, the highest particle yields will be seen at low polar angles, such as the inner zone of the TRD wall. Here, a 2D position sensitive architecture is proposed [1] [2] for increased tracking efficiency.

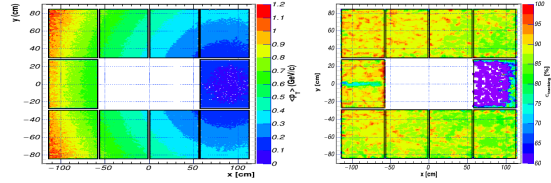


Figure 1: Mean p_t distribution at mid-rapidity of protons and K^+ for all particles which are reaching the inner zone of the last TRD station and have at least three hits in the STS (left) and the efficiency of STS seed tracking in TRD for the same selections (right).

The CBM dipole magnet acts as a mass spectrometer for different charged particle species, projecting the image of the vertex at various distances from beam axis. In Fig. 1, left, the vertex expansion of protons and K^+ at mid-rapidity is projected at TRD layer 0, situated at 410 cm from the target (SIS100 electron setup). On the right, the efficiency of particle reconstruction is depicted when only STS is used for track finding. Comparing the two plots, it is obvious that STS alone will loose low p_t tracks entering TRD.

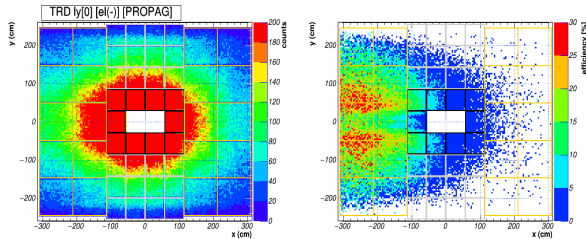


Figure 2: The electron component seen by the TRD if all trackable tracks are considered (left) and the efficiency of the actual STS seeding wrt. TRD hit matching (right).

Another example of incomplete tracking with the default CBM reconstruction scenario is for the electron component. In Fig. 2, left, a representation of all electrons with at

least three hits in the STS is given. The inner modules of the TRD wall are emphasized in black. The efficiency to reconstruct them is given on the right. Comparing the two one can see that for the highest yield regions in the inner part the efficiency is mainly under 5 %.

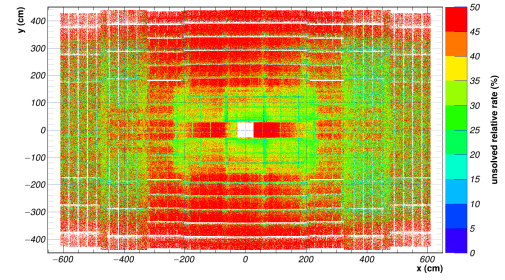


Figure 3: Relative (wrt. to total) particle rate in the TOF detector which is *not resolved by STS* entering ToF from upstream.

Last but not least is the case of downstream detectors wrt. TRD. The amount of particles produced outside the tracking capabilities of STS, which are generating hits in TOF is $\approx 38\%$. Partially they are background, but some may be linked to physics channels. Their identification is either way necessary in the large economy of the CBM reconstruction.

It has been shown that the TRD-2D doubles the reconstruction capabilities of the default TRD solution for the inner regions of the TRD wall. The physics cases presented above can be solved, independently from the STS track finding, by a stand alone TRD(-2D) particle reconstruction. Thus, such a system can beneficial complement the existing reconstruction scenario to access low p_t charged particle spectra and significantly extend the electron dynamics. It also might play a beneficial role to deconvolute background effects for downstream systems.

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Dielectron measurements with a TRD-day-1 setup

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The TRD is one of the main detectors for the identification of electron tracks, especially at larger momenta. It is designed with different module types that differ in granularity, to account for the higher track multiplicities in the inner part of the system. According to the current planning and funding schedule, a fraction of outer modules will be built after 2024 (see Fig. 1). Therefore, the physics performance with respect to dielectron measurements of the day-1 setup is investigated in this study and potential effects due to the reduced acceptance are explored.

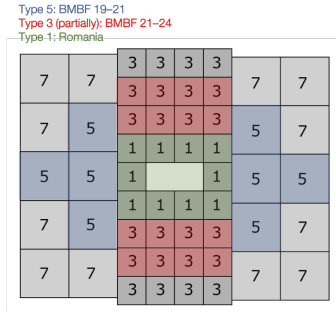


Figure 1: Depiction of the different module types. The day-1 setup is denoted by the colored areas.

The simulation consists of 2 million UrQMD Au+Au collisions at 12.4 GeV collision energy (0 – 10 % centrality). Additionally, a cocktail of low mass vector mesons and thermal dielectron pairs was added via the PLUTO generator. For the study of the day-1 setup the hits from the not installed modules were ignored in the reconstruction. However, the geometry still included the material of the respective modules. The majority of simulated signals are reconstructed in the inner part of the TRD, but there is still a significant loss in acceptance due to the missing modules (see Fig. 2).

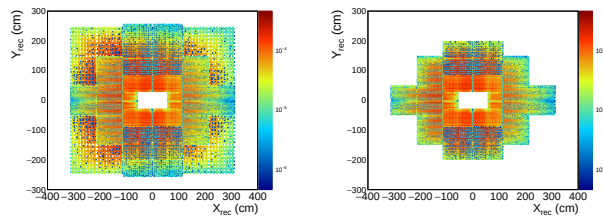


Figure 2: $x - y$ position distribution of reconstructed hits in all TRD layers for the two data sets (left: full geometry, right: day-1 geometry).

This can be especially challenging for multi-body decays, since a single daughter particle will only contribute to the combinatorial background. Figure 3 shows the phase space distribution of all unlike-sign pairs from the same event (left) and the ratio between the day-1 setup and the full geometry (right). A significant loss of pairs can be seen for small rapidities and large transverse momenta, as it would be expected due to the missing modules.

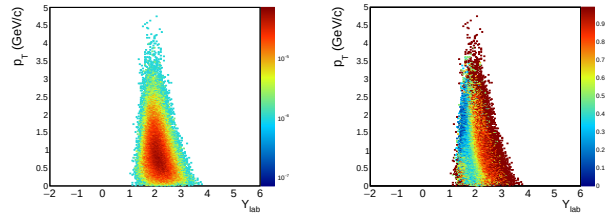


Figure 3: Left: p_t and y distribution of all unlike-sign pairs in the day-1 setup. Right: Ratio between the $p_t - y$ distributions of the day-1 setup and the full geometry.

The reduction of the dielectron signal was calculated as the ratio of the respective invariant mass spectra (see Fig. 4). On average, there is a decrease in yield of about 40 %, without significant dependence on invariant mass, above 0.5 GeV/c². The corresponding signal-to-background ratio is shown as a function of the invariant mass in the right panel. It shows a good agreement between both setups in the lower mass region, while there is a small decrease in the intermediate mass region.

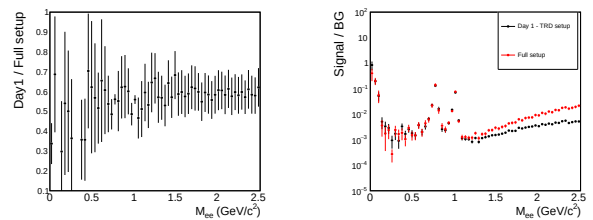
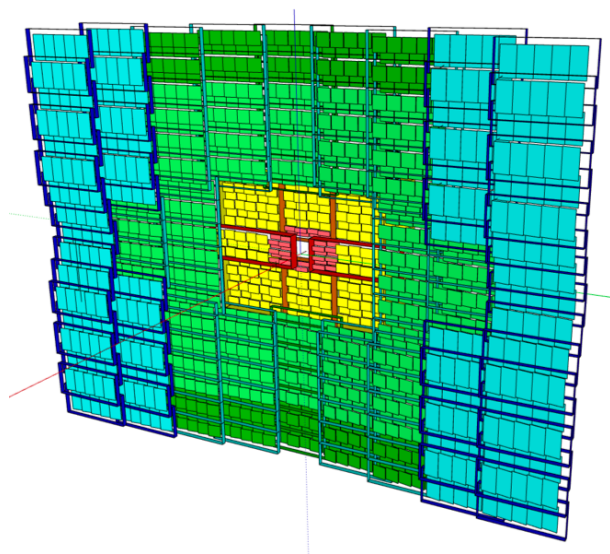


Figure 4: Left: ratio of all embedded signals. Right: signal-to-background ratio of the two configurations.

In conclusion, it should easily be possible to compensate the overall reduced statistics of dielectron pairs. However, it should be noted that the reduction will mainly be located close to mid-rapidity.

Time-of-Flight Detector



TOF - Summary

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The TOF activities in 2020 were focused on the following topics:

- Operation of eTOF during the data taking period (about 6 month) in 2020 in the scope of the FAIR phase 0 program including the calibration of the fixed target data set at $\sqrt{s_{NN}} = 7.7\text{GeV}$ (the status can be seen in this report [1])
- Analysis of the data obtained during the beam time at mCBM in 2020
- Aging tests performed at Bucharest and Beijing
- Search for alternative MRPC gases (see this report [2])
- Construction of 5 MRPC4 counters (for the most outer part of the TOF wall) to be integrated in the mCBM setup as module M6.1
- R&D activities on the BFTC especially on the module design and CBM root geometry
- Successful completion of the low voltage CDR

The biggest effort certainly was put in the successful operation of mTOF during the mCBM beam time in order to create the bases for upcoming TOF project milestones. Information about the HV current consumption of the detectors correlated with the incident charged particle flux as well as the FEE current consumption was obtained which is essential to finalize the HV and LV conceptual design. The LV CDR was passed successfully while the HV CDR is targeted for March 2021.

During the beam time in 2020 which was distributed over many campaigns [3], several runs at various rates starting from a few tens of Hz/cm^2 to up to $10\text{ kHz}/\text{cm}^2$ were performed. At moderate rates of a few hundred Hz/cm^2 an efficiency in the order of 97% homogeneously distributed over the full counter surface could be demonstrated for the MRPC3 prototype (conf. Fig. 1 left side). In the same line a preliminary system time resolution in the order of 70 ps yielding in a counter time resolution of about 50 ps could be demonstrated (see. Fig. 1 right side). However, tests results at higher rates which are mandatory in order to prove the full functionality of the counters at the targeted highest CBM interaction rates were difficult to obtain due to malfunction of the firmware resulting in data losses in the readout stream. The repetition of this high rate tests are scheduled for March 2021.

Due to the free streaming readout the dark rates of the RPCs could be distilled out of the data during the beam time and led to following observation. The dark rate increased rapidly within hours when the module was exposed

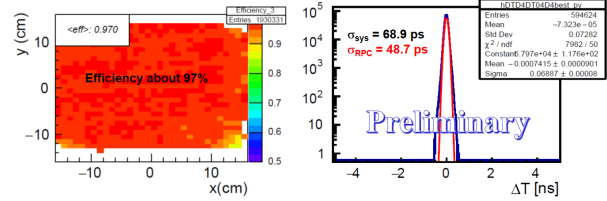


Figure 1: Left: Counter efficiency as function of the hit position. A average efficiency of 97% was measured. Right: Time difference ΔT between the counter under test and the reference counter (both MRPCs equipped with low resistive glass from type MRPC2.).

to a high particle flux (depicted in Fig. 2 left side). However, after a certain time at rest the dark rate recovers to its nominal value. The reason for such a behavior is most probably a contamination of the gas inside the gap and maybe also in the gas reservoir i.e. in the gas box. The first step towards mitigation was done by sealing the MRPC which leads to a rapid exchange of the gas around the MRPC. Such a counter is developed and currently tested and first results can be seen here [4]. The next step consequently would be to force the gas through the gaps.

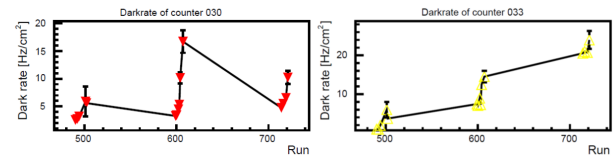


Figure 2: Dark rate as function of time (here expressed in run numbers). Grouped data points belong to one beam time campaign of a few hours. In between a relaxation time of a few days/weeks happened. For most of the counters the dark rate recovered to its nominal value (left plot). For some counters the recovery did not happen (left plot).

A second observation which was made, is that for some counters this relaxation of the dark rate with rest time did not happen (see Fig. 2 right side) even though they are located in the same gas box as the others. This phenomena is not understood yet and need further investigations. However, hit position measurements indicate, that the dark rate is entirely generated at the spacers. In order to investigate this behavior in more detail aging test were performed at the IRASM facility in Bucharest. Here a high gamma flux generated by a strong Cobalt60 source was used to expose the counter with an charged particle equivalent flux of several hundred kHz/cm^2 (about 20 times more than expected

at CBM). The results are described in detail in this report [5]. However, both observations made at the beam time could be confirmed. Currently the analysis of the chemical composition of the deposits stemming probably from generated gas radicals is ongoing. However, it was decided to test the counters in the next coming beam time without iso-Butane in the gas composition and reduce the SF₆ to a minimum content (about 2.5%).

For the next coming beam time it is planned to install the largest TOF module foreseen for the most outer part of the TOF wall. For this purpose firstly 5 counters with a active area of 50 cm × 32 cm and 32 read out strips were build in 2020. A photograph of the counter can be seen in Fig. 3. The counters are equipped with extremely thin float glass of 230 μm and have to cope with rates up to 2 kHz/cm² in the most critical regions. First rate tests with the smaller brother (MRPC3 prototype with 27 cm × 32 cm) indicate that this kind of glass could do the job.

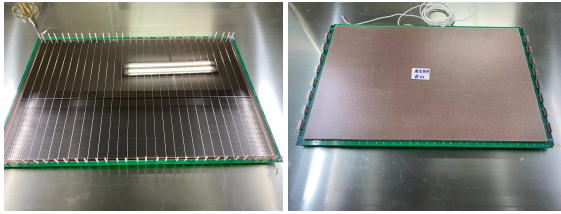


Figure 3: MRPC4 prototype. Left: open counter, spacers and glass stack is visible. Right: closed counter, honey-comb structure and connection pins from the readout electrode visible.

Substantial progress was also made in redesigning the Beam Fragmentation T0 Counter (BFTC). The current conceptual design foresees 4608 single cell ceramic MRPCs grouped in 24 modules around the beam pipe (conf. Fig. 4). It is under discussion where and how the BFTC should be mounted. From the three alternatives, (1) mounted on the tof frame, (2) on its own support, (3) on the PSD main support, the third alternative is for several reasons preferred. The beam hole of 20 cm × 20 cm is adapted to a beam pipe of 18 cm in diameter. The frond-end electronics will be the same as for the inner wall and is located as far as possible from the beam.

The frond-end electronics (FEE) for the inner wall got redesigned in 2020 as well. The idea is to install the front-end ASICs PADI XI and Get4 as close as possible on the same PCB (see Fig 5 left side) in order to minimize signal losses and guaranty a perfect impedance matching. Together with this new FEE PCB a new readout board containing the GBTx chip was designed and manufactured (see Fig 5 right side). The readout board will be located on the outer boards of the inner wall and is connected via 2 m long data cables with the FEE. The ASIC and the electronics engineering design reviews (EDRs) are targeted for the year 2021.

Along this lines also the firmware development for the

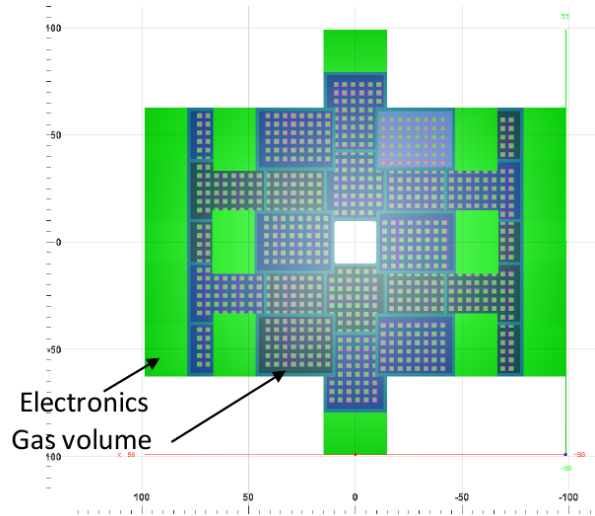


Figure 4: Layout of the Beam Fragmentation T0 Counter (BFTC). 4608 single cell ceramic MRPCs grouped in 24 modules around the beam pipe. The beam pipe hole is 20 cm × 20 cm.

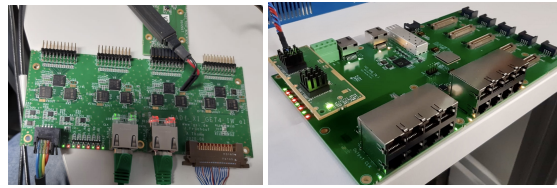


Figure 5: Readout chain for the inner wall and BFTC. Left: FEE board containing the PADI and Get4 ASICs on the same PCB. Right: Readout board containing the GBTx chip.

migration to the CRI started in Dec. 2020 and is on a very good track. New concepts of data aggregation were developed and are currently implemented in VHDL. The aim is to make use of all available 47 + 1 optical input links of the CRI.

In summary a substantial progress was achieved during the last year and we hope it will find its continuation in the year 2021.

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Preliminary results of aging studies for the MSMGRPCs based on low resistivity glass electrodes

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For the aging tests of the MSMGRPC prototypes based on low resistivity glass electrodes developed for the CBM - TOF inner zone [1] we used a 360 kCi ^{60}Co source at the Multipurpose Irradiation Facility (IRASM) of IFIN-HH, Bucharest. The ^{60}Co source is immersed in a stainless-steel pool of 6 m deepness and biological shielded by water and concrete. For the irradiation, the source is lifted from the water pool into the operating position by remote control. The mechanical support designed for positioning the MSMGRPC box centered relative to the slit in the concrete shielding of the ^{60}Co source is shown in Fig. 1 - left. The aging tests started with the exposure to gamma rays of a MSMGRPC of 30 cm x 9.6 cm active area. A 0.3 kGy/h

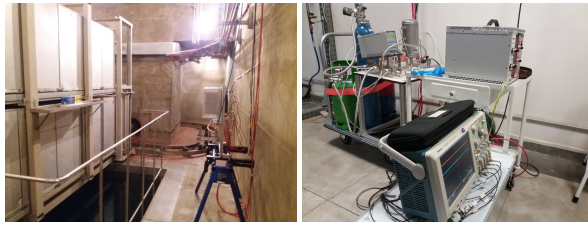


Figure 1: Experimental setup - left. Gas mixing station and monitoring equipment - right.

dose rate was measured, with not significant differences from the floor to the concrete ceiling and in similar values in the left and right directions relative to the counter position, assuring an uniform illumination of the counter.

Preliminary aging tests have been started in the fall of the 2020 year. The exposed MSMGRPC has a double stack differential architecture with five gaps per stack, each gap having 140 μm thickness [2]. The resistive electrodes are made of a low resistivity Chinese glass ($2 \times 10^{10} \Omega\text{cm}$) in order to cope with the anticipated high counting rates of the CBM-TOF inner wall, (from 30 kHz/cm² close to the beam pipe to 5 kHz/cm² to the merging zone with the outer wall).

The gas mixing station and the high voltage power supply were located in the close vicinity of the control room for the source manipulation. The counter has been flushed with the nominal operation gas mixture (90% C₂H₂F₄ + 5% C₄H₁₀ + 5% SF₆) and fed with applied high voltages up to the ones corresponding to the efficiency plateau. Signals picked-up directly from the counter connectors were monitored on an oscilloscope using 35 m length lemo cables. On front and back panel of the housing box, centered on

the active area of the counter, dosimeters which monitored the integral gamma dose had been installed. Once the ex-

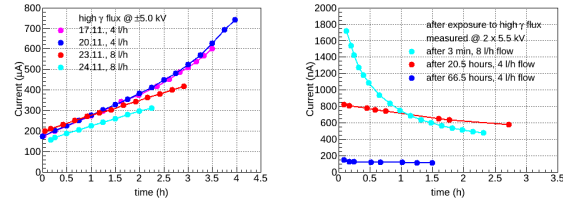


Figure 2: Current during irradiation - left. Dark current short term recovery - right.

periment had been set, the detector was powered with high voltage and exposed to the high gamma flux. During the measurements it was monitored the current as a function of the ramping up of the high voltage as well as its evolution in time under gamma exposure at a certain high voltage. In Fig.2 - left, it is shown the evolution of the current in time at 2 x 5.0 kV applied voltage, under high gamma flux, for two different gas flow rates of 4 l/h and 8 l/h. Using these measured currents and estimating the charge of an avalanche produced by an ionizing particle from the measured values of the counting rate and currents in the mCBM beam time [3] with prototypes with 140 μm gas gap thickness, a rough estimation of an equivalent charged particle flux up to 300 kHz/cm² can be made. These values overpass significantly the ones anticipated for the inner zone of the CBM - TOF wall. The increase of the current in time during irradiation could be due to the high charge density accumulated in the gas, at a given rate of the gas flow. This is demonstrated by the smaller slope of the curves measured at 8 l/h in comparison with those measured at 4 l/h gas flow. The decrease of the current during the breaks between two successive gamma exposures is shown in Fig. 2 - right. As it has been expected, a faster recovery is observed for the larger gas flow. Because the gas mixture contains tetrafluoroethane, isobutane and sulfur hexafluoride, radicals containing fluor (hydrofluoric acid, carbon tetrafluoride, etc.) and different ions which are capable to damage the glass surface and the nylon fishing line used as spacers could be created, as well as hydrocarbons which deposits on the glass surface.

After successive exposures to gamma rays summarizing more than 40 hours, a charge of 0.127 C/cm² was accumulated. At this step the counter was taken out from the cave and transported in the detector laboratory for detailed in-

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vestigations. Typical parameters to be investigated are dark current, dark counting rate, mapping of the possible microdischarges and efficiency. In order to study these parameters, 16 strips were equipped at both ends with front-end boards based on NINO chip and V1290A CAEN TDCs. First of all, a mapping of the operated area was performed using cosmic rays. In Fig. 3 it can be seen that one impor-

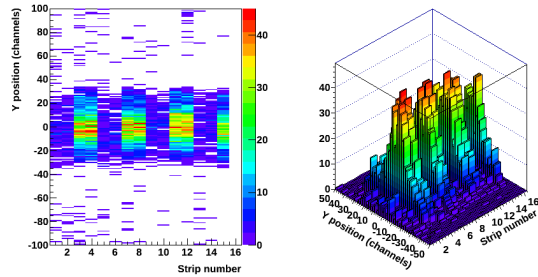


Figure 3: 2D and 3D plots of the cosmic ray mapping.

tant source of the high dark rate measured after the irradiation is the area around the spacers. This effect on the area around the nylon line was observed not only on the powered counter but also on an other one which was passively exposed, without applied high voltage. In parallel, the evo-

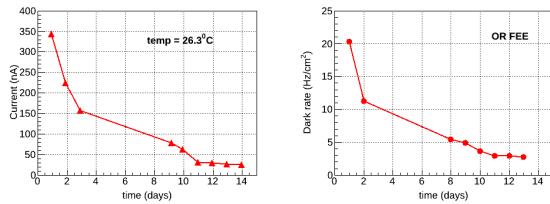


Figure 4: Dark current (left) and dark counting rate (right) post-irradiation recovery.

lution of the dark current and dark rate were monitored for about two weeks. A decrease of these parameters has been observed in time, as it is shown in Fig. 4 - left and Fig. 4 - right, respectively. The decrease is faster in the first few

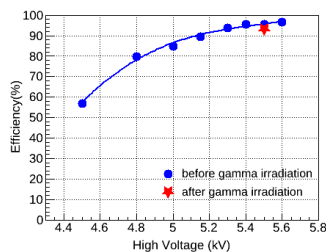


Figure 5: Efficiency before and after irradiation.

days of recovering and reaches a plateau after about two weeks, when a 25 nA dark current and 2.75 Hz/cm² dark rate were recorded. These values are still decreasing, but

much slower. Moreover, a quantitative estimation of the efficiency at 2 x 5.5 kV (in the efficiency plateau) shows only 2% decrease (93%) in comparison with the value measured before the irradiation (95%), as it is shown in Fig. 5.

After these tests, the detector was disassembled and all components had been carefully inspected. Different kind of depositions were observed on the two sides of the glass electrodes. While the side facing the cathode electrode showed thick colored deposition which can be washed out with distilled water, as it is seen in Fig. 6 - left, the surface facing the anode shows a deposition with more attenuated colors but which cannot be easily removed from the surface (Fig. 6 - right). Detailed studies concerning the elemental,

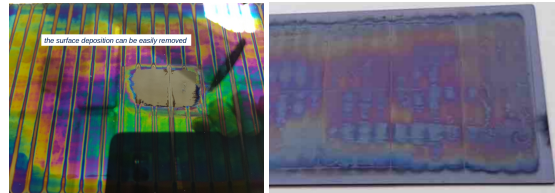


Figure 6: Side facing cathode - left and anode - right.

chemical compounds, electrical properties, etc. of the deposited layers are in progress. The color and flexibility of the nylon line were also changed, without a change in its mechanical property.

Foreseen to be operated in high counting rate for about two months per year for a ten years period, all components of the CBM experiment have to be tested such that the aging effects will not deteriorate the performance of the equipment during its expected life time. These preliminary studies will be continued with a reassembled counter with a gas flow guided through the gas gaps in order to remove faster the ionization charge from the gaps. It will be exposed to a reduced dose rate in a sequence which could be extrapolated to the aging process during the operation months of CBM experiment. A new design of the MSMGRPC which aims to reduce the observed effects is in progress.

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A potential Sealed MRPC to solve gas pollution for high luminosity CBM-TOF

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Sealed MRPC is a novel structure to reduce the gas volume for the MRPC gas container. It uses a 3D-printed sealing frame and two outermost glass electrodes to form a gas-tight chamber, which has much lower gas volume than the gas box in conventional uses. A sealed MRPC prototype was produced and tested using TRB3 cosmic test system [2]. The prototype has a geometry mostly the same as the CBM-TOF MRPC2 (former MRPC3a) detector: 2×4 gas gaps of 0.25 mm width, 7 mm strip width and 3 mm strip gap, and yet the $30.4 \times 25 \text{ cm}^2$ active area is smaller due to the extra space for the sealing frame. It features a much lower gas volume of 170 mL. The prototype has the same working point at $\pm 5.4 \text{ kV}$ with standard gas flow (Freon/ $\text{iC}_4\text{H}_{10} = 90/5/5$), where the efficiency reaches 98% and the systematic time resolution is around 60 ps. It should be highlighted that these excellent performances were maintained in a continuous operation of over 3 weeks, in an extremely low gas flow of 1 mL/min.

The results above encourage the related study on the experimental applications, especially for high luminosity situations like CBM-TOF, because the improved rate of gas exchange is approved by simulation to help regulate the pollution concentration in gas gaps [1]. As a gaseous detector, the ionization and avalanche in an MRPC will dissociate working gap molecules into F^- and other fragments. Clearly, a higher counting rate will lead to a higher rate of pollutant generation in gas gaps. The pollution related effects have been observed in STAR-MTD MRPCs [3], and in Tsinghua laboratory as well. An MRPC2 counter was irradiated by an X-ray source when the unexpected current growth was observed. The incident flux was estimated about 5.5 kHz/cm^2 , widely distributed on the whole active area of $33 \times 27.6 \text{ cm}^2$. During the exposure of 4 hours, the operating current rise in a slope of 40 nA/h , while the counting rate remained constant. Similar growth of 18 nA/h rate was also obtained during a 72h irradiation on another prototype [4] with $32 \times 0.108 \text{ mm}$ gas gaps and $25.8 \times 8 \text{ cm}^2$ active area. It is still not clear about the exact impact on MRPCs, but the current growth is a negative signal that may lead to problems in terms of noise and aging. Thus, it is necessary to develop a high rate version of the sealed MRPC for further investigations.

A high rate sealed MRPC prototype has been assembled. Concerning of the weak mechanic strength of the low-resistive glass, The outermost glass plates cannot be used as the panels of the sealed chamber. Instead, thin PMMA plates of 1 mm thickness are used. On the inner

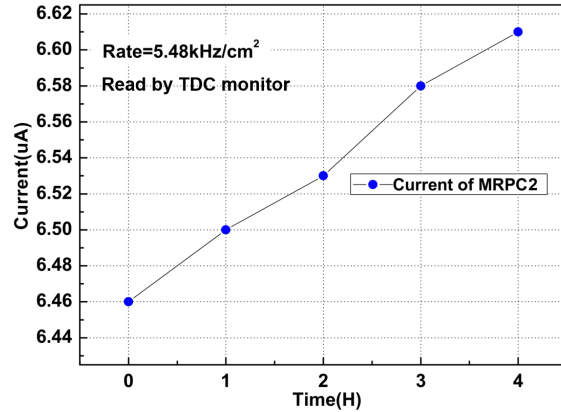


Figure 1: The current growth observed under X-ray irradiation on an MRPC2.

side of each panel, a square-shaped groove is reserved for the placement of High Voltage (HV) conductor, as shown in Figure 2. The prototype has the same geometry as MRPC2: 2×4 gas gaps of 0.25 mm thickness, 7 mm strip width and 3 mm strip gap. However, the total gas volume is as low as 170 mL. In former tests on the sealed prototype with float glass, the HV application could be safely started within 2 hours after we purged the chamber in a 20 mL/min gas flow. This favorable feature has been maintained on the high rate sealed MRPC prototype.

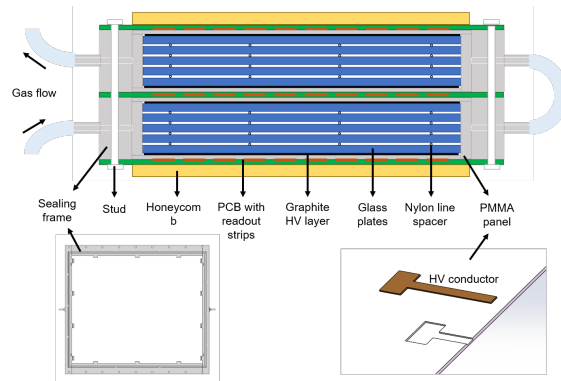


Figure 2: Structural view of the high rate sealed MRPC prototype.

The prototype was tested in cosmic rays along with 2 MRPC2 counters in the TRB3 test stand. The PADI threshold was set to 300 mV during test. The 3 MRPCs were

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piled with the prototype under test on the top. This layout is to test the prototype with X-rays, which will be discussed in the following. Standard gas mixture (Freon/ iC_4H_{10}/SF_6 in a fraction of 90/5/5) was streamed to the counters. The gas flow is 10 mL/min for the sealed prototype and 60 mL/min for the gas box that places two MRPC2 counters. Figure 3 shows the HV scan results which indicate a good performance under the low flux situation. The prototype reaches the working condition at 5.4 kV, which corresponds to an electric field of 108 kV/cm in gas gaps. The plateau efficiency is 97%, with a 1.6 cluster size and a 100 ps flight-time resolution. If we reasonably expect the same timing precision between two MRPCs, the systematic time resolution of the prototype is about 70 ps. During test, the dark current and the noise rate kept in reasonable levels, at around 20 nA and 1.5 Hz/cm² respectively.

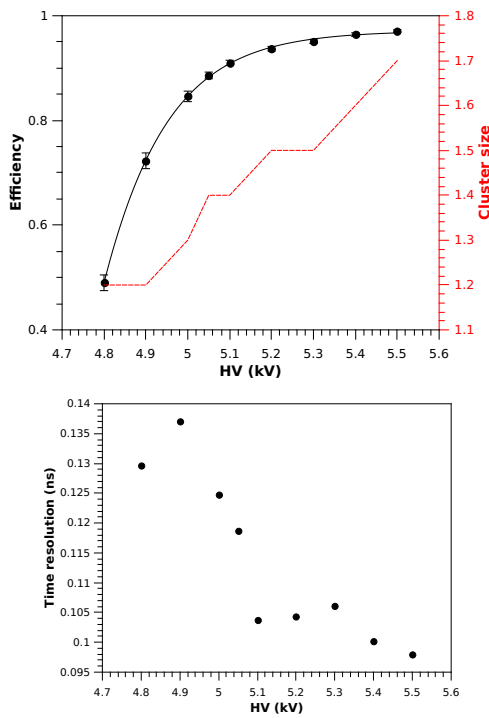


Figure 3: The performance of the high rate sealed prototype under cosmic rays.

In X-ray test, the source was placed on the top of the counter. Caused by the low energy, only the sealed prototype on the top can be tested in beam. The X-rays have a wide range to realize a full irradiation to the prototype. In the test, the counting rate was recorded by TDC, and the current of the counter was monitored by the HV power source in a precision of 10 nA. In cosmic background, the readings were both very low, as described former. The gas flow to the sealed prototype is 30 mL/min during the X-ray test, which indicates that the gas exchange of the whole gas volume can be realized in several minutes. The prototype was tested in a continuous run that lasts 9 hours. Figure

4 shows the current behavior since the X-ray was on. The prototype was first luminated for more than 6 hours, with the X-ray source operated in 42 kV / 0.3 mA. The counting rate kept at 3.4 kHz/cm², simultaneously the current of the counter was stable around 5 μ A. For 6 hours there was no sign of rise on the MRPC current, and the fluctuation was ranged within 20 nA. Afterwards, the flux was reinforced or intermitted for several times to see the current response, with the details found in Figure 5. It can be found that the current response is quite stable at various rate conditions, and is highly sensitive with changes. In Figure 5, when the X-ray was shut down, the current dropped to the dark current level of 30 nA in less than a half minute. The X-ray test has offered the potential prospect of the sealed MRPC to deal with mass pollutant production at high rate.

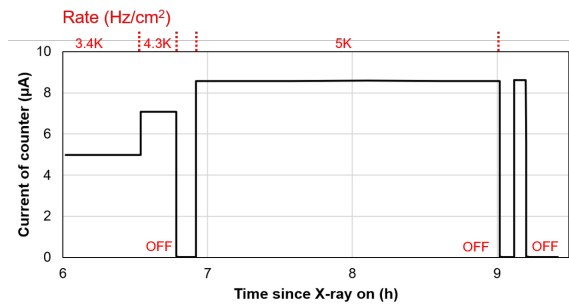


Figure 4: The current of the high rate sealed prototype under full X-ray irradiation. The current at the early 6 hours remains unchanged as well.

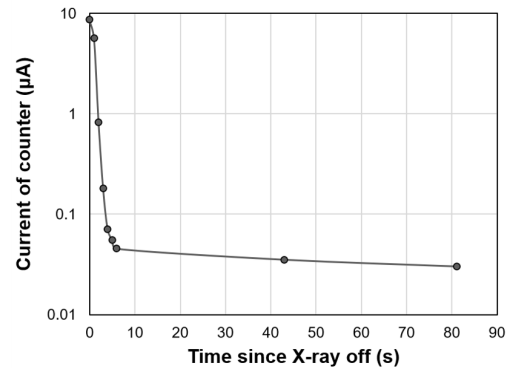


Figure 5: The Current decay since the X-ray was shut down.

In conclusion, a high rate sealed MRPC prototype has been tested in cosmic and X-rays. Excellent performance of 97% efficiency and 70 ps systematic time resolution is proved at low rate. Stable current behavior, which differs from that on the common MRPC with gas-streaming box, has been verified under X-ray full irradiation in the counting rate up to 5 KHz/cm². The sealed MRPC may develop as a solution for the high-rate CBM-TOF.

More investigations and tests in terms of material, aging,

or performance should be quickly started. Two high rate sealed prototypes are in shipment to GSI for further investigations. And more prototypes are being produced in case of the scheduled high rate tests. It is also believed that the manufacturing technique can be more improved and proficient during this process.

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Precise measurement of the parameters of gas mixtures based on Freon and HFO: 2020

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A laser test facility is developed in HZDR to measure the gas parameters of gaseous detectors under the high homogeneous electric field and atmospheric pressure [1]. It uses a focused pulsed laser to ignite primary ionization in the gas. We have achieved micro-meter spatial accuracy and picosecond pulse duration. For this experiment, we assembled a Resistive Plate Chamber (RPC) detector prototype with quartz windows to allow laser input. (Figure 1)

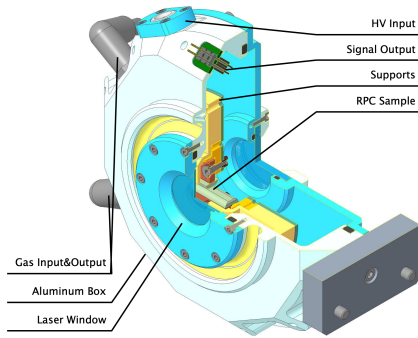


Figure 1: The RPC prototype.

RPC detector is used in the Time-of-Flight (TOF) system of Compressed Baryonic Matter (CBM) experiment. It is a type of gaseous detector with a high homogeneous electric field within its gas gap. In CBM experiments, the TOF detector is required to work at particle fluxes on the order of 1 to 5 kHz/cm^2 for the outer region and 5 to 25 kHz/cm^2 for the central region[2].

The goal of this research is to perform a reliable measurement of the electron avalanche parameters (effective Townsend coefficient α_{eff} and electron drift velocity v_{drift}) for two kinds of gas mixtures: the standard gas for timing RPC based on Freon (R134a), and a potential eco-friendly HFO-1234ze gas that could potentially replace Freon.

Various gas mixtures are measured in the experiments, including the standard RPC gas with 85% Freon + 10% SF_6 + 5% iso-Butane, and several gas mixtures with HFO + SF_6 + iso-Butane. The gas flow is set to 30 mL/min .

The high voltage is applied to the electrodes of the RPC prototype. The field strength is around 100 kV/cm in the RPC to perform like a realistic timing RPC. The parameters are measured on various field strengths.

The primary ionizations are ignited by the laser, and an electron avalanche is formed. A signal is read out from the electrodes and amplified by a 40 dB pre-amplifier, and

finally read by the oscilloscope. An automatic DAQ system is established to record and analysis the waveforms. The gas parameters can then be obtained from the waveforms, as presented in Figure 2.

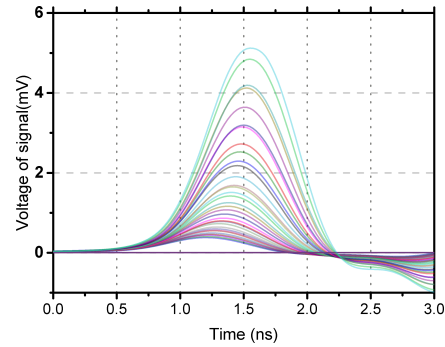


Figure 2: The waveforms with different drift lengths for avalanches.

The experimental data on Freon gas mixture shows that v_{drift} is comparable to the values from simulations in all the field strengths that are tested. Similar v_{drift} values apply for HFO gases, too, showing that v_{drift} is not sensitive to conditions.

However, differences is discovered between the α_{eff} of Freon gas mixture and simulation results[3] or the results measured in reduced pressure and field[4]. The results are shown in Figure 3.

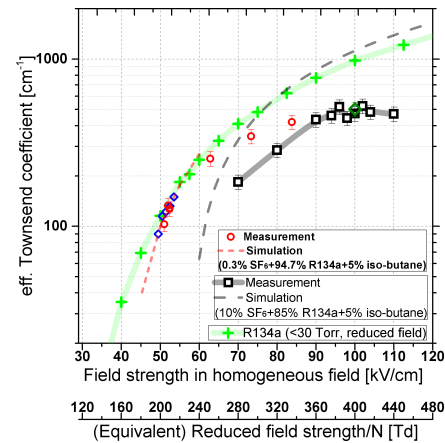


Figure 3: Effective Townsend coefficient for R-134a gas mixtures.

It can be concluded that:

- At the field strength of around 50kV/cm , the measurement α_{eff} is in agreement with the simulation.
- From 50kV/cm to 100kV/cm , the measurement value separates from simulation value eventually, until it is approximately half compared to simulation value at around 100kV/cm .
- α_{eff} saturates after the field strength is around 100kV/cm . There is not a significant increase of α_{eff} before breakdown.

The measurement of α_{eff} for HFO gases is then obtained and compared to the values of Freon gases. The results are shown in Figure 4.

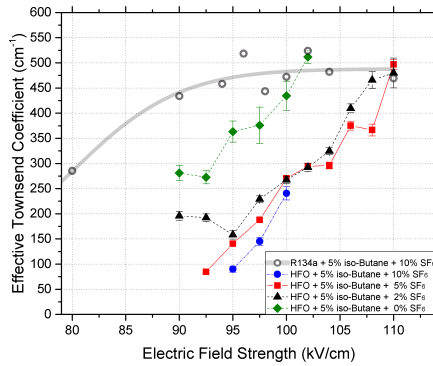


Figure 4: α_{eff} on dependence of the SF_6 percentage in HFO gas mixture.

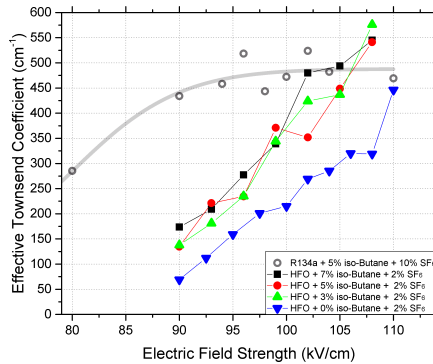


Figure 5: α_{eff} on dependence of iso-Butane percentage in HFO gas mixture.

Figure 4 shows the α_{eff} of HFO gas mixtures with a fixed percentage of iso-Butane and various percentage of SF_6 . Comparing the data with 0% and 2% SF_6 , the difference is significant. On the other hand, α_{eff} does not differ significantly when the percentage of SF_6 is from 2% to 10%.

Figure 5 shows the α_{eff} of HFO gas mixtures with a fixed percentage of SF_6 and various percentage of iso-Butane. Similar to former results, α_{eff} is sensitive to the

presence of iso-Butane, but less sensitive to its percentage when above 3%.

From the gas parameters of various HFO gas mixtures, we can conclude that:

- α_{eff} of HFO gas mixtures is on the same order of magnitudes compared to Freon mixtures.
- compared to Freon, HFO gas mixtures break down right after a specific field strength depending on the percentage of SF_6 or iso-Butane, but no plateau of saturation is found.

There is not a direct replacement between the two gases. Further research is needed to replace Freon gas mixture into a more eco-friendly gas.

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Systematic evaluation of eTOF performance in the STAR RUN20

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A systematic evaluation of the performance of CBM-TOF counters in the Run2020 of STAR has been done. Improvements in the calibration procedure and a more stable determination of the performance observables (time resolution and efficiency) lead to significantly improved results compared to the preliminary work presented last year. It is shown that the detectors were operated close to the CBM-TOF performance requirements of a detector efficiency $> 95\%$ and a full system time resolution $< 80\text{ ps}$.

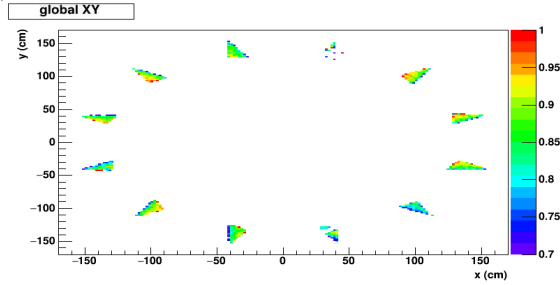


Figure 1: Counter efficiency determined from counter overlap in $\sqrt{s} = 7.7\text{ GeV}$ fixed target data.

In this analysis, the detector efficiency has been determined directly from the eTOF system, making use of the overlap region between eTOF modules. For each of the twelve eTOF sectors, one of the modules is partially behind a module of the previous sector. In this region, hits on the rear module which suffice the cut criteria (matched to a primary TPC track, matching distance to track $< 3\text{ cm}$, $p > 1.0\text{ GeV}/c$, $\beta > 0.95$) are considered reference hits. On the front detector, an intersection point is calculated from a straight line between the reference hit and the vertex. Any hit on the front detector within $< 8\text{ cm}$ radius around this intersection point is considered a matched DUT (detector under test) hit. The detector efficiency is the fraction of reference hits for which at least one matched DUT hit is found. This efficiency is evaluated in $2\times 2\text{ cm}$ bins across the surface for the reference detector. Figure 1 shows for most detectors a region in the center of the overlap with an efficiency $> 90\%$ (yellow or red areas), with a lower efficiency on the edge of the overlap region. Sector 23 is largely inefficient due to extremely high noise.

From the time difference between these matched pairs of reference hits and DUT hits, one can also determine the time resolution of eTOF without relying on other STAR subsystems. Figure 2 shows the combined time resolution of DUT and reference. Assuming equal contributions from

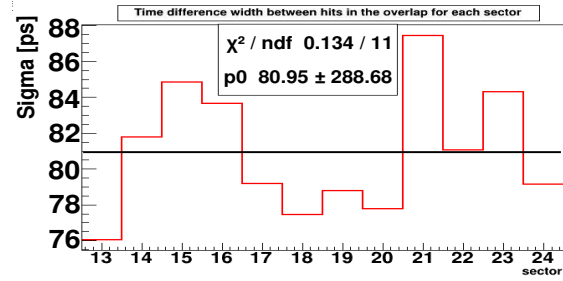


Figure 2: system time resolution determined from counter overlap in $\sqrt{s} = 7.7\text{ GeV}$ fixed target data.

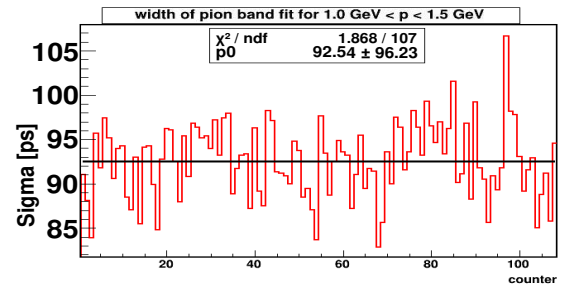
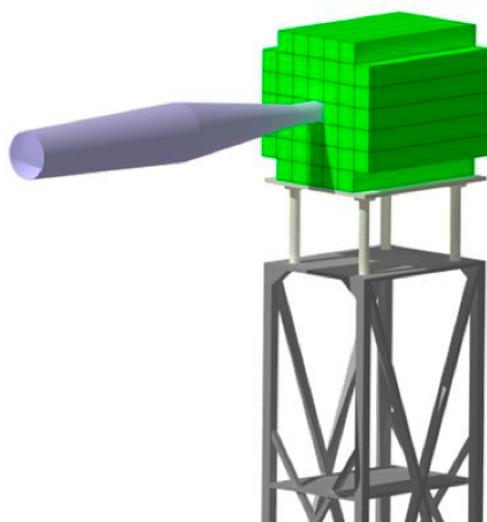


Figure 3: system time resolution for each counter with respect to the STAR TPC in $\sqrt{s} = 7.7\text{ GeV}$ fixed target data.

both counters, corresponds to single counter resolutions between 53 ps and 60 ps with a mean of 57 ps .

This time resolution measurement in the overlap has to be put in agreement to a measurement of the time resolution against the start time provided by the STAR bTOF. In this method, the time difference between the eTOF hit and an expected pion time is measured. The expected pion time is calculated from the STAR start time, the track momentum from the TPC and a pion hypothesis. Figure 3 shows the width of the pion band for a momentum of $1.0\text{ GeV}/c < p < 1.5\text{ GeV}/c$ for each counter. This width corresponds to the time resolution of the combined system. The start time resolution can be estimated under the assumption of independent measurements to be $\sim 33\text{ ps}$. Subtracting the start time resolution and the previously measured mean counter time resolution as well as $\sim 38\text{ ps}$ electronic resolution leaves a residual effect of $\sim 52\text{ ps}$ to be understood. This effect is assumed to be connected to the TPC track extrapolation as a similar effect can be seen in the STAR bTOF.

Projectile Spectator Detector



Projectile Spectator Detector - Summary

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The CBM PSD project has made substantial progress in various fields in 2020. Main achievements are highlighted hereafter and are further detailed in the individual contributions of this chapter.

The greatest successes in context with FAIR phase 0 were the successful participation of the CBM PSD group in the upgrade of forward hadron calorimeters in the BM@N (JINR, Dubna), and in the NA61/SHINE (CERN) experiments as well as participation in mCBM beam runs in spring 2020. Significant progress is achieved in the development of centrality determination methods and calibration of the calorimeters.

The new Forward Hadron Calorimeter (FHCa) at the BM@N including twenty CBM PSD modules has been fully assembled [1]. All modules of the calorimeter are equipped with front-end and readout electronics. For the data readout 8 ADC64s2 boards are used. Each board can read up to 64 differential input signals. All boards have been integrated into the common DAQ of the BM@N experiment. Presently, the FHCa is ready for commissioning and calibration. The first BM@N beam runs are expected in the fall 2021.

In 2020, the PSD group continued the work on the upgrade of the NA61/SHINE forward hadron calorimeters. Here 13 CBM PSD modules have been used in upgraded Main PSD (MPSD) [1]. During the analog electronics upgrade, the HV control of the HAMAMATSU MPPCs has been changed. The temperature stabilization of MPPCs gain is provided by adjusting the supply voltage according to the temperature of MPPCs. The same approach is planned to be used at the future CBM PSD. Amplitude-to-digital converters based on DRS4 chip will be used to read out of the MPSD at the NA61/SHINE. The cosmic data were collected for modules calibration. The first NA61/SHINE beam runs are expected in the fall 2021 for testing and calibrating the MPSD.

The biggest effort, however, was put to test mPSD during mCBM 2020 campaigns. The prototype of the CBM PSD readout system has been developed and constructed [2]. The prototype included front-end electronics (FEE) addon board and ADC FPGA readout board. Conceptual firmware and software parts were implemented in the mCBM DAQ and successfully tested at beam interaction rates up to 10 MHz [3], close to the final CBM environment. This firmware concept will be used for final CBM PSD setup. The data from the mPSD detector is transmitted to the mCBM common DAQ using the DPB board with modified firmware. The received data packets is monitored by the number of read GBT words. The control of

all transmitted information is carried out online with developed software module for data monitoring.

In the CBM, as well as in the BM@N and the NA61/SHINE experiments hadron calorimeters have a beam hole in the center, which is motivated by high radiation doses in central area of calorimeters. This feature gives no possibility to determine the centrality in heavy ion reactions only from the measurement of total energy deposition in the calorimeter. Therefore, new approach using machine learning methods was developed in 2020 to solve the problem of centrality determination with such type of calorimeters. This approach combines the total energy deposition in the calorimeter with the energy distribution of particles over full calorimeter surface [4].

Due to the unavailability of a muon beam at the CBM as well as at the BM@N, the PSD and FHCa cannot be calibrated directly on the beam. Taken into account a modular structure of the calorimeters and a sectional longitudinal segmentation of each module, a tracking method of energy calibration of the sections with cosmic muons was developed [5]. The muon tracks in this method are reconstructed with an algorithm, which searches for tracks in the 3D space of the calorimeter sections. Then, energies deposited in the sections of the calorimeter are corrected to the track length in the sections. The results of the developed method of energy calibration of FHCa modules by cosmic muons demonstrates an improvement in the calibration accuracy and the efficiency.

One of the very important achievement in 2020 was the successful site acceptance test of the upper part of the support platform for the PSD, which has been performed in mid-September 2020 in the FAIR [6]. This PSD support frame allows horizontal and vertical movement of the PSD with the precision of millimeters as well as rotation of the whole PSD with the weight about 23 tons around vertical axis. The platform was designed and build by Czech team and successfully tested.

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Development of PSD modules energy calibration with cosmic muons

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The PSD will measure signals from the minimum ionizing particles, which correspond to the energy deposition of about 5 MeV in calorimeter section, and up to about 1 GeV observed in sections in heavy ion collisions. The calibration of calorimeter is complicated due to the small amplitudes of the muons which are comparable to the noise signals.

The developed waveform fitting procedure, based on the Prony least squares method [1], allows to select the true events near the noise level and to accurately measure the signal charge. This technique was chosen due to the unprecedented speed of signal processing, since it requires only solving a single system of linear equations. The true signals are then selected by the developed fit quality assessment criterion, R^2 , measuring the agreement of the ADC waveform and the resulting waveform fit. The selected signals are then used in a new approach to muon calibration.

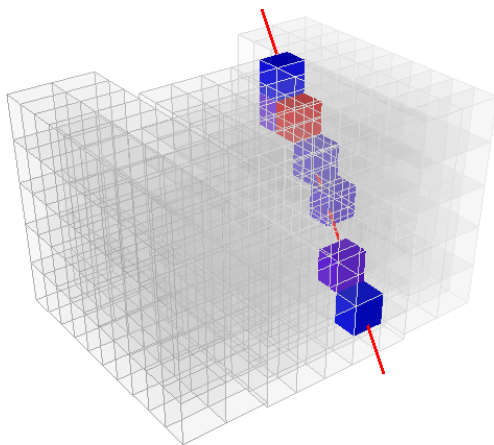


Figure 1: 3D-view of a muon track in the FHCAL.

Since muon beams are unavailable at the CBM setup, energy calibration of the PSD can only be performed by using cosmic particles. This is complicated by variation of deposited energy depending on the track position and orientation.

However, longitudinal and transverse segmentations of the calorimeter allow to reconstruct muon tracks to improve calibration efficiency. The procedure of cosmic muon track restoration is performed in two steps. First, the center of gravity of deposited energy in the sections of the calorimeter is found. In the frame of reference associated with the

center of gravity, the track of the cosmic muon is determined only by its direction vector. The search for the direction vector is constructed using the least squares method and is described in detail in [2].

The procedure of the cosmic muon calibration of calorimeter sections was tested with first data of the upgraded FHCAL of the BM@N experiment, JINR, Dubna, Russia within the FAIR phase 0 program.

An example of the cosmic muon spectrum in one of the FHCAL sections is shown in Fig.2. The blue spectrum shows the integral of the waveform of the signal; yellow - the integral of the corresponding fitting function; green - the integral of the fitting function, corrected for the length of the cosmic muon track in the section; the red line is the fit of the final distribution by the composition of the Landau and Gaussian functions.

The developed calibration method has good precision and drastically reduces the time of the FHCAL calibration by using almost all cosmic muon events.

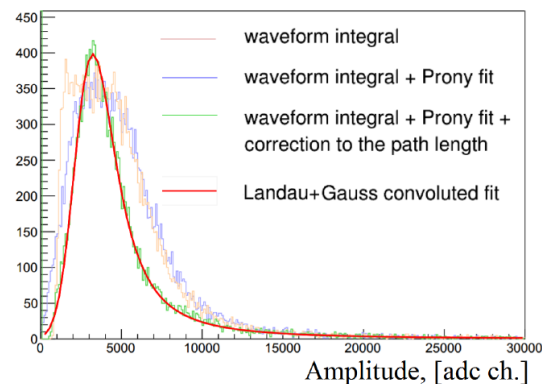


Figure 2: Track length correction in one of the FHCAL@BM@N sections.

References

- [1] N. Karpushkin, F. Guber, and A. Ivashkin, Application of the Prony least squares method for fitting signal waveforms measured by sampling ADC, AIP Conf. Proc. vol. 2163 (2019) 030006
- [2] S. Morozov et al., Methods of signal processing and cosmic muon calibration for the BM@N sampling lead/scintillator hadron calorimeter, JINST 15 (2020) no.05, C05050

Development of the PSD electronics

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Development of the readout chain and service equipment architecture of the PSD has been done in 2020. It is presented in the Fig.1:

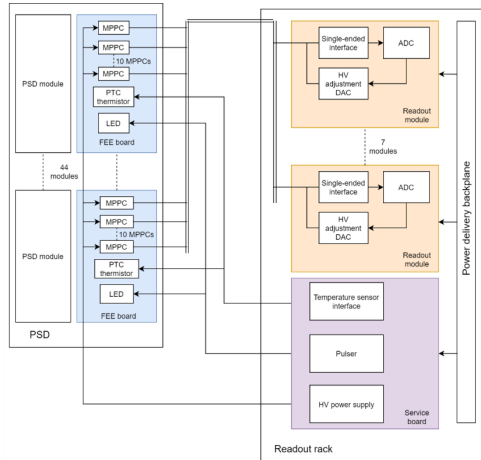


Figure 1: PSD electronics architecture schematic diagram.

The PSD electronics architecture consists out of a set of readout and service boards and radiation-hard front-end electronics (FEE) boards. Front-end boards are mounted directly onto the PSD modules, where high radiation doses are expected. Readout boards and a service board are placed in the readout rack, located in a radiation-safe environment. The readout part is connected to the front-end part via 40-60m long signal cables. [1]

The FEE boards host MPPCs, a temperature sensor (PTC thermistor), optical calibration LED, cable connectors and optical crosstalk protection hardware. These boards provide direct load of the MPPCs into 50 Ohm coaxial cables. FEE boards are fully designed, and a first batch of boards has been produced. One of them is currently assembled (shown in Fig.2) and is being used for testing purposes.

Optical protection hardware resulted in a reduction of MPPC's dark current and subsequent thermal noise reduction – from 200 nA to 80 nA per MPPC.

Readout module is an assembly of the ADC interface board and the ADC board itself (Fig.3). The ADC board used was initially designed for the ECAL detector of PANDA experiment. ADC interface board hosts single-ended to differential converters with adjustable input and output zero level, as well as high voltage correction circuit. High voltage correction is done through common mode compensation: board may apply a DAC-controlled DC voltage onto a signal line, adjusting the common 80V

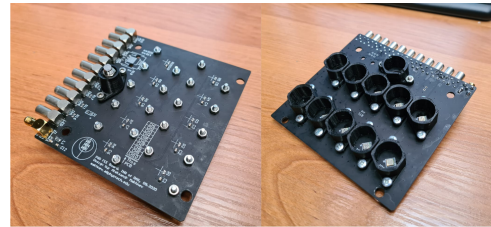


Figure 2: Front and rear side of the FEE board.

MPPC supply for each of the channels individually, leaving the AC signal unaffected. Both of the boards are designed and a first batch of boards has been produced. One of the assemblies is currently completed and used for testing and firmware development.

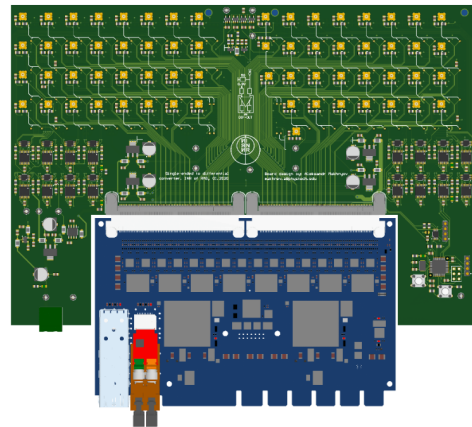


Figure 3: The design of the readout module.

Service board is a multi-functional unit, designed to serve PSD needs (Fig.4), that are not related to the signal chain. Service board hosts a high voltage supply for biasing the MPPCs, as well as monitoring of the MPPCs current with automatic protection against overcurrent, temperature sensor interface through resistance-to-digital converters, optical calibration LED pulse generator and drivers. Operation of the board may be controlled directly through manual switches or remotely via a slow control interface.

Control commands and configuration from DCS translated with single GBT link to ADC board and rerouted to MCU mounted on service board via I2C interface.

An evaluation version of the Service board has been developed, manufactured and is undergoing verification and

firmware development. Evaluation board may be easily scaled into a full-scale version.

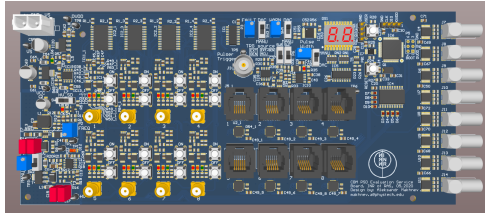


Figure 4: The service board design.

Since the readout part and the Front-end part of the PSD's electronics are connected via long signal cables, the cable's properties are very important for the system's functionality. Hence, a characterization process has been started to pick a suitable cabling option. Currently, three variants of signal cables of various lengths have been tested. Results of the frequency response tests are shown in the Fig.5. Mean RMS noise of the whole readout chain as measured at ADC is around 0.2 mV, with little dependence on the cable used.

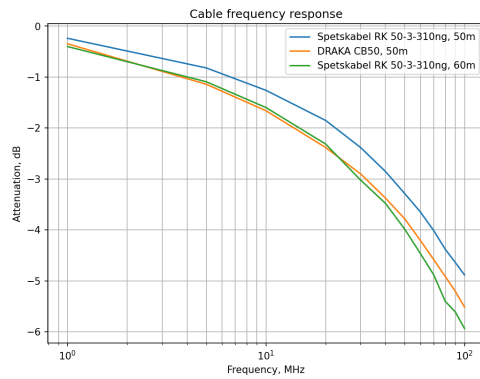


Figure 5: Results of the frequency response tests.

References

- [1] D. Finogeev et. al., 2020 J. Phys.: Conf. Ser. 1690 012059

The first mPSD beam test results at mCBM in 2020

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At the end of 2019 and beginning of 2020, beam tests at mCBM@SIS18 were carried out with Au and Pb ions at 1.01 - 1.22 AGeV energy range. Test of the mPSD prototype as a part of mCBM experiment allows to approve and verify the feasibility of the PSD readout concept. The prototype includes crucial parts of the readout such as Adon prototype board and ADC FPGA readout board. In this setup, Adon incorporated only the single-ended to differential converters and the necessary power systems. Photo of the assembled mPSD electronics setup is shown in figure 1.

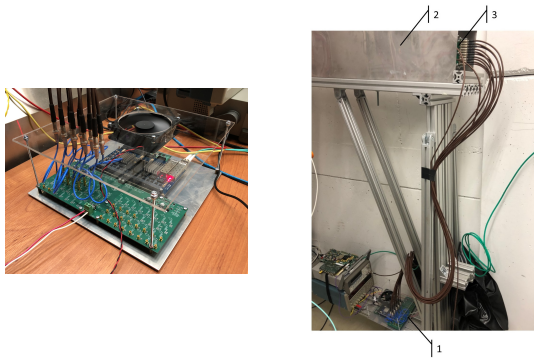


Figure 1: Photo of the ADC board assembled with the Adon board prototype (left); photo of mPSD module connected to FEE (right; 1 - Adon and ADC assembly, 2 - mPSD, 3 - MPPC board)

The ADC FPGA board was connected to mCBM DAQ via GBT protocol used for data transport, clock distribution and configuration purposes. ADC was used in 80 Msps digitization mode. Each channel is triggered independently by amplitude threshold crossing and extracts data points from the waveform of the input signal measured in a fixed gate. ADC takes data in trigger-less readout mode according to CBM DAQ requirements. In addition, prototypes of all crucial software parts such as data unpacker, event building and data monitor were developed and tested.

One of the prime aims of mCBM is to test and validate the data processing concept and the reconstruction software which are being developed for the full CBM experiment. mCBM thus will be a demonstrator for the computing concept of CBM, including the reconstruction of events and selection of data in real-time and the full offline data analysis. It is thus planned to use already existing software components as far as possible for both online and offline computing in mCBM. The challenge of the trigger-less readout

is time synchronization and event building procedure. It is necessary to construct events from signals based on their time stamps while data processing.

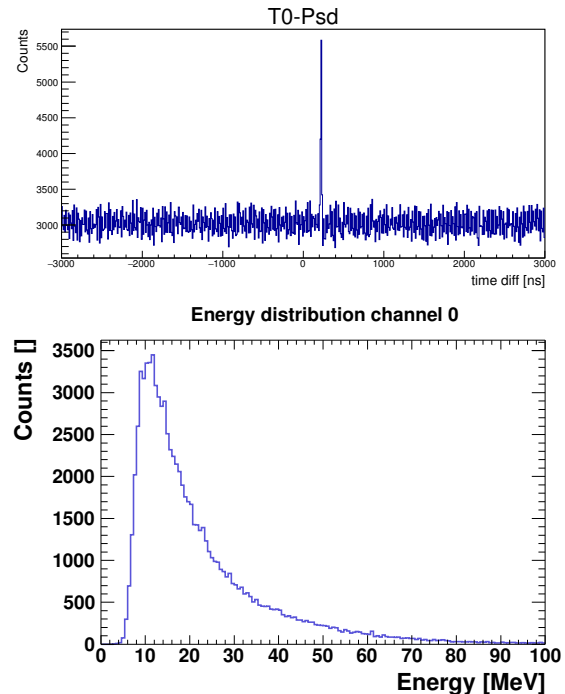


Figure 2: T0-mPSD time correlation (top); mPSD energy deposition in first section (bottom)

The conducted tests have shown the correctness of the chosen concept. The data analysis is in progress.

References

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- [2] Sernequet Sorli, Á. (2015). *A multichannel digitizer for the PANDA experiment*. <http://hdl.handle.net/10251/56722>.
- [3] Finogeev, D. et al., *Readout system of the CBM Projectile Spectator Detector at FAIR* JINST **15** (2020) no.09, C09015 DOI: 10.1088/1748-0221/15/09/C09015

Using the CBM PSD modules in the experiments during FAIR-phase-0

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The CBM PSD project has substantial progress in 2020 in preparation to CBM experiment. Twenty of already constructed CBM PSD modules have been used for the assembly the new FHCaI at BM@N experiment. The FHCaI has been assembled and equipped with FEE and readout electronics and installed at the BM@N. The first tests on the cosmic muons has been done. The photo of the calorimeter is shown in Fig. 1.

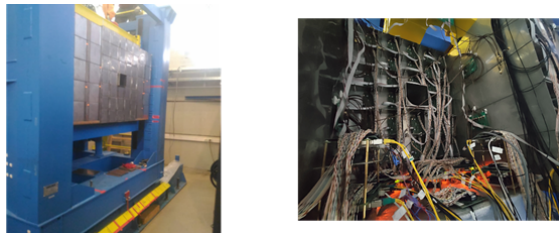


Figure 1: Left, photo of the FHCaI front view installed on the BM@N. Right, rear view of the calorimeter with installed FEE and readout electronics.

Other 13 PSD CBM modules have been used to upgrade the main PSD at the NA61/SHINE experiment at CERN. Four of them with tapered edges are used at the center of the calorimeter to provide the beam hole $60 \times 60 \text{ mm}^2$ and other 9 modules are placed on the top and lateral sides of the calorimeter. The photo of upgraded main PSD is shown in Fig. 2.



Figure 2: The upgraded NA61/SHINE MPSD which uses 13 CBM PSD modules.

The CBM modules are read-out with digitizers. At BM@N experiment the 64-channel ADC from AFI electronics (Dubna) is used. The NA61/SHINE experiment will use DRS4 based read-out boards. An example of testing the modules on cosmic muons is shown in Fig. 3.

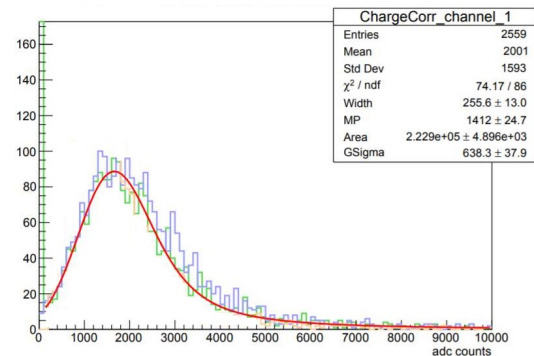


Figure 3: The cosmic muon calibration result for one section of PSD module at NA61/SHINE experiment. Blue: signal waveform integral. Green: signal integral corrected for the cosmic muon track length in section. Red: Landau convoluted with Gauss fit result.

The results of cosmic muon calibrations are led to the "passport" of module showing the calibration parameters for all sections of the module. An example of "passport" for one of the modules is shown in Fig. 4.

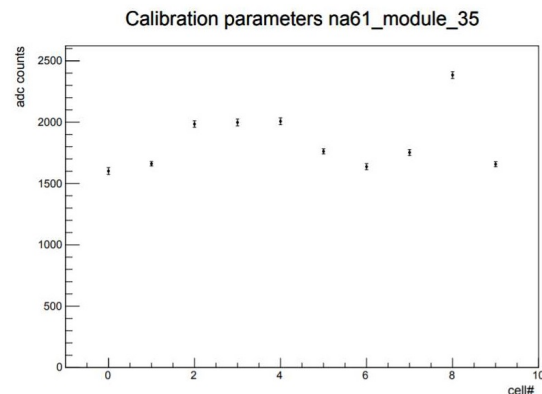


Figure 4: The cosmic muon calibration results for one PSD module.

References

- [1] F. Guber et. al., Transverse and longitudinal segmented forward hadron calorimeters with SiPMs light readout for future fixed target heavy ion experiments Nucl.Instrum.Meth. A958 (2020) 162728

Status of PSD platform development*

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Introduction

This article describes the PSD manipulator final design and conceptual design of the manipulator support structure. Development and requirements of the manipulator are described in CBM Report 2018 [1].

The CBM PSD Platform consist of two separate parts. The PSD manipulator which allows to move the PSD in three directions and is able to accommodate two different configurations of PSD and the manipulator support structure which keeps the manipulator respectively the PSD itself in the height of approx.5 meters.

PSD Manipulator

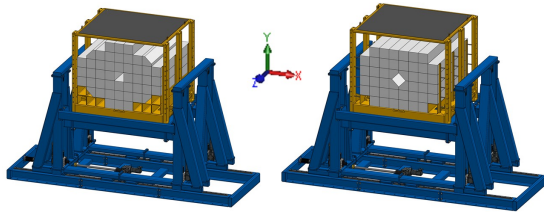


Figure 1: PSD manipulator 3D model overview with two PSD configurations. Left - 46 modules, right - 44 modules.

The PSD manipulator with two different configurations of PSD is shown in Fig. 1. The manipulator consist of three frames (in blue) and detector cage (in yellow). The base frame with one servo motor allows to move the PSD in horizontal direction within the range of $\pm 900\text{mm}$. The Y-frame with four servo motors and lifting gearboxes sitting on the base frame allows to move the detector in vertical direction within the range of $\pm 700\text{mm}$ and the rotation frame with two servo motors allows to rotate the detector within the range on $\pm 2.5\text{deg}$.

In the Fig. 2 there can be seen the manipulator with the PSD in all extreme positions and in working position. The ranges of movements are designed to be able to set working position of PSD, to target each PSD module with the beam and to set out of beam/parking position (underlined in red). The parking position is required for experiments setups where the PSD is not needed.

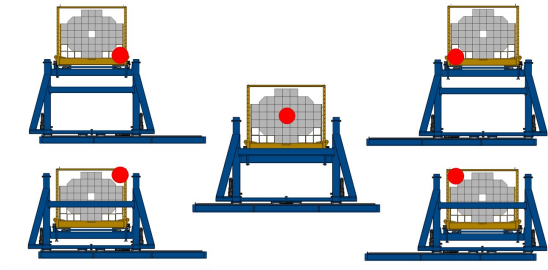


Figure 2: PSD manipulator (with 46 PSD configuration) in all extreme positions and in working position.

PSD Manipulator Support Structure

The first conceptual design of the PSD manipulator support structure can be seen in Fig. 3. The support structure (blue frame) is designed as simple steel structure sitting on two parallel rails to bring the PSD to required beam Z position.

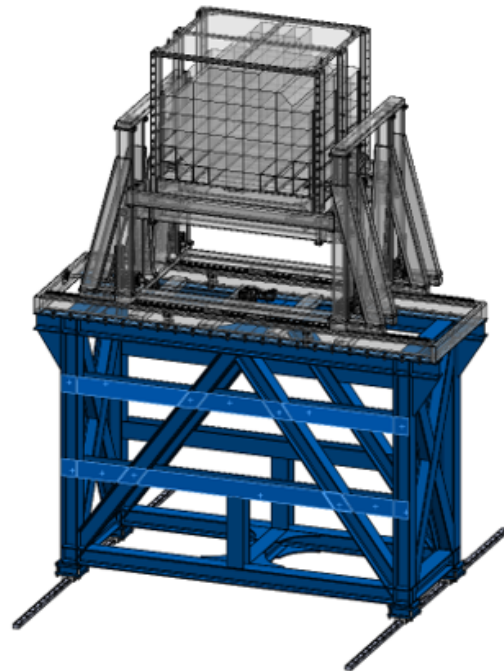


Figure 3: Conceptual design of the PSD manipulator support structure.

* Work supported by FAIR-CZ-OP (CZ.02.1.01/0.0/0.0/16 013/0001677) and by FAIR-CZ (LM2018112)

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FE Analysis

The finite elements analysis of the PSD platform is scoped to earthquake resistance as it is mandatory for all mechanical structures at GSI. Requirements and methodology is described by technical guideline [2].

Weight of the PSD is concentrated in its center of gravity. From this point the load of the PSD and the PSD cage (approx. 23tons) is distributed using rigid links to four corners of the manipulator rotational frame - the frame the PSD with its cage is sitting on.

In the Fig. 4 can be seen the deformation of the platform loaded by its own weight, weight of the PSD and by defined seismic action.

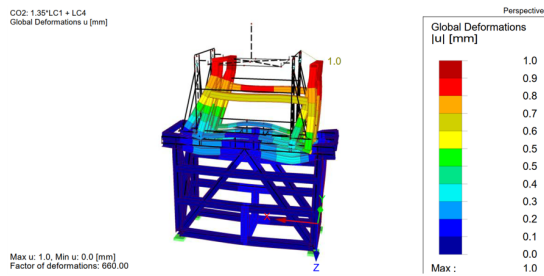


Figure 4: Deformation of the PSD platform.

In the Fig. 5 can be seen first two modal shapes of the platform with natural frequency of 3.705Hz and 6.109Hz.

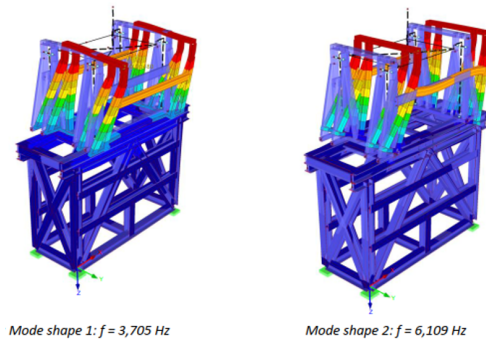


Figure 5: Finite elements modal analysis of the PSD Platform.

Conclusion

The manipulator was successfully finished and delivered to GSI in mid of 2020. In Fig. 6 is a photo of the manipulator in GSI storage facility after successful side acceptance test. Plan for next year is to update the design and FE analysis of the bottom part of the platform support structure. The design must be adopted to be able to place the platform on a CBM experiments carriage. This carriage is going to be the same for all experiments in CBM experimental cave.



Figure 6: PSD manipulator in GSI storage facility .

References

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Simulations of PSD performance at different energies

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The Projectile Spectators Detector (PSD) [1] is hadronic calorimeter dedicated to centrality and reaction plane determination using the spectators energy. The PSD is positioned at 8 meters and consists of 44 modules, each with 20×20 cm transverse dimension. The PSD has a polar angle acceptance of $0.2^\circ < \theta < 2.6^\circ$ with 20×20 cm beam hole in the center.

Spectators energy measured with PSD can be used as the centrality estimator. Similar to the centrality classes defined by the produced particle multiplicities [3], one can introduce centrality classes based on spectator energy or their number according to the following formula:

$$C_E = \frac{1}{\sigma_{AA}^{inel}} \int_0^E \frac{d\sigma}{dE'} dE'. \quad (1)$$

Here E is either the energy of spectators (e.g. measured using PSD) or their multiplicity N_{spec} (e.g. registered with a scintillator counter). Energy of projectile spectators might be modeled using parameters of collision geometry (b , N_{spec}) sampled from the MC-Glauber model [4, 5]. Details of procedure for centrality determination with PSD see in dedicated report.

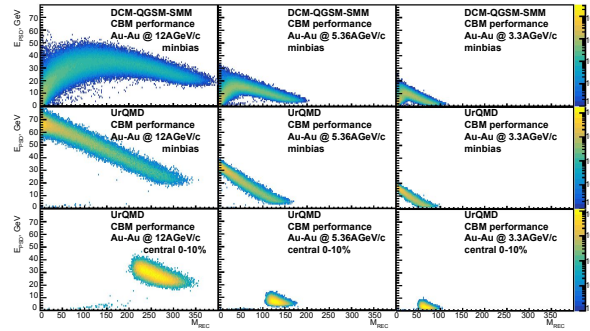


Figure 1: Correlations between energy measured in PSD detector and multiplicity of reconstructed tracks for DCM-QGSM-SMM and UrQMD models for different energies (12, 5.36 and 3.3 AGeV/c) and centralities (minbias and central 0-10%)

To investigate performance of CBM detector and of PSD particularly Au-Au events at different energies are simulated. To generate collisions UrQMD and DCM-QGSM-SMM model are used. After this generated events are transported through CBM setup with GEANT4 package.

One of the main results of this procedure can be found on Fig. 1. There are correlations between energy measured

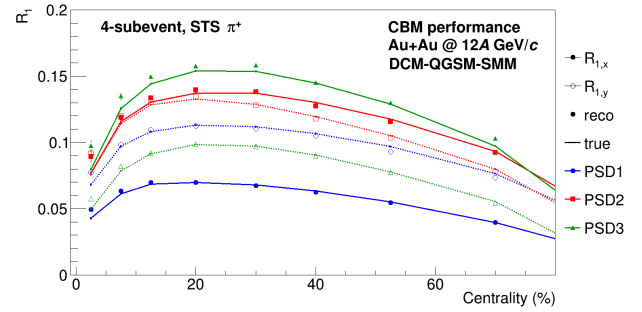


Figure 2: reaction plane resolution of the PSD.

with PSD and reconstructed tracks for DCM-QGSM-SMM model with fragments and for UrQMD model for three different energies (12, 5.36 and 3.3 AGeV/c) and two different centralities (minbias and central 0-10%). Central events were selected on generator (UrQMD) level according to CBM Events Preselection procedure based on information about produced charged particles tracks.

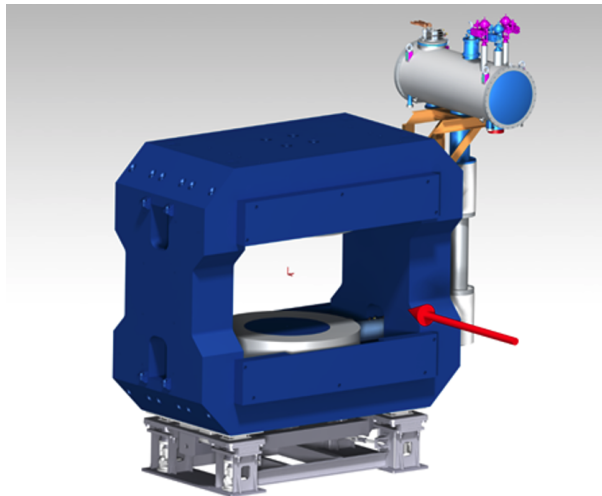
In the low multiplicity range on upper panels of Fig. 1 we can see breaking of the anticorrelation between PSD energy and multiplicity of reconstructed tracks. This effect observed due to 20cm hole in center of PSD detector. Also from this correlations one can make a conclusion regarding the procedure for determination using PSD energy. For all energies strong dependencies of collision geometry and PSD energy were observed. Therefore this observable might be used as centrality estimator.

Symmetry plane resolution correction factors $R_{1,j}^A\{B, C, D\}$ were calculated with the 4-subevent method, which reduces the bias from additional correlations between PSD subevents.

References

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- [4] M. L. Miller et al. ARNPS 57:205-243 (2007).
- [5] C.Loizides, et al., arXiv:1408.2549.

Magnet



The superconducting dipole magnet of the CBM experiment

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After approval of the Preliminary Design Review in December 2019, the work in 2020 focused on the preparation of the Final Design Review. However, it turned out that some of the planned activities were delayed due to the pandemic restrictions at BINP in Novosibirsk. Therefore, it was decided to perform separate FDRs for the different components of the magnet, in order to advance with the construction of major parts and to stick to the time line. For example, the FDRs of the magnet yoke and of the power supplies and the energy extraction system are scheduled for end of January 2021 and beginning of February 2021, respectively.

One of the important tasks, which suffered from the restrictions, was the construction of a realistic mock-up coil including the impregnation. The first attempts to test the impregnation technique with a straight section of a cable array were not satisfactory. It turned out, that the epoxy compound with Al_2O_3 powder, which should harmonize the thermal expansion coefficients of epoxy and copper, did not fill properly the space between the wires. In a second test, Al_2O_3 was replaced by Boron Nitride powder, which improved the homogeneity of the epoxy compound.

In the future, the following improvements are foreseen. The mock-up coil will have a cylindrical shape and the wire will be wound in a U-shaped mandrel like the real magnet coil (see figure 1). The wire layers will be isolated by a 0.3 mm thick G-10 foil with holes. The coils will be impregnated at a temperature of about 50-60°C in order to reduce the viscosity of the compound. Moreover, the coil will be impregnated inside a vessel at a pressure of 2-3 bar. Meanwhile, the steel mandrel and the winding tools are being manufactured in BINP workshop.

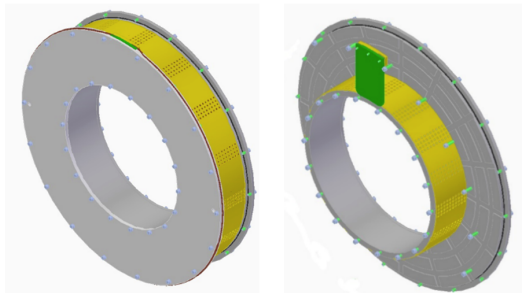


Figure 1: Sketch of the mock-up coil with the U-shaped mandrel and the insulation foil with holes.

Another important issue still to be clarified is the support strut of the coils. In 2019 it has been decided based on calculations to use one big ring strut in order to reduce the deformation of the stainless steel plate due to the mag-

netic forces, with respect to the eight single struts of the former design. The single ring support strut is shown in figure 2. It consists of two steel rings (indicated in yellow) and a ring made from glass fiber reinforced plastic in between the steel rings. However, the stability of this ring under pressure has to be checked by prototype tests, which requires a large-area mechanical press providing a pressure of about 300 tons, which is not available. If a realistic pressure test of such a single strut is impossible, the solution with eight struts will be reconsidered.

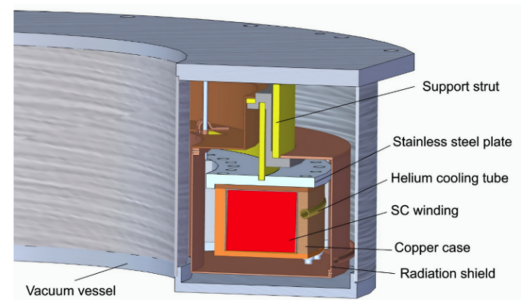


Figure 2: Cross section of the upper coil with the SC winding inside the copper case and the Helium cooling tube, the stainless steel plate the support strut, the radiation shield and the vacuum vessel.

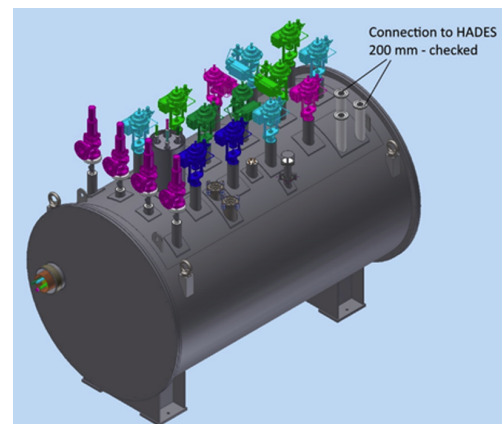


Figure 3: Branch box for distribution the liquid Helium to the cryostats of CBM and HADES.

Substantial progress was made concerning the layout of the cryogenic system. In joint discussions at several video meetings and at a workshop at GSI, the suggestions of the GSI experts concerning piping, valves, connections, safety aspects, etc. have been included in the design of the branch box (see figure 3) and of the cryostat (see figure 4). The

branch box distributes the liquid Helium coming from a cryo-plant to the CBM magnet, and to the feed box for the HADES magnet.

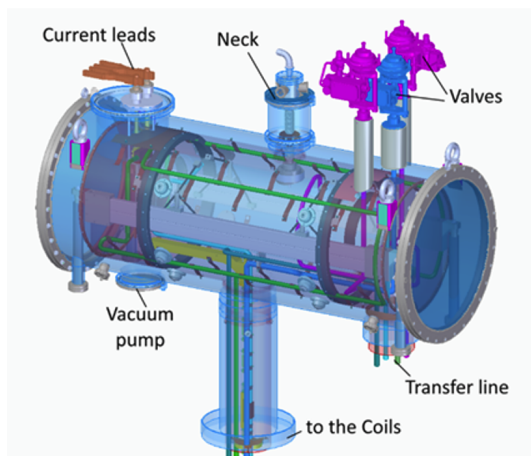


Figure 4: The cryostat of the CBM magnet

The cryostat is connected to the branch box via a transfer line of more than 30 m length. The branch box is sitting on a balcony at the wall of the cave as shown in figure 5.

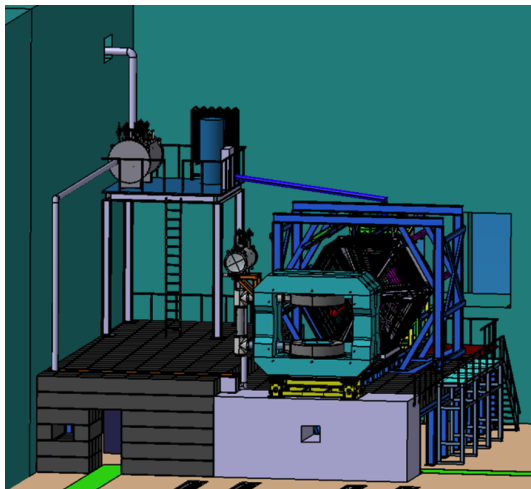


Figure 5: General view of the CBM magnet. The branch box on the balcony is connected to the cryo plant by a transfer line through the cave wall, and distributes the liquid Helium to the feed box of HADES on the balcony, and to the cryostat of the CBM magnet via a 30 m transfer line.

The magnet yoke and the pole shoes will be assembled from steel plates of about 12 cm thickness, resulting in a horizontal lamination of the yoke. According to ANSYS 3D calculations, the stray field in the region of the RICH photo detectors is 2.67 mT. Values between 3–4 mT are acceptable for the operation of the multi-anode photomultipliers. At the factory acceptance test (FAT) the magnet

field will be mapped also in the region of the RICH detector including a prototype shielding box, in order to measure the stray field. A drawing of the magnet yoke is shown in figure 6. The lamination is not indicated.

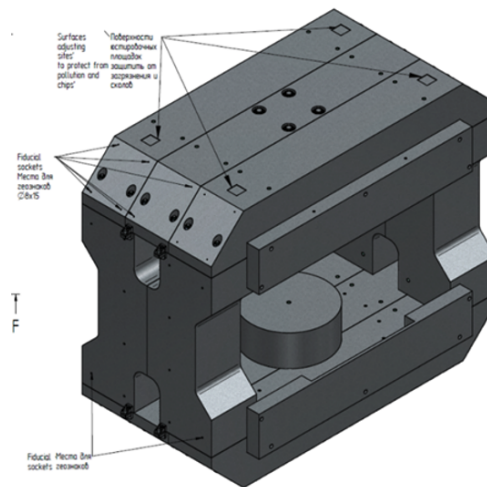


Figure 6: CBM magnet yoke with field clamps and pole shoes.

The testing hall for the factory acceptance test is ready for construction at BINP, as illustrated by the photo shown in figure 7.



Figure 7: Testing hall for the CBM magnet at BINP

The construction of the magnet yoke (including its support feet) and of the power supply will start in 2021, right after acceptance of the FDRs. The next milestone in 2021 will be the FDR of the cryogenic system, which is quite advanced. The FDR for the coil still requires impregnation tests with a mock-up coil, and stability tests of the coil support struts. The magnet control regarding cryogenics and safety requirements will be embedded into the GSI controls systems. The Factory Acceptance Test of the magnet is still planned for autumn 2022.

The CBM RICH magnetic shielding box modelling

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The CBM superconducting dipole magnet has to provide the bending power of ~ 1 T·m and low stray magnetic field in the region of RICH [1]. The 3D- model of CBM dipole magnet with RICH photodetector for the TOSCA [2] simulation is presented in Fig. 1. Three plane symmetries of magnetic field have been taken into account. About $5 \cdot 10^7$ elements and $11.5 \cdot 10^6$ nodes have been used for 1/8-th part of the model. The field integral is ~ 0.961 T·m for the current in each coil of 1.067 MA.

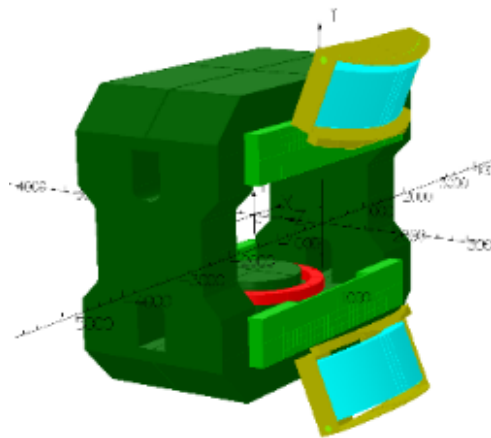


Figure 1: 3D model of CBM dipole magnet with RICH photodetectors.

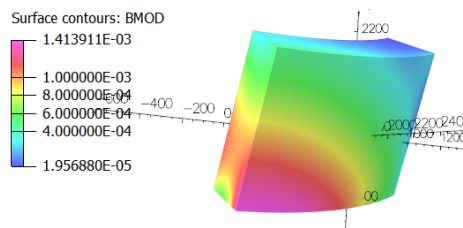


Figure 2: The field distribution inside the shielding box designed by Wuppertal-Giessen group [3].

Fig. 2 demonstrates the total magnetic field distribution inside the shielding box designed by Wuppertal-Giessen group [3]. The results are consistent with the calculations

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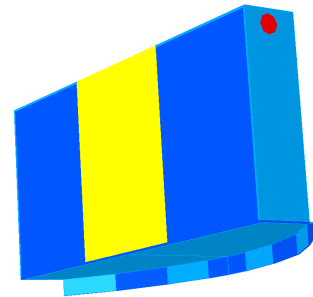


Figure 3: The back view of the RICH photodetector shielding box with a door.

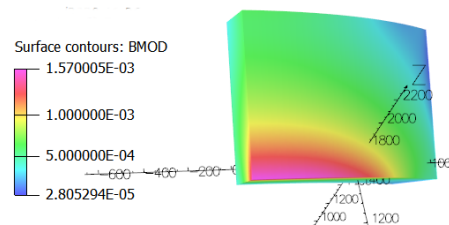


Figure 4: The field distribution inside the shielding box with a door.

performed using COMSOL [3]. The value of the magnetic field reaches ~ 1.4 mT in the significant part of the box volume. Design of shielding box with a door is shown in Fig. 3. The volume of the box is ~ 0.071 m³ being almost the same as for Wuppertal-Giessen group design[3] (~ 0.066 m³). The total magnetic field distribution shown in Fig. 4 demonstrates that the field concentrates near the surface of the box providing quite comfortable conditions for the RICH photodetector of ~ 0.5 mT.

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Effect of the yoke and poles lamination on the CBM magnet properties

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The yoke and poles of the CBM superconducting dipole magnet will be produced from the laminated steel. Therefore, it is necessary to investigate the effect of the lamination on the values of the bending power and stray magnetic field in the region of RICH [1]. The 3D- model of the 1/8-th of the CBM dipole magnet with the yoke and poles lamination for the TOSCA [2] simulation is presented in Fig. 1. The air gap is taken as 3 mm. Three plane symmetries of magnetic field have been taken into account. About $6.3 \cdot 10^7$ elements and $15 \cdot 10^6$ nodes have been used for 1/8-th part of the model.

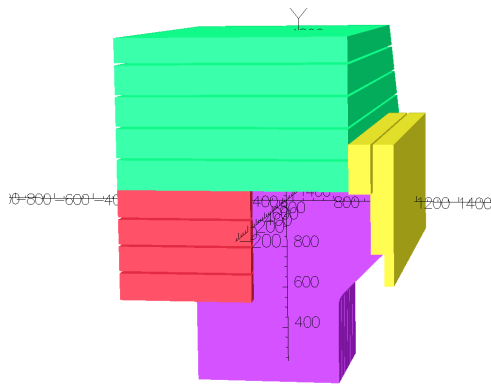


Figure 1: 3D model of the 1/8-th of the CBM dipole magnet with the yoke and poles lamination.

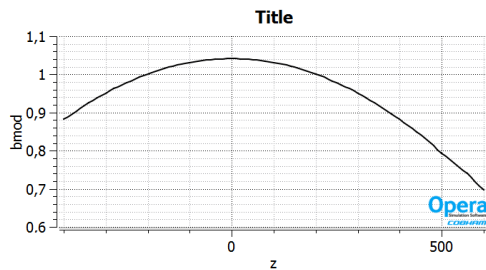


Figure 2: Vertical magnetic field component B_y distribution along the beam direction.

The B_y distribution along the beam direction is presented in Fig.2. The maximal value of the B_y component is ~ 1.05 T with the field integral of ~ 0.949 T·m for the current in each coil of 1.067 MA, that is only $\sim 2.2\%$ less than for unlaminated yoke and poles model [3].

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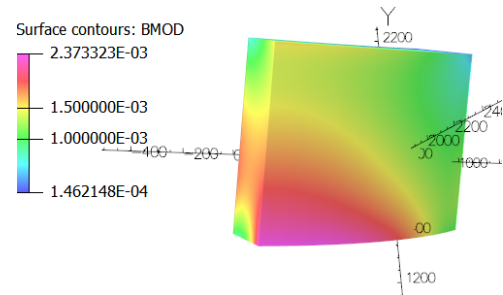


Figure 3: The field distribution inside the shielding box designed by Wuppertal-Giessen group [4].

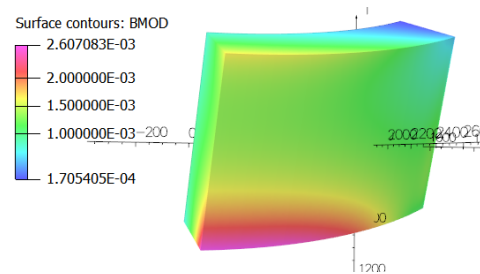


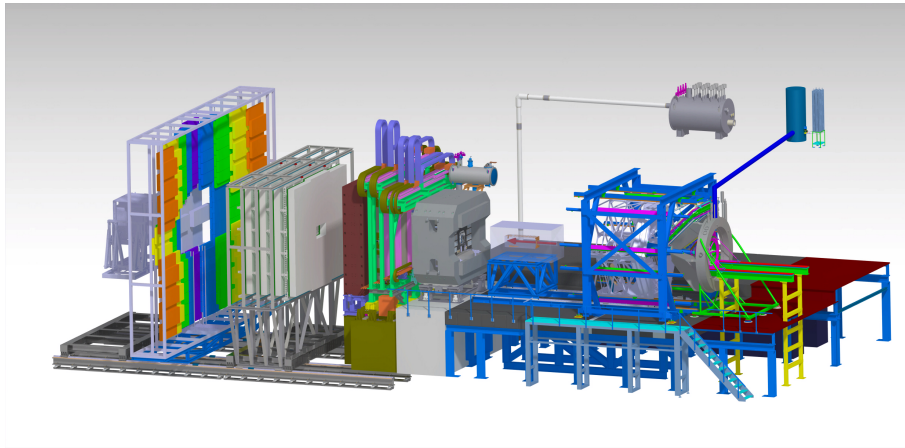
Figure 4: The field distribution inside the shielding box with a door [3].

Fig. 3 demonstrates the total magnetic field distribution inside the shielding box designed by Wuppertal-Giessen group [4]. The value of the magnetic field reaches ~ 2 mT in the significant part of the box volume. The same distribution is shown in Fig. 4 for the shielding box with a door [3]. The yoke and poles lamination increases the field in the region of the RICH photodetector up to ~ 1 - 1.5 mT to be compared with ~ 0.5 mT for the unlaminated case [3].

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Infrastructure



Digital mockup of the CBM experiment*

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Digital mockup

In order to seamlessly integrate all systems of the CBM experiment and ensure a proper installation of all components from collaborators, contractors and building services, a complete 3D model of the future CBM building is necessary. During 2020 a first version of this model was created and made available to the collaboration. The current model is, of course, work in progress and changes are made on an almost daily basis. Accordingly, only several select setups are generally published. This report provides an overview of the existing model in general and of the currently available setups specifically.

Both available setups contain the entire CBM building, designated L0608A (FAIR internal use) or G014 (construction companies and contractors). The building has a total of five floors, starting with E10, the actual cave and place of experimental setup, and ending with E50 as shown in Fig. 1. For all floors, the technical building infrastructure

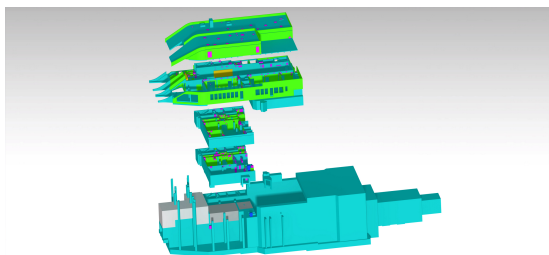


Figure 1: Exploded view of building L0608A with all levels from E10 at the bottom to E50 at the top.

(TBI) is included in the model and the planning of the experiment work and storage areas as well as transport corridors, can take the availability of (cooling)water, power and gases into account.

Muon setup

Muon setup consists of, from upstream to downstream, the MVD inside of target chamber within the STS box that is within the dipole magnet. Behind dipole is MUCH detector with all absorbers including the 5th, and downstream detectors on the rail system are staggered behind last absorber: TRD, TOF, BFTC and PSD. As shown in Fig. 2, in this setup MUCH detector is in its measurement position,

and RICH detector is placed on the upstream platform in its possible parking position.

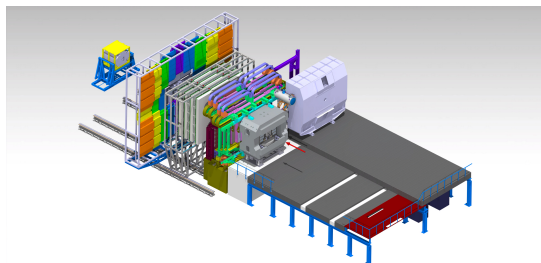


Figure 2: Rendered view of the CBM experiment in Muon configuration.

Hadron/Electron setup

The difference w.r.t. Muon setup is that RICH is in its measurement position behind magnet. The downstream detectors TRD, TOF, BFTC and PSD are moved closer to target since 5th absorber is removed. MUCH, in compact configuration, is placed in its parking position next to the cave wall.

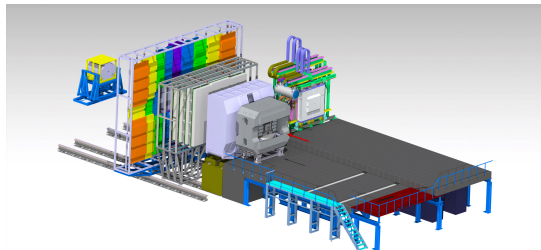


Figure 3: Rendered view of the CBM Experiment in Hadron/Electron configuration.

Both these setups are integration study cases which aim to investigate possible setting-up issues, but to determine exact configurations and positions for actual runs, a prior physics simulation is needed. In order to create the necessary correspondence between mechanical and simulation models, a regular exchange with the Physics work group (coord. by Eoin Clerkin) has been carried out. The goal of this joint effort is to ensure that simulated physics cases and experiment setups are also achievable mechanically and to optimize mechanical construction in order to minimize degradation of the detector performance.

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Design of beam monitors and T0-counters for CBM

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Introduction

The future Compressed Baryonic Matter Experiment (CBM) [1] at the FAIR accelerator facility in Darmstadt will be a fixed-target multi-purpose detector. It is developed to detect hadrons, photons, electrons and muons in elementary and heavy ion collisions over the entire energy range provided by the heavy-ion synchrotron SIS100, i.e. 3 - 11 A GeV for heavy-ions, 29 GeV for proton beam. The measurements will be performed at event rates from 100 kHz up to 10 MHz. To achieve this ambitious goal, the complex interaction of the detector systems with their free-streaming readout electronics and fast online event reconstruction and selection under realistic experimental conditions will be put into operation and tested at interaction rates of 10 MHz, i.e. with the miniCBM programme at the already existing heavy-ion synchrotron SIS18.

The aim of this project is to develop and deliver a high-speed time-zero (T0) detector on chemical vapour deposition (CVD) diamond basis. This detector must meet the requirements of the time-of-flight (ToF) measurement system for beams of protons and heavy ions. The system should have a time resolution of better than 50 ps (sigma) and stable long-term detector operation at high interaction rates of 10^7 particles/s with a detection efficiency of almost 100%. The beam detectors will be integrated inside the CBM beamline as shown in Fig. 1.

To achieve these goals, a fast detector is used in combination with fast readout electronics. At the same time, the detector could be used for the online beam monitoring and information on the beam profile and stability of the beam can be obtained, i.e. its position on the target, the amount of halo particles and the time structure of the beam.

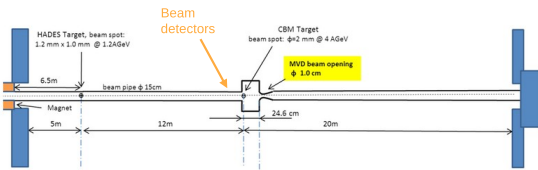


Figure 1: CBM beamline geometry. Taken from [2].

Concept of diamond based T0 detector for Day-1

Experiments with high-intensity heavy ion beams require fast and radiation-hard detection systems. For these

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purposes, pcCVD and scCVD diamond detectors (poly- and single-crystal CVD materials) are widely used. Its Radiation hardness and excellent timing characteristics make the diamond material an almost ideal choice for our application. In the proposed concept we plan to develop the time-zero start detector utilizing the commercially available electronic grade CVD diamond material produced by Element Six [3].

In physics production experiments with heavy ions, it could be shown [4] that a CVD diamond-based time-zero-start detector fulfilled the requirements in terms of time resolution and radiation hardness. The proposed CBM T0 sensor will be equipped with double-sided strip metallization with perpendicular strip orientation. Assuming the strip pitch of about 100 μm and the beam size of about 1 cm diameter we expect to be able to measure up to 10^8 particles/s keeping the particle rate per channel below of 10^6 ions/(s-channel), which is a moderate rate for the available read-out system.

In the preparation phase a set of the CVD diamond sensors is planned to be produced. Several pieces of CVD diamond material produced by Element Six have been ordered, sliced and polished, obtaining the final thickness of about 80 μm . The sensor thickness has to be kept below 100 μm to minimize the beam interaction probability in the sensor material and reduce the background events. The machined diamond plates for sensors have been optically inspected at the GSI Detector Laboratory showing excellent surface quality, an example pictures are shown in Fig. 2.

In Q2 2021 we plan to develop and establish the final geometry of the strips. It is necessary to correctly estimate the capacitance of the selected strip geometries in order to minimize the capacitive coupling between neighboring strips and between two sides of the detector. The strip metallization will be performed at the GSI Detector Laboratory.

The sensor will be mounted on a dedicated printed cir-

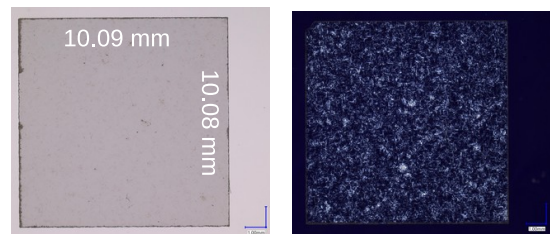


Figure 2: Optical inspection of CVD sensors. Picture by Michael Träger (GSI, Detector Laboratory).

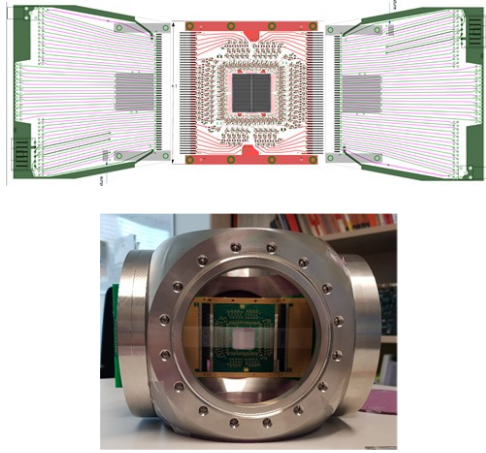


Figure 3: **Top:** Modular read-out board with the diamond sensor mounted in its center. Design by W. Koenig, GSI. **Bottom:** The beam detector will be mounted in the CBM beamline inside a cubic vacuum chamber.

cuit board (PCB) equipped with amplifier and shaping circuits. This board is connected to two additional PCBs, used as feedthrough to transport the analog signals outside the vacuum. A sketch of such PCBs is shown in Fig. 3 (left). The system will be mounted in the CBM beamline, inside of a cubic vacuum chamber, as shown in Fig. 3 (right).

Beam halo measurement concept

To ensure the stable operation of the CBM detector, it is necessary to minimize the amount of halo particles entering the detection system. For this purpose a dedicated beam collimation system is foreseen at the SIS100 accelerator complex. The CBM detector has to be equipped with a system capable of precisely measuring beam halo particles. The precise measurement must be based on the time of arrival of the individual particles. Additionally, a Time over Threshold (ToT) measurement is necessary, which will be used to monitor the efficiency and radiation damage of the system. For the beam halo measurement we plan to construct a detector by means of four active sensors positioned about 0.5 cm from the beam axis. The concept is shown in Fig. 4. Such an arrangement will allow us to monitor the position of the beam during the extraction process. The results of the measurement will be used for securing the detectors, mainly the Micro Vertex Detector (MVD) and the Silicon Tracking System (STS) against sudden changes in the position of the beam. Besides this, it is planned to have a direct connection of the beam halo detector to a beam abort system.

Mechanical integration

The CBM beam detector system is planned to consist of two detector stations. One will be used for the beam HALO and the second one for the T0 measurement. Both detectors

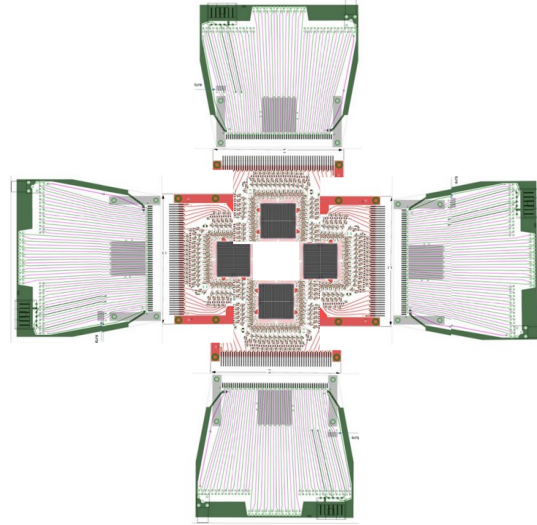


Figure 4: Beam halo measurement system by means of four active sensors positioned about 0.5 cm from the beam axis.

will be mounted inside a beampipe as schematically shown in Fig. 5. We propose to use commercially available vacuum elements and integrate them into the CBM beamline in front of the reaction target.

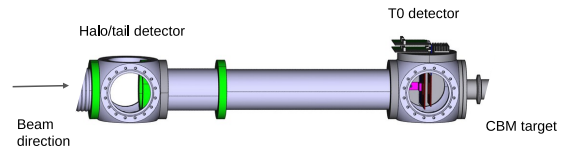


Figure 5: Beampipe with two stations of beam detectors which will be used for beam HALO and T0 measurement.

Read-out concept

The concept of the read-out system is currently being developed and its evaluation is based on the experiences of the HADES T0 detector. It takes into account the currently being developed readout chains of the CBM experiment, mainly TOF and Ring Imaging Cherenkov (RICH) detectors. The HADES collaboration has been using similar detectors for in-beam measurements and recently demonstrated excellent online monitoring capabilities of the system based on diamond sensors and TRB readout system [5].

The read-out concept for CBM is schematically shown in Fig. 6. The sensor signals are amplified on a Front End Electronics (FEE) and afterwards sent to dedicated discriminator boards. Then a fan-out of the signals will be ap-

plied. One branch will deliver the T0 measurement for the CBMs read-out electronics using either CBM TOF TDC system or the TRB based time-to-digital converter (TDC) system as proposed in CBM RICH detector. The second branch of the beam detectors readout, independent from the CBM DAQ system, will be used for an "online" beam monitoring purposes and for the fast beam abort system.

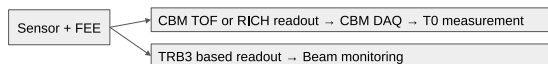


Figure 6: Read-out concept of the beam sensors. The T0 measurement has to be integrated into the standard CBM DAQ. A signal splitting will ensure a CBM-DAQ independent beam-monitoring.

Summary and outlook

The design of beam monitors and T0-counters for CBM have been shown. We are currently developing a sensor system based on CVD diamond technology. The system will be used for T0 measurement and beam monitoring purposes i.e. a beam halo particle measurement. Diamond sensors have been prepared. Next steps are to develop and establish the final geometry of the strips.

Currently the HADES collaboration is evaluating a new detector technology based on Low Gain Avalanche Detectors (LGAD). First beam test showed promising results to use this technology form in-beam detectors [6]. In parallel to the development of CVD diamond based sensors we will also evaluate this technology to use it in the CBM experiment.

Acknowledgements

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 871072. We would like to thank TU Darmstadt and GSI Detector Laboratory for the preparation of the diamond sensors.

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Experiment services room

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Overall design of the CBM building is driven by the size of full experimental setup on one side and radiation protection requirements on the other. This reflects it self in the concrete thickness of the cave walls and amount of built-in reinforcement iron. In particular, due to the radiation level in cave during running of experiments and possible activation of setup afterwards, the access to experiment (cave) is restricted or even prohibited. Therefore it is necessary to assure that vital controls and supplies to experiment are readily accessible and serviceable during running.

Apart from the service area underneath the upstream platform, which primary holds experiment power supplies, the room E30.012 (including E30.013) serves as technical services room and houses gas supply racks (mixing and recovery), high voltage/bias supplies, CBM magnet power supplies, STS cooling plant, etc. The layout of those services in the room is shown in Fig. 1.

The access to the room is during preparation phase via main stairways and elevator (c.f. Fig. 1 top), which also serves to bring in all equipment. During running periods those access ways are disabled/under control, as both can be used to access experiment area E10 (cave). Therefore only access via dedicated stairs (c.f. Fig. 1 top) can be used.

All the detector gas systems (both for HADES and CBM) are placed here. In particular, all gas systems that use flammable gases that can produce explosive mixture with air in case of leakage are placed in separated room E30.013. It is mandatory to use ATEX-certified equipment there within ("Ex"-labeled). The gas bottles are placed on ground level of CBM building and connection to service room is made via wall break-through

in ceiling. The supply of gas mixtures to detectors follows via vertical installation duct that can be accessed from the door right-down in Fig. 1.

The HV or rather biasing PSU are situated in racks on the right side of the room, the HV cables are routed over the cable trays hanged over ceiling and routed via the same duct into cave and up to the detectors. The HV cables are connected to PSUs directly, on the detector side they terminate in their patch-panels. Apart from PSUs, both racks with main DCS servers, campus internet switches, and accelerator network switches are located here. Due to relatively low heat dissipation, most of the racks do not require additional active cooling.

The magnet power supplies (HADES and CBM) are also situated here, the exact place have to be optimized in order to minimize needed cable length to magnets, but also to incorporate local control desk.

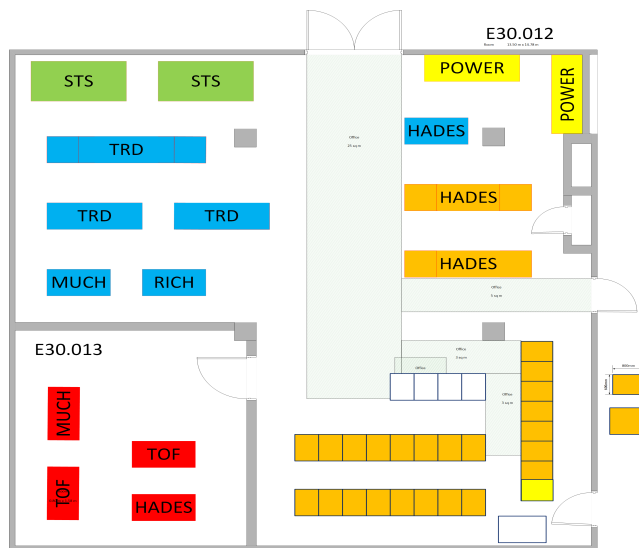


Figure 1: The layout of experiment services room; colors are indicating different types of devices: green - STS cooling plant, blue - gas systems, red - gas systems using flammable gases, orange - general electronics racks, yellow - power distribution, white - magnet power system.

Last major component in is the STS cooling plant; both for preparation of cooling liquid for detector electronics and cooling gas for sensors. The position of the plant is given by dedicated supply of cooling water.

Powering of all devices installed within the room is provided via two power distribution cabinets, depending on which power source is used. There are two power transformers in CBM building from which one is dedicated to powering of the experiment subsystems which includes powering, biasing, and readout in first place.

The possible sources of noise, e.g. pumps in experiment, or rest of HVAC within building are powered from second transformer.

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Cryo-platform - addition to upstream platform

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Liquid helium supply

Both the CBM dipole magnet and the HADES magnet are superconducting devices that require steady supply of liquid helium (LHe) for their operation. Presently, in its GSI cave, the HADES magnet is operated with both LHe and liquid nitrogen supply, while in CBM cave only helium will be used. In contrast to GSI facility, at FAIR the common cryo-plant will supply both accelerator magnets as well as experiment's magnets with LHe.

In CBM the supply line is entering the cave from left side (w.r.t. beam upstream direction, c.f. Fig. 1) through a wall window just below the cave crane, which further connects CBM and SFRS buildings via tunnel. The LHe distribution point DB2 in SFRS building supplies both buildings with LHe.

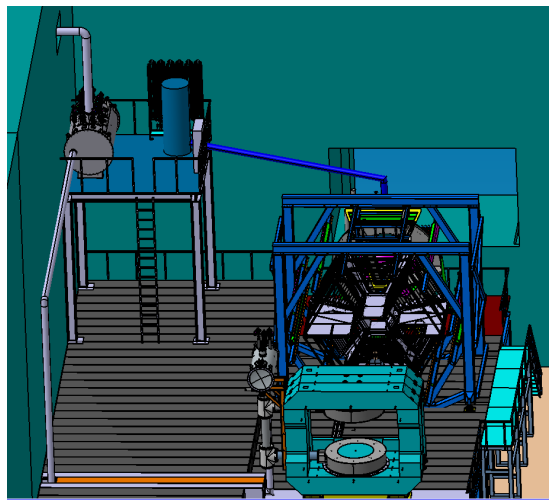


Figure 1: The cryo-platform (left) is constructed on the top of the upstream platform, both HADES setup and CBM dipole (right) are supplied with LHe by their own transfer lines.

The heat management of cryo supplies uses vacuum-isolated coaxial pipes with return lines in outer pipe to minimize the heat loss, implying that each branching/merging of the lines has to be regulated. The CBM branching box (designed at BINP together with CBM dipole) serves as LHe entry and exit point for both CBM and HADES magnets, and additionally incorporates CBM feed box which facilitates LHe supply and recovery (show in Fig. 2). For

HADES the existing feed box (attached to CBM branch box) will be used.

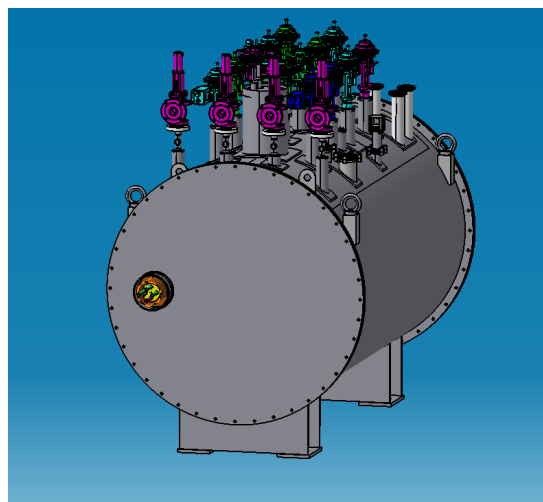


Figure 2: CAD model drawing of the CBM branch box.

Cryo-platform

While our initial concept of a cryo-balcony was made assuming much lighter parts, because of the full weight of the combined cryo-setup and position of HADES feed box, which was placed in exactly the same position relative to the magnet as it is installed in HADES present configuration, a somewhat larger construction concept was necessary. In this case the transfer line between HADES feed box and magnet is also kept unchanged.

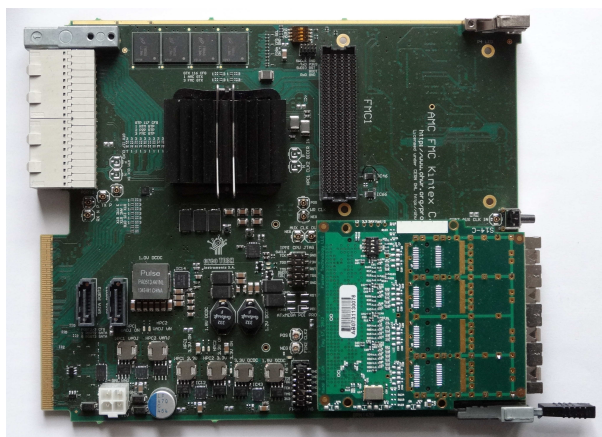
The new concept, shown in Fig. 1, is called cryo-platform; it provides approx. 4.5 m×4.5 m area at some 5.3 m above existing upstream platform. Service access to the platform follows via built-in ladder. It is estimated that cryo-platform including devices on it brings up to additional 20 tons of weight on the upstream platform, which therefore needs to be reinforced in accordance with this concept.

Position of the branch box is optimized for the installation of the transfer line that is mounted along and down the cave wall up to the end of the upstream platform and follows an recess in the shielding concrete up to the magnet.

Since position of the HADES transfer line is fixed to the present design, its weight is supported by the cryo platform on one, and the HADES magnet support on the other side.

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Data Acquisition and Online Systems



Migration towards the CRI-based RICH read-out system

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Preparations for the 2021 mCBM campaign

The mCBM campaign in 2021 will mark the transition of the mCBM read-out system from the deprecated *data-processing boards* (DPBs) to the *common read-out interface* (CRI). Many of the changes and additions to the FPGA firmware written for the DPBs are common to all subdetectors and will be part of a shared firmware base project.

In the case of the RICH, additional work is required for the downlink connections to the detector front-end. In previous mCBM campaigns with DPB-based read-out, the RICH used an intermediate solution for the data aggregation from multiple front-end modules¹. A *hub board*, using the TRB3sc FPGA platform, implemented a Trb-Net hub that collected data from multiple combiners and routed slow-control commands and replies between the RICH slow-control PC and the front-end modules.

The DPB was the only part of the mRICH read-out chain synchronized to the global mCBM clock and time. TDC-timestamp synchronization was achieved with a trigger signal generated by the DPB and distributed to the combiners through the *central trigger system* (CTS) in the hub board. Absolute hit times were reconstructed in software from the time difference between TDC hits and triggers.

CRI and combiner FPGA firmware

Figure 1 shows a simplified diagram of the CRI-based mRICH read-out system. The CRI board connects to six combiners directly, making the in-between hub board obsolete. The data-flow in the RICH-specific part of the CRI firmware requires two main building blocks: the *TrbNet* hub and the *microslice* generator.

The TrbNet hub routes slow-control commands and responses between an uplink and up to 47 downlinks (the number of optical links on the FLX-712 board currently used for the CRI). We ported the TrbNet hub previously implemented on the external hub board to the CRI platform and extended it to more than twelve ports using a nested architecture. The hub also makes the TDC-data packets from each combiner available to the microslice generator.

The TRB3sc still acts as a slow-control uplink, passing messages between a slow-control PC and the TrbNet hub in the CRI. A bridge interface allowing TrbNet access through Wishbone registers will later replace this mechanism.

The microslice generator will collect the data packets from all downlinks and pack them into microslice contain-

¹*Front-end module* here refers to a backplane with a *combiner* board, acting as a hub, and twelve *DiRICH* cards for the read-out of six PMTs.

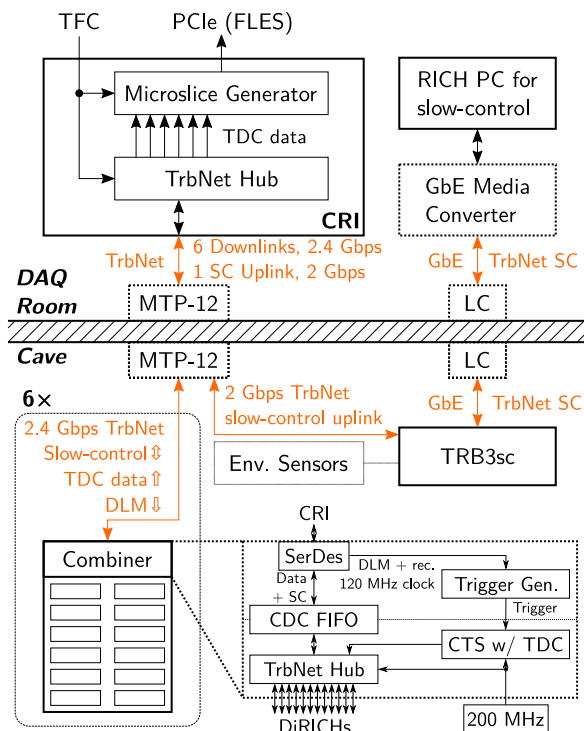


Figure 1: mRICH read-out components and data flow

ers for the FLES input logic. Merging is based on a common trigger number embedded in the data streams. Work on this firmware block will start in early 2021.

The combiner FPGA firmware also required major changes. Due to the omission of a common trigger signal, we moved the CTS previously contained in the hub board to the combiners. Every combiner now creates its own trigger signal and can be considered free-running. This requires synchronization with the global CBM clock and time.

In order to achieve clock synchronization, we changed the line rate between CRI and combiners from 2 Gbps to 2.4 Gbps. This allows the use of the 120 MHz CBM clock as reference clock and its recovery on the combiner side.

Time synchronization will be achieved by *deterministic-latency messages* (DLMs) sent from the CRI board to the combiners. We implemented the TrbNet DLM mechanism on the sender and receiver sides. First measurements showed that time synchronization could be achieved as long as the transmitter logic on the CRI board was not reset. This will likely be solved by bypassing the elastic buffer in the CRI's serial transmitter.

FPGA-related development for CBM DAQ *

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Continuation of the DPB firmware development

In the first half of 2020, the development was significantly focused on the maintenance and improvement of the DPB firmware. The beam tests have exposed the problem of hits that have been assigned an incorrect timestamp value. The effect was visible at higher hit rates. A thorough investigation has shown that the cause was an incorrect behavior of the heap sorter in case of overflow. The significant advantage of the heap sorter is the perfect sorting of hits. However, its behavior at high rates is not acceptable. As a solution for that problem, a new concept of the hit sorter has been proposed. It utilizes the bin (bucket) sorting, where hits are stored to the appropriate buffer depending on their timestamp's lower bits. The hits in each bin are not sorted, but correct handling of overflow is much easier. If a hit is received for an already filled bucket, the hit is dropped and the bucket is marked as overflowed. If a too-much delayed hit is received for an already closed bucket is received, the hit is dropped, and an error flag may be set.

The architecture of the proposed bucket sorter is shown in Figure 1.

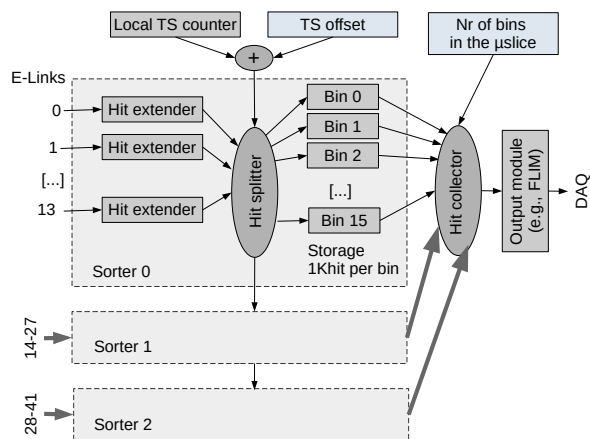


Figure 1: Block diagram and the concept of the bucket (bin) sorter.

* Work partially supported by GSI, partially by statutory funds of Institute of Electronic Systems. This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 871072.

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Preparation of the CRI firmware

The second development area was the planned reimplementation of the DAQ firmware on the CRI board. A very important difference between DPB and CRI is that the DPB was controlled via Ethernet using the IPbus protocol and interface, while CRI is controlled directly via the PCIe interface. That gives a possibility to significantly speed-up the control operations and allows the opportunity to move certain control operations from firmware to software, reducing the FPGA resource consumption. Of course, that requires significant refactoring of the firmware. The software for control of the CRI board – the Device Control Agent (DCA) is prepared at GSI by Walter F.J. Müller.

Development of debug version of the PCIe core

The most challenging task to be performed by the PCIe interface is the high-performance transfer of the readout data. The responsible IP core is developed at FIAS by Dirk Hutter. However, for the first tests of the CRI PCIe capabilities, a simple PCIe core using Xilinx's high-level blocks was developed. The solution was based on the Versatile-DMA1 [1] design, ported from Virtex 7 to Kintex Ultrascale FPGA. The obtained project has been successfully used to test the achievable throughput for simultaneous transmission of data via DMA and control transaction. The core allowed to perform approx. 320 000 of control operations (consisting of a single write followed by a single read) with simultaneous DMA transmission at 56 Gb/s in both PCIe devices provided by CRI.

The developed core was also successfully used to debug BIOS limitations in the entry-node servers (done in cooperation with David Emschermann) and investigate problems with CRI boards not booting correctly.

Development of the PCIe to WB bridge

The last version of the DPB firmware uses the Wishbone bus to access the control registers, and this solution is reused in the CRI. Therefore, a crucial task is to create a bridge translating the PCIe transactions to the Wishbone accesses.

Theoretically, the PCIe read and write transactions may be directly translated into the local bus accesses in the FPGA. However, for improved testability and reliability, a more complex approach was proposed by Walter F.J. Müller, where the 64-bit PCIe accesses are used both to transfer data in the lower half of the data word and additional meta-information (e.g., about possible errors) in the

upper half of the data word. Additionally, a special, directly accessible "Bypass" area in the address space was proposed by Ingo Fröhlich, which contains the special registers responsible for describing "supervised" access to the standard part of the WB bus and additional configuration and debug registers.

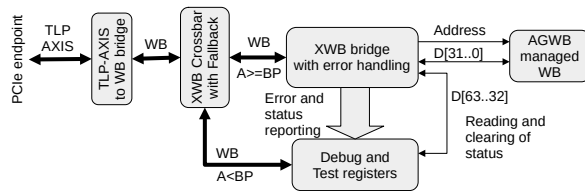


Figure 2: Block diagram of the PCIe to Wishbone bridge. BP - the bypass address separating the special address space with configuration, status, and debug registers from user address space.

The block diagram of the created PCIe to WB bridge is shown in Figure 2.

AGWB development

Preparation of the CRI firmware has posed new challenges for the AGWB [2,3] system to generate the Wishbone control bus address map. The original AGWB was prepared to map registers into C structures directly, so the register's reading or writing could be implemented as access to a member of such a structure¹. That solution was designed mainly for the creation of kernel drivers written in C. It requires that the address map is known at the time when the software is compiled. After each change of the address map, the software must be recompiled. In the CBM control system, however, another approach is used. The control software will operate in the user space and will be written in C++². Additionally, it is required that the same software should support various versions of the firmware without recompilation. It is similar to the IPbus operation, where the address map is loaded at the run-time. Unfortunately, the IPbus address map format has a significant drawback – it does not support the vectors of blocks and registers. Each element requires a separate entry in the map file. A new address description format, "AMAP XML," was proposed to solve that issue, based on the IPbus XML format, but with a possibility to define vectors. Another challenge for AGWB is associated with the fact that the FPGA chip used in CRI is split into two Super Logic Regions (SLRs). Its efficient usage requires two similar but separate subdevices, controlled by separate PCIe interfaces (and hence separate Wishbone buses). Therefore, a single HDL design must instantiate two separate AGWB systems

¹Of course, such access must be subjected to limitations related to the hardware access. Therefore, the structure must be declared as volatile, and special "memory barrier" functions should be used to ensure proper ordering of operations.

²The DCA - Device Control Agent written by Walter F.J. Müller.

that are similar but not identical (certain blocks are implemented only once in the whole FPGA - so they are present only in one of those systems). It is desired that both systems are described with the same XML file, also containing a description of differences. Unfortunately, due to the limitations of VHDL³, a finding of an appropriate solution appeared to be non-trivial. It has been finally solved at the beginning of 2021.

The last significant modification of AGWB in 2020 is associated with the previously mentioned modification of the internal Wishbone bus. The new implementation requires that the master can abort unsuccessful access (e.g., due to timeout or incorrect slave address). That simple change required significant modification of the WB CDC block used by AGWB.

Preparation of the tester firmware

The third development area was the preparation of the SMX tester firmware for QA testing of SMX ASICs and assembled Frond End Boards. In 2020 a version supporting testing of FEB-C boards was prepared. The firmware was based on the GBTxEMU [4] firmware written in previous years. The developed firmware supports up to 2 FEB-C boards or 2 pogo-pin testers connected via any 2 connectors available in the gDPB FMC board. The associated software, written in Python, automatically scans the connected FEBs, automatically detects connected uplinks, and synchronizes them. The user may modify the provided scripts to create the automated test procedure, or may use them in interactive mode, performing the manual debugging of the connected FEB or ASIC.

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³VHDL does not support the selection of the instantiated entity depending on the generic. Similarly, it is impossible to have the same block instantiated once with one VHDL library and then with another one. The "if-generate" statements cannot be used in the declarations section.

Computing



Summary of activities in the EDC computing project in 2020

P.-A. Loizeau and the EDC work group

FAIR, Darmstadt, Germany

EDC

As a reminder, the Experiment and Detector Control project is a computing project tasked with the development of the control software for both the Hardware and Software components of CBM. It therefore includes

- the Detector Control Systems (EDC), which are taking care of the Hardware supplies (HV, gas, LV, ...),
- the software controlling and configuring the readout chain (interface to DAQ), en-globed in the Detector Control Agent (DCA) and its user interfaces,
- the Experiment Control System (ECS), which provides an interface to the shift crew on one side for controlling the state of CBM sub-systems and the experiment global state and on the other side for controlling the experiment configuration,
- all necessary interfaces to the configuration and logging databases needed to ensure a complete and permanent knowledge of the experimental conditions.

DCS

In 2020, the DCS part of this project saw progress in two directions. First, a strong collaboration with the other FAIR experiments DCS groups was set in place, with monthly meetings and a common drive towards shared tools such as EPICS Docker images [1]. On a separate front, almost all detector groups made progress with their DCS prototypes during the 2020 mCBM campaign, see for example [2].

DCA

A first prototype for the DCA was developed in close coordination with the firmware development groups in the DAQ project. It provides for now the core part of what will be the DCA, with:

- a framework to handle the different software objects representing the physical components of the readout chain
- the interface with the PCI-E driver for the CRI.

It is now able to communicate with the first version of the CRI Base firmware and allows to test the register access concept [3].

ECS

The existing proof of concept (alpha stage) was imported in our Gitlab environment and cleaned up, now reaching the first beta prototype version. A strict and consistent Continuous Build (CI/CD) system was set in place to ensure that further developments are merged in the official version only if they obey formatting, testing coverage and typing coverage minimum levels. The state monitoring and state control part of this prototype will be tested for as an optional tool during the 2021 mCBM campaign.

A specification document for the ECS was started and will be brought to the level of a Technical Note in 2021.

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The Containerized Detector Control System for mSTS in mCBM

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The first prototype of the Detector Control System (DCS) for the mini-Silicon Tracking System (mSTS) in the mini-Compressed Baryonic Matter (mCBM) experiment was developed and tested during the beam campaign in 2020. The main aim of this prototype was to design a structured, easily usable stack of software, different applications for monitoring and controlling the detector. To achieve this, all building parts of the DCS were deployed in containers¹. Containerization or, in other words, operating-system-level virtualization allows to run a lightweight, standalone, executable package of software that includes all the needed parts to run an application: code, runtime, system tools, system libraries and settings (Docker, Singularity etc.). This effort is being realized through the work among sub-systems of the CBM experiment, in particular with the MVD group, as well as with the PANDA collaboration [1].

Containerized DCS

The DCS is based on the Experimental Physics and Industrial Control System (EPICS) [2] which provides specific network protocols for high-bandwidth software in real-time networking applications. Input/output controllers provided within EPICS are deployed in containers inside the DCS network and used to control and monitor low and high voltage power supply modules, temperature sensors as well as the Lauda water chiller for mSTS electronics cooling.

The multi-container control system, schematically shown in Fig. 1, features several applications which interact with each other and provide a description of the status

¹<https://git.cbm.gsi.de/m.bajdel/>

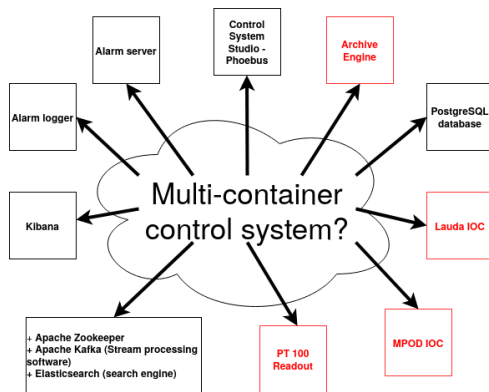


Figure 1: Schematic view of the DCS structure.

of the detector. The performance of the containers is also being tracked by Weavescope [3] which is a visualization and monitoring tool for containers. The mCBM experiment provides perfect conditions to test different DCS architectures and to assess best candidates for logging, alarming, monitoring and archiving. The following subsections focus on the particular elements of the DCS which were proposed for the mSTS prototype.

Operator interfaces (OPIs)

An OPI is an operation node, which facilitates Control System Studio (Phoebus) [4], Kibana visualization dashboard and an archiver web server. Phoebus serves not only as an application to monitor and control particular channels (devices) in the experiment, but also provides graphical user interfaces for alarm-server, alarm-logger, and database.

Archiver instance

For the mSTS experiment an archive engine [8] instance together with PostgreSQL database were implemented. It can save any channel provided by the EPICS IOC and periodically archive its status in a database. The archiver engine provides also a web interface which allows to monitor its performance. Taking advantage of the container architecture of the DCS, it is in addition possible to easily introduce different archivers e.g. EPICS Archiver Appliance [9] which was also tested and is foreseen to replace the archive engine during the next beam campaign.

Alarm server and logger

Alarm server and logger [10] are dependent on Apache ZooKeeper [5], Apache Kafka [6] and Elasticsearch [7]. Moreover, the above mentioned elements are integrated with the IOCs' databases and Phoebus. The alarm server monitors a given set of channels and tracks their alarm state. When a process variable (PV) goes into an alarm state, it is indicated in the alarm system user interface and logging UIs. There is likewise a possibility to communicate the alarms via email to the people that may respond to the state. The same approach applies to the alarm logger which delivers important PVs state changes to Phoebus and Kibana (via Elasticsearch).

Implementation

Figure 2 depicts the situation at mCBM at the end of the last year's beam time. The architecture is divided into 3 layers: supervisory layer, control layer, and field layer.

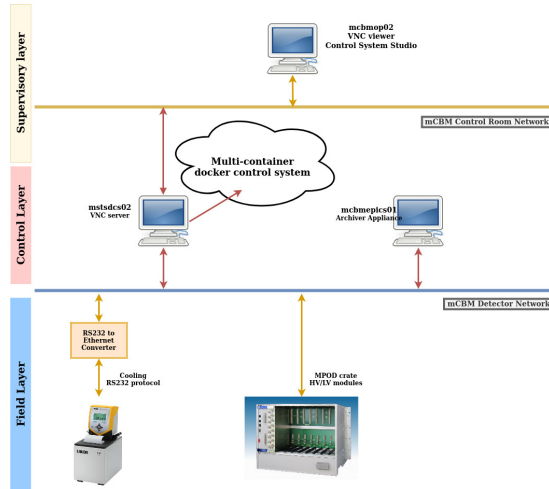


Figure 2: Detector Control System architecture.

1. The supervisory layer consists of the operator node and the control room network and is a level at which the operator monitors and controls the detector.
2. The control layer hosts all the services and applications used to control and monitor the detector, as well as to archive channels.
3. The field layer consists of all the devices, as well as interfaces for those devices which are used for the experiment. As for beam campaign in 2020 the following IOCs were used for the mSTS:

- **Power Supply - MPOD crate**
To provide bias voltage for silicon sensors and low voltage for the front end electronics (FEE), an MPOD crate with HV and LV modules is being used. The crate is controlled with the EPICS IOC over SNMP protocol. During upcoming beam campaigns mSTS will be equipped with a new MPOD controller (CC24) which has a built-in EPICS IOC.
- **Lauda Chiller**
A Lauda water chiller is being used to cool down the FEE of the detector. The communication with the device is based on a serial protocol and is controlled by an IOC running on the main node of the DCS. Proper cooling of the FEE is a crucial feature of the detector and its alarm status needs to be closely monitored by the operator.

Environment sensors

Several PT100 sensors with MVD readout board were used to monitor temperature inside the detector enclosure. Humidity and temperature sensors (SHT85 - I2C bus) will be used to monitor the conditions inside the next iteration of the mSTS detector.

Conclusions

A functional prototype of the DCS was designed and deployed during the mCBM beam campaign 2020 (Figure 3). The DCS operated without any major issues for more than 3 months.

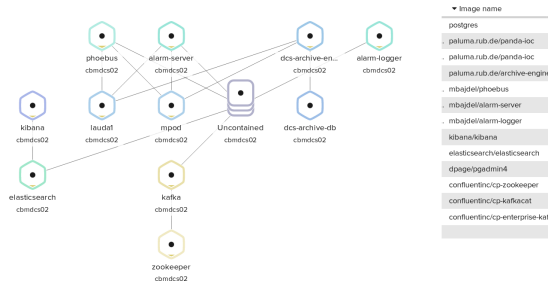


Figure 3: Weave Scope view of the DCS

Several building pieces of the DCS are still missing, i.e. sequencer, save and restore services, status of the FEE and an interface to the Experiment Control System (ECS). These mentioned parts will be added to the DCS for the next beam campaign. The system is in principle designed to handle much larger systems (thousands of channels) than the mSTS, nevertheless, it serves as a prototype which can be later used to scale up the system.

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A flexible online interface to CBM timeslices

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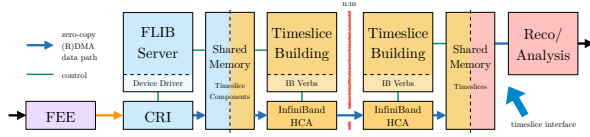


Figure 1: Overview of the main data path in the FLES data management framework.

The data path for raw detector data in the CBM online data management, as summarized in Fig. 1 is optimized for reliability and performance. Data received from the detectors is buffered in the entry nodes' main memories. Then, the software uses zero-copy RDMA mechanisms to efficiently combine the data from all entry nodes over a network to timeslices on many target nodes. On the target nodes, the timeslice data is stored in a shared memory segment, ready to be consumed by the online analysis software chain. The flesnet software [1] and its timeslice API have been in productive use for many years.

With the recent advent of more evolved online analysis setups in the context of the mCBM experiment, the need for a more flexible interface to timeslices arose. This includes the demand for:

- several independent timeslice consumer processes,
- more control over back pressure generation, and
- greater flexibility in starting and stopping consumers.

The revised online timeslice interface presented here aims to fulfill these requests. As illustrated in Fig. 2, it supplements the shared memory with a new item distributor entity, which communicates with timeslice producer and consumers over local ZeroMQ Inproc and IPC sockets.

Decoupling the start and stop of producer and consumer processes requires careful implementation and testing because of the large number of possible event sequences. The presented solution makes it possible to independently control data transport and online analysis (through EDC), and also takes into account potentially crashing consumer processes.

The revised timeslice consumer API is compatible with the previously existing interface but allows for several additional parameters to be chosen per consumer. These parameters include an *offset* and *stride*, which specifies a controlled subsampling of the timeslices, and a queueing policy (cf. Tab. 1). Using these parameters, a wide variety of scenarios can be covered from dependable timeslice

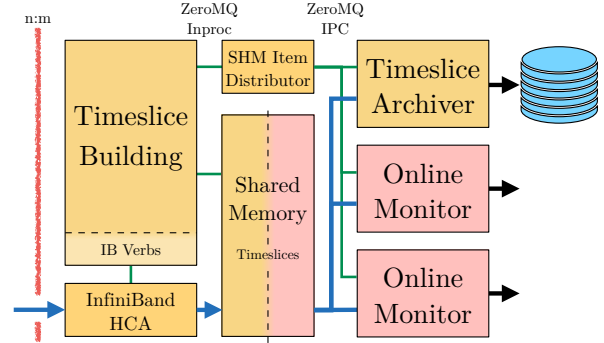


Figure 2: The new interface employs a dedicated distributor for *shared memory items* to connect timeslice producer and consumers.

Policy	Effect
QueueAll	All items are queued and eventually delivered; can create back pressure.
PrebufferOne	Opportunistic delivery; keeps consumer busy but may skip items.
Skip	Always wait for the newest item, do not queue; may skip items.

Table 1: Different queueing modes can accommodate a variety of consumer use cases.

archiver processes, best-effort online analysis and highly responsive online monitoring to full online analysis.

All consumer processes share access to the timeslice data from the same read-only shared memory segment and only correspond with the distributor agent through short messages. Thus, there is no need to copy any raw data in memory, which maximizes memory efficiency and performance on the node.

The new interface is fully implemented and available in the flesnet repository [1]. Initial tests of the revised timeslice API have been successful.

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Load balancing mechanism for FLESnet

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Abstract

Time slices for analysis are built by FLESnet and its Data-Flow Scheduler (DFS). It is able to reach the maximum network throughput, but that might take some time due to a slow-start phase and some drawbacks of the fault-tolerance mechanism. In addition, DFS distributes the time slices evenly among the compute nodes, although they might be heterogeneous or face a temporary higher load than others while running. To overcome these limitations, we implemented and present a load-balancing mechanism in DFS that dynamically (re-)distributes the network and computational load. We show improved aggregate bandwidth over time and thus reduced latency with the enhanced DFS for time slice building on our OmniPath testbed in scenarios with a faulty and a slow node.

Introduction

The First-Level Event Selector (FLES) compute cluster builds timeslices (TSs) for analysis using *FLESnet*¹, which was ported to Libfabric [3]. FLESnet distinguishes ‘input nodes’ and ‘compute nodes’. Each input node (IN) receives data from the sensor links in a single, circular memory-buffer and chops the stream into micro-slices (MSs). Compute nodes (CNs) collect MS contributions from all INs to build complete TSs for further analysis. All INs distribute their MSs timely coordinated to CNs in a round-robin schema to avoid congestion in endpoints and to establish parallel independent pairwise data transfers with a data flow scheduler (DFS) [4, 6].

We presented a fault-tolerant variant of our Data-Flow Scheduler (DFS-FT) that detects and dynamically (re-)assigns load of failed nodes to the remaining compute nodes equally [5]. Large scale analysis on an OmniPath supercomputer raised three caveats: (1) a slow-start phase delays DFS reaching high throughput, (2) the aggregate bandwidth might drop after a node failure and does not recover, (3) DFS might not reach the achievable aggregate bandwidth in heterogeneous systems because it distributes the load evenly on compute nodes. In the following, we describe how we address these challenges.

Slow-Start Improvements

On startup, FLESnet often experiences a slow-start phase of the interconnect and thus distributes MSs with a

relatively low injection rate. On a regular basis, DFS attempts to increase the injection rate by a fixed configurable percentage (SUP) when the bandwidth variance (BwV) of different INs is below a configurable percentage (VP). This way, we are annealing the maximum aggregate bandwidth while avoiding heavy network congestion. But with a small SUP, it takes time to reach good throughput.

We updated DFS to use a more aggressive speedup mechanism on start-up that doubles the SUP each interval as long as the BwV remains below the threshold. Once BwV exceeds the VP, DFS uses the calmer SUP for the rest of the run. By doing so, DFS reaches the maximum achievable bandwidth much faster and still reduces the injection rate before too much network congestion occurs.

DFS-FT Improvements

When a compute node fails or becomes unreachable by any input node, DFS-FT detects the failure using a heartbeat messaging mechanism, determines the last completed TS of the failed node, and then reaches an agreement between all remaining nodes to redistribute the future TSs of the failed node on other CNs fairly. DFS-FT recovers the failure in a few seconds but, with some interconnects, the latency between pairs of nodes after the failure recovery fluctuates. This leads DFS to lower the injection rate for reaching a stable state. To overcome this problem, DFS-FT now uses a stabilizing phase after node failures that enforces the last stable injection rate for a few intervals. This mechanism allows DFS to recover high throughput quickly.

Load Balancing Mechanism

Input and compute nodes are highly coupled; a slow node reduces the throughput of others. FLESnet considers a node slow, compared to others, when (1) the message latency to a specific node is higher, or (2) TS completion or processing duration at a CN takes longer. When a CN is slower than others or the latency between a node and any of the input nodes is higher, it should receive fewer TSs to process so that it will not be blocking the progress of other nodes [1]. Such an approach consequently can increase the aggregate bandwidth. We extended DFS to collect statistics about each node for each time interval during TS distribution so that it can determine slower nodes. Then, a new distributed and dynamic load balancing mechanism (DFS-LB) in our DFS redistributes the load over CNs fairly based on the collected statistics to maximize the aggregate bandwidth over time [2].

¹<https://github.com/cbm-fles/flesnet>

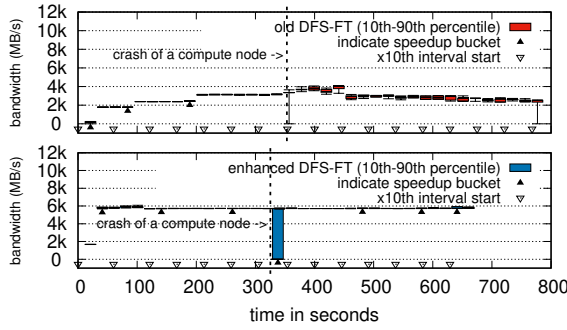


Figure 1: The bandwidth building TSs (min, 10th and 90th percentile, median, and max) observed per second at 40 DFS-INS (sending to 40 DFS-CNs) bucketed per 20 s over elapsed time when a failure occurs after 348 s / 320 s.

Experimental Evaluation

We tested FLESnet with Libfabric on OmniPath² with 80 nodes. Each node has 2x Intel Cascade Lake Platinum 9242 (CLX-AP) with 48 cores, 384 GB RAM, 1x Intel OmniPath host fabric adapter. Each micro-timeslice is 1 MB, and the receive-buffer for each IN at each CN is 1 GB. Each node embodies either an IN or a CN. The DFS divides the runtime into intervals of 50 000 TSs each.

Slow-Start Enhancements. Fig. 1 depicts the achieved bandwidth of DFS when (1) the aggressive speedup mechanism and failure stabilizing phase are used (lower plot), and (2) previously presented results of DFS-FT [5]. The lower plot uses initial SUP and VP set to 5 %. Once the BwV exceeds the limit during start-up, the SUP drops back to 5 % for the rest of the run. On the other hand, the upper plot uses 5 % SUP for the whole run. The aggressive speedup mechanism handles the slow network start better.

Fault-Tolerance Enhancements. Fig. 1 shows the bandwidth with and without the stabilizing phase after a node failure. We forced the first node to die after around 320–350 seconds. The bandwidth drops to zero MB/s for up to 3 seconds while reaching a recovery agreement. The upper plot failure occurred before reaching the maximum achievable bandwidth, which is about 6 GB/s. Using five consecutive stabilization intervals (lower plot) allows DFS to maintain the bandwidth also after the failure.

Load Balancing Enhancements. Fig. 2 depicts a scenario when a CN suddenly processes TSs slower. It compares the achieved bandwidth with and without DFS-LB. Once the observed variance of processing duration at different CNs exceeds a limit, DFS-LB redistributes load to other stable CNs. When the DFS-LB detects that the slow node becomes faster again, it redistributes the load accordingly. DFS-LB shows better aggregate bandwidth over time.

²<https://www.hln.de>

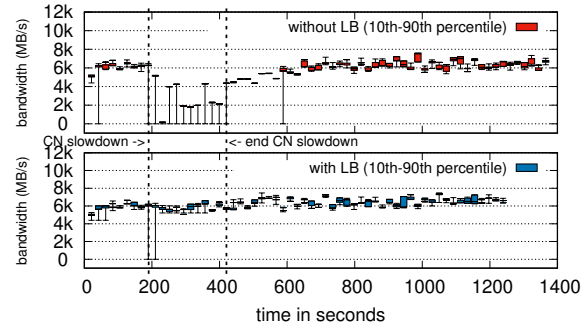


Figure 2: The bandwidth building TSs (min, 10th and 90th percentile, median, and max) observed per second at 40 DFS-INS (sending to 40 DFS-CNs) bucketed per 20 s over elapsed time when a CN slows down from $t(180)$ to $t(420)$.

Conclusion

We presented enhancements of DFS’ fault-tolerance to recover a high injection rate quickly after a node failure by enforcing a stabilizing phase. We also described a dynamic load balancing mechanism to make the TS distribution more resilient against slow compute nodes. Combined with an improved start-up phase, these mechanisms lead to a better and more stable aggregate bandwidth and shorter overall runtime, as the evaluation shows.

Acknowledgments. The project received funding from the BMBF grant 05P19ZAF1. The authors thank the HLRN for computing time on the Omnipath system.

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Event rate calculation after event building with mCBM data

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In this report, we will discuss techniques to extract event rates based on events generated by different event building algorithm from the data streams recorded during the beam time of the Mini-CBM experiment in March 2020.

Mini-CBM or mCBM, a FAIR Phase-0 experiment at the SIS18 facility of GSI, is an experiment not only for detector tests and their triggerless free-streaming read-out chains but also for the development of the data analysis software. The data flow in the final experiment is explained in reference [1]. The data streams from the different detector systems are combined in so called timeslices on a large scale compute cluster (First-Level Event Selector). Such a timeslice then contains all the detector data from the different systems for a short period of time. The assignment of detector data to the correct timeslice is possible since the data contains an accurate time information. After its creation the timeslice is send to one of the compute nodes for further reconstruction and analysis. A timeslice normally contains many events such that finding these events (event building) is one of the first steps of the reconstruction. An event building algorithm *CbmMcbm2018EventBuilder* was developed for this task.

Event building algorithms

If a beam particle interacts with an ion of the target many new particles will be produced and emitted. Some of them will traverse the detector setup of the mCBM experiment and will produce signals from the detector systems.

The introduced algorithm is based on two major assumptions. The first assumptions is that in case of a reaction in the target the amount of detector signals (digi) in the data streams is much higher for a short period of time compared to times with no interactions. The second assumption is that such reactions are well separated in time such that events can be defined as large clusters of detector data in the data streams. The events are then defined by the data found in a time interval around these clusters.

To find the events in an efficient way two slightly different approaches were implemented. Both of them rely on time sorted data streams in the input and start with the digi which has the smallest absolute time. After an event was defined the procedure starts again with the remaining input data. The first approach uses a fixed time window of adjustable length and define an event as all digis which are inside the time window started by the digi with the smallest time. Also the second approach starts with the fastest digi but adds the next digi to the event only if the time difference is below an adjustable time gap. The procedure is then continued until a digi is found which has a larger time

difference than the time gap. This digi then defines the start of a new event. Since both approaches would also classify noise data, which is not correlated with an interaction in the target, as an event, events are discarded which do not have a minimum number of digis for the different detector systems. A good suppression of noise events is already found by correlated signals in the T0 detector in front of the target and the Tof detector which is the detector furthest away from the target.

Since the algorithm is based on the time information of the detector data the relative time calibration between the different detectors is essential. These time offsets are constant within a run, and can be determined before the actual data taking.

Event rate calculation

For the calculation of the event rates we have used both event building approaches (Fixed Time Window and Maximum Time Gap). Due to problems in some of the prototype detectors not all detector systems were included in the event building. A significant noise was observed from the MUCH detector setup also, but after removing a few defect and noisy readout channels the noise reduced drastically. The used method to achieve this noise reduction is discussed in reference [2]. Even if the event building algorithm was developed for low beam intensities it showed to work also for high beam intensities. However, it is very challenging to tune its parameters properly for the high intensity runs such that probable event candidates are selected precisely. The event building was performed for both a low and a high intensity runs with a fixed time window of 100ns and the a selection cut for “good events” consisting of at least 1 T0 digi and 10 TOF digis. The event rate is finally defined by the average number of events per second during a spill. A spill is the time when the accelerator delivers a beam of particles to the experiment. Figure 1 compares the event rate of a low and a high intensity run. The spill structure can nicely be seen in the figure by periods of time with a high number of events (spill) which are separated by times with no events. Each spill is about 10 secs, and the event rate is calculated by averaging the number of events during 7 secs at the middle plateau region of a spill. The event rate was found to be 22.7 kHz and 1.12 MHz for the low and the high intensity runs respectively. Table 1 shows a comparison of expected event rates and calculated event rates for both event building approaches and for different intensity runs. The expected event rate was calculated as number of beam ions hitting the target per second $\times$ the interaction probability (I. P.)

Table 1: Comparison of different event building methods at low and high intensity runs

Run intensity	Expected event rate	Fixed time window = 100 ns	Maximum time gap = 50 ns	Using MUCH digi cut
low (run 831)	22 kHz	(22.7 ± 1.26) kHz	(22.43 ± 1.24) kHz	(17.14 ± 1.03) kHz
high (run 859)	1.1 MHz	(1.12 ± 0.12) MHz	(0.78 ± 0.069) MHz	(1.12 ± 0.12) MHz

with the target. The number of beam ions per spill is information delivered by the accelerator. The approximate I. P. = 0.01 for the thin target (0.25mm) and = 0.1 for the thick target (2.5mm). We studied also the effect of including the mMUCH detector for the definition of the “good event” criteria by using an additional minimum number digis (=1 digi) from the mMUCH detector in the event selection. It is observed that the event rate slightly decreases with the introduction of this additional cut for both the intensity runs. This is explained by an introduction of a detector with an approx 20% smaller acceptance compared to the TOF detector system which is due to the removed noisy channels.

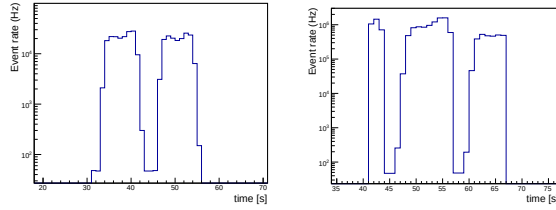


Figure 1: Comparison of high and low intensity runs with thick target. In both plots the spill structure from the accelerator is clearly seen. (a) Left: Event rate vs time for the low intensity Run 831 (2×10^6 ions/spill). (b) Right: Event rate vs time for the high intensity Run 859 (1×10^8 ions/spill).

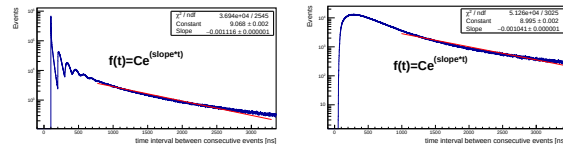


Figure 2: Comparison of the different event building approaches for a high intensity run. Shown is the number of events as function of the time difference between consecutive events for (a) Left: Fixed time window=100ns. (b) Right: Maximum time gap=50ns.

The event rate can also be calculated from the distribution of time differences between two consecutive events which should follow Poisson statistics. Nuclear events or collisions follow the Poisson statistics where the occurrence of a particular event is random and independent of others. Figure 2 shows the distribution of time differences between two consecutive events for both event building methods. As shown in Figure 2, the distribution can be well described with a Poisson function $f(t)=C \cdot e^{-(\lambda t)}$, where C is the Constant of the fit and λ (Slope of the fit) is the

event rate (by the definition of Poisson distribution). Since the time difference is in ns, one can calculate the event rate $=(\lambda) \text{ ns}^{-1}$. From the slope, we get an event rate of (1.11 ± 0.001) MHz for event building with the fixed time window (=100ns) method and (1.04 ± 0.001) for maximum time gap (=50ns) method. For both investigated methods for the event rate calculation, we have found a smaller event rate for the maximum time gap method. With the maximum time gap method it can happen that an event merging may take place, since there is no limit in the event size or the time duration of a single event. It is highly possible that two events that are close by in time, may get merged, leading to an underestimation of the number of events. This event merging is more probable for high intensity runs which can also be seen from table 1. For low intensities the extracted event rate is similar for all methods whereas there is a large difference for the maximum time gap (=50ns) method when comparing results from high intensity runs. The event characteristics such as event size (digis per event) are also studied. For a $^{208}\text{Pb}(67+)$ beam of energy 1.06 AGeV colliding with a Au target of thickness 2.5 mm, there are about 60 digis/event on an average including all subsystems. Figure 3 shows the event size for different subsystems.

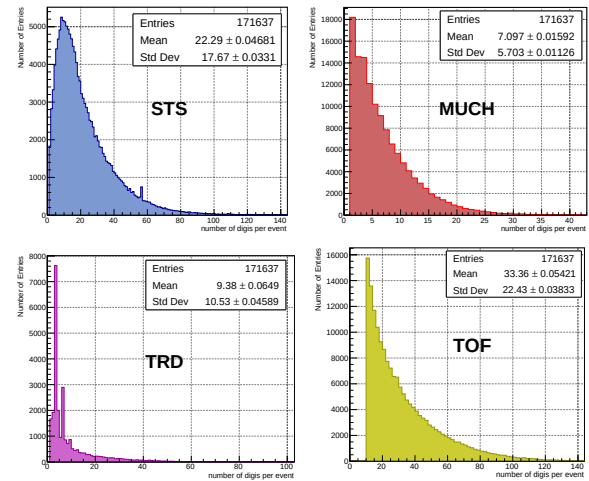


Figure 3: Event size: digis per event distribution for different subsystems.

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Reconstruction algorithms

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Time-based tracker for STS

The core of the track reconstruction in the CBM experiment is the Cellular Automaton (CA) based algorithm used for the Silicon Tracking System (STS). It takes as an input hit measurements from the time-slices produced in the CbmRoot framework using time-based cluster and hit finder algorithms.

To study the track reconstruction efficiency and the influence of high rates, 1000 AuAu UrQMD minimum bias events at 10 AGeV collision energy have been simulated and reconstructed, varying the interaction rate (IR) from 0.1 MHz to an extreme case of 10 MHz. Also, the event-by-event (3D) reconstruction efficiency with no event overlapping is provided for the comparison. Here we define the efficiency as a ratio of reconstructed to reconstructable tracks. A track is considered reconstructable if it has at least four consecutive Monte-Carlo (MC) points. A reconstructed track is assigned to a generated particle if this particle has produced at least 70% of its hits. A generated particle is regarded as found when at least one reconstructed track has been assigned to it. A reconstructed track is called a ghost if it is not assigned to any generated particle according to the 70% criterion.

Efficiency, %	3D	0.1MHz	1MHz	10MHz
Long high-p prim.	99.5	99.8	99.8	99.7
All tracks	91.4	92.7	92.1	85.3
Prim. high-p	96.5	97.7	97.1	90.0
Prim. low-p	91.6	93.2	92.6	86.9
Sec. high-p	96.5	97.7	97.1	90.0
Sec. low-p	63.8	66.5	66.2	59.7
Clone level	1.30	0.70	0.70	1.38
Ghost level	1.2	1.0	1.1	2.6
Hits per MC track	6.84	6.83	6.78	6.36

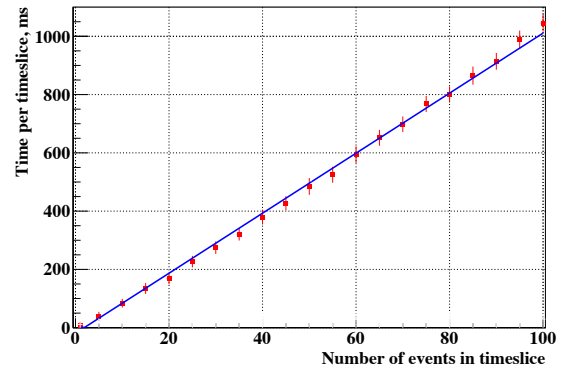
Table 1: Track reconstruction efficiency performance for minimum bias Au+Au collisions at 10 AGeV in case of event-by-event reconstruction and time-slice-based reconstruction at 0.1 MHz, 1 MHz, and 10 MHz interaction rates.

As one can see from Tab. 1, for the low IR case, the overall track reconstruction efficiency is even higher than for the 3D case due to additional time measurement of hits, which is not present for the 3D case. For the highest IR scenario, the efficiency degradation of about 6% is observed. Here one has to note that the effect is not solely due to the tracking but is already seen at the hit finder level. The number of hits produced per MC track shows that some hits are not produced due to the current dead strip time of the STS

detector (800 ns), so that we lose about half a hit per MC track, which complicates the track finding. This statement is also proved by the fact that the efficiency of tracks, which have a hit in every detector station (long high-p prim.) is the same for all IR.

High momentum primary tracks that have particular importance for physics are reconstructed with an excellent efficiency of about 96%, which varies within 6.5% up to 10 MHz. The efficiency for low momentum tracks is 63.8% due to multiple scattering in the detector material. It changes within a 4% window in the case of the highest IR. The ghost fraction remains at an acceptable level (less than 3%) for all cases.

Figure 1: The time the CA track finder takes to reconstruct a time-slice as a function of number of events in the slice. The dependence is fitted with a straight line.



However, not only the efficiency but also the speed of the reconstruction algorithm is crucial for successful performance in the case of CBM. We have studied the time the CA track finder needs to reconstruct a time-slice as a function of the number of events in a time-slice (Fig. 1). The results show that up to a hundred events in a time-slice, the dependence varies very little from a linear one. This result corresponds to the case of 3D analysis and allows in future to split time-slices delivered by local reconstruction algorithms to so-called sub-slices containing about 100 events for track reconstruction and reconstruct them with no speed degradation. The splitting algorithm is currently under development.

Track Finder for mCBM

The CA tracker used in STS was modified and adapted for the mCBM case, where it reconstructs straight tracks in the absence of a magnetic field. The modified algorithm consists of the same steps as the original one: it builds triplets through the whole detector system and bins them into tracks. However, the extrapolation is performed with a straight line track model, momenta are not defined and filtered, and binning triplets into tracks is done with no momentum cut.

To test the reconstruction performance, 1000 AgAg UrQMD central events at 1.65 AGeV collision energy were simulated using the `mcbm_beam_2020_03` setup. For the current development stage, v20d mSTS and v20b mTOF (Time-of-Flight) sub-detectors were included. For efficiency calculations, the same definitions were used as for the full CBM case. The resulting tracking efficiency is about 96% with a ghost fraction of about 18%. It is expected to improve after including all the sub-detector systems.

A similar approach of extending the existing CA track finder is used for the global CA-based track reconstruction algorithm, which is currently under development.

Event builder

We are currently in the process of exploring different algorithms for raw event building, which obtain definitions of raw events as collections of digis using the digi time stamp only. Subsequent reconstruction algorithms can operate on thus defined events as input data. At present we focus on event-based reconstruction, which can be used at low interaction rates, where the interference of data from different collisions can be neglected.

The most promising approach is based on the “streaming to triggered” event builder of eTOF@STAR and uses clusters of digis in one reference detector as “event seeds”. Separate time windows around these seeds are used to select digis of the different detectors. The approach hence emulates old-school hardware trigger systems. Three different modes are supported to deal with pile-up events, which occur when a seed is detected within the widest time window around the previous one: “no overlap”, “merge overlap” and “allow overlap”. In the first case the new seed is rejected. In the second case it is included in the the current event and the time windows are extended correspondingly. In the third case a new event is created from the seed, which implies that digis may end up in multiple events. The third option is preferred at present, as it preserves the largest amount of information.

The current implementation employs the FairTask model and accesses digis through the `CbmDigiManager`. There are ongoing efforts to abstract from the FairRoot framework and switch to a `std::vector` interface. At present, the T0 detector is used as a seed detector, which is appropriate for the most recent mCBM geometry. There are plans to switch to the STS instead, which is suitable for the

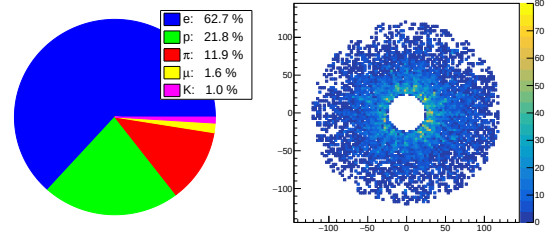


Figure 2: QA visualizations. Left: Pie chart for particle ratios in MUCH. Right: XY distribution of MC points in MUCH.

present full CBM geometry. Furthermore, a full separation of the seed finding and event finding parts of the algorithm is in progress, such that different seed finders can be implemented, which e.g. use multiple reference detectors at once. QA classes will also be added, which test the efficiency of event building on Monte Carlo data.

Automatized Quality Assurance

The full production chain at CBM and mCBM encompasses many sub tasks, ranging from unpacking / digitization over event and track reconstruction to data analysis. To ensure the integrity of the results at each step along the chain, a large number of test programs (i.e. “QA tasks”) are provided, which gather a wide range of diagnostic data. At present, there are ongoing efforts to place these on more a systematic footing. The goals of these efforts can be summarized as the following:

- To provide standardized test templates which streamline the implementation of new QA tasks.
- To standardize the output of QA tasks.
- To ensure that QA tasks are as modular as possible, such that distinct classes can be tested independently.
- To include QA in automated test chains, run nightly or during merge requests, and produces automated warnings and error reports.

Most recently, three new storage classes were implemented to support these efforts: `CbmQaCanvas`, `CbmQaHist`, `CbmQaPie`. These inherit from corresponding Root classes and enable an efficient and stable access to QA visualizations stored in output files. Based on the above requirements, a restructuring of the class `CbmMuchHitFinderQA` was also carried out, and several new visualizations were added, e.g. pie charts to display particle ratios (see Fig. 2). The extension of these efforts to other steps of the production chain and additional detectors is ongoing.

Inter-system time offsets at digi level

One project has focused on improving the determination of the time shifts between different detector systems for Mini-CBM [1]. Determining the inter-system time shifts is an essential step for data processing both in the offline and also in the envisaged online processing scheme. Based on the input of digis from all detector systems, the corresponding time shifts can be obtained at digital level by evaluating the differences in time stamps between system digis and reference time digis from the T0 counter. If the relevant systems are stable during data taking and sufficient digis are available the distribution of these time differences should display a clear peak at the position of the time shift. By default, the outcome of these differences is stored in histograms, the maximum peak is considered and the evaluation is performed over all time slices of a run leading to significant run times. The scope of the project [2] has been to improve the following aspects: Deriving measures to process only a minimum number of digis per detector to establish a stable peak position for the distribution of time differences. Also procedures for fitting the corresponding peaks have been tested in some cases. Finally more efficient data structures based on flat standard vectors have been tested replacing the histograms provided by the Root framework.

GPU framework for online reconstruction

Work is currently underway to investigate the feasibility of using GPUs for online reconstruction in CbmRoot. The high degree of data parallelism that is present in the reconstruction algorithms and the fact that their runtime is usually memory bound suggest a natural fit. However, GPU development is not straightforward for a number of reasons. The hardware that the online processing will run on is not yet known. Therefore the software must be written in a way, that avoids vendor lock-in and keeps all options open. Furthermore the ability to run the reconstruction software on CPU should be retained. Such that offline processing can still be run without the need for additional hardware.

Out of the various APIs that exist for GPU programming (HIP, CUDA, SYCL and OpenCL), only SYCL is designed to fulfill both of these requirements. However, the open source SYCL compilers that exist are still beta software at best and there is no guarantee that they will have support for state-of-the-art GPUs a few years down the line. So instead of betting on a single API, a different approach was chosen. A library is being written that acts as an abstraction layer between the GPU software and a specific API / compiler. First of all, the GPU code will be compiled as regular C++ using the system compiler alongside all the other code. If additional GPU compilers are present, then the GPU code is compiled again into a separate library using that compiler. At runtime the device can be selected where the reconstruction should run on. If that device is the CPU, the kernels are just run on CPU with optional parallelization via OpenMP. If a GPU was selected, the library associ-

ated with that device is loaded and run instead. In addition to defining and running kernels, abstractions for common GPU operations are provided as well. These include for example memory allocations on the device, device-side math functions and block-wide operations like reductions. In addition to this GPU abstraction layer, the STS Hitfinder is currently being ported to it, as a proof of concept.

It should be noted that this is approach based on the GPU reconstruction in the ALICE O² framework, which works in a similar way and is already in use successfully [3].

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Time-based track reconstruction with the muon setup

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Simulation input

This study was performed to test the present CBMROOT software for simulated data without event definition, i.e. using only the time information of the digitized data. The trunk version of the CBMROOT from 02.11.2020 was used together with the CBM muon setup, which comprises the Silicon Tracking System (STS), the muon system (MUCH), the Transition Radiation Detector (TRD), and the Time of Flight Detector (TOF). The MUCH consists of four hadron absorbers and four tracking stations: the first two stations consist of GEM detectors, the 3rd and 4th station are built from RPC detectors [1]. The study was performed using 8 AGeV/c Au+Au minimum bias UrQMD [2] events.

Simulation steps

The simulation includes three steps:

- transport of the generated UrQMD events, and, separately, of the Au beam ions (*macro/run/run_transport.C* and *macro/run/run_transport_beam.C* respectively);
- digitization (*macro/run/run_digi.C*);
- reconstruction (*macro/run/run_reco_tb_track.C*).

The transport of the generated events can be made either using GEANT3 [3] or GEANT4 [4]. For the transport of the beam ions, however, one has to consider the following:

- GEANT3 takes only into account electro-magnetic interactions of the beam ions with target or beam pipe, i.e. only deltas and gammas will be produced;
- GEANT4 is able to take into account also hadronic interactions producing hadrons and fragments in addition to deltas and gammas, depending on the physics list used.

If the beam interacts only with the target, hadron production is simulated by UrQMD, and GEANT3 takes care the generation of deltas and gammas. However, GEANT4 is preferable if also the possible interaction of the beam with the beam pipe and other materials has to be taken into account. In this case one has to remove hadron production by the beam in the target, because these processes are already included in UrQMD. Fig. 1 displays three projections of

one Au ion event passing the target generated by GEANT4. For this study, UrQMD and GEANT3 have been used for particle generation and transport.

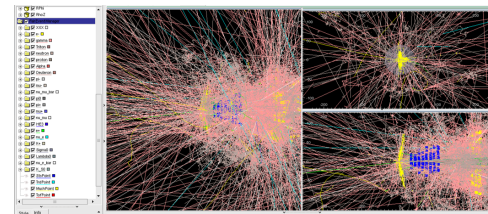


Figure 1: Event display: three projections of the tracks produced by one Au ion passing the target as calculated by GEANT4.

In the digitization step, the files with the UrQMD events and the beam events will be merged with different intensity. In this study, the highest foreseen beam intensity of 10^9 Au ions/s was used, corresponding to 10^7 interactions per second. The length of the time slice was fixed to 1 μ s.

Track reconstruction

The last step of the study is reconstruction. Fig. 2 left illustrates the hit distributions in the different detectors over time (see explanation in figure caption). The bin sizes correspond to the time resolution of the detectors: STS - 2 ns, MUCH - 4 ns, TRD - 8 ns, TOF - 80 ps. Please note, that Fig. 2 left illustrates the most extreme situation, with partly overlapping events. The time resolution of the TRD is not sufficient to separate the events, but using the hits in STS and MUCH one can try to build the events. The TOF detector cannot be used for event building, as only very few particles pass the hadron absorbers of the MUCH system.

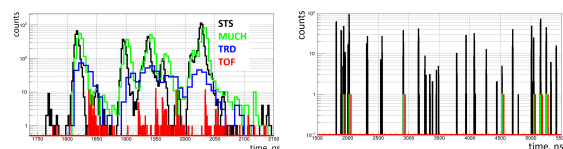


Figure 2: Left: hit distributions for the different detectors over time: STS (black), MUCH (green), TRD (blue), TOF (red). Right: tracks reconstructed in the STS distributed over time (black lines). STS tracks which are part of the global tracks are marked in green. Hits in TOF are shown in red. The bin size corresponds 1 ns time resolution.

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After hit finding the tracks will be reconstructed. The track reconstruction procedure consists of two steps: the track reconstruction in STS, and the global track reconstruction, which is based on the extrapolation of the tracks reconstructed in the STS through the downstream detectors MUCH, TRD, and TOF. The reconstruction efficiency for primary tracks in the STS is presented in Fig. 3 for an event-based analysis (black symbols), and for two time-bases analyses with different sizes of the time slice. The reduction of the efficiency for the time-based reconstruction method is due to the fact, that some of the events are split by the time slice definition, i.e. the digis from one events show up in different time slices. This happens more frequently for shorter time slices, therefore, the track reconstruction efficiency for time slices of 100 ns (blue symbols) is lower than the efficiency for time slices of 1 μ s (red symbols). To overcome this problem, new approaches with partly overlapping time slices are under development.

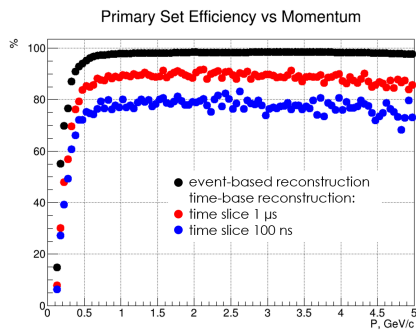


Figure 3: Track reconstruction efficiency in the STS as a function of momentum. Black symbols: event-based reconstruction. Red symbols: time-based reconstruction with 1 μ s time slice. Blue symbols: time-based reconstruction with 0.1 μ s time slice.

Fig. 2 right presents the tracks reconstructed in the STS as distributed over time. The events are clearly separated. In the CBMROOT version, which was used for this study, only STS tracks are used for event building. However, this event builder does not yet take into account hits from other detectors, and, hence, event building based on global tracking is not yet possible.

The goal of this study was to test the reconstruction of global tracks within one time slice. In order to compare the result to event based simulations, the global tracks have been combined to events by choosing the same time difference of 0.4 ns between neighbored STS tracks as for the MC tracks from the event-based simulation. Fig. 4 depicts the invariant mass distributions of the reconstructed muon pairs from combinatorial background for time-based simulation results (red) compared to event-based simulations (black). The two invariant mass spectra look very similar. However, one should note that this agreement between time-based and event-based simulations depends strongly on the chosen time difference between neighbored STS

tracks. When increasing this time window, the number of combined tracks increases, and, hence, the yield of background muon pairs.

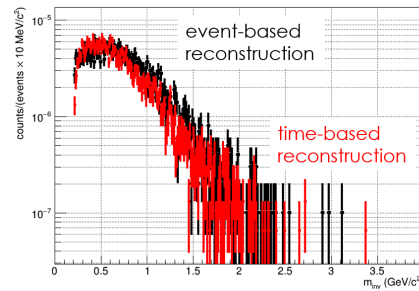


Figure 4: Invariant mass spectra of the reconstructed muon pairs from combinatorial background. Black histogram: event-based reconstruction. Red histogram: time-based reconstruction (see text).

Conclusions and requirements

In order to perform realistic time-based simulations, the following features have to be implemented into the reconstruction software:

- Realistic beam pipe geometry;
- Realistic detector performance including noise, dead time, etc.;
- Realistic event definition, taking account the information of all detector systems;
- Primary vertex reconstruction as additional criteria for event definition
- T0 measurements for particle identification in TOF;

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Importance of momentum estimation in the track based alignment method in absence of the magnetic field

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Introduction

The objective of the alignment procedure of a tracking detector is to determine the accurate space coordinates and the orientations of all of its components. In a complex hierarchical detector like the Silicon Tracking System (STS), a track based alignment algorithm [1] has been employed [2], aiming to achieve a spatial precision of $\sim 10 \mu\text{m}$ for all the components. It is important to estimate the momentum of tracks to be used for the conduct, especially when the magnetic field is switched off, yielding straight tracks, with no opportunity of calculating the momentum. In simulations, the momentum and mass of the generated particles are of utmost importance, to include the Coulomb multiple scattering [3] (sourced from the material budget of the STS), during the track reconstruction stage.

This short report will address that how the momentum of tracks can be estimated from the track quality, quantified by the statistical hypothesis test χ^2/NDF .

Sample preparation

Ten sets of 10 AGeV Au-Au central UrQMD [4] generated events, with and without magnetic field have been generated for the purpose. While, during the reconstruction step, a set of tracks has been reconstructed with the proper input momentum (with the magnetic field on) and the other sets of tracks were reconstructed, assuming momenta of 1 - 10 GeV/c (externally seeded, keeping the magnetic field off). Additionally, the pion mass ($139.57 \text{ MeV}/c^2$) has been taken as the common input mass for all the generated particles, as pion is the most abundant particle at this beam energy. All 10 sets of tracks are summarized in Table 1 as follows:

Table 1: Sets of tracks with their input conditions.

Set No.	Momentum (GeV/c)	Magnetic field
1	1	Off
2	2	Off
3	2.5	Off
4	3	Off
5	3.5	Off
6	4	Off
7	5	Off
8	7	Off
9	10	Off
10	Real input	On

Result

It is not very straight forward to assume the proper particle momenta for all the particles in absence of the magnetic field, as UrQMD produces particles in a wide range of momentum and of different masses. So, just taking the average momentum (or the most probable value) of all the particles will not help, as the masses are different, too. One way to deal with this kind scenario would be to check different momentum inputs to plot the χ^2/NDF distributions of all the particles and then to select the input momentum that provides a distribution, similar to the plot given by the set with the magnetic field on.

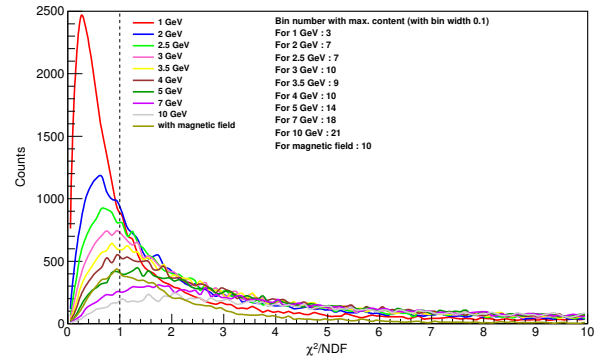


Figure 1: Track quality (in terms of χ^2/NDF) of 10 different set of tracks with varying input momentum.

Figure 1 shows the track quality (in terms of χ^2/NDF) of 10 different sets of tracks with varying input momentum. From the result, it is shown that, 3 to 4 GeV of assumed particle momentum is of acceptable range. But it is to be noted that, lower the momentum, larger are the errors to be included during the track fit, which results in better track quality. So, final estimation can only be made at the testing of the alignment procedure.

References

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ML approaches to centrality determination with the PSD

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A design feature of the PSD@CBM forward hadron calorimeter [1] is the presence of a beam hole in the center, which is motivated by the radiation doses. The presence of a beam hole in the center of calorimeter leads to the fact that a certain part of the energy is lost due to heavy fragments escaping through the hole. In this case the dependence of the total energy deposition in the calorimeter on the impact parameter becomes non-monotonic, making the task of determining the centrality more difficult, than in a monotonic case. However, the total energy deposition in the calorimeter is not the only observable in the event. The modular structure of the PSD@CBM makes it possible to use the spatial transverse distribution of energy in separate modules of the calorimeter. The deposited energies in all modules, forming together the so-called "energy surface", allow, within certain limits, to solve the centrality problem.

The energy surfaces of the hadron calorimeter serve as input data for machine learning (ML) methods and are used in a manner similar to image analysis. ML techniques have proven themselves well in pattern recognition and image classification. Application of ML methods to determine centrality classes allows using a larger amount of available information from hadron calorimeters comparing to existing approaches, making it possible to determine centrality over the entire centrality range. To determine collision centrality, two ML approaches have been developed, the supervised approach and the unsupervised approach [2].

ML approaches for centrality determination with segmented forward hadron calorimeters

Supervised approach

The supervised approach is a straightforward application of ML techniques on the labeled data. The entire available dataset is divided into training and testing sets. The training set is used to tune the parameters of a model consisting of dense layers that form a neural network. The parameters are adjusted to the best determination of the target variable, which is the impact parameter of the collision. After the training stage, the model parameters are fixed and the model can be tested on an unused testing set. Since data labeling that can only be achieved with a specific physical model is necessary in this approach, the approach is unlikely to be applied to real physical data. However, it may serve to confirm that using the calorimeter energy surfaces one can separate events into centrality classes and also serves as a reference for the unsupervised approach.

Unsupervised approach

The unsupervised ML approach of centrality determination with forward hadron calorimeters is based on the recent work of clustering analysis [3]. This approach uses an autoencoder of data and a deep embedding method, which allows to divide the available data into clusters according to the similarity of the energy surfaces of the calorimeter.

The clustering algorithm starts with training the autoencoder. The main goal of an autoencoder is to reduce the task dimension, which improves clustering. Supplying the calorimeter energy surfaces to the autoencoder input, we expect to have the same energy surfaces at the autoencoder output. The trick here is having a bottleneck in the middle of the autoencoder. Autoencoder is trained in such a way that the mean square error loss function between input and output is minimal, and when this is achieved, one can say that the encoding part is good for reducing the task dimension to the dimension of the bottleneck.

The second step is to evaluate the centroids of future clusters. Centroids are the centers of clusters in a reduced-dimensional space, namely after the encoder. This is done using the tSNE [4] and KMeans [5] algorithms. The tSNE algorithm copes well with the so-called "crowding problem", which is relevant when applied to the problem of determining centrality, since peripheral events are usually observed in a much greater proportion comparing to central ones. The resulting interpretation of events is then divided into clusters by the KMeans algorithm, and the centroids of the resulting clusters are estimated in the after-encoder dimension.

The third stage is the process of deep clustering with implementation, which is discussed in details in work [3].

The advantage of the approach is its independence from the model, since clustering is carried out on the entire available dataset without involving the target variable. In this approach, all available data are divided into groups of equal size. No preliminary training of the model is required, clustering can be performed directly on experimental data. This feature can be interpreted as model-independence, since the division of experimental data into clusters can be carried out directly. The only question that remains open is the ordering of the received clusters. This ordering can be accomplished by using the multiplicity measured by the independent tracking system. The only information required is the value of the average multiplicity in each ML centrality class. An alternative way to order the clusters is to use the energy asymmetry in hadron calorimeter [6].

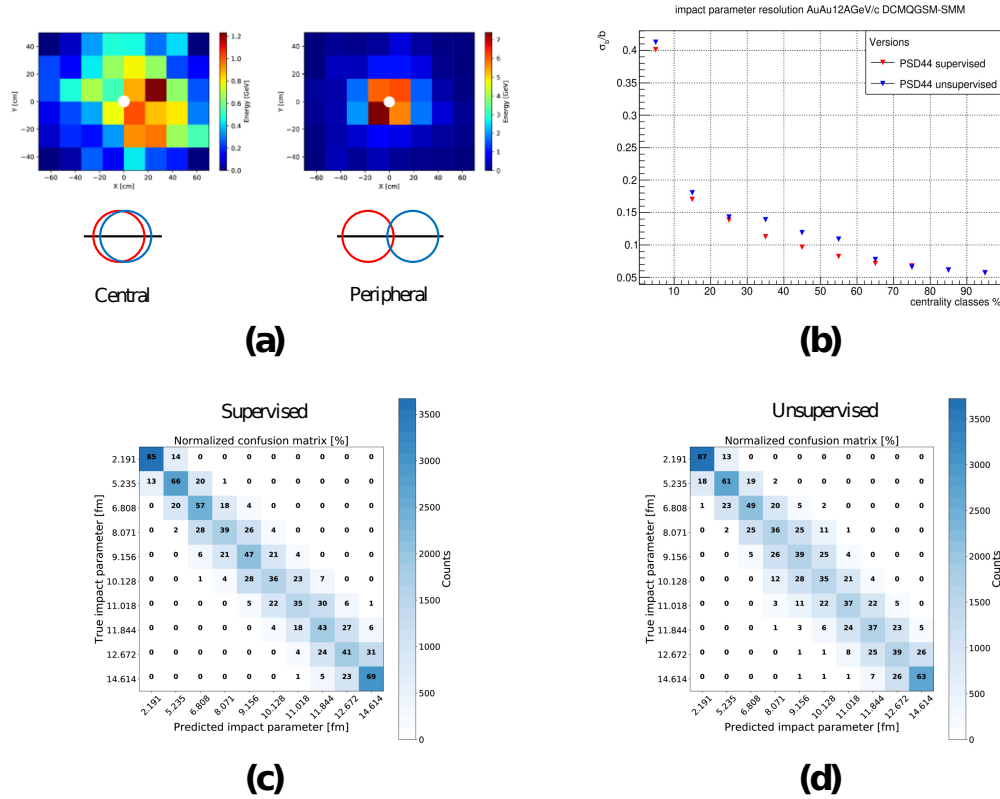


Figure 1: ML application to CBM@FAIR Au+Au 12A GeV/c collision data. Spatial distributions of particles over the calorimeter surface "energy surfaces" for central and peripheral collisions (a), impact parameter resolution and mean impact parameter values in centrality classes (b), confusion matrix of supervised ML approach (c), confusion matrix of unsupervised ML approach (d)

Application results

The supervised and unsupervised ML approaches for centrality determination were applied to CBM simulation events of AuAu collisions with a momentum of 12A GeV/c generated with the DCM-QGSM-SMM model. The noticeable difference between a central and a peripheral collision (Fig.1 (a)) is used to distinguish the collisions centrality classes. The impact parameter distributions were analysed in the ML-predicted centrality classes. The resolution and the mean values of impact parameter are shown in Fig.1 (b). Two confusion matrices obtained with supervised and unsupervised ML approaches are presented in Fig.1 (c) and (d), respectively. In a confusion matrix, predicted centrality classes are plotted along the horizontal axis, and the real classes from the simulation are plotted along the vertical axis. Each two-dimensional bin of this matrix contains a digit indicating the probability of hit on the bin. The sum of the values in each row is 100%. The diagonal elements of the confusion matrix reflect the purity of the centrality classes determination. Comparing the results of the supervised and unsupervised ML approaches, one can see that

the unsupervised approach shows slightly worse results for semicentral collisions.

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Parameters and Databases in CBM

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Introduction

Parameters and Databases (PDB) is a new project in the CBM Computing project structure. It was created to provide the database accessibility for collaboration members and to respond to the need of the centrally managed data storage of many types. These are detector components, physics parameters and conditions, physics analysis tags, geometries, publications and figures, etc.

Software solution

The database functionality is based on TGenBase [1] - a software solution developed for the STS component databases. The framework comprises a Laravel based web server which accepts the requests, handles security and user authentication; a thin caching layer to improve the response times and a database layer which then takes care of persisting the data to disk. The requests can be logged and visualized on demand. The software is containerized with Docker engine to improve the maintainability and portability. Many of these components are interchangeable - e.g. caching can be realized based on Memcached or on Redis and database can be based on the SQLite for local development, on PostgreSQL for production deployments, or others. The web server implements the insert-only data versioning model in which the data can not be deleted, but rather new versions of them with certain validity interval are created.

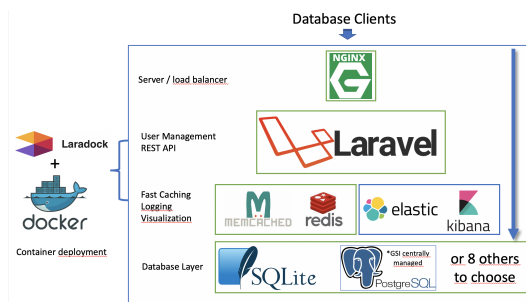


Figure 1: Technologies used in the software solution.

Figure 1 shows software stack used in our solution. Data flow is depicted with an arrow pointing down.

We provide a graphical data definition interface [2] in which the user can describe the objects of interest, their properties and relations between different objects. From

this description the web server software and the client libraries can be generated, which provide the means to communicate with the database. We support C++, Python, Javascript and LabVIEW clients which are most popular among our users.

Component databases

One of the most extensive use cases of our solution are the detector component databases. Detector component represent a hierarchy of objects with their properties, such as vendor and quality data, their spatial arrangement, etc. The STS workgroup used the component database extensively during the sensor and module quality assurance campaign. The database connectivity has been integrated directly into measurement stations in the laboratory. The data collected was then extensively analysed and visualized in ROOT and Python environments, which substantially helped the campaign to progress. Figure 2 shows an assortment of plots obtained by analysing the data queried from the DB.

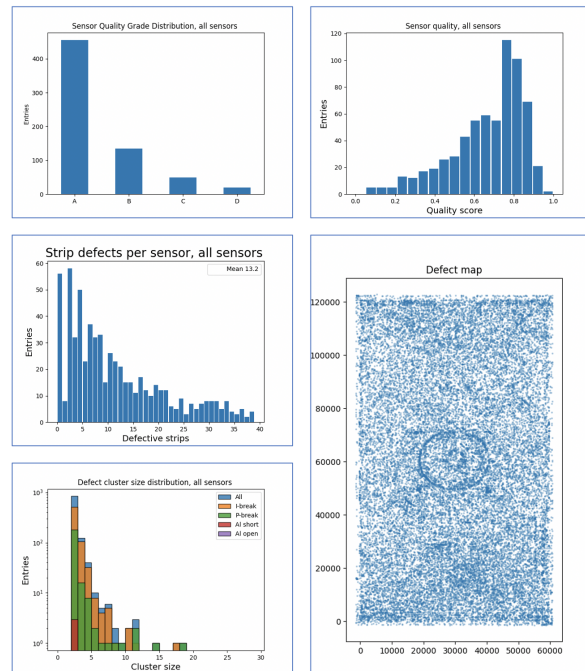


Figure 2: Quality assurance plots for the data queried from DB.

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Collaboration services

The developed software solution is well suited not only for detector component data but virtually for anything. We have applied it to build the collaboration services of the CBM experiment [3]. First of these is an index of collaboration members with the information about their institutional affiliations, etc., synchronized with the LDAP service of GSI and used to authenticate and authorize users with TGenBase. We propose a solution for the collaboration materials - articles and figures released to public. They are categorized by many criteria based on the data they refer to, such as collision system and energy, physics working group they belong to, their visibility, etc. The articles and figures can be looked up by their abstract text and captions, respectively.

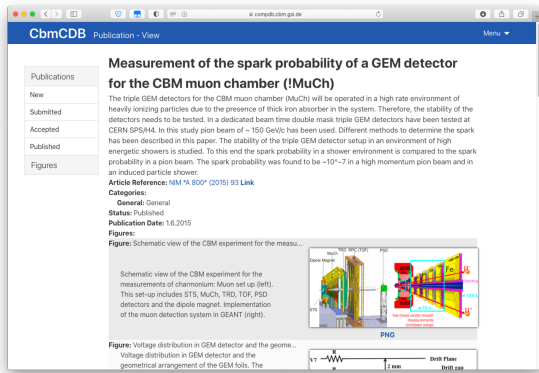


Figure 3: Collaboration database with an index of published articles and figures.

Figure 3 shows the web page of the CBM collaboration service. A published article with its abstract, journal reference and figures included in it are listed.

Parameter management

Based on the software solution described above, the Parma framework was developed. It is used from CbmRoot to get and store in database the parameters relevant to the physics tasks, such as particle transport and event reconstruction. The framework allows to store the CbmRoot parameters and detector conditions to be serialized and stored in different formats in various backends. The serialization formats supported are text based and human readable JSON format or compact binary serialisation with Boost or ROOT. The backends are filesystem based (ROOT or JSON files) or remote storage services such as TGenBase (SQL databases) or fast in-memory key-value storage Redis. The framework is modular and can be extended to support other serialization formats and storage backends.

Figure 4 shows the structure of the Parma framework. The arrows pointing down depict the request flow to reach the storage backend.

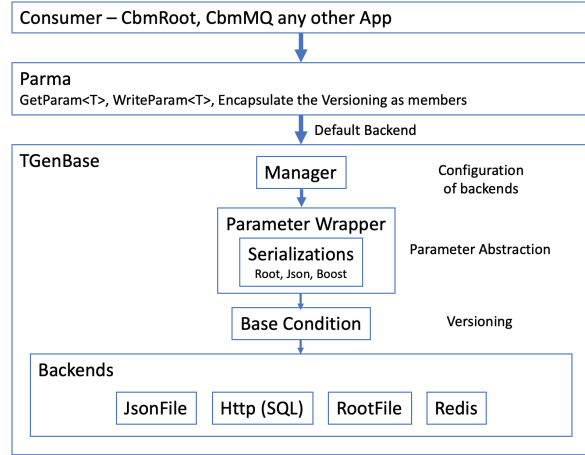


Figure 4: Structure of the Parma framework.

Summary

In this contribution we have presented the "Parameters and Databases" project within the CBM Computing board structure. The project has a broad scope with many applications most needed in the CBM experiment. These applications are based on the commonly developed software solution, which provides the means for database communication.

The applications in production mode are deployed with the database connected to the PostgreSQL centrally managed by the GSI IT department. These databases are automatically backed up and replicated to prevent the loss of data.

References

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Recommended SIS100 subsystem positions for simulation of the future CBM experiment at FAIR

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Introduction

In response to concerns voiced by the Technical Coordinator and CBM Collaboration Board, the two authors conducted an extensive comparison of CAD and GEANT geometries for each subsystem of the future CBM experiment at FAIR. The CAD geometry of a subsystem is used to tackle the many manufacturing challenges in its design and are submitted by a subsystem engineer to us (staff at FAIR/GSI) in order to coordinate the process between subsystems and the technical inclusion of a subsystem into the global design of the experiment. The GEANT geometry of a subsystem is generated by a physicist typically working within a subsystem group to be used to computationally validate that the subsystem is suitable for requirements and quantify the detectors sensitivity. These are shared among subsystem groups in CbmRoot geometry repository not only to be used to plan important hardware and software data processing provisions for real data analysis but also to model the CBM experiment to investigate key fundamental physics questions the CBM experiment may address. It is suspected that good communication between the engineering and simulation personnel within a subgroup is not always guaranteed.

The approach of our comparison study was to meticulously compare the dimensions and positions of the CAD and GEANT geometries for each subsystem. Often particular attention needed to be focused on the distance between sensitive layers of the detectors and the target as a crucial factor in maintaining accuracy between the simulation of detector response and future experimental data. Unfortunately during the course of the survey, it became apparent that unacceptable divergence between the CAD and GEANT geometries had become commonplace across multiple detector subsystems over the last number of years which required immediate action by the subsystem teams to rectify. Our study was communicated immediately within the CBM collaboration at several internal presentations and discussion rounds as well as at CBM Collaboration week in October 2020 [1]. Change requests to the respective subsystem groups, focused on corrections in the lengths and placement along the beam line with inconsistencies of width and height seen as less crucial initially as their inaccuracies were contained within the subsystem and not propagated to downstream subsystems. The critical issues were immediately addressed by the respective subsystem groups which meant size variation and shifts of more than one meter in some cases.

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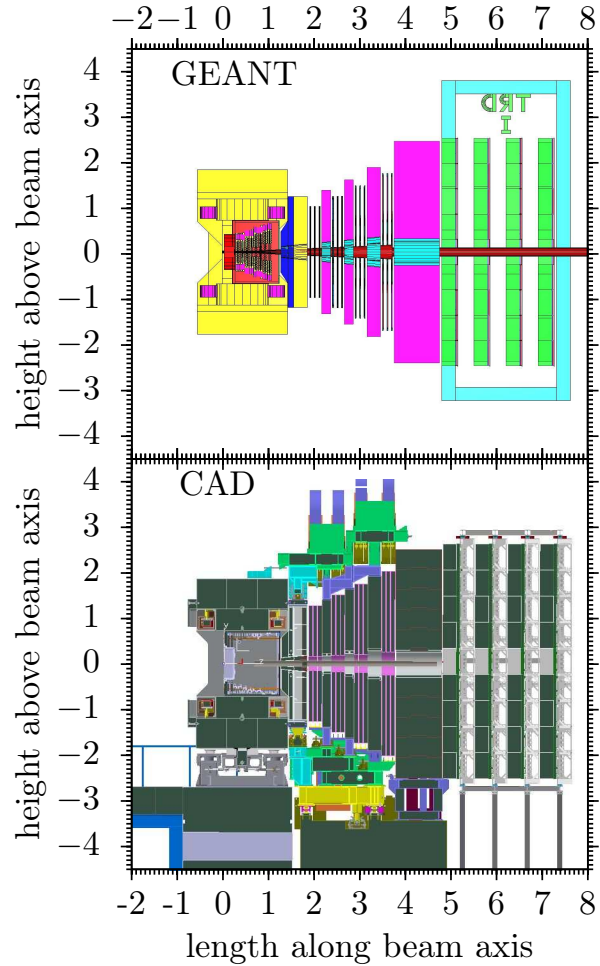


Figure 1: The default J/ψ muon setup of the CBM experiment in its compact configuration. The GEANT geometries (top) and the CAD geometries (below) are displayed as their orthogonal projection onto the $x=0$ plane with front material ($x < 0$) clipped to allow visual penetration of subsystems.

This document does not report on the changes made to individual detector subsystem over the last few months as these are recorded in the subsystem sections of the CBM progress report, in several technical notes and elsewhere. Instead this report's aim is to address the communication issue which may have lead to this divergence and to emphasise the currently recommended geometries for simulation and their agreed placement considering physical lim-

itations. This is intended to ensure that simulation studies have maximum impact in helping steer engineering design. In particular, this documents contains standard dimension and placement information for each subsystem as can be best agreed between the GEANT and CAD geometries. It should be strongly emphasised that most information in this report will change in the coming years as technical and physics decisions are made before manufacture of the subsystems and the final construction of the CBM cave at FAIR. It is however a reasonable anticipation that these changes will become less consequential and less frequent as day zero of our experiment approaches. The data in this report is the best current knowledge for the placement of geometries of the future CBM experiment and may be used for configuration of simulations during year 2021 A.D. but ought to be considered defunct soon thereafter.

Official Experiment Setups

In preparation for the start of the CBM experiment and its investigation of the physics frontier, there are four standard setups of the experiment which are widely distributed within the CbmRoot software framework and encouraged for preparatory simulation. These setups differ in the types of detectors and subsystems installed as well as their placement with respect to the target and their internal configuration. Tab. 1 lists the default GEANT geometries recommended to be used for simulation of the CBM experiment when it is configured to be in the Electron setup, the Hadron setup, the J/ψ muon setup and the low mass vector mesons (LMVM) setup. The detector selection for each of these setups listed in this table coincide with those defaults in legacy setup files in the CbmRoot geometry repository and are not necessarily a recommended detector set for specific physics investigations.

SUB	Electron	Hadron	J/ψ	LMVM
MAG	v20a	v20a	v20b	v20b
PIPE	v16b_1e	v16b_1e	v20a_1m	v20a_1m
MVD	v20c_tr	v20c_tr	-	-
STS	v19a	v19a	v19a	v19a
RICH	v17a_1e	-	-	-
MUCH	-	-	v20a*jpsi	v20a*lmvm
TRD	v20b_1e	v20b_1h	v20b_1m	v20b_1m
TOF	v20b_1e	v20b_1h	-	-
PSD	v20a	-	-	-
PLAT	v13a	v13a	v13a	v13a

Table 1: The 2020 geometry versions recommended for each subsystem (SUB) for simulation of electron, hadron, J/ψ and low mass vector meson (LMVM) experimental setups of the CBM experiment at FAIR. The '*' abbreviates '_sis100_1m_' in the tag name.

Subsystems' Geometries Summary

Fixed Position Subsystems

The magnet's GEANT geometries comes in a variant with clamps 'v20a' and without clamps 'v20b' as listed in Tab. 1 and as a visible in Figs. 1 and 2. The clamps are used when the Ring Imaging Cherenkov (RICH) detector is installed on the mount directly behind the magnet, Fig. 2. The 19 cm long field clamps limit the stray field of the magnet to a maximum of around 0.5 mT in the RICH photon detectors [2] and lead to the difference, between the two versions seen in Tab.2, in distance between the target and the magnet's most upstream point. A mini rail allows the RICH to be pushed neatly into position between the top and bottom clamps [3]. When the MUCH is instead required, the clamps are removed and it is pushed into place by a hydraulic drive, moving the whole array of sensors and absorbers perpendicular to the beam axis [4].

The first absorber of the MUCH matches the shape of the magnet, so that a part of it slides inside the yoke before operation. It is noted that the CAD measurements remain the same due to the frames required to hold the detector layers and absorbers in place irrespective of whether the MUCH is in a configuration with three absorbers or with four absorbers. In the case of the "START" configuration, the space of the 4th absorber is still needed for additional mounting brackets that counter the otherwise uneven weight distribution and so there is no space saving from using one less absorber. Behind the MUCH, a 5th absorber may be installed, in particular for the J/ψ setup, which is visible in the CAD panel of Fig. 1. In the case of the GEANT geometries, the MUCH comes in three variants, one optimised for simulation of low mass vector mesons (LMVM) with 4 absorbers and one for J/ψ setups which has all 5 absorbers as default. A "START" geometry, "v20b" is also available with 3 absorbers and 2 GEM stations for Au beams less than 4A GeV. The 5th absorber consumes 1 m length of the experiment and can be seen as the large pink

SUB	width	height	length	position
MAG	4.4	3.7	2.0	-0.6
MAG (clamps)			2.38	-0.79
MVD (TR)	0.8	0.8	0.525	0.04
MVD (VX)				0.01
STS	2.38	1.423	1.338	0.3
RICH	6.0	5.478	2.2	1.788
MUCH (J/ψ)	5.0	5.0	3.52	1.25
MUCH (LMVM)	3.88	4.03	2.5	1.25
MUCH (START)	3.258	3.258	1.6	1.25
5th Absorber	5.0	5.0	1.0	3.77

Table 2: Position and dimensions of stationary detectors. All measurements are in meters, width is the left to right view looking at the subsystem (SUB) from the beam perspective, height is vertical, and lengths are along the beam axis. The subsystems are centred on the beam axis.

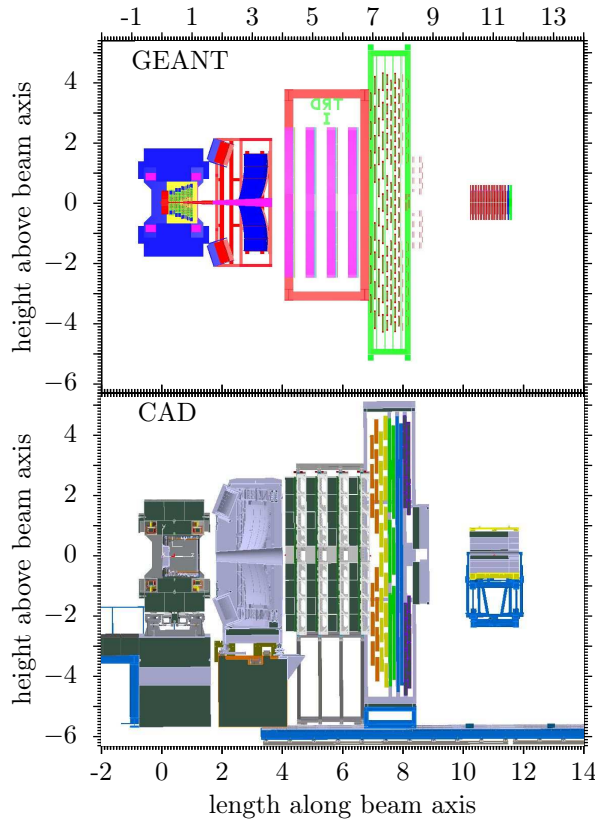


Figure 2: The Electron setup of CBM experiment in its compact configuration. The GEANT geometries (top) and the CAD geometries (below) are displayed in their orthogonal projection onto the $x=0$ plane with material closest the observer clipped to allow visual penetration of the subsystems. All subsystems are placed in their default positions except the PSD which is centred on the beam axis at 10.2 m from the target.

rectangle before the transition radiation detector (TRD) in the GEANT panel of Fig. 1 and as the green rectangle in the CAD panel of the same figure. Although, not observable in our diagram, the proportion of the block, also green, immediately below the 5th absorber is entirely removable when not needed. However, when installed it reduces the closest placement possibilities of downstream detectors by up to 1 meter, cp. difference between min and min* columns of Tab. 3.

Enclosed inside the magnet yoke between its two coils [5], the silicon tracking system (STS) box is placed such that its 2nd station is positioned at the centre of the magnet, ergo its magnetic field. The STS forms the basis of the tracking and reconstruction for the CBM experiment and therefore present in all the standard experiment setups. Germane information regarding the CAD and GEANT geometries of the STS are contained in the Technical Note, Ref.[6], and the references therein. The “v19a” version of the STS geometries is currently recommended for all

four setups, although as some recent changes are waiting approval to the STS CAD, it is expected that an updated GEANT geometries will follow soon. Inside the STS enclosure, adjacent to the target with a few centimetres, the micro-vertexing detector (MVD) is situated. The MVD GEANT geometries come in two variants, or modes, one intended for vertexing (vx) and one intended for tracking (tr), where the internal sensor module design, their configuration and spacing between modules are modified. Details are the recorded in the technical note [7]. The currently recommended “v20c_tr” for tracking simulation where the most upstream volume of the sensor layer comes to 4 cm from the target and “v20c_vx” for simulation using vertexing mode where the upstream volume of the sensor is 1 cm from the target. Although the beam pipe is not a focus of this manuscript, we note that it is currently under active technical consideration and several CAD geometries were received. The two beam pipe geometries listed in Tab. 1, one to be used in conjunction with the RICH and one when the MUCH is instead installed, are therefore expected to change in the coming year. It is noted that for all geometries which are relatively close and in fixed position with respect to the target, i.e. all those in Tab. 2 use the target as their internally defined origin in the GEANT root file. It has been proposed that this may change in the future. Tab. 2 contains the measured dimension and placement according to the CAD model for the fixed position subsystems.

Detectors on Rails

Detectors listed in Tab. 3 are further from the target than those in Tab. 2 and are mounted on a system of rails which is visible in the bottom half of the CAD panel of Fig. 2. This allows them to vary their position with respect to the target. The “min” column of Tab. 3 contains the minimum distance between the centre of the target on the beam axis and the most upstream part of each detector projected on the beam axis. In Cartesian coordinates defined with the target as its origin, this would be the standard z component of the vector to the most upstream point of the detector. For the special case when the MUCH’s fifth absorber is installed, such as for Fig. 1, the closest placement of the detectors in Tab. 3 are pushed back, and the new closest position relative to the target is listed in the “min*” column. In general the closer a detector is to the target, the greater the total interactions of the beam and target which falls under the steradian suspended by the height and width of its sensors. It is therefore of active interest for many detector subgroups to keep the values in the “min” and “min*” as small as possible, and the *compact configuration* of a setup is thus a useful configuration to study and simulate. It should be cautioned however that these compact positions as yet do not take safety margins and gaps between the detectors into account but merely prevent material collisions between the detectors. The furthest distance that each detector may be placed from the target is the same across all setups and is shown under the “max” column of Tab. 3. The

SUB DET	width	height	length	placement range		
				min	min*	max
TRD	9.9	8.55	2.9	4.1	4.8	12.2
TOF	13.5	10.78	2.19	6.9	7.7	15.1
BFTC	1.98	1.98	0.59	9.4	10.0	16.2
PSD	4.85	10.04	1.96	10.1	10.9	18.3
lat.				-0.9	-0.9	0.9
vert.				-0.7	-0.7	0.7
angle				-3°	-3°	3°

Table 3: The position and dimension for the downstream detectors. Dimensions, not labelled, are in meters from the target to the most upstream point of the subsystems projected onto the beam axis where the “min” column contains the closest placement and “max” its furthest placement. The “min*” column contains a modified closest placement when the MUCH’s 5th absorber is installed, cf. Tab. 2. The PSD frame allows it to shift its lateral, vertical and angular placement with respect to the beam axis.

electron setup in its most compact configuration is shown in Fig. 2 with distances from the target corresponding to the “min” column of Tab. 3, whilst Fig. 1 shows the J/ψ setup in its compact configuration where the TRD, the only detector on rails in this setup according to the current defaults shown in Tab. 1, is placed at a position consistent with the value in the “min*” column of Tab. 3. The TRD may be moved on its rail system from 4.1 m to 12.2 m from the target when the 5th absorber of the MUCH and its base is removed. Information regarding the design and mounting frame of the TRD is contained in Ref.[8]. Downstream for the TRD, the Time of Flight (ToF) detector is intended to be omnipresent during the lifetime of the experiment although it may be pushed back to more than 15 m from the target. Its frame extends more than 5 m above the beam axis which is more than 13 m above the ground of the cave although the top and bottom 50 cm of the frame contain no sensors in the current official designs. It is pointed out that the left most sensors of the ToF within 1 meter from the beam axis in the CAD panel of Fig. 2 are invisible in the diagram due to the choice of white being used for both the sensors and the background of the diagram.

Following a presentation [9] at the 36th CBM Collaboration Meeting and its subsequent discussion, it became apparent to the authors of a strong desire within the collaboration to make a concerted effort to make space provision for inclusion of the proposed Beam Fragmentation T0 Counter (BFTC) detector. It is proposed that the BFTC will match the acceptance of the projectile spectator detector (PSD) which is directly downstream. A length of 30 cm for the BFTC with a 20 cm gap to the ToF detector and a 80 cm gap to the PSD was communicated following the results of simulations. As the frame of the ToF detector already allowed for the necessary gap on its side, a 1.1 m length of the beam axis was allocated. Subsequently it has emerged that the size of the BFTC is most likely to be larger

than first anticipated. This change would increase the closest approach “min” and “min*” of Tab. 3 of the PSD by 29 cm and the the maximum extension “max” of Tab. 3 for the TRD and the ToF may need to be reduced by the same amount.

As a consequence of its bespoke frame, visible in the CAD panel but absent in the GEANT panel of Fig. 2, the PSD is capable of moving vertically above or below the beam axis, laterally to the left or right of the beam axis, or rotating its pointing angle in the horizontal plane, cf. Ref.[10]. As the manipulator frame has been manufactured and currently being stored in a warehouse, further design modifications are highly unlikely. On the other hand, the rail system on which the PSD manipulator frame will be mounted has not yet been officially submitted. It is for this reason, in the CAD panel of Fig. 2, the PSD is unsupported at present. Although it is noted that a possible design for the mounting frame is contained in this journal in Ref.[10]. The four rows in Tab. 3 give the range of movement for each of these four degrees of freedom. Some of these possible placements are not intended for simulation of normal operation of the experiment but rather for detector calibration. The currently recommended version “v20a” of the PSD geometry may be shifted and moved as desired using its translation matrix within the CbmRoot software packages. The current default placement is at 10.5 m along the beam axis with no vertical displacement shifted to the left of the beam axis by 12.95 cm and rotated by $(\frac{3}{4})^\circ$ in the horizontal plane, in order to be consistent with a 12 AGeV/c beam.

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CBM-MVD: Updated MVD simulation geometry

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This report summarizes the recent updates of the simulation geometry of the CBM-MVD. Details about them were also published in a CBM computing note [1]. The simulation geometry is a virtual mock-up of the detector for use in the software simulation of the CBM experiment: CbmRoot. Primitives – basic three-dimensional volumes – are used to implement simplified models of the relevant matter making up the detector. This serves two purposes in the simulation of heavy ion collisions: (1) to simulate the detector response, and (2) to model the material entry in front of all subsequent detectors, which can affect their performance due to multiple-scattering and conversion.

In the past years, the MVD geometry v17 was part of multiple experimental simulation setups of CBM (for example in the setups sis100_electron, sis100_electron_sts_long, sis100_hadron, sis100_hadron_sts_long, and sis300_electron as of the APR20 release of CbmRoot). In order to adjust the expected material budget of the detector and to comply with the new CbmRoot standard to place detector geometries in the experiments' coordinate system, updates were necessary to the MVD geometry. The updated geometries version tag starts with 'v20' (except for v17b, which was unchanged except for placement and was also introduced in 2020).

Main Changes in the the new Geometry Versions:

First of all, it's important to note that the MVD geometries of the v17 and v20 series are in most part very similar or even identical. Most notably, the dimensions of the sensors, their number and placement is identical across all of the different versions.

There are, however, a couple of significant changes between the different versions and the major changes are outlined below:

- v17a → v17b: identical, but different placement in the global coordinate system (motivated by change request of STS).
- v17 → v20: TPG carrier in the second station instead of diamond (vx configuration); increased thickness of TPG carriers, increased thickness of heat sink Al, corrected diamond density; addition of a top and bottom plate.
- v20a → v20b: increased TPG thickness even further (dedicated variant to study the potential impact of a higher material budget).

- v20a → v20c: identical, but different placement in global coordinate system.

Please refer to [1, Table A.1] for a detailed comparison of the major differences and features of the geometries v17a/b and v20a/b/c.

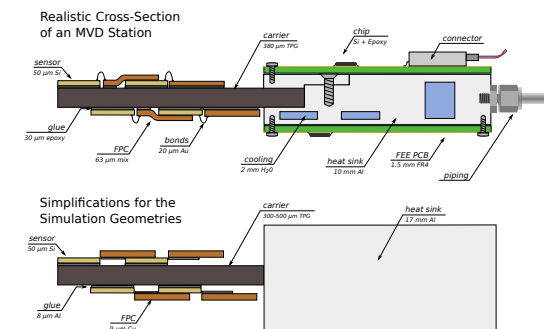


Figure 1: Compare lower to upper figure for simplifications for the simulation geometries

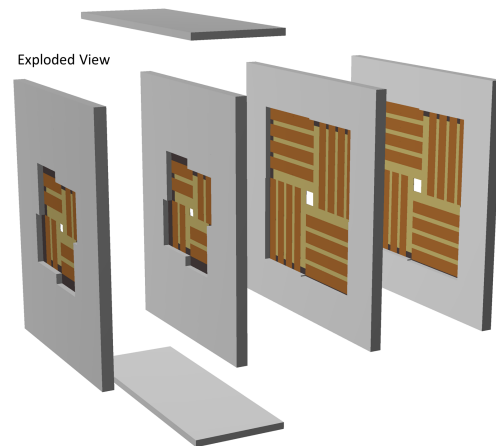


Figure 2: Exploded view of the simulation geometry v20c_tr of the CBM-MVD.

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Software developments within the TRD project

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In the last years a **framework for simulation and reconstruction** of TRD data was successfully developed and used. These efforts were now documented in a dedicated internal note, which focusses on the digitizer developments [1].

One of the most important challenges for the CBM-TRD software project during 2020 was the **integration of the reconstruction and analysis of real data** into the existing framework. The data taken during the DESY 2019 and mCBM 2020 campaigns (see [2, 3]) provide the opportunity to test and expand the given framework for real data reconstruction and analysis.

As example for the successful reconstruction of TRD data from the mCBM beamtime 2020 see Fig. 1 and the corresponding article in this report [3].

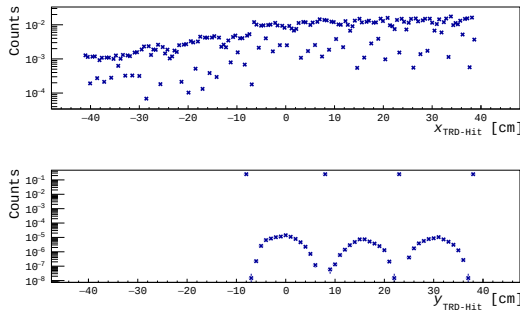


Figure 1: Spatial distribution along x (top) and y (bottom) of the reconstructed TRD hits, measured during run 831 of the 2020 mCBM campaign. The observed distributions meet well the expected combination of acceptance $\times$ efficiency. The asymmetries seen over the extend of the installed chamber result from the combination of the position of the chamber in the setup and a not fully symmetric active readout of the chamber. Since the installed chamber is a prototype with large readout-pads along the y -direction, only a very reduced spatial resolution is expected along this direction.

Part of the efforts required to enable a successful data reconstruction is a parameter based calibration of the data. This is now fully integrated into the framework, based on the FairRoot parameter functionalities. In the latest developments of the real data reconstruction the TRD was successfully included into the common data reconstruction

chain, which is an important step towards more complex analyses including the TRD (see also [4]).

As well understood reference for the **position-reconstruction performance**, a center-of-gravity algorithm (COG) is implemented as default for the reconstruction of the hit position in modules with rectangular readout-pads. However, the COG approach introduces biases into the position reconstruction, for example due to hard cutoffs at low energies. In former analyses different algorithms have already been investigated to overcome these biases [5]. One of these algorithms, the so-called "SECHS" algorithm (see e.g. [6]) is now implemented as alternative option to the COG.

Revision of the geometry representation in GEANT: in order to proceed towards a more realistic version of the TRD, a first design of a detailed support structure was developed [7]. On the software side this requires the inclusion of the support structure into the GEANT representation of the TRD. As first step the expansion of the TRD along the beam direction, as required by the current support structure, was varied to investigate the influence on the TRD physics performance. The current version, depicted in Fig. 2, corresponds to the maximal additional elongation of the TRD of 100 cm along z . It will be set as default for the SIS100 GEANT representation of the TRD.

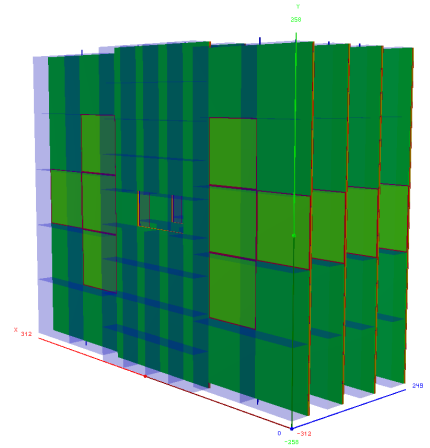


Figure 2: TRD GEANT geometry with 71 cm thick layers.

As next steps, the complete software used to produce the GEANT geometry of the TRD will be revised. The inclusion of the support structures themselves in full detail will be

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part of this effort.

At the end of 2019 a detailed **code documentation project** was started within the TRD group. The project is based on the *GitLab Pages* package [8] and published on the CBM git server. Since then, the "CBM TRD software guide" is being constantly updated. Up to now, it contains information about the geometry, simulation, reconstruction, parameter, analysis and DAQ software of the TRD project and it will be continuously expanded as further software developments proceed.

Work in progress and outlook for the next year

- Radiator simulation: together with the analysis of the data taken during the DESY 2019 campaign [2], which is supposed to further investigate the radiator performance, the software structures handling the simulation of the radiator are being revisited.
- TRD-Analysis-Framework (TAF): with plenty of beamtime data already recorded and much to come in near future, e.g. mCBM 2021, the need for a well structured, TRD focussed analysis framework is given. Therefore, an effort was started to implement such a framework.
- Energy and time reconstruction: currently algorithms are developed which are fast enough to run online and still allow a high precision reconstruction of the hit time and energy.

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CbmRoot containerized environment

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Introduction

CbmRoot is the main analysis package of the CBM Experiment. It is based on the ROOT C++ framework, a long time standard tool of every high energy physics experiment. The experiment software stack comprises three levels of software dependencies: FairSoft - an umbrella framework of extra tools and packages, FairRoot - a common software framework for all FAIR software projects, and finally CbmRoot - software packages which directly relate to the CBM experiment. The software is distributed in the form of the source code and users are expected to build it themselves. Building the software requires user to have appropriate skills and have the software prerequisites installed in the system. Building times are long and might take hours.

This contribution explores the possibility to harness the power of the Docker [1] containerization engine.

CbmRoot in Docker containers

The software containers provide an encapsulated working environment which is the same for every user, eliminating possible environmental issues and reducing maintenance costs. The containers are built with Dockerfile - text-based recipes which contain all necessary actions to get to the desired working environment. Once built, the containers can be distributed among computing resources and deployed rapidly on many modern operating systems, including Windows, macOS and Linux.

In this work we have built the CbmRoot containerized environment. It allows both running physics tasks (such as particle transport or event reconstruction) and further development of the CbmRoot itself from within the container. The graphics visualisation based on the X Server is available to the host machine. The source code is available in the repository [3].

Jupyterhub graphical interface

Project Jupyter [2] provides the web-based interactive programming environments for data scientists and application developers. It was mainly used in conjunction with Python programming language, but other languages such as R and C++ are also supported. ROOT framework has Python bindings since a while and Jupyter notebook integration since 2015 with ever-improving functionality.

In this work we also have built the Jupyter container which allows to load the CbmRoot libraries and execute

the custom user analysis code with them. We demonstrated that Jupyterhub can be used for the analysis of the mCBM data taken in spring 2020.

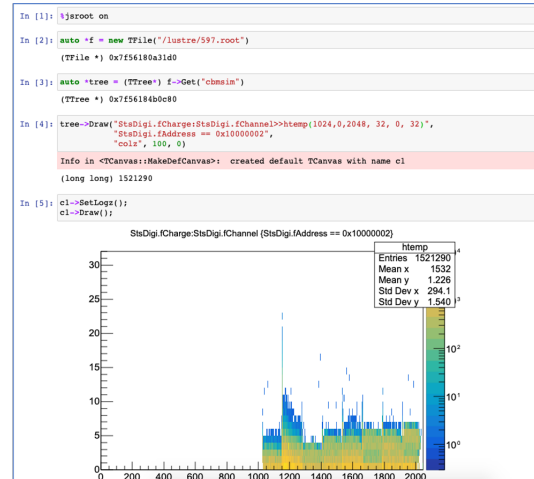


Figure 1: Caption

Figure 1 shows a snippet of a program to monitor the quality of data arriving from the Silicon Tracking System's read-out electronics.

Summary

In this work we have developed the containerized environment for the CbmRoot. It substantially reduces the hurdle to start working with CbmRoot by removing the necessity to build the software yourself - instead it will be downloaded and preconfigured.

The Jupyterhub container built in this work allows for easier start into data analysis with a support for interactive immediate visualization of user's data.

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The long way from Subversion to GIT

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In this report, we will discuss the migration from the previously used version control system *Subversion* to the new version control System *git* and why we did this migration.

Version Control Systems

For members of an experiment like CBM it may be needed to reanalyse data with an older version of the analysis software which means being able to use exactly the software from that point in time. In software engineering such tools for source code management are very common. Such source code management or version control systems are tools responsible for the management of changes to software, documents or other collections of information. In the following we will use always the term source code for any information managed in a version control system and the complete managed information as repository. All changes to the source code are identified by a revision which allows to access the state of the code for any point in time when knowing the revision for the point in time. For the development of the the CbmRoot software the CBM collaboration has used meanwhile three different version control systems. The development of CbmRoot started in July 2004 with the Concurrent Version System *CVS* [1] which was used till September 2006 when the repository was migrated to a the new version control system *Subversion* [2]. *Subversion* was then used over a period of nearly 14 years till June 2020 when the migration to a new version control system was done. Since June 2020 the development of CbmRoot is done with *git* [3]. One of the main new features of *git* and also one of the reasons for the migration to it was that *git* is a distributed version control system whereas *CVS* and *Subversion* are central version control systems.

One of the main drawbacks of *Subversion* was that the development workflow is to a large extend defined by the version control system. When using *Subversion*, the workflow for the development of CbmRoot allowed a large number of developers to commit their changes to different parts of the repository which results in situations when the state of the central repository was broken such that it was impossible to use or even compile CbmRoot. The new source code management system should therefore allow to check the changes and potentially rejects them before they could enter into the central repository. With a central version control system it is also not possible to keep track of local developments without committing the changes to the central server, so the new system also should allow to have the full history of the local development available locally. Only the final stage after finalising the development is then commit-

ted to the central repository.

After long discussions which took more then one year and some in detail testing it became clear that *git* is the choice for the new distributed version control system.

With *GitLab* [4] we choose also a web-based frontend to the *git* repository server which not only allows the source code management. *GitLab* also allows to implement a new development workflow with automatic Continuous Integration or a review process before code is accepted.

Cleanup of SVN repository

Over the 16 years of CbmRoot development the repository has grown to a size of more than 2GB and to a very complex directory structure, so the migration from one code managment software to another one was also used for a cleanup of the content and the structure of the software repository.

To make the transition as simple as possible all changes were done still inside the *Subversion* (SVN) repository and only the final revision was imported into the new *git* repository. This results in a clean first revision of the *git* repository without losing the history which is still accessible SVN repository. The last revision in *Subversion* and the first revision in *git* are absolutely identical.

The main reason for the large size of the SVN repository was a large number of binary files which were added over the years. For text files only the differences between two versions are stored in the repository which are only of small file size. Besides the normally larger size of binary files the difference between two versions is always the complete file. So in the cleanup most of the binary files were removed from the CbmRoot repository and moved into separate repositories if still needed. Currently there are three such repositories which contain binary files. The parameter repository which contain parameter files, the geometry repository which contain the geometrical descriptions of the detector systems stored in binary files and the input repository which contain for example the field maps of the magnet which are also stored in binary format. All three external repositories are included into the CbmRoot source directory automatically when building CbmRoot such that there is no visible difference for the CbmRoot users.

There were also a large number of files which were in the repository only for historical reasons, for example code for detector systems which were planned in the beginning of the CBM project but meanwhile have vanished from the current plan of CBM. All of these files were also moved from the working branch of the SVN repository into some

legacy branch such that they are still available in future from the old SVN repository if they are needed.

Due to the long history of the SVN repository and also due to the SVN workflow the director layout and also the dependencies between different parts of the code were not according to the needs but mostly legacy. Before reworking the directory and also the dependency structure there were nearly 40 directories on the top level, one for each detector subsystem and then many with names which do not explain their intention. After the rework only roughly ten directories survived. The main ones are core, sim (simulation of the experiment), reco (data reconstruction) and analysis (data analysis). The core directory contains code which is needed by more than one of the other top level directories. It contains for example data classes which are needed for simulation, reconstruction and data analysis. Inside these four top level directories there is now always a clear substructure with a naming scheme which explains the intention of the directories. The new structure also helped to cleanup the dependencies between the different parts of the code and to remove some circular dependencies. Finally for example there is no longer a dependency between code residing in the sim and the reco directory.

Preparation of GIT repository

Parallel to the cleanup of the SVN repository the preparation of the GIT repository was pushed forward. The main two issues which had to be implemented on the git or more precisely GitLab side were the implementation of the new development workflow and the for this purpose needed implementation of the Continuous Integration (CI) pipeline.

During the parallel development in SVN and GIT a read-only version of the CbmRoot repository was available in GitLab for testing. This version of CbmRoot was synchronised from the official CbmRoot SVN repository for each commit.

The implemented workflow described here is inspired by the workflow used for the development of the FairRoot project. It should solve the problem that broken and not approved code enters the repository and aims at providing a stable repository at any time and should allow a simultaneous development by several users.

Every development starts from the official repository on the GitLab server and finally ends there again when the user development is incorporated into it. The actual development is separated from the official repository and is done in a copy of the official repository in the user account on the GitLab server. The user development can only enter the official repository when the user requests that his code should be incorporated, it is not possible by any user to simply change the official repository without such a Merge Request. Before the Merge Request can be incorporated (merged) the changes have to pass the Continuous Integration pipeline and finally have to pass additionally the review process by a responsible person. So no code can enter the official repository without automatic

testing and manual code review. A detailed tutorial which explains the development workflow in detail and guides a new user through the workflow step by step is found at <https://git.cbm.gsi.de/notes/computing/gitlab-tutorial>.

Since the development is completely decoupled from the official repository the user has only to synchronise his developments with the current state of the official repository before he creates a Merge Request. Every user is therefore able to do his developments without interference with other users. Because only tested and reviewed code enters the official repository the workflow produces a stable state at any time.

The current workflow as well as the CI pipeline was implemented with tools provided by GitLab. The CI pipeline finally starts on several test computers the scripts developed by the CBM Collaboration. This separation allows us to concentrate on the tests itself but not on the question how and where to run the different tests. The development started with only one test in one stage testing if the current state of the repository including the changes from the Merge Request correctly compiles. Meanwhile the pipeline is much more complex as can be seen in figure 1 and consists of three stages. Most of the new tests were added when a problem was found, either in the developments workflow or the code itself. In the first stage it is tested if the Merge Request can be properly merged. Only if both tests of this stage succeed the tests in the second stage start. In this second stage it is tested if the file format is correct and if the code is properly formatted according to the coding conventions. In figure 1 the test of the code format did not succeed such that the tests of the third stage of the pipeline are not started at all. In the last stage of the pipeline the code is compiled on several different operating systems and finally the test suite is run. Only if the complete pipeline succeeds a reviewer will manually review the code.

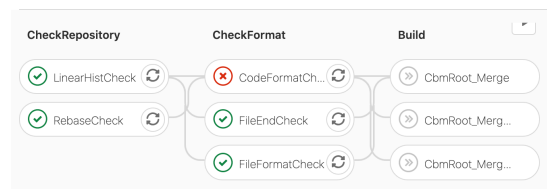
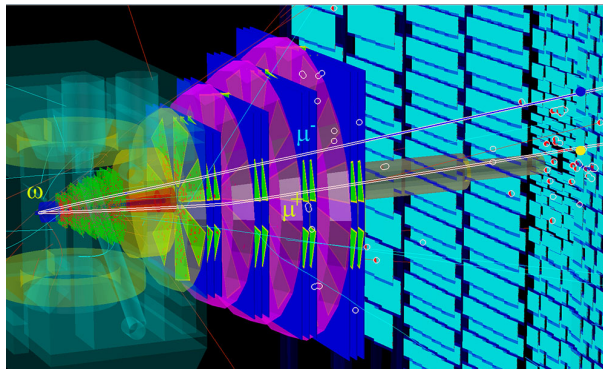


Figure 1: Continuous Integration pipeline

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Physics Performance



Machine learning application for lambda baryon physics analysis

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Enhanced production of strange baryons can identify the formation of quark-gluon plasma in heavy-ion collisions [1]. Lambda (Λ) is the most abundant strange baryon produced at FAIR energies. It weakly decays, with a branching ratio of 64%, into a proton and a negatively charged pion (π^-). To reconstruct Λ all proton and π^- tracks are combined to make its invariant mass spectrum. For the reduction of combinatorial background specific selection criteria are applied to the proton and π^- tracks.

In the already existing Kalman Filter Particle Finder (KFPF) package for online reconstruction and selection of short-lived particles in CBM, these criteria have been manually optimized. These selection-cuts have been selected to maximize the signal to background ratio (S/B) of the Λ for a certain energy on a collisions generator. The selection criteria mainly depends on the collision energy, decay channel and detector configuration. Unlike the current implementation, the selection criteria based on Machine Learning (ML) algorithms can be adjusted automatically by the algorithm for different input data-set. Another advantage of using ML is that it applies a final non-linear and multi-dimensional selection criterion. To optimize selection criteria for Λ and other particles, ML can use as many variables as one wants associated with particle candidates. In this work we are only using the variables used by KFPF i.e.: squared distance between the daughter tracks and primary vertex (PV) divided by its error, the closest distance between tracks, squared distance between daughter tracks divided by its error, and distance between PV and secondary vertex divided by its error.

Following the footsteps of the ALICE collaboration [2], ML algorithm Gradient Boosting from XGBoost library [3] is used in our work. For training and testing, a UrQMD simulated sample has been used. This data-set contains 90k Λ candidates and 270k background candidates. For the algorithm's hyper-parameters search i.e. to tune the various parameters of the algorithm so that it fits better on the training data, Bayesian optimisation [4] is used. Over-fitting of the algorithm on the training data are controlled with the help of the Receiver Operating Characteristic (ROC) and Area Under the Curve (AUC). The algorithm returns a probability distribution between 0 and 1 for given input variables. Candidates which are close to 0 are considered as background with most certainty and vice versa. On this probability distribution, approximate median significance [5] is used to maximise S/B.

The trained-tested model is then applied on a simulated UrQMD file containing 10k events and 12909 Λ s, after cleaning the data by removing outliers. The Λ s selected

by XGB, true positives, are 10513 (81.4 %), and by KFPF are 9877 (76.5 %), revealed by the Monte-Carlos (MC) information through Confusion Matrix (CM) investigation. Also CM shows that XGB suppresses the background two times better than KFPF. The invariant mass histogram of the Λ is shown in Fig. 1 after the selection cuts of KFPF and ML algorithm XGB. Our code is available on Google's colab on this link [6].

The algorithm will be tested for stability on different energies of UrQMD, DCM-QGSM-SMM and SMASH, in the near future. Other variables, for example cosine of the angle between Λ and proton tracks, will be included in the selection criteria after performing correlation studies on them with invariant mass and momentum. Also it will be tested on other strange and multi-strange particles and nuclei. When the experiment will start acquiring data then the background in the train-test data will be taken from that data, this will make our algorithm partially independent of collisions simulating models.

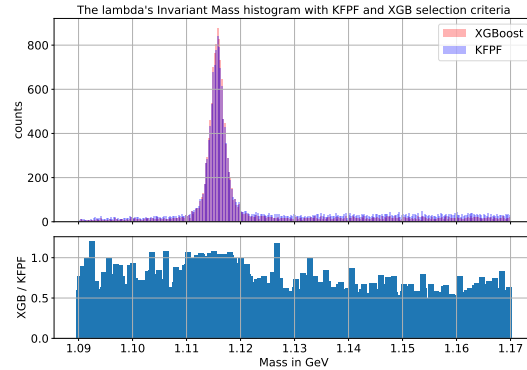


Figure 1: The upper histogram shows XGB and KFPF extracted signal out of a UrQMD simulated data set containing 10k events at 12.4 GeV/c. The lower bar graph is the ratio of the above two histograms i.e. XGB/KFPF.

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Reconstruction of hypernuclei with PFSimple

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At beam energies of around 12.4 GeV at FAIR in combination with the high interaction rates at CBM the conditions for an exceptionally high amount of measurable hypernuclei will be created [1]. For the analysis of hypernuclei, the PFSimple package [2] was developed further. PFSimple is a software to reconstruct hadrons, based on the KF Particle Finder [3]. The updated version of PFSimple now allows the user to analyse any 2- or 3-body-decay and adjust the cuts as required. The reconstruction of ${}^3_{\Lambda}\text{H} \rightarrow \text{d} + \text{p} + \pi^-$ (BR: 40.1 % [4]) is presented as an example.

As simulation input, ${}^3_{\Lambda}\text{H}$, as well as light nuclei like deuterons, tritons and ${}^3\text{He}$, were embedded into 45,000 UrQMD-events (Au+Au, $p_{\text{beam}} = 12.4 \text{ GeV}/c$, 0-5% most central). For realistic multiplicities of ${}^3_{\Lambda}\text{H}$ (0.087 per event, extrapolated from $dN/dy|_{y=0}$ [1] to 4π) also events without ${}^3_{\Lambda}\text{H}$ were produced and scaled accordingly. The p_T - and the y -distributions of the embedded particles were based on a fit of experimental data from E864 [5] with a thermal distribution for p_T and a double Gaussian in momentum space for y [6].

The reconstruction of a 3-body-decay in PFSimple is executed in two steps: First a temporary mother of two daughters is reconstructed at their point of closest approach (PCA); then the third daughter is added at the secondary vertex (SV) of the temporary mother. To reconstruct ${}^3_{\Lambda}\text{H}$, the following cuts were applied as a starting point: χ^2 to primary vertex (PV) > 18.42 for all daughters, distance between the first two daughters (p and π^-) at PCA $< 1.0 \text{ cm}$, χ^2 of temporary mother < 3.0 , distance d_{SV} of d and SV $< 1.0 \text{ cm}$. Further cuts were applied and tested to improve the reconstruction quality. The signal-to-background-ratio S/B and the efficiency ϵ of three cuts are shown in Fig. 1: on the distance d_{SV} , on the decay length L of the mother particle and on χ^2 to PV of the temporary mother. The mass spectrum for $d_{SV} < 0.1 \text{ cm}$ is shown in Fig. 2. A S/B = 7.52 at an efficiency $\epsilon = 0.16$ inside the acceptance¹ can be achieved.

Further developments of PFSimple will include the implementation of a realistic detector PID, replacing the current MC PID; the TRD- dE/dx information will be incorporated to separate d and ${}^4\text{He}$. The reconstruction of rare hypernuclei like ${}^5_{\Lambda}\text{He}$ and ${}^6_{\Lambda\Lambda}\text{He}$ will be studied. Using PHQMD events, different combinations of target- and pro-

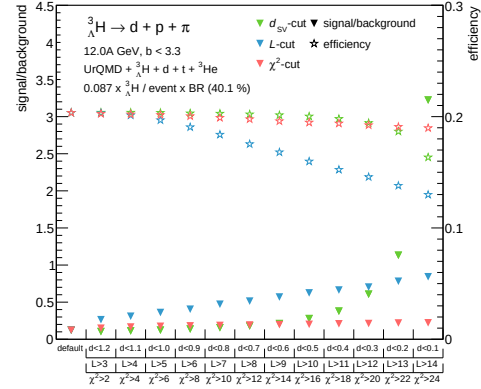


Figure 1: S/B and ϵ vs. different cut values for three cuts: $d_{SV} < d_{max}$, $L > L_{min}$ and $\chi^2 > \chi^2_{min}$.

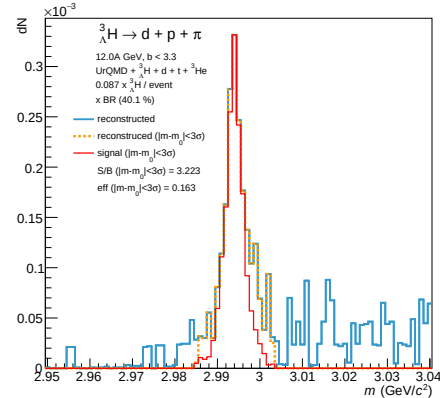


Figure 2: Mass distribution for ${}^3_{\Lambda}\text{H}$ for 45,000 UrQMD-events with embedded (hyper-)nuclei signals.

jectile nuclei, beam energies and centralities will be analysed in order to develop an ideal scenario for the measurement of hypernuclei.

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¹The detector acceptance for the 3-body-decay of ${}^3_{\Lambda}\text{H}$ is 0.2857 for a minimum of three MC hits for all daughters.

Proton rapidity-transverse mass spectra reconstruction in CBM experiment

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Rapidity (y) and transverse mass (m_T) distributions of net-baryons are sensitive to the different equations of state (EoS) [1, 2]. Since we can't measure the neutrons and the number of antiparticles at CBM energies is significantly less than number of particles, we will use the proton rapidity distribution instead net-baryon one's. In this report CBM performance on proton y - m_T spectra reconstruction is studied.

CBM will be a fix-target experiment at the SIS-100 accelerator in GSI, Darmstadt, Germany. The momentum range for Au beam will be 3.5-12A GeV/c, the detector acceptance will cover range $2.5^\circ < \theta < 25^\circ$ in azimuthal angle. In this work Au+Au collisions are simulated using the THESEUS model generator with the crossover EoS[3]. For the proton selection correction UrQMD model has been used. Generated events were passed through the CBM detector simulation and reconstruction software (CbmRoot version Apr20). The impact parameter is fixed at $b = 2$ fm for both models, beam energy is 10A GeV and the statistic is 95k events.

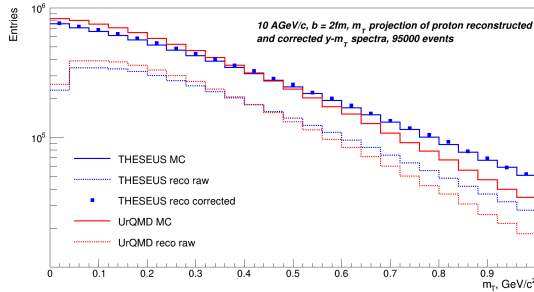


Figure 1: THESEUS (crossover EoS) and UrQMD m_t spectra at midrapidity before CBM and reconstructed.

For the hadron reconstruction the KFPARTICLE Finder package has been used. On the figure 1 a m_T projection at midrapidity $\in [-0.5, 0.5]$ of crossover EoS of THESEUS and UrQMD is shown. Solid lines are original spectra from the models and dashed lines are uncorrected reconstructed spectra. We observe a large difference in reconstructed and simulated spectra, so correction is needed. Correction function could be defined as the ratio between reconstructed and accepted with TOF cut, and Monte-Carlo generated protons: $corr = N_{reco}/N_{MC}$. Since in real experiment we don't know about the original spectra of particles before passing them through de-

tectors, we must find out reconstruction correction separately to the data spectra measurements. Considering THESEUS data as only experimental results without Monte-Carlo information, we should use correction function from another model, like UrQMD. Therefore, corrected THESEUS experimental $y - m_T$ spectra will be presented as ratio between reconstructed data and UrQMD correction: $N_{corr} = N_{reco}/corr_{UrQMD}$. Total error is a sum of N_{reco} and correction error:

$$\Delta N_{corr} = \sqrt{\sum (\partial f / \partial x_i)^2 \delta^2 x_i} = \sqrt{(1/corr \cdot \sqrt{N_{reco}})^2 + (N_{reco}/corr^2 \cdot \Delta corr)^2}$$

Corrected spectra of m_T projection of $y - m_T$ at midrapidity is shown on figure 1 with blue markers. The slope of $1/m_T$ for original Monte-Carlo and reconstructed THESEUS data has been calculated via an exponential fit by the maximum Likelihood method. For the range $m_T \in [0.2, 1]$ GeV/c² the slope of the THESEUS original data is -5.198 ± 0.002 , for the reconstructed and corrected data is -4.930 ± 0.035 . Therefore, in the range $m_T \in [0.2, 1]$ GeV/c², current method of reconstruction has systematic error of about 5%. The main source is the difference in correction factors between models, as shown in the 2D plot in the figure 2. This could be explained by different particle species ratios and different multiplicities at fixed impact parameter in those models. Further investigation is needed to improve systematic uncertainty.

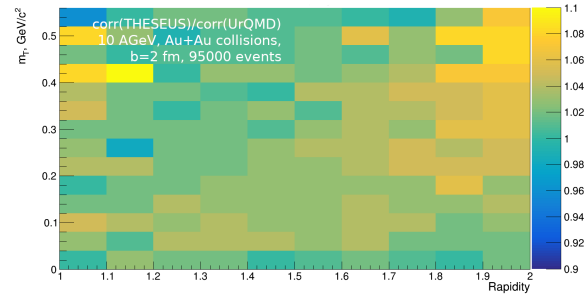


Figure 2: THESEUS Crossover EoS and UrQMD $y - m_T$ correction ratio at midrapidity and low m_T

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Particle ratios at CBM experiment energies

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Nuclear collisions at SIS-100 in the initial stage can produce a net baryonic density of 2-3 orders of magnitude greater than the saturation density. We can expect the appearance of a new phase of the nuclear matter, in which quarks are still confined, but the chiral symmetry is partially recovered [1, 2]. Particle ratios have their importance to eliminate the ratio value fluctuations and are good instruments for the identification of possible phase transitions.

In this report we present some numerical computations for the Au-Au central collisions at 6-20 A GeV energies for the rapidity interval $0 < y < 0.8$ (with the AMPT generator). These results come as a continuation of the previous published results (from 2019), in which we presented the identification of some antiparticle to particle ratio equalities for 2-3 increasing energy points, which suggested pre-equilibrium (for $\frac{K^-}{K^+}$, 0-20% centrality, and $0 < y < 0.8$ interval rapidity). Otherwise, we observed similarities between fluctuations of interest - short plateaus - of the excitation function specific to the antiparticle to particle ratios for kaons and protons, in the same energy interval. For the $\frac{K^+}{p}$ and $\frac{\bar{p}}{\pi^+}$ ratios, we also see equalities for the ratio values for small intervals of energy, and also a non-monotonic behaviour in the 10-14 A GeV interval of interest (Fig. 1 up and down).

The analyses in this article were performed using the UrQMD 3.3 generator, integrated in the YaPT system, with $t = 200$ fm/c, for which the state equation is defined by the cascade mode, and the AMPT 2.26t7 generator, which uses the string fragmentation Lund model and the popcorn mechanism (baryon stopping). Maybe the most interesting result - the plateau form - which can suggest the existence of the mixed phase, can be observed in Fig. 2 [3]. A similar, but less pronounced plateau form can be seen again in Fig. 3 for $\frac{\bar{p}}{p}$ ratio (done with AMPT) for the 10-12 A GeV interval for the 0-20% centrality.

Plateau-shaped results are in good agreement with the results in [4], where they are compared with AGS (Au-Au) and SPS (Pb-Pb) data for regions with anomalous thermodynamic properties.

Surely, we can ask ourselves if we can indeed obtain a mixed phase with energies up to 14 A GeV. We can speculate the idea that an insignificant quantity of QGP can occur. Another idea is the possibility that a "sequence" of gluonic plasma be formed, locally, in a restrained space, which can evolve into QGP, such that a confrontation between QGP and the hadronic gas can take place - that is, a mixed phase.

The multi-strange hyperon ratios are very good instru-

ments for the study of very dense nuclear matter degrees of freedom, in the Au-Au collisions. Thus, we plan to analyse in the future some ratios that contain Ξ^- si Ω^- . The measurement of these ratios can offer the possibility of studying the equation of state or of baryonic fluctuations at densities where we can have first order phase transitions.

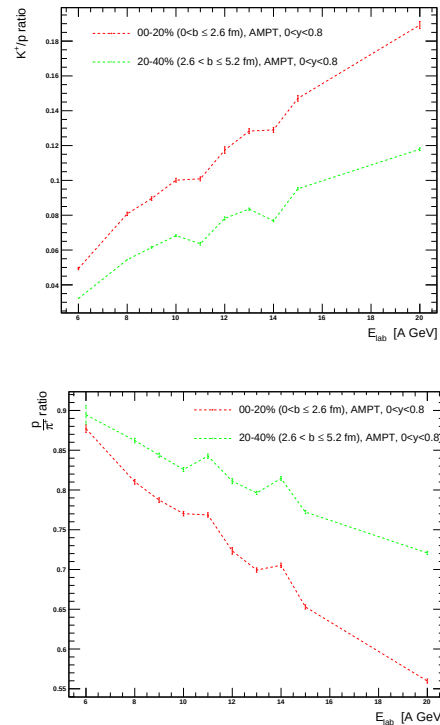


Figure 1: AMPT ratio distribution at rapidity interval $0 < y < 0.8$ and two centralities, considering different collision energies: up) $\frac{K^+}{p}$; down) $\frac{\bar{p}}{\pi^+}$

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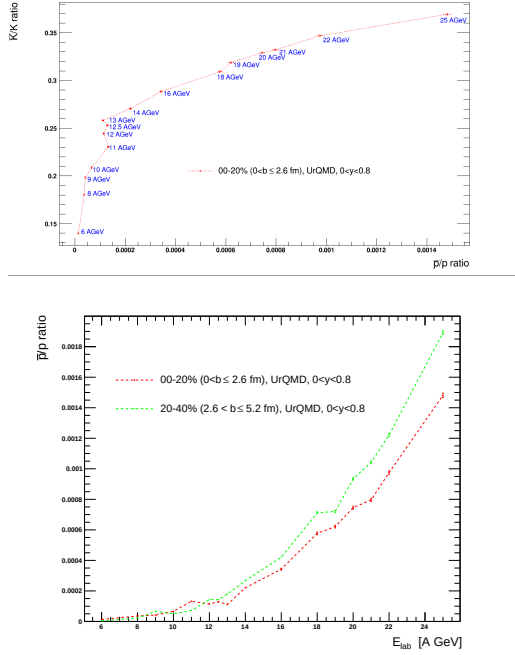


Figure 2: UrQMD studies at different collision energies: up) dependence of $\frac{K}{K}$ ratio to the $\frac{p}{p}$ ratio; down) $\frac{p}{p}$ ratio distribution for two centralities [3]

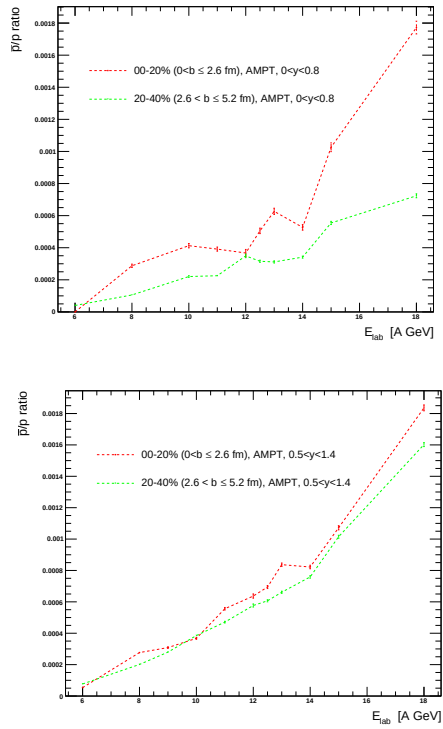


Figure 3: AMPT $\frac{p}{p}$ ratio distribution for two centralities, considering different collision energies and two rapidity intervals: up) $0 < y < 0.8$; down) $0.5 < y < 1.4$

Energy dependence of ϕ meson yield at FAIR energies

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At CBM energies, it will be interesting to look for changes in the behaviour of observables as a function of energy to establish deconfined phase in high energy collisions [1]. The energy dependence of $\phi(s\bar{s})$ meson production will play a crucial role in this regard, since it has small hadronic interaction cross section and freezes out early as compared to other non strange hadrons[2,3]. The $\phi(1020)$ vector meson's proper lifetime is about 45 fm/c, and it decays into charged kaons $K^+ K^-$ with a branching ratio of 49.2%, and more rarely into the dilepton pairs $e^+ e^-$ (B.R. of 2.97×10^{-4}) and $\mu^+ \mu^-$ (B.R. of 2.86×10^{-4}). In AMPT string-melting model, strings (or hadrons) are converted into partons by converting the mesons to a quark and antiquark pair, the baryons to three quarks. Quark coalescence Model is used for hadron formation and the subsequent hadronic interactions are described by a hadronic cascade based on relativistic transport (ART) Model[4].

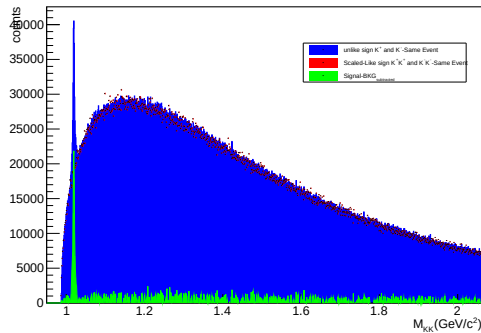


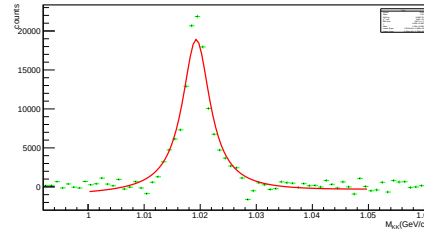
Figure 1: Invariant mass of $K^+ K^-$ pairs to reconstructed ϕ peak

• Simulations

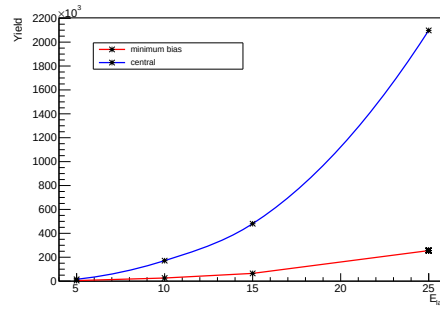
In current work, we have used 2.5 Million minimum bias and central Au-Au events from AMPT(string-melting) model at beam kinetic energy E_{lab} from 5A GeV- 25A GeV. Lund String fragmentation parameters were taken as : $a = (2.2)$ and $b = (0.5)$. Parton-parton cross section is taken to be 10 mb (using strong coupling constant $\alpha_s = 0.47d0$)

• Data Analysis

The ϕ signal in the mid-rapidity region ($|y| \leq 1$) was reconstructed from K^+ and K^- with the same-event method. The large combinatorial background arising



(a) ϕ signal fitted with BreitWigner



(b) variation of ϕ yield with E_{lab}

Figure 2: ϕ yield via $K^+ K^-$ decay channel

from uncorrelated k^+ and k^- pairs is calculated with the mixed-event technique. The mixed-event spectra, normalized to the same-event one outside of the peak region, is then subtracted from the same-event one, to obtain the ϕ signal candidates.

The yield is calculated by fitting the subtracted ϕ signal with BreitWigner (Fig. 2(a)). As can be seen from (Fig. 2(b)) the ϕ yield shows a substantial increase with energy. The increase is more prominent for central events .

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Production of Ω^- , Ξ^- and Λ^0 at FAIR energies

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One of the proposed signatures of a phase transition from nuclear matter to a deconfined quark gluon plasma phase is the relative enhancement of strangeness production [1]. The production of multi-strange hadrons has the potential to probe the density and the EOS of the medium. Also, the yield of particles carrying strange quarks is expected to be sensitive to the fireball evolution. The CBM detector has the unique capability of handling unprecedented high interaction rates. It is therefore, likely to produce hadrons having higher numbers of strange quarks. Therefore it will provide an opportunity to measure yields and directed and elliptic flow of multi-strange baryons in heavy-ion collisions at different beam energies and sizes of the colliding nuclei.

A systematic model-based study of the production of Ω^- , Ξ^- and Λ^0 in central Au+Au collisions at E_{lab} energies from 2-35 GeV/A is carried out in the present work. The energy dependence of the yields of strange particle is investigated. The analysis is done using the particles produced in the mid rapidity region, $|y| < 1$. For this study, we have employed two types of models: (1) the microscopic transport models UrQMD in pure and hybrid mode using “hadron gas” EOS and “Chiral” EOS respectively and (2) HSD (hadronic and partonic version). The average multiplicities of Ω^- , Ξ^- and Λ^0 particles per event are plotted as function of beam energy in figure 1, 2 and 3 respectively.

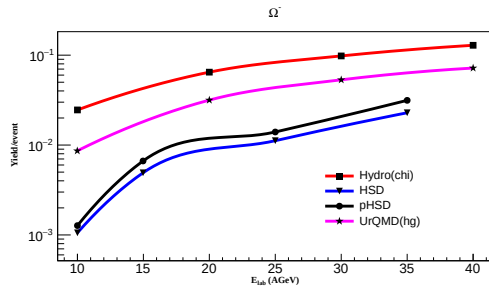


Figure 1: Excitation function of the yields of Ω^- in central Au+Au collisions obtained from pHSD, HSD, UrQMD(HG), and UrQMD+HYDRO(CHI)

Yields obtained from various models are compared. All models predict a steep excitation function up to $E_{lab}/A \approx 30$ GeV, for higher energies the increase is more moderate. Above a beam energy of about 30 AGeV the predicted values from models are more or less saturated and keep their relative differences. However, at beam energies below 30 AGeV, the different models exhibit different slopes

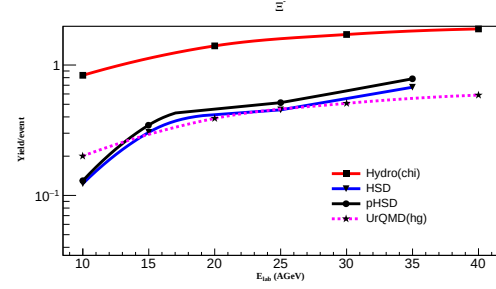


Figure 2: Excitation function of the yields of Ξ^- in central Au+Au collisions obtained from pHSD, HSD, UrQMD(HG), and UrQMD+HYDRO(CHI)

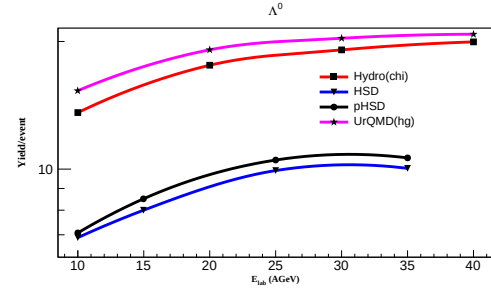


Figure 3: Excitation function of the yields of Λ^0 in central Au+Au collisions obtained from pHSD, HSD, UrQMD(HG), and UrQMD+HYDRO(CHI)

as displayed by the figures. This is particularly true for the two versions of the UrQMD and HSD transport model. Yields from UrQMD hydro (Chiral EOS) is higher than in UrQMD (HG EOS) for Ω^- and Ξ^- but lower for Λ^0 , however with a smaller difference. The partonic version of HSD shows slightly higher yields than its hadronic version for all particles.

The observation of enhanced production of multi-strange particles in the partonic mode of HSD and hydro mode with chiral EOS of UrQMD at FAIR energies suggests that these observable are sensitive to the formation of a partonic medium.

In summary, our study shows that multi-strange hyperons are very promising diagnostic probes of the density reached in the fireball and hence, of the equation-of-state of dense QCD matter.

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Magnetic field scaling and multi-strange hyperon reconstruction performance at CBM

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The successful execution of the CBM physics program requires the measurement of multi-strange hyperon excitation functions using heavy and light ion beams, in order to study systematically the evolution of various observables as function of beam energy and size of the collision system. Two operation scenarios are studied: a constant deflection angle for all energies, and the maximum possible deflection angle for each beam energy as defined by the beam dump.

In order to investigate parameters like invariant mass resolution for strange Λ and multi-strange Ξ^- hyperons, their signal to background (S/B) ratios and the track momentum resolution for different magnetic fields, simulations of Au+Au collisions have been performed within CBMROOT (release APR20). For the calculations the hadron and electron setup were used. An aluminum beam pipe inside the STS with a wall thickness between 0.6 and 2.5 mm, depending on z position and diameter. The events were generated by the UrQMD generator, and transported through the CBM setup using the GEANT3 code. Secondary particles have been reconstructed with the CBM KF particle finder. In Fig. 1 the invariant mass spectra are presented for Λ and Ξ^- hyperons for an Au beam with a momentum of 4A GeV/c as simulated for the electron setup with magnetic field scaling of 30% (upper row) and 70% (lower row). Both the width of the invariant mass distribution and the S/B ratio improves with higher magnetic field.

Fig. 2 depicts the momentum resolution for primary (black dots) and secondary (red dots) charged particle tracks as function of momentum, as simulated for central Au+Au collisions at a beam momentum of 4A GeV/c using the electron setup. The magnetic field was scaled to 70% (lower panel) and to 30% (upper panel) of the maximum value. The track momentum resolution for the low field is more than a factor of two worse than for the high field.

Conclusion

For magnetic fields below 50% of the maximum value, the physics performance of the CBM experiment decreases substantially. The particle acceptance of the TOF wall does not exhibit a dependence on the magnetic field. The performance improves substantially for higher field values, which can be achieved with maximum allowed beam deflection angles. The implementation of a flexible beam pipe with low material budget would allow to maintain the CBM physics performance.

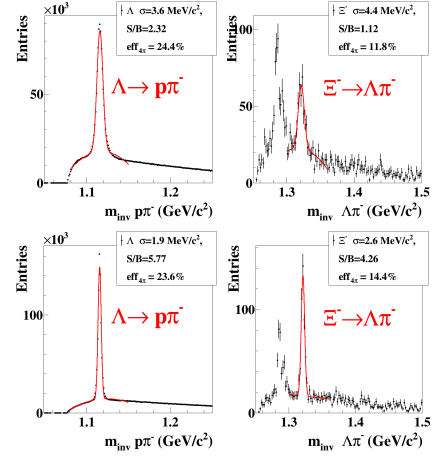


Figure 1: Invariant mass spectra of Λ and Ξ^- hyperons simulated for central Au+Au collisions at a beam momentum of 4A GeV/c, reconstructed for the electron setup. The magnetic field was scaled to 30% (upper row) and 70% (lower row) of the maximum value.

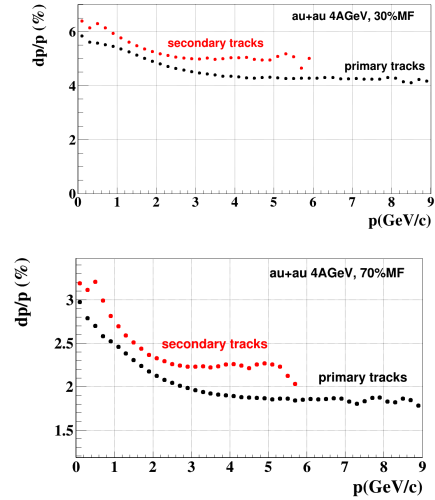


Figure 2: Momentum resolution for primary (black dots) and secondary (red dots) charged particle tracks as function of momentum reconstructed for central Au+Au collisions at a beam momentum of 4A GeV/c. The simulation were based on the electron setup (MVD, STS, RICH, TRD, TOF). Lower panel: magnetic field scaling 70%. Upper panel: magnetic field scaling 30%.

Estimation of J/ψ production cross-section in 30 GeV p+A collision at CBM SIS100

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The observation of J/ψ suppression in relativistic heavy-ion collisions is considered as an important signature for the formation of QGP medium [1]. If QGP is created at the collision zone, the $c\bar{c}$ binding potential gets shielded due to the Debye screening of the colour charges leading to the reduction of the J/ψ yield. A considerable amount of J/ψ suppression is observed in p+A collisions and commonly attributed to the dissociation of the evolving pre-resonant (or resonant) $c\bar{c}$ pairs via inelastic collisions with the spectator nucleons inside the target nucleus. This effect is known as Cold Nuclear Matter (CNM) effect. Proton-Nucleus (p+A) collisions are studied extensively to get a measure of the nuclear matter effect on J/ψ production. The J/ψ production in p+A collision has been studied extensively in several fixed-target experiments at SPS in the beam range of $E_b = 158 - 450$ GeV and with variety of nuclear targets [2, 3, 4, 5]. A traditional way to characterize the nuclear effects in J/ψ production is the so-called α -parametrization, which is in vogue to study the nuclear target dependence of all the hard processes including charmonium production. In this method the target mass (A) dependence of the charmonium production cross-section is fitted with a simple power-law [6];

$$\sigma_{pA}^{J/\psi} = \sigma_{pp}^{J/\psi} \times A^\alpha \quad (1)$$

where σ_{pA} and σ_{pp} are the J/ψ production cross-section in p+A and p+p collisions respectively, A denotes the mass number of the target and the exponent α extracted from the fitting of the experimental data encodes the nuclear matter effects. In absence of CNM effects, the value of α is expected to be unity. The value of $\alpha < 1$ will indicate the suppression due to the cold nuclear matter effects. In order to obtain σ_{pp} , available data from different experimental collaborations are obtained from ref [7] and tabulated in Table 1. The energy evolution of $\sigma_{pp}^{J/\psi}$ is then parameter-

Experiment	Reaction	$\sqrt{s}$ (GeV)	$\sigma_{J/\psi}$ (nb/nucleon)
CERN-PS	p+p	6.8	0.732 ± 0.13
WA39	p+p	8.7	2.35 ± 1.18
NA3	p+p	19.4	120 ± 22
UA6	p+p	24.3	171.42 ± 22.21
ISR	p+p	52	716 ± 303
PHENIX	p+p	200	4000 ± 938
ALICE	p+p	2760	29912.6 ± 5384.3
ALICE	p+p	7000	54449.4 ± 8494

Table 1: Total ($\sigma_{J/\psi}$) production cross sections in p+p collisions.

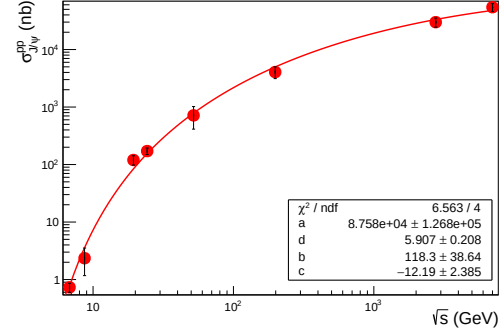


Figure 1: Energy dependence of inclusive J/ψ production cross section in p+p collisions.

ized using the relation [7],

$$\sigma_{pp}^{J/\psi}(\sqrt{s}) = a \times y_{max}^d \times e^{\frac{-b}{y_{max}+c}} \quad (2)$$

where $y_{max} = \ln(\frac{\sqrt{s}}{m_{J/\psi}})$ and a,b,c,d are free parameters.

The variation of $\sigma_{pp}^{J/\psi}$ as a function of centre of mass energy ($\sqrt{s}$) and its parameterization is shown in Fig 1. The fit procedure is based on χ^2 minimization technique, as available in ROOT, is used to fix the best fit parameters. σ_{pp} so obtained can now be used as an input in Eqn. 1 which can now be applied to fit the available pA data to extract the values of α . For the present study, pA data from all three different fixed target experiments at SPS namely NA38, NA50 & NA60 are employed. In Fig. 2, only the fitted data from NA60 experiment is shown explicitly and the extracted α values from different experiments are tabulated in Table 2. The extracted α values show a weak depen-

Experiment	$\sqrt{s}$ (GeV)	α
NA38	19.42	0.88 ± 0.02
NA60	17.27	0.91 ± 0.01
NA60	27.42	0.93 ± 0.02
NA50	27.42	0.93 ± 0.01
NA50 (HI)	29.08	0.93 ± 0.01
NA50 (LI)	29.08	0.94 ± 0.01

Table 2: Value of α obtained from the fitting of different experimental data.

dence on $\sqrt{s}$ which we have attempted to parameterized using a 1st order polynomial. The parameterization is shown in Fig. 3. From the parameterization, the following relation

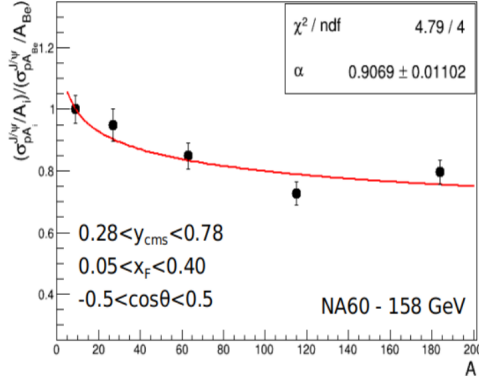


Figure 2: Energy dependence of inclusive J/ψ production cross section in p+p collisions.

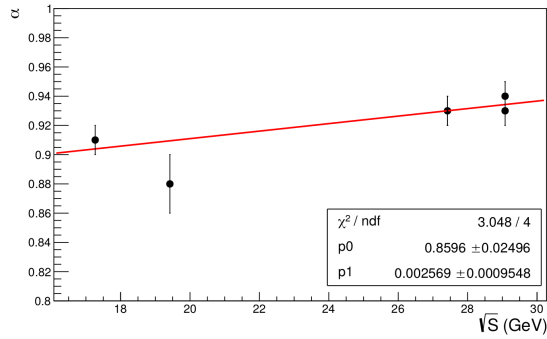


Figure 3: Variation of α as a function of $\sqrt{s}$ and fitted with a 1st order polynomial.

is obtained,

$$\alpha = 0.8596 + 0.0026 \times \sqrt{s} \quad (3)$$

The prescription can now be extrapolated to the FAIR energy domain to estimate J/ψ production cross section in p+Au collisions. The maximum available proton energy at SIS100 is 29 GeV which correspond to a centre of mass energy ($\sqrt{s}$) of 7.61 GeV and thus using Eqn. 3 we obtain the value of $\alpha = 0.879$. Therefore the J/ψ production cross-section in p+Au collision at FAIR energy ($\sqrt{s} = 7.61$ GeV) can be obtained using Eqn. 1 as following,

$$\begin{aligned} \sigma_{pA}^{J/\psi} &= \sigma_{pp}^{J/\psi} \times A^\alpha \\ &= 1.655 \times (197)^{0.879} \\ &= 172.04 \text{ nb} \\ \sigma_{pA}^{J/\psi}/A &= 0.87 \text{ nb/nucleon} \end{aligned}$$

Thus using the α parameterization, the J/ψ production cross-section in p+Au collision at $\sqrt{s} = 7.61$ GeV is found to be $0.87(\pm 0.12)$ nb/nucleon. The errors quoted here is associated with the fitting of different α values using a 1st order polynomial.

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J/ψ measurements in nuclear collisions at CBM SIS100

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Muon reconstruction performance

The motivation for this study is a prediction of the sub-threshold charmonium production in nuclear collisions via the excitation of nucleon resonances in multiple collisions, which then decay like $N^* \rightarrow J/\psi + N$ [1]. The charmonium measurements with the CBM muon setup will be performed with the muon system (MUCH), which consists of five hadron absorbers and four tracking stations: the first two stations consist of GEM detectors, the 3rd and 4th station are built from RPC detectors [2], with the 5th iron absorber of 1 m thickness located after the last tracking station. The CBM muon setup includes also the Silicon Tracking System (STS), the Transition Radiation Detector (TRD), placed after the 1 m thick iron as tracking station, and the Time of Flight Detector (TOF) for particle identification. The study is performed for central Au+Au collisions at a beam momentum of 8 AGeV/c, with the background generated by the UrQMD code [3], and the J/ψ mesons generated by Pluto [4]. The J/ψ multiplicity of 10^{-6} per central Au+Au event was taken from [1]. The muon reconstruction performance is presented in Fig. 1. The muon reconstruction and identification efficiency (Fig. 1 right) varies between 40 and 60% depending on momentum.

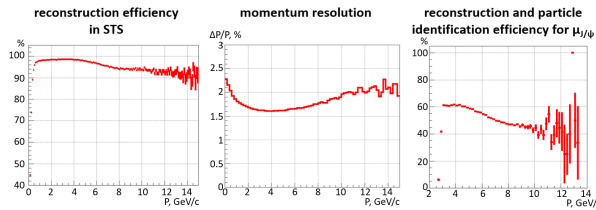


Figure 1: Reconstruction performance for primary tracks as a function of momentum. Left: reconstruction efficiency in STS. Middle: momentum resolution. Right: reconstruction and particle identification efficiency for MC muons from J/ψ .

Analysis results

The muon track candidates are used to calculate the dimuon invariant mass spectrum (see Fig. 2 left). The signal-to-background ratio for the J/ψ is 0.2. The J/ψ reconstruction efficiency is up to 10% for high momentum particles (see Fig. 2 right). Figure 3 shows the phase-space

as a function of transverse momentum and rapidity of the J/ψ in the Pluto input, and of the reconstructed J/ψ .

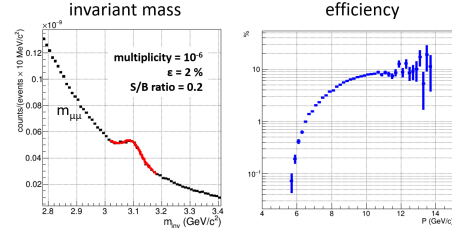


Figure 2: Analysis results. Left: invariant mass spectrum. Right: MC J/ψ reconstruction efficiency as a function of momentum.

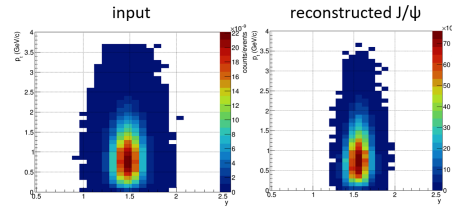


Figure 3: Transverse momentum (P_t) versus rapidity (Y) for MC J/ψ . Left: distribution of PLUTO input. Right: distribution of the reconstructed MC J/ψ .

Conclusions and next steps

J/ψ measurements are feasible with a signal-to-background ratio at the level of 0.2 calculated in 2σ window around the J/ψ peak, if the J/ψ multiplicity is at the level of 10^{-6} per central Au+Au event. Next steps will be the efficiency and acceptance correction, and a multi-differential analysis.

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Generation of input signals for dilepton simulation using Pluto event generator

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This report presents the status of the generation of the input signals for the dilepton simulation and its testing. Dilepton measurement is one of the major goals of the CBM experiment. Thanks to unprecedented interaction rates (up to 10 MHz) foreseen with the FAIR accelerator system, precise physics measurements become possible. Therefore it is very important to perform detail feasibility studies in the dilepton sector. The PLUTO event generator was originally developed for the HADES experiment but successfully used by other collaborations in the hadronic physics field as well. Its design has improved the flexibility and provided new features which allow to meet the new challenges arising from the detector studies for the new FAIR experiments such as PANDA and CBM. According to the thermal fireball model used in the PLUTO event generator, vector mesons are generated with a thermal transverse mass (m_T) and a Gaussian rapidity spectra and decay isotropically into dileptons. A more detailed description of the PLUTO event generator is reported in Ref [1].

beam energies namely 12 AGeV, 8 AGeV and 4.5 AGeV are simulated and tested for the most 0-5% central collisions. The respective meson multiplicities are taken from the Thermal-FIST model. Di-lepton spectra for beam energy 12 AGeV ($\sqrt{s_{NN}} = 5.1$ GeV) are shown in Fig. 1 for the di-electron and di-muon decay channel.

The respective meson multiplicities and the invariant mass distribution of the cocktails for different energies can be found at Ref [2]. To generate the input signals, only two input parameters namely beam energy and temperature of the system are provided. The list of the input parameters is tabulated in Table 1.

System ($\sqrt{s_{NN}}$)	Beam energy	Temperature
Au+Au (3.44 GeV)	4.5 AGeV	0.1 GeV
Au+Au (4.3 GeV)	8 AGeV	0.12 GeV
Au+Au (5.1 GeV)	12 AGeV	0.13 GeV

Table 1: Input parameters of PLUTO for different beam energies

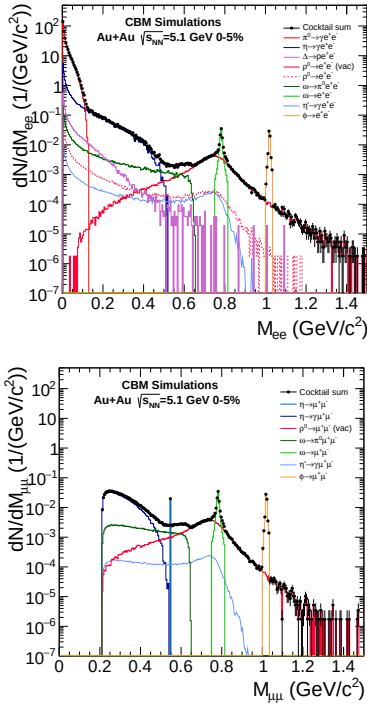


Figure 1: Di-lepton cocktail for $\sqrt{s_{NN}} = 5.1$ GeV in the di-electron channel (top) and di-muon channel (bottom)

Dilepton cocktails for Au+Au collision at three different

In Fig. 2 and Fig. 3, the typical rapidity (Y) and transverse momentum (p_T) distribution of the ϕ meson for three different energies are shown. The p_T spectra is fitted with

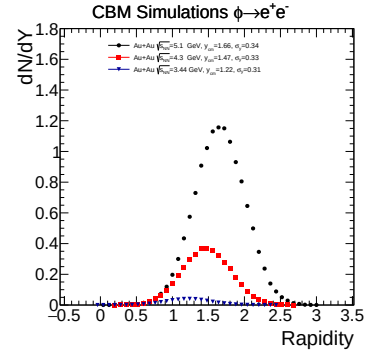


Figure 2: Rapidity distribution of ϕ mesons for three different beam energies. The respective mid rapidity values are quoted in the legend.

a functional form as shown in Eqn. 1,

$$dN/dp_T \propto p_T m_T K_1(m_T/T) \quad (1)$$

where K_1 denotes the Bessel function of the second kind, m_T is the transverse mass and T is the temperature. The fitted p_T spectra are shown in Fig. 3 and the slope

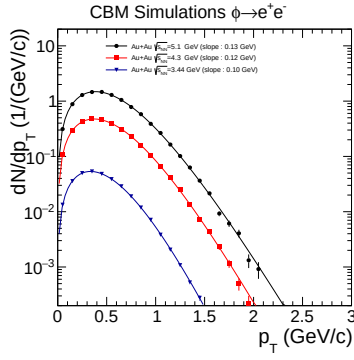


Figure 3: p_T spectra of ϕ meson for three different beam energies. Legend indicates the different slope values extracted from the fitting.

of the fitted spectra gives the temperature. The extracted temperature matches well with the input temperature. In some cases, it is observed that the rapidity distribution is not peaked at half of the beam rapidity and also the extracted temperatures do not match the input temperature. Further investigations are ongoing to understand this artefact.

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A machine learning procedure for the selection of muon track candidates

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Input to the simulations

This study is based on the CBM muon system (MUCH) comprising four hadron absorbers and four tracking stations: the first two stations consist of GEM detectors, the 3rd and 4th station are built from RPC detectors [1]. The study was performed for 8 AGeV/c central Au+Au collisions. The background is generated with the UrQMD code [2], while the ω -mesons decaying to dimuon pairs are generated by Pluto [3]. The muon track reconstruction procedure consists of two steps: the track reconstruction in the STS, and the global track reconstruction, which is based on the extrapolation of the tracks reconstructed in the STS through the downstream detectors MUCH, TRD, and TOF. Muon track candidates are selected from the reconstructed tracks using the following parameters:

- χ^2 in primary vertex (selection of primary tracks);
- tracks have to pass all detector subsystems;
- tracks with good quality (χ^2 cut in each detector subsystem, see Fig. 1);
- tracks are identified as muons in TOF (see Fig. 2).

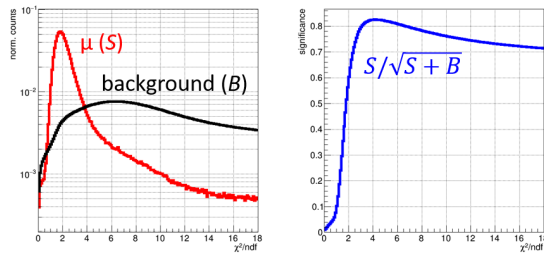


Figure 1: Left: χ^2 of tracks in MUCH for MC muons (red line) and for background (black line). Right: significance of χ^2 cut for muon track candidate selection.

Cut optimization

There are two possibilities to optimize the cuts for the selection of the muon track candidates: either manually, or using a machine learning technique. The manual optimization can be deduced from the significance: if the cut parameters for muons and background differ significantly, one observes a maximum in the significance distribution

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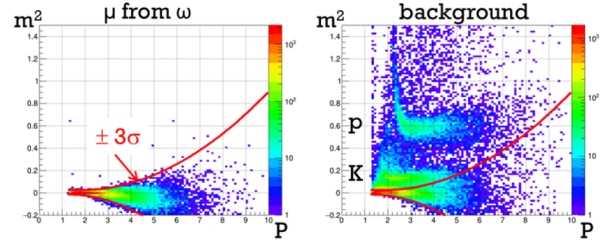


Figure 2: Particle identification in TOF detector. Left - MC muons from ω -meson; right - background. Red lines define 3σ region for selection of muon track candidates.

(Fig. 1 right). In other cases, if the cut parameters for muons and background are very similar (for example the χ^2 distribution) one can choose a reasonable value (2 or 3). Such a manual optimization is useful, if there are only few and independent parameters to optimize. However, the global tracks in the muon setup have correlated parameters (see example on Fig. 3), and the distribution of parameters for signal and background are different (see Fig. 1 left and Fig. 2). In such a case the use of machine learning techniques may be preferable.

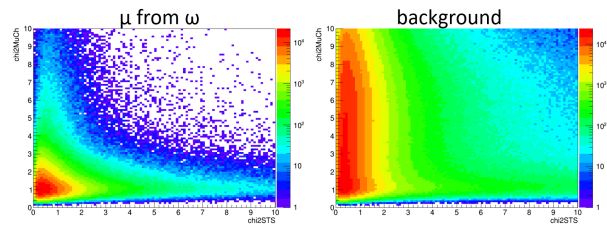


Figure 3: χ^2 of global tracks in MUCH versus χ^2 in STS. Left - MC muons from ω -meson; right - background.

For cut optimization, the machine learning procedure TMultiLayerPerceptron [4] was used. The Artificial Neural Network (ANN) was trained using χ^2 at the primary vertex, in STS, MUCH and TRD, for momentum and velocity from time measurements in TOF for positive and negative charged particles separately. The Fig. 4 illustrates the results of the ANN training for positively charged particles.

Reconstruction results

Fig. 5 illustrates reconstruction efficiency, the signal-to-background ratio and the significance for the ω -meson for

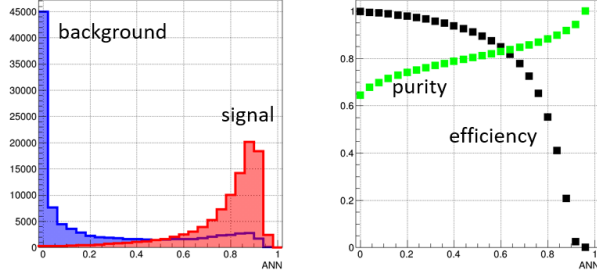


Figure 4: Results of the ANN training for positive charged particles. Left: ANN probability for background (blue region) and for signals (red region). Right: purity (green symbols) and efficiency (black symbols) of ANN particle identification.

different ANN values for global tracks of positive and negative particles. The ω -to-background ratio and the signifi-

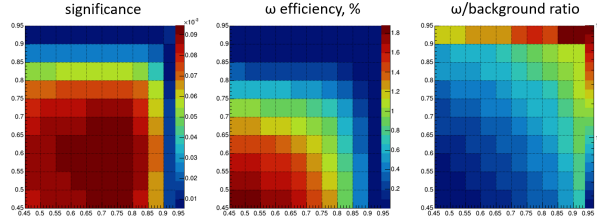


Figure 5: Reconstruction results using the ANN track selection for positive (X axes) and negative (Y axis) particles: left - significance, middle - ω reconstruction efficiency, right - signal-to-background ratio.

cance obtained by the reconstruction procedure with manually optimized cuts are compared to the results of the ANN particle identification method for the same ω reconstruction efficiency. The ANN results exhibit a 2.5 times higher signal-to-background ratio and a 60% increase of the significance. Fig. 6 presents the reconstructed invariant mass spectrum of ω -mesons including combinatorial background for the manual and the ANN track selection. The acceptance of the reconstructed ω mesons is very similar for both cases (see Fig. 7). The right picture indicates that the ANN method selects some more ω -mesons at high rapidity, and some less at low rapidity. The possibility to use ANN for muon track candidate selection was added to the CBMROOT muon analysis.

Robustness of the ANN selection

In order to study the robustness of the ANN selection, the results of the ANN training with UrQMD background events were applied to background events generated by the DCMQGS-MMM code [5]. The ANN cuts can be tuned such, that the results are the same in both cases.

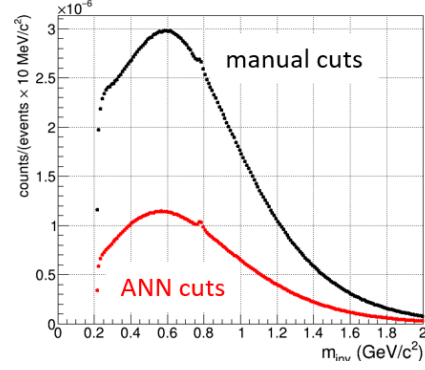


Figure 6: Invariant mass spectrum ω -mesons including combinatorial background with manual track selection (black) and ANN (red) for the same ω reconstruction efficiency.

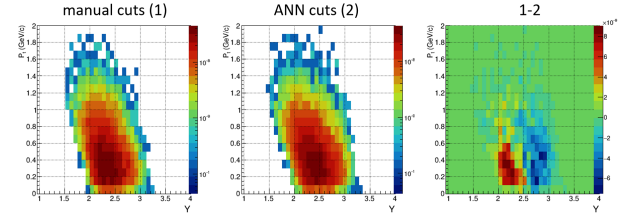


Figure 7: Acceptance of the reconstructed ω -mesons: left - manual cut optimization, middle - ANN optimization, right - difference between left and middle distributions.

Next steps

As a next step, the ANN method will be used for other dimuon signals, in particular for those with flat mass distribution, and for J/ψ mesons. Moreover, the robustness of the ANN method will be tested for other event generators.

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Reconstruction of di-muon cocktail using GEANT3 & GEANT4

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In this article, the reconstruction performance of di-muons coming from the decay of η , ω and ϕ mesons with a realistic detector model optimised for SIS100 collision energies and with different transport engines (GEANT3 and GEANT4) is reported. It includes a complete range of functionality including tracking, geometry and different physics models [1]. In all the former di-muon simulations, GEANT3 has been used as the default transport engine but since the upgraded version of the toolkit is available therefore it is important to compare the physics performance results with both the transport engines.

The simulations are performed with the latest CbmRoot release (APR20) and with central Au+Au collision at beam momentum of 8 AGeV/c. The phase-space distribution and decay of $\eta \rightarrow \mu^+ \mu^-$, $\omega \rightarrow \mu^+ \mu^-$, and $\phi \rightarrow \mu^+ \mu^-$ have been simulated using the PLUTO event generator. The signal muon pairs are embedded into the background, generated using the UrQMD event generator. One signal particle from PLUTO is embedded per event into the background. All the particles are then transported through the entire CBM setup using GEANT3 and GEANT4 transport engines separately. The standard analysis procedure is followed to obtain the invariant mass spectra by combining the oppositely charged muon track candidates [2]. The possible muon track candidates are identified by applying a set of single track quality cuts to the reconstructed global tracks. It is found that, after the reconstruction, the number of muon track candidate increases significantly and, as a result, also the di-muon combinatorial background increases with GEANT4 as compared to GEANT3 transport engine. This might be due to the increase of the particle production in the MuCh hadron absorbers in GEANT4 as compared to the GEANT3 transport engine.

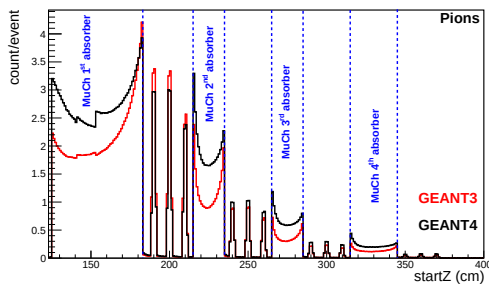


Figure 1: Production of secondary pions in MuCh hadron absorbers with GEANT3 and GEANT4 transport engines.

This behaviour of the production of secondary pions is investigated because the di-muon background is mostly

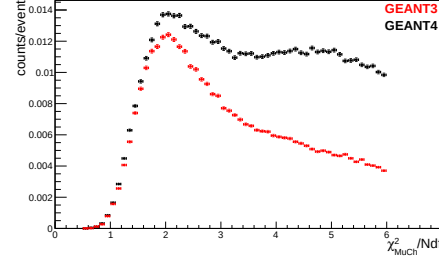


Figure 2: Distribution of χ^2_{MuCh}/Ndf with different transport engines.

populated with weak decays of pions ($\pi^+ \rightarrow \mu^+ + \nu_\mu$, $\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$). In Fig. 1, the production of secondary pions (extracted using Monte Carlo Particle ID) is shown and it is observed that a larger number of pions is produced in the MuCh hadron absorbers with GEANT4 than with GEANT3. The same behaviour is also observed with other hadrons. The increase in the secondary particles is possibly due to a more accurate modelling of hadronic interactions by GEANT4 compared to GEANT3. To compare the reconstruction performance, the track parameters of the different detector subsystems are investigated. In Fig. 2, the

Signal	Transport engine	Cut on χ^2_{MuCh}/Ndf	Reconstruction efficiency (%)	S/B	significance
η	GEANT3	≤ 2.35	0.16	0.38	158.5
η	GEANT4	≤ 2.16	0.14	0.30	135.0
ω	GEANT3	≤ 2.4	0.34	0.04	23.7
ω	GEANT4	≤ 2.18	0.24	0.03	17.8
ϕ	GEANT3	≤ 2.8	0.99	0.04	29.8
ϕ	GEANT4	≤ 2.46	0.82	0.04	26.1

Table I: Cut on χ^2_{MuCh} to select the muon track candidates from the reconstructed global tracks for different transport engines (GEANT3 and GEANT4).

χ^2_{MuCh} distribution is shown only for background tracks extracted from the generated UrQMD sample. It is observed that the χ^2 distribution in MuCh is very different in the simulations performed with GEANT3 or GEANT4. No such prominent change is visible for χ^2 distribution of the STS track segment and of the primary vertex. The reconstructed global tracks having associated STS hits ≥ 7 , MuCh hits ≥ 11 , TRD hits ≥ 1 , TOF hits ≥ 1 , $\chi^2_{VERTEX} \leq 2.0$, $\chi^2_{STS} \leq 2.0$ are selected as muon track candidates. Since only the shape of the χ^2_{MuCh} distribution is sensitive to the choice of the transport engine, different χ^2_{MuCh} values are tested to calculate the pair reconstruction. Ta-

ble I shows different values of χ^2_{MuCh} for GEANT3 and GEANT4 and the corresponding reconstruction efficiency, S/B and significance for different di-muon sources.

Due to the increase in the di-muon combinatorial background with GEANT4 as compared to that of GEANT3, stricter cuts have to be applied on χ^2_{MuCh} to bring the background to the same level obtained with GEANT3. As a result, the reconstruction efficiency and the signal to background ratio decrease with GEANT4. The invariant mass distribution for ϕ meson with GEANT3 and GEANT4 transport engines is shown in Fig. 3.

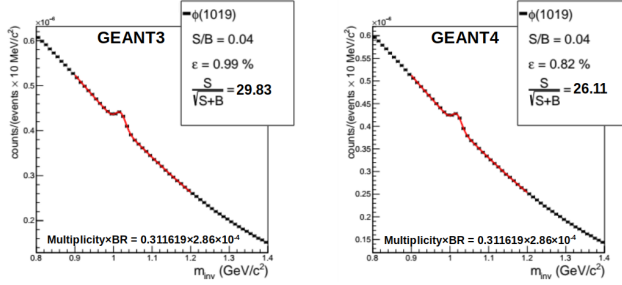


Figure 3: Reconstruction of ω meson using GEANT3 (left) and GEANT4 (right) transport engines. Multiplicity is extracted from Thermal-FIST model.

Further investigations are going on to understand in more details the reconstruction performance and the observed increase in the secondary particle production with GEANT4 in MuCh hadron absorbers affecting the overall di-muon performance.

Acknowledgements

Authors would like to thank Michael Deveaux and Iouri Vassiliev of GSI for their useful comments in the course of this study.

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Muon reconstruction with and without Micro-Vortex Detector

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CBM setup and muon reconstruction

This study is performed to understand the possible contribution of the Micro-Vortex Detector (MVD) to the performance of muon reconstruction. The standard CBM muon setup comprises the Silicon Tracking System (STS), the muon system (MUCH), the Transition Radiation Detector (TRD), and the Time of Flight Detector (TOF). The MUCH consists of four hadron absorbers and four tracking stations: the first two stations consist of GEM detectors, the 3rd and 4th stations are built from RPC detectors [1]. The study is performed for central Au+Au collisions at 8 AGeV/c, with the background generated by the UrQMD code [2], and the low-mass vector mesons (ω , η , ρ^0 , ϕ) generated by Pluto [3].

The muon reconstruction includes three steps. The first step is track reconstruction in the STS with or without MVD. The reconstruction performance for primary tracks in front of muon system is presented in Fig. 1. The reconstruction efficiency (left panel) is slightly better for the setup with MVD. For tracks which pass the hadron absorbers of the MUCH, i.e. with momenta above 1.2 GeV/c (black dashed line), the efficiency is about 2% higher for the setup with MVD. The right panel of Fig. 1 presents the momentum resolution of the reconstructed tracks, which is about 1.5% for the setup with MVD, and somewhat worse without MVD.

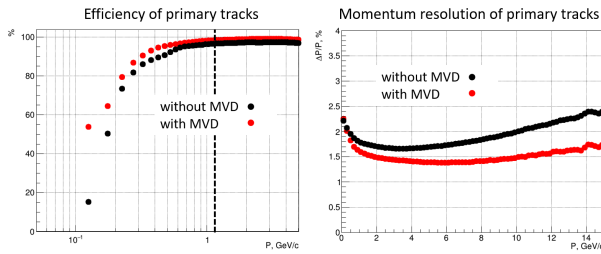


Figure 1: Track reconstruction performance for the primary tracks in the STS with MVD (red symbols) and without MVD (black symbols). Left: track reconstruction efficiency as a function of momentum. Only tracks with momenta above 1.2 GeV/c (black dashed line) pass the hadron absorbers of the MUCH. Right: Reconstructed momentum resolution as function of momentum.

The second step is global track reconstruction. The tracks reconstructed in the STS are extrapolated through

the downstream detectors MUCH, TRD, and TOF. The last step of the muon reconstruction is a selection of the muon track candidates from the reconstructed global tracks using following criteria:

- χ^2 in primary vertex (selection of primary tracks);
- tracks have to pass all detector subsystems;
- tracks which pass the χ^2 quality cuts in each detector subsystem;
- tracks are identified as muon tracks in TOF.

The muon reconstruction performance is presented in Fig. 2. The background (random combinations of muons, or miss identified (punch through) hadrons) suppression (left panel) is similar for the setup with MVD (red symbols) and without MVD (black symbols). The ω reconstruction efficiency (right panel) is about a factor of 2 higher using the setup with MVD.

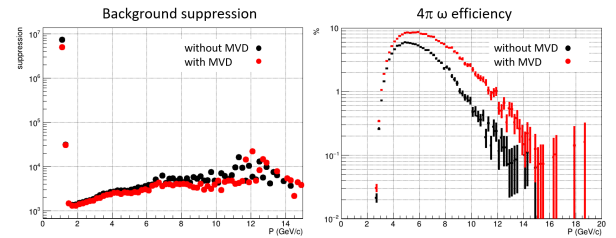


Figure 2: Muon reconstruction performance after global tracking and selection of muon track candidates. Left: background suppression as a function of momentum. Right: ω reconstruction efficiency as a function of momentum. Black symbols: without MVD. Red symbols: with MVD.

The mass resolution for the reconstructed ω -mesons improves by 10% when using the setup with MVD, which is a consequence of the better momentum resolution (see right panel in Fig. 1).

Analysis results

The muon track candidates are used to calculate the dimuon invariant mass spectrum. The resulting distribution for the combinatorial background is shown in the left panel of Fig. 3. The right panel of Fig. 3 depicts the signal-to-background ratio for the vector mesons under study, with visible contributions from η -Dalitz, η , ω , and ϕ , whereas

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the ρ^0 is hardly seen. Fig. 3 illustrates, that the combinatorial background and the signal-to-background ratio increases when including the MVD in the track reconstruction. The increase of the combinatorial background is caused by the increasing number of reconstructed muons from weak decays when using the MVD.

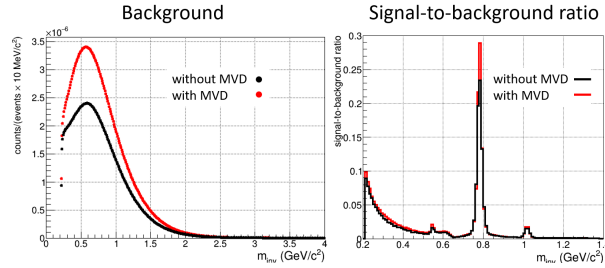


Figure 3: Invariant mass spectrum of the dimuon combinatorial background (left panel), and dimuon signal-to-background ratio (right panel) for central Au+Au collisions at 8 AGeV/c. Black curves: setup without MVD. Red curves: setup with MVD.

Next step

The next step will be to study the possibility to reduce the dimuon combinatorial background by rejecting muons from weak decays applying the missing-mass method from the KFPP package, which requires the MVD.

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Background rejection via the usage of the Micro-Vertex Detector for the dielectron case

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Motivation for the MVD usage

The analysis of thermal dielectron pairs is one of the main physics cases for the CBM-experiment. However, every kind of pair analysis is very sensitive to combinatorial background contributions due to the nearly quadratic scaling to the number of charged tracks. Therefore, it is essential for the conclusive results to have a potent background rejection strategy. While the hadron suppression is done with the particle identification detectors (mainly the RICH detector and the TRD [1]), there is still a significant contribution of dielectron sources e.g. $\gamma \xrightarrow{\text{material}} e^+e^-$ and $\pi^0 \rightarrow \gamma e^+e^-$.

These decays are drastically contributing to the pair spectra, increase the combinatorial background and decrease the access to the thermal dielectron signal. However, via the usage of the MVD detector and its exceptional position resolution near the target, we can define the distance to the closest reconstructed hit in the same detector station (d_{MVD}) and use the decay topologies of these contributions [2]. Figure 1 shows the distance to the closest hit in the MVD detector as a function of the momentum. The two distributions show a very distinct behavior that can be used to reject a large fraction of γ -conversions at low momenta.

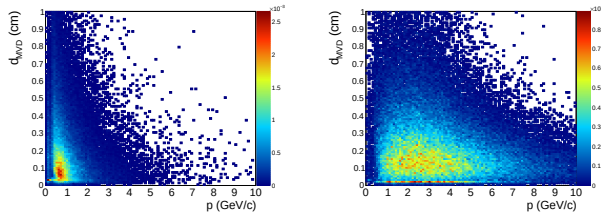


Figure 1: Distribution of the distance to the closest hit in the same MVD station as a function of the momentum for γ -conversion (left) and thermal dielectron pairs (right).

Comparison between STS and MVD usage

This rejection strategy is not necessarily limited to the MVD and can be performed with the STS as well. The analysis without any MVD usage was performed on a dataset that does not include any MVD material. Therefore it should also profit from a smaller amount of multiple scattering in front of the STS. Figure 2 shows the invariant mass spectra of all combinatorial background contributions scaled to the yield per event. The MVD usage clearly outperforms the dataset without the MVD. The ratio between

these two spectra shows an average improvement of about a factor 3.

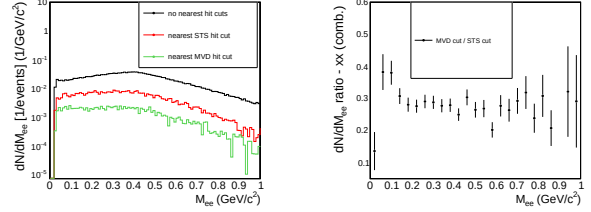


Figure 2: Left: Invariant mass spectra of all combinatorial background contributions. Right: Ratio between the two datasets.

Even though this background rejection obviously comes with a small decrease in signal acceptance, the signal-to-background ratio increases significantly, while the significance is relatively unchanged (see Fig. 3).

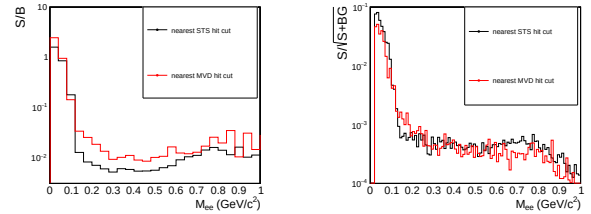


Figure 3: Signal-to-background ratio (left) and significance (right) for the two datasets as a function of the invariant mass.

Overall, the introduction of additional material is more then compensated by the improved background rejection and the background rejection strategy performed exceptionally well even in a non-final state of optimization.

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Muon reconstruction for different magnetic field settings

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The goal of this study is to understand the influence of different magnetic field settings on the muon reconstruction performance, in case of low energy collisions.

Muon reconstruction

The CBM muon setup comprises the Silicon Tracking System (STS), the muon system (MUCH), the Transition Radiation Detector (TRD), and the Time of Flight Detector (TOF). The MUCH consists of three hadron absorbers and two tracking stations equipped with GEM chambers [1]. The study is performed for central Au+Au collisions at a beam momentum of 4 AGeV/c (beam energy 3.1A GeV) generated with the UrQMD code [2], and ω -mesons generated by the Pluto event generator [3]. For such low beam momenta, the magnetic field has to be reduced in order to make sure that the beam still hits the beam dump. The maximum possible beam deflection is 100 cm at about 26 m downstream of the target, which, for a 4 AGeV/c Au-beam, corresponds to a reduction of the magnetic field to 70% of its nominal value. Such an individual scaling of the magnetic field according to the beam rigidity is possible in case of a variable bending angle of the beam pipe. If, however, the beam pipe has a fixed bending angle constructed according to the deflection of a Au beam with an energy of 11 AGeV at the nominal magnetic field (1 Tm), the magnetic field has to be scaled down to 30%, so that the Au beam with momentum 4 AGeV/c still fits into the beam pipe.

The muon track reconstruction consists of two steps. First, the track is reconstructed in the STS. The reconstruction performance for primary tracks in STS is presented in Fig. 1. The reconstruction efficiency (left panel) for tracks, which pass through the muon absorbers (with momentum larger than 0.8 GeV/c, black dashed line) does not depend on the magnetic field, but the momentum resolution degrades from 2-3% at 70% magnetic field to 5-6% at 30% magnetic field (right panel).

The second step is the global track reconstruction, which is based on an extrapolation of the reconstructed tracks through the downstream detectors MUCH, TRD, and TOF, and on a selection of muon track candidates from primary global tracks using the following criteria: (i) the tracks have to pass all detector subsystems, (ii) a track quality selection based on a χ^2 cut in each detector subsystem, and (iii) tracks are identified as muons in the TOF detector.

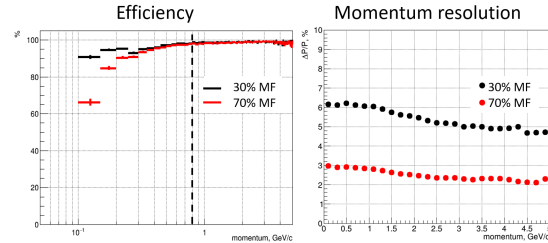


Figure 1: Track reconstruction performance for the primary tracks in STS. Left: track reconstruction efficiency as a function of momentum. Black dashed line shows momentum cut due to absorption in MUCH. Right: Resolution of the reconstructed momentum. Black symbols: 30% magnetic field. Red symbols: 70% magnetic field.

Analysis results

The muon track candidates are used to calculate the dimuon invariant mass spectrum (see Fig. 2). The reduction of the magnetic field leads to a decrease of the mass resolution, and, as a consequence, to a decrease of the signal-to-background ratio for the ω meson.

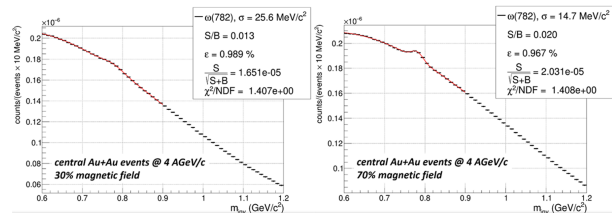


Figure 2: Invariant mass spectra of the combinatorial background with ω -meson. Left: 30% magnetic field. Right: 70% magnetic field.

The Fig. 3 presents the reconstruction performance. The ω reconstruction efficiency (left picture) with 70% magnetic field (red symbols) is higher for high momentum mesons, but the ω reconstruction efficiency with 30% magnetic field (black symbols) is higher for low momentum mesons. Nevertheless, the comparison of the acceptance for reconstructed ω does not show significant differences.

Conclusions

A strong reduction of the magnetic field, down to 30%, results in a degradation of the momentum resolution, and

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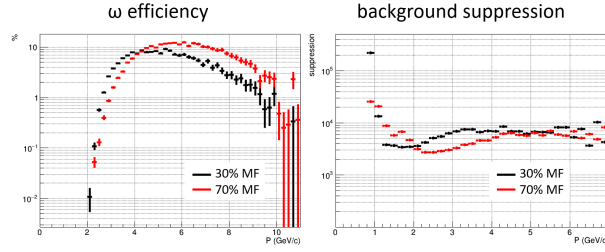


Figure 3: Muon reconstruction performance after global tracking and muon track candidate selection. Left: ω reconstruction efficiency as a function of momentum. Right: background suppression as a function of momentum. Black symbols: 30% magnetic field. Red symbols: 70% magnetic field.

as a consequence, in a degradation of the mass resolution. While the reconstruction efficiency for ω -mesons is similar for 70% and 30% magnetic field, the signal-to-background ratio is almost a factor of 2 lower for the 30% magnetic field.

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Centrality determination with charged particles multiplicity and spectator fragments

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There are two main approaches for centrality determination in CBM: using multiplicity of charged hadrons provided by the CBM silicon tracking system (STS) and the energy of spectator fragments estimated with the CBM projectile spectator detector (PSD).

Multiplicity of produced charged particles is modeled using collision geometry parameters (N_{part} , N_{coll}) sampled with the MC Glauber model. A number of produced particles is calculated as $M_G = \sum_{a=1}^{N_a} M_a$, where M_a is a number of particles produced from individual source (ancestor) "a" and N_a is the total number of sources (ancestors). To evaluate N_a a two-component model, $N_a = fN_{part} + (1-f)N_{coll}$, is used. For each ancestor "a" the number of produced particles M_a is sampled according to the Negative Binomial Distribution (NBD) $P_{\mu,k}(n)$ with mean μ and width k as free parameters. They are fixed by scanning the phase space of k and f for a minimum of χ^2 between the simulated MC-Glauber multiplicity distribution and experimental measured one. A value of μ is defined by the method of golden ratio for each pair of f and k on the grid. This procedure is implemented in the CentralityFramework package [2].

Using best fit parameters the average values and the distribution width of initial geometry parameters (b , N_{part} , and N_{coll}) for each centrality class was extracted. The result for impact parameter b is shown in Fig. 1 (upper panel). A small (1-2%) difference between average impact parameter values obtained separately from UrQMD and MC Glauber model is observed.

The possibility to determine centrality using the CBM PSD and Monte-Carlo Glauber model is also investigated. The main steps of this procedure proposed procedure are: (1) using a high statistics sample of the simulated collisions with the fragmentation formation model, prepare the following maps (distributions) for the fragments mass number (A) and (a) impact parameter, b ; (b) spectator rapidity, y ; (c) spectator energy, E . The charge of the nucleons is not considered as it is not affecting the total energy of the spectators for centrality determination. (2) Use the map $A : b$ to generate a set of fragments for each collision with impact parameter and N_{spec} sampled from the MC-Glauber model: (a) Generate a mass number A_i of a fragment i . Iterate until $A_i < N_{spec}^i$. (b) Calculate the number of remaining spectators nucleons for next iteration: $N_{spec}^{i+1} = N_{spec}^i - A_i$. (c) Iterate the two steps above until $N_{spec}^{i+1} = 0$, i.e. no more free spectators nucleons remained. As a result a sample of n fragments with mass numbers $A_1 \dots A_n$ will be generated. (3) Using maps $A : E$ and $A : y$

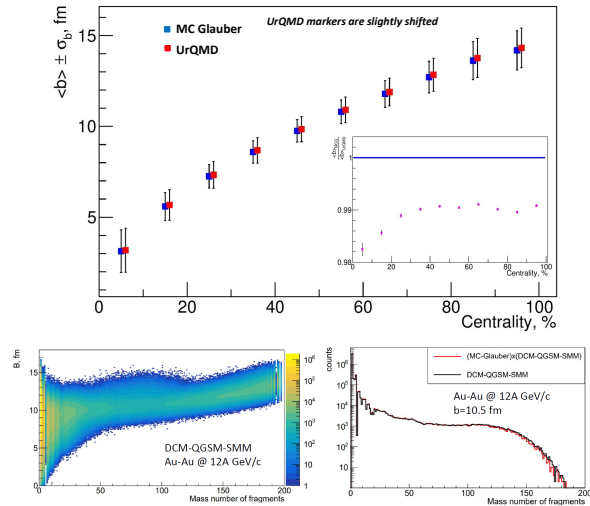


Figure 1: Upper panel: Average impact parameter b and its width vs. centrality. Lower panels: (Left) Distribution of b and fragments mass number simulated with the DCM-QGSM-SMM model. (Right) Projection for a given impact parameter ($b = 10.5$ fm) simulated with the DCM-QGSM-SMM model and sampled distribution.

to generate values of energy and rapidity for each fragment in the event $A_1 \dots A_n$. (4) Using a high statistics sample of the transport simulations (e.g. with GEANT4 simulation package) prepare a map (distribution) of the detector response for a given rapidity and energy of the spectators.

An implementation of the steps 1(a) and 2(a)–2(c) is illustrated in Fig. 1 (lower left panel), which shows the correlation between impact parameter and mass number of fragments obtained from the DCM-QGSM-SMM model. The implementation of step 2 is illustrated in Fig. 1 (lower right panel).

In summary, the procedure based on charged pion multiplicity and MC-Glauber model is implemented. Implementation of the procedure based on spectator's energy and MC-Glauber model is in progress. Sampling the mass number of the fragments for individual MC-Glauber events is implemented using the output of the DCM-QGSM-SMM model.

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CBM performance for measurement of directed flow of charged kaons

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Flow of hadrons with strange quark content can shed light on the compressibility of nuclear matter. A sample of 5M Au+Au collisions at beam momentum of 12.4 GeV/c produced with DCM-QGSM-SMM event generator [1] was used as an input for charged kaon directed flow performance study. The Monte-Carlo simulation of the CBM detector response to the generator particles is performed with GEANT4 transport package. Particle identification was performed utilizing Bayesian approach based on time-of-flight information from the TOF detector and a combination of the track charge and momentum provided by the tracking system (see Ref. [2]).

Anisotropic flow was calculated in the kinematic regions where reconstruction and identification efficiency is close to being uniform and therefore no correction for $p_T - y$ dependence of the efficiency is needed in flow measurements. The correction for the non-uniformity of detector azimuthal acceptance (see Fig. 1) was applied using data-driven procedure [3] implemented in the QnTools framework [4], an extension of the QnCorrections [5] framework originally developed for the ALICE experiment.

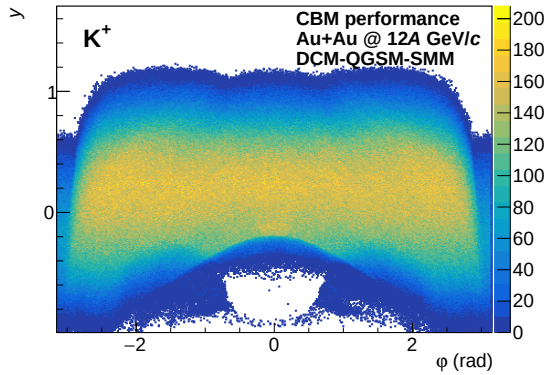


Figure 1: Rapidity- ϕ distribution of tracks identified as positive kaons.

Figure 2 presents the rapidity dependence of directed flow calculated relative to the true reaction plane for the tracks matched to generator-level positively charged kaons and tracks identified as kaons using time-of-flight information. Line shows the values obtained from the Monte-Carlo model. This comparison reveals significant bias in flow calculations due to the impurity of kaon selection in the backward region, where a fraction of tracks from protons and positive pions are passing the Bayesian selection criteria. The impurity of the kaon selection in the backward region

has significant effect on extracted flow signal. To account for this effect multi-differential Bayesian parametrization of squared mass distributions of simultaneous analysis of flow contributions of pions, kaons and protons as a function of squared mass may be required.

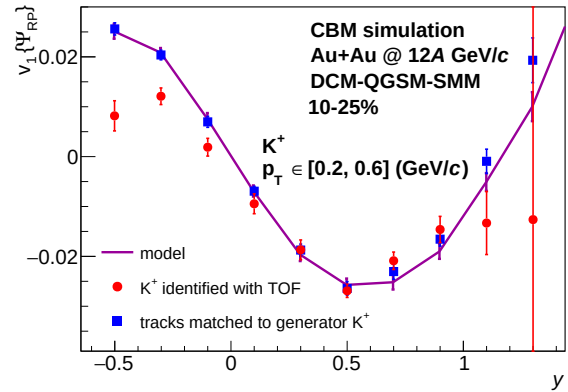


Figure 2: Directed flow of selected positively charged kaons, K^+ , as a function of rapidity in 10-25% centrality class reconstructed relative to true reaction plane.

Performance for flow calculation relative to reconstructed spectator symmetry plane revealed additional correlations between azimuthal distribution of tracks identified as positive kaons and transverse energy registered in PSD. These correlations are most probably caused by the contamination of the kaon sample with protons.

Summing up, performance of the CBM experiment for differential measurements of the directed flow of positively charged kaons is ongoing for the Au+Au collisions at beam momentum of 12.4 GeV/c. Further improvements of identification and flow extraction procedures are required to account for the impurities of kaon selection.

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A simulation study on the forward-backward multiplicity correlation in Au+Au collision at 30A GeV

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In this report we present some simulation results on the short and long-range correlations among charged hadrons emitted in the forward and backward rapidity hemispheres in Au+Au collisions at $E_{\text{lab}} = 30A$ GeV. The forward-backward correlation strength (b_{corr}) is defined by a dependence of the average charged particle multiplicity in the backward hemisphere $\langle N_b \rangle$ on the event multiplicity in the forward hemisphere N_f like [1]: $\langle N_b \rangle = b_{\text{corr}} N_f + a$. Here the constant a is related to the uncorrelated particles. This correlation strength is also measured as [2]

$$b_{\text{corr}} = \frac{\langle N_f N_b \rangle - \langle N_f \rangle \langle N_b \rangle}{\langle N_f^2 \rangle - \langle N_f \rangle^2} = \frac{D_{\text{bf}}^2}{D_{\text{ff}}^2} \quad (1)$$

where D_{bf}^2 and D_{ff}^2 are, respectively the forward-backward (fb) and forward-forward (ff) multiplicity dispersions. Depending upon whether there is a correlation or anti-correlation in the rapidity space, the correlation strength parameter b_{corr} can be positive or negative valued, with limiting magnitudes $0 \leq |b_{\text{corr}}| \leq 1$. Whereas $b_{\text{corr}} = 0$ denotes a completely uncorrelated emission of particles, $b_{\text{corr}} = \pm 1$ indicates a perfect correlation or anti-correlation. Another variable of interest is the variance σ_C^2 in the fb multiplicity asymmetry C

$$\sigma_C^2 = \frac{D_{\text{ff}}^2 + D_{\text{bb}}^2 - 2D_{\text{fb}}^2}{\langle N_f + N_b \rangle}, \quad (2)$$

where

$$C = (N_f - N_b) / \sqrt{N_f + N_b}. \quad (3)$$

By definition the parameter C would be sensitive to both short- and long-range correlations [3]. An intrinsically long-range correlated emission of particles from a single source would give rise to equal number of particles in the forward and backward hemispheres, resulting thereby $\sigma_C^2 = 0$. On the contrary, if particle production follows a binomial partitioning then $\sigma_C^2(N_f - N_b) = N_f + N_b$, and consequently $\sigma_C^2 = 1$.

From some previous measurements presence of strong short-range correlations was observed over a rapidity interval of $|y - y_c| = 1.0$ in e^+e^- and hA experiments [4]. y_c is either the cms rapidity of the colliding system or the centroid of the rapidity distribution of the charged particles. In high-energy nuclear collisions, due to multiple partonic (hadronic) interactions, the fb multiplicity correlations among charged particles are expected to go

beyond $|y - y_c| = 1.0$ rapidity unit [2]. Measurements of the STAR experiment at top RHIC energy [5] has indeed confirmed the existence of long-range multiplicity correlations in Au+Au collisions.

We have taken a sample of 10^6 UrQMD [6] simulated Au+Au events at $E_{\text{lab}} = 30A$ GeV for the analysis. All charged particles but the spectator protons are considered. Figure 1 shows the dependence of D_{bf}^2 , D_{ff}^2 , b_{corr} and σ_C^2 on the centrality of the collisions, measured in terms of the average number of participating nucleons (N_{part}). The results are obtained for a rapidity window $\Delta y = 0.5$ located symmetrically at $y = y_c \pm 1.5$. With increasing centrality D_{ff}^2 monotonically increases and shows some kind of saturation in central collisions. Multiplicity dispersion measured within a small y -interval in the forward hemisphere, may be attributed to fluctuations in the number of small particle producing sources and/or resonance decays. In central collisions perhaps due to multiple rescattering and mixing of many sources, D_{ff}^2 remains unchanged. On the other hand D_{bf}^2 , a measure of long range correlation, increases almost linearly with increasing N_{part} . The observation may be attributed to

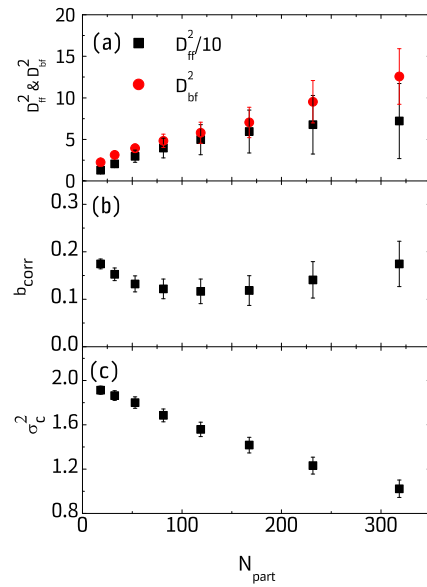


Figure 1: Centrality dependence of (a) the dispersions D_{bf}^2 and D_{ff}^2 , (b) the correlation strength parameter b_{corr} and (c) the variance of fb multiplicity asymmetry σ_C^2 .

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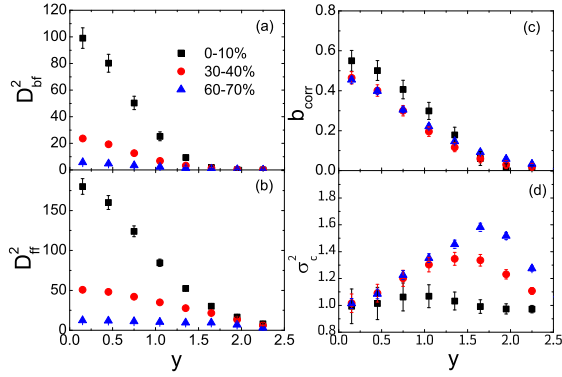


Figure 2: Rapidity dependence of (a) D_{bf}^2 , (b) D_{ff}^2 , (c) b_{corr} and (d) σ_c^2 , for 0-10%, 30-40% and 60-70% centrality bins.

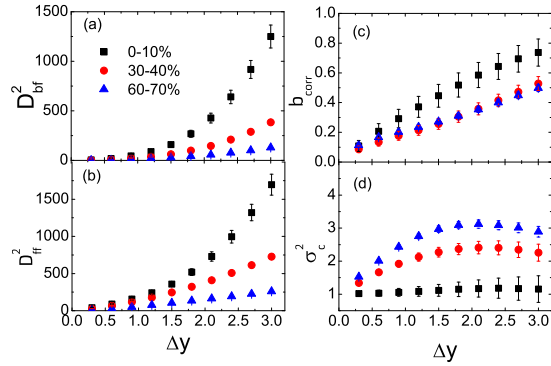


Figure 3: Rapidity window dependence of (a) D_{bf}^2 , (b) D_{ff}^2 , (c) b_{corr} and (d) σ_c^2 , for 0-10%, 30-40% and 60-70% centrality bins.

a geometrical effect. Long range correlations, if there is any, presumably originate from more exotic phenomena, which is not incorporated in the framework of UrQMD. From extreme peripheral to very central collisions b_{corr} changes only marginally. Its small value once again suggests a weak (strong) long (short) range correlation. The fluctuation measure σ_c^2 monotonically decreases from $\sigma_c^2 \approx 2.0$ at the most peripheral to $\sigma_c^2 \approx 1.0$ (binomial limit) at the most central collisions. With increasing centrality once again perhaps due to multiple rescattering and mixing of multiple sources, the correlation effects are significantly washed out.

In Fig.2 we plot different correlation measures of interest against the fb rapidity gap y for three centrality bins. For these plots we set $\Delta y = 0.25$. We see that both D_{bf}^2 and D_{ff}^2 rapidly fall with increasing y , and as expected also with increasing centrality. The shape of the short-range correlation function $C_s(y)$ has a peak at and is symmetric about midrapidity [7]. Such a correlation function can be

approximated by a Gaussian function

$$C_s(y) \propto \exp[-y^2/\delta^2] \quad (4)$$

which we fit with our $b_{corr}(y)$ results. The short-range correlation length λ is obtained from the width δ as $\lambda = 2\delta/\sqrt{\pi}$. The λ values are found to be 1.5 ± 0.45 for 0-10%, and 1.8 ± 0.6 for the other two centrality bins. Note that the values are slightly larger than what is expected only for an intrinsically short-range correlation scenario. The variable σ_c^2 in each centrality bin shows a skewed distribution with y . This is perhaps due to the broadening of the rapidity distribution from the central to peripheral collisions. At large y the particle density reduces significantly that does not allow enough correlation to grow. The parameter σ_c^2 is influenced by both short and long range correlations. The dominance of short range correlation is visible for the most central collisions. In the peripheral bin the peak value of $\sigma_c^2 \approx 1.5$, matches with the prediction of a hadron resonance gas model [8].

In Fig.3 we plot the correlation measures D_{bf}^2 , D_{ff}^2 , b_{corr} and σ_c^2 against rapidity window size Δy , while keeping the distance between the forward and backward bin fixed at 3.0 rapidity unit. With increasing width of the windows, the dispersions increase non-linearly. The b_{corr} parameter on the other hand increases almost linearly with Δy , and the values for the 0-10% central events is consistently larger. Comparing the dependence of b_{corr} on y and Δy , we may argue that the parameter is not as sensitive to the short-range correlation as σ_c^2 . The values of σ_c^2 for the midcentral and peripheral collisions increases initially with Δy , but saturate beyond $\Delta y \approx 1.5$. From the Gaussian parametrization of $b_{corr}(y)$ we obtained the limiting value for the short range correlation at about $y \approx 1.5$. The increasing trend of σ_c^2 with Δy upto ~ 1.5 could be an artifact of increasing short-range correlation. Above this value the contribution of long range correlation is marginal. For the most central 0-10% events $\sigma_c^2 \approx 1.0$ over the entire Δy window. A more detailed analysis of our simulated data is being undertaken to identify the physics issues related to the above observations.

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CBM performance for measurements of pion-pion correlations

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Femtoscopy is a technique that makes possible to extract information about the size of the source that emits particles. It is currently the only known method that gives direct access to such information. The spatio-temporal information is crucial to understand the dynamics of the collision. Femtoscopy uses so called Correlation Function (CF) defined in equation 1. The P is the probability of measuring single (or pair) of particle(s) with given momentum (momenta): p_1 and p_2 :

$$C(p_1, p_2) = \frac{P(p_1, p_2)}{P(p_1)P(p_2)} \quad (1)$$

In an experiment, the denominator is created from mixed pairs; each particle in the couple belongs to a different event. Some theoretical functions fit the correlation function. For the Gaussian-like shape of the source, the correlation function of non-interacting bosons with spin 0 is equal to 2. The parameter R is femtoscopic / HBT radius, λ is the incoherence factor describing the fraction of correlated pairs. The CF is also sensitive to the interactions between particles. Typical parametrization of the CF including quantum statistical effects is:

$$C(q) = 1 + \lambda e^{-q^2 R^2} \quad (2)$$

where q is the momentum difference.

The measured CF depends, however, not only on the shape of the source. The non-femtoscopic effects that create additional correlations (e.g., jets) might also change the measured CF's shape. The detector effects also contribute. The limited momentum resolution usually smears the correlations peak. The reconstruction of pair of tracks as a single particle decreases the value of CF. The merging effect decreases the value of CF. The effect opposite to the merging - the splitting is the reconstruction of a single track as two separate ones, and it increases the value of CF[2]. What is more critical, merging and splitting are the strongest at $q \approx 0$; the same position where correlation peaks exist. Therefore removing (suppressing) those two effects is "sine qua non" of the femtoscopic measurements.

The studies of femtoscopic measurements base on CBM in SIS-100 electron configuration. CbmROOT from the end of 2019 and UrQMD 3.3 data are used with standard macros to simulate reconstructed data. The 2.3 millions of Au+Au events with beam momentum of 10 GeV A are input of the simulations. Analysis of data is performed by using the CbmROOT framework with the NicaFemto module implemented for femtoscopic analysis.

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Cut	Min	Max
Event cuts		
V_{xy} [cm]	0	0.4
V_z [cm]	0	0.02
Track cuts		
p_T [GeV/c]	0.2	2
$N_{hits \text{ in STS}}$	6	8
DCA [cm]	0	0.1
charge	-1	-1
m_{TOF}^2 [GeV^2/c^4]	0	0.05
Pair cuts		
STS exit sep. [cm]	0.5	500
$ \Delta\eta \Delta\phi^* $ [rad]	0.02;0.05	-

Table 1: Criteria of data selection in analysis.

Criteria of data selection are listed in table 1. Monte Carlo (MC) models like UrQMD do not contain the femtoscopic correlations, and the pure MC sample analysis was used to optimize cuts. In principle, such a correlation function should be flat (as shown in the simulations with pure UrQMD data). Analysis based on pairs of the negative pions, as the positive pions are contaminated with too many protons. In figure 1 is presented CF calculated without two-particle cuts, splitting effect is visible. Applying cut on the distance between two tracks at the last STS station (STS exit separation) is used to suppress splitting. The merging effect appears after removing the splitting. To reduce this effect, cut based on $\Delta\eta^*$ and $\Delta\phi^*$ is used. The asterisk means the pseudorapidity and azimuthal angles are calculated at 25 cm from the vertex position.

After optimization of selection criteria (cuts), the femtoscopic correlations are included in simulations. It is done by assigning a femtoscopic weight for each pair of particles. It was estimated that the incoherence factor (λ) is set to 0.5. The Gaussian shape of the source was assumed, the size of the source corresponds to the femtoscopic radii measured by STAR for central Au+Au collisions at $\sqrt{s_{NN}} = 11.5$ GeV [3].

The estimated systematic uncertainties are listed in table 2. The systematic uncertainties smaller than statistical are denoted by red color. The total systematic uncertainty is 9.6 and 14.2 % for radius and incoherence factors, respectively.

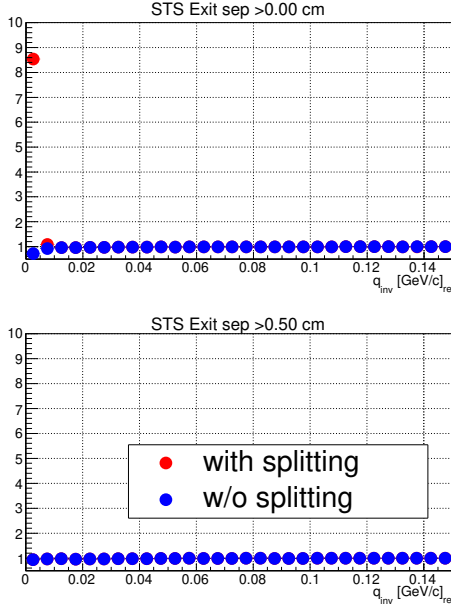


Figure 1: Normalized correlation function without femtoscopic effects without (top) and with (bottom) anti-splitting cut.

It roughly corresponds to the uncertainty reported by ALICE collaboration in similar measurements - 11-12 % and 34 % for radius and incoherence factor. The systematic uncertainties might be underestimated due to relatively large statistical uncertainty. Any event-selection-related uncertainties are not taken into account. Poor description of results can be explained by assuming bad shape; the similar problem is also observed in ALICE results [4]. The example of correlation function, together with their χ^2 fit is shown in figure 2.

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	R	Λ
Fit	6.12 fm	0.41
Stat. Error	0.11 fm	0.03
Stat. Error (%)	1.7	7.3
Systematical errors		
Source	$\Delta R\%$	$\Delta \lambda\%$
Numerical	0.04	0
Normalization	3.58	1.47
Fit range	3.10	7.86
Momentum	0.00	2.46
Purity	0.00	0.74
Pair cuts	5.96	10.07
Track cuts	5.88	5.41
Total sys.	9.63	14.19

Table 2: Estimated uncertainties of femtoscopic measurements in CBM.

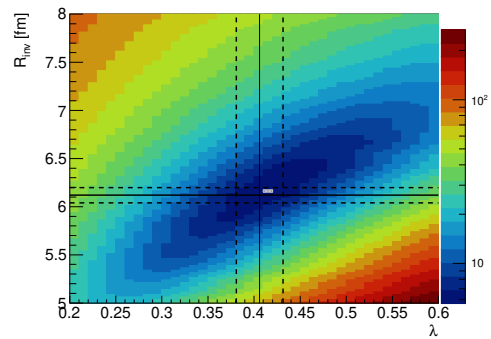
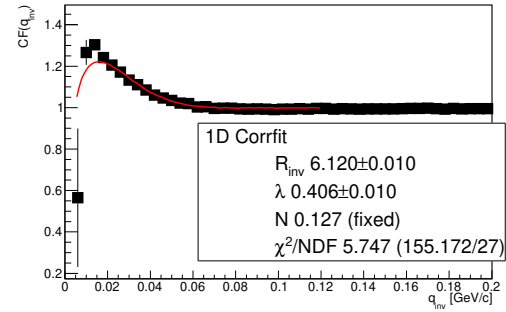


Figure 2: Fit of CF with χ^2 map. The full lines represents the fitted parameters whereas dotted lines correspond to estimated statistical uncertainty. The white bin corresponds to the bin with the smallest χ^2/NDF

CBM performance for measurement of proton directed flow

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Anisotropic transverse flow is one of the most important observables to constrain transport properties of the matter created in heavy-ion collisions. Analysis of proton directed flow [1] is performed using a sample of 5M Au+Au collisions at beam momentum of 12A GeV/c produced with DCM-QGSM-SMM event generator [2]. Particle transport through the CBM subsystems is simulated using GEANT4 package. Bayesian particle identification is based on time of flight information [3]. To minimize the effect of finite efficiency on reconstructed flow values the analysis is performed in kinematic regions with higher reconstruction efficiency.

Due to rectangular shape of the transverse layout of the detectors and presence of magnetic field, the azimuthal acceptance of the CBM tracking system and the hadron calorimeter PSD are non-uniform in the transverse plane (see Fig. 1). The effect of the detector asymmetry is corrected for using data-driven procedure [4] implemented in the QnTools framework [5], an extension of the QnCorrections [6]. Independent estimates of directed flow v_1 are obtained with the scalar product method using x and y components of flow vectors and different symmetry plane sources. Four-subevents method is used to calculate the symmetry plane resolution correction factor.

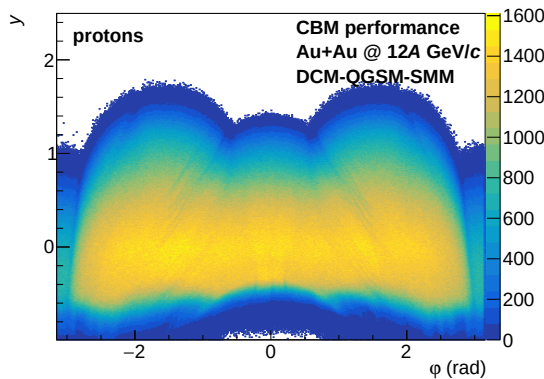


Figure 1: Rapidity- ϕ distribution of identified protons.

Figure 2 shows proton directed flow as a function of rapidity for the 10–25% centrality class. Dependencies obtained using information from Monte-Carlo simulation (lines) are compared with the calculations based on reconstructed tracks relative to the true reaction plane (green triangles) and symmetry plane reconstructed from four central modules of PSD (PSD1) using true resolution based on generator information about reaction plane angle (blue cir-

cles) and fully data driven result for resolution calculation (red squares). Filled markers show results obtained with x components of flow vectors, empty markers represent the y components. Good agreement is found between reconstructed and input values of directed flow in wide rapidity range for symmetry plane estimated from the innermost group of PSD modules.

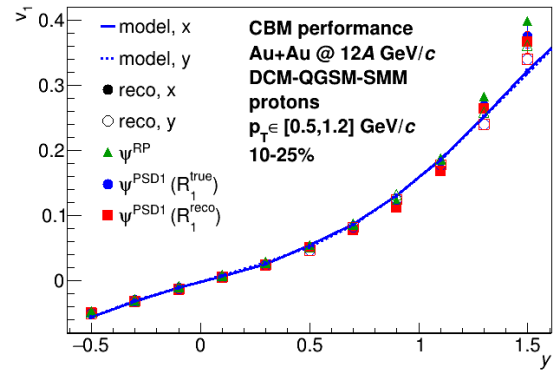


Figure 2: Directed flow v_1 of identified protons extracted relative to reaction plane or symmetry plane from central PSD modules (PSD1) with the use of true and reconstructed resolutions. Lines show the values obtained from the collision generator.

In summary, performance study was conducted for differential measurements of proton directed flow relative to the projectile spectator symmetry plane in Au+Au collisions at the top SIS-100 beam momentum. Realistic procedures for centrality determination and particle identification are used. Corrections for effects of the detector azimuthal non-uniformity are applied.

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Performance for Λ hyperon directed flow measurements

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Strange quarks do not exist before the heavy-ion collision and are produced at its early stage, which makes the strange and multi-strange hyperon production an important tool to extract the properties of the created QCD matter. Anisotropic flow of produced particles, in particular with the strange quark content, is sensitive to the equation of state and the degrees of freedom in the early fireball. In CBM the short lived particles (e.g. K_0 and Λ) are reconstructed via their weak decay products. Reconstruction algorithm of the decays is implemented as the Kalman Filter Particle Finder [1]. For the current analysis we used its simplified version, the PF Simple [1], which was optimized for efficient Λ hyperon reconstruction and background rejection. Application of the machine learning technique for the Λ selection criteria optimization is described in [2].

Anisotropic flow can be characterized by coefficients of a Fourier series of produced particles azimuthal angle distribution. The directed flow $v_1 = \langle \cos(\phi_\Lambda - \Psi_{RP}) \rangle$ describes particle emission in preferred direction relative to the reaction plane. The scalar product method was used to calculate the directed flow. Procedure for estimation of the reaction plane and its resolution using the PSD is discussed in [3]. For this analysis the reaction plane angle Ψ_{RP} was taken from the event generator. Non-uniformity of the CBM acceptance and inefficiencies in azimuthal angle ϕ (sensitive volume, magnetic field, additional material etc.) biases results for directed flow. This non-uniformity was corrected according to the procedure described in [4] and implemented in QnTools and QnAnalysis frameworks [4]. Additionally, the (p_T, y) -dependent reconstruction efficiency correction was applied as weights for individual tracks. Monte-Carlo closure test showed that with QnTools [4] the input flow values are reproduced within statistical precision of the simulated sample.

A sample of 5M Au+Au collisions at $p_{beam} = 12A$ GeV/c was generated with the DCM-QGSM-SMM model. GEANT4 was used to transport particles through the CBM detector material. These events were reconstructed with the CBMROOT software and used for the Λ hyperon flow studies. In order to check validity of the correction procedure as implemented in the analysis frameworks [4] the results of the data-driven analysis were compared to the known Monte Carlo input. The estimates of the v_1 coefficient from X and Y component correlations ($v_{1x} = \langle q_{1x} \cos \Psi_{RP} \rangle$, $v_{1y} = \langle q_{1y} \sin \Psi_{RP} \rangle$) were calculated as functions of rapidity and transverse momentum. A positive slope of Λ $v_1(y)$ is reproduced, with v_{1x} and v_{1y} being consistent with the statistical precision of the simulations (see Fig. 1, top). The p_T dependence of v_1 is shown

in Fig. 1, bottom. There is an indication of a small difference between v_{1x} and v_{1y} at small $p_T \sim 0.5$ GeV/c, which requires further investigation with higher statistics.

In summary, performance of the CBM experiment for directed flow of Λ hyperons was investigated using flow analysis framework. After applying all corrections for azimuthal non-uniformity and efficiency weights the Monte Carlo input is reproduced within statistical precision. The future plans are to use the simulated PSD signals for reaction plane estimation, deploy the invariant mass fit method for signal-background separation in hyperon reconstruction, and perform p_T , y , and centrality differential analysis.

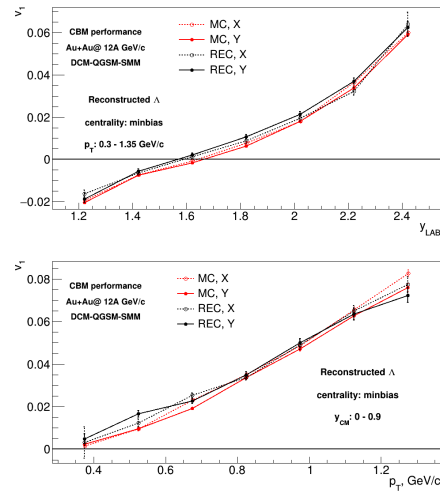


Figure 1: Directed flow of Λ hyperons vs. (top) rapidity and (bottom) p_T .

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Feasibility study of femtoscopic measurements of nonidentical particle correlations and $\Lambda - \Lambda$ pairs at the CBM experiment at FAIR

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Geometry and dynamics of the source produced due to heavy-ion collisions can be studied via the femtoscopy method. Correlations of two particles at small relative momentum are sensitive to Quantum Statistics and the Final State Interactions. They allow one to explore the source's space-time properties, which are of the order of 10^{-15} m and 10^{-23} s, respectively. CBM experiment will cover an essential part of the QCD Phase Diagram with beams of heavy-ions. It is a baryon-rich region that can be studied via femtoscopy method. On the one hand, meson-meson correlations are the most commonly studied, and baryon-baryon systems, together with two-meson and meson-baryon correlations, provide complete information about source parameters. On the other hand, non-identical particle combination measurements complement our knowledge about space-time asymmetries during the emission process. The physics of heavy-ion collisions is successfully deduced basing on studies of the properties of the particle-emitting source.

To define a femtoscopic correlation function [1], [2] in the case of identical particle combinations a Longitudinally Co-Moving System (LCMS) is used which is defined as $p_{L,1} + p_{L,2} = 0$. $p_{L,1}$ and $p_{L,2}$ are longitudinal components of momentum for single particles. Using LCMS system the correlation function is defined using variable:

$$q_{\text{inv}} = \sqrt{(p_1 - p_2)^2 - (E_1 - E_2)^2} \quad (1)$$

In the case of non-identical particle combinations, Pair Rest Frame (PRF) reference is used, which defined variable:

$$k^* = p_1 = -p_2 \quad (2)$$

PRF reference can be also used for identical pairs of particles and then $q_{\text{inv}} = 2k^*$.

The definition of the correlation functions is as follows:

$$C(k^*) = \frac{A(k^*)}{B(k^*)} \quad (3)$$

or

$$C(q_{\text{inv}}) = \frac{A(q_{\text{inv}})}{B(q_{\text{inv}})} \quad (4)$$

Correlated pairs of particles (from the same event) enter the numerator $A(k^*)$ or $A(q_{\text{inv}})$ and uncorrelated pairs of particles (from different events) enter the denominator $B(k^*)$ or $B(q_{\text{inv}})$ of the correlation function.

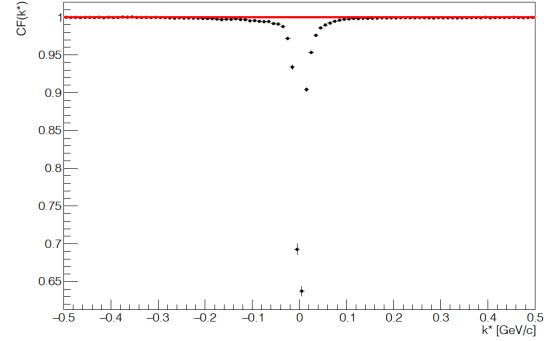


Figure 1: Example of $\pi - K$ correlation function (identical charges) for moving-away scenario (left) and catching-up scenario (right)

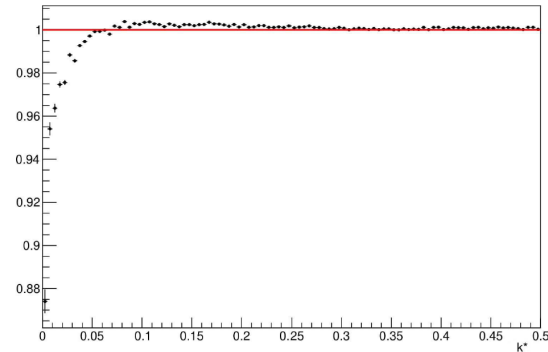


Figure 2: Example of $\pi - K$ double ratio (identical charges) for moving-away scenario and catching-up scenario

These studies rely on Monte Carlo simulations of UrQMD model. 30 millions of minimum bias data are generated for $Au + Au$ collisions at energy $E = 10$ AGeV. Pions are chosen in the transverse momentum range: $0.2 < p_T < 1.2$ GeV/c and kaons within $0.2 < p_T < 1.2$ GeV/c. Protons and antiprotons are chosen in the transverse momentum range: $0.4 < p_T < 2.5$ GeV/c. Lambdas and antilambdas are chosen in the transverse momentum range: $0.4 < p_T < 2.0$ GeV/c. As a result of the heavy-ion collision, a hot and dense system produces different types of particles. Using the femtoscopy method, it is possible to learn about the source's geometrical and dynamical properties. Geometrical parameters are related to sizes and dynamical

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ones to space-time emission sequence of particles of different species. Femtoscopy enables one to study of space characteristics of source emitting pairs of particles. Thus, it is impossible to explore the whole source's information but rather to its part, emitting considered pairs of particles. It explains why source sizes extracted from various studies are different depending on the supposed system. So the geometry of heavy-ion collision can be studied via femtoscopic parameters describing source sizes of emission areas.

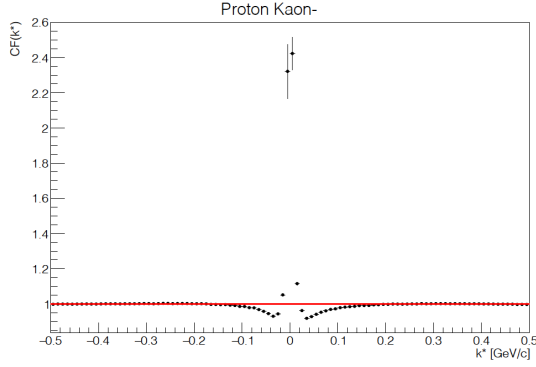


Figure 3: Example of $K - p$ correlation function (opposite charges) for moving-away scenario (left) and catching-up scenario (right)

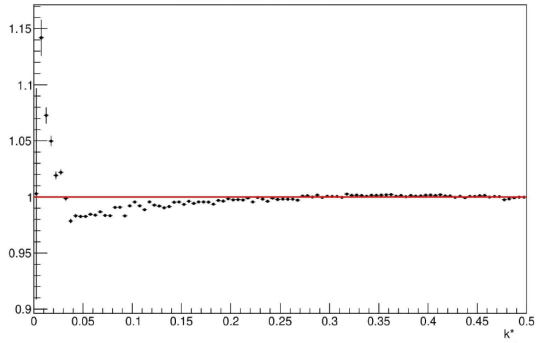


Figure 4: Example of $K - p$ double ratio (opposite charges) for moving-away scenario and catching-up scenario

The dynamics of the collision can be studied using femtoscopic methods using only non-identical particle combinations. It is possible to study the emission sequence in the case of distinguishable particles. Collision dynamics can be related to space and time aspects. The femtoscopy method is sensitive to the emission asymmetries related to the spatial shifts (particles of different types statistically emitted from different areas of the emission source) and the time intervals between the two different particles' emissions. However, it is impossible to distinguish whether space and/or time asymmetry is deduced. Fig. 1 shows

correlation functions for $\pi - K$ systems and for pion-proton systems. To measure possible asymmetry in the $\pi - K$ pair's emission process, there are considered two possible scenarios: catching-up and moving-away of the lighter particle in the pair. Fig. 2 shows ratio of functions calculated for both scenarios. Obtained results suggest that lighter particles (pions) are statistically emitted closer to the system's center and/or earlier than heavier particles (kaons). Similar results are obtained for other particle species: kaon-proton. Fig. 3 presents correlation functions for $K - p$ system and Fig. 4 their double ratio. Such asymmetries are caused by the flow phenomenon, which affects particles differently with different masses.

Femtoscopy is a unique technique that allows one to study strong interactions. There will be possible to search for bound states, e.g., H-dibaryon (composed of two Λ hyperons). Fig. 5 shows $\Lambda - \Lambda$ correlation function from UrQMD model assuming contribution of quantum statistics and strong interactions. The below result suggests possible studies of strong interactions using the method of femtoscopy.

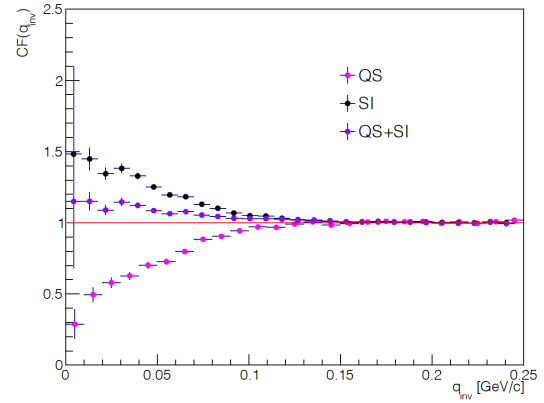


Figure 5: Example of $\Lambda - \Lambda$ correlation function taking into account quantum statistics and strong interactions

Discussed results of femtoscopic correlation functions for nonidentical particles and $\Lambda - \Lambda$ confirms possible measurement of two-particle correlations at the CBM experiment.

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FAIR Phase-0 Activities

mCBM - achievements and plans

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The Compressed Baryonic Matter experiment (CBM) at FAIR is designed to measure nucleus-nucleus collisions at an unprecedented interaction rate of up to 10 MHz which will allow study of extremely rare probes with high precision. To achieve this high rate capability, CBM will be equipped with fast and radiation-hard detectors, which are readout via a triggerless-streaming data acquisition system, which will transport data with a bandwidth of up to 1 TB/s to a large scale computer farm, allowing for event reconstruction and first level event selection.

In order to commission and optimize prototypes and pre-series productions of CBM detector systems with their triggerless-streaming read-out chains under realistic experiment conditions, a CBM full-system test-setup named mCBM@SIS18 (short “mCBM”) has been constructed at the SIS18 facility of GSI/FAIR. The primary aim of mCBM is to commission and optimize (i) the triggerless-streaming data acquisition system including data transport to a high performance computer farm inside the Green IT Cube at GSI, (ii) the online track and event reconstruction and event selection algorithms and (iii) the offline data analysis as well as the controls software packages. mCBM comprises of final prototypes and pre-series components of all CBM detector subsystems and their read-out systems. Hence, the setup offers additional high-rate detector tests in nucleus-nucleus collisions under realistic experiment conditions. The experiences gained during the complete mCBM campaign will significantly shorten the commissioning period for the full CBM experiment at SIS100. The promising results obtained from the first commissioning phase underlines the key role of mCBM as a demonstrator and powerful tool towards the realization of the CBM experiment.

The Experimental Setup The mCBM experiment was setup in 2017 and 2018 at the detector test area HTD situated at the beam entrance of the experimental area Cave-C (HTC), hosting the nuclear structure experiment R³B. As depicted in Figure 1, the mCBM test-setup is positioned downstream a solid target under a polar angle of about 25° with respect to the primary beam towards a beam dump located 7 m downstream at the south end of the experimental area. mCBM does not comprise a magnetic field, and, therefore, measures charged particles produced in nucleus-nucleus collisions traversing the detector stations following straight trajectories. While the completion of mCBM is ongoing, the present mCBM setup (as of May 2020) includes detector stations of all CBM subsystems, shown in the photograph of Figure 1 as well as in the corresponding ROOT geometry (lower panel of Figure 1). De-

tails are listed in Table 1.

For track reconstruction, the May 2020 mCBM-setup comprises 1 (half) STS station (mSTS), 2 MUCH (mMUCH) and 1 TRD station (mTRD) making 4 tracking layers which provide redundant position information. The 5x super-modules of the mTOF subsystem has been grouped into a double- and triple-stack for the first commissioning period enabling tracklet searches within the mTOF system as well as detector tests incl. efficiency measurements of TOF-RPC modules. The high-resolution time-

mT ₀	fast and radiation-hard time-zero (T ₀) diamond counter, consisting of 8 vertical strips each of 2 mm width, mounted inside the target chamber, 20 cm upstream of the target, readout by TOF electronics (PADI and GET 4).
mSTS	2 6 x 6 cm ² STS prototype modules mounted on a half-ladder, positioned on the 1st station (station 0). Each module contains 1024 channels on each sensor side, readout with 8 STS-XYTER v2.1 located on a FEB-8, interfaced to a GBTx ROB-3.
mMUCH	2 GEM prototype stations consisting of M2 modules with 2304 pads. Each module is equipped with 18 STS-XYTER v2.1 mounted on a single FEB each, interfaced to the GBTx ROB-3.
mTRD	1 TRD prototype module, type 8, 95 x 95 cm ² large, with 768 rectangular pads, 6 FEB-4x1-2 per module interfaced to the GBTx ROB-3.
mTOF	5 TOF M4 prototype modules each containing 5 MRPC counters (32 x 27 cm ²). The readout is performed with PADI and GET 4 electronics interfaced to the GBTx ROB-1, in total 1600 read-out channels.
mRICH	2 aerogel radiators each with size 20 x 20 cm ² , equipped with 36 MAPMTs, connected to 72 DiRICH modules, readout with TRB3.
mPSD	a single PSD module, readout by a PANDA TDC board.

Table 1: Detector stations of the mCBM test setup as of May 2020.

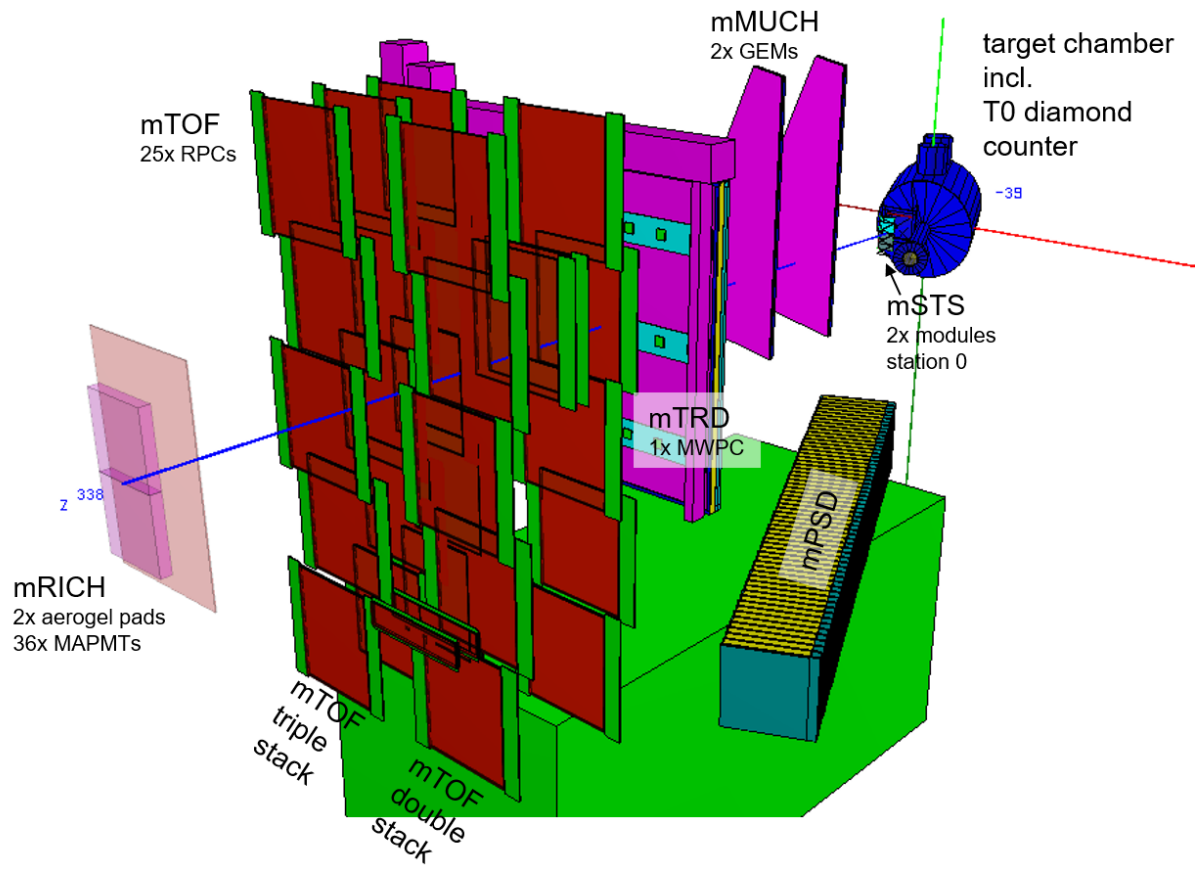
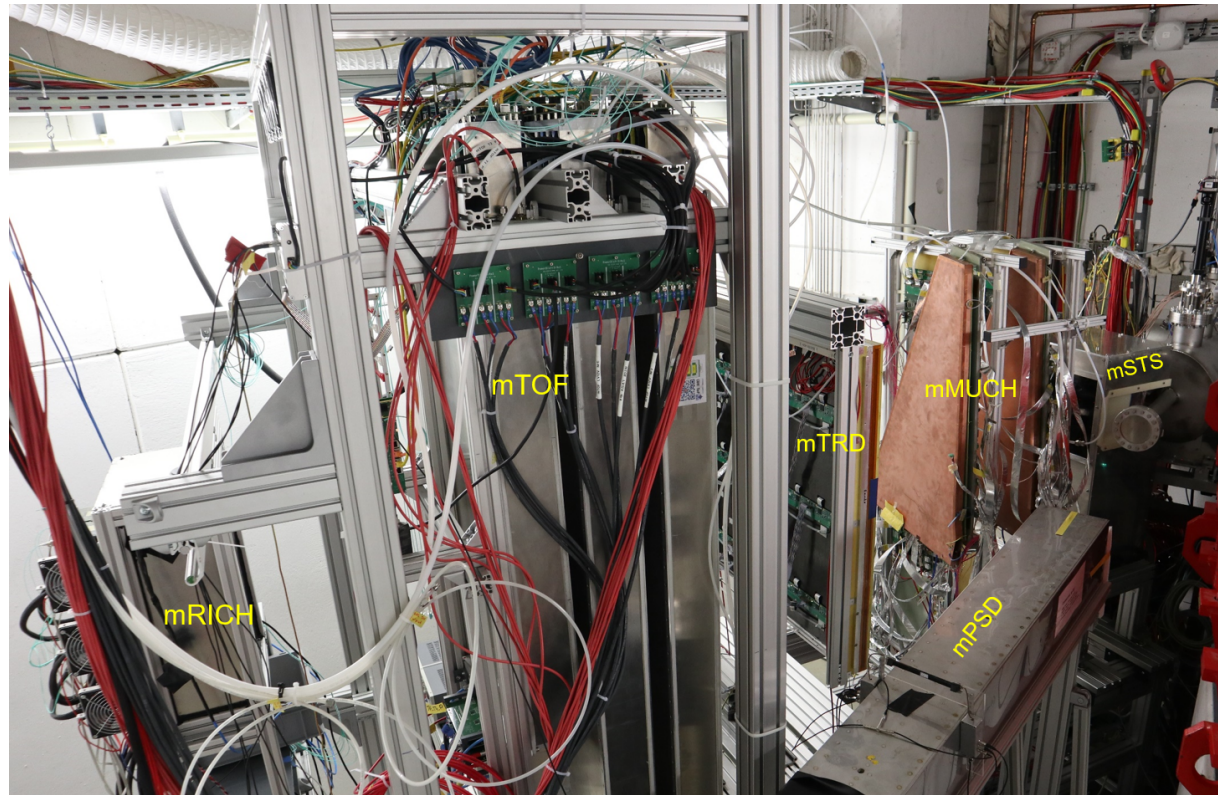


Figure 1: Photograph of the mCBM setup inside the HTD cave and ROOT geometry (lower panel) of the present mCBM setup as of May 2020. The beam enters from the right.

of-flight system consists of a fast and segmented diamond counter for time-zero (T_0) determination positioned 20 cm upstream of the target and a TOF stop wall (mTOF). The mRICH subsystem using 2x aerogel radiators is placed directly behind the mTOF detector and delivers a second measurement of the particle velocity in a selected acceptance window. Additionally, mCBM is equipped with a single PSD prototype-module (mPSD) positioned directly under the optical axis of the primary beam, 5° tilted relative to the beam axis while pointing to the target.

In the period Q3 2020 – Q1 2021, it is intended to expand the setup by integrating 5x STS ladders (mSTS), 3 MUCH stations (mMUCH) and 2 TRD station (mTRD). These will provide 6 tracking layers in total, offering redundant position information and allow to perform tracklet searches. Accordingly, the mTOF is going to be supplemented by a 2nd layer of RPC modules. Additional tests of MUCH RPCs, TRD modules of the TRD inner part (mTRD-2D) and high-rate TOF modules for the inner region are foreseen for the beam campaign in 2021. Furthermore, the mCBM vacuum system is to be completed as well as the cooling of the experimental area is to be upgraded. In a later stage, MVD stations (mMVD) will be added into the test-setup enabling a high-precision vertex reconstruction.

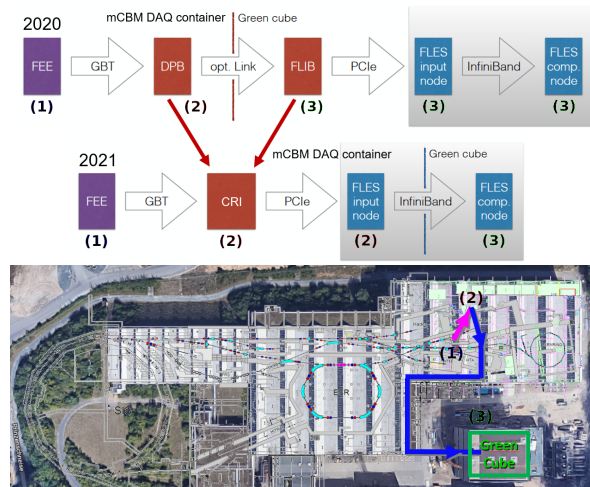


Figure 2: The mCBM readout chain in operation until May 2020 (top) consists of 2 distinct FPGA boards, the DPB and the FLIB. In view of the upgrade of the readout system for spring 2021, both FPGAs will be replaced by a single FPGA entity, the CRI (bottom). As a consequence, the entry nodes housing the CBI boards will have to be relocated from the Green IT Cube (3) into the mCBM DAQ container (2). The 300 m long optical link between the entry node cluster and the processing node cluster will be operated employing standard Infiniband network technology. Bottom panel: site map of the components in the mCBM triggerless-streaming readout chain (background image taken from Google Maps).

DAQ/Data Transport The CBM experiment at FAIR will measure relativistic nucleus-nucleus collisions with collision rates up to 10 MHz leading to data rates up to 1 TB per second. To achieve the required performance a triggerless-streaming data acquisition system is being developed, see Figure 2. It includes ultra-fast and radiation-tolerant ASICs as front-end chips followed by CERN GBTx-based radiation-tolerant data aggregation units. Further down-stream, the data streams are handled by Data Processing Boards (DPB) containing powerful FPGAs. Next, they are forwarded via FLES Input Boards (FLIB), a PCIe based FPGA card, into the First-Level Event Selector (FLES), a computer farm, which performs on-line event selection. At mCBM these components of the readout chain are spread across different locations, see Figure 2. The described high-performance readout hardware needs high-performance firmware for the FPGA layers up to a fast and highly parallel on-line track and event reconstruction and analysis software.

The mCBM readout chain based on DPB and FLIB, as operated until May 2020 is depicted in Figure 2 (top line). The mCBM subsystems installed in the cave (1) are equipped with individual front-end electronics. These front-ends are interfaced by the GBTx ASIC, which forwards the detector data via optical GBT links. All GBT links are received by the Data Processing Board (DPB) layer located at 50 m distance inside the DAQ container (2). The DPB is a FPGA based board, which allows for sub-system specific pre-processing of the arriving data stream. A 300 m long optical link connects the DPB output to the FLIB board installed in the FLES entry node inside the Green IT Cube (3). The optical link paths on the GSI campus are sketched on a map in Figure 2. The FLIB transports the arriving data in a micro-slice format into the memory of the FLES entry node. An InfiniBand network links the FLES entry nodes to the FLES processing nodes. Upon reception in a FLES processing node the micro-slices originating from all active subsystems are grouped into larger time-slices. These time-slices are then used for the online data reconstruction.

In 2019/2020 the mCBM detector front-ends are time-synchronized by the Timing and Synchronisation (TS) system, which relies on a simple clock and pulse-per-second (PPS) distribution. The detector front-end digitizes signals above threshold and assigns a time stamp to the hit. This data is then forwarded via an electrical connection to the GBTx readout board, where the electrical signals acquired through a large number of e-links are converted and merged into an optical GBT link operating at 4.48 Gbit/s. These GBT links are the detector interface to the Data Acquisition (DAQ) chain. The detector subsystems are presently readout using read-out chains based on existing prototype implementations of DPB and FLIB. As current prototype hardware, an AMC FMC Carrier Kintex (AFCK) board is used for the DPB, a HiTech Global HTG-K700 PCIe board for the FLIB. Both boards are based on a Xilinx Kintex-7 FPGA.

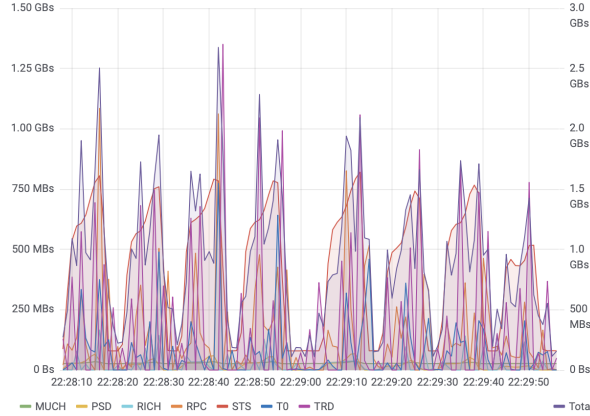


Figure 3: Total data rate (scale on the right) and break down to subsystem data rates (scale on the left) observed by the FLES processing nodes inside the Green IT Cube, May 4, 2020, run 858.

Figure 3 shows the total data rates (scale on the right) as well as data rates broken down by subsystem (scale on the left) observed by the processing nodes of the first-level-event-selector (FLES) inside the Green IT Cube of GSI. The peak total data rate exceeds 2.5 GB per second while the average total data rate measures to 0.85 Gb per second in ^{208}Pb on Au collisions at a collision rate of about 1 MHz (run 858, May 4th, 2020). The largest contribution had been delivered by the mSTS, the smallest by the mPSD and mRICH subsystem.

Early 2021, DPB and FLIB will be replaced by a prototype of the Common Readout Interface (CRI) in the FLES entry stage (see Figure 2), as it is foreseen for the CBM experiment. To reduce the number of FPGAs operated in the chain, these two will be substituted by a single device, the CRI.

Results from the First Commissioning Phase 2018 - 2020 Commissioning with beam has started during the machine engineering runs in December 2018, followed by first the year's main commissioning beam time during

Year	mCBM commissioning with beam	beam	kin. beam energy
2018	Nov. 24, Dec. 13	^{108}Ag	1.20 AGeV
2019	Mar. 12, 16, 23, 28, 30	^{108}Ag	1.58 AGeV
	Nov. 27, Dec. 12	^{40}Ar	1.70 AGeV
2020	Mar. 27, 29, 30, 31,	^{206}Pb	1.075 AGeV
	Apr. 1, 2, 3, 5		
	Apr. 24, 28, May 4	^{208}Pb	1.060 AGeV
	May 24	^{209}Bi	1.078 AGeV

Table 2: mCBM commissioning with beam.

March 2019, see Table 2. The second year's campaign started with first tests during machine engineering runs in November and December 2019, while the main commissioning with beam took place from March 27th to May 24th of 2020, which used completely the granted contingent of beam time. As experienced to date, 8 - 12 h beam blocks with breaks of at least two days in between, turned out to be the most efficient commissioning mode, since it allows to perform reasonable test sequences with beam, while permitting adaption of the setup or improvements of the firm- and software during breaks.

Significant improvements of the detector subsystems have been made during this first commissioning phase. This includes the data transport starting at the front-end ASICs through the data aggregation ASICs (CERN GBTx) to the FPGAs of the data processing boards (DPB). Hence, the DPB firmware development has been, and still is an essential part of the mCBM commissioning. In particular, timing stability of subsystem data streams at high data loads approaching resource limits of the DPB FPGA remains challenging, but could be handled during the recently completed beam campaign (see Table 2). The data analysis technique for the individual subsystems as well as for the common data analysis is still under development while the data analysis of May 2020 data is ongoing.

Recent, preliminary results of the mCBM commissioning selected for this document have been obtained from the beam campaign March - May 2020, representing the present status of the mCBM experiment (as of May 2020). Data have been taken with a common synchronized data transport including all detector subsystems. The peak total data rate observed by the processing nodes of the first-level-event-selector (FLES) inside the Green IT Cube exceeds 2.5 GB per second while the average total data rate measured to 0.85 Gb per second in ^{208}Pb on Au collisions at a collision rate of about 1 MHz (run 858, May 4th, 2020).

The key requirement for a triggerless-streaming DAQ system is the timing stability of its detector read-out systems to be verified by time correlations between subsys-

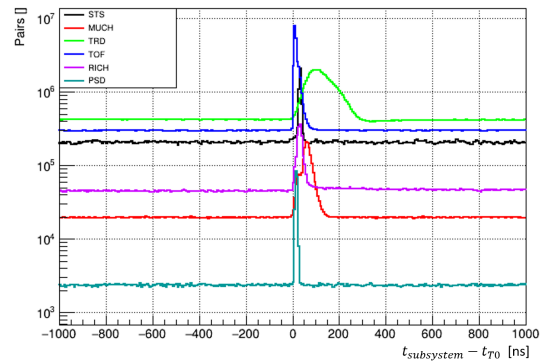


Figure 4: Time differences $t_{\text{subsystem}} - t_{T_0}$ demonstrating the time correlation of all subsystems (May 4, 2020, run 831). Individual subsystem time offsets were corrected - see Table 3.

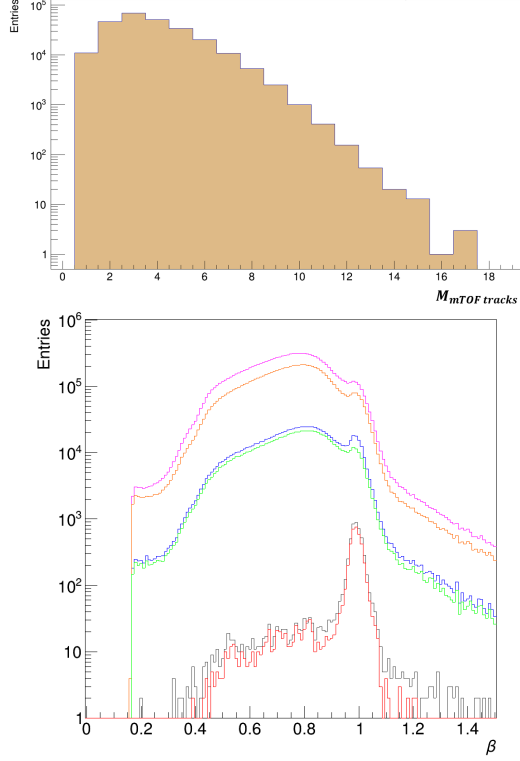


Figure 5: (left) mTOF track multiplicity, (right) β distribution of reconstructed mTOF tracks, (top=1 to down=6 with added event and track selections) (1) magenta: $M_{mTOF \text{ digi}} = 3$, (2) orange: $M_{mTOF \text{ digi}} = 10$, (3) blue: $+ M_{mRICH \text{ digi}} = 5$, (4) green: $+ mRICH \text{ hit}$, no ring, (5) grey: $+ \text{closed ring in } 20\% \text{ enlarged radius}$, (6) red: $+ \text{good rings}$.

tems, as shown in Figure 4. Accordingly, the time distributions of the subsystems are plotted with respect to the time-zero counter $t_{\text{subsystem}} - t_{T_0}$. Data were taken on May 4th, 2020, in a common, synchronized data transport into the Green IT Cube including all subsystems. All pairs $(t_{\text{subsystem}} - t_{T_0})$ within a time slice of length 10.28 ms are taken into account, Figure 4 shows a zoom-in on a $\pm 1 \mu s$ range. The depicted time t results from time stamps assigned to the raw hit messages by their front-end ASICs, converted into digis with unit [ns] during the unpacking stage of the data analysis. Individual time offsets of the subsystems are corrected during the unpacking (see Table 3). No detailed time calibration procedures were applied. In general, the subsystem time offsets remain constant between runs which includes a synchronization sequence prior to each run start. Exceptions caused by detector malfunctions and a non-optimized synchronization sequence of a subsystem were observed.

After data unpacking, a simplified event building is performed by a time-cluster-search within a fixed time window of 200 ns. So, event candidates which are found are then selected for a minimal requirement on the T_0 and mTOF

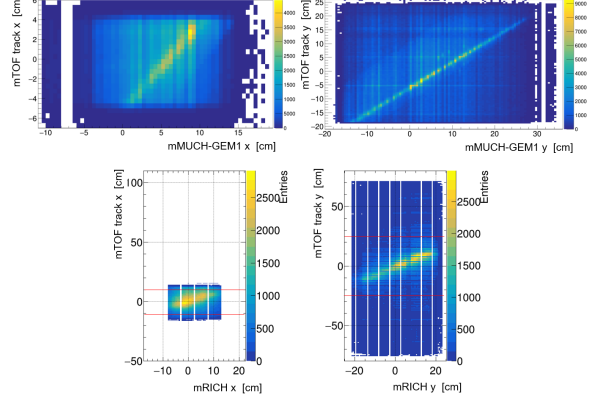


Figure 6: Correlations between spatial coordinates: mTOF tracks projected on the mMUCH-GEM1 plane vs. reconstructed mMUCH hits (top) and mTOF tracks projected on the mRICH plane vs. reconstructed mRICH hits (bottom). Data were taken in $^{208}\text{Pb} + \text{Au}$ collisions at 1.060 AGeV on May 4th, 2020, run 831. A deviation from the bisecting line is caused by alignment uncertainties.

multiplicity: $M_{T_0 \text{ digi}} \geq 1$ & $M_{mTOF \text{ digi}} \geq 10$. Subsequently, detector hits are identified by the subsystem specific cluster and hit finding. Based on reconstructed hits, mTOF tracks are formed by a tracklet search using the three layers of the mTOF triple stack configuration. Figure 5 shows the multiplicity of mTOF tracks (left side) and their corresponding normalized velocity ($\beta = v/c$) distribution (right side). An interesting feature of the β spectrum is visible, an enhancement at $\beta = 1$ (speed-of-light). That this peak is caused by electrons is supported by the fact that it is relatively enhanced by matching the mTOF tracks to reconstructed mRICH rings. Comparison to low β tracks originating from hadrons show the enormous suppression power of the RICH system already in this rather limited geometry. The potential source of these electrons is the Dalitz-decay of neutral Pions π^0 . Furthermore, the peak provides a physical calibration point for the absolute timing calibration of the TOF system.

The spatial correlations of mTOF tracks pointing to the mMUCH and mRICH planes to reconstructed mMUCH and mRICH hits are depicted in Figure 6. The observed time and spatial correlations between detector subsys-

Subsystem time offset [ns]					
mSTS	mMUCH	mTRD	mTOF	mRICH	mPSD
985	885	25	-25	310	240

Table 3: Subsystem time offsets [ns] in respect to the T_0 counter were corrected during the unpacking stage of the data analysis. The “negative” mTOF time offset is induced by a long cable connection of the T_0 counter to the mTOF system.

tems demonstrate a first conceptual verification of the triggerless-streaming DAQ system of CBM. The extension to the other detector subsystems is ongoing.

Summary The primary aim of the mCBM setup is to commission and optimize the complex interplay of the different detector systems with the triggerless-streaming data acquisition and the fast online event reconstruction and selection. In particular, it allows testing of the detector and electronics components developed for the CBM experiment as well as the corresponding online/offline software packages under realistic experiment conditions up to the top CBM interaction rates of 10 MHz.

Construction of the mCBM cave (HTD) incl. experiment infrastructure started in September 2017, directly after acceptance of the initial proposal, and was completed by mid 2018. This was subsequently followed by the setup of first detector stations. Optical fibers connect the mCBM setup with the mCBM DAQ container and furthermore with the Green IT Cube hosting the entry and processing nodes for online reconstruction and selection as well as data storage. Commissioning with beam started during the machine engineering runs in December 2018, followed by a main beam period in March 2019. With tests during the machine engineering runs in November and December 2019 we proceeded with the second year of commissioning with beam, followed by the main beam time March 27th to May 24th, 2020, which used completely the granted contingent of beam time. First results show time and spatial correlations between the synchronized data streams of the detector subsystems demonstrating for the first time a conceptual verification of the triggerless-streaming read-out and data transport of CBM.

Next Steps In the second half of 2020 major mCBM upgrades on the detector subsystems as well as on the triggerless-streaming DAQ system have started. Hence, the goal for 2021 is to commission the mCBM experiment to reach the design performance of the triggerless-streaming DAQ system and perform online event reconstruction and selection. Further high-rate tests of detector subsystems are in preparation.

	M_Λ	shifts	total N_Λ
Ni + Ni 1.93 AGeV	3.9×10^{-5}	3	100k
Au + Au 1.24 AGeV	2.2×10^{-5}	6	120k

Table 4: Rate estimation for Λ reconstruction with mCBM, taking as a basis an average collision rate of $10^5/\text{s}$, assuming a spill length of 10 s, 4 spills per minute and a duty cycle of about 0.5, which results to 9×10^8 collisions per 8h-shift.



Figure 7: Cover page of the submitted beamtime application for the mCBM experiment, June 10th, 2020.

Having established full performance, we intend to perform the 1st benchmark run in 2022 targeting Λ reconstruction in Au + Au collisions at 1.24 AGeV and Ni + Ni collisions at 1.93 AGeV. Both have the advantage of previously published data, the former by the HADES experiment [1], the latter by the FOPI experiment [2]. For the rate estimation, a Monte-Carlo simulation was performed for a feasibility study, which was presented in the first mCBM proposal (submitted to the GSI G-PAC on June 19, 2017) [3]. Since mCBM does not include a magnetic field for momentum measurement, the reconstruction has to be done via time-of-flight (TOF) and track topology. It had been demonstrated that the limited information available for Λ reconstruction is sufficient. Our rate estimation is given in Table 4.

Hence, in June 2020 we have submitted a beamtime application to the G-PAC of GSI/FAIR (see cover page, Figure 7) applying in 2021 for

- (1) 9 shifts as secondary user for the commissioning part, taken as single shifts (8h-blocks) with at least 2 days break within shifts,
- (2) 6 shifts in one block, 2 days respectively, as main user as preparation for the benchmark runs starting in 2022.

For the benchmark runs in 2022 we have applied for

- (3) 6 single shifts with at least two days break between shifts as preparatory phase and
- (4) 15 shifts in total as main user, 5 days respectively, including a setup-day (3 shifts) per collision system.

The submitted application was ranked "A" (experiment number S514) and has been therefore fully granted in October 2020 by the G-PAC (44th meeting) and the GSI/FAIR management.

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Application of the Missing Mass Method in STAR BES-II fixed target program

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The main goal of modern experiments with heavy ions, such as CBM (FAIR/GSI, Darmstadt, Germany), ALICE (CERN, Geneva, Switzerland) and STAR (BNL, Upton, USA), is a comprehensive study of the QCD phase diagram in the quark-gluon plasma (QGP) region and the possible phase transition from the hadron to the QGP phase.

Strange particles are sensitive probes of the medium formed during heavy ion collisions. However strange particles decays with at least one neutral daughter particle cannot be registered in a tracking detector system. For their identification we proposed and implemented the method of missing mass.

This method is presented for the reconstruction of $\Sigma \rightarrow \pi n$. It consists of the following steps: (a) The tracks of the mother (Σ) and the charged daughter (π) particles are reconstructed in the tracking system; (b) A neutral daughter particle (n) is reconstructed from these tracks; (c) From the charged and reconstructed neutral daughter particles, the mother particle is constructed and a mass spectrum is obtained for it from which the particle can be identified.

The missing-mass method has been repeatedly and successfully tested on simulated data of the CBM experiment, showing its relevance for the physical program of the experiment. As part of the FAIR Phase-0 program, the method has also been successfully tested offline on the $K^+ \rightarrow \pi^+ \pi^0$ and $K^- \rightarrow \pi^- \pi^0$ decay channels with real STAR AuAu collisions at $\sqrt{s_{NN}} = 200$ GeV (2016).

Here we present the results of the missing mass method with real STAR data taken in 2020 as part of the BES-II beam energy scan program with a fixed target AU+Au collisions for beam energies of 5.75, 7.3, 9.8 and 26.5 GeV/n and reconstructed online by express data processing and analysis. The method was used to search for $\pi^+ \rightarrow \mu^+ \nu_\mu$, $\pi^- \rightarrow \mu^- \bar{\nu}_\mu$, $K^+ \rightarrow \mu^+ \nu_\mu$, $K^- \rightarrow \mu^- \bar{\nu}_\mu$, $K^+ \rightarrow \pi^+ \pi^0$ and $K^- \rightarrow \pi^- \pi^0$ decays.

The launch of the new iTPC detector in STAR, as well as the fixed-target mode operation, required substantial adaptation of both the CA Track Finder and the KF Particle Finder. Express data processing was carried out on the HLT cluster under conditions of limited computer resources and disk space in order not to interfere with the traditional HLT tasks of analyzing and selecting heavy ion collisions in real time. Note also that the online reconstruction and analysis of the data in the express processing were performed with incomplete detector calibration and alignment, which created additional challenges for the reconstruction and analysis algorithms.

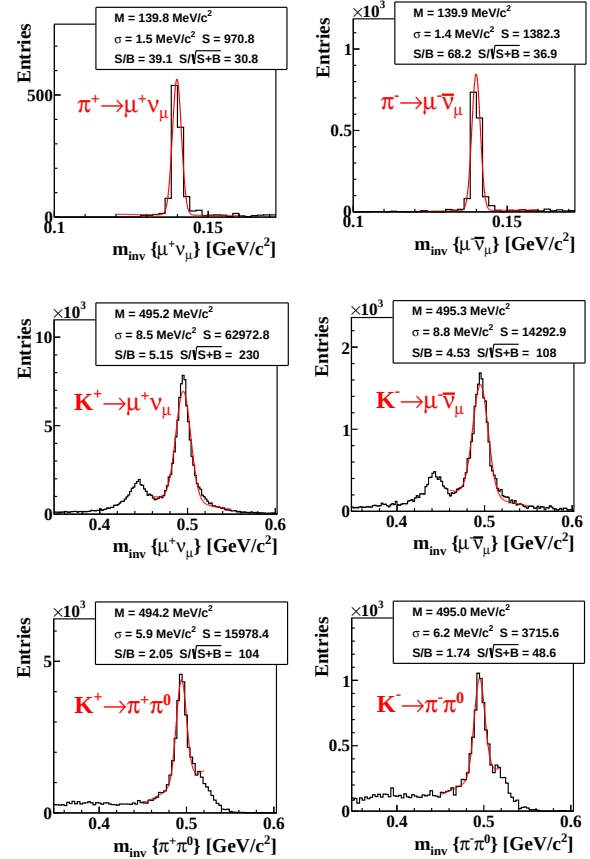


Figure 1: Invariant mass spectra of π^+ , π^- , K^+ and K^- obtained with the missing mass method cumulated for 2.2M mbias AuAu collisions at 5.75, 7.3, 9.8 and 26.5 GeV/n beam energies processed within the express production on STAR HLT farm.

The results shown in Figure 1 demonstrate the high quality of the short-lived particle reconstruction by the missing mass method in the express processing and analysis of the 2020 data. As part of the KF Particle Finder, the missing mass method can be applied to physics analysis of data for other decays as well, such as real-time search and analysis of hypernuclei.

The authors are very grateful to Dr. Maksym Zyzak for his help and advice in processing the data, as well as for his active participation in the discussion of the results.

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The KF Particle Finder approach for the on- and offline reconstruction of strange and multi-strange hyperons at fixed-target collisions in STAR

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The exploration of the QCD phase diagram is the main goal of the CBM experiment and the prime motivation of the RHIC beam energy scan program. Strange and multi-strange hyperons are sensitive probes to identify the phase boundary or the onset of deconfinement. One of the predicted signatures of the phase transition from nuclear matter to a deconfined phase is the enhanced production of multi-strange particles. Additionally the yield of particles carrying strange (anti)-quarks is expected to be sensitive to the fireball evolution and formation of the Quark Gluon Plasma (QGP).

The KF Particle Finder package, initially developed as a reconstruction tool for the CBM experiment, was intensively tested by the CBM collaboration during the last decade on the simulated data. The application of the KF Particle Finder package on real STAR data started a few years ago, and now is continuously used by STAR as one of the main tools for the data analysis. The use of the CBM KF Particle Finder package for the fast analysis of real data is also an important goal of the FAIR phase 0 program. The main goal of the STAR Fixed-Target Program is to extend the collision energy range in BES II to energies that are likely below the onset of deconfinement. The energies range from $\sqrt{s_{NN}} = 7.7$ GeV to $\sqrt{s_{NN}} = 3.0$ GeV corresponding to baryon chemical potentials from 420 MeV to about 720 MeV. The STAR experiment has taken data in Au+Au collisions at $\sqrt{s_{NN}} = 3.0$ GeV in the year 2018.

A detailed description of the experimental setup and the sub-detectors for tracking, particle identification, etc., can be found in [1]. The reconstructed STAR Time Projection Chamber (TPC) tracks were used as an input for the KF Particle package together with the reconstructed primary vertex. The z-coordinate of the primary vertex is shown in Fig. 1. The z-vertex resolution is about 1.2 mm and the center is located at -200.6 cm. The accepted

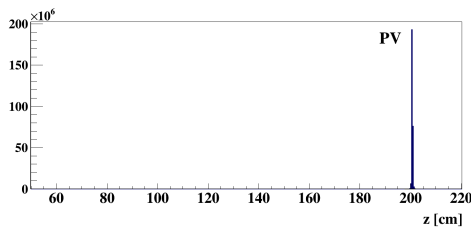


Figure 1: Primary vertex z-distribution for the Fixed-Target $\sqrt{s_{NN}} = 3.0$ GeV Au+Au collisions with clearly seen gold target. The z-vertex resolution is about 1.2 mm.

amount of minimum bias events was about $280 \cdot 10^6$. The dE/dx was used for the identification of the charged daughter particles $\pi^\pm$, $K^\pm$ and $p, \bar{p}$.

In the Fixed-Target mode strange (Λ) and multi-strange (Ξ^-) hyperons were successfully identified online by their decay into charged hadrons, using the KF Particle Finder selection technique developed for CBM. Standard CBM-like cuts on a track χ^2_{prim} , reconstructed particle vertex cut, L/dL cut and topology constrained cut χ^2_{topo} , etc are used. In Fig. 2 the reconstructed invariant mass spectra of Λ and

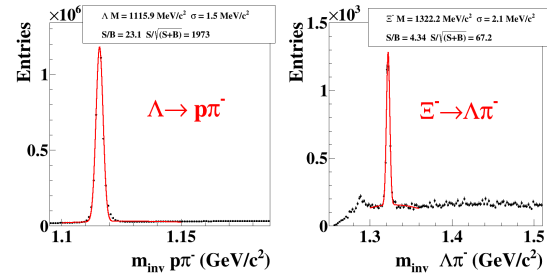


Figure 2: The reconstructed invariant-mass distribution of Λ and Ξ^- particles in Au+Au minbias collisions at $\sqrt{s_{NN}} = 3.0$ GeV, the red line indicates the signal plus background fit by a polynomial plus Gaussian function.

Ξ^- particles are shown. All signals are clearly visible with excellent signal to background ratio well above 4 even for the challenging Ξ^- hyperons. The position and width of the peaks are in a good agreement with the PDG data.

In conclusion, the KF Particle Finder package for the reconstruction of short-lived particles and their life times including strange and multi-strange hyperons was successfully tested online with the STAR BES-II data at $\sqrt{s_{NN}} = 3.0$ GeV. The most challenging Ξ^- particles are reconstructed with excellent signal-to-background ratio.

The authors are very grateful to Dr. Maksym Zyzak for his help and advice in processing the data, as well as for his active participation in the discussion of the results.

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Performance of the upgraded HADES RICH in Ag+Ag collisions at 1.58 AGeV*

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The HADES RICH, upgraded with multianode photo tube detectors (MAPMTs) and front end electronics foreseen also for the CBM RICH, was used to identify electrons and positrons in Ag+Ag collisions at 1.58 AGeV with a triggered event rate of 16–18 kHz. A total of 15.3×10^9 recorded events demonstrated the successful operation of the HADES detector setup [1] over a 4 week beam time.

The RICH was operated at ambient pressure with C₄H₁₀ (Iso-butane) as radiator gas. The spherical mirror with a radius of curvature $R = 871$ mm focused the Cherenkov photons onto two staggered photon detection planes. The two planes at $z = -80.9$ mm and $z = -208.9$ mm (with respect to the target) approximate the focal surface of the mirror resulting in rings of typically $d \simeq 45$ mm constant diameter across the whole detection area. The latter was assembled with 428 Hamamatsu H12700 MAPMTs (64 pad pixels each) connected to the DIRICH and TRB3 read-out chain. The windows of the innermost MAPMTs were coated with p-terphenyl as a wave length shifter. A more detailed description of the HADES RICH upgrade can be found in [2, 3, 4].

The present report will concentrate on detector features recently exploited to improve the quality of the measured di-electron invariant mass spectra and on a detailed study of the RICH timing performance.

A sample RICH event with a pair of Cherenkov rings is depicted in Fig. 1 and highlights the low signal background situation. Fig. 2 gives a closer look and shows the large detected photo-electron yield per ring accompanied with an excellent discrimination of single and double rings. On average about 16 fired pads are reconstructed per single ring as demonstrated in Fig. 3. The measured distribution compares well with the expectation based on full scale GEANT simulations. The large spread in radiator path length (40 - 70 cm) exhibits a varying photon yield with increasing polar angle. Even at low polar angles $\theta \simeq 18^\circ$ with smallest radiator length ($l = 37$ cm) a signal with well above 10 photons per single ring could be reconstructed.

The capability of identifying close-by double rings has been investigated in detail since it allows for an effective rejection of electron-positron pairs from external $\gamma\gamma$ -conversions and hence suppression of combinatorial background in the e^+e^- pair analysis.

The ring finder software allows to identify double rings

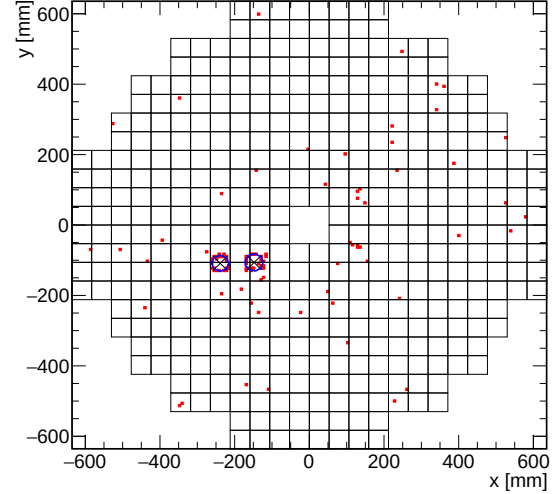


Figure 1: Single event display with two reconstructed rings. Black squares indicate single MAPMTs, red dots show registered photon hits.

with maximum reconstruction efficiency down to opening angles of about 3 degrees equivalent to a ring center distance of about 2 cm. For overlapping rings with smaller center distances the efficiency drops significantly. However, very close double rings as shown in Fig. 2 (right) can be identified by the number of fired pads in the area around an identified ring center which is matched to a reconstructed particle track. The observed pad multiplicity distribution in a fiducial area covering twice the ring diameter is depicted in Fig. 4 and exhibits two well separated Gauss type contributions for single (green) and double (red) rings. A polar angle dependent cut on a maximum of around 24 hits results in a single ring identification efficiency of 98.8% and a purity of 63.5%.

Applying this additional close pair rejection on top of an opening angle cut based on tracking suppresses the $\gamma\gamma$ -conversion further and yields a factor 6-7 improvement in the signal-to-background ratio of di-electron invariant mass spectra. The resulting signal-to-background ratio is so far unprecedented and reaches 1 already around invariant pair masses of $M \simeq 500$ MeV/c² and rises further towards the

* Work supported by GSI, BMBF contracts No. 05P19PXFCA and 05P19RGFCA, and the TRB working group

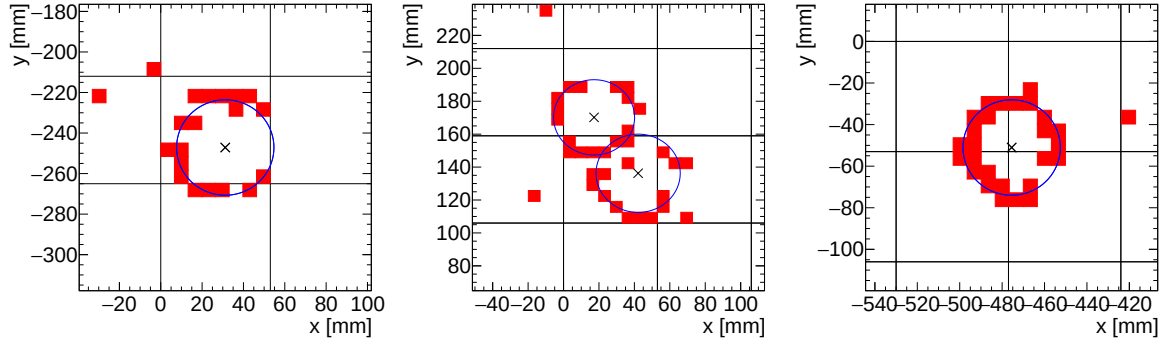


Figure 2: From left to right: Detected pad patterns for an isolated single ring, a double ring, and an overlapping double ring identified via the number of fired pads.

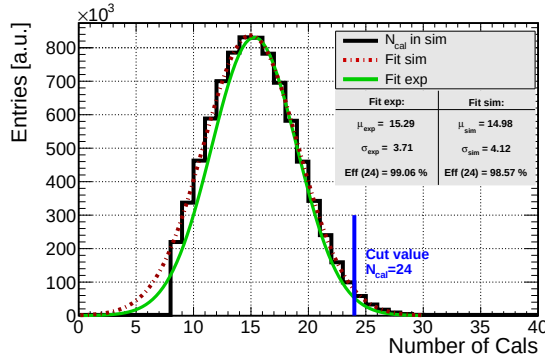


Figure 3: Number of fired pads per ring after cuts in simulation (histogram, red line) and data (green line). Both distributions are scaled to the same maximum.

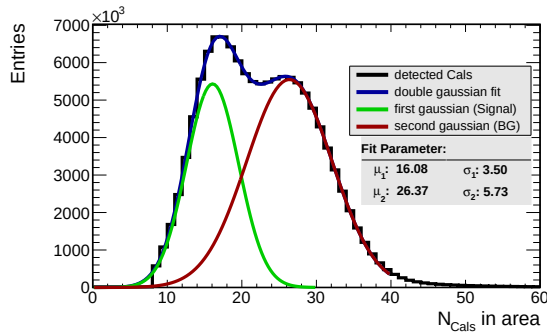


Figure 4: Number of fired pads in a radius of twice the ring radius around a found ring qualified as electron candidate.

low-mass vector-meson region.

Another key observable utilizing the fast MAPMT read-out is the achievable average timing precision. This observable is of particular importance for the upcoming CBM RICH and the high anticipated interaction rates of up to 10

MHz. Since the HADES RICH read out chain contains the same front-end boards as will be used in the CBM RICH, the available experimental data offer a good opportunity to investigate the full system timing performance.

The timing precision extracted from bare LE-ToT distributions (LE: leading edge) in heavy ion experiment data may suffer from time over threshold (ToT) and occupancy related effects. These include leading and trailing edge walk effects and artificial broadening due to capacitive cross-talk in the MAPMTs. It is not yet clear to what extent these effects can be corrected for.

In a first step we have therefore constructed a LE timing difference distribution between the HADES T_0 detector (START) signal and individual MAPMT channels. We have restricted these to fired pads on rings correlated to well identified electron track candidates in order to suppress systematic errors. In a two dimensional LE-ToT distribution we have then selected a small ToT window of 0.1 ns width only to reduce walk effects. The resulting LE time projection distribution has then been fitted with a Gaussian profile to extract the timing precision (standard deviation).

Fig. 5 shows the extracted timing precisions separated for WLS coated and standard MAPMTs. The overall timing precision is $\sigma_{LE} = 225$ ps, averaged across the whole detection area. WLS MAPMTs show a slightly worse ($\sigma = 255$ ps) precision than the remaining bulk of MAPMTs ($\sigma = 220$ ps).

The assumption of a Gaussian profile for the timing width distribution is only of limited validity, since the measured LE times are not distributed symmetrically. This is particularly apparent for the WLS coated MAPMTs which exhibit a tail in the LE time distributions with a decay constant of about 2 ns. Hence, the timing precision given above might be estimated a bit too good.

The obtained values may be compared to the average transit time spread (TTS) of the HAMAMATSU H12700 MAPMT. The latter reflects the intrinsic sensor timing precision and is listed to be FWHM = 350 ps ($\sigma \approx 149$ ps) in the data sheet [7]. In addition, the timing precision of the in-beam T_0 (START) reference signal has to be accounted

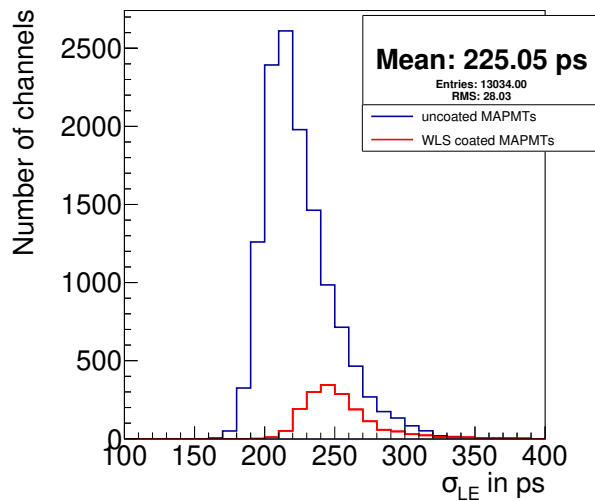


Figure 5: Widths of time difference distributions measured with the leading edges of HADES T_0 detector (START) and photon detector signals.

for. The installed CVD diamond type detector offers a timing precision in the order of 50 ps and contributes only little. In summary, the measured precision of the full system allows for a clean event selection with very low background hits in the photon detector from uncorrelated sources (e.g. scintillation light, secondary charged particles, etc.). The obtained results lay a perfect basis for the high rates anticipated at CBM.

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