

Compressed
Baryonic
Matter
experiment
at FAIR

2022

PROGRESS REPORT



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Front cover: That's how it will look like. Holographic projection of the CBM experimental apparatus into a photograph of the existing CBM cave.

Preface

The Russian attack on Ukraine on 24th February 2022 followed by sanctions caused severe consequences for the FAIR project and for the CBM experiment. The freeze of our cooperation with Russian institutes resulted in the cancelation of the Russian in-kind contributions to FAIR. The CBM experiment suddenly lost the superconducting magnet, the Projectile Spectator Detector (PSD), mechanical structures for the RICH and the MUCH setups, the MUCH hadron absorbers, a forward time-of-flight detector, an assembly lab for the STS, and, last but not least, about 20% of the collaborators. In order to mitigate the consequences of these losses, the GSI/FAIR management defined a list of high priority projects including the CBM magnet, which should be financed by available project funds.

The CBM collaboration has immediately started activities in order to compensate the lost items. Detailed functional specifications of the CBM dipole magnet have been worked out together with GSI experts, and the call for tender has been released in January 2023. Our Czech colleagues are designing a new scintillator-based forward detector to replace the PSD, the RICH and MUCH groups intend to build prototypes and inquire additional funding sources for the construction of the mechanics and the gas systems, and the STS team is upgrading the assembly capacities in the GSI detector laboratory.

Two important sources of funding for CBM, the EU CREMLINplus project and the Russian-German Roadmap, which originally were devoted to support joint Russian-European or JINR-FAIR projects, have been refocused on activities in Europe (EURIZON) and for FAIR/CBM.

The international Committee for “First-Science and Staging Review of the FAIR Project” submitted a report to the FAIR Council in October 2022. The committee recommends to prioritize the completion of SIS100 with beams into the S-FRS (“First Science”) plus setting up and commissioning of the CBM experiment (“First Science +”) in order to offer a world-class science program at FAIR. This recommendation acknowledges the CBM physics case and supports the timely realization of the CBM experiment.

Despite the adverse conditions resulting from the war in Ukraine, the CBM collaboration made in the year 2022 substantial and, we think, impressive progress towards the realization of the project, which is once again documented in this report. We thank all collaborators for their engagement in the CBM experiment and all authors for their contributions to this volume.

Darmstadt, February 2023

Peter Senger

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Several of the contributions to this volume also appear in the GSI Scientific Report 2022.

Executive Summary: Status of the CBM Experiment

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In the beginning of 2022 CBM was well on track to start the execution of its long awaited physics program in 2025. However, in February 2022, with the beginning of the Russian war in Ukraine the plans had to be revised. The CBM experiment lost major parts of its setup, the former Russian in-kind contributions of the superconducting dipole magnet, the projectile spectator detector (PSD), mechanics and gas systems of RICH and MUCH and parts of the STS assembly infrastructure. In addition, it became clear that the timeline of FAIR cannot be kept due to the sanctions imposed on Russia. An international commission was setup to evaluate the scope of FAIR considering cost and science reach. The current proposal is to focus the resources on initially constructing a reduced facility called *FS+* which contains CBM in its original scope. A new timeline is still being discussed at the time of writing this report. Tentatively, 2028 is targeted as a new starting date of beam on target operation of the SIS100 machine.

The main focus of the work was to consolidate the preparations of the subsystems and find replacements for the missing items. The shifted FAIR schedule also enforced a new timeline for CBM and allowed to reconsider design choices made 20 years ago. Thus the PSD will be replaced by a highly granular scintillator wall and the STS will be modularized.

The most significant achievements reached in 2022 are briefly described below, more details can be found in the body of this progress report.

Common Systems

Cave and experiment integration The shell construction of the CBM building was completed in 2022 up to the ground level. Inside the cave, the crane was installed and is now operational for installation tasks. Furthermore, the steel support structure of the upstream platform was tendered (CAS in-kind), the construction of the magnet foundation is in preparation and a new concept for the rail system was approved and is being prepared for tendering in 2023. Design work on the RICH-MUCH platform had to pause as the developments on the mechanical integration for both detector systems was frozen. On the beam pipe system, the section downstream of the RICH and MUCH was produced (excl. bellow) and tested end of 2022. The produced beam pipe section measures 14.25 m in length and is divided in several parts providing vacuum inlets for pumps and pressure sensors.

Magnet An important milestone could be reached in 2022 by working out and fixing the functional specifica-

tions of the CBM s.c. dipole magnet, hand in hand with GSI experts. The adapted design provides a larger gap to host a modified STS. Accordingly, the call for tender could be released in January 2023.

DAQ/FLES To proceed on developing and optimizing the DAQ and data transport system for CBM, the mCBM experiment was populated with additional CRI boards (v1.0 produced at BNL). In this regard, the Infini-band bandwidth to the Green-IT-Cube was doubled as well as the disk storage capacity significantly increased. With the upgraded readout system several mCBM beam tests were performed with collision rates up to 10 MHz collision using heavy beams between March and July 2022 and, stable operation over long periods was achieved for successful data taking during the benchmark runs.

Computing The computing and software activities were focused on the development on an online-capable system to digest the extreme data rates CBM will deliver. While the main software components for event reconstruction and analysis are at hand and being used offline with simulated data, their adaption to the special needs of real-time, parallel computing requires significant development efforts. Substantial progress was made in the development of a prototype online processing system which is intended to be used in data taking for the next mCBM beam campaign in 2023 - 2025. This system will enable selection of event data in real-time with respect to Λ baryon candidates and will serve as a demonstrator for the full CBM experiment.

Detector Systems

BMON The Beam MONitor detector system (BMON) for the CBM experiment will provide beam monitoring as well as time-zero (T0) measurement. For the 2022 beam campaign, a prototype sensor based on poly-crystal (pc) chemical vapour deposition (CVD) diamond technology (pcQVD) has been installed in mCBM, integrated inside the vacuum vessel of the target chamber. The metallization of the $1 \times 1 \text{ cm}^2$ diamond sensor is partitioned in 16 strips on both sides, vertically and horizontally aligned. The new T0 diamond counter was successfully operated with up to 4×10^8 Au-ions per spill providing very useful beam monitoring as well as stable T0 information with excellent time-resolution in the mCBM data stream.

MVD As a main task for 2022, the extensive beam test program was continued validating MIMOSIS-1, the first

full-size pixel sensor for the CBM Micro Vertex Detector (MVD), which has paved the way towards the submission of MIMOSIS-2. These activities have been accompanied by a systematic evaluation of the TPG-carrier quadrant regarding integration yield and thermal performance. Furthermore, a stand-alone TRB-based readout is being prepared for future sensor characterization during the series production period of the MVD.

STS As the major activity in 2022, a modular design of the Silicon Tracking System (STS) was introduced, splitting into an upstream and a downstream building block while leaving its internal components unchanged. In preparation of STS production readiness for detector module and ladder assembly, 10 pre-series modules were assembled with all final (or most recent) prototype components at GSI. The assembled detector ladders will be mounted in an upgraded E16 experiment at J-PARC through our collaboration partners at KEK. Furthermore, the read-out ASIC STS-XYTER v2.2 was series-produced in UMC 180 nm technology. 100 wafers of 350 ASICs each were delivered to AGH as the in-kind provider. During mCBM's 2022 beam time with heavy-ion collisions at SIS18, the mSTS contributed to the acquisition of new data.

TRD The pre-production of Transition Radiation Detector (TRD) modules for the outer detector region has started, which is an important step towards the production readiness review. Detailed physics performance studies were performed for the TRD-2D (inner region), demonstrating a substantial acceptance gain in the low-pt region with a modified setup. The TRD-2D prototypes installed at the mCBM experiment were successfully operated, providing important data for the data-driven detector alignment and track reconstruction.

MuCh Two modified full-size prototype GEM stations of the CBM Muon Chamber (MuCh) system have been installed in mCBM as well as for the first time a full-size MUCH RPC detector module. To overcome the observed read-out instabilities, the HV distribution of the GEM detectors was modified as well as the drift PCBs of the GEM stations. Accordingly, the read-out stability has been significantly improved and, hence, the performance of the GEM stations was systematically studied in rate scans with U- and Au-beams up to 10^9 /spill beam intensity. Moreover, the RPC was successfully integrated into the mCBM DAQ system and operated during data taking with Au-beams.

RICH In 2022, the progress of the Ring Imaging Cherenkov (RICH) detector was severely affected by the termination of our collaboration with PNPI Gatchina as a result of the Russian invasion of Ukraine. However, first important steps have already been taken to close the gaps left by the Russian partners. Most importantly, the re-design and re-prototyping of the entire RICH mechanics was started. Undisturbed from those developments

was the successful production of the first photo-detector plane, which is presently used for testing the handling, mechanical stability, and the cooling system. Moreover, the power module of the RICH electronics has been successfully tested to work with low noise DCDC converters and the next batch of DiRICH electronics is about to be produced. Software developments saw a strong increase in the inclusion of AI routines for background suppression or ring finding.

TOF A major milestone for the Time-of-Flight Detector (TOF) was achieved with the acceptance of the CDR on the mechanical structure of the wall. A real size mock-up frame for the lower part of the central column of the TOF wall was installed for studies of stability and interfacing to the infrastructure. After realizing the gas pollution effect when operating MRPCs at high particle fluxes new, gas-guided prototypes of different granularity were designed, build and tested new gas guided prototypes in order to study and mitigate counter aging. An improvement could be observed in this regard even-though the reached intensities were not fully sufficient during the mCBM campaign 2022 to draw final conclusions.

Forward Wall The Czech group, who was also involved in the construction of the PSD, proposes to build a new, scintillator-based forward detector system with a Silicon photo-multiplier (SiPM) readout, and, hence, will apply for funding from the Czech ministry.

Physics Performance Studies

In the context of the scientific evaluation of the FAIR project The capabilities of the CBM experiment were scrutinized with respect to the currently most relevant physics observables: criticality (proton number fluctuations), emissivity (di-lepton yields and spectra), global polarisation (alignment of hyperon spins with reaction plane) and hypernuclei production (yields and branching ratios). It could be demonstrated that the CBM experiment with its design goal of a peak rate capability of fully analyzed 10^7 interactions per second is world wide unique and will offer otherwise impossible new insights to the properties of dense baryonic matter.

To obtain stable and reproducible results common productions were executed employing well tested and documented software releases operating on well defined experiment setups whose versions and history is also maintained in git repositories. Efforts are ongoing to include all background sources as realistically as possible.

FAIR Phase-0 experiments

CBM detector technology, the free-streaming DAQ and data transport system and packages of the CBM online/offline software are presently being used at running experiments of the FAIR phase-0 program and, hence, are

being extensively tested and further optimized under realistic experiment conditions.

The mCBM experiment at SIS18 The primary aim of the mCBM experiment is to test prototypes or pre-series productions of the CBM detector systems and to commission and optimize the complete data chain developed for the CBM experiment under realistic experiment conditions. In 2022, a series of systematic high-rate studies were performed explicitly for the MUCH and TOF detector system using heavy beams yielding up to 10 MHz collision rate. The data analysis of the extensive rate scans is ongoing.

To further validate the read-out and data processing concept of CBM, the production yield of Λ baryons is studied serving as a benchmark observable, which will allow comparison with published data. Since the Λ baryon is a rare probe at SIS18 energies the reconstruction of Λ baryons with the mCBM experiment is an adequate test case for CBM. Accordingly, first benchmark runs were measured in May 2022 taking Ni + Ni collisions at 1.93 AGeV and in June 2022 measuring Au + Au collisions at 1.23 AGeV. Data analysis steps like calibration, track reconstruction and data-driven detector alignment have been further optimized, serving as a prototype data analysis chain for CBM. Having scanned a fraction of the measured statistics a clear Λ signal has been identified for Ni + Ni collisions at 1.93 AGeV.

The CBM RICH photon detector at HADES In 2022 the HADES detector had 4 weeks of beamtime collecting p + p data at two energies. The RICH detector was running with excellent stability and performance. First performance analysis show very stable results compared to the last beamtime in 2019 and first physics analysis an excellent quality of electron-identification.

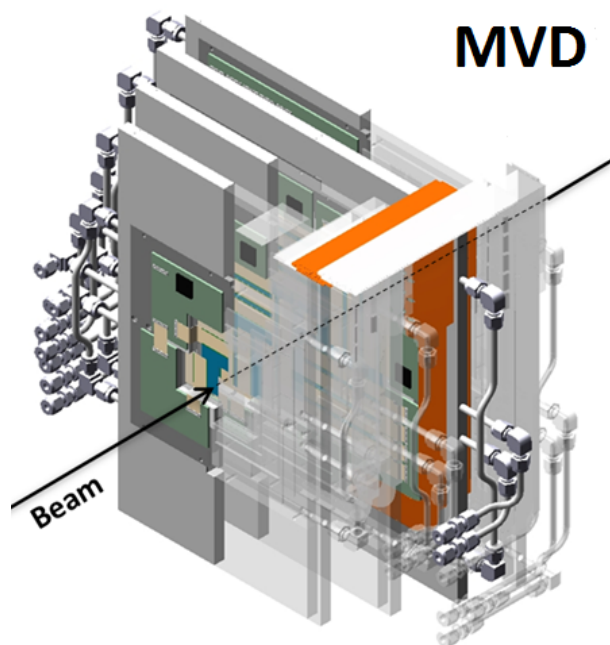
The end-cap TOF at STAR using CBM TOF RPC modules After the successful data taking in the years 2019 - 2021 the calibration of the eTOF-subsystem has now reached a maturity that mayor production runs can be executed. Important goals of the project could be demonstrated, e.g. an overall system timing resolution of better than 80 ps was reached, even with partially damaged electronics. After properly dealing with the observed deficiencies a matching efficiency of eTOF hits to TPC tracks of about 50% can still be obtained although this is significantly lower with respect to the 70% of the fully functional system. The observation of the damages under long term running conditions is used to strengthen and improve the eTOF system components.

Towards commissioning of CBM

Summarizing the current situation the CBM collaboration successfully dealt with all the difficulties and is back on track again for start of operation with the first ion beams extracted from the SIS100 machine, expected to happen in

2028. To realize a smooth and efficient startup time it is of utmost importance to train the experiment components under realistic conditions. This includes the full data acquisition and analysis chain which needs to be setup in a user-friendly way and operable by non-experts. While the basic chain is already realized in mCBM now, the implementation of production algorithms, their optimization and the control of the complex system is a challenging task with many opportunities for improvements. Looking back to the experiences and achievements in 2022 the collaboration appears to be well set to master these challenges.

Micro-Vertex Detector



Micro Vertex Detector - Summary*

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Abstract: 2022 was dominated by the continuation of the extensive beam test program validating MIMOSIS-1, the first full-size CBM MVD pixel sensor, and by the design completion of MIMOSIS-2, the last prototyping sensor before MIMOSIS-3, the day-1 sensor. The MIMOSIS-1 test data analysis and its outcome were all integrated in the design of MIMOSIS-2, presently being fabricated. These activities have been accompanied by a systematic evaluation of the TPG-carrier quadrant regarding integration yield and thermal performance. Developing a stand-alone TRB-based readout represents a prerequisite for future sensor characterization during production of the MVD.

Sensor: The development of MIMOSIS has passed a crucial milestone with the validation of the full-scale prototype MIMOSIS-1, conducting test beam and irradiation campaigns. Its characterization has shown that several of its design variants comply with the radiation tolerance and the precision in spatial hit reconstruction required for the MVD. E.g., the "p-stop" epitaxial layer variant combined with AC pixels provides excellent detection efficiency, exceeding 99.5 % even after a radiation load corresponding to the end of lifetime dose, together with a spatial precision ranging from about 5 to 6.5 μm , depending on the load and the in-pixel discrimination threshold.

SEE might be triggered by heavy ions and fragments, eventually leading to a damage of the sensor. The analysis of a test campaign with a several AMeV Ca beam at the GSI/UNILAC M3 beam line, translating in a LET of 20 MeV cm^2/mg , yielded an upper limit of the latch-up cross section, since no latch-up has been detected.

Fragment PID: Operating the MIMOSIS-1 telescope in the deuterium beam of COSY allowed to assess particle ID capabilities of the sensor. For the overall low cluster multiplicity due to reduced charge sharing, a damped sensitivity on the particle's energy loss is observed, still more pronounced for DC-coupled pixels because of their reduced epitaxy depletion. This, propagated to all sensor hits per track and accounting for a potentially increased active volume, might supplement the PID power of the CBM Si tracker.

The results have produced the necessary ingredients and improvements to progress towards the last prototyping step, namely the fabrication of MIMOSIS-2, currently in progress at the foundry.

Sensor integration, QA and readout: The day-1 MVD will employ the tracking (TR) detector geometry with four equidistant stations between 8 and 20 cm downstream the target. Hence, the focus is put on sensor integration of stations with TPG carriers, suggesting to further characterize and optimize the quadrant design. The thermal performance of this module is well understood and in specs. The baseline layout, employing doubled-sided sensor integration, has been re-evaluated w.r.t. integration yield. A ladder-based concept is not recommended, due to alignment and acceptance issues. Separating front and backside sensor integration would translate in an increased material budget and an additional, risky post-merging of two large-area TPG sheets with follow-up issues regarding vacuum compatibility and alignment. A more aggressive PGS-foil/RVC carbon foam based solution would require a factor of about five lower power dissipation of the sensor to meet the specs.

Quality assessment, important for the production phase, is being tackled by developing a dedicated probe-card and multi-purpose read-out electronics for sensor characterization. The readout board (IKF proxy) is already in operation, so far focusing on DAC scans. It uses the existing TRB5sc FPGA platform with a custom Add-On. Only firmware development and preparing the ROOT (DABC, Go4) analysis package required.

Detector services - Cooling: NOVEC-649 was confirmed as the baseline cooling fluid, by means of small-scale setup in vacuum allowing for systematic measurements of temperature differences, 2D temperature distributions of a TPG carrier mounted in a MVD heat sink, introducing a realistic power entry guided by MIMOSIS-1. The studies yield an estimate for coolant flow of MVD of about <20 l/min, allowing for planning the MVD cooling service, eventually together with the STS,

Simulations: A systematic survey on the MVD physics performance has been started by getting the existing software package of MVD up-to-date and focusing on questions related to acceptance for the beginning. The detector geometry and realistic material budget are being revisited, employing charge pions as benchmark probe for tracking performance. A key question will be the interplay between the MVD and the STS regarding tracking of e.g. low-momentum charged particle tracks and background issues in dielectron measurements.

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MIMOSIS Sensor Prototype - Development Update*

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MIMOSIS is the CMOS monolithic active pixel sensor developed to equip the CBM Micro Vertex Detector (MVD). The sensor development has passed a crucial milestone with the validation of MIMOSIS-1 as a first full-scale prototype being able to fulfill ambitious experiment requirements. The intense MIMOSIS-1 test program has been continued in 2022 along with the MIMOSIS-2 design. The MIMOSIS-2 comprises improvements resulting from the tests of its predecessor and introduces new functionalities. It was sent to production in January 2023 and is expected to be fabricated and tested in the months to come.

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MIMOSIS-1 test results: A comprehensive introduction of the MIMOSIS-1 detector is given in [1]. In 2022, further MIMOSIS-1 characterizations were performed, comprising three test beam campaigns at DESY, COSY and CERN. Two of them, at CERN and DESY, complemented studies done in 2021 on measurements of detection efficiency and spatial resolution with a focus on sensors being previously irradiated with consecutive (mixed) neutron and X-Ray irradiation. In particular, we studied the sensor performance after applying the anticipated end-of-lifetime dose of $1 \times 10^{14} \text{ n}_{\text{eq}}/\text{cm}^2$ and 5 MRad. Moreover, the sensor response to inclined tracks was measured. The last test beam at COSY was devoted to the sensor capacity to identify nuclear fragments, using the cluster multiplicity as a probe of the fragments' linear energy transfer.

The most up-to-date results of key MIMOSIS-1 features can be found in Fig. 1. The example of the “p-stop” epitaxial layer for AC pixels is shown, proving excellent detection efficiency, in excess of 99.5 % even after a radia-

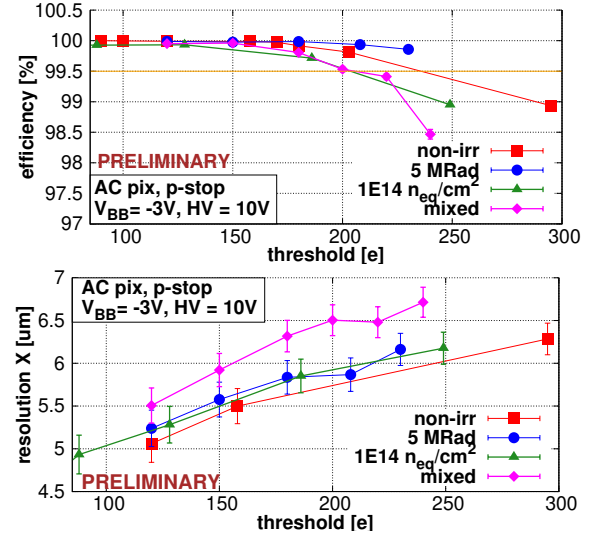


Figure 1: Detection efficiency (top) and spatial resolution (bottom) for AC pixels as a function of in-pixel discrimination threshold, for various sensor radiation loads.

tion load corresponding to the anticipated end-of-lifetime dose. The spatial resolution is ranging from about 5 to 6.5 μm, depending on the radiation load and in-pixel discrimination threshold. The resolution is still subject of a refined analysis incorporating improvements of the telescope and Device Under Test alignments. The analysis of the data collected with inclined tracks is still on-going.

MIMOSIS-2 submission: The pixel matrix of MIMOSIS-2 will feature the two most promising pixel flavors out of the four incorporated in MIMOSIS-1. The largest part of the pixel array (896 columns out of 1024) is composed of AC-coupled pixels. The remaining 128 columns keep ALPIDE-like DC pixels [2], foreseen to serve as reference.

The design of MIMOSIS-2 improves a number of individually minor weaknesses, which were spotted during the test of MIMOSIS-1. This includes improvements of the analog test output of the pixels, the DACs for steering the matrix, the clock tree and the phase-lock loop (PLL). Significant layout optimizations were implemented to alleviate voltage drops of the power grid causing discriminator threshold shifts across the pixel array [3]. Moreover, a triple-vote logic implemented in the sensor digital circuits was completed, as well as the on-chip clustering circuitry.

MIMOSIS-2 is being fabricated on a 25 μm thick high-resistivity epitaxy as MIMOSIS-1, as well as with a 50 μm

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thick epitaxial layer expected to benefit to the sensor spatial resolution and non-ionising radiation tolerance. The fabrication of MIMOSIS-2, started in January 2023, is expected to end in May.

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SEE tests with MIMOSIS-1 at GSI's M3 Beam Line*

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MIMOSIS-1 is the first full-size prototype for the final CMOS Monolithic Active Pixel Sensor (MAPS) called MIMOSIS, which is foreseen to equip the CBM-MVD. MIMOSIS-1 was tested in various beam tests to assess its vulnerability to Single Event Effects. This report summarises activities performed within a dedicated SEE beam test in the medium LET and high intensity range.

Requirements. Besides having to cope with occasional impacts of slow target fragments with a linear energy transfer (LET) of $\sim 45 \text{ MeV cm}^2/\text{mg}$ [1], MIMOSIS will have to withstand sizable amounts of relativistic heavy ion impacts. Most of these relativistic ions are expected to stem from the beam halo. Beam halo ions travel significantly outside the ca. 1 mm radius focused ion beam, and feature a kinetic energy close to the beam energy. Additionally, the sensor can be impacted by the full 10 MHz SIS100 beam, should the beam steering malfunction. The sensor's design specifications mandate the sensor to withstand a constant beam ion flux of 10 Hz/mm^2 without frequent loss of functionality, and to tolerate a full beam impact of 300 MHz/cm^2 until the beam abort triggers ($\gtrsim 100 \mu\text{s}$) without destruction of the sensor [2]. These relativistic ions at SIS100 energies have a LET of $< 20 \text{ MeV cm}^2/\text{mg}$.

Beam characteristics and results obtained. Tests on MIMOSIS-1's tolerance against SEEs have previously been conducted, albeit in non-dedicated beam tests as a parasitic user with little control over the beam characteristics [3]. A first dedicated beam test was conducted in 2022 at GSI's M3 UNILAC beam line. The supplied Ca beam had a kinetic energy of 4.8 A MeV , which was reduced to $\sim 2.8 \text{ A MeV}$ after traversing a Kapton vacuum pipe window and $< 5 \text{ mm}$ of air. Beams of this energy penetrate Si and Al only for some tens of μm . Two independent SRIM simulations confirmed that the ions indeed reach the depth of the transistors when the sensor is top-illuminated. The LET deposited in the relevant depth in Si amounts to $\sim 20 \text{ MeV cm}^2/\text{mg}$ under the assumption of ions fully stripped of their electrons. The usage of a low-energy ion beam allowed to shield the sensor by means of a $600 \mu\text{m}$ thick Aluminum sheet, in which holes were cut out with a precise laser cutter. This allowed to focus on individual structures on the sensor and to probe them independently one from another. The mask was then placed above the sensor with a microscope and the regions not under test could be covered with Aluminum tape.

In total, about 60 % of the sensor was exposed to the beam. The area covered all potentially vulnerable struc-

tures as chosen by the designers of the sensor and thus can be considered representative for the whole sensor. The regions under test were illuminated with a beam intensity of $\sim 10^7 \text{ Hz/cm}^2$ up to an integrated fluence of $\Phi = 3 \times 10^{10} \text{ ions/cm}^2$. The beam was operated with a 2.5% duty cycle of 5 ms long spills, turning into an exposure of the sensor to beam intensities of $\sim 400 \text{ MHz/cm}^2$ during the spills. This confirmed *en passant* the requirement of the beam loss scenario.

Contrary to our initial expectations based on [3], no latch-ups were observed. With this outcome, one gets a latch-up cross-section upper limit. When calculated according to [4], it amounts to:

$$\sigma < \frac{3.7}{3 \times 10^{10} \text{ ions/cm}^2} = 1.2 \times 10^{-10} \text{ cm}^2,$$

where the factor 3.7 is chosen to associate the upper limit to 95 % confidence. The sensor reacted in fact strongly to hits nearby its DAC circuitry, confirming the hypothesis of a faulty Hamming code protection. For the fluxes available at the facility, the current drawn by the sensor fluctuated with every ion bunch, hampering the possibility to quantify a precise bit-flip cross-section.

Conclusion. MIMOSIS-1 was validated for its resistance to SEEs caused by relativistic beam ions. No latch-ups were detected. A precise bit-flip cross-section could not be given due to constraints on the fluxes available at the test facility. This also indicates to interpret signatures previously identified as latch-ups in [3] rather as bit-flips. A more thorough description and discussion of all SEE tests conducted can be found in [5].

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Exploring Particle Identification Capabilities of MIMOSIS*

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The future MIMOSIS sensor is not optimized for performing particle ID by means of linear energy transfer, i.e. dE/dx , analysis. Its $27 \times 30 \mu\text{m}^2$ small pixels are equipped with a discriminator, which masks the signal amplitudes. The $25 \mu\text{m}$ thin active medium provides a most probable signal remaining below 2000 e, moreover with sizable Landau fluctuations. Still, CMOS Monolithic Active Pixel Sensors (CPS) like MIMOSIS show charge sharing between individual pixels. The number of pixels per hit cluster correlates with the particle dE/dx , which allowed to identify nuclear fragments with previous generation CPS [1]. Based on this observation, we studied if light nuclear fragments such as relativistic alpha particles could be identified with MIMOSIS. If so, this might help identifying e.g. hyper-matter decaying within the CBM-MVD.

We operated our MIMOSIS-1 telescope in a deuterium beam at the COSY synchrotron. The beam momentum was 0.8 GeV/c or 1.4 GeV/c, creating a mean dE/dx of 1.58 keV/ μm and 0.77 keV/ μm , respectively, according to the Bethe-Bloch equation (as computed with the online tool Beamcalc [2]). This corresponds to about four and two times the dE/dx of a minimum ionizing particle, respectively. The 0.8 GeV/c beam provides the same dE/dx as expected for “minimum ionizing” alpha particles.

Sensors with DC-coupled pixels on standard epitaxial layer (split 1) and with AC-coupled pixels with p-stop (so-called “split 4”) sensing element as introduced in [3] were tested. The first pixel type is only partially depleted, which favours charge sharing and thus a high cluster multiplicity. The latter pixel type is optimized for depletion by means of additional implants and a $\sim 13 \text{ V}$ instead of $\sim 4 \text{ V}$ depletion voltage, which improves radiation tolerance on expense of charge sharing.

Figure 1 shows the average hit cluster multiplicity of MIMOSIS-1 as a function of the pixel discriminator threshold and the beam properties. Results collected with same setup at the 5 GeV electron beam of the DESY beam test facility are displayed as reference. Best results are reached for the split 1 DC-pixels (upper panel). Here, a relativistic alpha particle would provide at least twice the mean cluster multiplicity of a minimum ionizing particle. The radiation hardened “split 4” AC-pixel type (lower panel) shows a substantially reduced identification power.

The first results shown suggest that the MVD may provide a restricted particle ID capability. This holds despite an overlap of the cluster multiplicities is to be expected due to Landau fluctuations, which remains to be studied. More-

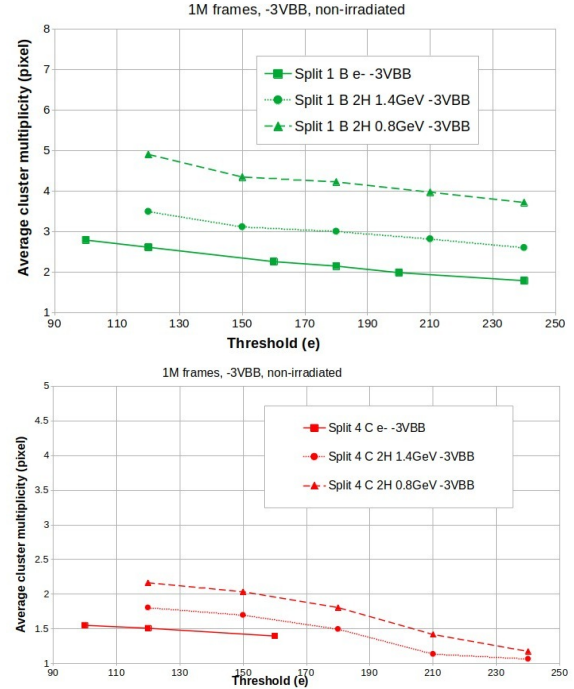


Figure 1: Average cluster multiplicities vs. in-pixel discriminator threshold, for two deuterium momenta and compared to electron beam results. See text.

over, the potential needs to be balanced with the required radiation tolerance of the sensors. Improved compromises may be reached with MIMOSIS-2. This sensor optionally features a thicker ($50 \mu\text{m}$) active volume, which is predicted to provide simultaneously a increased signal amplitude and charge sharing. This will most likely come out as beneficial for both aspects of the sensor response.

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Towards probe-testing the MIMOSIS sensor family *

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The MIMOSIS sensor [1] for CBM-MVD is currently being developed and characterized. Its second, upgraded, version was submitted for production and it is expected to be available for testing in 2023. All MIMOSIS upgrades are compatible w.r.t. the location of bonding pads and the sensor form-factor with their predecessors. This allows already now to develop probe-card and multi-purpose read-out electronics for sensor characterization and preparing sensor QA procedures. This report will summarize the status of the test system development.

Status of the readout boards: The readout board, called also "IKF proxy" and adapter cards (see figure 1(1) and figure 1(2) and (3) respectively) were delivered in Q1/22 [2]. The components were assembled and the cards were debugged, production flaws have been fixed and the board was set into operation. The use of fine-pitch components places high demands on the assembly and recommends to review the board design and selection of components to increase the production yield in upcoming iterations.

Status of a dedicated probe-card: A simple probe-card comprises two major components: the host PCB and the dedicated connector with needles mounted in a dedicated slot (see figure 2(1)). The probe-card proposed will be a passive PCB providing mostly interconnections between sensor pads and the IKF Proxy card with the mechanical stability and precision required. The two probe-card PCBs were produced and one of them has been sent to the Probecard Division of htt Group company [3] for mounting the connector with probe needles. This step is required for gaining experiences with all mechanical and electrical challenges before arriving to the final version of the probe-card for MIMOSIS sensor family, which will then be distributed to our partners for sensor QA. Having the probe-cards in hand will allow for applying dedicated test procedures, which will emerge from already existing sensor characterization routines, so far used for more elaborated test procedures applied to MIMOSIS-1.

Outlook: We expect soon to routinely probe-test the MIMOSIS sensors as well as to address questions regarding the maximum FPC length tolerated by the MIMOSIS chip, necessity of a double-layer FPC design, existence of passive filters in a vicinity of the sensor, direct powering

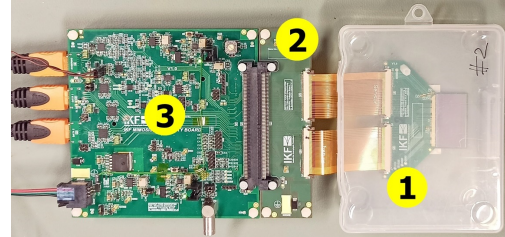


Figure 1: MIMOSIS-1 sensor mounted on a dedicated PCB (1) and connect by means of the two FPC cables and the adapter board (2) to the readout electronics (3) .

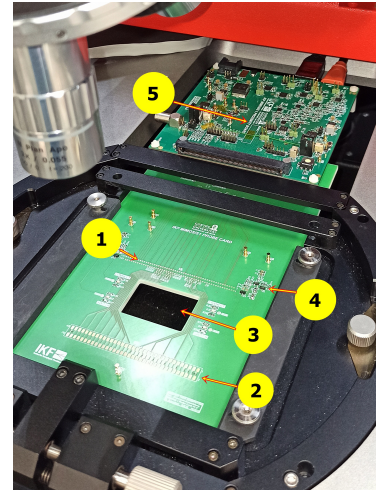


Figure 2: The probe-card PCB: (1) Connector for mounting the needles. (2) Connector for electrical integrity checks. (3) A hole for the needles. (4) Passive components co-operating with edge needles. (5) The IKF Proxy

from the FEAST DC/DC converters, as well as, implementation of an over-current protection and current monitoring.

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Alternative carrier concepts and material validation*

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For the largest CBM-MVD module (representing a station quadrant), three alternative sensor integration concepts are under evaluation, also allowing for the verification of thermal performance of the chosen material. The thermal simulation package ThSim was calibrated on these measurements and subsequently also employed to elaborate on comparing the different concepts on their performance. A preliminary recommendation which designs to pursue is given.

Following up on last years progress report [1], the thermal properties of the chosen carrier materials were verified inside the vacuum chamber UFO. A TPG strip (8 cm by 2.5 cm by 380 μm thick TPG [6]) and a PGS compound strip (8 cm by 2.5 cm by 40 μm thick PGS [5] and 2 mm RVC [4]) were built. Figure 1 (top) compares measured values to the manufacturers specifications, as well as reference measurements with copper and other results [7]. The findings show that the manufacturer significantly understates the actual thermal conductivity and allowed for more accurate simulations of the proposed carrier designs with ThSim [2], a simple SPICE-based [3] thermal simulation software. The resulting temperature differences ΔT , figure 1 (bottom), turned out to describe the measurements within ± 1 K, validating ThSim as a feasible tool for carrier optimization, i.e. studying ΔT vs. sensor power density for different configurations.

Calling for $\Delta T < 10$ K, the options "Baseline", "Ladder" (option 1) and "TPG150" (option 2a) show the best performance (TPG based) for the expected MIMOSIS power density ($O(100) \frac{\text{mW}}{\text{cm}^2}$). The PGS based option is competitive only if the sensor power density falls below $O(25) \frac{\text{mW}}{\text{cm}^2}$. The selection is further constrained by the viability for mass production and mechanical stability, leaving baseline and option 2a as the two most likely candidates. The next step is now to produce full-scale prototype carriers of each chosen design for further characterization.

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* Project funded by BMBF (05P21RFFC2), GSI and HIC for FAIR

+ Post-doctoral position funded by EU project EURIZON.

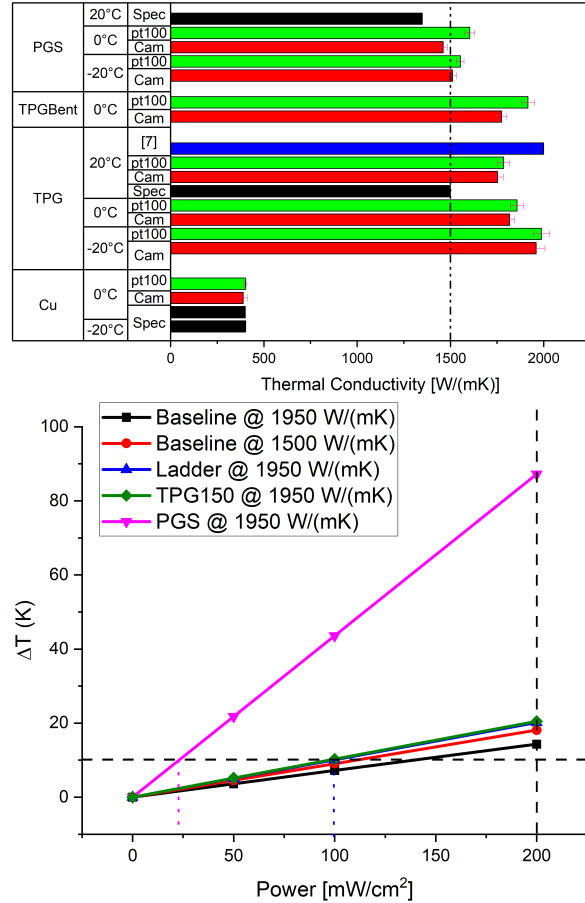


Figure 1: Top: Measured thermal conductivity of material strips. "TPGBent" denotes a measurement where the strip sample was bent at a 90° angle then straightened back out to simulate possible damages. Bottom: Simulated temperature difference for various carrier design options (see text) vs. sensor power density. Dashed lines: pursued ΔT (horizontal), resulting power densities (vertical).

Using Novec-649 as the Coolant for the MVD*

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The feasibility of Novec-649 as the coolant for the CBM-MVD using the latest generation of heat sinks and the baseline carrier design has been evaluated in a small-scale prototype of the MVD cooling loop. The measured performance is in agreement with expectations from simulations and analytical estimates. Operation at temperatures below 0 °C with temperature differences on the carrier not exceeding 10 K, is reached with a moderate flow assuming the power consumption of MIMOSIS-1 sensors.

The thermal performance of the largest TPG-based quadrants is evaluated by measuring the temperature on different points on the carrier and on the heat sink for different coolant temperatures and flows with Pt100 temperature sensors in a vacuum. The heat dissipation of the sensors is mimicked with heating foils on both sides on the carrier. Details of the setup and theoretical considerations can be found in last year's progress report [1] and a dedicated CBM Technical Note [2].

The results are displayed in figures 1 and 2. The temperature difference increases linearly with the power and decrease with the flow for turbulent flow as expected from theoretical predictions. Efficient cooling relies on a flow high enough to keep the temperature rise inside the heat sink small. The temperature difference between the hottest point of the carrier and the coolant at the inlet has been estimated with analytic calculations and simulations to be $\Delta T_{\text{Calc.}} = 6.2 \text{ K}$ assuming 230 mW per sensor [3] and a flow of $\dot{V} = 1.9 \text{ l/min}$. This value has been measured in a prototype of the MVD cooling loop to be $\Delta T_{+20^\circ\text{C}} = (5.6 \pm 0.2) \text{ K}$ and $\Delta T_{-30^\circ\text{C}} = (8.0 \pm 0.2) \text{ K}$ at +20 °C and -30 °C, respectively. The measurements agree well with the expectations (see figure 1). The deviation at lower temperatures is a result of the thermal radiation from the environment which is only present in this test setup, causing an additional heat load on the carrier, which is in the same order of magnitude as the sensor's (at -30 °C: $\langle p_{\text{rad}} \rangle = (16.3 \pm 0.1) \text{ mW/cm}^2$, while $p_{\text{sen}} = 43 \text{ mW/cm}^2$).

The temperature difference between the coolant and the hottest sensor is dominated by the temperature gradient across the carrier ($\approx 80\%$ of total ΔT), despite of a high-performance material. When correcting for the environmental influences, the performance is almost independent of the absolute temperature. Moderate coolant flows (full MVD: $< 20 \text{ l/min}$) are sufficient to reach the cooling goals.

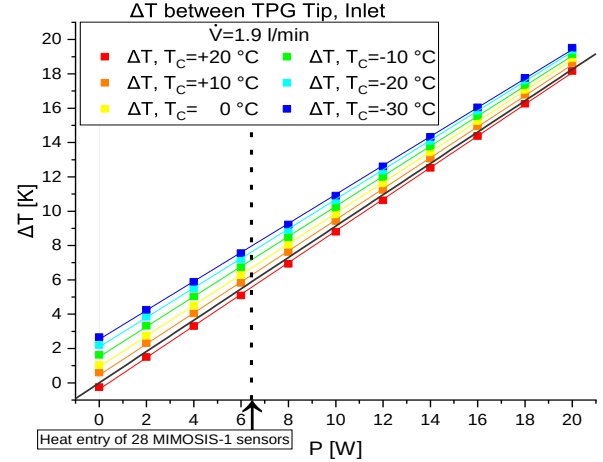


Figure 1: Temperature difference between carrier (hottest point) and coolant (inlet) with linear fits, $\dot{V} = 1.9 \text{ l/min}$. The performance is in agreement with the theory (grey line).

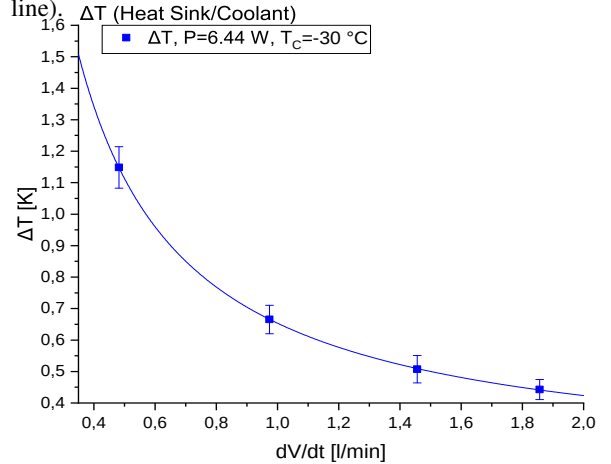


Figure 2: Temperature difference heat sink (bulk)/coolant(inlet), $T_{\text{Coolant}} = -30^\circ\text{C}$, $P = 6.44 \text{ W}$ with a hyperbolic fit. The performance is in accordance with the theory.

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Mimosis: Stand-alone sensor read-out for development purposes*

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The development of the CBM-MVD, based on MIMOSIS pixel sensors, requires an in-depth understanding of their operation. Sensors need to be tested in the lab before integration into the detector. This calls for an easy to operate and small setup for both read-out and configuration of the sensors. This system is based on TRB hard- and software that was initially developed for the HADES spectrometer and now is in use in numerous experimental setups worldwide.

Due to the high expected hit rates in the MVD detector, mainly caused by delta-electrons in heavy ion experiments, the MIMOSIS sensors do have a data interface with 8 parallel lines running at 320 MBit/s each.

The final read-out system will need to be able to cope with the full data rate of up to 2.56 Gbit/s from each of up to 300 individual sensors. For testing purposes such a read-out system is clearly oversized. Therefore our aim was to build a small stand-alone system that is able to handle data from few sensors and doesn't need to transport all data without dead times. The system also needs to supply the sensor with a 40 MHz clock signal, an I2C bus for configuration as well as a start/reset signal.

The platform of our choice is the TRB5sc [1] FPGA board. Figure 1 shows the board combined with a custom AddOn board (to the left) that provides the necessary connectors to receive data and send control signals to the Mimosis sensor board.

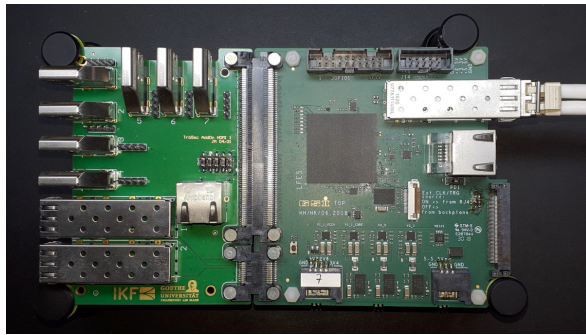


Figure 1: The TRB5sc read-out board with Ethernet link for data transport and HDMI connectors for sensor data input

The TRB framework provides the setup with all kinds of communication features and a software framework for both

* Project funded by BMBF (05P21RFFC2), GSI and HIC for FAIR

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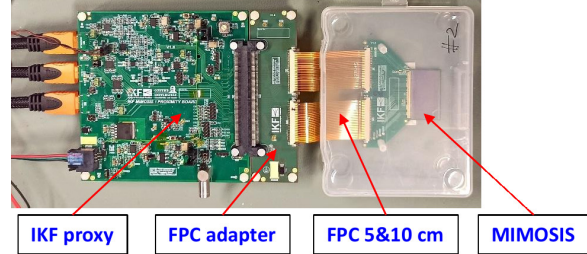


Figure 2: The sensor (MIMOSIS-1) proxy board. Flexible connections allow the use e.g. at a probe station or with different length flex cables.

slow control and data analysis. The only new developments necessary for this project were the FPGA firmware for receiving and handling sensor data and the ROOT-based data analysis software.

One main aspect of the sensor configuration tool chain was the easy reconfiguration, storing of default settings and the possibility to use scripts for automated test procedures. Hence, all functionality was implemented in command line tools and text-based files. As a simple proof-of-concept an automatic scan of the sensor internal, adjustable voltages (DACs) was implemented. This process requires a constant change of settings and read-back of voltage levels and is able to handle several hundred measurement points per second.

The data handling chain receiving data from the sensor consists of several automated building blocks: The FPGA detects both bit boundaries as well as word boundaries to assure a error-free reception of data. This feature can also be used to quickly assess the quality of the digital data stream. Sensor data is stored in a small on-chip memory before it is transported via Ethernet to a computer. Here, it is received and analyzed by ROOT-based software (DABC for data reception, Go4 for data analysis). The software provides all means for datad checks, statistical analysis as well as an interface to possible external automation scripts for chip testing.

References

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Status of the MVD Simulations*

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CBM's Micro Vertex Detector (MVD) will help identify rare particles emitted in violent heavy ion collisions at FAIR and supplements the main tracker (STS) with high-precision pointing capability close to the target. This places high demands on the material budget of the sensor which in turn has an impact on the performance of the detector. Thus, the detector has to be optimized w.r.t. multiple scattering and adding unwanted background tracks originating from external conversion of photons.

What is simulated? To characterize the performance of the detector, the simulation program CBMRoot is available as a tool. There are implementations of the detector in CBMRoot as well as ready-made simulations. CBMRoot imports on the one hand the data of the particles created in the fireball and on the other hand the detector setup and simulates the chain consisting of the transport/propagation of the particles, the digitization in the pixel sensors and the subsequent reconstruction of the particles from the obtained information to the trajectories. For the introduction into the environment the current analysis environment with the settings aimed at for the experiment is used.

collision system	Au+Au
centrality	0 - 10 %
p.beam	12 AGeV
fairsoft	jun19p1
CBMRoot	ARP20
cbmsim	apr20_fr.18.2.1_fs_jun19p1

This contribution focuses on the tracking properties of the MVD detector, supplementing the STS detector positioned in the magnetic field downstream of the MVD, but no longer in vacuum. To do so, tracks of the lightest numerous produced hadrons, charged pions, serve as probe to benchmark the tracking performance. In the long term, the analysis of the reconstruction of dielectrons is of importance.

AnalysisTree To be able to analyze the output data from existing CBMRoot simulations in a suitable way, this data is translated into a format called AnalysisTree. Here the data is stored in the form of different objects and is accessed through a branch structure: TrdTracks, VtxTracks, TofHits, SimEventHeader, RecEventHeader, RichRings, SimParticles and PsdModules. [1]

Preliminary Results To get a better idea of the acceptance of the detector, plotting the transverse momentum over the rapidity is useful, since the rapidity is additive un-

der lorentz transformation, i.e. difference of rapidities is lorentz invariant under boost in z-direction. In principle, it is possible to compare particles from different branches from the AnalysisTree data format. Relevant here are the branches "SimParticles" and "VtxTracks". In the first one you get all physical quantities from the particles generated by Monte-Carlo methods, in the second one you have access to all paths reconstructed by MVD and STS hits. In the branch "VtxTracks" alone no particles can be identified. This is done by a matching process in which the Monte-Carlo particle with the closest match to the hits of a track from VtxTracks is assigned to it. To understand how AnalysisTree performs the assignment, the reconstruction is compared for the following cases: Simulated pions, reconstructed pions and reconstructed pions with at least 3 hits in MVD+STS. It can be seen that there are pions reconstructed by MVD+STS that have less than 3 hits in the detector system. It turns out that AnalysisTree does not require at least 3 hits for matching particles to trajectories as in track reconstruction but does so even with fewer. In fact, matching at least 2 hits in STS is already considered a necessary condition for matching in CBMRoot. So, in order to be able to properly check the performance of the MVD, there must first be clarity about how CBMRoot and AnalysisTree can be used to ensure that only the particle reconstruction is evaluated within the acceptance of the detector.

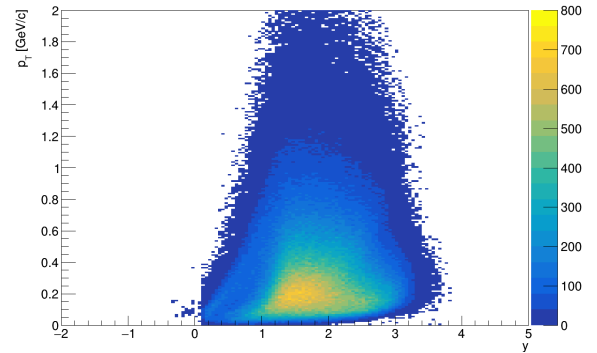


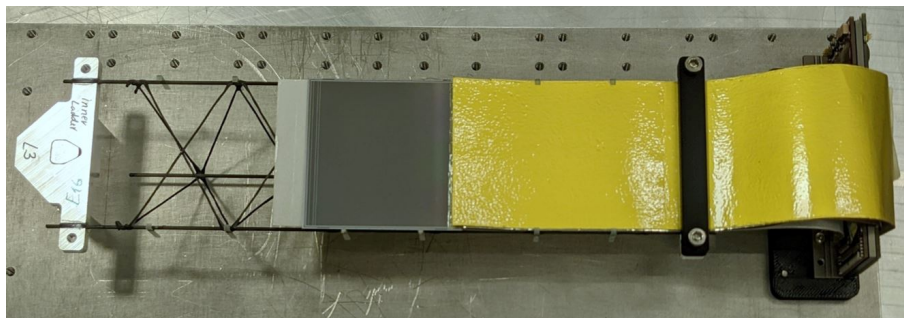
Figure 1: Phase-space diagram of simulated pions with at least 3 hits in MVD and STS.

References

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Silicon Tracking System



Silicon Tracking System – Summary

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The reports in this chapter inform on progress that the STS project teams [1] managed to achieve in 2022 – despite of the disruption of plans, and necessary re-orientation due to sanctions put in place in response to Russia’s war on Ukraine. The project timeline, though, remains essentially unchanged, with the beginning of component series production by mid 2023, and detector ready for installation into the CBM cave at the end of 2026. This puts high work load on the remaining two assembly centers GSI and KIT; compensation for missing workforce is to be found.

A major activity concerned a change to the STS mechanical design [2]. With CBM’s dipole magnet not being available as in-kind contribution from Russia any more, the search for a new provider offered also the opportunity to revisit design specifications – and to optimize the STS detector residing in its gap. A slightly higher, and also wider, magnet gap can accommodate a mechanically modified STS system, now made of two assembly blocks of tracking stations instead of a single one, while leaving its internal components unchanged. The two upstream and downstream building blocks can be assembled individually before joining them into one system in the integration laboratory. This may facilitate a possible upgrade in the future, while leaving the detector’s physics performance for CBM’s day 1 configuration essentially unchanged. This optimization work is part of the re-defined EU project EURIZON as work package 2.1 [3].

In preparation of production readiness for detector module and ladder assembly, the pre-series construction of 10 modules with all final or most recent prototype components was achieved at GSI. The full chain of steps, from sensor selection based on quality-control data, chip testing, chip-cable assembly, over bonding to sensor and front-end board integration, and the in-assembly testing to final module characterization, was practised in a row, allowing to assess and improve various details under realistic conditions. The modules have been specifically tailored for installation in the E16 experiment at J-PARC [4]. Together with our associated collaborators at KEK, we look forward to gaining insight into the system performance, and eventually its application to the physics program. The photo in Fig. 1 shows some of the modules. The first module mounted on a mechanical ladder, ready for dispatch to KEK, is shown on the STS chapter’s title page.

The read-out ASIC STS-XYTER v2.2, available already since two years through a pilot-production of few thousand dies, was finally series-produced in UMC 180 nm technology. In Fall 2022, 75 Wafers of 350 ASICs each were delivered to AGH, Krakow, as the in-kind provider. The remaining 25 wafers of the full production arrived in De-

cember. Quality control of the ASICs will be done mostly at AGH, to a smaller part also at GSI, expecting to yield more-than-enough ASICs for the project.

The front-end electronics board has been further developed in its third version. A variant with lower outgoing bandwidth is being applied to the pre-series modules for the E16 experiment. A design with high bandwidth is available as a first prototype. Also the power boards were produced in final form.

Microcable production was resumed at LTU, Kharkiv, Ukraine, despite of the difficult situation. The detector layout changes allowed starting to finalize the lengths of the remaining about 40% of microcable sets, mostly for modules on ladders in the central part of the detector, close to the beam pipe.

The carbon-fiber beam pipe itself was further optimized. The target window joint to the pipe was made more resistive, excluding critical forces during handling and installation. The final dimensions of the structure have been determined. A full-size prototype is under construction.

On the way to construction readiness of the STS detector, a demonstration of the cooling concept is being prepared. The construction of a thermal demonstrator, mimicking with dummy components the dissipation and cooling scenarios of STS, was achieved. A test cooling plant was set up in a container outside of the STS integration laboratory and connected through a distribution system to the laboratory. Commissioning is a milestone for early 2023.

The demonstration system mSTS confirmed in further refined analyses the high performance of the developed components. New data was acquired in 2022 during mCBM’s beamtime with heavy-ion collisions at SIS18.



Figure 1: STS pre-series modules for J-PARC E16.

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New concept for the Silicon Tracking System: STS-3+5, simulation geometry and performance

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Introduction

The Silicon Tracking System (STS) is the main tracking detector of the Compressed Baryonic Matter (CBM) experiment under construction at the Facility for Antiproton and Ion Research (FAIR) in Darmstadt. It is expected to be ready for commencement of data collecting operations by the end of 2026. The STS plays a crucial role for the experiment in tracking of and the momentum determination of charged particles produced by nucleus-nucleus(Au+Au) collisions. It has been designed to measure up to 700 charged particles produced in nucleus-nucleus collisions at interaction rates of up to 10 MHz [1], and achieve a momentum resolution better than 2% in the 1 Tm dipole magnetic field [2].

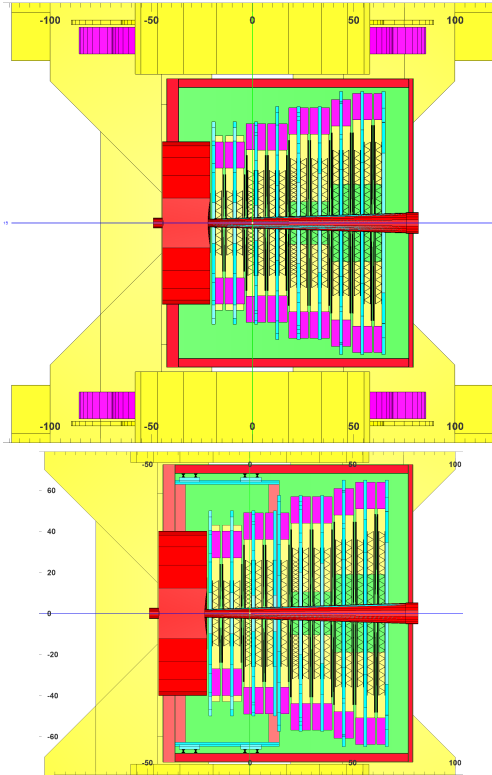


Figure 1: Schematic of the STS-8 design (CBMROOT geometry v21e) (above) and new design STS-3+5 (geometry v22c) (below) placed inside the new magnet.

STS employs silicon microstrip sensors of $320 \pm 15 \mu\text{m}$ thickness in 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 $6.2 \times 12.4 \text{ cm}^2$) arranged along the beam axis in a “monolithic” structure of 8 tracking stations. This is referred to as STS-8. However, due to external geopolitical events during 2022 and the current status of the CBM experiment, the magnet originally as designed and realised is no longer acquirable. This setback has allowed a new “modular” design of the STS to be conceived, known colloquially as the STS-3+5. These old and new designs are shown in Fig. 1. The STS-3+5 consists of a STS-3 module and a STS-5 module independently assembled. Compared to STS-8, the distance from the target to the first three stations is kept the same as well as the 10.5 cm pitch between successive stations, however, due to the need for an additional supporting C-frame between the STS-3 and STS-5 blocks an additional 2 cm is required between the last station of the STS-3 and the first station of the STS-5 making the overall z length of the STS sensors stations 2 cm longer for STS-3+5 than STS-8. The new design will allow for the assembly of different components, such as low voltage, high voltage, front-end electronics and independent cooling system, whilst providing an upgradability option [3, 4, 5] for the STS in the future.

Updates in STS simulation geometry: v22c

A Root based simulation geometry matching only the essential additional elements introduced by the new conceptual design of the STS-3+5 over the previous STS-8 design was produced. This intermediate STS simulation geometry (v22c) with only passive hardware components that were already included in the version of the STS-8 (v21e) reference geometry was created for the purpose of studying the change brought about by the conceptual change. The following additions were implemented for v22c simulation geometry.

1. Enlarged box in XY direction around the active area of the STS;
2. Gap of 2 cm between STS-3 and STS-5 block;
3. Inclusion of the additional needed C-frame;
4. A support frame and railing system around the STS-3 block.

Momentum (AGeV/c)	Magnetic Field (Tm)
2.0	0.5
12.0	1.0

Table 1: Different beam momenta at varying magnetic field used during the physics performance simulations.

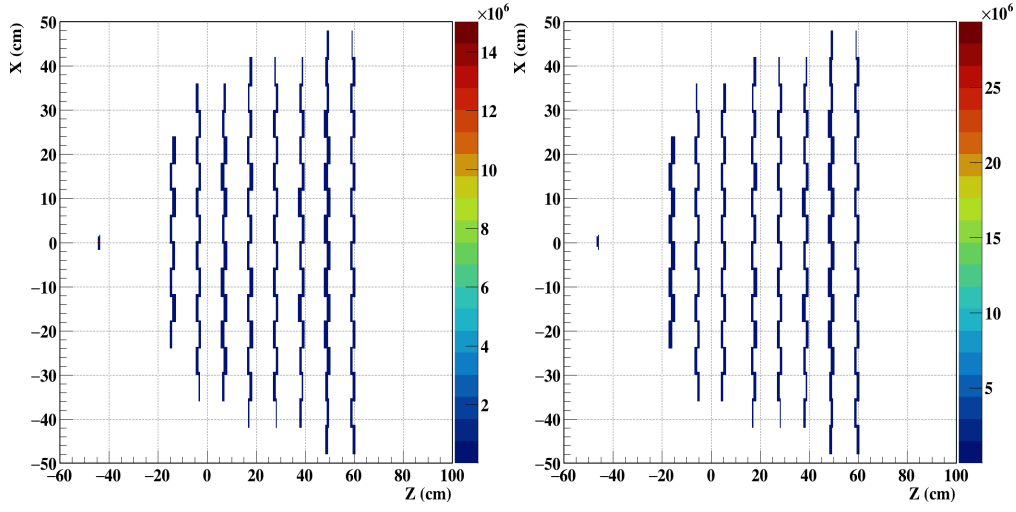


Figure 2: Monte-Carlo points on the silicon sensors for STS-8 (left) and STS-3+5 (right). Additional 2 cm separation between the STS-3 and STS-5 modules is visible.

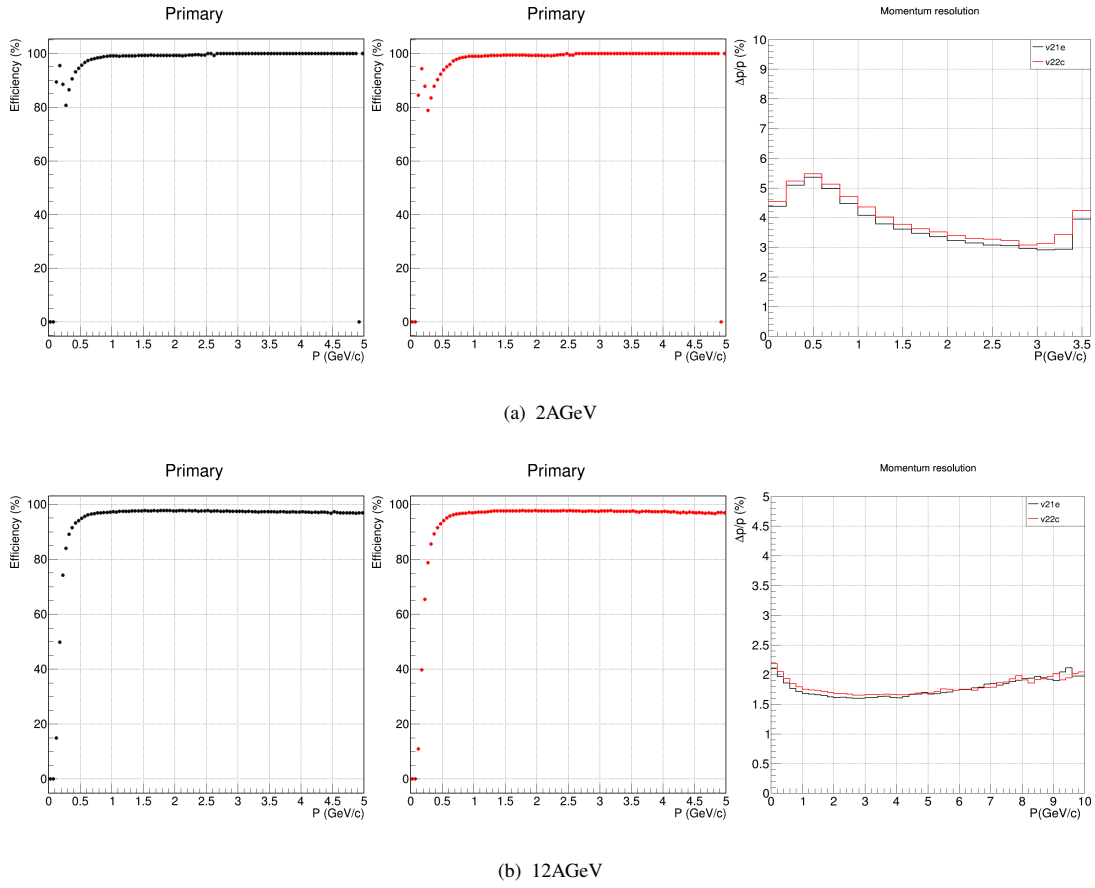
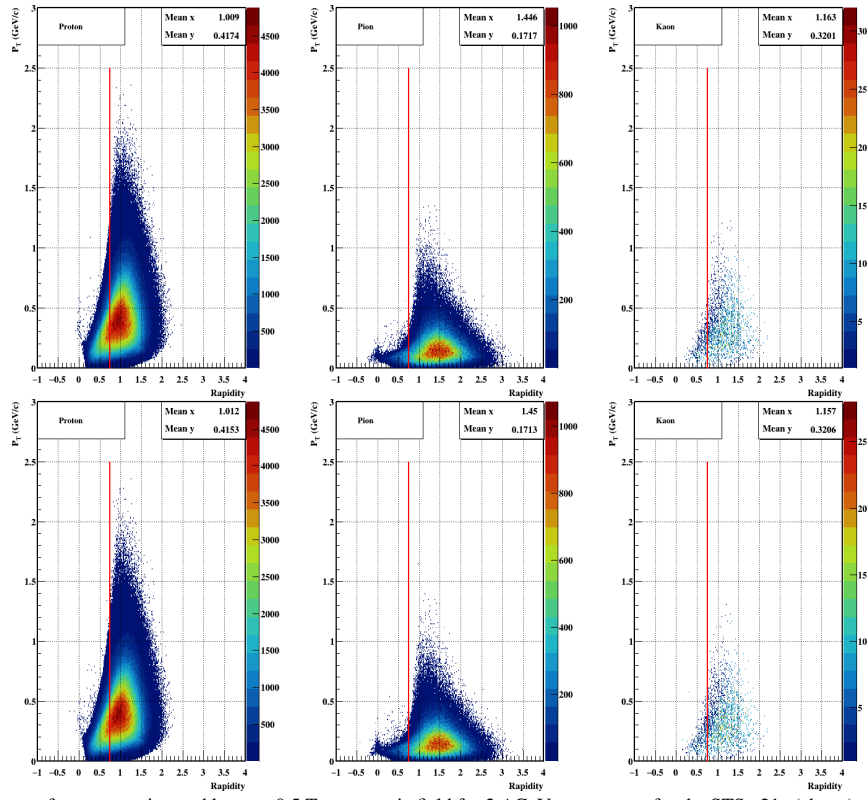
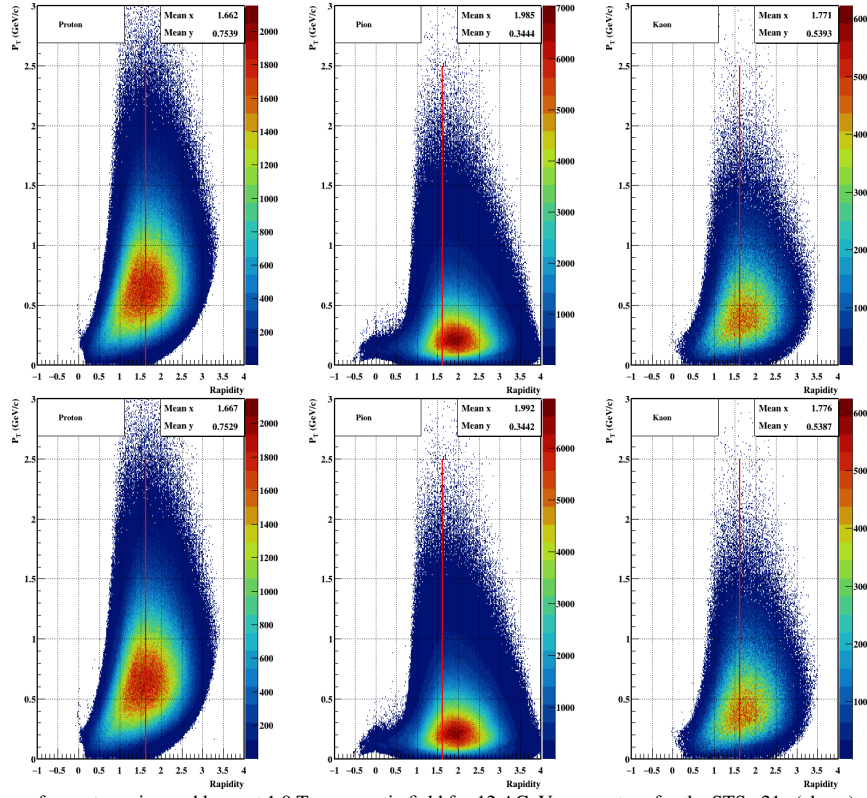


Figure 3: Efficiency performance of the STS v21e (left) and v22c (middle), and the momentum resolution (right) for the primary particles at 0.5 and 1 Tm magnetic field for 2 AGeV (above) and 12 AGeV (below) beam momentum, respectively.



(a) P_T -y acceptance for proton, pion and kaon at 0.5 Tm magnetic field for 2 AGeV momentum for the STS v21e (above) and v22c (below).



(b) P_T -y acceptance for proton, pion and kaon at 1.0 Tm magnetic field for 12 AGeV momentum for the STS v21e (above) and v22c (below).

Figure 4: P_T -y acceptance for proton, pion and kaon for 2 AGeV (a) and 12 AGeV (b) momentum.

Performance of the tracking: STS-8 vs. STS-3+5 geometry

In order to evaluate the tracking performances for the STS-8 (v21e) and STS-3+5 (v22c) geometries, the magnet and its magnetic field needed to also change as a minimum change necessary for compatibility. Magnet (v21a) with field (18a) and magnet (v22a) with field (22a) was used for the STS-8 and STS-3+5 studies respectively. See Ref. [2] of this report for discussion of this topic. Data from UrQMD initial interaction data for Au+Au collisions for beam momenta of 2 AGeV/c and 12 AGeV/c were simulated with particle transport through the detector provided by GEANT 3. The magnetic field was adjusted in order to maximise the acceptance at lower beam energy as described in Table 1. It is noted that the magnetic field strength for 2.0 AGeV/c is different than that which is recommended in Ref. [6], and would not be compatible with the downstream beampipes or the hitting of maximum extent of the CBM beam dump as already installed. It nevertheless suffices for this purpose of this investigation.

The XZ distributions of Monte-Carlo points in the STS-8 and STS-3+5 are shown in Fig. 2 along with a target position at -44 cm relative to the centre of the magnet and its field. In Figure 3, the efficiency and momentum resolution for primary particles as a function of momentum for 2 AGeV/c and 12 AGeV/c at 0.5 Tm and 1 Tm magnetic field respectively is shown. There is no noticeable difference for the efficiency between the two detector designs, however there is a slight increase in momentum resolution for the STS-3+5 design, probably due to the longer distance between the first and last stations. Figure 4 shows the acceptance as a function of momentum and rapidity for the STS-8 and STS-3+5 detector separately for primary pions, kaons, protons, for the 2 AGeV/c and 12 AGeV/c simulations. The red line indicates mid-rapidity, which is clearly covered in the distributions although only barely for the pions at 2 AGeV/c. Again, no significant difference is observed between the two detector design concepts.

Updates in STS geometry: v22d

Passive components play a crucial role in the physics performance, e.g. as conversion material but also in the absorption of delta rays. Therefore it is necessary to implement all the possible design hardware with proper materials. In order to best understand necessary changes due to the redesign and those changes already realised although not implemented in simulation geometries, a two stage approach to the update of the STS simulation geometry was implemented. STS v22d is a successive version of the STS-3+5 v22c design, and is shown in Fig. 5. Therefore, in addition to the changes introduced for v22c simulation geometry, the following updates were included for v22d geometry:

5. Carbon support bars around the STS;
6. Cooling tubes along to the central ladders;

7. Cooling pipes;
8. Support structure to the C-frames;
9. Optical cables;
10. Power cables;
11. Low-Voltage (LV) cables;
12. High-Voltage (HV) cables;
13. Beam-pipe flange.

A simulation study on the effects of these new volumes and material introduced in this geometry is planned in 2023.

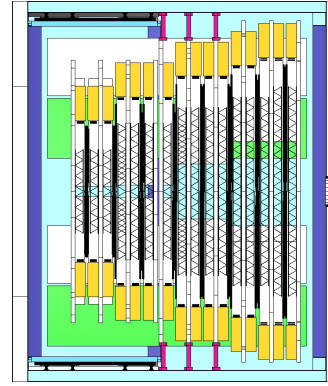


Figure 5: Schematics of the modular STS version v22d.

Summary

Since the CBM magnet cannot be acquired as previously planned, a new concept for the STS (modular STS, STS-3+5) was developed which allows assembly of different hardware component independently in the system whilst allowing an upgradability option for the detector system with different silicon sensor technology in the future. The basic performance studies, such as efficiency, momentum resolution and p_T -y distribution were done for the STS variant v21e (STS) and v22c (STS-3 + STS-5) using a new magnet with a higher and wider gap. There is no significant difference in the performance, besides a small increase of 1% in the momentum resolution. The p_T -y distribution covers the mid-rapidity in both the geometry cases.

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Modular redesign of the STS detector

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With the progress of CAD on the general and subassembly level, it became obvious, that once assembled, the detector is a monolithic structure. Upgrading and maintenance require full disassembly in a clean environment. It is also required to disconnect electrical, cooling and read-out chains, which increases risks of connector failures during reinstallation. Considering the fact, that core detector components e.g. carbon fiber structures, silicon sensors and micro cables are already produced and delivered, an introduction of modularity is only possible on the structure level above C-Frame assemblies. Splitting the tracking layers in two groups and introducing an option of mechanical separation of those groups fulfills the requirements. A comparison of the monolithic and modular setups is illustrated in Fig. 1.

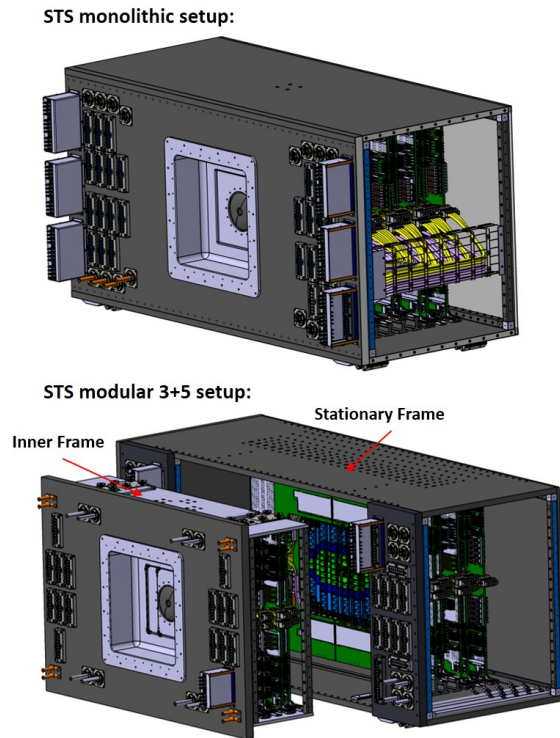


Figure 1: STS setup overview - monolithic (top) and modular (bottom).

The first three STS units are mounted on a separate, so called, Inner Frame and the rest of the detector remains in a Stationary Frame. The inner frame itself is mounted on an additional rail system, that allows linear movement

along the beam direction. The required unit services – cooling, powering and read-out – are fully separated from the residual units. The conceptual service routing for the Inner Frame is shown in Fig. 2.

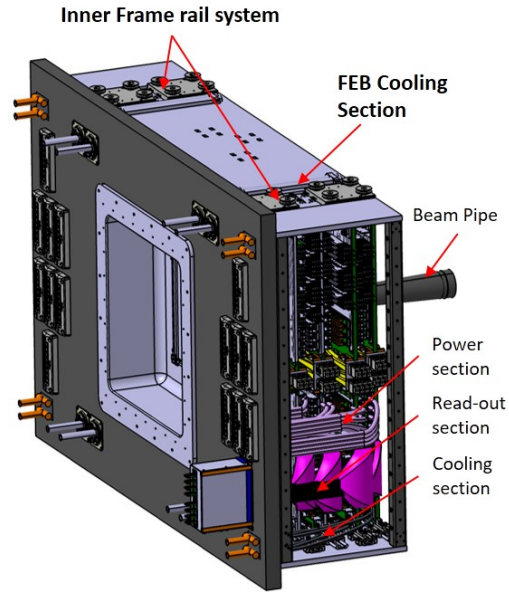


Figure 2: CAD overview of the Inner Frame and services.

Additional space requirements and advantages of the modularity upgrade

The introduced additional degree of freedom, as well as full service separation between the Inner and Stationary Frames requires an increase in occupied space. The current level of CAD allows precise definition of new general dimensions of the detector: width is increased from 2900 mm to 3250 mm; height is increased from 1425 mm to 1450 mm; length remains unchanged with 1219 mm. The main advantage of the introduced modularity is a possibility of partial detector disassembly during maintenance and upgrades. The extraction of the Inner Frame is possible while the remaining units on the Stationary Frame are moved laterally in X direction on the corresponding unit rail systems. Lateral movement is required due to the conical beam pipe shape, that is attached to the target chamber of the Inner Frame – see Fig. 2. Such manipulations require the detector being removed from the magnet and brought to the assembly laboratory.

Update on STS module and ladder design

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Introduction

In 2022, a pilot production of 20 modules has been finished at GSI and KIT. The modules were build with the previous version of the Front End Board (FEB8-2v2). After testing, 10 modules have been assembled onto two ladders (half equipped) and mounted on two adjacent C-frames of a mechanical demonstrator. Figure 1 shows the two half ladders in the mechanical demonstrator (left) and the measured deviation from the nominal positions of the sensors on the Ladder well below $\pm 100 \mu\text{m}$ (right). In addition, three ladders with non-functional sensors have been build for vibration studies [1].

After the pilot production a pre-series of ten STS modules in the latest design have been build for the E16 experiment at J-PARC, Japan [2].

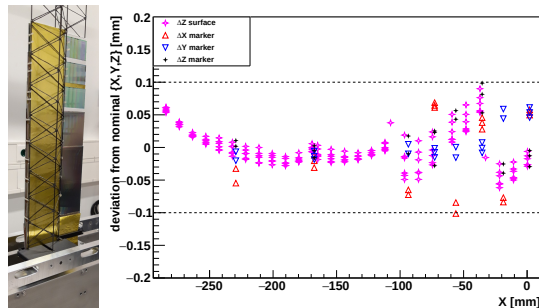


Figure 1: The two half ladders in the mechanical demonstrator (left) and the measured deviation from the nominal positions of the sensors on the Ladder.

Module design update

The pre-series modules have been assembled with an optimized workflow and enhanced quality control procedures [3]. After the production the modules have undergone performance tests [4]. The latest design of the module features the following updates:

- FEB8-2v3 [5].
- HV filtering integrated on the FEBs;
- Ground connection through grub screw in the fins;
- Additional isolation on the back side of the FEBs;
- Anodized fins for improved electric isolation;
- Micro cable shielding with improved isolation on the edges.

Ladder assembly

After the quality control tests and characterization of the modules the first two ladders for the E16 experiment have been assembled. For the shipping they are mounted on an aluminium plate (Fig. 2). The Ladders are covered with 3D printed housing out of ESD material and stored in transportation boxes (Fig. 3).

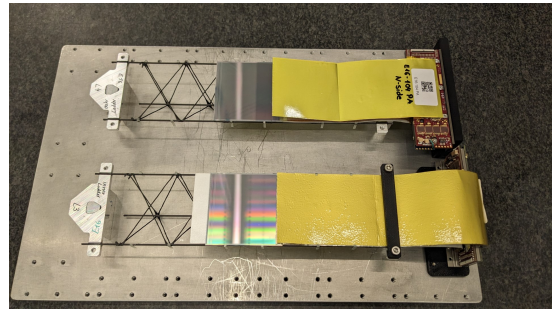


Figure 2: The first two ladders for the E16 experiment mounted on a transport plate.

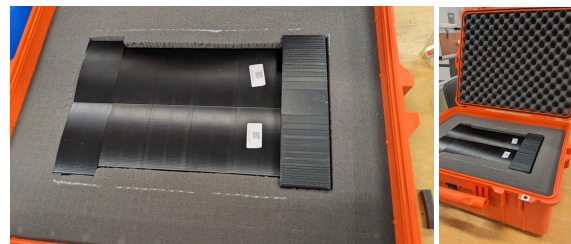


Figure 3: The ladders covered with ESD boxes packed in a transport case.

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Pre-series STS module production at GSI

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Test system

During the year 2022, the hardware and software tools for the CBM-STs assembly site at the GSI detector laboratory were very intensively developed. The development was based on the experience acquired during the intensive test phase in 2021, which is described in several progress reports contributed to [1]. The modified method for extended ASIC tests (for the XYTER chip v2.1 and v2.2), including calibration of diagnostic circuit and charge sensing amplifier (CSA) calibration, was included. To test each readout channel during the detector assembly process, the ESD materials are used to induce moderate charge noise for the chip cable test. Finally, the fully assembled modules were tested to finalize all channel connectivity between micro-cable and semiconductor detectors. The test procedure was successfully used during module assembly for the E16 experiment at J-PARC, which is almost identical to CBM-STs modules.

The software for the new 20 MHz clock EMU boards was developed. It includes the test of ASIC without and with a micro-cable connection. Also, the test modules for front end board FEB8-2 with 2 uplinks and newly developed FEB8-5 with 5 uplinks. The test results are automatically stored in the central PostgreSQL database and on a clean room Linux PC, which also has daily backup into the GSI Tivoli backup system.

The web interface is also running on the cbdpc001 [2] Linux PC for ease of access. The web interface is currently based on PHP back end and PostgreSQL, but it is planned to rewrite into python, which will allow us to reuse test software modules.

Figure 1 shows the calibration of ADC of the ASIC internal diagnostic circuit using an external voltage source. The calibration is essential for further chip quality evaluation. It is improving the internal chip temperature estimation and CSA supply voltage readout. The voltage supply for the ASIC test socket is equipped with sens wires which give us sub-millivolt calibration precision.

Figure 2 shows the calibration of CSA current consumption. The information can be used for ASIC quality control. The current is measured with an external voltage source supplying the 1.2 V CSA separately, also with sens wiring for high precision.

After calibration, every chip is tested by injecting charge in every channel before bonding. The corresponding figure is shown in Fig. 3 where all fast and all slow discriminator channels are operational. After the ASIC passes all tests successfully, the unique ID is burned, and the chip can be

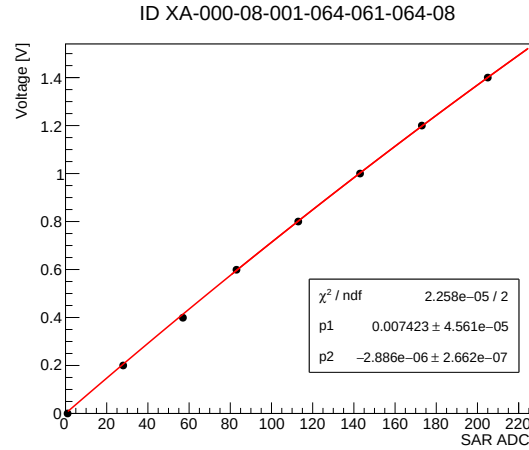


Figure 1: Calibration of the ASIC internal diagnostic circuit using an external voltage source.

used for further tests. We also have developed a new PCB for ID burning based on the Arduino microcontroller.

Finally, the noise performance of every input channel on ASIC is measured. Figure 4 shows the discriminator distribution for all channels. This measurement is done after the TAB-bonding of chipcables, where all the connections are tested. If results are favorable, no channels are missing,

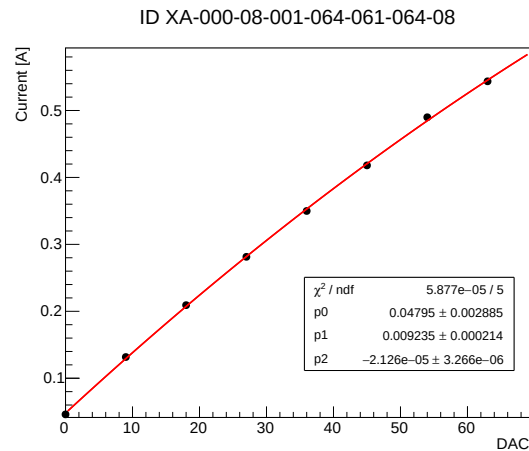


Figure 2: Calibration of the charge sensing amplifier's current consumption by setting the DAC values for all input channels from min. to max. and monitoring the current.

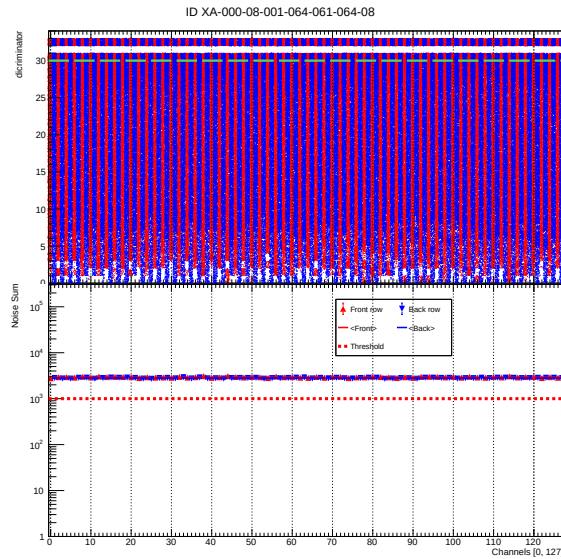


Figure 3: Generated charges by the ASIC internal generator. Top: two-dimensional histogram of discriminator values vs. channel. The discriminator values correspond to 0 (maximum) to 31 (minimum) charge signals. Channel 33rd represents the fast discriminator values. Bottom: Histogram of discriminator hit statistics.

and all channels see a similar noise level produced using the ESD cover. After this step, all chips with cables can

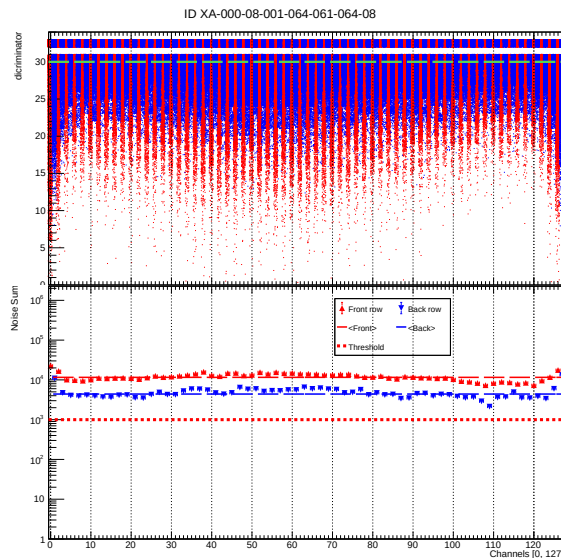


Figure 4: The same histogram as Fig. 3, but with the injected signals from the micro cable.

already be glued on the FEB. Before we start bonding the sensor, two more tests are done. First, we glue the first row of the chips-cables, solder the shilding, and test again. If no problems occur, the second row is glued and tested as

well. As mentioned before, all these steps are stored and available online [2] at any moment for cross-checking and problem tracking. Finally, the bonding process on the sensor finishes the module assembly in the clean room. Here as well, a side-by-side bonding and testing approach is also applied. Assuming all goes well and the sensor has no failing strips, we must observe all channels are functional.

Summary

The final results confidently show the effectiveness of the step-by-step test procedure. The average broken read-out channel per FEB was estimated as less than 5 (out of 1024), which, in turn, is less than 10 per detector module. *Meaning less than 1% broken channel per detector module.* Most probably, missing channels can be explained as a failing channel on the sensor or a lousy connection between the micro-cable and the sensor. At this moment, most of the failing modules were assembled at the beginning of the production process. In the end, the detector assembly procedure was highly efficient, which gave us confidence in the CBM-STs production readiness.

The E16 modules were relatively straightforward to test due to their big sensor size and short connecting cables. Whereas, for the CBM-STs, the biggest challenge is to develop a testing method for the minor-size modules connected via the most extended cables. Figure 5 shows the final test of the module, where all missing channels are identified and reported. The history of the assembly process can be checked via the web interface. We intend to develop the laser beam-based module testing and a station where the revers biasing of the sensors will also be applied.



Figure 5: The final test of a module in the clean room.

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Test and characterization of STS pre-series modules produced at GSI

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The test and characterization of fully assembled modules have become one of the most important tasks for the STS team. It allows not only to get insights into the reliability of the assembly procedures, but also to study the performance of the modules and to improve their operation. The test and characterization of modules produced for the J-PARC E16 experiment [1] is still an ongoing task. In this contribution we will report on the performance and operation of the produced modules, which account to the STS project as pre-series production.

The E16 modules

The design and assembly of the E16 modules resembles the standard procedures used for the STS modules [2, 3]. A total of 10 modules have been produced with the final STS components (FEB8-2v3, LDOs, SMXv2.2 ASICs, silicon sensors and microcables). All of them have similar dimensions, and they were built using 6.2×6.2 cm sensors and sets of microcables with average lengths from 12 cm to 21 cm. A distinctive characteristic in 8 of the 10 modules is the use of equal-size p-side and n-side microcables to match the J-PARC E16 experiment construction requirements.

Experimental setup and operation

The modules were installed into the module carrier frames featuring mechanical support and protection, and also necessary powering services and data links. They were then placed into a light-tight aluminium box for the performance evaluation and calibration. The grounded metal box provided additional protection against the electromagnetic interference. The use of the latest version of the FEB8-2v3, which implements the high voltage filtering and signal return path on board, has direct implications on the ground and power scheme of the setup. These considerations were taken into account when modifying the test box to accommodate the E16 modules. In addition, the test box implements all necessary services: low and high voltage, readout and FEB cooling. 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.

After installation, the modules were visually inspected. No issues were found or reported, and therefore, they moved for to the next testing phase. Each module was powered on, output voltages and current consumption for

each LDO on the FEBs were measured. This check allowed to identify electrical shorts and malfunctioning components on the FEBs. For a specific module (E16-103.PB), an electrical short due to a faulty capacitor was responsible for bringing down the 1.2 V potential for an entire row of ASICs. This issue was identified using a thermal camera and the capacitor was replaced. After the repairing, the entire module was operational.

The evaluation of the modules performance is carried out in multiple steps [4]. The following list gives a brief description of the tests and their corresponding order:

1. measurement of the sensor/module voltage-current characteristics;
2. synchronization of the DAQ chain and ASIC configuration;
3. measurements of the VDDM potential and temperature of the ASICs using the built-in diagnostic circuit;
4. calibration of the ASICs analog front-end (AFE);
5. measurement of the module's noise levels and verification of the calibration via an S-curve scan.

Module design adjustment and test setup retrofit

The essential features of the operation of the recently produced E16 modules were new version of the front-end boards (FEB8-2v3), usage of the module carrier for the first time, and large variety of mechanical design of the individual module.

The FEBs required an additional connection between their virtual grounds that it is manually established after the module assembly. After several iterations, it was found that a high-frequency impedance of the interconnecting wire place a critical role on the noise performance. The best result were obtained with a short, relatively wide braided wire coming around the edge of the FEB assembly. It is now recommended to be used in such fashion for the further module production, instead of the previously planned direct wire connection through the hole in the cooling fin. However, further studies upon the mechanical compatibility with the low-voltage cable should be performed.

The usage of the module carrier proved to be useful for the mechanical stability of the most fragile components of the detector module: silicon sensor and ultra-thin microcables. Non of these parts were damaged during the module installation, operation and test. Also, the number of the mating cycles for the powering and data connectors was

reduced to the necessary minimum. Instead, the outside connectors on the integrated module carrier patch-panels were used (one D37 for LV, a pair of 2-pin LEMO for HV, and two custom-made ZIF adaptors for data cables). Being more robust and large, they allowed safe and convenient multiple connections of the module.

After the significant mitigation of the noise by introducing of the interconnecting wire, the further improvement was achieved by shielding the outside data cables with a grounded copper foil. Additionally, the ferrite flat rings mounted on those cables reduced the noise down to the expected level.

Performance of the modules

The results presented here corresponds to 3 out of the 10 produced modules. The first step on the module's testing protocol is the measurement of the sensor voltage-current characteristics, hereafter referred as IV curve. This check is performed using a dedicated setup built from two Keithley 708B power supplies. Figure 1 shows the IV curves measured for the module E16-108_PB. For reference, the corresponding IV data from the sensor electrical inspection [5, 6] is also displayed. The main difference between the two IV curves measured at the module testing stage relies on whether or not the connection of the system low voltage is present. This feature can be appreciated in the data (green line) where an ohmic behavior beyond the full depletion voltage is observed.

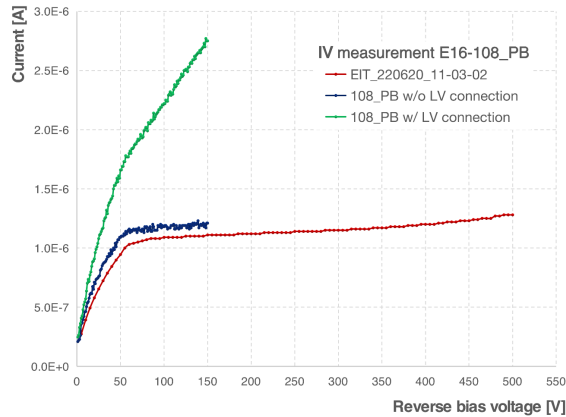


Figure 1: Module E16-108_PB voltage-current characteristics as measured in the Laboratory. Two different measurements corresponding to the same module, with and without LV connection are shown.

Each module was brought into operation and data link initialization and synchronization processes were launched. From the characterized modules, all 48 SMXs ASICs were operated reliably during the tests. Figure 2 shows the distribution of the temperatures and VDDM potentials for each module side in the form of an statistical *box-whiskers plot*. Temperature and VDDM potentials were measured

on each ASIC using the built-in diagnostic circuit [7]. The dark line of the plot represents the median value, the box limits illustrates the first and third quartile and the whiskers or error bars determine the minimum and maximum values of the data.

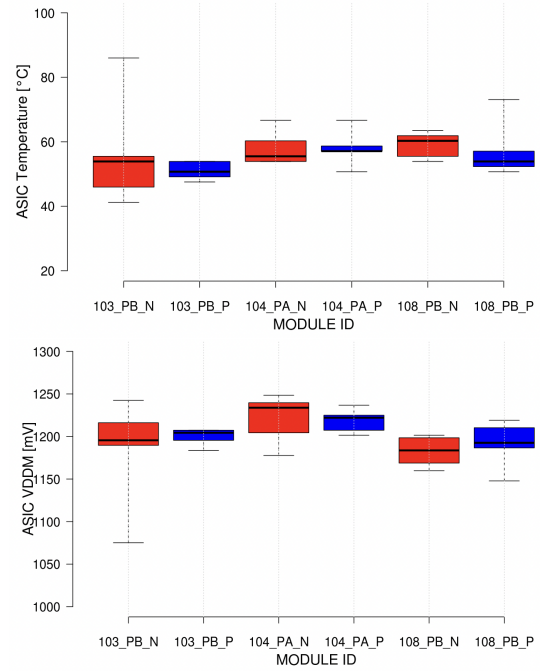


Figure 2: Temperature and VDDM potentials for each module side measured with the built-in diagnostic circuit.

The next step was the calibration of the AFE of the SMX ASICs. This procedure adjusts the non-uniformities of the in-built discriminators of the flash ADCs and channel-to-channel differences. This also ensures an homogeneous signal response in the entire module. The channel's 5-bit flash ADC are accurately calibrated with a gain of 0.336 fC/LSB, resulting in a dynamic range of approximately 10.4 fC. Table 1 summarizes the results of the calibration for E16 modules, where a channel-to-channel spread below 10% was achieved for each sensor side.

The ENC levels of module E16-104_PA measured at a symmetric bias voltage of 150 V are shown in Fig. 3 to illustrate the typical procedure. Among the well-understood structures determined by the Z strip in the first 134 channels of p-side, or the unconnected channels marked with a black arrow, it is also possible to observe a very low discrepancy between odd and even channels. The ENC average results for each tested module are also summarized in Table 1.

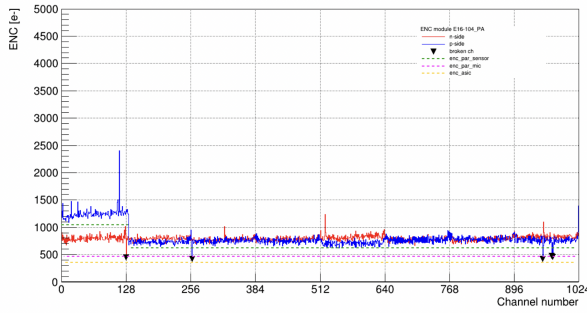


Figure 3: Noise across all channels in module E16-104_PA.

During the different stages of the module assembly a quality control procedure is performed with the purpose to find out possible issues and to ensure a high production yield. One of these issues is an excessive number of broken or unconnected channels, that could lead to a deterioration of the detector performance. Therefore, this observable represents an important indicator that should be monitored during the module testing. Among the identified faulty channels, many were tracked back to the assembly processes. A summary of these statistics are presented in Table 1, where the number of faulty channels, identified during the assembly process, are displayed within parenthesis. Figure 4 illustrates how they distribute according to their absolute noise level, and hence the place where the connection was broken.

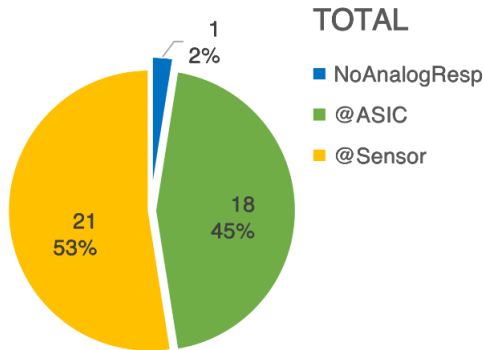


Figure 4: Unconnected channels can be classified according to their noise level, and hence the place where the connection failed.

Summary

The characterization of E16 modules was essential for proving their functionality after the assembly and before the system integration. All modules were classified as operational, matching the QA requirements for their installation on the ladders and operation at J-PARC E16. All ASICs proved functional and in good state. The AFE of each ASIC was properly calibrated in a dynamic range of approximately 10.4 fC. The channel-to-channel spread of the ADC parameters such as the gain and threshold were reduced by a factor 10 after calibration. The average noise of the modules was measured to be about 800 e ENC and 750 e ENC for n- and p-side, respectively. For both sides, odd-even difference were significantly reduced. These results were considered acceptable for the experiment operation. The average number of broken channels per module increased with respect to the previous testing stage; however, the overall number of broken channels were kept below 30 in almost every case, i.e., below 1.5% of the total number of the module's channels, which is a very good result for the overall detector.

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Table 1: Test results for E16 modules. Every parameter, with exception of the total number of broken channels, is given as the mean value of the corresponding distribution. The errors denote the standard deviation of the given values.

MODULE ID	Pol	ENC [e]	ADC gain [fC/LSB]	Threshold spread [e]	Broken channels (Before) After
E16-103_PB	n	952 ± 73	0.336 ± 0.002	176	(4) 7
	p	810 ± 32	0.336 ± 0.002	165	(8) 25
E16-104_PA	n	795 ± 20	0.336 ± 0.002	224	(1) 1
	p	756 ± 30	0.337 ± 0.002	163	(0) 4
E16-108_PB	n	1395 ± 115	0.337 ± 0.003	420	(1) 0
	p	791 ± 45	0.335 ± 0.005	356	(2) 3

STS as the most inner tracking device for the J-PARC E16 experiment*

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Introduction

J-PARC E16 experiment [1,2] measures dielectron spectra in 30 GeV pA collisions at the high-momentum beam line of J-PARC Hadron Experimental Facility, Ibaraki, Japan. The objective is a systematic study of the in-medium spectral change of vector mesons in cold nuclear matter. The interaction rate is 10 MHz under the irradiation of 10^{10} protons per 2 s spill with thin C, Cu, Pb targets with a thickness of up to $0.5\% X_0$ (radiation length).

Figure 1 shows a cut-view of the spectrometer. Experimental targets are placed at the center of the spectrometer and are surrounded by detectors. Silicon Strip Detectors (SSD) and three layers of GEM Trackers (GTRs) are installed for particle tracking in the magnetic field. Hadron Blind Cherenkov detectors (HBD), and Lead Glass calorimeters (LG) are installed to identify electrons.

We define a module as a group of detectors that covers 30 degrees horizontally and vertically. Eight modules are drawn in Fig. 1. More modules are added in upper and lower sides of the eight modules and the beam penetrating area, and finally 26 modules will be prepared. For the 1st physics run (Run 1), the eight modules are installed together with two partial modules that contain only SSD and two GTRs sitting in forward upper left. A commissioning run is planned in 2023.

The currently installed SSD are not satisfactory as they have thick and large frames. The availability is also limited. Therefore, we have decided that we replace it by the CBM-STS based system. It is suitable due to its light weight configuration, high-rate capability with fine-segmentation, and double-sided readout. Required position resolution is $30 \mu\text{m}$ and timing resolution is about 6 ns.

Mechanical Design

Figure 2 shows a 3D-image of the setup for the commissioning run in 2023 and Run 1. Ten of $62 \times 62 \text{ mm}^2$ sensors with FEB8-2v3 are mounted onto eight ladders. A ladder is 231 mm in height and can accommodate three sensors for future upgrade. The sensors are labeled with three digits HXX where H represents the height position and XX indicates the horizontal position anti-clockwise. Eight sensors (101-104, 106-109) are mounted at the center of the ladders. Two sensors, 206 and 207, are placed above the

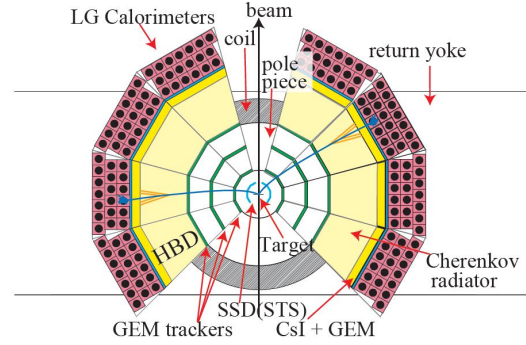


Figure 1: J-PARC E16 spectrometer.

sensors 106 and 107, respectively. Inside the setup, a target chamber will be installed that contains experimental targets at its center.

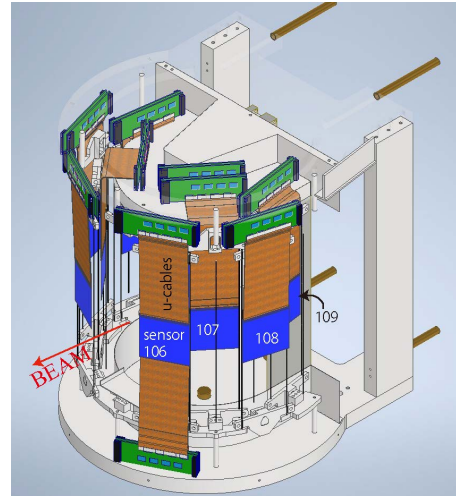


Figure 2: 3D image of the configuration in 2023.

Figure 3 shows a picture of the constructed structure of the J-PARC STS chamber. Because no thick materials are allowed in the acceptance and the beam-penetrating area, the J-PARC STS chamber was designed so that the top and bottom plates are supported with only two pillars in the upstream of the configuration. Two copper pipes run inside the plates to cool the FEB8's. We have adopted old version of bearings due to the space limitations. Aluminized-mylar sheets will cover the outer ($R = 170 \text{ mm}$) and in-

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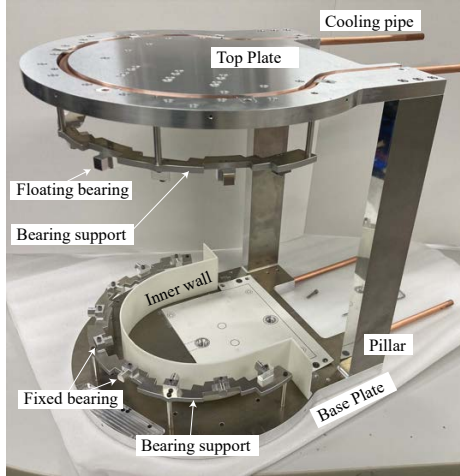


Figure 3: Structure for the J-PARC STS chamber. Made by Hayashi-REPIC [3].

ner ($R = 105$ mm) sides of the structure to avoid light and electrical noise.

Table 1 describes some of the specifications of ladders to be constructed. At the time of the decision, custom μ -cables could not be produced. Therefore, cables are chosen among already produced ones that fit the required compact configuration. Some modules have the same cable length on P and N sides, which is not the case for CBM-STS.

Table 1: Ladders to be constructed for Run 1

Ladder No.	Sensor No.	μ -cable length [mm]		Est. data rate / ASIC [Mbps]
		N	P	
L9	109	142	131	110
L8	108	121	121	110
L7	107	121	110	240
L6	207	172.5	163.1	240
	106	207.7	207.7	320
L4	206	121	121	320
	104	121	121	240
L3	103	172.5	163.1	160
L2	102	121	121	80
L1	101	142	131	80

Readout electronics

A schematic of the readout electronics of J-PARC STS is shown in Fig. 4. The FEB8s are configured and read-out through GBTxEMU and GERI boards. The expected average data rates are summarized in Table 1. Since the maximum average rate is 320 Mbps and up to two uplinks per ASIC are available for FEB8-2v3, ASIC should be operated in 160 MHz (320 Mbps). The firmware and software is under development.

The spectrometer magnet has large fringing field. Therefore, GBTxEMU, which does not work in a magnetic field, has to be placed 10 m away from the FEB8. The 60 cm Axon Flexible Flat Cable (FFC) is extended using Cat6a Ethernet cables with a help of a special LVDS repeater that has been developed with GIGA inc. [4]. Figure 5 is one of the repeater boards which are under laboratory test.

A special mezzanine card for GBTxEMU is under development to accept two uplinks per ASIC through Ethernet cable.

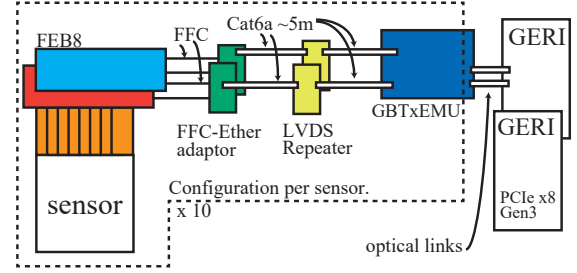


Figure 4: Readout of J-PARC STS

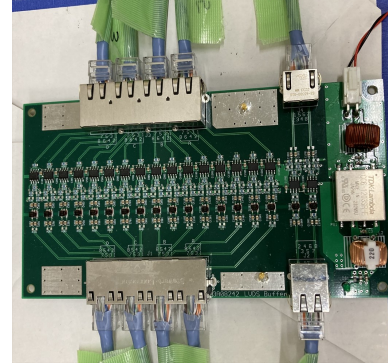


Figure 5: LVDS repeater for J-PARC STS.

Acknowledgements

We would like to thank the STS team for their kind supports and the hard work for the module construction.

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Gamma source induced energy measurements with a STS detector module

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In this contribution we report about the performance of the STS modules on the measurement of the energy deposited by an ^{241}Am gamma emitter. This study brought to us the possibility to evaluate the sensor charge collection efficiency, to reconstruct the source spectrum and to check the linearity of the threshold settings of the analog circuits of the STS-XYTER ASIC.

The measurements were taken using the module 03Tl_3, produced for the mSTS project, and a non-collimated source of ^{241}Am . The source has a well-defined 59.5 keV gamma line, which can deposited an average charge in a silicon sensor of approximately 16 400 e.

During the testing, the ^{241}Am source was placed outside of the sensor window, at a distance of approximately 3 cm [1].

The module, shown in Fig.1 consists of a double-sided, double metal $6.2 \times 6.2 \text{ cm}^2$ silicon sensor, connected via a stack of microcables of 42 cm to a pair front-end boards (FEBs) with 8 ASICs (STS-XYTERv2.1) each. 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 FEBs, and it integrates a holder for accurately positioning of a radioactive source [2].

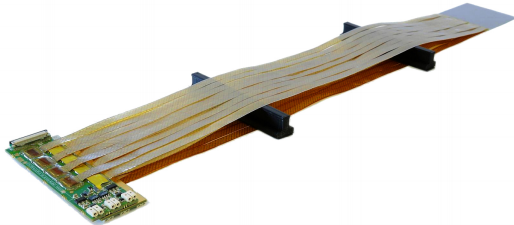


Figure 1: STS module.

In order to have a better energy resolution, the module was calibrated in a small ADC range ($\sim 3.4\text{fC}$) with the next settings as in Table 1:

Table 1: ADC calibration parameters for module 03Tl_3.

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

Results

The data were recorded at different VRef_T values (between 51 to 58 LSB, with step of 1 LSB) with and without the ^{241}Am source. The background runs were subtracted from the source measurements after normalizing to the number of time slices (TS), $\sim 20\,000$ TS in each run. The reconstruction of the data collected was done the CBMROOT, the software package for simulation, reconstruction and data analysis for the CBM experiment.

Figure 2 shows the hit rate for all channels of the module: 0-1023 (n-side) and 1024-2047 (p-side) when the source is centrally located along sensor at an effective threshold of VRef_T = 58, or 9838 e. The different colours correspond to different kinds of clusters, being the magenta line shows the distribution of all clusters, while the red line shows the distribution of clusters correlated in p- and n-side to form a hit.

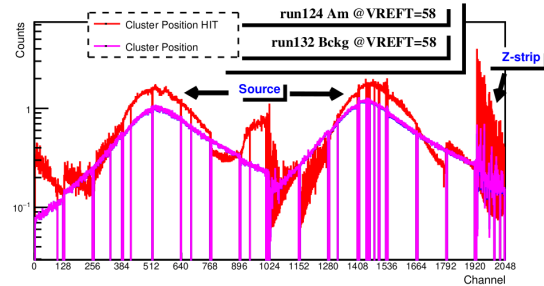


Figure 2: Hit rate for all channels of the module(n-side: channels 0-1023, p-side: channels 1024-2047).

In both cases, it was found the position of the source on the sensor around the channels 384-768, for n-side, and 1280-1664, for p-side, respectively; in the plot, it is also possible to recognize a strange behaviour in the cluster reconstruction, when the hit condition is applied. The unphysical structures that appear in the red distribution arise from clusters correlated more than once, which occurs in particularly noisy ASICs.

Figure 3 shows a 2D map reconstructed of the ^{241}Am source as a function of their geometrical position in X and Y. The region with intense yellow colour shows the location of the source.

Figure 4 shows the distribution of the cluster size versus the charge in ADC units. The gamma rays emitted by the ^{241}Am source do not deposited energy along its trajectory, but instead via a Photoeffect or Compton scattering. Both

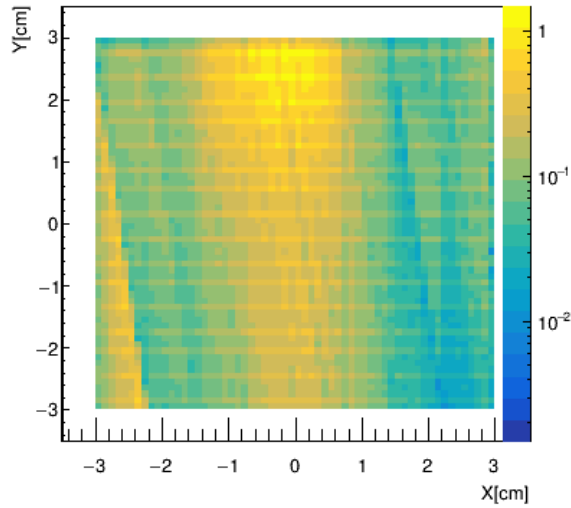


Figure 3: Hit rate illuminating different locations on the sensor.

cases describe point-like interaction scenarios where all the energy or part of it is deposited onto an electron of the material. This plot illustrates this effect by showing that most of the hits generate 1-strip cluster. By projecting this plot onto the X axis, it is possible to obtain the charge spectrum of the source for 1 and 2-strip cluster, respectively. The picture in the insert also shows the relative contribution of 1 and 2-strip clusters.

The peak corresponding to a gamma photopeak of 59.5 keV of the ^{241}Am source. In the plot presented the threshold was the highest, $V_{\text{Ref.T}} = 58$ and approximately 9838 e.

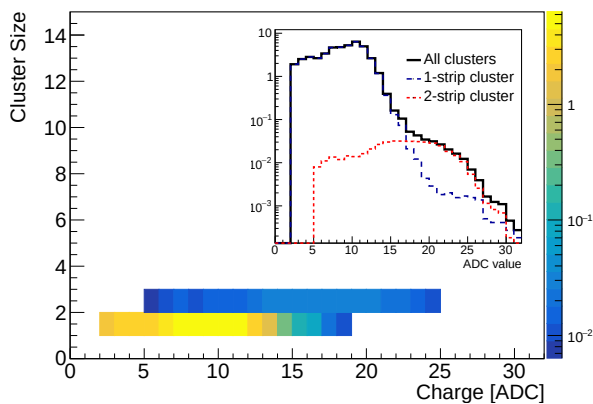


Figure 4: Cluster size distribution for each ADC value.

The charge spectrum in ADC units is shown in Fig. 5 for the ASIC 4 of n-side at selected $V_{\text{Ref.T}}$ values. With the decrease of the thresholds a shift of the peak, to higher values of ADC, is seen.

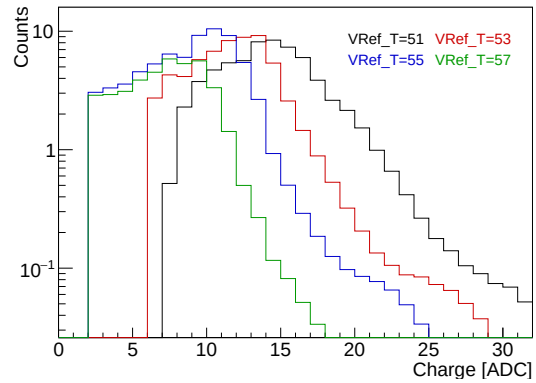


Figure 5: Gamma spectrum of a ^{241}Am source at different thresholds values.

The centroid value is obtained using a Gaussian fit and a combination of error function and Gaussian function to describe the continuum. An example of the fit is shown in Fig. 6 for the n-side at an effective threshold of $V_{\text{Ref.T}} = 56$, or approximately 8426 e. According to the ADC calibration, Table 1, and the method described in detail in [2], the deposited energy collected on the n-side was 15 619 e. The procedure was repeated for all ASICs on both sides and at the different thresholds values.

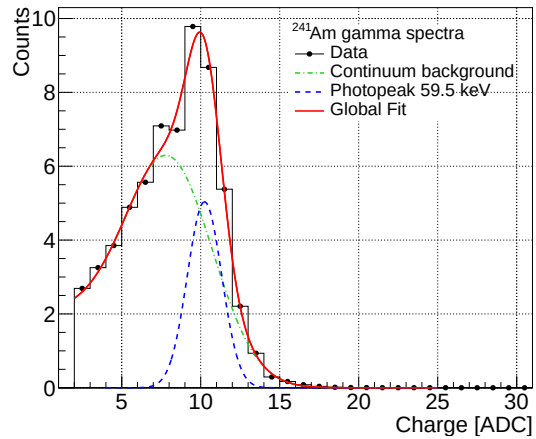


Figure 6: Gamma spectrum of a ^{241}Am source for n-side.

The position of the 59.5 keV peak at different threshold allows to checking the linearity of the $V_{\text{Ref.T}}$ setting. This is shown in Fig. 7, where the transfers functions of the $V_{\text{Ref.T}}$ parameter was calculated to be 711 and 593 e/LSB for n- and p-side, with a deviation below of 3% for the different ASICs.

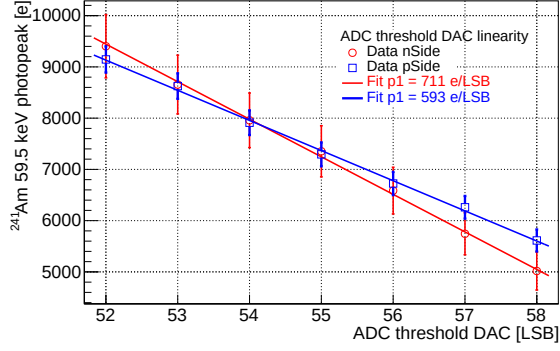


Figure 7: Linearity check of the VRef_T DAC using the 59.5 keV gamma line of a ^{241}Am source.

Summary

In summary, the reconstruction of the gamma peak of ^{241}Am was measured for both sides. On the n-side, a charge of ~ 15619 e was reconstructed; the peak position of the source spectra was obtained fitting a combination of error function and Gaussian function. It was also possible to reconstruct the location of the source on the sensor by combining the events from both sides. The linearity of VRef_T was checked with a good accuracy (deviations below 3%) and the transfer functions for both sides have shown results of 711 e/LSB and 593 e/LSB for n- and p-side, respectively.

References

- [1] A. Toia, J. Lehnert, O. Maragoto Rodriguez and A. Rodriguez Rodriguez, *Performance studies of prototype STS modules*, CBM Progress Report 2020, p. 44
- [2] A. Rodriguez Rodriguez et al., *Verification of the STS-XYTERv2.1 energy calibration using a ^{241}Am source*, CBM Progress Report 2020, p. 26

Overview of STS module assembly at KIT

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Module pre-pre production phase

After successfully finishing the production phase for five mechanical STS-Detector modules, KIT progressed to the Pre-Pre Production phase (PPP). The PPP aims to build five modules for ladder L12. Several production steps, like tab-bonding, have been optimized and adapted to new requirements and revised Front-End-Boards. KIT installed electrical test equipment and procedures and performed the first tests to glue the FEBs to T-shelf cooling.

Tab-bonding and module mounting

The build-up phase of the mechanical samples revealed a mechanical weakness between the tab-bonded interconnections and the Read-Out Chip (ROC). Insufficient tab-bonding parameters caused these weak connections. Changing the parameters reduced the over-bonding of the cables' aluminum strands; hence, the interconnections stability significantly improved. Figure 1 depicts a chip-cable connection that is strongly shaken. Electrical tests reveal that no connection broke.

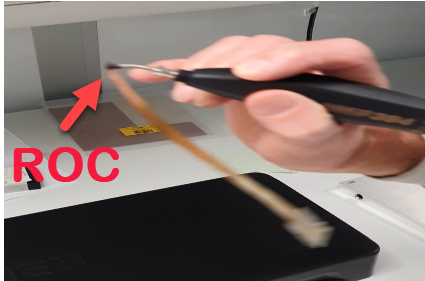


Figure 1: Shaking of a chip connected to a cable.

After mounting the chip cables to the FEB, the free end of the cable is tab-bonded to the sensor module. Firstly during the Pre-Pre-Production phase, the shortest cables of the detector had to be bonded to the module. As the formerly used mechanical flat-lying fixtures were unsuitable for the process, we developed a fixture set only for the short cables (see Fig. 2).

Testing

During the production phase, quality assessment is a mandatory step. Hence, GSI transferred most of the equipment to test the modules to KIT. The equipment includes a Pogo-pin-based ROC tester, including the test software. Next to the ROC tester, a chip-cable tester to validate the

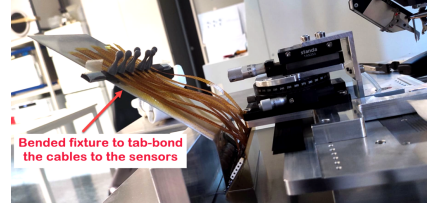


Figure 2: Bent fixture to handle short chip cables during the tab bonding process with the sensor.

ROC and cable interconnections has been installed. Additionally, a FEB tester is in operation to check the status of the ROC and low dropout voltage regulators (LDOs) mounted onto the FEB. The training to run these tests, document, and upload the test results onto the database server has been successfully finished. The module test is currently unavailable at KIT as the carrier boxes' design must be finished. KIT built twenty module carrier box frames as well as the signal distribution PCB (see Fig. 3).



Figure 3: Signal distribution for the module carrier box.

T-shelf glueing

Currently, KIT is evaluating the gluing of the aluminum T-Shelf to the ROCs. The first results look promising (see Fig. 4), although the glue distribution can be improved. The cause for the uneven glue distribution is related to the 3D-printed jigs. Hence, the process and the tools still need to be optimized and finalized for total module production.



Figure 4: PVC Dummy Feb glued on T-Shelf.

References

- [1] T. Blank et al., CBM Progress Report 2021, p. 34

Final quality control and grading results of the STS silicon microstrip sensors

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Quality control and grading of the series-produced sensors

The double-sided silicon microstrip sensors for the STS detector were series-produced at Hamamatsu Photonics, Japan, in 2019 and 2020. Upon reception at GSI, the yielded 1200 sensors underwent thorough quality control applying optical and extended electrical tests in addition to the certification results provided by the manufacturer. The outcome in terms of grading and sensor deployment across the tracking stations has been reported in [1], stating the availability of high quality material for the full detector construction. During testing, a sub-set of about 250 specimen showed various discrepancies in their current-voltage (IV) curves when comparing the measurements done at Hamamatsu and with the re-measurements at GSI. We have investigated several sensors during long-term studies, and after thermal treatment as recommended by the vendor.

Investigation of the current-voltage behaviour from a sample of a sub-set of the sensors

During testing, a sub-set of about 250 specimen showed various discrepancies in their current-voltage (IV) curves when comparing the measurements done at Hamamatsu and with the re-measurements at GSI. This includes:

- measured at low bias voltage current values are compatible, but at higher bias voltage shapes of two curves differ from each other;
- measured at GSI current is higher than expected and IV has a different shape;
- shape of IV differ at low bias voltage and parabolic rise of the current is observed;
- shape of IV at low bias voltage is in good agreement and parabolic rise of the current at higher bias voltage is observed;
- also, decreased leakage current after long time (approx. 6 months) storage in a nitrogen cabinet was observed.

We have investigated a sample of 21 sensors during long-term studies, and after thermal treatment as recommended by the vendor, and with variations to it in terms of temperature and heating duration. We report on the procedure and conclusions in reference [2]. Figure 1 shows one example

of a well-behaving sensor, and a further one that starts having rising currents starting at lower voltages than during factory inspection.

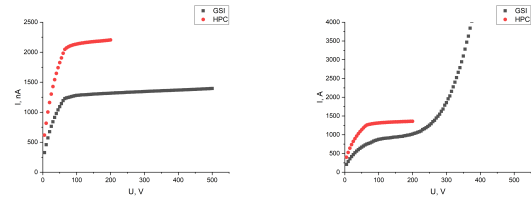


Figure 1: IV-curves of two sensors of the same variant ($62 \times 62 \text{ mm}^2$), overlaying the measurements done at Hamamatsu and at GSI. The maximum bias applied at GSI was higher than at the vendor. Also the ambient temperatures were different (Hamamatsu: 25°C , GSI: 20°C). While the shapes of the IV curves for the sensor in the left panel are the same, we see a current rise starting to occur for the sensor shown in the right panel.

Thermal treatment

The sensors were heated in a climatic chamber, initially without but then later with temperature and humidity monitoring. The entire procedure was carefully developed, including the mechanical placement on a support, the duration and temperature adjusted, also the cooldown before taking out the sensor for placement on the measurement fixture. One environmental sequence is exemplarily shown in Fig. 2.

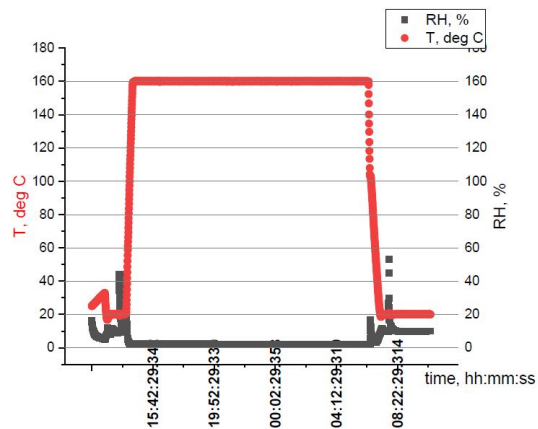


Figure 2: Temperature and relative humidity in the climatic chamber during baking on 28-29 of June 2022.

In addition to the thermal treatment, we verified that the main sensor parameters relevant for its performance remain unchanged. This included the doping profile, measured through the change of the sensor capacitance as function of the applied reverse bias voltage, being proportional to $\frac{d(1/C^2)}{dV}$, and the control of the inter-strip capacitance and resistance.

Results and conclusions

We can group the observations made into the following general classes:

- Most of the sensors, which did visibly improve IV after heating, were exposed to a temperature $\geq 150^\circ\text{C}$. They initially did not show parabolic increase of the reverse current but a higher or linearly growing current only (Fig. 3).
- Essentially all of the sensors, which did not demonstrate noticeable improvement of the current after heating at high temperature, had shown the parabolic increase of the leakage current.
- The remaining sensors were heated at low temperature, 105°C maximum and did not show significant improvement of current.
- Two sensors had improved current due to storage at room temperature alone and did not change after thermal treatment at 150°C .

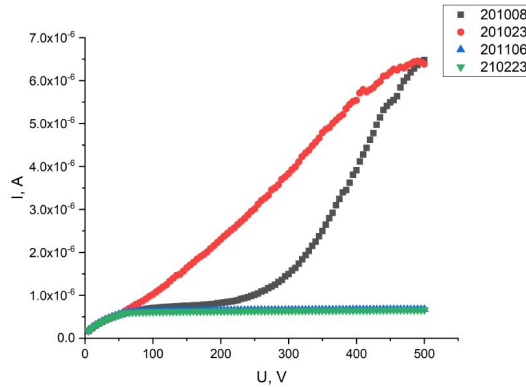


Figure 3: Example of a sensors exposed to a sequence of thermal treatments: developing an improved IV curve. The digits in the legend denote year, month, day of the test.

We conclude that no clear treatment protocol can be formulated. We attribute the effects to uncontrollable surface effects reacting on humidity, as it was also noticed by other detector projects [3]. In order to not endanger our sensors with extra and maybe unnecessary stress coming from thermal treatment and related handling, we thus recommended to define the electrical grades of the sensors according to

the existing criteria, i.e. assigning them a somewhat lower voltage holding grade, and to perform an IV and CV measurement for the sensors identified prior to module assembly for final confirmation of it. As to the current grading based on the electrical control, re-printed in Tables 1 and 2 after reference [1], we have sufficient high quality sensors, even of better grades than required, in stock for the assembly of the complete STS detector with its 8 tracking stations. This includes also extras for pre-series and demonstrator assemblies.

Table 1: Required number of sensors for STS construction, grouped according to their operation voltage holding needs.

Sensor size	Grade A	Grade B	Grade C	Grade D
U_{op}	$\geq 350\text{ V}$	$\leq 350\text{ V}$	$\leq 250\text{ V}$	$\leq 200\text{ V}$
22 mm	76	4	0	0
42 mm	184	56	32	0
62 mm	72	68	64	0
124 mm	20	84	148	68
sum		876		

Table 2: Available sensors after electrical quality control and final grading. A small number of delivered sensors with clear optical defects was excluded from the list.

Sensor size	Grade A	Grade B	Grade C	Grade D
U_{op}	$\geq 350\text{ V}$	$\leq 350\text{ V}$	$\leq 250\text{ V}$	$\leq 200\text{ V}$
22 mm	99	3	4	0
42 mm	267	20	50	0
62 mm	256	28	44	21
124 mm	222	37	84	47
sum		1182		

References

- [1] O. Bertini and J.M. Heuser, *Quality grading and position mapping of the STS silicon sensors*, CBM Progress Report 2021, pp. 22-23
- [2] O. Bertini et al., *Study of thermal treatment to STS sensors with striking IV-behaviour*, Technical Note, CBM-TN-22007, 21 November 2022
- [3] J. Fernandez-Tejero et al., *Humidity sensitivity of large area silicon sensors: Study and implications*, NIM A978 p. 164406 (2020)

Quality assurance at CBM-STS analog microcable production

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Ultra-light microcables

Ultra-light micro-cables are the key component for the CBM-STS and employed to realize the analogue signal interconnection between silicon sensors and readout electronics, providing minimized material budget. Such micro-cables are realized based on aluminium-polyimide adhesiveless dielectric with 14 μm thick aluminium and include 64 signal lines. Their length is in range from about 100 mm up to about 500 mm. The required total amount of microcables and meshed spacers for the STS exceeds 75 thousands.

Quality assurance at microcable production

Key point at production stage for such special microcables is ensuring their high quality and matching to all requirements stated in specification document for such microcables [1]. For this end RPE LTU performs quality control through visual and electrical inspections of all manufactured microcables.

Taking into account lot of technological operations during manufacturing microcables, for ensuring their high quality technological controls and inspection during production on each stages and output control before the packaging are performing. All results of the technological inspections are filled-in and documented in respective technological documents. Results of output control and inspection are prepared as Excel sheets in accordance to requirements of the specification document.

In case that a microcable or flexible layer does not match requirements of the specification document at final step or do not match technological requirements during production, it is rejected from production and will not be delivered.

Taking into account the requirements for the microcables, a key parameter of which is the trace width, every microcable does need to pass several stages of inspection.

At the production stage several quality verifying measurements were performed and redone by the customer GSI on more than 660 individual analog microcables that had been delivered. During this investigation the width of traces was measured in the bond area (more than 6 600 traces) and in the long work area (more than 3 300 traces). The results of these verifying measurements are given in histograms shown in Figs. 1 and 2.

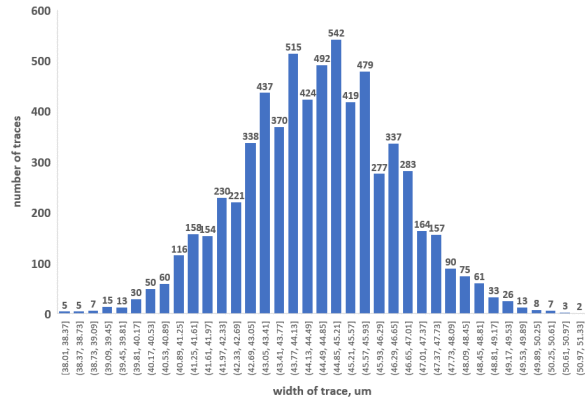


Figure 1: Trace width measured in the bond area of microcables. The required trace width is $45 \pm 5 \mu\text{m}$.

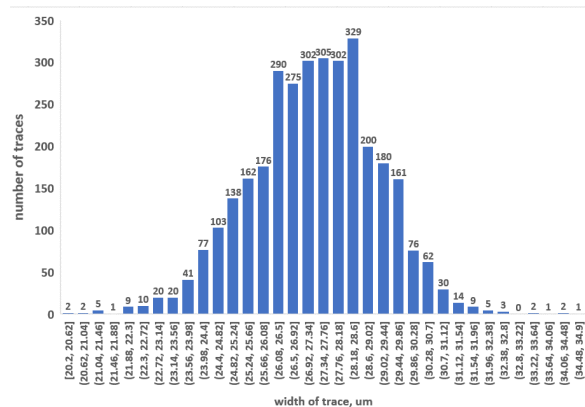


Figure 2: Trace width measured in the long work area of microcables. The required trace width is $25 \pm 10 \mu\text{m}$.

References

- [1] V. Borshchov et al., *Micro-Cables for the CBM-STS Detector Modules*, CBM Technical Note CBM-TN-20003, v22, 16 December 2021

Status of the STS-XYTER ASIC volume production and testing

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This paper¹ discusses status of the STS/MUCH-XYTER (SMX2.2) volume production and testing. It's a full-size final design of a 128-channel amplitude and time digitization ASIC tailored for the needs of the STS and MUCH detectors. It's a tested and production-readiness reviewed chip that evolved throughout several prototypes: STS-XYTER 1.0, STS-XYTER 2.0, STS-XYTER 2.1 (2018) and STS-XYTER 2.2 (2020) being the final one.

The production wafers were ordered in Q1 2022 as a result of tender published in Q4 2021. The global crisis in microelectronics caused many unknowns in the production including completion date at the moment of ordering. The production was finally split into two lots, 75/100 (delivered in Oct. 2022) and 25/100 (delivered in Dec. 2022).

The fabricated chips need to be tested and classified before being used for module assembly. The main tasks of testing are:

- Reject dead chips (i.e. bad current, no digital response, etc), expected ≤ 10000 ppm of the volume.
- Classify functional chips into the classes depending on number of bad channels (if any).
- Initially calibrate converters (i.e. in-channel ADC, diagnostic ADC).
- Burn unique ID in e-fuse memory.
- Keep additional forensics data.

The key point is to keep the test time / chip short. For example 4 min./chip results in $35000 \text{ chips} \times 4 \text{ minutes} = 97 \text{ days}$ excluding wafer handling, maintenance etc. Multiple direct and indirect testing methods were discussed, designed and used in the past. Best practices and techniques from pogo-prober, pre-module assembly testing will be re-used.

The wafer probe card is a PCB with test needle assembly that serves as an interface between the test equipment and the DUT that needs to fit the dedicated slot in the wafer prober. Two PCB designs were prepared (one design per wafer prober).

A dedicated space for SMX2.2 testing was deployed at AGH University. It is a 13 m² clean-room with hepa-filter ceiling, equipped with two wafer probers: Semi-automatic Cascade Microtech REL-6100 unit and an automatic Tokyo

Seimitsu (Accretech) UF-200SA with associated vacuum, compressed air installations, wafer handling tools and laboratory equipment such as DAQ cards, oscilloscopes, arbitrary generators, power supplies.

The volume testing of the chips requires automated procedures and remote control of the instruments. Both wafer probers are more than 15 years old, and the team is observing several issues. Even though it was used in the past for volume testing, the Cascade wafer prober is exhibiting frequent issues with GPIB interface module. The use of alternative DDE Server Communications is investigated to enable automated testing and chip-swapping. The Accretech prober, was acquired recently and its architecture prevents from "dry-tests". The operation without complete wafer probe card assembly with needles prevents from progressing with remote command handling. The wafer-prober PCBs are already ordered, the wafer-card needles' assembly order is in progress. The test setup will also be upgraded by CBM from the previous-generation AFCK boards to the latest communication systems.

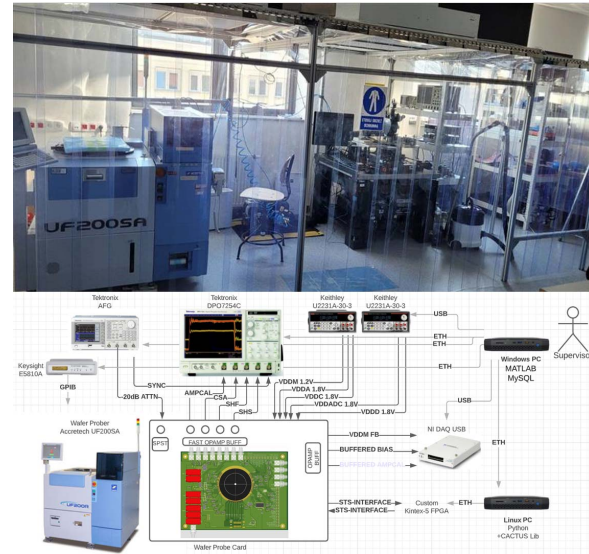


Figure 1: Clean room and test systems.

Assuming no further issues, it is expected that the wafer testing will be completed in 2023 and the delivery for module assembly will be done in batches as needed.

¹This work was partially developed using resources of the Interdisciplinary Research Laboratory (ILB) at AGH University of Science and Technology. The research results presented in this paper have been developed with the use of equipment financed from the funds of the "Excellence Initiative—Research University" program at AGH University of Science and Technology.

Development and performance of STS front-end boards FEB8-2 and FEB8-5

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Introduction

For a module of the STS detector two FEB8 electronics boards are needed, one for P-side and one for N-side. In the mSTS modules, FEB8 versions A2 and B2 PCBs with two uplink channels have been installed and tested. Based on the experiences during assembly and operation of this setup, two FEB8-2 derivatives A3 and B3 with multiple optimizations have been developed.

FEB8-2 version 3 improvements

The main modifications are [1]:

- Elimination of the mechanical sensitive 3D-arranged coupling capacitor array
- Use of a smaller ZIF connector in order to get space on the PCB for the coupling capacitors
- Integration of the HV filter circuit with cooling fin as reference potential
- LV powering over Sumida PANTA FIX POWER flat cable soldered directly to the PCB
- HV bias voltage of up to $\pm 250\text{V}$ over shielded miniature coax cable soldered to PCB pads
- Additional powering option (LV and HV) over pin header connector

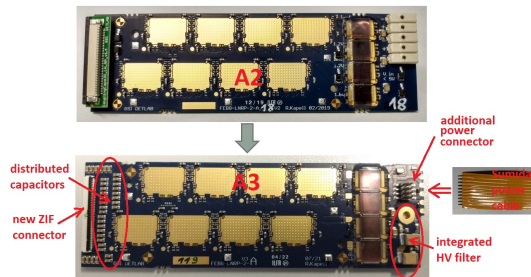


Figure 1: Differences between FEB8-2 PCB version A2 and A3.

The 3D-arranged coupling capacitors of FEB8-2 version A2 are very sensitive concerning shear forces. In the past, several of these capacitors got damaged while handling and the connected ASIC did not respond anymore. Therefore this capacitor array has been replaced by capacitors distributed on the FEB8 PCB TOP side. To get the required space for the coupling capacitors, a smaller ZIF

data cable connector has been selected in version A3 and B3 PCBs (Fig. 1).

The single wire clamps in version 2 PCBs are also not feasible for the new power flat cables, which have to be used due to space limitations. The solution is to solder the power flat cable directly to the PCB before installing the module on the ladder. To power the FEBs during production test procedures, an additional power connector has been added (Fig. 2).

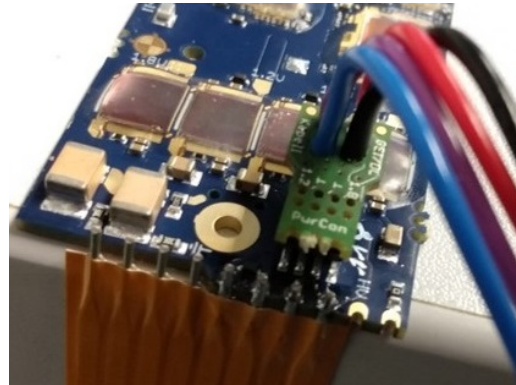


Figure 2: FEB8-2 A3 powering options.

FEB8 PCB version A with 5 uplinks

To support the maximum number of readout links required in STS, a new FEB8-5 version A2 PCB with 5 uplinks per ASIC and with a 100 pin ZIF data cable connector has been developed. The challenge was to find space for 84 coupling capacitors instead of 36 parts on the FEB8-2 PCBs.

All other modifications of FEB8-2 version 3 have also been included in the FEB8-5 A2 design (Fig. 3).

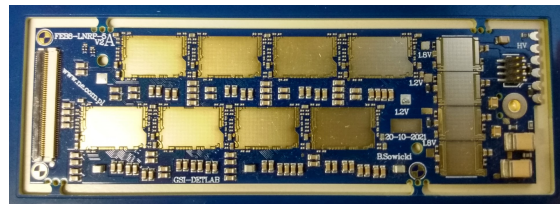


Figure 3: FEB8-5 A2 PCB.

FEB8-5 test setup

To operate a FEB8-5, additional new peripherals are necessary. A suitable data cable with 42 impedance controlled LVDS signal pairs and double sided shielding is needed. Two different cable versions were procured for this purpose: one version from LTU (Al lines with a length of 46cm) and one from a Chinese supplier (Cu lines with a length of 80cm). A new FMC adapter PCB with one Hirose FH29 100 pin ZIF connector has been designed to complete a FEB8-5 test setup shown in Fig. 4.

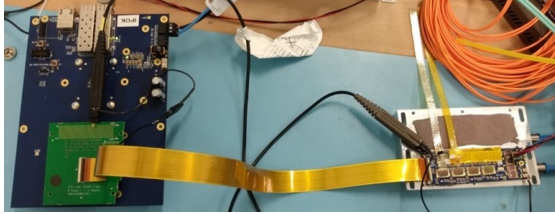


Figure 4: FEB8-5 test setup with LTU data cable.

First FEB8-5 tests

The operation of the new FEB8-5 with both cables has been tested in the shown FEB8-5 test setup. All 40 uplinks work properly and ASICs can be controlled from each uplink individually or from any combination of the available uplinks. The stability of the communication was confirmed with continuous R/W operations for 1h without a single failure. The functionality of the data generation from the analog frontend was checked. To test the signal quality of the LVDS data lines, the eye diagrams for clock and data links were measured (Fig. 5) with 1GHz differential probes. No weaknesses in the PCB and data cable design were visible.

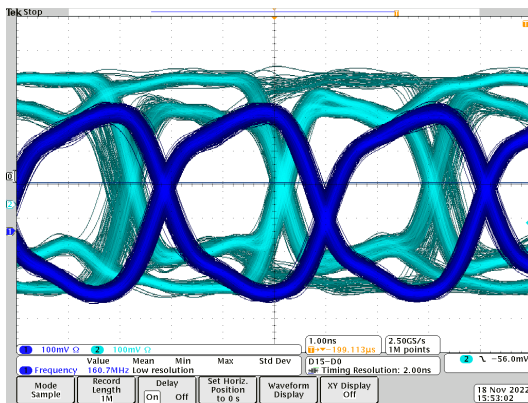


Figure 5: Eye diagram for the FEB8-5 communication showing clock and downlink.

FEB8-5 ASIC assembly

With the first prototypes of the FEB8-5 A2 PCBs, assembly and bonding of the STS-XYTER 2.2 ASICs has been tested. It became apparent that the ASICs in the second row lift up while the glue was curing (Fig. 6). This happens because the capacitors, which are arranged just below the micro cables, force the micro cable together with the bonded ASIC upwards. As a result, the thermal contact to the PCB surface is insufficient and bonding from the ASIC to the PCB becomes difficult. Therefore, a redesign of the PCB was necessary. Shifting the capacitors under the micro cables to uncritical positions will minimize this effect.

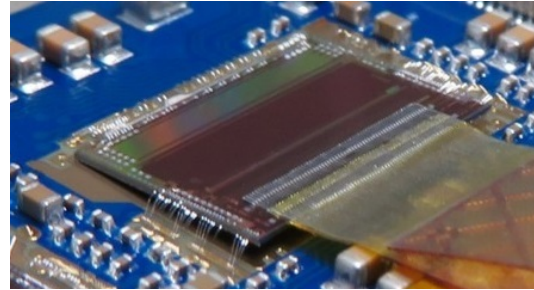


Figure 6: FEB8-5_A2 with bonded ASIC.

Redesign of FEB8-5 PCBs

The next FEB8-5 version 3 PCBs (A & B) will be mainly optimized to have no coupling capacitors in the areas of micro cables connected to the second row ASICs (Fig. 7). Tests with a dummy FEB8-5 (paper printout of the new layout glued on an old FEB8 PCB) have shown, that the second row ASICs won't lift up anymore with version 3 PCBs.

Furthermore, the length of the signal return wire, soldered between FEB8-5 A and FEB8-5 B, is shorter in the redesigned layout versions. That helps to optimize the noise performance of the analog signal channels.

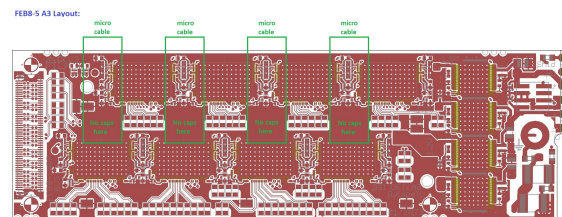


Figure 7: FEB8-5_A3 Layout screenshot.

References

- [1] U. Frankenfeld, *Update on module and ladder design*, 40th CBM Collaboration Meeting, Warsaw, October 2022; and this report

Development and test of prototype CBM-STS data cables

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B. Podliesniy², N. Chernikova², L. Klimova², and M. Tykhomyrova²*

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Ultra-light microcables

CBM-STS data cables are intended for connecting Front-end boards (FEB) with read-out electronics located on the periphery of the STS detector. Every FEB carries 8 STS read-out ASICs of 128 channels each to receive the 1024 sensor output channels of one side of an STS sensor module and needs to be connected by flat microcable with about 40 high-speed LVDS signal pairs for data transfer. The routing lengths of such microcables are in range of about 50 to 100 cm [1].

Initial data for the development of prototypes

One important limiting point for the development of the data cables is the very limited space for the cabling between the FEB boxes (Fig. 1).



Figure 1: Photo of a mockup illustrating the narrow gap between the FEB boxes available for cabling.

Based on the requirements and possible approaches for the realization of similar microcables, the following initial data and specifications for their development were defined:

- data cables need to be realized as flat flexible cables (FFC) which allows to realize compact designs of electrical conductors in one flat profile with reduced space and weight;
- the thickness of the cable should not exceed 0.35 mm;
- the width of the cable should be less than 26 mm;
- the cable should be suitable for the transmission of 42 high-speed LVDS signal pairs (84 signal lines), i.e. a 100 Ohm impedance controlled layer structure needs to be realized;
- trace pitch $\approx 0.2/0.4$ mm;
- the flat cable should be suitable for connector HIROSE FH29DJ-100S-0.2SHW at both ends;
- shielding layers on one or on both sides of the cable.

Realization of data cable prototypes

For the realization prototype data cables, the following steps have been done:

- base approach for creating data cables developed;
- for ensuring 100 Ohm impedance, precise structures of the cables were defined;
- the structures of the cable were defined (Fig. 2): each data cable consists of one signal layer (with signal traces), one or two shielding layers and one or two Kapton spacer layers (for ensuring the required impedance);
- designs of the prototypes both with single and two shielding layers and components were developed;
- assembly work flows were developed and verified.

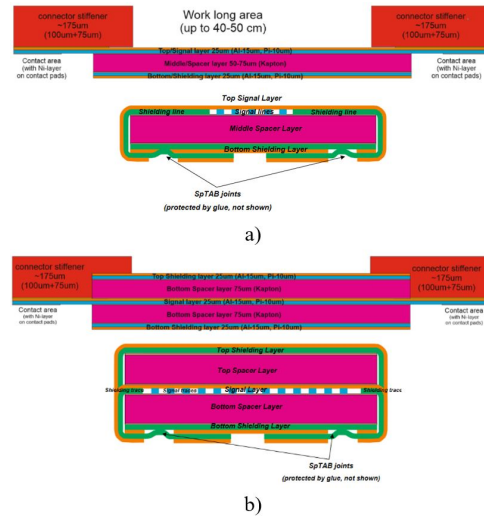


Figure 2: Composition and schematic cross sections of the data cable prototypes: a) with one shielding layer; b) with two shielding layers.

For further investigations and tests few prototypes both with one and two shielding layers were manufactured (Fig. 3). The prototypes manufactured are about 46 cm long because of technological limitations at manufacturing flexible layers. Flexible layers (signal and shielding layers) with aluminium conductive layer for data cable prototypes are made of similar material as for ultralight CBM-STS analog microcables [2], namely

aluminium-polyimide adhesiveless filed dielectrics (aluminium 14-15 μm thick, polyimide 10 μm thick). Spacer layers are made of Kapton film. Flexible layers are manufactured using precision photolithography and chemical wet etching. For the assembly of data cables lamination and SpTAB were used. In connector areas the contact pads are coated with a Ni-layer ($\approx 2 \mu\text{m}$). In the connector areas on both ends of the data cable, additional spacer stiffeners made from Kapton film are laminated, 200 μm thick.



Figure 3: Prototype of a CBM-STs data cable.

Setup for testing data cable prototypes

The manufactured data cable prototypes have been investigated using a specially created test setup based on a Tektronix TDP1000 oscilloscope and P6247 1 GHz Differential Probes. For investigations of clock/downLink/uplinks on the data cable prototypes, board variant FEB8-5 has been used. See Figs. 4 and 5.

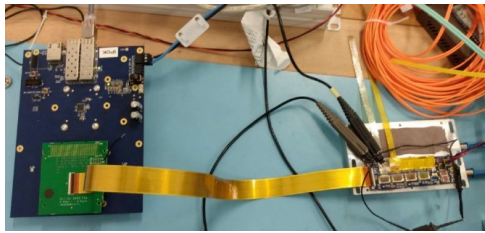


Figure 4: Setup for testing clock/downlink/uplink lines with connected data cable prototype.

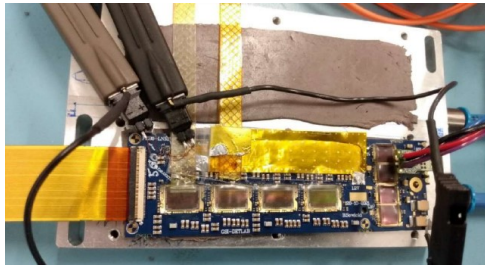


Figure 5: Connecting the data cable prototype to FEB8-5 via HIROSE FH29DJ connector (left part of photo).

Results

Tests were performed both for prototypes with one and two shielding layers. An example of a recorded oscilloscope measurement is shown in Fig. 6. The results obtained allow to conclude the following outcome:

- both types of the data cables (with one and two shielding layers) have good electrical properties;
- the required differential impedance of 100 Ohm has been achieved well;
- some small reflections, which have been seen during testing, seem to come from other sources (impedance change on the PCB, for example at the ZIF connector or due to vias);
- double-sided shielding is necessary to have a stable data transmission and to minimize noise contribution to the analog signal lines.

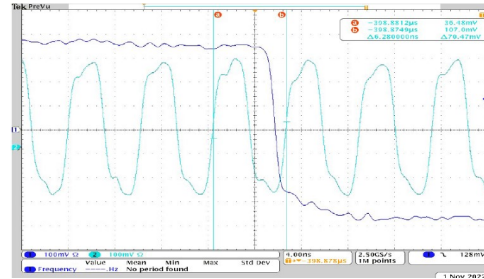


Figure 6: LVDS waveforms of clock and downlink for a prototype with two shielding layers.

Conclusions

Special flexible flat data cables for the connection of STS modules' FEB boards to the read-out electronics have been developed, designed, and prototypes of about 46 cm length have been manufactured and tested. The obtained test results allow to conclude that tested data cable prototypes (both with one and two shielding layers) have good electrical properties; the required differential impedance of 100 Ohm has been achieved well. However, for a stable data transmission and to minimize noise contribution to the analog signal lines double-sided shielding is preferable. But, taking into account the possible length of the data cables of up to 80 cm or even 120 cm for some modules, an approach for the realization such elongated data cables needs to be developed and verified. Such elongated cables might be realized as composite microcables and will consist of two or three parts each up to about 40 cm long.

References

- [1] J. Heuser et al., Technical Design Report for the CBM Silicon Tracking System (STS), GSI Report 2013-4
- [2] V. Borshchov et al., *Micro-Cables for the CBM-STs Detector Modules*, CBM Technical Note CBM-TN-20003, v22, 16 December 2021

Automized quality control procedure for FEB8 version 3

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The FEB8 test is one of the first QC test in the module assembly process. Therefore a reliable test procedure and setup is necessary to avoid production rejects in later stages where many hours of work and more expensive components would be wasted. The test setup consists of three major parts - the FEB8 test box as an adapter for the power lines to the FEB8 PCB, the power supply and the software for controlling the test procedure and analyzing the results.

FEB8 test box

The FEB8 test box is a 3D printed box with an integrated microcontroller. It can be connected to a PC via the exposed Micro-USB port of the microcontroller. It features a lever mechanism to open the top part of the FEB8 adapter. The adapter features different pins to connect to the power connectors of the FEB8 PCB. The FEB8 test box is connected to and controlled by a lab computer with the FEB8 test software (Figs. 1 and 2).



Figure 1: Complete setup with computer, power supply and FEB8 test box (from left to right).

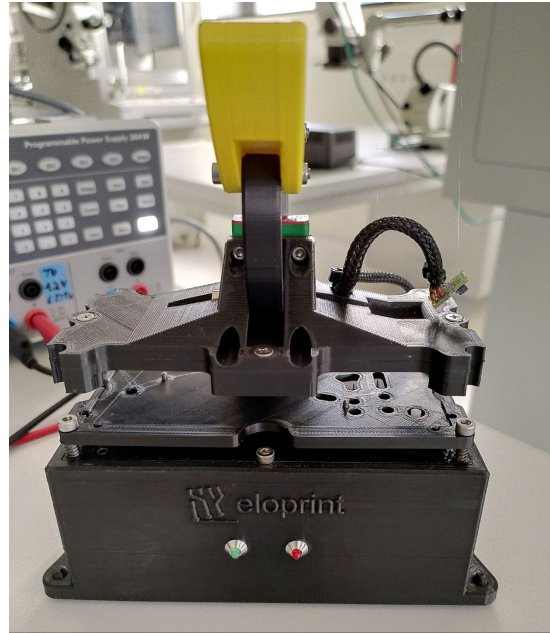


Figure 2: FEB8 test box with open lid and without a FEB8.

Power supply

The power supply must be remote controllable by the FEB8 test software. This is necessary to read out current values needed for the first part of the QC procedure. Currently used are power supplies of type *HMP4040* by Rohde & Schwarz (former Hameg HMP4040).

Test setup

The “production ready” test setup consists of three major parts. First the previously mentioned FEB8 test box including necessary cabling for power and data. Second the power supply (also including necessary cabling for the network connection). Lastly a lab computer with the test software. The power supply connects to the FEB8 test box via four power cables (two for each voltage level). Additionally an ethernet cable needs to be connected to a network socket. The lab computer also needs a connected network cable and a USB cable for the connection to the FEB8 test box.

Test method

The whole test setup is controlled via the test software. First a measurement of the current draw without any load is performed to detect certain types of short circuits. After this test was successful an automated test sequence is started. All four LDOs are tested in parallel at three different load levels (no load, nominal load and maximum load). The results are then transmitted to the lab computer and analysed.

Data export

The raw data is exported to a text file for further import into the components database. The processed and analyzed data from each test is collected and exported into one elog readable file at the end of each session (session = from opening to closing the test software). Currently the file needs to be manually imported into the elog but it is envisaged to automate this process as well (see Fig. 3).

→ Entry 52 posted by Bjoern Schmitt on Fri Dec 9 15:07:54 2022	
Message ID: 52	Entry time: Fri Dec 9 15:07:54 2022 In reply to: 51
Author:	Bjoern Schmitt
FEB8-ID:	FEB8-LNRP-5-5007
Amount of uplinks:	5
FEB8-type:	LNRP (A)
FEB8-SN:	5007
LDO-Assembly-Site:	GSI
LDO-Assembly-date:	09.12.2022
LDO-bond-check:	true
LDO-Measurement-date:	09.12.2022
LDO_AVDD18 [V](no load):	1.832
LDO_AVDD12_1 [V](no load):	1.230
LDO_AVDD12_2 [V](no load):	1.232
LDO_VDD18 [V](no load):	1.808
LDO_AVDD18 [V](nom. load):	1.828
LDO_AVDD12_1 [V](nom. load):	1.224
LDO_AVDD12_2 [V](nom. load):	1.224
LDO_VDD18 [V](nom. load):	1.804
LDO_AVDD18 [V](max. load):	1.826
LDO_AVDD12_1 [V](max. load):	1.220
LDO_AVDD12_2 [V](max. load):	1.220
LDO_VDD18 [V](max. load):	1.800
I(AVDD18) valid at all loads:	true
I(AVDD12_1) valid at all loads:	true
I(AVDD12_2) valid at all loads:	true
I(VDD18) valid at all loads:	true
QA-Status:	true
FEB8-Assembly-Status:	tested
I(Ch_2.2V; min):	8.9
I(Ch_2.2V; max):	8.9
I(Ch_2.8V; min):	11.6
I(Ch_2.8V; max):	11.8

Figure 3: FEB8 test result entry in the elog.

Overview of (data-) logistics activities as part of STS quality management

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The *QM & Logistics* group worked during the year 2022 intensively on the streamlining of processes to be performed prior, during and after the technical module assembly process itself among the participating assembly sites. The logistic part does not only cover the needed hardware, but also includes the needed data-logistics to be centralized and homogenized through the participating module assembly sites, where the latter one is strongly correlated to the QA/QC envisaged to be performed for the corresponding components/compounds.

The development of an adequate logistic process-scheme was focused on establishing reliable, transparent and practical procedures of logistics, which – in the case discussed in this report – will be strongly correlated to the technical module assembly procedure. In case of identified needed information to be provided by the *QM & Logistics* to the technical Module Assembly Teams, input from the corresponding teams has been requested and implemented in such a way, that it still ensures the mandatory consistency with already existing logistic procedures, QM and Logistics documentations. This is also required regarding risk minimization for logistical mishaps on all assembly sites prior, during and after the assembly of the individual STS-modules up to detector operation.

User videos

For adequate streamlining of procedures, especially if those do affect more than one site, a platform for coordination of work and information exchange between – or to be distributed to – the individual working groups, has been figured out to be of crucial importance.

For the STS-group this kind of platform is realized by usage of CBM Redmine. In order to becoming familiar with the usage of the Redmine system in general, some introductory “User-Videos”, covering different basic topics, have been produced by the *QM & Logistics*, following user request.

Logistics logbooks

Fixture, tool (and test-material) distribution

Prior to production-start of the STS-modules several tools, fixtures and also material for test devices and, e.g., for training purposes are shipped between the different module assembly sites prior to their storage until usage. To be able to follow-up the shipment and the status of the equipment/material available at the different sites, an additional electronic logbook (ELOG) has been set-up. To make its usage as practical as possible, the Module Assem-

bly Teams assigned feedback. This was sequentially implemented into the structure as well as on some features of the logbook, to bring it into its current status that can be found under the link: <https://elog.gsi.de/cbm-sts/Jigs+Tool+distribution>. A more detailed description of its usage, apart from corresponding email notifications, can also be found on the STS-Logistics Wiki page [1], where also the corresponding mind-map is available for download or printout.

Microcable shield replacement

The design of the micro-cables shields was modified according to assembly experience. The current design of the shieldings is described in the corresponding technical note [2]. Consequently, new shieldings had to be ordered for micro-cable sets already delivered, and were received during the second half of 2022. Therefore, the already existing shieldings of several micro-cable sets have to be exchanged by these updated ones prior to their usage during module assembly. To follow-up this necessary replacement procedure at the different assembly sites, and to avoid possible mixing up of shielding versions, an additional electronic logbook (ELOG) was set up, which can be found under the link: <https://elog.gsi.de/cbm-sts/Shielding+Replacement>.

Labeling

Regarding the labeling procedure for components and/or compounds used for technical module assembly, a QA note [3] as well as a mind-map, visualizing the individual labeling steps, have been written. They can be found on the corresponding STS-Logistics Wiki page [1], which was intensively updated during the last year. Following common practice, feedback was required by the *QM & Logistics* from the KIT assembly team, which may have additional requirements on logistic processes based on special boundary conditions (e.g. compared to GSI) which had impact on finalizing the necessary labeling sequence. For that purpose the corresponding module label sets as well as additional documentation have been provided to the KIT colleagues prior to feedback received.

As a final step of evaluating this procedure, the quality of the labeling procedure itself will be controlled by the *QM & Logistics* team via additional spare labels, being provided as part of the module label set to be used in case of possible mishap (here: label loss), which could be easily identified after module assembly and could therefore be used for possibly necessary adoptions of this procedure.

During the development process, several labels needed to be adopted and tools had to be designed, e.g. for cutting of very small labels (c.f. Fig.1) related to space constraints. This iterative process was practised to ensure proper labeling taking into account the different boundary conditions at the sites as well as environmental boundary conditions during several testing steps during and after the technical assembly of the STS-modules. The latter one does have severe impact on the material and glue of the labels to be used.

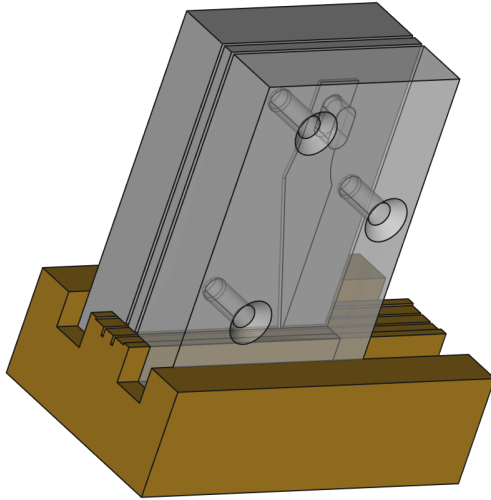


Figure 1: Sketch of one of the cutting tools used to provide labels of the envisaged maximum width of 2 mm to be cut out of the chosen labeling tape, which is commercially not available with widths needed for this designated STS logistics purpose.

Also the position and accessibility of the label has influence on its content and format and the way of possible encoding of information to ensure usage of e.g. barcode readers. The list of requirements on the labels (including glue) were collected in 2018 by the STS team for the first time and does not significantly change until the time being. It was slightly modified and enlarged due to general developments on this sector during the recent years and could be looked up on the STS logistics Wiki page [1].

Currently all needed information for module specific label printing is foreseen to be added to some kind of database as feature of the labelprinter software to be able to print out the labels for production automatically by just entering the corresponding required module ID. Most templates of the labels corresponding to one designated module label set have been setup already by taking into account the implementation of the corresponding database input fields.

References

- [1] <https://cbm-wiki.gsi.de/foswiki/bin/view/STS/Logistics/>
- [2] C.J. Schmidt et.al., *Micro-Cables for the CBM-STs Detector Modules*, CBM-TN-20003, v22, 16 December 2021
- [3] A. Wilms, *QA protocol on labeling steps to be performed during and after module assembly for the CBM-STs*, CBM-QA-STs 22002, 14 October 2022, <https://cbm-wiki.gsi.de/foswiki/bin/view/STS/Documentation/>

Power board v4 for the STS

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Requirements

Power is delivered to the STS front-end electronics over distances of about 25 m from the power crate to the C-frames carrying the ladders with detector modules. The initial voltage of 12 V is converted by the power boards (PoB) to about 2.5 V necessary to supply the front-end boards. The power boards have to satisfy the following requirements:

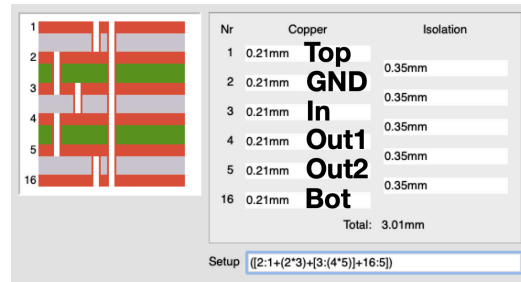
- provide a compact solution using one input connector and four output connectors;
- use SMD type connectors only in order to use the backside of the board for flat mounting on the surface and heat transfer;
- provide a design with trace routing and layer structure robust against electromagnetic interference;
- use thick copper traces (thickness $>175 \mu\text{m}$) to minimize voltage drop;
- provide holes for mounting screws.

Board design

A PoB is located at the C-frame and carries 16 FEASTMP radiation and magnetic field tolerant DC-DC converters as mezzanine boards [1] matching the 8-fold topology of the low-voltage power supplies. Since every front-end board (FEB) requires two supply voltages to operate, one input channel of the PoB is split between the two FEASTMP modules resulting in two different DC voltages at the output. One PoB with 8 input voltage channels will thus have 16 output voltage channels to power four detector modules with two FEBs each (4 modules $\times$ 2 FEBs $\times$ 2 DC voltages). The typical current for the input channel is about 1.5 A. The two output channels deliver about 2 A each at 2.6 V and 2.9 V, respectively. The maximum current provided by the FEASTMP DC-DC converter is 4 A and needs to be considered in the output connectors' current rating. A dual-row right-angle Molex MicroFit 3.0 connector with 2×8 pins is used at PoB input. The four output connectors, serving one detector module each, are standard 8-position SMD sockets with 2.54 mm pitch (Samtec model SSM-108-L-SV). The sixteen connectors compatible with FEASTMP modules are Samtec model SFM-106-02-L-D-A. Due to the operation of front-end electronics (FEE) at high reference potentials of +250 V and -250 V for n - and p -side, respectively, the input and output connectors are required to have a voltage rating of higher than 500 V.

Layer stack-up

The layer structure is crucial for the electromagnetic compatibility (EMC) of a circuit and effects directly the noise performance and noise immunity of any PCB. The PoB v4 is based on a 6-layer printed circuit board (PCB) with $210 \mu\text{m}$ copper layer thickness in order to minimize voltage drop on the metal traces. The board has been manufactured by Vika PCB (Shenzhen, China). The top and bottom layers are used for component placement and routing (see Fig. 1). The internal layers from top to bottom are used as ground, input, and two output layers, respectively. Special care has been taken to route the traces belonging to a given channel on different layers precisely overlaid in order to reduce the loop area.



Nr	Copper	Isolation
1	0.21mm	0.35mm
2	0.21mm	0.35mm
3	0.21mm	0.35mm
4	0.21mm	0.35mm
5	0.21mm	0.35mm
16	0.21mm	0.35mm
Total:		3.01mm

Setup: ((2:1)+(2*3)+(3:(4*5))+16:5))

Figure 1: Layer stack-up of POB v4 with top and bottom layers used for component placement and auxiliary routing.

In order to improve the production yield, blind vias have been avoided in the design. Thus, only buried vias between adjacent layers and through-hole vias connecting all layers were allowed in the design.

Manufacturing report

The manufactured PoB v4 PCB populated with connectors is shown in Fig. 2. The input connector is shown on the left-hand side of the board and four output connectors are on the right-hand side. The silkscreen labeling indicates the numbering of the input and output channels as well as the pairwise grouping of the FEAST modules to form a pair of DC voltages needed to power a FEB.

A detailed manufacturing report has been provided by the manufacturer giving details on the thickness of technological layers (e.g., copper and solder mask thickness), board thickness, size of drill holes, etc. An extensive electric test has been performed including current/voltage load quantifying the conductive and insistance resistance and

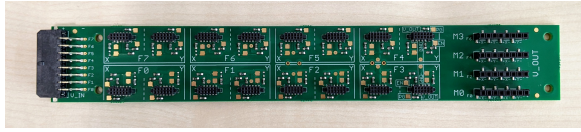


Figure 2: PoB v4 printed circuit board populated with connectors.

trace integrity (open, short). Thirty boards have been manufactured, of which 20 have been populated with connectors. All manufactured boards are up to the specifications. An electric test with FEAST modules equipped has yielded the expected performance.

Conclusions

A new design of the STS power board has been manufactured with an 8-fold number of FEASTMP DC-DC converters. The manufacturing report has confirmed the design specifications of the delivered boards. The available PCBs have been populated with connectors and tested under full electric load confirming the targeted performance.

References

- [1] FEASTMP. Radiation and magnetic field tolerant 10W DC/DC converter module (datasheet rev 2.1), https://espace.cern.ch/project-DCDC-new/Shared/%20Documents/FEAST2Mod_Datasheet_gb2016.pdf

A full-size prototype of the STS beam pipe: Design improvement, fabrication

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STS beam pipe section

The vacuum beam pipe segment passing the volume of the STS detector consists of a conical structure as shown in Fig. 1. At its upstream end, it is attached with a membrane (“window”) to the back side wall of the target vacuum chamber with its circular opening. The downstream end of the beam pipe is coupled to a sliding interface in the rear STS wall, sealed with an O-ring. All material of the beam pipe and the window are made from resin impregnated carbon fiber. The concept and a study made to assess its performance to vacuum stability, sturdiness, and manufacturability has been summarized in last year’s report [1]. The study yielded that the conical part can be constructed at the targeted 1 mm thickness, using a laminate built-up with 6 fiber orientations and high-modulus carbon fiber. It yielded rigidity against bulging under internal vacuum with a large safety margin, and was vacuum tight. FEM studies of the window, however, showed that forces on the 0.5 mm thick window, in the interconnecting region to the conical section, could become critical as inter-fiber break occurred at 7 N (radial) and 350 N (axial).

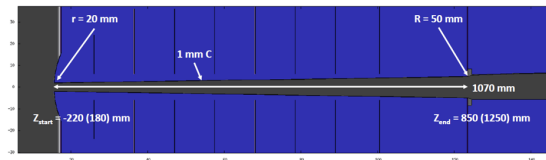


Figure 1: Beam pipe geometry, here implemented for radiation studies with FLUKA. The z coordinates are given in the current and old (in round brackets) coordinates referring to the respective origin in the magnet.

Design improvement

Therefore a follow-up study was carried out at the engineering company¹ entrusted with the works. The window was modelled in a finer and orthogonally segmented grid, based on the properties of a specific CFK fabric with a resin matrix. A sample fabric laminate produced yielded the targeted thickness of 0.5 mm and was of high quality, ensuring vacuum tightness. In the FEM model, the laminate build-up in the transition region to the cone was modified, changing gradually from 0.5 to 1.0 mm. Grid, fabric and the characteristic cut-off parameter are shown in Fig. 2. The FEM analysis [2] of this structure (see Fig. 3) shows an

¹ICM-Composites GmbH & Co. KG, 64331 Weiterstadt, Germany; <https://icm-composites.de/>

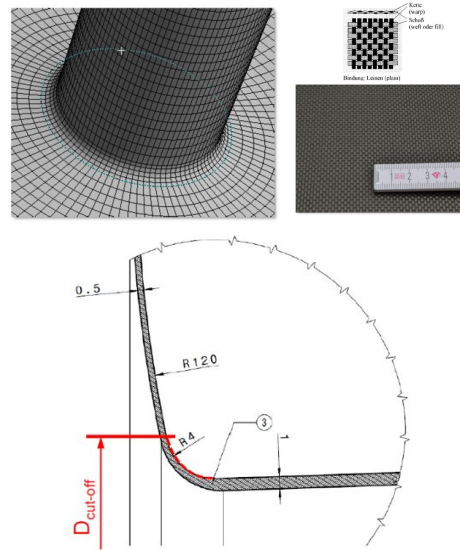


Figure 2: Details of the window improvements: (top) adapted grid for FEM evaluation; fabric chosen (T300B 1K 66 tex, 6 Fd/cm, thickness 0.15 mm, 80 g/m²). (bottom) Cross section of the window joint with cut-off parameter D w.r.t. the symmetry axis. The chosen variant has $D = 80$ mm.

improvement of radial fiber breaks occurring at 22 N instead of 7 N with a constant window thickness. The corresponding deflection of the pipe when kept fix at the window end is 132 mm. This is very safe as it should never occur on such scale. The pipe hanging free at the mounted window end, under its own weight of 622 g, leads to a sag of 27 mm at its upstream end, thus a safety factor exceeding 10 is present.

Also, in 2022, we have further developed and detailed the STS mechanical design [3], including the concept of a tool and procedure to be used for the installation of the beam pipe. This tool will prevent the beam pipe from accidentally tilting by any significant amount when already connected to the target chamber. Together with the improved sturdiness of the window joint to the conical part of the beam pipe, this presents a reassuring picture. The beam pipe is compatible with the dimensions of the “modular” STS design as the respective distance between target box and rear STS wall did not change. Detailed adaptation of the distances of the sensors on the central ladders to the beam pipe were anyhow still pending [4] and could be resumed finalizing the microcable lengths accordingly.

References

- [1] J. M. Heuser et al., CBM Progress Report 2021, pp. 55-58
- [2] ICM report, STS Construction Meeting, 30 Nov. 2022, <https://indico.gsi.de/event/16416/>
- [3] O. Vasylyev et al., this report
- [4] I. Tymchuk et al., CBM Progress Report 2021, p. 39

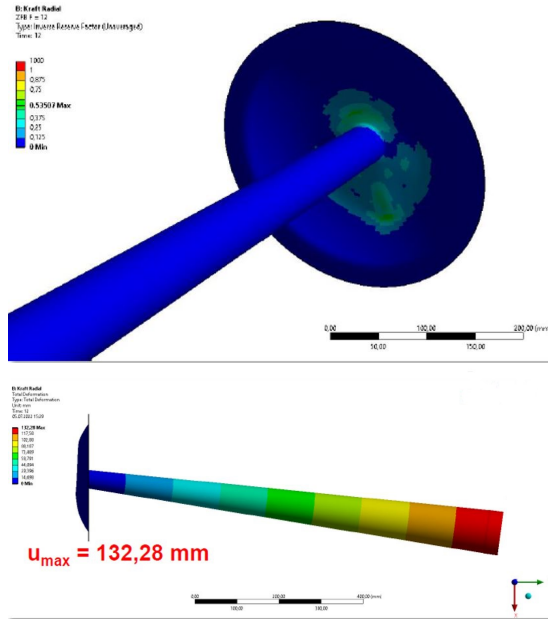


Figure 3: (top) Inter-fiber breaks in the joint start occurring at a radial force of 22 N. (bottom) This is equivalent to an deflection of the pipe's rear end from the center axis by 132 mm.

Full-size prototype

In Spring 2023, the full-size prototype beam pipe that is currently under manufacture at ICM GmbH will be subjected to various studies regarding its performance and handling. A test stand is currently being prepared at GSI (see Fig. 4). The setup will allow evacuation of the pipe structure to the anticipated target chamber pressure 10^{-3} mbar. It also serves to evaluate the concept of a strain-relieving mechanical interface to the downstream beam pipe sections of the MUCH/RICH detectors that is to be integrated into the STS downstream wall.

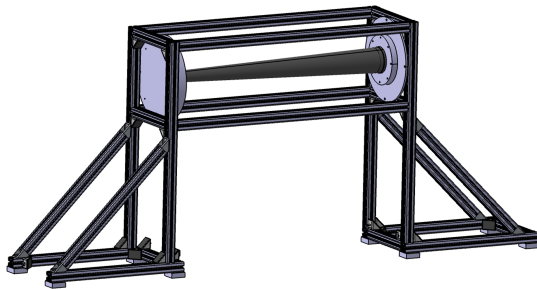


Figure 4: Engineering drawing of the beam pipe test stand.

Performance investigations of fiber optical sensors for relative humidity and temperature in STS

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The design of the Silicon Tracking System (STS) defines the requirements for ambient sensors. The ambient temperature will reach -10°C at the end of the STS's lifetime. The cooling liquid (3M NOVEC 649) will be circulating at temperatures close to -40°C . Therefore, the first boundary condition arises: the frost point and dew point inside the STS has to be below -40°C to avoid ice formation or condensation on the Frond End Electronics (FEE). During the first few years of operation, the temperatures will be higher and Relative Humidity (RH) can be measured more accurately.

During the detector's lifetime (10 years), there will be limited opportunities to perform any upgrades. Therefore, the sensors have to withstand the radiation accumulated during that period (about 10 kGy). As some sensors will be placed in the vicinity of the beam pipe, the total dose could reach more than 10 kGy. The humidity measurements will be distributed, implying that different sensors may face different doses. The humidity sensors have to be insensitive to the magnetic field of 1 T m since the whole detector resides in a dipole magnet. An ideal humidity sensor should also meet the following requirements:

- small dimensions and mass (especially when placed close to the active area of the system),
- accurate relative humidity readouts at temperatures down to -20°C ,
- ideally, respond to a wide range of RH values from 0% to 80%,
- high repeatability and low hysteresis,
- reliable operation across long distances (the readout device will be at least 20 m away from the detector).

On the other hand, due to overpressure conditions inside the STS enclosure, a low response time (seconds) is not necessarily needed. In terms of detector safety and implementation of the sensors readouts in the hardware and software interlocking, the time response up to minutes is considered to be acceptable.

The Fiber Bragg Grating-based Fiber Optic Sensors (FBG FOS) are going to be a part of the ambient monitoring system. Their features ensure accurate operation in the magnetic field and also after irradiation. A first approach to calibrate and characterize such sensors is summarized in [1, 2]. The mentioned contributions focus also on the working principles of this technology.

¹performance of commercial RH sensors usually decreases below 0°C .

RH FOS and measurement setup

The calibration and performance analysis of the RH FOS were performed with two methods. In the first ones, three different saturated salt solutions (NaCl, MgCl_2 , LiCl) were used to control the humidity and determine the humidity sensitivity. The second method was based on a commercial climatic chamber, which was used to control humidity (the calibration was performed stepwise from 10% to 80%). In both cases, the temperature was controlled with the climatic chamber. Other sensors parameters like time-response, repeatability and hysteresis were also investigated.

The setup was controlled by the developed EPICS based framework. The custom written IOCs were used to obtain data from the temperature and humidity sensors, as well as from the climatic chamber. The data related to the fiber optic sensors were collected through ENLIGHT software, and a custom IOC connected to it. Subsequently, all the data was stored using an archiver appliance to a Redis database.

The test subjects were two hygrometers (15 μm polyimide coating) and 5 RH sensors (20 μm) polyimide coating in an array with 15 cm distance between the subsequent sensors.

Results

The comparison of the humidity and temperature sensitivity obtained with different methods for the hygrometer is presented in Table 1. The results acquired with the method involving saturated salt solutions have much higher uncertainty, what is related to the fewer calibration points and less stable humidity inside the test chamber.

Table 1: Comparison of temperature and humidity sensitivity obtained through calibration based on different approaches.

Means of controlling humidity	$S_{RH}[\frac{\text{pm}}{\%RH}]$	$S_T[\frac{\text{pm}}{^\circ\text{C}}]$
Saturated salt	2.17 ± 1.12	10.25 ± 0.4
Climatic chamber	2.09 ± 0.06	10.87 ± 0.02

The humidity and temperature sensitivity calibration results are depicted in Figure 1 and 2. The sensors with a thicker polyimide coating have a higher humidity sensitivity. The temperature sensitivity is around $11 \frac{\text{pm}}{^\circ\text{C}}$ for the sensors.

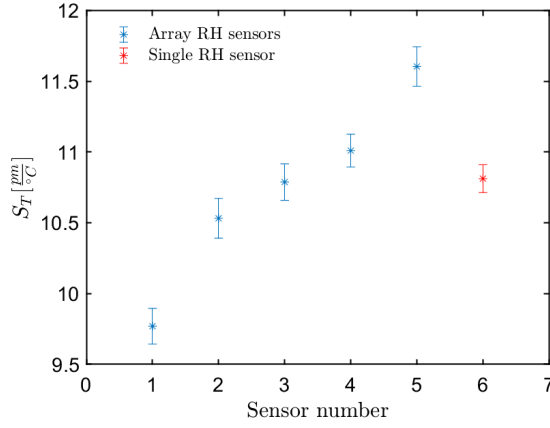


Figure 1: Humidity sensitivity S_{RH} of the sensors with the corresponding uncertainty.

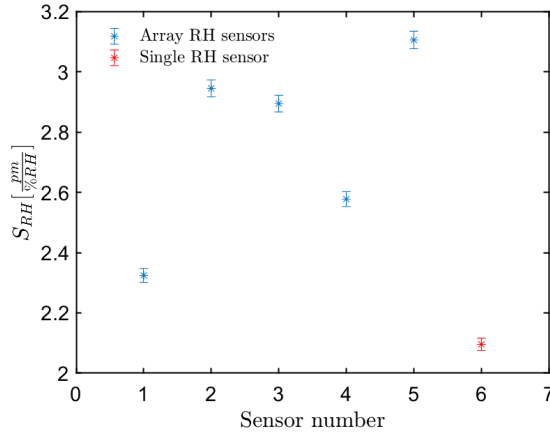


Figure 2: Temperature sensitivity S_T of the sensors with the corresponding uncertainty.

The thicker coating of the sensors also results in the longer response time. Therefore, the coating thickness is a compromise between the humidity sensitivity and time response. The total uncertainty of the hygrometer measurement obtained after including the calibration error and the hysteresis is 1.7%RH. For the array sensors, the uncertainty is about 4%RH. Nevertheless, the RH array turned out to be less reliable than the hygrometers.

Apart from the total uncertainty, the hygrometer's performance below 0 °C was investigated. Figure 3 and 4 depict the dew point measurements at different temperatures inside the climatic chamber. Measurement of RH of 1% and lower is characterized by either very low accuracy or no data at all, what marks the limitation of the polyimide coated FBG based relative humidity FOS.

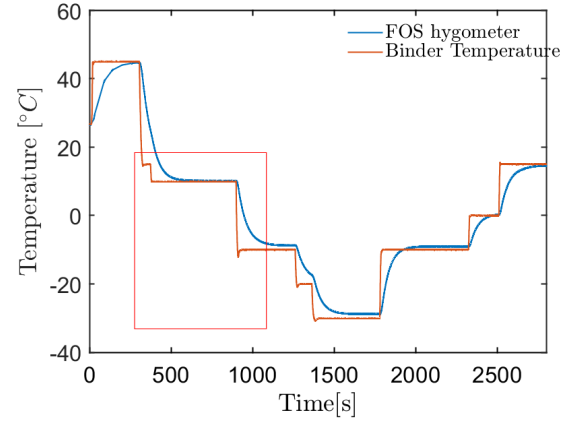


Figure 3: A comparison of the readouts from the temperature sensors inside the Binder chamber with the FBG-based hygrometer.

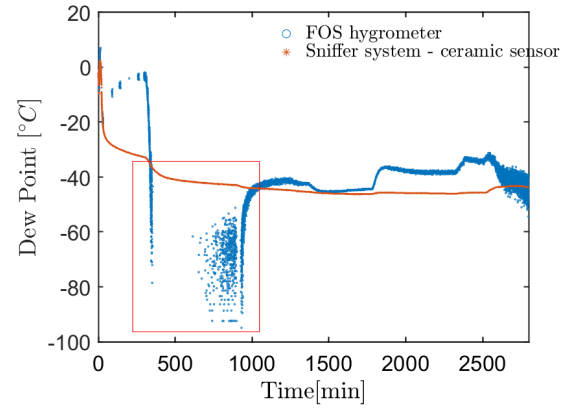


Figure 4: Dew point during the changing ambient conditions per the hygrometer and the ceramic sensor.

The RH FBG-based sensors work in harsh conditions, providing reliable relative humidity measurements. Their use in STS, together with commercial capacitive sensors and precise dew points sensors, will ensure the operational safety of the system.

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- [1] M. Bajdel et al., CBM Progress Report 2020, pp. 49-50
- [2] M. Bajdel et al., CBM Progress Report 2021, pp. 65-66

Pilot cooling supply for STS

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Introduction

The pilot cooling supply is designed for verifying cooling concepts with the help of technology demonstrators, testing the thermal performance of the STS detector cooling components, and finally pre-commissioning STS without a beam. Two cooling agents are provided by the cooling supply system: perfluor(2-methyl-3-pentanone) aka “dry water” or 3MTM NOVEC 649TM as a liquid coolant (7.5 kW rated power, rated temperature -40°C) and dry air (rated power 300 W, rated temperature -10°C). The first cooling agent is intended to be used for electronics e.g. FEBs, while the second is for the silicon sensors. For the liquid coolant supply, the key components are the pilot or “baby” cooling plant [1,2], balancing and outlet heaters, a cooling test rig, and a drainage system. The cold air supply is provided by a new air handling system. The word “pilot” in relation to the cooling supply means that the system is a prototype of a more capable cooling supply system for STS operating during the experiments in the CBM cave at SIS100.

By the end of December 2020, the pilot cooling plant was installed in a separate container C17 on the GSI campus. In June, 2021, supply and return lines for the liquid coolant were mounted from the container to the lab room; however, a suitable connection to the experimental equipment was not available. For this purpose, a cooling test rig has been designed [3], which not only allows for connecting the liquid cooling system thermal of the demonstrator through standard flange connection DN25, but also monitors parameters of the liquid coolant during the tests: flow rate, inlet, and outlet temperature and pressure. In addition, the drainage system can be connected to the rig to drain, store and refill the coolant. Despite these efforts, a few problems associated with the pilot cooling plant were revealed in 2022: the gas volume in the membrane expansion tank was not enough to maintain acceptable operating pressure, and the minimum cooling demand required for the steady-state operation is not satisfied by the heat dissipated in the thermal demonstrator.

In the following chapters, more detailed information on the progress of completing each component of the pilot cooling supply is given.

Expansion tank of the pilot cooling plant

After the design of the cooling test rig was completed, the total volume of the liquid system was estimated to be 151 l for pre-commissioning the final STS detector units. A

decrease in temperature from the ambient to the rated one contracts the volume of NOVEC 649TM by 17 l, which in turn would decrease the static pressure in the liquid system to the extent that it would create a vacuum if existed expansion tank would have remained. With a vacuum, the circulation pump in the plant would experience cavitation and subsequent fast wear out; the declared pressure-flow characteristic would not be fulfilled. An additional factor in the replacement of the tank was the doubt about the compatibility [4] of the material of the expansion tank membrane (EPDM with potentially high plasticizers content).

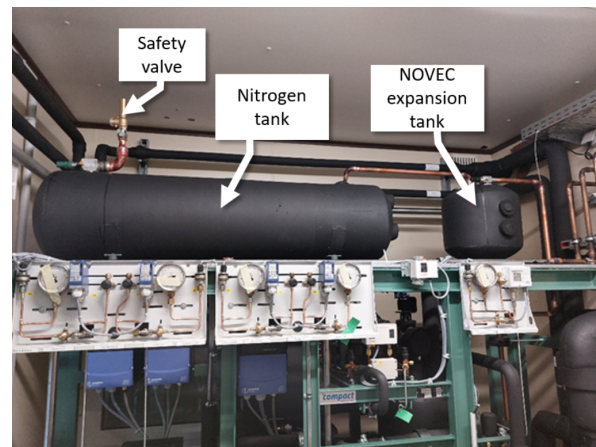


Figure 1: Newly installed nitrogen and NOVEC 649TM expansion tanks in the pilot cooling plant.

To resolve the issue, a new design with two tanks was implemented by the contractor in March 2022: the first tank is used for storing the volume of NOVEC 649TM that undergoes visible contraction, while the second tank is filled with nitrogen to keep the required excessive pressure 4 bar(g) (Fig. 1).

Minimum cooling demand, balancing and outlet heaters

For steady-state operation, the pilot cooling plant requires 4,6 kW @ -40°C ... 10,3 kW @ -25 °C of heat flow rate coming to the evaporator. This value is due to the minimum required rotational speed of reciprocating compressors. Taking into account heat generated by the circulation pump, and heat losses in the pipelines, a device connected to the cooling test rig needs to generate at least 3,8 kW of heat flow rate for the liquid cooling. To cover the mismatch

between the minimum cooling demand and the dissipated heat generated by the thermal demonstrator, an 11 kW rated power balancing heater was installed in the return coolant pipeline. An additional requirement was also formulated to expand the temperature range at the outlet of the pilot cooling plant. The original operation included the range -40°C ... -25°C . With an additional 24 kW rated power heater outlet heater, installed in the supply pipe, this range has been extended up to 10°C . Both heaters were finally installed at the end of December 2022 (Fig. 2).

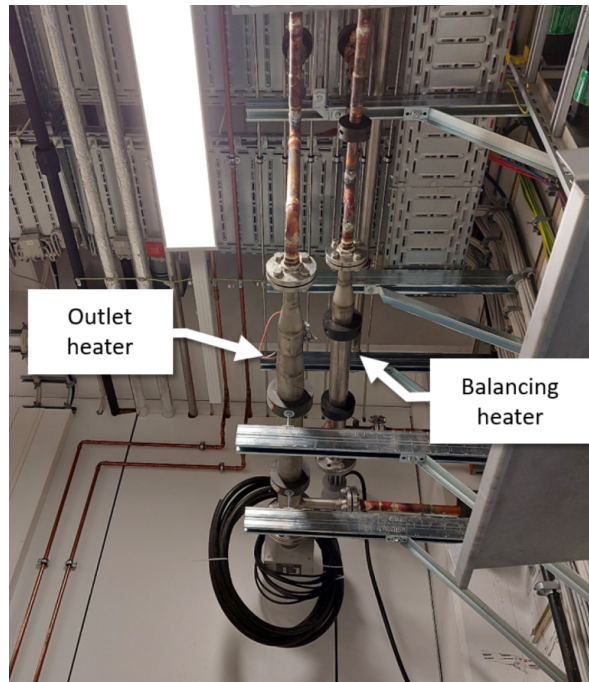


Figure 2: Balancing and outlet heaters in respective casings.

Smooth power control in the entire power range is provided by solid-state voltage regulators from the control cabinet. The controller in the heaters control cabinet will be connected to the pilot cooling plant for implementing unified supervision.

Cooling test rig

By the end of December 2022, the right half of the assembly of the cooling test rig, suitable to operate the thermal demonstrator, is close to completion (Fig. 3). The final layout will provide additional ports for connecting up to four STS detector units. Small changes also affected the measuring instruments - indicating pressure gauges were abandoned, and the rig will solely depend on the electronic read-out.



Figure 3: Cooling test rig during assembly.

Drainage system

NOVEC 649TM cooling agent needs to be collected from the devices that no longer undergo tests for reusing. This is due not only to the requirements of industrial waste treatment but also due to the price and long delivery times.

The drainage system consists of components freely available from the refrigeration industry: a refrigerant recovery device, dip-tube tank, portable vacuum pump, and hoses (Fig. 4).

The basic working principle can be described by the “pull - push” sequence. Air pressure is applied to drain the liquid out of the device under test to the dip-tube tank. For refilling, the procedure is the opposite: the air pressure is applied through the gas port of the dip-tube tank, which in turn forces the liquid to flow back to the respective device. The shut-valves, which divide the test rig and pipelines from the cooling plant, stay closed during the entire operation to minimize the involved volume of the liquid.

Air handling system

The air handling system is the last component of the pilot cooling supply, which was designed, built, and tested in 2022. Its purpose, as was mentioned, is to provide the silicon sensor cooling system in the thermal demonstrator with dry and cold air. For the most part, it consists of com-

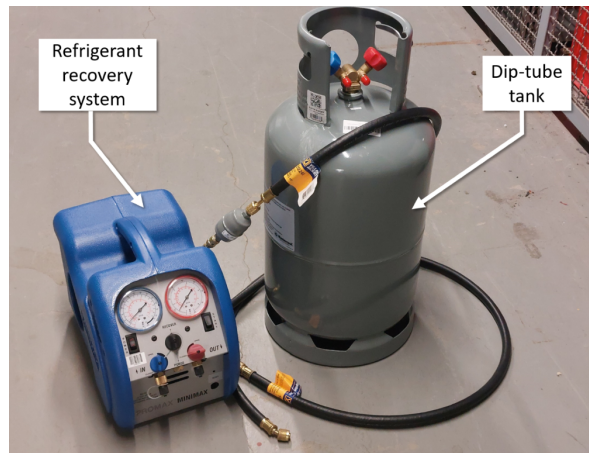


Figure 4: Drainage system.

ponents that were available immediately on the spot. Thus, it was possible to significantly reduce the assembly time.

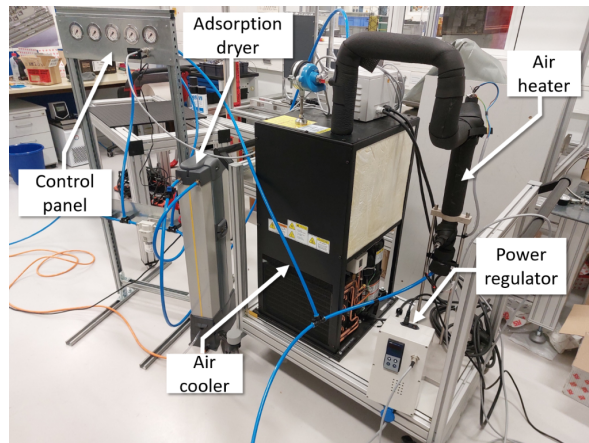


Figure 5: Air handling system.

The crucial components of the air handling system are the control panel, adsorption dryer, air cooler, heater (Fig. 5), and distribution box with back-pressure valves at the exhaust and rotameters coupled with regulating valves. The dew point of the air at the outlet is approx. -60°C . A power regulator sustains the outlet set-point temperature.

Conclusion

By the end of 2022, the cooling supply acquired its final form. The issues associated with the pilot cooling plant were solved by installing a new membrane-less tank pressurized with nitrogen and a balancing heater to cover the mismatch between the minimum required demand and heat flow rate taken from the device under test. An outlet heater was installed to extend the temperature range of the liquid cooling agent. The cooling test rig, which is needed for connecting the liquid cooling system of the devices un-

der test, is planned to be completed in January 2023. The drainage system compliments the test rig by allowing for draining and filling NOVEC 649TM without its loss. Finally, the air handling system has confirmed the declared characteristics for supplying a prototype silicon sensor air cooling in the thermal demonstrator.

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- [3] I. Elizarov et. al, *A system for distribution of cooling liquid to STS test and assembly stands*, CBM Progress Report 2021 (2022), p. 51
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STS operating temperatures: From module operation point-of-view

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CBM particle identification requirements mandates that the STS reconstruct high-multiplicity Au+Au collisions with high efficiency ($\geq 95\%$) and good momentum resolution ($\sim 1.5\%$). This performance is expected to remain consistent over the detector's lifetime during which the innermost STS silicon sensors are foreseen accumulate non-ionising fluence (Φ_{eq}) of up to $10^{14} n_{eq}(1 \text{ MeV})/\text{cm}^2$ (end-of-lifetime (EOL) fluence) [1]. Based on STS detector performance simulations, this requirement translates to ensuring that the Signal-to-Noise Ratio (S/N) for all STS modules remain ≥ 10 [2]. This contribution aims to pin down the operating temperature for STS sensors at EOL fluence by maintaining $S/N \geq 10$.

STS sensors have been electrically characterised at EOL fluence at various irradiation campaigns [3,4] which has allowed to estimate STS sensors' Hamburg Model parameters [5]. Moreover, based on the extensive electrical characterisation of prototype STS modules, an analytical model has been developed to estimate the noise of STS modules (within $\pm 20\%$ of experimental data) [6]. Therefore, the aforementioned information can be combined to extract the varying noise behaviour (ENC_{IL}) of STS modules as a function of Φ_{eq} and temp. (T_{Sensor})¹.

The results for the longest and innermost STS sensor module (located on ladder #1008) are shown in Fig. 1 and Fig. 2 for CCE = 100% and 70%² and mean cluster size = 1.52 (taken from [2]). Based on these, the following could be inferred:

- At EOL Φ_{eq} , STS sensors could be operated at higher temp. ($\approx 0^\circ\text{C}$), as opposed to previously inferred -10°C and still fulfill the criteria to obtain $S/N = 10$.
- STS sensors need not be operated at lower EOL temp. throughout their lifetime to maintain $S/N = 10$ and can be operated at higher temp. ($\approx 20^\circ\text{C}$) for initial years of operation when lower Φ_{eq} is accumulated.
- The sensor cooling concept must be designed operate at higher temp. and to cope up with higher power dissipation values ($\approx 18 \text{ mW}/\text{cm}^2$ at 0°C) and still ensure sufficient margin from thermal runaway.

¹Please note that the signal extracted, i.e., the Charge Collection Efficiency (CCE) also deteriorates with fluence, but has been shown to be recovered completely by raising the bias voltage to 500 V [4].

²CCE = 70% represents the loss of CCE at high discriminator threshold for large-cluster sizes. Although this is unrealistic because EOL Φ_{eq} isn't expected to be reached for sensors with large-cluster sizes.

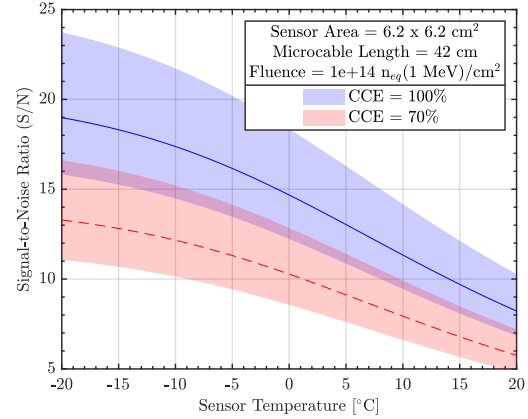


Figure 1: Variation of module S/N with sensor temp at EOL Φ_{eq} . The shaded bands indicate 20% modelling error.

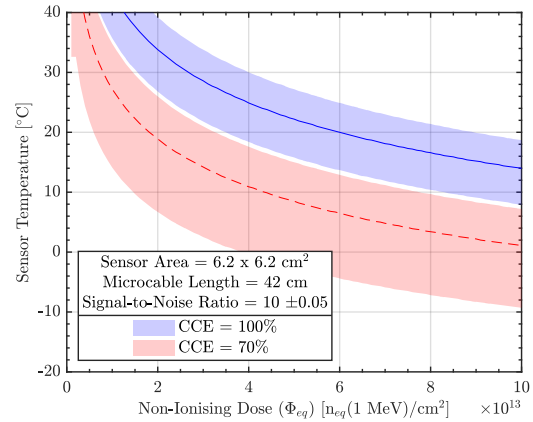


Figure 2: Variation of the sensor temp. with accumulated fluence to maintain $S/N = 10$. The shaded bands indicate 20% modelling error.

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Air Cooling simulations for STS sensors

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Due to CBM's fixed-target geometry, the non-ionising fluence (Φ_{eq}) isn't uniform across a STS station and exponentially falls radially. Therefore, the innermost sensors (located closest to the beampipe; $\Delta x = \Delta y \leq \pm 10$ cm) of every STS station are foreseen to be exposed to $\Phi_{eq} \approx 10^{14}$ n_{eq} (1 MeV)/cm² till their end-of-lifetime (EOL). On the contrary, the accumulated Φ_{eq} at the periphery of every station is orders of magnitude lower [1]. Consequently, the sensor leakage current and power dissipation also follows a similar behaviour, with innermost sensors dissipating ≈ 6 mW/cm² at -10°C at EOL Φ_{eq} . The sensor power dissipation will be removed by using cold air to minimise the material budget in STS's physics acceptance. The highly non-uniform power dissipation across a STS station will be neutralised by different cooling methods for central and peripheral sensors described below. Moreover, their respective thermal runaway behaviour will also be discussed.

Central Sensors: These power-intensive sensors are cooled by forced air convection. Perforated tubes made from carbon-fibre are the cooling elements placed in front of the inner four ladders of every station. This allows to redirect the input cold air (entering from both ends of the tube) on to the exposed sensor surface. The tube's geometry is based on 'Impinging Jets' to enhance the heat transfer. Theoretical correlations [2] allows to optimise the tube's geometry (see Tab. 1) within STS's mechanical boundary conditions, ensure equal air flow through all perforations and estimate the heat-transfer properties.

Inner Diameter (D_0)	3.50 mm
Shell Thickness	0.25 mm
Material Budget (local maximum)	0.68% x/X_0
Material Budget (averaged over sensor area)	0.02% x/X_0
Perforation Diameter (D)	1.00 mm
Perforation Pitch (S)	14.00 mm
Length (L) per half with perforations	100.00 mm
Number of perforations (N) per half	8
Height (H) from the innermost sensor of a normal (central) ladder	12.50 mm (10.50 mm)

Table 1: Perforated tube's geometric properties.

Peripheral Sensors: The substantially lower power dissipation of these sensors ($\lesssim 1$ mW/cm² at -10°C) means that natural convection at ambient temp. is potentially enough to cool down the sensors. Theoretically, this represents a standard scenario where sensors could be assumed as vertical plates dissipating a constant power in the given ambient conditions, and could be simulated by using empirical correlations [3].

Theoretical and CFD Calculations: The empirical correlations mentioned in [2,3] along with the Computation Fluid Dynamics (CFD) simulations in SolidWorks® allow to estimate the sensor temp. for varied boundary conditions. Since STS is a complex object to reliably simulate for CFD calculations, the most critical ladders were chosen to individually simulate cold air flow and the resulting temp. profile on the sensors (see Tab. 2). The varia-

Ladder Type	Remarks
1101_104	- Central ladder cooled by impinging jets ($H = 10.5$ mm for innermost sensor) - Highest sensor power dissipation in STS (6 mW/cm² at -10°C)
1107_708	- Central ladder cooled by impinging jets ($H = 12$ mm for innermost sensor) - Max. H in a central ladder - Sensor power dissipation of 5 mW/cm² at -10°C
1109_102	- Normal ladder cooled by natural convection - Highest sensor power dissipation to be cooled by natural convection (0.37 mW/cm² at -10°C)
1022_811	- Normal ladder cooled by natural convection - Longest ladder to be cooled by natural convection - Sensor power dissipation of 0.17 mW/cm² at -10°C

Table 2: Scenarios for which CFD simulations have been performed. The respective ladder and unit types are in accordance with the geometry STS v21b-1.

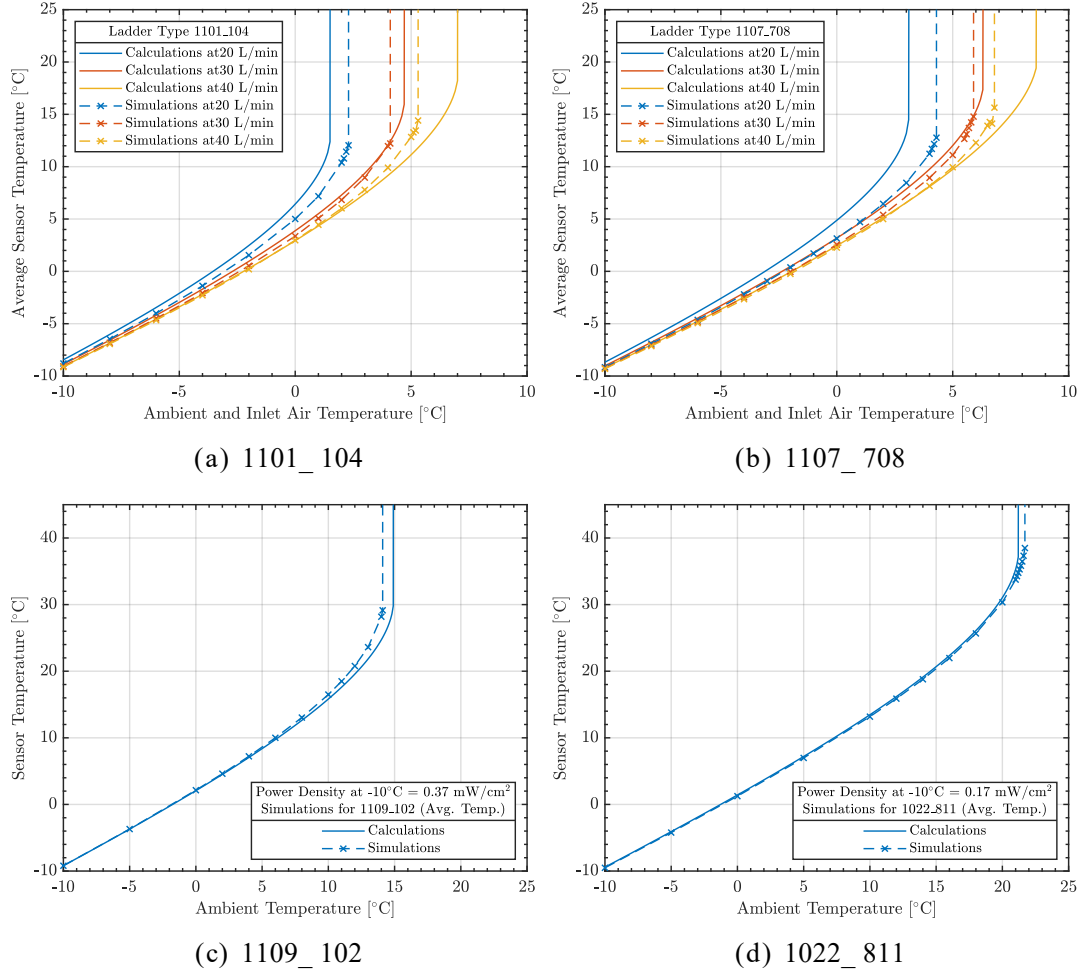


Figure 1: Thermal Runaway behaviour, shown in terms of variation of sensor temp. as a function of inlet and ambient temp., for different test cases (see Tab. 2) calculated by empirical correlations and CFD calculations (see text). The sensor temp. shown are for the innermost sensor, thereby the most power intensive sensor, on the respective ladder. Top panels: Plots for the central ladders cooled by impinging jets from perforated tubes. The air flow is varied between 20 and 40 l/min. Bottom panels: Plots for peripheral ladders cooled by natural air convection.

tion of sensor temp. as a function of ambient and inlet air temp. was calculated to understand their thermal runaway behaviour (see Fig. 1). Please note that other STS services, such as the heat producing power cables and front-end electronics weren't simulated, therefore any residual heat transfer between these services and the sensors aren't considered. Based on these, the following could be inferred:

- Perforated tubes based on the impinging jets can cool the most power intensive sensors at the studied flow rates of 20...40 L/min. Moreover, sensors vibration due to the air flow is limited to $\sim 1\mu\text{m}$ and doesn't excite the underlying eigenfrequencies (reported in [4]).
- Peripheral sensors can be cooled by free convection.
- Both, the central and peripheral sensors, with their re-

spective air cooling concepts are sufficiently far away from thermal runaway. This, in combination with the STS module's signal-to-noise behaviour at EOL Φ_{eq} (reported in [5]), provides a possibility to operate sensors at higher temp. ($\approx 5^\circ\text{C}$) instead of -10°C .

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Moving towards the commissioning of the STS thermal demonstrator

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The STS Thermal Demonstrator has been designed to test the STS cooling concept, both for silicon sensors [1] and the front-end electronics [2] including their thermal interplay, under realistic boundary conditions by using pre-production and dummy components. This report highlights the progress in integration and commissioning of the STS Thermal Demonstrator, with the underlying components been produced and tested (some described previously in [3]). The recent updates regarding the cooling systems and laboratory infrastructure are addressed in [4].

Sensor cooling through perforated tubes

Based on the updated perforated tube specifications mentioned in [1] for enhanced silicon sensor cooling, newer tubes based on carbon fibre (CF) were manufactured with customised end-connections (see Fig. 1). Their leak-tightness and mechanical stability was tested under their nominal operating conditions and have been mounted on to the C-frames. Moreover, this version of tube has also been tested for vibration measurements of STS ladders [5] and has not reported any long-term operational or handling issues.

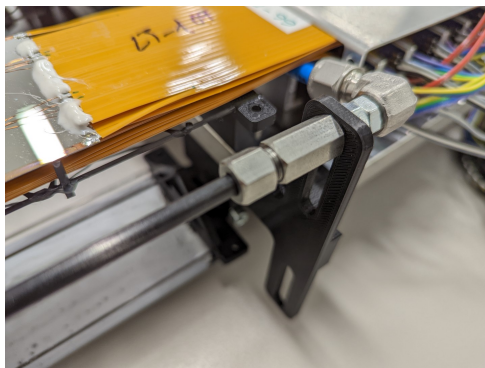


Figure 1: The updated CF perforated tubes mounted on the C-frame. The end-connection and the respective mounting support is visible on the right.

Electronics cooling services

The commissioning and first operation of 3MTMNOVECTM649-based electronics cooling of the STS Thermal Demonstrator is planned to happen with

JULABO PRESTO W50¹. The chiller is connected to the experimental setup by using commercially available insulated transfer lines² (see Fig. 2-top). The subsequent connection to the distribution manifold is made via a custom feed-through solution to ensure the gas-tightness and thermal insulation to avoid any moisture ingress and condensation on the thermal enclosure (see Fig. 2-bottom). This is achieved by sealing the feedthrough against the atmosphere with O-rings to ensure the overpressure of the detector gas cooling and filling the cavities around the feedthrough with EPDM³ insulation. Please note that these feedthroughs are even compatible with the vacuum-insulated transfer lines described in [3]. To absorb the bending and torsional forces, the transfer lines are screwed to the feedthrough with clamps.

Powering and readout

The assembled C-frames, equipped with thermal dummy ladders comprising of dummy FEBs and silicon sensors, have been cabled up to their respective power supplies⁴ via a network of distribution blocks⁵. No issues were observed during commissioning upon powering them to their nominal power dissipation. A LabVIEW based data-acquisition system, tasked to readout the temperature and humidity values, is currently under development. PT-100 temperature sensors on silicon dummies alongside other sensors, such as the analog pressure, flow and temperature sensors on the distribution manifold are interfaced with National Instruments readout. The temperature sensors⁶ on dummy FEBs and humidity sensors⁷ for environmental monitoring have been partially tested by using an additional readout step via Arduino⁸. Further redundancy in humidity measurements is ensured by Sniffing-Tube Systems⁹ and Fibre-Optical Sensors [6].

¹ <https://www.julabo.com/en/products/highly-dynamic-temperature-control-systems/presto-process-systems/presto-w50>

² <https://www.julabo.com/en/products/accessories/tubing-insulation/metal-tubing-m30x1-5-100-c-350-c-3-m-8930274>

³ Ethylene Propylene Diene Monomer

⁴ TDK-Lambda GEN8-180 and R&S[®] HMP4000, respectively

⁵ WAGO 261-112 Terminal Block
Phoenix Contact PTFIX 6/12X2,5
T Tocas 100A BusBar Box

⁶ Maxim Integrated DS18B20 (1-wire[®] readout)

⁷ IST HYT-221 (I²C readout)

⁸ STM32H747-microcontroller based Arduino Pro Portenta H7

⁹ Michell Instruments ES20 Compact Sampling System

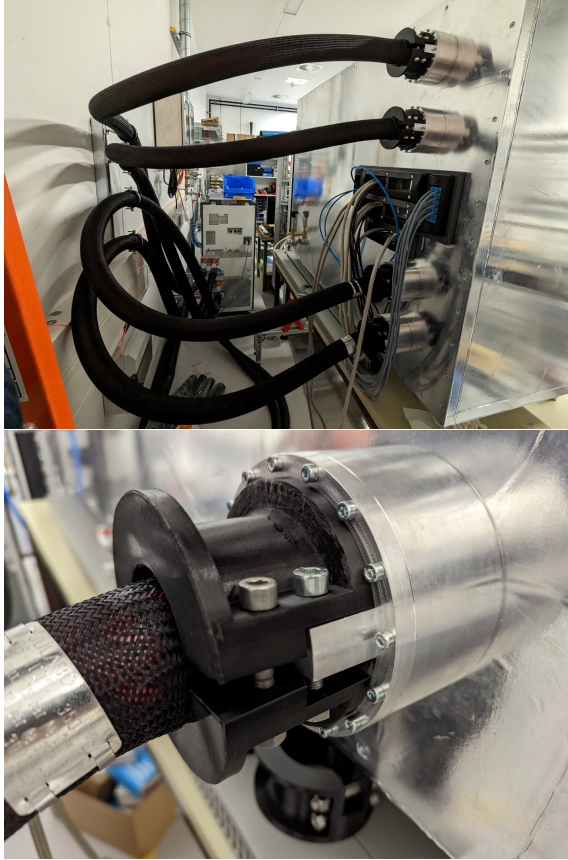


Figure 2: Top: Front-side of the thermal enclosure showing the all services, including the 3M™NOVEC™649 transfer lines between the enclosure and the JULABO chiller. Bottom: Prototype of the gas-tight and insulated feedthrough between the transfer lines and distribution manifold.

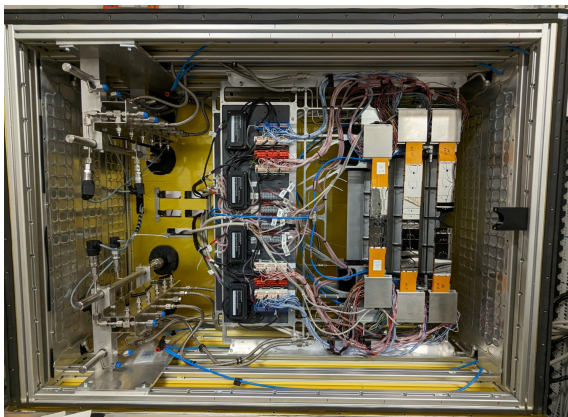


Figure 3: View onto the opened back side of the insulated carbon sandwich box with mounted active and passive C-frames and Novec manifold for the FEB cooling plates.

C-Frame integration and next steps

The integration of the C-frames into the thermal enclosure and remaining cabling with the power supply and read-out electronics are in progress (Fig. 3). The next steps are to complete the assembly of the C-frames in the box and align the gas cooling. Then the FEB cooling circuit can be closed and put into operation, and the cables and gas lines can be sealed. After commissioning the demonstrator electronics and the external cooling systems, test operation can commence.

References

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Study of STS ladder vibration as impact of air cooling

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During the operation of STS, power dissipation from the sensors is expected to be up to $\sim 6 \text{ mW/cm}^2$. Thus they need be cooled to avoid thermal runaway. The sensors of the inner ladders, close to the beam pipe, will be heated more because of higher radiation, hence these sensors need active air cooling and the peripheral sensors can be cooled down using the natural convection.

To cool down the sensors, a perforated tube has been designed based on the theory of impinging jets to blow the air on sensors surface. Each tube will be placed at the middle of the ladder and fixed on the adjacent C-frame. Following simulation results, it has been optimised that there will be 16 holes in the middle of each tube irrespective of ladder length to blow the air on sensors with a constant flow rate of 30 l/min [1]. After the optimisation of flow rate, another important step is to check for the impact of cooling on the ladder vibration.

To measure the impact of air cooling on the sensors, a ladder was assembled with 10 mechanical dummy modules as shown in Fig. 1. The main idea to build this ladder was to measure the amplitude of vibration due the air flow. Also, to check for the stability of the ladder, it is important to know about the natural frequency of the ladder. Therefore, another identical ladder was built and has been tested at University of Oxford [2]. This report will focus on measurement of the eigen frequency of a fully assembled ladder as well as the amplitude of vibration in the ladder because of air flow.

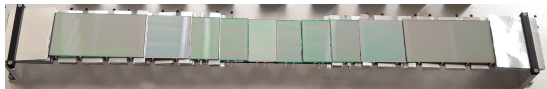


Figure 1: A ladder with 10 non-functional modules.

Measurement of eigen frequency

The CF ladder sent to Oxford university was mounted on a shaker table and the bearings of the ladder were fixed to the clamps of the shaker table. On both ends of the shaker table, two accelerometers were mounted referred, as can be seen in the Fig. 2. To measure the displacement in the table due to the accelerometers, two capacitive sensors has been fixed to both ends of the table near the ladder bearings. To measure the displacement in sensor's surface, one capacitive sensor has been placed in the middle of the ladder. To get the displacement coming from the sensors without the impact of the table, the measurements from both the sensors attached to the table ends was averaged and subtracted from the sensors measurement. The displacement mea-

surements for averaged table sensors and the middle sensor has been plotted with respect to the frequency as shown in Fig. 3. The dotted line in the plot shows that the first eigen frequency for an assembled STS ladder is around 67 Hz.

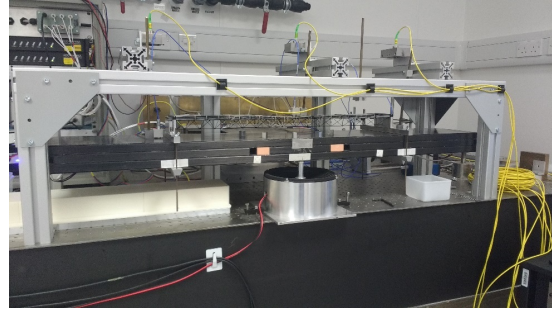


Figure 2: A ladder fixed on a shaker table.

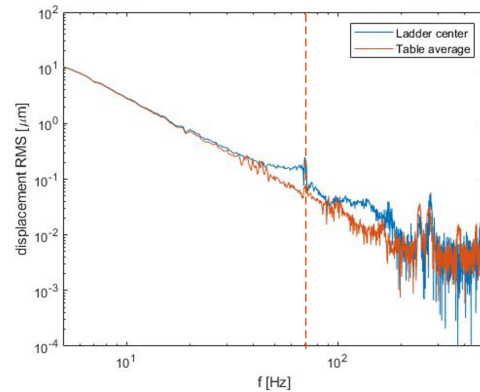


Figure 3: Displacement as function of frequency.

Vibration measurements in STS ladder because of air flow

The another identical ladder built in similar way with the non-functional modules has been setup in the lab in GSI to test under the air flow [3]. As per the flow simulations, updated version of perforated tube was taken with the inner diameter of the tube 3.50 mm with the shell thickness of 0.25 mm. Also, to minimise the impact of external environment, the tripod stand and the ladder under test were fixed on the same optical bench as shown in Fig. 4.

To test the ladder under air flow in the lab, the perforated tube was clamped on the ladder baseplate so as to maintain a gap of 10 mm from the sensor's surface. Two FLK-2216



Figure 4: Setup for vibration measurement using a Laser Doppler Vibrometer.

Acrylic flow meters (range 4-20 l/min) [4] were fixed to the top and bottom end of the perforated tube to blow the air onto the sensors. A Laser Doppler Vibrometer was used to measure the vibration amplitudes at the sensors.

To observe the maximum impact of vibration, flow was measured on the either side of the perforated tube in the middle of each sensor and several of such points have been measured at different flow. From the thermal simulations, it has been optimised that having a flow of 30 l/min flowing through the ladder will be enough to cool down the sensors. Therefore, the measurements are taken with flow rates ranging from 20 to 40 l/min to get estimate the amplitude of vibration at lower and higher flow rates. Since during the time of measurements with the air flow, there will be some impact of background as well. Therefore, to get rid of the background just after the flow measurement each point is measured in the absence of the flow. The background measurements are then averaged per sensor and hence subtracted from the flow measurement to get the amplitude of vibration in sensors from the air flow.

Using the LDV, Power Spectral Density (PSD) is plotted for each point for a defined frequency range. The spectra for a point in middle sensor of the ladder at different air flow can be seen in the plot of Fig. 5. The different colours represent the different flow rates and black colour denotes the measurement without any air flow referred as background measurement. From the plot it can be seen that there is no excitation observed in the ladder at 67 Hz, hence the eigen frequency is not excited because of the air flow.

The PSD spectra are used to derive the vibration amplitudes for each point measured on the ladder. Here, the

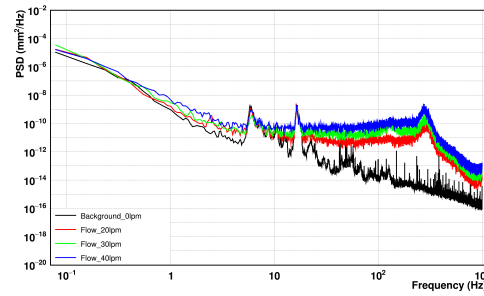


Figure 5: Power Spectral Density vs frequency for a point on the middle sensor, at different flow rates (lpm denotes l/min).

RMS value is calculated according to equation (1). Before, the background spectrum is subtracted from the spectra obtained during the flow measurement.

The integral is taken for the whole frequency above 1 Hz since lower frequency had high contribution from the seismic noise and impact is seen even in the background measurements.

$$\text{RMS} = \sqrt{\int_{f_1}^{f_2} \text{PSD}(f) df} \quad (1)$$

From the preliminary analysis, it has been optimised that vibration below 1 Hz then will not have an adverse impact on the particle tracking. The amplitudes of vibration for each sensor, calculated according to the RMS formula, are shown in Fig. 6. The maximum vibration under a flow at rate of 30 l/min is below 1 μm and thus not critical at all.

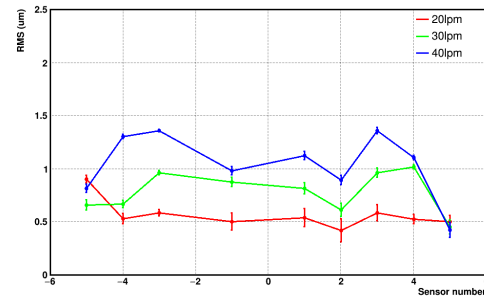


Figure 6: Amplitude of vibrations for different sensors along the ladder, at three flow rates.

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STS front-end electronics power-cycled at low temperatures

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The STS front-end electronics boards (FEBs) will dissipate up to 14 W power which have to be removed through thermal interfaces into a liquid cooling system. The cooling liquid may be as cold as -40°C , even though detector operation temperatures will be at around -5° . Low-temperature power off/on is one of the riskiest expected scenarios that STS modules might undergo, thus further investigation of the sturdiness of the front-end electronics boards was suggested [1].

Experiment setup and procedure

As the main housing for the experiment a climatic chamber of manufacturer Binder has been employed. To avoid condensation on the electronics a cooling plate supplied by an external liquid chiller was set up, maintaining a constant temperature gradient. The FEBs have been glued on fins with a thermally conductive glue according to the previously investigated patterns and materials [2]. Power supplies, cooling devices, and data acquisition were set up and automated using the EPICS architecture. A Python script with cycling and device operation instructions had been created. The experiment begins with the climatic chamber and freezer cooling down to -30°C while FEB tests are performed. This is proceeded with sudden power-off to the electronics, with the waiting time of temperature equilibrium. After equilibrium is reached power is restored, FEBs are again tested while reaching the upper equilibrium followed by sudden power off, and the cycle repeats.

Results

Under the scope of the cold start-up cycling experiment, 11 FEBs were examined. All underwent more than 150 cycles. The FEBs were in a variety of glob top configurations, protecting wire bonds of its mounted ASICs. Two FEBs without read-out ASICs replaced with corresponding resistors and with bare LDO regulator ASICs were tested, as well as three freshly assembled FEBs with the most current glob top.

During low-temperature cycling, low (a few hundred milliamperes) or no current consumption has been observed on some FEBs (Fig. 1). This tendency remained consistent in low temperatures, though only several permanent failures remained. Somehow current consumption was being restored at room temperatures (Fig. 2). Under the low-temperature cycling, all FEBs tended to lose connection with at least one of the ASICs, while recovering the connection at room temperature.

On all of the FEBs tested, optical and electronic tests were performed before and after the experiment. These tests partially confirmed and explained the failures that were seen, most of which were related to the FEB's LDO section, i.e. bond wires at LDO pads lost electrical contact due to the thermal stress. FEBs that had previously been active/passive cycled were much more prone to failure than new FEBs. The new glob top did not introduce a new pattern of malfunction. FEB failures with no ASICs and no glob tops on LDOs have not been observed. Further investigation of the above-mentioned observations is needed in order to fully understand the origins of the malfunctions. Also the really required minimum temperature of the cooling liquid to withstand will be reconsidered.

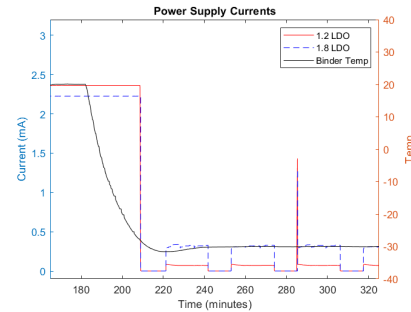


Figure 1: LDO currents drop at low temperature.

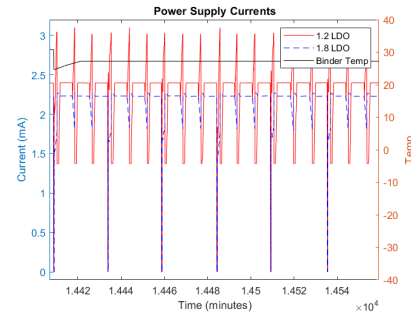


Figure 2: LDO currents at room temperature, shown over several power off/on cycles.

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Performance of mSTS in Ni+Ni collisions at 1.93 AGeV

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Introduction

In the mCBM 2022 beam campaign at SIS18 (GSI), Ni+Ni collisions at 1.93 AGeV was measured with a beam intensity up to 10^{10} ions per spill, and approximately 400 kHz interaction rate.

The mini-STs (mSTS) setup consisted of 2 tracking stations covering a total area of $12 \times 12 \text{ cm}^2$ and $18 \times 18 \text{ cm}^2$ respectively, arranged in 4 units with a total of 11 modules: two modules with $62 \times 124 \text{ mm}^2$ and 9 with $62 \times 62 \text{ mm}^2$ double-sided double-metal silicon sensors equipped with 2 Front-End Boards (FEBs), each comprising 8 SMX (STS/MUCH-XYTER) ASICs each for the readout, plus two service FEBs for the pulser signal injection, 5 CROBs for readout, and 5 POBs providing LV for FEBs and ROBs [1].

Commissioning and operation

Prior to the installation in the mCBM cave, an energy calibration was performed to adjust the dynamic range of the ADC using a calibrated the internal pulse generator and dedicated counters in the chip to record the S-curves. The estimated baseline noise level corresponds to ENC below the targeted system noise of 1000 e^- .

During the data taking time, all mSTS modules were operational under the following status:

- 1st station (U0 and U1): 2 ASIC missing
- 2nd station:
 - central ladder complete (U2),
 - right ladder: one FEB missing in the central sensor and 2 ASICs missing in the bottom sensor.
 - left ladder: 8 ASICs missing and very noisy.

The modules were operated with significantly different thresholds (between 2730 and 12650 e^-). The first station modules and the central ladder of the second station were set up with relatively lower thresholds, and only lateral ladders of the second station were operated with high threshold values due to the considerable noise in Unit 3. This, however, allows systematic performance studies.

Hit reconstruction

Reconstruction chain

The reconstruction chain is performed by two main consecutive steps: first, the unpacking of raw detector data,

and second, the reconstruction of hits out from Digis. The first step transforms raw detector data into human-readable structures called Digis. The Digi is a construct containing all information for a single-fired strip. The first step for hits reconstruction is creating a new structure by grouping neighboring fired strips within a given time window (20 ns): clusters. The reconstructed hit is done by correlating two clusters of different sides of the sensor, which must fall under configurable boundaries of space-time: cluster must intercept inside the sensor's active area and within a time window (22 ns).

These two main steps can be performed as long as there are Digis to process. However, other sources, such as noise or background, can also produce a fired strip. Then, identifying Digis belonging to events is an intermediate task implemented before the hits reconstruction. The following parameters define an event:

- Minimum amount of T0 Digis: 1
- Minimum amount of STS Digis: 2
- Minimum amount of STS layers: 1
- Minimum amount of MUCH Digis: 2
- Minimum amount of TOF Digis: 8
- Minimum amount of TOF layers: 4
- Minimum amount of RICH Digis: 0
- T0 time frame: [-50, +50] ns
- STS time frame: [-60, +60] ns
- TRD1D time frame: [-300, +300] ns
- TRD2D time frame: [-200, +200] ns
- TOF time frame: [-60, +60] ns
- RICH time frame: [-60, +60] ns

Time calibration

Time calibration for mSTS setup is ASIC-dependent, fitting the time difference vs. charge (in ADC units) to a 3rd-degree polynomial. The purpose of such a method is to contain not only the time offset to the reference detector but consider the dependence of the timing with the signal amplitude (time walk effect). The T0 detector was used as a reference as it is the most precise time from all detectors available at the Digi level. Figure 1 shows an after and before of the time calibration. As the time resolution of the T0 detector is much smaller than the STS capabilities, fitting the peak of the time difference of T0 vs. mSTS provides the time resolution of our setup: 4.26 ns. Such fit is shown in Fig. 2.

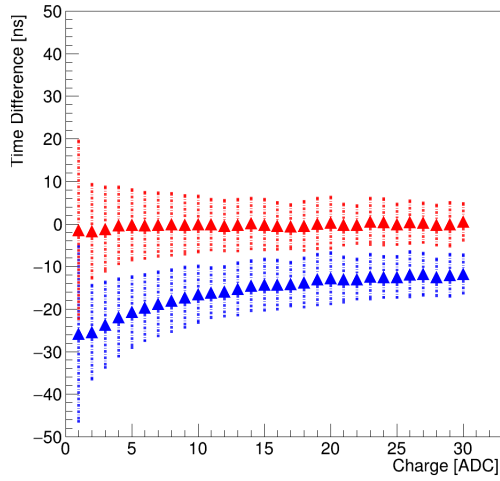


Figure 1: Time Walk correction, as a function of the signal charge (in ADC units): blue) time difference between mSTS-mTOF Digis; red) time difference after Time-Walk correction.

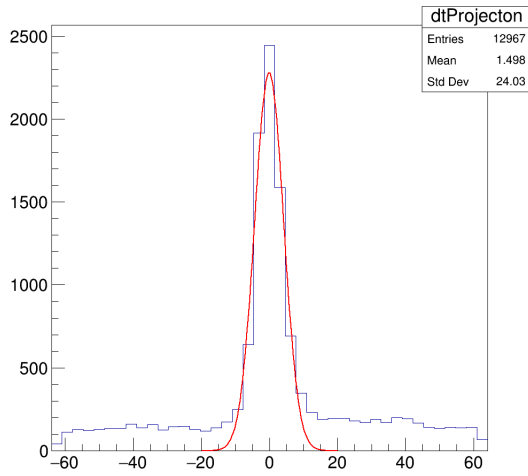


Figure 2: Fitted time difference between mSTS-T0 Digis.

Hit reconstruction

Figure 3 shows the transversal projection of the reconstructed hits coordinates for the mSTS setup. Dead areas result from the dead channels and missing ASICs described above.

Vertex reconstruction

The fact that mSTS setup is formed by two stations allows a vertex reconstruction attempt. Using the track-lets built by two hits from different stations, and extrapolating to the target plane, Figure 4 was obtained. The figure shows

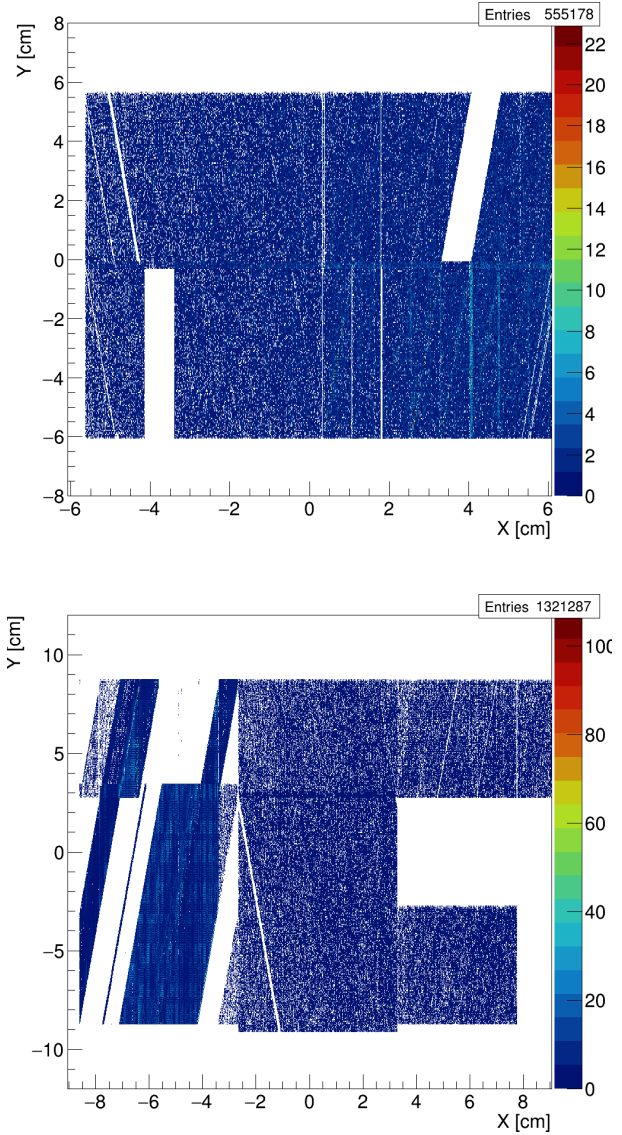


Figure 3: Hit's map projection to XY plane: (top) station 1, (bottom) station 2.

such a procedure split into different sensor combinations. From that, not all the possibilities point to the target region. For those that it does, a 2D-Gaussian distribution arises. A residual analysis between the distributions produced by different pairs and minimizing the transversal distribution spread size provides a way to align STS sensors internally.

The dimensions of that intense region are characterized by the $\sigma_X = 0.32$ cm, $\sigma_Y = 0.43$ cm obtained by fitting the distribution after merging individual pairs contributions. Those parameters should be in agreement with the beam shape. This can be roughly approximated along the X direction by fitting the Digis profile for the T0 detector whose strip dimensions are well known (Figure 5).

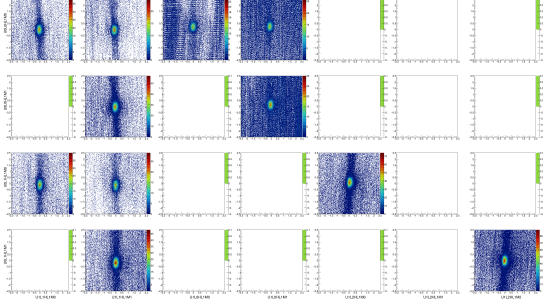


Figure 4: Vertex reconstruction split into sensor pairs: station 1 (4 sensors) along the Y direction, station 1 (7 sensors) along the X direction. Vertex sample area: $[-2.5, 2.5] \text{ cm} \cup [-2.5, 2.5] \text{ cm}$.

The T0 distribution shows a beam profile in X with a sigma of 2.39 strips. The dimensions of the diamond are 10 mm (X) $\times$ 10 mm (Y) $\times$ 80 μm (thickness) with 16 channels in X for 10 mm, leading to single strip coverage of 0.625 mm in this direction. Then, the X beam profile is approximately 0.15 cm.

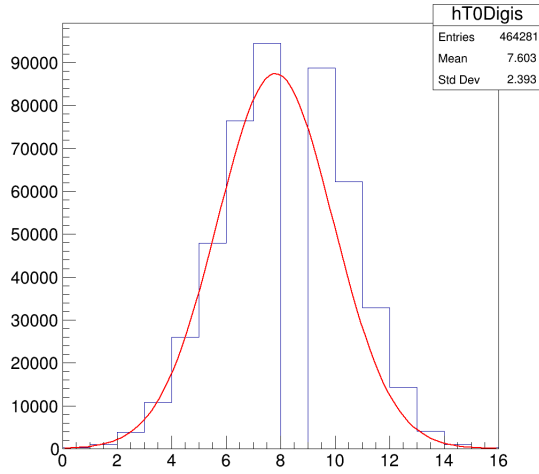


Figure 5: T0 Digis profile fit.

Space correlations

Building space correlation between different detection systems allows checking simultaneously important information such as the goodness of the alignment and the time calibration.

STS-TRD correlations

Figure 6 shows the reconstructed hit correlations between mTRD and mSTS. A good correlation can be appreciated, yet significant combinatorial background exists, mainly caused by preliminary alignment.

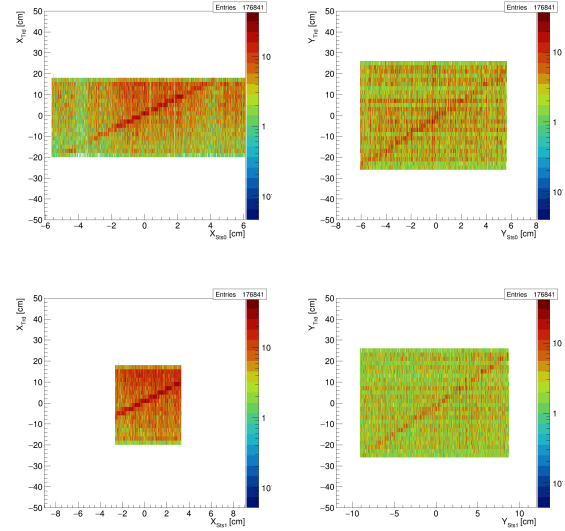


Figure 6: Hits correlation: left column – X correlation, right column – Y correlation; (top) mTRD vs. mSTS station 1, (bottom) mTRD vs mSTS station 2.

STS-TOF correlations

Figure 7 shows the reconstructed hit correlations between mTOF and mSTS. In this case, the correlation is not as good as the previous year [2], but still visibly existent. Not only did preliminary alignment cause such detriment, but also the found gas contamination of the TOF detector during this run.

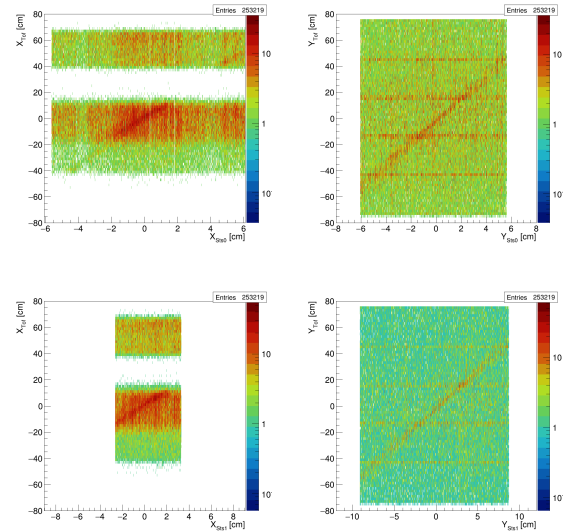


Figure 7: Hits correlation: left column) X correlation, right column) Y correlation; (top) mTOF vs. mSTS station 1, (bottom) mTOF vs. mSTS station 2.

Summary & outlook

The mSTS setup comprising two tracking stations and 11 modules was operated during the beamtime campaign. The targeted STS system noise of around $1000\ e^-$ was achieved, excluding the modules of unit 3, whose noise level was significantly higher. Besides a small number of unconnected channels, and two broken ASICs, three detector units were operational. An outstanding vertex reconstruction was achieved for all possible sensor pairs. Despite preliminary alignment conditions, space correlations between different detection subsystems (TOF and TRD) were successfully obtained. Performing hit reconstruction efficiency analysis, and as a function of threshold, using outer detector correlations and full tracking is an open possibility.

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Survey on upgrade options and its gain factors for the CBM silicon tracker

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Introduction

In the framework of the EU project EURIZON [1] activities we started assessing the development and implementation of Monolithic Active Pixel Sensors (MAPS) for the realization of large-area tracking systems in future high energy physics experiments. We report here on a comparative analysis of CBM's silicon tracking detector (STS) features in its original (double sided silicon strip sensors) and upgraded (MAPS) versions. Assuming successful development of such pixel detector technologies in the forthcoming 10-15 years, we conclude on a feasibility of CBM-STs Upgrade (STS-CBM-UP) in order to take full advantage of the high density matter physics opportunities at SIS-100's or beyond heavy ion beams. The upgraded detector will build on the strength and expected achievements of the original CBM detector, which is currently under construction. It will consist of re-designed sub-systems that can operate at a luminosity of $2 \times 10^{31} \text{ cm}^{-2}\text{s}^{-1}$, ten times that of the original detector. New and improved detector components will increase the intrinsic performance of the experiment in certain key areas. In particular, the installation of a monolithic active pixel sensors (MAPS) in the Silicon Tracking System (STS) will widen CBM's capabilities for identification of decays involving di-leptons, multi-strange hyperons, charm, ρ_0 , ω mesons, from loop-level processes. Corresponding upgrade workgroups of the CBM Collaboration are just being formed and will work out a common understanding of both physics aim and technical approaches for the future phases of the experiment.

MAPS detectors for a STS upgrade

The status of MAPS development and applications in building large area tracking detectors in current and future experiments on high energy physics is presented in Table 2. The characteristics of existing MAPS devices and those under development became the basis for upgrading tracking systems of experiments in high energy and nuclear physics for the coming decades.

The decisive, advantageous feature of MAPS is that its hit's sensitive volume and signal processing unit are built in a single silicon wafer. It provides essential Gain Factors (GF) in comparison with other micro detectors separating those two procedures. Commercial submicron CMOS production technologies of MAPS give rise for their pick-up free stable performance with high Signal/Noise Ratio (SNR), low fake rates, extremely low material budget, high granularity and radiation hardness, low operational voltage,

simplified supporting infrastructure, low price (a factor of two or better), etc. More details on the GF are given in Table 2. It presents features of the CBM-STs Original (CBM-OR) and CBM-STs Upgraded (CBM-UP) with a summary column showing the gain factor (GF) of CBM-UP. The features correspond to the general requirements: hit reconstruction efficiency $> 99\%$, track reconstruction efficiency $> 95\%$ and momentum resolution $< 1\%$ for $p > 1 \text{ GeV}/c$.

A comparison of Gain Factors (GF) for the STS equipped with double-sided silicon sensors (Original version) and MAPS (Upgraded) indicates unambiguous feasibility of the STS upgrade.

Keeping in mind the R&D stage of the STS MAPS production, the assessment system of prototypes comprising a laser scanning microprobe (position resolution of $0.5 \mu\text{m}$) and a setup for studying the response to minimum ionizing particles (2 ns time resolution) has been upgraded at KINR [12]. Table 1 shows an assumed timeline of CBM data taking and running conditions for the Original and Upgraded experiment. The future years of data taking will be interrupted by a Long Shutdown (LS1) in 2033.

The CBM Upgrade will allow the experiment to accumulate data corresponding to a minimum of 1 fb^{-1} , and enable many important observables to be measured with a precision unattainable at any other experiment. This will extend the SIS-100 and SIS-300's capabilities to search with an improved precision for effects of the hot/dense medium. The precise measurement of phase transitions in fireball evolution is a powerful tool to seek out manifestations of new physics phenomena. The CBM-STs Upgraded will provide precise timing for charged tracks. This information, approaching a resolution of a few tens of ps per particle, will allow charged tracks to be associated to the correct interaction vertex, thereby suppressing combinatorial background and also allowing for time-dependent measurements (event-to-event fluctuations) of various observables.

Table 1: Assumed CBM data taking for the Original experiment and an Upgraded version. The running conditions, Au+Au interaction rates 10^7 s^{-1} in Run 1 and 10^8 s^{-1} in Run 2, have been expressed as resulting max. instantaneous and integrated luminosities $\mathcal{L}$.

Run / Detector configuration	Period of data taking	Max. $\mathcal{L}$ [$\text{cm}^{-2}\text{s}^{-1}$]	Integrated fb^{-1}
1 / Original	2029 - 2033	2×10^{30}	0.1
2 / Upgraded	2035 - 2039	2×10^{31}	1.0

Table 2: MAPS applications for large-area tracking systems in current and future experiments on high energy physics.

Experiment, Name of MAPS, Technology	Thickness, Pixel area, Noise	Time stamp, Bias Voltage before/after irradiation	Status, Reference	Radiation hardness
ALICE (CERN), ALPIDE-ITS, TowerJazz 180 nm CMOS Imaging P	(25+25) μm , (Total) 30 $\times$ 30 μm^2	1.0 μs , ~ 4 V	Operational ITS2 2022 - 2025 [2]	$>1.7 \times 10^{12}$ 1 MeV n_{eq}/cm^2
LHCb (CERN), PicoPix, TowerJazz 28 nm CMOS I	38 $\times$ 38 μm^2	(20-25) ps	Prototypes 2022 - 2034 [3]	6×10^{16} 1 MeV n_{eq}/cm^2
LHCb (CERN), MightyPix1, TSI (180 nm node)	30 μm 50 $\times$ 150 μm^2 20 e	5 ns 70/80 V	Prototypes 2022 - 2025 [4]	3×10^{15} 1 MeV n_{eqv}/cm^2 (cryogenic cooling)
ATLAS (CERN), ATLASPIX3.1, MALTA-Cz, 180 nm CMOS	20 μm 50 $\times$ 150 μm^2 20 e	5 ns 70/80 V 2 ns	Prototypes 2022 - 2030 [5, 6]	1.5×10^{15} 1 MeV n_{eq}/cm^2
ALICE (CERN), ALPIDE-bent, 65 nm CMOS	50 μm <100 e		Prototypes 2022 - 2034 [7]	
CBM (FAIR/GSI), MIMOSIS-2, 180 nm CMOS	50 μm 27 $\times$ 30 μm^2	5 μs	Prototypes 2022 - 2028 [8]	10^{14} 1 MeV n_{eq}/cm^2
Mu3e MuPix8 180 nm CMOS,	50 μm 80 $\times$ 80 μm^2	13 μs	2021 Prototypes [9]	
RHIC (STAR)	50 μm 20.7 $\times$ 20.7 μm^2	(read-out) 185.6 μs	Operational [10, 11]	

Table 3: Approximate detector features of STS CBM Original (CBM-OR) and expected STS CBM Upgraded (CBM-UP).

	STS CBM-OR	STS CBM-UP	Gain factor	Remarks
Sensor type	Double-sided Si microstrips	Pixels (MAPS)		
Sensor pitch, μm	58×58 stereo angle 7.5 degree	30×30		
Strip length, mm	60 - 300	Not applicable		
Hit position resolution, n- / p-side, μm	15 / 150	10 / 10	1.5 / 15	Essential advantage
Time stamp, ps	5000	25	200	Essential advantage
Affordable rate per channel, kHz	25	100	4	
Capacitance per channel, pF	4.5 - 45	0.01	400 - 4000	Essential advantage
Connection to read-out ASIC, Double metallization technology, micro-cables	Up to 50 cm long cable	Direct, inside the same wafer	Very important	Essential engineering advantage
Mechanical and electrical reliability, e/m pick-up	Complexity of bonding, sensitivity to mechanical vibrations, possibility of e/m pick-up	Very robust, no way for pick-up	Very important	Essential advantage
Sensor thickness, μm / material budget	$320 / 0.35\% X_0$	$30 / < 0.1\% X_0$ with support/cooling	$\gg 10$	Essential advantage
Signal (MPV), e initial/irradiated	24 000 / 21 000	2 400 / 2 200	0.1	Signal-to-noise ratio matters (see below)
Noise, e/c	800 - 1500 / 1 600 - 3 000	20 / 100		Very low noise
Signal-to-noise ratio initial/irradiated	25 - 15 / 15 - 7	120 / 22	5 / 3	Essential advantage
Bias Voltage, V initial/irradiated	100 / 1000	20 / 20	5 / 50	Engineering advantage, low operational voltage
Production technology	Customized, complex multi-step, low yield	Commercial CMOS, 180 - 28 nm		High output, lower price
Ghost rate	high	low		Essential advantage

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First considerations for a STS upgrade

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As it is exposed to massive radiation during operation, the STS of CBM has a limited working life time and will be subject of a scheduled replacement after some years of operation. This gives room for a technology upgrade for the detector. This report discusses some first considerations on the goals and strategy of a future full detector upgrade.

The upgrade would take place in the mid 2030's after slightly above five years of STS operation at high rates. It might aim toward a combination of improving the momentum resolution of the STS in particular for lower SIS100 energies, extending the acceptance toward the backward rapidity region and increasing the rate of the detector. While the first goal may be reached by modifying the STS alone, reaching the two latter goals will likely require according modifications of the more downstream detectors. A rough estimate of the interplay of the parameters is given by the Gluckstern-Formula [1], which gives the momentum resolution of a detector formed from N equidistant stations with individual radiation length x/X_0 and a total length L with:

$$\left(\frac{\sigma_p}{p}\right) = \frac{0.0136}{0.3 \cdot \beta \cdot L^2 \cdot B} \sqrt{\frac{(N-1)x}{X_0}} \sqrt{C_N}$$

Here, B denotes the homogenous magnetic field, the normalization factor C_N varies from 1.33 to 1.44 depending on N . The contribution of to limited spatial resolution of the sensors is not shown as it is negligible for a combination of particles with $p < 1$ GeV/c and the detector technologies discussed in the following.

While the average particle velocity β shrinks once lowering beam energy and, moreover, the field B has to be reduced to control the unwanted bending of the beam, L is constrained by the magnet size and might even be reduced to obtain the targeted acceptance improvement at given magnet geometry. Thus reducing the material budget x/X_0 of the detector below the already very good values of the present STS remains as parameter for keeping or improving the momentum resolution of the detector.

This and cost considerations suggest the use of ultra-light CMOS Monolithic Active Pixel Sensors (CPS). The typically $50 \mu\text{m}$ thin sensors should be held with lightest possible support structures, which introduces a preference for forced air cooling and in consequence the need for a very low power dissipation of typically few 10 mW/cm^2 . The need for this low power budget has to be balanced against the precision of time stamping and rate capability as fast signal rise times and data transport come with a cost

in power. Therefore, unless the possible STS upgrade becomes part of a global rate upgrade of CBM, the requirements on sensor speed should remain reasonably relaxed for the benefit of better momentum resolution. An operation at the present CBM top rate (10 MHz Au+Au) would require a time stamping of $\mathcal{O}(10 \text{ ns})$ to separate the events and an average rate capability of $\mathcal{O}(20 \text{ MHz/cm}^2)$ plus a safety margin for beam fluctuations. The spatial resolution of the sensors, though of secondary importance for tracking, should remain at about $10 \mu\text{m}$, which imposes a squared pixel pitch of about $35 \mu\text{m}$.

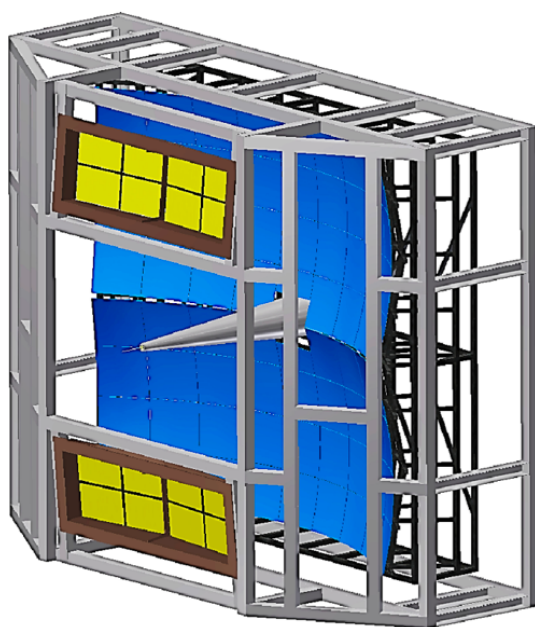
A survey of present trends in CPS R&D supports the feasibility of matching the above performance values. The requirements on rate capability are met by the MIMOSIS-sensor foreseen for the CBM-MVD at a power budget of $50\text{-}100 \text{ mW/cm}^2$. The required time stamping has been demonstrated among others by the MALTA sensor at similar power budget [2]. Despite being optimized for different purposes, both designs share building blocks and both report having reached necessary spatial resolution and radiation tolerance of few $10^{14} \text{ n}_{\text{eq}}/\text{cm}^2$. Merging their features into one single system and reducing its power dissipation appears as realistic R&D goal. This may be done in synergy with the ALICE-3 outer tracker project, which aims for CPS with similar requirements though at relaxed rate capability [3].

The tracking stations of the STS may be complemented by a timing layer based on very rapid CPS. A time resolution of 36 ps combined with 99.9% m.i.p detection efficiency was reported from a CPS relying on a novel $130 \text{ nm SiGe BiCMOS}$ process [4]. Despite the reported power density of few 100 mW/cm^2 forces liquid cooling, the additional material of the layer is likely acceptable as it will ease event building at high rates substantially. Still, the cited paper reports on a tiny demonstrator formed from few pixels. Therefore, numerous questions on the feasibility of scaling, radiation tolerance and device thinning remain to be answered before considering this technology as an alternative to e.g. LGAD-pixels.

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Ring-Imaging Cherenkov Detector



RICH summary*

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In 2022, the RICH project had to face severe challenges due to the Russian invasion into Ukraine. The end of collaboration with all Russian partners within the FAIR project has strong impact on the progress and completion of the RICH detector. With PNPI Gatchina, St. Petersburg having been one of the three main partners in constructing the RICH detector, a comprehensive reorganization of responsibilities in the project became necessary and is currently being carried out. Important milestones, planned to be achieved in 2022, were the mechanical engineering design review (EDR) to be followed by a production readiness review (PRR) early 2023, as well as the PRR of the gas system. These reviews had to be postponed and have not been carried out, yet. The engineering design of many - if not most - mechanical components at PNPI was far advanced, already. In the upcoming year, significant engineering work and prototyping has to be redone in order to keep up with the former status. Closing the gap that has been created in engineering manpower within the RICH project is currently of highest priority.

First steps in this direction have been achieved already: the mirror holding structures have been redesigned and first prototypes been built, soon to be followed by a demonstrator of a full mirror pillar and a setup for glueing the mirror tiles.

Progress on the RICH photon camera prototype is less affected by the current situation. Here, the mechanics of the prototype could be finalized and the prototype cooling system was taken into operation, followed by still ongoing measurements on and optimization of the validation of the RICH cooling concept. An important milestone in production of the DIRICH readout electronics was achieved by completing manufacture and series testing of all 220 backplane PCBs which are now ready for installation. Completion of the electronics EDR and PRR (as well as the mirror PRR) are important next milestones to be reached in the first half of 2023.

The recent change request regarding the dipole magnet design, put up by the STS group in order to allow for more space inside the magnet yoke, is closely followed by the RICH group, since any changes in the material budget upstream of the RICH detector, as well as changes in the magnetic stray field, have direct influence on the PID performance of the RICH detector due to increasing number of secondary electrons.

The steady PID performance degradation over the last years due to ever increasing material budget is a constant cause of concern, and must be closely monitored. However, detailed simulations using the new magnet geometry (together with accordingly updated magnetic field maps by our group) do not show severe impact of this particular magnet design change.

In order to compensate the loss in performance with increasingly realistic material budgets a lot of effort is invested into more advanced reconstruction techniques of the RICH detector signals. Different strategies are followed: Application of convolutional neural networks (CNN) in the cleaning of hit patterns, but also in the ring finding as possible alternative to the currently applied Hough transformation are studied in detail. The first point is relevant in particular for mCBM data analysis, where additional hits in the center of rings (caused by the charged particles directly passing the mRICH) can effectively be suppressed, improving the ring finding- and fitting process. Improved realism in the Monte Carlo simulations here allows for more efficient training of these networks. Application of convolutional neural networks pose a possible alternative to the Hough transformation used for ring finding. Currently, in simulations a slight improvement in reconstruction of ring parameters (position, radius) is already achieved, however still accompanied by significantly lower reconstruction speed. First results are promising and work is being continued in this direction.

Apart from application of CNNs in the RICH reconstruction, also other approaches are followed: Critical for the PID performance of the RICH detector is the proper matching of Cherenkov rings to the correct track candidate. This matching is hindered by the large number of secondary electrons without corresponding STS track candidates, as well as possible deflection of electron tracks due to magnetic field after the STS tracking. The application of momentum dependant correction maps was tested and slightly improves the electron finding efficiency. Even more promising are new approaches applying stand-alone track fitting inside the 4-layers of TRD detector, allowing to combine TRD and RICH information even for tracks not seen inside the STS tracking system (which is the case for most conversion electron tracks inside RICH).

In summary, work on completing the CBM RICH detector in time for first beams at SIS100 is actively continued, and many efforts are undertaken in order to optimize the reconstruction performance and to maximize the physics reach of the CBM RICH detector.

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Slow control interface for airflow measurements

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Introduction

Cooling of the CBM RICH photon detector will be achieved using a sophisticated air cooling and distribution system: Cool air will be blown into the enclosed photon camera boxes, internally distributed over the ~ 1500 individual electronic modules, and then recirculated after cooling in an external water heat exchanger. Sufficient air flow is enforced using an external blower. Presently, we are testing and developing this system using the first full-scale prototype of a complete RICH camera module (see [1, 2] for more details).

Sensors and readout

In order to measure airflow and to optimize the air distribution, two kinds of sensors are used: BOSCH HFM7-R5 (see Figure 1 top) is a calibrated air mass-flow sensor (primarily used in automotive applications) covering a large dynamic range of up to 480 kg/h, ca 6.5 m³/min, and already including the (analog) readout interface. This sensor allows to monitor the total cooling air flow into each RICH camera module, also including temperature measurement. For development of the distribution system, additionally 8 small sensor elements of type FLW122 are used (see Figure



Figure 1: The BOSCH HFM7-R5 (top) is a pre-calibrated mass-flow sensor to be used for measuring the total cooling airflow into the CBM RICH air distribution system. FLW122 (bottom) is a "naked" mass flow sensor without further readout electronics. It comes without any pre-calibration (which will depend on the exact installation situation anyway), and will allow to measure air flow at different locations inside the camera.

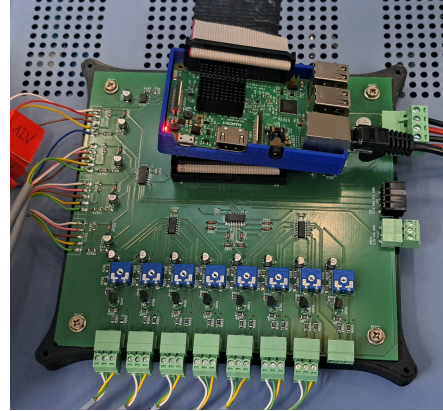


Figure 2: The slow control interface used to connect up to 4 BOSCH mass flow sensors (connected to on left side) and up to 8 FLW22 mass flow sensors (connected on the bottom side), including the necessary measuring bridge amplifier and control circuits. Readout of the ADCs and implementation of an EPICS IOC interface is accomplished using a RaspberryPi computer.

1 bottom). Applying the same (thermal) measurement principal, these sensors are small, uncalibrated, and need external circuitry for readout. They come without any housing, and can be used very flexibly. For simultaneous readout of all sensors a dedicated slow-control module (see figure 2) has been developed, providing all necessary interface circuitry and ADCs for fast sampling of both sensor types. Connection to a RaspberryPi allows to run EPICS on the interface, useful for later integration into the RICH monitoring system.

Test- and calibration measurements

The thermal measurement principle of both mass flow sensors result in a highly non-linear response function of the analog output signal, which has to be calibrated to obtain quantitative measurements. The BOSCH sensor comes with a (common) calibration curve provided by the manufacturer, where the FLW122 calibration depends on the individual installation situation. In order to assure accuracy (over a large dynamic range) and reproducibility of the BOSCH sensor, we tested if they would measure the same amount of air mass flow in a test setup where the input air flow (measured by a first BOSCH sensor) is split into three equal parts, measured by another three BOSCH



Figure 3: Setup of the first test measurement of the BOSCH mass air flow sensors: incoming air is equally distributed into three output channels through the three-way splitter (black), homogenised within conventional tubes that are attached (grey) and finally measured with the sensors.

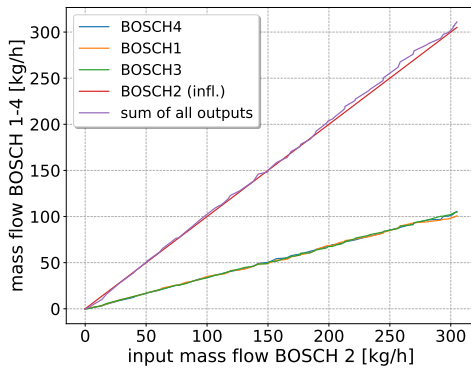


Figure 4: Comparison of input air mass flow (BOSCH2) and output flow (BOSCH1, BOSCH3, BOSCH4) after 1:3 splitter. The sum of all three output sensors (red) matches very well the input flow, despite the fact that input and output sensors are operated at quite different mass flow ranges.

sensors (cf. Fig. 3). Initial measurements revealed differences, which could be attributed to the occurrence of turbulent flow and uneven flow patterns caused by the splitter (the BOSCH sensor utilizes a small measuring cell positioned in the center only); these effects could be suppressed adding tubes between splitter and sensors, providing valuable experience for all further measurements to come. Final results are shown in Fig. 4: the measured airflow is now equally distributed over the three output channels and their sum matches well the amount of air blown into the first sensor despite the non-linear measurement principle, demonstrating the good accuracy and reproducibility of this sensor.

In a second step, all 8 FLW122 sensors were calibrated, with the sensor elements mounted in a custom 3d-printed

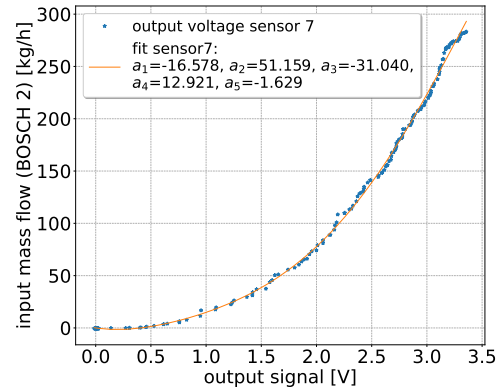


Figure 5: Calibration curve of the seventh FLW122 sensor. A fifth degree polynomial was chosen as the fit function. The same procedure is applied to the remaining six sensors.

housing to be used for the first measurement task. In the calibration setup, the incoming air (measured by the previously tested BOSCH sensor) is routed through a single FLW122 sensor housing, and the sensor response compared to the measured inlet air mass flow. The calibration curve of a single FLW122 sensor can be seen in Fig. 5 where the output signal is plotted against air mass flow rate of a reference BOSCH sensor.

Next steps

With all FLW122 sensors being calibrated in the same manner, we will now start the first test measurements on the prototype setup. In the RICH cooling concept, incoming air is distributed over each 7 individual columns of read-out modules using air distribution boxes, where equal distribution of the airflow into each outlet will be achieved using internal "guiding blades" inside the box. Optimizing the design of these guiding blades is done by means of CFD (Computational flow dynamics) simulations using the software package COMSOL, closely accompanied by measurements on the prototype detector using the properly calibrated sensors.

Acknowledgement

Work supported by BMBF (05P19PXFC1, 05P21PXFC1), "Netzwerke 2021", an initiative of the Ministry of Culture and Science of the State of Northrhine Westphalia, and GSI.

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Magnetic field simulations for the CBM dipole magnet*

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Introduction

Following a change request by the STS group, a new, slightly larger CBM dipole magnet design v22 has been adopted, giving a free aperture of 1470 mm (v18 design +30 mm) in vertical direction and 3300 mm (v18 design +300 mm) in horizontal direction, in order to provide more space for the STS detector system. Consequently, also the coil current has to be adjusted to the changed dipole magnet yoke geometry and the vertically shifted position (± 15 mm) of the two superconducting coils such, that the original magnetic field integral along the beam axis over a length of 1 m from the target [1] is maintained (~ 1 Tm for v18a including field-clamps), as shown in figure 1.

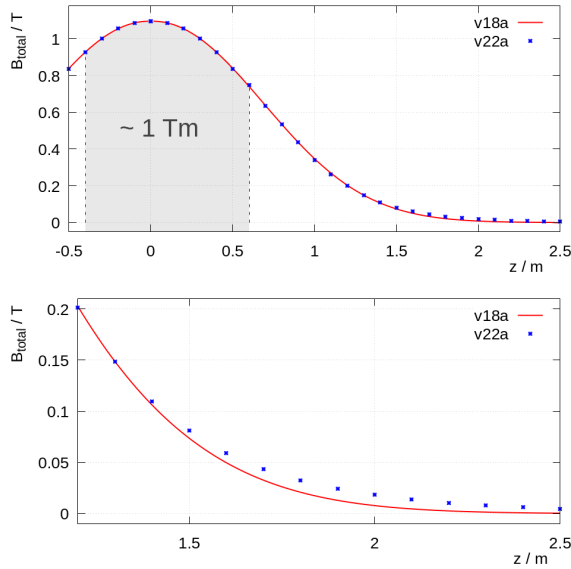


Figure 1: Simulated magnetic field distribution of B_{total} along the beam axis ($x = y = 0$) for the dipole magnet geometries v18a and v22a (dipole magnet with field clamps) generated with COMSOL. Upper plot: main-field inside magnet; lower plot: stray-field inside RICH gas-vessel.

Simulation of the dipole magnet design v22

To simulate the magnetic field of the dipole magnet design v22, cluster computing assisted 3D magnetic field FEM simulations were performed within COMSOL mul-

tiphysics 6.0 using the AC/DC module. The RICH camera magnetic shielding box version v20 [3] and an additional plate of KOVAR alloy (with large magnetic susceptibility) representing the MAPMTs KOVAR housing were created with the CAD software CATIA 5 and exported in STL format for their further use in COMSOL. Due to technical difficulties in importing the parts of the magnet and the field clamps, these were rebuild using the geometry builder within COMSOL, which has already worked well for previous simulations. Since the geometry of the dipole magnet, the magnet field clamps, and the spherical total bounding box (radius of 7.5 m) are symmetric around $\pm x$, $\pm y$ and $\pm z$ a simulation model consisting only of "octant zero", which is depicted in figure 2, was created in different variants: geometry v22a (magnet with fieldclamps, without RICH shielding box), v22b (without field clamps and without shielding box), v22c (including field clamps and shielding box and KOVAR), and v22d (including field clamps and KOVAR, but no shielding box).

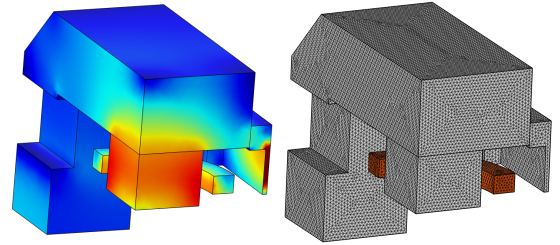


Figure 2: Showing the "octant zero" ($x, y, z \geq 0$) geometry of the dipole magnet with field clamps (v22a) generated with COMSOL.

In the simulation, low carbon steel 1010 was selected as material for the magnet yoke, the field clamps, and the magnetic shielding box of the RICH camera. The two coils were each specified as a single circular winding made of superconducting material, loaded with an effective current density equivalent to the wound coil.

In a series of simulations, the coil current was iteratively increased until the specified field integral was reached, finding that the coil current for the larger magnet v22a geometry must be increased by approximately 4% as compared to the original v18a geometry in order to achieve the same main-field inside the dipole-magnet.

* Work supported by BMBF (05P19PXFCA, 05P21PXFCE) and GSI

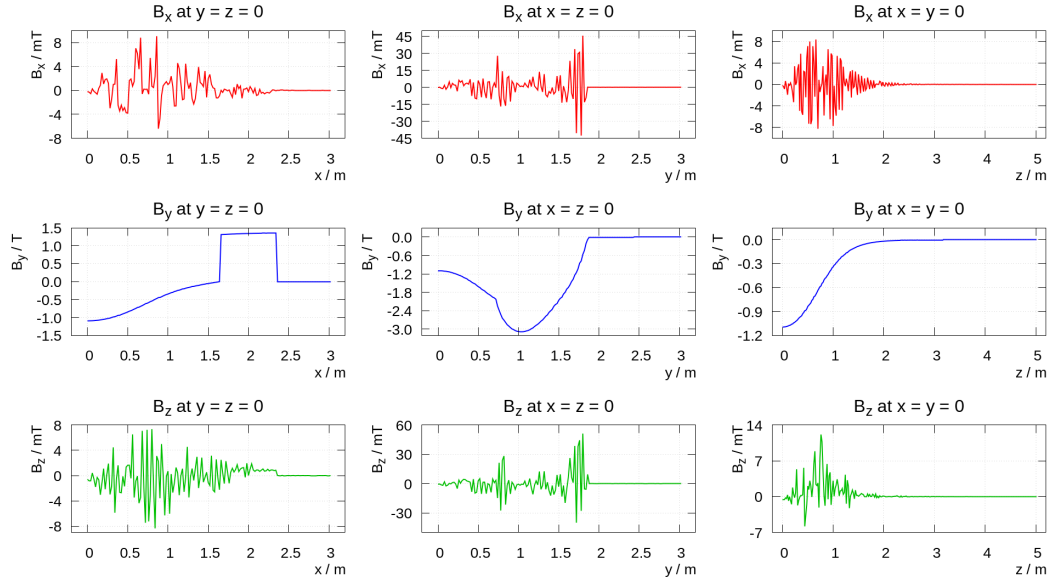


Figure 3: Simulated magnetic field distributions of the magnetic field components B_x in mT, B_y in T and B_z in mT (from top to bottom) at $y = z = 0$, $x = z = 0$ and $x = y = 0$ (from left to right) of the symmetric detector geometry v22a (dipole magnet with field clamps).

Magnetic stray field of v22a geometry

Although both field distributions (for old and new magnet design) along the beam-axis are matching perfectly in the range from 0 mm to 1500 mm as shown in figure 1, after further analysis of the simulated data it was found that the magnetic stray field of the geometry v22a extends farther than that of the geometry v18a. The field integral along the beam-axis in the range of the radiator vessel (see figure 1 lower plot) amounts to 36.9 mTm for the new v22a geometry (up- and down-stream field-clamps, no shielding box) as compared to 35.1 mTm for the old geometry v18a. Thus, the field integral roughly increases by 5 %. Adding the shielding box to both old and new magnet results in a similar comparison.

As this could have a harmful impact also on the closely located photon detection cameras of the RICH detector, it is essential to investigate the magnetic stray field in the area of the magnetically sensitive MAPMTs further. To ensure reliable comparisons and eliminate systematic errors, the magnet geometries v18 (v18a: magnet with field-clamps, v18c: adding shielding box and KOVAR) was also re-simulated in parallel to the new simulations. A comparison of the two magnetic stray field distributions on the photon detection plane, derived from the simulation results of the geometries v18c and v22c, is shown in figure 4. The region with stray fields $B_{\text{total}} > 2.5$ mT is enlarged for v22c on the photon sensitive plane in columns 4 to 7, while the maximum of B_{total} even crosses the MAPMT critical threshold of 3 mT in column 7, i.e. the center of the photon detection plane. In columns 2 to 6 B_{total} increases by approximately 5 % on average, still staying below 3 mT.

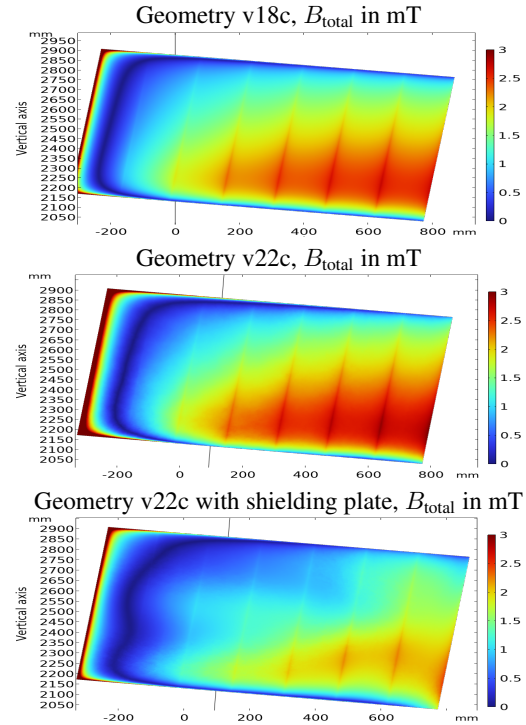


Figure 4: 2D projection of the photon detection plane, comparing the magnetic stray field B_{total} when using geometry v18c and v22c and v22c with additional shielding plate, showing MAPMT column 1 to 7 (from left to right) of the left half of the photon detection plane.

By using an additional shielding plate consisting of steel 1010, with 2m horizontal length and 1m vertical height and a thickness of 20 mm, placed in the area between the magnet field clamps and the RICH camera shielding box, the stray magnetic field can be reduced by $\sim 25\%$ in column 7, i.e. the center region, and even reduced by $\sim 50\%$ in column 1, i.e. the edge region.

Magnetic field maps of v22 geometry

Several different geometries have been simulated, in order to create new magnetic field maps to be used in all Monte-Carlo simulations. These field simulations explicitly simulate a range starting at the center of the dipole magnet and beam-axis with $152 \times 152 \times 252$ steps of 20 mm resulting in a volume of $3040 \text{ mm} \times 3040 \text{ mm} \times 5040 \text{ mm}$ totalling 5822208 data points. Starting at $x = y = z = 0$, the simulated range always covers one octant of the full field map.

Shown in figure 5 are the retrieved field maps for this single octant using geometries v22a, v22b, v22c and v22d. Using the field map derived for "octant zero", one can now derive field maps for all other octants, taking into account the according symmetries in the magnetic field. Hereby one can (to a certain degree of accuracy) also mix different geometries to produce e.g. a final geometry with a field clamp only on one side of the dipole magnet. However, as revealed by latest simulations of full 3d geometries (without applying symmetry constraints) it turned out that there are difficulties combining geometry v22b and v22c, as installation of the upstream field clamp significantly modifies the strayfield pattern downstream of the magnet. Further studies verified the importance of installation of all four field clamps, both upstream and downstream, for the best possible suppression of strayfields in the region of the photon detector.

Summary

In summary, increasing the magnet gap as proposed in the recent change request only has minor influence on the stray field characteristics; the coil current has to be increased by roughly 4 % in order to achieve the same main field integral as before; the stray field inside the RICH radiator (for similar main field) is increased by roughly 5 %, similar to the stray field increase in the region of the MAPMTs. Significant improvement can be obtained by adding additional field-clamps also on the upstream side of the magnet and / or adding an additional shielding-plate in-between the field-clamp and RICH camera. Combining both measures results in a maximum stray field of roughly 2.5 mT which would provide some safety margin.

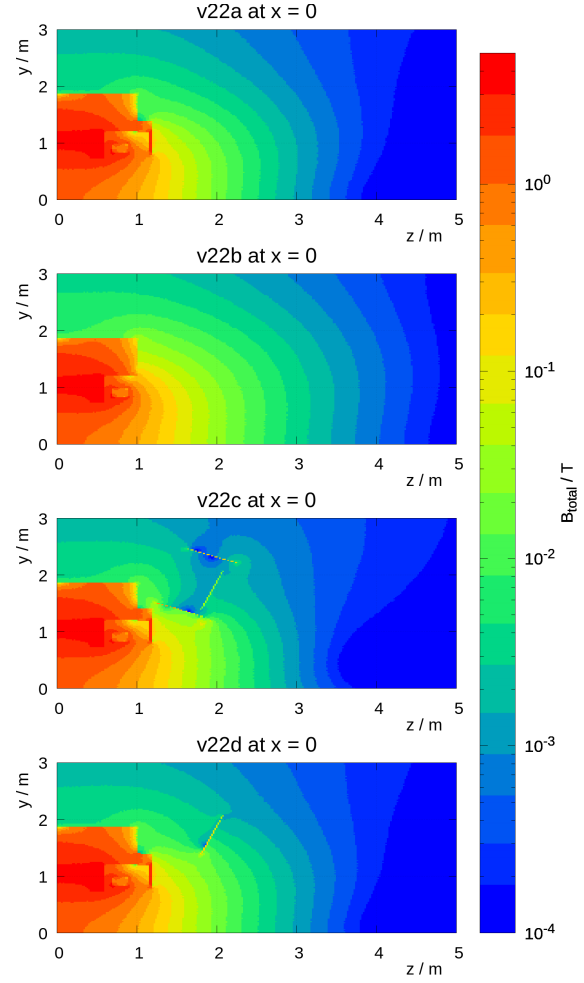


Figure 5: zy -projections at $x = 0$ of the resulting magnetic field maps. Geometry v22a features the dipole magnet with field clamps, v22b just the dipole magnet, v22c the dipole magnet with field clamps, the RICH shielding box [2] and the KOVAR alloy of the MAPMTs [3], v22d the dipole magnet with field clamps and the KOVAR alloy of the MAPMTs.

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STS - Magnet updated geometry and its impact on the RICH performance

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Introduction

With the STS changing its design from an eight station setup *v21e* to a modular 3 + 5 station setup *v22c*, a new STS geometry was implemented in CBM-ROOT to test the impact of this change in design to the performance of the RICH detector. Accordingly, the enclosing magnet had to be redesigned resulting in the new geometry *v21a* (*v22a* before). The corresponding field map was derived (*v22c*) to account for this change in geometry.

To understand the impact of the new STS setup including necessary changes in the magnet geometry on the RICH performance, three different setups were simulated. The first setup features the old geometries and builds the reference baseline for this study. The second setup uses the new geometries of STS and magnet and makes use of the accordingly derived new magnetic field. In the third setup we use the old magnetic field map (*v18a*) but the new STS and magnet geometries in order to separate effects of the magnetic field from those of the new geometries. Obviously, the results derived with the new geometries but old magnetic field need to be taken with caution, since the old field map does not correspond to the newly introduced material budgets. Simulations were performed using two different data sets, each consisting of 10^5 box generator events. Here, each event features one electron and one positron within standard acceptance and $p_T < 3$ GeV/c. The other data set consists of 10^5 central Au+Au UrQMD events at 12A GeV/c.

Impact on primary electrons

Using the FairBox generated electron sample one can study the impact of the new geometry and magnetic field on primary electrons. The geometric acceptance as function of momentum for all three configurations is shown in Figure 1. The geometric acceptance is calculated by dividing the number of electrons and positrons that left at least seven MC hits on the RICH photon detection plane by the number of all generated $e^\pm$. Comparing the derived acceptance results for the old geometry to that of the new geometry one observes a slightly reduced acceptance. This slight degradation in the acceptance is even seen to a slighter effect when using the new geometries but old field map. The degradation is mainly seen at low momenta, suggesting that the effect is mostly related to an increase in the magnetic stray field and increased multiple scattering of low-momentum particles. A similar effect can be observed

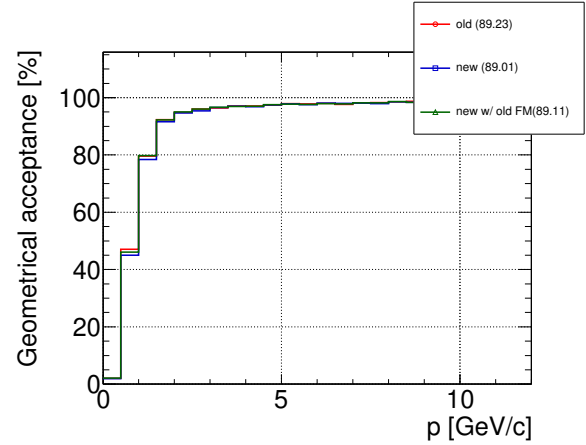


Figure 1: Geometric acceptance as defined in the text for primary $e^\pm$.

when comparing the ring-track distance for low momentum positrons shown in Figure 2 (similarly for electrons, not shown here). Here, the new geometry with new magnetic field map is compared to the old detector setup indicating a slight degradation in the reconstructed track to true ring position matching. All the observed effects are however small such that one can summarise that the analysis using the box generated electrons reveals no major differences between old and new geometry setup.

Tests on basis of a realistic electron sample

To compare the impact of the new geometry to photon conversion, an UrQMD sample is generated and analyzed. In a first test, the number of MC points per event integrated over the full detection plane is presented in Figure 3. MC points hereby refer to all photons hitting the photon detection plane without taking into account any photon efficiency effects. Additionally, the measured number of photon hits is displayed in the same figure. We observe an average reduction of $\sim 3\%$ in number of hits and MC points for the new geometry when comparing it to the old geometry. However, when comparing the old geometry to the new one but using the old magnetic field map one observes an increase in the number of hits and MC points by about 2.5%. Both effects are very small leading to the conclusion, that neither the new geometry nor the new magnetic field result in large changes in the number of detected hits. Still, one might interpret this observation as an increased

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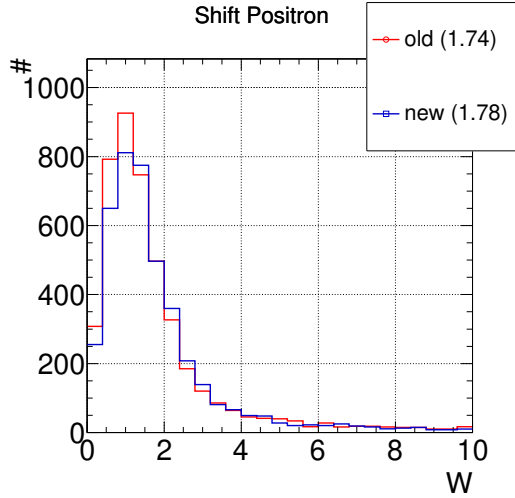


Figure 2: Ring-track distance for $p < 1$ GeV/c. Using reconstructed STS tracks of electrons but the true ring centre information. Compared are the old geometry to the new geometry setup with new magnetic field map.

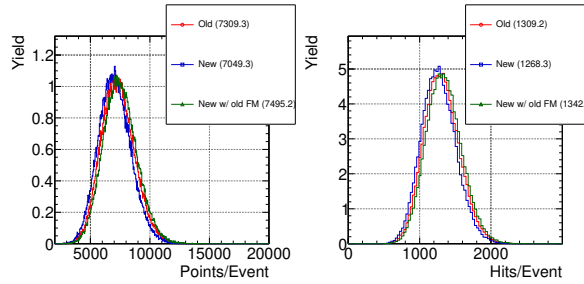


Figure 3: Number of MC-Points (left), and number of Hits (left) per event for a UrQMD sample.

material budget due to the new STS and magnet geometries producing more secondary electrons, which are bent out by a stronger magnetic stray field. Figure 4 now compares if

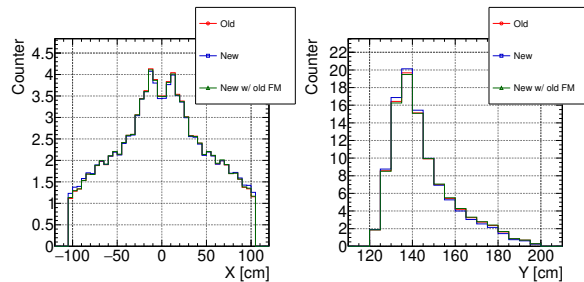


Figure 4: Distributions of MC points along the camera plane in X and Y for the UrQMD sample.

not only the absolute number of MC points is similar between the old and new geometries, but if also the spatial

distribution of this measure stays the same. Examining the distribution of the MC points on the camera plane in X and Y ¹ one again observes no major differences between the two geometries. In a final test, the number of rings and the number of hits per ring are compared for the three simulation setups. This is depicted in Figure 5 where one observes no change in the number of hits per ring but small differences in the number of rings over the full detection plane. Hereby, the number of rings is changed by same amount as the number of hits per event discussed before. This indeed supports the possible explanation of having more material budget in the new geometry and also having slightly stronger magnetic stray fields in the new magnetic field map.

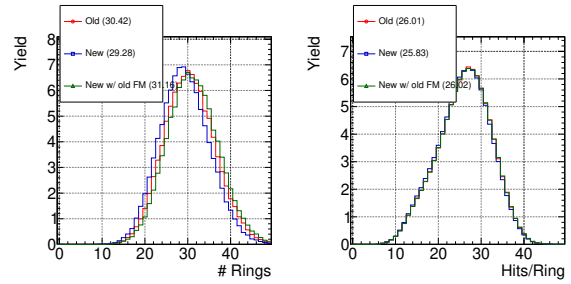


Figure 5: Detector integrated number of rings per event (left) and number of hits per ring (right) using the UrQMD sample and derived for old and new STS and magnet geometries.

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¹ Y is displayed only for the top half of the detection plane.

Current status of the development of the mirror supporting frame*

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Introduction

At PNPI Gatchina, the development and construction of the mirror supporting frame and mirror holders was quite advanced (see Fig. 1) when the cooperation with Russian institutes was abandoned in February 2022 after the Russian invasion into Ukraine.

In order to proceed with the RICH mechanics, we decided to continue on the basis of existing (technical) drawings. As the mirror holding system was most advanced, we started to re-design the mirror holding structure including new technical drawings in CATIA and prototyping in order to experience the manufacturing process, tolerances etc..

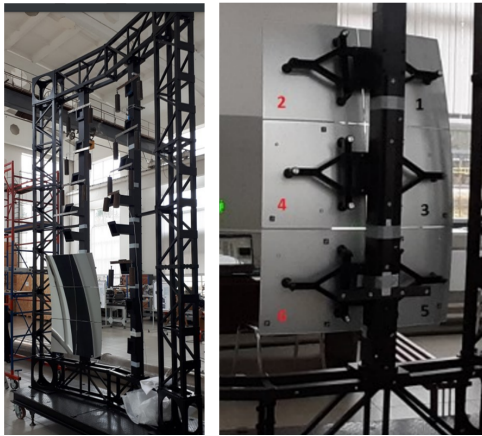


Figure 1: The mirror supporting frame and mirror holder as they were developed and produced at PNPI, Gatchina. [1]

Mirror Holder and Gluing Setup

Drawings of the mechanical parts including dimensions (step files) of the mirror holders were available from the cooperation with PNPI, therefore the development had not to be done from scratch. With the help of these drawings, first parts were re-drawn in CATIA in particular also including tolerances, and a proper description of holes or threads. Based on these updated drawings, first parts of a mirror holding structure were already produced (see Fig. 2), the production of the remaining parts is still in progress.

The aluminum mirror holders are made up of a triangle-like frame, carrying three small base plates onto which the

mirror will be glued. These base plates are connected to the frame via Cardan joints. Each two triangle-like frames are connected by two bars of varying size depending on the mirror row of the RICH mirror plane as each of the four rows has slightly different dimensions of the mirrors. Those pairs are then fixed to the pillars.

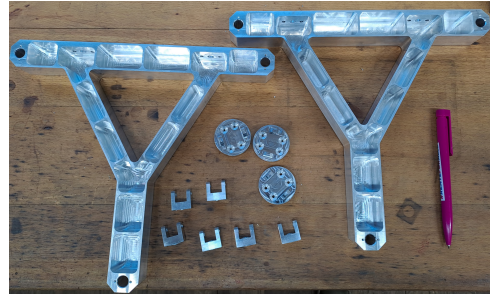


Figure 2: Some of the first mirror holding parts that were produced in Gießen so far. Shown are the triangle shaped holder with base plates and parts of the Cardan joint.

As next step, a setup is being built which can be used for precise gluing of two mirrors to a mirror frame, see Fig. 3. The gluing setup can be adopted to all four different sizes of mirrors and connecting bars.

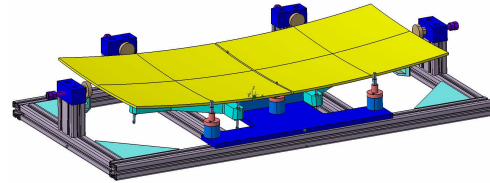


Figure 3: Draft of a mirror holder (central green parts, largely hidden), carrying two mirrors (yellow), embedded into the gluing setup (grey and blue tiles).

As next step, a pillar including connecting pieces to the mirror holders will be built. A pair of mirrors can then be fixed and the adjustment be tested.

References

- [1] *CBM RICH mechanics conceptual design*; Yury Ryabov, CBM Collaboration Meeting in March 2021

*Work supported by BMBF (05P19RGFCA, 05P21RGFC1) and Helmholtz Forschungssakademie Hessen für FAIR (HFHF), GSI Helmholtzzentrum für Schwerionenforschung, Campus Gießen.

Updated RICH geometry QA tests

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Introduction

The RICH detector geometry description in GEANT has recently been updated, and is now more realistic in terms of shielding box design, mirror tilt angle, and MAPMT active area. In this report we compare the new geometries to the previous standard geometry with respect to possible changes in the RICH performance.

Updated RICH geometry

Main changes in the updated RICH geometry are:

- change to 12° mirror tilt angle (from previously 10°).
- Reduced active area for MAPMTs (52 mm × 52 mm → 48.5 mm × 48.5 mm).
- Inclusion of most recent shielding box design, in particular including the iron "wing" structure reaching close to the main acceptance cone.

The study is based on a comparison of three different RICH geometry definitions as shown in Figure 1. These are:

- **v21a**: Same as v17a, only shifted along Z -axis by 40 cm; $Z = 0$ now in the center of the magnet following CBM convention.
- **v22a**: New geometry including shielding box and shielding wing.
- **v22b**: New geometry excluding shielding box and excluding shielding wing.

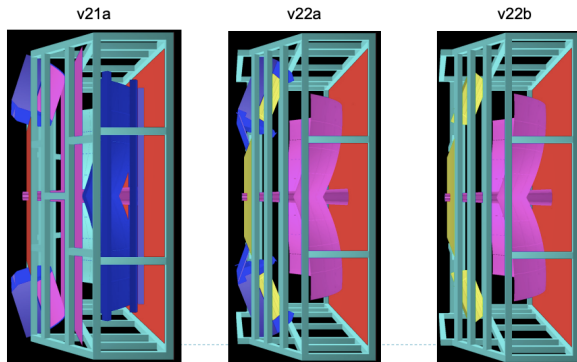


Figure 1: Different RICH geometries used for comparison.

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Besides the RICH geometry details noted above, the following geometries were used in the simulation setup:

- Magnet geometry v21a
- Beampipe geometry v21d
- STS geometry v21e
- Magnetic field map v18a.

Two different data sets were used in the simulation: one consisting of 10^4 events from a box generator with each event featuring five electrons and five positrons within the standard angular acceptance and $p_T < 3$ GeV/c. The second one is consisting of 10^4 minimum bias Au+Au UrQMD events at 8A GeV with the aforementioned box generated electron sample being embedded, 5 additional electrons and 5 positrons per event.

Results for box-generated sample

The geometrical acceptance for primary $e^\pm$ as function of momentum for the different geometries is compared in Figure 2, where a lepton track is considered "accepted" if it generated ≥ 7 MCtrue hits in the RICH photon detection plane. Only a very slight reduction of the efficiency can be observed. In Figure 3, the number of MC

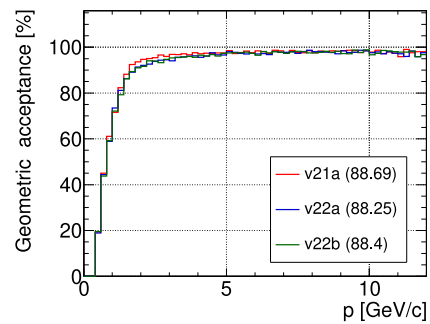


Figure 2: Geometric acceptance for primary box $e^\pm$.

points per event (i.e. GEANT-simulated photons hitting the PMTs) and number of hits per event (i.e. number of detected photons after applying wavelength-dependant quantum efficiency) are compared. Both numbers in average are reduced to 90% in the v22-geometries compared to v21a, matching exactly the loss in active area of the MAPMTs in these geometries ($\frac{48.5^2}{52^2} = 0.9$). By comparing v22a and

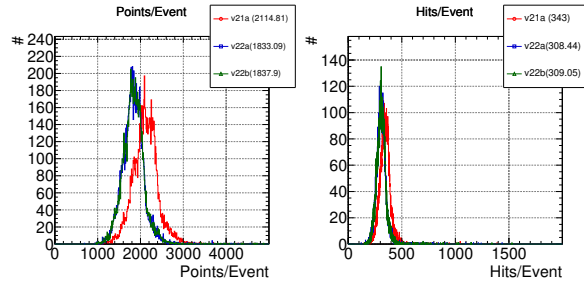


Figure 3: (Left) MC points per event, (Right) Hits per event for box $e^\pm$ sample.

v22b, it can be concluded that the shielding box (and wing structure) have only very minimal effect.

In order to further analyze the effect of the reduced number of hits on the ring finding quality, the number of found rings per event and number of hits per ring is depicted in Figure 4. The number of found rings per event is affected only on a sub-percent level while the number of hits per ring is reduced by $\sim 10\%$, in good agreement with the reduced number of hits per events in v22 geometries as compared to v21a. No significant difference between v22a and v22b can be observed.

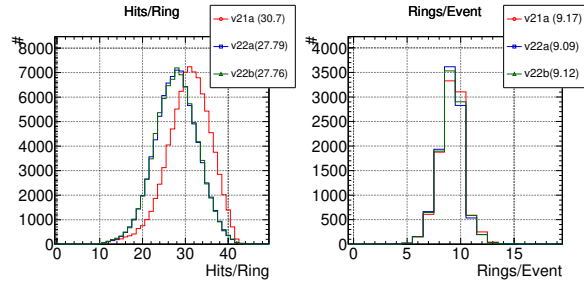


Figure 4: (Left) Hits per ring, (Right) Number of rings per event for the box-generator $e^\pm$ sample.

Results for UrQMD+box-generator sample

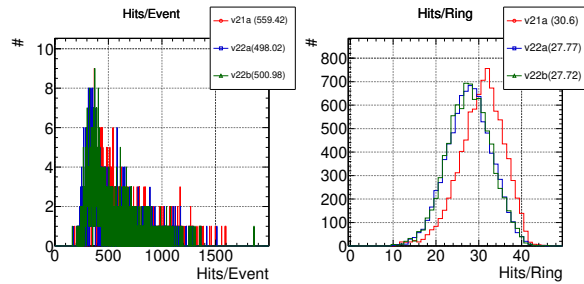


Figure 5: (Left) Hits per ring, (Right) Number of rings per event for the UrQMD + FairBox sample.

Similar QA studies were conducted using the UrQMD+box-generator sample with results shown in Figure 5. Comparing the number of hits per event and number of hits per ring for the different geometries in both Monte Carlo samples confirms that no significant additional background due to photon conversion is caused by the shielding box, and in particular by the iron wing structure reaching very close to the acceptance cone (cone of direct view onto the target area). Blocking of the optical pathway between mirror and camera due to the shielding box and wing can also be excluded.

Finally, in Figure 6 we compare the standard tracking performance plots for primary electrons for the three different geometries under study. Again, no significant differences can be observed for all three Monte Carlo geometries.

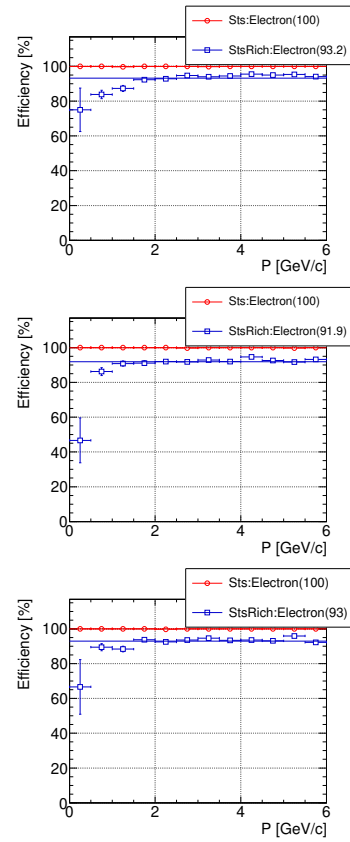


Figure 6: Global tracking efficiency for primary electrons (From Top) for v21a, v22a, v22b geometries respectively.

Acknowledgement

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RICH reconstruction performance improvement *

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Introduction

The CBM RICH is designed for efficient PID of electrons with momenta up to 6 GeV/c. The PID performance of the RICH significantly depends on Ring - STS track matching efficiency. The STS tracks are extrapolated and projected to the RICH photon detection plane searching for the closest ring candidate for the projected track. Due to the magnetic stray field and other effects there could be a systematic shift between the projected track and ring. In this report we present a correction for such systematic shifts and evaluate its effectiveness with regard to improving the matching performance.

Systematic correction for track projection

The following tests and results are based on a simulation of 10^5 UrQMD Au+Au central collisions at 8A GeV/c with one embedded Pluto $\omega \rightarrow e^+ + e^-$ per event. The used geometry setting combines *Magnet v22a*, *MVD v20d_tr*, *STS v22c*, *RICH v22a* and *field map v22c*.

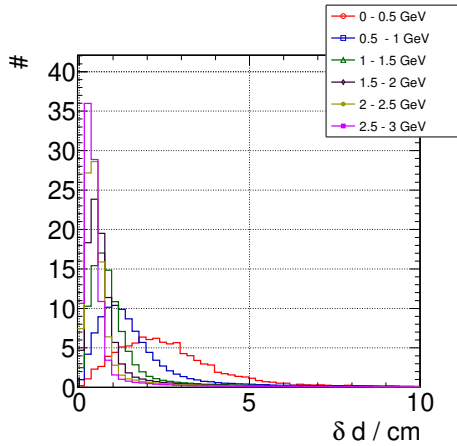


Figure 1: Absolute ring-track distance at the photo-detector plane for electrons of different momenta.

Figure 1 shows the absolute ring-track distance

$$\delta d = \sqrt{(x_{ring} - x_{track})^2 + (y_{ring} - y_{track})^2}$$

for primary e^- for different momenta¹. Here, x_{track} and y_{track} refer to the projected position of either a true, or

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¹ Positrons (e^+) are not depicted but feature similar characteristics.

reconstructed STS track onto the RICH photodetector. Visibly, the δd distribution shifts and widens for lower momenta which in parts can be explained by the aforementioned magnetic stray fields. In order to correct for these systematic effects we derive correction maps to be applied during normal reconstruction using simulations of a pure electron sample produced by the box generator. For this purpose, 10^6 events with three e^+ and three e^- are generated in the standard acceptance with $p < 3$ GeV/c where δd is calculated differentially in 15 momentum bins, 10×10 spatial bins in the RICH and two charge bins. The procedure is repeated using three methods,

1. Using MC true momentum and MC true ring centre.
2. Using STS fitted momentum and MC true ring centre.
3. Using STS fitted momentum and found ring centre.

The idea behind method two and three is to test and account for biases in the momentum reconstruction and ring finding.

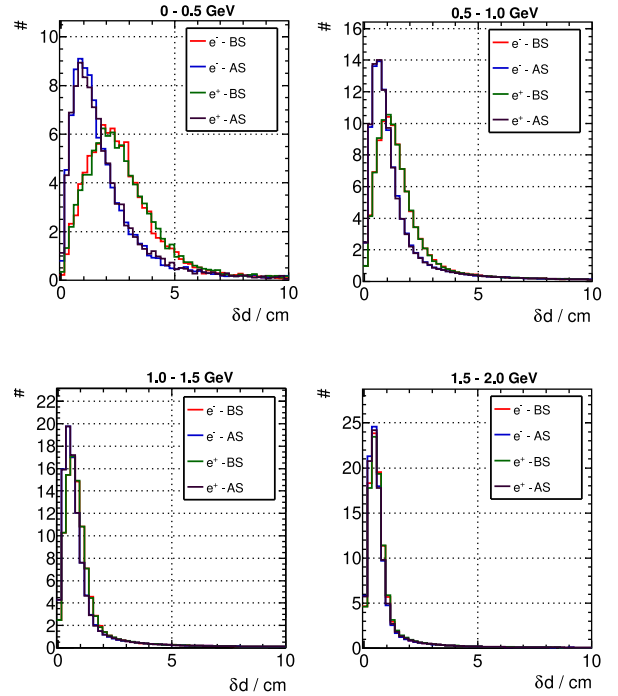


Figure 2: Absolute ring-track distance for electrons and positrons at different momenta before (BS) and after (AS) correction.

Results and discussion

In a first test the correction methods were analysed on basis of the box generated electrons and positrons that were used to derive the correction maps. Applying the correction derived on basis of the true ring-track differences (method one) one observes an improvement in δd especially for low electron momenta. This is shown in Figure 2 where δd is depicted before and after correction for different momenta. In Figure 3, the three different correction maps are applied during the reconstruction process, and similar results are observed. Accordingly, one can state that the derived procedure should also work in the real experiment, where only reconstructed momenta and ring centres are available, and where the correction could be even derived from data directly (instead of Monte Carlo).

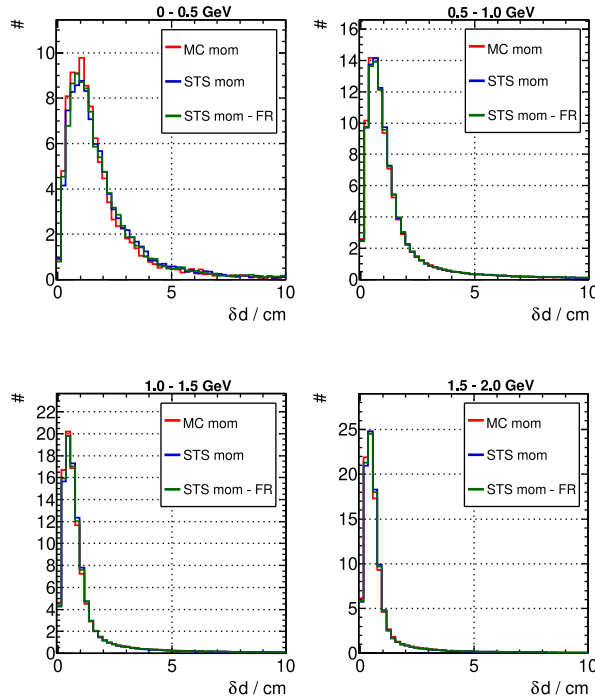


Figure 3: Absolute ring-track distance for electrons and positrons at different momenta after correcting using method one (red), method two (blue) and method three (green).

In a second step the correction was tested on basis of an UrQMD sample. In Figure 4 the electron efficiency and the pion fraction are displayed as functions of the maximum ring-track distance allowed in the matching process. Efficiency hereby refers to the fraction of reconstructed electrons divided by the number of electrons with at least seven MC hits in the RICH detector, with the additional requirement that the reconstructed ring has a radius of $r > 4$ cm. Pion fraction refers to the fraction of pions incorrectly matched to reconstructed rings, again featuring the same ring radius requirement. Expectedly, applying the correction improves the electron efficiency for a given ring-track

maximum distance condition while having no major impact on the pion fraction. This improvement is mostly observed for strict ring-track distance conditions as most correctable systematic shifts lie in this region.

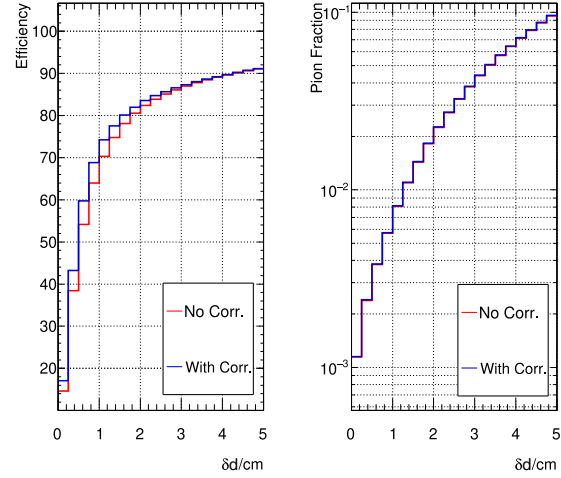


Figure 4: Electron detection efficiency and pion fraction as function of absolute electron ring-track distance.

In summary, it can be said that the described correction method might help correcting for systematic effects like the impact of the magnetic stray field. However, track by track deficiencies, for example caused by multiple scattering, cannot be corrected by this approach. Therefore, as outlook, we currently try to extend this correction by using TRD hits for a second level correction along with the STS projection. This way we hope to further improve the ring track matching.

Acknowledgement

This project is receiving funding from the programme "Netzwerke 2021", an initiative of the Ministry of Culture and Science of the State of Northrhine Westphalia. The sole responsibility for the content of this publication lies with the authors.

Pattern recognition on mRICH simulation data using machine learning*

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Introduction

The mRICH is build as a proximity focusing RICH detector, which results in charged particles passing directly through the MAPMTs producing additional digi (sometimes referred to as “noise”) clusters. Those clusters are typically inside ring structures and are causing the ring finding algorithm based on the Hough Transformation [1] to reconstruct a lot of false rings. Since those digi clusters are strongly enhanced in real data compared to simulations, additional digis have been added to simulations for a more realistic detector response. Having a simulation which compares well with real data, a convolutional neural network (CNN) is trained [2] to classify those “noise” signals and exclude them for the subsequent ring finding process.

For this analysis, the UrQMD files ‘urqmd.auau.1.24gev.mbias’ 701 to 900 have been used, separated in two halves for training and testing data. The events were simulated using the ‘mcbm_beam_2022_06_16_gold’ geometry with a 2.5 mm thick Au target.

Simulation adjustments

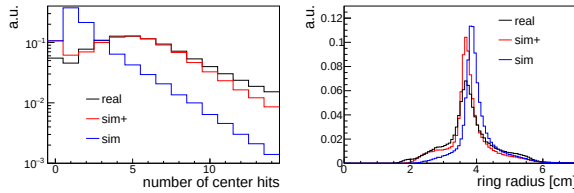


Figure 1: (left) number of “center hits” with a hit-center distance of $\leq 0.8R$ of the ring radius R with $\Delta t \leq 5$ ns. (right) ring radius distribution, comparing real, adjusted simulation (sim+) and simulation (sim) data.

In order to create a more realistic detector response, the parameters of the current simulation (sim) are adjusted and additional noise is added (sim+). The simulation parameters are adjusted in a way to match real data (real), for which the first 200 time slices of run 2511 are used as reference data. For simulated events mostly 1-2 hits are inside a ring center, while for real data it is very common to have

more than 4 center hits (see Fig. 1 left), already applying the ToT cut of 23.7 ns to 30.0 ns on real data. Charged particles are expected to be the main contributor of those clusters. Even when including the glass window in front of the MAPMTs, the amount of center hits is not sufficient, however at the cost of quite some computational time. Therefore, additional artificial noise digis are added randomly (with decreasing probability based on distance) in a 5×5 kernel around the digi which is connected to the charged particle crossing the MAPMT (RichPoint). Additionally, the added noise is restricted to the same MAPMT as the digi containing the charged particle.

$$r_c(X, Y) = \sqrt{(X_c - X)^2 + (Y_c - Y)^2} \quad X_c, X, Y_c, Y \in [0, 7] \quad (1)$$

$$P_c(X, Y) = \begin{cases} \frac{\varphi}{r_c(X, Y)}, & \text{if } |X_c - X|, |Y_c - Y| \leq 2. \\ 0, & \text{otherwise.} \end{cases} \quad (2)$$

$$t_c(X, Y) = t_c + \mathcal{N}(0, 1) \quad (3)$$

The local MAPMT indices X_c, Y_c and the time t_c are from the digis generated from a charged particle. With the distance definition in equation 1, a noise digi with local MAPMT indices X, Y is added with the probability $P_c(X, Y)$ (Eq. 2) and time $t_c(X, Y)$ (Eq. 3) with $\mathcal{N}$ being the normal distribution. The CenterNoiseDigiRate φ is a new parameter introduced to adjust the amount of center hits. For parameter adjustment and better comparison of simulation and real data, the simulation is running in time-based mode to eliminate differences based on the Event-Builder. Parameters used for the simulations are shown in table 1.

Setting	sim	sim+
CollectionEfficiency	0.45	0.45
TimeResolution	1.0	1.0
Aerogel refraction index	1.05	1.046
CenterNoiseDigiRate	-	0.40
NoiseDigiRate	150.0	150.0

Table 1: Simulation parameters, comparing the previous simulation to the adjusted simulation parameters (sim+).

The aerogel refraction index was slightly changed to 1.046 to match the observed ring radius peak for real data in figure 1 (right). Adding additional noise leads to many

* Work supported by BMBF (05P19RGFCA, 05P21RGFC1), GSI, and Helmholtz Forschungsakademie Hessen für FAIR (HFHF), GSI Helmholtzzentrum für Schwerionenforschung, Campus Gießen.

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more mismatches in simulated data (sim+), a typical mismatched ring reconstructed from center hits is shown in figure 2.

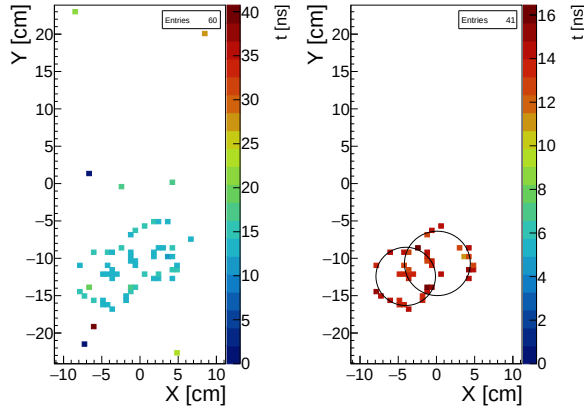


Figure 2: Left: Single-event-display (SED) in mRICH with all hits. Right: SED after ring finding with only ring hits shown; the Hough Transform is confused by the additional hits in the ring centers. Colour scale: hit time in ns.

Even though this simple approach is for now completely independent of any particle properties, similar patterns compared to real data are now also observed for simulations. Two anomalies previously only seen in real data are now also visible in the simulated data: an additional peak in the ring radius distribution for small radii (see Fig. 1 (right)) and the observation that rings are more often found in between MAPMTs (see Fig. 3).

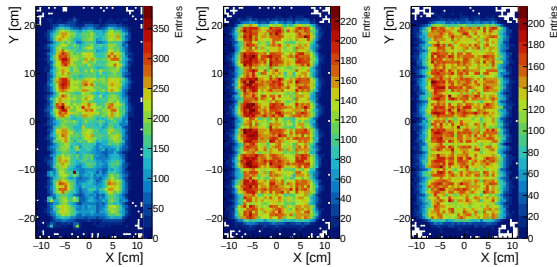


Figure 3: Ring center positions in the mRICH plane for (left) real, (middle) sim+ and (right) sim data.

Labeling and preprocessing

For the following sections, the event based mode is used in simulations to have proper access to Monte Carlo (MC) information. Supervised learning requires labeled data, which is gained using MC information with the following definitions:

- “True” hit: a RICH hit containing at least 1 Cherenkov photon produced inside the aerogel volume

- “Noise” hit, all other hits

A CNN is trained to classify between true and noise hits, only using time and position of the respective hits as input for the network. Since CNNs require a unique input for each input variable, non overlapping time windows with a minimum hit requirement of 7 hits and a length of 25 ns are used. This utilizes the fact that each channel has a dead time of ≥ 30 ns for both simulations and real data (due to the readout electronics). To normalize the input for the CNN and differentiate empty pixels from hits, all hit times t_i with respect to the start of a time window t_{TW} are mapped by $\hat{t} = \frac{t_{TW} - t_i + 1 \text{ ns}}{26 \text{ ns}}$, for all hits in the respective time window.

Simulation results

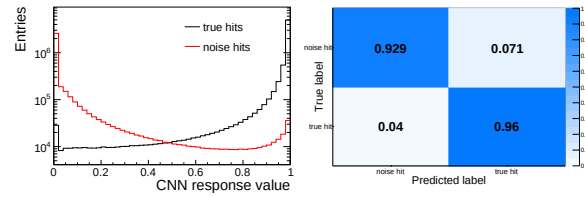


Figure 4: (left) CNN response value, (right) confusion matrix (cut value of 0.5) for true and noise hits.

For training and testing the CNN, $4.45 \cdot 10^5$ time windows are used each. The resulting classification performance summarized in figure 4 shows a very good separation between true and noise hits. Hits with NN response values ≥ 0.5 are used for the subsequent HT ring finding, while hits with values < 0.5 are rejected. Comparing the previous single-event-display (SED) (figure 2) to the result including “noise” suppression via the CNN before ring finding in figure 5, shows a very good classification of center hits and a correct ring reconstruction.

The overall ring finding quality is evaluated using MC information and the following definitions for accepted rings and true reconstructed rings are applied:

Accepted rings: Count the number of hits generated by Cherenkov photons produced inside the aerogel for all charged particles. If this number exceeds a certain threshold (7 hits) for a certain mother particle, this is defined as an accepted ring. This is obviously a very simple definition of the expected number of rings, but gives a reasonable estimate.

True reconstructed rings: Find the main contributor to the found ring, i.e. the charged particle which has the largest proportion of ring hits containing photons produced by this charged particle inside the aerogel. In case the ring has no accepted ring counterpart, it is declared as a false ring. If one charged particle has a contribution to 70 % of the total ring hits, it is considered a true reconstructed ring or good ring. The ring reconstruction purity is defined as $\text{Purity} = N_{\text{true reconstructed}} / N_{\text{found}}$ with N_{found} being

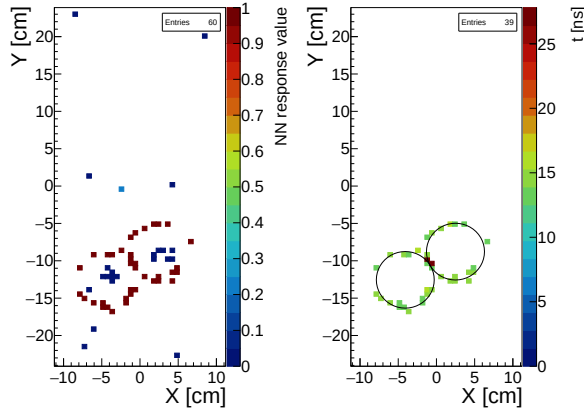


Figure 5: Left: Single-event-display (SED) in mRICH with all hits. Colour scale: CNN output, Right: SED after CNN "noise" suppression (NN response value ≥ 0.5) and ring finding with only ring hits shown; now the rings are correctly found. Colour scale: hit time in ns.

the number of found rings and efficiency as $\text{Efficiency} = N_{\text{true reconstructed}}/N_{\text{accepted}}$. The number of accepted rings in the test dataset is $4.638 \cdot 10^5$. Table 2 compares 3 different settings, the "base" setting running only the HT ring finder and the "cnn" setting applying the CNN before the HT ring finder. The "ideal" setting is shown as reference for a perfect noise removal according to the labeling process using MC information. Although the number of found rings decreases, the amount of actual good rings increases and therefore also the overall ring quality.

	found rings	true reconstructed rings	Purity	Efficiency
base	$3.708 \cdot 10^5$	$2.767 \cdot 10^5$	0.746	0.597
cnn	$3.191 \cdot 10^5$	$2.978 \cdot 10^5$	0.933	0.642
ideal	$3.227 \cdot 10^5$	$3.077 \cdot 10^5$	0.954	0.663

Table 2: Purity and efficiency calculations for found rings.

The number of hits inside a found ring drastically decreases when applying the CNN and shows near perfect accordance to the ideal setting (see Fig. 6 (left)). For the distribution of the ring radius in Fig. 6 (right) the peak for small ring radii completely vanishes, indicating the removal of fake reconstructed rings correlated to "noise" hits.

Conclusion and Outlook

The inclusion of noise correlated to charged particles in simulations, has shown patterns and anomalies which were previously only seen in real data. This has enabled the possibility to properly test and optimize the reconstruction algorithm of ring finding for the mRICH, in this case by classifying noise patterns using a CNN. For further improvement and potential applications for the CBM RICH,

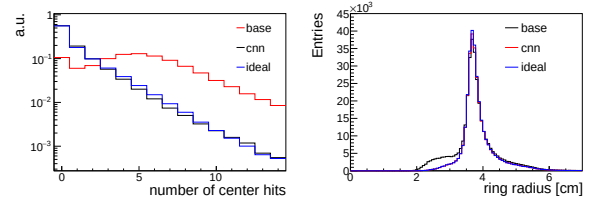


Figure 6: (left) number of center hits inside 0.8 of the ring radius with $\Delta t \leq 5\text{ns}$. (right) ring radius distribution.

different neural network types are investigated, which operate more efficiently on sparse input data and don't require time windows.

References

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- [2] M. Beyer, Masterarbeit, Justus-Liebig Universität Gießen, October 2022, <https://indico.gsi.de/event/14448/contributions/66896/>

mRICH beamtime 2022 ring recognition analysis using machine learning*

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The following study is the continuation from [1], where a convolutional neural network (CNN) was trained on adjusted simulation data. The simulation was adjusted in such a way that characteristic patterns so far only seen in real data (i.e. hit clusters inside ring structures) are artificially added to the simulation. In addition, the aerogel refraction index used for the simulation was changed from 1.05 to 1.046, to match the ring radius distribution observed in real data. The CNN is now applied to real data from the mCBM 2022 June beamtime with the runId 2511 [2].

For this study two settings are compared, “base” using only the Hough Transform ring finder (HT) and “denoised” applying the CNN before running the HT ring finder. The number of hits with a hit-center distance of $\leq 0.8R$ of the ring radius R in figure 1 (left) show a drastic decrease in “center” hits. For the distribution of the ring radius (Fig. 1 (right)) the real data matches very well with the simulated distribution also applying the CNN. Especially the “shoulder” for small radii is disappearing.

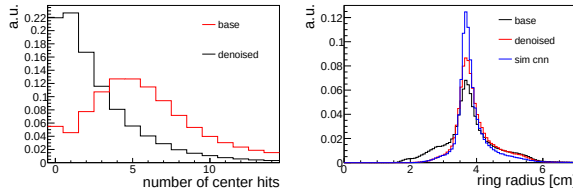


Figure 1: (Left) number of “center hits” with a hit-center distance of $\leq 0.8R$ of the ring radius R with $\Delta t \leq 5$ ns. (Right) distribution of the ring radius, comparing the base and denoised setting with simulations.

The simulation study [1] shows that the observation of finding rings more often in between MAPMTs is correlated to the amount of “center” hits. Figure 2 shows the distribution of ring centers in the mRICH plane. An improvement of finding rings more homogeneously across the mRICH using the CNN (right) is visible but the structure still remains.

For the position of hits associated with a ring (“ring hits”) in figure 3, a pattern shows up when applying the CNN. Rings are less often reconstructed with hits located in the far right pixel column of each MAPMT. This changes for each third MAPMT in vertical direction since those are rotated by 180° . When looking closely in figure 3 (left) this pattern is already slightly visible, but not as enhanced as in

figure 3 (right) using the CNN. The pattern is not seen for simulated data and can not be correlated to the CNN, since the CNN operates only locally and without any knowledge about the absolute position of each hit. Further studies are ongoing to understand this effect.

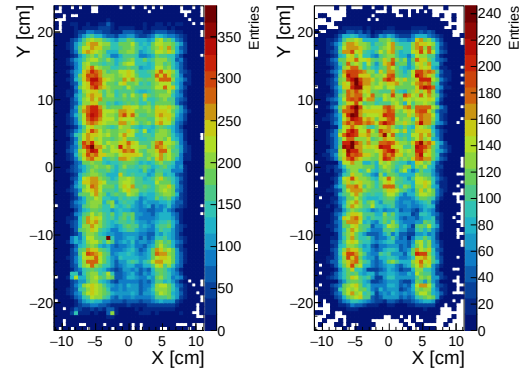


Figure 2: Position of ring centers in the mRICH plane for (left) base and (right) denoised setting.

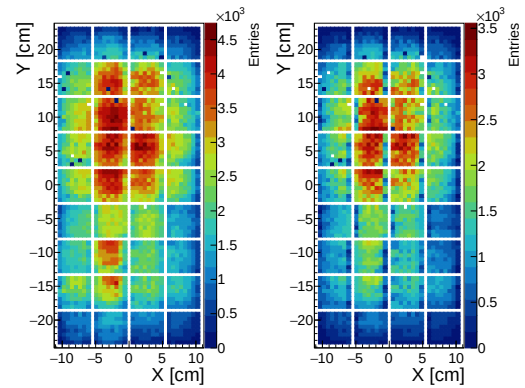


Figure 3: Position of ring hits in the mRICH plane for (left) base and (right) denoised setting.

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Ring reconstruction based on Convolutional Neural Networks for the mCBM RICH detector *

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In the previous report of last year, we presented a convolutional neural network (CNN) model for ring reconstruction in the mRICH detector [1]. Since then, the model has been further optimized through the use of different learning rate schedules and an improved architecture [2]. Additionally, another model with a different approach was developed.

Furthermore, the recent integration of ONNX runtime into CbmRoot has enabled the easy conversion of models trained with popular frameworks, such as TensorFlow and PyTorch, into the ONNX format for use within CbmRoot.

Regression model

The same input/output structure as in the previous report was used for the regression model. The input data consists of 72×32 pixel images representing the mRICH detector. The output is a 5×5 matrix representing the reconstructed ring position and radius.

The model architecture that was used is a convolutional neural network (CNN) with five convolutional blocks. Each block consists of a series of 2D convolutional layers, batch normalization, and max pooling layers. The number of filters in each block is doubled with each block, starting with 32 filters in the first block and increasing to 512 filters in the fifth block. A flatten layer is used to flatten the output of the last convolutional block before it is passed through a fully connected layer with 25 neurons. The final output layer reshapes the output to 5×5 shape. This architecture is shown in Figure 1.

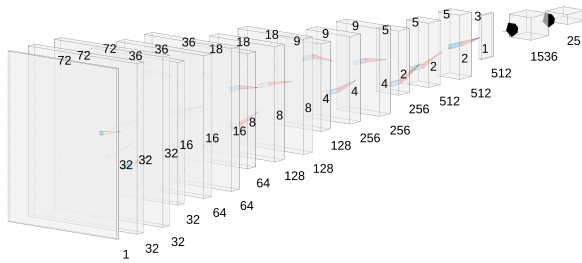


Figure 1: Architecture of the CNN model.

The model is optimized using the Stochastic Gradient Descent (SGD) optimizer with a momentum of 0.95. The learning rate schedule applied is the “1cycle policy” with cosine annealing, which starts with a low learning rate, gradually increases it to a maximum value, and then decreases it back to a low value [3]. A similar schedule is

used for the momentum, with the difference being that the momentum starts at a high value and decreases to a low value before increasing again. This schedule allows the model to converge faster and achieve better performance compared to a gradually decreasing learning rate schedule.

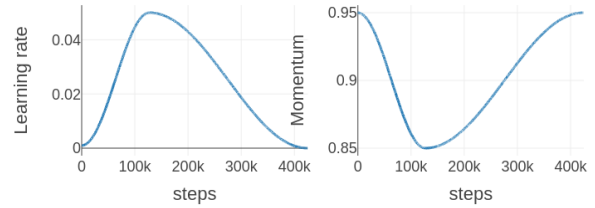


Figure 2: “1cycle” learning rate schedules for the learning rate (left) and momentum (right).

The initial and maximum learning rates were determined by using the “LR range test” [3]. This test trains the model for a few epochs with a learning rate that is increased linearly with each step until the loss starts to diverge. The loss is then plotted against the learning rate. From this plot, which is shown in Figure 3, the initial and maximum learning rates can be determined. .

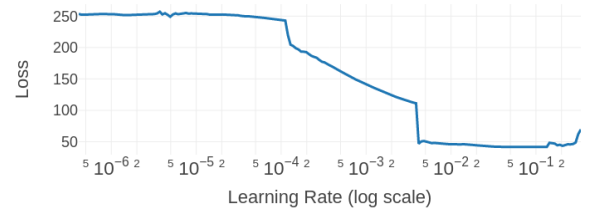


Figure 3: “LR range test”. The initial learning rate was set to 10^{-3} and the maximum learning rate was set to $5 \cdot 10^{-2}$.

Detection model

For the second model a different approach was used. First, a detection model was trained to detect rings on the mRICH detector and return bounding boxes around the rings as well as a confidence score for each bounding box. The bounding boxes are then used to crop the input images and pass them to a regression model to reconstruct the ring position and radius. This regression model is very similar to the one explained in last section, with the main difference being that the input and output shapes are different. Here the inputs are 20×20 pixel images and the output is

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a 1×5 matrix representing the reconstructed ring position and radius for a single ring. The reconstruction procedure is shown in Figure 4.

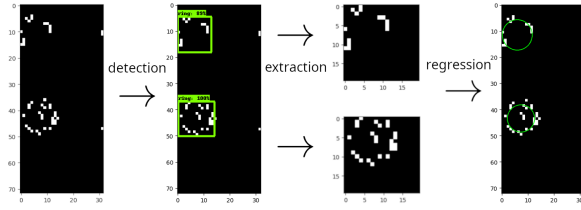


Figure 4: Ring reconstruction procedure for the detection model on denoised [4] mRICH event displays from UrQMD-simulated Ag+Ag-collisions at 1.24 AGeV beam energy.

The key benefit of this method compared to the regression model is, that there is no limit on the maximum number of rings. In the regression model, so far, this was set to 5 which of course is not appropriate for the full CBM RICH.

Model performance

The regression model was trained for 5 epochs with a batch size of 200 on a dataset of 17 million events created by a toymodel of the mRICH detector. Training and validation losses are shown in Figure 5. The model was then tested on a dataset of 125,000 events created by the same toymodel resulting in a test loss of 0.087.

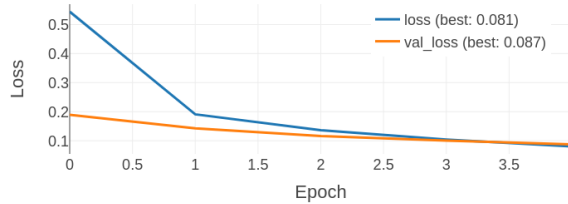


Figure 5: Training and validation losses for the regression model. The loss function used is the mean squared error.

The detection model's regression component was trained similarly to the separate regression model, resulting in a validation loss of 0.036. 5000 toymodel images were used to train the ring detector component with a batch size of 4 over 6000 steps.

In order to compare the CNN models to the Hough Transform (HT) algorithm currently used in CbmRoot, a dataset of denoised [4] UrQMD-simulated Ag+Ag-collisions at 1.24 AGeV beam energy was used. Due to the lack of a better option, the ideal ring finder was used as truth for the ring parameters. The ideal ring finder accesses Monte Carlo information, however due to scatterings or in case of rings at the borders, ring parameters can still be incorrect.

The root mean squared errors (RMSE) of the CNNs and the HT with respect to the ideal ring finder are compared in Table 1. All errors are given in pixels and are of similar order, although astonishingly large. This overall size is yet to be understood. However, both CNNs show smaller errors than the HT in all three parameters, with a clear advantage for the regression model.

Loss	x (pixel)	y (pixel)	r (pixel)
$\sqrt{MSE_{CNN_1-iRF}}$	2.74	6.08	0.87
$\sqrt{MSE_{CNN_2-iRF}}$	3.13	6.97	1.21
$\sqrt{MSE_{HT-iRF}}$	3.27	7.28	1.51

Table 1: Mean squared errors of the CNNs (CNN_1 , CNN_2) and the standard HT with respect to the ideal ring finder (iRF).

Table 2 shows the mean prediction time of the CNNs and the HT. Both CNN models are noticeably slower than the HT, with the regression model being about 4 times slower and the detection Model more than 2 orders of magnitude slower.

Model	prediction time
CNN_1	2.6 ms
CNN_2	87 ms
HT	0.7 ms

Table 2: Prediction time of the CNNs and the HT (Intel i7-8700K CPU 3.70GHz).

Conclusion

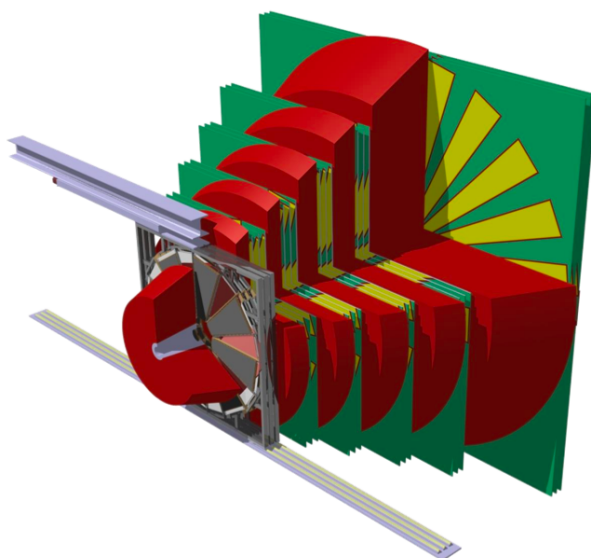
Although the CNN approaches are not as fast as the HT, they show a better performance in terms of accuracy. While the regression model is the most accurate, it requires a maximum number of rings to be specified. On the other hand, the detection model is more flexible but also much slower, which is mostly due to the lack of optimization.

Both models show potential, especially if prediction times can be reduced. At the moment, the regression model is being implemented in CbmRoot with the help of the recently integrated ONNX runtime, which also could help to speed up predictions.

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Muon Detection System



Optimization of the Muon Chamber(MuCh) for the CBM experiment at FAIR

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The Compressed Baryonic Matter (CBM) experiment at the FAIR accelerator complex in Darmstadt aims to probe the phase space of strongly interacting matter via the measurement of di-muons (μ^+ , μ^-) produced by the decay of low mass vector mesons (lvm) (such as ω, ϕ, ρ). The MuCh detector is designed for the measurement of such muons at SIS100 energies. The optimized MuCh detector consists of one absorber made of 28 cm of low-density graphite ($\rho = 1.78 \text{ g/cm}^3$) and 30 cm of concrete and three subsequent absorbers made of iron with thickness of 20 cm, 20 cm and 30 cm respectively. Four layers of triplet gas detectors are sandwiched in between the absorbers. The first and second stations feature Gas Electron Multiplier (GEM) detectors to accommodate the high particle density of the CBM experiment. The third and fourth stations consists of low granularity Resistive Plate Chamber (RPC) detectors as the particle density is significantly lower in these stages due to the presence of iron absorbers, allowing for the use of tracking detectors with low rate capabilities.

The absorbers effectively filter out hadrons produced during collisions to improve the accuracy of dimuon measurements. But at low SIS100 energies it is necessary to study whether the absorbers are stopping the low momenta muons. Therefore, it was necessary to analyze the phase space of the dimuon channels detected with the current MUCH configuration and optimize it to improve muon detection efficiency, particularly in the low momentum region of the $y-p_T$ phase space of the detected muons. The $y-p_T$ phase space of the current MUCH configuration was analyzed in order to improve its performance. Setup A is referred to as the original configuration consisting of station 1 and 2 with GEM modules and station 3 and 4 with RPC modules with absorber width of 58 cm, 20 cm, 20 cm and 30 cm. A different configuration, named Setup B was evaluated consisting of the same detector configuration as the original, but with the width of the iron absorbers reduced to 15 cm, 15 cm, and 25 cm. Note that the radiation length of low-density graphite, concrete and iron used in the simulation of the detector are 23.9 cm, 11.5 cm and 1.75 cm respectively. The iron absorbers were reduced in a way that improved the coverage of the phase space and allowed the reconstruction of the dimuon channels with significant efficiency and signal-to-background ratio. In

both of the configurations, central Au+Au collision at 8 AGeV beam energies are transported via the Geant3 transport engine. The decay process $\omega \rightarrow \mu^+ \mu^-$ was simulated using the PLUTO model, and the resulting dimuon signal was embedded into background events generated by UrQMD.

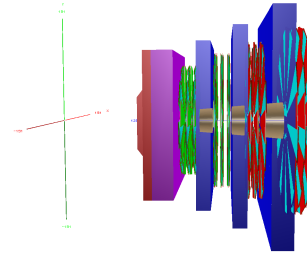


Figure 1: Optimized MuCh detector(Setup A). The 1st absorber is made up of 28 cm of low-density graphite (in red) and 30 cm of concrete (in purple), while the remaining absorbers are made of iron (20cm-20cm-30cm)(in blue). GEM-like detectors are used in the first two stations, and RPC-like detectors are used in the last two stations. The detector modules are trapezoidal in shape.

With different configurations, the radial distribution (Monte Carlo point density per unit area per unit event) of different stations is show in Fig. 2 and 3 respectively.

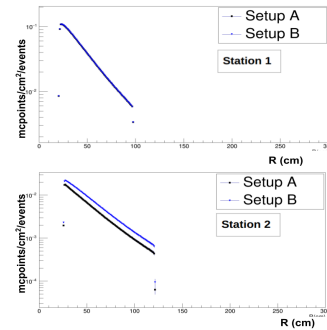


Figure 2: Radial Distribution of MuCh Points of Monte Carlo tracks of all Station 1 and 2

Since in all the setups, A and B, the first station and absorber is same, the radial distribution is also same for both setups. Reduction in second absorber

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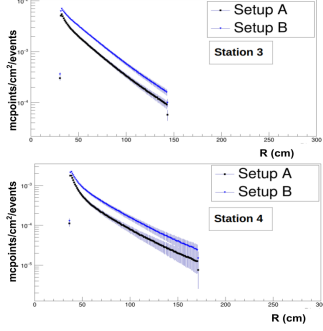


Figure 3: Radial Distribution of MuCh Points of Monte Carlo tracks of all Station 3 and 4

in Setup B (in blue) leads to more radial distribution for both primary and secondary tracks in the second station as compared to the other two setups. The same trend is seen for the third and fourth stations. In the reconstruction of the dimuon candidates the global reconstructed tracks for all the setups have STS hits ≥ 7 , MUCH hits ≥ 11 , TRD hits ≥ 1 , $\chi^2_{vertex} \leq 3.0$, $\chi^2_{STS} \leq 3.0$ and $\chi^2_{MuCh} \leq 3.0$. An additional 2σ cut on the reconstructed ToF mass was applied to reduce the non-muonic tracks. The multiplicity and branching ratio for ω decaying into dimuons is 2.28721 and 7.4×10^5 respectively.

Setups	S/B	ϵ_ω (%)	Significance
Setp A	1.51	0.71	26.9
Setup B	1.11	0.81	26.8

Table 1: Reconstruction efficiency, Signal-to-background ratio and significance for ω in central Au+Au collision at 8AGeV for different configurations.

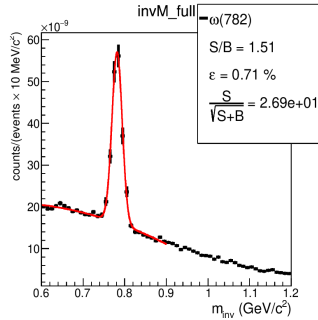


Figure 4: Invariant mass distribution of ω mesons in Setup A

Signal extraction is performed from the set of events by selecting opposite-charge muon tracks, one per event. Background calculation is done using the super event (SE) technique, which combines one muon track with all other opposite-charge muon tracks to

determine the combinatorial background. The invariant mass distribution of the reconstructed ω decaying into dimuons ($\mu^+\mu^-$) for setup A is shown in Fig. 4. Table 1 shows the different signal-to-background ratio, efficiency (%) and significance of all the configurations. The reduction in the widths of iron absorbers decreases the signal-to-background ratio and significance from the original setup. The increase in efficiency (%) indicates the acceptance of more dimuon candidates with the reduction of iron absorbers' width. The ratio of combinatorial background and signal with respect to setup A is shown in Fig. 5. A thorough analysis

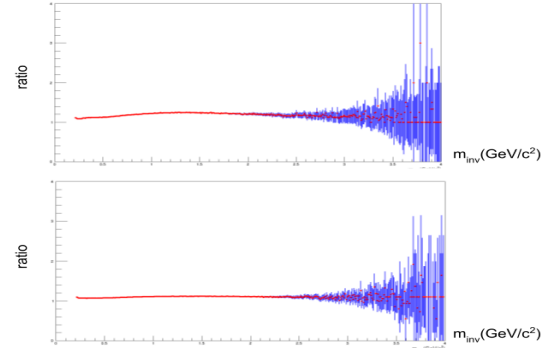


Figure 5: Ratio of combinatorial background (above) and combinatorial signal (below) with respect to Setup A

of the $y - p_T$ phase space was conducted across all configurations. The mean values of y and p_T of the $y - p_T$ phase space of dimuon channels reconstructed with STS hits ≥ 7 , MUCH hits > 12 and $\chi^2_{STS} \leq 3.0$ is shown in table 2. For all the above mentioned analysis, APR21 patch of the CbmRoot framework was used.

Setups	Mean y	mean p_T (GeV/c)
Setp A	2.33	0.51
Setup B	2.27	0.48

Table 2: Reconstruction efficiency, Signal-to-background ratio and significance for ω in central Au+Au collision at 8AGeV for different configurations.

In summary, it is seen that by reducing the widths of iron absorbers, the mean rapidity, y , reduces by a factor of 0.06 and the mean p_T reduces by a factor of 0.03. In both the configurations the reconstruction of ω mesons via super event reconstruction was possible with a significant signal to background ratio and significance.

Preliminary test results of real size GEM modules in nucleus-nucleus collisions at mCBM campaign 2022

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Introduction

The future Compressed Baryonic matter (CBM) experiment will study phase space diagram of strongly interacting matter at finite baryochemical potential. However, before the actual experiment, a mini-CBM experiment ("mCBM") has been setup as a precursor and demonstrator at SIS-18 beamline to facilitate prototype tests of all CBM subsystems. In this regard, two large size triple GEM detectors developed at VECC have been installed and commissioned there. For the mCBM campaign of 2022, data were taken with upgraded GEM modules and CRI based DAQ for the first time along with dedicated high intensity runs. The runs were taken in two phases: The first phase of data taken was in March-April, 2022 where Uranium beam was incident on Gold target (2.5 mm) at $T = 1.0$ AGeV while the second phase took place in June, 2022 where Gold beam was incident on Gold (2.5 mm) and Nickel (4 mm) targets at $T = 1.23$ AGeV. In this report, we present the preliminary test results of heavy ion collisions data taken during March-April. During this period, several runs dedicated runs were taken for understanding the stability and rate handling capability of the Muon Chambers (MuCh). The detectors were tested for the first time up to an interaction rate of 10^9 ions per spill under various detector thresholds and operating voltages. In this document, we focus on the rate handling capability of our detectors.

Run Number	Intensity (Ions/10s)	Total Voltage (GEM 1, GEM 2) (V)
2254	1.0×10^7	4800, 4400
2256	5.0×10^7	4800, 4400
2257	1.0×10^8	4800, 4400
2258	5.0×10^8	4800, 4400
2262	1.0×10^9	4800, 4400

Table 1: Runs for intensity scan

Data analysis

Several data runs were performed at mCBM during March - June, 2022. Table 1 shows a list of selected high intensity runs. Figure 1 show the spill structure (signal counts vs. timeslice) from U-Au run. The runs were acquired with different set of conditions like threshold, operating voltage, beam intensity etc. For the U-Au intensity scan, data

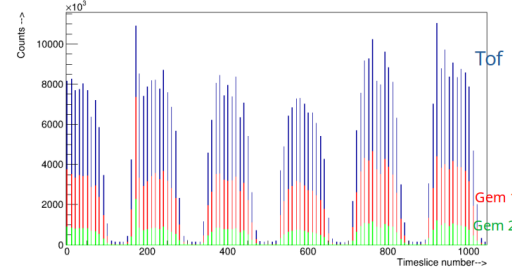


Figure 1: Spill structure of GEM 1, GEM 2 and Time of flight (TOF) detector for U-Au collisions at intensity of 5.0×10^8 ions per spill (Preliminary)

runs with similar operating conditions were identified for the two GEM modules (termed GEM 1 and GEM 2). Several data cleanup operations were performed to remove the noisy channels. Apart from that several pads on the detector readout were masked to ensure common acceptance for all the runs. Subsequently, number of digital signal (digs) per Timeslice (64 ms) vs. counts plot were plotted and fitted with gaussian for all intensities for both modules. The mean, sigma and number of data points under the curve were extracted from these fits.

Results

Fig. 2 shows the response of the mean number of digs (with error-bars) vs. intensity. While the response is initially linear, non-linearities are observed at very high beam intensities for both modules. The same maybe inferred from fig. 3 and 4 which show a linear behaviour of digi correlations between GEM 1 and GEM 2 at low intensities and non-linearity in the high intensity regions. A detailed investigation on the nature of this variation is under progress. The detailed experimental layout and detector geometries will be presented and discussed.

Acknowledgement

We acknowledge the efforts of all the members of CBM collaboration who helped make mCBM experiment a success.

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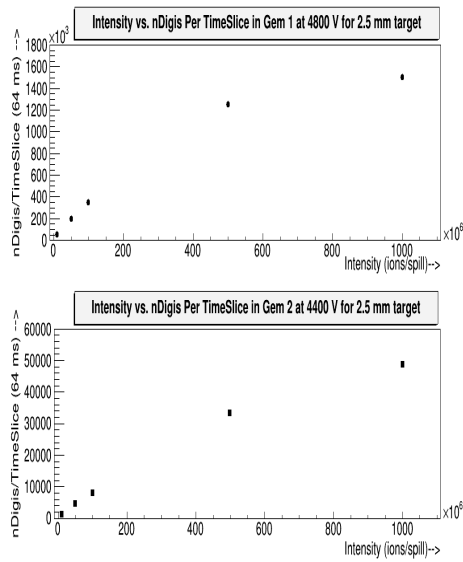


Figure 2: Intensity response of GEM 1 (top) and GEM 2 (bottom) with intensity for U-Au at $T = 1.0$ AGeV (Preliminary)

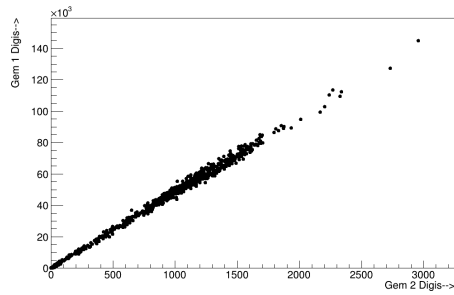


Figure 3: GEM 1 vs. GEM 2 digi correlation for U-Au collisions at lowest intensity (10^7 ions per spill) (Preliminary)

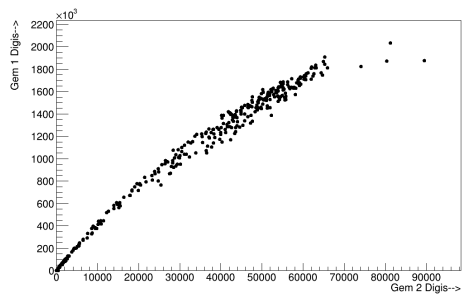


Figure 4: GEM 1 vs. GEM 2 digi correlation for U-Au collisions at highest intensity (10^9 ions per spill) (Preliminary)

Study of uniformity for a single mask triple GEM detector

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The Gas Electron Multiplier (GEM) [1] detector will be used as the muon tracker in the first two stations of CBM Muon Chamber (MuCh) [2] sub-system due to its high rate handling capability and good spatial resolution. The standard GEM foils are made of 50 μm thick Kapton film with 5 μm Copper cladding on both sides. A large number of holes, act as the amplification region for the primary electrons, are pierced in the film using the photo-lithographic technique [3]. The presence of the dielectric medium (Kapton) inside the active volume of the GEM chamber changes its behaviour when exposed to external irradiation. This phenomenon is known as the charging-up effect [4, 5]. The uniformity in the performance of the detector is an essential criterion for any tracking device. Therefore, the uniformity in the performance in terms of gain and energy resolution of a 10 cm $\times$ 10 cm Single Mask (SM) triple GEM prototype is carried out before and after the charging-up of the GEM foils. The chamber is operated with Ar/CO₂ gas mixture in 70/30 volume ratio and irradiated using a ⁵⁵Fe X-ray source (~ 20 mCi) of 5.9 keV characteristic energy.

The drift gap, transfer gaps and induction gap of the chamber are kept at 3 mm, 2 mm and 2 mm respectively. The GEM foils are biased using a resistive divider chain.

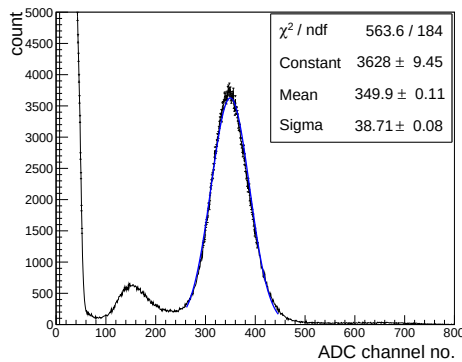


Figure 1: Typical ⁵⁵Fe spectra at -5075 V. The ΔV across each of the GEM foils is ~ 402.7 V. The ratio of sigma to mean is ~ 0.11 (colour online).

The readout pad of the chamber is segmented in 256 XY strips. For this study, the signal is taken using sum-up boards instead of the individual readout from the XY strips. The signal from the sum-up board is fed to a charge sensitive preamplifier having a gain of 2 mV/fC and shaping time of 300 ns [6]. The output of the preamplifier is

put in a linear Fan-In Fan-Out (FIFO) module. One output from the FIFO is fed to a Multi Channel Analyzer (MCA) to store the X-ray spectra on the desktop. Another output from the FIFO is fed to a Single Channel Analyzer (SCA), the output of which above the noise threshold is counted using a NIM scaler. The threshold to the SCA is kept constant at 0.6 V throughout the measurements.

The typical ⁵⁵Fe X-ray spectrum is shown in Fig. 1 for High Voltage (HV) of -5075 V, corresponding to ΔV of ~ 402.7 V across each of the GEM foils. The gain and energy resolution of the chamber is calculated by fitting the X-ray 5.9 keV peak with a Gaussian distribution. The mean of the fitted Gaussian spectra gives the information of the total output charge by using the MCA calibration factor and the gain of the preamplifier. The full width at half maxima of the Gaussian fitted spectra is used to quantify the energy resolution of the chamber [4, 7].

The 10 cm $\times$ 10 cm active area of the SM triple GEM chamber is divided into 4 $\times$ 4 regions. A collimator, made of G-10 material, having a diameter of 8 mm and a height of 32 mm is used to irradiate the chamber using the ⁵⁵Fe source. To measure the uniformity in the characteristics of the chamber, the source is placed on the top of the collimator and the collimator is placed at the respective positions on the active area of the chamber. The data taking is done using two different methodologies.

In the first case, the HV is kept ON for ~ 60 minutes before starting the measurement to ensure that there are no effects on the measurement due to the dielectric polarisation and the data taking is started as soon as the source is placed on the chamber. The X-ray energy spectra are recorded for 1 minute and then the source along with the collimator is moved to the next position manually. As a result, the foil does not get sufficient time to get charged up. Therefore, the results we get are essentially with the uncharged GEM foils. In Fig. 2, the variation in gain and energy resolution over the scanned area is shown at a ΔV of ~ 402.7 V across each of the GEM foils. The variation in gain is found to be $\sim 10\%$ and the variation in energy resolution is found to be $\sim 13\%$.

In the second case, the HV is switched ON and the source is placed on the detector as soon as the HV is reached its specific set value. The data taking is started as soon as the source is placed on the chamber. The spectra are recorded every 30 seconds without any intervals. The data is collected and then normalised to eliminate the effect of temperature ($T=t+273$ K, t in $^\circ\text{C}$) and pressure (p in mbar) variations on the gain and energy resolution of the chamber [8].

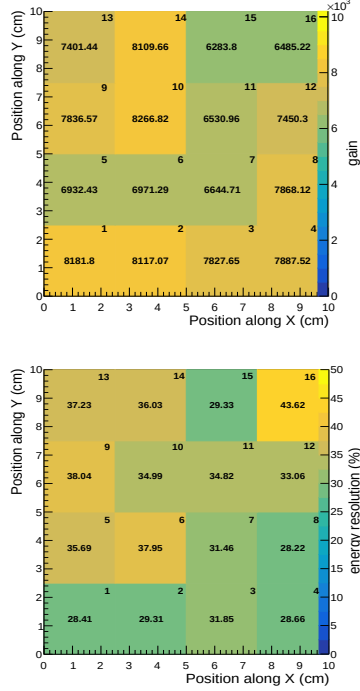


Figure 2: Variation of gain (top) and energy resolution (bottom) over the scanned 10 cm $\times$ 10 cm area of the SM triple GEM chamber with HV of -5075 V before the charging-up of the GEM foils. The ΔV across each of the GEM foils is ~ 402.7 V (colour online). The numbers at the top right corner of each box identify the respective grids where the source is placed for data taking.

To find out the variation in gain and energy resolution after the charging-up phenomena is completed, the gain and energy resolution are measured after ~ 150 minutes of exposure of the chamber with X-ray from ^{55}Fe source. The variation of the gain and energy resolution over the surface with the charged-up GEM foils are shown in Fig. 3. Over the scanned area, the gain and energy resolution are found to be varied $\sim 10\%$. No significant change is observed in the uniformity of the chamber over the scanned area in terms of gain and energy resolution. Only the absolute value of the gain is found to be more in the second case because of the charging-up effect of the GEM foils. Due to the increased gain, the energy resolution improves in the second case. The mean values of the gain and energy resolution without charged up GEM foils are found to be 7375 (± 171.5), 33.31 (± 1.08) % and that with the charged-up GEM foil are found to be 8325 (± 139.1) and 26.94 (± 0.48) % respectively.

The observed variations in gain and energy resolution both before and after the charging-up of the GEM foils may appear due to the non-uniformity of the geometrical parameters of the GEM foil.

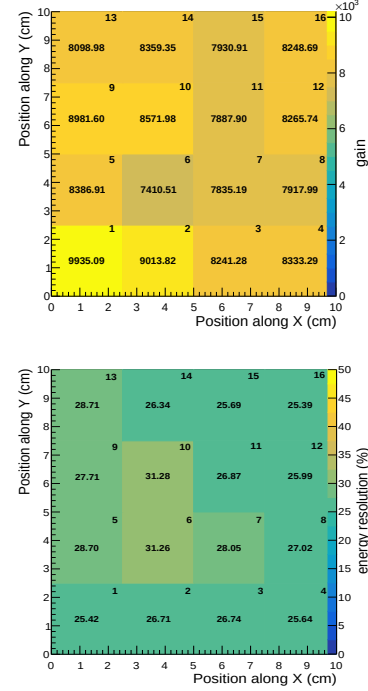


Figure 3: Variation of gain (top) and energy resolution (bottom) over the scanned 10 cm $\times$ 10 cm area of the SM triple GEM chamber with HV of -5075 V after the charging-up of the GEM foils. The ΔV across each of the GEM foils is ~ 402.7 V (colour online). The numbers at the top right corner of each box identify the respective grids where the source is placed for data taking.

Acknowledgment

The authors would like to thank the RD51 collaboration for the support in building and initial testing of the chamber in the RD51 laboratory at CERN. We would also like to thank Mr. Subrata Das for helping in building the collimators used in this study.

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MuCh-GEM high rate results from mCBM, June 2022 beamtime

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During mCBM June, 2022 beamtime MuCh acquired high rate data with two GEM modules (equivalent of station-1 size) and one RPC module. Gold (Au^{69+}) beam of 1.23 AGeV with an intensity range of 10^7 to 2.5×10^8 per 10 sec spill were made incident on gold(2.5 mm and 0.25mm) and nickel(4mm and 0.4mm) target. MuCh system has recorded data for around 100 runs and in most of the runs the high voltage(HV) of GEM1 was 4750V with current(I) of 739 uA and 741uA for two halves respectively and the GEM2 was powered by a single channel indigenously built spellman supply with HV=4365V and I=1478uA. Intensity variation data set were acquired with the above mentioned HV values and at a fixed threshold value of $V_{\text{refp}} = 50$ of MUCH/STS-XYTER ASIC. Data with threshold variation were also taken at low and high intensity of beam.

During the April, 2022 U-Au beamtime a gas mixing unit was introduced for MuCh-GEM gas system as shown in Fig.1 and the same has been used in present beamtime also. This consists of 2 mass flow meters and the values were adjusted to get a 70:30 ratio of $\text{Ar}:\text{CO}_2$.



Figure 1: Gas Mixing Unit

The new GEM2 module installed during April, 2022 was fabricated with modified drift PCB with staggered optocoupler configuration, which is the final version to be used as main CBM MuCh station-1. During April 2020 mCBM beamtime, with voltages higher than 4800V, some spikes were observed from the detector modules which resulted in link instability of read-out electronics and asynchronized DAQ at the start of a new run. Timing offsets in MuCh data were observed during the run. To overcome this issue, two resistances were introduced at the input and output legs of each optocouplers, which results in isolation of

each optocoupler from the other as shown in Fig. 2. This has been implemented in the modified drift PCB to improve link stability.

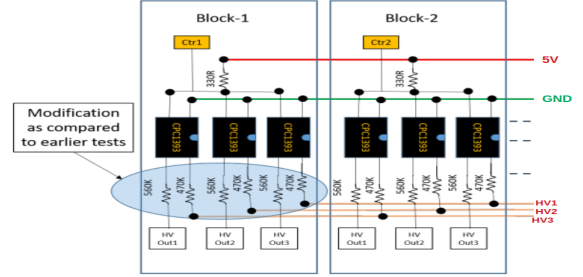


Figure 2: Modified HV layout on new Drift PCB

GEM1 and GEM2 both acquired data with 9 FEBs each using CRI based DAQ system. Link stability was checked for each FEB and it was found to be stable for around 10 number of analysed high intensity runs.

The spill structures of GEM1, GEM2 and TOF is shown below for run 2570, at intensity= 2.5×10^8 /spill with thick nickel target of 4mm and GEM1 HV= 4800V, GEM2 HV=4412V and $V_{\text{refp}} 50$.

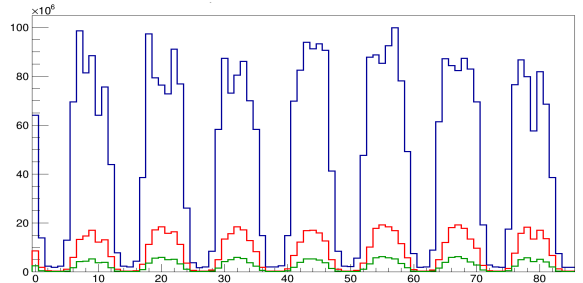


Figure 3: Spill structure, Red: Gem1, Green: Gem2 and Blue: TOF

Time-offset stability of GEM1 FEB3 wrt TOF during the entire run 2570 is shown in Fig. 4. There was one single event where a detector spike was observed in GEM2 which resulted in 13 ns time offset of GEM2 data wrt TOF. The detector gain also dropped and got recovered within 40 ms, during this time period some data loss of GEM2 FEBs were observed. Fig. 5 shows the variation of GEM2 FEB8 ADC with time and a dip can be observed. GEM1 LV is well isolated from that of GEM2, so we didn't observe any time offset or gain drop in any of the GEM1 FEBs.

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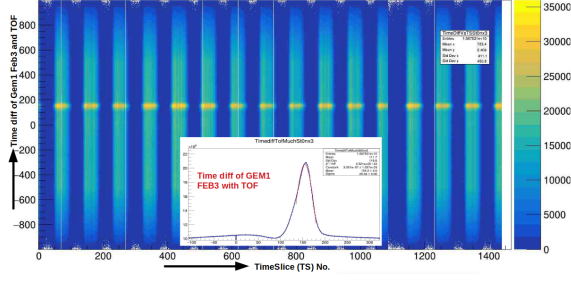


Figure 4: Run: 2570: Time diff vs TS of GEM1 FEB3 with TOF

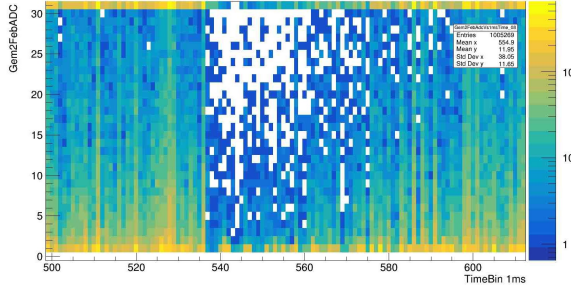


Figure 5: Gem1 average digi per spill vs Number of Interactions (Preliminary)

Digi correlation between GEM1 and GEM2 were studied for a high intensity run 2570 and for a low intensity run 2516, keeping all the parameters identical for both modules. At high intensity 2 lines were observed in the correlation as shown in Fig.6. Under further investigation for the entire on spills and off spills, it has been found that digi correlation slope for the rising part of the spill is higher than that of the falling part, hence 2 lines are observed. Apart from this the correlation plot tends to be bending upward in the highest intensity region of a spill. For low intensity run no such double line or bending were observed.

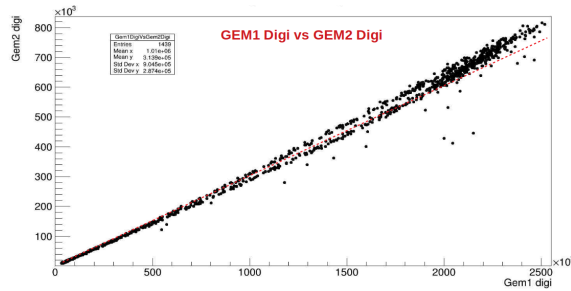


Figure 6: GEM2 digi vs GEM1 digi (Preliminary)

Run 2545 ($I=10^7$ /Spill), 2561 ($I=8 \times 10^7$ /Spill) and 2565 ($I=1.5 \times 10^8$ /Spill) has been studied to check the digi behaviour of both GEMs wrt total no of interactions within a spill. Fig. 7 and Fig. 8 shows the varia-

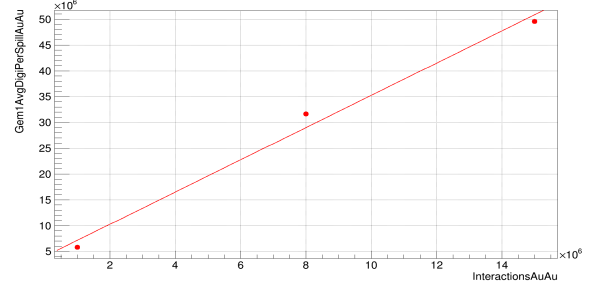


Figure 7: Gem1 average digi per spill vs Number of Interactions (Preliminary)

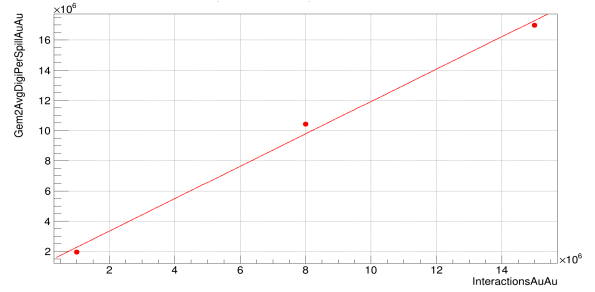


Figure 8: Gem2 average digi per spill vs Interactions(Preliminary)

tion of average number of digi in a spill for GEM1 and GEM2 respectively wrt total no of interactions within a spill. The three points in the figures have been fit with a straight line.

Data taken at 2.5×10^8 /spill were only with nickel target, so this point couldn't be included with the gold target data points in Fig. 7.

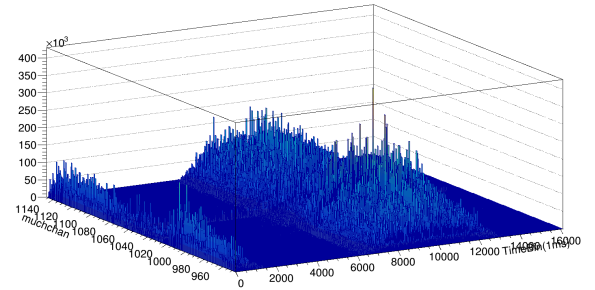


Figure 9: Digi rate of Gem1 readout pads in Hz/cm^2 (Preliminary)

Digi rates were calculated for each readout pads of GEM1 and GEM2 and were further normalized to each pad area. Fig. 9 shows time (ms bin) in x-axis, readout channel no in y-axis and digi rate (Hz/cm^2) in z-axis for 1 off-spill and 1 on-spill. Average digi rate is found to be around $200 \text{ KHz}/\text{cm}^2$.

Further analysis based on correlation with other detectors at highest intensity is ongoing.

Gas flow monitoring system for GEM detectors of CBM-MUCH

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GEM and RPC detectors are planned to be used in the CBM-MUCH detector system. Gain stability and detector performance of both GEM and RPC heavily depends on the gas flow in the chamber. Thus to ensure the stable behavior of the GEM detectors, a low cost gas flow monitoring system is developed at VECC which can cater the requirements of both GEM and RPC detectors of CBM-MUCH. This report describes the development of the gas flow monitoring system, its technical characteristics and calibration with the required gas mixtures.

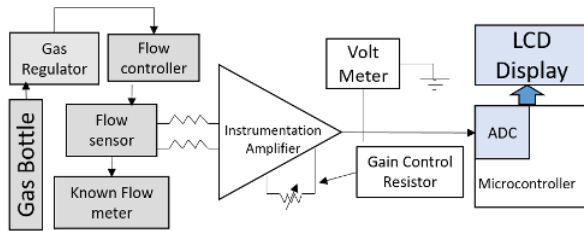


Figure 1: Gas sensor calibration and monitoring setup

The schematic of the gas flow sensor calibration setup and monitoring scheme can be seen in Fig. ???. A gas sensor is put in series to the gas line via a gas regulator and flow controller. The output of the flow controller is connected to a known Agilent ADM flow meter (G6691A) for calibration purpose. The mass flow meter used is HONEYWELL's AWM92100 having 1 ms response time and flow sensing range of ± 200 SCCM. The flow sensor output is taken to an instrumentation amplifier (INA141U). Amplifier can be operated in dual gain with a control resistor. With the lower gain of ten, sensor can achieve the range of 2 SCCM to 200 SCCM which will be required for the GEM detector system, where as with higher gain of hundred range of the sensor can be confined from 0 to 2 SCCM. This range will be useful for the flow rate measurement in the RPC detector.

The mass flow meter and the circuit is put in the metal box to shield the circuit to reduce the overall noise induced with EMI and PCB ground was coupled with the chassis. Figure 2 (left) shows the first prototype of the gas sensor the had been made at VECC while (right) shows the display arrangement to see the measurements. The single ended analog output of the instrumentation amplifier is fed to a 10-bit ADC of mini microcontroller (DFR0282).

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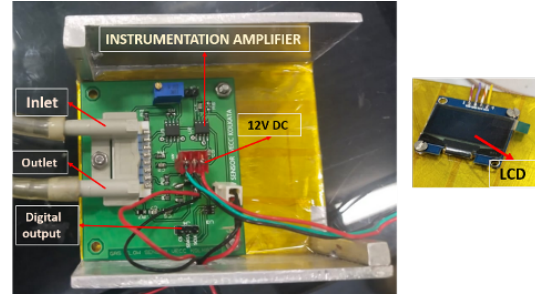


Figure 2: (left) Prototype of flow sensor, (right) LCD display connected to microcontroller

A mini microcontroller controls the whole process serially from digitization (via ADC) to display (via LED). Controller converts digitized voltage to gas flow (millilitre/minute) via calibration curve shown in the Fig. 3. The gas flow output displayed on the LCD screen.

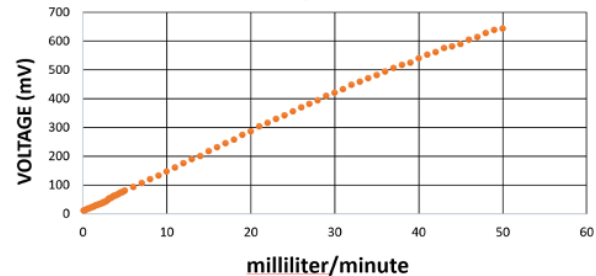
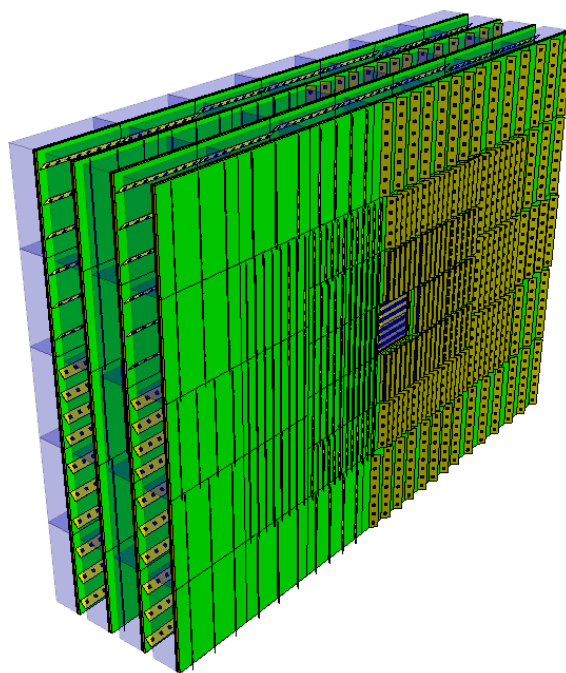


Figure 3: Calibration curve for the sensor

Mass flow sensor is calibrated against the standard Agilent mass flow meter. Gas used was premix Ar-CO₂ (70:30). Gas flow was adjusted manually for obtaining different readings keeping primary and secondary sensors in the series. As shown in the Fig. 3 minimum and maximum flows that can be measured by this sensor are 0.1 millilitre/minute to 700 millilitre/minute. No appreciable hysteresis was found during the calibration.

The measurement results of this device shows wide range of measurement, no countable hysteresis and linear characteristics. This makes the prototype a suitable candidate for mass flow meter to be used with the CBM-MUCH detector systems. This device can be further used for RPC and GEM detector R&D in the lab.

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.

TDR addendum

An addendum to the TRD technical design report, describing a new design of the inner region of the TRD based on two-dimensionally position sensitive chambers (TRD-2D), has been submitted to the FAIR ECE in 2021. A first review by the committee members resulted in a request for a more detailed physics performance study to substantiate the benefits for the CBM physics program achievable by such a change. Such a detailed study was meanwhile performed [1]. It clearly demonstrates that the proposed design enlarges the acceptance by using the TRD as seeding

detector, in particular in the very important low transverse momentum region $p_t < 150$ MeV/c, in relation to what is accessible with STS tracking alone. The momentum resolution and the achievable PID performance for this case has been evaluated as well and was found to be on a high level.

Pre-production

For the outer modules of type-5, the pre-production has finally been started in Münster and Frankfurt [2]. Even though the beginning was somewhat delayed due to delivery problems of several components, in particular by the insolvency of the pad plane PCB producer, all problems with the material procurement have now been sorted out and the completion of the first type 5 chamber is expected in first quarter of 2023. Based on the detailed evaluation of these pre-series, the production readiness review (PRR) will be done in the second half of 2023, followed by the mass production of the remaining modules of type-5 and type-3.

Also on the TRD-2D prototype for the inner region of the TRD a lot of progress has been made in the Bucharest laboratory [3]. All procedures have been exercised and a first prototype to be evaluated in the context of a PRR has been prepared.

Infrastructure

An essential component of the TRD will be its gas system. It will have to fulfil stringent requirements in terms of pressure stability, gas purity and leak tightness. As xenon is a very expensive gas, the system has to be recirculating and gas recuperation has to be foreseen. In Münster a first prototype of a gas system with one line has been developed and is being tested [4]. It can easily be scaled-up to the full system, consisting of 5 – 6 lines, provided the required funding can be secured. One important and welcome step in this direction is the expression of interest by the group at ICSI, Bucharest, in contributing a gas purification system to the TRD. A corresponding memorandum of understanding was signed recently.

mCBM data analysis

The TRD continued to take data in the mCBM runs of 2023. These data provided important informations on the performance in a realistic high particle density environment. The time residuals and the two-dimensional position information on the TRD-2D prototype are reported in

[5]. For the outer TRD chambers a new offline time reconstruction, based on a lookup-table, was implemented and verified with mCBM data [6], resulting in time residuals well below 25 ns. A corresponding online feature extraction algorithm was also developed and successfully applied to the data [7].

The TRD data provide important information on the relative alignment of the different detectors in the mCBM-setup. This improved the reconstruction of Λ substantially. The additional PID information provided by the TRD modules will further enhance the signal-to-background ratio in the near future.

Software and reconstruction

Extensive electron test beam data taken at DESY in 2019 allow to perform a detailed verification of the simulation of the TRD detector response. In particular, one has to make sure that the specific energy loss inside the xenon gas mixture is described properly, as this is the basis of further simulations of the TRD PID performance. A comparison of test beam data and simulations on this topic has been performed in [8], resulting at first order in a good agreement and allowing in a further step for detailed adjustments. Also, the material budget of the TRD geometry was updated according to the latest development stage of the front-end boards.

As the TRD construction will enter into the mass production stage soon, a component database will be indispensable. A corresponding prototype has been implemented to the TDR and will be developed into a system to be used during the construction and operation of the TRD [9].

Front-end electronics and readout

The SPADIC 2.2 is being used for the readout of the outer chamber prototypes in the mCBM-setup and was operated very reliably and stably. However, it was obvious that remaining issues with this version, mainly with the noise level, required another iteration. For this purpose the test versions 2.3a+b were designed and submitted. Unfortunately, detailed tests of these ASICs revealed that, while all bugs in the digital part seem to be fixed, the analog part had serious problems [10]. Therefore, it was decided to completely replace the ADC part of the ASIC by a different version, which is currently under design. It is planned to submit this next version in April 2023 and test it in the second half of the year.

Once the final ASIC version is available, the mass production of the front-end boards (FEB) can start. Each of the FEBs will be subjected to an extensive QA procedure, to ensure their proper operation when installed on the modules in the cave. For this purpose a testing framework with a user friendly graphical user interface was developed [11].

The TRD-2D modules for the inner region will be read out via FASP based front-end electronics. For the chamber operated in mCBM a complete prototype readout has been

assembled, which was extended during 2022 in order to enlarge the acceptance for data taking [12].

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Status of the TRD MWPC production*

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Introduction

We report on the status and plans for the TRD MWPC production, namely of 32 chambers of the large type 5, as well as of the first batch of 64 chambers of the small chamber type 3. After additional delays caused by delivery problems, the production process will start now in February 2023. Updated production plans are included.

Chamber type 5

Tooling and process evaluation

While the complete production start of type 5 chambers was delayed by delivery problems of, e.g., the segmented cathode pad plane, it was nevertheless possible to begin with the pre-production of components and to progress on the working place commissioning, as well as to refine the tooling. To be highlighted are:

- A positioning procedure of the pad plane vs. the back panel and the wire layers.
- A drilling tool for precisely positioned high-voltage feed throughs (wire layer supply, see Fig. 1).
- A refined temperature control to reduce the time required for production of the pre-stretched foil entrance windows.
- Transport boxes for the exchange of pre-products between the institutes (entrance windows, back panels).

Production plan update

The pre-production of back panel carriers, i.e. the frames made of four aluminium ledges surrounding the honeycomb plates, which support the full chamber and carry the cathode pad planes, is ongoing. The completion (wiring and closing) of the first type 5 chamber is expected in first quarter of 2023. Production processes will be controlled carefully and continued until the completion of four type 5 chambers (pre-series). The finalisation of the PRR of this chamber type 5 is foreseen in autumn 2023. It will mainly focus on the required high gas tightness and gas gain homogeneity to be confirmed with the above mentioned four pre-series chambers. The completion of the production of an overall amount of 35 type 5 chambers (32 to be installed, 3 spare chambers) is scheduled beginning of 2025.

* Work supported by BMBF grants 05P21RFFC1 and 05P21PMFC1.

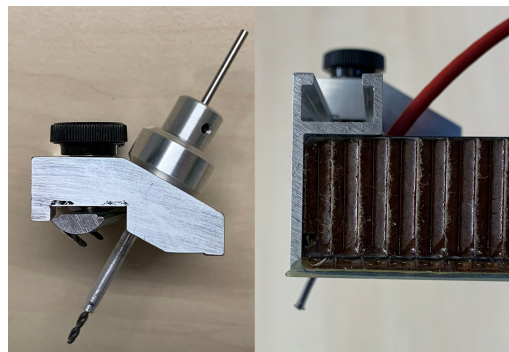


Figure 1: New tool for the insertion of the HV supply cables for the anode and drift wire layers into the chamber back panel (left). Installed HV supply cable (right).

Chamber type 3

Design optimisations

The production of type 3 chambers (small chamber type) is being prepared in parallel to the previously mentioned production. Last design optimisations are ongoing. Those are, in particular, efforts to further increase the active area by few mm, as well as the minimisation of the number of the necessary FEB types by adjusting the signal cable layout. Reports on these investigations will follow soon.

Production plan

The procurement of components for the first batch of 64 type 3 chambers has started. The pre-production of those chambers will start overlapping with the completion of the type 5 chamber production, with a start during first half of 2024. With the *first-of-series* still during 2024, we expect a production completion of these 64 type 3 chamber at end of 2025. This speed-up in contrast to the first chambers is possible as we will switch to a parallel production scheme at the two German institutes (Frankfurt, Münster).

Summary and outlook

The production of all TRD type 5 chambers is foreseen to be finalised early in 2025. The production plans and the procurement of the first batch of type 3 chambers is ongoing, while current expectations see the finalisation of this production at end of 2025. This way, a significant fraction of the overall TRD detector area shall be ready for installation in time with respect to the overall CBM schedule.

TRD-2D prototype for the Production Readiness Review *

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A complex R&D activity dedicated to the development of a Transition Radiation Detector (TRD) prototype together with the associated front-end electronics for the low polar angles region (inner zone) of the CBM-TRD detector, the most demanding in terms of particle rates and hit multiplicity, is summarized in the reference [1]. This activity led to an optimized TRD architecture [2, 3], as a compromise between a fast readout for chamber performance in high counting rate operation and maximisation of the absorption of the transition radiation in the chamber volume, as well as to a dedicated front-end electronics [4, 5].

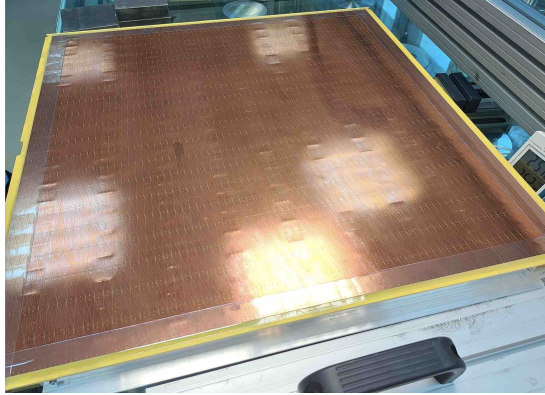


Figure 1: Triangular pad readout electrode.

The developed TRD prototype has a triangular pad architecture of the readout electrode [2], which provides two-dimensional position informations within a single layer [3, 6]. A real size prototype for the CBM-TRD inner



Figure 2: Assembling of the readout electrode.

zone was successfully integrated in the mCBM experimen-

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tal setup together with its associated readout electronics, as show the results reported in [7].

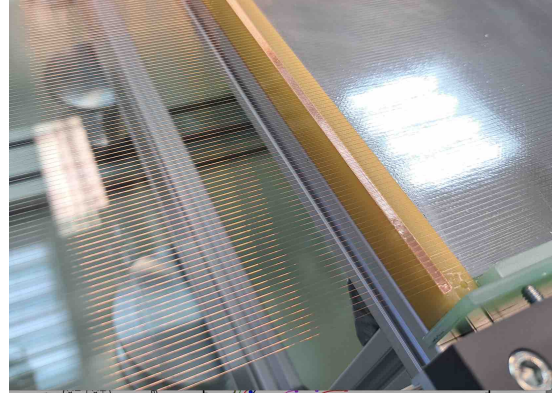


Figure 3: Cathode wire plane stretched on top of the entrance window at 4 mm distance.

Following these successful steps, we summarize here the assembling and testing steps of a production readiness review prototype, in order to show that the system design is mature enough for the transition to the construction phase.

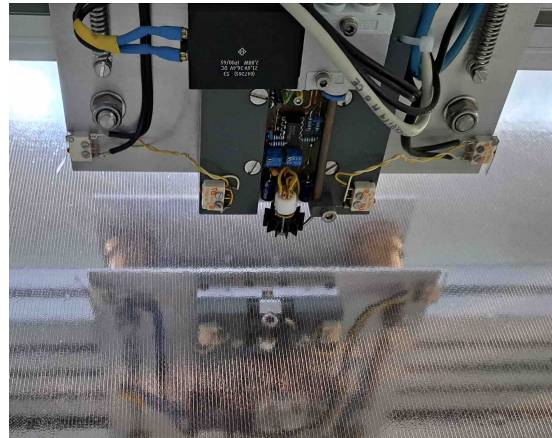


Figure 4: Measurement of the mechanical tension.

The assembling of the chamber is based on a rectangular frame made of G10 composite material, which is closed on the two sides by preassembled components. On one side the "entrance window" is positioned (sandwiched thin carbon foil/Nomex honeycomb/kapton foil structure) with

a minimized absorption for TR photons [7, 8]), and on the other side the readout electrode is placed, as shown in Fig. 1.

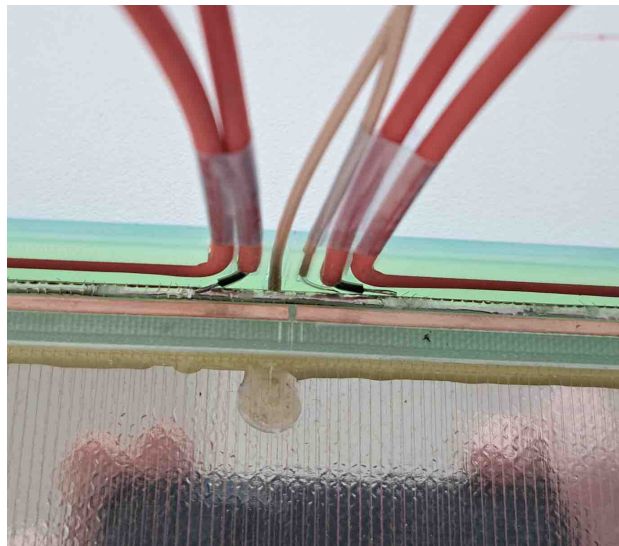


Figure 5: Electrical connections of the high voltage electrodes (4 anodes, 1 drift and 1 cathode).

The details on the structure and assembly of the entrance window were reported in [8]. Fig. 2 shows details on the assembly of the readout electrode, i.e. the pad-plane circuit reinforced by a back panel. Between these two outside planes, the cathode (CuBe alloy of 80 μm diameter) and the anode wire (Au plated W of 20 μm diameter) planes are equally spaced at 4 mm. Figure 3 shows the cathode wire plane stretched on top of the entrance window.

Fig. 4 shows the measurement of the mechanical tension in the wires of the cathode plane. In order to achieve the

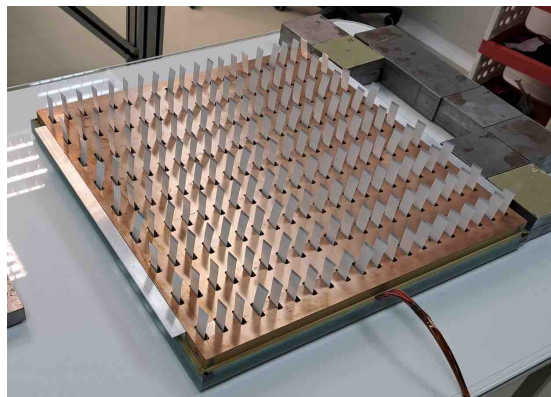


Figure 6: Assembled chamber.

best performance in terms of position resolution not only across the pads, but also along the pads, the middle of each pad row has to be crossed by an anode wire. For this reason, not only the alignment requirements of the cathode wire plane (1.5 mm pitch) to the anode wire plane (3 mm

pitch) are very tight, but also the alignment of the readout electrode relative to the anode wires.

An assembly device was specially designed for keeping the chamber components very well aligned relative to each other. Fig.5 shows details of the high voltage electrical connections for the anode and the cathode, as well as for the drift electrodes. In order to be able to deal with the high currents anticipated for the operation at a high counting rate (up to 100 kHz/cm²), the electrical connections of the anode plane are split in four sections, corresponding to the four red high voltage cables seen in the photo.

The final assembled prototype is shown in Fig.6. It was installed in the testing laboratory and connected to the gas flow. After flushing the chamber for 24 h at 5 l/h flow rate with a 80%Ar+20%CO₂ gas mixture, a 30 ppm oxygen contamination was obtained.

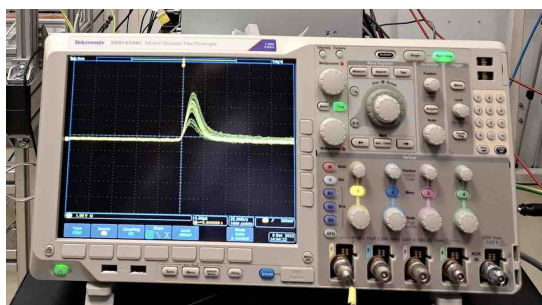


Figure 7: ⁵⁵Fe signals.

Signals obtained using a ⁵⁵Fe radioactive source at 1900 V anode and 600 V drift voltage are shown in Fig. 7. The signals were processed by an ORTEC 142 charge sensitive amplifier and 673 spectroscopy amplifier. A clear separation between main and escape peaks shows that the chamber works as expected. Detailed tests using the dedicated front-end electronics and readout chain are in progress.

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Construction of the first line of the TRD gas system*

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Introduction

The gas system of the TRD has to supply the detector chambers with a gas mixture of Xe/CO₂ (85:15), while the differential pressure has to be kept within a range of 0.7 mbar relative to local atmospheric pressure [1]. To minimize the material budget caused by the gas support structure, the detector chambers at the same height in the same layer are connected in series. To supply this structure, the TRD detector rows are subdivided into groups which are at the same height and have consequently the same hydrostatic pressure. This allows to provide 20 different detector groups with just 5 regulation lines, each supplying the 4 layers of TRD. To fulfill these requirements, precise pressure control is needed to compensate the changes in the environment pressure, which are typically in the magnitude of a few mbar per day, but can also reach mbar/h with stormy weather. To ensure the gas quality in the detectors, sensors which constantly monitor the CO₂, O₂ and the H₂O content in the detector gas are planned for the gas system [2].

Gas System Construction

The gas system is foreseen to be placed at the support area E30, which results in a distance of about 50 m with a height difference of 18 m. A first line with a tube length of 50 m forward run and return path has been constructed and built. This line is used to set the parameters for the control routines and to confirm the calculated pressure distribution in one row of serially connected detectors. The height difference will give an additional hydrostatic pressure of 7.2 mbar. Since this pressure is constant, it can be accounted for by adjusting the pressure at the long supply pipes. A CAD drawing of the system installed for commissioning and characterisation in the laboratory in Münster is shown in Fig. 1.

Furthermore, a test of the flushing procedure and a determination of the time needed will be done. The gas injection panel is shown in Fig. 2. The gas will be injected through two inlets, which are also utilized for corrections in the gas mixture.

To ensure tightness and to maintain the high gas quality, stainless steel tubing has been used.

Summary and Outlook

A local version of the first line of the gas system has been designed and mounted. The aim is to adjust the control cir-

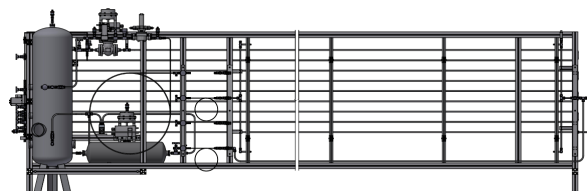


Figure 1: This CAD drawing shows the mounted gas system. For better visibility, the long tubing in the middle is cut out. The steering valves, the buffer volume and the gas injection are shown at the left side of the picture. The whole system is able to carry four large TRD chambers which will be supplied by the system. The whole setup has a length of about 6 m.

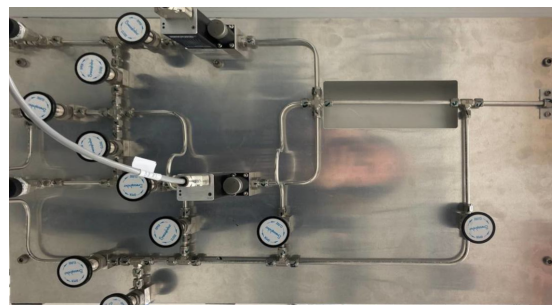


Figure 2: The injection panel for the gas system. This layout allows to inject a mixture of CO₂ and a noble gas (Ar or Xe), or just one of the components, to adjust the gas composition if needed. The free space is a mounting point for a mixing volume if necessary.

cuits and to monitor the pressure development in the system. This gas system will initially supply a dummy TRD chamber. After a successful conclusion of this test, the supply of a real detector line is the next step. These tests of the reliability of the system will be done with an Ar/CO₂ gas mixture. This line is to be transferred and, if necessary, adapted and expanded, in the CBM setup at FAIR.

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* Work supported by BMBF grant 05P21PMFC1 and 05P19PMFC1.

TRD-2D at mCBM – Data quality for the benchmark run $^{58}\text{Ni} + ^{58}\text{Ni}$ at $T_{\text{lab}} = 1.93 \text{ AGeV}^*$

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The TRD-2D detector was installed at mCBM at GSI, Darmstadt in 2021 [1]. First performance results of the system, measured with limited acceptance, were already reported [2]. A significant extension of the detector acceptance was accomplished [3], which together with improved calibration and tracking delivered the final proof of its performance.

Event reconstruction

The analysis of data for relatively low interaction rates is based on event identification followed by tracking. Events are defined based on the time correlation with the T0 detector. In Fig. 1 the time residuals between TRD-2D and event time reference are presented at two levels of analysis: the measured data-digits and reconstructed hits attached to tracks. The distribution of the later observable is consistent with a Gaussian distribution (red line) with a time resolution of less than 30 ns.

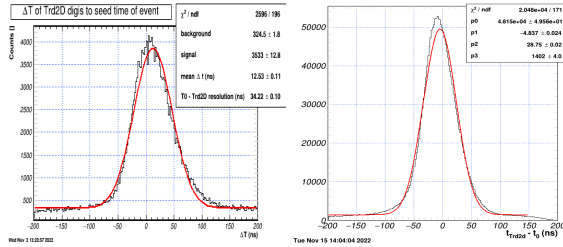


Figure 1: Time residuals of the TRD-2D detector wrt. the event definition for digits (left) and hits (right) respectively.

2D position performances

An unbiased demonstration of the $x - y$ position information performance of the TRD-2D was obtained from the correlation of these observables with track projections defined by the upstream STS and downstream TOF detectors. In Fig. 2 such a correlation is presented for tracks which are initiated by selections of STS hits (see also [2]). The plots span the whole TRD-2D acceptance illuminated by such tracks narrowly distributed around the main diagonal.

In Fig. 3 we have repeated the analysis for similarly defined tracks but seeded by the TOF mechanism. The TRD-2D to track correlation is also observed for both coordinates on a relatively more noisy background. The appearance of

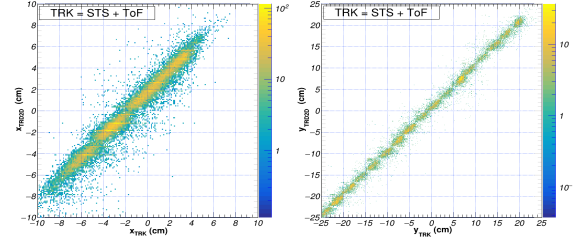


Figure 2: Correlation of the TRD-2D position with track projection as defined by the STS and TOF detectors for the x (left) and y (right) coordinates and STS track seeding.

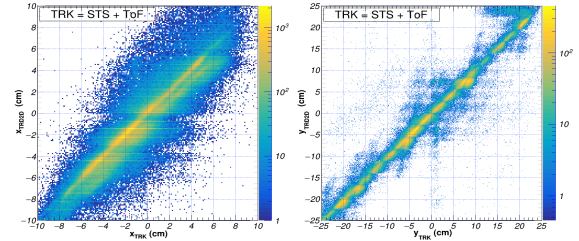


Figure 3: Same as in Fig. 2 but for TOF seeded tracks.

secondary structures in the two plots is indicative for misalignment and mis-calibration of mCBM detectors, which is work in progress. Nevertheless the sensitivity to such effects is proof of the importance of an intermediate tracker between the STS and TOF detectors even if they are less than 3 m apart.

Conclusions

The unique 2D position measurement capabilities of the TRD-2D were demonstrated by track correlation with the STS and TOF detectors of mCBM. Integration of the TRD-2D in the mCBM tracking will prove the concept of an intermediate tracker described in [4].

References

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* Work supported by Romanian Ministry of Research, Innovation and Digitization NUCLEU Project Contract PN 19060103, RO-FAIR Project FAIR-03/16.11.2020.

Offline time reconstruction for the TRD *

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Introduction

The signal time is in its simplest form determined by the sampling frequency of the TRD of 62.5 ns. However, the time resolution for efficient track and particle reconstruction needs to be more precise. As there will be a few saved samples for every hit, their information can be used to improve the time reconstruction. At the moment two methods are being developed to improve the time reconstruction. One method, which can be implemented online, is based on an analytical calculation of the timeshift by using two samples [1]. The other method will be presented in the following and uses a lookup table to improve the precision of the time reconstruction in the offline reconstruction.

Time reconstruction with a lookup table

In Fig. 1 one can see the correlation between the first sample after the pre samples and the time shift for different values of the signal maximum. The effect of the time shift on the different signal samples is illustrated in Fig. 2.

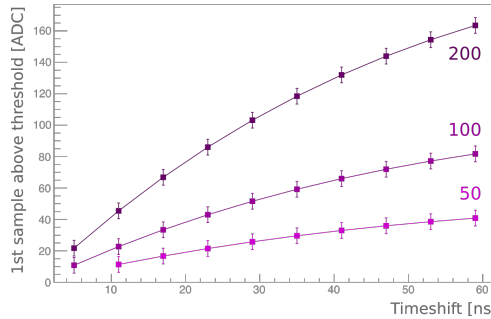


Figure 1: The correlation between the value of the first signal sample and the time shift is shown for different values of the signal maximum [2].

Both signals are exactly the same and just shifted a few ns against each other. From the figure one can easily see why the lookup table can improve the time reconstruction significantly by only taking the first sample and the maximal value into account.

The signal shape is described by the theoretical SPADIC response function with the shaping time as the only free parameter, and is therefore used to fill the lookup table. For the shown results a value of 180 ns is used. The final lookup table contains the maximal signal values from 0 ADU to 512 ADU and also time shifts from 0 ns to 100 ns.

* Work supported by BMBF grant 05P21RFFC3 and by HFHF

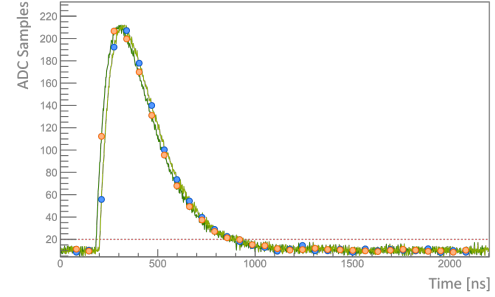


Figure 2: Two identical signals shifted by a small time shift are drawn. The blue and orange points show the correspondingly sampled values [2].

Results from mCBM22

Figure 3 shows a comparison of the time resolutions obtained by using the time bin position ("sampling only") and by employing the lookup table ("Lookup table"). One can see that the time reconstruction is much more precise using the new method. The width of the Gaussian fits are $\sigma = 33.04$ ns for the sampling only method and $\sigma = 24.00$ ns for the lookup table method. It is found that the impact of the signal height on the time resolution is quite low.

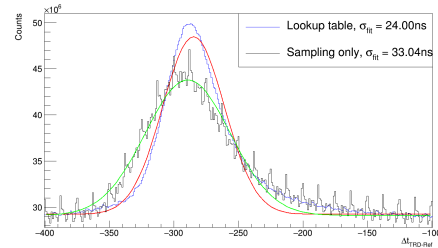


Figure 3: Time resolution obtained by using the time bin position (black line) and by employing the time reconstructed via the lookup table (blue line). Both graphs are fitted with a Gaussian fit.

References

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Verification of TRD detector simulations *

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Introduction

To ensure the best functionality of the Transition Radiation Detector (TRD), it is crucial to simulate the detector response as precisely as possible. Further adjustments and optimisations to the TRD digitization class have been conducted and first simulation results on the specific energy loss will be presented and compared to results from the DESY testbeam campaign of 2019. Moreover, an estimation of the material budget with a more realistic geometry has been performed via simulations.

Comparison of the test beam data to simulation results

A comparison of the simulation results with DESY 2019 data, obtained with the SPADIC version 2.2, has been conducted. Within the simulations, an electron beam with a fixed momentum of 3 GeV/c was created using a box generator and the same geometry as in the measurement setup. The results on the self-triggered pulse shapes, cluster sizes and energy depositions can be seen in Figs. 1 and 2. A calibration of the DESY data has been conducted via a measured ^{55}Fe spectrum. Generally, data and simulation agree well, but there are still small differences that will be investigated further.

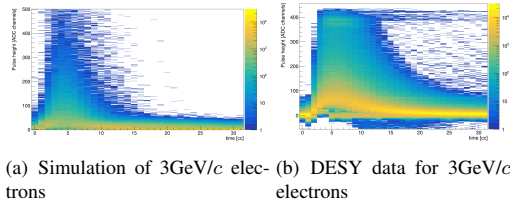


Figure 1: Comparison of simulated self-triggered signal shapes and measured signal shapes from the DESY data at a momentum of 3 GeV/c.

Material Budget

Several changes were made to the TRD geometry to simulate a more realistic design of the front end electronic. Regarding the front end boards (FEB), the copper volumes in the circuit boards were estimated and implemented into the geometry as a single layer of maximal 0,014 cm thickness above the G10 circuit board material. The size and

* Work supported by BMBF grant 05P21RFFC3 and by HFHF

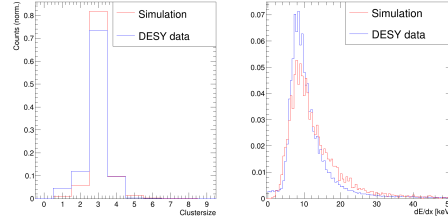


Figure 2: Left: Comparison of the cluster sizes measured at the DESY 2019 beamtime and simulation results. Right: Reconstructed specific energy loss compared to DESY 2019 results, shown for three pad clusters.

the thickness of the FEBs were narrowed down in the Y-direction and Z-direction according to a more recent FEB design. This allowed the inclination angle to be changed to 0 degree on all module types. Moreover, an additional copper volume has been introduced around each SPADIC to represent other electronic components. Holes containing copper cylinders were inserted at regular intervals in the FEBs, representing the mounting holes. The SPADIC numbers and positions were changed to fit the current construction plans. It could be shown that the material budget of 15.14 % achieved with an upper limit of copper volumes stays below the desired value of 20 % [1]. For the modules with high FEB density (type 1 and 5, both TRD-1D design), it can be seen in Fig. 3 that in the active detector areas contribute more to the material budget. This is a result of the additional copper volumes.

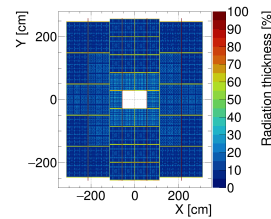


Figure 3: Distribution of the material budget for all four TRD detector layers, as calculated by GEANT3.

References

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Towards a Component Database for the CBM-TRD*

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Introduction

A prototype database system for the management and storage of component parameters has been developed, tested and evaluated for the use by the CBM-TRD group. This first prototype was based on TGenBase [1], and it was ultimately not deployed for production use, due to the expectation of long-term maintainability issues. Instead, a new database system for component parameters is currently being conceptualized for the CBM-TRD group, based on the lessons learned from this prototype.

This report will provide a short overview over the previous prototype setup and lessons learned for a successor system.

Database Prototype based on TGenBase

The original prototype for the component database was based on TGenBase. A set of necessary database fields was compiled, based on the production process for the TRD MWPCs, originally by Kristin Nissen and updated by Philipp Kähler.

While these fields can be simple data points like time-stamps, it is possible to include complex timeseries, like a pressure graph during a gas tightness measurement, and 2D-histograms, like a gain map that may be collected with a future automated test stand. The wide variety of available data types provides great flexibility to tune the generated solution to the specific needs of our detector.

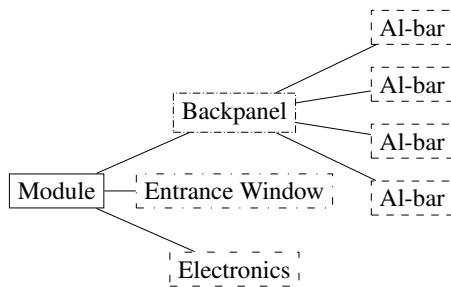


Figure 1: The relations of individual components in a outer TRD MWPC. The set of collected electronics component data/tests is not yet decided.

The database was set up to depict the chain of relations between the components, see Fig. 1, since the individual components are produced and tested separately. This allows an operator to check individual components for com-

monalities of certain parameters and flag potentially afflicted higher level components.

This system was equipped with a rotating backup system of the following hierarchy:

1. Daily backups going back 1 week
2. Weekly backups going back 4 weeks
3. Monthly backups going back 3 months.

Each backup was fully self-contained and could be used to redeploy the setup on a freshly installed machine within an hour.

Data entry, retrieval, and queries were extensively tested along with retrieving previous versions of individual records.

Lessons Learned

The main challenge with the existing TGenBase-based system stems from its complexity and the resulting long-term maintainability issues. Still, many of the characteristics of this solution remain desirable and should be carried over to the successor framework. Support for complex datatypes should be kept and support for data visualization should be added, but less required features like the C++ client generator should be excluded to reduce complexity.

One feature that should be evaluated is an improved migration step to a newer database schema. This could be used to append database fields and new components to existing records, if the testing procedure is updated later.

The rotating backup system should be kept and integrated into the base installation scripts, with an option to keep monthly backups indefinitely.

Summary and Outlook

A component database system based on TGenBase [1] was implemented and deployed for evaluation as a long-term database for component parameters that could be relevant for the operation of the experiment.

A successor for the current prototype database is in early conceptual stages, with several potential courses of action in the running.

References

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* Work supported by BMBF grant 05P21PMFC1.

Status of the SPADIC based readout*

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Introduction

The Self-triggered Pulse Amplification and Digitization asIC (SPADIC) was developed in Heidelberg and forms the central component of the outer TRD [1] signal processing chain. In the course of the project development, it was necessary to adapt the SPADIC to changing requirements, such as the switch from CBMnet to GBTx [2]. In the following, we provide a summary of the status of the current chip versions.

SPADIC 2.2

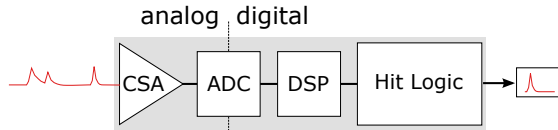


Figure 1: Diagram of the signal processing chain for a single channel of the SPADIC.

Version 2.2 of SPADIC is currently in use at mCBM. It includes the latest feature requests and some bug fixes, for instance an optimized data format in the e-link frames to maximize bandwidth and a versatile logic to detect hits in the digitized data stream (see Fig. 1). While providing a very reliable and stable readout of the TRD in mCBM and in laboratory setups, we observe two main issues:

- The noise in the digitized baseline exceeds the design value and our target of $\sigma < 2$ ADU. Laboratory measurements in Münster show $\sigma = (1.44 + C/pF \cdot 0.056)$ ADU with a high sensitivity to pick-up noise of several ADUs.
- While some of the 32 ADCs on each chip have a satisfying linearity (proving that the design is fundamentally ok), few ADCs on nearly each chip show degraded characteristics. This points to a large sensitivity of the design to production variations.

SPADIC 2.3

Two new chip versions were developed to address these issues. SPADIC 2.3A introduces minimal changes to schematic and layout of the ADC with the goal to improve matching. In SPADIC 2.3B, a presumably critical component of the ADC is fully redesigned. On both chips, features to study noise are introduced: The size of the input

protection diodes is varied in different channels and various on-chip input capacitors are added to allow noise measurements with minimal risk of signal pickup. In addition, test charges can now be injected into all channels.

Despite the only minimal changes, 2.3A shows even worse behavior than 2.2: The fraction and level of ADC nonlinearities increased and - unexpectedly - the output signal of the CSA breaks down for input capacitances > 20 pF (which is not observed in 2.2). Despite a rigorous investigation, simulations and comparisons to 2.2, these findings cannot be explained. Errors in the production process might be a reason, even though highly unlikely. 2.3B shows similar issues and was not investigated in detail.

Outlook: SPADIC 2.4

The ADC of SPADIC uses - historically - a complicated pipelined current mode architecture with 1.5 bit/stage. This offers many possible sources of nonlinearities and is difficult to debug. We have therefore decided to switch to a more conservative classic Successive Approximation ADC design (Fig. 2). (This is eased by the by now reduced operation speed). The ADC will be centered around an available silicon proven DAC and will benefit from a previous similar ADC design in Heidelberg. Although this represents a major change in the design of SPADIC, we believe that it is currently the most efficient path towards a final ASIC. The submission is planned for April 2023. After first test chips have been received, characterizations of the newly achieved fluctuation level will follow with high priority.

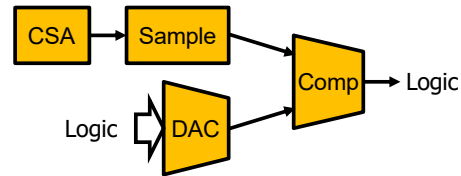


Figure 2: Concept of the new ADC.

References

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* Work supported by BMBF grants 05P21RFFC1 and 05P21PMFC1.

Introducing a graphical user interface for SPADIC chip testing^{*}

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Introduction

During the production of the outer detector modules of the TRD, a quality control of the front-end-electronics has to take place. For this purpose software is required that automatically executes defined tests and can display the results on the screen, as well as save them for later referencing. A basic version of such a software was developed for the SPADIC version 2.2 [1]. It is called "Spadic-Chiptest".

Software Design

Spadic-Chiptest is based on a prototype readout-chain using an AFCK board and the IPbus protocol, presented in [2]. It is written in Python 3 and implements the μ HAL library from the IPbus software framework. The graphical user interface was developed with PyQt5. Here, the graphical user interface and the backend-classes that control the SPADIC and AFCK remain separated, which facilitates further development.

Features

Currently, the software offers the following functionalities:

- Performing an automated connectivity test of a front-end-board.
- Trigger the SPADIC and show pulse-shapes of all 32 channels.
- Measure the baseline of all 32 channels.
- Automatically adjust the baseline of all channels to a given value.
- Show, edit, save and load the most important settings of the SPADIC.

Inside the GUI it is also possible to set up the DAQ-chain by programming the AFCK board and starting the IPbus control hub daemon. Figure 1 shows a screenshot of Spadic-Chiptest after a baseline-measurement was performed.

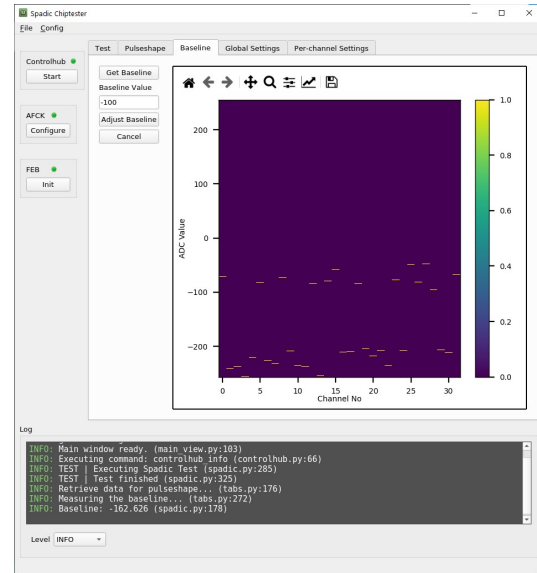


Figure 1: Screenshot of the graphical user interface of Spadic-Chiptest, showing the result of a baseline measurement.

Summary and outlook

A framework has been developed for quality control of detector electronics. Since the development of the final SPADIC version is still ongoing, adjustments to Spadic-Chiptest will be necessary before the series production of detector modules starts. In addition, some more features could be added to Spadic-Chiptest in the near future, for example: a connection to a component database, that is being developed [3], to store the test results. Also, a tool that makes investigation of noise levels easier might be useful.

References

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- [3] P. Munkes, "Towards a Component Database for the CBM-TRD". This report.

^{*} Work supported by BMBF grant 05P21RFFC3 and by HFHF

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TRD-2D at mCBM, FEE and DAQ for the mCBM 2022 campaign *

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The TRD-2D detector is operated with a dedicated FEE/DAQ based on the FASP ASIC and FASPRO FEB. Further integration in the mCBM DAQ is done based on the common CBM solution based on GBTx/CROB and CRI boards. A first successful step was already accomplished in the 2021 campaign [1] for 384 read-out channels representing a total of $\approx 13\%$ of total detection area. In order to match the STS-TOF acceptance and increase the quality of track definition the TRD-2D FEE was expanded.

TRD-2D 2022 FEE upgrade

The FEE-DAQ solution used for reading out the TRD-2D in mCBM is a development version based on small FEBs of six FASP ASICs, single channel ADCs and two Microsemi FPGAs for communication with the CBM DAQ. These readout units can be seen in Fig. 1 (left) where the back side of the detector is shown. A total of 18 such units were installed increasing the potential read-out to 60 %.

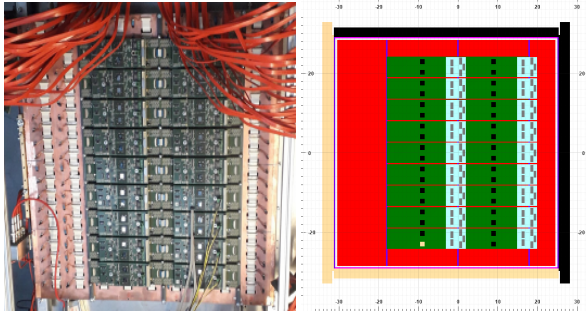


Figure 1: The distribution of the 18 FASPRO boards installed on the TRD-2D chamber at mCBM as they are mounted on the physical detector (left) and as they are modeled in the CbmRoot geometry (right).

The upgrade of the FEE hardware (HW) was accompanied by the extension of the system on all levels, i.e. CROB, CRI and the increase in the number of LV and HV channels. The modifications were further followed in the CRI firmware (FW) and CbmRoot software (SW) used to pack and unpack the data. At software level, e.g. the geometry was modified as in Fig. 1 (right) to account for the new hit positions and material budget calculations. One can see

the degree of similarity with the real object shown in the left panel.

TRD-2D FEE-GEO mapping

The manipulation of big data (volume and rate) at various degree of integration along the data transport chain can easily become messy. For the TRD-2D we faced problems in both readout channel position identification but also time correlation of signals. Both problems were solved and the image of the active area of the TRD-2D, operated by FEE/DAQ was obtained as can be seen in Fig. 2.

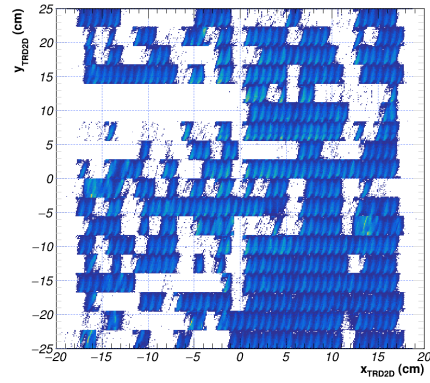


Figure 2: Hit distribution for the TRD-2D detector showing the 2D capabilities of the system but also the DAQ areas which were masked-out.

The area read out by the FEE of TRD-2D is smaller than the actual installed 60 % due to some malfunctioning FEBs which were also produced. A positive consequence is given by the possibility to check precisely the HW $\rightarrow$ FW $\rightarrow$ SW mapping by comparing the empty spaces in Fig. 2 with the list of masked channels/boards from DAQ configuration.

Conclusions

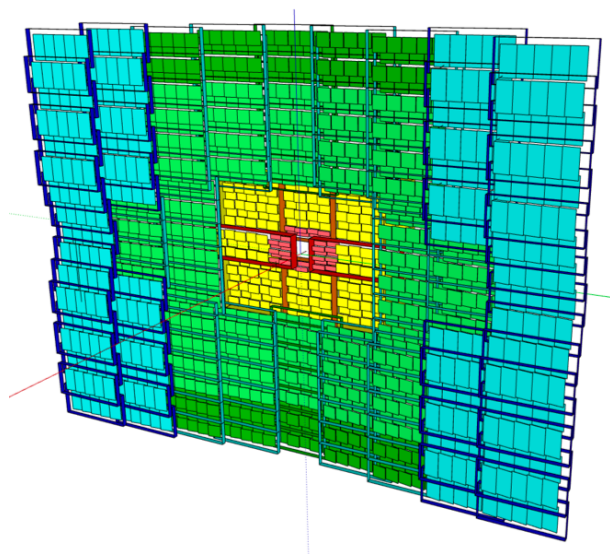
With the TRD-2D upgrade and building support for multi CROB/CRI the system came closer to CBM-DAQ integration. For maximising track acceptance using existing boards, a particular FEB configuration was demonstrated, based on a good coordination of all DAQ elements in the chain. Thus, steps for a common description of HW to be used in FW and SW were developed.

References

- [1] A. Bercuci et al., CBM Progress Report 2021, p121.

* Work supported by Romanian Ministry of Research, Innovation and Digitization NUCLEU Project Contract PN 19060103, RO-FAIR Project FAIR-03/16.11.2020.

Time-of-Flight Detector



TOF - Summary

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The main focus of TOF, also this year, was on the investigation of gas and counter aging observed first in 2020 [1] and described for instance here [2, 3, 4] and on the development of new MRPCs prototypes [5, 6, 8] in order to mitigate the observed gas pollution effects. The proposed strategy is, to develop methods to exchange the counter gas in between the gaps in a much more rapid way compared to gas diffusion which led to the development of sealed MRPCs [7]. By now the first prototypes were tested and evaluated (see [8, 9, 10]) and further X-ray tests were performed [9, 11] in order to consolidate the success of the mitigation strategy. However, the data analysis of the latest two high rate beam campaigns performed at mCBM in the year 2022 is still ongoing.

Ongoing is also the calibration effort for eTOF at STAR which is far progressed by now. The status is shown in an overview table in Fig. 1. During the last two years the calibration algorithms got steadily improved as can be seen by comparing the status reported in PR 2020 [12] and PR 2022 [13]. In summary the eTOF system operates in meanwhile at a time resolution below 80 ps.

Energy GeV $\sqrt{s_{NN}}$	14.5	19.6	9.2	11.5	3.5	3.9	4.5	5.2	6.2	7.7	9.2	11.5	13.7	3.0	7.7
Year	2019		2020								2021				
Mode	Collider				Fixed Target										Coll
Status	flawed	produced	under calibration for reproduction								calibrated				calibrated
#Events	320 M	580 M	150 M	230 M	100 M	50 M	100 M	100 M	100 M	50 M	50 M	50 M	50 M	3 B	100 M
Dmg	XX	XX	X							X		X	X	X	X

Figure 1: Status on eTOF calibration for BESII at STAR. Row 1 denotes the center of mass energy of the taken runs, row 2 the year and row 3 the mode. Row 5 shows the number of events taken. Row 6 denotes with XX the runs with the first electronic damage and X the runs with the second electronic damage.

A substantial progress has been achieved in the engineering design of the TOF main frame and an EDR could be feasible in Q2/2024. Currently a test substructure (see Fig. 2) comprising a half column with 12 modules is under constructed at the Physikalisches Institut in Heidelberg. With this frame mock-up test stand the practicability of the mounting procedure, connectivity handling of the infrastructure and cable routing strategies can be exercised.



Figure 2: Mock-up stand simulating the lower part of the central column of the TOF wall. Lower photos show a stress test with heavy weights placed inside the module.

Currently TOF is in the re-baselining phase and a pre-production of 40 MRPC counters (8 modules for the outer wall) is almost completed. Based on the test results of these counters a PRR is foreseen for beginning of 2024.

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Aging suppression for high time resolution and 2D-position sensitive Multi-Strip Multi-Gap Resistive Plate Counter in high irradiation dose *

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The Multi-Strip Multi-Gap Resistive Plate Chambers (MSMGRPCs) of the inner zone of the CBM-TOF wall were designed to withstand the high counting rates (≤ 50 kHz/cm²) anticipated for the CBM-TOF wall with the required performance in terms of an efficiency above 90% and a system time resolution better than 80 ps. The obtained results in the in-beam tests performed using the mini-CBM (mCBM) experimental setup [1] showed an efficiency better than 90% and ~ 50 ps single counter time resolution up to 30 kHz/cm² (the highest delivered counting rate in the in-beam test) [2]. However, as it is well known, the long term operation of MRPCs with C₂H₂F₄ and SF₆ based gas mixtures leads to complex aging effects [3]. In order to maintain the detector performance over the CBM lifetime, detailed aging investigation are of utmost importance. In the aging studies performed using a high activity ⁶⁰Co source existing in the multipurpose irradiation facility (IRASM) of IFIN-HH in Bucharest, a gas pollution effect was evidenced by the depositions of chemical radicals on the anode side and by the ablation/etching processes observed on the cathode side of a MSMGRPC prototype [4]. Enhanced depositions and higher counting noise rates were also observed around the spacers used for defining the gas gaps between resistive electrodes. In the reported aging studies, the gas exchange inside the counter's gas gaps took place via diffusion process. Previous studies [5] showed that the polymerization is inverse proportional with the gas flow. In order to avoid the deterioration of the counter performance and to keep the electrode surfaces as clean as possible, two MSMGRPC prototypes with a direct gas flow through the gaps between resistive electrodes were assembled. Their inner geometry is identical with the one of the high granularity prototypes with gas exchange via diffusion, presented in detail in [6], but the spacers were positioned outside the active area, at 1 mm distance from the glass edge, as shown in Fig. 1 - left. The width of the glass plate is 6 cm, while the width of the HV electrode is 5.6 cm and the distance between the two spacers is 5.8 cm. A first prototype, called here P1, was preliminary tested in the detector laboratory of Hadron Physics Department (HPD)/IFIN-HH, in Bucharest. Further on, it was successfully tested in-beam in the mCBM experimental setup. An efficiency working curve similar with the one

obtained for the prototypes with the same inner geometry and gas exchange via diffusion and a single counter time resolution of 51 ps were measured [2]. However, due to some instabilities observed at higher applied voltages, we did not apply more than 2×5.9 kV, while the efficiency plateau for the chamber with gas exchange via diffusion (and spacers positioned at 3.8 cm pitch) was obtained at 2×6.4 kV.

In order to understand the observed instabilities, the chamber was exposed to a high X-ray flux delivered by two Amptek mini-X ray tubes, in the detector laboratory of HPD/IFIN-HH. At 2×6 kV applied voltage, under high X-ray flux exposure, continuous discharges were developed. The footprint of the discharges, observed on the middle of the glass plates along the full glass length (across the strips), showed that the glass plates are bending under the action of the high electric field, reducing the effective size of the gas gap, (as confirmed also by some estimations of the electrodes deformation in the electric field of the MSMGRPC). Therefore, a new prototype, called here P2, was assembled with an additional spacer positioned in the middle of the chamber, as can be seen in Fig. 1-right. The first ag-

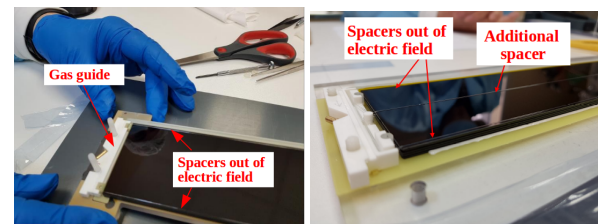


Figure 1: Spacer running only outside the electric field lines - left and with an additional one in the middle of the active area - right.

ing investigations for the P2 prototype [9], were performed using the two mini-X ray tubes mentioned above. The tubes were aligned at about 14 cm in front of the chamber, exposing the full active area almost uniformly. The chamber was equipped at both readout strip ends with front-end electronics cards (FEE) based on NINO chips [7]. These OR signals delivered by the FEE cards had been processed using a logic electronic scheme and the obtained output signal was fed into the input of a scaler. We exposed the counters at the highest X-ray flux ($\gtrsim 20$ kHz/cm²) between five to seven hours per day, monitoring the current (Fig. 2 - left)

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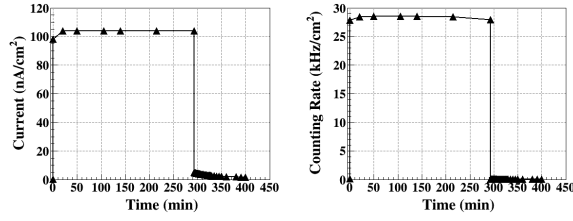


Figure 2: Current (left) and counting rate (right) at the highest X-ray flux.

and the counting rate (Fig. 2 - right) over this period. After this time interval the irradiation was stopped and the decay of the dark current and dark counting rate have been monitored for a certain period of time. It was investigated the influence of different gas flow rates on the decay of the dark current and dark counting rate. In Fig. 3 it can be observed the improvement brought by a higher gas flow rate, which confirms a gas pollution effect and not a glass aging effect. Over 6 l/h any significant improvement was observed. For a 6 l/h gas flow, a gas exchange rate of 2.5 volumes per minute was estimated.

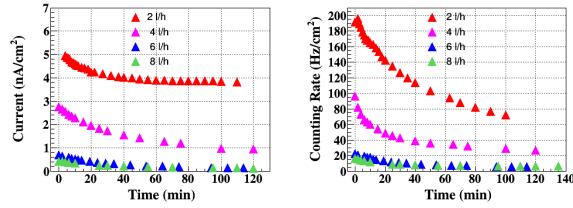


Figure 3: Dark current (left) and dark rate (right) versus time at different gas flow rates.

The above results were obtained using a mixture containing 97.5% tetrafluorethane and 2.5% SF_6 . Further on, a 5% iso- C_4H_{10} (isobutane) was added in the gas mixture, decreasing the tetrafluorethane to 92.5% and keeping the 2.5% of SF_6 . Fig. 4 shows that the dark current and dark counting rate were smaller for a gas mixture containing isobutane, being known that the isobutane improves the stable operation of glass RPCs due to its high absorption of UV photons resulted from recombination processes [8]. As

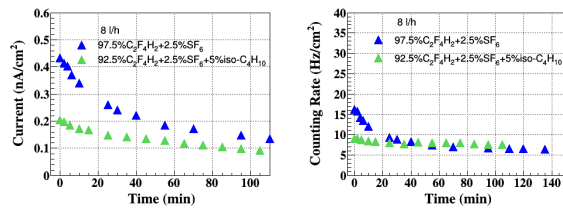


Figure 4: Dark current (left) and dark rate (right) versus time at 8 l/h without/with isobutane in the gas mixture.

Fig. 5 shows, the dark current and the dark counting rate are

almost the same for a gas flow rate of 4 l/h without isobutane and a gas flow rate of 2 l/h with isobutane. After the

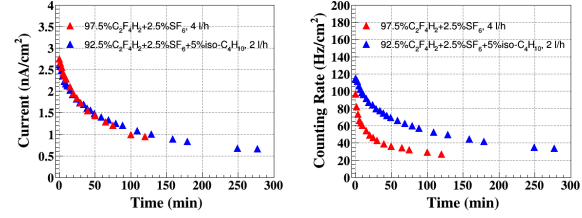


Figure 5: Dark current (left) and dark rate (right) versus time at 4 l/h/ 2l/h without/with isobutane gas mixture.

last exposure to the high X-ray flux, the output signals of the FEE boards were fed into the input of CAEN V1290N TDCs and the DAQ system was triggered by their OR signal (operation in a self-triggered mode). Based on the difference of the times recorded at the two ends of the 32 strips, the position along the strips (y) was reconstructed. A two dimensional (2D) and three dimensional (3D) repre-

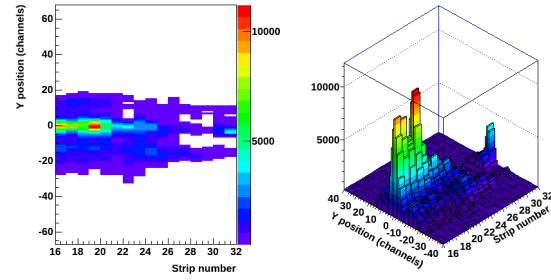


Figure 6: Position along the strip (y) versus strip number.

sentations of the position along the strip versus strip number (see Fig. 6) show that the main source of the dark counting rate is, as expected, the additional spacer positioned on the middle of the active area. The obtained results will be used for an optimization of the detector design, gas composition and gas flow rate to minimize the aging effects.

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In-beam test in the mCBM setup of the high time resolution and 2D-position sensitive MSMGRPC for high rate experiments *

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The Multi-Strip Multi-Gap Resistive Plate Counters (MSMGRPCs) were designed to cope with the high counting rates and track densities of the most challenging zone of the CBM-TOF wall. They confirmed their performance in terms of time resolution and efficiency in high counting rate [1] in the in-beam tests performed in the mCBM experimental setup [2] (FAIR Phase-0). The MSMGRPC aging tests performed at the multipurpose irradiation center of IFIN-HH in Bucharest evidenced mainly a gas pollution effect [3]. For the mitigation of the observed aging effects a new detector architecture with a direct gas flow through the gas gaps was proposed. Following the successful in-beam test of the first direct flow prototype (called P1) [4, 1] a second prototype, (called P2), assembled with the improvement described in reference [5] was assembled and tested in the mCBM setup during June 2022 mCBM in-beam test campaign. A photo of the counter installed in the mCBM setup, sandwiched between the mTOF chambers, is presented in Fig. 1. The in-beam tests were per-



Figure 1: Direct flow P2 prototype in the mCBM setup.

formed using a Au(65+) beam on a Ni target of two different thickness. The thin Ni target of 0.4 mm was used for the evaluation of the detector performance at low counting rates, while the thick one of 4 mm was used for obtaining

high counting rates at high intensity particle beam. The beam intensity varied between 1×10^7 to 4×10^8 particle per spill. During the in-beam test the mTOF chambers as well as the tested MSMGRPC prototype were exposed for 8 hours at the highest beam intensity. The P2 reconstructed

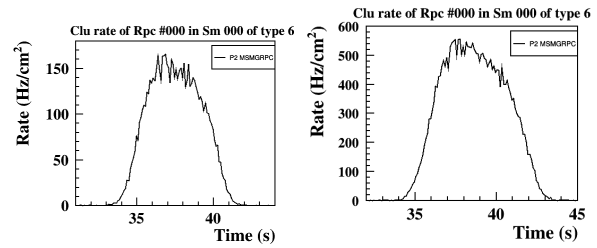


Figure 2: P2 beam spill profile at different counting rates.

spill shape in terms of counting rate per unit area as a function of time is shown in Fig. 2-left for a counting rate of ~ 0.15 kHz/cm² and in Fig. 2-right for an increased one of ~ 0.5 kHz/cm² (preliminary results). Fig. 3-left shows the P2 reconstructed spill shape at the highest delivered beam intensity, when a counting rate of ~ 5.5 kHz/cm² was estimated. Fig. 3-right shows the beam spill shape reconstructed with P2 overlapped with the one for the diamond beam reference counter, both histograms being normalized to the corresponding number of entries.

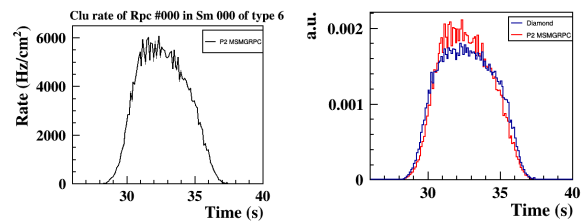


Figure 3: Beam spill profile: left - P2 at high rate; right - at the same rate, overlapped for P2 and diamond.

Data analysis is in progress.

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Development and test of a sealed MRPC with mylar pad spacers *

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The unprecedented rate condition is a real challenge for the MRPC-based CBM-TOF in terms of not only the rate capability but also the operation stability. The aging effect, which is usually considered a dose-related long-term effect, has been observed in the high-rate test runs of the mTOF. With further investigations, the TOF group has confirmed the contribution from the accumulation of gas pollutants whose yields are proportional to the flux rate. The effort to solve gas pollution is to introduce gas guidance to MRPCs for a pressure-driven gas exchange instead of diffusion. The sealed MRPC developed at Tsinghua University has shown the promoted gas exchange from short gas purge time and the fast in-beam current response[1]. Benefiting from the continuing evaluations of high-rate MRPCs in the laboratory and mCBM, we are able to collect and analyze more results. Some evidence that possibly comes from the abnormal discharge around spacers has been observed, which includes:

1. The noise hit distribution with fishline pattern, see Figure 1;
2. The significant asymmetry of Sodium concentration between the glass surface at fishline region[2], see Table 1;
3. The dark current increase correlated to fishline density, see Figure 2.

We raise the possible explanations as follows for the principle of the spacer effect:

- The circular cross-section of the fishline spacer. Although fishline is well applied as spacers for its high resistivity ($10^{14}\Omega\text{cm}$ level), it may still cause the high electric field due to the edge conditions it introduces, even double the usual value according to a simulation[3] at the non-contact space to the glass.
- The electrical creepage on the fishline spacer. Similar to the electrical creepage considered in the routing of the Printed Circuit Boards (PCB), the avalanche products around the spacer might affect the surface quality of the spacer, leading to the charge spread along the fishline.

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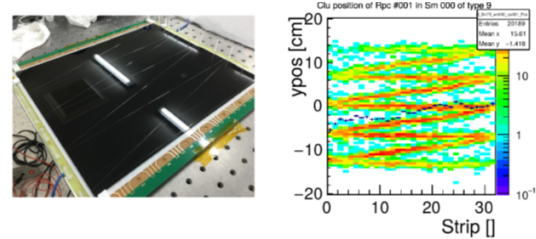


Figure 1: A naked-eye inspection of the returned MRPC2.

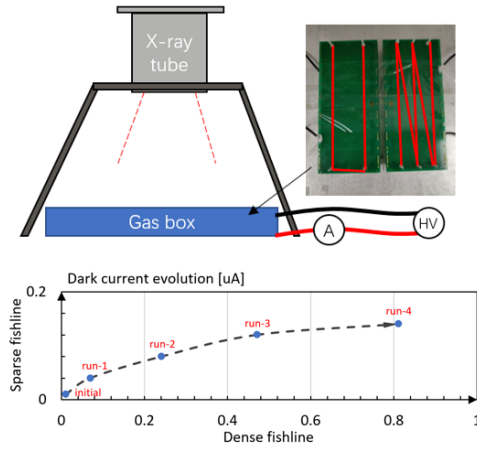


Figure 2: Upper: Setup of the comparative study. Lower: Dark current (24 h after exposure) evolution of two prototypes during four cycles of irradiation. Currents were measured by the HV power system with a precision of 10 nA.

This work aims to mitigate the spacer effect by achieving marginal improvements on the sealed MRPC. Mylar film has been chosen as a candidate of spacer material. It has a bulk resistivity at a level of $10^{17}\Omega\text{cm}$, higher than fishline. More importantly, by proper cutting techniques we can collect small mylar pieces with rectangular cross section. In this way, not only can we modify the cross section of the spacer, but also the contacting area and the continuity. A sealed MRPC2 has been assembled with mylar spacers of 0.25 mm thickness, $3\times 3\text{ mm}^2$ shape. For each gas gap, a 6×7 array of spacers with 5 cm interval are pasted one-sided on the glass plate. As the same treatment as the former sealed MRPCs, sealing frame and PMMA panels help hold the position of the stack in all dimensions. It should be noted that the bonding material is epoxy for both the spac-

		New glass	Aging glass		
		Arbitrary region	Gap region	Fishline region	Discharge region
Na(%)	Anode surface	14.3	11.2	0.4	0.5
	Cathode surface	14.3	14.4	43.2	28.7
F(%)	Anode surface	<0.1	12.5	20.7	8.4
	Cathode surface	<0.1	10.9	45.1	48.7
	Average	<0.1	11.7	32.9	28.6

Table 1: Summary of the elemental analysis.

ers and the sealing chamber. Figure 3 shows the pictures of the detector assembly and the finished prototype. The prototype was first tested in cosmic rays in order to examine the performances. A plateau efficiency of 93% is measured and the efficiency reaches 96.2% at 5.7 kV. Accordingly, time resolution reaches 75 ps in working condition.

An X-ray tube was then used to conduct a high-rate test. The counting rate of the mylar spacer prototype was measured by the same readout chain as described in 3.2. The prototype has been tested for three cycles of irradiation under a rate condition of 7.2 kHz/cm². Figure 4 shows the current behavior during and after irradiation. After a likely training procedure, the operating current of the mylar spacer prototype keeps at a stable level for the tested 10 hours. When the X-ray tube is off, the dark currents recover fast to a reasonable level under 100 nA, and there is no significant difference in relaxation observed between the cycles. The mylar spacer sealed MRPC prototype has shown good first results in laboratory. As next steps more prototypes will be assembled for the future in-beam tests.

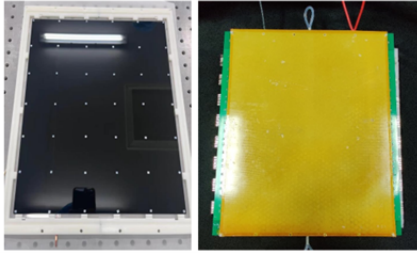


Figure 3: Left: picture taken when stacking the low-resistive glass electrodes. Right: the sealed mylar spacer MRPC prototype.

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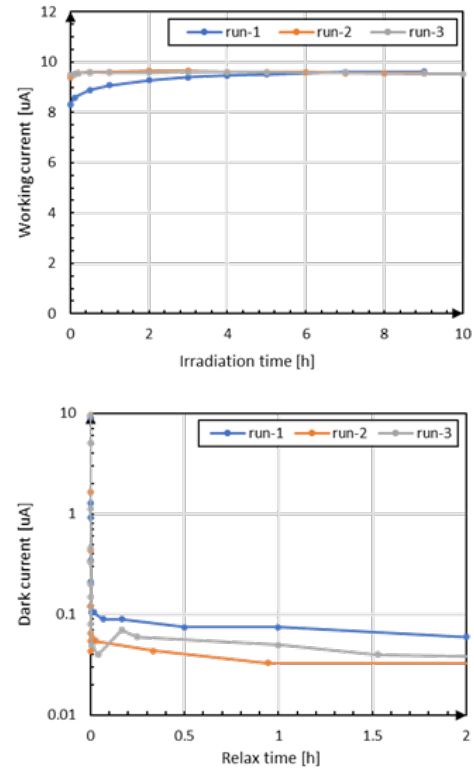


Figure 4: Current behavior of the mylar spacer prototype under 7 kHz/cm² counting rate.

Performances of two new MRPC3/4 prototypes

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Since CBM-TOF is foreseen to work under high flux environment for more than 10 years, new MRPC prototypes have to be developed to decrease the aging effect. In this contribution, we will report the performance of semi-sealed CBM-TOF MRPC3/4 counters, which have been tested under cosmic-ray. Moreover, prototypes with cylinder spacers have been built and tested which may weaken the gas aging effect around the former fish line spacers.

semi-sealed CBM-TOF MRPC3/4

In order to decrease the gas aging effect, a 3D printed sealing frame (figure1(a)) has been used in semi-sealed MRPC3/4 to speed up the gas exchange rate [1]. The working gas mixture is composed of 95% Freon and 5% SF_6 for semi-sealed MRPC3 and 90% Freon, 5% $\text{iso-C}_4\text{H}_{10}$ and 5% SF_6 for semi-sealed MRPC4. Figure 1(b) and 1(c) show the efficiency and time resolution of semi-sealed MRPC3 and MRPC4 respectively. The efficiency reaches 93.4% and time resolution is about 58 ps for MRPC3 at ± 6200 V, and the efficiency reaches 94% and time resolution is about 61 ps for MRPC4 at ± 6200 V. These results indicate that the semi-sealed MRPCs show the same performance as the normal ones.

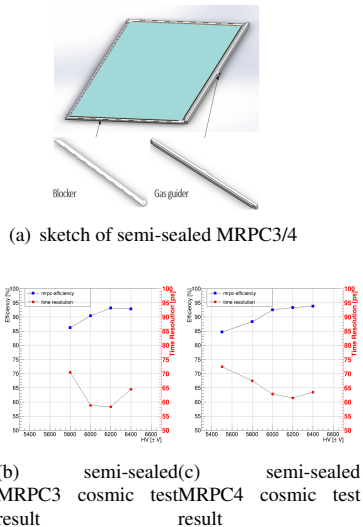


Figure 1: The semi-sealed MRPC3/4

MRPC with cylinder spacers

The electric field intensity around the fish lines is prominently larger than the parallel gas gaps owing to its circular

cross section. But if the normal fish lines are replaced by cylinder spacers, the electric field distribution will be more uniform. On the other hand, fish line spacers block the gas diffusion in the direction vertical to the fish line. In the gas gaps built with cylinder spacers, the diffusion rate will be much faster and the aging effect will decrease accordingly. Based on above considerations, a new MRPC prototype with cylinder spacers has been proposed. 2 mm diameter, 240 μm thick cylinder PET spacers are used to replace fish lines.

The structures of MRPC3/4 with cylinder spacers are basically the same as normal MRPC3/4. The conceptual design of spacers is shown in figure 2(a) and figure 2(b). The interval of spacers is set to 19 mm, which is the same as the interval of the former fish line spacers. In order to check the thickness uniformity of such a structure, the total thickness has been measured after the spacers have been stuck between two glass sheets. The result verifies that the uniformity is excellent.

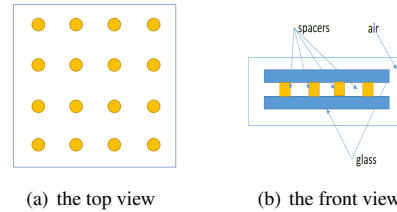


Figure 2: The conceptual sketch of MRPC3 with cylinder spacers.

MRPC3 prototypes with cylinder spacers have been assembled and tested under cosmic rays. The working gas mixture is composed of 93% Freon and 7% SF_6 . The very preliminary results show that the efficiency reaches 95% and time resolution is about 64 ps at ± 6800 V.

Conclusion

In conclusion, two new MRPC prototypes (semi-sealed MRPC3/4 and MRPC3/4 with cylinder spacers) have been developed to cope with the aging effect observed after the high rate operation of MRPC. Both methods show stable performance under cosmic ray test. More studies and tests in terms of performance, aging and material stability will be executed in the future.

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Status and performance of the EToF detector at STAR

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The Endcap-Time-of-Flight (EToF) detector at STAR is composed of 108 MRPC's designed for the CBM experiment and was successfully operated during the Beam-Energy-Scan II (BESII). Over the course of the last year, the calibration and production of several datasets featuring EToF made significant progress and further improvements on the systems performance could be achieved. The results presented here are from the most recently produced RUN20 Collider-Mode datasets at Energies of 11.5 GeV and 9.2 GeV $\sqrt{s}$. During April and September of the RUN20 data acquisition, two events caused damages on the Front-End-Electronics (FEE) which resulted in a loss of read-out efficiency. The 11.5 GeV dataset is unaffected by this damage while the 9.2 GeV showed clear signatures of efficiency losses. The Matching-Efficiency at 11.5 GeV is in the plateau region at momenta $p > 1$ GeV at roughly 70% (see Fig. 1). The Matching-Efficiency is defined as the fraction of TPC Tracks, intersecting the active area of EToF, that could be successfully matched to EToF Hits. The 9.2 GeV data show with about 50% Matching-Efficiency a loss of 20 %, however the time resolution is unaffected by the damage (see Fig. 2).

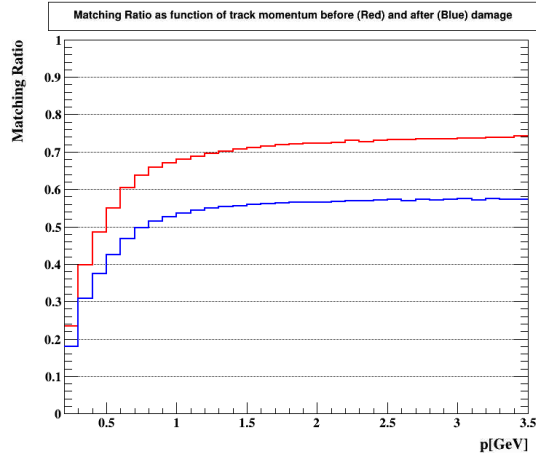


Figure 1: Matching-Efficiency pre FEE-damage (red at 11.5 GeV) and afterwards (blue 9.2 GeV).

The full system time resolution benefited from an improved start-time resolution (now in the order of 22 ps) and is on average at about 75 ps at 11.5 GeV and at 9.2 GeV with about 72 ps even slightly better. The time resolution is extracted from the difference of measured and expected time of flight for pions in the momentum range $1.0 \text{ GeV} < p < 1.5 \text{ GeV}$. The expected time of flight is calculated from

the STAR start-time, the track momentum from the TPC and a pion hypothesis. The time resolution is then given by the width of this pion band and shown in Figure 2. for all counters for the 11.5 GeV (blue) and the 9.2 GeV (red) dataset.

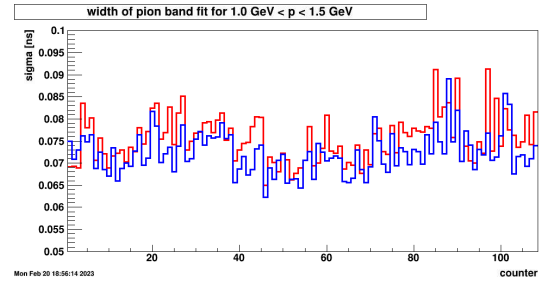


Figure 2: System time resolution for each counter at 11.5 GeV (red) and 9.2 GeV (blue).

With a full system time resolutions around 75 ps EToF is now below the benchmark of 80 ps it was originally aiming for. For the 11.5 GeV this enables kaon/pion separation for momenta of over 2 GeV (see Fig. 3)

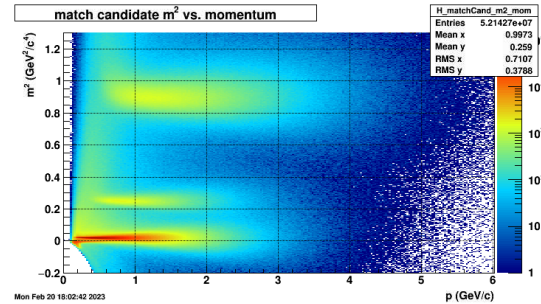
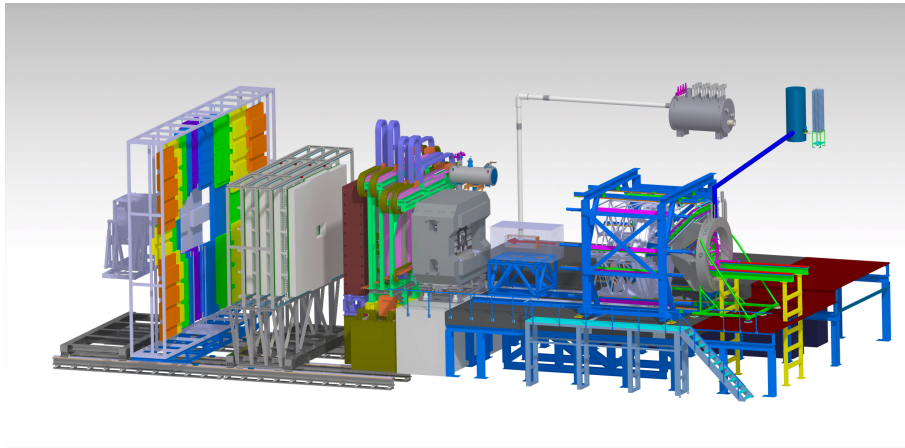


Figure 3: m^2 vs. momentum at 11.5 GeV.

Improvements on the software included an upgraded correction algorithm for clock instabilities and the Track-Hit matching algorithm is under revision at the moment, aiming for a reduction of miss-match based background. This might prove especially valuable for the RUN20 fixed-target runs, which are next in line for production and rely heavily on EToF for particle identification. To gain a better understanding of cause and effect of the electronics damage, in March 23 the FEE's of one of the 12 EToF sectors will be replaced. The new version of the FEE's is equipped with an improved protection diode to minimize the possibility of future damages.

Infrastructure



The superconducting dipole magnet of the CBM experiment

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After the Russian attack on Ukraine and the subsequent sanctions against Russia resulting in the cancelation of the Russian in-kind contributions to FAIR, the GSI/FAIR management defined a list of high priority projects including the CBM magnet, which should be financed by available project funds. This decision paved the way for the call for tenders for the magnet.

The central document of a call for tenders is the Detailed Specification (DS) of the magnet. In order to benefit from the expertise of the bidding companies, a functional specification was written, in close collaboration with the expert groups from GSI. The requirements include:

- Warm iron yoke (vertical and horizontal beams)
- Warm cylindrical poles
- Removable field clamps
- Cylindrical NbTi coils wound on cylindrical bobbins, cooled with LHe
- Conductor with a Cu/NbTi ratio larger than 6.0
- Thermal shield cooled with Helium gas (50-80 K)
- Two independent coil casings and one cryostat
- Vertical forces transferred from the coil casings to the coil vacuum vessel and finally to the yoke
- Maximum field 1 T, field integral 1 Tm (-0.5 m to + 0.5 m)
- Fringe field < 10 mT at the location of the photodetectors

In particular, the coil cooling concept (indirect cooling or He-bath) and the technical solution for the compensation of the vertical forces between coils and yoke (equivalent to 300 t) is not specified, but should be designed and realized by the company. Moreover, geometrical boundary conditions have been defined:

- Magnet minimum free aperture: 1.47 m vertically x 3.30 m horizontally
- Free minimum vertical space at the position of the field clamps: ± 0.76 m
- Free space upstream of the magnet: > 2 m
- Magnet maximum size approx. 4.7 m x 3.73 m

- Maximum magnet length: 2.0 m without field clamps, 2.38 m with field clamps on both sides
- Maximum total weight of the magnet (including stand and feet): 200 t

The gap of the magnet has been slightly enlarged with respect to the previous design in order to accommodate the increased size of the modular STS. Moreover, the components and the location of the cryogenic system have been defined. The branch box distributes the Helium to the feed box of HADES, while the feed box for CBM is integrated in the branch box. The liquid Helium is transported via a transfer line to the cryostat, which is mounted on the CBM magnet yoke. The arrangement of the cryogenic system is sketched in Fig. 1.

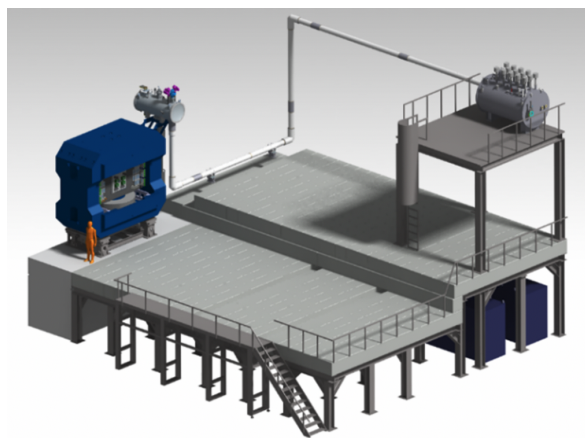


Figure 1: Sketch of the magnet including the cryogenic system with branch box, transfer line and cryostat

Preliminary magnetic field calculations for the new magnet geometry with the enlarged gap have been performed by the RICH group in Wuppertal using the COMSOL Multiphysics software package. The results are shown in Fig. 2. According to the calculations, the fringe field at the position of the photodetectors (boxes in Fig. 2) is within the required limits.

The call for tenders has been announced, and the deadline for offers is 22.02.2023. After selection of the company and negotiations on the deliveries, the contract may be concluded mid 2023. The Conceptional Design Review is planned for 6 months later, the Final Design Review 12 months later, and the Factory Acceptance Test 30 months

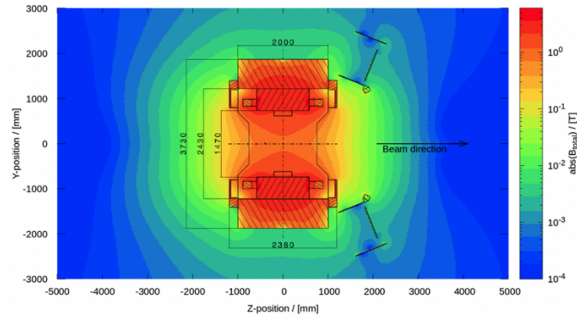


Figure 2: Magnetic field (absolute value) distribution in the y-z-plane at $x = 0$. The boxes correspond to possible positions of the RICH photodetector.

after conclusion of the contract. The shipment of the magnet to FAIR, the Site Acceptance Test, and the final acceptance of the magnet at FAIR will take another 6 months, so that the magnet might be ready for use mid 2026. Before installation of the STS, the mapping of the magnetic field has to be performed for several currents.

Status of diamond and LGAD based beam-detectors for the CBM experiment

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Introduction

In this report the activities in 2022 around the monitoring system (BMON) for the CBM experiment will be summarised. We will discuss progress made for the high-speed time-zero (T0) and beam halo system (HaloBAS). The detector system must meet the requirements of the time-of-flight (ToF) measurement for beams of protons and heavy ions. The system should have a time precision of better than 50 ps (sigma) and allow stable long-term detector operation at high interaction rates up to 10^7 particles/s maintaining a detector efficiency at 100%. The detector technology planned for CBM Day-1 physics is chemical vapour deposition (CVD) diamond [1], but also new Low Gain Avalanche Diode (LGAD) [2] technology is under consideration.

The CBM beam monitoring and T0 concept for Day1

The BMON system [3] will consist of two detector stations located in front of the CBM target chamber. The T0-station is foreseen to measure the start time of the reaction, while the halo-station will be used for beam halo monitoring. Both systems are currently build-in into the technical drawings of the CBM beam-pipe and a system is developed which allows a moving out of the T0 sensor in case CBM will run with rates higher than 10^7 particles/s. Both detectors will be integrated into the CBM beam-pipe using commercially available vacuum elements, as schematically shown in Fig. 1.

The sensor of the T0-station, currently planned on polycrystal CVD (pcCVD) diamond technology, will cover the area of $1 \times 1 \text{ cm}^2$ and is equipped with a metallization arranged in 16 strips on both sides. The strip segmentation and orientation, will be orthogonal, which allows to extract a position information of the beam particles. The halo-station is foreseen to be used as an independent beam monitoring system. The halo detector will consist of a mosaic arrangement of four sensors, each metallized with four strips on both sides. The sensor arrangement is schematically shown in Fig. 1. This composition allows to monitor the beam position and its rate during the experiment. The BMON System is also planned to be used as part of a fast beam-abort-system.

The read-out scheme of the CBM T0 detector is schematically shown in Fig. 2. As discriminator, the PADI ASIC[4] is used and as a Time-to-Digital-Converter

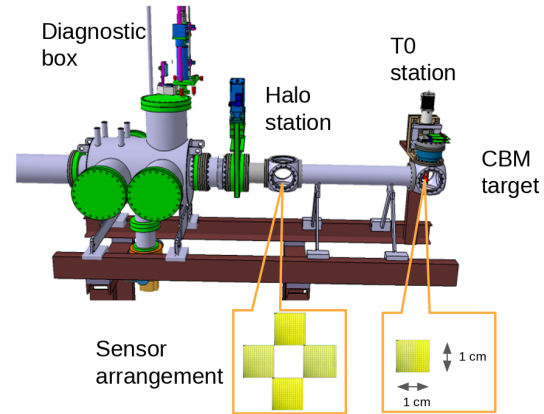


Figure 1: Schematic illustration of the CBM BMON system, located in-front of the CBM target. Two stations of beam detectors will be used for beam halo and T0 measurement and are mounted in standard CF 100 vacuum chambers. For the T0 measurement a single sensor will be used and for the halo measurement a mosaic structure of four sensors is foreseen.

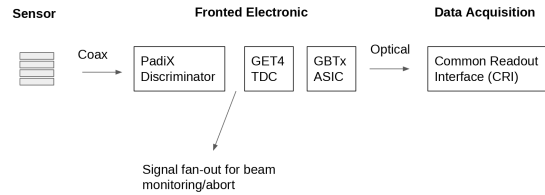


Figure 2: Planned readout scheme of the double sided T0 sensor. In total, 32 detector channels are read out by 16 GET4 ASICs in order to achieve the maximum rate capability. Data of the eight GBTx is sent to a single CRI board. An LVDS fan-out of the detector signal is needed for an “stand-alone” beam monitoring system.

(TDC), the Get4 ASIC[5]. In total, 32 analogue detector channels of the T0, and the halo detector, will be read out by 32 GET4 ASICs in order to achieve the maximum rate capability, which is 14 MHz per ASIC. Data of the eight GigaBit Transceiver ASICs (GBTx) is sent to a single Common Readout Interface (CRI) board. It is planned to implement a signal fan-out after the PADI discriminator in order to provide a beam monitoring functionality, which can run independently from the CBM DAQ system.

A detailed description of the BMON concept will be

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described in the Conceptual Design Report (CDR), which will be available in the early 2023.

T0 detector prototype tests at the mCBM experiment

A prototype sensor which is foreseen to be used for T0 measurement has been prepared using pcCVD diamond material. It has an active area of $1 \times 1 \text{ cm}^2$ and a sample thickness of $70 \mu\text{m}$. The sensor is equipped with a double-sided strip segmented metallization (16 strips, each $300 \mu\text{m}$ wide). In total sixteen channels in x -direction and sixteen channels in y -direction on the other side allow beam profile measurements. The sensor should be able to deliver a time precision better than 100 ps (RMS) for heavy ions and can handle rate capabilities up to 10^7 particles/channel·s, which is the limit of the planned read-out system. A close-up picture of the sensor is shown in Fig. 3.

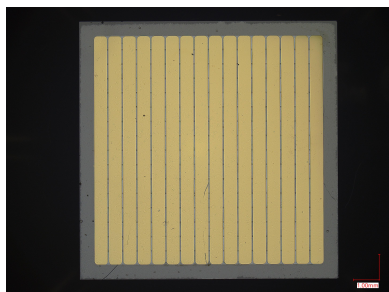


Figure 3: Close-up photograph of the pcCVD diamond based prototype sensor for the T0 measurement. The metallization is arranged in 16 strips (each $300 \mu\text{m}$ wide) on the front and back side which allows beam profile measurements [3].

A prototype T0 detector has been build and tested during mCBM benchmark runs. The T0 detector is based on the described pcCVD diamond prototype sensor. A photograph of the detector is shown in Fig. 4. The T0 detector was successfully used as a beam monitoring tool located in front of the mCBM target. In May and June 2022 the detector system has been operated with Nickel and Gold beams, where a stable operation could be demonstrated. An on-line beam profile is shown in Fig. 5 which shows clearly the beam spot and the beam halo. A detailed data analysis of the recorded T0 data is currently being prepared.

Research and development of LGAD technology for proton beams

Beam detectors based on Low Gain Avalanche Diode (LGAD) technology allow high precision timing and position measurements paired with a high radiation hardness and low production costs. These properties make them a promising candidate for in-beam detectors. At the moment we are actively investigating the possibility to use LGAD



Figure 4: Prototype T0 detector build for the mCBM experiment. The diamond sensor is bonded on a PCB which is pneumatically driven into the beam-line in front of the target [3].

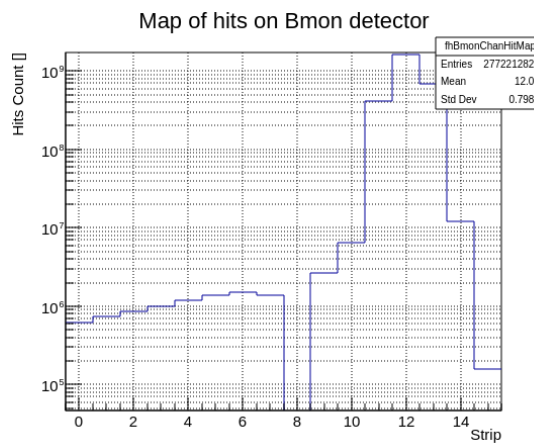


Figure 5: Beam profile measurement using the prototype T0 detector in mCBM. The focused beam has its maximum at strip no. 12, a beam halo is visible on strips no. 0-9. Strip no. 8 shows no data due to a bulk material problem [3].

technology especially for proton beams in the CBM experiment.

Using highly segmented LGADs, timing precision below 50 ps could be demonstrated [6]. Recently a successful operation of LGADs as a T0 and beam-monitor detector in the HADES experiment, utilizing a 4.5 GeV proton beam, was achieved [7]. In HADES two $2 \times 2 \text{ cm}^2$ orthogonally arranged, single-sided LGAD strip detectors with a sensor pitch of $387 \mu\text{m}$, a total thickness of $200 \mu\text{m}$ and a fill factor of 94% each, have been used. A smaller geometry $0.5 \times 1 \text{ cm}^2$ from the current LGAD sensor production was used as a beam monitor for the S-DALINAC at TU Darmstadt, Germany [8]. The main goal was to resolve the 3.3 GHz time structure of the electron beam, corresponding to a time difference of 333 ps between the bunches. The time difference between consecutive particle events, measured in two different channels of the sensor, was determined. After implementing a dedicated calibration procedure, a mean time difference of 333.4 ps was obtained, which is in perfect agreement with the expected time structure of the S-DALINAC electron beam. End of

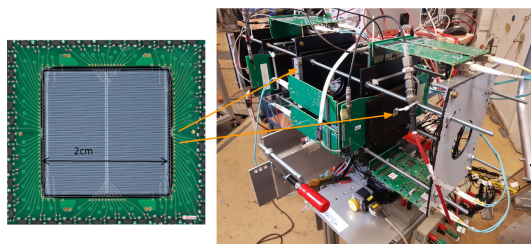


Figure 6: In total, four $2 \times 2 \text{ cm}^2$ single-sided LGAD strip detectors with a sensor pitch of $387 \mu\text{m}$, and a thickness of $200 \mu\text{m}$ have been installed in a telescope set-up

2022 a new telescope setup with four LGAD sensors with the $2 \times 2 \text{ cm}^2$ geometry has been successfully installed and tested at TU Darmstadt with electron beam. A photograph of the LGAD sensor and the telescope set-up is shown in Fig.6. The recorded data is currently being analysed.

Summary and outlook

The concept of the CBM BMON detector consisting of T0- and halo-station has been prepared. Currently the system is planned to be based on pcCVD diamond technology. It will be used for T0 measurement and beam monitoring purposes. A prototype T0 detector based on pcCVD diamond material has been prepared and installed in the mCBM setup. The detector was successfully used for beam monitoring purposes and to provide a T0 information in the data stream of the mCBM experiment. A systematic data analysis is currently ongoing. For the future we plan further tests at the mCBM facility. In parallel to the development of CVD diamond based sensors we will evaluate LGAD technology for its use in the CBM experiment.

Acknowledgements

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Target exchange device for the CBM experiment at FAIR

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During the year of 2022 the development of the Target Exchange Device, first presented in [1] has been ongoing. The Mounting and movement of individual target shells has been refined, a drive mechanism is chosen and the conceptual design of a vacuum vessel for integration into the beamline has been completed. Prototyping has been integrated in the iterative design process and will continue in 2023, to achieve a mechanical demonstrator. This report shall mainly focus on a few key differences and changes in the design.

Shell housing - In the prototype presented earlier, the shells are simply clamped by compliant mechanisms - that is to say, the fittings between the wheel and the shells have been chosen such, that the wheel holds on to the shells without external drive simply by the spring forces of flexing the material. This leads to the tricky situation of having to transfer the shells from the magazine wheel to the shifting bolt and back to the wheel. While the current design still only uses a single shifting bolt, this bolt now does not have to clamp the shells. The task of guiding and holding the shells has been incorporated in the shell housing which is now part of the magazine. While this adds some material in the outer regions of the beam, it cuts down on failure points and makes it easier, to provide shielding for irradiated targets.



Figure 1: Housing for a target shell.

Pneumatic drive - The previous design used a single pneumatic cylinder to drive both the rotation of the magazine and the translatory movement of target shells into the measuring position. While this is already a much simpler design than originally envisioned, the necessary gears of the

Geneva drive provide a point for potential failure and would require maintenance. Furthermore, the required stroke lengths for rotation and translation are now so vastly different due to the design of the vacuum vessel, that it is ultimately better to decouple the two systems and use an individual cylinder for each of them. For the translatory movement of shells, two cylinders have been added close to the primary beamline. The use of two cylinders is purely for safety reasons since the exerted forces are so low, that either cylinder would be able to drive the system on its own.

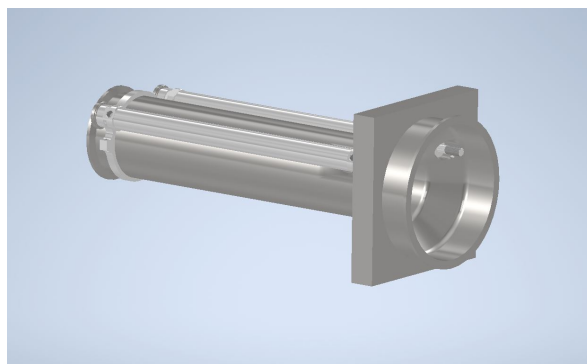


Figure 2: Pneumatic cylinders mounted to a section of the vacuum vessel.

Vacuum vessel - The vessel has been designed to be manufacturable from a wide range of materials but envisioned to be made from carbon fiber or other composites in order to save weight. It features a drum style vessel for the magazine, that can be pressure tested individually and a tubular part incorporating the shifting bolt, that is integrated into the beampipe and can disconnect the magazine with only a few manual actions.

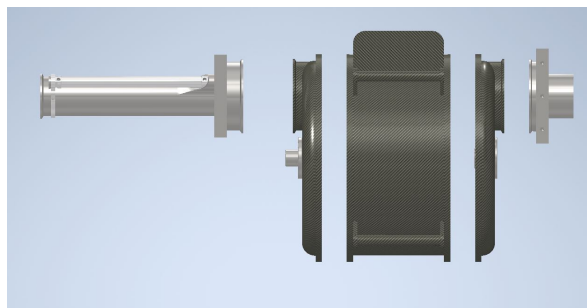


Figure 3: Sections of the vacuum vessel

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Simulations - While it was planned to integrate the simulation process into the development from the start, the amount of design changes in the past have made it infeasible, to produce GEANT geometries for all versions. Now that mechanically feasible design is produced, more work can be invested in GEANT simulations. For ease of use and also for the benefit of other CBM subsystems, an automatic conversion from CAD data to GEANT data should be developed. This is however an extensive project requiring lots of research time.

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Status of mechanical infrastructure of CBM

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The 2022 was crucial for the CBM experiment in many aspects. The shell construction was almost fully finished, i.e. only the very roof of the building is still under construction. Also connecting tunnel to the SIS-100 is finished and ready for installation. The first crane inside of the CBM Cave was installed and is now available for the installation works within. On the other hand, 2022 was also very disruptive for the CBM and FAIR project as whole w.r.t. the consequences of Russian aggression on Ukraine. While Covid pandemic influenced the collaboration work through some delays, the cancellation of all contracts and collaborative activities with Russian institutions left a void within the collaboration that still needs to be filled up. In particular no Russian contribution to the common mechanical infrastructure was contracted, but some detector subsystems were severely affected, PSD is discontinued, and CBM dipole has to be re-ordered from another supplier.

Another effect of the events in past year was steep rise of prices in general, which makes revision of present installation plans necessary and re-planning, as long as prices do not stabilize, more challenging. Due to missing funds the installation of experiment infrastructure is now under revision in order to provide plausible installation stages where possible. From three major mechanical installation parts: upstream platform, rail system, and RICH-MUCH foundation, development of the later is now suspended while no complementary developments are being made for RICH and MUCH at the time.

The upstream platform CDR [1] for steel structure support, cf. Fig. 1, was accepted and the CTU has provided static calculations for it. The design was frozen and tendering started. The contract will be signed in 2023 and installation should take place in Q1/2023. Also the change request was filed with FSB to add the concrete foundation for CBM dipole into the cave. This was accepted by the management and planning will be carried over by FSB and concrete casting by the building construction company. It is expected that magnet foundation will be available in Q2/2023. In order to finish the upstream platform, shielding (movable) concrete blocks will have to be ordered and brought to the cave, however, for installation the unloading crane in the entry hall of CBM building has to be available and according to present planning that take place in the 2nd half of 2023. Also access road to the building should be finalized around the same time.

After the first tender for rail system in 2021 was canceled due to elevated costs, the new concept was developed

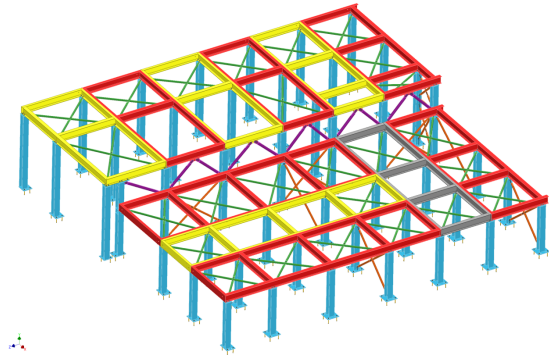


Figure 1: The steel structure of the upstream platform, optimization was made w.r.t. expected loads of full HADES detector including calorimeter (M. Janda).

with less demanding installation requirements. It was discussed with and approved by TRD and TOF groups that are directly influenced by changes. Instead of machined rails with fixed block sliders, the common crane rails with steel wheels, cf. Fig. 2, will be used. The mounting will use standard H steel profiles that will be anchored into floor. Also the sub-frames i.e. carriages that are carrying support frames for detectors are newly developed introducing a concept for detector frame leveling. The new tender will be issued in 2023 after announced project re-baselining.

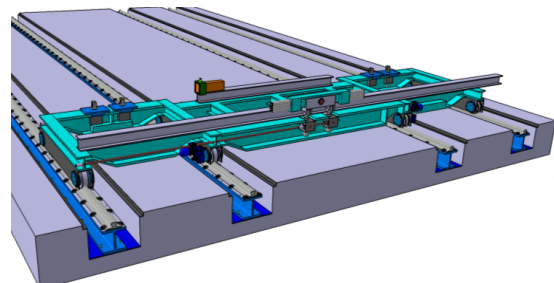


Figure 2: Concept for the rail system using standard DIN 536 crane-rails and corresponding wheels (J. Thaufelder).

Most development for the beam line was paused during 2022, nevertheless, the carbon fiber pipes for the downstream part of the beamline behind RICH/MUCH are being procured by CTU.

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CBM Beam Pipe*

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Overview

This contribution directly conveys the articles concerning the experimental infrastructure within the CBM Progress Report 2021. [1]

During the period of the year 2022, the mechanical design of the Downstream section of the CBM beam pipe (PSD Beam Pipe) was finalized and its production started. Furthermore, the beam pipe GEANT4 geometries were developed for the physics simulation purposes. The pumping devices and their placement were introduced in relation to the vacuum studies of the CBM beam pipe. First design of supporting frames for CBM beam pipe has been introduced but the concept needs an improvement based on the issue of the vacuum forces balance within the beam pipe.

Bending connector

The latest trend in the design the bellow assembly is to reduce the weight of its components as much as possible. Therefore, composite materials represent a fair alternative to metallic materials. For example, the main contribution in the material budget reduction will be substitution of steel flanges of the bellow for carbon fibre composite pieces with glued screw inserts for connecting mating parts of the beam pipe. Crucial for further research will be testing of the glued connection of steel end tube of the bellow weldment with the composite flanges. The changes concerned also the design of the kinematic mechanism support plate.

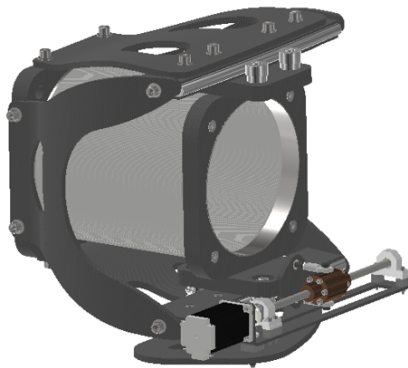


Figure 1: Bending connector assembly

* Work supported by The European Union's Horizon 2020 research; Project infrastructure program under grant agreements FAIR-CZ LM2018112 and LM2023060 and FAIR-CZ-OP II. CZ.02.1.01/0.0/0.0/18_046/0016066

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Downstream area of CBM beam pipe

The CBM Beam Pipe is a composite tube with carbon fibre reinforcement and resin matrix, that provides the isolation of charged particles, produced by the particle accelerator SIS100 colliding with the target material. The parts of the PSD beam pipe are in production, which will be finished till the end of April 2023. The beam pipe was designed as a self-supporting thin shell. The wall-thickness is 3 mm and the inner diameter 180 mm. Different lengths of its segments allow to change the position of connections to vacuum pumps and measuring equipment along the experimental setup. The beam pipe is a mechanical vacuum system with inner underpressure. Therefore, the below described analysis has been performed.

Since all particles have an impact on the results of the measurement it is necessary to keep the total amount of the particles within the beam pipe system as low as possible, which is guaranteed by high vacuum inside the beam pipe of $\approx 10^{-4}$ mbar. The comparison of analytic calculations and simulations performed via the MolFlow software developed by CERN have been done in order to provide a reliable vacuum analysis.

The software works on the following principles. Each particle is generated on one side of an object and the probability of its flight direction is determined by cosine distribution during pumping. A few particles can pass straight through the entire pipe, but the majority will hit the surface, stick to it for a very brief moment, and then continue in a random direction from the inner surface of the tube. The angle of incidence for a particle in a vacuum is not equal to the angle of reflection, but it is given by the cosine distribution. Transition probability is then given by the ratio of absorbed particles in the pumping area to the desorbed particles on the opposite side. [2]

In our specific case, the simulation of the vacuum distribution was related to the whole downstream area of the CBM beam pipe. The pumping speed at the inlet A was assumed 30 l/s and at the inlets B and C were 55 l/s. The inlets B and C are perpendicular to the beam axis, the inlet A is parallel to the beam axis. Their positions are in Fig. 2. The outgassing rate $q = 10^{-6} \text{ hPa} \cdot \text{l} \cdot \text{s}^{-1} \text{ cm}^{-2}$ was assumed. [3] Our goal was to figure out the distribution of the pressure inside the beam pipe and use this knowledge for future designs of the vacuum system. In the Fig. 3 is depicted a model of a detailed vacuum distribution

within the downstream area of the CBM beam pipe with 3 operating pumping stations created in the MolFlow software.

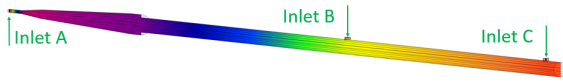


Figure 2: vacuum inlet positions of downstream beam pipe

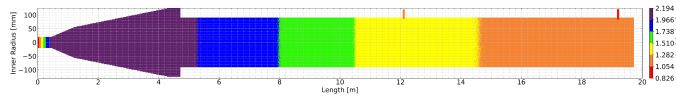


Figure 3: Vacuum distribution along beam pipe for case with 3 pumps (A+B+C)

Furthermore, several simulations of the vacuum distribution for different combinations of the activated pumps in different positions have been done in order to determine the pressure profiles along the beam pipe axis. According to the results in the Fig. 4 it is evident that the best solution is using of all 3 pumps. The lowest pressure occurs at the ends of the system at the positions of the inlets A and C. The highest pressure is in the conical part at $Z \approx 0.7m$, because the vacuum pumps B and C are too distant from this point with highest pressure and the vacuum conductance at the beginning of the beam pipe at the inlet A is low. Our next step will be to discuss whether it would be worth decreasing the amount of pumps in order to reduce the material budget at the expense of lower vacuum quality.

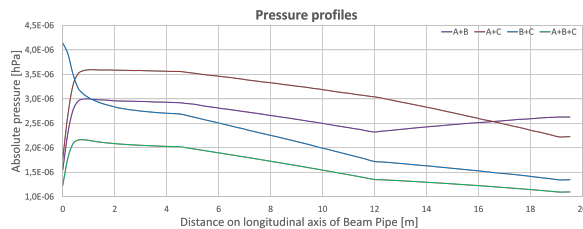


Figure 4: Pressure profiles

Experiments

A few small specimens of carbon fibre tube were tested for the resistance under irradiation as well as vacuum conditions. The experiment was performed due to TR-24 Cyclotron in the Irradiation chamber of the Nuclear Physics Institute of the Czech Academy of Sciences. [4]

In order to prove the stability of the CBM beam pipe, one specimen with the real dimensions of one segment of the beam pipe had been produced (Fig. 5). The test was successfully performed under vacuum conditions and strain measurements of the tube were done.



Figure 5: Specimen of beam pipe segment

Geometries for simulation purposes

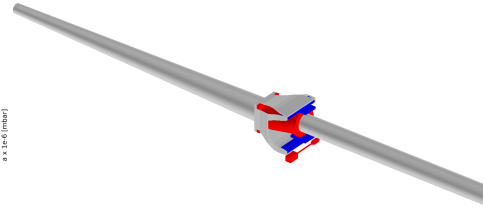


Figure 6: GEANT representation of beam pipe geometry

In terms of the physics performance of the infrastructure, it is necessary to perform Monte Carlo simulations with defined geometry and material of all components. Therefore, the parts of the beam pipe were transformed into the GEANT geometry. The aim is to find a balance between the demands on both mechanical stability and material budget of the beam following components. During the last period, 4 different positions of the downstream section of the beam pipe were prepared, which is related to defining of different deformations of the bellow.

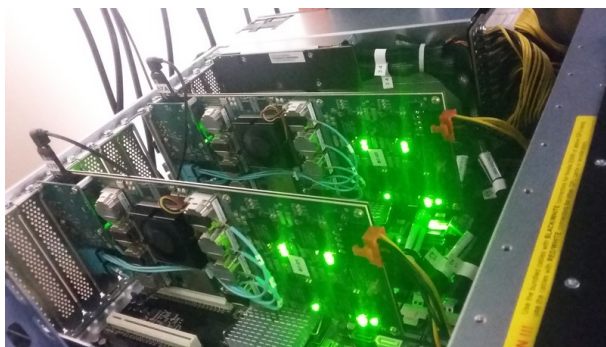
Prospect

The main challenge for further research is balancing of axial vacuum forces acting on the beam pipe support structures that impact on huge frame dimensions which is necessary to reduce with respect to the positioning of the downstream detectors. This issue is related to the new design of the support structures at the end of the CBM beam pipe. The focus will be put on the bending assembly, where it is necessary to reduce the mass of its components.

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Data Acquisition and Online Systems



FPGA-related development for CBM DAQ * †

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Development of the GERI-based readout for test sites

The GERI board is an alternative commercial board suitable for communicating with the GBTxEMU or ROB-3 boards and reading the data from the front-end ASICs.

In 2022 the HLS-implemented DMA engine for the GERI board was finally completed. Its development was associated with creating the sophisticated test architecture enabling thorough testing of the model of the DMA engine together with the kernel driver and the application in QEMU [1]. Also, the simplified data aggregation tree was developed for GERI, where the raw ASIC data with the origin marker is split into packets based on arrival time. The GERI firmware containing those components has been integrated and tested in the test stand in GSI. Additionally, the firmware and accompanying firmware have been passed to the group from the Technical University of Darmstadt, which prepares the readout chain for the PFAD [2] experiment.

Preparations for the CRI2-oriented readout

Preparing the technical requirements for the new CRI2 boards is associated with developing a new FLIM interface and a compatible aggregation tree. One of the goals is to provide the possibility to aggregate the data from multiple links with bandwidth sufficient to transfer all the incoming data to the FLIM input buffer. The first assessments have shown that 32-bit data from 9 GBT links should be aggregated to the 256-bit FLIM words. A simple assessment of input and output bandwidth shows that it is possible. The calculations are based on the assumption that the 30-bit 8b/10b-encoded E-Link data frame is converted into a 24-bit data word, which is later extended to a 32-bit output word. The input data bandwidth:

$$\frac{9 \text{ GBT links} \cdot 14 \frac{\text{E-Links}}{\text{GBT link}} \cdot 320 \frac{\text{bits}}{\text{s}}}{30 \frac{\text{bits}}{\text{data}}} = 1344 \frac{\text{Mwords}}{\text{s}}$$

is lower than the available FLIM input data bandwidth:

$$8 \frac{32\text{-bit words}}{\text{FLIM word}} \cdot 250 \frac{\text{FLIM words}}{\text{s}} = 2000 \frac{\text{Mwords}}{\text{s}}$$

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† The authors acknowledge contribution of Bartosz Zabolotny from Warsaw University of Technology, who suggested the solution based on Benes network.

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However, even though the problem is solvable, the solution is not trivial. For efficient readout, it is necessary to eliminate the dummy hits and other non-data frames from the incoming frames. The trivial solution would be to browse the input data using the round-robin approach and fill the output word with the desired data. A queue with 32-bit input and 256-bit output could be used for that purpose. Unfortunately, that would require browsing the data from GBT links at the frequency of 1344 MHz, which is impossible.

The problem of arbitrary routing of data words is well known. One possible solution is the Benes network [3]. The aggregator may collect the 9-word data at the frequency of 160 MHz, combine them into 18-word sets, and then process them as a three 6-word sets by 6x8 Benes network. The block diagram of the proposed solution is shown in figure 1. Of course, the open question remains the de-

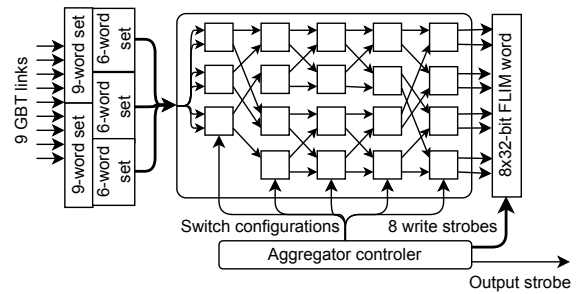


Figure 1: Block diagram of the proposed data aggregator based on the Benes network.

sign of the aggregator controller that controls the switches in the network and generates the write strobes and the output strobe based on the known states of the network, the output word, and the input data.

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Status of CRI2 Prototyping

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Overcoming limitations of CRI1

CRI1 cards require an architectural update, due to the Avago Minipod transceivers entering an obsolete production-cycle phase [1]. Also, the XCKU115 FPGA used in CRI1, requires a PEX 8732 PCIe switch, to connect two x8 PCIe links into a single x16 link. The switch adds a layer of complexity that could possibly lead to reliability issues concerning link establishment. The solution for the above concerns is to proceed with a newer version for CRI, that also aims at improving the testability and self-remedy booting mechanism [2].

Tandem-boot testing on 3 different hosts

A prototype HTG-Z920 board is used to test x16 PCIe GEN3 link, with tandem booting. This feature allows the PCIe related logic in the bitstream file to be booted before the rest of the firmware logic, thus decreasing the FPGA boot time.

Three different candidate hosts were chosen to test the PCIe tandem-boot operation, where the enumeration time windows differ. The HTG-Z920 proved to be capable of enumerating as a full x16 GEN 3 PCIe link in all of the three hosts, using the tandem image. Mainly tested were:

- devel12 - ASUS ESC 4000 E10 (Intel)
- devel100 - ASUS ESC 8000 G4 (Intel)
- devel102 - ASUS ESC 8000 G3 (Intel)

Preparation for GTY transceiver testing

Another critical feature to be validated is the usage for GTY transceivers with the GBTx data rate. Since the chosen XCKU15P FPGA for implementation in the final CRI2 version does not have enough number of GTH transceivers to accomodate all the planned three FireFly connections, it will be needed to move at least one FireFly connector to the GTY side. Therefore, it would be necessary to ensure that there are no timing violations that come as a result of migrating from GTH.

A hardware setup consisting of the HTG-Z920 card with a mounted QSFP+ module, that is connected to GTY quads, is built as shown in figure 1. In terms of mechanical fitting, it was possible to install the card with the mounted module in the host: devel102. Next step is to modify the CRI1 firmware, to handle the new GTY transceiver.

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Figure 1: HTG-Z920 board with a mounted QSFP+ module for testing GTY functionality

Fixing software and hardware issues

On the software side, the Zynq SoC on the HTG-Z920 was programmed with a BOOT.bin, having the three partitions: First Stage Bootloader (FSBL), Platform Management Unit (PMU) firmware and the x16 GEN3 PCIe bitstream file, respectively. The FSBL and the PMU were generated from the default application in Xilinx Vitis 2021.2. The function: `usleep(XFSBL_PL_PWRUP_WAIT_MICROSEC)`; was commented in `xfbsl_bs.c`, to prevent a boot hang. In addition, the security isolation of the PCIe core is removed in Xilinx Vivado, so that all ARM cores can access the UART. Finally, the Flash-ROM was only programmable through Xilinx SDK 2017.3 in x4-Parallel-QSPI format, where newer Xilinx Vitis 202xx.x tools failed to identify the ROM on the HTG-Z920.

For the hardware, a 10nF capacitor is soldered on the C200 placeholder slot, in order to delay the assertion of PS_POR_B and PS_SRST_B, to meet the power sequencing requirements of the ZYNQ. Moreover, a jumper: JP2 was connected to the board, to connect PRSNT#1 and PRSNT#2 signals on the card. When it was left floating, the devel100 host was not able to identify the correct presence of the x16 card.

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SPADIC Level One feature extraction on the FPGA in mCBM *

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Introduction

The SPADIC ASIC used by the TRD in CBM provides an oscilloscope like sampling of the detector signal. A single trigger message can obtain up to 32 ADC samples, in most cases however, this configuration would exceed the link bandwidth by a lot, therefore the samples per trigger are reduced to 5 or 7. By transmitting the entire signal shape a lot of information is encoded in the trigger messages. See [1] for a more detailed specification.

The extraction of the features within one trigger message is what we call *level one feature extraction*, whereas the reconstruction of clusters is called *level two feature extraction*. In the following the implementation of the level one feature extraction in the FPGA will be described.

SPADIC Messages

The SPADIC trigger messages consist of multiple 24 bit frames. One message contains the channel ID, the trigger timestamp, a hit type specifying the trigger source, a multi-hit indicator if the message was triggered during the sampling of a previous trigger, a number of samples indicator from which the number of samples in the trigger message can be calculated, and of course the ADC samples. In the case of 7 ADC samples a trigger message comprises 4 SPADIC frames.

HLS Message Decoder

The decoding algorithm is implemented with C++ High-Level Synthesis (HLS). HLS greatly benefits if as much information as possible is available at compile time. Therefore, using template programming whenever possible improves performance and resource consumption in most cases. As the position of the ADC samples varies between frames and one ADC sample can be split between two frames but is always the same for a given frame number, the extraction of the ADC samples has been implemented using template programming.

The implemented template function is called *decodeRDA* and takes the count of raw data (RDA) frames as the template argument. In the function the bit positions of the ADC samples are calculated and added to the decoded message. In the main decoding state machine the function is implemented as many times as needed for the expected number of RDA frames. This is handled by an unrolling

template function, which recursively calls the *decodeRDA* function. In the end a *struct* with all the information of the trigger message is returned, which can then be used for further processing.

Baseline Correction and maxADC

With the ADC samples available the first steps of the feature extraction, the baseline correction and determining the maximum ADC value, are straight forward. For the baseline correction a feature of the SPADIC is used, which calculates the average ADC value whenever no hit is triggered. The averaged sample is transmitted as the first ADC sample in the trigger message. This sample is subtracted from all the other samples to correct the baseline.

After that, to find the maximum ADC value, the samples are compared within a peaking range and the position of the maximum ADC value is stored. The next step is to reconstruct the trigger time, which is more computationally challenging but still very feasible to do on an FPGA.

Time reconstruction

The SPADIC has a relatively low sampling period of 62.5 ns compared to the other ASICs in the experiment. But as the SPADIC provides multiple samples in a trigger message it is possible to reconstruct a more precise signal time than just the time provided by the sampling.

The SPADIC response function is

$$f(T) = A \cdot \frac{T}{\tau} \cdot \exp -\frac{T}{\tau},$$

$$T = t + \sigma_{ts},$$

where A is the signal amplitude, τ the peaking time, t the sampling bin and σ_{ts} the time shift of the sampling relative to the physical event. The peaking time τ is a hardware constant with a theoretical value of 120 ns, which was used in the time reconstruction. However, mCBM has shown that this value is closer to 160 ns. Figure 1 shows the SPADIC response function at different time shift values.

The time shift σ_{ts} can be calculated analytically with two arbitrary points of the response function. The algebraic

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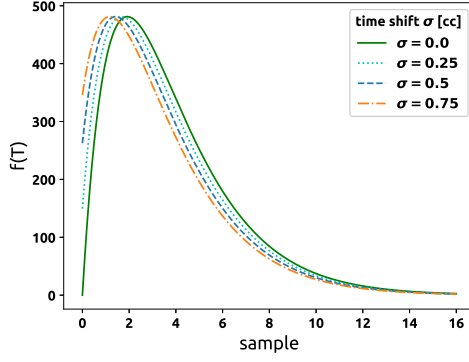


Figure 1: The SPADIC response at different time shift values. The time shift is in values of the SPADIC clock cycle.

steps to solve for the time shift are shown below:

$$\frac{f(T_1)}{f(T_2)} = \frac{T_1}{T_2} \cdot \exp \frac{T_2 - T_1}{\tau}, \quad (1)$$

$$\frac{f_1}{f_2} = \frac{t_1 + \sigma_{ts}}{t_2 + \sigma_{ts}} \cdot \exp \frac{t_2 - t_1}{\tau}, \quad (2)$$

$$\sigma_{ts} = \frac{f_2 t_1 \cdot \exp(t_2/\tau) - f_1 t_2 \cdot \exp(t_1/\tau)}{f_1 \cdot \exp(t_1/\tau) - f_2 \cdot \exp(t_2/\tau)}. \quad (3)$$

Using $t_1 = 0$, this simplifies to

$$\sigma_{ts} = \frac{-f_1 t_2}{f_1 - f_2 \cdot \exp(t_2/\tau)}. \quad (4)$$

The exponential terms in equation 3 can be calculated beforehand, therefore the most complicated operation is just one division, which makes this a viable implementation on the FPGA. And with the auto-pipelining of HLS a very high throughput is easily achievable.

For the time shift a 4 bit unsigned fixed-point number with four fractional bit was chosen. This yields a precision of about 4 ns, which is sufficient for what is achievable with the SPADIC. However, it was shown that in special cases it is possible to have time shifts greater than one clock cycle. Therefore, it is necessary to add one non-fractional bit to the calculation.

Results from mCBM

In the mCBM beam campaign of summer 2022 an FPGA design, which implemented the level one feature extraction side by side to the raw data aggregation tree, was used to test the implementation described above.

Data format and unpacking Without feature extraction each SPADIC frame has a size of 4 B in the aggregated message stream. In mCBM 2022 the SPADIC was configured to transmit seven ADC samples. A trigger message with seven samples consists of 4 frames, totaling 16 B for a single trigger message. The information stored in the feature extracted message adds up to 34 bit. Additionally, an

extended epoch timestamp of 13 bit was added to the message, which should fit for all reasonable microslice durations. In total the decoded message is 6 B large, reducing the size per trigger message by 62.5 %.

In principle it is possible to reduce the message size to 5 B, by reducing the timestamp in the decoded message. But as this would have required additional epoch generation logic and time was constrained the easier 6 B message was chosen.

For the raw data version the unpacker needs $3.03 \mu\text{s}/\text{digi}$, whereas for the feature extracted data it needs $0.09 \mu\text{s}/\text{digi}$. Extracting the features on the FPGA yields an unpacking performance increase of factor 33.6.

Time reconstruction results Figure 2 shows the time difference of a TRD trigger to a T0 trigger. Only TRD triggers with a maximum ADC value exceeding 250 ADU were considered. The broadness of the resulting peak is a measure for the time resolution of the detector. The feature extracted data shows a improvement of 24 %. However, only the rising edge of the peak was fitted to achieve this result, as the peak has a shoulder on the falling, where the time reconstruction seems to fail. The reason for this failure is currently under investigation.

The time reconstruction using a look up table approach was also implemented in software by Marius Kundold [2].

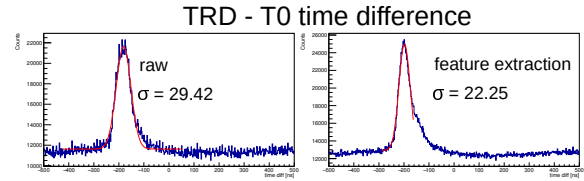


Figure 2: Comparison between the time difference of the TRD to the T0 detector with raw data and with feature extracted data. Recorded in mCBM run 2469.

FPGA utilization and performance FPGA resource utilization is an important factor to keep the cost per input link as low as possible. However, as CBM is a free streaming experiment with the goal of online-event selection a trade off between on FPGA processing and resource utilization has to be found.

Without feature extraction the LUT utilization per input link is 453 LUT/link. With feature extraction it is 516 LUT/link, which is an increase of 13.9 %. The marginal increase in resource utilization is dwarfed by the improvements of the unpacking performance.

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PCIe Performance Evaluation of the FLES Input Interface*

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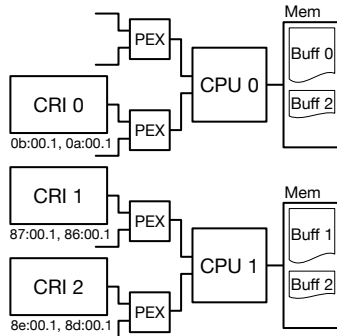


Figure 1: Test system configuration. One CRI was connected to NUMA node 0, while the other two cards were connected to NUMA node 1. The DMA buffers were equally distributed across the NUMA domains.

The design of the FLES entry stage foresees equipping entry nodes with multiple CRI cards, which provide connectivity to the detector systems. A possible scenario is to equip each entry node with three CRI cards and one Infini-Band HCA for network connection. To show the feasibility of such a setup and evaluate the performance impacts of the simultaneous operation of multiple high-speed PCIe devices in one node, measurements with a focus on scaling to multiple sources were performed.

All measurements were performed with a BNL-712 v2 card, which serves as the current CRI prototype, and the generic CRI FPGA design, which includes the FLES interface module (FLIM) [1]. Data was generated by internal pattern generators simulating detector microslice streams. The host system was equipped with two Intel Xeon E5-2650 v4 CPUs and 128 GB of 2400 MHz DDR4 main memory. It supports up to eight x16 Generation-3 PCIe extension cards, two of which each share a PCIe switch on the mainboard.

The configuration of the test system is depicted in Figure 1. Three CRI cards were installed, each connected to a separate PCIe switch. One CRI was connected to NUMA node 0, while the other two cards were connected to NUMA node 1. Each CRI card features two PCIe x8 Generation-3 endpoints, which are combined by an additional on-board PCIe switch to a physical x16 interface. Thus, each physical card is enumerated as two PCIe devices. To mimic a realistic scenario, the DMA buffers were distributed equally across both NUMA domains. The first

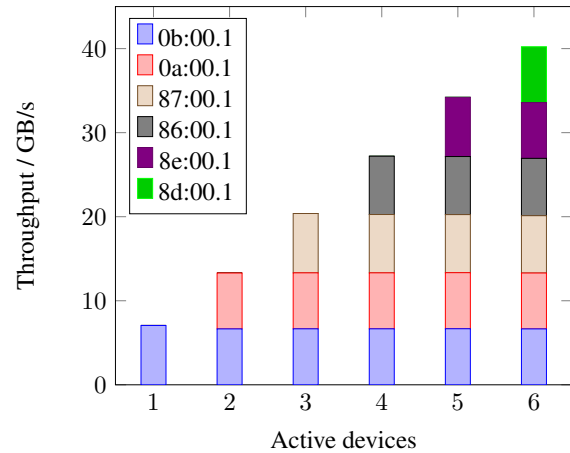


Figure 2: Measured payload throughput for multiple CRIs in one host. Each CRI features two PCIe devices. The total throughput scales nearly perfectly with the number of devices and CRIs.

CRI in each domain only used memory on the local NUMA node. The memory for the second card in domain 1 was interleaved across both NUMA nodes, requiring a certain amount of inter-CPU communication.

Figure 2 shows the achievable payload throughput for different numbers of active PCIe endpoints. The measurement was performed at a microslice size of 100 μ s, a DMA package size of 256 B, and 6 microslice streams per endpoint. The measurement shows a very good scaling of the throughput with the number of devices. A single device reaches up to 7.06 GB/s, which equates to 95 % of the theoretical maximum at the given package size. Throughput per CRI decreases slightly to around 6.65 GB/s when both endpoints of one card are used simultaneously. This effect is not present if multiple endpoints from different CRIs are used, leading to the conclusion that it is a limitation of the PCIe switch of the CRI. The total measured throughput reaches 40.2 GB/s with a fair distribution across all devices. The measurements show that it is possible to operate a host with 3 CRIs in a realistic scenario without significant performance decrease. It can be expected that a more modern host system supporting PCIe Generation 4 or 5 will provide similar or better performance.

References

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* Work supported by BMBF

Computing



Core classes and development environment preparation for a CBM Experiment Control System prototype *

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The Experiment Control System (ECS) will have to coordinate all Hardware and Software elements needed for the online operation of CBM. Each controlled system, be it a central and common one like the Timing and Fast Control (TFC), or a detector one, will be reporting its state and responding to commands through a process called “agent”. Most of these commands will be either requests to perform specific state transitions or assignments of tags indicating the sets of parameters to apply. Detector systems will be combined to form so-called “Partitions”, each of which will be supervised by a process called “partition agent” or PCA. These PCA will derive the state of the partition from the state of the participating detector systems and central systems, therefore implementing the main state machine for online acquisition. A top process called “experiment control agent” or ECA will control the various partitions and perform the assignment of detector system to given partitions. The ECS core is therefore a top-down pyramid of agents, where commands flow from top to bottom and state update flow from bottom to top. User interfaces will in a later stage be added, mostly for interaction with the ECA and PCA, but eventually also for the system agents to provide a “debug” mode.

There were already a few attempts to development frameworks or examples for this ECS, but none reached the stage where it could be used for a real example and called a prototype

Project review and changes

Following a review of the specifications for the ECS in 2020 and 2021, it was realized that the existing proof-of-concept [1] could not be easily adapted/scaled-up to provide the expected command features in addition to the state management ones. Experience acquired during the operation of other Python based command software for the 2020-2021 mCBM campaigns also showed that the `pipenv` tool used for managing/deploying the Python dependencies and our internal libraries had low performances when the project complexity increased.

For these reasons, a clean restart of the code repository was done with

- a new project environment based on the `poetry` tool, used both for dependencies management, to control the CI tools and for libraries and binaries creation,

- usage of the `flakeheaven` tool for code-style and conventions check,
- usage of the `mypy` tool for explicit typing enforcement,
- a focus on core/generic features to keep hard-coded system specific values only in derived classes,
- two independent test developments to validate separately core classes for the command propagation and the state management.

Standalone cores development and testing

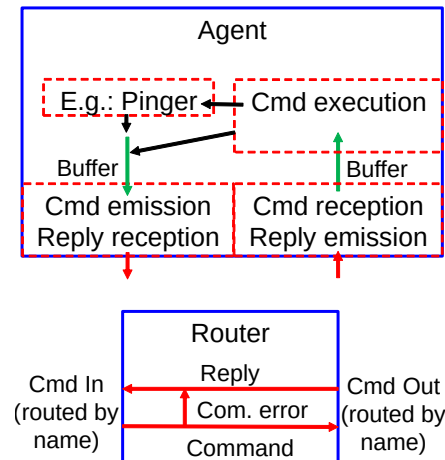


Figure 1: Threads in the command Core instances and Router flow.

For the command propagation, the following features were implemented and tested standalone:

- the methods used for communication through ZMQ sockets are defined in a generic way in the `Core` class;
- two sockets and 3 threads are used to separate command emission, reception-reply and execution, see Fig. 1;
- an instance can send only one command at a time (wait for reply);
- an instance can receive and store multiple commands in a buffer before their execution;
- an instance executes only one command at a time, but this call may start a background thread (in which case the developer of the command has to provide proper thread safety in the derived class);

* Work funded by the Horizon 2020 grant agreement No. 871072 (CREMLIN+/EURIZON W.P.2).

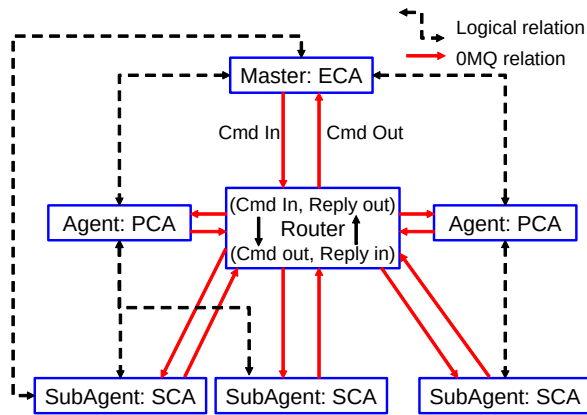


Figure 2: Flow of commands and replies between Testing instances.

- replies are emitted by the reception thread asynchronously from execution, after each command reception or after a pre-defined time without new command;
- the “commands to code” link is done by pairs of a string keyword and a method handle, stored in a dictionary;
- the command messages contain the keyword, the source and target, the arguments and a timeout value;
- the reply message contains the original command, the source and target, a status tag and the reply itself;
- the Core class provides only common technical commands such as ‘ping’;
- additional commands can be added in derived classes, e.g. “testing methods” are added in a Base class
- the Core class also defines members and commands used to implement relationships between instances as “master-subagent”;
- as test case, a Testing class derived from the Base one is providing the methods for instantiating the “master-agent-subagent” relation chain;
- a small Router class is used to decouple the command emission and reception between agents and to avoid needing frozen topology definition (agents master may change), see Fig. 1 and 2.

An example of the command-reply flow between Testing instances can be found in Fig. 2. This was used to check each of the features listed above as well as doing first measurements of the throughput of the Core (not optimized yet).

For the state management, the following features were implemented and tested standalone:

- ECS agents have two related states: the global one which has to match some centrally defined list and the local one which may represent sub-states of interest for the agent operation;

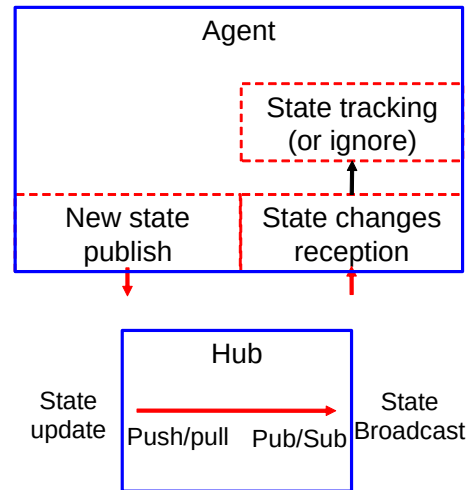


Figure 3: Threads in the state Core instances and Hub flow.

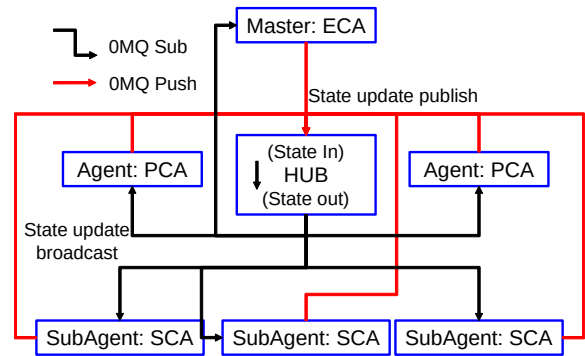


Figure 4: State updates flow.

- only the global state has to be published and needs to be tracked by other (related) agents to eventually perform automatic transitions;
- a Core class provides the methods used to handle state updates and to perform global state transitions;
- one ZMQ sockets and 2 threads are used to separate global updates reception and tracked updates reaction, see Fig. 3;
- the Core class provides a way to unify the interface for external state transition requests with
 - a two levels dictionary between “source state, target state and transition method handle”,
 - an interface method to first check that the current state is matching, then find and call the corresponding transition method and finally check that the state afterward is matching the targeted one (Success/Failure),
- failures are handled through the emission of Python Exceptions;

- state updates are emitted in the transition interface method only when the global state changes (no dedicated thread);
- only one state transition may be ongoing at any given time;
- a small Hub class is used to receive each state update and then broadcast it to all agents, see Fig. 3 and 4.

An example of the state updates flow between instances can be found in Fig. 4.

ECS state and command core

Afterward, these two cores were brought together and adapted toward the structure described in Fig. 5. The `Testing` classes were adapted to provide the same tests as during the standalone development but within the `pytest` environment. Work will now focus on developing the base class for all (m)CBM ECS agents, adding typing information to all sources and preparing the first examples of concrete agents. When this is done the various detector and central systems groups will have with the ECS for the mCBM 2023 campaign the opportunity to implement first prototypes for a full experiment topology. User-friendly interfaces such as GUIs or user right management will be added as a top layer only in a later stage.

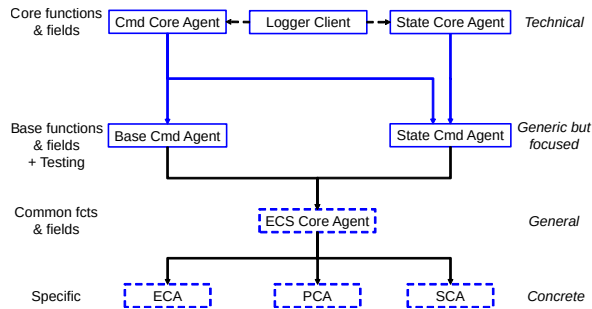


Figure 5: Core classes and their relations. Full boxes are implemented and tested, dashed ones not yet implemented.

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Towards efficient sorting of STS digis

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Operating the CBM experiment at interaction rates up to 10 MHz necessitates data reduction in real-time. This poses high requirements for the online processing of measurements and the underlying algorithms. As a first step in the workflows for local reconstruction, the sorting of incoming digis is challenging particularly since the size of the input data from raw timeslices is larger as compared to subsequent steps of processing. Therefore the actual throughput achieved here has significant impact also for the overall performance of the reconstruction chain. In order to improve existing strategies, we have developed highly efficient sorting algorithms, first focusing on the STS system.

Previous work and setup

In the previous report [1] we have summarized an optimization of STS reconstruction algorithms for parallel execution on CPUs or GPUs. In the related project [2] the corresponding algorithms developed for efficient and data-local clustering have lead to a significant acceleration. Similar to the previous setup, the Cbmroot framework has been used to simulate up to 2000 central collisions of Au-Au in one time slice leading to number of digis ranging up to 30 millions, serving as input to sorting and reconstruction. As an interface between CPU and GPU function and corresponding copies in memory, the XPU framework [3] is utilized, also in order to measure runtimes of specific parts of the algorithms.

Efficient sorting before hit reconstruction

Within the XPU framework the current sorting algorithm is accessible in XPU using `xpu::block_sort` which is a multi-phase divide-and-conquer general sorting algorithm. It uses block-wise radix sort, based on NVidia's CUDA component framework CUB [4] and a XPU implementation of GPU merge path [5], a parallel merge algorithm implemented in XPU [2]. This algorithm requires a theoretical running time of

$$O(n/p \cdot k) + \theta(n/p \log n) \quad (1)$$

where the input of size n is divided into $p + 1$ blocks and each block is sorted by NVidia's implementation of radix sort (`cub::BlockRadixSort`) corresponding to a theoretical running time complexity of $O(n/p \cdot k)$ and a key size k of 64-bit. It is important to note that “ θ -notation bounds a function to within constant factors. [...] O -notation gives an upper bound for a function to within a constant fac-

tor.” [6]. Thus $O(1)$ defines a constant running time which is independent of the input size n .

Each of these sorted blocks is then combined with the parallel merge algorithm, since each block is sorted individually but a concatenation of each solution is not sorted yet. Hence, a final merge step is required with a theoretical running time of $\theta(n/p \log n)$ with additional temporary storage of n and the sorted result is written to a separate output array of size n , requiring in total $2n = \theta(n)$ memory.

Sorting digis in linear time

An alternative to this approach has been explored to further improve the runtimes with an *adaptive* sorting algorithm designed to exploit the specifics of the recorded STS streaming data, instead of sorting arbitrary inputs. Looking at any segment of the recorded STS measurements in form of timeslices one can see that digis of the same channel on the right have been also recorded later in time (Fig. 1).

Channel 2 Time 12	Channel 2 Time 22	Channel 1 Time 8	Channel 1 Time 12	Channel 2 Time 41	Channel 1 Time 45
----------------------	----------------------	---------------------	----------------------	----------------------	----------------------

Figure 1: Segment of a time-slice. The 5th element of channel 2 has a higher timestamp than the 2nd element.

Concatenating all elements belonging to the same channel (for each channel) leads to a set of monotonically time-sorted channel sequences (Fig. 2).

Channel 2 Time 12	Channel 2 Time 22	Channel 2 Time 41	Channel 1 Time 8	Channel 1 Time 12	Channel 1 Time 45
----------------------	----------------------	----------------------	---------------------	----------------------	----------------------

Figure 2: Channel-wise concatenation of the elements results in channel-wise monotonically time-sorted segments.

By exploiting this property, the running time can be reduced to $O(n/p)$ with additional total shared-memory of $O(p \cdot k) = \theta(p)$ (k is constant with $k = 2048$, i.e. number of channels). This adaptive algorithm is not divide-and-conquer and not in-place-based, i.e. requiring more than a constant amount of additional memory. However, it places the elements of the semi-sorted input sequence directly into the correct position in an output array, which will then contain the sorted results. This can be achieved by parallel channel counting and index computation. The algorithm, referred to as ConcatSort, consists of four phases, illustrated in simplified pseudocode below:

- (1) Initialize an array of size k to zero (channel count):

```
int count[k];
for(int i=0; i < k; i++)
    count[i] = 0;
```

- (2) Count the channel frequencies by hashing (linear example):

```
for(int i=0; i < n/p; i++)
    count[digis[i].channel]++;
```

- (3) Compute the exclusive-sum on the count array to determine each channel index offset:

```
int sum = 0;
for (int i = 0; i < k; i++) {
    const auto tmp = count[i];
    count[i] = sum;
    sum += tmp;
}
```

Phases 1 and 3 take $\theta(k) = O(1)$ and the second counting step traverses all digis in the input and counts the occurrence of each channel in $O(n/p)$ in parallel.

Finally, a single thread (on each GPU block) writes all the input digis in the correct output indices:

```
if (xpu::thread_idx::x() == 0) {
    for (int i=0; i < n/p; i++) {
        output[count[digis[i].channel]++]
            = digis[i];
    }
}
```

This last step must be executed by a single thread (per GPU block) in order to prevent race conditions. This leads to a total running time of:

$$2 \cdot O(1) + 2 \cdot O(n/p) = O(n/p)$$

with $\theta(p) + \theta(n)$ additional memory, eliminating the entire merge term and an additional term k from equation 1 leading to a *linear running time sorting algorithm* that can be parallelized across p .

This algorithm has overall significantly less overhead but has the limitation that in phase 4 only one thread on each GPU block has to write the final result. This issue is however naturally mitigated by the fact that data is already pre-grouped into STS module buckets, which can be individually sorted. There are also further techniques which can increase the parallelism and fine-tune the threading performance, which will be discussed elsewhere.

Results

Runtimes needed for sorting of STS digis on GPUs as a function of input digis for different algorithms and block sizes are shown in Fig. 3. These results demonstrate the linear scaling and also underline the potential for high throughput processing in the step of sorting digis on GPUs. It is interesting to note that in the current version of the

ConcatSort algorithm the final step of sorting is not yet parallelised. The full potential for optimization will become evident when the preprocessing steps are aligned with the unpacking workflow and also the subsequent step of cluster finding is seamlessly attached.

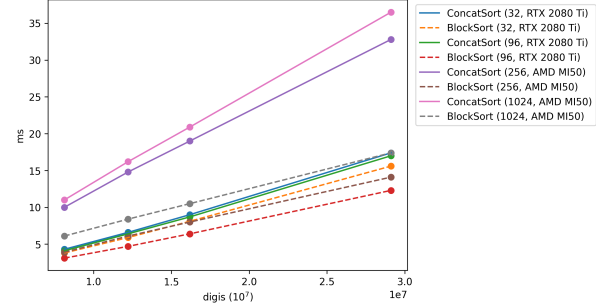


Figure 3: Runtimes (in ms) needed for sorting of STS digis on GPUs as a function of input digis for different algorithms. Different block sizes and used GPUs are given in brackets, respectively.

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Online-capable software for the TOF, T0 and MUCH detectors

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Introduction

With the advent of real experimental data from the mCBM full-system prototype, the demand for software to be applied in real-time arose and has been ever increasing since. Efforts to establish an online-capable software stack as part of the CBM software collection `cbmroot`, to inspect the full raw data stream and select physically interesting data based on this inspection, were started in 2021 and have been pursued throughout 2022. Ref. [1] laid out a number of design considerations, which guided these developments, and include:

- data structures with minimal memory footprint,
- proper data interfaces and containers which avoid data rearrangement,
- separation of algorithms from framework layers,
- target smallest independently treatable data units to enable concurrency,
- use modern C++ and minimize dependency on ROOT,
- separate monitoring and QA from the algorithms,
- implement code which is concise, modular and optimized for execution speed.

For the algorithm layer, a new top-level directory `algo` was introduced, in which no dependence from ROOT is allowed. The long-term goal is to completely replace the existing reconstruction software and use the new packages for offline data analysis as well.

In this contribution, we report on a range of different developments in this spirit, which were achieved in 2022. These include unpackers for different systems, as well as an optimized hit reconstruction algorithm for TOF. We conclude with discussing recent efforts to apply multicore parallelization, using OpenMP.

Unpackers

For many years, ‘unpackers’ for the different subsystems in mCBM had been developed independently for each subsystem. First steps towards a stronger integration of unpackers in a unified scheme were taken in 2021 and lead to a separation of the framework-bound and algorithmic parts of the unpackers, as well as separation between the processing code and the configuration code in the algorithmic parts [2]. These developments were continued throughout 2022 and resulted in the following main achievements:

- the implementation of an optimized, fully ROOT-free, unpacker for the MUCH detector in the `algo` namespace, which operates on a single timeslice component and uses modern C++,
- similarly optimized, ROOT-free, unpackers for the TOF and T0 detectors; a full separation of these two systems, which were treated as a single unit in previous implementations, was thereby achieved and a proper class for T0 digis (previously only distinguishable from TOF digis by their address) introduced,
- a FairMQ device which enables the online execution of the new unpackers, and supplements the exiting FairTask.

The implementation of a new unpacker for STS was already completed previously [1]. All new unpackers are supplied with configuration classes and are fully integrated into `CbmTaskUnpack`, the central class which manages configuration, execution and framework-interaction of all unpackers.

TOF hitfinder

An important precursor to further reconstruction steps is the identification of individual detector hits, which often result in the production of multiple digis in the data stream. A simple algorithm which identifies hits in the TOF detector by searching for spatially and temporally localized clusters of digis is provided by the class `CbmTofSimpClusterizer` in `cbmroot`. The logic of this algorithm is summarized as follows:

- 1) calibrate digis (apply offset to time, gain and walk correction to charge),
- 2) separate digis into `std::vectors` (one for each SM, RPC and channel),
- 3) build digi clusters for each RPC:
 - loop over channels,
 - require digi on each “side” of channel,
 - add other digis in spatial and temporal proximity to cluster,
- 4) build hits from clusters for each RPC:
 - get hit position and time from charge-weighted digi distribution of cluster,

- get time error from detector resolution,
- assign channel address of weighted position.

Based on the existing class, an online-capable version was implemented, which is fully compliant with the specifications above. A single resistive plate chamber (RPC) was thereby identified as the smallest logical unit. The algorithm requires information about the detector geometry, which is obtained from the framework through the `TGeoManager` class at the task level. Mathematical classes from the `ROOT::Math` libraries are used by the algorithm, which are “ROOT-free” in the sense that none of the supplied classes inherit from `TObject`. By consistent application of encapsulation and object-oriented programming, it was possible to reduce the number of lines to less than half of the original implementation.

Furthermore, a direct comparison (where monitoring functions were removed from the original hitfinder to make the comparison meaningful), carried out on the first 10 timeslices of the file `2391_node8_0_0008.tsa` from the 2022 beamtime, whereby, averaged per timeslice, 723078 hits were built from 2282889 TOF digis, reveals that the average execution time per timeslice is reduced from around 1000ms to around 200ms on a Intel Core i9 13900K CPU at factory settings: a factor 5 increase in performance. This can likely in large parts be attributed to the persistent storage of detector geometry information in `structs` during initialization, and the subsequent avoidance of accesses to `TGeoManager` during algorithm execution.

The class `CbmTofSimpClusterizer` represents a simplified hit finder, which is at present mainly used for simulated data. In future work, the newly introduced classes will be extended to cover the functionality of the `CbmTofEventClusterizer`, which uses a more realistic hit definition and is the main tool for real experimental data at present time.

Investigating OpenMP parallelization

In light of the desire to enable concurrency in the readout chain, to make cost-efficient use of the available computing capacities, an explorative study of the use of `OpenMP` directives to speed up the newly implemented TOF hitfinder on multicore CPUs was recently carried out. To this end, three distinct phases of the hit finding process were identified, which are carried out at the task level:

- 1) Bucket-sorting (by RPC index) of digis.
- 2) RPC-wise algorithm execution.
- 3) Merging of algorithm output.

Of these, parallelization is straightforward for step 2) and was easily achieved. Step 3) is more involved, as it requires a parallel-merging of several `std::vectors`, but a working solution has been implemented. The first step remains as a single-threaded process, as the definition of the input data format is likely to change in the future. First tests

show a speedup of $\sim 40\%$ on > 8 cores, which is far from competitive with process-level parallelization, but work on further optimizations is ongoing.

Acknowledgments

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Cellular Automaton Tracking

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CA Track Finder for mCBM

The Cellular-Automaton tracker used in STS has been 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, and binning triplets into tracks is done without a momentum cut, but with an additional cut on the slope of the triplets.

The code for the mCBM version of the tracker has been merged with the CBM version, and there are only a few places in the code where the mCBM case differs from the CBM one; otherwise, the code is unified.

The algorithm reads the geometry automatically and technically supports all available mCBM setups. It runs on both real data and simulated data.

Global CA Tracker for CBM

A similar approach is used to extend the existing CA track finder for the global CA-based track reconstruction algorithm, which is currently under development. This algorithm should entirely or partially replace the existing approach that propagates STS tracks through other detector systems using the Kalman-filter track-following method.

Combinatorial reconstruction outside STS is particularly important for the TRD-2d detector, which registers tracks that do not pass through STS, making track-following reconstruction impossible. Given the importance of TRD-2d reconstruction, we are focusing on the global tracker development on this detector system.

Recently, simulation, digitization, and hit reconstruction for TRD-2d have been developed, allowing work on tracking. The global CA tracker in TRD-2d is already demonstrating good performance (see Figure 1). The high ratio of fake tracks is caused solely by overestimated errors in the hit finder and will be rectified soon.

Eff. All tracks, $P_t > 0$ GeV	93.9 %
Eff. Primaries, $P_t > 0.1$ GeV	100.0 %
Eff. Primaries, $P_t < 0.1$ GeV	98.3 %
Eff. Secondaries, $P_t > 0.1$ GeV	84.6 %
Eff. Secondaries, $P_t < 0.1$ GeV	84.6 %
Clone rate	0 %
Ghost rate	25.7 %

Figure 1: Efficiency of the global CA tracker in TRD-2d region.

Since the TRD-2d detector is placed outside the magnetic field, it is essential to know whether we can reconstruct the momentum of the tracks. The analysis shows that even without STS hits, the momentum of TRD-2d tracks can be reconstructed with an accuracy of 12%. To estimate the momentum, one extrapolates the track to its vertex through the magnetic field and adds the vertex position as a measurement to the Kalman filter. Having at least one STS hit improves the resolution to 3%. Therefore, we can reconstruct the momentum of the tracks even if they are outside or at the edge of the STS acceptance.

The next step in the global tracker development will be linking TRD-2d and STS tracks, particularly matching STS hits to TRD-2d tracks.

The global and mCBM CA trackers initially used special fit utilities for no-field regions. Now all fit utilities are unified, allowing for further fit development, including the development of a new track model, described below.

Simple parameterization of the search windows

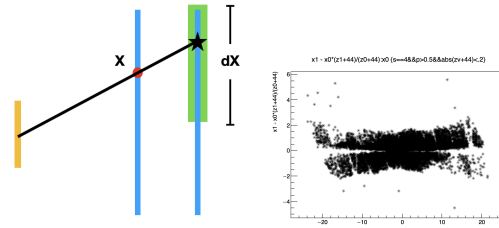


Figure 2: Construction of a doublet and the search window distribution.

When the CA tracker builds tracklets, it uses a Kalman filter to estimate the search window for the next hit (Figure 2, Left).

However, looking at these search windows, one can see that they have simple dependencies on hit coordinates and can be well described by polynomials (Figure 2, Right). Therefore, using such a complex algorithm as the Kalman filter is unreasonably expensive here.

We are going to replace the Kalman filter with polynomial approximations when constructing search windows. The new approach should significantly speed up and simplify the algorithm, given that our Kalman filter code is SIMDized and requires complex data repacking at each step. The work is ongoing. A module that calculates the

search windows already exists, and its implementation in the tracker code is underway.

Improved Track Model

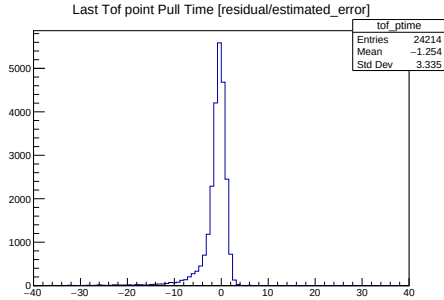


Figure 3: Pull of the STS track time propagated to TOF. Old track model.

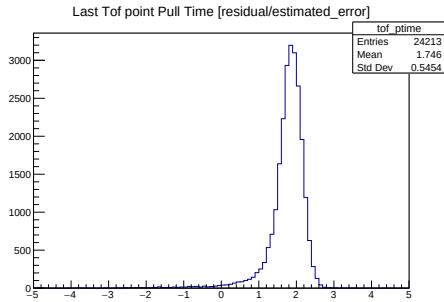


Figure 4: Pull of the STS track time propagated to TOF. New track model.

The current track model used in CBM comprises of five measured parameters: $x, y, t_x, t_y, q/p$ at a specific z position, along with the corresponding 5×5 covariance matrix.

Continuous readout of CBM necessitates 4-D reconstruction in time slices. To account for the measured time, the track model included the parameter t , which is the estimated track time at its position z . However, knowing the time at a particular position is insufficient. One needs to know the track's velocity to extrapolate the track time from one z to another.

Initially, the speed of light was taken as the velocity, which is precise enough to move a track inside the STS detector, where the inaccuracy in velocity is overshadowed by the inaccuracy of the time measurement (which is $1.17ns$ for the STS track).

However, when extrapolating the time to faraway detectors such as TRD and TOF, the velocity error starts to dominate, and the actual error of the extrapolated time can be 30 times larger than the expected error (as shown in the Figure 3).

To improve the velocity estimate, we calculated it from the measured track momentum. Unfortunately, this ap-

proach did not improve the situation much since this calculation involved an unknown particle mass. Consequently, the velocity of a proton and an electron could differ by a factor of two for the same momentum, and the mass uncertainty was not considered since the mass does not appear in the covariance matrix. Moreover, calculating velocity from momentum is impossible in the mCBM setup and in field-free areas of the CBM setup where the momentum is unknown.

To address these issues, we introduced a new track model with seven measured parameters to accurately estimate the track time: $x, y, t_x, t_y, q/p, t, v_i$. Here, the new parameter v_i is the inverse velocity of the particle. Unlike the previous approach, this parameter has an estimated error stored in the covariance matrix. The velocity error is estimated from a range between the speed of light and the speed of the lowest-momentum proton we want to propagate.

With the new model, the time error is correctly calculated when extrapolating an STS track to TOF. One can see in the Figure 3 that the actual error stays within ± 3 estimated error range. If a more accurate velocity measurement appears later, such as velocity calculated from the momentum and some mass hypothesis, it can be easily taken into account. The refined track time and its error estimate can be calculated from the covariance matrix without any refit of the track.

Eliminating Material Maps

The current tracker utilizes precomputed material maps to consider multiple scattering and energy losses. However, these maps complicate experiment development. Detector groups must create them for each new version of detector geometry; otherwise, tracking will not run.

In case of changes in the tracker requirements for the material or if a bug is found in the material map macro, all material maps for all geometries must be recalculated.

A new approach will simplify development.

The approach will generate material maps on-the-fly when the reconstruction task initializes for the first time. These maps will be stored in the parameter file. The tracker will create new maps internally without any effort from detector groups.

To calculate the material budget, we will manually trace straight lines through the detector using the ROOT TGeoNavigator class, instead of transporting the "rootino" particles with GEANT, as currently done. Our analysis demonstrates that tracing 10,000 straight lines takes only 3 seconds on a single CPU. Even if we need to trace 100,000 rays, the initialization time of 30 seconds will remain acceptable.

Currently, the new approach to material maps is being prepared.

Code base refactoring

The existing implementation of the CA tracking algorithm has proven to be robust and highly performant, meeting all requirements for accurate and speedy data reconstruction. This success has enabled it to be used for online event reconstruction. However, years of development and testing have led to a complex interaction between the algorithm and other blocks in the framework, as well as various features, resulting in a large list of hard-coded parameters and hacks. To address these issues, several development contributions have been made.

Algorithm configuration

The tracking algorithm requires external information about the detector's geometry. In the new code version, the initialization of this information is now encapsulated in a manager class (`L1InitManager`), which provides a uniform initialization interface independent of the detector type. The input information for each detector subsystem used in the tracking is organized into the detector-interface, which defines a tracking station¹ as a plane perpendicular to the beam axis that provides a measurement of the charged particle hit and its properties in a uniform manner. The detector interfaces dramatically increase code reuse and clear the tracking steer class. Additionally, they provide fast and lightweight QA for geometry parameters, such as checks for station order, parameter consistency, and NaN values.

To enhance track finding performance, the tracking algorithm runs in several steps, each corresponding to a specific track group and having different cuts on the tracklet selection. In the new code, these cuts are organized into run-time modifiable structures (`L1CAIteration`). This not only allows selecting the cut values on the fly but also defining an arbitrary sequence of track-finding steps.

Both geometry and cuts parameters are provided from the outside and were encapsulated into a solid parameter class (`L1Parameters`). The parameter object is formed inside the `L1InitManager` instance and passed to the algorithm at the beginning of the run, which guarantees its immutability throughout the run. The cuts part of the parameters can be controlled from a YAML-configuration file via the `L1ConfigRW` class.

A similar approach is provided for time-slice initialization. The input data object (`L1InputData`) is formed with an instance of the `L1IODataManager` class and sent to the algorithm. All the data objects introduced above utilize boost serialization model and can be sent among MQ-devices in an online reconstruction chain (see last section in this report), as well as can be archived for running tracking in a standalone mode or debugging.

The introduced interfaces have already reduced ad-hoc conditions used for different geometry configurations and

given a possibility for treating full-CBM and mCBM setups identically.

Monte-Carlo information handling

The tracking algorithm itself does not contain MC-information initialization, but the latter is used for performance studies, QA, and debugging. In the old code, MC-information handling, as well as performance and QA definition, was highly integrated into the tracking steering class. At the moment, a separate tracking MC-module (`CbmCaMCMModule`) is being developed, providing fully independent procedures for MC-data handling in the related tasks. MC-data from different detector subsystems are translated to tracking internal detector-independent objects (`ca::tools::MCData`), which can be accessed outside of the tracking block (for example, for output tracking QA).

Quality Assurance

QA Tasks for Tracking Input and Output

Modifications to either the reconstruction framework or detector geometry can introduce bugs and failures. To provide continuous checks for newly introduced modifications, quality assurance (QA) modules should be introduced for each block of the reconstruction framework. The tracking algorithm is sensitive to any inconsistencies in the input data, which can include the absence of hits on a particular tracking station, shifts in the position and time of hits, wrong station arrangements in the provided geometry, and more.

To address these problems, we have implemented QA tasks for the STS, MuCh, TRD, and TOF detectors, such as `CbmCaInputQaSts`. Each of these tasks provides monitoring of hits and MC-point occupancy distributions, consistency between the provided geometry and data, hit reconstruction efficiency, pool and residual distributions for hit positions and times. Additionally, we are currently developing a separate tracking output QA task.

QA Checker Framework

We have automated quality assurance in the tracking algorithm development with a QA checker framework, which provides tools for comparing QA histograms obtained from different versions of the code. The comparison can be carried out in two different modes: direct bin-by-bin comparison of the histograms or statistical test application. The direct comparison is especially useful in code refactoring, which should not modify algorithm output. The second mode provides a tool to test how new algorithm or geometry features affect different reconstruction blocks.

Currently, the developed QA checker is ported to the official repository and will be used in the continuous integration tests of different QA-task results.

¹A tracking station is defined as a plane perpendicular to the beam axis, providing measurement of the charged particle hit.

CA Tracking as a Part of Online Reconstruction

An online reconstruction chain for CBM is organized as a topology of FairMQ devices. Each device represents a standalone process, which receives a message with a packed data object, executes an algorithm on it, updates it with the results, and sends it further down the stream in real-time. For this purpose, several requirements are applied to the algorithms, such as independence from ROOT libraries and transparency of initialization and data flow. The implemented interfaces and data structures allow the tracking algorithm to be ported onto the FairMQ device with almost no additional effort. The main challenge here is to split the tracking code into three libraries: one for the core, another for the CbmRoot steer class², and the last one for additional classes (namespace `ca::tools`) that are not specific to CBM but are not needed for the reconstruction itself (mostly MC-data structures and performance/QA code).

The new code is planned to be organized as follows. The tracking parameters object will be constructed on a separate device, which has access to the general parameters database and geometry interfaces, and will be sent to the main track reconstruction device. On a time-slice basis, the track reconstruction receives a `RecoEvent` message, which contains a time-slice header and an array of hits reconstructed in different detector subsystems. After the tracking procedure, the main device adds reconstructed tracks to the reco-event objects and sends it down the data stream.

²Including all initialization methods

ANN4FLES: A neural network package for applications in CBM

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Artificial Neural Networks for First Level Event Selection (ANN4FLES) in CBM is envisaged as a fast C++ package that enables the user to construct a variety of neural network architectures with minimal additional programming. The package comes equipped with a Graphical User Interface (GUI) where the user can not only select the type of network but also adjust the various hyperparameters. The package is designed to be modular so that users who wish to implement additional non-trivial features can do so without changing the basic structure of the package. Currently ANN4FLES can implement the following networks: Multilayer Perceptron (MLP), Convolutional Neural Network (CNN), Recurrent Neural Networks (RNN) and Graph Neural Networks (GNN).

We have tested all networks implemented in the package on many standard datasets like MNIST, CIFAR, Cora etc and compared with PyTorch. In all cases we find the performance of ANN4FLES and PyTorch to be comparable. This gives us confidence that the basic algorithms being implemented are correct.

MLPs are the simplest kind of neural networks. We are using MLPs for particle identification and also at the end of CNNs, RNNs and GNNs.

CNNs are neural networks specialized for processing structured data. CNNs aim to learn some common features in the data which are useful for the desired task. This feature-extraction ability motivates us to find potential applications in event reconstruction and selection. We are currently investigating using CNNs for ring finding in the RICH detector.

RNNs are used for sequential or time-ordered data. They can even be used to generate further time-steps in the data. This property may be useful in improving the event building stage. ANN4FLES can implement Hopfield and Long Short Term Memory (LSTM) networks at the moment.

Finally, GNNs are designed to work on data which can be represented as graphs. For example, the hits on the planes of a detector can be the nodes of a graph and the edges can be the trajectory of the particle. Then the problem of track finding becomes an edge-classification problem which can be solved using GNNs. This approach can potentially improve the Cellular Automaton track finder used in CBM today.

We now give two examples of how this package can be used in CBM.

In particular, we consider K_s^0 mesons and Λ hyperons, both of whose decays produce π^- . The problem is to assign the secondary track to the correct parent [1]. ANN4FLES is being used for this classification problem. An MLP is

created using our package, which takes as input the true and reconstructed masses of the parents to predict the parent particle.

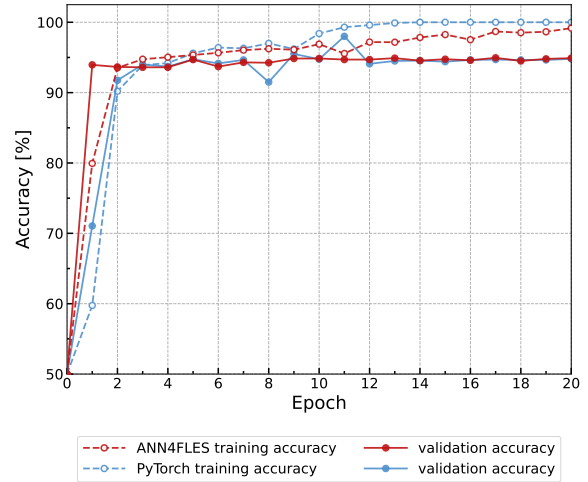


Figure 1: ANN4FLES compared to PyTorch. We use two convolution CNN layers followed by two fully connected MLP layers to classify events.

Neural networks in ANN4FLES have been built to identify Quark–Gluon Plasma (QGP) simulated within the Parton-Hadron-String Dynamics (PHSD) approach for central Au+Au collision at a fixed energy [2]. Fig. 1 shows the results of training on a simulated dataset, containing 5000 events each with QGP on and off, which is generated using the PHSD model. The simulations were performed for Au+Au central collisions at 31.2 AGeV. The training set contained 8000 randomly chosen events with the rest used for validation. We also benchmarked ANN4FLES performance by comparing results with a PyTorch model with the exact same architecture (see Fig. 1).

Other types of artificial neural networks will continue to be added to the package.

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Validation of time-based simulation

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With technology improvements of detectors, data processing and storage, it is possible to measure ever higher event rates to collect more statistics. At moderate event rates up to $\sim 10^5$ events/s, events have been characterized by a physical trigger, typically some reference detector, and then everything within a predefined time-window is stored as one event. For high collision rates at 10^7 events/s, collisions are close in time such that they cannot be easily distinguished by setting specific time-windows with respect to a physical trigger. Instead, tracks should be reconstructed from the detector hits as a free stream of data. Making use of the detector knowledge, i.e. how long a particle travels from the one detector to another, taken into account secondaries which are slower, one can still define a specific time-window for each detector subsystem with respect to a reference system. For this study, the STS detector [1] serves in this regard. The data collected in a time-window may refer to several collisions, but the time information can be used to assign the reconstructed tracks to an event, which is called event building [2].

To validate the performance of the reconstruction algorithm and event builder (EB), the standard event-by-event (EbE) simulation is not sufficient. Instead, a time-based (TiB) simulation chain was developed for CBM [3], in which the events are placed randomly inside a pre-defined time-slice (TS). This allows to control the probability of two events to overlap.

The TiB simulations are validated at low collision rates, i.e. 10^3 events/s, while using a TS of 10^5 ns, such that the results can be compared to the EbE simulation.

The EB (and also reconstruction algorithm) can be validated too, by using its operation modes: it can be used in "ideal" mode, where each reconstructed track is assigned to the Monte-Carlo event from which it was simulated, or in "real" mode using a reference detector and specific time-windows as described above.

A basic comparison are event observables, such as the number of tracks assigned to an event. This track multiplicity is of particular interest, as in TiB it is possible that several events are reconstructed out of one initially simulated event. Typically, these events should show up with very low track multiplicity.

With real EB it is possible that for overlapping events, a significant amount of tracks may be assigned to the wrong event, resulting in very high track multiplicities.

All these features can be seen in the track multiplicity plot displayed in Fig. 1. In the underflow bin corresponding to events without any reconstructed track (track multiplicity = -1), as expected the TiB mode has the most

entries.

In the TiB with real EB sample, track multiplicities of > 400 are visible, which are not present in the other distributions. This could be a feature of tracks assigned to another event, when events are generated at the edge of a TS which should increase at higher interaction rates. Another feature to be checked is that in TiB mode with ideal EB, the curve is consistently lower over the whole range with respect to the other distributions.

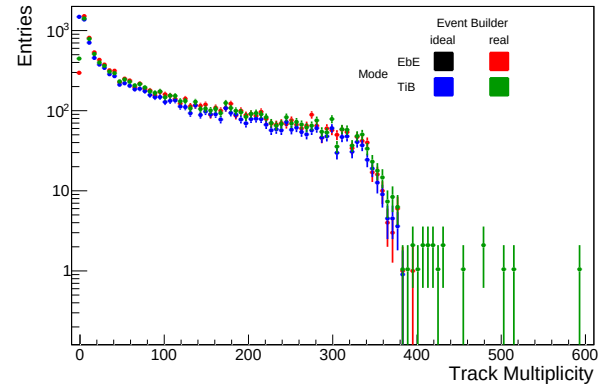


Figure 1: Multiplicity distribution of reconstructed tracks selected by $|DCA_{X,Y}| < 0.2$ cm and $\chi^2_{\text{Vertex}} < 10$. Four different samples consisting of $10k$ simulated events each are shown: ideal event builder in EbE (black) and in TiB mode (blue), real event builder in EbE (red) and TiB mode (green). The underflow bin, i.e. track multiplicity = -1, indicates the amount of simulated events, in which no track could be reconstructed.

The next step is to increase the interaction rate and to include additional noise coming from electrons, originating from interactions with the beam pipe. This will allow to study the performance loss on physics observables directly and helps to identify limits of the current implementation and/or to optimize the reconstruction framework for the CBM setup.

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Transition to a modern CMake-based build system for CbmRoot

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CMake [1] is a tested tool that helps programmers design a robust build environment. Modern CMake can be used, among other things, for handling multiple build targets, automating pre- and post-build tasks, and coordinating cross-platform toolchains. CMake can generate a native build environment that incorporates executables, compiles source code, and generates libraries and wrappers. CMake can generate a build environment across platforms and users by generating a variety of build contexts, from the more traditional Makefiles to the more recent Ninja build system. Also, the generation of the specific config files for various IDEs is possible as the output of a CMake execution. Because of these facts, CMake has been widely adopted in multiple projects to allow smooth cross-platform integration.

Beginning with CMake 3.0, new features were introduced in CMake, which allows to define the dependencies on a different level. This change was called by some CMake users “modern CMake”. One of the main differences between “old” and “modern” CMake are the introduction and refinement of targets. With modern CMake, targets are no longer limited to the level where they are defined but as global objects. Before the new feature CMake defines targets on the directory level such that they are not known in other directories or even one level up in the hierarchy. With modern CMake, one can even reuse targets and functions defined by other projects in their installations. In old CMake, sometimes it was necessary to know some the hidden dependencies of the used direct dependencies. Another common problem was the definition of the internal properties of the dependency explicitly. Because of this, there were lots of scope variables defined in the CMake-List.txt file. With modern CMake, the target contain the information about its dependencies such that when using a target, the full information about compile definitions, compile options, compile features, include directories and library dependencies are available for the consumer of the target. All these properties propagate themselves to another dependent target such that the developer does not need to understand the whole system when he is only interested in a single target. The build system handles transitivity.

The concept of a target

If one has ever used GNU Make, one has probably come across the concept of a target. It is a recipe used by a build system to compile a list of files into another file. It can be a .cpp implementation file compiled into an .o object file, a collection of .o files packaged into an .a static library,

or any combination of these which allows to build an executable from source files directly. To create a Makefile for make one has to define all these transformations. CMake knows how to generate object files from source files or how to link libraries for all supported platforms and compilers. One does not need to specify how this is done in detail. One needs only to define on a higher level the input and the output. Therefore, most of the steps like compiling any object files doesn't require writing a specific recipe. If a special step is needed like generating ROOT dictionaries it can be added using the flexible and powerful macro language of CMake.

Finding installed packages

Every system has its method of installing and managing packages. Finding the correct path of a package installation can be difficult and time-consuming, especially if one needs to support the majority of today's OS systems. Fortunately, the CMake command `find_package()` can often handle this issue for the user if the needed package has a config-file that allows CMake to determine the necessary variables to support the package. Many projects today already provide such a CMake config-file during installation. If any library or package doesn't provide such a file, there are chances that CMake have bundled such a config file with CMake itself (these are called find-modules to differentiate from config-files). If neither of the previous options is supported the user needs to provide a find-module himself.

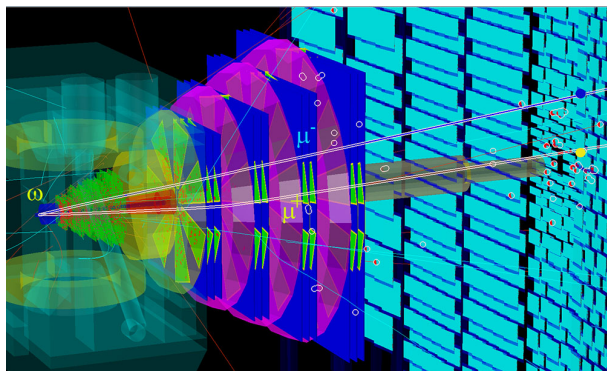
The CBM software framework (CbmRoot) is based on the FairRoot simulation and analysis framework which is built using CMake. Keeping in mind the advantages of the new CMake features, the build system of CbmRoot was rewritten. The transition from the old to the new build system was done in a gradual process always being able to build CbmRoot and not to interfere with the ongoing development of the project. Each step of the transition was always carefully tested using the continuous integration system of CbmRoot. After the transition the build system code was reduced by more than 25%.

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Physics Performance



Estimation of J/ψ production cross-section in p+A and A+A collisions at FAIR and SPS energies

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The suppression of the production yield of J/ψ mesons in heavy-ion collisions with respect to proton-proton (p+p) and proton-nucleus (p+A) collisions was proposed as an experimental signature of deconfinement transition and formation of Quark-Gluon Plasma (QGP) [1, 2]. The p+p collisions are usually believed to mimic the QCD vacuum. On the other hand, in p+A reactions, the nascent J/ψ mesons during the pre-resonance or resonance stage of evolution may interact with the nucleons present in the target nucleus, the so-called primary medium, which might lead to their dissociation. Quantification of such Cold Nuclear Matter (CNM) effects was traditionally attempted within the Glauber model framework, by analyzing the target mass dependence of the production cross-section of J/ψ mesons in p+A collisions [3]. In nuclear collisions, no measurement on J/ψ production below top SPS energy (158 A GeV) has been attempted till date, owing to extremely low charm production cross-sections. The Compressed Baryonic Matter (CBM) at FAIR and NA60+ at CERN-SPS aim to extend the existing study on charmonia production by performing the J/ψ measurement via the dilepton decay channel at the center of mass energy range of $\sqrt{s_{NN}} \sim 2.7$ -17 GeV [4, 5]. Thus with the data from CBM and NA60+, the dynamics of the J/ψ , likely to be produced in the early stages of the collisions, can be probed over a large energy range, in a rather unexplored energy domain.

A data driven parametrization is employed to calculate the J/ψ production in elementary p+p collisions. The corresponding production cross-section in p+A and A+A collisions are estimated within the Glauber framework, where the so called CNM suppression effects are incorporated via an effective absorption cross-section. No additional medium effect is incorporated in our calculations, even for A+A collisions. These estimations would thus serve as a reference baseline for the upcoming measurements, with respect to which possible genuine secondary medium effects on charmonium production if present, can be isolated.

To estimate the inclusive J/ψ production cross-section in proton induced reactions at lower energies, the parametrization as reported in Ref. [6] is adopted and independently fitted the inclusive J/ψ production cross-section in p+p, p+Be and p+Li collisions, as reported in TABLE I of Ref. [6]. The energy evolution of the $\sigma_{NN}^{J/\psi}$ in our adopted parameterization [6] is given below

$$\sigma_{NN}^{J/\psi}(\sqrt{s}) = a \times y_{max}^d \times e^{\frac{-b}{y_{max}^c}} \quad (1)$$

where $y_{max} = \ln(\frac{\sqrt{s}}{m_{J/\psi}})$. The free parameters a, b, c

and d are fixed from fitting the selective p+N data subset as stated above. The MINUIT fit package based on minimization of χ^2 , available within ROOT [7] software framework is used in the present work. The variation of $\sigma_{NN}^{J/\psi}$ as a function $\sqrt{s}$ and its parameterization using Eqn. 1 is shown in Fig. 1. Other parameterizations are also available

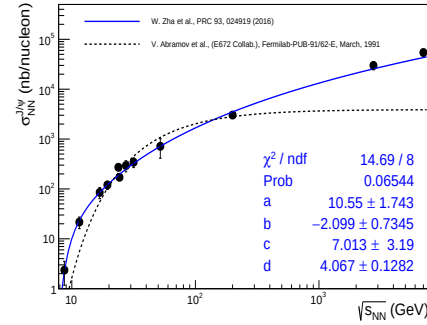


Figure 1: Energy dependence of inclusive J/ψ production cross-section in p+p, p+Li and p+Be collisions.

in the literature like the so called Schuler parameterization obtained by the E672 collaboration [8], the parameterization available from the E771 collaboration [9]. However, none of these previous parameterizations is seen to explain the global data, particularly at higher energies. This can be seen from Fig. 1. The black dotted line represents the Schuler parameterization, with parameters fitted explicitly using our selected data corpus. The same holds for the other parameterizations, though not explicitly shown here. Hence in this work, the parametrization given by Eqn. 1 is used and extrapolate to predict the inclusive J/ψ production cross-section at lower energies.

Using the Glauber model calculations, the J/ψ production cross-section in p+A collision can be expressed as;

$$\frac{\sigma_{pA}^{J/\psi}}{A} = \sigma_{pp}^{J/\psi} \exp(-\sigma_{abs}^{J/\psi} \rho L) \quad (2)$$

This is popularly called “ ρL parameterization”, where ρL represents the average amount of nuclear matter traversed by the nascent charmonium state from the point of production inside the target nucleus till it exits the nuclear medium. The $\sigma_{abs}^{J/\psi}$ as implemented in the above equation is extracted from the fitting of the measured J/ψ cross-sections from the NA50 [10] and NA60 [11] experiments. The effective quantity ($\sigma_{abs}^{J/\psi}$) encode the convolution of all effects of the cold nuclear medium responsible for the reduction of J/ψ yield. In Fig. 2, only the fitted data from the NA60 experiment is shown explicitly and the extracted values are tabulated in Table 1.

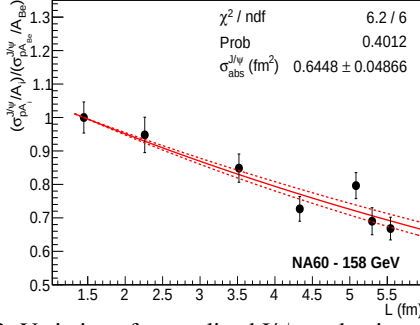


Figure 2: Variation of normalized J/ψ production cross section as a function of the average distance (L) of the nuclear matter of the target nucleus traversed by the J/ψ .

Experiment	$\sqrt{s_{NN}}$ (GeV)	$\sigma_{abs}^{J/\psi}$ (mb)
NA60	17.27	6.45 ± 0.49
NA60	27.42	3.92 ± 0.62
NA50	27.42	4.27 ± 0.34
NA50 (HI)	29.08	4.04 ± 0.70
NA50 (LI)	29.08	3.95 ± 0.98

Table 1: Value of $\sigma_{abs}^{J/\psi}$ extracted from the fitting of different experimental data on inclusive J/ψ production in p+A collisions at SPS.

To estimate the magnitude of the CNM suppression at the foreseen energies of CBM and NA60+ experiments, the centre-of-mass energy dependence of $\sigma_{abs}^{J/\psi}$ is parameterised using two probable functions namely a 1st order polynomial and an exponential function. The resulting parameterizations are shown in Fig. 3 and the fit results are

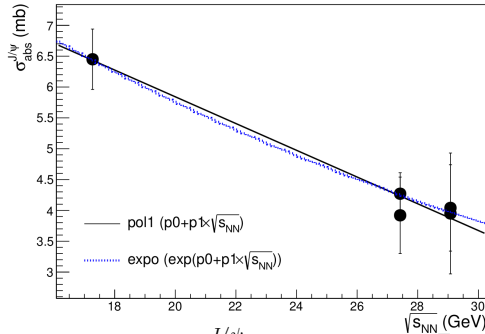


Figure 3: Variation of $\sigma_{abs}^{J/\psi}$ as a function of $\sqrt{s}$ and fitted with a 1st order polynomial and also with an exponential function.

summarized in Table 2.

Fitting function	Parameters	χ^2/ndf
pol1	$p0 = 10.18 (+1.35)$, $p1 = -0.22 (+0.05)$	0.11
expo	$p0 = 2.59 (+0.23)$, $p1 = -0.04 (+0.01)$	0.09

Table 2: Details of the parameterization of $\sigma_{abs}^{J/\psi}$ as a function of $\sqrt{s_{NN}}$.

Both energy dependent parameterizations have comparable (within error bars) fit qualities. The values of $\sigma_{abs}^{J/\psi}$ as

extrapolated from the linear parameterization (pol1) along with the corresponding values of J/ψ production cross-section using ρL parametrization, for a variety of nuclear targets are used to estimate the J/ψ production cross-section for CBM and NA60+ energies. The per nucleon J/ψ production cross-section is shown in Fig. 4 for pA (top) and AA (bottom) systems. For AA collision systems, three dif-

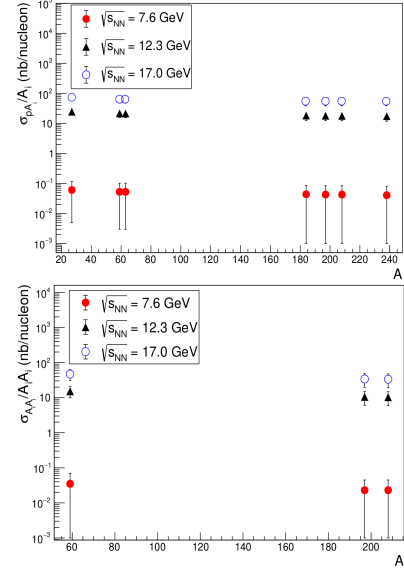


Figure 4: J/ψ production cross-section per nucleon for pA (top) and AA (bottom) collision systems at the center of mass energies relevant for CBM experiment at FAIR and NA60+ experiment at SPS. The errors shown in the plots are associated with the fitting parameters.

ferent collision systems namely Ni+Ni, Au+Au and Pb+Pb are used. Seven different collision systems namely p+Al, p+Ni, p+Cu, p+W, p+Au, p+Pb and p+U are used for the pA systems [12].

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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], a software to reconstruct hadrons based on the KF Particle Finder [3], is currently developed. The results of the reconstruction of the 3-body-decay ${}^3_\Lambda\text{H} \rightarrow \text{d} + \text{p} + \pi^-$ (BR: 40.1 % [4]) with MC-PID was presented in [5].

Recently, the detector PID was implemented into the PFSimple software. The PID-framework [6] is used to provide the required information from the TOF detector: for every track the purity for all possible particle species is identified based on its TOF- $mass^2$ and its momentum by comparing it with a MC-track-distribution. With a similar approach, the TRD- $\langle dE/dx \rangle$ information is added to improve the reconstruction efficiency in the case that a track does not have a TOF-PID. The average differential energy loss for a given track is calculated by using the so called *truncated mean*; that means out of four or three TRD-hits, the two hits with the lowest energy loss are selected to compute $\langle dE/dx \rangle$, in order to reduce the fluctuations due to the underlying Landau distribution.

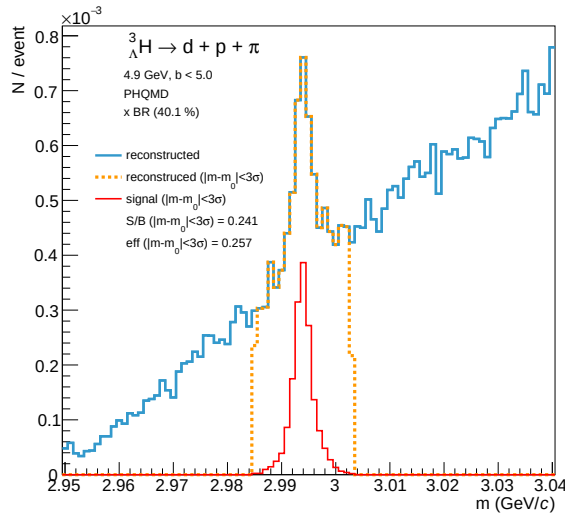


Figure 1: Mass distribution for ${}^3_\Lambda\text{H}$ -3-body-decay for 1×10^6 central PHQMD-events at $\sqrt{s} = 4.9$ GeV for a branching ratio of 40.1 %.

* Work supported by DFG 405580046.

For the 3-body- ${}^3_\Lambda\text{H}$ -decay, the additional TRD-information can increase the efficiency by a factor of two. The PID information has been implemented into PFSimple in a way that the required purities can be adjusted easily for every daughter-specie. It has been found that the reconstruction performance in the case of ${}^3_\Lambda\text{H}$ is optimal, if tracks must have a minimum TOF purity of 70 % for p or π candidates, whilst for d the minimum value is set to 20 %. For the TRD- $\langle dE/dx \rangle$ a purity above 20 % for p and π , for d above 5 % gives the best results. Additionally, electrons are suppressed by the RICH detector. To further increase the efficiency, all tracks with no detector-PID are considered as p and d, if they have a positive charge and as π , if they are negative. An efficiency of 26 % at a signal-to-background-ratio of 24 % can be reached for a dataset of 1×10^6 central PHQMD-simulations [7] at $\sqrt{s} = 4.9$ GeV.

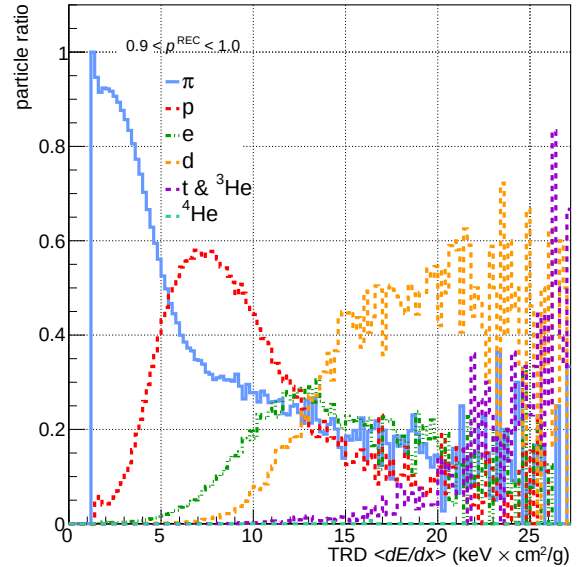


Figure 2: Purity for different particle species depending on $\langle dE/dx \rangle$ for $0.9 < p^{REC} < 1.0$ GeV/c based on the MC-information from 1×10^6 central PHQMD-events at $\sqrt{s} = 4.9$ GeV.

In order to evaluate the detector performance depending on the detector area, two datasets were simulated where the – so far unknown – phase-space distribution of ${}^3_\Lambda\text{H}$ is represented in two different ways. For the first dataset the ${}^3_\Lambda\text{H}$ signal was generated according to the multiplicities of the thermal model (0.087 per event) [1] with a phase-space

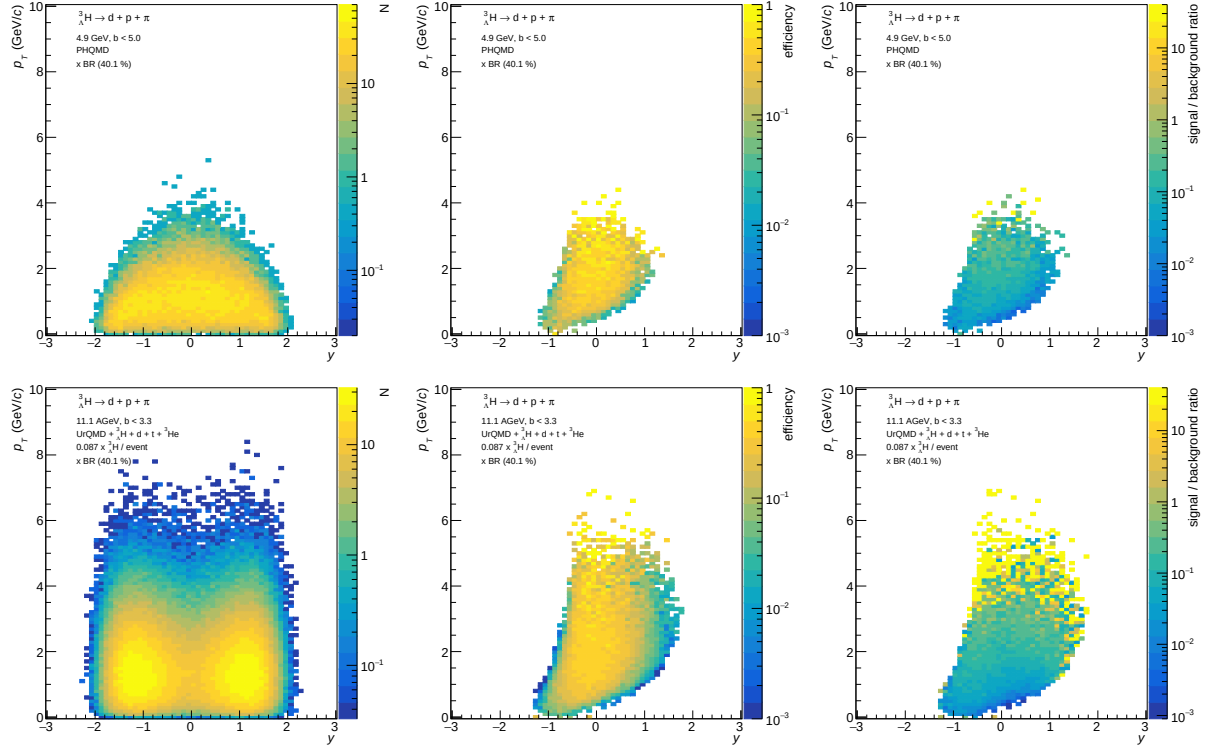


Figure 3: p_T vs. rapidity for simulated ${}^3_\Lambda\text{H}$ (left), reconstruction efficiency (middle) and S/B -ratio (right) for 1×10^6 PHQMD-events (top) and 0.45×10^6 UrQMD-events with embedded signal (bottom) at $\sqrt{s} = 4.9$ GeV.

distribution following the experimental triton distribution [8]. Here the rapidity has the form of a double Gaussian [9] with two maxima at target- and projectile rapidities and a minimum at midrapidity. This thermal signal was embedded into 0.45×10^6 UrQMD [10] Au-Au-simulations at $\sqrt{s} = 4.9$ GeV (for more details see [5]). Contrary, the ${}^3_\Lambda\text{H}$ rapidity distribution of the second dataset, generated with the PHQMD model, a novel n-body microscopic transport approach including the dynamic formation of nuclei and hypernuclei, has a Gaussian form with a maximum at midrapidity. Additionally, the PHQMD-data show a steeper p_T -distribution for ${}^3_\Lambda\text{H}$ compared to the thermal signal. The different phase-space distributions allow to study two extreme scenarios.

It can be shown, that the detector performance is best at mid-rapidity and, as a consequence, the detector coverage resembles rather the PHQMD signal distribution, leading to a higher total efficiency for the PHQMD signal (approx. +20 %). As the S/B -ratio is improved towards higher p_T , the thermal signal leads to a higher S/B -ratio.

As a next step, systematical uncertainties will be estimated based on simulations from the two datasets, as well as on the signal extrapolation to the full rapidity and transverse momentum range. The experimental sensitivity to properties of ${}^3_\Lambda\text{H}$, such as its lifetime, will be evaluated.

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Performance studies of CBM-ToF detector for a few global observables

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Introduction

The facility at FAIR will accelerate a variety of nuclei right from Hydrogen to Uranium with beam energies ranging from 2 – 45 AGeV. FAIR is unique in the sense that it will provide beams with unprecedented beam intensity with brilliant beam quality [1, 2]. Along with bulk particles, the main thrust of the CBM experiment is the detection of early messengers of the fireball created in such heavy-ion collisions. These are the particles such as ψ' , J/ψ , D_0 etc with relatively heavier mass and very low production cross-section, also known as rare probes of HIC. To measure these rare probes, the CBM experiment will be run under an extreme reaction rate. For some observables, there will be dedicated runs with luminosity up to 10 MHz. To work efficiently under such an unprecedented reaction rate requires development of ultra-fast and extreme radiation hard detectors and electronics. Simulation studies of detector geometry and physics performance studies of various sub-detectors of CBM experiment thus becomes inevitable.

A time-of-flight (ToF) detector with a polar angular coverage of 2.5–25 degree, that is set at a distance of 10 metres from the target is the most crucial tool for hadron identification. According to simulations, the cell occupancy must be limited to < 5% while separating pions, kaons, and protons up to a few GeV/c momentum, which calls for a ToF resolution of 80 ps at high efficiency [3]. The studies of physical observable at such unprecedented rate of 10 MHz using such a high efficient and wide acceptance Time of Flight (ToF) detector will be a very important aspect of CBM experiment. It, thus, becomes very pertinent to undertake CBM-ToF simulation and physics performance studies to realize its applicability under high luminosity, high reaction rate, and particularly at central nuclear collision scenario. In this investigation, an attempt has therefore been made to identify light flavoured hadrons, namely, pions ($\pi^\pm$), kaons ($K^\pm$), and protons (p , $\bar{p}$) using CBM ToF geometry. As the width of rapidity distribution and transverse momentum spectra are two important global observables of heavy ion collision studies, attempts will be made to estimate rapidity and transverse momentum spectra for pions, kaons, and protons identified with the below-mentioned CBM-ToF simulation softwares. Such plots also serve as the quality assurance plots for our particle identification with the considered ToF geometry.

Analysis Details

In the present study, UrQMD event generator is used to generate the monte carlo events at $E_{lab} = 10 AGeV$ for central ($b = 0 - 3 fm$) Au-Au collisions. For this ToF simulation study, *CbmRoot-JUN16* of *FAIRROOT-nov15p7* and the ToF geometry *tof_v16a_1h.geo.root*, STS geometry *sts_v16x.geo.root* are used. The other relevant attributes of the simulation softwares and analysis details are listed below:

Detector setup: *sis100_hadron*.
 Transport Engine: *GEANT3*
 Cave geometry: *cave.geo*
 Pipe geometry: *pipe_standard.geo*
 MVD geometry: *mvd_v15a.geo.root*
 $n\sigma$ cut: 2

Results

For identification of π , k , p using the considered CBM-ToF geometry, the variation of $1/\beta$ against p/q and m^2 distribution were plotted and reported in our contribution to earlier CBM progress report [4] and in ref.[5]. In Fig.1, as a quality assurance check, the $y - p_T$ plots for ToF identified light flavoured hadrons are plotted. It can be readily seen that the most of the entries fall within the expected $y - p_T$ range.

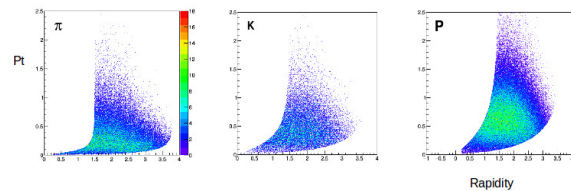


Figure 1: $y - p_T$ acceptance plot of identified (a) pions, (b) kaons, and (c) protons.

The rapidity distribution and transverse momentum (p_T) spectrum of pions, kaons, and protons identified with CBM-ToF detector are shown in Fig. 2 and Fig. 3 respectively. In Fig. 2, the solid lines represent the Monte Carlo (MC) (UrQMD generated) and the solid circles represent the reconstructed tracks (Reco). It is seen that the rapidity distribution of pions, kaons, and protons peak at about mid-rapidity. The peaking of rapidity distribution of proton at mid-rapidity is consistent with a high degree of stopping and thus high baryon density as expected for the such

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collisions. The widths of the rapidity distribution of the identified π , k , p are obtained with the single gaussian fit, shown by dotted line in the figure, and the values are listed in table-1. As could be readily seen from this table that the rapidity width follows the mass ordering as expected from kinematic consideration.

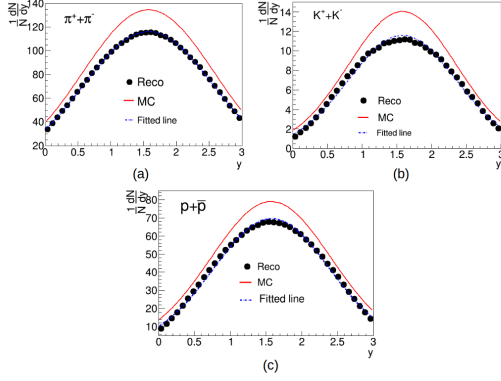


Figure 2: Rapidity spectra of identified (a) pions, (b) kaons, and (c) protons.

Table 1: Widths of the rapidity distribution of $(\pi^+ + \pi^-)$, $(K^+ + K^-)$, and $(p + \bar{p})$

Particles	Rapidity width
$\pi^+ + \pi^-$	1.9997 ± 0.0293
$K^+ + K^-$	1.6129 ± 0.0404
$p + \bar{p}$	1.5476 ± 0.0227

In Fig. 3, the p_T spectra are obtained with reconstructed (black circles) and monte carlo (red triangles) π , k , p . As could be seen from these figures that the reconstructed p_T agrees well, both qualitatively and quantitatively, with the p_T spectrum obtained with MC data. The p_T dependent ratio of reco to MC is shown in Fig. 4 and is found to be flat almost over the entire studied p_T range. Thus, from the results obtained from this investigation, it could be concluded that the ToF geometry considered in *tof_v16a_1h.geo.root* under *CbmRoot-JUN16* of *FAIRROOT-nov15p7* is able to identify light flavored particle at SIS100 energies of the upcoming FAIR CBM experiment.

Acknowledgement

The authors thankfully acknowledge the contribution of CBM simulation team for developing various simulation software used in this study. The authors also acknowledge the Department of Science and Technology (DST), Government of India, for providing the computing facility, through the Project No. SR/MF/PS-01/2014-GU, which has been used to generate Monte Carlo (MC) events.

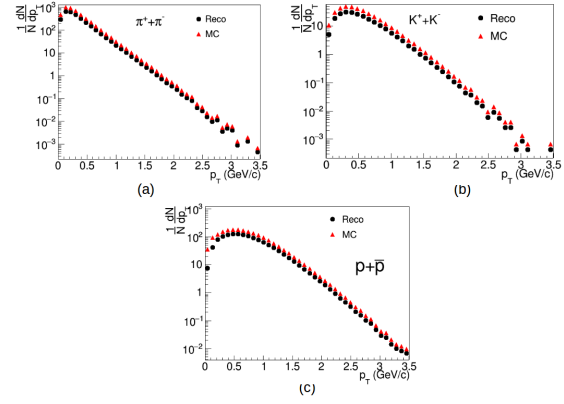


Figure 3: Transverse momentum spectra of identified (a) pions, (b) kaons, and (c) protons.

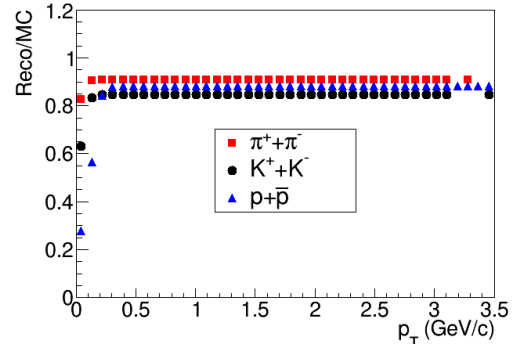


Figure 4: Transverse momentum dependent efficiency for identified (a) pions, (b) kaons, and (c) protons.

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Development of code for femtoscopic analysis of V0 particles*

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Femtoscopia is a method used for measurements of the geometrical properties of the fireball created during heavy ion collisions. This experimental technique uses two-particle correlation to extract information about the size of the source that emits particles. Another application of femtoscopia is a measurement of the interaction between particles.

Femtoscopia

Experimental femtoscopia uses the so-called Correlation function 1. In this equation, q is the momentum difference between the pair of particles, N is a distribution of particles from the same event, and D is a distribution of particles from different events.

$$C(q) = N(a)/D(q) \quad (1)$$

The main factors that define the shape of the CF are: the size of the source of particles and the type of the particles (that define the interaction between them and influence of quantum statistic effects in case of pairs of identical particles) [4].

Therefore if we know the interaction between particles, we can measure the size of the sources (probe the process of heavy ion collisions), and if we know the size of the source, we can measure the interactions between particles. Usually, we do both at once - we measure the size of particles with known interactions (like protons), and then, by having "general information" about the size of the source, we measure the interactions between particles like Λ , Σ [1]. Measuring interactions of exotic particles like Λ might be crucial for understanding the behavior of matter at high densities like in neutron stars [3].

Software

The code for V0 analysis depends on three codes:

- PFSimple that is a code for finding V0 particles
- Analysis Tree that is a code/format for data storing in CBM
- HAL (High energy physics Analysis Libraries) that is a code for femtoscopic analysis

PFSimple is an interface to KFPARTICLE code that was mainly developed for CBM collaboration but is also used by STAR and ALICE collaboration. This code can find various types of particles that decay - not only V0 but, e.g., also Xi particles [?].

Analysis Tree is a flexible format of data storage. In contrast to other approaches used in high-energy physics experiments, Analysis Tree does not require a code change each time a user changes the number of event/track/hit parameters stored in a file. What is more important different types of data (e.g., from STAR or CBM experiments) can be opened with the same framework.

HAL is a set of libraries that allow performing femtoscopic analysis. In principle, it is a successor of the NicaFemto framework. HAL was created in the spring of 2022. Developing code for V0 was also an excellent opportunity to test relatively new HAL code.

Code development

The code development was performed in four steps.

- Creation of new Hal::Event structure. Up to this time, the event's structure was relatively simple - the event contained parameters of the event and an array of tracks. It was changed - an additional array to store V0 parameters was added. Therefore to have complete information about the V0 particle user must have access to an array with "general" track properties (e.g., track momentum) and V0 parameters (like indexes of daughter particles). It allowed for keeping relatively low memory usage. It is important that much effort in this stage was related to developing code that does quite complicated things but is still relatively easy to use.
- Development of code for reading two Analysis Tree files at once. It is because the first file contains only charged particles, whereas the second contains only V0 candidates. To have an option on charged-charged, charged-V0, and V0-V0 particle analysis, we need to have the option to process two files simultaneously.
- Interface for reading the data from Analysis Tree format. At this stage, we check the first step of the analysis. Many bugs related to memory management were detected and fixed. Also, we check if the interface for event usage is simple enough.
- Development of the code for V0 selection and monitoring (so-called cuts and cut monitors). This step

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was relatively simple but showed that adding cuts/cut monitors to HAL is time-consuming. The same problem was visible when the interface for reading STAR data was developed. This issue was solved by adding a special helper that generates most of the code needed to create new cuts/cut monitors.

At each step of this work, the code was tested to ensure no problems with memory leaks or wrong conversion of the data. Finally, we obtained the plots that describe V0 track parameters. Unfortunately, we did not have enough statistics to calculate the $\Lambda - \Lambda$ correlation function.

Summary

The first version of code for processing the V0 particles was created and tested. However, the code was not yet implemented into the main version of the CbmROOT code. We plan to do this after calculating Lambda baryons' first correlation functions. Because of the enormous statistic required for such calculation, we consider two options: embedding Λ into data samples or embedding Λ and calculating the $p\Lambda$ correlations - this should be much simpler due to the high abundance of protons at CBM energies. Successful implementation of code for V0 analysis allows us to study the performance of the CBM detector for femtoscopic measurements of these particles. Later we would like to test predictions from theoretical models to find out what kind of physics we can extract from this type of correlation.

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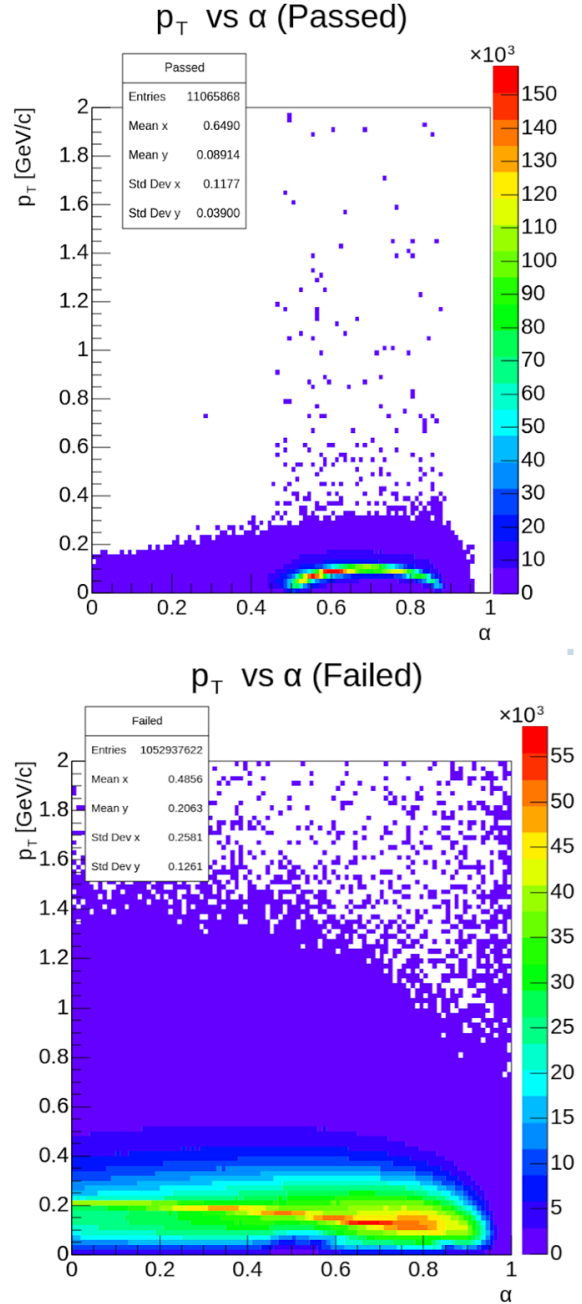


Figure 1: The report from HAL code. This report shows the Armenteros-Podolaski plot before (lower plot) and after (upper plot) application of cuts for Λ selection. The sample is based on 2 mln events of Au+Au for beam momentum $p = 12$ AGeV/c from UrQMD model.

Performance study for Λ^0 hadron yield using Machine Learning

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A first-order phase transition, from hadron gas to a deconfined phase of QCD matter, is expected from effective-model calculations in the region of the QCD phase diagram above 450 MeV baryon chemical potential (μ_B) [1]. The augmentation of strange quarks is one of the indications of the deconfined phase, and Λ^0 hyperon, the most profusely produced hyperon at FAIR SIS-100 energies, is pivotal for finding the augmentation. A performance study is presented for the reconstruction and selection criteria (SC) optimization of the short-lived Λ^0 via its decay to proton (p^+) and π^- . The SC are optimized using the Machine Learning (ML) algorithm of boosted decision trees of the XGBoost (XGB) [2] library.

DCM-QGSM-SMM (Model A) [3], and UrQMD (Model B) [4] collision generators were used to produce Au-Au collisions at 12A GeV/c and the resulting products were transported through the CBM setup using GEANT4. Model A is utilized as simulated data while Model B as experimental data. Cellular automaton and Kalman Filter Particle (KFParticle) based PFSimple package [5] are used for track finding, fitting, and decay kinematics reconstruction. All negatively charged tracks are combined with all positively charged tracks to reconstruct Λ , in one collision. The combinatorial background is diminished through selection criteria optimization on seven variables. These variables are the squared distance between the daughter tracks and primary vertex (PV) divided by its error, the distance of the closest approach between the two tracks, the squared distance between daughter tracks divided by its error, and the distance between PV and secondary vertex divided by its uncertainties. Also used is the $mass^2$ information from the Time of Flight wall for the individual daughter track.

Data from both models are selected in an interval of charged particle multiplicity (200 – 400) with a corresponding mean impact parameter of 5 and a standard deviation of 1, transverse momenta p_T (0 – 0.6 GeV/c), and laboratory frame system rapidity y_{LAB} (0 – 1.6). Λ signal candidates are selected from model A, in the 5σ region around the peak on the invariant mass distribution, while the background is selected from model B in the 1.077-1.1 and 1.13-1.2 GeV/c^2 mass region. The XGB algorithm is trained on the signal and background samples, and it returns its probabilistic predictions. It is checked that the performance of the XGB model is similar on the train and test sets, and when this condition is satisfied then the model is deployed on 2M events of models A and B.

A multi-step and differential in p_T and y_{LAB} fitting routine is implemented to extract the raw yield from model B. A Double-Sided Crystal Ball (DSCB), a Gaussian with

power-law tails, is used for signal distribution approximation and a 4th-order polynomial for background. The raw yield is obtained by integrating the DSCB function. The Efficiency factor ε for model A (ε = geometrical acceptance $\times$ reconstruction and selection efficiency), is used to correct the raw yield for model B. Since the raw yield is dependent on the selection applied to the XGB output, therefore the corrected yield (CY) is calculated for different selections on the XGB score. Fig. 1 shows the CY at the default XGB score (red circles), significance maximized selection, for different p_T intervals, while $y_{LAB} = [1.2, 1.5]$. The standard deviation of the corrected yield as a function of the XGB score is considered as XGB systematic, they range between 1 – 2% for the various transverse momentum intervals. The difference (less than 2%) between the yield from the DSCB integral and the MC true counting at the default XGBoost score is taken as fitting systematic. The fitting and the XGB uncertainties are added in quadrature, plotted as the blue-shaded area on Fig 1. The CY agrees with the true simulated yield (black squares on Fig 1) within the statistical uncertainties.

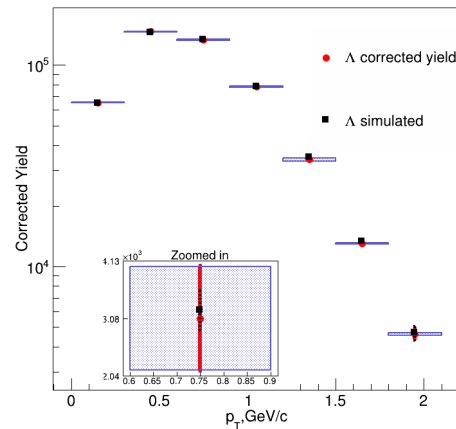


Figure 1: Comparison between the efficiency corrected yield and the simulated yield.

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Tuning of UrQMD model for hadron study at CBM energy range

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For the simulation studies of the CBM experiment, the Ultra-relativistic Quantum Molecular Dynamics (UrQMD) event generator is frequently employed. We will be able to better visualize particles, especially hadrons, if we fine-tune the UrQMD model in relation to various parameters, including equations of states and particlization scenarios.

CBM experiment covers the energy range of the QCD phase diagram where first-order phase transition takes place, and Quark-Gluon Plasma (QGP) gets formed. One possible observable for analyzing the overall consequences of the created medium is the anisotropic flow of the particles produced in noncentral relativistic heavy-ion collisions. For this study, we take UrQMD generated Au-Au non-central (5-9 fm) collision events in the beam energy range of $E_{lab} = 2A-40A$ GeV, which cover the CBM energy range. We look at the effect of different equations of state (EoS) and particlization scenarios on the anisotropic flow coefficients and particle production for proton. We are trying to predict the best combination of particlization scenario and EoS that could be taken for simulation study using the UrQMD model, which could explain the experimental data very well.

Hydrodynamics gets switched on when two Lorentz-contacted nuclei cross each other, and all baryon scattering and energy deposition have taken place. Hadron gas (HG), chiral + deconfinement EoS, and bag model EoS are various hybrid models for the intermediate hydrodynamical stage that are included in the UrQMD model in addition to the pure transport method. With time, fluid dynamical de-

scription is changed to particle description using Cooper-Frye formalism, known as "Particlization". In the hybrid UrQMD model, there are three different particlization scenarios available for fluid-to-particle transition, which are gradual particlization scenario (GF), isochronous particlization (ICF), and iso-energy density particlization scenario (IEF). More details about the working of the UrQMD model, their EoS, and particlization scenarios can be found in the ref. [3, 4]

The particlization scenario decides the exact time at which fluid-to-particle transition will take place, and hence it will cease the fluid dynamic evolution at different times. Particlization will affect the flow of different particle species due to spending more or less time in evolution. We could look at anisotropic flow coefficients to see the effect.

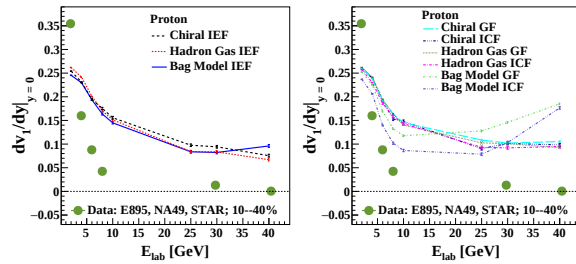


Figure 1: Slope of the directed flow of protons with respect to beam energy at midrapidity for different EOS and particlization scenarios of UrQMD. Also compared with experimental data from E895 [1] and STAR [2] experimental results in Au-Au collisions.

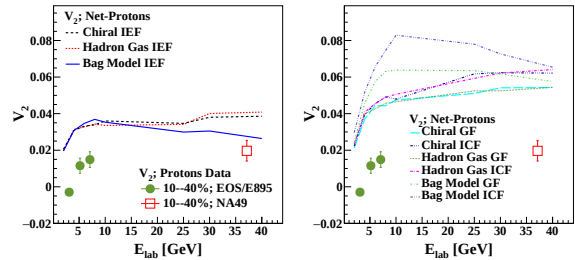


Figure 2: p_T integrated elliptic flow v_2 of net-protons with respect to beam energy for different EoS and particlization scenarios of the UrQMD model. Compared with experimental data from E895 [5], and NA49 [6] experiments for Au-Au and Pb-Pb collisions.

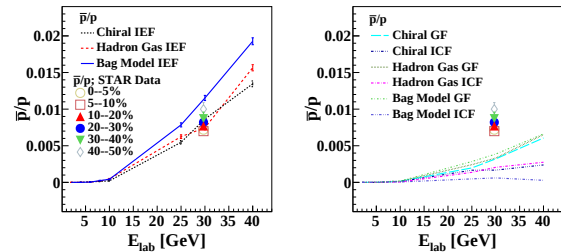


Figure 3: Anti-proton to proton ratio with respect to the beam energy for different EoS and particlization scenarios of the UrQMD model. Compared with experimental results of STAR [7] experiment for Au-Au collisions.

scriptions remain no longer applicable. At that time, fluid

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Figure 1 shows the slope of the directed flow of protons

as a function of beam energy for different EoS and particlization modes. A hint of splitting could be seen for the bag model at beam energy around 30A GeV. IEF scenario is giving more consistent results in spite of different EoS. When we look at the elliptic flow (v_2) for net-protons in figure 2, the same kind of consistency could be seen for the IEF scenario. There is way more fluctuation for the other two particlization cases. In the $\bar{p}/p$ ratio in figure 3, the ratio appears to be more susceptible to the particle scenario than EoS due to potential changes in particle configurations. In the case of ICF, the production of anti-protons is negligible, even for a high energy range, which is quite unrealistic. These kinds of studies have been done for other hadrons as well, and we found out that the IEF scenario is better at predicting the experimental results in combination with any EoS. Although, there are other parameters as well to check in the UrQMD model, which could affect the outcomes.

In conclusion, this study shows that the use of the IEF particlization scenario should give better agreement with the experimental results compared to the default GF scenario, without having so much direct effect of different EoS.

Acknowledgement

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Expected performance for strange hyperons directed flow and global polarization measurements

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Strange quarks are produced at the early stage of a heavy-ion collision and strange particles can provide information about the properties of the nuclear matter, its equation of state and compressibility. Anisotropic flow of produced particles is an important observable for understanding the dynamics and evolution of the QCD matter created in the collision. In particular, the slope of the directed flow is sensitive to the equation of state of created matter.

Anisotropic flow can be characterized by coefficients of a Fourier series of produced particles azimuthal angle distribution. The directed flow $v_1 = \langle \cos(\varphi - \Psi_{RP}) \rangle$ describes particle emission in preferred direction relative to the reaction plane. The procedure of anisotropic flow evaluation and CBM performance for strange hadrons anisotropic flow measurement are described in [1].

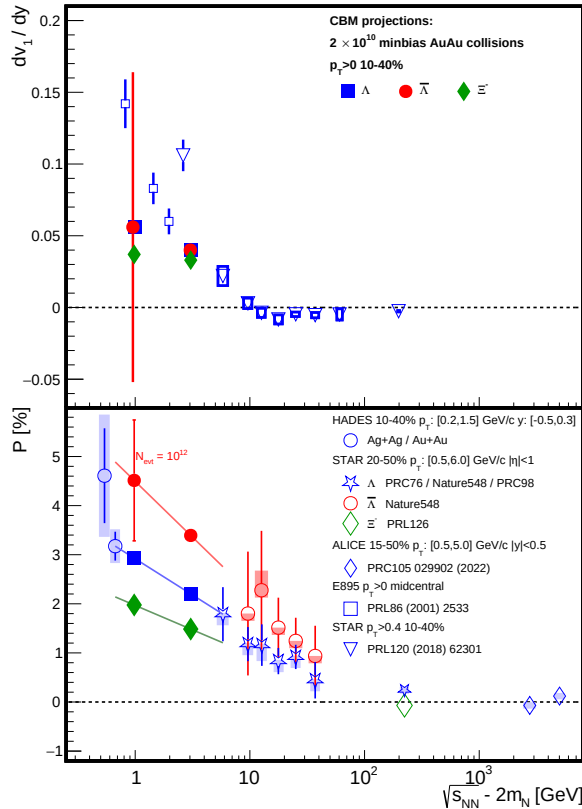


Figure 1: **(top)** Directed flow slope $\frac{dv_1}{dy}$ and **(bottom)** global polarization coefficient as a function of collision energy of (multi)strange hadrons - world data and expected CBM performance.

Fig. 1 (top) shows CBM projections for the statistical errors on the slope of the directed flow, dv_1/dy , for (multi)strange hadrons in comparison with existing world data as a function of collision energy. Values of anisotropic flow of Λ and Ξ^- at are calculated in [1], and anisotropic flow of $\bar{\Lambda}$ is assumed to have the same magnitude as Λ . Statistical errors are estimated by extrapolation of statistical errors obtained in [1] with 5M statistics into expected 20G statistics at FAIR run, and in assumption that yields of (multi)strange hadrons at different energies are predicted by the thermal model [2].

Global polarization coefficient is a numerical quantity describing produced particles spin alignment along angular momentum of the colliding system [3]. Fig. 1 (bottom) shows expected CBM performance for global polarization coefficient P measurement in comparison with measurements at HADES, STAR and ALICE. Values of $P\{\Lambda\}$ are estimated by interpolation of HADES and STAR data along energy axis; values of $P\{\bar{\Lambda}\}$ and $P\{\Xi^-\}$ are calculated in assumption that they have the same ratio to $P\{\Lambda\}$ as measured by STAR at higher energy ranges. Statistical errors are calculated in the same way as for directed flow slope as described in paragraph above and in assumption that relative errors of global polarization coefficient and directed flow slope have the same magnitude at the same statistics. Note that error bar for $\bar{\Lambda}$ at $\sqrt{s_{NN}} = 2.9$ GeV is shown for 10^{12} events statistics.

In summary, the CBM performance for (multi)strange particles anisotropic flow and global polarization measurement is compared with that of another experiments and projections for statistical uncertainties with high statistic data at CBM are estimated. With 20G events CBM will be able to measure with extremely low statistical error directed flow and global polarization coefficient of Λ , Ξ^- in full SIS-100 energy range and of $\bar{\Lambda}$ at highest SIS-100 energy. But measurement of $\bar{\Lambda}$ at lowest SIS-100 energy will require higher statistics.

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Current status of low mass vector meson analysis*

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Introduction

In this report, the current status of the low-mass vector meson analysis using the “di-electron” package in CbmRoot is presented. Feasibility studies are shown for 5M central Au+Au collisions at 8 AGeV beam energy, i.e. UrQMD files from /lustre/cbm/prod/gen/urqmd/auau/8gev/centr/ and PLUTO files from /lustre/cbm/users/galatyuk/pluto/epem/8gev/ are used for this analysis. Those particles that only rarely decay in the medium, e.g. the ω and ϕ -mesons, are generated with PLUTO and are scaled with the scaling values given at the cbm-wiki page [1]. Additionally, the ρ -meson with in-medium mass distribution ($\rho_{\text{in med}}$) and the QGP radiation are scaled with mass-dependent scaling values.

Analysis Cuts

Analysis cuts are important to select a clean electron sample, however still at a reasonable efficiency. In general, those two effects can be played against each other. For the analysis presented here, the following cuts are used:

Single track cuts for reconstruction Each track is required to have a certain number of hits (diger) in each detector, i.e. 4 (MVD + STS), 7 (RICH), 2 (TRD), 1 (TOF). The track fit with regard to the primary vertex is required to have $X_{\text{prim}}^2 < 3$.

Single track cuts for electron identification As a next step, the electron identification is applied. A track (or ring, resp.) is classified as stemming from an electron if it is classified as electron in each of the subdetectors (STS, RICH, TRD, TOF). All ID cuts are implemented as 2D cuts, see Fig. 1 as example for the RICH cut. In the following, the dominating thresholds will be indicated in brackets with either the lower or upper values (LV or UV).

In the STS, the classification is based on the energy loss of the particle ($UV \approx 30 \text{ e}/(300 \mu\text{m})$). The RICH detector uses data of the ring position, shape and angle to calculate the probability for the ring to originate from an electron with the help of a neural network (see Fig. 1; LV = 0). Two values from TRD are used to decide between an electron and not-electron: the electron likelihood value which

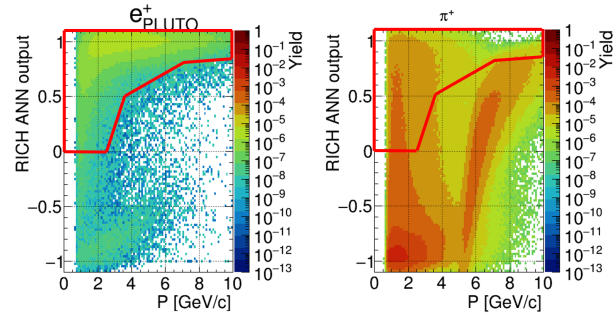


Figure 1: RICH ANN values vs. momentum for positrons generated with PLUTO (left) and π^+ (right) after X_{prim}^2 cut. The red line indicates the course of the two-dimensional cut. Tracks that are located inside the lines are kept, the others are rejected.

is calculated on the basis of energy loss of the track in the TRD ($LV = 0.4$) and the track quality X_{TRD}^2 in this detector ($UV = 9$). Currently, likelihood values are only available for $p > 1 \text{ GeV}/c$, thus the TRD is not used for tracks with smaller momentum than this. Finally, in TOF the calculated m^2 value decides on the classification of the track.

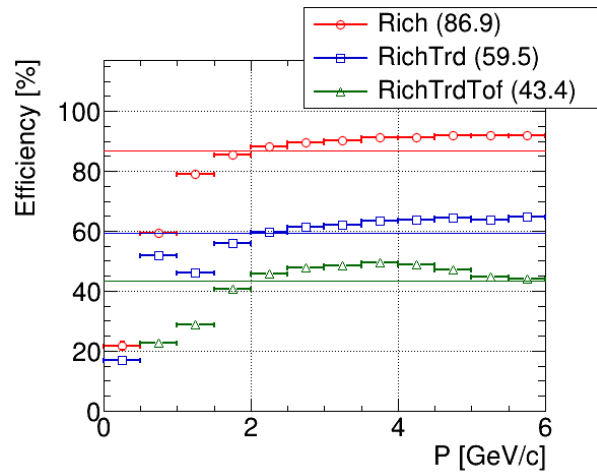


Figure 2: PID efficiency vs. momentum for various detector combinations.

Pair cuts To reject electron tracks stemming from γ conversion and π^0 Dalitz decays, pair cuts are applied. In a first step, both tracks of a pair are rejected if their invariant

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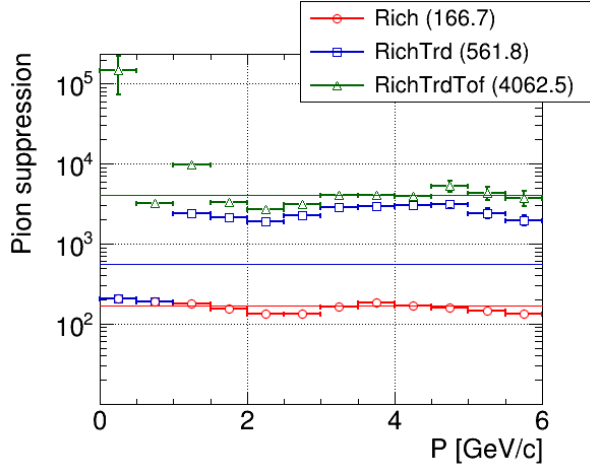


Figure 3: Pion suppression versus momentum for various detector combinations. TRD and RICH show the same values for $p < 1$ GeV/c as the TRD can currently not be used for momenta smaller than this.

mass is below $25 \text{ MeV}/c^2$. To reject more electrons from γ conversion and π^0 Dalitz decays, also tracks are considered that are not reconstructed in all of the detectors. For that, each fully reconstructed electron candidate is paired with various track fragments (‘‘topology cuts’’), i.e. tracks in (MVD+)+STS only, (MVD+)+STS+STRD or tracks being fully reconstructed ((MVD+)+STS+TRD+TOF) but not identified as electron. As soon as a partner is found with an angle $\theta_{\text{cand-fragm}}$ below a certain threshold (depending on $\sqrt{P_{\text{cand}} \cdot P_{\text{fragm}}}$), the electron candidate is sorted out.

Single track p_T cut Finally a cut on the transverse momentum (p_T) of single tracks is applied. This cut is to be handled with care, since it can reject also larger amounts of signal electrons.

Status

With this set of cuts the tracking efficiency considering tracking in STS, RICH, TRD and TOF is about 72 % for all particles and 82 % for electrons, whereas the overall PID efficiency for electrons reaches about 43 %. The pion suppression is about 4100 considering RICH, TRD and TOF together (see Fig. 3).

Invariant mass spectra are shown in Fig. 4 for two different steps, right after electron identification and after the preceding background rejection steps. Obviously, they help increasing the signal-to-background ratio, although not by large, see Fig. 6. The light green line describes the calculated combinatorial background from like-sign e^-e^- pairs and event mixing. The composition of the background (gray) can be seen in Fig. 5. Physical background, i.e. pairs of electrons from gamma conversion and π^0 Dalitz decays, forms the largest contribution. Background pairs containing misidentified pions are the next large con-

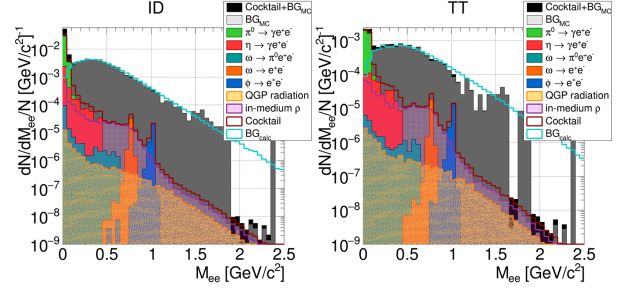


Figure 4: Invariant mass spectra after electron ID (left) and including all pair-cuts (except last single-track p_T cut; right) for 5M central Au+Au collisions at 8 AGeV beam energy.

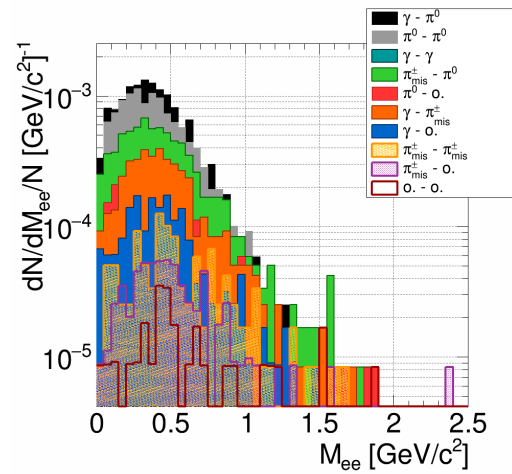


Figure 5: Invariant mass spectra of the various background contributions after electron ID cut. Physical background is the largest contribution in lower mass regions, whereas at higher masses misidentified pions are dominating.

tribution in the lower mass regions and are dominating in the higher mass regions. The signal-to-background-ratio is shown in Fig. 6 and is about 1/100 for masses around $500 \text{ MeV}/c^2$.

In Figure 7 the yield of e^+e^- pairs (red) is shown along with the calculated combinatorial background (blue). Furthermore, the difference of both curves (green), which is the calculated signal, is compared here with the MC cocktail (black). The spectra are shown after the electron-ID as the subsequent cuts do reduce the statistics even further, see Fig. 4. Obviously due to the large statistical fluctuations even here, not much can be said regarding the precision.

Figure 8 shows the ratio of the calculated background and the MC background (blue). As can be deduced from that, currently the background can be specified with a precision of about 10 % in the low invariant mass region only. Since the signal-to-background-ratio is of the order of 1/100, much more statistics is needed to get a reasonable

precision of background description to reliably extract the signal by means of calculated combinatorial background techniques.

Error Discussion

The error of the signal S can be denoted as $\Delta S = \sqrt{(\Delta N)^2 + (\Delta B)^2} \approx \Delta B = 0.1B$, with N representing the yield of e^+e^- pairs and the background B with an error of 10%. With the given signal-to-background-ratio of $S/B=1/100$ the error of the signal thus reaches up to $\Delta S = 0.1B = 0.1(100S) = 10S$. Hence, to get an error of about 10% for the Signal, one would need an error of 0.1% on the Background, i.e. 10,000 fold more statistics, which would require $\sim 50 \times 10^9$ events.

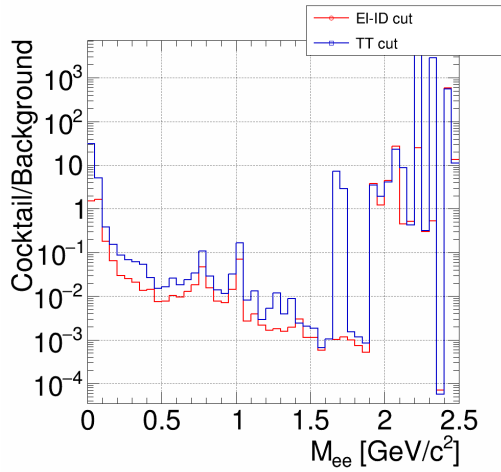


Figure 6: Signal-to-background-ratio after electron ID (red) and including all pair-cuts except last single-track p_T cut (blue).

Outlook

In order to further test the precision of the background calculation as well as the feasibility of precise measurements for masses beyond $1 \text{ GeV}/c^2$, higher statistics are mandatory. Thus, an implementation of a fast simulation techniques is ongoing to enhance statistics by several orders of magnitude. Furthermore, a new reference file exists for the TRD enabling electron identification for momenta below $1 \text{ GeV}/c$ which certainly will improve the pion suppression for low momenta.

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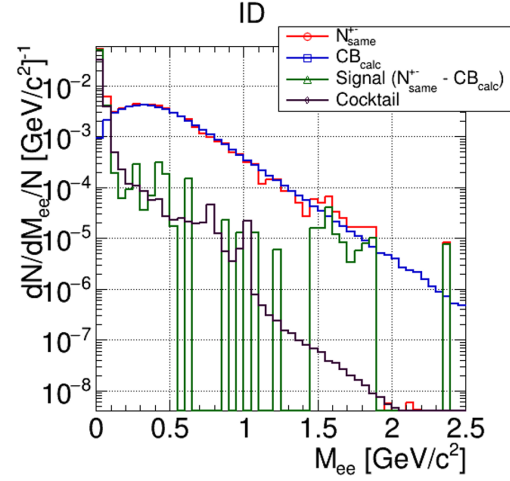


Figure 7: Invariant mass spectra for all e^+e^- pairs (red) and the calculated combinatorial background (blue) after the electron identification. The signal (green) is obtained by the difference of both. A comparison of the signal with the MC cocktail (black) shows a certain level of agreement in the lower mass region.

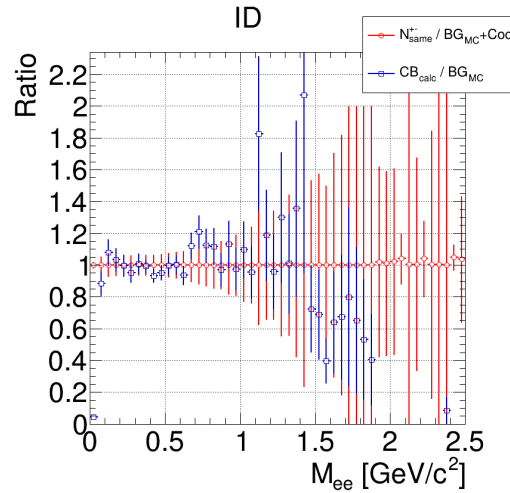


Figure 8: Ratio of e^+e^- pair yield over the sum of background and cocktail shown in red and ratio of the calculated combinatorial background over MC background (blue) after electron ID step. With the current available statistics, the background can be specified with a precision of about 10 % in the intermediate mass region.

Topological cuts for background rejection in dielectron analysis*

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Introduction

To extract physical observables from a measured dielectron invariant mass distribution it is essential to have efficient background reduction methods. On the one hand, this requires excellent particle identification to reject as many hadrons as possible. On the other hand, it is important to reduce the number of electron tracks which stem from physical background such as photon conversions or π^0 Dalitz decays. Their most prominent features are the low invariant mass of the resulting e^+e^- pair ($\lesssim 25 \text{ MeV}/c^2$ for conversion, $\lesssim 150 \text{ MeV}/c^2$ for π^0) and their small opening angle. For a cut on the invariant mass it is necessary that both particles are first identified as electrons, requiring both tracks to reach a particle identification (PID) detector such as RICH and/or TRD, which is not the case for many of these decays due to the low momenta of the decay products. For this reason, the track topology is used to match and reject tracks stemming from such decays.

This analysis was carried with the *PairAnalysisPackage* (PAPA) framework in cbmroot, described in [1]. As input data, 12 A GeV Au+Au collisions simulated with UrQMD were used, with embedded e^+e^- originating from decays simulated by PLUTO.

Topology of photon conversion and π^0 Dalitz decays

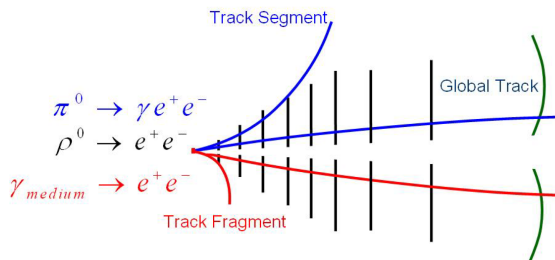


Figure 1: Different classes of electron tracks from decays [2].

When investigating decay topology in dielectron analysis it is useful to categorize the tracks into three different classes (see Fig. 1):

1. Track Fragment:

- Less than 4 hits in MVD+STS
- Not tracked by global tracking

2. Track Segment:

- At least 4 hits in MVD+STS, but no hits in RICH or TRD
- Tracked by global tracking, but can not be identified as an electron

3. Global Track:

- At least 4 hits in MVD+STS, hits in RICH and TRD
- Tracked by global tracking and identified as an electron

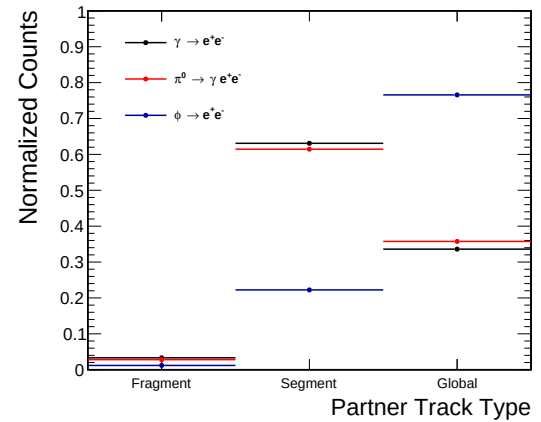


Figure 2: Relative amount of reconstructed tracks in each class for different decays. Only filled in case the first track from a decay is a global track.

Fig. 2 shows the relative amount of tracks in the different classes for different particles. Note that the histogram is only filled for decays in which the first track is a global track. As can be seen, for decays from higher mass particles (e.g. ϕ) both tracks reach the PID detectors in the majority of cases, while for photon conversion and π^0 the decays with one global track and one track segment dominate. Track fragments are not visible when looking at reconstructed tracks, since they are not tracked by definition. For decays in which one track is a global track and the other

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is a track segment, the latter will be rejected by the PID cuts, while the former will contribute to the combinatorial background. By itself, the global track is indistinguishable from signal electrons and can only be rejected by matching it with its original decay partner (i.e. the track segment) and rejecting both tracks based on the topology.

Matching and rejection of photon conversion and π^0 Dalitz decays

For the rejection, each global track is matched with the track segment from the same event which has the smallest opening angle to it. In case of conversion and π^0 decays the

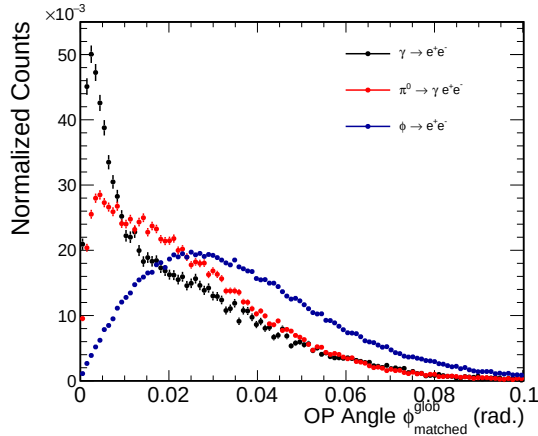


Figure 3: Normalized distribution of opening angles between global track and matched track segment for different decays.

matched track segment will often be the true partner, while for decays with larger opening angles the match is mostly random which results in different distributions of opening angles (see Fig. 3). Using also the momentum information of each of the matched tracks, a two-dimensional cut is implemented, which can be seen in Fig. 4.

Results

By using the cut described above, the amount of tracks from photon conversion and π^0 decays could be reduced by 44% and 34% respectively, while only losing about 10% of ϕ tracks. The general combinatorial background was reduced by 50%. A comparison of the achieved signal to background ratios with and without this cut is shown in Fig. 5. As can be seen in the lower part of Fig. 5, the cut improves the signal to background ratio by a factor of about 1.5.

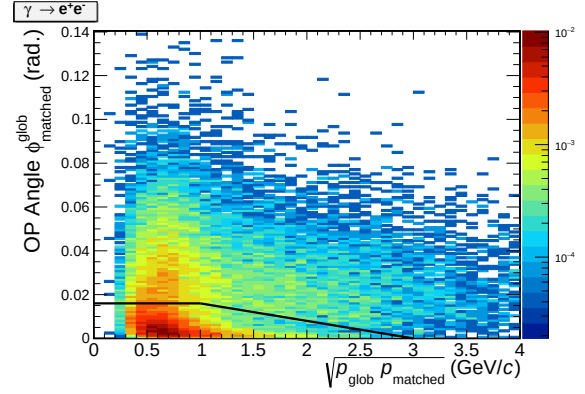


Figure 4: Opening angles between global track and matched track segment plotted against $\sqrt{p_{\text{global}} \times p_{\text{matched}}}$ for photon conversions. The implemented cut is shown as a black line, with track pairs lying below being rejected.

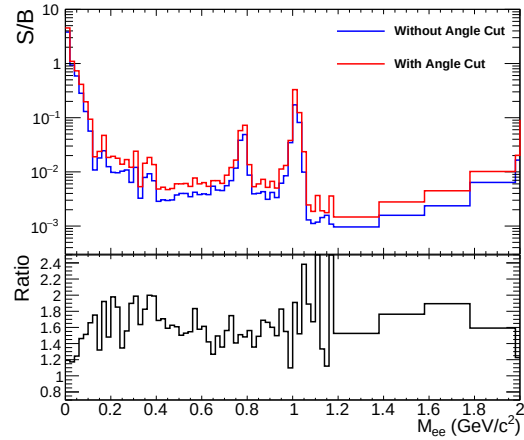


Figure 5: Signal to background ratios achieved with and without the opening angle cut and their ratio. No further pair cut for photon conversions is implemented here.

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Transverse sphericity dependence of two-particle correlation in $^{197}\text{Au}+^{197}\text{Au}$ collision at $E_{\text{lab}} = 10A$ GeV

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In this report we present an event shape classification scheme based on the transverse sphericity parameter (S_0) [1], and study its implication on the two-particle correlation among the final state charged hadrons coming out of $^{197}\text{Au}+^{197}\text{Au}$ events generated by the UrQMD model [2] at an incident beam energy $E_{\text{lab}} = 10A$ GeV. Transverse sphericity for a collision event is defined as [1],

$$S_0 = \frac{\pi^2}{4} \left(\frac{\sum_i |\vec{p}_{t_i} \times \hat{n}|}{\sum_i p_{t_i}} \right)^2 \quad (1)$$

where $\hat{n} = (n_T, 0)$ is a transverse unit vector, known as the sphericity axis, chosen in such a way that the ratio in Eq. (1) is minimized, and $\vec{p}_{t_i}$ is the transverse momentum of the i -th particle (charged hadron) of an event. The summation is taken over all final state charged hadrons falling within the considered kinematic limit. By definition S_0 has been made free from the longitudinal boost as well as infrared and collinear safe [3]. For any event the S_0 value should lie between 0 and 1. Based on the value of S_0 we classify an event either as a jetty event ($S_0 = 0$) or as an isotropic one ($S_0 = 1$). In high-energy collisions jets originate from hard QCD-processes corresponding to high- p_t partons which result in a pencil-like emission structure in the final state. On the other hand, the isotropic events have a large number of soft-hadrons coming out isotropically with small- p_t . Due to the differences in their geometrical structures, it is expected that the jetty and isotropic class of events will exhibit significant differences in their two-particle correlation results.

Two-particle correlation is measured as a function of the differences in rapidity Δy and azimuthal angle $\Delta\phi$ of the participating pairs of charged hadrons. Following [4] the correlation function $C(\Delta y, \Delta\phi)$ is calculated as,

$$C(\Delta y, \Delta\phi) = \frac{N_{\text{mix}}^{\text{pair}}}{N_{\text{sim}}^{\text{pair}}} \frac{D(\Delta y, \Delta\phi)}{M(\Delta y, \Delta\phi)} \quad (2)$$

where $D(\Delta y, \Delta\phi)$ and $M(\Delta y, \Delta\phi)$ are respectively, the number of pairs of charged hadrons taken from the same (simulation) event and different (mixed) event falling within the interval $(\Delta y, \Delta\phi)$. Both $D(\Delta y, \Delta\phi)$ and $M(\Delta y, \Delta\phi)$ are normalized to the total number of pairs $(N_{\text{sim}}^{\text{pair}}, N_{\text{mix}}^{\text{pair}})$ present in the respective distribution. Our minimum bias sample contains 10^6 $^{197}\text{Au}+^{197}\text{Au}$ events. All charged hadrons in the rapidity interval $|y - y_0| \leq 0.5$

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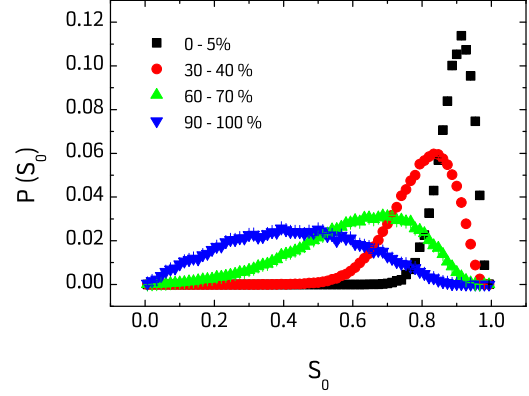


Figure 1: Transverse sphericity distribution of charged hadrons in $^{197}\text{Au}+^{197}\text{Au}$ collision at $E_{\text{lab}} = 10A$ GeV at four different centralities.

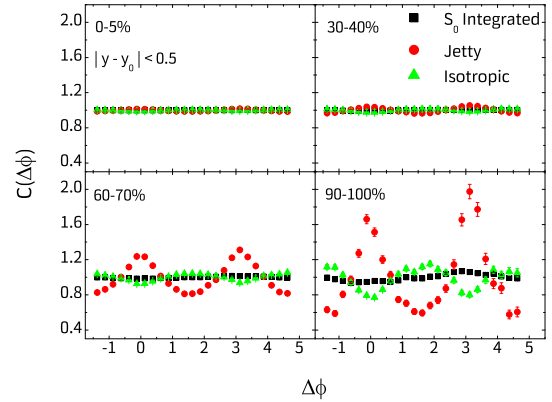


Figure 2: Azimuthal correlation $C(\Delta\phi)$ for the jetty, isotropic and S_0 -integrated events in $^{197}\text{Au}+^{197}\text{Au}$ collisions at $E_{\text{lab}} = 10A$ GeV.

are taken for analysis, where y_0 is the centroid of the overall rapidity distribution corresponding to a particular centrality class. For the S_0 calculation it is ensured that at least three such particles are present within the rapidity interval mentioned above. The %-centrality is determined by using the multiplicity distribution of charged hadrons. Figure 1 shows the distributions of transverse sphericity of events belonging to different centrality classes. The S_0 -distribution in the (0 – 5)% centrality class is sharply peaked, as almost all the events correspond to a very narrow range ($0.8 \lesssim S_0 \leq 1.0$). As we move from the

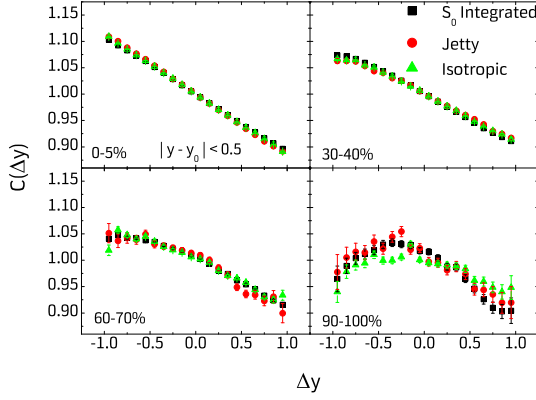


Figure 3: Rapidity correlation $C(\Delta y)$ for the jetty, isotropic and S_0 -integrated events in $^{197}\text{Au}+^{197}\text{Au}$ collisions at $E_{\text{lab}} = 10A$ GeV.

(0 – 5)% most central to the semi-central and peripheral classes of events, not only the distribution gradually becomes wider and more platykurtic, but its peak position also shifts towards a relatively small value, as low as $S_0 = 0.4$ for the (90 – 100)% most peripheral class. At $E_{\text{lab}} = 10A$ GeV neither the cross-section of jet production is very significant, nor any QCD process is incorporated in the framework of UrQMD. Even if some rare pencil-like structures are created due to hadronic jets, in the central collisions they are either destroyed by multiple rescattering or absorbed while passing through the collision region. Jetty events are predominantly found in the peripheral collisions, where the overlapping part of the colliding nuclei is quite small in size. Hence pencil-like structures, if there is any, have a greater chance to penetrate through to the final stage. Since the S_0 -distribution is not well localized, for a particular centrality class, subsamples of events with the bottom 10% and top 10% of the S_0 -values may respectively, henceforth be considered as jetty and isotropic events. The event sample devoid of any such criterion over the S_0 -values is termed as the S_0 -integrated sample.

Figure 2 shows the azimuthal correlation functions for the jetty, isotropic and S_0 -integrated events for four different centrality class. For the (0 – 5)% most central events no significant two-particle correlation is found in our simulated data. Due to a large number of particle producing sources and large amount of rescattering experienced by the particles, the correlations are washed out. However, as we move towards more peripheral collisions, a periodic pattern gradually develops in the variation of $C(\Delta\phi)$ both for the jetty and isotropic events. For the jetty events the amplitude of oscillation in $C(\Delta\phi)$ is larger than and opposite in phase to that of the isotropic events. As a result, the S_0 integrated events produce almost uniform $C(\Delta\phi) (\approx 1.0)$, indicating no correlation. A similar

near-side ridge at $\Delta\phi = 0$ and away-side ridge at $\Delta\phi = \pi$ has been observed in the two-particle azimuthal correlation in pp collisions at the LHC energy ($\sqrt{s_{NN}} = 13$ TeV) [5]. A significant part of the correlation in ϕ -space observed in our simulated data, is due to resonance decays and kinematic conservation rules followed by the emitted particles. It has also been observed that the event shape geometry significantly influences the collective flow parameters in simulation studies [6, 7]. Particularly the elliptic flow parameter v_2 is enhanced to a large extent in the jetty events due to their geometric anisotropy. Whether the enhancement in the two particle correlation function observed in the present study, has any bearing on the large values of elliptic flow seen in the jetty events, should be interesting to investigate.

In Figure.3 we present the two-particle longitudinal correlation integrated over the ϕ -space. Within statistical uncertainties $C(\Delta y)$ is a monotonically decreasing function of Δy for all the centrality classes. However, in all the cases $C(\Delta y \approx 0) = 1.0$, as should be the case for an uncorrelated emission. It implies that some degree of long-range correlation is present in the longitudinal y -space. We do not see any significant influence of the transverse sphericity on such longitudinal correlations. As S_0 classifies events based on the particle distribution in the transverse plane, its effect is not prominent on the particle correlation along the longitudinal direction.

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Dimuon simulations for Au + Au collisions at 2A GeV beam kinetic energy*

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The CBM Muon chamber system for low SIS100 beam energy.

The CBM muon chamber (MUCH) system for Au beam kinetic energies from 2A to 4A GeV was proposed in the Physics Note [1]. It consists of one absorber made of 60 cm carbon with additional Al and Pb shieldings around the beam pipe (5.7° degree), two iron absorbers each 20 cm thick, and triplets of tracking detectors behind each absorber layer: the first two stations consist of GEM detectors, the 3rd and 4th stations comprise RPC detectors [2]. The results of the simulations presented in the note [1] showed, that in such a setup only ω mesons at forward rapidity will be accepted. In this report the possibility is investigated, to increase the acceptance of ω mesons for Au + Au collisions at 2A GeV.

Acceptance study for ω mesons.

The simulations were performed for three muon system configurations: with 3 absorbers (see Fig. 1 right panel), with 2 absorbers (see Fig. 1 centre panel), and with only the first absorber (see Fig. 1 left panel). The ω meson

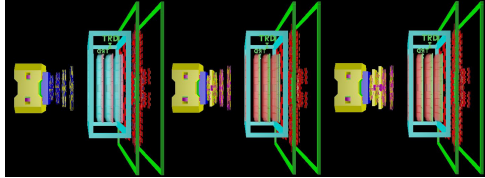


Figure 1: The muon system configurations under study: Muon system with one absorber (left), muon system with two absorbers (center), and muon system with three absorbers (right).

yield and momentum distributions were generated by the PLUTO code [3]. The detector acceptance in the plane transverse momentum versus rapidity is presented in Fig. 2 for the muon system with one absorber (left), for muon system with two absorbers (center), and with three absorbers (right). The black dashed lines indicate mid-rapidity for 2A GeV ($y = 0.9$). The acceptance conditions are the following: the muon tracks from ω decay produce at least 4 points the Silicon Tracking System (STS), at least 10 points in the muon system (MUCH), and at least one point each in the Transition Radiation Detector (TRD) and the Time

of Flight Detector (TOF). Fig. 2 clearly demonstrates, that the acceptance is shifted towards forward rapidity region with increasing number of absorbers.

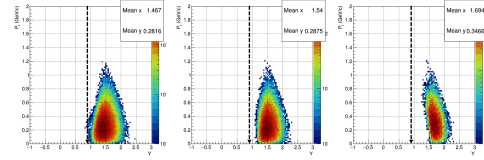


Figure 2: Detector acceptance for the ω mesons for different muon system configurations. Left: Muon system with one absorber. Centre: Muon system with two absorbers. Right: Muon system with three absorbers. The black dashed lines indicate mid-rapidity for 2A GeV ($y = 0.9$).

The total ω meson acceptance for the different muon system configurations and detector components is presented in the left panel of Fig. 3. The total acceptance for ω mesons is 1.2% for the setup with one absorber, 0.6% for the setup with two absorbers, and 0.14% for the setup with three absorbers. The right panel of Fig. 3 depicts the total ω acceptance of the different muon systems as a function of the ω momentum. In the next section, the combinatorial background will be investigated for the different muon systems.

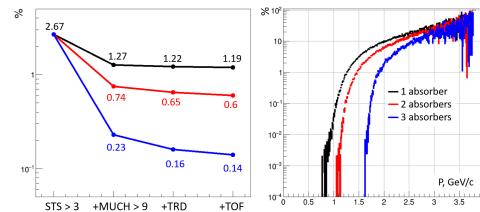


Figure 3: Left panel: Total ω acceptance of the different muon system configurations: MUCH with one absorber (black line), MUCH with two absorbers (red line), and MUCH with three absorbers (blue line). The numbers indicate the total acceptance in % for a particular detector system including the previous ones. Right panel: Total acceptance as a function of ω momentum.

Combinatorial background study.

The study was performed for central Au+Au collisions at a beam kinetic energy of 2A GeV, with the combinato-

* Work supported by EURIZON.

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rial background generated by the UrQMD code [4]. In order to select muon track candidates after track reconstruction, several cuts were used, including the selection of primary tracks. The resulting invariant mass distributions of the combinatorial background as shown in the left panel of Fig. 4 have to be compared to the expected multiplicity of dimuons from ω mesons. The branching ratio into the dimuon channel times multiplicity for ω mesons at 2A GeV is at the level of 10^{-5} per central event. After taking into account the acceptance, about 10^{-7} ω mesons per central event for 1 absorber MUCH and 10^{-8} for MUCH with 3 absorbers are expected. Hence, the level of the combinatorial background is several orders of magnitude higher than the estimated ω meson yield, which clearly requires further reduction of the combinatorial background. First of all, the machine learning procedure could be used for cut optimization, the result is shown in the right panel of Fig. 4 as red curve, in comparison to the result for manual cuts (black line). But more important to understand is the quality of the track reconstruction procedure, in particular the matching between global tracks and hits in TOF.

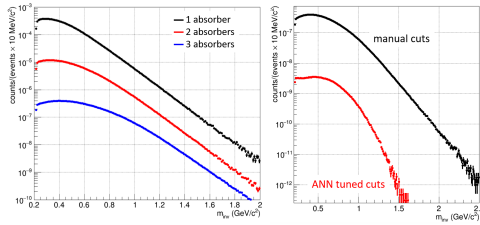


Figure 4: Invariant mass distribution of the combinatorial dimuon background. Left picture: MUCH with one, two, and three absorbers, as illustrated by the black, red, and blue line, respectively. Right picture: invariant mass distributions of the combinatorial background after manual cuts (black line), and after cuts tuned by a machine learning procedure (red line).

The results of the matching study are presented in the left panel of Fig. 5. The X coordinate of the plot represents MC particle identification of the track reconstructed in the STS, the Y coordinate illustrates MC particle identification of the TOF hit. The yellow lines select the region of the physical background: pions, kaons and muons from weak decays. These particles represent about 77% of the selected muon track candidates. In order to investigate the origin of background further, the MC decay vertex of muons is illustrated by the red line in the right panel of Fig. 5. Despite the fact, that only primary tracks were selected, many secondary muons were accepted as primary muon track candidates. There are possibilities to reduce this part of background:

- Reconstruction of tracks of mother (π , K) and daughter (μ) particles separately, using the present STS or an upgraded tracking system with an increased number of detector layers;

- improve the quality of the fit to primary vertex using pixel-like detectors with low material budget.

About 23% of the combinatorial background illustrated in the left panel Fig. 5 comprise mismatches of primary protons with TOF hits from other particles (light green lines), mismatches of particles with TOF hits from secondary electrons (magenta lines), and other random mismatches. These mismatches could be removed by optimization of the TOF hit matching with global tracks.

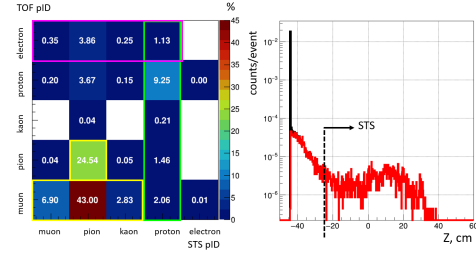


Figure 5: Left: Results of the matching study. The X coordinate represents the MC particle identification of the track reconstructed in the STS, the Y coordinate shows MC particle identification of the TOF hit. The color lines indicate mismatches involving particular particles (see text). The numbers reflect the contribution of the particular matching to all muon track candidates. Right: the MC vertex production of the muon track candidates with cut on primary vertex. Black line: All particles. Red line: MC decay vertex of muons. The black dashed line selects the position of the first STS layer.

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Primary proton reconstruction in Au + Au collisions at 2A GeV*

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CBM setup for hadron measurements at low beam energy.

The CBM setup studied for hadron measurements at low SIS100 energies consists of the Silicon Tracking System (STS) inside magnet together with the Time-of-Flight Detector (TOF) positioned between 3 and 5 m downstream of the 250 μm Au target. Two different target z positions were investigated: $z = -44$ cm and $z = -24$ cm from the center of magnet. The simulations presented in this report are performed for Au + Au collisions at a beam kinetic energy of 2A GeV. Central collisions generated by the UrQMD code [1] were used as an input for the simulations. The magnetic field was scaled by 50% in order to dump the beam properly.

Acceptance for primary protons.

Fig. 1 depicts the transverse momentum as a function of rapidity for primary protons. The left picture presents the initial 4π distribution, the center picture illustrates the STS acceptance for a target position at $z = -44$ cm, and the right picture displays the STS acceptance for a target position at $z = -24$ cm. The STS acceptance is determined by a minimum number of STS MC points, which is equal to 4 in this study.

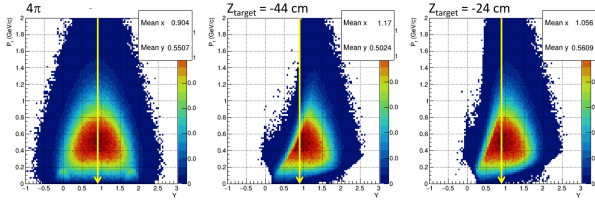


Figure 1: Transverse momentum as function of rapidity for primary protons, simulated for central Au + Au collisions at 2A GeV. Left: 4π distribution. Center: target at $z = -44$ cm. Right: target at $z = -24$ cm. Midrapidity for 2A GeV is $y = 0.9$, as indicated by the yellow arrow.

Fig. 2 depicts the total acceptance as compared to 4π for primary protons as a function of momentum (left column) and rapidity (right column). The top and the bottom row refer to target positions of $z = -44$ cm and $z = -24$ cm, respectively. Different colours correspond to different MC acceptance conditions, as indicated in the top left picture.

* Work supported by EURIZON.

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The acceptance for primary protons increases for target positions closer to the STS. For example, the proton acceptance around midrapidity is about 20% higher for the target at $z = -24$ cm, as compared to $z = -44$ cm.

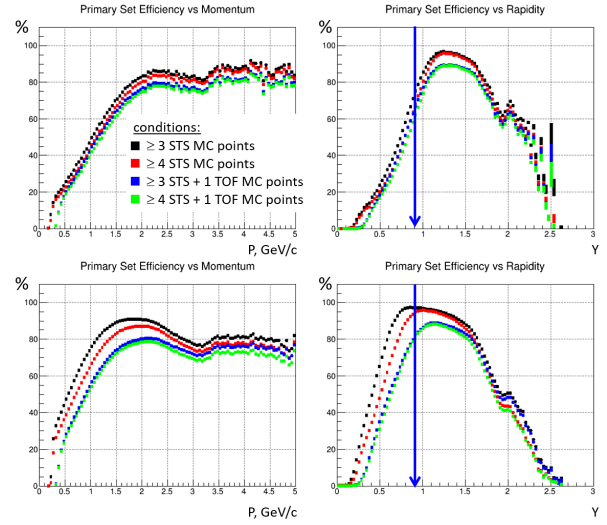


Figure 2: Total acceptance compared to 4π for primary protons as a function of momentum (left column) and of rapidity (column). The upper and lower row correspond to target positions of $z = -44$ cm and $z = -24$ cm, respectively. The blue arrow indicates mid-rapidity. The different colors refer to different MC acceptance criteria, as indicated in the top left panel

Primary proton reconstruction and identification.

The first step of the reconstruction is a track finder procedure in the STS. The track reconstruction performance for all primary particles is presented in Fig. 3. The reconstruction efficiency for tracks with momentum above 1 GeV/c is close to 100% (left panel), while the momentum resolution varies between 3-5%, depending on momentum (right panel).

The tracks reconstructed in the STS were extrapolated to the TOF detector. The right panel in Fig. 4, which depicts the m^2 distribution of the reconstructed particles as function of particle momentum $\times$ charge, illustrates the selection of protons by the dashed black lines based on the TOF measurement. The left picture presents χ^2/ndf for

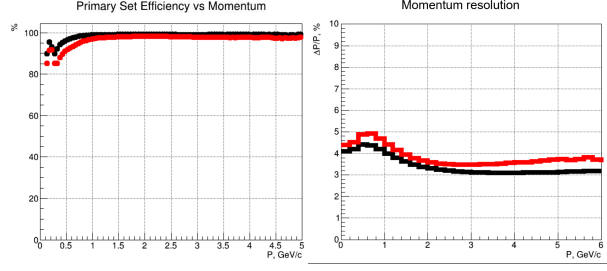


Figure 3: Track reconstruction efficiency as a function of momentum (left panel) and momentum resolution (right panel) for primary tracks. The efficiency plot is normalized to number of "reconstructable" tracks, which have at least 4 consecutive MC points in STS. Black symbols: $z_{target} = -44$ cm, red symbols: $z_{target} = -24$ cm.

reconstructed tracks in primary vertex, and illustrates the selection of primary protons.

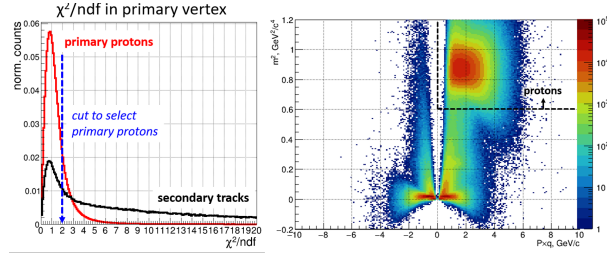


Figure 4: Primary protons selection. Left picture: χ^2/ndf for reconstructed tracks in primary vertex. Red line: distribution for primary protons; black line: secondary tracks. The blue dash line illustrates the selection of primary protons. Right picture: m^2 versus momentum $\times$ charge calculated from time measurements. The lack dashed line represents the cut for the selection of protons.

The primary proton reconstruction and identification efficiency compared to 4π is depicted in Fig. 5 as function of momentum (left panel) and of rapidity (right panel). The total efficiency for primary protons with realistic particle identification is 36% for $z_{target} = -44$ cm, and 34% for $z_{target} = -24$ cm. The proton misidentification is at the level of $2-3 \times 10^{-3}$.

Finally, the distribuion of reconstructed primary protons in the plane transverse momentum versus rapidity is presented in Fig. 6. The red lines illustrate the accepted polar angles and momenta: 3° - 40° for $z_{target} = -44$ cm (left panel), and 4.5° - 50° for $z_{target} = -24$ cm (right panel). In the first case, 66% of the phase space for primary protons is experimentally covered, and 71% in the second case.

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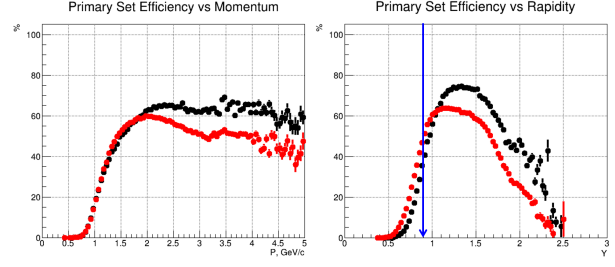


Figure 5: The 4π reconstruction and identification efficiency for primary protons. Left picture: as a function of the momentum; right picture: as a function of rapidity. Black symbols: $z_{target} = -44$ cm; red symbols: $z_{target} = -24$ cm. The blue arrow select mid-rapidity value.

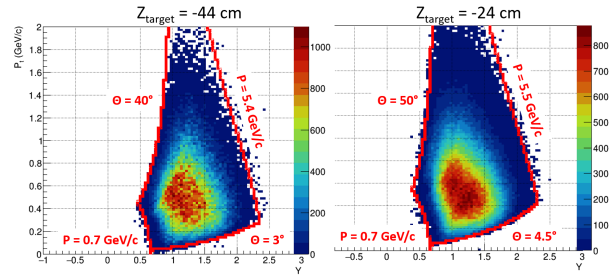


Figure 6: Transverse momentum as a function of rapidity for reconstructed primary protons. Left panel: $z_{target} = -44$ cm; right panel: $z_{target} = -24$ cm. The red lines illustrate the accepted polar angles.

J. Konopka, G. Mao, L. Neise, S. Soff, C. Spieles, H. Weber, L. A. Winkelmann, H. Stocker, W. Greiner, Ch. Hartnack, J. Aichelin and N. Amelin: Microscopic Models for Ultrarelativistic Heavy Ion Collisions, Prog. Part. Nucl. Phys. 41 (1998) 225-370

Anisotropic flow measurements of identified hadrons in Au+Au collisions at $E_{lab} = 25$ A GeV using the HSD model

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The azimuthal anisotropy of the particles created in heavy-ion collisions is one of the key indicators for the formation of quark-gluon plasma (QGP)[1,2]. It has its origin in the initial spatial anisotropy of the overlapping region between the colliding nuclei and appears as momentum-space anisotropy in the final states. Therefore, it is sensitive to the early stages of the collision and provides information on the system dynamics in the initial stages. The azimuthal anisotropy is usually characterised by the Fourier coefficients given by $v_n = \langle \cos[n(\phi - \psi_n)] \rangle$ [3]. Here ϕ is the particle's azimuthal angle, n is the flow harmonic order, and ψ_n is the event plane angle. The second Fourier coefficient (v_2), also known as elliptic flow, measures the azimuthal anisotropy of produced particles in momentum space with respect to the second harmonic event plane angle. The identified hadrons elliptic flow offers important information on the particle production mechanism. One finding is that when the identified hadrons v_2 is divided by the number of constituent quarks n_q and plotted against $(m_T - m_0)/n_q$, it follows a universal curve. This scaling is known as number of constituent quark (NCQ) scaling.

In this work we report the transverse momentum p_T dependence and centrality dependence of v_2 for identified hadrons at mid-rapidity ($|y| < 1.0$) in Au+Au collisions at $E_{lab} = 25$ A GeV using the Hadron String Dynamics (HSD) model. The NCQ scaling of identified hadron v_2 is also discussed. For this work, we have used 50 million minimum bias events from the HSD model. The measurements are done using the η -sub event plane method in different centrality classes which cover central to peripheral collisions.

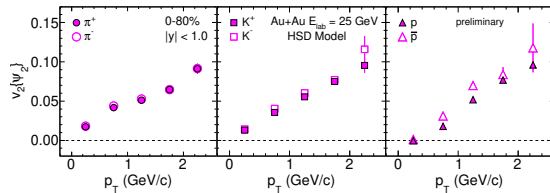


Figure 1: v_2 vs p_T of identified hadrons for 0–80% Au+Au collisions at $E_{lab} = 25$ A GeV using the HSD model.

Figure 1 shows the p_T dependence of v_2 for identified hadrons ($\pi^\pm$, $K^\pm$, p , and $\bar{p}$) for minimum bias (0–80%) Au+Au collisions at $E_{lab} = 25$ A GeV from the HSD model. The v_2 increases monotonically with p_T for all the hadrons. $v_2(p_T)$ values of pions, kaons and their antiparticles show similar magnitude. We observe a difference in

v_2 values between protons and antiprotons, which might be the effect of baryon stopping at low energies.

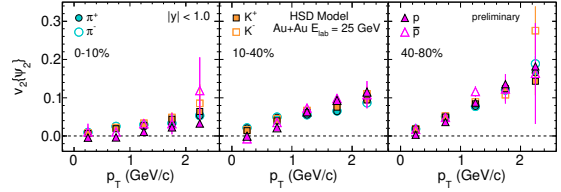


Figure 2: v_2 vs p_T of identified hadrons ($\pi^\pm$, $K^\pm$, p , and $\bar{p}$) for 0–10%, 10–40%, and 40–80% central Au+Au collisions at $E_{lab} = 25$ A GeV using the HSD model.

Figure 2 shows the centrality dependence of identified hadrons ($\pi^\pm$, $K^\pm$, p , and $\bar{p}$) $v_2(p_T)$ in Au+Au collisions at $E_{lab} = 25$ A GeV from the HSD model. We observe a centrality dependence of v_2 of identified hadrons at mid-rapidity. The values of v_2 are lower for central collisions (0–10%) compared to peripheral collisions (40–80%).

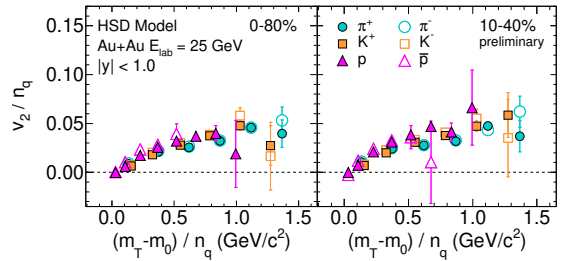


Figure 3: The Number of Constituent Quark (NCQ) scaled elliptic flow, v_2/n_q versus $(m_T - m_0)/n_q$, for 0–80% (left) and 10–40% (right) central Au+Au collisions for identified hadrons ($\pi^\pm$, $K^\pm$, p , and $\bar{p}$) at $E_{lab} = 25$ A GeV using the HSD model.

Figure 3 shows v_2 scaled by the number of constituent quarks (n_q) as a function of $(m_T - m_0)/n_q$ for 0–80% and 10–40% central Au+Au collisions. v_2 of baryons and mesons when divided by their constituent quarks follow a universal curve. We do not observe a good NCQ scaling of v_2 for identified hadrons in Au+Au collisions at $E_{lab} = 25$ A GeV in the HSD model.

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Online measurements of hypernuclei in Au+Au collisions at $\sqrt{s_{NN}} = 3$ GeV with the STAR detector^{*†}

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Studying the mechanism of hypernuclei production in the high baryon density region of the QCD phase diagram at BES-II, determining their lifetimes and decay branching ratios will provide information on hyperon-nucleon interactions, which are essential ingredients for understanding the equation of state for nuclear matter at high densities and, consequently, the structure of neutron stars.

The high statistics data from fixed-target Au+Au collisions at $\sqrt{s_{NN}} = 3$ GeV, taken in 2018–2021 by the STAR detector is very suitable to study light hypernuclei 3-body decay channels of ${}^3_\Lambda\text{H} \rightarrow \text{dp}\pi$, ${}^4_\Lambda\text{He} \rightarrow {}^3\text{He}\pi$ and even ${}^5_\Lambda\text{He} \rightarrow {}^4\text{He}\pi$. All these decay channels have been reconstructed online and analyzed at the HLT computer farm. Two triggers based on heavy fragment selection in the STAR Time Projection Chamber (TPC) and optionally corresponding hit in the TOF have been successfully used to enrich the hypernuclei sample at $\sqrt{s_{NN}} = 3$ GeV in the Run 2021. In Fig. 1 the distribution of dE/dx as a function of momentum p for electrons, $\pi^\pm$, $K^\pm$, p , $\bar{p}$, $d^\pm$ and $t^\pm$ and heavy fragments such as ${}^3\text{He}$, ${}^4\text{He}$, ${}^6\text{He}$, ${}^6\text{Li}$ and ${}^7\text{Li}$ are shown. The left plot shows the minimum bias data collected in 2018; the right plot shows the data triggered by heavy fragments. The dE/dx provided by TPC were used to identify charged particles and heavy fragments such as ${}^3\text{He}$ and ${}^4\text{He}$.

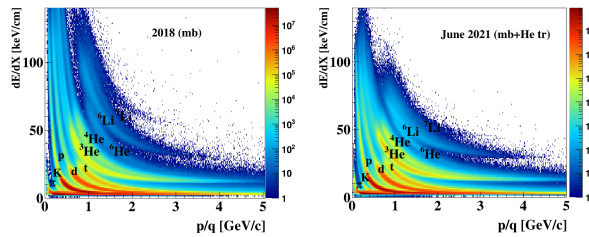


Figure 1: Distribution of dE/dx as a function of momentum p for electrons, $\pi^\pm$, $K^\pm$, p , $\bar{p}$, $d^\pm$ and $t^\pm$ and heavy fragments such as ${}^3\text{He}$ and up to ${}^7\text{Li}$. The units of dE/dx and momentum p are keV/cm and GeV/c, respectively. The particle loci follow a corresponding Bichsel's prediction.

Together with 2-body channels, decays with three daughters in the final state allow to measure hypernuclei

^{*} Data from express stream (Au+Au $\sqrt{s_{NN}}=3.0, 3.2, 3.5, 3.9, 4.5, 5.2, 6.2, 7.7$ GeV) are not with the final calibrations.

[†] Work supported by BMBF, FIAS and HFHF.

decay branching ratios. One more advantage of 3-body channels is sensitivity to the quantum numbers of the hypernuclei ground state, which can be studied with the Dalitz plot technique.

The KF Particle Finder [1] package developed for the CBM experiment was used within the FAIR phase-0 program on real STAR data online as a data quality monitoring tool. A short path from data acquisition to physics, including data calibration, processing, and physical analysis, was developed and successfully tested in Au+Au collisions at $\sqrt{s_{NN}} = 3.0$ GeV (fixed target mode) in 2018 and has been continuously developed and used further.

A detailed description of the experimental setup and sub-detectors for tracking, particle identification, etc. can be found in [2].

The reconstructed TPC tracks were used as input to the KF Particle package along with the reconstructed primary vertex. Typical distributions of the primary vertex for fixed-target runs are shown in Fig. 2. The edge of the gold target, located at $y = -2$ cm, is clearly visible in the two-dimensional XY distribution. The vertices formed by the beam tube and the vertices formed by the pile-up were marked, and the tracks from these vertices were removed from further consideration. This procedure greatly reduces the background in the three-body channels.

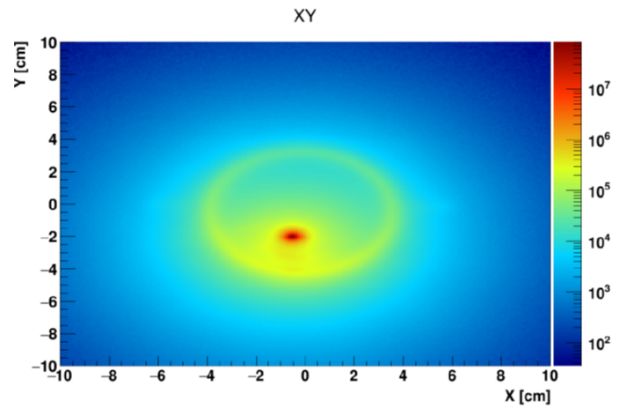


Figure 2: 2D XY distribution of primary vertices for Au+Au fixed-target collisions at 3.85 GeV with a clearly visible gold target edge located at $y = -2$ cm.

Reliable CA tracking combined with excellent particle identification provided by TPC, bTOF, and eTOF allows

the reconstruction of complex light hypernuclear decay topologies online using the KF Particle Finder package and a selection technique developed at 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. 3 the online reconstructed invariant mass spectra of ${}^3\Lambda\text{H} \rightarrow {}^3\text{He}\pi$, ${}^3\Lambda\text{H} \rightarrow \text{dp}\pi$, ${}^4\Lambda\text{H} \rightarrow {}^4\text{He}\pi$, ${}^4\Lambda\text{H} \rightarrow \text{tp}\pi$, ${}^4\Lambda\text{He} \rightarrow {}^3\text{He}\pi$ and ${}^5\Lambda\text{He} \rightarrow {}^4\text{He}\pi$ candidates are shown. All signals are clearly visible with an excellent signal to background ratio. The position and width of the peaks are in good agreement with the PDG data. Typical mass resolution is about 1.4 to 1.8 MeV/c². The statistics collected are sufficient to measure the yield, lifetime, p_t , and rapidity spectra of these hypernuclei.

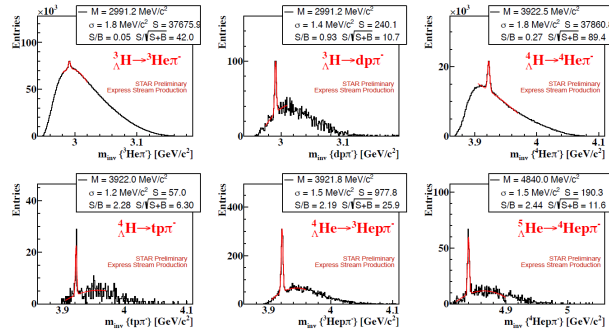


Figure 3: Standard and express reconstruction of hypernuclei using 2018, 2019, 2020, and 2021 data collected at different energies in the collider and fixed-target modes.

The decay of ${}^5\Lambda\text{He} \rightarrow {}^4\text{He}\pi$ was observed first time in the heavy ion experiments. The combined invariant mass spectra of all different energies Au+Au $\sqrt{s_{NN}} = (3.0, 3.2, 3.5, 3.9, 4.5, 5.2, 6.2, 7.7)$ GeV collected in the years 2018–2021 are shown in Fig. 4. Express stream production results were given “STAR preliminary” status and were presented at the Quark Matter Conference [3] and was published at [4]. The signal of ${}^5\Lambda\text{He} \rightarrow {}^4\text{He}\pi$ is visible with a significance of 11.6σ .

In conclusion, the express production provides a high quality dE/dx measurement for particles up to heavy fragments and together with eTOF and bTOF measurements allows to obtain clean spectra with high significance. The method is implemented directly on the HLT farm and allows to perform the physics analysis of the data during the process of data taking. The express chain provides access to the processed data with a delay of only about one day, which is necessary for the production and copying of picoDST files from HLT to RCF, and allows to do the physics analysis of the experimental data in the regular environment. We have already processed all the currently collected energies of BES-II, which allows us to study a wide range of physics including hyperons and hypernuclei in one go using the KF Particle Finder package.

The authors would like to express their sincere gratitude to Dr. Maksym Zyzak for his leadership in the analysis with

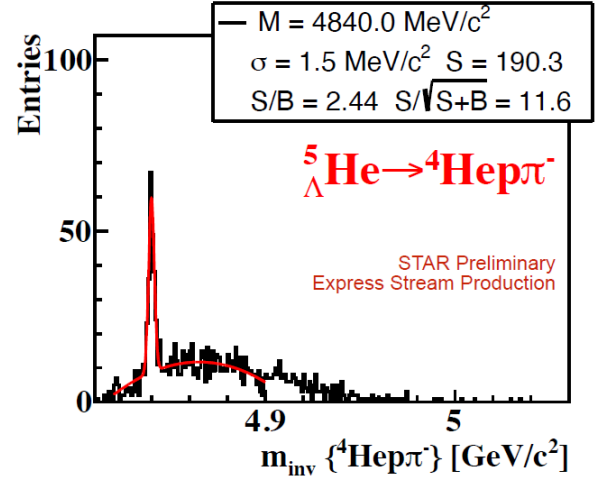


Figure 4: Combined invariant mass spectrum of ${}^5\Lambda\text{He}$ for all different energies collected in the years 2018–2021. The signal of ${}^5\Lambda\text{He} \rightarrow {}^4\text{He}\pi$ is visible with a significance of 11.6σ .

KF Particle Finder, new ideas and useful discussions.

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Elliptic flow of inclusive charged hadrons at $E_{lab} = 25$ A GeV using the HSD model

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The CBM experiment that will be conducted in the future is a fixed target experiment. It is intended to operate for different observables at very high interaction rates up to 10 MHz. The study of elliptic flow (v_2) is predicted to be sensitive to the initial conditions, transport coefficients and thermalization of the medium created in heavy-ion collisions. At low transverse momentum (p_T), the larger value of v_2 observed in non-central collisions has been well explained by hydrodynamics.

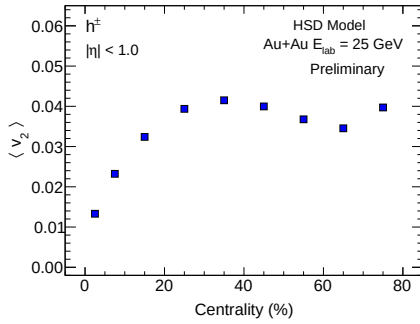


Figure 1: Inclusive charged hadron $\langle v_2 \rangle$ as a function of centrality at mid-rapidity ($|\eta| < 1$) in Au+Au collisions at $E_{lab} = 25$ A GeV using the HSD model.

Elliptic flow (v_2) for inclusive charged hadrons in Au+Au collisions is studied at $E_{lab} = 25$ A GeV using Hadron String Dynamics (HSD) transport model [1]. HSD model is a microscopic transport method which considers the off-shell dynamics associated with self-energies for the hadronic interactions.

Analysis details

We simulated 50 million events of Au + Au collisions for inclusive charged hadron v_2 from the HSD model at $E_{lab} = 25$ A GeV. The v_2 is calculated in the mid-rapidity ($|\eta| < 1$) using the η -sub event plane method [2]. In this method, the v_2 is calculated with respect to estimated 2^{nd} order event plane angle (ψ_2) and then divided by resolution for correction as, $v_2 = \langle \cos(2(\phi - \Psi_2)) \rangle / R$, where $R = \sqrt{\langle \cos(2(\Psi_2^A - \Psi_2^B)) \rangle}$. There is an η gap of 0.15 introduced between positive and negative η -sub events for reducing the auto-correlation effects.

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Results

Figure 1 represents the inclusive charged hadron $\langle v_2 \rangle$ as a function of centrality in Au+Au collision at $E_{lab} = 25$ A GeV using the HSD model. We observe $\langle v_2 \rangle$ increases upto 40% centrality and then decreases slowly. In Fig. 2, we show v_2 as a function of p_T for different centrality classes-0-80%, 0-10%, 10-40% and 40-80% in Au+Au collisions at $E_{lab} = 25$ A GeV using the HSD model. We see that v_2 increases monotonically with p_T and its value is more in peripheral collisions than central collisions. The results of v_2 as a function of η is shown in Fig. 3. We observe that $v_2(\eta)$ remains almost constant for all centralities.

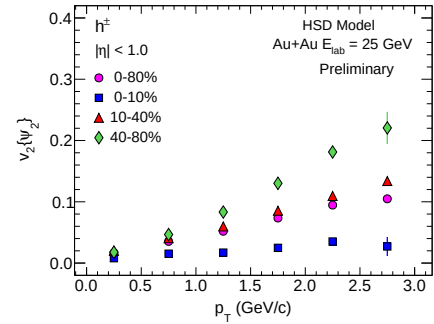


Figure 2: Charged hadron v_2 as a function of p_T in Au+Au collisions at $E_{lab} = 25$ A GeV using the HSD model.

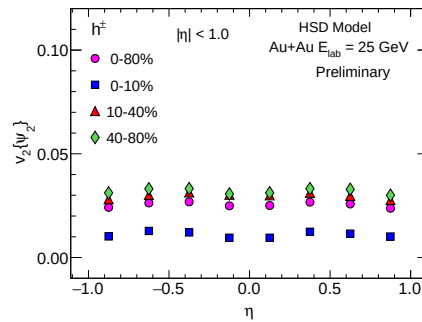


Figure 3: v_2 as a function of η for charged hadrons in Au+Au collisions at $E_{lab} = 25$ A GeV.

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Development of CBM software based on the experience of STAR collaboration*

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Femtoscopy is a technique to probe the spatio-temporal structure of the source that emits particles. This method allows us to measure the fireball's size (length of homogeneity, related to the range of correlations between two particles) created during heavy-ion collisions. Such information also provides information about the dynamics of the event collision process.

STAR experiment (Solenoidal Tracker at RHIC) is an experiment at Brookhaven National Laboratory (BNL) in the USA. STAR has been collecting data for more than two decades. Originally STAR was designed to operate at high energies (e.g., $\sqrt{s_{NN}} = 200$ GeV in collider mode. However, after some upgrades, it was possible to register collisions at much lower energies (down to 3 GeV in $\sqrt{s_{NN}}$) at fixed-target mode. This energy range and operation mode are very close to the operational regime of the future CBM detector.

In this report, we present a result of a comparison of femtoscopic calculations obtained by STAR data with STAR and CBM codes.

Motivation

CBM is a future experiment and STAR is a currently operating experiment. STAR has collected data for two decades. Therefore the STAR collaboration gained a huge experience in data analysis. A few years ago, it was decided that STAR would measure lower collision energies. Also, it was decided that this detector will collect data at fixed-target mode [1]. This operation mode and energy range are very close to the energy range and operation mode of CBM detector [2].

CBM collaboration already has a developed framework for femtoscopic analysis. However, it was never used in the analysis of the real data. The possibility of testing this code with real data and comparison with results obtained with the well-tested code of STAR is an excellent opportunity to test CBM code. There are two main goals of such comparison: first, finding potential mistakes in code, and second, adding functionality that is crucial in the working experiment but was not yet added.

Femtoscopy

Femtoscopy uses two-particle correlations to get information about the correlation range in the source that emits particles [3]. The core of the femtoscopic analysis is the calculation of the Correlation function defined by 1.

$$C(q) = N(q)/D(q) \quad (1)$$

In the equation above, the q is the momentum difference between two particles in pairs, N is the distribution of correlated pairs (from the same event) called the numerator, and D is a distribution of uncorrelated pairs (each particle in pair comes from different event) called denominator.

Software in CBM and STAR

In STAR, there are two types of software for HBT analysis - the older one - StHbtMaker, was primarily used to analyze data in collider mode, and there is also the newer one used for the analysis of data at $\sqrt{s_{NN}} = 3$ GeV in fixed target mode. It was decided to compare CBM software with the code used for the analysis of the collision at fixed target mode (FTX).

In CBM, at the beginning of 2022, only one software for HBT analysis was NicaFemto. NicaFemto is currently replaced by HAL (High energy physics Analysis Libraries). HAL is a successor of the NicaFemto; whereas the general structure of both codes is similar, there is also a significant difference between both frameworks. HAL, in contrast to NicaFemto, can be installed without FairRoot/CbmRoot frameworks.

For storage data, we used the Analysis Tree format. This was also a test of this framework. Analysis Tree was created as a flexible data storage format for CBM (and potentially other collaborations) but was not tested on real data. Therefore this test is also an excellent opportunity to improve the Analysis Tree code.

Data preprocessing

The real STAR data were used for tests; that data contained Au+Au collisions at $\sqrt{s_{NN}} = 3$ GeV. STAR data are stored in so-called "pico-dst" files. These files contain many data - some are not needed to perform femtoscopic analysis, and some are not stored in these files. Some parameters (related to event properties) are calculated by unique, complicated algorithms implemented in STAR software. These missing parameters were calculated

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and written in "flat" files to simplify the data analysis process. "Flat" files are files with straightforward structures and contain all data needed to reproduce analysis done by STAR collaboration. The flat files were later copied from the STAR computing cluster to the local computer; here, the conversion to Analysis Tree was performed.

Data analysis

The AnalysisTree format was used to store the input of data analysis. The first test was related to comparing the content of files at the event level - e.g., the number of events per file, the order of events in a tree, number of tracks per event. All these tests showed that the conversion from "pico-dst" through "flat" to "AnalysisTree" format was done correctly.

A more sophisticated analysis was done for the comparison of tracks. Here some tiny differences appeared; these differences were related to the limited precision and differences in the structure of data stored in code for HBT analysis in STAR. For example, HAL/Analysis Tree stores track's momenta in cartesian coordinates (p_x, p_y, p_z) whereas code for HBT analysis in STAR use spherical coordinates (p_T, ϕ, η). It presented minor differences, e.g., in the number of accepted protons by both algorithms (1).

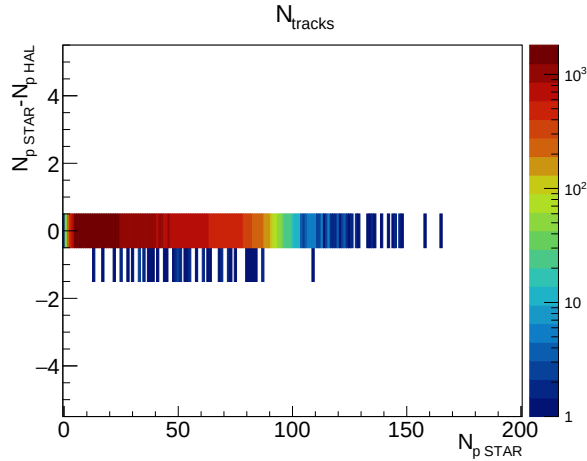


Figure 1: Differences in the number of tracks accepted as protons by STAR and HAL codes as a function of protons accepted by STAR code.

Then proton-proton analysis was performed with both algorithms. Correlation functions obtained by both codes seem to be almost exactly the same (2). The difference does not appear when we look at the Correlation Functions. The discrepancies are visible only at the level of pair distributions, e.g., in the numerator of the CF (3). It proves that the CF's produced by these two codes are very similar.

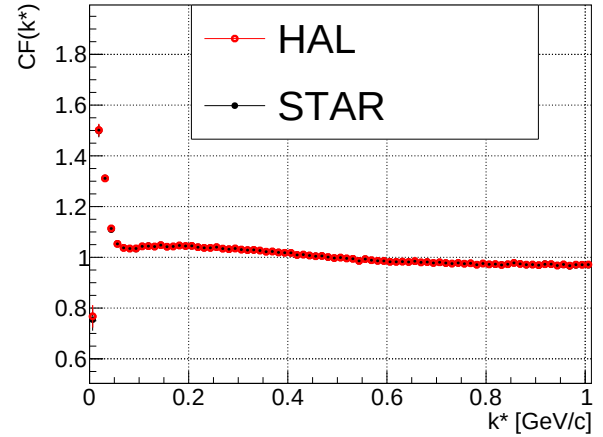


Figure 2: Comparison of CF's calculated with HAL and STAR codes. The differences are present but not visible at this scale.

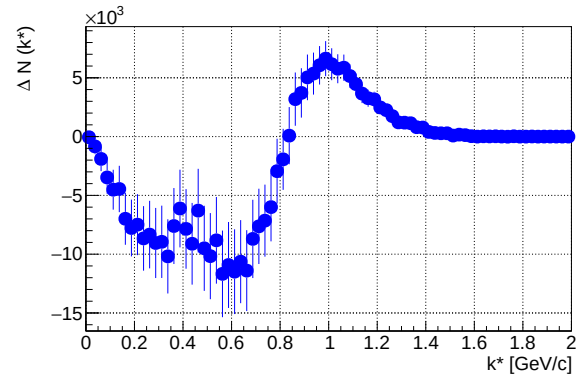


Figure 3: Difference between a number of pairs in numerator calculated by HAL and STAR codes.

Summary

This work shows that HAL software can be used for femtoscopic analysis in real experiments. However, it also shows that HAL code has some problems, one of the main problems was that the creation of an interface for data reading is too complicated. Also, it was noticed that creating selection algorithms requires writing much code. These problems were solved by simplification of the interface for data reading and creating a unique application that helps write code for data selection.

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FAIR Phase-0 Activities

Achievements of the mCBM beam campaign 2022

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The CBM full-system test-setup named mCBM@SIS18 (short “mCBM”) was set up 2017 and 2018 at the GSI experimental area Cave D (HTD) of the SIS18 facility of GSI/FAIR. The primary aim of the mCBM experiment is to test prototypes or pre-series productions of the CBM detector systems and to commission and optimize the complete data chain developed for the CBM experiment. In particular, it allows testing of the free-streaming (trigger-less) read-out electronics and data transport to a compute cluster as well as the online reconstruction and selection under realistic experiment conditions up to the top CBM interaction rates of 10 MHz. The mCBM experiment is taking SIS18 beam since 2019 within the FAIR Phase-0 program. After years of development the final CBM configuration of the DAQ and data transport system could be realized and commissioned with beam in 2021, integrating a FPGA based Common Readout Interface (CRI) and a first version of a Timing and Fast Control System (TFC). To further validate the read-out and data processing concept of CBM the production yield of Λ baryons is studied in nucleus-nucleus collisions serving as a benchmark observable, which will allow comparison with published data measured with the FOPI [2] and HADES [1] experiments. The Λ baryon carries strangeness and hence, is a rare probe at SIS18 energies due to its high production threshold. Accordingly, the reconstruction of Λ baryons with the mCBM experiment is a well suited test case for CBM.

The Beam Campaign 2022 The intensive preparation phase for the beam campaign 2022 started with first dry runs in December 2021. Cosmics runs were added in January 2022 studying detector response and system timing as well as testing a first version of an (FairMQ based) online selection based on correlated hits within detector system-specific time windows. First commissioning with beam was conducted in March 2022 taking a few hours $^{12}\text{C}(6+)$ beam at 2.0 AGeV and $^{56}\text{Fe}(26+)$ at 1.8 AGeV kinetic projectile energy T_{proj} . Table 1 summarizes the mCBM data taking in 2022 starting with high-rate studies performed especially for the TOF and MUCH detector systems with $^{238}\text{U}(73+)$ beam at 1.0 AGeV end of March and with $^{197}\text{Au}(67+)$ at 1.13 AGeV in June 2022. The first benchmark run was measured in May 2022 taking Ni+Ni collisions at 1.93 AGeV. With a total run duration of 5 h 55 min approx. $5 \cdot 10^9$ collisions were collected on 30 TB timeslice archive (tsa) files storing the raw hit messages. The second benchmark run was taken on June 16 - 18, 2022, measuring Au + Au collisions at 1.23 AGeV with a total run duration of 34 h 33 min collecting approx. $2 \cdot 10^{10}$ collisions on 180 TB tsa files.

2022	March 29 - April 1	May 26
Projectile	$^{238}\text{U}(73+)$	$^{58}\text{Ni}(28+)$
T_{proj}	1.00 AGeV	1.93 AGeV
Beam intensity per spill (10s)	$10^7 - 10^9$	$4 \cdot 10^7$
Average collision rate	100 kHz - 10 MHz	400 kHz
Objective	high-rate studies TOF & MUCH	benchmark run I

2022	June 16 - 18	June 19 - 20
Projectile	$^{197}\text{Au}(69+)$	$^{197}\text{Au}(67+)$
T_{proj}	1.23 AGeV	1.13 AGeV
Beam intensity per spill (10s)	$2 - 4 \cdot 10^7$	$1 \cdot 10^7 - 4 \cdot 10^8$
Average collision rate	200 - 400 kHz	100 kHz - 4 MHz
Objective	benchmark run II	high-rate studies TOF & MUCH

Table 1: The mCBM beam campaign 2022.

The mCBM setup in 2022 Figure 1 shows a photograph (upper panel) as well as the corresponding GEANT geometry (lower panel) for the 2022 setup of the mCBM experiment. Due to the limited space inside the experimental area, mCBM does not comprise a magnetic field, and, therefore, measures charged particles produced in nucleus-nucleus collisions traversing the detector stations under straight trajectories. Full-size prototype or pre-series detector stations of the CBM detector systems T0 (BMON), STS, MUCH, TRD, TOF and RICH were included in 2022, positioned around a polar emission angle of 25° with respect to the primary beam.

To cope with extremely high collision rates up to 10 MHz the CBM DAQ and data transport has been developed as a free-streaming (triggerless) system, which is already under test at the mCBM experiment since 2021. Briefly sketched, ultra-fast and radiation-tolerant ASICs are deployed as front-end chips digitizing signals above

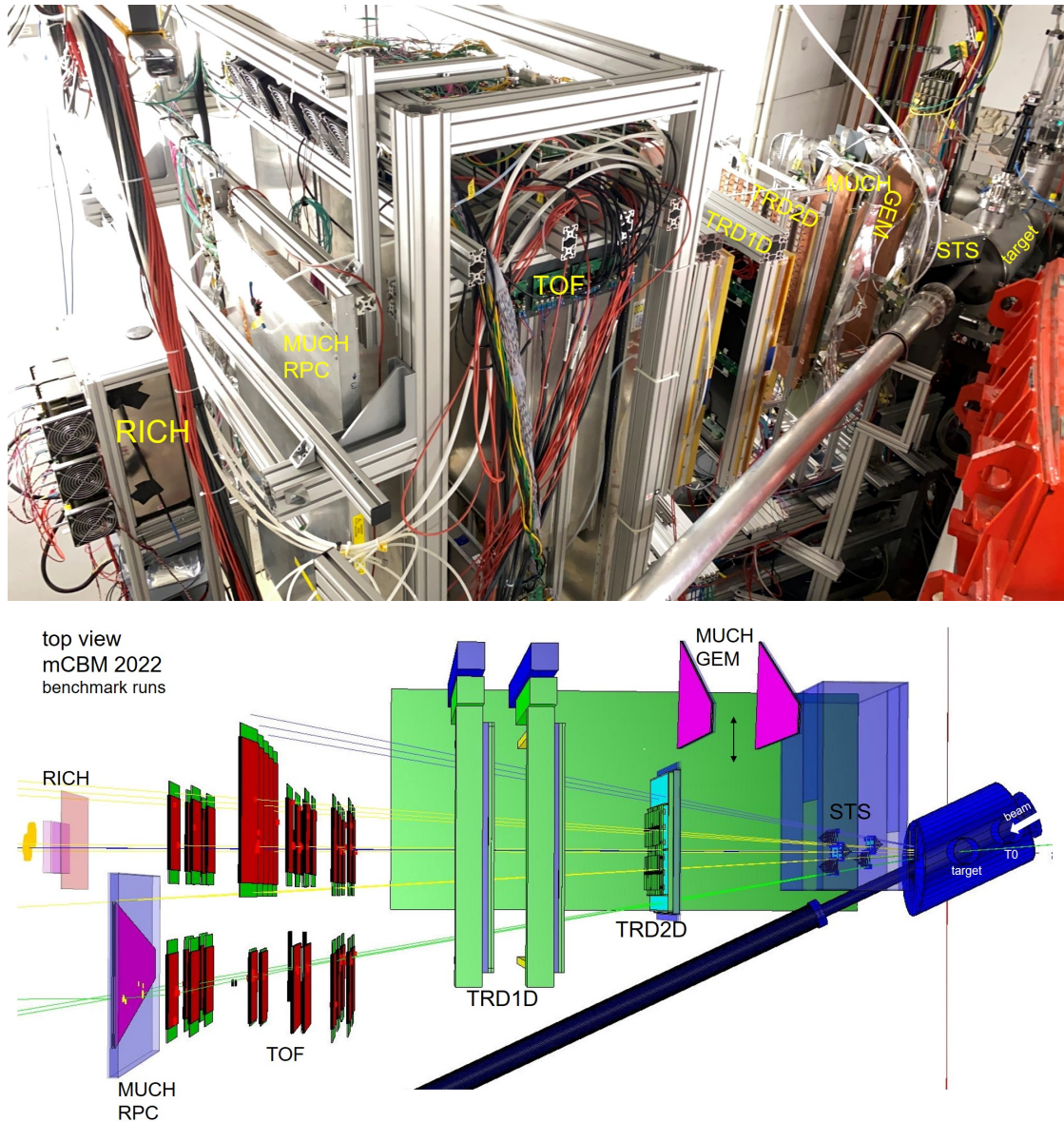


Figure 1: Photograph of the mCBM setup inside the HTD cave (upper panel) and GEANT geometry of the mCBM 2022 setup (lower panel). The beam enters from the right. The following CBM detector subsystems are installed in the mCBM experiment: the fast and segmented diamond counter for time-zero (T0, part of BMON) determination positioned 20 cm upstream of the target, the Silicon Tracking System (STS) subsystem equipped with 11 (full-size) modules on 5 ladders in 2 stations, the Muon Chamber (MUCH) subsystem, which consists of 2 GEM modules and 1 RPC module mounted downstream of the TOF detector, the Transition Radiation Detector (TRD) subsystem, comprising of one detector module for the inner TRD region (TRD2D) complemented with two large detector modules for the outer TRD region (TRD1D), the Time-of-Flight (TOF) subsystem with RPC modules grouped into two stacks and the Ring Imaging Cherenkov (RICH) subsystem using two aerogel radiators placed directly behind the TOF detector delivers a second measurement of the particle velocity in a selected acceptance window.

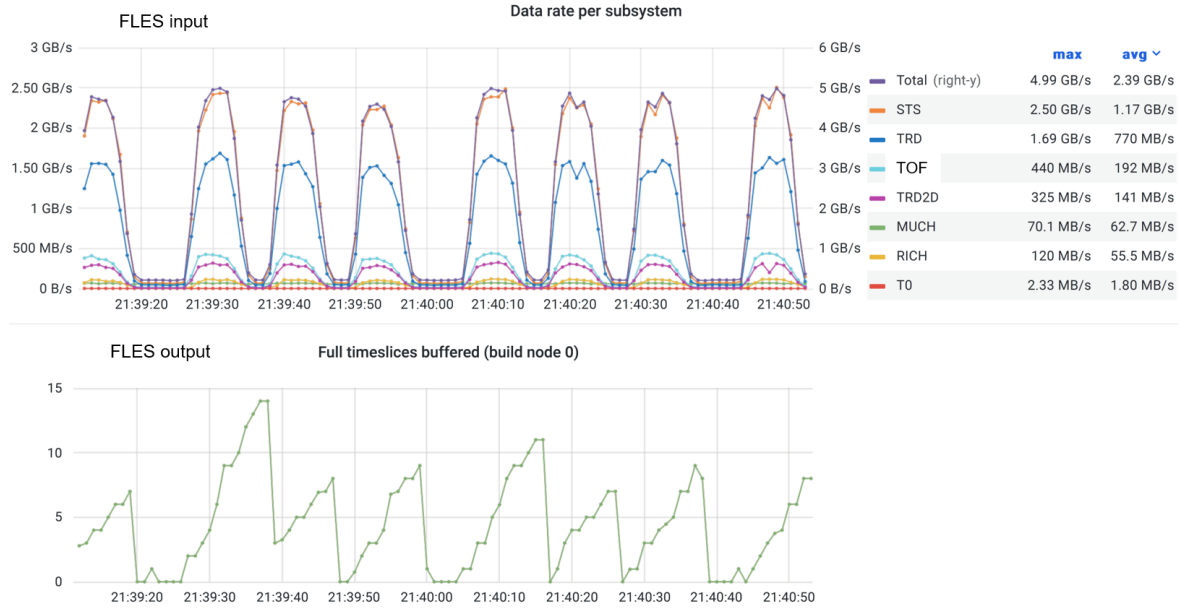


Figure 2: (Grafana plots) Incoming data rates (upper panel) and number of buffered timeslices (lower panel) observed for the mCBM run 2448, taken in Au+Au collisions at 1.23 AGeV kinetic projectile energy at an average collision rate of 300 - 400 kHz, June 2022 [5],[6].

threshold and assigning time stamps to the raw hit messages. By means of a Timing and Fast Control (TFC) system, the detector front-ends are time-synchronized to the nanosecond level. Via the CERN GBTx based data aggregation unit the data streams are transported to the entry nodes of the First Level Event Selector (FLES). Here, FPGA-based PCIe boards are integrated in the FLES entry nodes serving as a Common Readout Interface (CRI). The FLES processing nodes mounted in the Green IT Cube of GSI/FAIR conduct a final timeslice building containing the time-sorted raw hit messages of all detector systems. On this base, a parallelized event reconstruction and selection will be performed on the FLES compute cluster.

As of 2022, the mCBM cave was interfaced to the mCBM DAQ container by means of 3 trunk cables, each containing 144 multi-mode optical fibers. The entry level stage of the mCBM FLES consisted of 6 entry nodes hosting a total 14 CRI(v1.0) cards, synchronized with one TFC-Master node. The long distance connection to the Green IT Cube is realized by a 300 m long trunk cable holding 144 single-mode optical fibers. The InfiniBand links offering 800 Gbps total bandwidth are used to forward the timeslice components from the entry nodes to the processing nodes inside the Green IT Cube, where additional 4 processing nodes and the FLES master server are located. The processing nodes are equipped with a second InfiniBand interface allowing them to forward the data to the GSI Virgo cluster for further analysis and storage.

The upper plot of Figure 2 shows the measured FLES input data rates (total, right vertical scale), subdivided into individual data rates received from the detector subsystems

(left vertical scale) [5], [6]. Data shown here originate from run number 2448 on June 16, 2022, taken in Au + Au collisions at 1.23 AGeV kinetic projectile energy with an average collision rate of 300 - 400 kHz. As expected, the spill profile of the SIS18 beam is visible in the data rates of all subsystems (except T0 due to a misaligned beam, mainly missing the T0 diamond counter). The STS system provides the largest contribution of approximately 50% of the overall data volume. The total input data rate reaches 5 GB/s in this run. The bottom plot of Figure 2 depicts the corresponding number of timeslices buffered by the FLES processing nodes after timeslice building while writing to internal disks [5], [6]. Since the maximum data rate exceeds the write-bandwidth of the disk array, the number of buffered timeslices rises during spill. The spill breaks are then used to store the remaining data, smoothing the data rate across spills. Data were recorded to local storage at an average data rate of 2.4 GB/s which overall limits the performance of this setup under the given experimental conditions.

First results from 2022 data As a first step of the data processing, the raw hit messages packed and compressed in timeslice archive (tsa) files are being unpacked and converted into CbmDigis by applying individual subsystem time-offset corrections as well as involving the detector channel mapping and first calibration steps. As observed, the subsystem time-offsets remain constant during runs as well as between runs. Hence, a stable timing of the front-end electronics of all detector subsystems was observed within the expected time resolution (e.g. see STS [10],

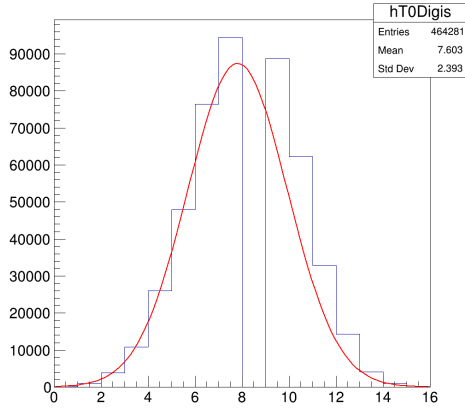


Figure 3: Horizontal beam profile measured with the T0 diamond counter (16 strips, $300\ \mu\text{m}$ each) in Ni + Ni collisions at 1.93 AGeV (run 2391, May 2022) [10],[9].

TRD [12], MUCH [16]), fulfilling the key requirement of a free-streaming read-out system. After the data unpacking, a first, simple event building is performed based on a time-cluster search within a time window defined by the timing response of a reference detector system (see [23]). Identified event candidates are then filtered based on Digi-multiplicities of selected detector stations or its combinations and stored as CbmDigiEvents in ROOT files for further analysis steps. Typically, event candidates are accepted including at least one Digi-hit in the T0 diamond counter and at least four Digi-hits in different TOF detector modules (e.g. see [7],[10]).

Prior to the benchmark runs in May and June 2022, a new time-zero (T0) counter has been installed integrated inside the vacuum vessel of the target chamber [9]. It is a prototype sensor of the CBM beam monitor system (BMON) based on poly-crystal (pc) chemical vapour deposition (CVD) diamond technology (pcCVD) with a thickness of $80\ \mu\text{m}$. The metallization of the $1 \times 1\ \text{cm}^2$ diamond sensor is partitioned in 16 strips on both sides, $300\ \mu\text{m}$ each, vertically and horizontally aligned, which additionally enables a 2D beam profiling (the read-out of the horizontal strips will be added for the upcoming beam campaign). Figure 3 shows the measured horizontal beam profile observed in Ni + Ni collisions at 1.93 AGeV (run 2391, May 2022) [10],[9]. With a standard deviation of $\sigma = 2.4$ strips and a strip width of $300\ \mu\text{m}$ the horizontal beam-spot size results to approx. 1.7 mm FWHM (20 cm upstream of the target).

The tracking system of the mCBM experiment consists of (see Figure 1)

- 2 STS stations with 11 STS modules on 5 ladders [10]. The first station (station-0) is composed of $2 \times 2\ 62 \times 62\ \text{mm}^2$ STS double-sided silicon-strip sensors ($58\ \mu\text{m}$ pitch, 1024 channels each side), resulting to $12 \times 12\ \text{cm}^2$ active area, and the second station

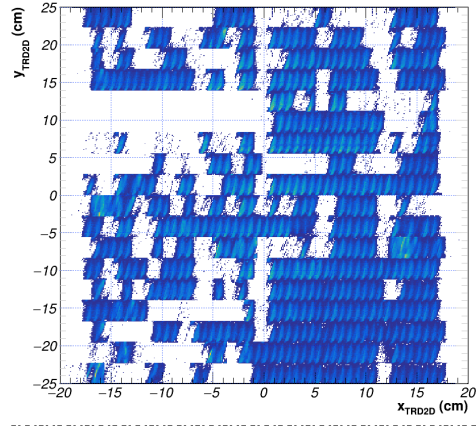
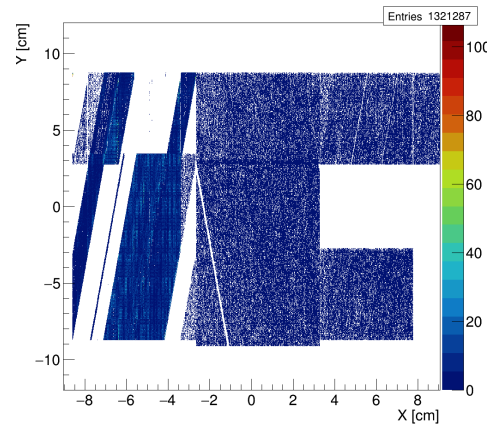
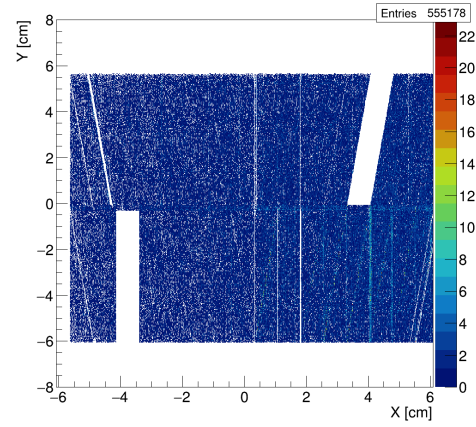


Figure 4: x-y hit-maps of both STS stations, station-0 (upper panel) and station-1 (middle panel) [10], and of the TRD2D station (lower panel) [11].

(station-1) with $18 \times 18\ \text{cm}^2$ active area composed of $2 \times 62 \times 124\ \text{mm}^2$ and $5 \times 62 \times 62\ \text{mm}^2$ sensors. The corresponding x-y hit-map of both STS stations for the 2022 beam campaign is depicted in the upper and middle panel of Figure 4 [10].

- 1 TRD2D station with an active area of $36 \times 50\ \text{cm}^2$, a MWPC read-out by triangular pads for a 2-

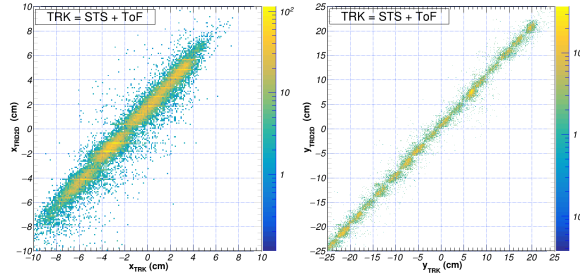


Figure 5: Correlations of spatial coordinates between the intersection of STS - TOF tracks with the TRD2D plane vs. reconstructed TRD2D hits, left panel: x-x correlation, right panel: y-y correlation [12].

dimensional (x,y) hit reconstruction. The x-y hit-map resulting from 2022 data is shown in the lower panel of Figure 4 [11].

- 2 TRD1D stations with an active detector area of $95 \times 95 \text{ cm}^2$ each, MWPCs read-out by rectangular pads with the size of $7.18 \text{ mm} \times 150 \text{ mm}$. The upstream station (x) is equipped with vertically aligned pads, the downstream station (y) with horizontally aligned pads. The TRD1D time reconstruction method and thus the time resolution has recently been improved [14].

A preliminary version of a data-driven detector alignment has been used as it is e.g. described in [7]. Based on that, tracks were formed from STS and TOF hits. Figure 5 shows the intersection of STS - TOF tracks with the TRD2D detector plane displayed vs. reconstructed TRD2D hits [12], horizontal coordinates (x-x) on the left side and vertical coordinates (y-y) on the right side. Offset shifts and deviations within the spatial correlations are still visible for which reason the alignment procedure can be improved and, hence, will be further developed towards a prototype alignment procedure for CBM. However, Figure 5 demonstrates the 2D-reconstruction capability of the TRD2D detector system and gives rise to use the TRD system as an intermediate tracking detector for CBM (see therefore [13]).

The CBM Cellular Automaton (CA) track finder has been advanced and can now be applied more generally, explicitly to field-free volumes [21]. It does no longer require a momentum cut nor needs external material maps while importing the geometry and therefore, supports all available CBM and mCBM setups. The application to mCBM 2022 data has started which then will be used as input for the CBM KFPARTICLE package. Furthermore, the RICH ring finder has been advanced and further stabilized by a denoising mechanism based on a training of a convolutional neural network (CNN) [18],[19],[20]. Especially the data analysis of the mCBM data will profit from this development since charged particles traversing directly the RICH MAPMTs mounted in the mRICH detector generate a center cluster which can now be eliminated and, hence, do not further irritate the ring finding.

As visible in Figure 1, the TOF detector subsystem was grouped into 2 stacks adapting the setup for high-rate studies. Accordingly, the TOF frame was moved and rotated closer to the primary beam axis positioning the inner stack at a center polar emission angle of 12.5° and the outer stack at 25° . Hence, the charged particle flux was significantly enhanced for the inner TOF stack, reaching (averaged) 5.5 kHz/cm^2 in-spill for the second prototype P2 of the Multi-Strip Multi-Gap Resistive Plate Counters (MSM-GRPCs) observed in Au + Ni collisions, June 2022 [17].

Two modified MUCH GEM stations had been installed between the STS and TRD subsystem, as well as for the first time a full-size MUCH RPC detector module was mounted at the downstream side of the TOF frame. As indicated in the GEANT geometry (see lower panel of Figure 1), the GEM stations were moved into the acceptance for detector tests, while positioned outside the acceptance during benchmark runs due to a large material budget of the MUCH GEM stations. To overcome the observed instability of elinks (front-end ASIC $\rightarrow$ GBTx ASIC) the optocoupler based HV distribution of the GEM detectors was modified as well as the drift PCBs of the GEM stations [16]. Accordingly, the elink stability has been significantly improved and, hence, the performance of the GEM stations was systematically studied in rate scans up to the highest collision rates with U-beam [15] and Au-beam [16]. The data analysis is ongoing, however, first results indicate a high rate capability towards the design specs.

Reconstruction of Λ baryons The assignment of a particle mass to the track candidate is based on the decay topology of the Λ decay into a proton p and a negatively charged pion π^- as indicated in the upper panel of Figure 6, depicting a Monte-Carlo simulation of a single Λ decay within the corresponding GEANT geometry of mCBM. Details of the applied Λ reconstruction are given in [7]. Due to its mass the proton carries most of the Λ momentum and is being therefore emitted mainly in the direction of the decaying Λ while the much lighter π^- is more likely to be observed at larger angles with respect to the flight direction of the mother particle. Hence, the pion track projected to the target features a larger distance to the primary vertex in the target plane and therefore is being distinguished to a proton track by its larger distance-of-closest approach (DCA). Additionally, the measured velocity is required to fall into a predefined proton or pion range which was determined by Monte Carlo – simulations of Λ decays. Pairs are formed from proton and pion candidates applying further selection criteria like on pair DCA or on the opening angle between the proton and pion candidate. The preliminary invariant mass distribution M_{inv} of the so-selected proton-pion pairs is shown in the lower panel of Figure 6, observed in Ni + Ni collisions at 1.93 AGeV kinetic projectile energy [7]. All selected pairs are displayed in blue color (Same event) and the combinatorial background in cyan color (Mixed events). The combinatorial background was determined by pair combinations of protons and pi-

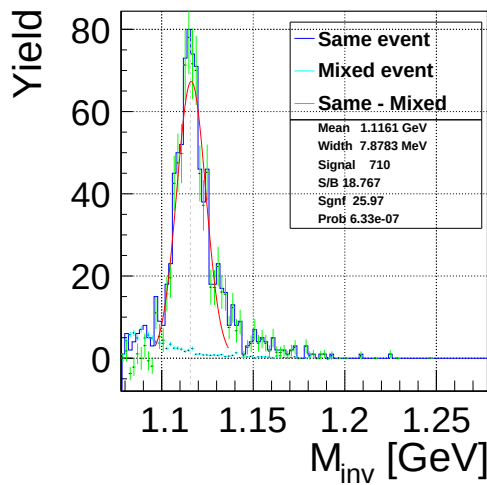
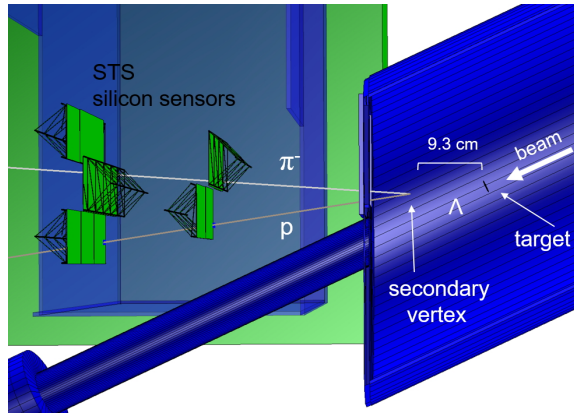


Figure 6: (Upper panel) A Monte-Carlo simulation of a single Λ decay is shown within the corresponding GEANT geometry of mCBM. (Lower panel) Preliminary invariant mass distribution M_{inv} of pairs formed from proton and pion candidates in Ni + Ni collisions at 1.93 GeV kinetic projectile energy: all selected pairs in blue color (Same event), the combinatorial background in cyan color (Mixed events) and in green color after background subtraction (Same – Mixed) [7]. The applied Λ reconstruction is described in detail in [7].

ons which stem from different events (mixed events) to exclude correlations. Even without background subtraction a clear Λ signal with a signal-to-background ratio (S/B) of about 19 is observed. After background subtraction (Same – Mixed, green distribution) a Gauss fit (red curve) results to a signal yield of 710 at a mean invariant mass of about 1.116 GeV. The signal yield amounts to an integrated probability of $6 \cdot 10^{-7}$ in the selected event sample. The raw data sample of 8.1 TB tsa files (run 2391) was taken at an average collision rate of about 400 kHz on May 26th, 2022, in a total run time of about 2 h.

The identification of Λ baryons with mCBM demon-

strate the feasibility to reconstruct rare signals with the CBM detector systems involving the full CBM data chain. Detailed Monte-Carlo simulations are in preparation determining the acceptance and reconstruction efficiency to convert the observed Λ yield into a production probability for minimum-bias collisions. Furthermore, 180 TB raw data (tsa) files were taken in June 2022 for Au + Au collisions at 1.23 AGeV kinetic projectile energy. The lower projectile energy reduces the Λ production probability significantly (sub-threshold production) while the track reconstruction and selection has to cope with increased ambiguities with respect to the Ni system. Hence, the much more challenging signal-to-background ratio requires a further fine-tuning in terms of the calibration, alignment, track reconstruction and selection criteria.

As one of the CBM central common systems, a scalable Experiment Control System (ECS) is being developed [24]. The task of the ECS is to coordinate hardware and software components required for the operation of CBM. First prototype elements have been embedded into the DAQ and data transport system, used and tested during the mCBM beam campaigns. Next stages are being designed to be applied and tested at mCBM. Although a first version of a simple online selection based on the unpacked, time-offset corrected subsystem data was tested during the 2022 beam campaign raw data were completely archived. Based on the 2022 data, the online selection algorithms are further developed and optimized towards the upcoming beam campaign 2023 - 2025 (e.g. see [22]).

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Λ - baryon reconstruction with mCBM

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One of the goals of the mCBM demonstrator experiment is to exercise the full data acquisition and data analysis chain up to a level that is relevant for physics interpretation. As proposed in the Letter of Intent [1] Λ - baryons can serve as a rare probe at SIS18 energies. Their reconstruction in a setup without a magnetic field would prove the quality of the preseries detectors implemented in mCBM in terms of resolution and stability.

Towards achieving the goal raw messages of all subsystems were recorded in May and June, 2022, for the two reactions Ni+Ni at a beam kinetic energy of 1.93 AGeV and Au+Au at 1.23 AGeV (see mCBM overview [2]). In the following the status of analyzing the data with the tool already used for the feasibility study in [1] is shown. The tools to provide the necessary calibrated and aligned MRPC hits needed to be developed.

Data processing

The recorded raw message data are first converted into C++ objects called *CbmDigis* which contain the raw information with a software oriented addressing scheme. This step was carried out within a FAIR-MQ framework and can be operated in a online compatible way. At the same time the event selection and building step is carried out in an additional FAIR-MQ device. For the following, events are required to have at least one hit in the start counter and four hit candidates in different Tof detectors. Finally the collection of *CbmDigis* is combined to so called *CbmDigiEvents* which are stored in root-files for calibration and further analysis.

Fig. 1 shows the multiplicity distribution of the Tof-Hits in the available event sample of $1.2 \cdot 10^9$ events found in the raw data sample of 18 TB which was collected in a real run time of about 5 h. The unpacked and event selected *CbmDigiEvent* - files have a total size of 1.8 TB demonstrating the potential of significant data reduction by simple algorithms. The purple histogram in Fig. 1 represents the signal region described below.

Tof calibration

Since not all cells of the Tof detectors are hit by trackable particle trajectories, a new method was devised employing only single hit information. The hit times are adjusted such that the velocities calculated with respect to the start counter time show an edge at speed of light. The result of the procedure is shown in Fig. 2 for the Tof counters available in the Ni runs.

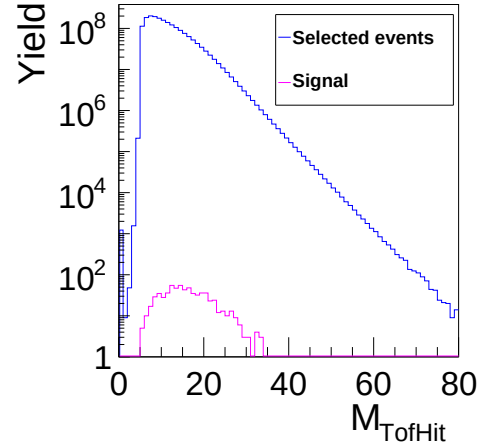


Figure 1: Multiplicity distribution of mTof hits in the selected event sample.

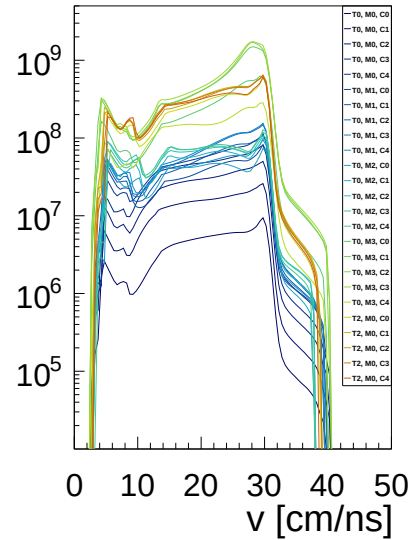


Figure 2: Velocity spectra of all MRPC counters used in the analysis. The curves are labeled with the module type (T), module number (M) and counter number (C).

The quality of the Tof calibration enters directly into the invariant mass resolution since time of flight is the only measurement that gives access to the momenta of the particles.

Sts-Tof alignment

The particle candidates fed into the analysis the subsystems have to be aligned with respect to each other. This is achieved by minimizing the distance of the measured Sts hits to the reference Tof position which is obtained by projecting the measured Tof hit to the plane of each Sts module under the assumption that the track stems from the origin of the coordinate frame, i.e. in this step it is assumed that all reactions take place at (0,0,0). The deviations are corrected by means of alignment matrices. Fine tuning of the Sts position is done with Sts hit pairs. The final position of each Sts module is determined by minimizing the distance of the Sts hits to the straight line from the nominal vertex to the Sts hit pair which was preselected in the first step of the alignment procedure.

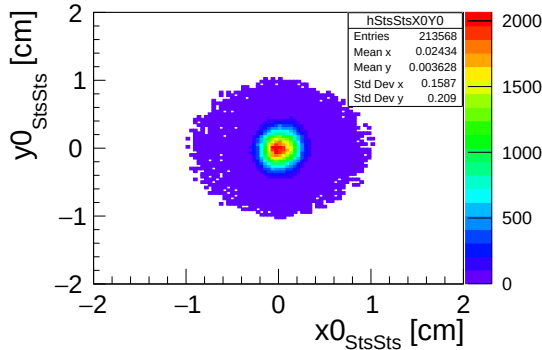


Figure 3: Residual position deviation between the two Sts stations. For details see text.

The method is delivering an image of the interaction region. Releasing the condition that the line connecting the preselected Sts hits are originating from the nominal vertex one can calculate the intercept of the line with the plane at $z=0$ as it is shown in Fig. 3. The widths of the vertex distribution in x- and y- direction is compatible with the expectations.

Trd-Tof alignment

With the prealigned Sts and Tof hits Trd hits can be easily put into the same analysis frame. After adjustment of x-, y- and z- coordinates of the detectors the residuals with respect to the expectations from Tof-Sts triplets show a deviation of the mean value below 1 mm with a width of 1.5 cm which is sufficient in accuracy to confirm a charged particle track hypothesis of a given Tof - Sts triplet.

Particle candidate selection

The particle assignment is based on the decay topology of the Λ -decay. The proton gets most of the Λ -momentum and is emitted into the direction of the mother particle with small deviation. The pion is much lighter and the deflection from the original direction is much larger. Therefore the assignment of masses is done according to the distance-of-closest approach (DCA) of the Sts-Sts line extrapolation to the target plane. With two delimiting radii $R_1 < R_2$, triplets with $R < R_1$ are called primary tracks, triplets with $R_1 < R < R_2$ are named secondary protons and anything with $R > R_2$ is assigned the pion mass if additionally the measured velocity falls into a predefined range which was determined by MC - simulations. Typical values for the involved parameters are $R_1 = 0.5$ cm and $R_2 = 1$ cm. The velocity ranges for the data shown in Fig. 4 are $15 \text{ cm/ns} < v_{\text{proton}} < 27 \text{ cm/ns}$ and $25 \text{ cm/ns} < v_{\text{pion}} < 29.5 \text{ cm/ns}$.

Pair analysis

For the candidate pairs topological quantities are calculated and used for pair selection. The list is given in the following table with the values used to obtain the result shown in Fig. 4.

distance of closest approach of pair lines	0.1 cm
opening angle between pair lines	0.1 rad
min distance of intercept of pair lines to origin	5 cm
max distance of intercept of pair lines to origin	25 cm
max pointing angle of pair sum momentum	0.03 rad

The term pair lines refers to the straight lines connecting the two Sts -hits of the particle candidates. For pairs fulfilling the selection criteria the invariant mass is calculated as shown in Fig. 4.

The pair distribution is shown by the blue histogram, while the mixed event background is shown in cyan color. The mixed event background is constructed by combining each pion candidate in a given event with 20 proton candidates found in previous events in the same TofHit multiplicity bin. 10 multiplicity bins of equal width were used to cover the distribution shown in Fig. 1. The mixed event distribution was normalized in the interval $1.08 \text{ GeV} < M_{inv} < 1.09 \text{ GeV}$ to the same event distribution. A clear signal is visible even without background subtraction. The signal-to-background ratio is about 18. Subtracting the background gives rise to the green histogram for which also the statistical errors are shown. The observed signal has a statistical significance of about 26. The current choice of selection values is not the optimal in terms of maximizing the significance. The distribution just serves as an example that mCbm reached its goal to demonstrate the feasibility to reconstruct rare signals. The integrated probability of the signal derived from a Gauss fit shown by the red line amounts to $6 \cdot 10^{-7}$ in the event sample. Monte Carlo simulations of the acceptance and efficiency are necessary to

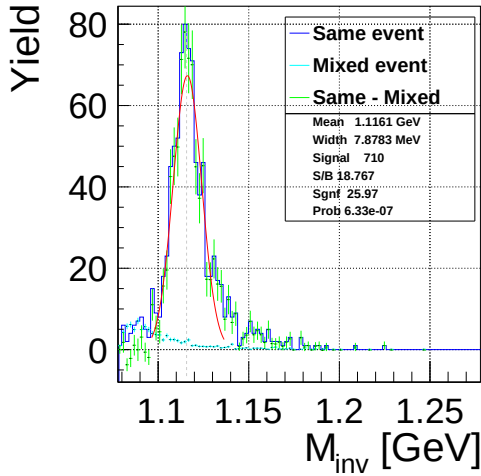


Figure 4: Invariant mass of proton and pion candidate pairs. For details see text.

convert this number into a production probability for min. bias events. It should be noted that the mean value of the signal peak is strongly depending on the Tof counter calibration, changing the speed-of-light edge of the time of flight spectra by 50 ps shifts the peak position by 3 MeV.

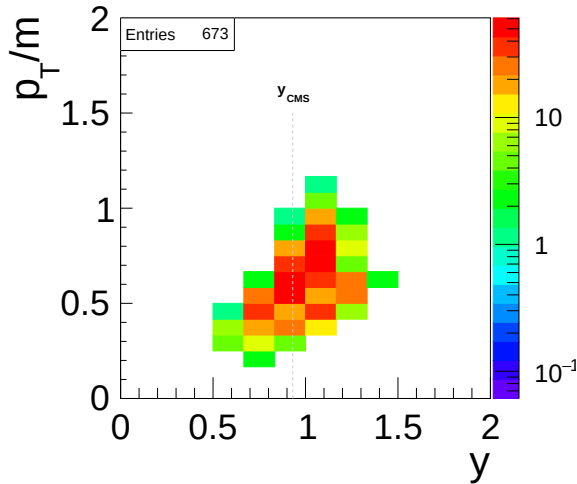


Figure 5: Reconstructed phase space distribution of the Λ -baryon signal.

Fig. 5 displays the phase space coverage of the experimental setup in the plane transverse momentum divided by mass versus rapidity in the laboratory frame. The reconstructed Λ -signal is covering the midrapidity region albeit with a limited p_T -acceptance. Differential efficiency corrections obtainable by full setup Monte Carlo or by em-

bedding techniques are needed to correct the reconstructed distributions. Corresponding efforts are ongoing.

180 TB of raw data are available for the system Au+Au at 1.23 AGeV where the Λ -production probability is reduced by about a factor of 4 with respect to the Ni system presented above. The raw data sample is reduced to 2.8 TB when employing the same algorithm as used for the Ni - data. $3.6 \cdot 10^9$ events are available for further analysis. Fine tuning of the calibration, alignment and selection cuts is necessary to cope with a much more challenging signal-to-background ratio.

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Event selector and its application to mCBM

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Reconstructing events that are useful for the CBM physics analysis is an important and challenging task, since CBM will be a trigger-less experiment with a free-streaming read-out chain. Currently, the event reconstruction scheme is a three stage process: 1) Event trigger - to find seed times for the events using the trigger or seed finding algorithm (currently implemented in the class `cbm::algo::TimeClusterTrigger` in CbmRoot [1]). 2) Event building - collecting digis from all subsystems around a trigger or a seed, using separate time windows for each detector [2, 3], then grouping them into events, 3) Event selector - applying cuts to define good events, e.g. by filtering events on the basis of number of detector layers hit. This report introduces the concept of the event selector and discusses its application on the full chain, from CBM digi-event reconstruction to mCBM simulated data as well as measured data from the mCBM 2022 beamtime [4, 5].

mCBM Event Building (Simulation vs. Data)

A transport simulation was carried out for mCBM, using an UrQMD input file for Ni + Ni at 1.93 AGeV mbias, with the geometry `mcbm_beam_2022_05_23_nickel`. Figure 1 shows the mCBM geometry setup of the 2022 beamtime, implemented in the CbmRoot software. Digitisation was done in time-based mode at a moderate event rate of 10^5 Hz. Detector noise was switched off in the simulation. For mCBM 2022 data, TOF was chosen as the event seed finder or trigger detector. In a time based simulation at a moderate event rate of 10^5 Hz (trigger efficiency = 100%), the event trigger parameters settings were: trigger thresh-

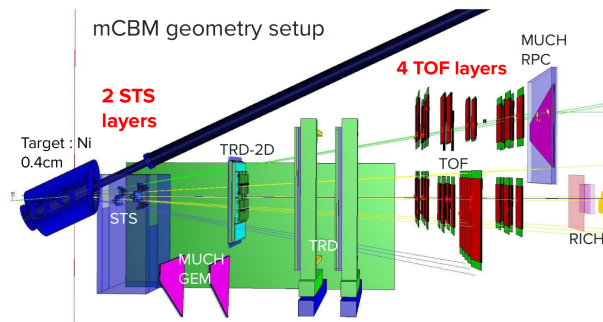


Figure 1: The mCBM geometry including the STS, MUCH, TRD, TOF and RICH detector subsystems (setup tag: `mcbm_beam_2022_05_23_nickel`).

Sub-system	Simulation		Data	
	Min. digis /event	Event window (ns)	Min. digis /event	Event window (ns)
STS	6	(-20,+30)	10	(+20,+100)
RICH	0	(-10,+40)	5	(-10,+30)
TRD	0	(-100,+150)	0	(0,+280)
TOF	10	(-10,+40)	16	(-5,+30)

Table 1: Event builder settings. Parameters used for mCBM time based simulation (system: Ni+Ni) and data (Run 2391, system: Ni+Ni).

old = 10 TOF digis, the trigger window = 10 ns, trigger dead time = 50 ns. The same parameters were used for triggering events in the measured mCBM data. The data was unpacked from mCBM beamtime run number 2391. The event building parameters for STS, RICH, TRD and TOF used in this simulation and for the data are given in Table 1. The event builder was operated in ‘AllowOverlap’ mode [2]. The parameters of the event trigger and event builder, in particular the event time windows, were optimised for best QA results [1, 6].

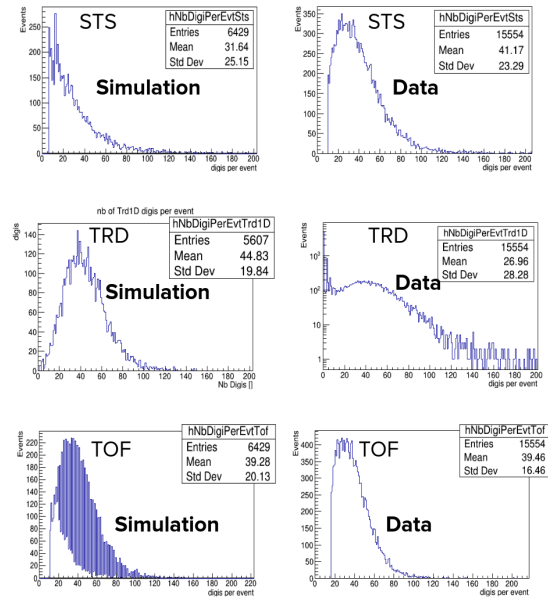


Figure 2: Number of digis per event in mCBM for different subsystems obtained using the digi event builder (time based simulation vs. data).

From the simulation, the average number of STS and TOF digis/event is 31 and 39 respectively. It is evident from Figure 2 that the digis/event distribution of STS and TRD are different for simulation and measured data. This is due to the presence of noise, which is not taken into account in our simulation, whereas for TOF, the simulated digis/event matches very well with data. This might be caused by the choice of TOF as trigger detector in our study. From Figure 3 details that the width of STS digi time distribution is 6.0 ns in simulation and 7.3 ns in measured data, for RICH it is 1.4 ns and 3.8 ns, for TRD it is 8.2 ns and 55.0 ns, for TOF it is 1.5 ns and 4.7 ns in simulation and measured data respectively. The large difference in digi-time widths (simulation vs. data) for TRD can be

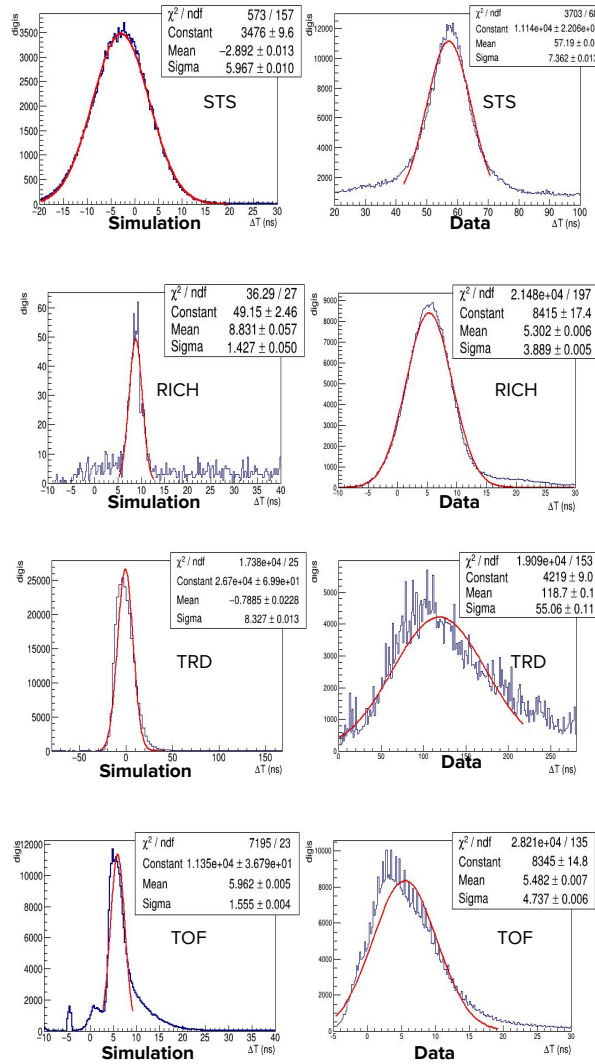


Figure 3: Digi time distribution within an event for different subsystems in mCBM obtained using the digi event builder (time based simulation vs. data)

due to noise during the experiment. However, for other subsystems, there is slight difference in digi-time widths (simulation vs. data), which may be attributed either to the CBM digitizer or the event builder performance.

Event Selector and its performance

The event selector is used after the event building to select on particular events. Event selection is done on the basis of number of layers/stations hit in each subsystem in an event. The advantage is that it allows to filter out events interesting for physics studies and provides a better rejection of noise. The event selector is currently implemented in the class `cbm::algo::DigiEventSelector`. The purpose of this class is to apply a cut on events by imposing a minimum number of STS and TOF layers hit. Currently, there are only 2 STS layers and 4 TOF layers in the mCBM experiment setup. A simulation (similar to the one mentioned in the previous section) was performed to test the functioning of the event selector. The event selector was also applied on mCBM data (2022 beamtime, run 2391). Table 2 shows the % selected events for different layer numbers which were hit in STS and TOF. From the table it is evident that the events hitting all STS layers (2) and TOF layers (4) is only 35% of the total reconstructed events. Also, the % selected events for hit conditions in different layers of STS and TOF matches in simulation roughly with the value in measured data.

Min. STS layer	Min. TOF layer	% selected events (Simulation)	% selected events (Data)
0	0	100	100
1	0	77	91
2	0	49	74
0	1	100	99
0	2	98	90
0	3	85	74
0	4	60	43
2	4	35	36

Table 2: Performance of the event selector in simulation and in measured data.

Conclusion

In this work, we applied the full event reconstruction chain (1. event trigger, 2. event builder, 3. event selector) to the mCBM time-based simulation data (Ni + Ni) as well as to measured data from the mCBM beamtime 2022 (run 2391, system: Ni + Ni). The digis per event and the digi-time distribution for different subsystems were obtained. The simulation results were compared with the mCBM beamtime data and differences were observed, which requires further investigation on CBM digitizers. Furthermore, an event selector algorithm is currently implemented in the CBM software to allow selection of only those events that are interesting for physics analysis.

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