

CBM

Compressed
Baryonic
Matter
experiment
at FAIR

2023

PROGRESS REPORT



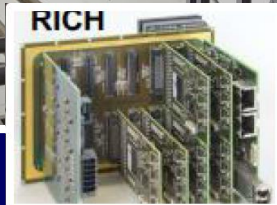
TOF



FSD



MVD



RICH



TRD2D



MUCH



RICH



TOF



STS



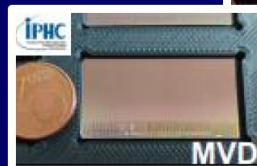
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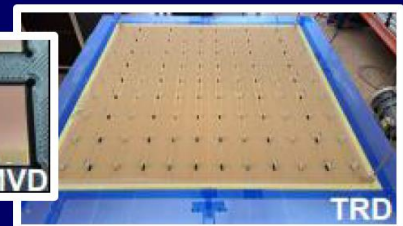
STS



DAQ



MVD



TRD

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Preface

As we present the CBM Progress Report for 2023, we reflect on a year marked by significant advancements and collaborative efforts to realize the key heavy-ion experiment to address fundamental properties of strong-interaction matter at high μ_B . This report covers our progress, detailing key achievements, ongoing research, and future directions. It highlights the dedication of our diverse team of scientists, engineers, and students.

In 2023, the CBM collaboration has achieved remarkable milestones, including the successful integration and test of detector subsystems as well as necessary steps towards demonstrating a proof-of-principle for the CBM online data processing and selection concept. The physics performance studies have been advanced, and increasingly realistic simulations have been performed.

The FAIR civil construction is completed, and the roof of the SIS100 experimental hall, the home of CBM, has been finalized. CBM, being one of the first customers of SIS100 beams, pursues with high priority the completion of the Day-1 experimental setup to be ready by end of 2028. The development of the cave infrastructure continued, and work on the dipole foundation and upstream platform design has progressed substantially. The CBM dipole magnet was defined by the GSI/FAIR Management (and approved by the FAIR Council) as an item for urgent re-procurement - this is an utmost important step towards realization of the key CBM milestone. The Technical Design Report for the Online Systems – Part I as well as Transition Radiation Detector-2D TDR Addendum were recommended for approval by the Expert Committee Experiments and approved by FAIR in June 2023.

NuPECC has launched the process of creating a new Long Range Plan, identifying opportunities and priorities for nuclear science in Europe. The CBM Collaboration has submitted its input on “Exploring the high-density region of the QCD phase diagram with CBM at FAIR” and emphasized that the extraction of significant information of the QCD phase structure requires systematic measurements of excitation functions, system size dependencies and multi-differential phase-space distributions of various observables, and thus requires a high rate capability detector. In a whitepaper for US participation in the CBM experiment (arXiv:2209.05009 [nucl-ex]), the importance of performing measurements in the SIS100 energy range was highlighted, and the high discovery potential underlined. CBM is well positioned for a challenging and far reaching physics program at SIS100. An important role is played by the FAIR Phase-0 activities, which CBM is successfully pursuing. Extension of the CBM physics program employing SIS100 proton beam and targeting exclusive channels has been consolidated.

The CBM Collaboration has welcomed a new full member institution – the University of Bochum (GSI and FFN), Germany, and an associated member institution, the Hiroshima University, Japan.

We extend our gratitude to our funding agencies, partner institutions, and all collaborators whose unwavering support has been instrumental in our journey. As we look forward to the challenges and discoveries, we keep committed to fostering a vibrant scientific community and to advancing our understanding of QCD matter properties at high baryon densities.

A lot of progress in 2023. Many challenges, but also a bright – and I heartfully hope, peaceful - future ahead!

Darmstadt, October 2024

Tetyana Galatyuk, CBM Spokesperson

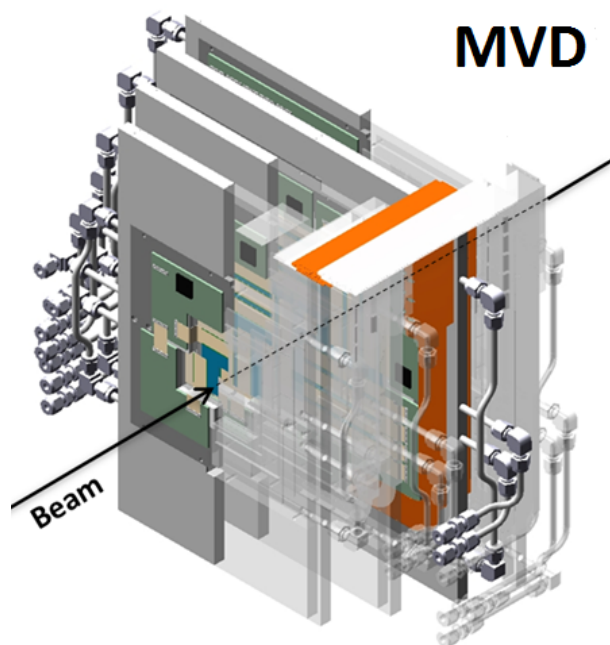
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Micro-Vertex Detector



Micro Vertex Detector - Summary

C. Müntz¹, A. Besson³, M. Deveaux^{1,2}, J. Stroth^{1,2,4}, and the CBM MVD team^{1,2,3}

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2023 was dominated by sensor R&D, i.e. by concluding the evaluation of MIMOSIS-1 and with starting the characterization of the last prototype sensor MIMOSIS-2, where issues in the digital output were spotted, preventing further studies of the sensor in already scheduled beam tests. Consequently, a re-submission (MIMOSIS-2.1) has been initiated. Sensor control and read-out was further consolidated with a focus on our TrbNet-based stand-alone concept, optimized for probe-testing, sensor characterization and beam tests. In parallel, activities towards a CBM-DAQ compatible control and readout with GBT-SCA and CRII, respectively, have been launched. Integration activities, as well, are driven by the MVD core EDR scheduled for 2025. The fabrication of a pre-series quadrant of the largest station was prepared by refining the baseline integration concept, focusing on yields, re-workability and the TPG carrier. Pre-series heat sinks were delivered, and further detailing of the CAD model of the detector is in progress. Simulation studies on the sensor digitizer and physics performance did complement our activities.

Sensor: The submission of MIMOSIS-2 followed an intense test campaign on MIMOSIS-1, which demonstrated the excellent detection capabilities of this first full-size sensor prototype. MIMOSIS-2 hosts complex new features including a grouping of fired pixels for the purpose of data compression and a triplicating the clock tree. The numerous internal upgrades came with the need to redesign the vast majority of the building blocks of MIMOSIS-2. First tests of MIMOSIS-2 have confirmed the successful elimination of a significant part of the issues observed in MIMOSIS-1. However, three new problems limiting the testability of the device were spotted: Two errors in the digital data path, i.e. a reset of the pixel prior to readout and insufficient powering of some output drivers, and delay blocks unable to handle 320 MHz clock frequency. Device simulations prior to submission did not allow to spot these flaws. Therefore, the whole verification process prior to further submissions has been updated. In addition, studies with sensors reworked by the Focused Ion Beam method (FIB) have verified these issues, finally leading to the re-submission (denoted MIMOSIS-2.1) with a few modified masks only by end of the reporting period. Despite of the MIMOSIS-2 shortcomings, systematic studies could be conducted utilizing the analog output to measure the response of pixels to X-rays. S-curve measurements were possible with FIB-corrected sensors.

Sensor integration: Activities are driven by the need to conclude the prototyping phase, and to prepare the engineering designs of various components, with a focus on the TPG carrier quadrants. Pre-series heat sinks have been designed and delivered. The TPG carrier clamped in the heat sink will serve as mounting jig for the sensors. TPG as material for thin, large area carriers calls for a detailed understanding of handling and QA. Corresponding studies were conducted and documented in two MSc theses. Gluing on Parylene-coated TPG sheets was systematically studied, and machining of TPG sheets with a laser ablation device available in the GSI electronics department has been established for high-precision machining, both material ablation (hatching) and cutting. This work was closely accompanied by updating the (CAD) technical design of both the quadrants and the detector.

Sensor readout: Two different setups are currently being advanced in the laboratory. One is fully based on the TRB framework and provides an easy-to-use, portable system for sensor characterization, test beam campaigns and mass needle probe-testing. Having resolved probe-card contact issues, the latter setup is ready for final consolidation and duplication. The other setup aims at the final CBM-MVD and initially targets the participation in mCBM in 2025. In a first step, the sensor configuration via GBT-SCA was successfully exercised, together with the TrbNet-based setup for DAQ and controls. This serves a prerequisite for the next step, i.e. readout via the CRI board used as standard in mCBM.

Simulations: MVD as part of the CBM "Inner Tracker" extends the acceptance towards lower particle lab-momenta and adds redundancy. Simulations systematically study the capability of the combined tracking system, with a focus on MVD, and point to the need for a refined track reconstruction algorithm which is tuned to the needs for reconstruction of low-momentum tracks by relaxing on processing speed.

The sensor digitizer urgently requires an update to the MIMOSIS sensor properties, which translates in providing a fast accessible lookup table for charge collection efficiencies to be imported in CBMRoot. To do so, AllPix² simulations have been conducted based on all known pixel features. Tunable system parameters have been preliminarily constrained by successfully reproducing measured cluster multiplicities. However, further iterations are required to arrive at a robust and realistic representation of all parameters and the final pixel response.

MIMOSIS sensor prototype - development update

*B. Arnoldi-Meadows¹, J. Baudot², G. Bertolone², A. Besson², R. Bugiel⁺², G. Claus², C. Colledani², H. Darwish^{1,2}, M. Deveau^{1,3,4}, A. Dorokhov², G. Dozière², Z. El Bitar², M. Goffe², A. Himmi², C. Hu-Guo², K. Jaaskelainen², O. Keller⁺³, M. Koziel⁺¹, F. Morel², C. Müntz¹, H. Pham², M. Specht², J. Stroth^{1,4,5}, I. Valin², Y. Zhao², M. Winter^{*2}, and the CBM MVD team^{1,2,3,4,5}*

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MIMOSIS is the CMOS Monolithic Active Pixel Sensor developed to equip the CBM Micro Vertex Detector (MVD). After the successful test of the first full-scale prototype MIMOSIS-1, a follow-up sensor MIMOSIS-2 was sent to production. Tests of the new prototype showed numerous improvements but also some major issues restricting the testability of the prototype. After analyzing and fixing them, an improved sensor MIMOSIS-2.1 was submitted in December 2023.

The submission of MIMOSIS-2 followed an intense test campaign on MIMOSIS-1, which demonstrated the excellent detection capabilities of the latter sensor. Even after an end of lifetime dose of $1 \times 10^{14} \text{ n}_{\text{eq}}/\text{cm}^2$ and 5 MRad, a detection efficiency in excess of 99.5 %, a spatial resolution of 5 to 6.5 μm and a dark rate of $\lesssim 10^6$ per pixel were observed [1]. This matches the requirements of CBM.

However, the complex ASIC contained weak points including e.g. some flaw in the slow control of the sensor, non-operational analog outputs, and weaknesses in the analog power distributions. Moreover, dedicated tests carried out at the UNILAC revealed a weakness in the recovery of bit-flips as caused by direct heavy ion impacts in the status registers steering the DACs of MIMOSIS-1. In consequence, the sensor got reversibly disabled in the event of a bit-flip.

MIMOSIS-2 hosts complex new features including a grouping of fired pixels for the purpose of data compression and a triplication of the clock tree, which is to further improve the tolerance of the sensor to single event effects. Despite they were not intended to change the major performance parameters of the sensor as seen by the end-user, the numerous internal upgrades came with the need to redesign the vast majority of the building blocks of MIMOSIS-2.

First tests of MIMOSIS-2 showed that a significant part of the issues observed in MIMOSIS-1 were successfully eliminated by the modifications performed. However, three new issues limiting the testability of the device were spotted. These consisted in two errors in the digital data path: A modified pixel steering and readout sequence aiming to further reduce the power consumption of the device accidentally resets the pixel prior to readout, which effectively disconnects the working analog pixel readout chain from the digital readout circuits. Unwanted data repeaters, which were automatically placed into the biasing lines of some

	2023				2024			
	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
MIMOSIS-1 tests (irradiation, SEE)								
MIMOSIS-2 fabrication								
MIMOSIS-2 tests								
MIMOSIS-2.1 design								
MIMOSIS-2.1 fabrication								
MIMOSIS-2.1 lab tests								
MIMOSIS-2.1 test beams							DESY	CERN

Figure 1: MIMOSIS1/2.1 workflow as by Feb. 2024

output drivers, cut the powering of those drivers. Finally, delay blocks used for the novel internal deskewing of the delays of the eight parallel outputs failed to reach the 320 MHz clock frequency suggested by their documentation.

Remarkably, the issues were not detectable by the intense device simulations carried out prior to the chip submission. Spotting them typically required additional, labor and CPU intense, analog simulations of the complex digital circuits affected, which triggered a revision of our simulation strategy. Therefore, the whole verification process prior the next submissions has been updated.

Once known, the bugs were fixed in by means of a focused ion beam process (FIB), which allowed to create traces bypassing or disabling the erroneous building blocks in individual sensors. However, the FIB process only allowed to correct 4 columns of few sensors (as expected by the process). The reworked sensors were tested and our understanding of the origin of the observed issues as much as validity of the repair strategy were successfully confirmed. Based on the understanding obtained, a repair concept of the full sensor requiring only few individual masks (hence reducing the costs of a re-submission) was developed and the reworked sensor (denoted as MIMOSIS-2.1) was submitted for production in December 2023. Similarly to MIMOSIS2, MIMOSIS-2.1 is manufactured with 2 epitaxial layers variants (i.e. 25 and 50 μm) and 2 doping profiles variants. It is expected that MIMOSIS-2.1 will be available in April 2024. A new test beam campaign is foreseen in the second half of 2024.

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* Now at IJCLab, Orsay.

Validating the internal amplification and readout chain of MIMOSIS-2

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Due to a shortcoming in the design of the new MIMOSIS-2, the envisaged test protocol for this newly received sensor could not be used to assess the sensor's performance. Specifically, this shortcoming prevented the hit data to be read out out of pixel registers. We report on non-standard activities conducted to validate the performance of the MIMOSIS-2 readout chain.

Validation of in-pixel amplifier-discriminator and related structures. The origin of the shortcoming concerning missing data output initially was unclear. Fortunately, certain pixels on MIMOSIS-2 feature an analog output. This test output allows to view on an oscilloscope the pixels response to charge injected into the pixel structure. Several MIMOSIS-2 sensors were set to proper steering for the in-pixel amplification-discrimination line, which closely resemble the ones used in [1] and in MIMOSIS-1 lab and beam tests.

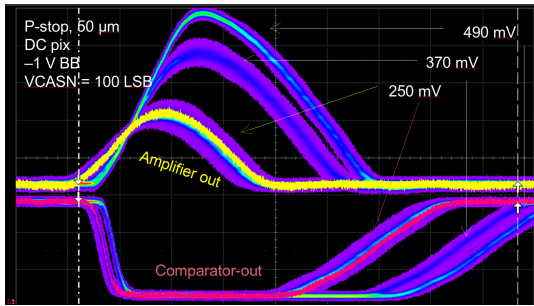


Figure 1: MIMOSIS-2 analog test outputs on oscilloscope. Violet shows output after the comparator, yellow output after the amplifier. The different wave forms correspond to different signals injected into the pixel.

Figure 1 shows the signals of one MIMOSIS-2 sensor's analog outputs. It closely resembles other plots of analog test output signals which have been taken with MIMOSIS-0. Hence, the behavior of the pixels probed corresponds to expectations from studies in [1, 2]. The sensors also show good analog response to X-rays from an ⁵⁵Fe source and the sensor's built-in pixel pulsing mechanism. Hence, we conclude that the in-pixel analog line and the associated DACs used to generate the pixel steering voltages and currents are properly implemented.

Probing the register readout after modifications with a focused ion beam. As reported in [3], the source of the shortcoming could be identified. The shortcoming manifests itself by the fact that the pixel's hit register is moved to an off state before it is read out. To validate a corrected readout design, previously qualified MIMOSIS-2 sen-

sors were sent off to SERMA for modifications by means of the Focused Ion Beam (FIB) method. This allowed to test the improved design on two individual double columns.

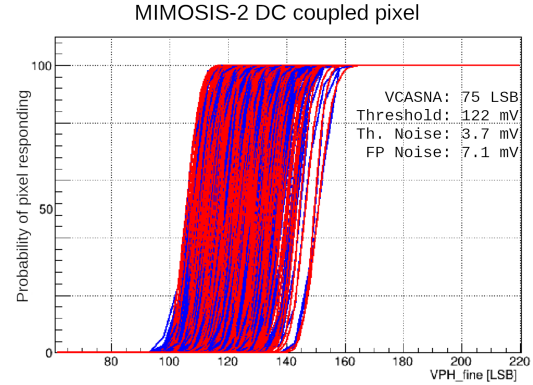


Figure 2: Representative S-curve scan fits and associated results achieved with a DC coupled pixel on a MIMOSIS-2 double column after correction with FIB, see text..

Few sensors were found to be functional after the procedure. The pixels located on the modified double columns on this sensors were characterized for their response for different injected charges, in a similar fashion to tests conducted with MIMOSIS-1. Figure 2 shows the results of the S curve scans of these pixels. The results on the pixels threshold, thermal noise and matrix' fixed pattern noise indicate proper behavior of the improved readout design.

Conclusion. A shortcoming in MIMOSIS-2's readout design hampered MIMOSIS-2's envisaged test protocol. The shortcoming was located by teamplay between the sensor designers of and feedback by the test team in the lab. Furthermore, an improved readout design was validated. This new readout design was implemented in the design of a replacement sensor, MIMOSIS-2.1.

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Simulations with Allpix² for the MVD digitizer

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The digitizers of the CBMRoot simulation framework are to simulate the response of sensors to charged particles. They have to be updated in response to progresses in sensor R&D. This holds true for the digitizer of the MVD of CBM [1], which describes nowadays obsolete MAPS produced in AMS 0.35 μm technology. We report on activities aiming to update the underlying model toward the MIMOSIS-sensor.

The input of the digitizer of the micro-vertex-detector (MVD) consists in the entering and exiting point of charged particles into the sensor volume as simulated by GEANT. It simulates the sensor response by estimating the number of signal charge carriers generated in the active silicon volume of the pixel sensor and distributing this charge uniformly along the interpolated particle trajectory. Next the drift/diffusion toward the collecting diodes is modeled.

The drift/diffusion process of signal charge carriers in CMOS Monolithic Active Pixel Sensors is steered by diffusion, build-in-voltages as caused by doping and explicitly applied depletion voltages. The two latter processes depend on the doping profiles, which have to be guessed due to a lack of publicly available data. The initially available model avoided simulating this complexity by parametrizing measured responses under the implicit assumption that the charge carrier movement is dominated by diffusion. While being justified for the sensors available at the time, this simplifying assumption does not hold for MIMOSIS as the TJ 180 nm process used for its production allows for depleting a sizable part of the active volume. Therefore, explicit simulation of the charge carrier movements is required, which is too CPU intense for the statistics needed for CBMRoot simulations. It was thus decided to perform this simulation with the dedicated AllPix² package [2], to summarize the results in lookup-tables (LUT) and to use the LUT for fast simulations in CBMRoot.

The sensor model in AllPix² works as the following: First, the detector geometry and sensor model representing the MIMOSIS-1 sensor is build. Reasonable guesses on the doping profiles are used to estimate electric fields in the active volume of the sensor which are then imported to AllPix². 10^4 signal electrons are spawned at each point of a $30 \times 30 \times 30$ point grid in the $30 \times 27 \mu\text{m}^2$ sized and $25 \mu\text{m}$ thick active volume of the pixel. After depositing the charge carriers, their drift/diffusion toward the pixel diodes are simulated with AllPix² accounting for fields and doping. We account for the drift toward the diode of the seed-pixel into which the charge was initially deposited, and for the first crown of pixels surrounding this seed pixel. From the collected charge we construct a look-up table

holding the Charge Collection Efficiency (CCE), which is defined as the total collected charges by a given pixel over the total deposited charges, as function of the deposition point of the charge. This pre-computed lookup table is then imported into CBMRoot and read to simulate the charge carrier drift/diffusion in a CPU efficient way during the physics simulation.

The simulation model had some free parameter that were

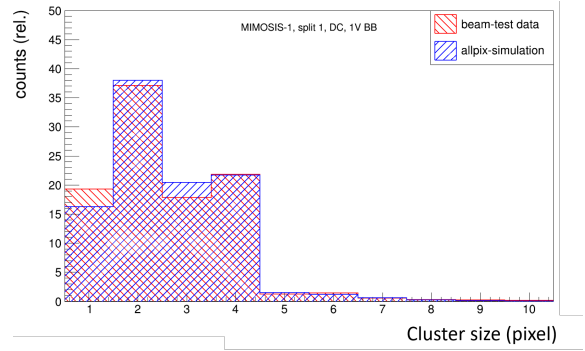


Figure 1: Cluster size distributions for MIP's both for beam-tests (red) and AllPix² simulation (blue).

adjusted to match with the experimental beam-test data obtained in 2021-2022. A preliminary result comparing the distribution of the cluster size produced by a minimum ionizing particle (MIP) hitting the sensor, both for beam-test data and AllPix² result, is shown in Fig. 1. This multiplicity is considered as a particularly sensitive measure for the quality of the simulation and well reproduced. Still, the underlying set of model parameters include unrealistic assumptions. The model is thus considered as sufficient to match our primary goal - reproducing the response of the sensors - but not yet suited to simulate the device physics in a realistic way. Next, the look-up table obtained from the AllPix² simulation will be imported and tested in CBMRoot.

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Advances in sensor integration on carriers made of TPG

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Large-area sheets of Thermal Pyrolytic Graphite (TPG) serve as the baseline carrier material for all MVD stations, employed in the dedicated Tracking Geometry. This report summarizes recent advances in processing this material to recommend its use as thermal leveler and mechanical support in high-precision, low-mass tracking devices operated in vacuum. For the MVD, the findings are essential for the station's pre-production, i.e. the integration flow.

TPG combines a good rigidity ($E=1050$ GPa) and large radiation length ($X_0=19.03$ cm) with an excellent thermal conductivity ($\lambda > 1500$ W/mK) and low prize (~ 0.15 €/mm³). Its major drawbacks have been addressed during prototyping:

Bulk Properties: The orthotropic material is soft and delaminates easily, impeding precise mechanical machining. Laser vaporization ablation and cutting has been identified and optimized as a processing technique allowing for high-precision (~ 20 μ m), high-yield (100 %) machining of TPG without introducing mechanical stress. TPG can be cut and, with μ m-precision on the depth, even hatched to arbitrary form factors.

Surface Properties: The surface of bare TPG is rough (~ 50 μ m), easily abrasive, and electrically conductive surface. Post-processing includes a polishing of the surface and a subsequent Parylene-C coating (~ 5 μ m) [1]. To prepare the hydrophobic coating for gluing of silicon sensors with low-viscosity epoxies, the surface energy is increased by a factor of 3 in a plasma activation process. The activation level is stable for ~ 7 days [1], opening up a sufficiently large time window for sensor integration. The high-precision cutting and well-controlled optimization of the surface properties, including also the subsequent gluing on the coated surface, underlines the recommendation of using TPG as carrier material not only for the MVD, but also in other planar tracker applications with the need of efficient heat evacuation (in vacuum).

Laser ablation and cutting allows for evenly, precisely, and reproducibly hatching the surface of TPG to any desired depth and form factor (MVD carriers: $\sim 150 \times 150$ mm²). This opens up the door for a different approach to the sensor integration, moving away from dedicated jigs. The sensors are placed in dedicated hatches (depth of ~ 50 μ m) on the carrier which simplifies the placement and alignment of the sensors on the carrier. Fiducial holes in the carrier allow for precise placement of the sensor hatches, aligning also the front- and back-side in a double-sided assembly. The distance between adjacent sensors can be controlled by leaving a small bridge (~ 70 μ m) between adja-

cent pockets. The surface coating and activation is compatible with this technique. Figure 1 is demonstrating the new integration technique with thinned MIMOSIS-1 sensors placed in hatches in the TPG.

Figure 2 depicts a close-up of the μ -tracker demonstrator, emphasizing the precision in machining of TPG with a laser ablation device. The results shown are part of [2].

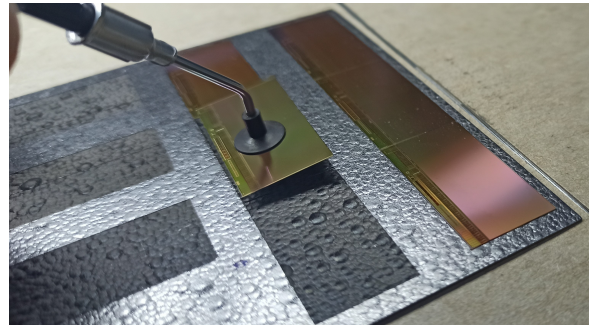


Figure 1: MIMOSIS-1 sensors (thinned to 60 μ m) placed in TPG hatches.

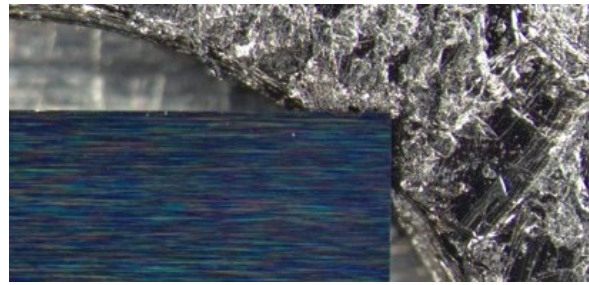


Figure 2: Close-up of a sensor-supporting TPG corner of the μ -tracker demonstrator.

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Status of the MVD engineering design

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This report summarizes the advances in the engineering design of the MVD, based on an updated CAD model of the detector. With the finalization of the heat sink design the engineering design of the detector modules is mostly finished and promotes the MVD to the verge of the pre-series production.

A fully parametric CAD model of the MVD with close to final form factors of the module constituent parts has been set up in Autodesk Inventor. The highest feasible level of detail is implemented. The model is work in progress and the current status is presented here, see figure 1. Several parts of the detector mounting structures, cables and the services are not fully implemented and engineered yet.

For the active part of the detector, the model has been finalized. This includes the heat sinks, two of which have been optimized and produced together with CTX [1] and are currently being characterized.

The keep-in volumes defined in a CBM Technical Note [3] have been confirmed, also after having changed to the STS read-out-boards (ROB) which are plugged outside to customized feedthroughs mounted in the front flange. Actively cooled top plates have been designed and space for up to 94 FEAST DC/DC converters is reserved there. The coolant manifolds, mounting structure, master table and remote positioning system, and the feedthrough flanges still need to be designed and included subsequently. Also, the pipe and cable routing towards the front flange, including the feedthroughs, needs to be finalized.

The model can be used to spot static, but also dynamic collisions between components, *e. g.* during integration or when moving the half-detectors in lateral direction during beam tuning. The sensor and detector integration flow can be dynamically visualized and optimized in this CAD model. The assembly and accessibility of the MVD and target exchange device can be evaluated. After finalizing the CAD model, it serves as the basis for an updated MVD GEANT model for simulations based on a more realistic evaluation of the material budget.

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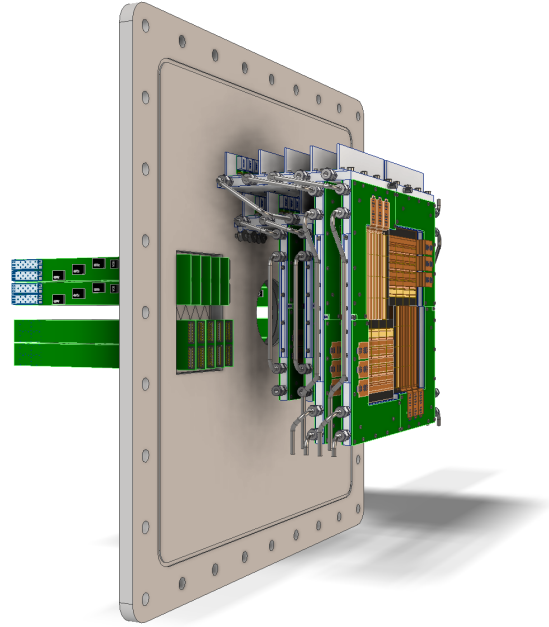


Figure 1: Side view of the MVD setup, vacuum flange with feedthroughs and read-out boards, currently implemented in CAD.

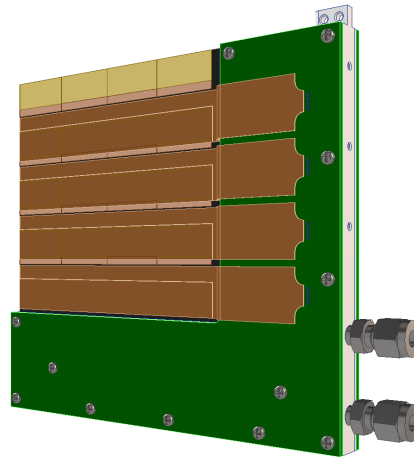


Figure 2: Close-up of a quadrant with sensors, FPCs, heat sink, and FEB.

Status of the MIMOSIS needle probe testing

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Needle probe testing as quality assessment for MIMOSIS sensors is in preparation for mass testing. The probe testing setup is currently optimized with generation-1 sensors to then adapt it to the next generations. The setup is compatible with all generations due to frozen form factor, pad geometry and pad coordinates. The readout is TRB-based and employs dedicated testing routines and logging. Hard- and software is designed such that the work can easily be outsourced to different institutes once the final sensor is available.

Mechanics: The sensors will be probe tested after thinning and dicing and a visual inspection. A custom needle probe card [1] is used to power, program, and read out the chip. It features 102 tungsten needles connecting the 151 bonding pads of the sensors. The probe station in the IKF laboratory is a motorized, manual Suss MicroTec PA 200. The sensor is mounted on a custom, 3D-printed ESD-safe vacuum chuck. The co-planarity of the needle tips with the bonding pads has been improved to 3 μm between the left- and right-most pads.

Connectivity: Severe connectivity issues have been observed in preceding tests. These could be traced back to aluminum oxide on the bonding pads and residues from the production. Dedicated cleaning procedures have been tested and validated. Wet-etching with either diluted phosphoric acid or a commercial product (VIGON PE 196A, [2]) does significantly improve the connectivity. After cleaning, a stable contact can be established after a single touchdown with $\sim 70 \mu\text{m}$ instead of ~ 10 touchdowns with $\sim 100 \mu\text{m}$ overdrive.

Readout: The powering, programming, and readout is all done on the probe card. A custom front-end board ('Proxy') connects it with the a board for the slow control and data acquisition (TRB-based [3]).

Sensor characterization: The test procedure concept is following the procedure developed for the mass-testing of the ALPIDE sensors [4], which feature a similar architecture. The test procedure itself is a sequence of consecutive tests ranging from simple powering to a detailed characterization of every pixel and is currently being optimized for both, full characterization and mass-testing of sensors. The focus lies on powering, steering DACs, and hot, noisy and dead pixels. It can be executed using a custom shell script. The average values and acceptable limits have been determined experimentally in laboratory tests, but are subject to tuning based on test results obtained with the probe station.

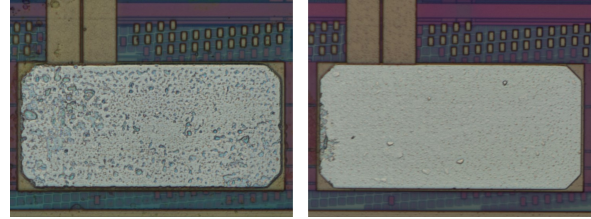


Figure 1: Picture of two bonding pads on MIMOSIS-1, before (left), and after (right) wet-etching with diluted phosphoric acid as cleaning agent, see text.

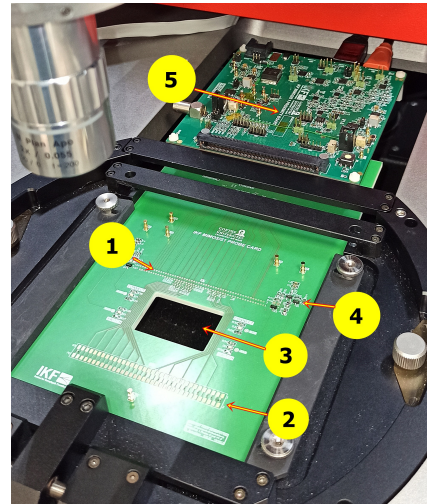


Figure 2: The probe-card PCB: (1) Connector for mounting the needles. (2) Connector for electrical integrity checks. (3) A hole for the needles. (4) Passive components co-operating with edge needles. (5) The IKF Proxy board

References

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Improvement of the stand-alone read-out of MIMOSIS for development and characterization purposes and first steps towards CBM compatibility

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For the readout of the MIMOSIS sensors, two different setups are currently being used in the laboratory. One is based on the TRB framework and provides an easy-to-use, portable system for testing and beam times. The other is aimed at the final CBM-MVD and based on the boards of the CBM DAQ.

Like any newly developed ASIC the MIMOSIS sensor needs thorough testing. For one, to get a good understanding of the behavior under the extreme conditions in the experiment. On the other hand, the basic functionalities need to be confirmed before mass deployment and integration into the detector. The read-out and slow control system that makes these tests possible is the TRB system [1], which provides FPGA boards and software for control and data transfer. Around the existing TRB software a MIMOSIS specific library was developed, that reduces the most common tasks to simple shell commands: reading and writing registers, masking and pulsing of pixels as well as more complex tests, like DAC and S-curve scans. For the sensor mass testing phase, this set-up can easily be duplicated to share the workload among several laboratories.

The GBT system [2] will be used on the readout and front-end boards of the MVD. Therefore, it is of great interest to know whether the sensor lets it self configure via their slow control chip, the GBT-SCA. For this, a transient test setup consisting of the VLDB development board and a Trb5sc was build, as shown in fig. 1. The Trb5sc is connected via an E-Link to the GBT-SCA. This chip provides the I2C bus MIMOSIS uses for configuration. As a proof of a stable communication, the sensor was programmed in such a way, that data taking is possible. Additionally, a scan over all settings of the internal DACs was done with an external ADC, also driven by the SCA. The ADC monitors the DAC voltages on dedicated monitoring pins on the proxy board. The successful operation proves that the sensor can be reliably controlled using the final interface hardware planned to be used in CBM.

This setup, however, is only a temporary solution, because the full GBT chain was not available at the moment. As next step a slow control test will be performed using the CRI (Common Readout Interface) together with the GBTx and GBT-SCA.

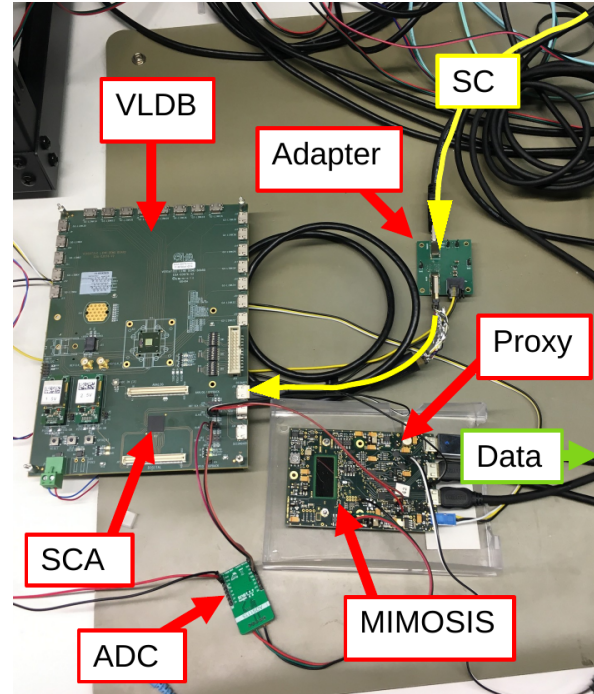


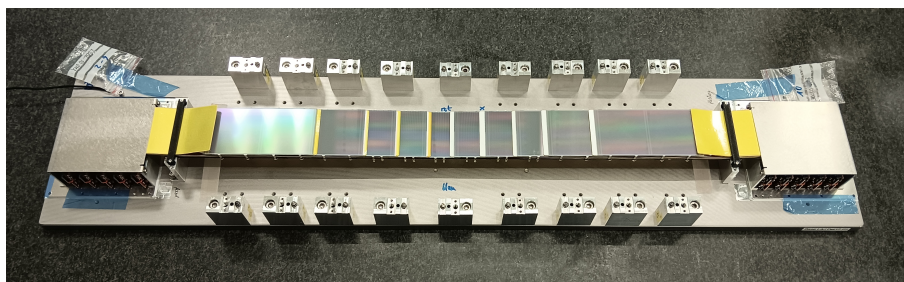
Figure 1: Setup Versatile Link Demo Board (VLDB) with MIMOSIS-1 sensor mounted on a Proxy board. A Trb5sc FPGA board (not in the picture) provides the control link to the GBT-SCA through a level converter and adapter board. Because the SCA needs SLVS at its inputs, but the Trb5sc can only provide LVDS, an adapter board was needed, to make the necessary level translation. The data output of the sensor is fed directly to the Trb5sc.

[2] GBT Link System, <https://ep-ese.web.cern.ch/project/gbt-and-versatile-link>

References

[1] TRB Collaboration, <https://trb.gsi.de>

Silicon Tracking System



Silicon Tracking System – Summary

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The title page of this chapter shows the first STS series detector ladder assembled – construction of the STS detector was started in the reporting year 2023, an effort of all the project groups [1]. Modules and mechanical carriers for further detector ladders under preparation are depicted in Fig. 1. In February 2023, the teams met at the University of Tübingen for a two-day retreat on module and ladder production [2]. The focus was on the transition from pre-series assembly to the final objects and procedures, including quality control and “burn-in” operation cycles. Beyond, an outlook on the planning of C-frame assembly, system integration and the related test procedures was made. The core component to be finalized at the time of the retreat was the front-end electronics board in its two variants of output data rates. In the course of the year, those could be finalized, a Final Design Review was held [3] and first-of-series batches of FEB8-2 and FEB8-5 were produced. While the boards with standard readout bandwidth went into the beginning STS ladder construction, the high-bandwidth board was first used in a module upgrading the mSTS demonstrator detector in the mCBM experiment at SIS18.

The engineering design of the STS detector was completed in Fall 2023. The work was supported by EU Project EURIZON [4] and served as deliverable within its work programme 2. Full detailing of the mechanical parts of the mainframe with thermal enclosure for installation into the re-designed superconducting dipole magnet, the cabling and piping for cooling was established. The procurement of mechanical parts can thus now be carried out. This includes the cooling plates for the detector’s front-end and powering electronics, enabling heat evacuation through a circulating cold liquid. The cooling system, the plant and distribution for the liquid, and the additional gas cooling of the silicon sensors was topic of an Engineering Design Review [5] held in July 2023. It addressed the STS system design with respect to its thermal operation and sensor lifetime requirements in the radiation field. Those were extensively studied with a thermal demonstrator of the STS detector system. The results have confirmed the concept including sufficient safety margin in cooling. The project was also presented at the FAIR ECE 18 review, November 2023, and endorsed.

Integral part of the STS detector is its sector of the CBM vacuum beam pipe, attaching to the target box and passing through the detector to a coupling interface at its downstream wall. A full-size prototype of the all-carbon-fiber structure was produced in late 2023. Thorough verification in terms of margin for structural integrity and handling is forthcoming.

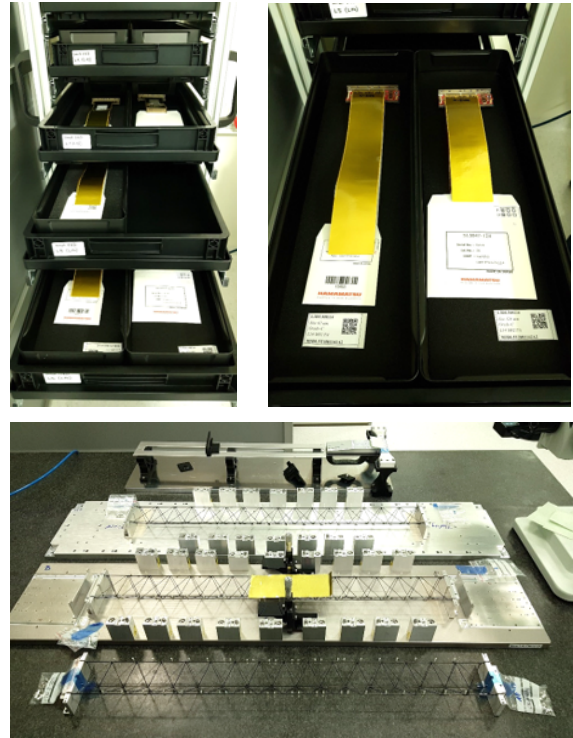


Figure 1: STS modules and carbon fiber structures for the initial three first-of-series detector ladders. After assembly, their evaluation will be in the center of the Production Readiness Review in 2024.

In the detailed reports of this chapter, the contributing authors elaborate on those and further achievements obtained towards the realization of the STS detector system in the coming years.

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Finalization of the front-end electronics boards FEB8-2

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Introduction

Testing of FEB8-2 version A3 and B3 boards has shown, that there is further improvement needed to come to the final PCB version. Especially the data cable and the ZIF connector type used in version 3 have some disadvantages. The very small ZIF connector has not enough holding force, so the data cable easily slips off. Also, there is no mechanical locking function available. These issues have been solved by using the Hirose FH29 ZIF connector, which is also used on the FEB8-5 A3 and B3 boards. Therefore, also new data cables and new FMC adapters were needed to operate a module with two FEB8-2 PCBs.

FEB8-2 version 4 PCB improvements

The main modifications are shown in Fig. 1:

- Use of Hirose FH29 100 pin ZIF connector with mechanical lock function;
- Rearrangement of the 36 coupling capacitors similar to FEB8-5 version 3 PCB design.

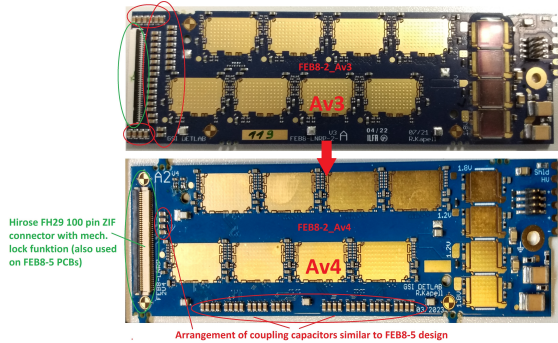


Figure 1: Changes from FEB8-2 PCB version A3 to A4.

The new Hirose FH29 100 pin ZIF connector needs more space on the PCB, so the coupling capacitors cannot be arranged beside the ZIF connector anymore. Instead of that, almost all coupling capacitors are now positioned at the edge of the PCB. Placing these capacitors as far away from the micro cables as possible is also advantageous for reducing noise pickup from LVDS lines to the micro cables. In addition, the layout of the passive components between the ASICs now also is based on the FEB8-5 layout, which further optimizes the ASIC to PCB bonding.

FEB8-2_Av4 and FEB8-2_Bv4 panels

Assembly of the passive components will be done in GSI's Experiment Electronics department. In order to reach a high throughput on the assembly machine, the two versions of the FEB8-2_v4 boards are arranged in panels with four PCBs (Fig. 2).

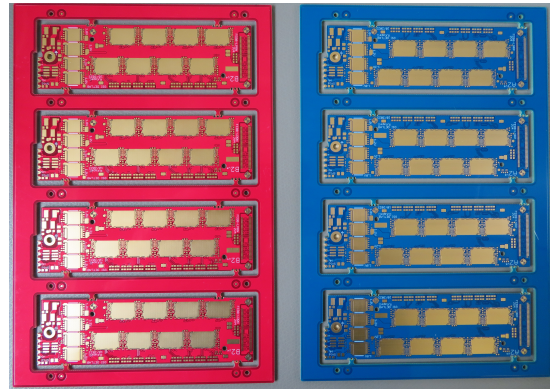


Figure 2: FEB8-2_Bv4 and FEB8-2_Av4 panels.

Series production of the boards has started in summer 2023 with 100 PCBs of each version. Further 700 pieces of A and B version PCBs have been delivered to GSI for the next assembly run (2 × 100 pieces in March 2024).

FEB8-2_v4 data cable

To operate a FEB8-2_Av4 or FEB8-2_Bv4, a new data cable with 18 impedance controlled LVDS pairs and double sided shielding is needed. Figure 3 shows the data cable with a length of maximum 1 m from the Chinese manufacturer BEST Technology:



Figure 3: FEB8-2_v4 data cable.

Using only 50 pins of the Hirose FH29 100-pin ZIF connector has the advantage, that the design of the data cable is less complex compared to the FEB8-5 data cable, where access to both pin rows is necessary. With the FEB8-2_v4 data cable, all two neighboring pins of both connector rows are connected. Also 10 additional ground lines are foreseen between groups of LVDS pairs. This cable has connector pads at both ends of the cable on the same side. At the moment there is also a cable version with pads on opposed side under development, which is needed in the final detector.

FEB8-2_v4 adapter boards

At various production test setups, STS modules with two FEB8-2_v4 boards have to be connected to CROB or GBTxEMU boards. Beside new data cables, also new FMC adapter cards have been designed as an interface between FEB8-2_v4 and the readout electronics. There is one version available with 5 ZIF connectors, where 5 FEB8-2_v4 boards can be operated with 1 Uplink per ASIC (Fig. 4). A second version with 3 ZIF connectors assembled can handle 2 FEB8-2_v4 boards with 2 Uplinks plus 1 FEB8-2_v4 with 1 Uplink per ASIC (Fig. 5).

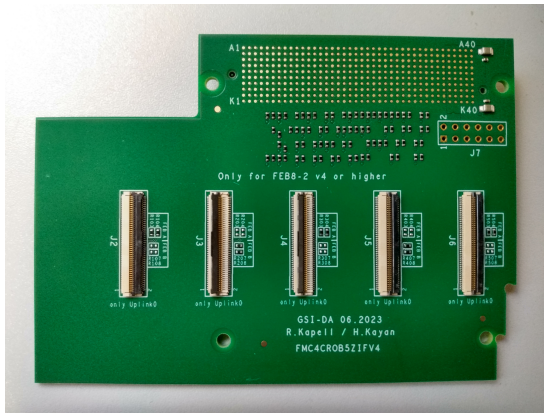


Figure 4: FMC adapter board with 5 ZIF connectors.

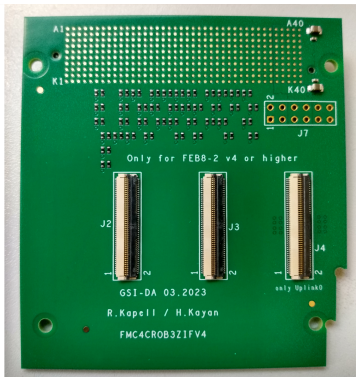


Figure 5: FMC adapter board with 3 ZIF connectors.

FEB8-2_v4 test setup

With the new boards and cables available since mid of 2023, different test setups have been installed successfully in the laboratory. Figure 6 shows two FEB8-2_v4 data cables connected to a GBTxEMU board.

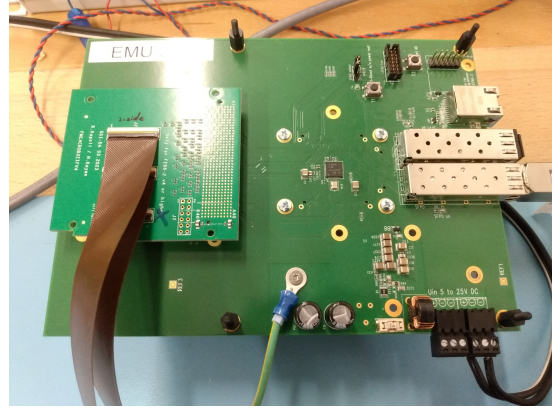


Figure 6: Test setup with GBTxEMU and FMC (3 ZIF).

A complete STS module consists of one FEB8-2_Av4 and one FEB8-2_Bv4 board, each glued on opposite sides of a cooling fin. The micro cables are covered by a shielding foil to avoid noise pickup. After mounting in a module carrier, various tests can be done with such a test setup (Fig. 7).

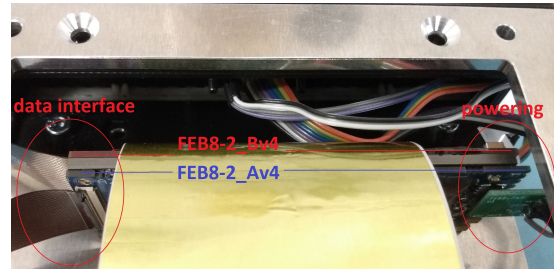


Figure 7: FEB8-2v_4 in a module carrier.

On the left side of the picture, the two data cables are connected to the FEB8-2_Bv4 (red PCB on the back side of the cooling fin) and to the FEB8-2_Av4 (blue PCB on the front side). Powering of the FEBs is maintained on both boards over the pin stripe connector. Also applying HV biasing is possible with this setup.

STS module assembly chain at GSI and KIT

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Introduction

In 2023, a major step was taken to prepare for the final production of STS modules and their components in the GSI's Detector Laboratory (DTL) clean room. In addition, the KIT site was equipped for the first time with the necessary software and hardware tools to monitor the quality of the production and assembly process. In parallel, the comprehensive data logging based on a PostgreSQL database [1] and its web interface was further developed. Currently, four (GSI and KIT) different test stations are connected to the central database and a fifth is planned for wafer level testing of XYTER (SMX) ASICs at GSI. We have adopted the QR Code based standards for micro cable set and module labeling according to the new naming convention.

ASIC and Microcable

In total, more than 5000 ASIC tests have been performed and stored from three different stations. More than 3000 microcable tests were carried out and stored for further assembly preparation. Many new tests and experiences have been gained. All chips have been calibrated, mostly more than once, and the corresponding graphs are shown in the web database. In summary, the test procedure is very comprehensive and successful. Both sites, GSI and KIT, work in parallel and exchange their experiences on a daily basis.

Wafer-level test

In 2023, we started having a wafer prober up and running in the DTL and later in the Heck Hall rooms, where the final testing will take place. The test software is based on the ASIC quality control and will test, assign unique ID and store all data in a database for further analysis. Very first test have already been done with a dummy wafer and an old middle (probe) card. In the next step we have used already a functional pre-series wafer where few tests with SMX chips were done. The system is functional and will test more than 75 wafers until summer 2024.

LDO tester

Beginning in September 2023, we have created modified hardware with new firmware and software for LDO testing before SMX chips are placed on FEBs. The LDO test procedure is as follows: First, we test all power regulating LDO ASICs for current consumption without any external

power load. The next step is to switch to a nominal external load corresponding to normal FEB operation. In the third step, we overload the ICs to initiate the LDO shutdown function. Finally, we power cycle all the ICs and check the nominal external load again. The procedure and the hardware work seamlessly at both sites, GSI and KIT.

FEB and Sensor

During the assembly process, FEBs are tested in two steps, first when the first row of chip cables is mounted, and then when the second row is also mounted. This procedure ensures that the FEB production is 100% functional, while the chips with micro cables are already tested. In some cases the chip has to be replaced. In these cases, all but the chip is sealed with glue and the chip is replaced. This procedure has been done several times and it saves a lot of material. After FEB A and B have been produced with appropriate chip cables, the sensor bonding process is also monitored separately for both sides. This also makes our production process 100% accurate.

Module testing

To study the noise performance of different types of sensors, a new module test setup has been developed. The main components are, remotely controlled, a lithium-battery based power supply, which makes both FEB floating potentials following the HV supply. The noise level of the battery powered FEB's is very low. All the noise introduced in the system will be from the external HV supply. A infra-red (IR) laser pulser has also been developed and tested. This process has potential to be used in the assembly process.

Summary

Overall, significant progress was made towards final module production, which was reflected in the number of STS modules assembled at the end of the reporting year. The quality of the produced objects exceeds all expectations and is almost loss-free.

References

- [1] Web interface: <http://web-docs.gsi.de/~dtl-sts/>

Summary on module testing for series production

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During 2023, valuable experience was collected while testing STS pre-series modules built with different versions of the final front-end boards (FEB). The full characterization of 10 STS modules built for the E16 experiment at J-PARC [1] and other objects assembled for laboratory studies and the mSTS Station 0 [2] contributed to optimizing the testing protocol, calibration procedures, and test setups to face series production. This report describes the functional testing results of STS series modules.

Optimization of the testing setup

The functional characterization of the STS modules is carried out in three identical testing setups, the main component of which is the module carrier. Another essential component is the cooling interface, which is devoted to evacuating the heat produced by the FEBs in the module. Data readout and control are based on the GBTx-EMU boards. The module carriers are built from aluminum frames combined with 3D-printed components. They are specially designed to hold the fragile silicon sensor, support the microcables and shielding layers, and serve as an interface for low and high voltages. To ensure the necessary light-tightness during operation, the carriers are placed inside a compact 3D-printed black sleeve. After assembly, the modules are carefully installed in the carriers, where they remain during all testing stages.

The module carrier proved to be helpful for the mechanical stability of the most fragile components of the detector module: the silicon sensor and ultra-thin microcables. These parts were not damaged during the module installation, operation, and tests. The 3D-printed sensor holder is currently undergoing a slight modification to account for the extra space required in the bonding area of the microcables. After several iterations of the patch panel, it was decided to use a DSub9 connector for LV and a 4-pin LEMO connector for HV.

Performance of series modules

The testing of the STS modules consists of multiple steps, in which not only the electrical and functional performance of the modules [3] but also the thermal interface between the cooling fins and the FEBs are evaluated. Figure 1 shows the main steps of the testing sequence. This work discusses the results of steps 1 and 2 shown in the flow diagram. The results of the module thermal tests are presented in [4].

To date, a total of 28 assembled modules have been

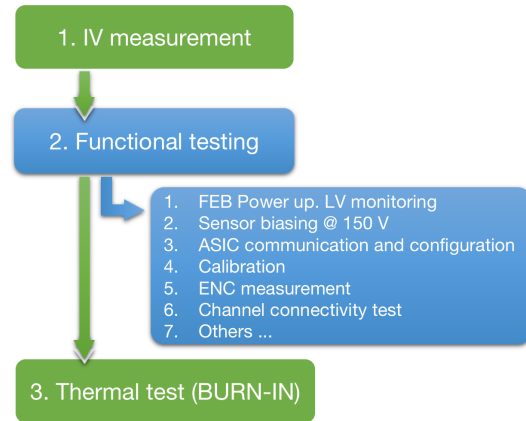


Figure 1: Flow diagram of module testing.

tested, from which 26 were successfully characterized. They correspond to modules from ladders L3DL100112, L3DL300112, and L3DL500114 of STS Unit 3. Although the overall outcome of the testing is positive, significant issues were identified in two modules. In both cases, the problem was related to the current-voltage (IV) characteristics of the sensors that did not fulfill the requirements for their operation in the final STS. These modules were replaced by new ones; however, due to the issues found, each module was required to undergo an extra measurement of the sensor IV characteristics after the assembly and before gluing the FEBs to the cooling fin.

Figure 2 shows the current-voltage (IV) characteristics for the 26 modules grouped by ladders. For this purpose, a dedicated setup was built from two Keithley 708B power supplies. A unique feature of this setup is the possibility of directly comparing it with the existing data from the electrical inspection of the sensors. The IV measurements were carried out up to the operational voltage of the sensors in the final STS, i.e., following the electrical grade of the sensor [5, 6]. The curves are not normalized to temperature, but it can be observed that the full depletion voltage can be identified in each sensor at around 60 V.

Each module was brought into operation and data link initialization and synchronization processes were launched. Communication could be established with all 416 ASICs, reliably operated during the tests. The average current consumption for each power domain in all the FEBs was monitored, resulting in 2.57 A and 2.23 A for the 1.2 V and 1.8 V LDO, respectively. The spread of the mea-

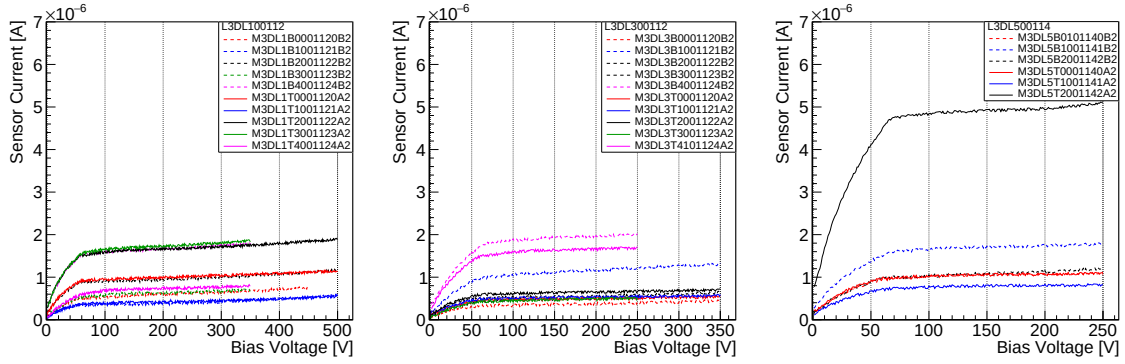


Figure 2: Current-voltage characteristics measured for the 26 modules, grouped according to their corresponding ladder. The measurements were carried out up to the final operational voltage of each module in STS.

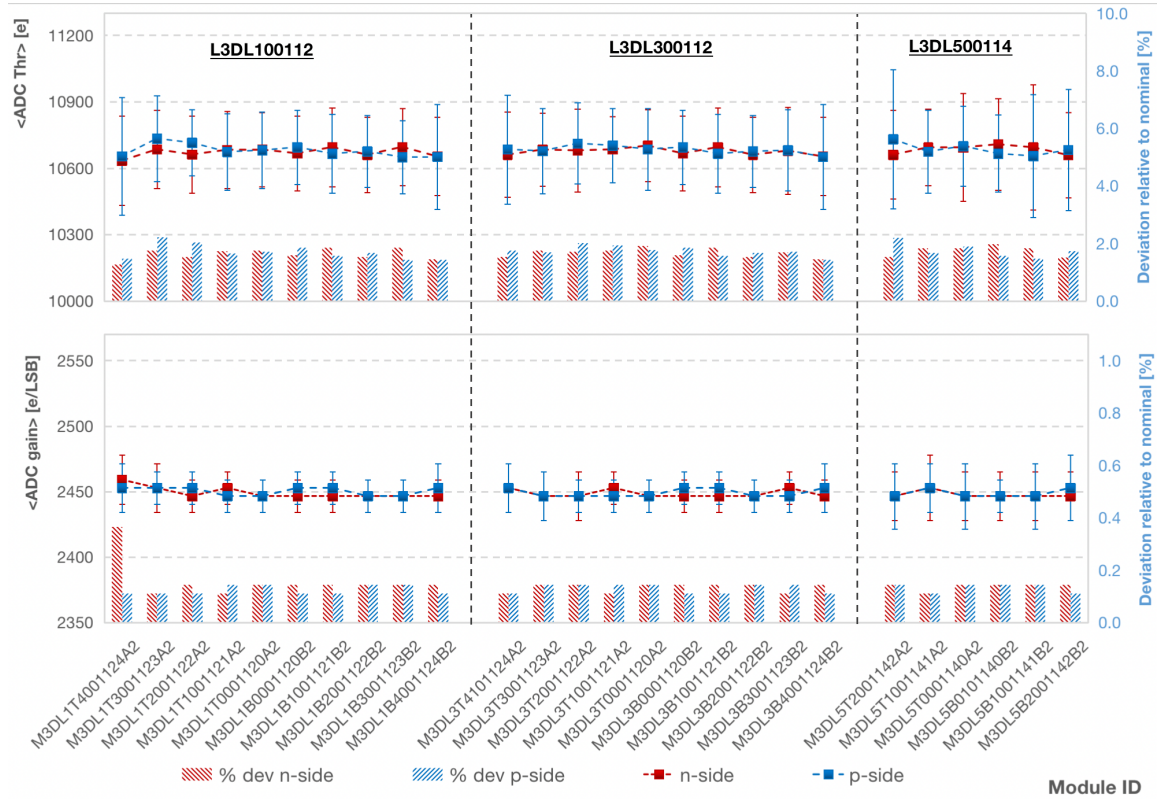


Figure 3: ADC parameters measured for the 26 modules after calibration. Percentual deviations, below 2% and 0.5% for the ADC threshold and gain, respectively, show good agreement with the nominal calibration parameters.

sured current values is below 2% in both cases. The average ASICs temperature and VDDM potential were approximately 52 °C and 1206 mV, respectively. The calibration of the channel's amplitude and timing circuits was also performed for each ASIC. Figure 3 shows the results of the ADC gain and the ADC threshold distributions for

n- and p-side in each module. The deviations concerning the nominal calibration values are shown in each case to demonstrate the quality of the procedure.

A significant milestone of the STS module testing is the evaluation of the noise performance. Figure 4 summarizes the ENC results for each module to be mounted on the lad-

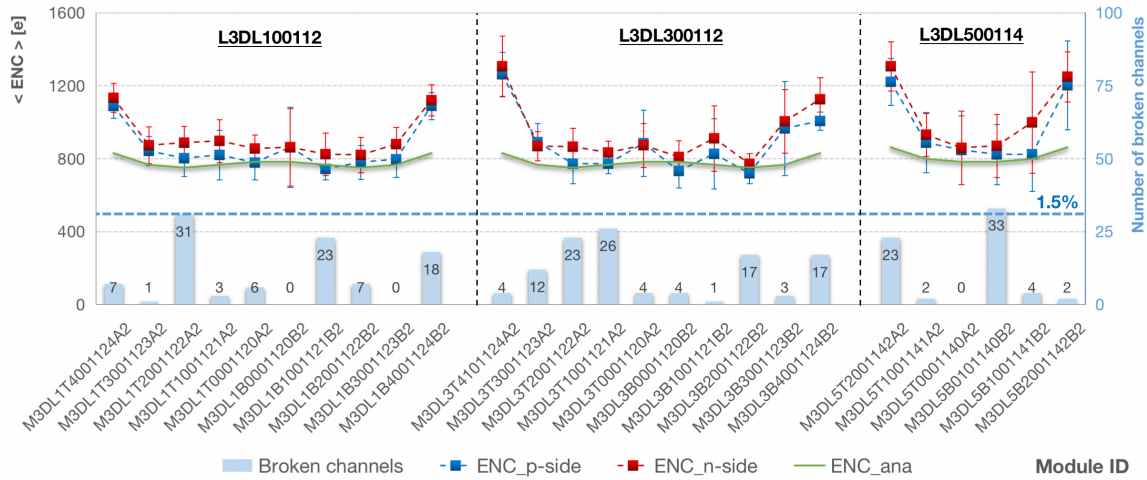


Figure 4: ENC performance and the number of broken channels identified for the 26 modules. The green lines depict the noise parametrization based on the overall module capacitance. The assembly goal for the number of broken channels is depicted in a blue-dashed line.

ders at a reverse bias voltage of 150 V. The green line describes the ENC parametrization [7] based on the overall module capacitance. A very good agreement, within 10%, can be found for almost all modules built with sensors of 4.2 cm and 6.2 cm in length. In the case of modules built with larger sensors, i.e., modules located at the edges of the ladders, the noise parametrization does not properly describe the measured data. In addition, Fig. 4 depicts the total number of broken channels per module. The production target of 31 broken channels, or 1.5% channels per module, is marked with a dashed blue line. This condition was achieved in almost all produced objects. However, it is important to remark that a large fraction of broken channels (approximately 30%) are mostly distributed at the edges of the microcables.

Summary

Characterizing STS series modules was essential for proving their functionality after the assembly and before the next integration step. From a total of 28, 26 modules were classified as operational, matching the quality requirements for their installation on the ladders and operation at STS. All 416 ASICs were synchronized, configured, and reliably operated during all tests. The analog front-end circuits of each ASIC were properly calibrated in a dynamic range of approximately 12.2 fC, with channel-to-channel spread below 2%. The average module ENC agrees with expectations for modules built with sensors of

4.2 cm and 6.2 cm, respectively. These results are considered acceptable for the STS operation. The average number of broken channels per module was kept below 31 in almost every case, which is a very good result for the overall detector.

References

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Module burn-in: successful application in series production

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Motivation for the burn-in

Burn-in of electronic components is a critical reliability improvement process in the electronics industry. It involves subjecting components to stress testing under sometimes elevated conditions in order to detect potential failures at an early stage. For example, in semiconductor manufacturing, integrated circuits are burned-in to identify and eliminate defective units before they are integrated into electronic devices. Similarly, in aerospace applications, critical electronics components such as sensors and actuators are burn-in tested to ensure their reliability in demanding operating environments.

Over the lifetime of the STS detector, we expect its silicon microstrip modules to operate at sub-zero temperatures: the coolant temperature in the baseplate for cooling the front-end electronics will circulate at $\geq -20^\circ\text{C}$, while the ambient temperature inside the STS enclosure is expected to stabilise at around -10°C . We also expect stochastic shutdowns of the front-end and back-end electronics due to single event upsets induced by the radiation in the cave during the experiment.

By burn-in testing the silicon microstrip modules under conditions representative of their intended operating environment, we aim to increase their reliability and reduce the risk of failure during the course of the experiment.

Previous thermal stress studies

Previous thermal cycling studies of the stand-alone Front-End Boards (FEBs), carried out in 2021-2023, have identified patterns of low dropout (LDO) failures during thermal cycling. Initial investigations have identified six cases of LDO failure (almost every FEB had at least one LDO failure), resulting in subsequent modifications. In mid-2022, four FEBs were retrofitted with DYMAX 9001. Other modifications included filling two FEBs with DYMAX 9001, configuring two FEBs without ASICs and globtop, and equipping four FEBs with DYMAX 9008; temperature conditions were adjusted to higher levels. Despite these adjustments, LDO failures continued to occur on both the 1.2 V and 1.8 V power lines. To address this issue, a cold start (later referred to as power cycling) was introduced in late 2022 using DYMAX 9014 and involving three FEBs. These studies culminated in the adjustment of the detector operating temperature. The final stage of thermal studies of the stand-alone FEB is described in Ref. [2].

Setup description

At the heart of the burn-in setup is a climatic chamber supplied by BINDER [1]. Inside this chamber are cooling plates fitted with copper tubing, which are intricately connected to a LAUDA chiller to maintain precise temperature control. Mounted on these cooling plates are five sensor modules, securely housed in carriers as it is shown in Fig. 1. To mitigate any potential interference from external light sources, black sleeves are extended over the modules; they also facilitate nitrogen circulation to maintain a dry, inert atmosphere.

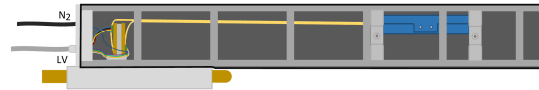


Figure 1: Schematic view of the module inside the carrier.

Modules are connected to power supplies via low-voltage interfaces, while high-voltage interfaces are used to properly bias the sensors. A dedicated GBTxEMU-based readout chain is used to retrieve data from the sensor modules, providing insight into their performance and characteristics during thermal cycling.

In the initial phase of our studies, a systematic approach is adopted, focusing on measuring one module at a time. This allows the behaviour and response of each module to be thoroughly investigated under controlled conditions. Both the experimental setup and the accompanying software have been prepared to ensure seamless execution and data acquisition throughout the burn-in process.

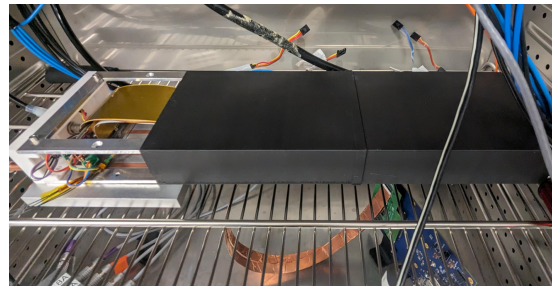


Figure 2: Detector module in a black sleeve installed in the climatic chamber.

Located within the TES building at GSI, the experimental setup is positioned to facilitate efficient monitoring and

management of the burn-in process. The controlled environment provided by the climate chamber, together with the environmental control instrumentation and comprehensive data acquisition capabilities, provides a framework for conducting burn-in tests on the sensor modules to improve their reliability and performance in real-world applications.

The measurement process involved assessing the performance and reliability of the components under varying thermal conditions. The Binder climate chamber maintained temperatures of 23°C and –10°C, while the Lauda chiller achieved temperatures of 13°C and –20°C respectively. Two high-temperature power cycles were performed, followed by ten low-temperature cycles to simulate real world operating conditions. The power supplies were regulated to 2.6 V for 1.8 V lines and 2.2 V for 1.2 V lines to ensure consistent performance throughout the test.

For the software aspect, a Python-based script was developed to facilitate test execution. This script includes the following functionalities:

ASIC control: Allows control of application-specific integrated circuits (ASICs), synchronisation and monitoring of parameters relevant to their operation.

Lauda Control: Allows control of Lauda equipment, facilitating synchronisation and monitoring of parameters essential for testing.

Binder Control: Facilitates the control, synchronisation and monitoring of parameters of the Binder climatic chamber.

Hameg LV power supply control: Allows manipulation and monitoring of parameters associated with Hameg low voltage power supplies.

highlight the impact of thermal stress on component performance and to inform subsequent reliability assessments. The sequence of measurements for the burn-in procedure is as follows (see Fig. 3 for the reference):

1. Set the chiller to 13°C and the climatic chamber to 23°C.
2. Wait for the temperatures to stabilise.
3. Switch on the power supply.
4. Read the power consumption of the channels.
5. Synchronise the FEBs and establish communication.
6. Read channel power consumption.
7. Read V_{DDM} and ASIC temperatures.
8. Switch off power supply.
9. Set the chiller to –20°C and the climatic chamber to –10°C.
10. Wait for ramp down (about 1 hour).
11. Repeat steps 3 to 8 five times.
12. Repeat steps 1 to 11 twice.
13. Set the chiller to 13°C and the climatic chamber to 23°C.

This sequential procedure ensures systematic testing under varying temperature conditions, with multiple repetitions to assess component reliability and performance over time.

Burn-in routine

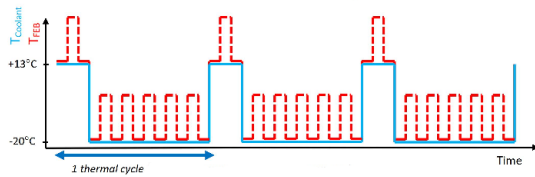


Figure 3: Schematics of the temperature and power cycling procedure.

Prior to thermal cycling, the modules were configured and equivalent noise charge (ENC) measured to establish baseline characteristics. During each power cycle, V_{DDM} and temperature measurements were recorded for each ASIC. At the end of the thermal cycling programme, a final assessment of the ENC was carried out to evaluate any changes resulting from the extensive testing. This post-thermal cycling comparative analysis was designed to

Recent results

The current status of the module burn-in process indicates that each module takes approximately seven hours to test, with three modules tested to date. Given the single burn-in setup available, the optimistic throughput projection is two modules per day. The current approach assumes that all modules will go through this procedure.

During the burn-in process, several data are collected for each module:

- A file named `Date.moduleID.result.info` is generated, capturing the V_{DDM} and temperature readings of each ASIC per power cycle, along with the corresponding FEB ID and polarity.
- An `lv.moduleID.dat` file records the energy consumption per channel per FEB over time (refer to Fig. 4).
- A `moduleID.log` file compiles all processes occurring in each power cycle over time.

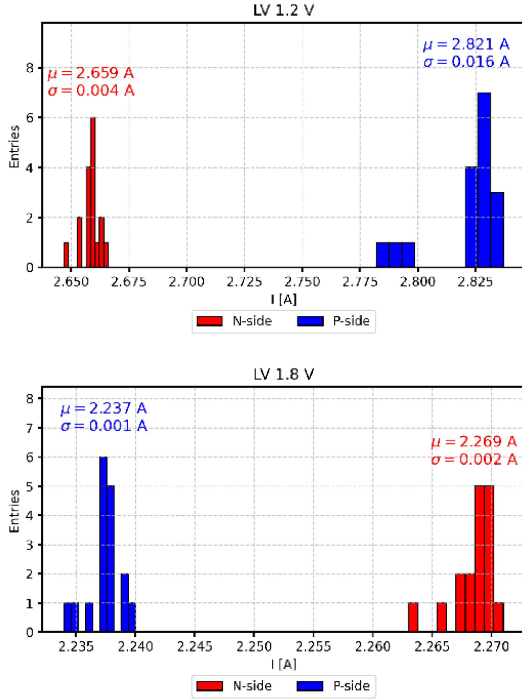


Figure 4: Histograms of the current consumed by the M3DL3T0001120A2 module during burn-in: 1.2 V power line (top plot) and 1.8 V power line (bottom plot).

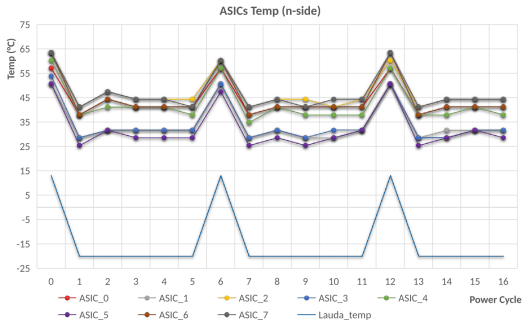


Figure 5: Measured ASIC temperatures of M3DL3T0001120A2, n-side, during thermal cycling.

- Lastly, a moduleID.dat file aggregates data for each cycle, including the module ID, date, EMU, number of synchronized ASICs, their IDs, power consumption per channel, and temperature and V_{DDM} readings for each ASIC.

These comprehensive data collection efforts provide valuable insights into the performance and behavior of the modules throughout the burn-in process, facilitating thorough analysis and quality assessment.

Table 1: Data from module M3DL3T1001121A2 burn-in.

ASIC address	$\langle T \rangle$ @ 13°C	$\langle T \rangle$ @ -20°C	$\langle V_{DDM} \rangle$ @ 13°C	$\langle V_{DDM} \rangle$ @ -20°C
n-side				
0	38.03	13.34	1225.00	1235.46
1	58.17	40.97	1155.80	1152.09
2	57.10	37.57	1163.80	1162.80
3	49.63	26.08	1187.63	1199.29
4	50.70	26.76	1189.60	1196.34
5	48.60	26.76	1195.50	1204.40
6	62.43	44.61	1159.80	1154.66
7	50.70	28.13	1199.43	1209.89
p-side				
0	38.03	15.78	1223.03	1231.31
1	51.77	30.16	1191.57	1195.92
2	58.17	35.79	1163.80	1173.91
3	57.10	37.79	1177.70	1182.41
4	45.40	19.34	1221.07	1234.63
5	39.10	16.45	1242.60	1253.04
6	44.37	22.96	1221.07	1225.00
7	40.13	19.34	1244.53	1247.57

Conclusions

The successful burn-in of the first three serious modules validates their performance under the expected thermal conditions. It indicates stable operation and reliability and confirms that the modules meet the required temperature tolerance specifications. In addition, the absence of any significant failures during the burn-in period indicates satisfactory reliability of the individual electronic components within the modules, including the ASICs and associated circuitry. This operational efficiency has a positive impact on the manufacturing and assembly processes, providing confidence for subsequent production batches. Overall, the successful burn-in underlines the readiness, component reliability and build quality of the modules, providing a solid foundation for future production and further integration.

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Test of a full-size prototype STS ladder

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The performance of STS modules assembled onto a ladder is fundamental for the operation of the final detector. This purpose led to construction of a prototype ladder with modules from the two STS assembly centers, GSI and KIT. A typical ladder type (L12), was chosen. The modules were produced following the final assembly protocol. However, the used components, i.e., silicon sensors, microcables, FEBs, and shielding layers, correspond to old version materials.

All the modules were tested before they were mounted onto the ladder. Once on the ladder, the modules were tested sequentially, and several parameters such as current-voltage characteristics of the sensor (IV), the number of functional ASICs, noise, and the number of broken channels (distinguishing the fault levels *Non-Analog Response*, *ASIC*, or *SENSOR*) were determined.

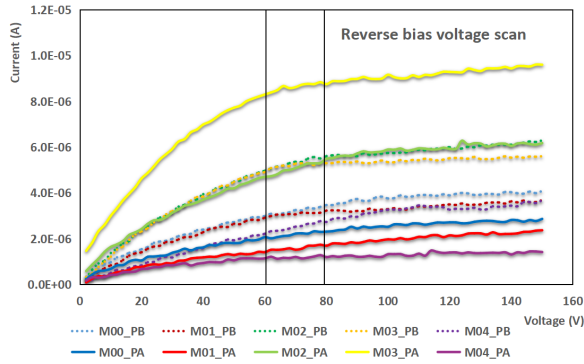


Figure 1: IV measurements for all modules on L12

The IV measurements of all modules on L12 are shown in Figure 1. The sensors were produced by two manufacturers (CiS and Hamamatsu). For all sensors, it is possible to identify a full depletion voltage between 60 and 80 V. Figure 2 represents the modules on prototype L12 and the corresponding testing results. Each rectangle symbolizes a module, where the name indicates the sensor size (e.g. *S06* $\equiv$ 6 cm strip length) and microcable length (e.g. *M27* $\equiv$ 27 cm).

The overall results demonstrate that all modules were functional after ladder assembly and all 320 ASICs could be operated. The noise (ENC, in e) values were found within our acceptance parameters. The number of broken channels remains similar to those found during the module testing.

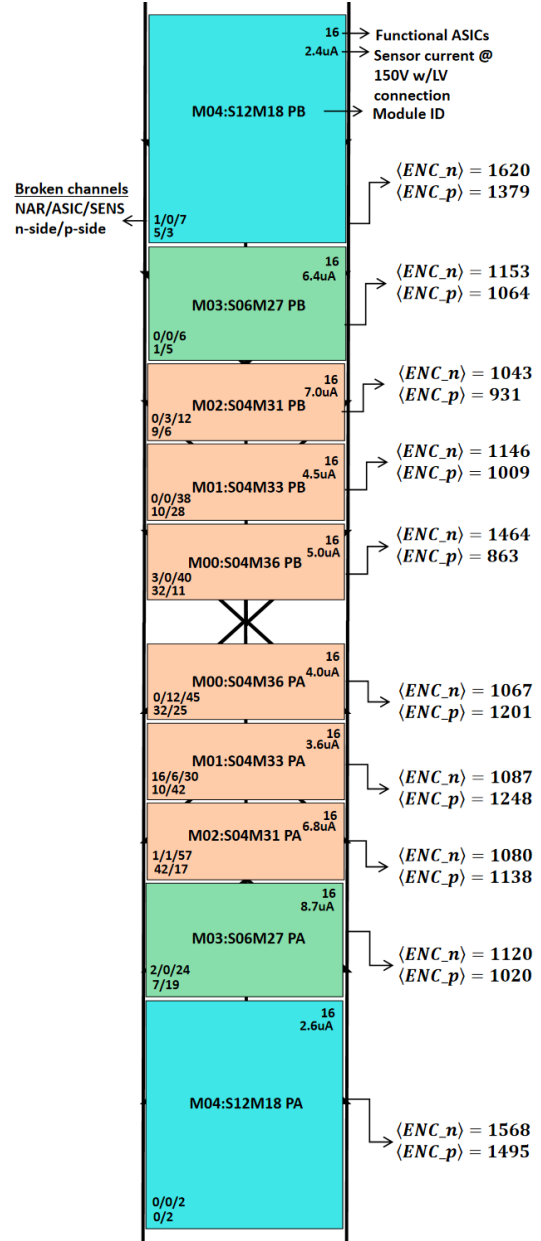


Figure 2: Schematic illustrating the modules on prototype L12 and the corresponding testing results. Different colors are associated with different sensor sizes.

First results from the STS thermal demonstrator with pilot cooling plants

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The STS sensors are characterised to withstand the end-of-lifetime (EOL) fluence of $1 \times 10^{14} \text{ n}_{eq} \text{ 1 MeV/cm}^2$. This fluence realistically accumulates after more than 30 years of CBM operation, with $0.24 \times 10^{14} \text{ n}_{eq} \text{ 1 MeV/cm}^2$ expected after 10 years [1]. Therefore, STS sensors are to be operated at $+10^\circ\text{C}$ mitigating reverse annealing by keeping sensor's full depletion voltage below 500 V and maintaining STS module's signal-to-noise ratio ($S/N \geq 10$ [2]. Consequently, STS front-end electronics boards (FEBs) should also operate at $+10^\circ\text{C}$ to minimise the heat transfer between the sensors and the electronics. This is achieved by using a minimum coolant temperature of -20°C (limit imposed by FEB survival behaviour upon thermal cycling [3]). The STS sensor cooling concept is based on cold air impinging-jets from perforated carbon-fibre tubes [2], while the electronics cooling relies on heat exchanger plates cooled by 3MTM NOVECTM 649 [4].

The STS Thermal Demonstrator tests the STS cooling concept, both for silicon sensors and the front-end electronics, under realistic boundary conditions with pre-production and dummy components. First tests reported here focused on understanding temperature map and thermal runaway behaviour of silicon sensors. Sensor power dissipation across the half-station is proportional to the irradiation distribution foreseen on the first STS half-station. Each FEB dissipate the maximum foreseen power (ASICs: 8.16 W, LDOs: 4.77 W), totaling 1.39 kW for all FEBs (including 105 W for cables). These tests have been performed in tandem with the pilot cooling plants [5]. The air handling system for the silicon sensors is set to -15°C (input temperature is $\approx -10^\circ\text{C}$) with 30 l/min flow rate per innermost ladder (LT201, LT202). The electronics cooling plant is set at $\approx -20^\circ\text{C}$ with a flow rate of 1.5 l/min per cooling plate. The cryo-trap or side-panel cooling is -20°C and is cooled separately with a smaller laboratory chiller.

The resulting thermal runaway distribution for the innermost sensor (LT201-2T) is shown in Fig. 1-Top. The stable operating temperature of $+10.3^\circ\text{C}$ and $+17.6^\circ\text{C}$ are achieved for fluence corresponding to 10 years ($0.24 \times 10^{14} \text{ n}_{eq} \text{ 1 MeV/cm}^2$) and 40 years ($1 \times 10^{14} \text{ n}_{eq} \text{ 1 MeV/cm}^2$) of STS operation, respectively. In both scenarios, a sufficiently safe margin from the critical thermal runaway temperature is maintained. The temperature map for the half-station corresponding to stable operating temperature is shown in Fig. 1-Bottom. Further measurements and analysis to explore the range of operational parameters are currently ongoing.

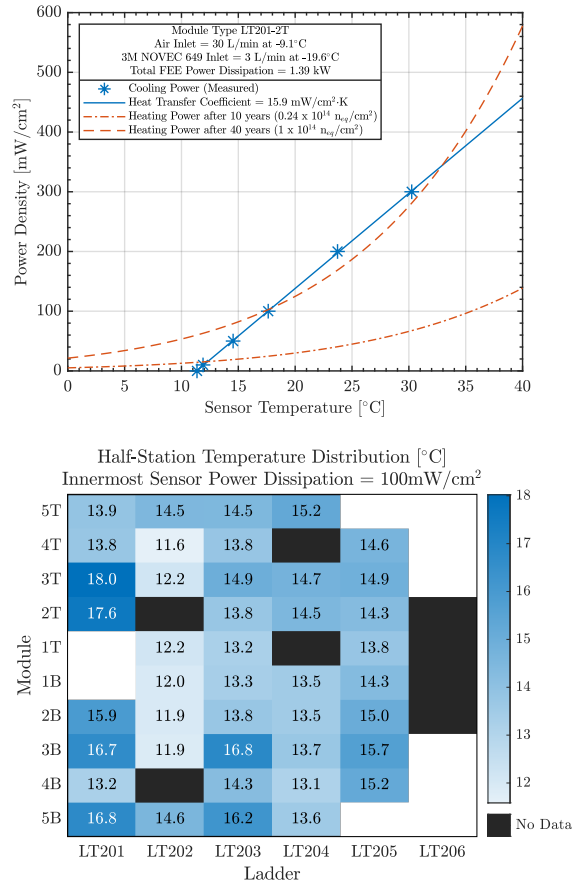


Figure 1: *Top*: Thermal runaway behaviour of the LT201-2T sensor shown as variation of the measured cooling performance (blue curves) with reference to sensor power dissipation corresponding to 10 and 40 years of STS operation (red curves). *Bottom*: Temperature distribution across the thermal demonstrator. The power dissipation on the innermost sensor (LT201-2T, LT201-2B) corresponds to 100 mW/cm^2 . The bins colored in black represent sensors with no data.

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The STS detector cooling: current status and further development

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Introduction

The pilot cooling supply was commissioned in February 2023 despite some issues as outlined further below. This includes a pilot cooling plant, outlet and balancing heaters as well as the cooling test rig [1]. Presently, an experiment verifying cooling concepts for the STS detector is ongoing with the thermal demonstrator, which is connected to the cooling supply system in the laboratory. When concluded, the next goal for the cooling supply is testing the STS detector ladder with silicon sensors on a C-frame, and eventually pre-commissioning the STS without beam.

Perfluor(2-methyl-3-pentanone) aka “dry water” aka FK 5-1-12 is used as a liquid cooling agent for the pilot cooling supply. It is sold as NOVEC 649TM by 3MTM. The same liquid coolant is intended to be used in the final cooling system for the STS detector in the CBM cave although a water-glycol solution is under consideration as an alternative. Due to the proposed EU ban of PFAS-substances and NOVEC 649TM production discontinuation, its usage puts certain pressure on the project: an alternative supplier needs to be found and the proposed legislation needs to be studied carefully for potential derogation (exemption).

In July 2023, the final cooling supply for the STS detector has been presented to the reviewers during an engineering design report and received approval. This gives green light to further clarification of specs, tendering and ordering. In November 2023, the cooling plates specifications for front end electronics were finalized and tendering started in January 2024.

The pilot cooling supply

The first experimental device that has been connected to the liquid cooling supply is the thermal demonstrator [2]. It partially verifies the liquid cooling system for the front-end boards as well as silicon sensors (see Fig. 1. The flow parameters that have been achieved during the operation are given in the table below. The thermal demonstrator experiment will be finished in March 2024.

Parameter	Units	Value
Power dissipation range	W	0 ... 1700
Temperature range	°C	-36 ... +15
Flow rate	l/min	1.5 ... 5.0
Inlet pressure @ 3 l/min, -20 °C	bar (g)	2.9
Outlet pressure	bar (g)	2.1

Despite being commissioned earlier last year, the actual experiment with the pilot cooling supply started only in November 2023. There are a few reasons why it happened:

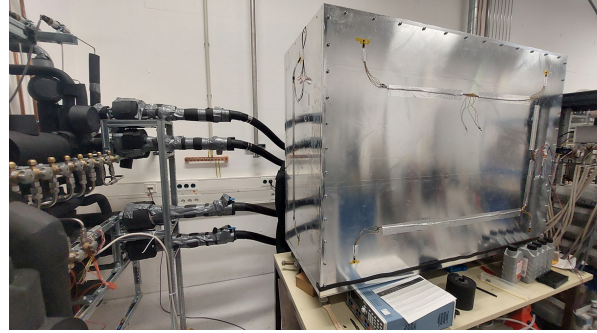


Figure 1: The thermal demonstrator and cooling test rig.

- The first attempts to run the pilot cooling plant revealed that the declared cooling capacity could not be achieved due to an incorrect settings of the thermal expansion valve. At the end of April 2023, a contractor’s representative made necessary changes in the settings.
- Two leaks have been found in the cooling plant on the NOVEC 649TM side. They were fixed by the contractor in August 2023. Subsequently, thermal isolation has to be remounted.
- In summer 2023 a few leakages were found in the cooling test rig from SAE 3/8” threads sealed with Loctite^(R) 511 and 577. Despite many efforts to redo the connections with the same compounds, recurrent leaking was observed. Remarkably, on a smaller thread SAE 1/4”, sealed with the same compounds, no leakage was noticed. In addition, a bronze adapter from 3/8” G to 3/8” SAE thread cracked during the disassembly after an attempt to fix the thread leakage. This fault was attributed to the material itself, because exactly the same failure happened later with the same fitting that was never exposed to NOVEC 649TM. As a response to these problems, bronze adapters-fittings were replaced with stainless steel ones with EPDM O-Rings for sealings (see Fig. 2).
- In September – October 2023 more leakages were found in the cooling test rig: at immersion sleeves (sealed with Loctite^(R) 511), sightglasses and at some of the drainage valves Danfoss BML 10 (membrane type). The first problem was solved by replacing Loctite^(R) with PTFE tape, the second problem was a consequence of a loosen thread on the glass lid most likely caused by the contraction-expansion cycles. The thread was reinforced with PTFE tape to

prevent spontaneous unwinding. To solve the problem with the leaking valves, caps with O-Ring seals were installed on the exit.

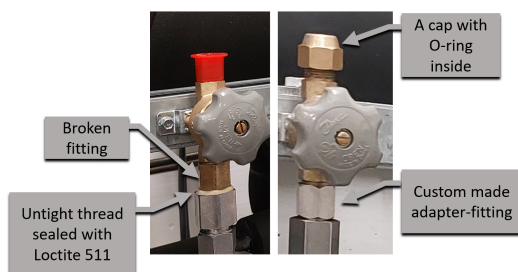


Figure 2: A vent valve area before (left) and after (right) the improvement.

A few minor problems listed below still remain with the pilot cooling supply. Negotiations to eliminate deficiencies began with the contractor at the end November 2023 (during the warranty period).

A prospective PFAS ban and FK 5-1-12 (NOVEC 649™) cooling liquid supply

From 2020 on, a number of the European countries have started working on a broad ban of per- and polyfluoroalkyl substances (PFAS) [3]. It is the broadest restriction proposal in history – around 10,000 substances fall under the proposal, including perfluor(2-methyl-3-pentanone) or FK 5-1-12, which is sold under NOVEC 649™ by 3M™. The main driver of the restriction is that PFAS have very strong chemical bonds, for this reason they called “forever chemicals”. PFAS stay in the environment and biological systems, which raises concerns by the public. In January 2023, the restriction proposal was submitted to the European Chemical Agency (ECHA) and, according to the initial estimate by the authors, should be put into power in 2025 by the EU members voting for it.

The restriction proposal suggests derogation (exemption) usage of PFAS substances based on their application and available PFAS-free substitutes for 5, 12 years or unlimited amount of time. For example, in the proposal document, a 12 year derogation usage for PFAS is applied for heating ventilation air conditioning and refrigeration (HVACR) installations built before the new legislation enters into force. This could potentially be applied to the STS liquid cooling system in the CBM cave, but the definition of HVACR in the document is vague.

Considering the time and resources spend on R&D already, it would be difficult to start over with the alternative coolant, even if some candidates like water-glycol solution [4] and CO₂ are readily available at the market – their usability needs to be confirmed for the STS detector. As a response, Physics Institute of Tübingen University (Prof. Schmidt) has filed a comment on the restriction proposal during the consultation phase on the ECHA’s website

in September 2023. Most importantly, the prepared comment suggests 12 year exceptional usage of FK 5-1-12 for high energy physics experiments [5]. In total the ECHA received more than 5600 comments from individuals, companies and other organizations.

Another problem with the cooling liquid supply is discontinuation of NOVEC 649™ production at the end of 2024, which already caused a supply shortage on global markets [6]. As a result, it’s no longer possible to purchase NOVEC 649™ in very large amounts that required by the final cooling system of the STS detector – an estimate is 2250 kg for 20 years lifetime of the detector. An alternative supplier has been found after market research was done in February 2023.

To prove the identity of the chemical composition, a gas chromatography–mass spectrometry (GC-MS) analysis was done on two samples: sample “A” – perfluor(2-methyl-3-pentanone) bought under ISO name FK 5-1-12 from the alternative supplier and sample “B” – the same substance sold as NOVEC 649™. The results of the analysis confirmed confirmed identity of the two samples (see Fig. 3); more details can be found in the report [7].

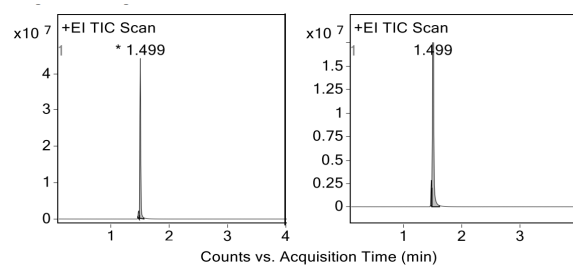


Figure 3: GC-MS chromatogram of sample “A” (left) and sample “B” (right).

Cooling plates ordering and the final cooling plant

The tendering for the cooling plates ends on March, 11th 2024: the first 4 cooling plates (see Fig. 4) are supposed to be delivered to GSI as pre-series production prototypes in May 2024. The remaining 36 plates will be delivered after the prototypes approval and further negotiations with prospective contractor.

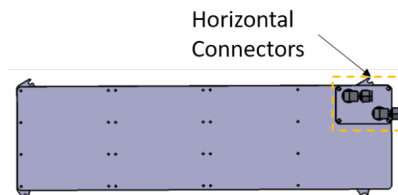


Figure 4: A cooling plate for up to six front-end board blocks.

Preliminary specifications of the final coolant plant (see Fig. 5) for installation on the technical floor E30 in the CBM cave has been approved during the engineering design report:

Parameter	Units	Value
Nominal cooling capacity	kW	50
Partial cooling capacity	kW	23
Balancing heater nominal power	kW	50
Primary side refrigerant	-	CO ₂
Secondary side coolant	-	FK 5-1-12
Outlet temperature	°C	-22.5
Inlet temperature	°C	-11.5
Flowrate	m ³ /h	20
Pressure difference	bar	2.7
Static pressure at the plant	bar	0.9

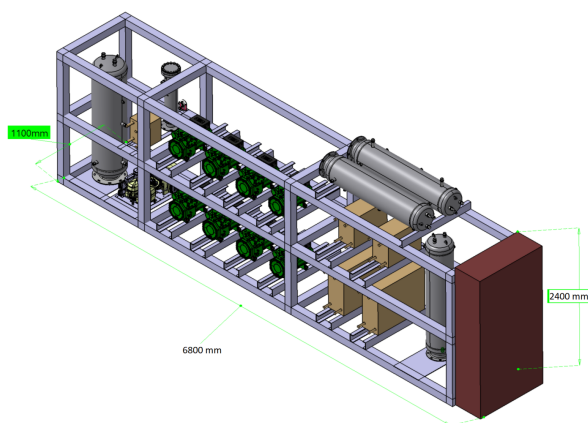


Figure 5: Approximate dimensions of the final cooling plant.

Conclusion

Valuable experience has been gained during pilot cooling plant commissioning: additional quality assurance procedures are required during manufacturing of the final cooling plant. These might include overseeing tightness tests directly on the manufacturer's production workshop, checking proper installation of the plant's components and equipment. As for pipelines, valves and fittings, threaded connections should be minimized – immersion sleeves can be welded directly into the pipelines. Based on the usage experience, sightglass installation can be avoided by checking the flow in the valves connected the highest local point of the system. Instead of membrane valves, ball valves should be used in the final system. A sniffing device Inficon GAS-Mate (uses Formiergas 95/5), which was proven to be effective for finding even minuscule leaks, has been purchased to improve leaking seeking. This will allow to mitigate the recurrent leakage problems like those that happened with the cooling test rig in summer – autumn 2023. The first batch of 250 kg undergoes purchasing

process with delivery to Hamburg port from the alternative supplier. We hope that the derogational usage of PFAS coolant minimum for 12 years would be granted by the European Chemical Agency (until 2039). Finalization of specifications and preparation of tender documentation for the final cooling plate are planned for September 2024, and the ordering is expected by March 2025.

Acknowledgement

On behalf of STS group, authors would like to thank Dr. Norbert Grzegorzec, the Head of Mass Spectrometry Department at Eberhard Karls University, Tübingen, for carrying out GS-MS analysis.

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Comprehensive thermal simulation of the STS detector on the Virgo computing cluster

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Introduction

In previous years, numerous thermal models of detector components were prepared: for the box of front-end boards (FEB) [1, 2], silicon sensors [2], confined air flow simulations [2], cooling plates for FEBs [3], cooling plates with FEB boxes [4], read-out boards (ROB) [5]. They were implemented in commercial finite element analysis software, e.g. Ansys Fluent, Dassault Systèmes SolidWorks, and analytical models coded in MATLAB and Python. These models provide a good idea of how these components perform in limiting conditions; however, they do not represent the complex character of these components interacting in the STS detector casing (thermal enclosure). This has been observed previously in an attempt to model thermal behaviour of the silicon sensors resulting in significant difference between simulated and measured results [6].

A new comprehensive thermal model that includes detector components interacting with each other might give more accurate representation of the STS detector thermal behaviour. Such a model is also capable of taking into account the power dissipation of silicon sensors induced by radiation damage and allows to estimate the corresponding electrical noise. Another important feature is that it will help to “scale up” experimental results acquired from the thermal demonstrator to the actual detector [7].

Implementing this comprehensive thermal model requires substantial computational resources. Fortunately, GSI/FAIR has built a powerful scientific data center on the campus – the Virgo cluster (Green IT Cube) that can be used for this purpose. Open-source software is used for solving computational fluid dynamics (CFD) tasks for this simulation.

Software and hardware used for simulations

A typical workflow for thermofluid simulation is shown in Fig. 1.

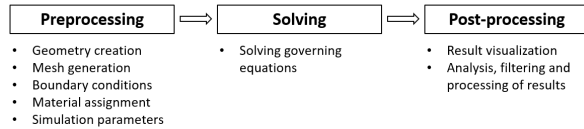


Figure 1: Workflow for thermofluid simulation.

Usually, commercial CFD combines all the functions in one software, but the used open-source alternative uses three independent programs: SALOME [8] for geometry

creation, OpenFOAM^(R) [9] for mesh generation and solving, ParaView [10] for results visualization and analysis. All the software products from the list are mature and have been being developed for more than twenty years.

A conjugate heat transfer solver’s code in OpenFOAM^(R) was modified to include a power dissipation model and analytical noise estimation (in post-processing mode) [11]. In addition, a script that converts Fluka [12] irradiation diagrams into the OpenFOAM^(R) format was written. It allows for direct imposition of the irradiation field on the silicon sensors in the finite element analysis (FEA) model to calculate power dissipation. This feature provides for comparison detector thermal performance in different irradiation scenarios as well as time-wise evolution.

OpenFOAM^(R) has been already installed and tested on the Virgo cluster. The cluster has the following resources available for a user in the STS group:

Partition	CPUs max	RAM max [TB]	Time limit
debug	2048	8	30 minutes
main	4096	16	8 hours
high_mem	2048	16	7 days

It is important that the cluster has large amount of available RAM that can accommodate a very large multi-regional mesh and field values. Naturally, more processors make computation faster: a comparison between a PC’s and cluster performance on the same computation mesh has been done, the results are shown in Fig. 2.

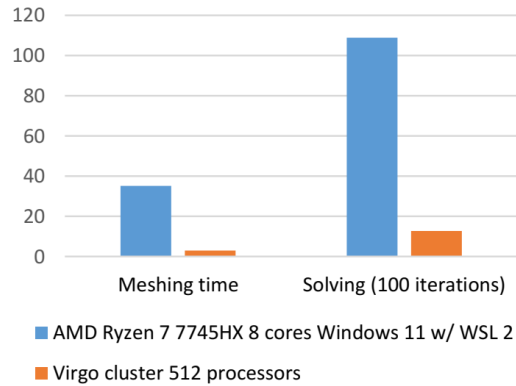


Figure 2: Elapsed time [min], mesh with 20.4 million cells.

Current status of the thermal model development

As a proof of the simulation concept, a few detector components were combined for exemplary CFD simulation (see Fig. 3): one C-frame, silicon sensors, casing, one PCB with a heat source, cooling fins, and a cooling plate with a NOVEC 649TM flowing in its channels.

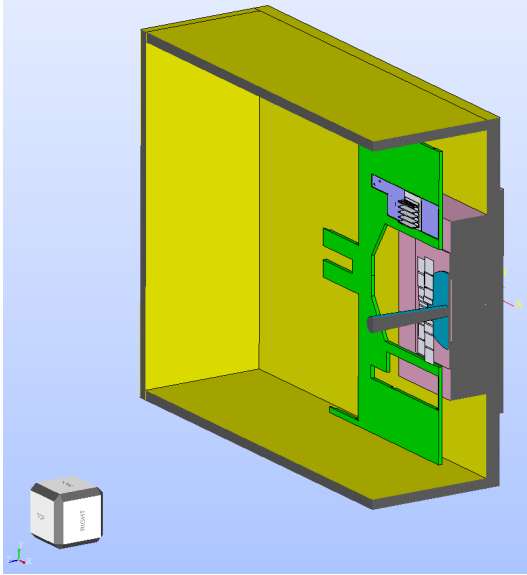


Figure 3: Geometry for exemplary CFD simulation of the STS detector prepared in SALOME.

As irradiation scenario, two months of Au-Au collisions at 10 AGeV was applied to the silicon sensors power dissipation model. The corresponding temperature field on the sensors is shown in Fig. 4. Another example of the results is the air velocity field inside the casing (see Figure 5).

At the moment it was decided to step back from the STS thermal model, and switch to the modelling of thermal processes in the thermal demonstrator [7] (see Fig. 6). This way, it would be possible to compare experimental results with the developing model and work on the improvements to minimize the discrepancy. The experience gained on this task can be directly applied to the thermal model of the entire STS detector.

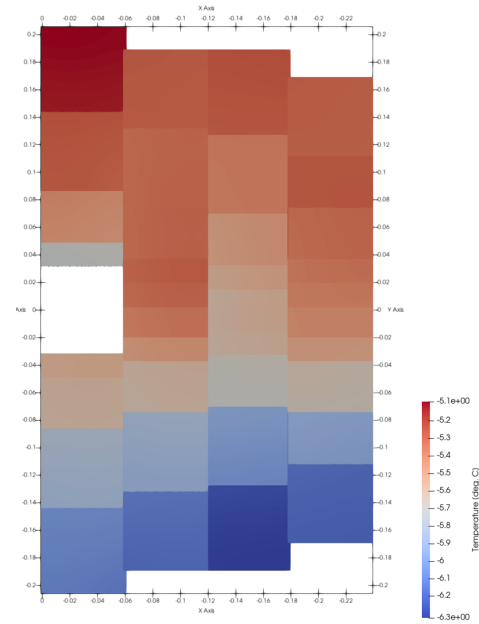


Figure 4: Temperature of the silicon sensors (proof of concept).

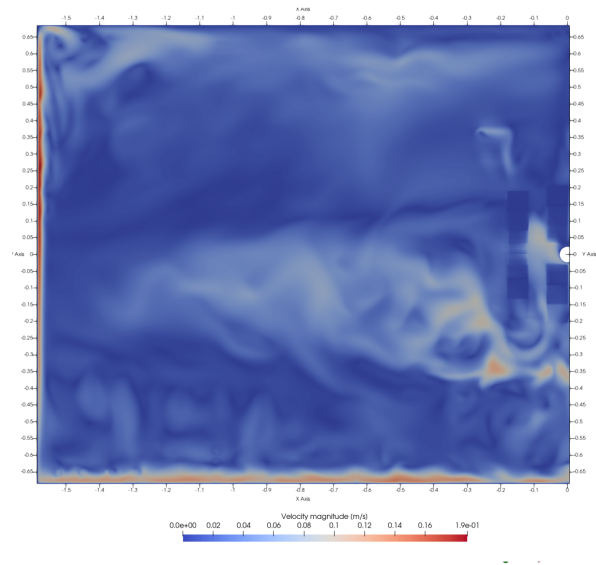


Figure 5: Air velocity field normal to Z-axis (proof of concept): natural convection current can be seen at the bottom and on the side wall.

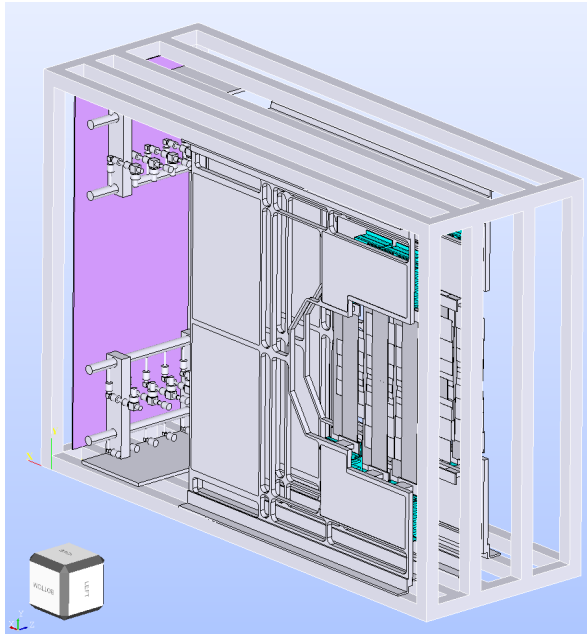


Figure 6: Thermal demonstrator geometry prepared in SALOME.

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Conclusion

Functional exemplary simulation of the STS detector has proven the possibility of creating a large and comprehensive thermal model of the detector with all the thermal mode related components.

Using free software for thermal simulation not only mitigates additional expenses, but has another benefit that is it allows to share simulation results within STS group and expands the circle of colleagues participating in model build-up and its parametrization.

At the moment, work on the modelling of the thermal demonstrator processes is on-going to confirm theoretical grounds of the model with the experimental results that can be “scaled-up” onto the final STS detector later this year.

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Completion of the STS mechanical design

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Finalisation of the design of the modular STS

This report documents the culmination of the mechanical design phase of the Silicon Tracking System (STS). This milestone represents the successful integration of engineering principles and collaborative efforts to develop robust mechanics and services for the tracking detector. Throughout this report, we detail the objectives, specifications, and methodologies essential to achieving the completed mechanical design of the STS.

More than a year after the initial idea for the modular STS design was conceived, we present the completed design for the Upstream STS (uSTS) and Downstream STS (dSTS) sections, previously referred to as STS-3 and STS-5 [1]. Key elements including the inner frame, units and their fixtures, cooling manifolds with mounting, piping and hoses, sensor cooling, cable routing with supports, and the rail system have been finalized. The CAD drawing of the STS is shown in Fig. 1.

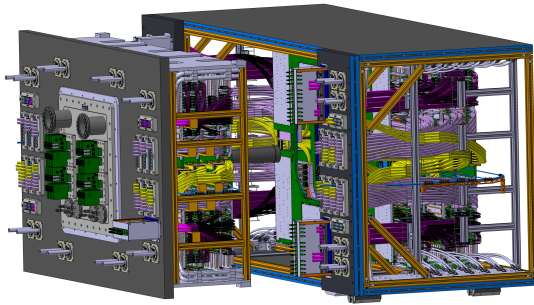


Figure 1: A view of the CAD model of the CBM Tracker: the uSTS part together with the MVD is drawn upstream, outside of the enclosure in which the dSTS is housed.

Half-Unit design and C-Frame optimisation

STS comprises nine units made of 18 C-Frame assemblies. These assemblies incorporate various components, including modular cable covers, carriages, mounting adapters, the C-Frame bottom section, HV cabling, connection boxes, and ROB/POB stacks. Each unit has been realistically configured to accommodate mounting mechanics, cooling blocks, and covers. The example of a Half-Unit assembly is shown in Fig. 2.

The HV connectors have been updated from Redel to D-Sub connectors to improve functionality and compatibility. Other updates include revised positioning and fixation methods, rail enhancements, and connector optimizations.

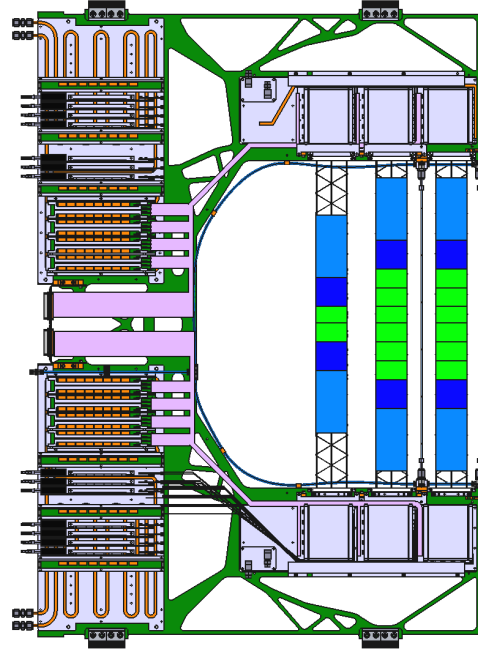


Figure 2: CAD model of the partially integrated Half-Unit U3DL (data cables are not fully included). It is the first one to be assembled for the STS detector.

Optimising the geometry of the aluminium support system is crucial for structural integrity on one side and minimized signal background and efficiency on the other. Our in-house topology optimization process takes a few days per unit and runs concurrently with production to streamline timelines. Collaboration between design and manufacturing ensures that final detailing aligns with production capabilities, especially for externally sourced components such as the baseplate. This iterative approach aims to balance the performance of the structure, feasibility of manufacturing, and efficiency of assembly.

Unit assembly

Design updates have been implemented, focusing on several key aspects. Firstly, the positioning and fixation of the U0-U3 Frames have been revised to enhance stability and functionality. Additionally, the rails for the C-Frames of the uSTS have been updated, resulting in reduced height compared to the previous C-Frame infrastructure. The full stack of the assembled Units is shown in Fig. 3.

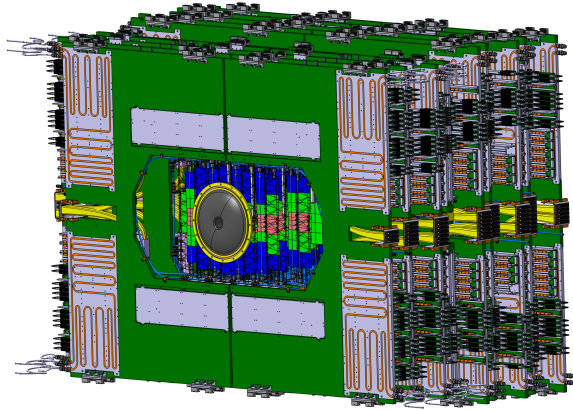


Figure 3: Assembly of the STS Units.

Mainframe and baseplate

The STS enclosure includes side areas for cabling, tubing, and cooling services. Expanding this area improves the system's functionality and performance. This highlights the importance of space allocation and design considerations for efficient integration and operation of STS components.

The subassemblies for both the dSTS and the mainframe have been completed, including essential components.

The uSTS rail system and its corresponding fixtures have been integrated into the mainframe, ensuring seamless functionality tailored specifically for the uSTS. At the same time, a rail system dedicated to the units has been incorporated into the mainframe's design. This attention to detail extends to the sealing concept, which ensures the structural integrity of the mainframe assembly by protecting it from environmental factors while maintaining optimal internal conditions. In addition, the front wall and strategically positioned feedthroughs have been engineered to facilitate easy access and connectivity for external interfaces and instrumentation.

The completed subassemblies are important milestones in the development of both the dSTS and the mainframe. They play a crucial role in ensuring structural robustness, operational efficiency, and overall system performance. Their completion indicates significant progress towards achieving project objectives and operational readiness.

Summary and Outlook

Key engineering issues within the project have been successfully resolved, paving the way for production commencement.

The design of cooling blocks for FEB and ROB components has been finalized, including conceptual design freezes and thorough validation of manufacturability. Additionally, alignment procedures and manufacturability checks for carbon fiber pillars and main sandwich plates have been completed.

Secondary parts supply, including FEB and ROB circuit boards, has been validated, ensuring compatibility and functionality within the system.

Both the FEB and ROB cooling blocks have been fully designed, simulated, and partially tested, meeting all thermal requirements and undergoing prototype validation. Connector designs outside of the C-Frame plane have been finalized for both components.

Alignment procedures have been implemented successfully, resembling a ladder assembly concept. Precision-milled plates have been utilized to achieve accurate alignment between various components, ensuring optimal functionality.

The modular cable tray system has been implemented and validated, with all secondary parts, including cable trays, thoroughly checked and verified.

All units have been designed successfully, and space availability has been rechecked. The rail system has been iterated for better functionality, fixtures have been designed for efficient assembly, and the C-Frame infrastructure has been updated. Topology optimization techniques have been applied to enhance C-Frame performance. The next steps include integration and testing, further refinement of the rail system, and manufacturing with a focus on continuous optimization.

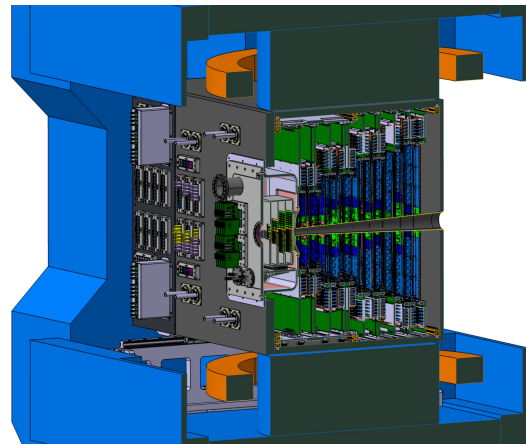


Figure 4: The STS and MVD detector inside the CBM dipole magnet.

The procedures for installing the CBM dipole magnet gap (refer to Fig. 4) are addressed. A dedicated rail system has been designed, and iterative alignment procedures are planned.

With all major engineering activities successfully addressed and resolved, the project is primed for production, ensuring its success and functionality.

References

- [1] O. Vasylyev et al., CBM Progress Report 2022, pp. 23

A full-size prototype of the STS beam pipe section

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The STS section of the CBM beam pipe

In the CBM experiment, the beam pipe guides the non-interacting fraction of beam from the target area through the detectors to the beam dump. It will be evacuated to 10^{-4} mbar, separated from the accelerator vacuum by differential pumping. The beam pipe comprises of several sections. The upstream section attaches to the target box, in which the target and the MVD detector will be installed, and crosses the STS detector volume at a polar angle just below 2 degrees. At the STS downstream wall, a connection to the next beam pipe section will be made, leading either through the RICH or the MUCH detectors, depending on the experiment's configuration. The concept of the CBM beam pipe and its STS section with an integrated thin window at the interface between target box and STS have been summarized in Refs. [1, 2].

The STS beam pipe section consists of a circular membrane ("window") and a conical structure. The window attaches to the circular opening in the back side wall of the target vacuum chamber, yielding a low-mass separation of the vacuum to the STS tracking volume in the STS physics aperture between the polar angles 2 and 25 degrees. The window is connected to a conical pipe of about 1 m length with 20 mm start and 50 mm end radii. The downstream end of the beam pipe is coupled to a sliding interface in the rear STS wall, sealed with an O-ring. The wall thickness of window (0.5 mm) and pipe (1 mm), as well as the shapes were optimized to satisfy CBM running at SIS100 with different beam energies and dipole magnetic fields. The design fits to the finalized STS engineering in its "modular" construction.

The full-size prototype

The prototype shown in Figs. 1 and 2 was produced in the reporting year 2023 at ICM-Composites GmbH¹. Based on preceeded FEM calculations, the window was built from 6 layers of carbon fiber laminate in different orientations, leading to the thickness of 0.5 mm required for STS tracking according to physics performance studies carried out. A gradual increase in thickness towards the joint with the 1 mm thick conical tube, built from 4 inner layers of carbon fiber fabric and two enclosing layers of wound thread, serves sturdiness in axial and longitudinal direction. For this prototype, the originally foreseen high-modulus carbon fiber fabric and roving had to be replaced with alternative

ones, as worldwide market availability was depleted due to high demand by the aviation industry. The roving chosen had a higher number of filaments (6k instead of 1k). This lead to winds with enlarged spread-out and gaps which, however, could be filled with epoxy resin. The window and the cone were produced separately on specific molds or hubs, involving vacuum infusion technology and baking, and then joined together with a shafting structure as part of the window with glue.

Before delivery to GSI, the structure was subjected to a simple vacuum test at ICM, confirming tightness. A full structural and handling test is being prepared at GSI, for which a dedicated test stand has been set up.



Figure 1: Full-size prototype of the STS beampipe.



Figure 2: Joint of the window to the conical section (outside view - left and inside view - middle). Window seen from the side attaching to the back wall of the target chamber (right).

References

- [1] J. M. Heuser et al., CBM Progress Report 2021, pp. 55-58
- [2] J. M. Heuser et al., CBM Progress Report 2022, pp. 51-52

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

Data rate study of the Silicon Tracking System using GEANT-4

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Introduction

At the Facility for Antiproton and Ion Research (FAIR), GSI, the Darmstadt Compressed Baryonic Matter (CBM) Experiment is under construction. It is, a fixed target experiment, built to explore the first order, second order phase transition and possibly look for a critical point in the phase diagram at lower beam energy from 2 AGeV/c to 12 AGeV/c using the Au-Au collision. STS is a main tracker to track the charged particle using its 8 tracking layers. Since the experiment will be running in a free streaming mode to collect the collision data, it is needed to check the capability of data rate handling by the read-out electronics and components that transfer the data to the storage system [1]. In this report, we present the study of the data rates for the STS detector by simulation using GEANT-4.

Simulation Setups and Data Rates

The study addresses the case of the highest possible load for the detector, i.e. Au-Au collision at 12 AGeV/c at an interaction rate of 10 MHz. We simulated the statistics of 10 ms, i.e. 10^7 beam events and, assuming a 1% interaction probability in the target, 10^5 Urqmd events using CBM-ROOT with the GEANT-4 transport engine. The setup used in the simulation is described in Table 1.

Simulation geometry	
Detector system	Geometry tag
STS	v22d
MUCH	v23a_sis100.1m_lmvm
Beam pipe	v21d:v21i
Magnet	v22b
Magnetic field map	field_v22b
Magnetic field	1 T

Table 1: Simulation setup used to study the data rates.

We have considered three major contributions for estimating the data rate based on simulation. (i) particles from nuclear collisions, (ii) delta electrons from beam-target interactions, and (iii) noise. Delta electrons are secondary electrons knocked out of atoms by the charged particles. They can originate from the beam's interaction with the target, beam interactions with the pipe or elsewhere in the detector system [2]. Table 2 shows the digitization parameter used to digitize the Monte Carlo (MC) points created by both UrQMD and beam events.

Parameter	Value
Dynamic range	75000 e
Number of ADC levels	32
ENC	1000 e
Threshold	4000 e
Dead time	200 ns
Time resolution	10 ns
Noise	Yes
Lorentz shift	Yes
Charge diffusion	Yes
Cross-talk	Yes
Dead channel fraction	0 %

Table 2: Digitization parameters.

Figure 1 shows that the rate of signal per channel per second, for all 8 STS stations, is mostly below 150 kHz, with a few exceptions. Figure 2 shows the distribution of the mc points from both UrQMD and beam transport. It is noticeable that due to the magnetic field low momentum delta electrons created in beam transportation affected more stations 0 and 1, particularly in a localized area of the stations on the left side. We can also see the central part of each station, which is close to the beam-pipe, also affected. Figure 3 shows the total digis created during digitization where it is seen that the signal read-out ASICs in those particular areas need to have higher bandwidth to process and transfer the signals.

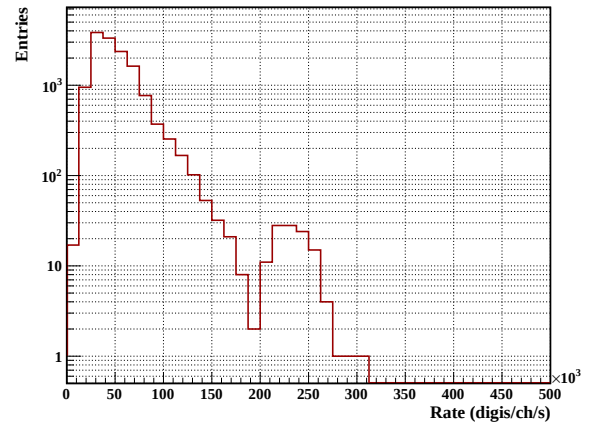


Figure 1: Signal rate in all 8 STS stations.

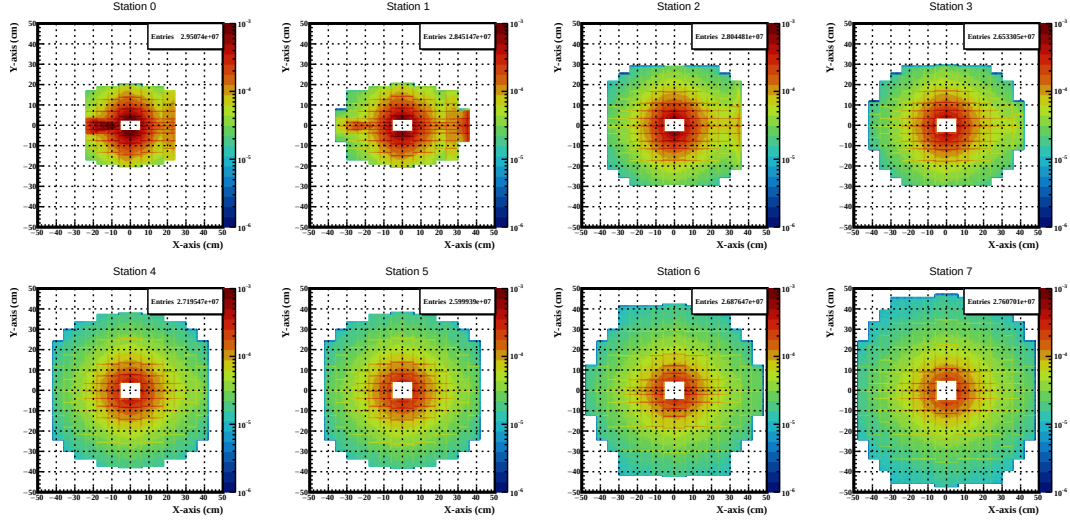


Figure 2: MC point distribution of all particle density for each STS station.

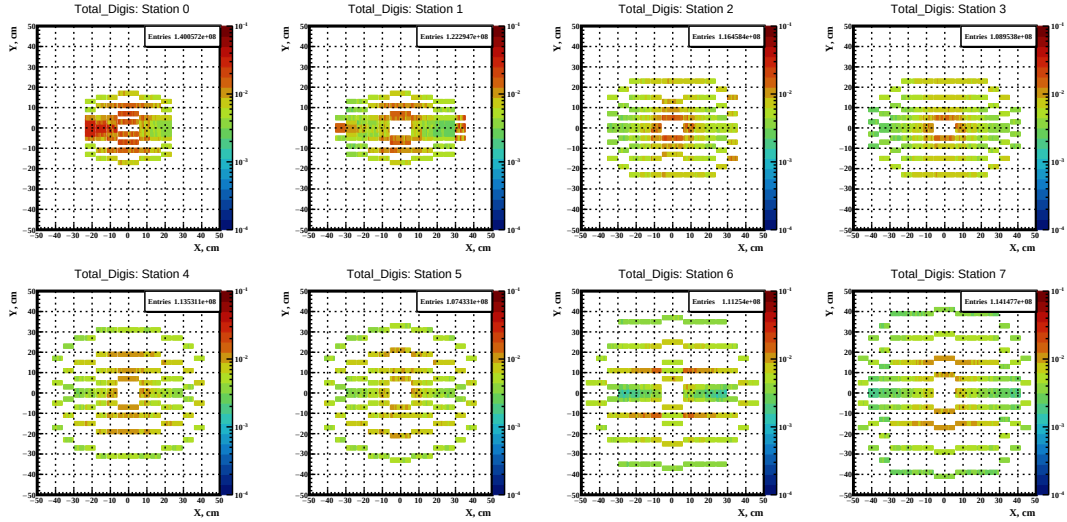


Figure 3: Distribution of total digis for each STS station.

Summary

The expected rate for the STS detector readout is studied for the highest possible detector load with time-based simulations that include Urqmd, delta electrons and detector noise. Table 3 summarizes the overall yield from the different contributions. Except for a localized region in the two upstream STS stations, particularly impacted by delta electrons, the expected channel rate remains below 150 kHz.

References

- [1] J. M. Heuser et al., Technical Design Report for the CBM Silicon Tracking System, 2013.
- [2] A. Toia et al., Studies of data rates in the STS detector, CBM Progress Report 2020.

Data rates	
Source	GB/s
UrQMD	136.41
Beam	208.23
Noise	3.36
Total	347.99

Table 3: Data rates from different sources.

Simulation of the analogue response of STS modules using LTSpice

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Introduction

LTSpice, developed by Linear Technology Corporation, is a widely-used simulation software for electronic circuits. Its interface allows for easy schematic entry, while its SPICE engine enables accurate simulation of analog and mixed-signal circuits. With a comprehensive component library, LTSpice facilitates analysis and optimization of circuit parameters [1]. Electronic simulations of the analogue response of the STS detector modules were performed using LTSpice. The results provided a better understanding of the behaviour of the system, including the response of faulty or damaged channels through transient analysis and noise level measurements.

Simulation with equivalent circuit diagrams

For a one-sided, single-channel detector, the equivalent circuit comprises the following key elements: a high-voltage source, a return path circuit (which stabilizes the SMX chip grounding and suppresses noise from the voltage sources), a sensor strip, a micro-cable line, and an SMX channel consisting of a charge-sensitive amplifier (CSA), a fast shaper for time measurement and a slow shaper for amplitude measurement.

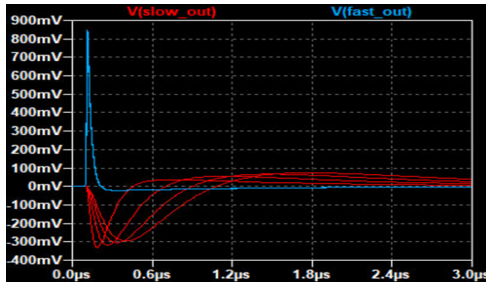


Figure 1: Fast (blue) and slow (red) shaper waveforms at 8 fC injected charge for different CSA shaping times.

The waveforms and signal amplitudes for both shapers were compared with those measured with the SMX ASIC [2] (Fig.1). The results suggest adequate simulation performance for the fast shaper, which reproduced the front of the signal waveform, and good performance for the slow shaper, which reproduced the waveform completely.

Another test assesses the SMX channel's noise level dependency on input capacitance. The results were reproduced using a schematic comprising a HV source, capacitor, CSA, and fast and slow shapers with shaping times of 30 ns and 90 ns, respectively.

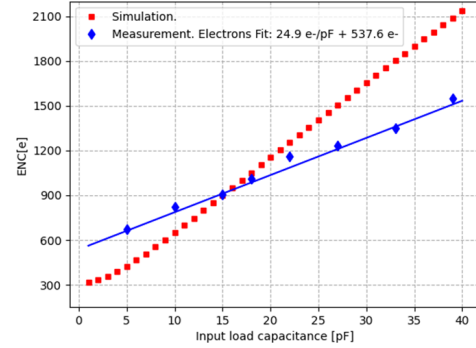


Figure 2: Noise level at the output of the slow shaper as a function of the load capacitance: Measured data (blue) [2], simulated data (red).

Multi-channel simulations

The influence of detached strips on the noise level and signal amplitude of the neighbouring channels was simulated using an 8-channel circuit, see Fig. 3.

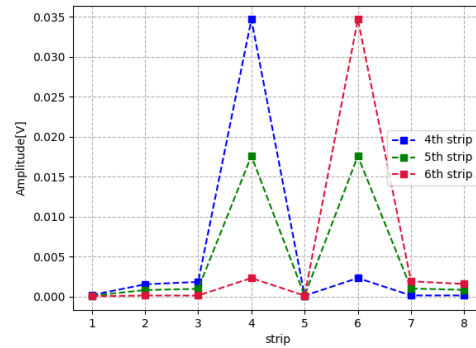


Figure 3: 8-channel simulation results (signal amplitude is measured at the CSA output) with 5th strip disconnected. The charge is injected sequentially in the 4th–6th strips.

Further research includes the simulation of the different module sizes and the improvement of the SMX channel performance and the parasitic capacitances between the p and n sides of the STS detector module.

References

- [1] Linear Technology Corporation (2023), LTSpice [Computer software], retrieved from <http://www.linear.com/ltspice>
- [2] O. Maragoto Rodriguez, Ph.D. thesis, Goethe Universität, Frankfurt am Main, Germany (2023)

Beam spot and vertex reconstruction with 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 were measured with beam intensities of up to 10^{10} ions per spill and approximately 400 kHz interaction rate. The mini-STs (mSTS) setup consisted of two 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 two 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 low voltage for FEBs and ROBAs [1]. The mSTS setup downstream of the target chamber is shown in Fig. 1. The detector's operating status has been described in [2].

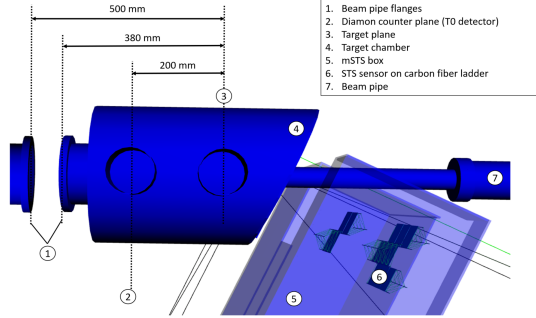


Figure 1: Schematics of mSTS setup and mCBM target chamber, with relevant distances to secondary targets.

Alignment to beam spot

All combinations of the 4 (7) sensors in the two STS tracking stations allow an independent reconstruction of the beam spot at the main interaction target. Using straight line tracklets resulting from two hits in different stations and extrapolating to different transversal planes in the beam path, the shape of the beam can be explored. The vertex spread is defined as:

$$S = \frac{\sum_{ij} (v_{ij} - \bar{v})^2}{N_{pairs}} \quad (1)$$

where v_{ij} is the vertex found by the sensor pair i,j and $\bar{v}$ is the average of all the vertices. Independent translations of all sensors are applied in a minimization procedure, and

the vertex spread is iteratively recalculated. A minimization of gradient descent shows a convergence after 8 iterations. Only independent translations were considered. The resulting sensor alignment translations, shown in Fig. 2, are consistent with the mechanical assembly.

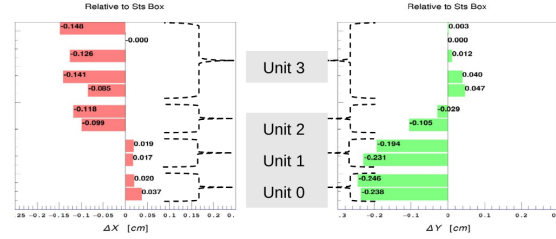


Figure 2: Alignment parameters for the different sensors, grouped by mechanical units.

Therefore, such extrapolation should find the primary and secondary targets along the beam path. The reconstructed vertex at the Ni target plane and the X, Y projections, shown in Fig. 3, is fitted, resulting in a beam profile at the target plane of $\sigma_{trg}^X = 0.1583(4) \text{ cm}$, $\sigma_{trg}^Y = 0.2167(13) \text{ cm}$. Possible secondary targets in the mCBM cave are indicated in Fig. 1. After preliminary alignment, the aforementioned procedure has reconstructed beam spots at four different planes. The X projections of mSTS tracklets at different z-planes are shown in Fig. 4. The dashed lines and the shadow boxes represent the expected position of such peaks, in remarkably good agreement with the measurement.

Event vertex

Event primary vertex reconstruction is of utmost importance in most data analyses. Our main reason is its crucial role in consolidating the reconstruction efficiency studies [2]. The approach chosen for vertex reconstruction is to average the position of multiple well-defined distances of closest approach (DCA) for global track pairs. This was performed using only tracks within the same event. Track selection has been shown to play an important role. For this purpose, global track selection was based on the number of layers with reconstructed hits for each subsystem: STS: 1, TRD: 1, and TOF: 3. The resulting vertex reconstruction, shown in Fig. 5, shows a well-defined shape consistently centered in the transversal plane with the beam spot profile. At this point, no further analysis has been done to distinguish the primary from the secondary tracks.

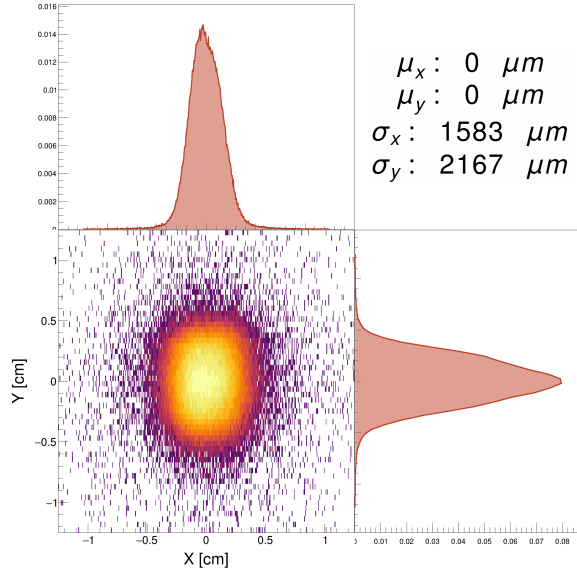


Figure 3: Beam spot reconstruction at the primary target plane $z = 0$.

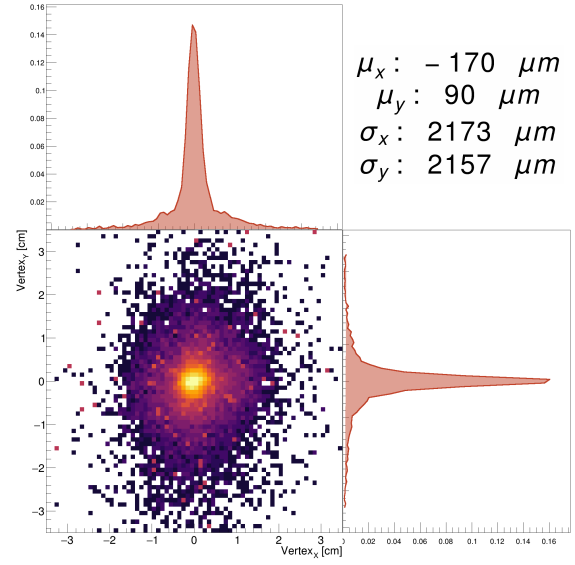


Figure 5: Reconstructed event vertex by global track DCA average.

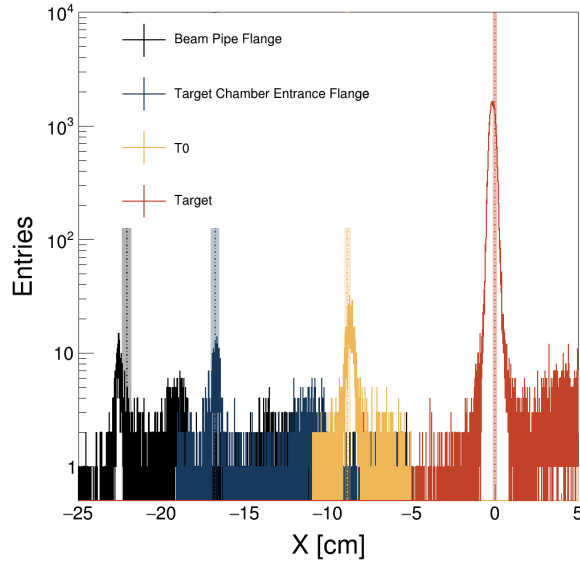


Figure 4: X projection of reconstructed beam spot for mCBM targets and their nominal positions.

consistent with the beam spot profile. Distinguishing primary from secondary tracks will enhance the overall insights gained from the mCBM 2022 and forthcoming beam campaigns.

References

- [1] M. Teklishyn and A. Lymanets, *Assembly, testing and comissioning of the mSTS detector*, CBM Progress Report 2021, pp. 62-64
- [2] D. Ramirez and A. Toia, *Performance of mSTS in Ni+Ni collisions at 1.93 AGeV*, CBM Progress Report 2022, pp. 66-69

Summary and Outlook

The mSTS stations allowed for independent beam spot reconstruction, exploring the shape of the beam by extrapolating straight-line tracklets to different transversal planes in the path of thge beam. Four different planes were identified, corresponding to secondary interaction targets. The reconstruction of the event primary vertex, a crucial aspect in data analysis, was achieved by averaging positions of DCA for global track pairs within an event. The resulting vertex reconstruction exhibited a well-defined shape

A new upstream station for the mSTS-2024 upgrade

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Various prototypes of STS modules have been installed in the mCBM setup, operational at SIS18 since 2018. Since 2021, the mSTS features 2 tracking stations (Units 1 and 2) at $z = 33$ cm and $z = 47$ cm from the target, covering a total area of 12×12 cm² and 18×18 cm² respectively, realized by 4 + 7 modules. Each of these modules is read out by two Front-End Boards (FEBs), of type FEB8-1, each comprising 8 SMX (STS/MUCH-XYTER) ASICs with one uplink each [1]. Physics performance measured with this setup have been reported in detail [2, 3, 4]. The rate capability was limited by the FEB readout.

For the beamtime 2024, one tracking station has been added upstream of the two existing ones, at a distance $z = 16$ cm downstream of the target (Unit 0). It consists of a single module built with series components, mounted on a short ladder, built with a 6×6 cm² sensor and installed in a separate box. The module is connected via 35 cm long microcables to two FEB8-5 boards with 5 uplinks for each of the 8 ASICs. A service box mounted on top of the existing mSTS box connects to the module box as shown in Fig. 1, and contains two common read-out boards (CROB) and one power board to provide supply voltages for the FEBs. The cooling is realized by sharing with the water chiller of one of the existing units (Unit 2). Figure 2 shows the module mounted on the ladder, ready to be installed in the box.

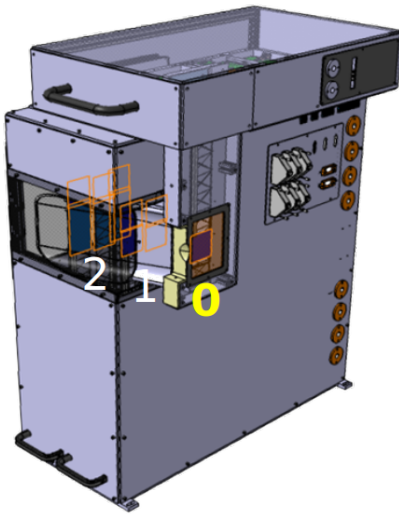


Figure 1: CAD design of the mSTS setup with its upgrade.

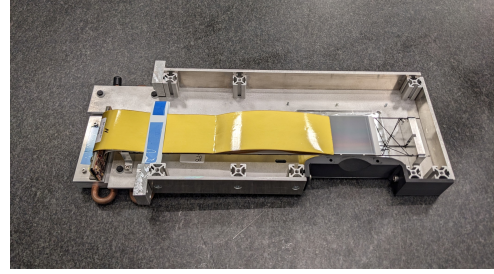


Figure 2: Module, mounted on the ladder, being installed in the system.

The noise performance of the module has first been measured after the assembly in the module carrier in the STS laboratory, and has been re-measured after integration on the ladder in the STS box and final installation in the mCBM cave. These measurements shown in Fig. 3 show that the noise level is consistent with the calculations which include the contribution of sensor and ASICs. A few more broken channels (11, on the p-side, visible on the right end of the figure) add to the 14, determined after the assembly process. In total they are below 1%, well within the standard STS acceptance criteria.

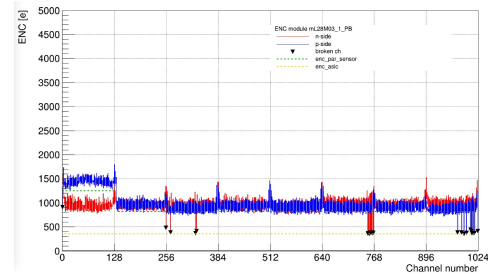


Figure 3: Noise performance (ENC) of the module after final installation in the cave.

The photos in Figs. 4 to 9 show some views of the new and the existing STS box installed in the mCBM cave.

References

- [1] M. Teklyshyn et al., CBM Progress Report 2021, 62-64
- [2] D. Ramirez et al., CBM Progress Report 2021, 69-73
- [3] D. Ramirez et al., CBM Progress Report 2022, 66-69
- [4] D. Ramirez et al., this report

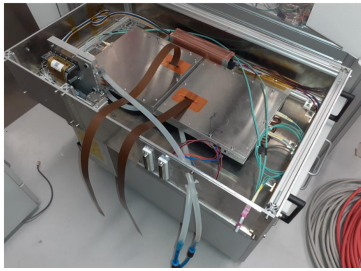


Figure 4: The new mSTS: Sensor box on the bottom and service box (still open) on top.

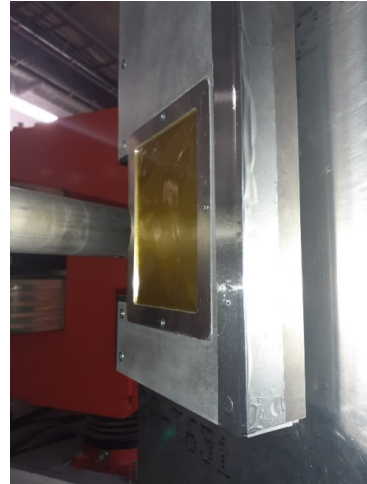


Figure 7: New sensor box with its entrance window. The beampipe is visible in the background.



Figure 5: Service box for the new mSTS module on top of the existing mSTS box.



Figure 8: Side view of the two mSTS boxes.

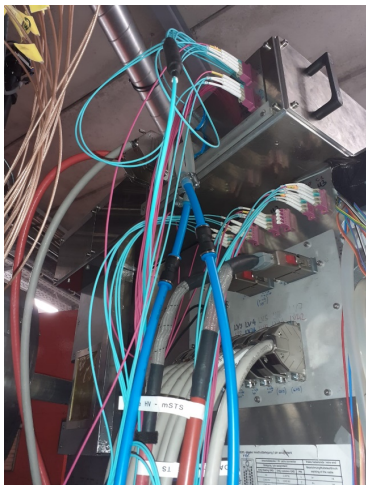


Figure 6: Service connections of the two mSTS boxes.



Figure 9: Low Voltage and High Voltage supplies located at the cave entrance.

J-PARC E16 STS: its status and results of a test experiment at KEK PF-AR

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Introduction

The J-PARC E16 experiment [1] is to measure dielectron mass spectra in p+A collisions at 30 GeV. The physics objective is to measure the in-medium spectral change of vector mesons which is a possible signature of a partial restoration of the chiral symmetry in QCD.

The innermost tracking detector of the experiment is made of the components of the CBM-STs. J-PARC E16 STS comprises eight + two sensors, each with a size of 62 mm × 62 mm that are equipped with FEB8-2v3 [1]. Figure 1 is a schematic of the STS readout chain. A FEB8 board is connected to a GBTxEMU board through a 60 cm Axon flat cable and five pairs of CAT6a cables in 5 + 5 meters. UTP single-wire CAT6a cables were chosen. In the middle of the CAT6a cables is an LVDS repeater board. A special FPGA Mezzanine Card (FMC) of the GBTxEMU was designed to accept the CAT6a cables. It also accepts the J-PARC E16 trigger and clock information through a CAT7 cable from Universal Trigger board 3 (UT3) [2]. The GBTxEMU are read out by GERI boards through optical cables. In a trigger-less mode, all the data are recorded in HDD, which is used in the beamtest described in this manuscript. In a triggered mode, which we intend to use in the J-PARC E16 1st physics run, an online selection of hits is made at GERI according to the E16 trigger timing. We discuss development since the last progress report [3].

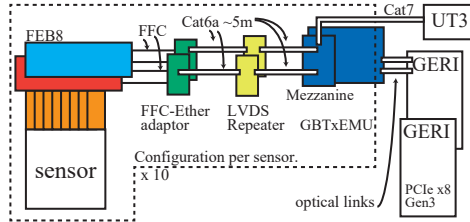


Figure 1: Schematic of J-PARC E16 STS readout chain.

Preparation status

Ten fully assembled sensors on eight ladders arrived in Feb and Mar. of 2023. After individual tests in Japan, they were installed into the E16 STS chamber as in Fig. 2.

Figure 3 is a photo of a special FMC of GBTxEMU boards delivered in Mar. 2023. Firmware was developed accordingly based on the firmware that was developed by W. Zabolotny et al. The E16 firmware differs in several key aspects: it accepts signals via the special FMC, supports 16

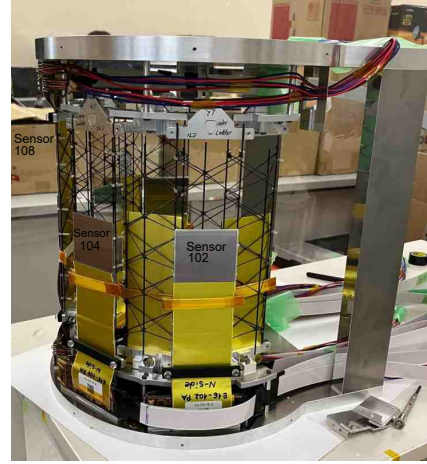


Figure 2: Picture of J-PARC E16 STS upside down. The sensor 108 is in the mirror image position of the sensor 102.

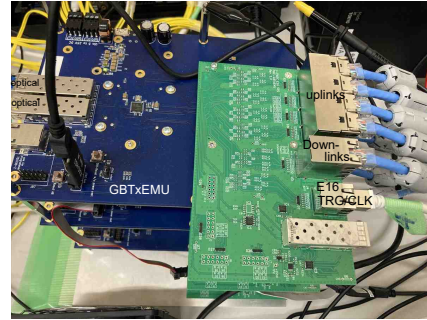


Figure 3: Special Mezzanine card that communicates with FEB8 through Cat6a cables and accepts E16 trigger and clock through a CAT7 cable.

elinks per board (with future support for 32 elinks) up to two elinks per ASIC operating at 160 MHz (320 Mbps), records 32 bit GERI timestamp (`geriTimestamp`) and includes E16 trigger and clock information.

Test experiment at KEK PF-AR

We've performed a test experiment at the KEK PF-AR test beamline to evaluate the performance of our system. An electron beam with a momentum of 3 GeV/c irradiated the sensors intermittently from Nov. 17 to Nov. 21 in 2023.

Four scintillators, each with a size of 10 × 10 mm², sandwiched the J-PARC E16 STS chamber. Two of them

were placed crossed in front of, and the other two were at the back of the chamber. The coincidence signal of the four scintillators was fed into the calibration port of a standalone FEB8 to record the scintillator timing. The coincidence rate was 20 Hz on the average. We tested in two setups A) and B). In A), only hits on both sides of a single sensor (108) were recorded, and in B) hits on both sides of three sensors were recorded simultaneously, where the beam penetrated them all. We only report selected results of N side of the sensor 108 in setup A). The noise level was $800 e$ (0.13 fC), and the threshold for ADC was typically 1.4 fC, and the fast threshold was typically 3.0 fC, later recognized that the fast threshold was too high.

Results of sensor 108N in setup A)

Figure 5 displays a hit profile of sensor 108N. The incident angle was 0 deg. Red (Green) is with (without) scintillator coincidence using `geriTimestamp`, demonstrating a successful operation of the system.

Figure 4 displays the time difference between the sensor hits and the scintillator coincidences measured in 320 MHz 10-bit SMX TDC (`tdcL10b`). The timing resolution was 4.8 nsec which is good enough for the E16.

Figures 6a) and b) display hit profiles for tracks incident at 0 deg and 16 deg, respectively. The red histogram was obtained with `geriTimestamp` cut, while the blue one was with an additional `tdcL10b` cut. The efficiency for 16 deg. is much worse under `tdcL10b` cut. This was attributed to too high TDC-threshold for the inclined tracks, where the charge deposit distributes over several strips, reducing the ADC of each strip. No significant efficiency difference was observed for the 0 degree tracks. The fast threshold must be carefully set low enough for good efficiency.

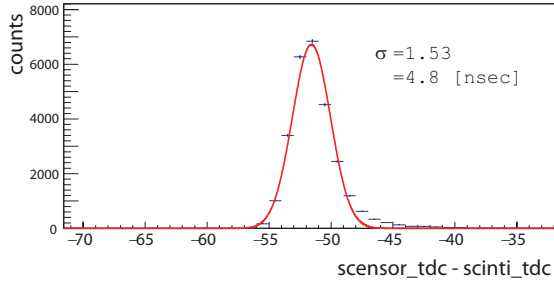


Figure 4: TDC difference between sensor hits and scintillator coincidence.

Summary and prospects

The assembled sensors in GSI were successfully installed into the E16 STS chamber. Hardware for readout chains was completed. Firmware development is ongoing. Remaining is an online event selection of hits at GERI. The overall system shows good performance of efficiency and timing resolution. Careful threshold settings are required

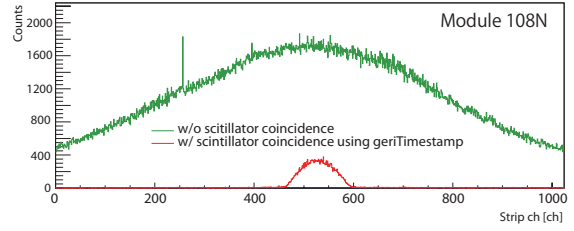


Figure 5: Hit profile of sensor 108N. Green (red) histogram is a hit profile w/o (w/) `geriTimestamp` cut.

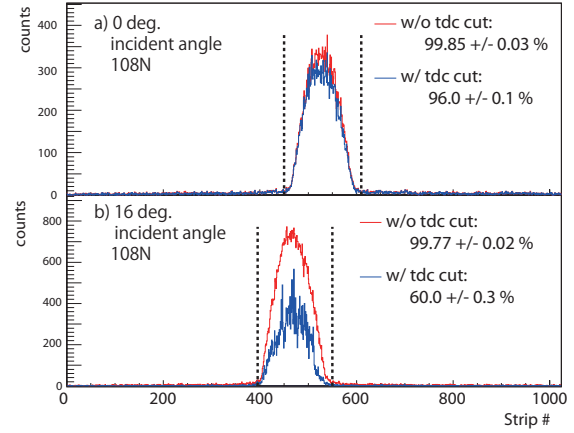


Figure 6: Hit profile for particles incident at a) 0 deg and b) 16 deg. Red shows profile with `geriTimestamp` cut and blue with `geriTimestamp` and `tdcL10b`. Geometrical cuts indicated in the figures are applied to obtain the efficiencies in addition to the timing cuts. Area is not proportional to efficiency as two or more hits may associate to a single scintillator coincidence count.

for good efficiency. We will reinstall the chamber and electronics to the E16 experimental area in Mar. 2024. We expect the beamtime for the beam line and the detector commissioning to start in April of 2024.

We would like to express our gratitude to the STS team for their kind support for the construction and operation of the STS.

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First considerations on a CBM Tracker Upgrade

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Motivation for the Tracker Upgrade

The Silicon Tracker is a core system of the Compressed Baryonic Matter (CBM) experiment. It consists of the main tracker, the Silicon Tracking System (STS), and the Micro Vertex Detector (MVD). The former is specified to measure the trajectory and momentum of charged particles produced in up to 10 MHz p-p, p-A and A-A collisions in the up to 1 Tm magnetic field. The ultra-thin and pixelated MVD complements precision vertexing and extends the low-momentum tracking capability of the system, but is currently limited to a 10 MHz (p-A) and 100 kHz (A-A) rate by the excessive particle rates and radiation loads found near the CBM target. It must therefore be removed during higher rate operation.

Despite their radiation tolerant design, the lifetime of the STS and MVD is limited to a few years. The planned sequential replacement allows for technology upgrades that take into account the rapid advances in detector technology, our improved understanding of detector requirements, and the continuous updates and expansions of the CBM physics mission. Recognising this, the CBM collaboration is developing a conceptual plan for detector upgrades that summarises the state of the art.

Goals of the upgrade

The current upgrade considerations are predominantly technology driven and aim to mitigate and eliminate the consequences of the compromises made in the design of the first generation detectors mostly due to technology limitations. This is particularly the case for the considered rate upgrade of the MVD from the current specifications of 100 kHz to 1 MHz Au-Au, which would substantially extend the reach of CBM for physics cases profiting from its presence and is thus considered a major goal. No rate upgrade is at present considered for the STS as it cannot be exploited without upgrading the more downstream CBM detectors. An STS upgrade should therefore rather accelerate the measurements by improving their sensitivity and data quality at present rates.

By now, four major, somewhat conflicting approaches toward this goal have been identified:

- The geometric acceptance of the tracker (as for the full CBM detector) shows the best performance for the upper SIS100 energies. Extending the polar acceptance from 25° to about 45° would significantly improve the mid-rapidity coverage for lighter particles at lower SIS100 energies.

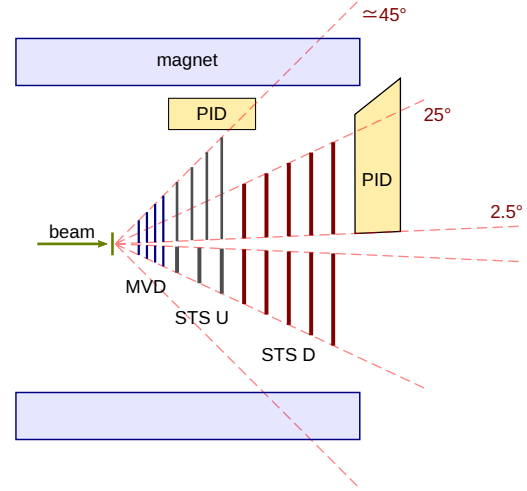


Figure 1: Schematic top view (not to scale) of CBM Tracker before (bottom) and after upgrade (top).

- Early STS designs included pixel detectors in the most upstream STS stations. Due to lack of access to the technology, these pixels had to be replaced by short silicon strips and the associated high occupancies, especially at the highest rates, had to be accepted. The return to pixel technology is expected to significantly improve the robustness of tracking at the highest collision rates.
- The CBM time-of-flight (TOF) system currently consists of an in-beam start detector and an RPC-based TOF detector. While the latter is designed for full CBM rates, the enormous radiation load limits the ion rates of the in-beam detector to $\mathcal{O}(10 \text{ MHz})$. It must therefore be removed at collision rates above 100 kHz, such as those produced by a 1% target. Overcoming this limitation by equipping the upstream part of the STS with a timing plane based on novel silicon timing detectors (e.g. LGADs) would greatly facilitate event reconstruction as well as TOF measurements at high rates. In addition, it would for the first time provide timing information for soft tracks that are bent out of acceptance before reaching the main TOF detector, allowing, for example, the detection and rejection of the tracks of δ -electrons emitted from the target.
- Currently, the momentum resolution of the STS is limited by its material budget (see details below). This

is particularly true at lower SIS100 energies, where the lower particle momentum results in stronger multiple coulomb scattering, and where the magnetic field in the tracker must also be reduced to limit unwanted bending of the primary ion beam. Reducing the detector material budget below the already very competitive present value would mitigate this effect.

Boundary conditions for the upgrade

Recognising the limited resources of the CBM collaboration, we aim for a cost-effective and local upgrade of the tracker. To limit the costs of R&D, production and detector operation, the upgrade should rely on technologies developed by a wider detector community, e.g. within the ECFA-DRD3. CBM should identify R&D partners and contribute to collaborative R&D to gain access to the technology and the know-how to adapt the technology to our specific needs.

The upgrade should at best reuse the existing CBM infrastructure. This is particularly true for the CBM dipole magnet, which will require the retrofitting of a novel detector with extended polar acceptance into its aperture of $1.47\text{ m} \times 3.30\text{ m}$ [3]. In addition, the upgraded detector must remain compatible with the continuous readout paradigm of the CBM-DAQ. This constraint limits the technological options, as it prevents the straightforward use of trigger-based technologies such as those developed for the large LHC experiments. Finally, the rate capability and acceptance of existing CBM detectors must be considered. This discourages an STS rate upgrade, but also complicates an acceptance upgrade in the sense that no PID is available in the extended acceptance region.

On the positive side, the first generation STS is divided into two functional units, the STS U consisting of three layers and the more downstream STS D consisting of five layers. Both units can be replaced separately, providing additional design options.

Design concept of an upgraded detector

Fig. 1 compares the first-generation tracker design with an upgrade scenario. The latter considers the replacement of the MVD and the STS U while the STS D may be reused. The polar acceptance of the replaced detectors will be extended from the present polar angle of 25° to about 45° . The part of the tracker covering this additional acceptance will be denoted as the outer tracker in the following. The number of stations in the STS U is extended to obtain a stand-alone tracking capability in its outer region. An extension of the STS D would be desirable but is hampered by the space constraints in the magnet. Local PID has to be added to the outer regions of the novel STS U, which is again complicated by space constraints. Possible options may consist of using dE/dx information of the silicon detectors, TOF information from an additional timing layer at the end of the STS U and/or adding a pre-shower detector

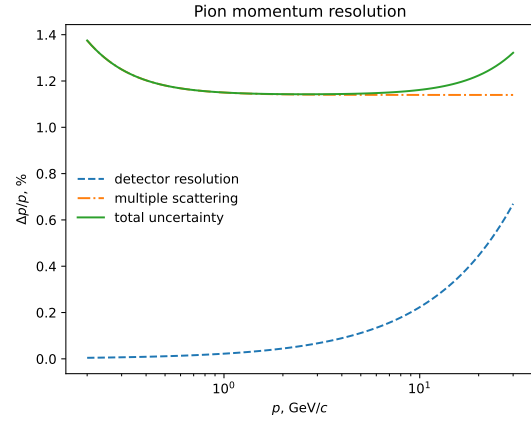


Figure 2: Analytical estimate of $\Delta p/p$ for a pion momentum measured with an idealized present STS. See text.

identifying electrons at the end of this detector. Each of those options has obvious weak points and additional studies are needed to arrive at a convincing solution.

Constraints from momentum measurement

A precise assessment of future detector performance can only be made with the help of a full set of Monte Carlo simulations. However, first simplistic estimates on the momentum resolution of the device can be extracted from analytical expressions for key detector characteristics, as demonstrated in [2] relying on analytical formulations described in [4]. This simplifying approach describes tracking detectors with N equidistant stations with an individual material budget of d , a spatial resolution σ being operated in a uniform magnetic field B . By modeling the present STS with a $N = 8$, $d = 0.64\%$ X_0 , $\sigma = 58\text{ }\mu\text{m}/\sqrt{12}$ and a distance of 105 mm between the stations, one obtains the momentum resolution displayed in Fig. 2. One notes that this resolution is dominated by the multiple scattering term, which is given for with:

$$\left(\frac{\Delta p}{p}\right) \approx \frac{0.0136\text{ GeV}/c}{0.3 \cdot \beta \cdot L \cdot B} \sqrt{(N-1) \cdot d} \quad (1)$$

According to this equation, adding further stations mostly adds multiple scattering hampering the momentum measurement. Increasing the length of the tracker and the magnetic field would improve the resolution but is not compatible with the existing magnet. The remaining handle for improving the momentum resolution of the inner STS consists in reducing its material budget as shown in Fig. 3.

Note that the length of the outer acceptance of the upgraded tracker reduced to $L \approx 50\text{ cm}$ as it is covered only by the uSTS and the MVD. This shrinks to $L \approx 21\text{ cm}$ if the STS U is operated alone. In consequence, one expects $\Delta p/p \gtrsim 7\%$ at best for an isolated tracking in the STS U which is improved to $\Delta p/p \gtrsim 3\%$ if MVD information is

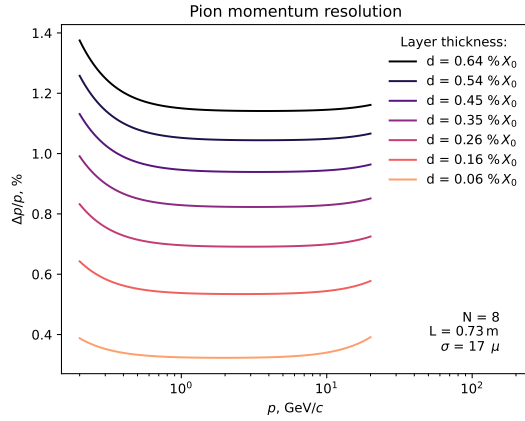


Figure 3: Analytical estimate of $\Delta p/p$ for a pion momentum measured with an idealized present STS as function of the material budget. See text.

added. This value worsens proportionally to a reduction of B as required for low beam energy runs. This questions if the outer STS U be operated stand-alone at the targeted low beam energies. Likely, the MVD will provide decisive benefits. If so, the additional polar coverage can then be exploited only to the collision rate limit of the MVD (1 MHz A–A).

Again, a rigorous reduction of the material budget is the only option to improve $\Delta p/p$. This is complicated by the fact that the material of the vacuum window located between MVD and STS, which is so far ignored, cannot be reduced. In the event of a rigorous reduction of the material budget, $\Delta p/p$ is no further dominated by multiple scattering and improving the spatial resolution of the sensors is beneficial. Equipping the STS U+MVD with stations with $d = 0.3\% X_0$ and a $\sigma = 5 \mu\text{m}$ as realized with the ALICE-ITS2, could improve $\Delta p/p$ to $\gtrsim 3\%$ or $\gtrsim 2\%$ for a outer tracker without or with MVD, respectively.

Constraints from system integration

As the upgrade plans are still in the phase of early discussions, no conclusive studies on system integration have been carried out so far. Obvious points to be addressed consist in the fact that the extended MVD will encroach the keep-out-volume of the STS U and that the extended STS U will encroach the keep-out volume of the STS D. It remains to be proven that these conflicts can be resolved. If considered for stand-alone tracking, the STS U should be formed from $N \geq 5$ stations to allow for robust track finding. While the STS is best installed in air or helium, the established arguments for installing the MVD in vacuum persist.

Past studies showed that the MVD should be formed from four stations to minimize the track matching errors over the 10 cm gap introduced by the vacuum window.

This gap can hardly be reduced as it is determined by the curvature of the vacuum window, which has to be extended in diameter. In consequence, the distance between the STS U stations would amount 4 cm as in the first-generation MVD. As neither the detector geometry nor the underlying considerations are subject to major upgrades, the integration concept of the MVD remains essentially valid. It is therefore proposed to follow and optimize its present integration strategy relying on holding and cooling the sensors with a highly heat conductive support. As discussed further below, the sensors of the timing plane will likely show a worse spatial resolution and a higher power budget as the pixel sensors of the remaining tracker. It should thus be studied if they can be placed within the actively cooled MVD.

As minimizing the material budget of the STS U is decisive for momentum measurements in its outer acceptance, a rigorous focus should be laid on this aspect. This material budget is at present dominated by the 300 μm thick strip detectors and the cables required for readout. Both can be reduced if modern pixel sensors like the 50 μm thin MAPS used in the MVD could be considered. This holds in particular as MAPS integrate FEE and edge computing circuits, which reduces the number of data links and thus the cable mass dramatically as compared to silicon strip detectors. Best results might be obtained if the ultra-thin MAPS could be combined e.g. with the ultra-thin cable technology used in the present STS. The draw back of this choice consists in the fact that the power budget of the FEE and the edge computing is moved from the detector periphery into the active volume. By doing so, the powering and cooling requirements of the active detector volume increases at best by one order of magnitude, which requires a revision of the cooling concept. The cooling challenge is alleviated by the fact that MAPS seem to be compatible with room temperature operation, and seem to show good tolerance to temperature variations and gradients even after significant radiation doses. Moreover, the integration of FEE end edge computing into the sensors makes the related infrastructure aside the detector obsolete. This aspect may be decisive for extending the polar acceptance of the detector.

The material budget of light pixel detectors is to a large degree determined by cables and cooling. This holds in particular as the edge computing circuits run at a low voltage of $\sim 1\text{V}$ and therefore even the currents related to a power consumption fair below 1 W may easily over-challenge the traces of thin micro-cables. A quantum step in material budget is obtained if air/gas cooling has to be replaced by heavier active liquid cooling and independently if direct powering has to be replaced by more powerful but heavier serial or DC/DC converted powering. Both considerations make the power consumption of the sensors a leading parameter for the detector performance. It is considered that the STS U should best rely on gas cooling and direct powering, which suggests that the power of the sensors should remain $\lesssim 100 \mu\text{W}/\text{cm}^2$. Obviously, detailed studies are required to scrutinize this number.

Constraints from particle rates

The CBM trackers will be exposed to high particle rates, which show strong gradients in space and fluctuations over time. The spatial gradients are caused by the fixed target geometry of CBM. In A–A runs, the primary particles arrive about in bunches created by individual A–A collisions. Moreover, a substantial number of δ -electrons is kicked out from the target by the primary ion beam. Those δ -rays outnumber the primary particles in particular in the MVD. Owing to their low momentum, their tracks are strongly bent by the magnetic field and focused to some hot spots found in only one hemisphere of the detector. Resulting from non-interacting ions, δ -electrons come in a quasi-continuous flow, dominate the local occupancy of the MVD and contribute substantially to the occupancy of some sectors of the STS U.

The bunched particle flow created by the Au–Au collisions constraints the time stamping capability of the tracker. One may either aim to separate individual A–A collisions or, way more challenging, to extract TOF information. While the threshold for separating the individual collision amounts a few 10 ns (for 10 MHz A–A, STS) or a few 100 ns (for 1 MHz A–A, MVD), extracting TOF information requires a time stamping of a few 10 ps as known from the TOF detectors. Intermediate time stamping such as a few 100 ps provides little added value beyond rejecting δ -electron hits by time information, which seems nice-to-have but not mandatory. Therefore, no significant design compromises should be accepted for obtaining a time stamping faster than ~ 10 ns in the upgraded tracker. This applies, with the obvious exception of the timing plane.

Despite first related R&D was started, we don't expect one single technology to simultaneously provide a few 10 ps time stamping, the required low material and power budget and good position resolution at the time of the upgrade. We thus foresee two different technologies to cover precision tracking with a time stamping sufficient for event separation for TOF compatible time stamping, likely at the expense of spatial resolution and higher material budget and power. Material budget constraints motivate to restrict the number of timing planes to one. This station should be located reasonably upstream in the system in order to reject most soft δ -electron tracks but neither hamper vertexing or the MVD to STS track matching. Those arguments favor the third MVD or STS U station, where using the MVD would be most efficient but create an obvious conflict with the absence of this detectors at rates above 1 MHz.

Estimates of the rate capability requirements of the sensors have to consider the expected occupancy gradients and time fluctuations. The latter are consequence of the fact that the intensity of real existing beams are not perfectly flat but show a micro-spill structure. Moreover, the collision probability at a given beam intensity is subject to a Poisson distribution. We consider that a peak-to-average of a factor three or above should be considered to account for this effect. To obtain a stable detector, margin to accom-

modate this fluctuation should be multiplied on top of the particle flux expected for the most exposed sensor in the detector. Due to the occupancy gradients, the maximum rate capability will only be required in individual sensors. The option to reduce the data bandwidth in order to save power, as demonstrated in the MIMOSIS sensor of the first-generation MVD, should thus be foreseen.

Considering the beam fluctuations, it is important to distinguish between the average rate (as relevant for the physics performance) and the peak rate (as relevant for the technology requirements) of the detector. In this communication, we interpret the aimed collision rates as *average* rates and a fluctuation margin of three will be added to the detector requirements unless otherwise specified.

A simplified CBMRoot simulation shooting Au-ions into a 1% Au target was used to obtain a first estimate on the expected rates. By using the GEANT4 description of the beam/target interactions, one obtains peak rates of 240 MHz/cm² for the most exposed cm² of the MVD. This number holds more or less independently of the beam energy as the reduced particle multiplicity a lower beam energies is compensated by increased δ -electron flow caused by the necessary reduction of the magnetic field. This rate is reduced by about a factor four if the first MVD station is shifted from 5 cm (as foreseen in the vertexing geometry) to 8 cm (as foreseen in the nowadays favored tracking geometry). A STS U station located 30 cm downstream the target would have to withstand a rate of peak rate of about 26 MHz/cm² for a 12 AGeV beam, which shrinks by a small factor if the beam energy is reduced to 3.5 AGeV.

Simple scaling from the known values of the present detectors suggest that the sensors will have to withstand doses of some 10^{14} n_{eq}/cm² and a few 10 MRad per year of operation of the MVD. As in the present design, we anticipate a scheduled yearly replacement of the most exposed sensors. Unless a rate upgrade is foreseen, this radiation tolerance would allow for several years of STS operation.

Technology options

Accounting for the above mentioned arguments and after having performed a market survey [1], we consider to upgrade the MVD and the STS U with silicon sensors. Due to their small thickness, excellent spatial resolution and excellent power efficiency, next generation Monolithic Active Pixel Sensors (MAPS) appear as a good choice for the tracking detectors. As this technology is already foreseen for the first-generation MVD, the CBM collaboration has the necessary access to this technology. However, the MIMOSIS sensor being developed for the first-generation MVD does not match the requirements of the upgrade in terms of time stamping and rate capability. This does not hold for next generation sensor prototypes as for example explored for future ALICE detectors. Such prototypes demonstrated a ~ 10 ns time stamping capability in combination with a reasonably low power budget and exploiting a novel time-over-threshold technology providing charge

measurement. The latter could potentially provide dE/dx information as needed for a local PID in the upgraded tracker. Also alternative MAPS technology streams aiming for different optimizations are being considered. While the sensing elements presented by the community already fulfill our requirements, they are not yet combined with a suited internal FEE. Significant R&D will be required to add those complex circuits and to obtain a fully developed sensor technology.

The timing plane would typically rely on LGAD detectors. LGAD strip detectors were successfully used at GSI as start detectors of the TOF of the HADES experiment. Again, the CBM collaboration has access to the technology. However, these well performing devices consist typically of individual sensors of few cm^2 size with discrete readout. Scaling this technology up to a full detector calls for dedicated ASICs and in consequence for another significant R&D effort, which may however find interest of further partners. It remains to be studied if such a strip based solution (providing probably the lowest power budget due to the limited number of channels) matches the requirements or if the use of pixelized solutions is mandatory. If the latter applies, it might be worth to follow the ongoing R&D of pixelized high-speed detectors being carried out in the context of the upcoming LHC upgrades.

The integration of MAPS will substantially benefit from the experience available from the design of the first-generation MVD, which is proposed as a blueprint for the upgraded detector. This design reflects the need for vacuum operation and integrates sensors on highly heat conductive, vacuum compatible cooling supports, which are clamped by themselves into liquid cooled heat sinks. The readout of the sensors is performed via conventional, copper based flex print cables. Despite its very light material budget, this design remains somewhat optimized for robustness and for handling the higher power budget of past MAPS generations. The latter feature allows for compromises in the power consumption of the sensors as desirable for operating highest rate MAPS or timing sensors. Alternatively, the material budget of this integration concept could be further reduced by reducing the material strength of the cooling supports. Independently, it might be worth to test the use of the way lighter cable technology of the first-generation STS for the numerous data links.

For integrating MAPS into an upgraded STS, the numerous solutions developed in the context of the ALICE-ITS2/3 upgrades should be considered. The ALICE-ITS2 design comes with a ultra-light and liquid cooled carbon fiber support holding the individual sensors. The sensors on the 30 cm long ladders are readout by a double layer flex print cable. To reduce the material of the cooling pipes and the flex print cable, the upcoming ITS3 upgrade considers the use of self supporting, bent and wafer-size MAPS, which are produced with so-called stitching technology. The material budget of the majority of the detector layer is therefore reduced to the sensor thickness of $\sim 50 \mu\text{m}$. However, at the time of this report and despite significant

progress, the feasibility of realizing this air cooled detector concept is not yet rigorously demonstrated and scaling it to our way more demanding requirements in terms of rates will form a challenge of its own. Currently, it is anticipated that a STS D integration concept would rather rely on conventional sensor sizes held by air cooled ladders.

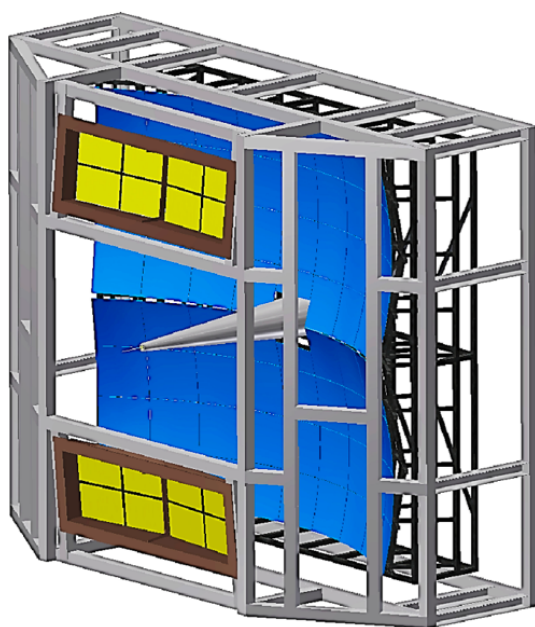
Summary and concept

Due to the limited lifetime of the first-generation detectors, CBM will have to consider a scheduled replacement of its tracking detectors expected in the 2030's. This replacement should be combined with a technology upgrade aiming for: i) a rate upgrade of the MVD by one order of magnitude to 1 MHz A–A, ii) an extension of the polar acceptance of the tracker to approximately 45° to improve mid-rapidity coverage at low beam energies, iii) the integration of a timing plane to improve TOF measurements and event building at high rates and iv) an improvement of the momentum resolution by reducing the material budget. For cost reasons, the upgrade should remain local and retrofit the existing infrastructure including the magnet. As technologies we propose ultra-light and highly granular MAPS, which should provide a time stamping of few 10 ns, a rate capability of up to 240 MHz/ cm^2 and a radiation tolerance of several $10^{14} \text{ n}_{\text{eq}}/\text{cm}^2$ together with a power budget of $\sim 50 - 100 \mu\text{W}/\text{cm}^2$ and a spatial resolution of approximately $5 \mu\text{m}$. In the MVD, the sensors should be integrated into a four layer detector inspired by the present geometry. In the STS, we propose to replace the first 3 stations (STS U) by five layers of MAPS. These layers should preferably rely on air-cooled ladders inspired by the design of the ALICE-ITS2 technology. Since the newly covered outer region ($25^\circ - 45^\circ$) is not covered by downstream particle identification detectors, a local PID system should be considered but a consistent concept has not been developed so far. The novel tracking detectors should be complemented by one timing layer relying on LGAD (of similar) fast detector technology, which would be best located at the third station of the upgraded MVD or STS. Substantial R&D will be required to develop the necessary technologies. However, all building blocks proposed are conceptually covered by the R&D activities proposed by the ECFA detector roadmap, which will allow to share the related effort with the broader community.

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Ring-Imaging Cherenkov Detector



RICH summary

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In 2023, the RICH project made large progress in particular in the construction of the first photodetector plane and cooling tests, the production of FEE electronics, the mechanical design of the mirror frames including first prototypes and a number of improvements in the RICH software. Keeping the future in mind, very interesting first steps have been undertaken investigating the use of SiPMs for single photon detection in rings in a free-streaming readout scenario.

The construction of the photodetector prototype was successfully continued. All backplanes were installed and a test of the gas tightness was performed. Initial leaks could quickly be identified and sealed. Aluminum masks for the air channeling of the cooling system were manufactured and installed. Also, a large part of the FEE electronics was installed and one full column was cabled and powered. A first prototype of the cooling system has been installed for half of the camera and was successfully tested in an open loop configuration. The cooling is running smoothly without strong noise or vibrations. Temperatures on the MAPMT side of the backplane remained below 30°C for the powered column. As all those steps were highly successful, so that this prototype is now considered to be the photodetector plane no. 1. A main milestone still to come is a closed loop system test of the air cooling.

Electronics production went on and by March 2024 1000 (out of 2500) DiRICHes, all 210 Combiner boards, and a preseries of 10 power modules have been produced in addition to the 220 backplanes produced 2022. The remaining power modules will be produced soon, however for the missing 1500 DiRICHes we are awaiting the funding decision of BMBF. Acceptance tests of the electronics are performed showing a very high acceptance level so far (> 95%).

The mechanical design of the RICH detector has strongly gained momentum in 2023 with a new engineer in the team. Starting from the available PNPI drawings, the mirror wall has been investigated in detail, optimized and in particular tested for stability in FEM simulations. By now, the mirror wall is fully designed also considering shocks from earthquake or accidental pushes at the pillars. A prototype mirror pillar and mirror mount have been built and will be tested in a full prototype setup being under construction.

The RICH software is currently undergoing main reworks. After many years since the first setup, all routines are re-evaluated, optimized and updated taking the real data

from the mRICH into account. In addition, new ansatzes are being tested in feasibility studies to reduce secondary electrons by using TRD standalone tracks or the excellent timing of the RICH detector. Very reassuring, we see gains of several percent in electron-ID from several of the new optimizations. Also, the RICH geometry in simulations is pushed to become more realistic. For complicated shapes a fast implementation and check using tessellated geometries is now available.

Looking beyond the CBM RICH detector as being planned now, R&D is ongoing to make use of SiPMs in RICH detectors, i.e. for single photon reconstruction. The challenge of the large noise level typical for SiPMs is even amplified by the fact that we will take data in a free-streaming environment. In order to investigate and eventually develop a working scenario, a test SiPM has been chosen which is currently investigated in the lab. First ideas on intelligent triggers are being tested.

2024 will see important milestones to be reached such as the mirror and mirror alignment EDR, the electronics EDR and first steps towards a RICH mechanics EDR. Risks remain, most importantly the unclear funding situation concerning funds for the RICH mechanical construction (former PNPI contract) and remaining electronics (BMBF). Also, no party has been found yet dealing with the RICH gas system. On top, manpower is on the limit, in particular concerning further firmware development for readout and slow control as well as for the RICH construction itself.

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

Status report of the mechanical design for the RICH mirror support structure

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Introduction

Due to the termination of the contract with PNPI Gatchina, St. Petersburg, the construction of the RICH detector has been taken over and shared between the Bergische Universität Wuppertal and the Justus-Liebig-University in Gießen. Based on the PNPI model, the pillars and the mirror wall frame were developed in Gießen to such an extent that a prototype of one pillar has already been built with a small frame prototype to come.

Pillar

The design of the original pillar (PNPI design, Fig. 1) was adapted so that almost all welded connections were replaced by screw connections (JLU design, Fig. 2). This was done because welding aluminum typically causes relatively large distortions. A first pillar prototype following the JLU design has been built (fig. 3).

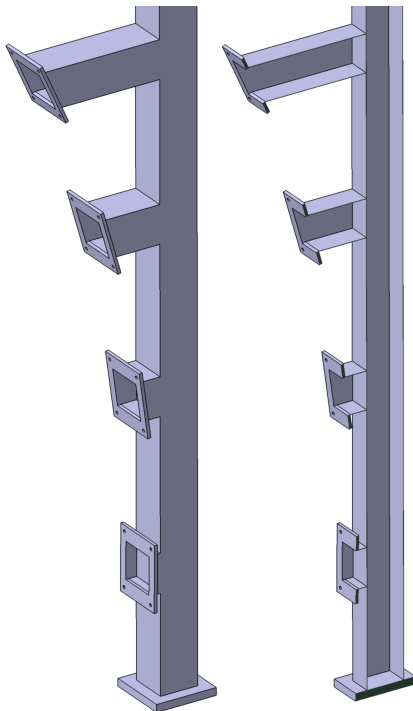


Figure 1: Lower half of the original pillar (left: isometric view PNPI design, right: cut view PNPI design)

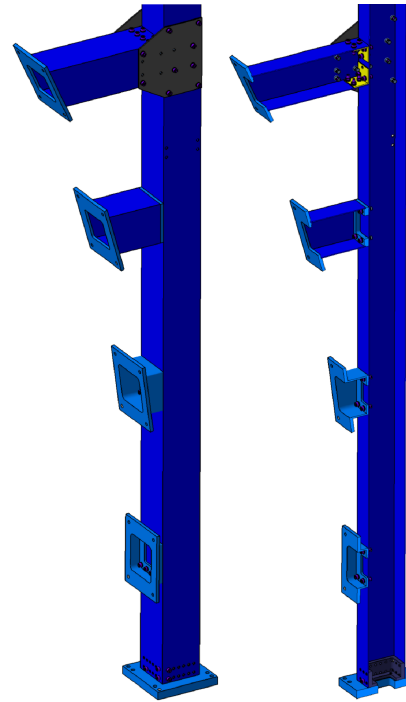


Figure 2: Lower half of the redesigned pillar (left: isometric view JLU design, right: cut view JLU design)

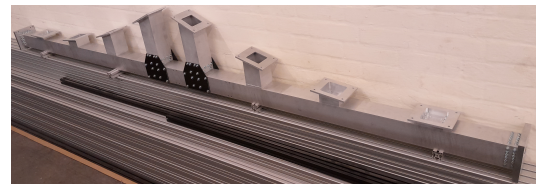


Figure 3: Finished pillar with bolted consoles (JLU design)

On the largest console (Fig. 4, left), the front plate (connecting plate for the mirror holder) is welded to a square tube. On the second largest console (Fig. 4, right), the front plate (connecting plate for the mirror holder) and the back plate (connecting plate to the pillar) are welded to a square tube. These are by now the only welded connections for the whole pillar.

To increase the stability of the middle mirrors (largest console), two reinforcement plates were attached to the outside of the central area of the column, as well as additional brackets on the inside. These additional components

are made of CFRP (carbon-fiber-reinforced polymers) and screwed to the pillar and console.

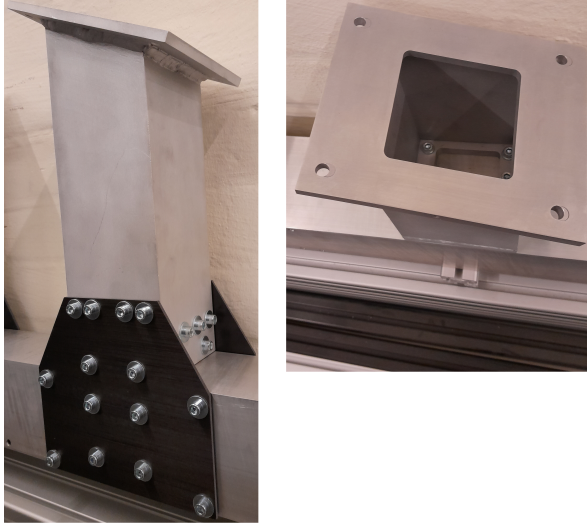


Figure 4: The two middle consoles (left: largest console, right: 2nd largest console), both attached to the pillar

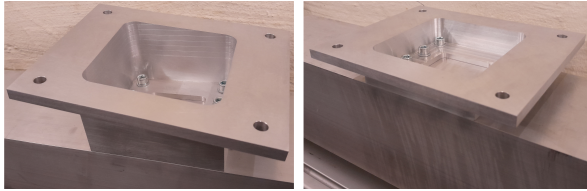


Figure 5: The two lowest consoles (left: 2nd lowest console, right: lowest console), both attached to the pillar. These two consoles are milled from solid aluminum.

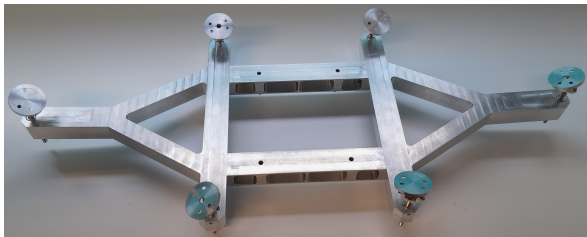


Figure 6: Bolted mirror holder with joints

Mirror wall frame

The original frame (PNPI design, Fig. 7) consists of bolted and welded aluminum components. The struts between the pillars are bolted and also from aluminum.

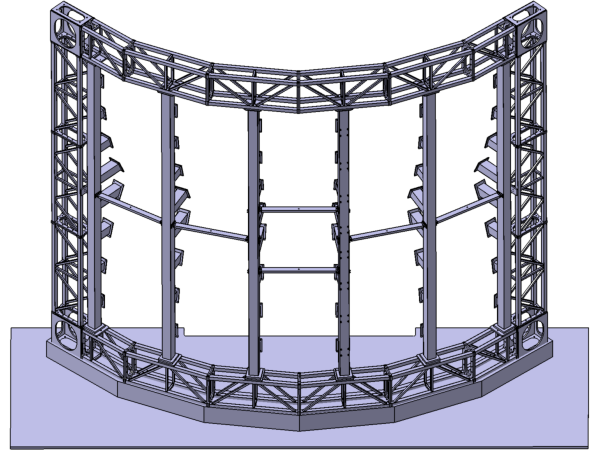


Figure 7: Original frame with pillars (PNPI design)

For economic reasons, the revised frame (Fig. 8) consists of aluminum trusses (standard components from event technology) at the sides and top. For the lower frame construction, the pillars are extended by around 1 m to have the same length as the side trusses. The pillars are attached to the platform via 45° struts made from steel or CFRP tubes in a truss construction.

The arrangement of the horizontal struts between the pillars was adopted from the PNPI design. The structure of those struts now consists of CFRP tubes that are bolted to the pillars using suitable adapters.

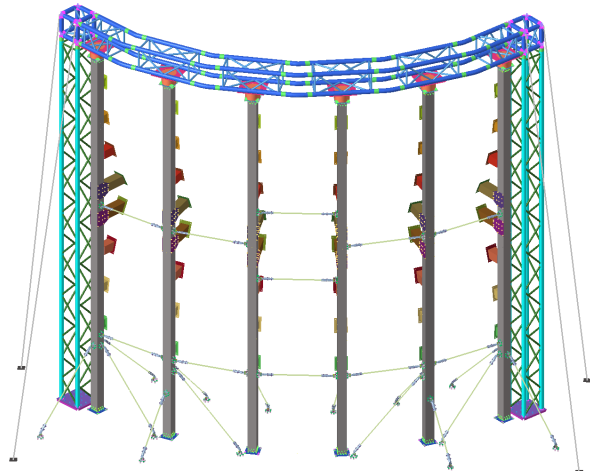


Figure 8: Reconstructed frame with pillars (JLU design) Due to the resulting larger mounting surface and steel cables at the corners, the entire mirror wall has greater stability compared to structures based on the PNPI design.

Pillar adjustment

Every component has production-related tolerances. These tolerances are permissible. However, to ensure the exact position of one or more components - such as the mirrors -, adjustment devices must be provided. The mirrors itself will be aligned by three adjustment screws, however have to fit in the overall frame.

In order to align the mirrors as precisely as possible, the pillars must first be aligned. Each pillar has an adjustment device at its upper (Fig. 9) and lower (Fig. 10) end for this purpose.

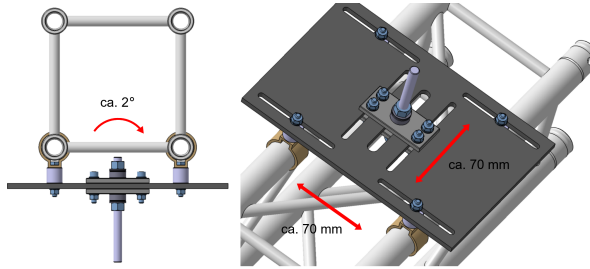


Figure 9: The top adjustment consists of three sliding plates that are attached to the frame with clamps. The top end of the pillar is attached to the lower end of the threaded rod.

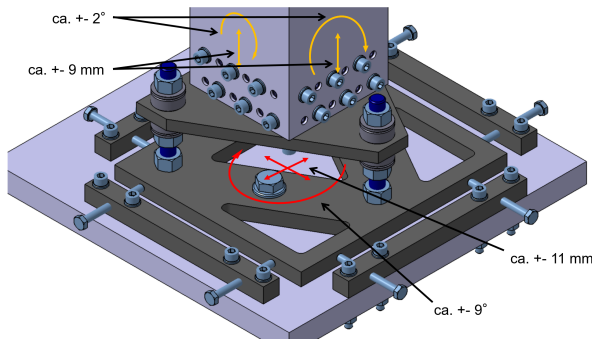


Figure 10: The bottom adjustment consists of a height-adjustable tilt plate mounted on a sliding plate. The side clamping steels are used for horizontal adjustment.

These adjustment devices allow each column to be rotated by a few mm or degrees around the vertical axis, moved horizontally in any direction, moved vertically and tilted in any direction. Any combination of the individual adjustment options is permitted.

Finite element analysis

A static stability check was made by FE simulations, see fig. 11. The program used was HyperWorks 2021.2 with the OptiStruct solver from Altair. Besides the calculation of deformations under the effect of gravity, possible displacements due to crane touchdown or accidental pushes against the frame were calculated. Always, deformations are below 1 mm and mirrors are never in danger to touch each other (standard distance 3-4 mm).

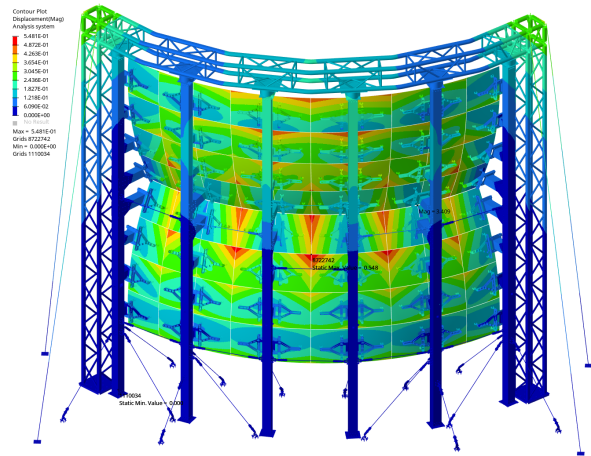


Figure 11: Result of FE simulations for all displacements under the effect of gravity.

The maximum value of 0.548 mm for deformations of mirrors due to gravity is within tolerances. This means that this deviation - compared to the force-free representation (Catia) - can be compensated for by the three adjusting screws of one mirror. The smallest distance between the mirrors is 3,409 mm.

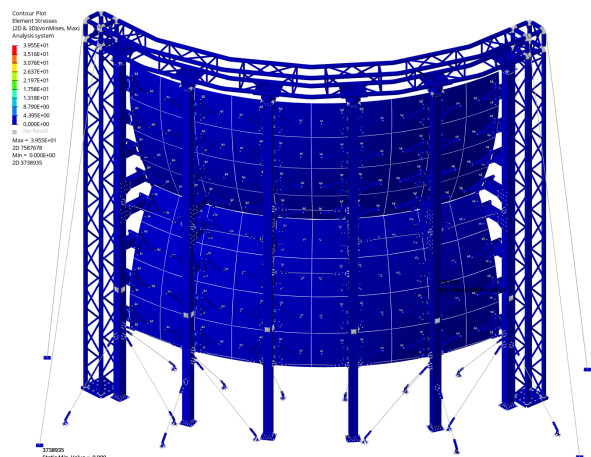


Figure 12: Result of FE simulations for all tensions under the effect of gravity.

An analysis of the tension due to gravity revealed that the maximum value of 39.554 MPa is located on a pillar and thus confirms the stability and high safety against deformation. The material of the pillars is the aluminum alloy EN AW 6060 T66 and has a yield strength ($R_{p0.2}$) of 160 MPa.

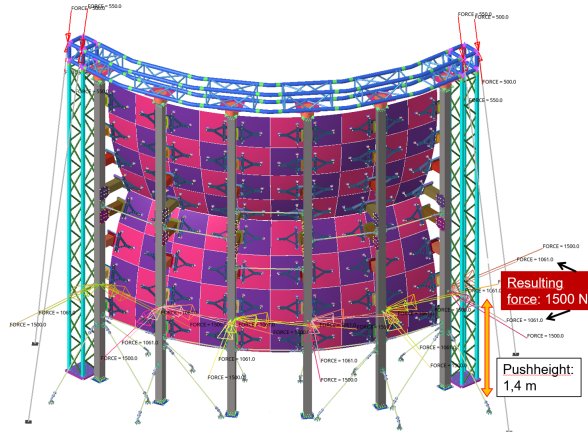


Figure 13: Investigation of various impact points at a height of 1.4 m

Results of impact tests due to unforeseen pushes against the pillars show that the minimum distance between mirrors is still larger than 2 mm under the conditions shown above (figure 13). However, the stresses in the affected pillar briefly increases to 150 MPa. As already mentioned above, permanent deformation of the pillar only occurs at stresses above 160 MPa.

Further investigations of setting down and lifting of the RICH-Detector by crane show that even in the worst case, the minimum distance between the mirrors is almost 3 mm. The worst case is when all three crane axes are moved simultaneously while the detector hangs crookedly on the crane (up to 7°, figure 14) and is placed on the ground during an earthquake.

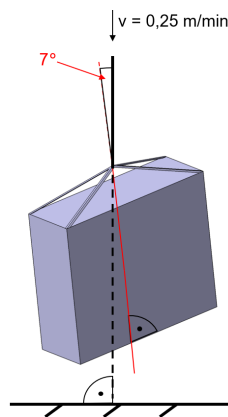


Figure 14: Sketch of the RICH-Detector hanging crookedly on the crane

Prototype

In order to investigate the realistic behavior of the mirrors and compare them with the simulations, a prototype (Fig. 15) with a pillar and four mirrors is being constructed in Gießen. Four mirrors are available and will be installed soon, the forces of the remaining twelve mirrors will be simulated with weights. This prototype will also be used to check the various adjustment options for weak points. Parts of the frame and the adjustment devices for the pillar of the prototype can be used for the RICH detector after approval.

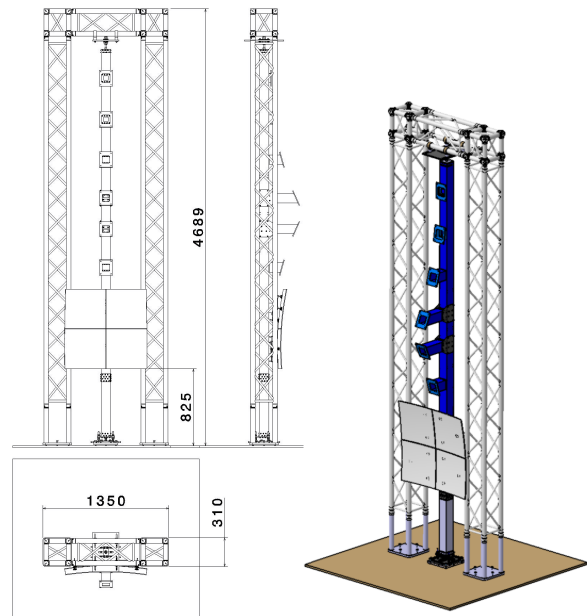


Figure 15: Drawing of the prototype with dimensions in mm. The isometric view is from Catia.

Summary

The PNPI design (pillars and frame) has been adapted because welding aluminum typically causes relatively large distortions. In addition, various changes have been made to increase efficiency and stability.

To compensate for manufacturing tolerances, each pillar has an adjustment mechanism at its upper and lower ends.

An FEA has confirmed sufficient stability against deformation and sufficient spacing between the mirrors.

A prototype with one pillar, four mirrors and a matching frame is currently being built in Gießen.

Progress in constructing the first CBM RICH camera module, cooling system and readout electronics

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CBM RICH camera

Work on final assembly of the first of the two photon camera modules for the CBM RICH detector has proceeded well over the last year. The first camera module is now finally assembled, following the previous, temporary test assembly aiming for confirmation of the overall design. The 14 CNC-milled aluminum column elements forming the cylindrical detection plane (curvature radius $R = 1650$ mm) are now permanently screwed and glued together, ensuring not only gas tightness, but also maximum structural stability. A well-defined sealing gap of 0.3 mm was maintained during mechanical assembly using spacer washers, and Loctite SI 5970 was used as a sealing compound in addition to the threaded connection. A reliable and permanent gas tight seal of all elements of the camera box is essential since the camera module is part of the gas vessel enclosure, keeping the CO₂ radiator gas contained inside [1]. The front side of the camera module has been fully equipped with $14 \times 7 = 98$ backplane PCBs (BKPLs) later carrying the photon sensors (camera front) and front-end electronics (camera inside). Each BKPL previously was rigorously tested (using a dedicated lab test setup) for full functionality, all measured test data are archived and available for later reference. A gas tight seal of the backplane PCBs (anticipated working pressure 2-5 mbar, max. test pressure 20 mbar) is assured using individual O-rings beneath each PCB, situated inside CNC-milled grooves on the camera front elements. An important milestone was the

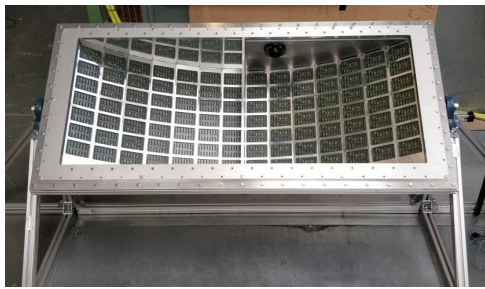


Figure 1: Camera module fully assembled and held by the maintenance rack, looking into the module where readout electronics will be placed.

test for gas tightness of the fully assembled module. To assess the gas tightness of the camera volume, the readout electronic volume was completely sealed with a metallic cover plate. Pressure inside the sealed camera module could be either raised using a CO₂ gas bottle with pres-

sure regulation valve, or reduced using the cooling system blower input port. Initial leak search was done in overpressure configuration, using a highly sensitive leak detector on the outside to pinpoint areas of impermeability. Five leaks were found, two of them due to leaks in the critical Loctite sealing between neighbouring column elements. The remaining leaks were found in improper sealing of several backplane PCBs. On closer observation, these leaks were caused by manufacturing tolerances in the groove depth for the O-rings being larger than initially anticipated. The problem could be solved by changing to slightly larger O-rings.

For the final test, the pressure within the camera volume was reduced to -20 mbar below ambient pressure, the inlet / outlet valve was closed, and the pressure increase monitored over longer time using a digital gauge.

As depicted in fig. 2, after all fixes, the sub-atmospheric pressure could be maintained for a duration of 16 minutes with an observed pressure drop of less than 0.2 mbar. Assuming a recipient volume of 0.5 m^3 , this results in an upper limit for the leakage rate of $Q_l = \frac{\Delta p V}{\Delta t} < 0.1 \text{ mbar l/s}$ (at 10x nominal working pressure gradient). This is well sufficient for safe operation of the camera module.

Establishing over/under pressure of up to ± 20 mbar inside the camera also posed a crucial test for the structural stability of the camera design. Only minimal deformation of the camera front ($\approx 1/10$ th of a mm) could be observed at maximum overpressure, in accordance with previous FEM simulations.

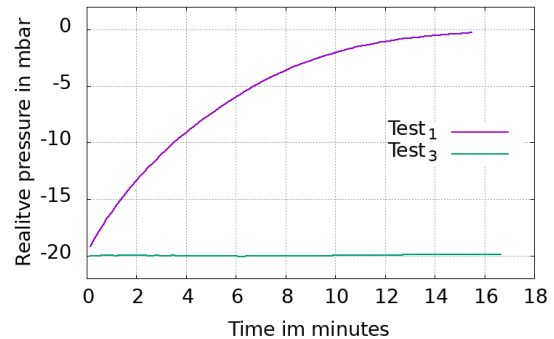


Figure 2: Measured pressure change in mbar vs. time in minutes. Based on the data from test 1 (purple curve), it can be seen that few initial gas leaks existed; after fixing these gas leaks, sufficient gas tightness of the camera module was achieved as demonstrated by test 3 (green curve).

Camera cooling system prototype

Essential progress has also been achieved in setting up the air-cooling and air-distribution inside the camera module. Based on experience with the HADES RICH detector, adequate cooling of the camera module will be of paramount importance. The cooling system has to handle the heat dissipation of 3 kW per camera module (1.5 kW/m^2), emitted into the closed camera volume (0.5 m^3). Its primary objective is to maintain the operating temperature of the MAPMTs below the critical threshold of $\approx 32^\circ\text{C}$, above which the MAPMT darkrate shows substantial exponential increase and unstable behavior [3]. The MAPMTs are in good thermal contact with the backplane PCB via numerous connectors. In order to prevent heat accumulation close to the MAPMTs and BKPLPs, the incoming cooling air is injected close to the backplane via a complex air distribution scheme, pushing the heat away from the PMT side, backwards into the camera box volume. Here, the warm air is extracted and recirculated via an external blower plus heat exchanger. A key component in this air distribution system is the so-called back plane cooling mask: These aluminum "masks", mounted in-between backplane PCB and front-end readout modules, not only provide mechanical fixation for the electronic modules; they also serve for distribution of the cooling air over the full readout plane. After finalizing the "mask" design over many iterative steps using 3d-printed prototypes, a first batch of 100 masks (200 be needed in total for both cameras) has now been manufactured out of aluminum. Each mask consists of two CNC-milled half pieces, screwed and pinned together for good mechanical tolerances, and can be manufactured in our local university workshop.

Air distribution from the upper and lower air inlet ports towards each front column is achieved using hollow, CNC-milled air distribution plates covering the inside of the camera top- and bottom plates. The active cooling of these large inner surfaces will additionally support the camera cooling. A photograph of the first air distribution plate can be seen in fig. 4.

The external air circulation system, consisting of a large water-air heat exchanger (to be later mounted inside the cave, close to the RICH) and a preliminary blower, which is now regularly used for testing the setup, had been previously presented [4].

Next Steps

With the construction of the first CBM RICH photon camera nearing completion, we are now looking forward to a final, full-size system test of the camera, fully equipped with readout electronics. A first batch of 1000 DIRICH modules (2500 needed in total for both cameras, including spares), and all 210 DIRICH-Combiner modules have already been produced (at GSI) and are being tested and programmed right now. Production of the full batch of 210 DIRICH-Power modules is currently sheduled and should proceed soon.

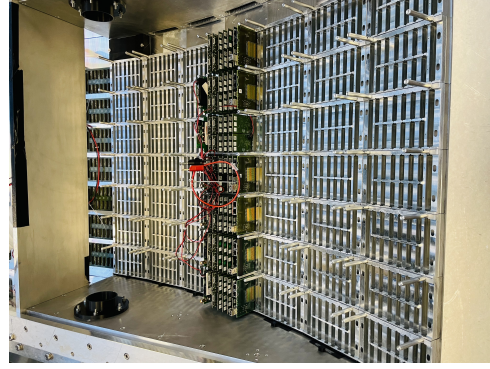


Figure 3: The air cooling system of one half of the camera, with a fully equipped column of read-out electronics in the center column.

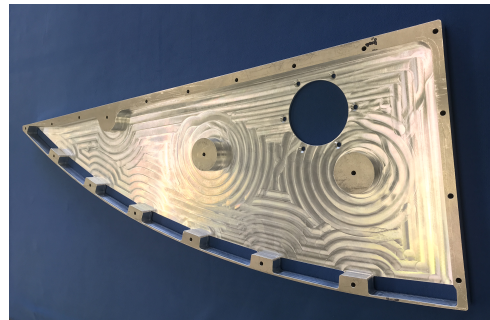


Figure 4: The air distribution plate, CNC milled out of a solid aluminum block ($1200 \text{ mm} \times 400 \text{ mm} \times 30 \text{ mm}$).

For a final test of the cooling system we plan to close the camera box volume, and operate the cooling system in closed loop, recirculating the heated air via the water-air heat exchanger. This test will not only represent the final validation of the cooling concept, but also provide valuable information on the required air flow capacity and performance rating of the final air blower system.

References

- [1] D. Pfeifer et al., Prototype of the CBM RICH photon detector, CBM Progress Report 2021, p. 79
- [2] D. Pfeifer et al., Camera cooling prototype - first measurements, CBM Progress Report 2020, p. 63
- [3] V. Patel et al., Temperature dependence of dark noise for H12700 MAPMTs, CBM Progress Report 2016, p.74
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RICH digitizer

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Update of the existing digitizer

With availability and experience with the free-streaming mRICH data, it became clear that for a more realistic simulation, a complete replacement of the signal processing and digi creation was necessary in the RICH digitizer. This update ensures that all MC signals from detected Cherenkov photons, charged particle tracks and noise signals are first buffered for each channel/pixel. In case of the time-based processing, the buffer gets only processed at each next event, until the timelimit $t_{Limit} = \text{CurrentEventTime} - \text{PixelDeadTime} - 5 \cdot \text{DigiTimeSmearing}$. This makes sure that all signals from different sources are buffered until this point in time. For event-by-event digitization, the buffer is fully processed after each event. When processing the buffer, signals for each channel are sorted in time first. Afterwards, signals are iterated sequentially and digis are created, taking into account the channel deadtime. Signals within the deadtime of a previous digi are added per CbmLink to this digi.

The mapping from RichPoints to channel addresses is now no longer done by position using the TGeoManager. Instead, the addresses are directly stored into RichPoints during transport, with no additional overhead since the current node is always known anyway. This results in a RICH digitization speedup of factor 3 and properly solves a boundary problem, increasing the number of RichPoints from charged particles by a factor of 2. Also, these changes ensured a proper handling of in particular noise.

Digitizer noise

A previously missing software feature was the knowledge about the neighbours of a given MAPMT pixel. In the current geometry hierarchy, individual pixels are only translated in x and y position in their parent volume (MAPMT volume). This is utilized to derive pixel indices from the geometry by sorting and comparing all pixel position translations for a given MAPMT in its parent volume. Given the pixel indices, two types of noise responses were implemented in the RICH digitizer in addition to the equally distributed random noise.

First, the re-implementation of crosstalk, where a MC signal (after quantum-efficiency check) has a certain probability to produce exactly one additional signal in a direct horizontal/vertical or diagonal neighbouring pixel. This crosstalk probability can be set individually for all 3 directions. Added crosstalk signals share the same CbmLink to the MCPPoint as the source signal.

Second, noise clusters, which are mostly caused by

charged particles directly passing through the MAPMT's. This is mostly predominant for the proximity focussing mRICH setup in the mCBM experiment [1]. Still, it will probably also be relevant for the CBM RICH, although the signals will be independent and not correlated to a ring. The noise clusters are randomly generated in pixels nearby MCPPoints from charged particles, while the overall maximum size and intensity of the clusters can be adjusted. Added signals from this source are marked with an index -1, the same as random noise. This feature is currently disabled by default. Both of the noise types only produce additional signals to neighbouring pixels on the same MAPMT as the source signal.

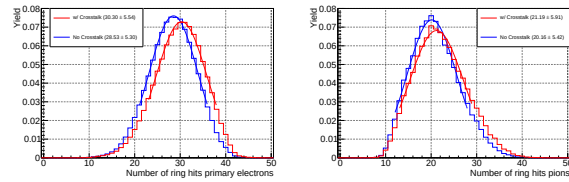


Figure 1: Number of ring hits for (left) primary electrons [BoxGenerator] and (right) pions with (red) and without (blue) crosstalk. Crosstalk probability: 2% for horizontal/vertical and 0.5% for diagonal pixels.

Crosstalk immediately increases the number of ring hits of found RICH rings. 100k UrQMD 12 AGeV Au+Au central collision events, together with 5e- and 5e+ embedded in each event using the BoxGenerator with $p_T \in [0, 3]$ GeV/c, $\theta \in [2.5^\circ, 25^\circ]$ and $\phi \in [0, 360^\circ]$ are simulated. Overall, the mean number of ring hits increased by 6.2% for primary electrons and 5.1% for pions, see figure 1.

Outlook

The RICH digitizer received many technical and detector response improvements, parameters such as crosstalk and digi time resolution might still be adjusted in the future. The good timing resolution of the RICH could possibly be used for more applications, as described in [2].

References

- [1] M. Beyer et al., Pattern recognition on mRICH simulation data using machine learning, CBM progress report 2022 p. 89-91
- [2] P. Subramani et al., RICH timing precision and its possible applications, this report.

Parameter optimization for the Hough Transform ringfinder

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Intoduction

The current RICH ringfinder [1] is based on the Hough Transform method (HT) by calculating circle parameters for triplets of hits defining a ring and filling the resulting ring center in a 2D and radius in a 1D histogram (HT histograms). This procedure is done for all hits individually and optimized by reducing the combinatorics, utilizing the minimum/maximum radius for Cherenkov rings and thus limiting the search distance for hits forming triplets. After accumulating the results of all triplets in the area, it is checked whether the entries of certain bins in the HT histograms exceed a defined threshold, which results in a ring candidate. Ring candidates are already here checked for true and false rings using a ring selection network based on an artificial neural network (ANN) architecture, together with a threshold value for the output of the ANN. Additional parameters are used to only match hits in a certain radius corridor to a found ring candidate. Last, ring candidates are then processed by checking for shared hits quota, reducing clone rings and resulting in the final reconstructed rings.

Main difficulties of finding rings in the RICH are caused by ring distortions from the residual magnetic field and the detector granularity. Also, overlapping rings increase the ring finding difficulty, which is common for the high hit density area in the central region of the RICH cameras.

Given the number of parameters of order 10 of the HT ringfinder algorithm, it is an optimization task to maximize the amount of correctly found rings from primary electrons and pions, while minimizing the amount of fake rings. So far this optimization was only done in an approximation by hand.

Procedure

The parameters of the HT ringfinder are floats and integers and are all highly correlated. This is a very difficult or even impossible task for gradient-based optimization procedures to optimize on such a non-contiguous and non-convex loss surface. Instead, a random search approach is used to explore the parameter space and find a more optimal parameter set. For this optimization study, the ring selection network is not used.

In order to quantify a parameter set, it is evaluated using the ring reconstruction efficiency for primary electrons, pions, all particles together and the overall ring purity. The ring reconstruction efficiency is defined as $\text{Efficiency} = N_{\text{true reco. rings}}/N_{\text{acc. rings}}$, where a ring is defined

as true reconstructed if more than 70% of its matched hits have a contribution from the same Monte-Carlo particle that produced the photons. Accepted rings have at least 7 hits containing photons from the same Monte-Carlo particle. To minimize fake rings, the ring reconstruction purity is defined as $\text{Purity} = N_{\text{true reco. rings}}/N_{\text{all reco. rings}}$.

To directly compare different parameter sets, those metrics are condensed into a single value defined by a weighted entropy-like loss function (Eq.1). Primary electron efficiency and purity are weighted with a factor of 2, to have a larger contribution in the to be minimized loss function.

$$\text{Loss} = -\frac{1}{6} [2 \log(\text{Eff. Primary electrons}) + 2 \log(\text{Purity}) + \log(\text{Eff. Pions}) + \log(\text{Eff. All})] \quad (1)$$

The optimization procedure was performed on 12 AGeV Au+Au central UrQMD events as background, with 1 PLUTO particle embedded in each event. The dataset used for optimization (training) contains 15k UrQMD events, with ϕ , ρ_0 and ω_{Dalitz} PLUTO particles embedded for each 5k events. Electrons from ϕ 's are mostly in the central region because of their momentum distribution and therefore suffer from overlaps with different rings. In contrast, ρ_0 and ω_{Dalitz} electrons have generally lower momenta, thus are populated more in the outer regions of the camera in horizontal direction and are generally more distorted because of track bending in the magnetic field, resulting in smearing of the Cherenkov photons. To balance out the dataset, ρ_0 and ω_{Dalitz} electrons are both used, since the geometrical acceptance is smaller and therefore also the sample size of rings compared to ϕ electrons.

The dataset is split up into 15 time slices (Ts) of 1000 events each to reduce memory consumption. Additionally, an early stop is used, which breaks the current parameter iteration if after any of the Ts the following condition is not fulfilled: $\text{Eff. Primary electrons} < 0.75$ or $\text{Eff. Pions} < 0.30$ or $\text{Purity} < 0.70$. This early stop mostly occurs after the first Ts and reduces the overall computation time by 87%. Out of 50k parameter sets, only 2942 remain.

Results

Two parameter sets are compared: the current parameters (Base) and the one found by the random search (New), minimizing the loss from equation 1. In figure 1 the parameter sets that survived the early stop are shown with their corresponding metrics. The *New* parameter set shows better performance for all metrics compared to the *Base*

Dataset	Parameter set	Eff. all	Eff. primary electrons	Eff. pions	Purity	Latency / Event
Train	Base	0.6265	0.8304	0.3329	0.7036	7.03 ms
Train	New	0.6730	0.8900	0.3930	0.7182	6.35 ms
Test	Base	-	0.8287	0.3324	0.7029	-
Test	New	-	0.8840	0.3902	0.7202	-

Table 1: Comparing various metrics for different data and parameter sets.

parameter set, even increasing the purity slightly. It is now located in performance regions, which only very few parameter sets can achieve and many of those only show good performances in individual metrics.

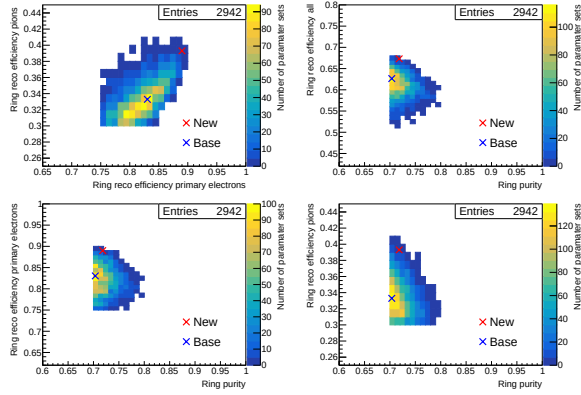


Figure 1: Comparing ring reconstruction efficiencies and ring purity for different metrics used in the loss function.

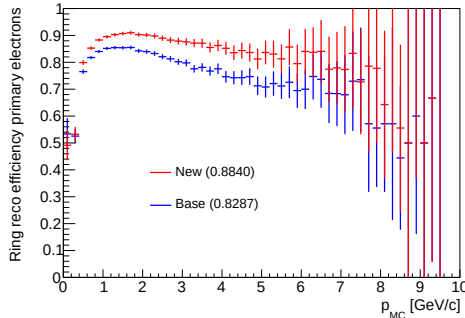


Figure 2: Ring reconstruction efficiency for primary electrons in dependence on momentum for different parameter sets.

Because of the computing time, only 15k events were used for the parameter optimization process. In order to validate the performance and avoid a potential overfit to the training set, the *Base* and *New* parameter sets are evaluated on a larger dataset (test). For this, 600k events are used with different PLUTO particles embedded. For each 100k events, a different particle is used from the following types: ϕ , ρ_0 , ω_{Dalitz} , ω , η and π^0 . In table 1 the data and parameter sets are compared, the values do match between

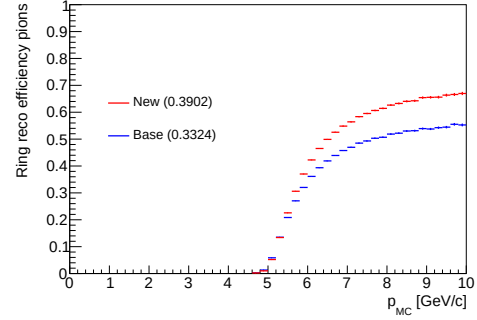


Figure 3: Ring reconstruction efficiency for pions in dependence on momentum for different parameter sets.

the training & test set and show no hints towards any overfit.

In figure 2 the ring reconstruction efficiency for primary electrons shows very clearly the performance increase compared to the old parameters, integrated over momentum the gain shows a 6.7% increase. Furthermore, for pions the integrated efficiency increases by 17.4% as shown in figure 3. Both of those improvements are even accompanied by increasing the purity by 2.5%.

Conclusion & Outlook

A random search approach is usually only the first stage in such a kind of parameter optimization, followed up by an optimization technique like a genetic algorithm. Such an optimization technique is more difficult to run in parallel and the performance increase will most likely be in the regime of the statistical error, which would then require an even larger *training* dataset for valid results. Whether the parameters can be further optimized this way remains to be studied. The parameter optimization procedure using random search showed a significant increase in ring reconstruction efficiency for both primary electrons and pions, while also increasing the ring purity. To further increase the purity, the current ring selection ANN will be updated. Furthermore, it will be investigated whether it can be placed at a different stage in the HT algorithm with fewer inferences, since using the ANN currently increases the runtime by a factor of 100.

References

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RICH track extrapolation and ring track matching

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Introduction

One part of the RICH reconstruction routine is the matching of found rings and STS track projections. For this, reconstructed tracks from the STS are extrapolated into the RICH cameras. The current procedure is separated into multiple steps, starting with the extrapolation of STS tracks into an extrapolation plane, which is a fixed plane at a certain z position. During this step, the magnetic stray field and energy loss in the medium are taken into account. After reaching the position in z , tracks are straight line extrapolated into the mirror. In the case of crossing the mirror, tracks are reflected and again straight line extrapolated into the RICH camera. Those track projections that reach the active area of the photcameras are then used for ring to track matching, whereas currently a ring is matched exactly to one track projection. There are typically around a factor 10 more track projection compared to reconstructed rings. This is because in each event, there is a large amount of pions and protons not exceeding the Cherenkov threshold and therefore not producing corresponding rings. Therefore, for particles that are measurable by the RICH, i.e. electrons and pions with $p > 4.65 \text{ GeV/c}$, precise track projections are required to avoid matching rings with projections from all the other background tracks.

Energy loss

For a precise STS track extrapolation into the extrapolation plane, the magnetic stray field and the particle's energy loss has to be properly taken into account. The current default extrapolation routine for the RICH is the LitExtrapolator, which showed biases in horizontal ring track distance depending on charge. In the case of the RICH extrapolation, an electron mass hypothesis is used for all STS tracks, in order to be as precise as possible for the ring track distance of primary electrons. The underlying problem that resulted in biases for the ring track distance in x direction, was the use of Bremsstrahlung to account for energy loss when using an electron mass hypothesis.

To get an idea on the consequences for low momentum primary electrons, electrons from the target position are produced using a BoxGenerator with $p \in [0, 2] \text{ GeV/c}$, $\theta \in [2.5^\circ, 25^\circ]$ and $\phi \in [0, 360^\circ]$, which are then transported using Geant3. When comparing the momentum residual ($p_{\text{Extra}} - p_{\text{MC}}$) in the RICH ReferencePlane¹ shown in Fig. 1 (top), the usage of Bremsstrahlung is clearly not a

¹ A plane (thin box with same material as surrounding volume) in front of the mirror, storing MCPoints from MCTracks entering the volume.

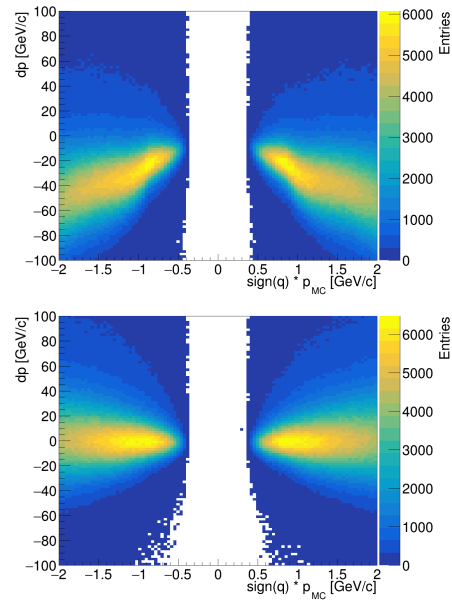


Figure 1: Momentum residuals for track extrapolation if using (top) Bremsstrahlung or (bottom) Bethe-Bloch energy loss for primary electrons (BoxGenerator).

correct description of the energy loss compared to Monte-Carlo (MC) data obtained from Geant3 (Geant4 looks identical). For the Nov23 release of CbmRoot, Bremsstrahlung was replaced with a Bethe-Bloch energy loss for electrons, which was already implemented but not used. This energy loss describes the particles momenta more accurately, and matches the Geant3 simulation (see fig. 1 (bottom)).

Further, the incorrect energy loss resulted in wrong trajectories and therefore biases for the ring track distance in the RICH. Comparing the CbmRoot version Nov23 (RC3_nov23 more precisely) and Nov23 with Bremsstrahlung (Nov23 w/ Brems) in figure 2, the biases mostly vanish. When extrapolating MC STS tracks from the last STS hit of a given global track (Nov23 Sts MC), the biases are further reduced, indicating a bias from the STS track fit. For a RICH independent comparison, the Nov23 versions and Feb23 with the current RICH geometry (Feb 23 w/ rich_v23a) are compared in figure 2. The reason for the additional bias seen in the Feb23 release is currently not known. Regardless of that, the bias reduced to $\mu_{dx} < 1 \text{ mm}$ in the Nov23 release. The overall smearing of ring track distance did also sharpen, which is probably related to improved momentum resolution for primary

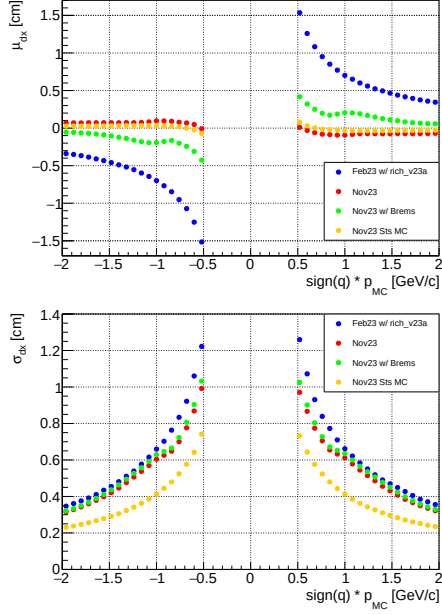


Figure 2: (top) Mean and (bottom) sigma of ring track distance for primary electrons (BoxGenerator) matched by Monte-Carlo.

electrons from the STS track reconstruction.

Effect on UrQmd + PLUTO

To get a grasp of the scope of these changes for realistic simulations including background, 300k UrQMD 12 AGeV Au+Au central collision events with ω_{Dalitz} , ρ_0 and ϕ PLUTO particles embedded for each 100k events are simulated using Geant3. As for electrons from the BoxGenerator, primary electrons from PLUTO particles are now also nearly unbiased and additionally sharper with the decrease of σ_{dx} (Fig. 3). For pions, the changes also led to a nearly vanished bias (Fig. 4). This shows that the extrapolation with an electron mass hypothesis for the energy loss is also sufficiently precise for pions with $p > 4.65 \text{ GeV/c}$.

To further isolate the ring track matching from other factors, the ring track matching efficiency in fig. 5 is defined as $\text{Efficiency} = N_{\text{true ring track matches}} / N_{\text{accepted ring track matches}}$. An *accepted ring track match* is a successful track projection and a found ring in the same camera from the same MC particle. A *true ring track match* is counted if the matching is correct using the current matching algorithm by closest distance.

The ring track matching efficiency is shown in figure 5 and 6 in dependence on momentum and position of the track projection in the RICH camera respectively. A significant efficiency increase is observed from Feb23 to Nov23 w/ Brems for primary electrons and pions across all momenta. This is most likely correlated to the overall reduction of global tracks from the tracking algorithm by 15.6% and track projection by 11.7%, which reduces the

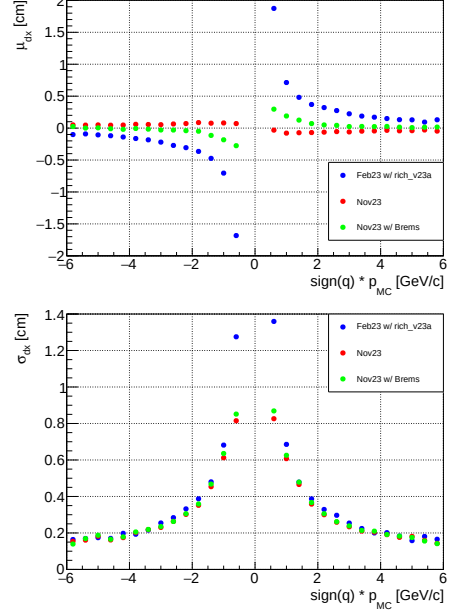


Figure 3: (top) Mean and (bottom) sigma of primary electron (PLUTO) ring track distance matched by Monte-Carlo.

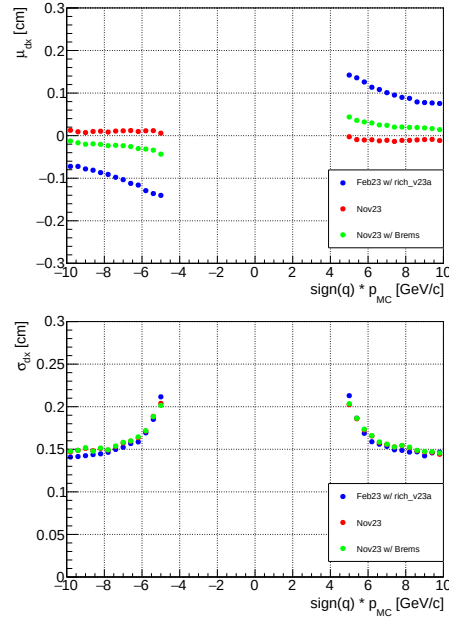


Figure 4: (top) Mean and (bottom) sigma of pion ring track distance matched by Monte-Carlo.

matching background and therefore the chance of wrong matches.

In figure 7 the ratios of rings (top) and track projections (bottom) in the camera are compared between Feb 23 w/ rich v23a and the Nov23 release. For both cases, the amount of rings and tracks decreased (about 3% for

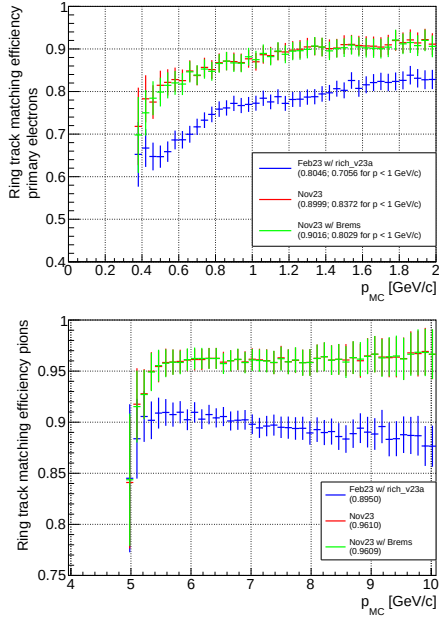


Figure 5: Ring track matching efficiency vs. momentum for (top) primary electrons and (bottom) pions.

RICH rings), although (rings) or probably because (tracks) the material budget of the STS geometry increased from v21e to v22d. For low momentum electrons, the matching efficiency increased from Nov23 w/ Brems to Nov23, due to the better description of energy loss. As expected, for high momentum electrons and pions, the now unbiased track projection has a negligible impact on the matching efficiency.

Summary & Outlook

Recently observed biases for the ring track distance in x direction were at least partially understood by the incorrect use of Bremsstrahlung for the energy loss as used in track extrapolations of electrons. For the CbmRoot release Nov23, biases for primary electrons are reduced to $\mu_{dx} < 1mm$. Also, a slight improvement in momentum resolution has been observed for electrons, resulting in improved matching efficiency. Additionally, the overall number of global tracks is reduced by roughly 15% compared to the Feb23 release, which might be correlated to the increased material budget of the new STS geometry. The significant increase in ring track matching efficiency is therefore a combined effect of the reduced number of global tracks, probably due to a different STS geometry, the discussed improvements in track extrapolation due to the usage of Bethe-Bloch energy loss, and a currently still unknown reason that caused additional biases.

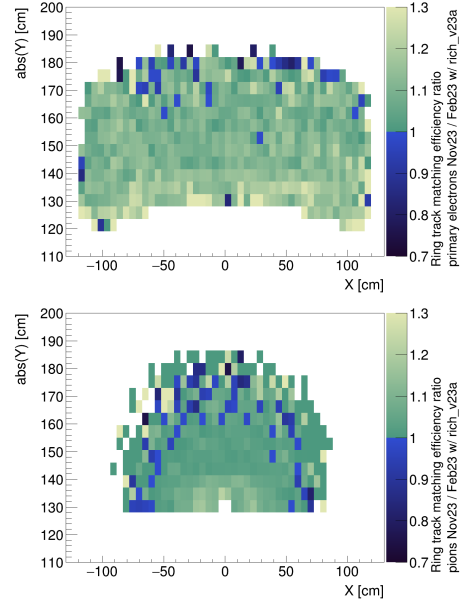


Figure 6: Ratio of ring track matching efficiency vs. xy-position of the track projection for (top) primary electrons and (bottom) pions.

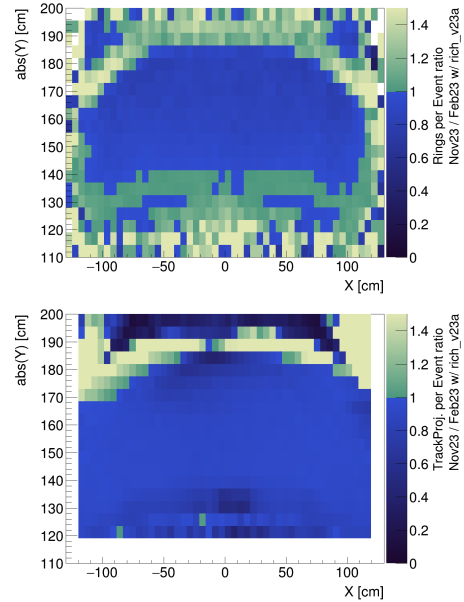


Figure 7: Ratio of (top) ring centers and (bottom) track projections.

Optimization of the extrapolation plane position for RICH ring-track matching

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Introduction

The CBM RICH is designed for efficient electron identification of electrons with momenta up to 6 GeV/c. The RICH rings are reconstructed standalone and are only later matched to STS tracks. The ring track matching procedure first extrapolates all STS tracklets to a particular Z plane in the RICH gas vessel called extrapolation plane assuming an electron mass hypothesis. After that, the tracks are extrapolated by a linear model to the mirror, where they are geometrically reflected and projected onto the RICH camera. This twofold extrapolation approach tries to take into account the curved electron track bent by the magnetic field as well as the Cherenkov photons emitted in a straight line. Hereby the position of the extrapolation plane plays a crucial part in the performance of the ring track matching procedure. The further downstream the plane is placed, the more accurate deflection in the magnetic stray field is accounted for, but also larger is the computational effort. This article will discuss the best position of this extrapolation plane and its impact on the ring track matching distance.

Method and results

To find the best position of the extrapolation plane Z , the distance of the track projections to the nearest ring (dx/dy) is measured differentially for different extrapolation plane positions and electron momenta. Each distribution of dx and dy is fitted with a Gaussian profile and the mean (μ) and standard deviation (σ) are extracted. Since a non-zero mean, i.e. a constant ring-track offset, is always correctable by applying simple correction maps (cf. [1]), main focus is put on the extracted standard deviations σ_{dx} and σ_{dy} displayed in figure 1. In this figure, the standard deviation along x is higher compared to that in y . This is mainly

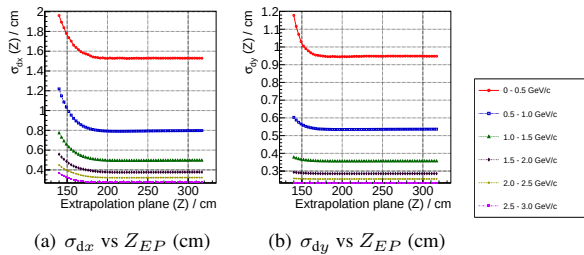


Figure 1: Standard deviation σ of the ring-track dx and dy distributions for electrons of different momenta.

due to the magnetic field inducing variances along the xz -plane. Similar results are observed for positrons (not shown here). To derive the optimal position of the extrapolation plane $Z_{optimal}$ the standard deviations in both dx and dy are used as feature variables. Since there is no correlation between dx and dy , both their variances can be minimized simultaneously giving the objective function:

$$f(Z) = \sum_{\{momentum\}} \left\{ -\frac{|\sigma_{dx}(Z)|}{|\sigma_{dx}|_{max}} - \frac{|\sigma_{dy}(Z)|}{|\sigma_{dy}|_{max}} \right\} \quad (1)$$

Where $Z_{optimal}$ is extracted to be the point where $f(Z)$ is largest:

$$Z_{optimal} = \underset{Z}{\operatorname{argmax}} f(Z) \quad (2)$$

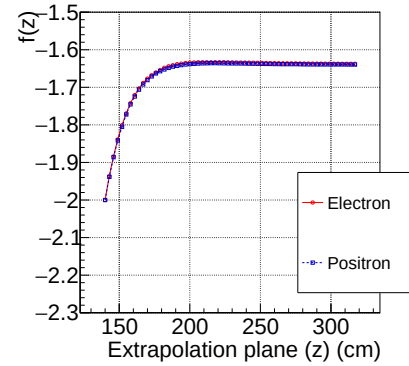


Figure 2: Objective function $f(Z)$ vs Z for an electron and positron sample.

The result of the optimization is shown in figure 2 for electrons and positrons. For both, electrons and positrons, the optimal extrapolation plane position Z is found to be $Z_{optimal} > 180$ cm. This is consistent with the current position of the extrapolation plane of $Z = 220$ cm.

Acknowledgments

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Using TRD-2D tracking for an improved ring-track matching

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Introduction

Backtracking - starting from TRD towards RICH - is a new method currently investigated aiming to enhance the ring-track matching accuracy, and hence electron identification capabilities of the CBM RICH detector. Individual hits in up to 4 TRD detector layers are combined to tracklets, which are then linearly extrapolated towards the RICH detector, independent of the current standard track finding in CBM. In this report, we compare the back-tracking extrapolation accuracy observed in the RICH plane using both standard TRD hit position resolution as well as enhanced hit resolution expected from TRD-2D with the standard forward extrapolation accuracy from STS. Backtracking accuracy from TRD naturally depends on the number of TRD planes present in the reconstructed TRD tracklet.

The measure of quality here is the observed distance (Δd) between the track (extrapolated to the RICH detection plane) and position of the closest found ring. The statistical width of the distribution of these distances has direct relevance for the ring-track matching accuracy, and subsequent pion suppression capability of the RICH.

Limited detector position resolution, multiple scattering, or magnetic stray fields adversely affect this distance distribution, resulting in larger width and / or systematic shifts. The direction of the CBM dipole magnetic field causes increased variance in Δx compared to Δy . Hence the overall spread in the Δd prevents us to apply sharper cuts for primary electron selection, leading to increased multiplicity of mis-identification of pions with no reference in RICH ($p < 4.5 \text{ GeV}/c$).

Simulation of TRD-2D

TRD-2D will be part of the standard TRD day-1 geometry. The triangular pads of TRD-2D will cover the inner region of acceptance where large track densities are expected. One of the advantages of the TRD-2D is its increased position resolution which is expected to be $\sigma_x \sim 100 \mu\text{m}$ and $\sigma_y \sim 800 \mu\text{m}$. At the time when these simulations were performed, the TRD-2D geometry was not yet available for standard simulations. Instead, in order to simulate the TRD-2D geometry, the standard TRD geometry was used, taking the MC-true hit positions of TRD hits subsequently smeared with the expected TRD-2D position resolution using gaussian smearing. This method of smearing on hit level preserves all digitizer effects on the MC points hence is comparable to a true TRD-2D geometry simulation. All simulations are based on a sample of 1×10^6

electrons and positrons from FAIRBox generator, covering the full CBM acceptance, and transported using GEANT3.

Analysis methodology

Hits inside the TRD (or TRD-2D) detector are fitted using a linear model. The fitted tracks are then extrapolated to the spherical RICH mirror (reconstructing the intersection of a vector with a sphere). From the point of intersection this vector is propagated towards the RICH camera where the nearest active pixel is determined. Finally, the differential distance (separated into δx and δy) between the track projection and the nearest ring found inside the RICH is histogrammed in multiple bins of the momentum of the corresponding electron track. The resulting δx and δy distributions are fitted using a gaussian function, and finally the distribution mean and standard deviation (for each momentum bin) is extracted. This same procedure is carried out for all three cases: TRD, TRD-2D, and standard STS forward tracking.

Results and conclusion

The mean deviations are not discussed here since systematic mean deviations observed in the ring track matching (if any) can always be corrected for in the camera plane [1]. Of larger importance is the standard deviation of the fits (See figures 1, 2), which is a measure of the statistical (back)tracking accuracy, and as such can not be corrected for using tables. On comparing TRD-1D and TRD-2D, the TRD-2D geometry shows better overall resolution in the fit both in Δx and Δy if compared to TRD-1D tracklets with less than 4 hits (hit layers). Only for TRD-1D tracks including all 4 layers the TRD-1D tracking accuracy reaches comparable accuracy as TRD-2D with at least 2 hit layers, hence the extrapolated ring-track matching resolution is also comparable. For TRD-2D tracking, the further benefit in tracking resolution when having 3 or 4 hit layers included is minimal compared to two hit layers. For Δy the TRD-2D matching resolution is worse than for Δx (by roughly $\sim 35\%$). This is expected since the hit position resolution along Y is worse than along X for TRD-2D. Similar results are obtained for positrons of same momenta which are not shown here. The STS forward track extrapolation is still slightly better in comparison with TRD-2D (roughly $\sim 80\%$ in Δx), which is not surprising given the position resolution of STS being $\sim 25 \mu\text{m}$.

Since TRD backtracking and standard STS-based forward track extrapolation are independent of each other,

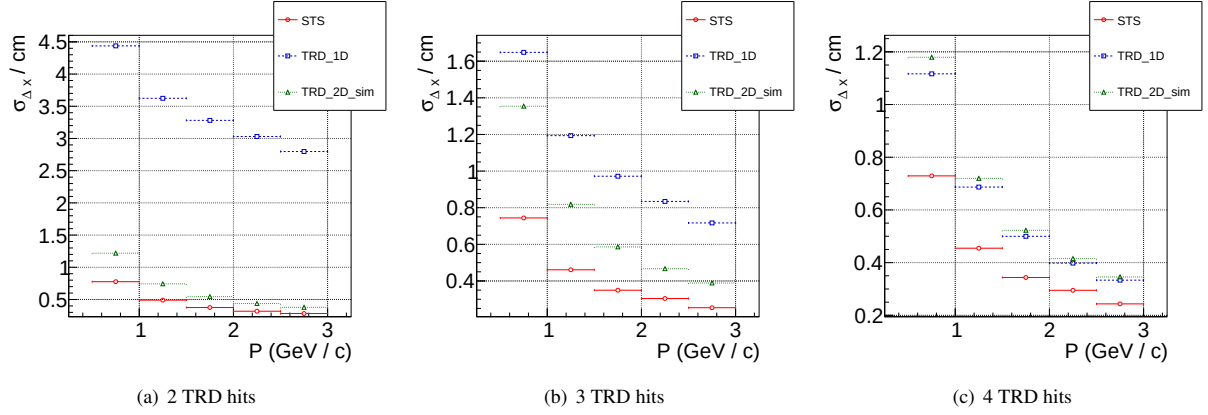


Figure 1: Standard deviation $\sigma_{\Delta x}$ of distribution of x-differences between STS / TRD / TRD-2D extrapolated electron track and corresponding RICH ring as function of momentum.

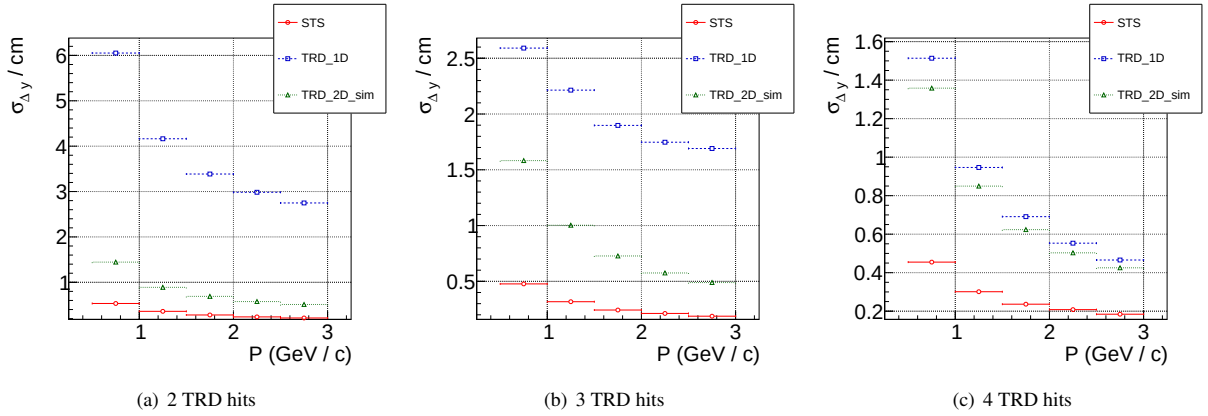


Figure 2: Standard deviation $\sigma_{\Delta y}$ of distribution of y-differences between STS / TRD / TRD-2D extrapolated electron track and corresponding RICH ring as function of momentum.

both approaches can principally be combined in a RICH matching neural network (weighted by their individual accuracy) in order to improve the overall pion suppression of the RICH detector. Such a combined approach is presently under investigation.

Acknowledgments

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Proof of concept for the TRD backtracking approach

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Introduction

One of the main backgrounds for the di-electron analysis is the mis-identification of hadrons (particularly pions) as electrons. In the CBM RICH the mis-identification at low momenta ($\leq 4.7 \text{ GeV}/c$) stems mainly from random matches of pion tracks to electron rings in their vicinity. Hereby the electron whose ring is taken by the pion might be tracked or not-tracked. If the electron is tracked but still the ring is taken by the pion closer to the ring center, one can employ the "priority matching strategy" where electrons identified by the downstream detectors are prioritized. Due to already good ring track matching for tracks reconstructed in both STS and RICH, this case is however seldom, and the possible gain is limited. In the majority of cases, where an electron ring is falsely matched to a pion, the electron is not reconstructed in the STS. Most often this is a result of electron pair production from photon conversion in the later STS layers or the entrance window of the RICH, causing additional Cherenkov rings. In order to improve the matching accuracy, as many of the additional conversion electron rings must be removed prior to matching remaining rings to potential primary electron tracks seen also in STS. A strategy to remove the rings from conversion electrons is to track those electrons (henceforth called **signal electrons**) in the detectors downstream of the RICH. This report presents a proof of concept for this "backtracking" approach using an ideal TRD2D standalone tracking.

Analysis method

The analysis procedure follows a two step approach, first removing all TRD hits which could already be matched to STS tracks. Since all leftover hits are uncorrelated with tracks measured by the STS they are likely to stem from electrons being the products of photon conversion (signal electrons). These leftover hits are combined to form tracks, fitted using a linear model and extrapolated back onto the RICH mirror and thus projected onto the RICH camera. Then these tracks are matched to the closest ring and if the matching conditions are satisfied, the rings are flagged as stemming from electrons from photon conversion and neglected during further electron identification steps.

In this report an MC-ID based tracking is performed and only these signal electrons are considered for the following analyses. This helps in finding optimal values for different variables in the analysis for the future application. For this analysis 1×10^5 central Au-Au collisions at 8 AGeV/c beam momentum were simulated, with a single Pluto $\omega \rightarrow e^+ + e^-$ embedded per event. The geometries used are

magnet(v22a), pipe(v21d:v21i), mvd(v20d.tr), sts(v22d), rich(v23a) and trd(v20b.1e). In report [1] we discussed already how TRD2D specific simulations can be obtained by artificial gaussian smearing of TRD1D true hit coordinates using the TRD2D resolution, and the same approach is applied here.

Characteristics of the signal

In order to assess if the backtracking approach can work, one first needs to study the signal traces left by the signal electrons in the TRD2D. The number of hits produced by the signal electrons in the TRD is shown in the figure 1 (a). It can be observed that almost 80% of the tracks have at least two hits in the TRD. Since at least two hits are needed to form a track (best would be three or higher), we consider the track accepted if $N_{\text{hits}} \geq 2$. Using only two hits to form tracks comes with the drawback of having more "fake" tracks due to combinatorics. In future, this might be mitigated by additionally requiring the track to feature a $\beta \approx 1$ based on time-of-flight measurement between RICH and TOF (after forward propagation of the TRD tracklet to TOF). This procedure is discussed in [2]. The momentum distribution of the signal electrons from photon conversion and the primary electrons from the ω -decay are shown in the figure 1 (b). Since the signal electrons stem from photon conversion they feature smaller momenta compared to the primary electrons from the ω -decays. Because of this their low momenta they barely produce any transition photons. This is visible in the figure 2 (a). Using the naive bayes classification, the TRD electron likelihood is calculated and shown for signal electrons in figure 2 (b) by assuming track momenta of 0.6 GeV/c (figure 1 (b)). This likelihood distribution clearly shows that using the electron reference in TRD for selecting the signal tracks is not beneficial because the pions also have the same characteristics.

Results and discussions

All found tracks are fitted by a linear model, and the χ^2/NDF for the tracks are shown in the figure 3. In this first implementation, the linear track fitting is done separately in X - and Y -coordinates. The tracks with $\chi^2\text{NDF}(X) \leq 1.0$ and $\chi^2/\text{NDF}(Y) \leq 1.0$ are selected and matched to the closest ring in the RICH. The ring-track distance is shown in the figure 4. The tracks are sharper along X compared to Y , because the positional resolution in TRD2D along Y ($\sim 800 \mu\text{m}$) is worse than along X ($\sim 100 \mu\text{m}$). This information can be used to distinguish false matches, where the background tracks having complimentary fit distance can

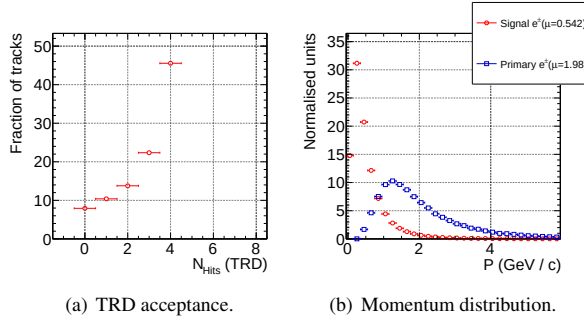


Figure 1: Number of TRD hits and momentum distribution of signal electrons. The momentum distribution plot also features the distribution of electrons stemming from the embedded ω -decay (primary electrons).

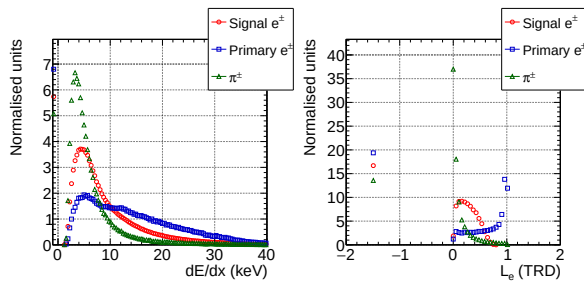


Figure 2: Energy loss in the TRD (left) and TRD electron likelihood for electrons from photon conversion, i.e. signal electrons and primary electrons (from ω -decay)

be eliminated. In this analysis the tracks are cut only on radial distance ($\delta d < 5.0$). The rings with matched backtracks are removed as final step in the procedure.

Now, the STS tracks are matched to the remaining rings. The resulting new efficiency for primary electrons and pion suppression factor are shown in the figure 5. The definitions of both are

$$\text{Efficiency} = \frac{\text{Tracks identified as electrons}}{\text{Tracks having at least 7 hits in RICH}}$$

$$\pi^\pm \text{ suppression factor} = \frac{\text{Multiplicity of } \pi^\pm}{\pi^\pm \text{ mis-id as } e^\pm}$$

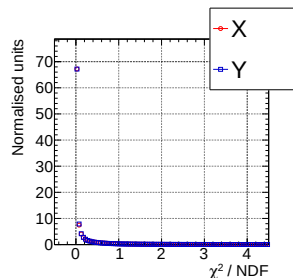


Figure 3: χ^2/NDF for the fitted TRD tracklets.

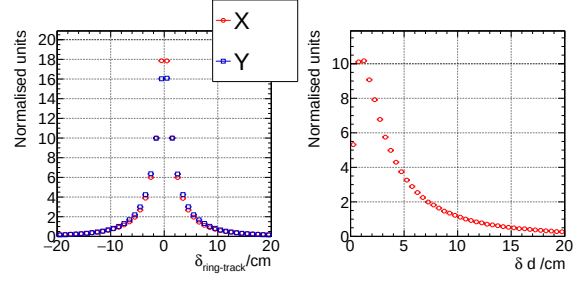


Figure 4: Ring-backtrack matching distance in X and Y separately (left) and as radial distance d (right).

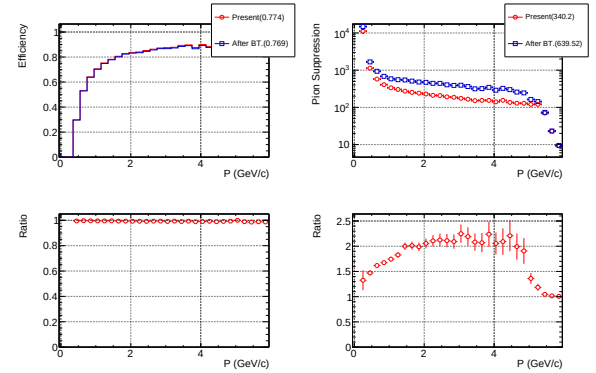


Figure 5: Electron detection efficiency (left) and pion suppression factor (right) with and without additional TRD backtracking.

Since the perfectly backtracked electrons always have rings in their vicinity, the chances of these tracks removing a random ring is very low. Hence the measured efficiency for electrons does not get deteriorated when using the backtracking technique. We observe only negligible difference in the efficiency for primary electrons. More drastically, a gain by a factor of 2 in the pion suppression factor is observed over the full momentum range. This demonstrates the potential in this strategy. A realistic simulation with all background hits and with the TRD2D geometry is still ongoing.

Acknowledgment

This work is supported by BMBF (05P19PXFCA, 05P21PXF1), “Netzwerke 2021”, an initiative of the Ministry of Culture and Science of the State of Northrhine Westphalia, and the GSI R&D program.

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RICH timing precision and its possible applications

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Introduction

The CBM ToF has a timing precision in the order of $\sigma \sim 60$ ps, which is used for the identification of hadrons (π/K , K/p separations) [1]. As reference time T0, the ToF uses the time measured by the CBM BMON detector which is designed to have a timing precision of $\sigma < 50$ ps [2]. Since the CBM RICH also has a good timing precision it might be beneficial to also use its ring times to further enhance the time of flight measurements in CBM. In this report we discuss lab measurements deriving the timing precision of the DIRICH front-end Boards (FEB) of the RICH and the possibility to use ring times as additional T0 reference.

Measurement of leading edge timing precision

In the BUW laboratory, a realistic miniature version of the CBM RICH camera which includes 3×2 MAPMT photon sensors and the DIRICH based readout setup was commissioned [3]. To measure the DIRICH-FEB's timing precision, a pulse generator is used to produce signals comparable to MAPMT signals. The signal from the pulse generator is fanned out into 16 outputs which are connected to a DIRICH FEB. To derive the leading edge (LE) timing precision and eliminate any path length effects, always two active channels on the same DIRICH FEB are compared. The LE time difference between two hits in different chan-

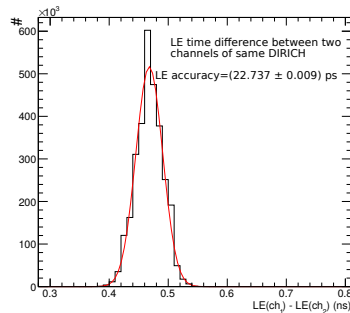


Figure 1: Leading edge time difference between two hits in distinct channels of the same DIRICH-FEB.

nels is plotted (figure 1). The distribution is fitted with a Gaussian profile and the width is obtained to find the LE spread and thus the timing precision. The measured timing precision is $\sigma_{LE} = 22$ ps.

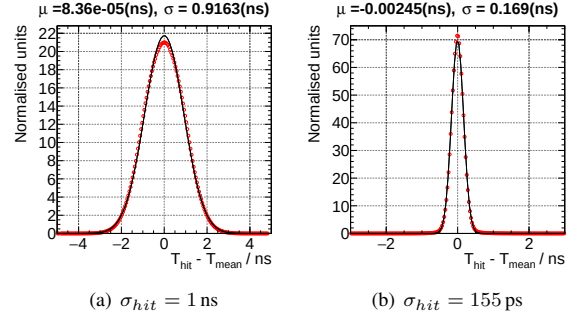


Figure 2: Simulated hit time deviation with respect to the mean time of the ring using two different values for hit time smearing of RICH hits in CBM simulations.

RICH hit time spread

A charged particle moving faster than speed of light in the radiator medium produces Cherenkov photons. These Cherenkov photons enter the PMT plane and produce photo electrons in the MAPMT's photo cathode. These single photo electrons are amplified in a dynode chain featuring ten stages. The resulting charge signal on the single pixel anode of the MAPMT is discriminated against a constant threshold voltage resulting in a RICH hit. The hit time depends on the Transit Time Spread (TTS) of the photo electrons in the MAPMT and the timing precision of the FEB. The TTS of the Hamamatsu H12700 MAPMTs is 350 ps FWHM [4]. Assuming a Gaussian distribution for the transit time, the standard deviation is hence $\sigma_{TTS} = 149$ ps. Therefore the theoretical hit time spread should be $\sigma_{hit} = \sqrt{\sigma_{TTS}^2 + \sigma_{LE}^2} = 150$ ps. For the simulation an additional 3% spread is assumed ($\sigma_{hit} = 155$ ps). However the status quo in CBMROOT is a 1 ns gaussian smearing (which will be modified accordingly in the next release). The comparison of the hit time spread in CBMROOT and the theoretical time spread are shown in figure 2. For the remaining studies in this report the theoretical time spread is set to ($\sigma_{hit} = 155$ ps).

Particle Identification via time of flight using the RICH ring time

This section focuses on the potential use of the RICH ring times in conjunction with the ToF detector time to enhance the particle ID. Hereby the time information of the RICH is always extracted for each ring individually and correlated to tracks at a distance of less than 2 cm. The

time and the position of the matched ring is found (t_{ring} , $\vec{r}_{\text{ring}}$) and the distance between ring and its origin on the mirror is measured, $d_{\text{ring-mirror}} = \|\vec{r}_{\text{mirror}} - \vec{r}_{\text{ring}}\|$. Next, the ToF hits are matched to the track and the time and position of the farthest attached ToF is measured (t_{ToF} , $\vec{r}_{\text{ToF}}$). Finally the distance between the mirror and ToF hit is measured $d_{\text{mirror-ToF}} = \|\vec{r}_{\text{ToF}} - \vec{r}_{\text{mirror}}\|$.

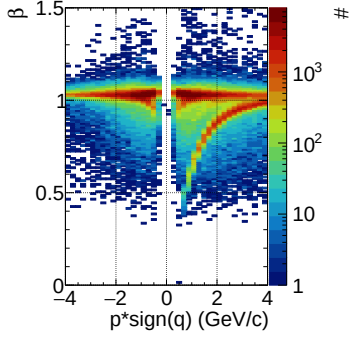


Figure 3: β vs momentum spectrum using RICH ring times and ToF matched hits to derive β .

The velocity fraction is then given by

$$\beta = \frac{d_{\text{mirror-ToF}}}{t_{\text{ToF}} - t_{\text{ring}} + \frac{d_{\text{ring-mirror}}}{c}} / c. \quad (1)$$

The distribution of β as a function of momentum is shown in figure 3. Visibly, protons are clearly separable from electrons and pions. However the separation is much weaker for high momentum electrons and pions. An electron/pion separation might only be possible at low momenta as shown in figure 4.

Conclusion and outlook

In this report we demonstrated the possible use of the RICH as a secondary timer. By using the ring time we could reject mis-identified protons being close to an electron ring in the electron sample. For the electron ID appli-

cation, this time information can be used independently or in combination with the T0 timer. This method is valuable for removing the low momentum hadron background in the backtracking approach, also discussed in this report [5].

Acknowledgments

This work is supported by BMBF (05P19PXFCA, 05P21PXFCA), “Netzwerke 2021”, an initiative of the Ministry of Culture and Science of the State of Northrhine Westphalia, and the GSI R&D program.

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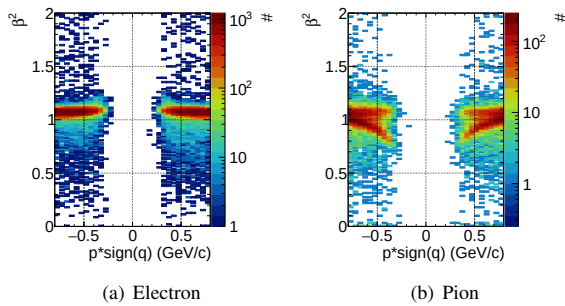


Figure 4: β^2 vs momentum spectrum for lower momenta using RICH ring times and ToF matched hits. Displayed separately for electrons (left) and pions (right)

New RICH geometry v24a and first Monte Carlo tests

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Introduction

The (Virtual Monte Carlo (VMC) based) RICH detector geometry description used in GEANT Monte Carlo simulations has recently been updated, and is now more realistic and in better agreement with the CAD design model. In this report we summarize the major changes, and compare the new geometry to the previous standard geometry with respect to possible changes in the RICH performance.

Major changes to RICH geometry

The following major changes have been included in this recent geometry update:

- changes to outer dimensions and RICH vessel
 - increased dimension in z from 1.9 m to 2.2 m.
 - increased width from 5.268 m to 6.0 m.
 - corrections to the shape of gas vessel (front corners).
- RICH front entrance window
 - change width from 5.268 m to 2.6 m.
 - add 20 mm thick aluminum flange of width 100 mm around the entrance window .
- RICH backside exit window
 - change of material from Kapton to Polycarbonate.
 - change of window width (5.268 m to 5.96 m) and height (5 m to 3.84 m).
 - increased window thickness from 5 mm to 10 mm.
 - added aluminum flange (width 100 mm, thickness 20 mm) surrounding the exit window.
- RICH mirror support structure
 - added to each pillar eight $100 \times 100 \text{ mm}^2$, 2 mm thick horizontal aluminum studs for mirror support.
 - added $25 \times 60 \text{ mm}^2$, 2 mm thick aluminum profiles connecting neighboring mirror pillars.
- slight shift of mirror pillar positions in agreement with CAD (but no shift of mirror tiles!)
- change of beampipe to beampipe tunnel.
 - increase of conical shape entrance radius from 74.2 mm to 164 mm, exit radius from 161.6 mm to 299 mm.
 - change material thickness to constant 3 mm (carbon fibre).

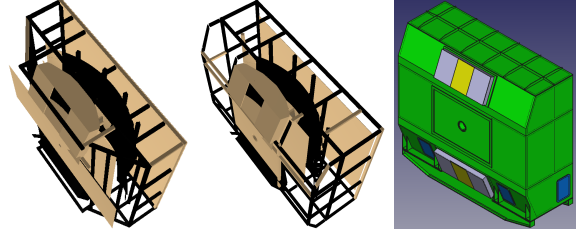


Figure 1: Pictures of the rich detector geometry. Previous version (left), new modified version v24a (center), and the latest CAD model (right).

- enlarged inner mirror tile cutouts (and belt) to accommodate larger tunnel radius, avoid overlaps.

A comprehensive Monte Carlo comparison of this new RICH geometry with respect to the previous geometry version v23a was carried out in order to assure that the new geometry works as expected. The previous RICH geometry v23a is identical to v22a, except for the "empty fake volumes" that were removed (a temporary bugfix which was now causing problems on MAC based computing systems).

Two different data sets were used for the simulation:

- a box generated electron sample, consisting of 10^4 events (five electrons, five positrons per event) within the standard angular acceptance and $p_T < 3 \text{ GeV}/c$.
- an UrQMD based sample, consisting of 10^4 minimum bias Au+Au UrQMD events, 8 AGeV beam energy.

Comparison based on electron sample:

As first observation, the number of MC points per event (i.e. GEANT-simulated photons hitting the PMTs) in the upper camera is shown for the new geometry v24a, and for the old reference geometry v23a in Fig. 2, together with a ratio plot of both distributions. Both distributions look similar and the ratio is approximate one, except for a clear reduction of MC points in the inner center region. This loss in acceptance is caused by the reduction of the size of the central mirror tiles (to accommodate the larger beampipe tunnel).

Similar observations are also made for the lower camera, both for the distribution of the RICH hits and for the distribution of the RICH rings. For the number of hits in each RICH ring or for the radius of the ring there isn't any difference between the two geometries observed.

Figure 3 shows z -positions of all MC secondary vertices where interactions took place (excluding Cherenkov

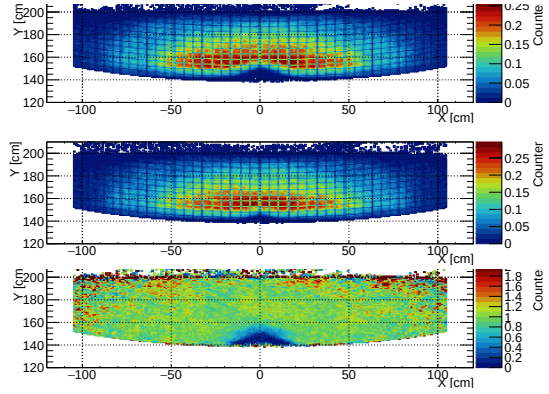


Figure 2: Distribution of MC points for electron box sample in upper camera: new geometry v24a (upper plot), reference geometry v23a (middle plot) and ratio of the Distributions for both geometries (lower plot).

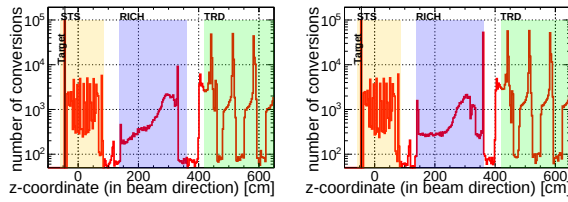


Figure 3: Distributions of secondary vertices without Cherenkov photons. Left for previous version v23a, right for new version v24a.

photons), visualizing differences in the respective material budget. The increased amount of conversion at $z = 140$ cm is caused by the additional flange around the entrance window. The shift of the peak at the end of the RICH is due to the extended z -dimension and corresponding shift of the exit window. The increase in material budget of the exit window is clearly visible, however, an exit window made of 5 mm capton only (as implemented in the previous geometry) is mechanically not realistic, given the size of the window area (6×4 m²). The RICH group is currently studying different options to fabricate this window out of composite sandwich material, in order to reduce the material budget again. The present implementation in the current geometry can be understood as an upper limit only, and might be reduced again later. Looking at the number of hits in each of the 4 TRD layers (see Fig. 4) reveals an expected increase in the number of hits by approximately 12 % mainly caused by the increased material budget of the exit window. The left plot in Fig. 5 compares the electron efficiency for both geometries, which decreases a bit especially at low momenta.

Comparing test with UrQMD samples

A similar simulation study has been performed using the UrQMD sample as input, showing similar results and ef-

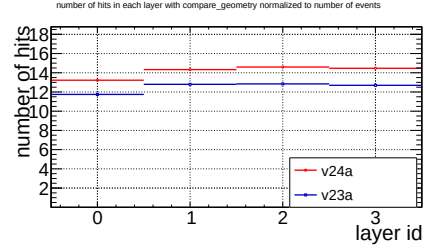


Figure 4: Number of hits in each TRD layer.

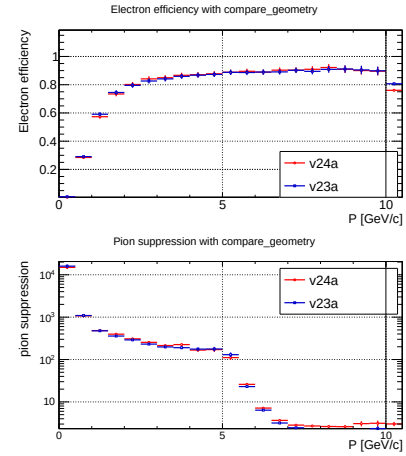


Figure 5: Comparison of electron efficiency for both geometries using box-generated $e^\pm$ sample (upper figure), and pion suppression factor using Urqmd sample (lower figure).

fects as already discussed previously. The pion suppression factor as function of momentum obtained for both geometries is compared in Fig. 5. Pion suppression has improved slightly with the new geometry, which might be explained by reduced ring-track mismatching due to the lower number of RICH rings in the inner region of the camera.

Results

The observed changes in RICH performance are minimal and mostly caused by the reduced area of the inner mirror tiles. The new RICH geometry v24a causes a slight increase in number of TRD hits due to the increased material budget of the exit window. The RICH geometry v24a is more realistic than v23a and more similar to the newest CAD model and should be soon be used as standard geometry in all upcoming simulations.

Acknowledgments

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SiPM electronics readout for the Ring Imaging camera of the CBM experiment

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Introduction

SiPMs offer a single-photon resolution, fast rise times, and immunity against magnetic fields. Compared to modern photo-multiplier tubes, SiPMs have higher Photo Detection Efficiencies (PDE) reaching up to 60%.

SiPMs' drawbacks, in particular in comparison to Multianode Photomultipliers, include high Dark Count Rates (DCR), temperature dependency, radiation susceptibility, and for MPPC arrays a slightly lower fill-factor. SiPM's typical DCR are five orders of magnitude larger $\mathcal{O}(100 \text{ kHz/mm}^2)$ in comparison with Multi-Anode Photomultipliers $\mathcal{O}(\text{Hz/mm}^2)$.

To design a SiPM photon camera for a potential future upgrade of the CBM RICH detector, we need to address all these challenges. Since CBM uses a free-streaming readout system, a local triggering system (implemented inside the front-end readout) that differentiates between dark and photon pulses is mandatory. Additionally a cooling/annealing system to compensate temperature/radiation effects in the SiPM-camera is needed.

In this report, we focus on the first steps in the development of a SiPM-based camera for the CBM RICH detector.

SiPM selection

We selected three SiPMs of different vendors that match the current MAPMT pixel size ($6 \times 6 \text{ mm}^2$). The Hamamatsu S14160-6050HS, BroadCom AFBR-S4N66P024M and OnSemi MICROFJ-60035.

SiPM	MICROFJ -60035	S14160 -6050CS	AFBR S4N66P024
Vendor	OnSemi	Hamamatsu	Broadcom
Area (mm^2)	6×6	6×6	6×6
Pixel pitch (μm)	35	50	40
Fill factor(%)	75	74	80[1]
V. operating (V)	30	40	45
PDE (%)	50	50	63
Wav. peak (nm)	420	450	420
Gain ($\times 10^6$)	6.3	2.5	7.3
DCR (kHz/mm²)	150	100	125
Crosstalk (%)	25	7	23
Afterpulsing (%)	5	-	1

Unlike the PDE of the H12700 MAPMT (33%) used in the present CBM RICH camera design, SiPMs MICROFJ-60035 and S14160-6050H reach a PDE of 50% and the AFBR-S4N66P024M of 63%. However, for these SiPMs the DCR reaches 100-150 kHz/mm² while for the H12700 MaPMT a DCR $\sim 0.4 \text{ Hz/mm}^2$ has been reported [3].

SiPM biasing

The SiPM biasing circuit displayed in Fig. 1 is composed of a resistor R_1 (1 k Ω) to limit the current flowing through the SiPM from the power supply, a load resistor R_2 (50 Ω), and a DC decoupling capacitor C_1 (100 nF). We implemented an LC filter connected in series with the bias voltage, to remove high frequency noise coming from the power supply.

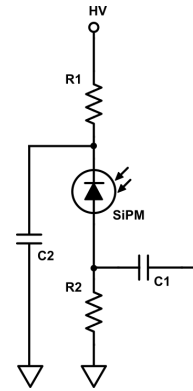


Figure 1: SiPM bias circuit.

Pulse processing

Typically, a SiPM pulse has a rising time of $\mathcal{O}(10^2 \text{ ps})$ and a falling time $\mathcal{O}(10^2 \text{ ns})$. This long decaying tail and the SiPM's high DCR $\mathcal{O}(\text{MHz})$ create a pulse pile-up effect in the SiPM's output as shown in Fig. 2. The pulse pile-up increases the average dark current, deteriorates the single-photon resolution, and increases the minimum amplitude threshold for discriminating between signal and noise (dark counts, after-pulsing and cross-talk).

Pulse-width shortening solves this pile-up effect. Pole-zero cancellation filters have demonstrated to be useful in shortening photo-sensor signals in order to keep timing properties, reduce signal pile-up and improve discrimination thresholds [2].

A pole-zero cancellation circuit functions as a RC high-pass filter. Unlike a common differentiator, the PZ circuit compensates the pulse under-shoot by connecting a resistor (R_s) in parallel to the filter capacitor (C_s) as shown in Fig. 3.

We set $R_g = 50 \Omega$ and $C_s = 100 \text{ pF}$ in the final PCB designs for the S14160-6050HS and AFBR-S4N66P024M SiPMs shown in Fig. 4. Using the pulse shortening cir-

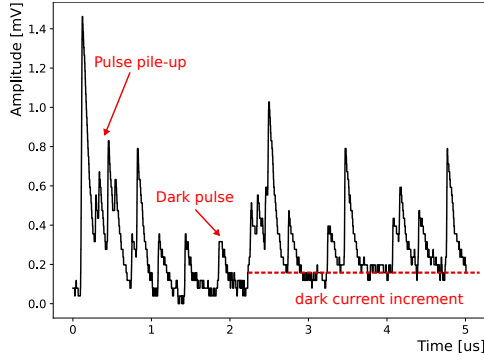


Figure 2: Pile-up effect observed in the AFBR-S4N66P024M SiPM.

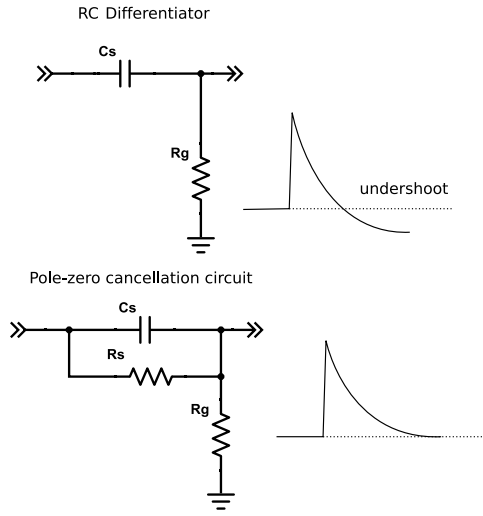


Figure 3: Pole-Zero cancellation circuit.

cuit in combination with SiPM AFBR-S4N66P024M effectively decreases the pulse falling time from ~ 150 ns to ~ 10 ns (Fig. 5).

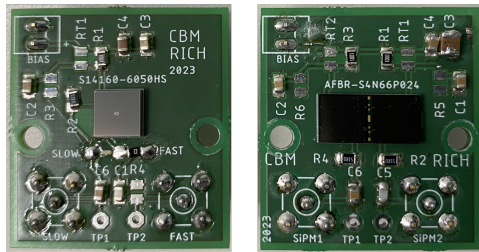


Figure 4: S14160-6050HS (Left) and AFBR-S4N66P024M (Right) boards. The S14160-6050HS board has a slow-output (100 nF DC decoupling) and a fast-output (pole-zero cancellation). The AFBR-S4N66P024M (2-SiPM package) board has two fast-outputs for each SiPM.

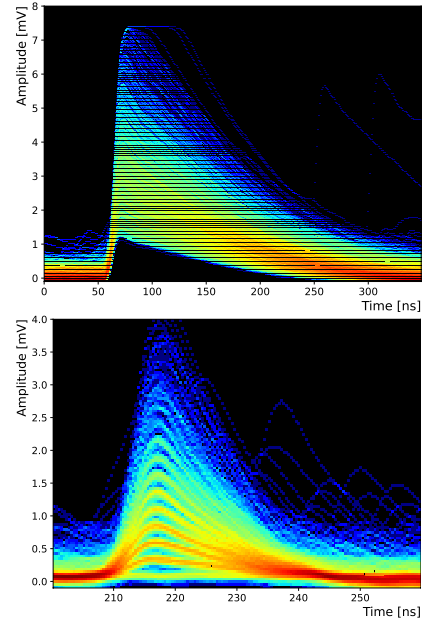


Figure 5: Pulse shortening. (Top) Raw pulse of the AFBR-S4N66P024M SiPM. (Bottom) Pulse shape after shortening. SiPM bias was set to 44 V at 20°C.

Signal amplification

A Class-A amplifier is used to amplify the SiPM signals. Class-A amplifiers are used in low noise/low gain blocks in RF applications because their flexibility, simplicity and signal preservation fidelity at high frequencies. The schematic of the implemented cascade amplifier is shown in Fig. 6.

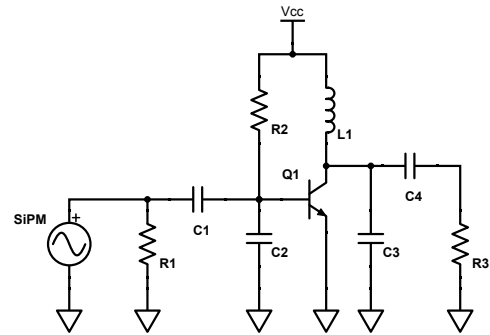


Figure 6: Single-stage of the amplification circuit.

In the amplification circuit, R_1 (50 Ω) defines the input impedance, C_1 (10 nF) blocks the DC component of the input SiPM signal, C_2 (1 pF) stabilizes the pulse baseline. The bias resistor R_2 (10 k Ω) sets the collector current in the transistor Q_1 (BFU760F) during cut-off mode. The current flows through the inductor L_1 (2 μ H) but no AC power is sent to the load resistor R_3 (50 Ω). Under active mode, the transistor's collector current rises/falls quickly and the load dissipates the AC power. The inductor stores energy in the

transistor's cut-off mode. During transistor's active mode the load dissipates twice the power by using an inductor instead of a resistor. The capacitor C_4 (10 nF) removes the DC component of the output signal. All the components used in the amplification stage must fulfill the bandwidth requirements.

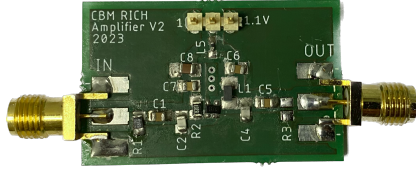


Figure 7: Amplification board. The bias terminal is connected to 1.1 V.

The amplifier uses a 1.1 V power supply. A LC low-pass filter is connected in series with the bias voltage to remove high frequency noise. The LC filter is composed by a ferrite bead BLM15HG601SN1D and a capacitor bank (10 μ F, 100 nF and 10 nF). The amplification board is shown in Fig. 7.

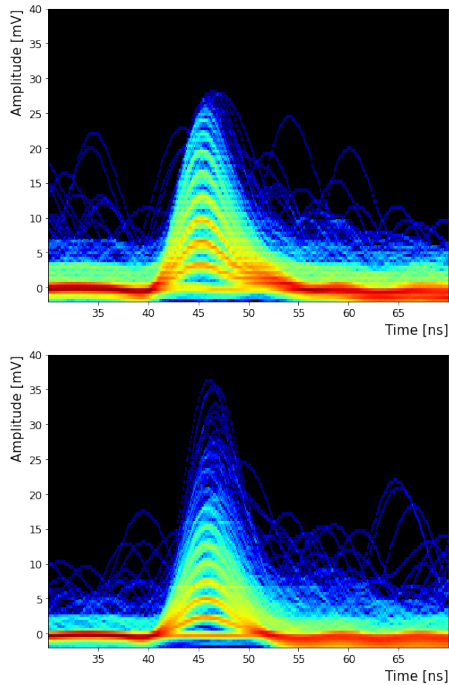


Figure 8: Amplified pulses of the S14160-6050HS (Top) and MICROFC-60035 (Bottom) SiPMs.

Figure 8 shows amplified pulses of the S14160-6050HS (45 V/17 °C) and MICROFC-60035 (32 V/17 °C) SiPMs. For the S14160-6050HS, a single photo-electron equivalent (spe) was amplified to 3.23 mV. On the other hand, the MICROFC-60035 spe was amplified to 2.52 mV. Both spe spectra are shown in Fig. 9.

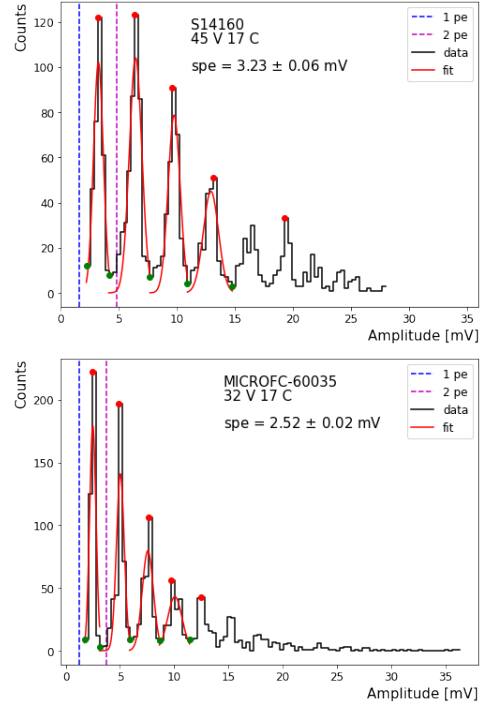


Figure 9: S14160-6050HS (Top) and MICROFC-60035 (Bottom) single-photon equivalent spectra.

Summary

In this report, we show readout electronics prototypes for evaluating the implementation of a SiPM-based camera in the CBM's RICH detector. We tested the biasing, pulse shortening, and amplification electronics for the S14160-6050HS and MICROFC-60035 SiPMs. We decreased the pulse falling time from ~ 150 ns to ~ 10 ns, reducing the pile-up effects on the SiPM performance (single-photon resolution, dark current and noise). We got an amplification factor of 12 while preserving the timing pulse features.

Acknowledgments

This work is supported by "Netzwerke 2021", an initiative of the Ministry of Culture and Science of the State of Northrhine Westphalia, and GSI.

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Testing a 2×2 SiPM matrix prototype for the CBM RICH

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Introduction

The Compressed Baryonic Matter (CBM) is a future experiment being installed at the SIS100 FAIR particle accelerator in Darmstadt. The CBM setup will be used to reconstruct heavy ion collisions in order to understand the early stages of the hadronic formation. The Ring Imaging Cherenkov (RICH) detector of CBM captures the Cherenkov light footprint of electrons and fast pions generated in ion collisions. In order to improve the RICH detection efficiency and granularity, we propose SiPMs as a candidate for a future detector upgrade to further improve the detector performance.

In this work, we present first results of implementing and testing a 2×2 SiPM matrix adapted to be coupled with the current CBM electronics readout. We used four AFBR-S4N66P024M SiPMs due to their high photo-detection efficiency (63%), gain (7.3×10^6), and fill factor (80% [2]). The system trigger is based on adding the signals coming from the individual SiPMs and setting a threshold above of which we can distinguish between majority coincidence signals and background. We report results of a 2×2 SiPM system performance.

Experimental setup

The circuitry setup is shown in Fig. 1. The signal of each SiPM is split in two by means of a capacitive charge divider commonly used in positron emission tomography [1, 3]. One of the two signals goes directly to a readout channel, while the other one is added together with the remaining channels to generate the trigger signal. We used 100 nF capacitors in the charge divider.

A Class-A amplifier is used to amplify the trigger channel. The amplification factor is ~ 12.2 and the power consumption 1.1 V/12 mA. The SiPM matrix was illuminated with laser pulses at a frequency of 100 kHz at an intensity of a few photons per SiPM. The SiPM bias voltage was set to 43 V. Signals were recorded by an RTO1044 oscilloscope with a sampling frequency of 10 GHz.

Charge splitting performance

Fig. 2 shows a scatter plot of peaks of the two outputs coming from a SiPM after charge splitting. We probed that the charge splitting circuit preserves linearity in the SiPM signal as well as the photon resolution. The channels A_S goes directly to the DiRICH readout and the channel A_T goes to the triggering adding node.

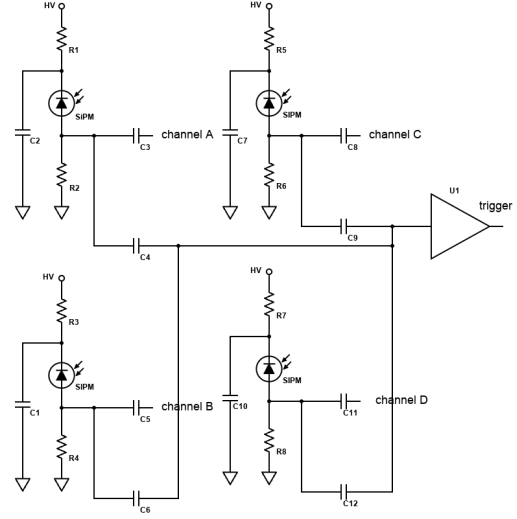


Figure 1: 2×2 SiPM matrix circuit.

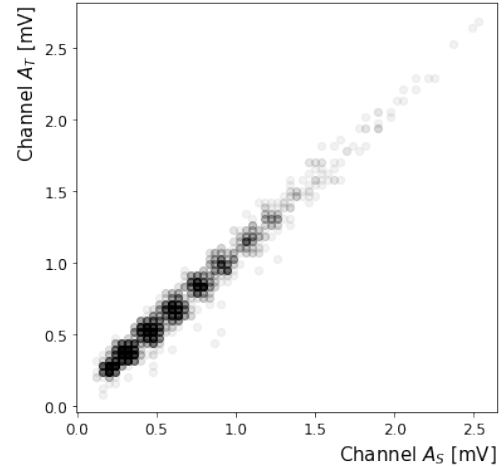


Figure 2: Joint peak spectrum of signals coming from the channel A splitter. Channels A_S refers to the signal going directly to the DiRICH readout and Channels A_T going to the adding node.

Once we tested the charge splitting linearity, we proceed to test the signal linearity after amplification. Fig. 3 shows the joint peak spectrum between the channel A_S and the amplified channel A_T . We observe the amplified signal is saturated above 35 mV, losing the signal linearity and the

photo-electron equivalent information. As conclusion, the upper limit of linearity in the amplification stage is 35 mV.

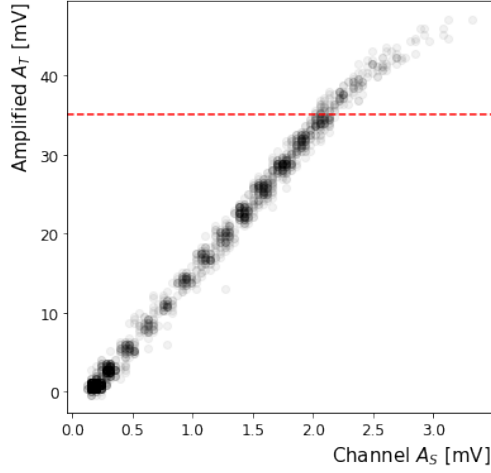


Figure 3: Joint peak spectrum of the Channel A_S and the amplified channel A_T . The amplifier saturation limit is 35 mV (red-dashed-line).

In the same way, we analyzed the signal behavior for identifying the DiRICH amplification saturation voltage. The joint peak spectrum between the pre-amplified channel and the DiRICH amplifier output is shown in Fig. 4. The peak spectrum remains linear till ~ 350 mV in the DiRICH axis.

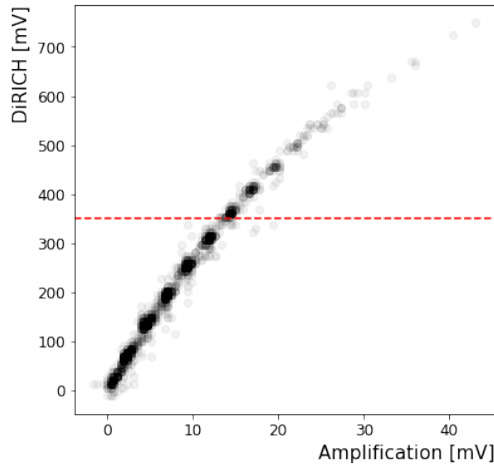


Figure 4: Joint peak spectrum of the amplified channel A_T and the DiRICH amplifier output. The amplifier saturation limit is 35 mV (red-dashed-line).

Trigger signal performance

The trigger signal was evaluated by using four SiPMs. Taking into account that not all SiPMs do have exactly the

same behavior as well as the corresponding biasing electronics circuitry, the triggering signal loses the photon resolution when the number of added SiPM signals increases. This hardware variability generates unaligned signals in time and with varying amplitude. In Fig. 5, we observe how the SiPM signal preserves the amplitude quantization but the triggering signal blurs the amplitude spectrum.

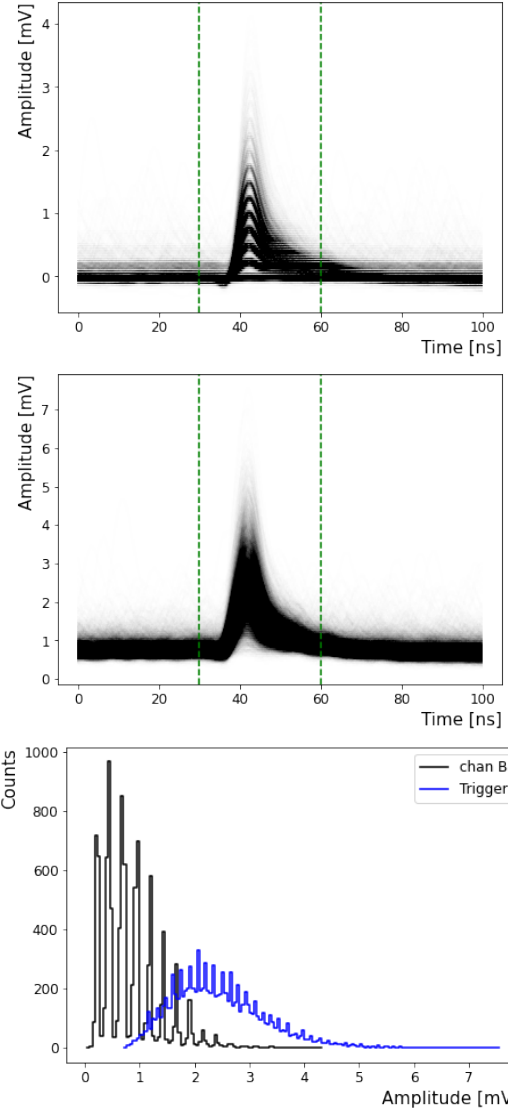


Figure 5: SiPM channel signal (top) and trigger signal (middle) for the 2×2 SiPM array. Peak spectrum comparison between a SiPM channel and the trigger channel (bottom).

We also assessed how trigger background affects the trigger signal. In this case, we compared the peak spectrum of the triggering channel under dark conditions (background) and under stimulus (signal). We analyzed triggering signals for 2-SiPM, 3-SiPM, and 4-SiPM arrays as is shown in Fig. 6.

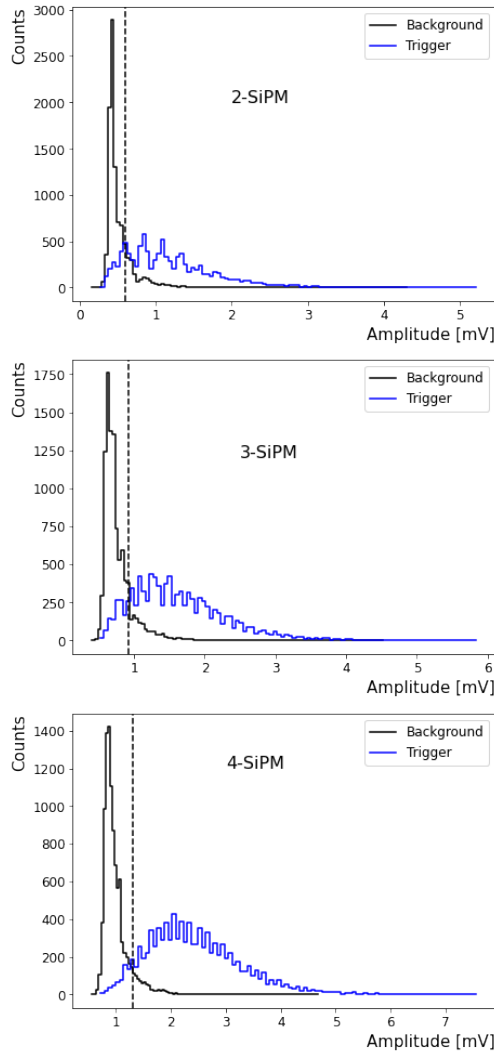


Figure 6: Peak spectra comparison between the trigger background (black-line) and signal (blue-line) for 2-SiPM, 3-SiPM and 4-SiPM configurations.

When the number of added SiPM signals increases in the trigger system, the background/signal discrimination enhances, that is, the probability of signal pollution decreases. On the other hand, despite the photon resolution decreases, the trigger performance should not be affected.

Summary

In this report, we analyzed the performance of a 2×2 matrix of AFBR-S4N66P024M SiPMs. We tested the linearity of the charge splitter, the pre-amplification and the DiRICH's amplification stage. We concluded the pre-amplification stage saturates at 35 mV (13 pe) and the DiRICH amplification at 350 mV (7 pe). These upper limits should not affect the SiPM-based RICH camera because Cherenkov Rings usually leave a light footprint of 1-2 pho-

tons per pixel.

Additionally, despite the trigger signal degrading the photon resolution with increasing number of SiPM, the discrimination distance signal/background increases. As future work, we are planning to carry out this test further incrementing the number of SiPMs.

Acknowledgments

This work is supported by “Netzwerke 2021”, an initiative of the Ministry of Culture and Science of the State of Northrhine Westphalia, and GSI.

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SiPM based CBM-RICH camera: pixel characterization

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Introduction

New developments in silicon based photo sensors, so called Silicon Photo-Multipliers (SiPMs), represent a feasible replacement for the well known vacuum photo tubes used in particle detection experiments. Some of the SiPM technology improvements are moderate noise levels, high photo-detection efficiencies, and high granularity. However, SiPMs also have key drawbacks as a strong temperature dependency and low radiation hardness. When being operated below the single photon threshold, such as in Cherenkov detectors, the dark rate is still orders of magnitude larger compared to photo multiplier tubes with standard Bi-alcalide photo cathodes. These disadvantages challenge their implementation in high radiation and noisy environments, in particular for single photon counting.

The Ring Imaging Cherenkov (RICH) detector of the Compressed Baryonic Matter experiment (CBM) plays an important role in the particle identification chain, specifically for electron/pion separation. Only electrons or high-momentum pions, when reaching the RICH radiator, produce Cherenkov radiation in the CO_2 gas volume. These Cherenkov photons are then reflected by a focussing mirror wall towards the detection camera, equipped with Multi-Anode Photo-Multipliers (MaPMTs). The RICH camera records the Cherenkov rings which help to identify the particle and its possible origin.

For a possible future upgrade of the CBM RICH detector, we consider the application of SiPMs instead of Multianode PMTs, in line with many other RICH detector groups world-wide. As first step, we evaluated different SiPMs on the market under different temperature and bias voltage conditions. Three different $6 \times 6 \text{ mm}^2$ SiPMs were selected for detailed evaluation: Broadcom AFBR-S4N66P024M, Hamamatsu S14160-6050HS and OnSemi MICROFC-60035. Only results of AFBR-S4N66P024M performance are shown here. The three selected SiPM types, together with their characteristic properties, are listed in Table 1.

Experimental setup

We installed the SiPMs in thermal contact with a temperature controlled aluminum plate inside of a dark box. A Raspberry Pi controls the SiPM's temperature by means of two Peltier cells attached to the aluminum plate. The plate temperature is then compared with the temperature set point and the Raspberry Pi varies the Peltier cell current till achieving the desired operating temperature of the

SiPM	MICROFJ -60035	S14160 -6050CS	AFBR S4N66P024
Vendor	OnSemi	Hamamatsu	Broadcom
Pixel pitch (μm)	35	50	40
Fill factor(%)	75	74	80[1]
V. operating (V)	30	40	45
PDE (%)	50	50	63
Gain ($\times 10^6$)	6.3	2.5	7.3
DCR (kHz/ mm^2)	150	100	125
Crosstalk (%)	25	7	23
Afterpulsing (%)	5	-	1

Table 1: Data sheet characteristics of the three evaluated SiPM models.

SiPM. A precision voltage source is used to supply the desired bias voltage to the SiPM. A laser source produces light pulses at a pulse frequency of 100 kHz to the SiPM. Those light signals are detected by the SiPM, and the SiPM signals are recorded by means of an RTO1044 oscilloscope. The schematic representation of the experimental setup is shown in Fig. 1.

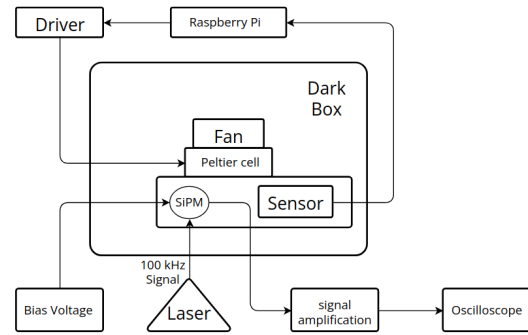


Figure 1: Schematic view of the experimental setup.

Peak spectrum and thresholds

We need to determine the pe (photo-electron) amplitude value for setting a proper signal threshold needed for determination of the DCR, crosstalk, afterpulsing and gain. We recorded the SiPM amplitude spectrum for each temperature and bias variation, then we fit a multi-Gaussian function to the spectrum and determined the mean separation between consecutive spectrum peaks. This value serves as a robust estimate for the mean signal amplitude for detection of a single pe. In Fig. 2 the pe voltage determination is shown.

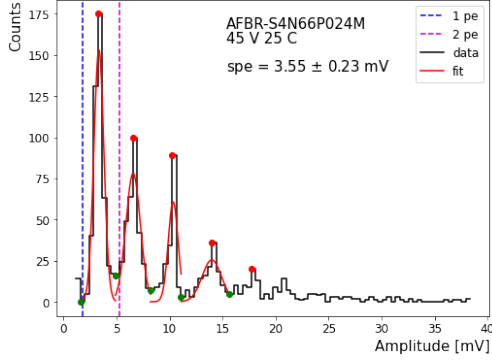


Figure 2: Photo-electron spectrum and threshold determination.

Results

We characterized the SiPM dark count rate (DCR), crosstalk, afterpulsing, and gain for applied bias voltages ranging from 40 V to 46 V and SiPM temperatures from 15°C to 40°C. The DCR was estimated having the SiPM in total darkness conditions. The remaining DCR is caused by thermal electron emission and should therefore decrease if the sensor is cooled.

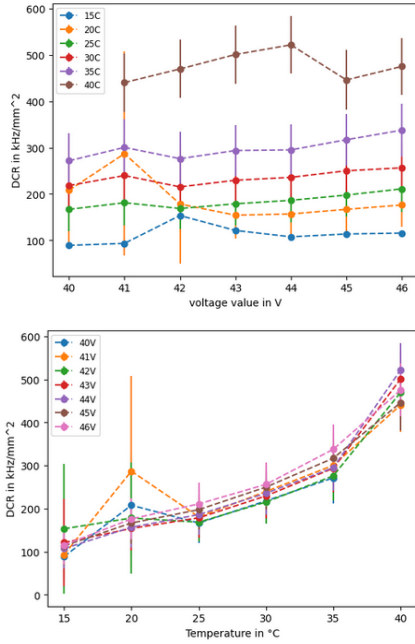


Figure 3: DCR of the AFBR-S4N66P024 SiPM plotted against bias voltage and temperature.

Fig. 3 shows the DCR behavior by changing the SiPM bias voltage and the temperature. We observe a small increase of the DCR depending on bias voltage (for constant temperature) due to the increase of the internal electric field in the silicon substrate and the corresponding increase in

probability for thermal electrons creating avalanche events. On the other hand, when we vary the SiPM temperature at constant bias voltage, the DCR increases strongly with temperature, ranging from $\sim 100 \text{ kHz/mm}^2$ at 15°C to $\sim 450 \text{ kHz/mm}^2$ at 40°C.

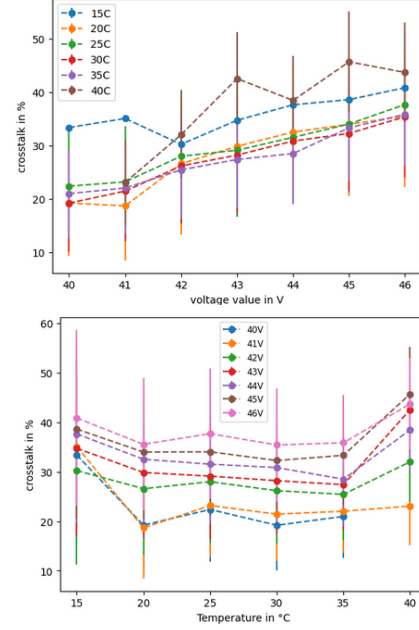


Figure 4: Crosstalk probability of the AFBR-S4N66P024 SiPM as function of bias voltage and temperature.

SiPM crosstalk is caused by the unwanted transmission of photons between neighboring SiPM cells creating ≥ 2 pe amplitude signals. The crosstalk probability is calculated as the ratio between number of pulses above 0.5 pe and above 1.5 pe under dark conditions. The crosstalk analysis results are shown in Fig. 4. The crosstalk increases from $\sim 20\%$ at 40 V to $\sim 33\%$ at 46 V showing a strong dependency on bias voltage. However, the temperature dependency of crosstalk is not clear at all.

The SiPM gain – assuming a single photo electron as input – can be calculated as

$$G = \sum_0^t \frac{\sigma v \delta_t}{A R e} \sim \frac{\sigma v_{pe} \Delta_t}{A R e}, \quad (1)$$

where v is the instantaneous signal voltage, δ_t the signal time step, v_{pe} is the pe voltage, Δ_t the pulse width at the baseline, σ is the charge attenuation due to high-pass filtering (signal shortening), A the electronics amplification factor, R the load resistance, and e the electron charge. In this rough approximation, a rectangular pulse shape is assumed.

As expected we observe a trend of increasing gain with bias voltage, going from $\sim 3 \cdot 10^6$ at 40 V to $\sim 5 \cdot 10^6$ at 46 V. However, there is no clear temperature dependence. The results for the gain are displayed in Fig. 5. The gain

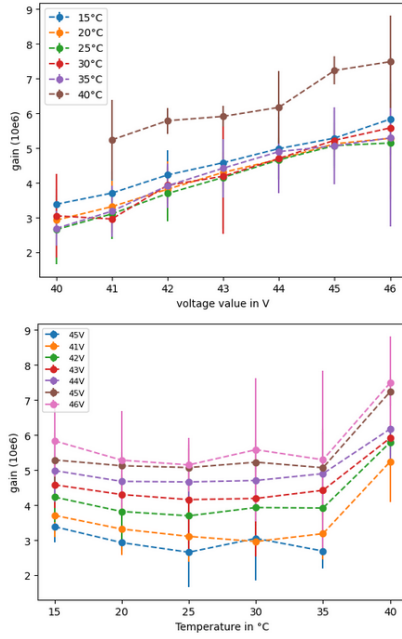


Figure 5: Gain values of the AFBRS4N66P024 SiPM plotted against voltage and temperature.

and DCR has an outlier behavior at 40°C, so we need to analyze deeper this measurement. The SiPM afterpulsing showed only little variation, less than 2%, as function of bias voltage and temperature variations.

Summary

In this report, we show the performance analysis of the AFBRS4N66P024 SiPM. We evaluated the DCR, crosstalk, afterpulsing and gain. The DCR increases strongly with temperature, demanding the need to keep the temperature of a SiPM-based RICH camera under a value where the trigger system remains unaffected. At 25°C, DCR is around 200 kHz/mm² which is 7.2 MHz in a 6×6 mm² SiPM, and 460 MHz in a 8×8 SiPM matrix.

Additionally, crosstalk increases as $\sim 2.1\%/V$, but remains almost constant with temperature. Afterpulsing has always a probability under 2%. The optimum operation point (bias voltage and temperature) is a trade-off between noise levels and gain. The next step in the SiPM-based camera implementation is the assessment of the triggering system under several temperature and bias voltage scenarios.

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Trigger system for a SiPM-based camera for the CBM's RICH detector: concept and first steps.

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Introduction

Using SiPMs for single photon detection in a Ring Imaging Cherenkov Detector (RICH), is a challenging task in view of the substantial dark noise rate $\mathcal{O}(100 \text{ kHz/mm}^2)$ of these kind of sensors when operated at readout thresholds below the single photon level. Application of such sensors in combination with a self-streaming readout system (like in CBM), where no external trigger signal is available for gating the SiPM signals, is even more demanding, and only possible in connection with clever local data selection concepts directly implemented inside the frontend readout electronics.

Typically, Cherenkov photons arriving at the camera photo-sensors (MaPMTs, SiPMs, APDs) create current pulses of the same amplitude as the dark count pulses (1 spe, single photo-electron). Due to the low dark rate of MaPMT-based photon detection systems, a free-streaming readout system can handle such rates by simply recording all the events, but in a SiPM-based camera with $\mathcal{O}(10000 \text{ channels})$ the resulting data rate would be impossible to handle effectively. The SiPM noise may principally be reduced by cooling, but the installation of a cooling system significantly increases the overall complexity, the material budget, and power consumption. In this order of ideas, we need to design a new trigger/data selection system for the CBM RICH camera.

Replacing the MAPMTs in the present CBM RICH photon camera with MPPC-SiPMs of similar pixel size would require 36 rows by 14 columns of MPPC-SiPMs, 504 in total for each camera. Based on the present readout concept, the MPPCs would be clustered in readout panels of 3×2 MPPCs. Each Multi-Pixel Photon counter (MPPC) array is made of 64 individual SiPM pixels ($6 \text{ mm} \times 6 \text{ mm}$) arranged in an 8×8 matrix. A DIRICH board reads 32 channels, so we will need 2 DIRICH modules to read a single MPPC array.

According to realistic Monte Carlo simulations of the CBM RICH, a typical Cherenkov ring ($\sim 8 \text{ cm}$ diameter) has an average of up to 27 detected photons (based on the quantum efficiency of presently used MAPMTs) [5]. The present RICH photon detector is using H12700 MaPMTs with 64 individual readout pixels of $4.85 \text{ mm} \times 4.85 \text{ mm}$ each. All electrons emitting Cherenkov photons basically travel through the RICH radiator with the same velocity (speed of light) as the generated photons, and due to similar path length all photons of a single Cherenkov ring arrive at the camera detection plane in a time window of $\mathcal{O}(10^2 \text{ ps})$, covering 4-8 neighbouring MAPMTs (or MPPCs).

The proposed trigger system is based on a majority voting and subsequent data selection based on a timing cut, utilizing the coincident photon arrival. The majority voting concept has been tested in Cherenkov Telescopes experiments [1] and timing cuts have previously been used in RICH detectors [6]. In this case the majority voting signal is generated by summing all pulses (64 channels) coming from a MPPC in a sharp coincidence window ($< 10 \text{ ns}$). This sum signal surpasses the noise threshold when a Cherenkov-Ring hits the MPPC.

In this report, we present results of evaluating two signal multiplexing methodologies for building the analog sum signal, one based on schottky diodes and another based on a capacitive splitting.

Charge multiplexing

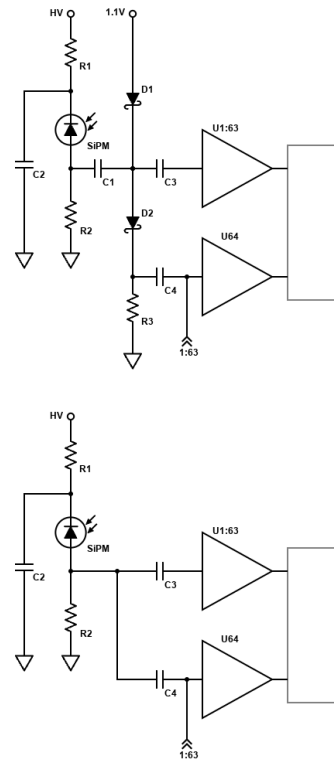


Figure 1: Multiplexing circuits of the SiPM signal . Schottky diode-based (top) and capacitor-based (bottom). The other 63 channels shall be connected to the 1:63 port.

The analog summing circuit must add all the individual SiPM's channels without disturbing the pulse properties or generating signal reflections due to impedance mismatch. We tested two approaches: signal multiplexing with schottky diodes and with capacitors.

In the first architecture, we split the SiPM signals by placing a Schottky diode D_2 between the SiPM and the summing amplifier U_{64} . A secondary Schottky diode D_1 sets the pulse DC baseline taking into account diodes have a minimum forward voltage. When the SiPM generates a pulse, the low forward resistance of D_2 allows current flow from the SiPM to the summing amplifier, while the high reverse resistance of D_2 blocks current flowing from the summing amplifier to the SiPM individual channel output. [2, 3, 4]. C_1 (100 nF)/ C_3 (100 pF) block the DC component coming from the diodes to the SiPM/amplifier. C_4 (100 pF) removes the baseline of the pulse coming from the diode D_2 .

We used the Schottky diode SMS7621-005LF in the final design. This diode has a forward voltage of 320 mV, a 0.2 pF capacitance, and may be used at frequencies up to 24 GHz. The power consumption of the schottky network is 1.1 V/34 mA per channel.

For the second, capacitive multiplexing circuit, we used $C_3 = C_4 = 100$ pF. The power consumption of the capacitor network is close to zero because it's passive.

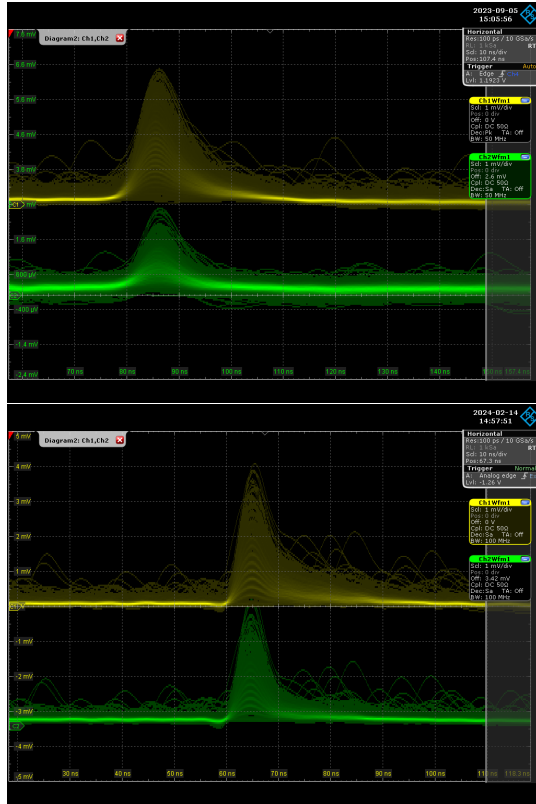


Figure 2: Signal behavior in the Schottky diode-based (top) and capacitor-based (bottom) multiplexing circuits.

Fig. 2 shows the behavior of both signal multiplexing approaches. In the Schottky diode network, the SiPM signal going through C_3 (yellow-line) preserves the amplitude quantization, but the signal passing by the diode D_2 (green-line) is attenuated and loses the photon counting resolution (Fig. 2-top). However, in the capacitor network, the amplitude quantization is preserved in both channels (Fig. 2-bottom).

Summary

We report the status and first ideas of the implementation of a local trigger system for a SiPM-based RICH camera. We proposed a majority voting trigger by summing all the channels of a MPPC. Two signal multiplexing architectures were tested. The use of schottky diodes for signal multiplexing is well known, however we found one of the two multiplexed signals is attenuated and loses the photon resolution. Additionally, the schottky diodes need a minimum bias current for being correctly polarized, setting a minimum power consumption of 37.4 mW per channel for functioning.

On the other hand, multiplexing by using a capacitive network preserves the signal properties (amplitude and timing) and reduces drastically the power consumption per channel. We conclude SiPM signal multiplexing using the capacitive network is the best option to continue with the local triggering system design.

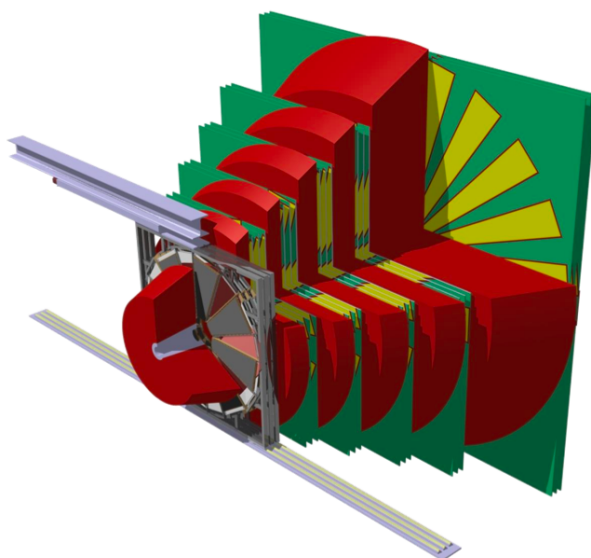
Acknowledgments

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Muon Detection System



Development and testing of a high rate capable RPC at GIF++, CERN in 2023

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Introduction

Resistive plate Chambers (RPC) [1] will be used in the 3rd and 4th station of MuCh where the maximum particle rates are expected to be 30 KHz/cm² and 10 KHz/cm²[3] respectively. A real-size RPC prototype for the 3rd MuCh station with a 2-mm gas gap has been produced and rigorously tested at the Gamma Irradiation Facility(GIF++), CERN in Sept. 2023. The RPC was clubbed with a real-size pick-up panel with pad-readout and integrated with self-triggered readout ASIC named MuCh-XYTER. Our current experiment aims to investigate the detector's resilience to high particle rates, examine the nature of the secondary time correlation peak more closely, and explore the behavior of cluster sizes. During the GIF++ test beam, we thoroughly characterized the detector's performance by measuring its muon detection efficiency at varying voltages and particle rate in the presence of high photon flux.

Experimental set-up

GIF++ accommodates a Cs-137 photon source with an activity of approximately 14 TBq (as of 2014) and a high-energy muon beam (up to 150 GeV/c). The RPC was housed within a rectangular aluminum enclosure equipped with an adjustable support structure, allowing for flexibility in positioning the detector relative to both the gamma source and the muon beam impact point on the detector (see Fig. 1).

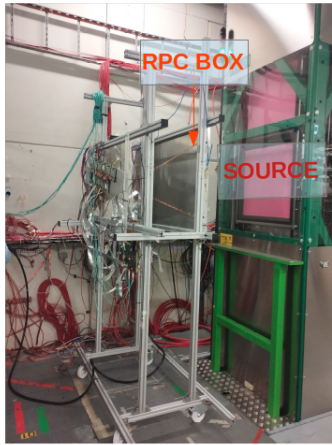


Figure 1: Experimental set-up at GIF++, CERN. The RPC box was positioned 60 cm away from the source wall in the downstream direction.

The detector specifications are as follows:

- The height of the trapezoidal shape detector is 116.1 cm
- The Gas gap of the detector is 2 mm.
- The thickness of the bakelite electrode is 1.2 mm with Bulk Resistivity in the order of $(3 \times 10^9 - 1 \times 10^{10}) \Omega cm$.
- The smallest pad size of the detector is $(1.01 \text{ cm} \times 1.01 \text{ cm})$,
- The largest pad size of the detector is $(5.0 \text{ cm} \times 5.0 \text{ cm})$.
- The Gas mixture consists of R134a : iC4H10 : SF6 in a ratio of 95.2 : 4.5 : 0.3, along with 40% humidity.

The detector underwent testing with both muons only and in presence of photon flux. The results of this testing are discussed in the following section.

Result with only muon

Figure 2 illustrates the typical time correlation spectrum of the detector at 9200 V with only muon-setup.

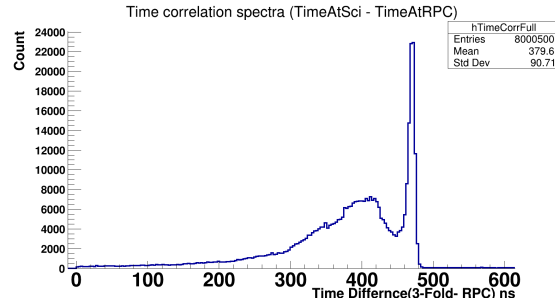


Figure 2: Time-correlation spectra at 9800 Volt

The detector achieved a muon detection efficiency exceeding 90 % at its operating voltage (see Fig 3). A secondary peak in time-correlation spectra, first observed in 2021 test-beam at GIF++, was thoroughly investigated this time.

The hits from the secondary peak are spatially distributed around the hits from the main peak. The pad distribution (Fig. 4) of the secondary time-correlation peak shows its distribution around the hit pads of the main

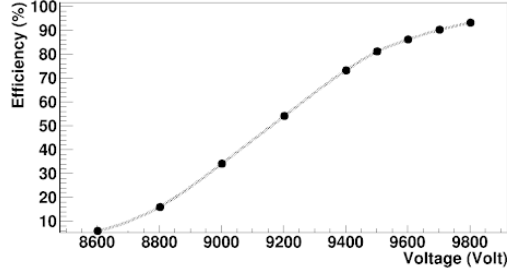


Figure 3: Efficiency of the detector as a function of voltages

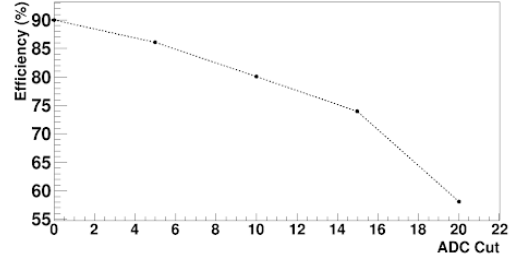


Figure 6: Efficiency of the detector as a function of ADC cut at 9800 Volt

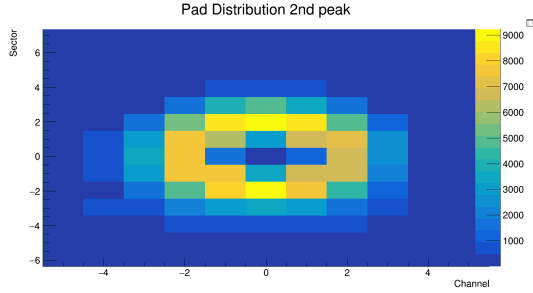


Figure 4: Projected pad distribution of the secondary time-correlation peak

peak. Furthermore, the hits from the secondary peak exhibit smaller ADC values.

Applying an ADC cut to all hits will decrease the secondary peak statistics as shown in Fig. 5. But unfortunately this is also associated with a reduction in overall detector efficiency, as illustrated in Fig. 6.

Results with source on

To assess the ability of the detector to handle high photon fluxes, we positioned it 60 cm from the source wall and varied the source attenuation factor from 146 to 15. Analyzing the recorded digital signal rate (digi rate), we observed an average rate of 62 kHz/cm² at an attenuation of 15 (see

Fig. 7).

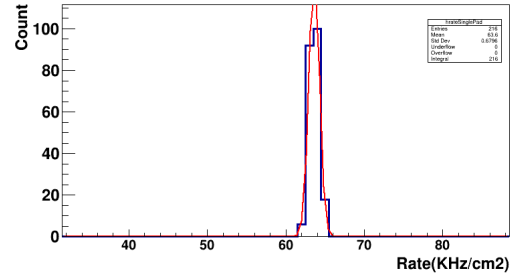


Figure 7: Average rate of a typical pad from the first FEB at 15 Attn. and at 9800 volt

Discussion

A real-size single-gap RPC was successfully tested with muons to determine its time-correlation, efficiency and rate handling capability. While a secondary peak in the time correlation spectrum, likely caused by crosstalk, exhibited lower ADC values, implementing a high ADC cut to eliminate it would unfortunately decrease the detector's overall efficiency. Notably, the RPC achieved an impressive efficiency exceeding 90 percent at its operating voltages. Furthermore, the detector demonstrated its ability to handle high photon fluxes, registering a maximum digital signal rate (digi rate) of approximately 62 kHz/cm².

Acknowledgement

We sincerely acknowledge Martin Jaekel, Giuseppe Pezzullo for their constant support and help throughout the testing period.

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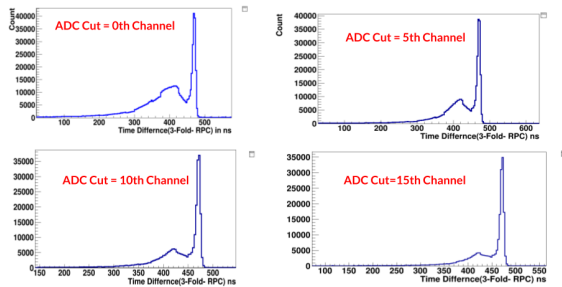


Figure 5: Time correlation with different ADC-cuts ranging from 0 to 20

Test results of real-size triple GEM detector with muons in presence of a high intensity gamma source at the GIF++ facility at CERN

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Introduction

An upgraded large size triple GEM detector for the first station of the Muon Chamber System (MuCh) was tested with high intensity Gamma source at the Gamma Irradiation Facility (GIF++) of the EHN1 beamline at CERN in Aug-Sept. 2023. The detector built at VECC was the first such detector to have all the components fabricated locally in Indian industry and this test with high energy particle beams at GIF++ is first such test of the indeginously built detector in high radiation environment. Along with the GEM detector, a real size RPC prototype for the third station of MuCh was also tested. The picture of entire experimental setup is shown in Fig.1.

The goal of this experiment was to study the response of the detectors towards muon detection in high gamma environment. The muon beam produced upstream from weak decays of pions was incident on our detector. An array of 3 plastic scintillators were used to provide the muon trigger in 3-fold coincidence. It was also for the first time that the detector was operated with all the 18 FEBs thus covering the full geometrical acceptance of its active region. The data were collected using a Common Readout Interface (CRI)-based system using a mobile data acquisition (DAQ) for the first time. In this document, we present two distinct results: the detector response to increasing bias voltage and response to increasing source intensity

Operational Parameters

Fig 1 shows images of the GIF++ cave with the Gamma source, RPC, and GEM modules as indicated. The detectors were mounted vertically as shown in the figure, with the muon beam crossing the middle of the detector plane(s). The scintillator detectors providing 3-fold coincidence were placed outside of the beam hall and were far off not to be influenced by gamma background. The GEM module was kept at various distances (101 cm to 146 cm) from a 137-Cs gamma source with a strength of approximately 11.34 TBq. We tested the detector response and characteristics at different operating voltages, source strengths, detector positions and spatial orientations.

Data Analysis

For the beam-test, data were acquired using STS/MuCh self-triggered electronics. Fig. 2 illustrates the spill structure, highlighting on-spill and off-spill regions after noise

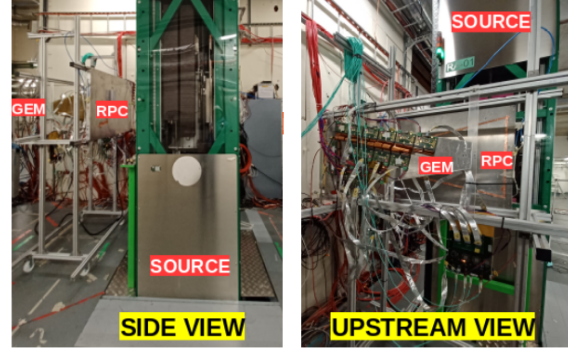


Figure 1: Side (Left) and Upstream (Right) view of GEM and RPC modules with respect to the gamma source at GIF++ 2023 experiment

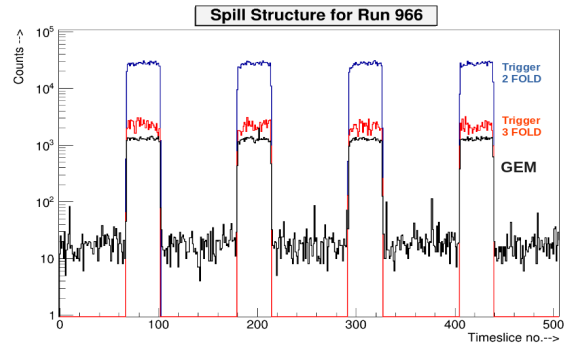


Figure 2: Spill structure as a function of timeslice (128 ms) of GEM, 2-fold and 3-fold Trigger

masking. Fig. 3 displays a 2D distribution of digital signals (digis) for the GEM plane, precisely locating the beam spot due to muon hits on the detector.

Fig.4 displays the Most Probable Value (MPV) of the cluster charge distribution vs. applied bias voltage, fitted by an exponential curve. In contrast, Fig. 5 presents a variation in MPV with the relative intensity as indicated by attenuation factors for two different voltages. When plotting the cluster charge distribution for both cases, only digis within a 3σ time window with respect to 3-fold scintillator trigger were considered. The gain response was observed to remain stable, even at the highest intensity for the bias voltages considered. Detector response stability is further evidenced by the average number of digis, which were ob-

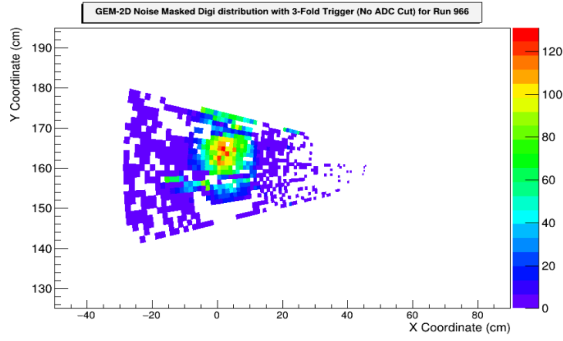


Figure 3: Upstream View of Hits for Run 966 after masking noisy pads. Beam spot is apparent after applying three fold trigger

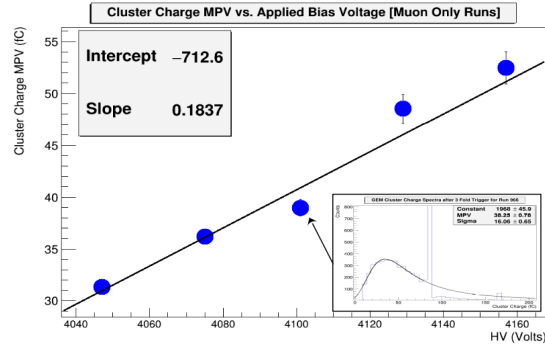


Figure 4: Cluster Charge MPV as a function of HV fit with exponential curve. A typical cluster charge distribution is shown in the inset.

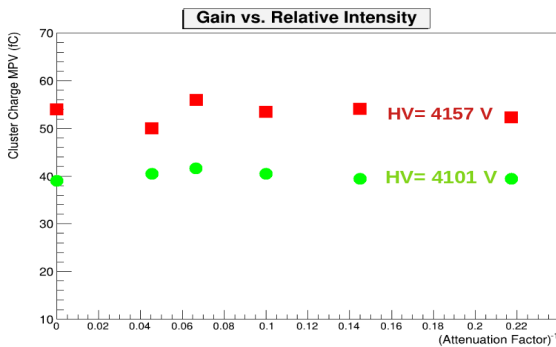


Figure 5: Cluster Charge MPV as a function of relative intensity at two different voltages

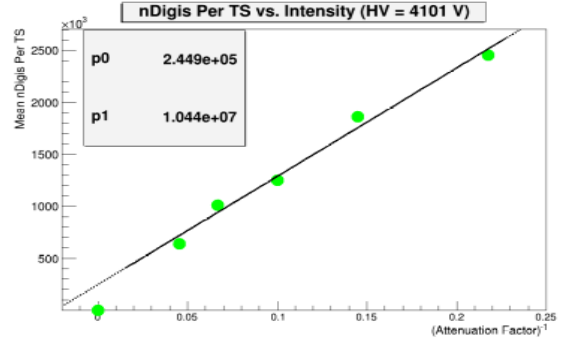


Figure 6: nDigis per Timeslice with increasing intensity fit with a straight line

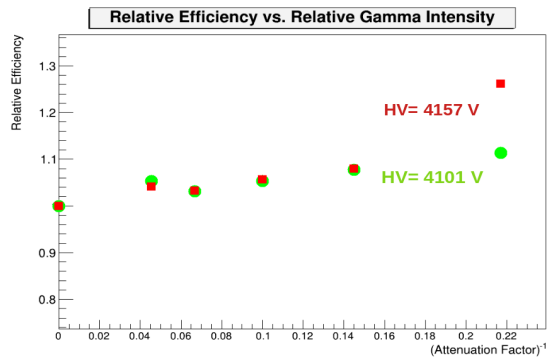


Figure 7: Relative efficiency vs. relative gamma intensity for two different voltages

served to increase linearly with relative intensity (see Fig. 6). The muon-only data point is shown by the point with attenuation factor "0". Fig. 7 shows an increase in the relative efficiency with increasing gamma intensity. For HV = 4101 V we see only 10% change but for HV = 4157 V we see an increase of upto 25%. This increase could be attributed to chance coincidences in our detector.

Acknowledgement

We extend a thanks to Eraldo Oliveri of RD51 collaboration and Giuseppe Pezzullo for GIF++ for their invaluable assistance during the beamtime.

Data analysis of CBM MuCh-RPC detector tests at the Gamma Irradiation Facility (GIF++) at CERN in 2023

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The CBM-MuCh is a dedicated detector for muon identification in CBM. For the third and fourth stations of MuCh, where particle rates are expected to be 30 kHz/cm² and 10 kHz/cm², respectively, low resistive bakelite RPCs are foreseen to be used as active detector components. Here we present test results for RPC prototype modules tested at CERN's Gamma Irradiation Facility (GIF++) in 2023 [1].

This facility is located at the H4 beam line in EHN1 [2], where high energy charged particle beams (mainly muon beams with momentum up to 150 GeV/c) are combined with a 14 TBq ¹³⁷Cesium-137 source. Figure 1 shows the test setup, where a real size RPC prototype was placed inside a rectangular frame and mounted on an adjustable support structure. There are in total four Front-end Electronics Board (FEBs) mounted on the PCB, which are further divided into 46 sectors and 10 channels. The detector was operated with a gas mixture consisting of R134a : iC4H10 : SF6 in a ratio of 95.2 : 4.5 : 0.3, along with 40% humidity, at a constant flow rate of 4.0 lt/hr.

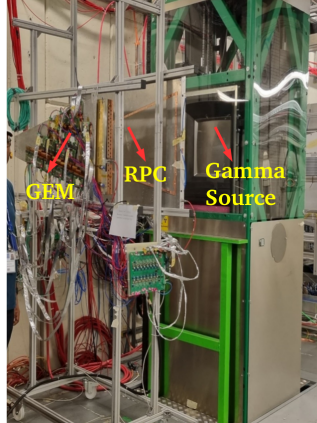


Figure 1: GIF++ setup at CERN

Data were taken for two different conditions, one with only muons and another with muons embedded in a gamma background of varying flux. A triggering scheme based on the coincidence of signals from three distinct scintillators, two positioned upstream and the other downstream of the RPC detector, was used in data acquisition. The aim of this work was to study different detector parameters such as timing response, rate handling capability, efficiency, etc. in a high particle flux environment.

The overall coverage of RPC-FEBs in-terms of sector and channel numbers are shown in the top panel of Fig .2.

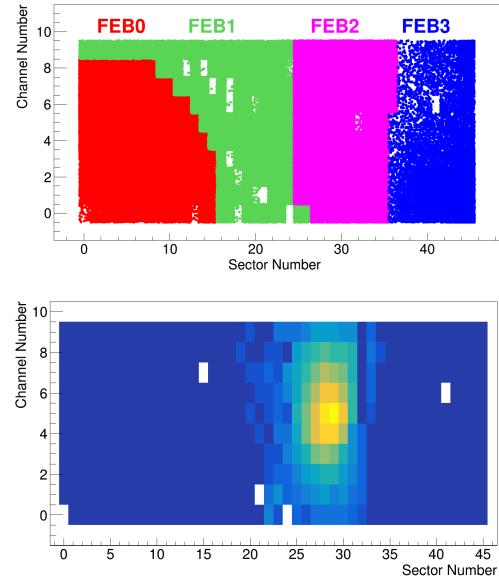


Figure 2: (Top) Total coverage of all four FEBs. Empty regions indicate masked channels. (Bottom) Beam spot on the RPC.

The bottom panel of Fig. 2 shows the count number in the RPC as function of sector and channel number. The beam spot, i.e, the region where the beam impinges on the RPC, is clearly visible.

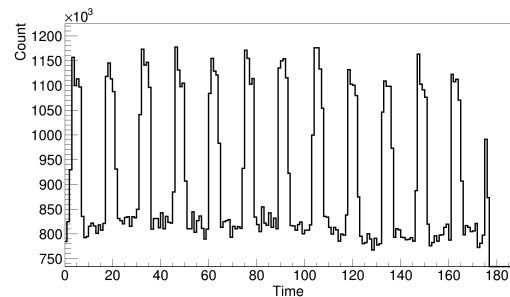


Figure 3: Spill structure as observed by the RPC

Figure 3 shows the spill distribution as observed via the count rate of the RPC detector for muon-only beam. In the spill pauses, ideally the hit count should be zero, but, because of noisy channels of the detectors and noise from

other sources, there is a background, which has to be suppressed. Noise suppression is done at the analysis level by identifying the noisy channels and masking them.

After removing the noisy channels, the time correlation between the trigger system and the RPC hits is obtained. The time of genuine RPC hits should be correlated to the trigger time. Figure 4 shows a time difference spectrum that exhibit two peaks, one narrow (main) and another broad one [3].

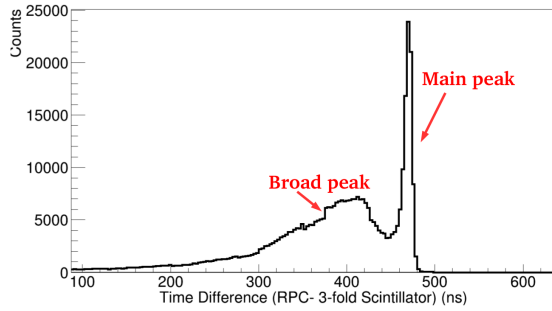


Figure 4: Distribution of the difference of RPC hit times and trigger time

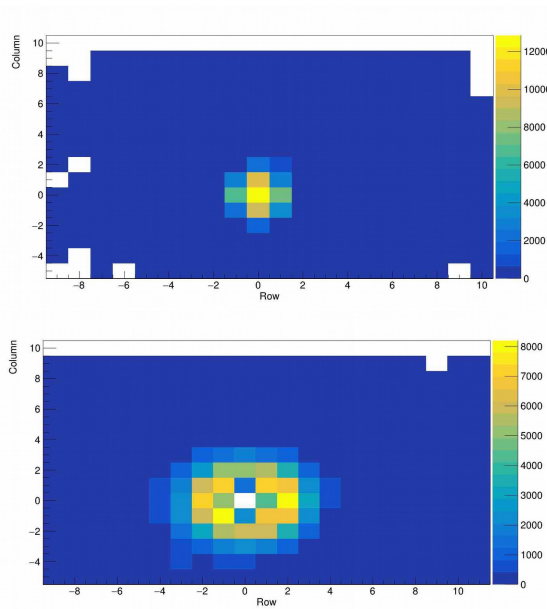


Figure 5: Pad distribution for (top) the narrow peak between 450-500 ns in the time difference, (bottom) the broad peak between 0-450 ns of time difference. For convenience of the representation, the pad under the narrow peak is taken as reference and shifted to (0,0). The pads under the broad peak are shifted accordingly.

The correlation peak with narrower width most likely corresponds to the true signal, whereas the broader peak is due to cross-talk from the neighbouring pads. This is clearly seen by studying the pad distribution for each of

these peaks in Fig. 5. Pads that correspond to the broad peak are distributed around the pad of the narrower peak. This indicates that there is a significant cross-talk which is responsible for the second peak in the time difference spectrum.

Finally, the efficiency of the RPC module is estimated by counting the total number of hits associated with each of the peaks with respect to the total trigger count and RPC. The efficiency is defined by

$$\text{eff} = \frac{\text{number of hits under narrow/broad peak}}{\text{Total number of three fold counts in trigger}}$$

Figure 6 shows the efficiency as a function of trigger count corresponding to the narrow (main) peak (top panel) and the broad peak (bottom panel), respectively. The average efficiency corresponding to the narrow peak is found to be around ~94%; for the broader peak it is about ~92%. The efficiency is found to be independent of the trigger count which indicates the efficiency value is statistically stable with time also.

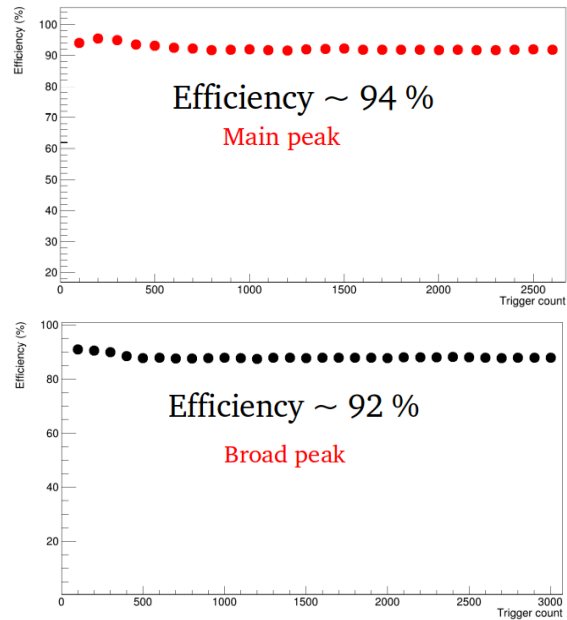


Figure 6: Efficiency as a function of trigger count (top) for the narrow peak and (bottom) for the broad peak

We estimated the cluster size in the main time correlation peak. The average cluster size is 4-5 and it depends on the RPC high voltage.

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Observation of some anomalous behavior in GEM Detector after long irradiation

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Introduction

Triple Gas Electron Multiplier (GEM) detector has been chosen as the muon tracker in the first two stations of CBM Muon Chamber (MuCh) sub-system because of its high rate handling capability ($\sim 1 \text{ MHz/cm}^2$) and good spatial resolution ($\sim 100 \mu\text{m}$) [1, 2, 3].

An initiative is taken to study the stability in performance of the triple GEM chamber prototype in the laboratory using external radiation for Argon/CO₂ gas mixture in 70/30 volume ratio. The effect of ambient parameters on the gain and energy resolution are studied. Very recently some behavioural changes in the performance of a Single Mask (SM) triple GEM chamber is observed. The latest results are reported here.

Description of the chamber and experimental set-up

In this study a SM triple GEM detector prototype having dimension of $10 \times 10 \text{ cm}^2$ is used in 3-2-2-2 configuration (drift gap - transfer gap 1- transfer gap 2 - induction gap). The details of the detector configuration, voltage divider network and electronics set-up are available in Ref. [4, 5].

For the stability test of the GEM detector a ⁵⁵Fe X-ray source is used to irradiate the chamber. The same source is also used to monitor the spectrum. The effect of temperature, pressure, relative humidity on the gain and energy resolution and the charging up effects are studied. The gain and energy resolution of the chamber is calculated by fitting the 5.9 keV main peak with a Gaussian distribution. The mean of the fitted Gaussian spectrum gives the information of the total output charge by using the gain of the preamplifier and the MCA calibration factor.

The mathematical formalism to calculate the gain, energy resolution, normalised gain, normalised energy resolution and accumulated charge per unit area are described in detail in Ref. [6].

Results

To test the stability of the SM triple GEM chamber, initially the high voltage (HV) to the chamber is set at -4500 V and the spectra are recorded for every 1 minute. The temperature (t), pressure (p) and relative humidity (RH) are also recorded for every 1 minute interval using a data logger made in-house [7]. The divider current is also recorded

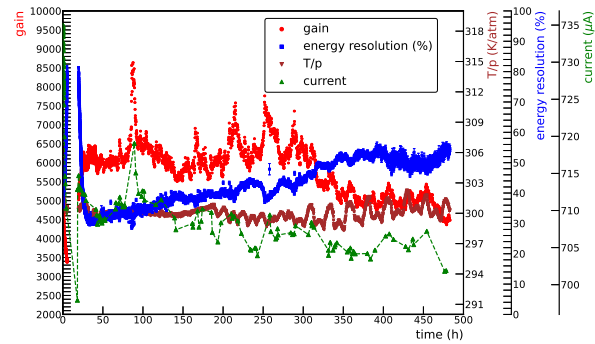


Figure 1: Variation of the measured gain, energy resolution, divider current and T/p as a function of time

time to time from the HV power supply itself. The variation of measured gain, % energy resolution, T/p ($T = t + 273$) and the divider current as a function of time are shown in Figure 1.

It is observed that immediately after applying the HV the bias current increases rapidly, reaches a maximum and then starts to decrease. The shape of ⁵⁵Fe X-ray spectra recorded are also changed with time. The current at the starting point (at HV of -4500 V) is measured to be about 729 μA which increases to a maximum value of 735 μA

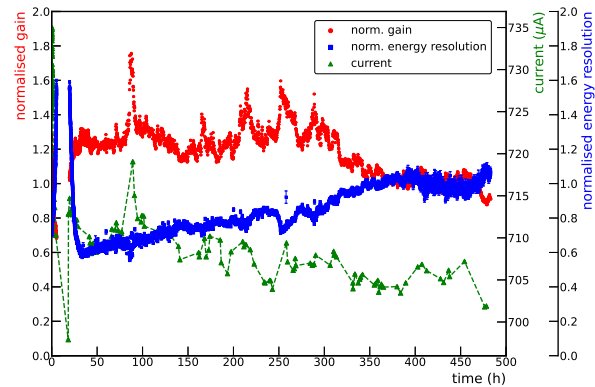


Figure 2: Variation of normalised gain, normalised energy resolution along with the variation of divider current as a function of time

and starts to decrease. After 24 hours of operation the current decreased to about $697 \mu\text{A}$ and the applied HV is increased to -4600 V to keep the gain constant. At that point, the divider current is again raised to a value $\sim 715 \mu\text{A}$. Subsequently, as time passes, the current drops slowly. Since the current decreases and fluctuates with time, the gain also decrease and fluctuate. On the other hand the energy resolution becomes worse as the gain decreases. This is discussed in detail in Ref. [6].

The normalised gain and normalised energy resolution as a function of time and those values as a function of charge accumulated per unit area are shown in Figure 2 and 3 respectively.

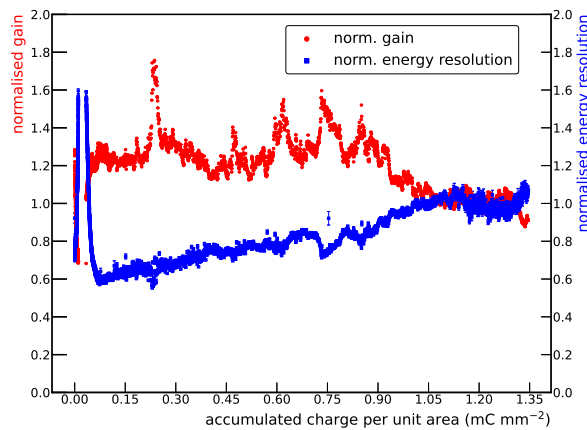


Figure 3: Variation of normalised gain, normalised energy resolution as a function accumulated charge per unit area

It is clearly visible from Fig. 2 that the normalised gain varies proportionally with the divider current. In contrast to normalised gain, the normalised energy resolution exhibits the opposite trend.

Summary

The stability study of the gain and energy resolution of a SM triple GEM detector under continuous high-rate ^{55}Fe X-ray irradiation is conducted using NIM electronics with a gas mixture of Argon and CO_2 in 70/30 volume ratio. The certain area of the chamber is continuously irradiated with X-ray for a period of about 500 hours which is equivalent to an accumulated charge of about 1.35 mC per mm^2 . In this continuous study it is observed that the T/p normalised gain decreases with time after initial charging up phase. The probable reason is that, although there is a sudden jump in the bias current observed at the beginning, after sometimes the bias current starts decreasing gradually. As a result the ΔV across the GEM foils decrease which in turn reduce the gain of the detector and increases the energy resolution value.

In addition to the above phenomena several other behavioural changes are also observed in the chamber. After

a continuous operation of the chamber if there is a break in operation and when the HV is ramped up then shape of some initial spectra are not as expected. It has been observed that the time taken for the spectra to come to its regular shape can take up to 10-12 hours. Actually this particular chamber has gone through several long-term tests since 2015. Several interesting results are being achieved from this particular chamber. During the charging-up studies good spectrum having clear main (5.9 keV) and escape peaks are visible immediately after application of the HV. However, since last year the bias current is decreasing with time which might be due to the ageing of the resistors in the divider chain. The take home message from this report is that, although it is found there is no ageing in the chamber, and the decrease in the normalised gain is directly proportional to the decrease in the bias current, but still something has happened to the chamber that could be attributed to the prolonged radiation over a few years. As a result immediately after applying HV the detector is not working properly, it is taking some time for conditioning, even the desired HV can not be applied directly without spark. Detailed investigations are ongoing.

Acknowledgement

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 of the collimators used in this study. This work is partially supported by the research grant SR/MF/PS-01/2014-BI from DST, Govt. of India, and the research grant of the CBM-MuCh project from BI-IFCC, DST, Govt. of India. S. Mandal acknowledges his UGC-NET fellowship for the support. A. Sen acknowledges the support of the DST-INSPIRE Fellowship (DST/INSPIRE Fellowship/2018/IF180361). S. Biswas acknowledges the support of the DST-SERB Ramanujan Fellowship (D.O.No. SR/S2/RJN-02/2012).

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Study of stability and time resolution of bakelite RPC built with new technique of linseed oil coating

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Introduction

The gaseous parallel plate detectors known as Resistive Plate Chambers (RPCs) [1] have very good time resolution ($\sim$ ns) [2], which makes them an appropriate choice for trigger and tracking device in High-Energy Physics (HEP) experiments [3, 9]. As the fabrication cost per unit area is nominal, very large area can be covered with RPCs in HEP experimental system. Moreover, it is very robust device and the construction procedure is easy.

In the first two stations of CBM Muon Chamber (CBM-MuCh), Gas Electron Multiplier (GEM) detectors will be used because of their high rate handling capability and good position resolution. We are exploring the possibility of using single gap bakelite RPCs as the options for the 3rd and 4th stations [4].

In bakelite RPC linseed oil coating [5] is done to get rid of the surface roughness of the resistive plates [6]. The linseed oil coating helps to reduce the noise rate of the detector and protects the electrode plates from the corrosive effect by Hydrofluoric Acid (HF). It also has photon quenching properties that reduce the UV sensitivity of the electrode plates.

In conventional linseed oil coated bakelite RPC, a serious problem was observed in the BaBar experiment. The coated linseed oil forms stalagmite that subsequently introduces conducting paths through the gas gap specially around the spacers and the discharge permanently damages the detector. The formation of stalagmite is due to the polymerization of uncured linseed oil droplets present on the surface [7]. However, lot of R&D is performed and the solution is found out for this issue [8].

Keeping in mind, the requirements of detectors having high-rate handling capability, cost-effectiveness, and large area coverage, to be used in CBM experiment, commercially available bakelite plates with moderate bulk resistivity are used to build RPC prototypes.

In the present work, a linseed oil coated bakelite RPC is built. However, a different technique for the linseed oil treatment is adopted. Contrary to the conventional procedure, the bakelite plates are coated with linseed oil before making the gas gap to ensure whether the curing is properly done throughout the entire surface. After the linseed oil coating, the plates are cured for 15 days. The advantage of this procedure is that, after the linseed oil coating the surface can be checked visually whether the curing has been properly done or any uncured droplet of linseed oil is present.

Description of the detector and experimental set-up

A 27 cm $\times$ 27 cm bakelite prototype RPC is built using indigenous material. A new technique of linseed oil coating on the bakelite plates [9] is introduced in which one can check visually whether there is any uncured oil present inside the gas gap. With this new technique one RPC prototype was built and tested with 100% C₂H₂F₄ gas and also with conventional C₂H₂F₄ and i-C₄H₁₀ mixture in the 90/10 volume ratio [10]. The details of the fabrication of the module are described in Ref. [9] and [10].

The prototype is tested for efficiency using cosmic ray trigger with three plastic scintillation detectors as described in Ref. [9] and [10]. The details of the electronics set-up is also described in those references. The same cosmic ray test bench is also used to measure the time resolution of the chamber as shown in Figure 1.

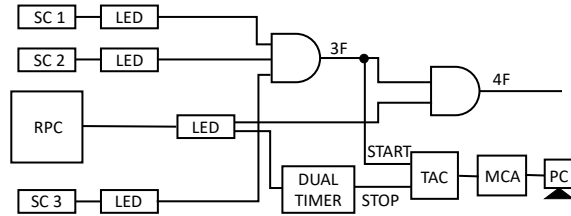


Figure 1: Schematic representation of the time resolution measurement set-up with cosmic rays. SC 1, SC 2 and SC 3 are the plastic scintillators of dimensions 10 cm $\times$ 10 cm, 2 cm $\times$ 10 cm and 20 cm $\times$ 20 cm. respectively. LED, TAC, MCA and PC are the Leading edge discriminators, Time to Amplitude Converter, Multi-Channel Analyser and Personal Computer respectively.

Result

The time resolution of the RPC prototype is measured with 100% C₂H₂F₄ gas as an active medium. While measuring the time resolution, the RPC signal is stretched to 500 ns to avoid the effect of double pulses or reflection pulses if there are any. The full scale of the TAC is set to 100 ns. In this case the START signal of the TAC is taken from the 3-fold scintillator trigger and the STOP signal is taken from the RPC. The distribution of the time difference between the master trigger and the RPC signal is fitted with the Gaussian function. By finding the σ of the distribution and subtracting in quadrature the contribution from

the scintillator, the intrinsic time resolution of the RPC is calculated. For this measurement no amplifier is used for the RPC.

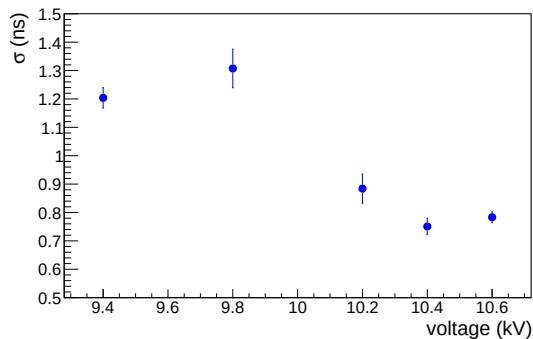


Figure 2: Time resolution (σ) of the linseed oil coated bakelite RPC as a function of voltage for 100% $C_2H_2F_4$.

The intrinsic time resolution (σ) of the RPC as a function of the applied voltage is shown in Figure 2. With the increase of applied voltage, the time resolution (σ) improves.

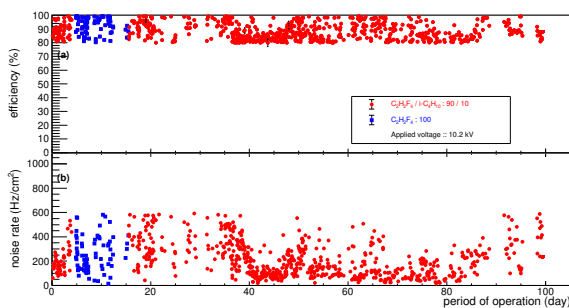


Figure 3: (a) Efficiency and (b) noise rate of the detector as a function of period of operation for two different gas composition at an applied voltage of 10.2 kV. Data points the error bars are smaller than the size of the markers.

The stability test is performed at an applied voltage of 10.2 kV, both with a $C_2H_2F_4$ and $i-C_4H_{10}$ mixture in the 90/10 volume ratio and with 100% $C_2H_2F_4$. Initially, the detector is operated with a mixture of $C_2H_2F_4$ and $i-C_4H_{10}$ and then it is continuously tested with 100% $C_2H_2F_4$ for next few days. After that it is again tested with the mixed gas. The measured efficiency and noise rate of the detector as a function of the period of operation for two different gas compositions are shown in Figure 3. The test is performed for more than three months. It is found that for $C_2H_2F_4$ and $i-C_4H_{10}$ mixture and 100% $C_2H_2F_4$ the average efficiencies are found to be $88 \pm 6\%$ and $93 \pm 6\%$ respectively whereas the average noise rates for two compositions are found to be $189 \pm 131 \text{ Hz/cm}^2$ and $208 \pm 129 \text{ Hz/cm}^2$.

Summary

A linseed oil-coated RPC prototype of dimension $27 \text{ cm} \times 27 \text{ cm}$ is fabricated using indigenous resistive bakelite plates. The linseed oil coating is done before making the gas gap. Before building the detector, electrode plates are checked visually whether the oil is cured properly or if any uncured oil is present on the surface. The time resolution of the prototype is measured with 100% $C_2H_2F_4$ gas and the stability test for efficiency and noise rate is performed using both 100% $C_2H_2F_4$ gas and conventional $C_2H_2F_4$ and $i-C_4H_{10}$ mixture in the 90/10 volume ratio. The best time resolution 0.8 ns (σ) is obtained for an applied voltage of 10.4 kV, which is comparable to the value obtained in conventional linseed oil coated bakelite RPC. To check the stability of the chamber the RPC is operated for more than three months. The average efficiencies are found to be $88 \pm 6\%$ and $93 \pm 6\%$ respectively whereas the average noise rates for two compositions are found to be $189 \pm 131 \text{ Hz/cm}^2$ and $208 \pm 129 \text{ Hz/cm}^2$ for $C_2H_2F_4$ and $i-C_4H_{10}$ mixture and 100% $C_2H_2F_4$ respectively.

Acknowledgement

We would like to thank Dr. Somen Gope for helping in data taking for the stability test and Mr. Subrata Das for technical help during this study. The authors would also like to thank Prof. Sanjay K Ghosh and Dr. Sidharth K. Prasad for valuable discussions and suggestions in the course of the study. This work is supported by DST Inspire Fellowship research grant [DST/INSPIRE Fellowship/2018/IF180361] and partially supported by the CBM-MuCh project from BI-IFCC, DST, Govt. of India.

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Rate calculation for the GEM detector at the mCBM experiment

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This report focuses on the particle rate measurement for the GEM detector within the mini CBM experiment conducted at the SIS-18 accelerator ring at FAIR. The Compressed Baryonic Matter (CBM) experiment aims to explore the QCD phase diagram in regions of high net baryon density at the FAIR facility in Darmstadt, Germany. The construction of the SIS-100 accelerator ring is currently underway and is poised to provide accelerated beams with energies reaching up to 30 GeV for protons, 15A GeV for light ions (e.g., C, Ca, Ni, ...), and 12A GeV for heavy ions (such as Pb, Au, In, ...). Anticipated interaction rates for the CBM experiment at SIS-100 are expected to peak at 10 MHz.

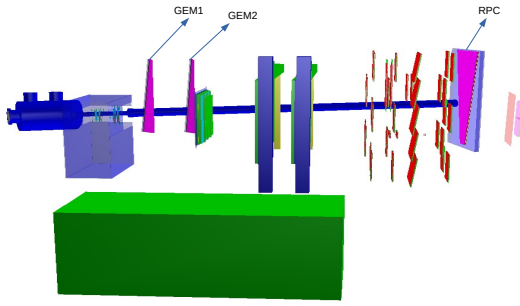


Figure 1: mini CBM experimental setup

At present, the SIS-18 accelerator ring is operating with beam energies of 1 GeV for Au 79+ ions and 4.5 GeV for protons. The mini CBM experiment is conducted to test and optimize detectors intended for use in the main CBM experiment. This report focuses on the calculation of the particle rate for the GEM detector of Muon Chamber (MuCh) detector within the mini CBM experiment setup. The mini CBM experimental configuration includes the Silicon Tracking System (STS), which is responsible for reconstructing tracks and determining the momentum of charged particles. The MuCh detector employs Gas Electron Multiplier (GEM) technology at its first two stations, where particle rates are notably high. The GEM-1 and GEM-2 modules are positioned after the STS detector in the mini CBM experiment setup, followed by the Transition Radiation Detector (TRD) and the Time of Flight (TOF) detector, which is utilized for hadron identification. The Resistive Plate Chamber (RPC) is located at the end of the setup and serves the third and fourth stations of the MuCh detector, where particle rates are lower due to the presence of hadron absorbers. The current study imple-

ments the *much_v22j_mcbm* geometry, matching the experimental runs numbered 2565 and 2541 of the mini CBM experiment.

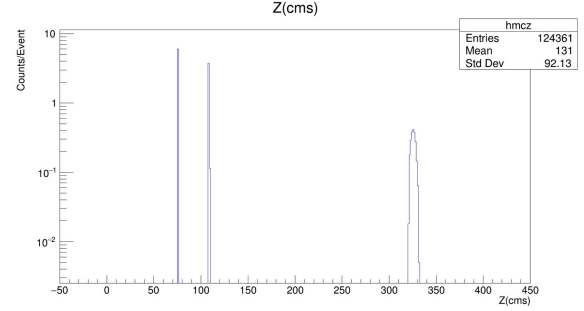


Figure 2: z coordinate of hits in GEM1 and GEM2 in the mCBM setup

The simulations utilize the NOV21 version of *cbmroot*. The rate calculation for GEM1 and GEM2 is based on the realistic configuration of the MuCh detector system in the mini CBM experiment, as depicted in Fig. 1.

During the simulation process, a collision scenario involving 10,000 mbias Au-Au collisions at $E_{lab} = 1.23$ AGeV is considered. These particles are traversed through the *much_v22j* mCBM detector geometry using the GEANT3 transport engine, resulting in Monte Carlo points across the detector. The detector response is then determined based on digitization parameters derived from these Monte Carlo points, resulting in what is referred to as digis.

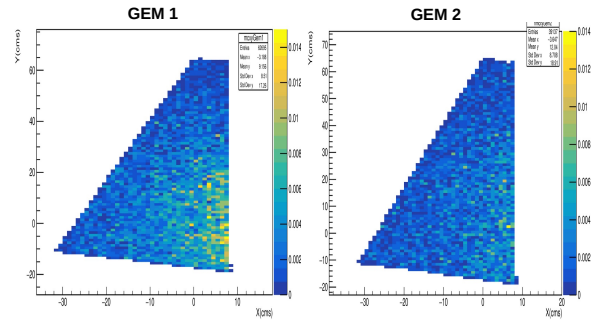


Figure 3: Monte Carlo point XY distribution for GEM1 and GEM2

The GEM1 and GEM2 detectors are positioned at distances of 75 cm and 110 cm from the interaction point, respectively (see Fig. 2). These modules span from 10 cm

near the beam pipe to -32 cm along the X-axis. Along the Y-axis, both GEM modules extend from the bottom side at -20 cm to the upper side at 62 cm, as illustrated in Fig. 3. Each module is segmented into 23 channels and 97 sectors, resulting in a total of 2231 pads across both modules.

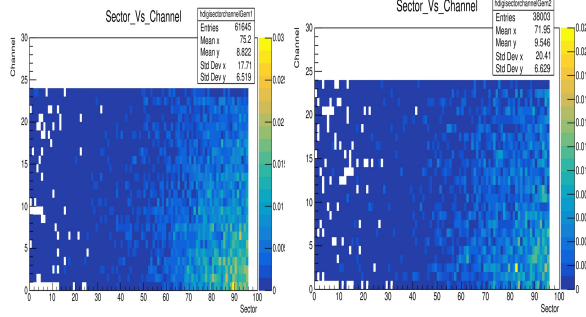


Figure 4: Sector and Channel digi distribution of GEM-1 and GEM-2

More realistic parameters have been employed for digitization. Each of the GEM-1 and GEM-2 detectors is allocated a total of 32 ADC channels. A spot radius of $500 \mu\text{m}$ is utilized, along with a mean gas gain of 5000 and a charge threshold of 6 fC, which is consistent across both detectors.

The beam intensity is set at 2.5×10^9 particles per spill, with each spill lasting approximately 10 seconds. Consequently, the beam intensity is estimated to be 2.5×10^8 particles per second. A gold target with a thickness of $2.5 \mu\text{m}$, equivalent to about 1% of the interaction length, is employed. As a result, the corresponding interaction rate reaches 2500 kHz.

The highest particle rate recorded for GEM1 occurs at Channel 0 and Sector 90, with a value of 0.025 per event, considering a pad area of 0.0966cm^2 . Similarly, for the GEM2 detector, the highest particle rate is observed at Channel 3 and Sector 82, registering a value of 0.022 per event, with a pad area of 0.0732cm^2 , as depicted in Fig. 4. The particle rate per event is multiplied by 2500 KHz to obtain the total rate. This total rate is then divided by the corresponding pad area to determine the particle rate per cm^2 . The maximum particle digi rate for GEM1 and GEM2 was calculated and is presented in Table 1.

Table 1: Maximum digi rate and flux for GEM1 and GEM2

	Maximum digi rate kHz	Maximum digi flux kHz/ cm^2
GEM 1	62.5	646.82
GEM 2	55.0	750.77

The digis obtained are subsequently utilized to generate hits on the detector through reconstruction algorithms, as illustrated in Figure 5. Some empty space is noticeable towards the wider extent of the GEM modules due to the larger pad size.

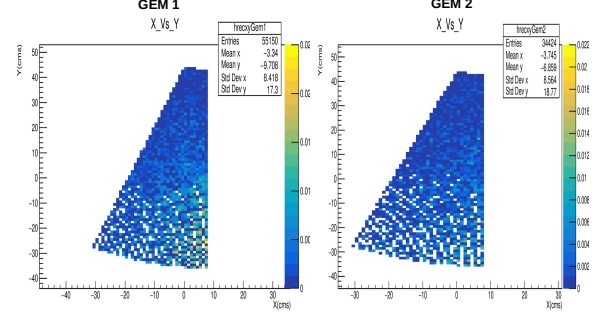


Figure 5: Reconstructed x-y coordinates of hits for GEM1 and GEM2

Acknowledgements

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Exploring the viability of a prototype Water-Based Cooling System for CBM MuCh

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Introduction

The Muon Chamber (MuCh) [1], a di-muon detection system, is scheduled for installation for the Compressed Baryonic Matter (CBM) experiment¹ at the Facility for Anti-proton and Ion Research (FAIR) in Darmstadt, Germany. This system aims to identify and track di-muons generated from the decay of low mass vector meson (ρ and J/ψ) particles during high-energy heavy-ion collisions using a beam with an energy range of 2 to 30A GeV. Its purpose is to identify low-momentum muons in dense particle environments using its three detector layers (stations) segmented by absorber layers. Its compact design, integrating absorbers and detector stations, minimizes background muons from weak meson decays, requiring minimal gaps between absorbers for tracking stations.

The Front End electronic Boards (FEB) in the MuCh detector system receive signals from modules and emit heat during operation. Each FEB in a module dissipates about ~ 90 W of heat, totaling around ~ 4.3 kW for the first station (48 modules) and ~ 5.4 kW for the second station (60 modules). To meet compactness requirements, the three layers of each station must fit within a 30 cm interval along the Z-axis. This concentrated heat dissipation increases temperatures around FEBs, affecting their performance. Optimal operation requires ambient temperatures of 20°C – 25°C . The detectors, GEM-based for the first two stations, are also temperature-sensitive [2, 3]. Hence, maintaining a stable ambient temperature within the acceptable range is essential for the reliable operation of the detectors and FEBs, necessitating continuous removal of the generated heat.

Since, the electronics intended for use in the MuCh system utilise wire bonding, making them susceptible to damage from vibration caused by air-cooling over time. Therefore, air cooling is deemed unsuitable as a cooling solution for the MuCh system. To address this issue within the confined space, a water-cooling system has been devised to effectively dissipate the substantial heat generated. While water cooling surpasses air cooling in efficiency, careful measures must be taken to prevent dew formation and consequent water droplets on the electronics.

Basic working principle and past developments

The compact cooling system has been achieved through the approach of utilizing a single metal plate that doubles as a mounting structure for the detector and a heat sink, featuring embedded coolant channels [4, 5, 6, 7]. Taking into account the factors such as accessibility and cost-efficiency, demineralized water emerges as the preferred coolant. Fig. 1 shows the flow-chart of the cooling system. A laboratory experiment validates the cooling system's proof-of-concept using a small-scale prototype with a copper plate [4, 5]. The full-scale setup at Bose Institute, Kolkata, comprises three modules with aluminum plates and embedded water channels [8, 9, 10, 11]. Two

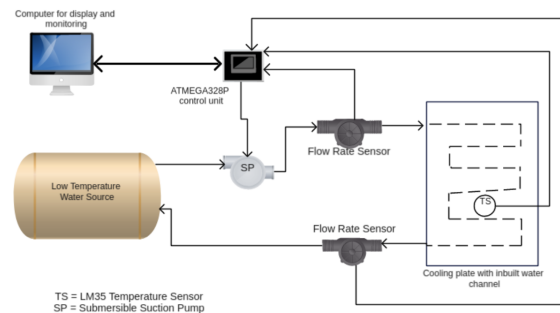


Figure 1: Flow-chart of cooling system [10].

embedding techniques are evaluated, with Technique-I expected to show superior heat transfer efficiency due to direct contact between water channels and the cooling plate while Technique-II offers leak protection advantage using Aluminum pipes. Despite both techniques exhibiting noteworthy cooling performance, achieving a stable temperature with a variation of only $\pm 0.5^\circ\text{C}$ on the surface of both plates [11].

A prototype module with new technique and test plan

The primary emphasis is on integrating a leak-proof coolant flow mechanism into the current system. The new prototype apparatus consists of a single Aluminium plate with a stainless steel pipe moulded into it (Fig. 2). This technique makes the cooling system mechanically more compact, reducing the thickness from 12 mm (as used in Technique-II [11]) to 10 mm, thus also decreasing the ma-

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Figure 2: The new prototype - single aluminium plate with molded stainless steel pipe.

terial budget. However, the key focus lies in assessing the efficiency of this cooling system since the difference between the thermal conductivity of aluminium pipe and stainless steel pipe is of ten order.

To test the cooling system, various components will be utilised, including a cooling plate, a microcontroller board to automate the coolant flow for maintaining a constant temperature, temperature sensors, a water chiller, and a suction pump. The heating elements will be brazed onto the top surface of the Aluminum plate to simulate a required heating load, powered by an external regulated power supply. Subsequently, these heating elements will be activated, and the temperature of the Aluminum plate and the water flow rate will be monitored for several hours to evaluate the cooling system's performance. Based on the results of this prototype test, a decision on building a real size cooling module using this technique will be made.

Acknowledgement

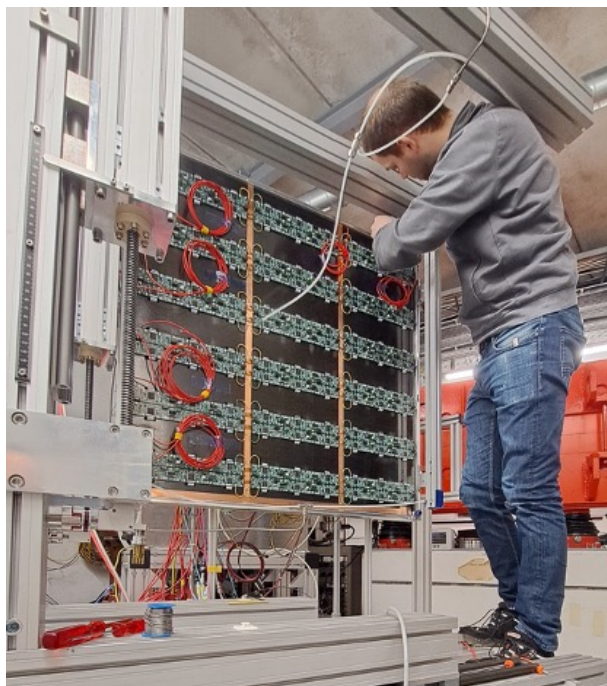
The authors express gratitude to the Department of Science & Technology (DST) and the Department of Atomic Energy (DAE), Government of India, for providing their support under the Project No. SR/MF/PS-02/2010 (E-6133), dated 08/10/2021.

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Transition Radiation Detector



Summary on the TRD project

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Introduction

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

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

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

Prototypes and pre-production

For the outer modules of type-5, the pre-production has finally been started in Münster and Frankfurt [1]. Two type-5 modules have been completed and were subjected to first QA tests and more detailed tests have been worked out. In particular, a procedure to establish the gas tightness of the chambers without using overpressure has been established [2].

The two pre-series modules have been integrated in the mCBM setup, in replacement of the previous four large prototypes, and are now operated in the on-going mCBM

data taking. Based on the detailed evaluation in of their performance, the production readiness review (PRR) will be done in 2024, followed by the mass production of the remaining modules of type-5 and type-3.

Components for the construction of the remaining type-5 chambers have already been procured. After the BMBF-funding of the current period has been released, also further components for type-3 modules will now be ordered.

After the acceptance of the addendum to the TDR, a lot of activities in the Bucharest laboratory addressed the preparation for the series production and test of the modules of type TRD2D foreseen for the innermost region of the TRD. This type employs a novel kind of pad plane with triangular pads, thus allowing the two-dimensional reconstruction of the hit positions with high precision. The laboratory has been equipped with newly designed wire winding frames, an alignment table and a new device for measuring the the wire tension [3].

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 built [4]. This prototype can easily be scaled-up to a full gas system, which will consist of 5 – 6 lines. The task of building the full system will now be taken over by the group in Jülich/Bochum, which has already purchased 3000 l of xenon gas required for a first filling of the system. Furthermore, the group at ICSI, Bucharest, will contribute by adding a purification stage to the gas system of the TRD.

A first engineering design of the TRD mainframe has been worked out by the group in Münster. After its implementation into the cbmroot geometry [5], a detailed evaluation of its impact on the downstream TOF detector has been performed [6]. Based on these studies, a possible revision is currently being discussed, in particular with respect to the question of whether the distances of the TRD layers should be reduced. A final decision on the mainframe layout should be done for the upcoming engineering design report.

Software

A lot of progress has been made on the reconstruction software for the TRD. The unpackers have been prepared

for online data processing and work on online hit finding algorithms is on-going.

An automated conversion procedure of the STEP-files for the TRD support structure, via GDML, into ROOT geometry objects has been developed. To provide a detailed description of its geometry it uses tessellated geometry objects which require a special treatment to enable a correct navigation [5].

To provide a flexible and reliable setup for the TRD geometry, readout and calibration parameters a new framework has been worked out [7]. It will be applied to the analysis of the TRD data taking with the mCBM setup.

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. Therefore, it was decided to completely replace the ADC part of the ASIC by a different, simplified version, based on a successive approximation procedure. Together with several other fixes, the design of this new SPADIC version 3.0 has been finalized and tested and is now being submitted to UMC. As soon as the new ASICs are available, extensive tests will be performed in order to quickly converge towards a final read-out.

The TRD-2D modules for the inner region will be read out via FASP based front-end electronics. A new design of the corresponding FASPRO FEBs has been worked out. It provides a significantly reduced material budget, a higher integration of its components and possibilities for a more efficient ways of data transfer [8]. It is foreseen to install the new read-out electronics on the TRD2D chamber in the mCBM setup as soon as possible.

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TRD production and QA status

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Overview

The production process of 32 type-5 TRD MWPCs was started in the course of 2023. The acquisition and delivery of all relevant upstream products could be completed. We are currently in the pre-production phase and aim to confirm the production process within the next months for the upcoming Production Readiness Review (PRR).

Upstream products

In a challenging market situation, the acquisition of upstream products underwent several adjustments. For instance, new suppliers for the cathode pad plane, the entrance window foil and the wire ledge system were identified. After delivery the components had to be checked again with respect to properties where changes could be suspected, e.g.: influences on MWPC ageing (wire ledges, cathode pad plane), humidity diffusion (entrance window) and HV insulation (wire ledges). A complete reporting of tests and results will be given in the PRR for the type-5 chambers, which is currently being prepared.

Production process

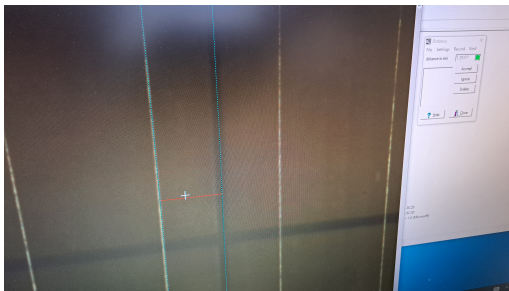


Figure 1: Alignment process of the anode wire layer above to the cathode pad plane.

MWPCs of type-5 are produced in a split mode at IKF Frankfurt and IKP Münster. The motivation is to focus the available people-power to specific production steps (specialisation) during production upstart, as well as to confirm helper tools as, e.g. a specific wire ledge positioning device, before copying those tools to the other production place. Transport demands still appear reasonably low for the large type-5 chambers in this split-mode.

The first 2 chambers have been manufactured, see also exemplarily Fig. 1 showing the alignment of the anode wire

layer relative to the cathode pad plane. In addition, the production of parts (subgroups) of the MWPCs is running already in larger numbers, as far as they are considered uncritical concerning possible PRR recommendations, to make effective use of the production places and people-power already. We could produce up-to-now:

- 2 complete type-5 chambers
- 25 entrance windows
- 13 backpanel (pad plane carrier)

QA

We distinguish three types of QA: i) checks on the upstream product, ii) monitoring within the production and iii) performance measurements on the resulting MWPCs.

Examples for i) upstream product checks:

- Pad plane: electrical test, i.e. connection test per pad and short-cut exclusion, test device commissioned

Examples for ii) production QA/monitoring:

- wire tension scans (oscillation-based), per wire
- wire contact checks, per wire
- HV tests, per construction step (*new)

Examples for iii) performance QA on resulting MWPCs:

- gas tightness measurement, see [1]
- HV stability series
- ^{55}Fe amplification characteristics, energy resolution
- gain scan

Testing places for serial production are being prepared. A complete report will be given in the upcoming PRR.

One of eight of the HV segments of the anode wire layer of the first two chambers show a characteristic discharge behaviour, while the other seven parallel segments perform normally up to nominal voltage level plus a margin. We address this issue by new stepwise HV checks during the next construction.

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Steps towards TRD2D assembly and tests

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A specifically designed MWPC detector - TRD2D, centered on an innovative pad read-out, was officially accepted by the CBM collaboration to be installed in the center of the TRD wall [1] of the CBM experiment. First details of the production chain for the 40 modules were reported previously [2]. Based on this experience optimizations of the production chain, in terms of costs and quality, were worked out and are detailed here.

Structural elements of the chamber

The read-out chamber has to fulfil the mutually exclusive requirements of lightness and mechanical rigidity, coupled with sub-millimeter precision of relative internal alignment of the components. As price correlates with increased ledge precision, a detailed analysis was performed in order to estimate, based on the assembly sequence, the minimal technological requirements for the structural elements. New partners were identified and some of the key components were redesigned in order to benefit from the CNC technology. The full production price was estimated.

Construction and installation of electrodes

Anode and cathode electrodes are used in the TRD2D design not only to generate charge amplification but also for the reconstruction of the particle position. They imply a strict requirement for a micrometer precision alignment wrt. the chamber and a well controlled mechanical tension during installation. Additionally, anode wires are costly and scarce on the market. Hence, their efficient usage has to be extremely well controlled.

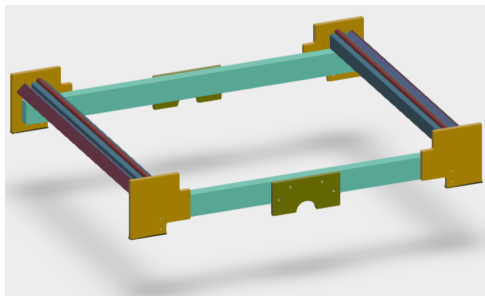


Figure 1: A new smaller and more versatile wire winding frame for anode and cathode wires.

Benefiting from the relative small size of the TRD2D modules ($54 \times 54 \text{ cm}^2$) a new smaller and more versatile wire winding frame was produced. The new device (see

Fig. 1) reduces the amount of wire usage to 50% relative to the old frame and can be integrated in the controlled production line sketched in Fig. 2.

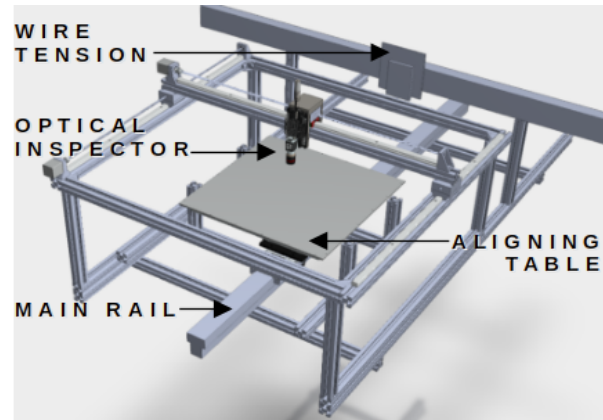


Figure 2: An integrated production structure for the TRD2D chamber with micrometer alignment precision.

A construction line, partially finalized, for TRD2D modules was designed to maximize precision during assembly. It allows for the monitoring and reproducibility of the process and integrates QA tests without chamber repositioning. The system contains a *main rail* which is used to transport the *aligning table* of the detector in various *assembly configurations*. It houses two QA devices, the *optical inspector* and the *wire tension* measuring device.

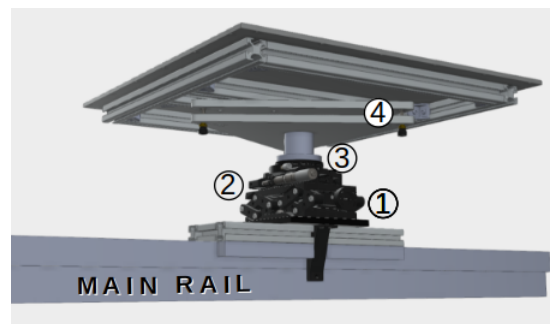


Figure 3: The aligning table for the pre-assembled TRD2D chamber, incorporating micrometer precision compensators to allow for four degrees of freedom.

The process is started by attaching the pre-produced reinforced entrance window rigidly on the aligning table (Fig. 3). The position of the table is controlled via high

precision and high accuracy micrometer screws for the following degrees of freedom: (1) perpendicular to the main rail, (2) rotational around center axis, (3) elevation wrt. the rail and (4) planar parallel wrt. the winding frame. The wire winding frame (Fig. 1) is inserted on top of the table and locked in position. The pre-produced chamber is aligned to the frame using the compensators from Fig. 3, such that wires are installed with micrometer precision on their design positions. The whole operation is performed under optical monitoring using the *the optical inspector* (see Fig. 4).

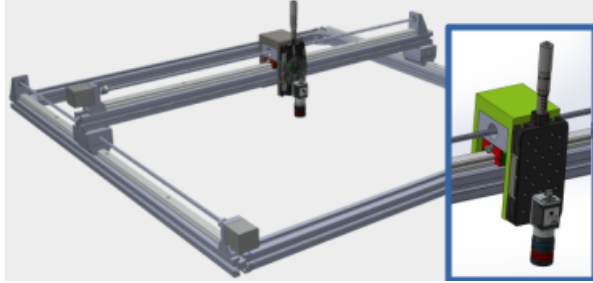


Figure 4: A monitoring camera for assuring quality and traceability of construction, positioned over the assembly field with micron precision via numerically controlled devices.

A two axes CNC driven optical camera is installed on top of the aligning table. This is used to visualize, measure and register the relative position of chamber elements, using a reproducible alignment. The aim being to reduce systematic effects of previous methods of plane-parallel projections alignment and assure a perfect wire installation. The possibility of automatic control of the wire quality is also under investigation.

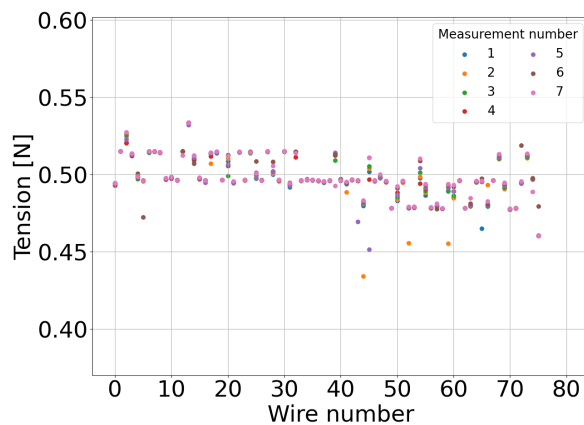


Figure 5: Repeated measurements of the (anode) wire tension on the winding frame showing the stability of the procedure.

The hardware of the device for measuring the wire tension, previously used for ALICE-TRD chambers, has been

reconditioned and the analysis software have been improved. In Fig. 5 the reproducibility of the anode tension measurement is presented for seven identical iterations. The results show a consistent value better than 1 cN accuracy.

With respect to the integration within the CBM experiment, significant steps have been performed on a new Front-End Electronics (FEB) [3] and High-Voltage (HV) filtering box implementation (Fig. 6). For the last item we are designing a compact board with SMD components, conditioned realistically by the spacing, radiation dose and connectivity expected in the final setup. Considerations of price, material stocks, detector upgrades and installation flexibility were investigated in order to come to a cost effective optimal solution.

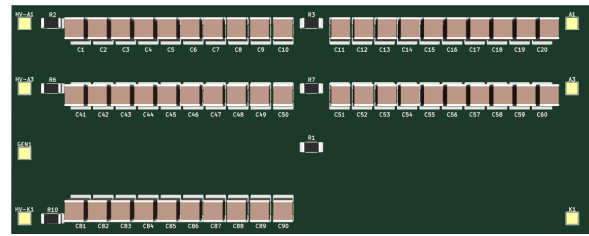


Figure 6: Design of a realistic HV box for the TRD2D at CBM using SMD components (work in progress).

Conclusions

Adding to the experience of the construction of the first prototype [2], we report here on improvements and optimizations of all assembly steps for the TRD2D chambers. Cost optimizations, quality monitoring and reproducibility were key features looked for. A list of QA tests have been introduced along production phases without further increasing systematic effects. A manual of construction is also closed to be finalized in order to pass the chamber construction knowledge efficiently to all people involved in the process.

Stocks of materials and external collaborators were identified along the way to assure the necessary input for the mass production of 40 chambers for CBM. Such estimations were mandatory for the realistic evaluation of production costs, manpower and execution time which should be formalized in the construction in-kind contract.

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Gas tightness measurement in TRD production QA

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Introduction

To minimize the gas losses for the TRD, the chambers have to be built as gas tight as possible. The chambers must have a gas loss below 1 ml/h per chamber [1]. Since a large pressure difference with respect to the environment leads to risky deformations which may break a chamber, usual methods to determine leakage rates using a vacuum or overpressure cannot be performed. A method to measure under operating conditions has therefore been developed.

Test stand and measurement

The setup consists basically of the measured chamber, a differential pressure sensor, an automated valve at the outlet and one at the inlet. The bubbler ensures the safety of the chamber. A sketch of the setup is shown in Fig. 1. After a flushing procedure, the gas flow in the chamber is decreased to 3 l/h and the outlet valve is closed. When a relative pressure of 0.5 mbar is reached, the inlet valve is closed as well. The relative pressure between the detector and the environment, as well as the barometric pressure, is logged over time. The data taken for the leakage test of the first detector of type-5 at a long term measurement for 20 days is shown in Fig. 2.

To determine the differential pressure loss over time, the relative pressure has to be measured at different points in time. To avoid corrections for changes in ambient pressure, points with the same barometrical pressure are chosen. E.g. intersections of the green line with the orange data in Fig. 2.

Using the fixed gas flow and the known inflating time provides the possibility to calculate the gas volume in the chamber. Therefore, the pressure losses can be converted into volume losses. The changes in the ambient temperature are logged, but can be neglected in the calculations. The inflating curve gives also the possibility to confirm a steady quality in the foil tension resulting in a similar bulging behavior.

Summary and outlook

The measurements for the first MWPC of type-5 result in a leakage rate of $0.8 \text{ ml/h} \pm 0.3 \text{ ml/h}$. Unfortunately, this measurement concept needs a long time for each chamber and depends of the weather conditions. On the other hand, as it is an easily scalable process, several chamber can be tested in parallel. The existing test stand is prepared to investigate the next chambers when they are assembled.

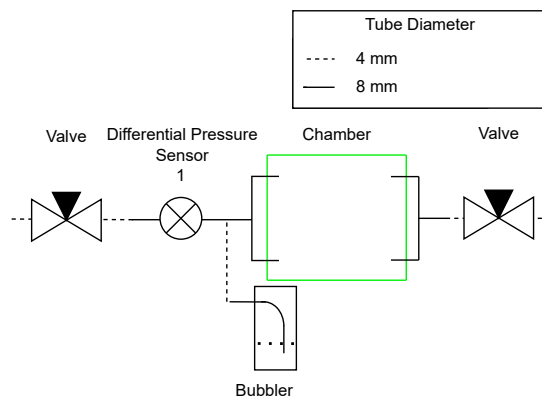


Figure 1: A sketch of the setup used to measure the gas tightness of the first type-5 TRD chamber is shown.

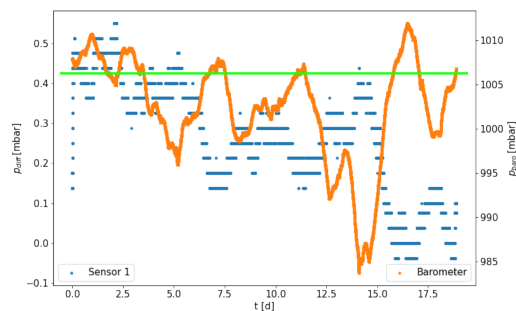


Figure 2: This plot shows the differential pressure in blue, measured over a time of about 20 days. The orange curve shows the barometric pressure. The green line is drawn to illustrate the data points at identical atmospheric pressure used in the analysis. The relative pressure data of those points are compared where the line intersects the barometric measurements. The error bars are not shown, but considered in the calculations.

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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 in a range within 0.7 mbar relative to local atmospheric pressure [1]. To fulfil these requirements, precise pressure control is needed to compensate the changes in the environmental pressure, which are typically in the magnitude of a few mbar per day, but can reach mbar/h with stormy weather.

Due to the high radiation environment near the detector, more complex electronics are stored in the area E18, which leads to pipes and a cabling of approximately 50 m. The system in Münster is constructed with a support structure to carry tubes of the final length and all large detectors which are used in one line. For a final test with chambers of type-5 and type-3 the support structure has to be slightly expanded. The mounted system, as it is installed in the laboratory, is shown in Fig. 1.

Control loop

There are three different monitored pressure levels in one gas line as it can be seen in Fig. 2. The controlled needle valve VR2 connects the detector pressure part (0.7 mbar relative, P3) with the pressure in front of the pump (-18 mbar relative, P5). The control loop gets the actuating variable from P3. The pump connects the pump pressure with the high pressure (1-3 bar relative, P6) and gets it actuating variable from P5. Both control loops will be PID controller. Between P6 and P3 there is no control system build in, the pressure is reduced passively. The main source of disturbance in this system are changes in the ambient pressure due to changes in the weather.

Summary and outlook

The circuit design of the gas system has been finalized and the system constructed. The programming and determination of the control parameters is ongoing. First filling and flushing tests have been performed successfully. Tests with dummy chambers to adjust control parameters are planned. After a successful conclusion of these tests, the supply of a real MWPC is planned. 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.



Figure 1: The setup of the gas system is shown. A dummy chamber, constructed with the same dimensions as the final modules of type-5, is mounted. For better visibility of the system, this picture shows the mechanical setup before the wiring was installed.

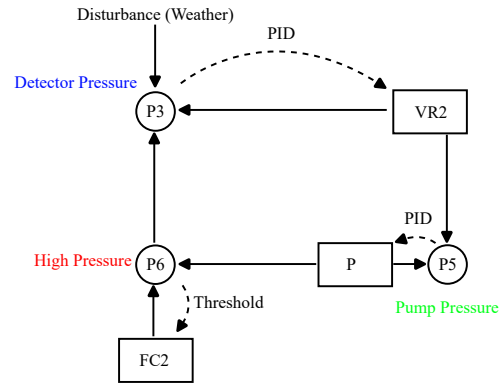


Figure 2: A scheme of the different pressure parts is shown. VR2 is a needle valve which connects the detector pressure with the pump pressure. P is the pump system which connects the low pressure part with the high pressure part.

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Towards an optimized TRD geometry

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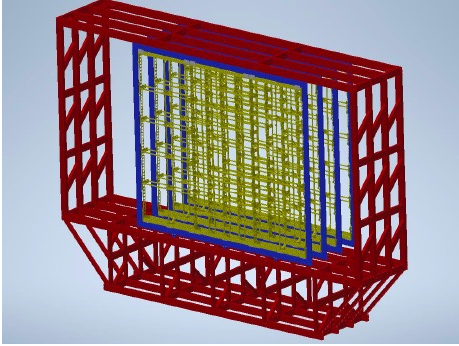


Figure 1: The detailed geometry of the TRD mainframe, as implemented in cbmroot.

A first engineering design of the TRD mainframe has been worked out by the group in Münster. It assumes a layer spacing of 71 cm in order to accommodate the default radiator dimensions. This design was recently imported into the cbmroot geometry (see Fig. 1) using an automated conversion procedure of the STEP-files, via GDML, into ROOT geometry objects. To provide a detailed description of the KANYA aluminum profiles, of which the mainframe will be assembled, it uses tessellated geometry objects which require a special treatment to enable a correct navigation [1].

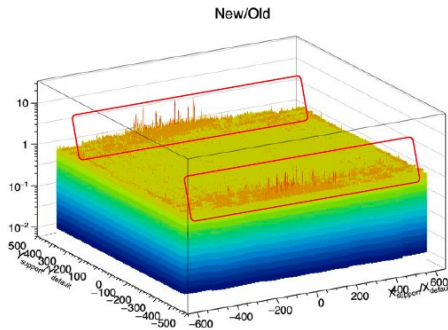


Figure 2: The ratio of the number of hits reconstructed in the TOF detector for the geometry w/o and with the detailed mainframe.

Using this detailed geometry description, the impact of the material introduced by the mainframe on the number of reconstructed hits in the downstream TOF detector was studied, see Fig. 2. In the current configuration it generates a significant amount of additional hits due to secondary

particles in the upper and lower region of TOF, which is mainly caused by the thick outer support bars of the TRD mainframe. A possible remedy would be to place these bars further outwards in vertical direction. However, the stability of this solution still needs to be evaluated with simulations.

Other ways of reducing the impact of the mainframe material are, on one side, the reduction of the distance between the TRD layers and, on the other side, a shift of its overall position closer towards the target (current default starting z -position of the TRD is 410 cm). However, the latter option depends on the design of the beam pipe, especially on whether a bulky bellow with dedicated support structure is necessary.

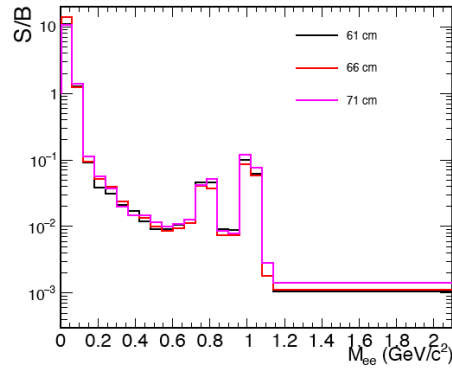


Figure 3: The signal-to-background ratio in the dielectron mass distribution evaluated for different layer spacings.

The consequence of the first option on the dielectron reconstruction with the TRD has been studied. While the reduced spacing on one side significantly increases the acceptance, it also requires on the other side thinner radiators with slightly reduced performance. As a net-effect the signal-to-background ratio seems to deteriorate to a small extent (see Fig. 3). However, the differences are small and might not be really significant. Therefore, a reduction of the spacing to, e.g., 66 cm might be a viable option.

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A more flexible and reliable description of the TRD setup

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The participation in the mCBM campaigns [1, 2] of data taking and related simulations brought to our attention the need for a fast and reliable configuration of our experimental setup. The addition of a new type of detector, TRD2D [3], adds to the complexity of describing various TRD setups. The flexibility of extending/modifying the parameter space without altering previously defined setups, became a major requirement with ever changing experimental scenarios. We have therefore proposed a new *modular* solution based on *compiled* code and a clear *versioning scheme* to address such issues.

A new description of the TRD setup

The TRD setup is described by the *Geometry*, the *Calibration parameters* and some *Meta information*. The last set is related to details of chamber Read-Out, Front-End Electronics (FEE), gas gain, etc. We present here a *top-down hierarchical* approach to connect such sets of data, hiding the details of the implementation from the user, while providing traceable access to any old configuration. A block diagram of the design can be followed in Fig. 1.

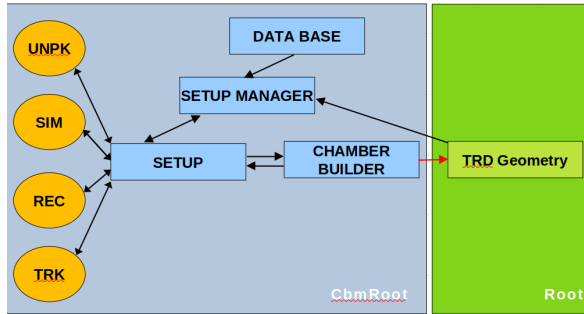


Figure 1: The block diagram of the new setup management infrastructure.

The building blocks of the design are the "Setup" object classes for various elements of the TRD design such as Read-out, FEE, Gas, etc. They *describe* a generic implementation (type) at a certain moment (version) of an element of the setup. An example is the read-out of the TRD chamber which can be of *type* 1D (rectangular pads) or 2D (triangular pads), each with different *versions*, such as "1", "3", "5" for "1D" and "mCBM", "CBM" for "2D". The inheritance/template features of the programming language makes them connectable in complex structures. Actual realizations of generic types are obtained by instantiating from a "Data Base" by a broker application, the

"Setup Manager". Such instantiations are uniquely identified throughout the setup by labels. The labeling system makes it possible to cross-reference each element in various representations *e.g.* geometry, calibration, etc.

The geometry represents the setup in terms of spatial correlations. Besides the alignment meta information, which is usually linked with this representation, equally important is the connection to the Read-out and FEE. The "Chamber Builder" application is used to convert the *SETUP* to ROOT in the "TRD Geometry" representation (Fig. 1). At run time, the geometry of the setup, which contains references (labels) to each element (*e.g.* chamber, ASIC, etc.), can be used by the "Setup Manager" to re-construct, on the fly, all the details of the setup.

In Figure 1, some generic data processing algorithms such as *e.g.* data unpacker "UNPK", simulator "SIM", re-constructor "REC", etc., are presented. They can be applied on measured and/or MC data but should always "see" the *same realistic* representation of the experimental setup. The design presented here assures this requirement by effectively packing a *complete* description of the experiment within the geometrical representation and its further usage at run time as detailed above.

Connecting the calibration info to a particular setup is transparent to measurement and MC data in the current design. A version control of calibration is also required for estimating performance (QA) evolution. In the future the "Setup Manager" will integrate also the "calibration representation" similarly as for the geometry.

Conclusions

The design proposed here will provide the basis for describing the TRD setup for the CBM and mCBM experiments. The proposal was extensively discussed in the collaboration [4] and the authors are deeply thankful for all suggestions.

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The TRD2D Front-End Board (FEB) for CBM

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The special read-out system [1] developed for the TRD2D of CBM is matched on the DAQ side by the FASP ASIC [2]. The chip offers analog and digital features like: charge amplification on native couple inputs, protection from charge over-shoot, baseline restoration, trigger on peak and flat top output. Basic ADC functionality as well as input-output and control features are implemented using commercially available digital components on a specific FEB. A demonstrator was first proposed [3] for data taking at mCBM with positive results.

The FASPRO FEB for CBM

The list of design requirements for the second version of the FASPRO FEB added: implementation one a single PCB layer parallel to the detector, greater integration, flexible DAQ connectivity and easy installation. With respect to the hardware used in the first version, two major modifications were performed: FASP was bonded by thermo-compression on a specially designed BGA substrate and the single channel ADC chip was replaced with a 32 channel one, improving the radiation tolerance characteristics.

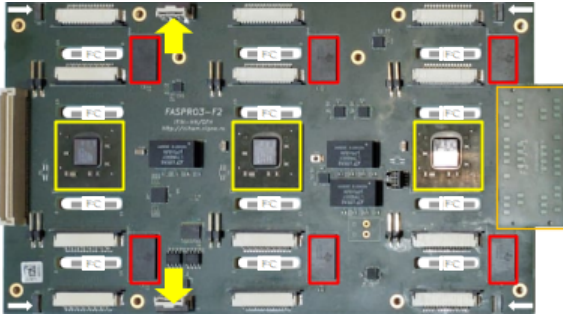


Figure 1: The FASPRO FEB with some of the key components emphasized by colors.

The upper side (away from the detector) of the FASPRO board is presented in Fig. 1. The board connects 12 *flat-cables* (marked *FC*) arranged in a 3×4 grid to 12 FASP chips (on the back side of the board) summing up to 192 DAQ channels. Data digitalization is performed by the 6 ADCs marked in red. Packing, control and input-output services are implemented in the 3 FPGAs marked in yellow. Transport of data towards *CRI boards* is foreseen to happen on the horizontal direction. The horizontal connection, from left to right, is routed via a generic connector (left in figure) using a bridge board (right in figure - orange). On the vertical, the board to board connection is accomplished

by FC, via two connectors marked by the yellow arrow, for transferring clock and control. FASP to FASP analog signal connections are also implemented (the 4 connectors on board's corners marked by white arrows in Fig. 1).

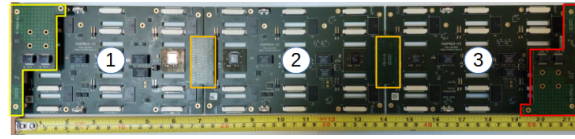


Figure 2: Setup of a 3-FEB-chain designed to operate the TRD2D at CBM. A scale is added for reference.

The read-out of a full TRD2D module requires the usage of 15 FASPRO boards organized in rows of 3 pieces as illustrated in Fig. 2. Board-board connections are realized by bridges marked in orange. The input-output operations are realized by auxiliary boards at the left and right of the figure. The output board marked in yellow is used for optical data transfer to CRI via the high speed transceivers in the FPGA. To the right, the board marked in red may be used to connect to the DCS. The data transfer and the boards control is flexible as multiple hardware can be used interchangeable. The lowest integrated configuration is the read-out of an individual FASPRO board and transport based on existing *CROB3*, similar to [3].

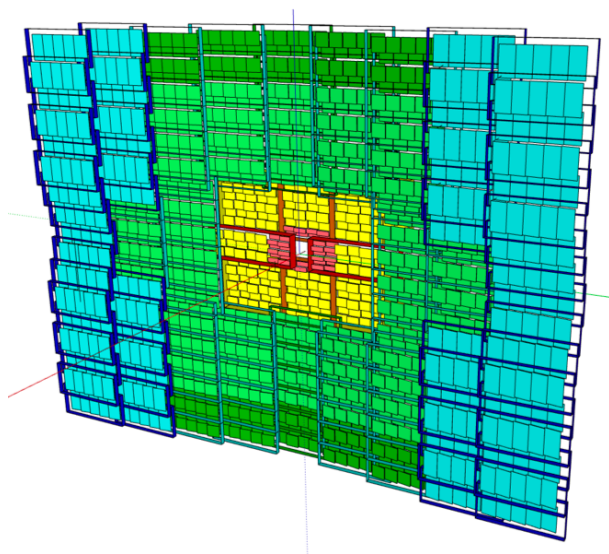
Conclusions

A new FEB was designed and is being tested to control the TRD2D DAQ chain. It features a smaller material budget, higher integrated components and the possibility to develop (at firmware level) more efficient and cheaper ways to data transfer. We have tested the acquisition and production chain of the board, as well as the QA procedures for the components. The current experience enable realistic estimations of the resources need to equip 40 TRD2D modules for CBM.

References

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Time-of-Flight Detector



TOF summary

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The CBM TOF team can look back again on a very successful year 2023. The main focus for TOF was the finalisation of the counter designs for mass production for all MRPC types. The first counter PRRs are targeted for mid 2024. In the current status the MRPC4 counter will have fishing line spacers while all other counter types will be equipped with pad spacers (see Fig. 1 and [1]).

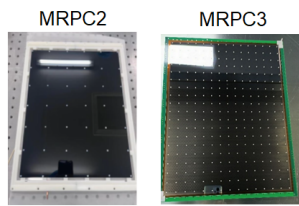


Figure 1: Counter of type MRPC2 and MRPC3 with pad spacers.

X-ray aging tests performed in Bucharest, Beijing and Hefei confirmed stability improvements by using pad spacers [1, 2]. Several prototypes have been build and tested in beam at mCBM. However, due to accelerator constraints an high intensity aging test could not be performed up to now and is postponed to later beam tests. In 2023 a counter pre-production was launched by building 10 MRPC4, 15 MRPC3 and 20 MRPC2 counter. All detectors arrived safely in Heidelberg where they are currently integrated in modules of type M6, M5 and M4. In Heidelberg a team of technicians from the mechanical workshop could be established to integrate the detectors in modules. Fig. 2 shows this team integrating MRPC2 counters in an M4 module. In total 7 modules are planned to be build in this pre-series.



Figure 2: Module production in Heidelberg. A team of three technicians are building an M4 module.

With the first 3 newly constructed modules a second miniTOF wall was realized and will help contributing in

the realisation of the benchmark goals. The modules for the outer wall reached by now a final design and a PRR will follow in late 2024. In Bucharest the first real size module of the inner wall with name M0 has been started to be build [3]. It contains 30 MRPCs of type MRPC1a, b and c. The production of these counter will start soon and goes in parallel. First test of the entire module could start in 2025.

Very good progress was made on the main frame. The engineering design is far progressed and first stability calculations including all module weights were performed. Fig. 3 shows a finite element simulation of the main frame structure.

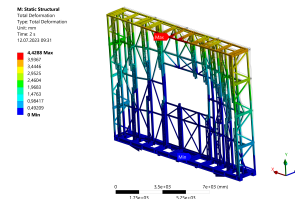


Figure 3: Finite element simulation of the main frame structure.

Far progressed is also the calibration status of eTOF at STAR. Clever algorithms to mitigate TDC dropouts were developed and applied so that about 99 % of the data could be used in the fix target runs. Fig 4 demonstrates a very good time resolution (left side) and a robust particle identification (right plot). The average time resolution of all 108 counter is in the order of 67 ps.

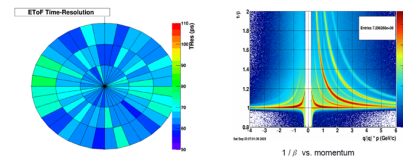


Figure 4: Left: time resolution of all 108 counter arranged in the end-cap wheel. Right: $1/\beta$ vs. momentum.

References

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- [3] V. Aprodu et al., this report.

Test of new MRPC prototype with pad spacer with X-ray irradiation

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Since CBM-TOF is expected to continuously run 2 months/year for about 10 years in high luminosity environments, various types of detectors have been developed to address the detector aging effect. In this contribution, we report tests conducted on an MRPC prototype with pad spacer under X-ray irradiation.

Test with X-ray

In order to decrease detector aging effects, cylindrical PET spacers, which have a diameter of 2 mm and a thickness of 240 μm , were considered as a replacement for fish-line as the spacers. Here, two MRPC prototypes are used for testing. They are both single-stack MRPCs with 5 gas gaps, one made with fishline spacer and another with cylindrical pad spacer.

One characterization of the detector aging effects is the continuous increase of working current of MRPC working under a charged particle beam. To observe the variation of working current of the MRPC with pad spacer under beam, X-ray is used here as a substitute of beam. With the working gas composed of 95% Freon and 5% SF_6 , the working current is recorded while the MRPC with pad spacer is working continuously under X-ray irradiation. The working voltage of the X-ray machine is set to 30 kV, with an operating current of 1 mA. Simultaneously, a MRPC with fishline spacer is placed parallelly to it in the same gas box for comparison. As shown in Figure 1, the X-ray is irradiated at a radiation angle of 26° , forming a circular beam on the detector plane. Their positions are adjusted to ensure that the X-ray radiation area almost entirely covers the effective areas of both detectors and that they are subjected to similar x-ray intensities.

The MRPC current variations are plotted in Figure 2 (a) and (b) respectively after turning on the X-ray machine. For better comparison of the trend of working current in both detectors, the ratio of their working current at each moment is calculated and plotted for visual comparison. ($\text{ratio} = \frac{\text{current_fishlineMRPC}}{\text{current_padMRPC}}$). Result is shown in Figure 2(c). By fitting the ratio, we observe a continuous increase in its value, indicating that the working current of the MRPC with fishline spacer is steadily rising compared to the pad MRPC, which implies that the dark current of the fishline MRPC accumulates continuously during X-ray irradiation. This can result in an increase in detector background noise, as well as a decrease in efficiency and time resolution.

Additionally, the process of current decrease after turning off the X-ray machine was also recorded, as shown in Figure 2(d). Clearly, the current of MRPC with pad



Figure 1: Test system under X-ray.

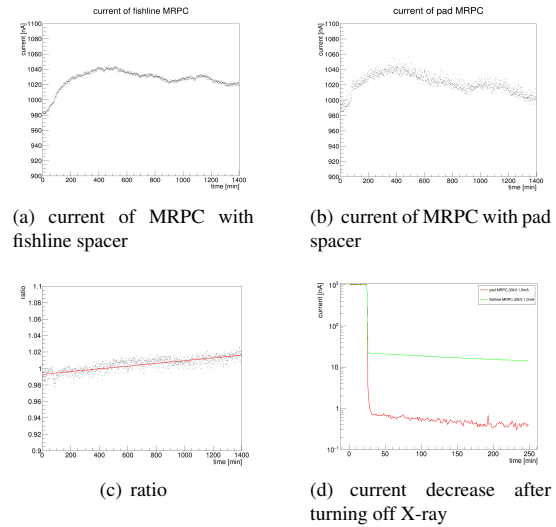


Figure 2: Current under X-ray exposure.

spacer quickly decreases to below 1 nA, while the current of MRPC with fishline spacer remains above 10 nA, indicating that MRPC with pad spacer accumulates very little dark current and can discharge quickly. And relevant calculations suggest that the accumulation of dark current of MRPC with fishline spacer during X-ray irradiation is roughly equal to the current of MRPC with fishline spacer after turning off the X-ray machine.

These results suggest that the MRPC with pad spacer indeed plays a role in decreasing the detector aging effects.

Conclusion

In summary, under X-ray exposure, much less accumulation of dark current of MRPC with pad spacer indicates potential of long-term stable work in high radiation environments. More studies and tests in terms of performance, aging and material stability will be executed soon.

Status of the construction of the first module (M0) of the CBM-TOF inner wall

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Our R&D activity addresses the most challenging region of the CBM-TOF wall [1, 2], positioned at low polar angles between 2.5° and 12° , called inner wall. It will be equipped with multi-strip, multi-gap resistive plate chambers (MSMGRPC) [3] which have to maintain their performance ($>90\%$ efficiency and better than 80 ps system time resolution) at counting rates in a range from $\sim 5 \text{ kHz/cm}^2$ up to a few tens of kHz/cm^2 and granularities which cope with the requirement of less than 5% occupancy.

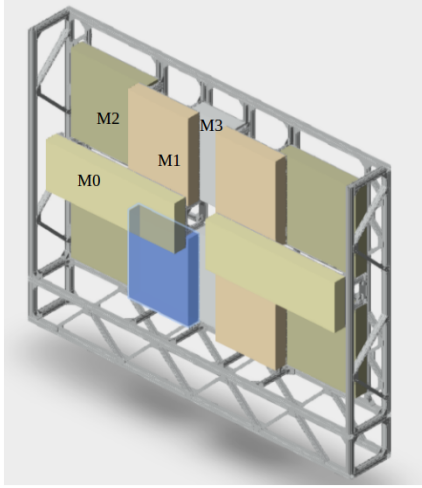


Figure 1: Modular design of CBM-TOF inner wall.

The design of the CBM-TOF inner wall is a modular one (Fig. 1) and comprises 12 modules of 4 types (M0, M1, M2, M3), equipped with 316 MSMGRPC chambers which count together 20224 readout channels. A mechani-

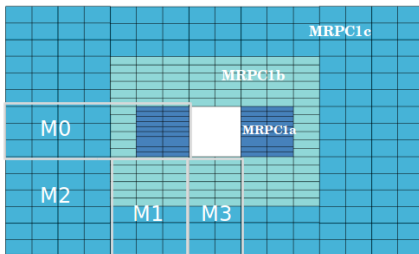


Figure 2: Chamber distribution across inner wall.

cal frame is designed taking into account the precise positioning of the modules with an optimization of the material budget. The current design of the inner wall is the result

of the optimization of the wall thickness along the z direction with a minimum overlap between the chambers inside a module as well as between the modules, in such a way to provide a continuous active area. This also leads to a minimization of the number of readout channels and consequently, of the costs. The 2D distribution of the cham-

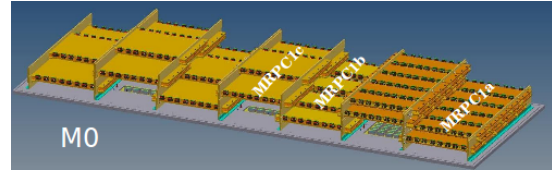


Figure 3: Design of the module M0.

bers across the surface of the inner wall is shown in Fig. 2. Depending on the polar angle, different regions of granularity are covered by three types of chambers, differentiated only by their strip length (MRPC1a of 56 mm, MRPC1b of 96 mm and MRPC1c of 196 mm).

For the mitigation of the aging effects [4] the chambers have a direct flow of the gas mixture through the gaps between the resistive electrodes and the continuous nylon line spacers were replaced by discrete polyimide spacers [5].

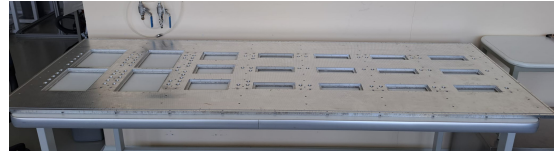


Figure 4: Back panel of the module M0.

The architecture of each module is based on a back panel made of an aluminum plate of 15 mm thickness closed by a housing box. The walls of the housing box are made of a light Nomex^R composite material sandwiched between a 0.2 mm FR4 plate on the outer side and a 0.2 mm FR4 plate covered by a 0.07 mm Cu layer on the inner side.

The modules of M0 type, the most complex ones, are positioned on the left and right side of the beam pipe. They can be translated up to 20 cm along the x axis in order to follow the beam bending due to the magnetic field. It will be equipped with all three types of chambers, counting 20 MRPC1a, 6 MRPC1b and 12 MRPC1c, as it is shown in Fig. 3. The size of a M0 module is $2145 \text{ mm} \times 738 \text{ mm} \times 202 \text{ mm}$.

The construction of the M0 module started with the manufacture of the back panel, shown in Fig. 4. It contains

rectangular holes for the PCB plates with signal connectors as well as circular feed-troughs for the gas and high voltage connectors, as can be seen in Fig. 4. Threaded holes are made for mounting the mechanical supports on the inner side, the supports for the front-end electronics on the outer side as well as to mount the module on the mechanical frame of the inner wall.

Along the long side of the back panel will be mounted the gas distributors of round shape with 10 or 6 distribution pipes, as shown in Fig. 5 - left. The lid of the gas distrib-

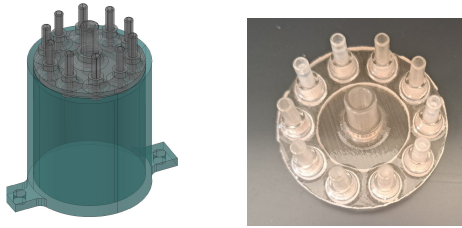


Figure 5: Design of a gas distributor (left). The 3D printed lid of the 10 pipes distributor (right).

utor, containing the gas pipes, is made of Vero Clear material, by 3D printing (Fig. 5 - right). The body is a cylinder made of aluminum. Such a geometry assures the equal gas flow rate distribution to the chambers.

Inside the module, the chambers will be positioned using special designed mechanical supports made of FR4 material, which can be seen in Fig. 6. Their design and very

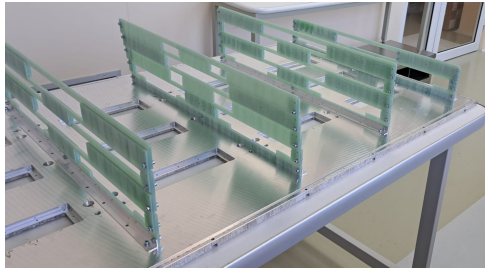


Figure 6: Mechanical supports mounted on the back panel.

good mechanical precision manufacture assure the staggering of the detectors in all three spatial directions for their optimal overlap, as mentioned above. An example of how the chambers will be mounted in the module is shown in Fig. 7. It shows chambers with the highest granularity of the CBM-TOF wall installed in the supports and also dummy gas distributors equipped with the gas pipes which will transport the gas mixture to the chambers.

The module will be closed by the gas tight and electromagnetically screened housing box shown in Fig. 8. The back panel will be first equipped with PCB plates with signal connectors, gas and high voltage connectors. Once this will be done, it will be closed with the housing box and the M0 housing will be tested for tightening. In a next step, the module will be ready to be equipped with the mechanical

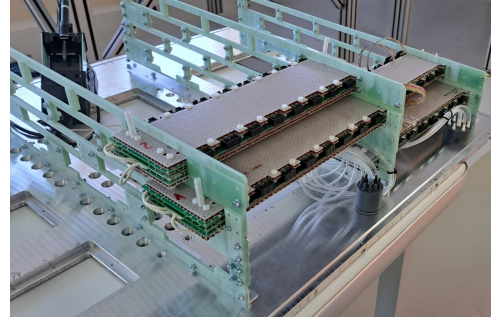


Figure 7: MRPC1a chambers installed.

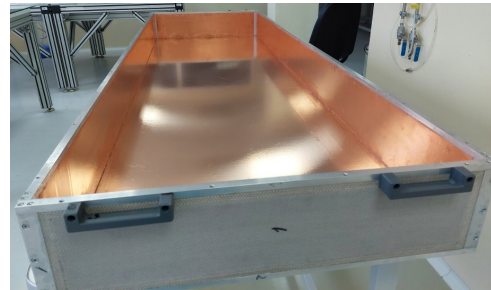


Figure 8: Housing box of the M0 module.

supports and the assembled chambers. Direct flow prototypes with discrete spacers proved a very good suppression of the aging effects [5]. They were tested in-beam in the mCBM experimental setup in December 2024 and data analysis is in progress. Once their performance (efficiency and time resolution) will be confirmed, the assembling of the chambers will start. After equipping the M0 with MSMGRPCs and its preliminary tests in HPD/IFIN-HH, the module will be transported to GSI and installed in the mCBM setup. It will be tested as a Production Readiness Prototype for the inner wall, before starting the assembling of all the other modules.

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Aging studies of direct flow MSMGRPC based on fishing line spacers

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In the current design of the CBM-TOF inner wall, as a function of the polar angle, (2.5° to 12°), different regions of granularity are covered by three types of chambers, differentiated only by their strip length (MRPC1a of 56 mm, MRPC1b of 96 mm and MRPC1c of 196 mm) while the pitch (9.02 mm) and the inner architecture are the same [1]. In order to cope with the challenging anticipated counting rates up to 50 kHz/cm^2 , they are equipped with a low resistivity glass ($\sim 10^{10} \Omega\text{cm}$) [2]. In view of their use over the lifetime of the experiment, detailed aging investigations were performed [3]. The obtained results evidenced a gas pollution effect reflected in the layers deposited on the resistive electrode surfaces, as well as enhanced depositions around the nylon spacers. The aging effects lead to an increase of the dark current and dark counting rate which might impact the chamber performance and also give rise to an artificial increase of the data volume in a free-running readout mode. As mitigation solution, we developed MSMGRPC prototypes with a direct gas flow architecture and minimization of the number of spacers in the active area. Two such prototypes with the highest granularity of the CBM-TOF wall (MRPC1a), together with their in-beam tests are comprehensively described in [4]. Detailed aging investigations showed less impact of the aging effects on the prototype with direct flow in comparison with a prototype with gas exchange via diffusion [5]. Further on,

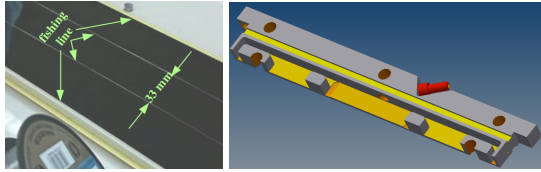


Figure 1: MRPC1b prototype: two spacers are positioned inside the active area (left). Design of the gas guide (right).

larger size prototypes with the same direct flow architecture were assembled using glass plates of the same length as for MRPC1a (300 mm), but a width of 100 mm for MRPC1b and 200 mm for MRPC1c, respectively.

MRPC1b chamber has two spacers out of four (Fig. 1 - left) outside of the active area, at 1.5 mm distance from the corresponding edge of the resistive electrode. The other two are positioned inside the active area, at 33 mm distance one to the other. The active area is defined by the strip length (9.6 cm) multiplied by the strip pitch (0.902 cm) and the number of strips (32). At the two ends of each stack (short side) were positioned gas guides (see Fig. 1 -

right) which force the gas flow through the gaps between the resistive electrodes.

The MRPC1c prototype has six spacers distributed across the surface of the glass of 200 mm width, with a distance of 38.6 mm one to the other. The outermost ones are positioned as for MRPC1b, at 1.5 mm distance from the edge (long side) of the glass electrode, outside the active area, while the other four spacers are positioned inside the active area. Around each stack, at 1 mm distance and parallel with the long side of the resistive electrodes, are positioned two epoxy glass fiber ledges. For both chambers, the two gas guides and the two ledges are closing the gas volume of each stack (as for MRPC1a [5]). After assembling, the measured gas transmission through the gaps was $\sim 100\%$ for both MRPC1b and MRPC1c prototypes.

Each chamber was closed in a gas tight and electromagnetically screened housing box and a gas mixture of 97.5% $\text{C}_2\text{H}_2\text{F}_4$ and 2.5% SF_6 was flushed through the gas gaps. The housing box was also flushed with gas mixture at 2 l/h flow rate, in order to avoid eventual contamination of the gas inside of the detector. The measured oxygen contamination of the gas mixture inside the gaps of the chambers was very low, $<10 \text{ ppm}$.

Two mini X-ray tubes were aligned in front of the housing box, at a certain distance which assured an almost uniform exposure of the chamber to the high X-ray flux. The strips of each prototype were readout at both ends by eight front-end electronics cards (FEE) based on NINO ASIC[6].

The MRPC1b prototype was exposed in successive days at increasing gas flow rates (2 l/h, 4 l/h and 6 l/h) for a period of about 6 h per day to a maximum X-ray flux which corresponds to a counting rate of $\sim 23 \text{ kHz/cm}^2$. After each period of irradiation, the recovery of the dark current and the dark counting rate were recorded for about 2 hours. The obtained results confirm the ones previously obtained for prototype MRPC1a [5]: the dark current and dark counting rate are smaller and also recover faster with the increase of the gas flow rates. However, taking into consideration the polar angles covered by the MRPC1b chambers in the CBM-TOF inner zone, where the maximum anticipated counting rate is lower than $\sim 10 \text{ kHz/cm}^2$, the chamber was further on exposed to a X-ray flux corresponding to a $\sim 12 \text{ kHz/cm}^2$. As is shown in Fig. 2, both dark current and dark counting rate have much lower values at $\sim 12 \text{ kHz/cm}^2$, at the same gas flow of 2 l/h flow.

The MRPC1c chambers will be positioned in the CBM-TOF wall at polar angles where the counting rate is estimated to be less than 6 kHz/cm^2 . For this reason the chamber was exposed to a X-ray flux corresponding to a

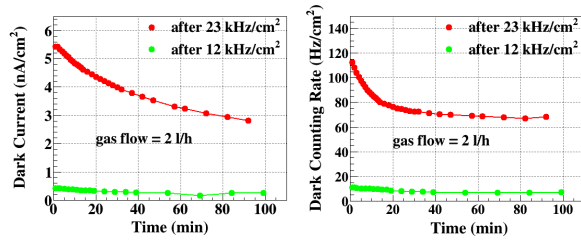


Figure 2: Dark current and dark counting rate of MRPC1b after the exposure to different counting rates.

maximum counting rate of 8 kHz/cm^2 , the accumulated charge being 2.4 mC/cm^2 . The values of the dark cur-

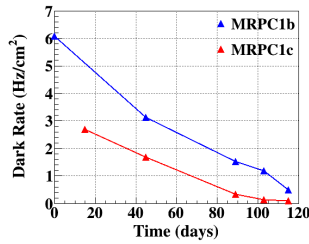


Figure 3: Long term evolution of the dark counting rate.

rent (0.02 nA/cm^2) and dark counting rate (2.7 Hz/cm^2) measured 24 h after the end of the last exposure have been very low. For the MRPC1b chamber, after an accumulated charge of 9.4 mC/cm^2 the dark counting rate reduced to 6.1 Hz/cm^2 and dark current to 0.05 nA/cm^2 at 24 hours after the end of the last exposure. Moreover, they are converging in time towards low values of the dark counting rate as is shown in Fig. 3 and also to a negligible dark current.

After the aging tests, the performance of the chambers in terms of efficiency and time resolution was tested using cosmic rays. We stacked all three chambers, closed them in the housing box and flushed each one with an equal gas flow rate of 2 l/h . MRPC1a and MRPC1c chambers sandwiched between them the MRPC1b prototype, as it is shown in Fig. 4 - left. The LVDS signals delivered by the FEE were fed into the inputs of CAEN V1290A TDCs. The

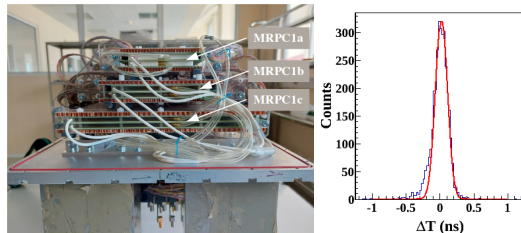


Figure 4: Stacked chambers for cosmic ray test (left). Time difference distribution (right).

measured efficiency for the MRPC1b chamber, defined as

the number of coincident signals in all three chambers divided by the number of coincident signals in MRPC1a and MRPC1c was of 95% for $2 \times 6 \text{ KV}$ applied high voltage. The time difference distribution between MRPC1b and MRPC1a, corrected for the slewing effect is shown in Fig. 4 - right. A single counter time resolution of $62 \pm 2 \text{ ps}$, supposing equal contributions of both chambers, was measured. A mapping of the active area of the chambers in

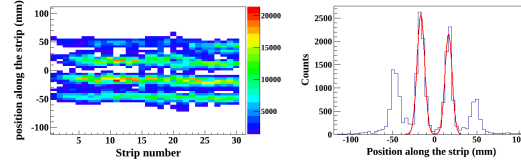


Figure 5: Position along the strip versus strip number (left) and projection along one strip (right), for MRPCb.

a self trigger mode operation of the DAQ system revealed the activity around the spacer positions, as can be seen in the two - dimensional representation of the position along the strip versus strip number, shown in Fig. 5 - left for the MRPC1b prototype. From the Gauss fit of the two middle peaks seen in the one dimensional projection along one strip (Fig. 5 - right), an accuracy of the position determination along the strip of $4.5 \pm 0.05 \text{ mm}$ was estimated. Based on the distance between the two middle peaks and the TDC calibration of 25 ps/bin , a 17 cm/ns signal velocity propagation along the strip was determined. The mapping in self triggered mode for the MRPC1c prototype evidenced a similar structure with a higher activity around the spacers. Similar results in terms of accuracy of the position determination ($4.9 \pm 0.05 \text{ mm}$) and signal propagation velocity (16.53 cm/ns) were obtained.

The mitigation solutions of the aging effects observed in the MSMGRPC based on gas exchange via diffusion was to modify their architecture in such a way to constrain a direct flow of the gas mixture through the gaps and to reduce the number of the fishing line spacers inside the active area. However, even if a significant reduction of the dark current and dark counting rate was evidenced, dark counting rate around the fishing line remains. In order to reduce further this effect, a direct flow architecture based on discrete spacers was developed [7].

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Aging studies of direct flow MSMGRPC based on discrete spacers

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In order to minimize the aging effects around the spacers [1, 2], we replaced the continuous nylon fishing line by discrete pad spacers (Fig. 1). In a first step, we manufactured rectangular spacers of 2 mm x 2 mm size and 200 μm thickness, (Fig. 1 - left) made of sticky polyimide (kapton type). We assembled a direct gas flow chamber with the same in-

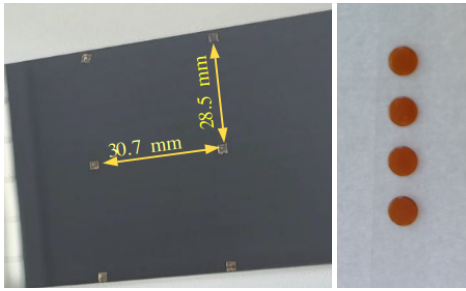


Figure 1: Glass electrode with rectangular spacers - left. Polyimide disc shape spacers - right.

ner architecture as previous ones (MRPC1a described in [3, 4]). It was exposed to high X-ray fluxes corresponding

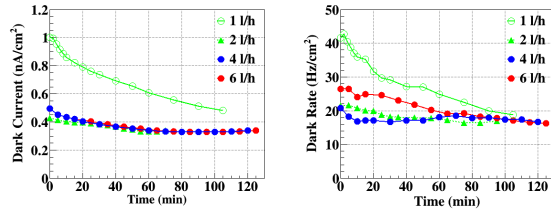


Figure 2: Dark current and dark counting rate at different gas flow rates.

to a maximum counting rate of $\sim 29 \text{ kHz/cm}^2$. The obtained results showed lower values of the dark current and dark counting rate, as well as a much less impact of the gas flow rate (varied between 1 l/h to 6 l/h) on these parameters, as can be seen in Fig. 2. Between 2 l/h and 6 l/h gas flow rate it was not observed any difference, the recovery of the dark current and dark counting rate being fast and converging towards similar values in a short time. Based on these positive results, we decreased the flow up to 1 l/h. The measurements showed still low values of the dark current and dark counting rate with the same fast recovery in time.

The two-dimensional mapping of the active area in self-triggered mode showed that the measured noisy signals are localized around the positions of the spacers. One possible

cause could be that their edges are not so smooth as resulted from the cutting procedure, having still micro-structure.

We found commercially available disk shape spacers of 2 mm diameter, made of polyimide (kapton type), shown in Fig.1 - right, with a maximum available thickness of 170 μm .

A new MRPC1a prototype was assembled using such spacers and exposed in successive days for 6 hours each day, at a maximum counting rate of 28 kHz/cm^2 . The dark current and dark counting rate recovery in time were recorded after each exposure for 2 h, at 1 l/h gas flow rate. The obtained results showed very low values of the dark current and dark counting rate after each exposure. We reduced the gas flow rate to 0.5 l/h and exposed the chamber for the same time interval for one more day. The results

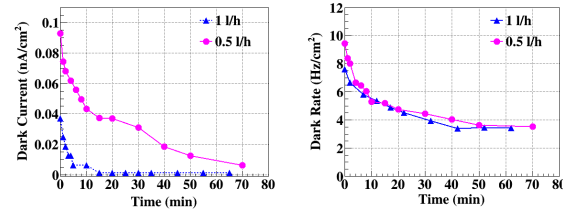


Figure 3: Dark current and dark counting rate at 1 l/h and 0.5 l/h gas flow rate.

presented in Fig.3 show that the dark counting rate has very low values, without significant differences from the ones measured at 1 l/h gas flow rate.

Taking into consideration these results, a direct flow architecture based on discrete spacers is considered as solution for the suppression of the aging effects in MSMGRPCs used for long time periods in high counting rate environment. The two prototypes based on discrete spacers were tested in-beam, in real experimental conditions in the mCBM setup in December 2023 to confirm the performance of this architecture. The data analysis is in progress.

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Other Systems

Status of the superconducting dipole magnet of the CBM experiment

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After the production of a tender document with the detailed specifications required for the CBM magnet during 2022, the call for tenders was submitted on January 20, 2023. Three companies applied: ASG (Italy), Bilfinger-Noell (Germany), and ELYTT (Spain). All three companies passed the qualification criteria and were asked to submit detailed offers including the cost. The power supply and the quench protection system will be procured separately because their specifications require a preliminary design of the magnet.

On May 31 the three companies submitted detailed offers including a cost breakdown. The offers were evaluated, and meetings to discuss the offers were organized with each company. After these meetings, the companies were asked to submit an updated offer.

The FAIR Council stated at its meeting in July 2023 that the superconducting dipole magnet of the CBM experiment is a time-critical item for which a favorable offer exists. Therefore, the council agreed to permit the FAIR Management to procure the magnet based on commitments from the non-German shareholders. The FAIR Management requested the council to allocate the necessary funding of 5 Mio. €, a value which should be verified by the tendering process.

The companies submitted their final offers in October 2023. After careful evaluation of the offers, the company Bilfinger Noell GmbH (BNG) was selected, which proposed a convincing technical concept with a price within the available budget. The purchase department prepared the contract and sent it in October to the GSI directorate for approval. The contract with BNG was finally signed by the GSI directorate at the end of December 2023.

Since then, BNG has started the design activities which are discussed with GSI experts in weekly meetings. The

proposed magnet concept of BNG is based on indirect cooling of the coils driven by a thermosyphon circuit. The magnetic forces between the coil and the yoke are compensated by a single-ring strut composed of two Glass Fibre Reinforced Polymer (GFRP) rings with a steel ring nestled in between. This construction is required to minimize the thermal conductivity of the support structure. A cross-section of the coil vacuum casing is shown in Fig. 1.

First magnetic field calculations based on the design of the magnet yoke and optimized field clamps show that the stray field at the place of the RICH photodetectors and the field integral along the beam axis inside the RICH radiator volume is below the requested upper limits.

As shown in Fig. 2, BNG has proposed a frame which enables transportation of the complete coil-cryostat system from the factory to FAIR without the need to cut it into pieces and weld it again at FAIR. Moreover, the frame allows a simple assembly of the magnet.

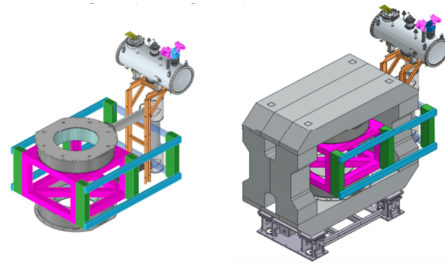


Figure 2: Frame for transport and assembly (see text)

The next major step is the review of the Preliminary Design Report which will cover (a) magnetic field calculations based on realistic models of the coils, yoke, and field clamps, (b) the coil design and quench calculations, (c) the cooling concept for coils, (d) the design of the cryogenic system (branch box, transfer line, cryostat), and (e) the design of the magnet support feet. The schedule proposed by BNG is depicted below.

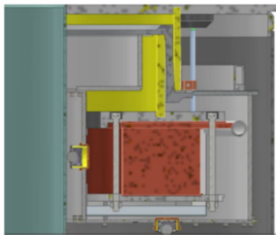


Figure 1: Cross-section of the coil vacuum casing illustrating the coil with the copper cooling plate connected to the liquid helium tube (brown). The coil support structure consists of two GFRP rings (yellow) surrounding a steel ring (grey).

Designation	Estimated Date
Award of contract	20.12.23
Preliminary Design Review (PDR)	20.03.24
Conceptional Design Review (CDR)	20.06/24
Final Design Review (FDR)	23.12.24
Final Acceptance Test FAT	24.04.26
Shipment incl. documentation	25.05.26
Site Acceptance Test (SAT)	09.09.26
Final Acceptance	20.01.27
Magnetic field mapping	20.04.27

Preparation of test modules for neutron detection at mCBM

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One component of the CBM-experiment will be the Forward Spectator Detector (FSD) which will allow determination of the reaction plane and the collision centrality in heavy ion reactions. It will consist of a segmented plastic scintillator wall with a thickness of about 5 cm for the detection of charged particles. In order to extend the performance, an additional neutron calorimeter (NCAL) is considered to be placed behind the FSD. Neutron detection will improve the determination of collision centrality and collective flow in heavy ion reactions and will be important for the analysis of various proton induced reaction channels. It is planned to cover the FSD scintillator wall at the backside by an array of long plastic scintillator modules coupled to photomultipliers using the energy-detector of the COSY-TOF-experiment [1]. For the modules BC-416 was chosen as scintillator material and photomultipliers of the type XP4592/PA from Photonis with an outer diameter of about 130 mm are used for the read out. In an analysis of the $pp \rightarrow pn\pi^+$ reaction channel in a measurement with a 2.7 GeV/c beam momentum performed at COSY, a detection efficiency for neutrons of up to about 40% was achieved [2].

In order to investigate the performance of such a detector component two detector assemblies consisting of seven scintillator modules each, have been prepared to be installed at mCBM for test measurements in 2024. The scintillator modules have a hexagonal shape with a side length of about 8 cm and a length of 45 cm resulting in an area of about 1200 cm² for each detector assembly. For the preparation of the detector assemblies the COSY-TOF detector was disassembled and separate scintillator modules packed in light tight black foil were prepared. One detector assembly will be positioned behind the TOF-detector of mCBM to correlate the particle tracks with the scintillator signals and the other assembly will be combined with FSD scintillator modules and placed close to the beam line to investigate the response to very high multiplicities and rates as expected in the CBM experiments. In Fig. 1 a photo of such a detector assembly is shown.

The measurement of the signal amplitude will be performed by a time over threshold (ToT) measurement in the mCBM data acquisition system and presently possible solutions for the integration of the scintillator signals are under analysis. In Fig. 2 a typical signal induced by a cosmic particle passage through the scintillator and the result of a test with cosmic data showing the correlation between the measured ToT-value and the integrated signal charge is shown. For the test, which was done with C. Pauly at the University of Wuppertal, the scintillator signal is split and

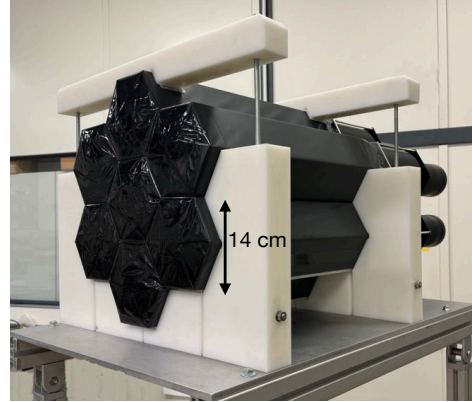


Figure 1: Neutron detector assembly consisting of seven scintillator modules with a length of 45 cm read out by XP-4592/PA PMTs.

connected simultaneously to an oscilloscope and a DAQ-system producing a ToT-value. For each event the area of the scope trace below a certain threshold as indicated by the red line in Fig. 2 is integrated and compared to the ToT-value for this event. A very good correlation is achieved with an energy resolution in the order of 5% due to the ToT measurement which is comparable to the expected accuracy in the determination of the energy deposited in such a scintillator module which is in the range of 5 to 10 %.

Presently the read out of the scintillator signals with the integration into the CBM data acquisition system is being prepared.

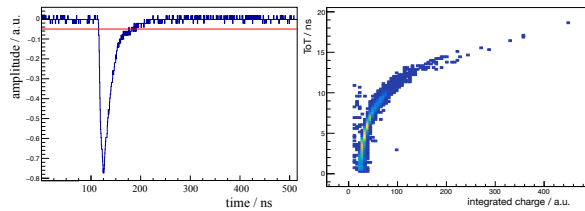


Figure 2: Typical signal induced by a cosmic particle passing through the scintillator (left side) and correlation between ToT-value and integrated signal charge (right side).

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CBM Upstream Platform

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Summary of 2023 period

The CBM Upstream Platform (UP) is a steel construction providing a support of the full HADES experiment, the CBM RICH detector and the cryoplatfom. The technical design of the platform has been introduced in the previous CBM progress report 2021 [1].

Starting from the tendering of the Upstream platform project, the contractor for its production and installation on the FAIR construction site in the CBM cave had been selected from three potential companies in the Czech Republic. The contract for the production and installation of UP was signed on 19th of January 2023 with the Research Centre Řež company (CVR). During the next weeks the parts of the platform were produced in the Czech Republic and transported to the FAIR building site. The installation of UP steel construction in the CBM cave took place in the first half of May. The installation was finished on 19th of May 2023 and the work has been handed over to FAIR based on the successful Site Acceptance Test.

The project was related to the delivery of the steel construction, which is an in-kind contribution of the Czech Republic to HADES/FAIR. The concrete beams laying on the top of platform were not a part of the contract and will be installed later, as well as magnet foundation concrete block. The platform will be additionally attached to that concrete block after its construction.

Design

The project is specified in the Conceptual Design Report (CDR). The document contains the general dimensional constraints, load conditions and stability requirements. The design description and the preliminary Finite Element Method is introduced [2].

Compared to the article in previous progress reports, there has been a change in the design of steel construction bracing. Also the procedure for anchoring of the platform has been clarified and defined.

The stability of UP has been analyzed and proved by group from the CTU in Prague and published in the static calculation report. The static calculations follow the European technical standards with German national annex. The execution class was set according to the standard DIN EN 1090-2:2008-12 as EXC2. The construction was analyzed for different static load cases determined by the movable setups of the detectors standing on the platform as well as for the seismic cases. The calculations of anchors guaranteed by the Hilti company are attached to the document of

the CBM UP static calculation report [3].

The final CAD design in step format as well as construction drawings have been given to FAIR for record keeping.

Production

The production of all parts was summarized in the Inspection and test plan (ITP) of the CVR contractor. ITP comprises control of the procurement of basic material for the manufacturing of the platform parts, control of qualification of welding and testing personnel, inspection of welding procedures, control of assemblies before welding, control during welding progress, visual inspection, control of all welds, overall dimensional inspection and final inspection on completeness before expedition from CVR to FAIR. The producer confirmed the finalization of the components manufacturing phase by the certificate of completeness and quality.

The production was accomplished based on the Factory Acceptance Test (FAT) which is corresponding with the ITP from the CVR.

Transport

The transport of the material for the installation was divided into three separate deliveries organized by the contractor. The individual parts of UP have been prepared by CVR as welded sub-assemblies of pillars with anchoring plates or welded sub-assemblies of frames before the transport from the production site in order to avoid any welding on the FAIR construction site, therefore allowing for the steel construction assembly on the site solely by bolting. The transport of the material on the FAIR building site was secured by the GSI Transport and Logistics team.



Figure 1: Manipulation tool for transport of frames through the tunnels of FAIR to the CBM cave (J. Thaufelder).

Installation

The fixation of the platform to the floor and wall of CBM cave was performed by mechanochemical anchoring. Since the platform serves as detector support, the installation preparation included marking of the platform position on the floor relative to the FAIR machine coordinate system. In addition the floor was scanned for drilling obstacles (reinforcing steel bars in concrete) in order to enable most suitable placement of anchors. The preliminary requirement was to avoid damaging those rebars as much as possible. Therefore, the exact position of anchors in the floor was designed after the analysis of the material in the floor due to a flexible design of the grooves in the anchoring plates for the screws fixed in the floor. The anchoring to the wall was performed in the same manner. The installation continued with building the pillars and frames aligned to the measured height levels of upper as well as lower section of the platform. Followed by the assembly of the bracing rods, the works were leading to the final treatment of the construction in terms of tightening of all screw connections according to the needed (calculated) torque, additional painting and cleaning. The installation in the CBM cave was finalized on 19th of May 2024.



Figure 2: Finalized UP steel construction installation in CBM cave.

Site Acceptance Test

The formal handing over of the platform to the FAIR was based on the Site Acceptance Test (SAT) and confirmation of all relevant authorities. SAT consisted of three major steps. First one was a visual check of the construction in the CBM cave after finishing the installation with all aesthetic drawbacks recorded in the SAT protocol. The second step involved control of randomly chosen screw connections i.e. torque check. Final part of the SAT protocol was the height control performed by the professional geodetic company where set of the selected points shown in the Figure 3 was measured. The result of the survey confirmed that the precision of the installation was corresponding with the designed geometrical tolerances.

Outlook

The steel structure of the CBM Upstream Platform has been produced, delivered to the FAIR and installed in the CBM cave. The final project documentation from the producer has been provided to GSI / FAIR. The report about

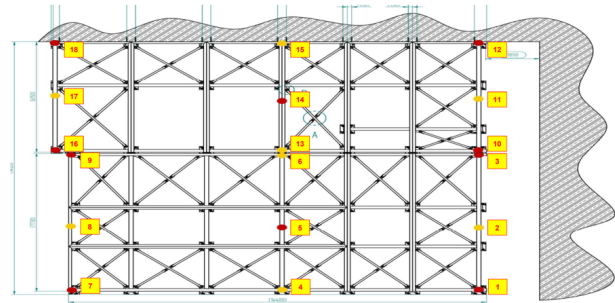


Figure 3: Dimensional control for SAT [4]

the performed anchoring and the result of installed anchors has been attached to the documentation from the contractor. The SAT was successful and confirmed by the CBM, HADES as well as NPI CAS technical coordinators. Last but not least, the acceptance protocol of the CBM upstream platform was signed by the HADES representatives. Next steps towards the completion of the full UP are grouting of the anchoring plates of the steel construction, building (casting) of the concrete magnet foundation, installation of concrete slabs on top of the steel platform and finally the construction of the branch-box platform on top of it.

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Beam Pipe for the downstream section of the CBM Experiment

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Activities during 2023

Delivery of the downstream segment of the CBM beam pipe has been done as an in-kind contribution of the Czech Republic to the Facility for Antiproton and Ion Research in Darmstadt (FAIR).

Since February 2023, downstream segment of CBM beam pipe have been fabricated in Czech Republic after selection of contractor through a public tendering process. The segment is comprised out of straight pipes of different lengths and connecting T/I-joints that were tested at the Czech Technical University in Prague, specifically at the Faculty of Mechanical Engineering, before being shipped to GSI/FAIR in Darmstadt. Following the delivery of the downstream beam pipe segment to FAIR in May 2023, preparations for the Site Acceptance Test (SAT) procedure commenced. Initial measurements were made on the beam pipe segments after its delivery.

This article summarize contributions to the CBM beam pipe development, as stated in the progress reports for the years 2021 and 2022. Additional details regarding the design can be found in the 2021 article titled "PSD Beam Pipe" [1]. However, the PSD beam pipe is now referred to as the downstream beam pipe for the Transition Radiation Detector (TRD), Time-of-Flight (TOF) detector, and the Forward Spectator Detector (FSD). The 2022 report primarily focuses on the analysis of vacuum simulations within the beam pipe [2].

Design

The CBM downstream section (from target chamber to beam dump) beam pipe consists of multiple segments made out of carbon fiber; two conically shaped segments through STS and RICH/MUCH, bellows segment (made out of steel), and multiple segments through downstream detectors comprised out of individual straight pipes and flangeless joints as depicted in Figure 1. This article is focused on the downstream segment with a length of 14.25 meters. The operating pressure on the target chamber side (STS segment) is 10^{-4} hPa with a maximum pressure of 10^{-3} hPa on the beam dump side. The vacuum is achieved by using at least two pumping stations within the downstream section of CBM beam pipe.

Based on observations acquired during the testing phase of the beam pipe prototype sample preceding the main production, a reduction of the wall thickness to 2 mm was made. That was the only modification in comparison to original 2021 concept.

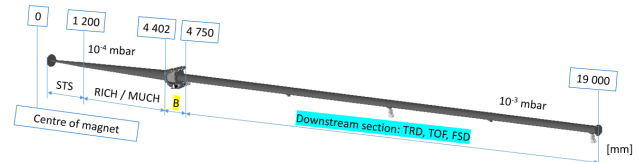


Figure 1: Overview of the downstream section of CBM beam pipe showing different segments.

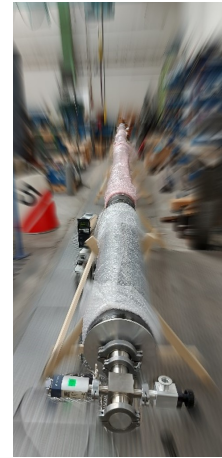


Figure 2: Full assembly of the downstream segment of CBM beam pipe

Production and delivery

The components of downstream segment were manufactured by the *Compo Tech PLUS, spol. s r.o.* company in the Czech Republic. Experimental evaluation of the beam pipe sample was performed in November 2022 which was followed by launching the production for the full assembly. Factory Acceptance Test (FAT) was performed at CTU after its delivery in April 2023.

FAT included a visual inspection of all five straight pipes of different length and all joints. It was followed by assembling the full downstream segment of the beam pipe and testing it under vacuum. Performance data, along with results from the leak/tightness test, were included into the FAT protocol. During the test the downstream segment was evacuated using single pumping station combining roots pump and turbo-molecular vacuum pump both with pumping speed of 55 l/s. With this sub-optimal setup we could reach vacuum pressure of $3.13 \cdot 10^{-3}$ mbar after 12 hours of pumping.

The subsequent FAT procedure was focused on the assembly/disassembly of downstream section. The goal of this test was to determine force necessary for disassembly of joint elements and straight pipes since the flangeless joint relays on a proper insertion only. A series of three subsequent measurements was done with 1, 2 and 3 o-rings installed on the joint element. Disconnecting force measurement was done with all components positioned vertically, without load of the setup. The measurement was done for two settings: in the first setting, the force sensor was attached to the straight segment using a spring, while in the second setting, the force sensor was connected firmly. The primary objective was to get better understanding on how different o-rings influence disassembly procedure. Prior to the test, it was determined that the predefined o-rings (175x2 FPM80) are sub-optimal for this application. The stiffness of the o-rings did not allow for their smooth deformation, therefore a non-negligible probability of o-rings damage during the assembly process existed. As an alternative, 165x2 NBR70 o-rings were used, providing a noticeable reduction in stiffness, which, combined with the reduction in diameter, greatly reduced the risk of o-ring damage during assembly procedure. While FPM material is more suitable for typical vacuum condition due to its low outgassing rate, the NBR material proves to be sufficient for our requirements.

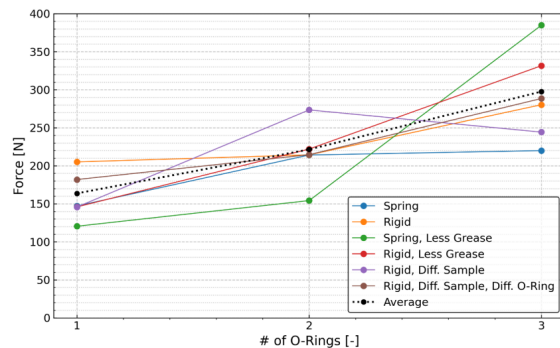


Figure 3: Single joint disassembly force under various conditions (see legend).

Preparation of SAT

The next measurement was arranged in GSI after downstream segment was delivered to FAIR in the end of May 2023. This initial test was a preparation for the upcoming Site Acceptance Test (SAT).

The test setup comprised a single straight pipe vacuum-encapsulated with aluminum caps allowing the connection of the vacuum pump and a gauge for monitoring the pressure. A pumping station composed out of turbomolecular pump and backing pump was used. Each delivered straight pipe of the downstream segment was individually tested during the measurement to detect major leaks and poten-

tial mechanical damage. Results from the initial measurement of the beam pipe segments confirmed the requested vacuum tightness of the delivered components. The maximum pumping time was 12 hours, however no leaks were detected during the period for any of the straight segments. The SAT was signed by the FAIR and NPI CAS representatives with a remark that testing of delivered beam pipe will continue during 2024 in order to get better understanding of its best operation practice.



Figure 4: SAT of downstream beam pipe segments at GSI.

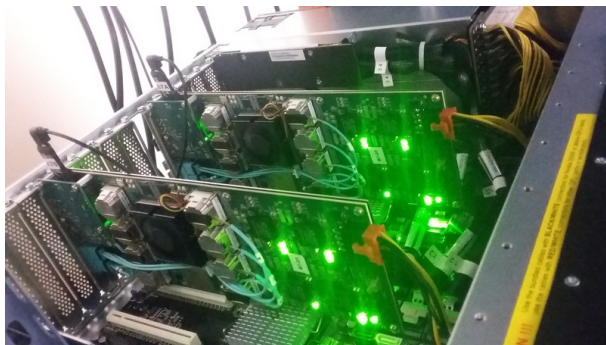
Outlook

During SAT it was verified that no transport damage occurred to the delivered components. Nevertheless, it was evident that better understanding of operation of carbon fiber beam pipes is needed, therefore additional comprehensive tests will be made. It is planned to continue testing under vacuum conditions to identify possible long-term vacuum exposure effects on mechanical properties, the possibility of optimization of the pump-down time by proper treatment before the evacuation and determination of the outgassing rate.

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Data Acquisition and Online Systems



DAQ-related FPGA firmware development

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GERI-based readout chain improvements

In 2023, the work on the GERI-based readout chain was aimed at further extending its functionality and performing the system's functional tests. In the GBTxEMU, the run-time selection of the E-Link clock frequency was added. That adds a possibility to choose between operations at 160 MHz or 80 MHz (e.g., for debugging) without reprogramming the FPGA. Additionally, the number of available E-Links has been increased to the limits set by the GBT-Link capabilities.

GERI can also work at 160 MHz or 80 MHz E-Link clock frequency. However, because frequency selection must be made before synthesis, separate firmware versions must be used to operate at each frequency. Further improvements to the DMA engine aimed at parallel processing of transmitted data have been introduced [1]. The data concentrator developed for the future versions of CRI (see the next section) has been integrated with the GERI datapath and tested.

A system for synchronizing the GERI-based readout via the GBT-link transmitted reference clock and time has been implemented. The synchronization has been tested in a dedicated setup prepared at WUT (see Figure 1). In the future, that solution may be adapted for compatibility with the TFC2 system developed for CBM.

CRI-based SMX readout improvements

The CRI1 firmware has been modified in response to the needs of the mCBM experiment. The number of ROB-3 boards supported by a single CRI1 board has been increased to 8. Changes enabling the reordering of GBT links have been introduced to enable better utilization of optical components. A special version of firmware with swappable selected downlinks has also been prepared to enable the reuse of an early series of FEB8-5 boards.

For future CRI2, a scalable data concentrator based on an interconnection network has been developed [2,3] and tested in GERI. The results show that full-speed concentration of 32-bit data, even to 512-bit words (needed, e.g., for PCIe Gen 4), is achievable.

The experience acquired using the AGWB system in readout firmware [4] has inspired Michał Kruszewski to develop a new method of defining the control interfaces – considering the data functionality instead of the physical register structure. The resulting Functional Bus Description Language (FBDL) is described in publication [5].

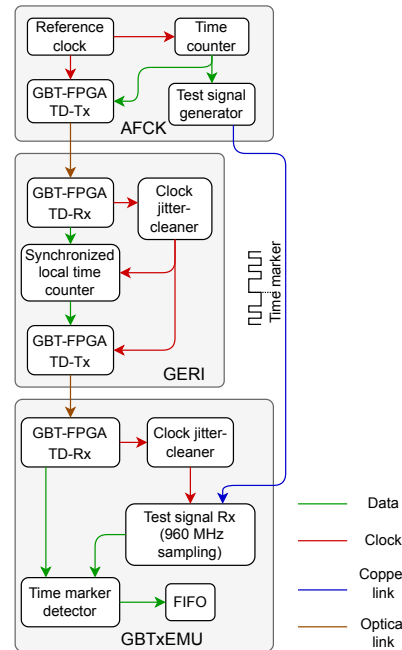


Figure 1: Setup for testing the synchronization in the GERI-based readout chain.

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Design Concept for the Next-generation FLES Interface Module

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The FLES interface module (FLIM) is an HDL module which provides the interface between the subsystem-specific readout designs and the FLES [1]. A functioning FLIM implementation for the current CRI card is available and in active use in all CRI-based CBM setups. With the upcoming second-generation CRI on the horizon and the lessons learned from these setups, a design concept for the next-generation FLIM has been developed.

The main objectives of the updated FLIM design are performance improvements, compatibility with the next-generation CRI card, the reduction of readout design complexity and improved component sharing between readout designs. The developed concept foresees to keep the general semantics of the microslice interface, but to increase the interface bandwidth and to rework the overload handling. An overview of the hardware architecture is depicted in Figure 1.

The FLIM multiplexes multiple input channels onto a single PCIe interface with dynamic bandwidth division. The total input bandwidth exceeds the bandwidth of the PCIe interface. A mechanism for handling overload conditions is therefore required.

The current FLIM has a closed backpressure path. If the output bandwidth is insufficient, the interface no longer accepts words and the backpressure is forwarded to the user logic. This design choice allows the derandomization buffers to be placed within the user design and optimized according to the characteristics of the subsystem. However, implementations of backpressure handling within the subsystem design have proven to be error-prone, and specific developments cannot be shared across designs.

It is therefore planned to introduce a common, generic overload handling as part of the FLIM and abolish backpressure forwarding. In the event of an overload, the data content of the microsllices will be discarded, while the descriptors are retained but marked accordingly. This step implies two design requirements. The main derandomization buffers must be implemented within the FLIM, as they can only function based on backpressure information. The subsystem-specific data path must support the full technical input bandwidth without the possibility of internal overload conditions. Otherwise, a second overload handling would be required. Both aspects were evaluated positively for the subsystem designs.

Dealing with overloads requires coordination with the central throttling system to ensure that a minimum number of physics events are affected. To enable the central throttling system to assess the overall system load well before an overload situation occurs, the fill level of the now central derandomization buffer can be published. Based on

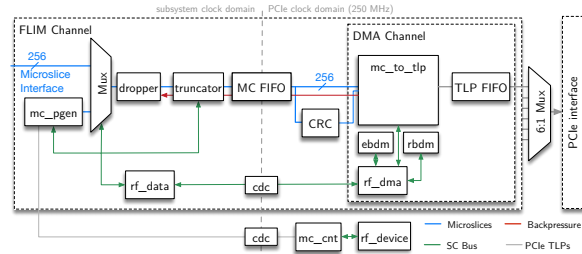


Figure 1: Overview of the updated FLIM architecture.

this information, the throttling system can control data production in such a way that overloads are avoided as far as possible.

The backpressure-free microslice interface needs to have sufficient bandwidth so as not to cause a bottleneck before the derandomization buffer. The bandwidth requirement is determined by the aggregation ratio of the subsystem design, i.e., how many input links are merged into one microslice stream, and by the data expansion factor from sensor messages to detector data format. An aggregation ratio of 6-to-1 is assumed to be feasible for all subsystems. Based on this, an interface width of 256 bit at a target frequency of 160 MHz was chosen. Assuming GBT input links, this leaves room for an expansion factor of 1.9. To fully connect a 36-link CRI, a total of 6 FLIM channels are required.

Simultaneous compatibility of the FLIM with the current and next-generation CRI can be achieved in the multiplexing stage between the FLIM channel and the PCIe interface without changes to the channel design. The 256-bit bus width fits to the internal bus of a PCIe x8 Gen-3 interface as used in the current CRI. The design criterion for the next-generation CRI is a PCIe x16 Gen-3 host interface. For this interface, the data bus can be upsized to the required 512 bit in the multiplexing stage. This flexibility also leaves open the option to subdivide the CRI data path to use two PCIe x8 interfaces instead of a single x16 interface, which can ease timing constraints.

Implementation of the updated FLIM has started and is assumed to conclude with the next generation of readout designs.

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Computing



Core package and proof of functionality of a CBM Experiment Control System prototype

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Core package

The preparation of an **ECS core** package was the continuation of the work described in the 2022 progress report [1]. The following features were added to the already presented command and state cores:

- an ECS agent base class inheriting from both the command and state branches (*EcsCoreAgent*);
- a configuration tag interface to
 - set configuration tags for an agent,
 - request the list of available tags for a given agent ID from a central service,
 - request eventual sub-agents configuration tags for a given [agent ID, tag] pair from the same service;
- a combined context/status tracking class, storing information relative to the last contact on the command and/or state interfaces;
- an automatic heartbeat to selected targets if no command contact with them since pre-defined time.

Whenever a stable and clean set of changes is ready locally, it is merged to the master branch of the Gitlab project, where an automatic CI/CD chain

- checks that the resulting code does not have any warning/error nor any typing inconsistency,
- checks that all declared tests are passing at least on our official **Python** version (**3.8**) as well as optionally with **Python 3.7** and **3.10**,
- builds a Python package and registers it in our Gitlab instance package repository [2],
- creates some **html** pages with the detailed results of the tests (coverage) and uploads them to Gitlab Pages.

The resulting core package was in its version **0.1.0** tested at **90%** (lines of code) and typed at **91%** (also LOC). The policy for testing and QA in this project will be that only code passing the following limits will be merged to make further versions of the package: **above 90% typing and above 90% testing (LOCs)**.

The package will stay in an “Alpha” stage (versions 0.1 to 0.99) until used in a complete ECS system or until the rate of backported changes dies down. The package is for now in version **0.2.5** with **91%** test coverage and **93%** typing coverage.

The main change (**v0.2.0**) was a separation of the command receive and reply emission in two sockets, which allowed the usage of polling and improved drastically the

CPU usage. The resulting interactions between an arbitrary *EcsCoreAgent* and the service processes are summarized in Fig. 1.

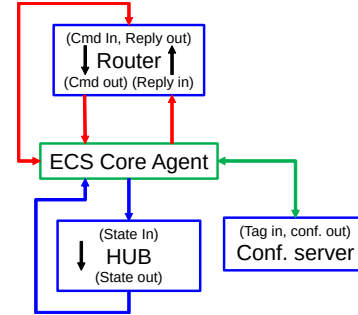


Figure 1: Interfaces between an *EcsCoreAgent* and the service processes available from the ECS Core.

Proof of functionality: QT based GUIs

Once the core package was available, a “proof of functionality” project [3] was started with a dependency on it. Its main goal is to test the interplay between multiple instances of agents derived from the *EcsCoreAgent* class and the three central services (*CommandRouter*, *StateHub* and *ConfServer*). It also allows to test the interaction with the Gitlab Pypi package repository and the usage of dependency versioning in Poetry.

In this project the following elements were created:

- agent classes emulating the ECA, central systems SCAs, PCAs, and subsystems SCAs
- for the central systems, both “main” agent classes representing the total resources and “partition” agent classes representing the share allocated to a given PCA
- two **QT** based GUIs: one for ECA, central systems SCAs and PCAs (see Fig. 2), and one for subsystems SCAs (see Fig. 3)

The main test mode for the functionality testing used “automatic state transitions”, where upon request a transition always succeed (including transitions to/from error states). The transitions of subsystems SCAs can then be triggered either directly from the dedicated GUI or through commands coming from the ECA/PCA GUI. With this mode which allows testing before implementing the first hardware bound agent, a complete cycle could be emulated from “no ECS agent existing” to “ECA up and active, central systems up and active, partition created, SCA attached

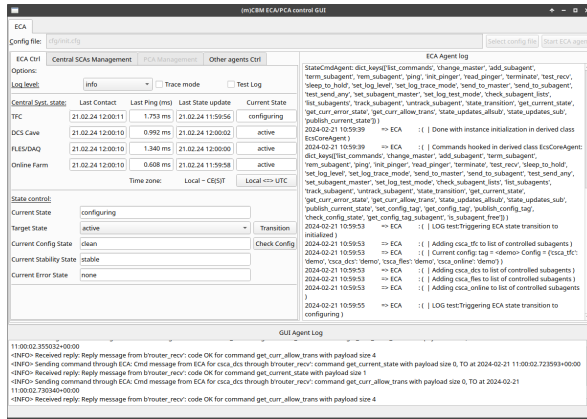


Figure 2: Example screenshot of the QT-GUI for the ECA, central SCAs and PCA.

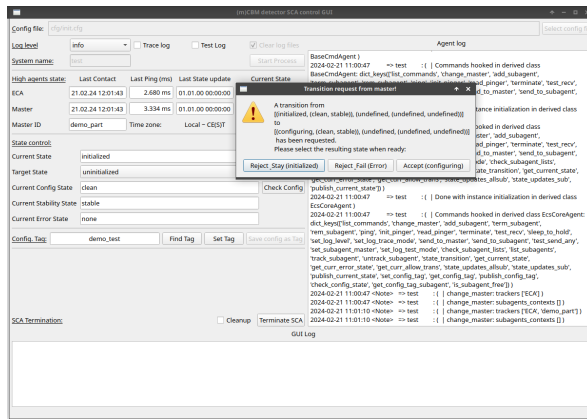


Figure 3: Example screenshot of the SCA QT-GUI operating in “mCBM user popup” mode.

to it and partition transitioned up to active”. The resulting relations between agent classes and interfaces between agents and GUIs are shown in Fig. 4.

In addition to this more technical oriented mode, a “mCBM” mode was added where the requests for state transitions of the SCA trigger a popup in the SCA dedicated GUI, asking the user to **Accept/Reject/Ignore** the transition. A similar popup is triggered for transition from error state to normal state to **Accept/Further error/Ignore**. With these it should be possible to improve the coordination of the shifts in the next mCBM beam campaign, and this should also allow a step by step implementation of the states (and detector specific local states) transitions.

The method of “functionality testing” before the full system implementation allowed a fast and easy feedback to the core package. All changes were first tested as overloaded commands in the derived classes in the new package before being backported to the core once tested and visibly shared between agents. This led to 10 new versions of the core (v0.1.0 to v0.2.5) in the last 6 months, bringing bug-fixes, feature-patches and performance improvements. This kind

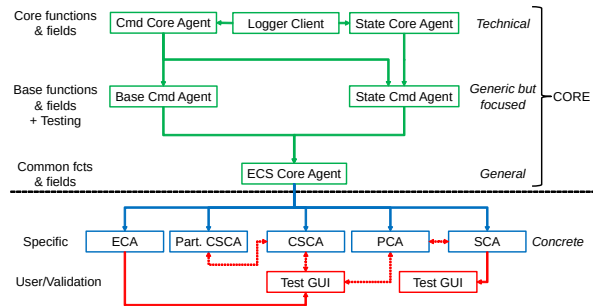


Figure 4: Relation between Agent classes and GUIs within the ECS Core and ECS proof of functionality. Green and blue arrows indicate classes inheritance. Full red arrows from agents to GUIs show internal instances interfaces while dashed one are for communication between independent processes.

of full/realistic test environment proved especially crucial for fixing elements of the multi-threading protection.

Next steps

The following changes will be added in the coming months to reach a first full demonstrator for mCBM, with some steps done in parallel: decoupling of the state agents from the GUIs into different processes, testing of the GUIs with the mCBM shift crew, integrating the first two central systems (Flesnet and Online Processing), integrating a first detector system, probably STS, and finally the development of the framework for the SCA layer.

These improvement will allow to separate the current proof of functionality project in two future oriented projects, one for the mECS with the agent classes (ECA, CSCA, PCA, SCA), on which the detectors systems elements can be built, and one for the mCBM QT-GUI, depending on the previous one. This should give us the capability in the future to have a variety of user interfaces (QT, web page, CLI, ...) for the same ECS, depending on the use case (shift crew, expert user, ...).

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Recent Flesnet developments and work in progress

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Technical Design Report Published

CBM's first technical design report (TDR) for central systems was approved and published by FAIR in July 2023 [1]—following the recommendation of the Expert Committee Experiments (ECE). It describes the hardware architecture of the FLES entry cluster, the timeslice building network (including Flesnet), and the data path until timeslices are built.

Data Challenges and mCBM

Flesnet was successfully used in several data challenges in the context of miniCBM. This included synthetic runs as well as high-rate TOF tests during machine engineering runs. No severe issues were revealed for Flesnet during these integration and operation tests.

Code Developments

For code maintenance and cleanup, several minor changes were applied. For example, some outdated functions are now explicitly declared as deprecated, raising a warning when the function is still used in client code such as *CBMroot*. The code was adapted to more recent compiler and library versions, which raised new warnings for some code constructs. Similarly, the minimally required *CMake* and library version was increased and adapted to the currently used Linux distributions in CBM.

Additionally, online timeslice compression was introduced using the *zstd* library. This achieves about 30 % data compression for raw data archiving with moderate CPU overhead. Furthermore, previously recorded timeslices can now be replayed directly into a shared memory region, making the data path more flexible. This feature has already been used during the data challenges.

Documentation

We extended and updated the documentation in different aspects to better serve new users and developers.

The project configuration for Doxygen, a tool to extract and present C++ code documentation, was updated for proper function and to include some additional documents that we provide separately.

We provide a tutorial for a Flesnet setup with InfluxDB and Grafana monitoring in Docker containers on a local machine. Such a setup aids the development of more detailed monitoring capabilities with local tests before eventually releasing them.

For an exemplary minimal Flesnet run, we wrote a guide to setup a data processing chain in software. It (1) generates microsllices and writes them to shared memory. (2) uses a Flesnet entry node process to read the microsllices from shared memory, builds timeslices and writes them to another shared memory region; and (3) reads the built timeslices and writes them to a timeslice archive in a final processing step. We describe the relevant command line flags and their interdependencies and explain how to use them.

Work in Progress and Next Steps

Several conceptual design discussions and developments are in progress but not yet finished to adapt Flesnet to new requirements and circumstances. These activities include, for example, (1) a more efficient shared memory layout and usage, which becomes possible as we plan to equip entry nodes with several CRI boards. Also, on the processing nodes, a different buffer layout may be beneficial to support the scalability of Flesnet in large-scale setups. (2) The dynamic addition and deletion of timeslice-building nodes by starting a new Flesnet instance (for example, as an additional SLURM job). (3) Revealing more detailed internal data of Flesnet to the monitoring dashboards using InfluxDB/Grafana. (4) Realistic large-scale timeslice-building runs by replaying data recorded by the mCBM campaigns at different scales and speeds. (5) Providing interfaces to the experiment control system (ECS) for status information and basic steering capabilities.

Acknowledgements

We thank all members of the CBM Collaboration, especially those involved in the online data management, FLES and Flesnet development as well as the online data analysis for their contributions and cooperation.

The reported work is not necessarily conducted by the authors themselves. Instead, the report shall provide an overview of recent developments for Flesnet in general without aiming for completeness.

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Accelerating online software development with CBM data challenges

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Development and testing of software, which is designed for CBM online computing, have motivated three dedicated data challenges (DCs) during 2023. Real-time event selection in the context of data analysis of the mCBM, the full-system prototype of the CBM experiment, demands highly efficient and robust software components.

Introduction

As discussed also in a previous report [1], efficient online data processing comes with special requirements for all data structures, interfaces, and algorithms. To this end, many efforts have been taken to separate the actual algorithms from framework layers and to focus developments on code relevant for reconstruction considering execution speed also from the beginning. In the context of online computing, aspects of integration of individual tasks are particularly relevant to ensure interoperability and reliable interfaces. Implementing regular data challenges every one to two months leads quite naturally to reasonable milestones and deadlines.

Executing the data chain using synthetic data also has the advantage that one can easily adopt the rate of incoming FLES data. Once the processing at a defined rate for the input is stable, an acceleration of incoming data can shed light on the scaling behaviour towards higher rates.

Since the CBM software cannot generate detector data formats from simulation, pre-recorded 2022 data from mCBM have been used. In order to emulate the actual online processing as closely as possible, we have chosen a setup based on mFLES nodes sending timeslice data to be processed by VIRGO nodes.

Setup

Four mFLES nodes were used for the replaying of archived timeslice (tsa) files, allowing a continuous playback at real time or faster rates. In total, 80 tsa files were sent to eight instances of the cbmreco binary being executed on each of the ten reserved VIRGO nodes.

These binaries are included in Aptainer containers, which were based on Debian 12 Linux operating system, and their execution was started as a Slurm job on the nodes of the VIRGO cluster. Thus, 80 instances of the cbmreco program were running in parallel.

Most of the tests have utilized multi-core CPUs on VIRGO cluster nodes with AMD EPYC processor architecture. In this case also parallelisation using OpenMP has been used, typically setting the number of threads to

twelve. For a shorter time also the execution of processing on three GPU VIRGO servers has been tested.

During a data challenge, inspection of online results including input and output data rates is indispensable, which is similar to the case when data-taking during beam-times. Therefore, performance data is collected in an Influx database interfaced to Grafana displays. It should be emphasized that in the setup for DCs, monitoring and data quality assurance were separated from the online algorithms. These algorithms provide monitoring data to higher-level instances, where their handling is managed.

Archived files from two mCBM benchmark data-taking runs with run id 2391 and 2488 served as input sources, which consist of 960 and 1123 tsa files, respectively. Data of the corresponding timeslices were first merged before splitting into 80 timeslice streams.

Integration of tasks and monitoring

The following basic tasks have been included in the reconstruction steps:

- Unpacker algorithms have been formulated to operate on one FLES microslice as the smallest independent data unit. The data challenges have included STS, TOF, MUCH, TRD, TRD2D, BMON and RICH unpackers. Several optimisations towards multi-threading on the task-level for unpackers have been implemented and are e.g. summarised for the STS in [2].
- Digis as output from unpacking can be used for digi-based triggering and subsequent event building. Identifying time-clusters in the time distribution of digis thus enables the definition of trigger-based events.
- Digis in the STS are the basis of local STS reconstruction, consisting of finding STS clusters and hits. Developments for highly efficient parallel execution on CPUs and GPUs have been tested during the data challenges, see also [3].
- Similarly an improved version of local TOF reconstruction has been developed, c.f. [4], in 2023 and could be tested during the data challenges.
- Using hits from STS or TOF, also tracking has been included. Details of developments of tracking software for mCBM are summarised in [5].



Figure 1: Numbers of digis per timeslice from different mCBM detector systems processed in DC 3. Also the corresponding numbers of digis after event selection are shown.

Results

Replaying timeslice data from mFLES nodes to processing at VIRGO worked smoothly. As an example, a total input rate of 8000 GB in 90 min has been measured during DC 2, corresponding approximately to 15 GB/s. During that time event building has been performed, typically at a rate between 1 GB/s and 2 GB/s. Variation of the input data rate allowed to increase and test incoming rates of up to a factor of eight as compared to the original speed.

Also the operation of 10 VIRGO nodes operating on timeslices in parallel has been realized. The prepared online processing binaries worked for hours demonstrating the stability of the systems. It should be underlined that this includes unpacking of timeslices containing STS, TOF, MUCH, TRD, TRD2D, BMON and RICH data as a basis for subsequent digi-based triggering plus event building. Fig. 1 gives an overview of numbers of digis from different mCBM detector systems processed in DC 3 displaying also the corresponding numbers of digis after event selection. It is interesting to note that the largest number of unpacked digis are from mSTS, whereas the fraction of mSTS digis actually selected is lower than e.g. for mTOF digis, also as a result of the definition of events.

Finally the software for mCBM online tracking using hits of TOF and STS has been integrated successfully. Also the online view of histograms for quality control of results from tracking has been achieved [6], forming the basis of future online selection of events containing characteristic tracks for physics analyses.

In order to store data in a resource-efficient way, outgoing data can be compressed. One option for file compression based on Zstandard has also been tested. For a period of two hours the processing has been done on three GPU servers using AMD Radeon Instinct MI100 at VIRGO. During that time STS unpacking plus subsequent HitFind-

ing optimised particularly for parallel GPU processing have been performed successfully. The actual performances of individual tasks can be further investigated including comparisons between runtimes on CPUs, GPUs and utilisation of VIRGO resources.

Outlook

The data challenge campaigns in 2023 have made software developments for CBM online computing more visible. At the same time also the principal readiness and robustness for data taking have been demonstrated. In order to enable fast validation of the reconstructed objects, an extension of online quality assurance histograms is foreseen. Also in the future regular data challenges are planned, focusing on integration of new online software developments and workflows implementing more complex event selections. As a complement of enabling software for physics analysis, also an efficient usage of computing resources at the VIRGO HPC cluster can be further investigated. Investigating performances based on runtimes for different numbers of threads will allow more efficient utilisation of CPU cores and at the same time show the potential for further optimisation of CBM online algorithms.

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Optimisation of the Muon Chamber (MuCh) digi storage

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CBM aims to do online data selection solely in software at an extremely high interaction rates, which for gold(Au) gold(Au) collisions is up to 10 MHz. Due to the unprecedented interaction rate and the use of self-triggered electronics, the CBM experiment will generate enormous amounts of data, which is in the order of few terabytes per second [1]. To optimise storage usage by the experiment, each digi, which is the smallest unit of a signal needs to be optimised. In this work, the MuCh digi has been revisited and the MuCh address scheme is revised. With these optimisations, MuCh storage requirement became nearly half when compared to the present implementation which leads to a reduction in memory usage during the unpacking of the raw data stream.

When the particle hits the detector, the signals are stored in MuCh digi object comprising basic information, namely: a) time-stamp of the digi stored as a 64 bit unsigned integer *fTime*, b) unique address of the digi stored as a 32 bit unsigned integer *fAddress*, following the *CbmMuchAddress* scheme described later c) charge of the hit in terms of ADC value stored as a 16 bit unsigned integer *fCharge* and d) a saturation flag stored as a Boolean variable *fSaturationFlag*. Time-stamp of the digi is computed from the data of Sts-MuCh-Xyter (SMX) ASIC [2], microslice and UNIX time. The spatial position information is formulated from the CRI (Common Readout Interface) based data acquisition readout chain and the hit message of SMX ASIC using *CbmMuchAddress* scheme. ADC represents the charge deposited on a particular sensor of the detector.

fAddress is based on the CBM MuCh Geometry [3]. The address of a pad is generated using 7 levels as listed down the first column of Tab. 1. This information is packed in a 32 bit number using bit shift operations which were carefully implemented in the *CbmMuchAddress* class as per Tab. 1. The subsystem ID being the least significant bit and moving in the above order such that channel ID forms the most significant bit. The current address scheme is shown in the second column of Tab. 1. As per above mentioned bit scheme and different variables of MuCh digi, presently the size of one digi is 120 bits.

Due to the enormous data volume as mentioned earlier, the digi storage container needs to be reduced as much as possible. To achieve this, the existing scheme is carefully studied and implications of every change has been evaluated. Digi is a standalone entity with absolute time of the particle when it hits the pad and therefore needs 64 bits to store. To reduce the digi storage for the entire CBM, this time is now stored relative to the ‘TimeSlice’ which is common for all the sub-systems of CBM. Free flow data stream

Table 1: CbmMuchAddress Bit Allocation Scheme

LEVEL Name	Curr. Allocation	Prop. Allocation
System ID	4 bits	4 bits
Station ID	3 bits	3 bits
Layer ID	2 bits	2 bits
Layer Side	1 bit	1 bit
Module ID	5 bits	5 bits
Sector ID	8 bits	7 bits
Channel ID	9 bits	5 bits
ADC Value	-	5 bits

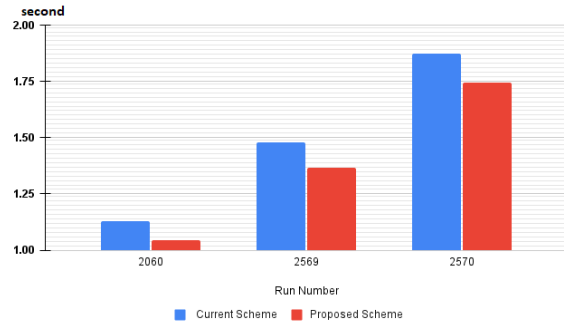


Figure 1: Time comparison per time slice for unpacking when ROOT Compression is ON.

is stored in form of the ‘TimeSlices’. In this respect, 32 bits are sufficient to store the time relative to the TimeSlice with nanosecond precision. Thus 32 bits of *fTime* variable is reduced by changing it from *uint64* to *uint32*.

In the SMX ASIC, charge deposition will be digitized using 5 bit ADC, therefore to store the ADC value 5 bits are sufficient.

Now coming on to the next variable which is *fAddress*.

Table 2: mCBM data taking runs for this study

Run No.	No. Of Digs Formed	Number of T.S.
2570	308900239	81
2569	243524977	80
2060	141988919	60

Table 3: ROOT Compression is ON

Run #	File Size(Current)	File Size(Proposed)
2570	1.3 GB	1.2 GB
2569	1.1 GB	890 MB
2060	514 MB	446 MB

For the latest MuCh geometries with the finalized address scheme [3], sector values are varying from 0 to 96 which requires maximum of 7 bits to store the Sector ID instead of 8 bits, similarly only 5 bits are sufficient to store the channel ID instead of 9 bits as the channel number ranges from 0 to 23. Thus one can have 5 empty bits in *fAddress*, as stated above, the ADC value also requires 5 bits of memory to be stored. So the bits of *fAddress* were rearranged and an additional level to store the ADC Value was added. Due to this, 16 bits of memory per digi is saved as *fCharge* variable has been removed all together. To implement this *CbmMuchAddress* class is updated to perform the required bit-shift operations. The 3rd column of TABLE 1 shows the new address scheme starting from the LSB (1st level) to MSB (8th level). Thus, we were able to save 56 bits per digi.

In the simulation software, digitization block is responsible for generating realistic digis which is called via *run_digi.C*. After changes in the MuCh Digi and related classes (*CbmMuchDigi* and *CbmMuchAddress*), simulation of different sets of collisions was done and transportation and digitization was executed. Thorough checks were done on different sets of simulated data, testing the number of generated digis and their corresponding values for time, charge, and address exactly match the prior existing implementation. By consequence, this verifies that physics observables would remain unchanged.

In the real experiment, gathered information from the data acquisition system will be in the form of hardware messages and to convert into subsystem or detector specific objects a software named "UNPACKER" is used [4]. To verify the correctness of proposed changes, the unpacking on different raw data sets of the mCBM runs from March-June 2022 data (as shown in Tab. 2) was performed and no change was found with respect to value of unpacked data.

To optimise storage consumption, ROOT has a feature of compression based on efficient lossless compression algorithms which compresses the data significantly without information loss [5]. But this compression comes with a time cost. On the basis of this, we performed the unpacking of raw data, which is available in forms of tsa files, using ROOT compression turned ON and turned OFF. In both the cases the proposed scheme performed better which can be seen from Tab. 3 and Fig. 1 for ROOT compression is "on" and Tab. 4 and Fig. 2 for ROOT compression is "off".

We have described the optimisation of MuCh Digi by storing the relative time stamp in the time field and rearrangement of the address bits, to accommodate ADC value,

Table 4: ROOT Compression is OFF

Run #	File Size(Current)	File Size(Proposed)
2570	4.4 GB	2.4 GB
2569	3.5 GB	1.9 GB
2060	1.9	1.1 GB

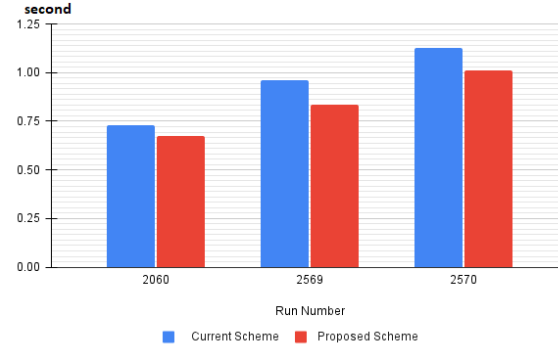


Figure 2: Time comparison per time slice for unpacking when ROOT Compression is OFF.

without affecting the actual values of variables. We also attempted to perform a systematic study on the impact of this optimisation with respect to file size which reduced by almost half and execution time reduction due to ROOT compression. We concluded that the processing time per timeslice is reduced significantly when we switch off ROOT compression. The modified class *CbmMuchDigi* will be committed in the *CbmRoot* repository.

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Data QA framework in CBM: recent developments

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Introduction

A complexity of data produced in a modern Physics experiment requires a continuous and detailed monitoring of its properties on different data processing stages. In the CBM experiment such a property can be occupancy distributions of different detector modules, algorithm efficiency, different reconstructed hit and track property distributions. This plays an essential role in algorithm development, early malfunction identification as well as preparing the experiment for further data taking. To address these requirements a quality assurance (QA) system is introduced to the Cbm-Root project.

The QA framework in `cbmroot` provides a flexible utility for automatic production and analysis histograms with different reference qualities on the basis of the event or the time-slice. To the current date, the QA framework comprises online and offline parts, which each meet different requirements on the corresponding data reconstruction regime and thus will be discussed separately.

Data QA framework for offline simulation and reconstruction

Similarly to data reconstruction tasks in the offline scenario each QA-task (`CbmQaTask`) is a `FairTask` class. A collection of the QA-tasks compose a task-tree and is executed sequentially on the reconstructed data. Each QA-task fully encapsulates the technical side of histogram handling (RW, configuration) simplifying the task creation and maintenance for the user, reducing the code duplication and unifying the QA processing. The same QA class can be used either for real data or for simulated data, which in the latter case can provide additional histograms due to existence of MC-true information.

One of the important QA-task features is a criteria checking routine. The properties of reference histograms can be automatically tracked on the statistical basis. For each property a set of boolean quality criteria can be registered in the QA-task, the failed criteria then affect the final success message of the QA-task tree, which in its turn signals a problem in a corresponding data processing module. This is used in the continuous integration tests: if some of the criteria fails after an introduced modification, the entire CI test fails as well, indicating the problematic criteria.

In the input tracking QA a typical criterion is the values of hit pull distribution mean and std. deviation in different tracking stations. Figure 1 shows a pull distribution of hits in TRD-2D and TRD-1Dx stations in

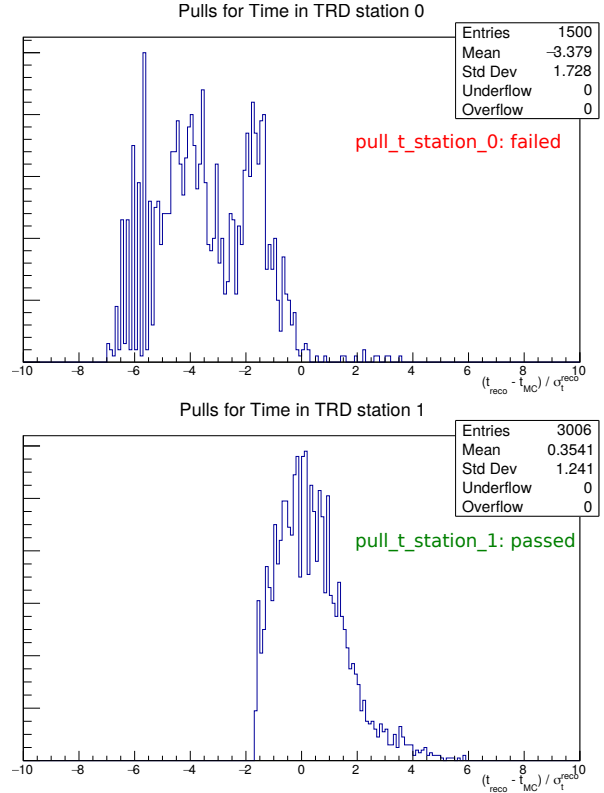


Figure 1: The time pull distribution for TRD-2D (top panel) and TRD-1Dx (bottom panel), obtained in the Ni+Ni@1.93AGeV simulations using mCBM setup in May 2022.

the `mcbm_beam_2022_05_23_nickel` setup, obtained in Ni+Ni@1.93AGeV simulations. The pull is calculated as a ratio of difference between reconstructed and true hit time and the uncertainty of the time measurement. In an ideal situation the pull distribution should be centered in 0 and have a unit standard deviation. The CA tracking accepts these values taken with their uncertainties to be within some range. For TRD-1Dx (bottom panel) the time pull distribution is mostly centered near 0, however its small tail slightly shifts the mean value to the right, the criterion is passed. Another picture can be observed for the TRD-2D (top panel): the time pull mean value is largely shifted to the left, and the corresponding criterion fails.

Another feature of the QA-task tree is an automatic comparison of the histograms with ones, obtained with the default reconstruction configuration. The comparison can be

done on a statistical basis (χ^2 test) or using a maximal ratio check as well as on a bin-by-bin basis, checking the full histogram equality, which is essential to prevent a malfunction introduction during an algorithm development. Along with the original plots comparison routine stores differences and ratios of the histograms, which can be conveniently used for systematic uncertainty estimation.

Data QA framework for online reconstruction

In contrast to the offline reconstruction scenario, the online reconstruction chain [1] has a solid structure and does not rely on ROOT libraries. Such a design was selected to provide a light-weight and fast executable, essential for a performant time-slice reconstruction. The QA modules are executed simultaneously after each reconstruction algorithm. Each QA module fills a set of reference histograms defined for a portion of data from the current time-slice. The histograms then are sent to the histogram server, which is a standalone process and provides the realtime histogram monitoring.

The communication between the reconstruction chain and the histogram server processes is performed with a ZeroMQ API. The histogram and canvas configuration message is produced during initialization step and consists from three parts. The first part is a pair of histogram and canvas numbers to be sent, the second part is represented with a vector of histogram names, and the third message is a vector of canvas configuration strings. During run the message is formed from the serialized container of histograms and profiles, filled with the data collected during the current time-slice. All these tasks are delegated to classes in the `cbm::algo::qa` namespace, making a creation of a particular QA-module flexible and user-friendly.

In order to avoid the dependency on ROOT libraries [2], it was decided to use the custom histogram and profile classes. The classes are based on the Boost histograms [3], but utilize additionally the ROOT histogram errors handling and provide only a limited functionality necessary for the online data QA. At the moment the QA modules for the STS unpacker and the CA tracking are available.

Summary and next steps

In summary, a flexible and user-friendly data QA framework was developed both for offline and online data reconstruction scenarios. The development of new features of the data QA is on-going, which can broadly separated into two main tasks. The first task concerns the integration of histogram comparison routine in the continuous integration tests. This should help to automatize the tracking of the effect of changes to the algorithm or the calibration at different data reconstruction stages. The second task is to merge of the online and offline QA frameworks, which will unify and simplify and thus gives the possibility to simultaneously handle the same set of reference histograms and use features of the offline data QA framework in the online

variant, for example, criteria checking.

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Online STS hitfinder on GPUs

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This article discusses the GPU hitfinder for the STS currently implemented in the online code of `cbmroot`. The hitfinder uses digis as input and performs two computational steps. The first step combines digis on one side of a sensor to clusters. The second step combines hits from clusters on the front and back sides of a sensor. Cluster and hit finding are trivially parallel across sensors, so this article focuses on strategies to parallelize within a sensor. Both steps are preceded by a sorting step. The cluster finder requires digis to be sorted by channel and time. The clusters are then sorted by time to reduce the combinatorics during hit finding. The implementation was written in `xpu`, available from [url](https://github.com/fweig/xpu)¹, which allows compilation as native CUDA, HIP or regular C++.

Implementation

Sorting For each sensor, a GPU block is started for sorting. A custom implementation of merge path [1] is used to parallelize sorting within the block.

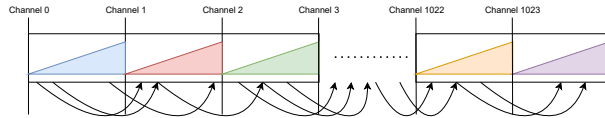


Figure 1: Illustration of the parallel cluster finding algorithm on a single STS sensor.

Cluster finding The offline implementation of the cluster finder iterates over time-sorted digis and assumes that all previous digis were fully processed [2]. This approach does not work well on GPUs as multiple digis within a block must be processed simultaneously in order to fully utilize the device. Instead, an alternative was developed [3], whereby cluster finding is split into two steps. The first step entails, as illustrated in Fig. 1, for each digi the searching of the next channel for another digi that belongs to the same cluster. Two neighbouring digis belong to the same cluster if they are within a certain Δ time. In this case a forward edge from the first to the second digi is created, while the latter digi is marked as having a predecessor. Sorting digis beforehand by channel and time enables an efficient implementation of this algorithm. Usage of atomic operations makes it possible to process all digis in a sensor independently. For the second step, the linked list of digis is traversed for every cluster, and the cluster

properties are computed. The cluster is created by the GPU thread that processes the first digi of the cluster, i.e. a digi with no predecessor. If this digi has no forward edge, it constitutes a single-channel cluster.

Hit finding The original hit finding algorithm developed in [4] is also used in the GPU implementation. To occupy the device, one GPU thread is started per front side cluster. Each thread then looks for candidates on the back side to combine both to a single hit.

Performance

Performance tests were done on a machine with an Intel Xeon 6130 (16 physical / 32 virtual cores) CPU, an AMD MI50, and an Nvidia RTX 2080 Ti. The test data were 20 timeslices from the 2022 mCBM run number 2391. The following times presented are those accumulated processing times for the timeslices. Running on a single thread, the STS reconstruction took 86.4 s of wall time, 75.1 s of which were spent in kernels. Using 32 threads, wall and kernel time are reduced to 17.5 s and 13.7 s. The run on the MI50 took 3.48 s. The kernel time was 1.83 s. Runtime with the 2080 Ti was 3 s with 1.46 s spent on the device in kernels. This corresponds to a kernel throughput of 1.02 GB s^{-1} and 0.82 GB s^{-1} respectively. The GPU runs also used 32 threads on the CPU side. In both cases, approximately 0.43 s were spent in host-device data transfer.

Future work

The input and output data formats of the hit finder, which are main contributors to GPU overheads, were not addressed. Digis are initially presorted by sensor, while the hits are split into streams and sorted by time for the input into tracking. Although data preparation takes place in parallel on the host, it remains to be ported to GPU.

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¹<https://github.com/fweig/xpu>

Time-based clustering for the Muon Chamber (MuCh)

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This report highlights the advancements in the Muon Chamber (MuCh) clustering algorithm utilised for organising detector data within the CBM setup. By addressing limitations of the previous approach and introducing dynamic adaptations to temporal patterns, the updated algorithm achieves more precise and efficient clustering. Furthermore, enhancements in spatial separation and hit formation contribute to improved accuracy and fidelity in identifying and analysing hits within the detector system.

The advancements discussed in this report are implemented within the `CbmMuchFindHitsGem` class which is used for hit reconstruction from the time stream digis, where significant changes have been made to enhance the clustering algorithm's functionality and performance.

The available clustering algorithm provided a foundational framework for organising detector data into clusters based on a fixed time interval `fClusterSeparationTime`. Figure 1 shows a basic flowchart of the existing clustering process which is used. This approach, while effective for basic event-by-event processing, had limitations when it came to handling more complex temporal patterns within the data. Recognising these limitations, the updated clustering algorithm introduces a series of novel conditions to dynamically adapt to the temporal characteristics of the data.

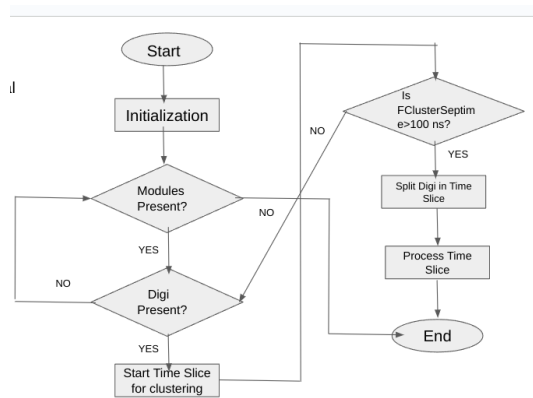


Figure 1: Basic flowchart of the existing clustering algorithm.

Modification-1 remains rooted in the original concept of creating new time slices when the time gap between consecutive digis exceeds the predefined threshold `fClusterSeparationTime`. Note: Term “Time Slice”

is local to this algorithm and for `CbmMuchFindHitsGem` only, it is not connected with the term “Time Slice” used in the mCBM data taking or used in Time Based simulation. This ensures that events occurring after a certain time interval are grouped separately, maintaining temporal coherence within each cluster. In the code implementation, this condition is achieved by iterating through the digis and checking if the time gap (t) between consecutive digis exceeds `fClusterSeparationTime`, upon which a new time slice is created.

Modification-2 represents a significant improvement by introducing a check for digis hitting already fired pads. This addition ensures that if a digi hits a pad that has already been fired within the current time slice, it is assigned to a different time slice. This refinement minimises the risk of erroneously grouping digis that belong to distinct temporal events. The code implements this condition by maintaining a set `addressesInCurrentSlice` to track addresses within the current time slice and checking if the address of the current digi is already present in the set, indicating a duplicate hit within the same time slice.

Modification-3 represents a more intricate level of refinement by considering the specific time differences between consecutive digis. It evaluates the time difference between the current digi and its neighbouring digis, allowing the algorithm to adapt dynamically to the temporal distribution of events. By comparing the time differences and adjusting the time slices accordingly, the algorithm can better capture the nuanced temporal patterns present in the data.

Overall, these enhancements represent a significant step forward in the clustering algorithm's capabilities. By incorporating dynamic adjustments based on real-time data characteristics, the algorithm can achieve more precise and efficient clustering, ultimately leading to improved hit detection and analysis within the detector system.

In addition to the advancements in time-based clustering, the updated algorithm maintains and enhances spatial separation capabilities present in the previous version. After the initial time-based clustering process, the algorithm proceeds to perform spatial separation to further refine the cluster organisation. This spatial separation step ensures that clustered digis are not only temporally coherent but also spatially contiguous, reflecting the physical layout and properties of the underlying detector system. By combining both temporal and spatial considerations, the algorithm achieves a comprehensive approach to cluster formation, capturing both the temporal evolution and spatial distribution of events within the detector. This integrated approach enhances the accuracy and fidelity of the clustering pro-

cess, leading to more precise identification and analysis of hits within the detector system.

Furthermore, the updated algorithm introduces a significant improvement in hit formation within clusters. Unlike the previous version, which selected only local maxima as hits without considering the contributions from neighbouring digis, the new approach incorporates the influence of all neighbouring digis within the cluster during hit formation, identifying the neighbouring pads for each pad in the cluster. This is achieved using the `GetNeighbours()` member function of the class. This enhancement allows the algorithm to generate hits that more accurately represent the collective signal strength and spatial distribution of the cluster. By accounting for the combined effects of neighbouring digis, the algorithm produces hits that not only capture individual local maxima but also reflect the broader context of neighbouring digis. Subsequently, the indices of the neighbouring pads are added to the `fNeighbours` vector. This vector maintains a record of the neighbouring pads for each pad in the cluster, allowing for efficient access during subsequent stages of the algorithm, leading to a more comprehensive representation of the underlying physical processes. As the algorithm progresses, local maxima within the cluster are flagged based on charge comparisons with neighbouring pads. The pads corresponding to these local maxima are then added to the `fFiredPads` vector, which serves as a repository for the pads identified as local maxima and then the algorithm proceeds to create hits directly using the `CreateHits()` function. Additionally, the algorithm addresses issues related to the storage and management of cluster count data, ensuring improved data integrity and accurate tracking and utilisation of cluster information throughout the algorithmic process.

The figure 2 presents a comparative analysis between the performance of the existing and modified clustering algorithms across varying interaction rate (10MHz, 1MHz, and 100kHz) in the time based simulation mode. Each subplot in the figure corresponds to a specific frequency, allowing for a comprehensive evaluation of algorithmic efficiency at all the proposed operating interaction rate at CBM.

Across all frequency settings, a noticeable increase in cluster count is observed with the implementation of the modified clustering algorithm compared to the previous version. This rise in cluster count indicates better clustering achieved by the updated algorithm.

It was observed that the enhanced algorithm produced noticeable improvements in the residual plot analysis. Figure 2 shows residual in the Y axis for reconstructed hits after the clustering and demonstrate improved accuracy in hit positioning, indicating enhanced accuracy in hit identification and clustering. X axis residual plots are not shown as those are similar. This improved visualisation in the residual plot provides valuable insights into the performance of the algorithm and its effectiveness in capturing the underlying physical processes within the detector system.

To summarise, the updated clustering algorithm im-

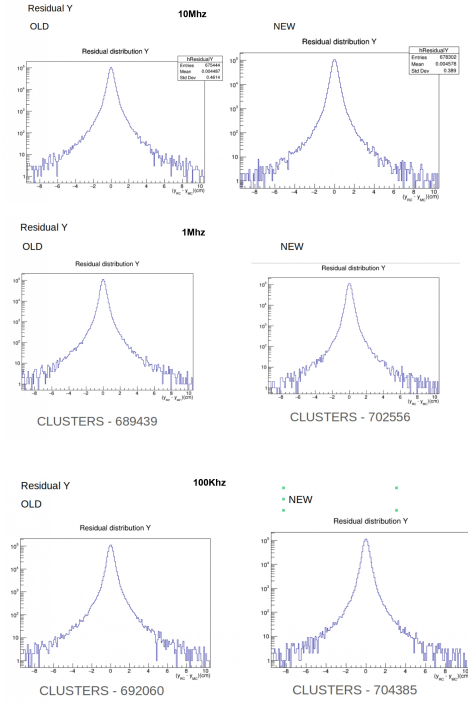


Figure 2: Residual plots for hit reconstruction, left side using existing algorithm and right side using modified algorithm.

proves upon the previous version by dynamically adapting to temporal patterns and maintaining spatial separation capabilities. It enhances hit formation by considering contributions from neighbouring digis within clusters, leading to more accurate representation of signal strength and spatial distribution. Further minute investigations are going on for the modified clustering; therefore the modified associated class `CbmMuchFindHitsGem` is not yet committed in the `CbmRoot` repository.

Online-capable hitfinder for TOF

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An important step of the reconstruction chain, is the identification of individual detector hits, which often result in multiple digis in the data stream. Hitfinding for the time-of-flight (TOF) detector proceeds by identifying spatially and temporally localized clusters of digi pairs. Within CBMRoot, the production-version of the TOF hitfinder is implemented in the class `CbmTofEventClusterizer`, which constructs `CbmTofHit` objects by iterating the following steps for each timeslice:

- 1) Calibrate digis (apply offset to time, gain and walk correction to charge).
- 2) Sort digis by super-module (SM), resistive-plate-chamber (RPC) and channel indices.
- 3) Loop over channels for each RPC. Build clusters for each given channel:
 - Require matching digis on each “side” of channel to build pairs.
 - Add other digi-pairs in spatial and temporal proximity to cluster.
- 4) For each cluster in channel, try adding other channels:
 - Loop through all digis of next channel.
 - For each digi, loop again to find partner on other side. Add pair if distance requirements met.
 - Iterate process (add next-to-next channel etc.).

As part of ongoing efforts to create an online-capable software stack within CBMRoot, a port `CbmTofEventClusterizer` was recently completed, which fulfills the requirements laid out in Ref. [1] and improves general performance.

A central problem with the above approach, is that in the best case scenario “add next channel” is called once for each cluster, leading to three nested loops:

- 1) digis / clusters in channel A (build initial cluster)
- 2) digis in channel B (find close digis)
- 3) later digis in channel B (find partner digis)

Indeed, a simple single-threaded benchmark on a Core i9 13900-K processor running at ~ 5 GHz confirms $\sim O(N^3)$ scaling of the algorithm and so exhibits a runtime of ~ 300 seconds for the fairly moderate input sample size of 1 million digis.

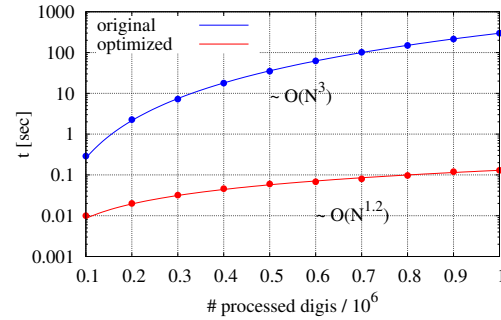


Figure 1: TOF hitfinder benchmarks on Core i9 13900-K at ~ 5 GHz. Model curve $f(x) = (x/a)^b$ with $b = 3.07 \pm 0.02$ and $b = 1.18 \pm 0.05$ for the original and optimized versions.

Improvements are possible by exploiting the time order of the input stream. This allows the following optimizations:

- 1) Break-condition for loop 3:
 - Break if hit time (average of digi times of the pair) is outside upper range of cluster.
- 2) Break-condition for loop 2:
 - Break if digi time is out of upper range of cluster (then hit time must also be).
- 3) Start position of loop 2:
 - Difference of digi times on channel sides gives y-position of hit. Use maximal difference for position “not outside detector”: start where valid partner digis place hit time in cluster range.
- 4) Re-use loop 2 start position:
 - Clusters are time ordered, so optimization 3 gives lower bound for subsequent clusters.

Combining these algorithmic improvements reduces the complexity to $\sim O(N^{1.2})$, as shown in Fig. 1. Further instruction-level optimization and parallelization brings the execution time on 8 cores down to ~ 50 ms for a typical timeslice of 2022 mCBM data, with $\sim 2.5 \cdot 10^6$ TOF digis.

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RCNet — Deep CNN for RICH ring reconstruction

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The Ring Center Net (RCNet) architecture is part of a novel ring recognition algorithm based on segmentation neural networks for the determination of candidate ring centers. It is basically a U-Net model [1] which is a popular model for semantic segmentation tasks. The main components of the network are shown in Fig. 1. The loss function used is *Mean Squared Error* (MSE) loss where the error is calculated for each and every pixel in the output image with respect to the true image and summed up. The optimizer used is Adam optimizer [2]. After the center candidates of the ring are found using the RCNet model, a modified least square fit [3] for circles of known centers is used to find the associated radius for all centers found from RCNet and these reconstructed rings are marked as ring candidates. After this, a final selection procedure is done for the ring candidates. This procedure takes into consideration the total number of hits on the ring, N_{total} , as a measure of ring quality.

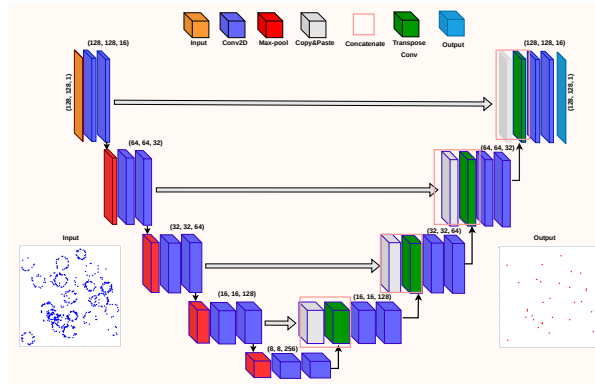


Figure 1: The Ring Center Net (RCNet) model architecture. The input image to the model and its final output from the model where only possible center pixels are with the value 1 and the remaining pixels are 0. The image dimensions above each layer are represented as (H, W, C) where H , W and C are image height, image width, and number of channels respectively. The convolutions followed by ReLU is shown in purple. Max pooling is in red colored blocks. The grey blocks show the features copied from the encoder network/contracting path. The pink rectangle shows concatenating the copied features and transpose convolution for up-sampling features. The transpose convolution is shown using green colored blocks. The grey arrows show skip connections. It shows copy and pasting the feature maps from the encoder network to the decoder network as shown by the grey blocks.

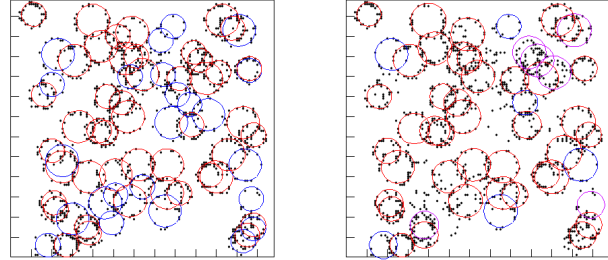


Figure 2: Simulated rings (left) and reconstructed rings (right) in a sample with 70 rings. A reconstructed ring is assigned to a simulated ring if there is at least 70% hits correspondence. A simulated ring is regarded as found if it has been assigned to at least one reconstructed ring. If the ring is found more than once, all additionally reconstructed rings are regarded as clones. A reconstructed ring is called a ghost (magenta) if it is not assigned to any simulated ring using the 70% criterion. Rings that consist of hits in the range $15 \leq \text{hits} \leq 35$ are considered as reference set (red). Rings that consist of hits in the range $5 \leq \text{hits} < 15$ are considered as the extra set (blue). The all set consists of rings from both sets. Here 40 reference set rings are reconstructed out of total 46 and 6 extra rings are reconstructed. In other words, there is 87% and 25% reconstruction efficiency for reference and extra set respectively. The ring density distribution is higher than expected at CBM.

An example of 70 simulated rings and the corresponding reconstructed rings from the ring finder can be seen in Fig. 2. Overall the model achieves an efficiency for the reference set in a range between 90% and 98% for a number of rings from 10–40. The high ring density occurs because the rings are restricted to a size 128×128 . Therefore, even the images with a relatively low number of rings considered in this analysis might have higher density than those rings that would be seen by the CBM RICH detector. The method outlined here is a standalone application.

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Cellular Automaton tracking for the mCBM experiment

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The Cellular Automaton (CA) track finder is a crucial part of the CBM reconstruction chain. It performs combinatorial reconstruction of tracks in STS and MVD whose functionality is now being extended to the other detectors. This existing CBM algorithm was adapted during 2023 to the mCBM experiment, where it reconstructs tracks in any detector systems — STS, MUCH, TRD, or TOF. The algorithm was successfully tested on 2022 mCBM data and will be applied to the online and offline reconstruction for the mCBM 2024 data-taking campaigns. It is essential to mention that our aim is to not developed any special bespoke code for mCBM but instead, we test the full-CBM tracking algorithm on the real data coming from the mCBM experiment whose essence should be equivalent albeit without the magnetic field. A typical mCBM event is shown in Fig. 1.

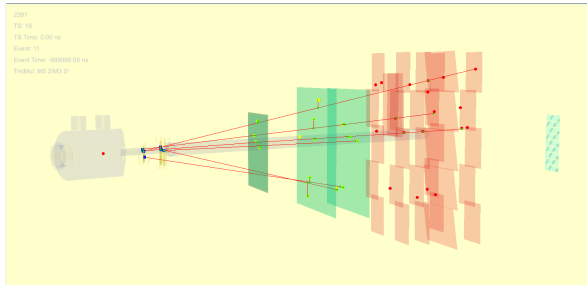


Figure 1: A reconstructed event from 2022 mCBM data with run id 2391. The grey shadow denotes the target box and beampipe. The green and pink transparent rectangles who extent of the trd and tof sensors respectively with their hits appearing as yellow and red dots. Red lines denote tracks.

The basic algorithm

The CA track finder is a combinatorial algorithm based on the Cellular Automaton. It builds short tracklets from the nearby hits and then combines the tracklets into long tracks.

We now explain the basic algorithm below with use of the sketch shown in Fig. 2.

1. As the first step, nearby hits are combined into tracklets. This step reduces most combinatorics, leaving only reasonable hit combinations for further processing.

The tracklet trajectories have five degrees of freedom (or four degrees without a magnetic field). At the

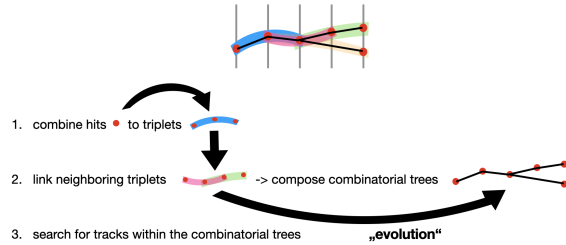


Figure 2: Cellular Automaton tracking scheme.

same time, they are measured with six measurements (that are three two-dimensional hits). Because of that, the tracklet fit is over-determined, and only reasonable tracklets survive the χ^2 -cut.

2. In the second step, those triplets that suit each other are linked. The links between the tracklets compose a combinatorial tree (see Figure 2).
3. In the third step, we search for tracks inside the tree of the linked triplets.

Tracking with the continuous readout

The CA track finder is adapted for the continuous readout of the CBM detectors. It can find tracks in large timeslices with no preparatory event building.

To process the timeslice, we divide its data into portions called time windows, which are processed one at a time. Inside the time window, the data is not sorted by time; all participating events are processed simultaneously as one large super-event. When constructing triplets and tracks, individual hit times are considered, so only hits close in time are combined into a track.

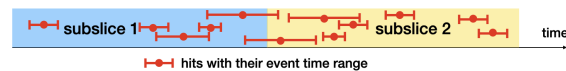


Figure 3: Split hits in time windows.

A special no-merging sliding window algorithm correctly reconstructs tracks on the border between windows. Therefore, the window width only affects the processing time, not the results. For now, the width is fixed to $1\mu s$. In the future, we want to determine it dynamically to distribute the data among the windows equally. The time-sliding window algorithm works as follows.

Each hit is assigned a time interval of a possible event to which it belongs. The interval is defined by the distance to the target and the time resolution of the hit.

As shown in Figure 3, hits may simultaneously belong to two or even more time windows. It requires special handling of the hits on the border between the windows.

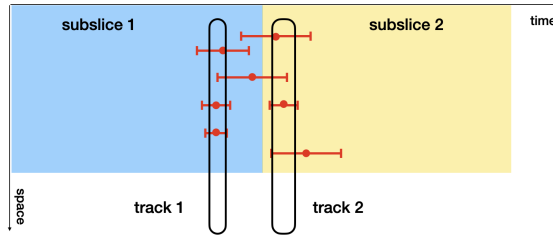


Figure 4: Tracking in time sub-slices.

To handle the shared hits, we do the following:

1. consider all not-yet-track-assigned hits that intersect the current time window;
2. find all the tracks in the current time window.
3. store only tracks with at least one hit not shared with the next time window. After storing the track, remove all its hits.
4. process the next time window, and so on.

The algorithm requires no changes in the tracking core and no special after-processing of the time window borders. It also correctly works in extreme cases when hits are shared between several time windows. This might be the case in the full-CBM setup with MVD hits with poor time resolution.

Tracking features in the mCBM

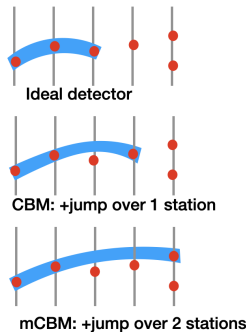


Figure 5: Dealing with the acceptance gaps.

When adopting the track finder for the mCBM setup, we faced several problems that could also occur in the full

CBM setup. The most important problem is the acceptance gaps.

Mini-CBM is a test setup aimed at testing the detectors; therefore, the acceptance coverage is poor. Detectors overlap only partially; besides that, there are dead or noise readout channels. In the upcoming 2024 setup, the acceptance coverage will be better, but we still need to account for the areas with a bad readout, which can also happen in the future in the full CBM.

When the CA tracker constructs triplets, it lets them miss one hit in one of the stations. For example, when creating triplets started at the tracking station 1, the following sets of stations are considered: $\{1, 2, 3\}$, $\{1, 2, 4\}$, and $\{1, 3, 4\}$.

In the mCBM, jumping over one station is not enough. Therefore, we let triplets skip over two stations (see Figure 5).

There have been many other modifications of the algorithm made for the mCBM setup:

- the algorithm can skip over two stations.
- hit error range is introduced. For non-gaussian error distributions, we consider the distribution shape instead of using the $\pm 3.5 \cdot \sigma$ range.
- MUCH detector was excluded from the tracking for the setups where it was placed apart from the other systems.
- we reduced the number of tracking iterations to one. It finds both the primary and the secondary tracks.
- we fixed several bugs that became visible on the mCBM setup.
- track quality criteria were adjusted. We also reconstruct short three-hit tracks.
- enlarged search windows to deal with misalignment/miscalibration.
- the tracking code was made ROOT-free and was ported to the online reconstruction library.
- we use ROOT-free tracking configuration.

Tracking in online reconstruction chain

Since the second data challenge, the CA tracking participates in the online reconstruction chain [1]. In this regime, the algorithm initialization relies on the binary parameter configuration file, which has to be generated in advance using the offline reconstruction program for a particular detector geometry. The parameter file contains the geometry information, including the arrangement of active tracking stations, material budget maps, nominal target position, and the magnetic field approximation, as well as the track finder configuration, misalignment corrections, and development flags. All these parameters, except the geometry information, can be additionally modified using the YAML-configuration files.

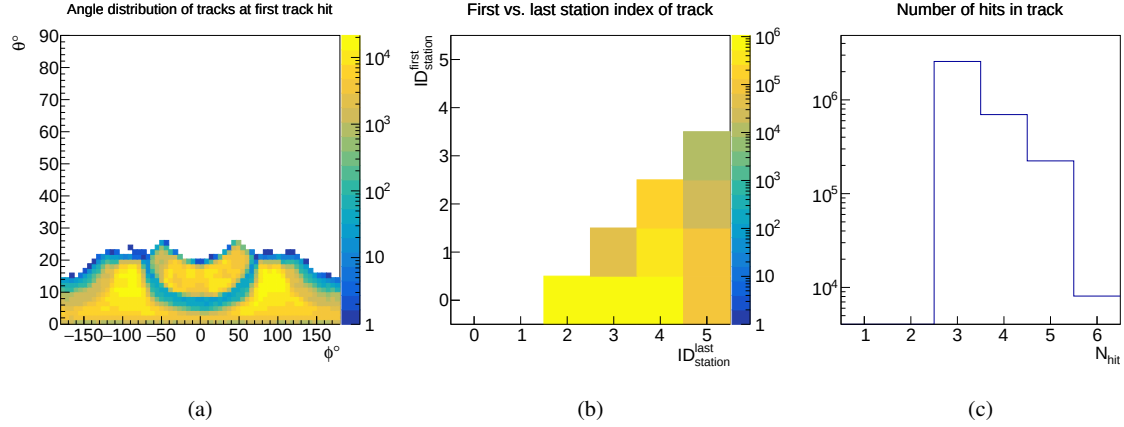


Figure 6: Distributions of different reconstructed track properties: (a) first vs. last station of track, (b) number of hits in a track, (c) angle distributions of tracks at first track station.

The online tracking chain was tested with the TSA files generated during the 2391 (Ni+Ni collisions at $T_{\text{beam}} = 1.93$ AGeV) and 2488 (Au+Au collisions at $T_{\text{beam}} = 1.23$ AGeV) SIS18 runs with the mCBM setup. The tracking chain uses the same geometry configuration for both tests, including two STS and four TOF active tracking stations (see Table 1). To account for the detector misalignment, a common tolerance of 0.2 cm for x and y coordinate measurements and of 100 ns for time measurements is applied to the input hit sample. Since the hit multiplicity in the mCBM Ni+Ni collisions is not large, it was decided to run the track-finding routine with only one iteration, which was initially tuned for efficient secondary track searching and has loose cuts.

Station ID	Detector	z_{ref} [cm]
0	STS	33.25
1	STS	46.75
2	TOF	233.169
3	TOF	249.967
4	TOF	266.346
5	TOF	289.29

Table 1: Tracking station configuration used in recent data challenges.

A monitor and a QA module were implemented for the online tracking chain. The monitor represents a collection of timers and counters and provides the main algorithm metrics. The QA module utilizes the online data QA framework reported elsewhere in [2], accumulating different reference histograms for the input hit and the output track samples.

Figure 6a shows reconstructed track polar and azimuthal angles distributions. The acceptance of the track reconstruction covers the full azimuth and $\theta < 25^\circ$. The track distributions in the first and the last station indices of reconstructed tracks and in the number of hits are presented

in Figures 6b and 6c. Most tracks start on the first STS station and consist of three hits. All of the tracks have at least one hit in TOF. Around 0.2% of reconstructed tracks have a hit on each tracking station.

Multi-threaded execution of the tracking algorithm

In the time-based tracking regime, the input hit sample is delivered from the entire timeslice. To improve the memory and time performance of tracking, the hit sample is split between time windows of a fixed duration. The time windows are ordered by time and can be processed independently from one another, allowing the track-finding routine to be parallelized over CPU threads.

The parallelization is performed using the C++ standard thread library. It simultaneously processes hits with different time measurements. The data is divided into sub-timeslices such that all threads process a similar number of hits. A border between two neighboring sub-timeslices coincides with the border between the last time window in the first sub-timeslice and the first time window in the second one.

The output data, including the reconstructed tracks, used hit indices, and a monitor data container, are stored in the intermediate data structures within each thread and then are sequentially updated to the final tracking algorithm output. It ensures that in the multi-threaded algorithm execution regime, the resulting track sample is highly sorted by time. However, a small number of tracks from the thread overlapping regions are expected to be unsorted.

To measure the boost of the tracking algorithm, the online data reconstruction was executed with the different number of threads on a Virgo node provided by the IT Department at the GSI. The selected node consists of 256 AMD EPYC 64-core processors. The input TSA file contains 56 timeslices and was recorded during Run 2391 of SIS18 with the mCBM setup.

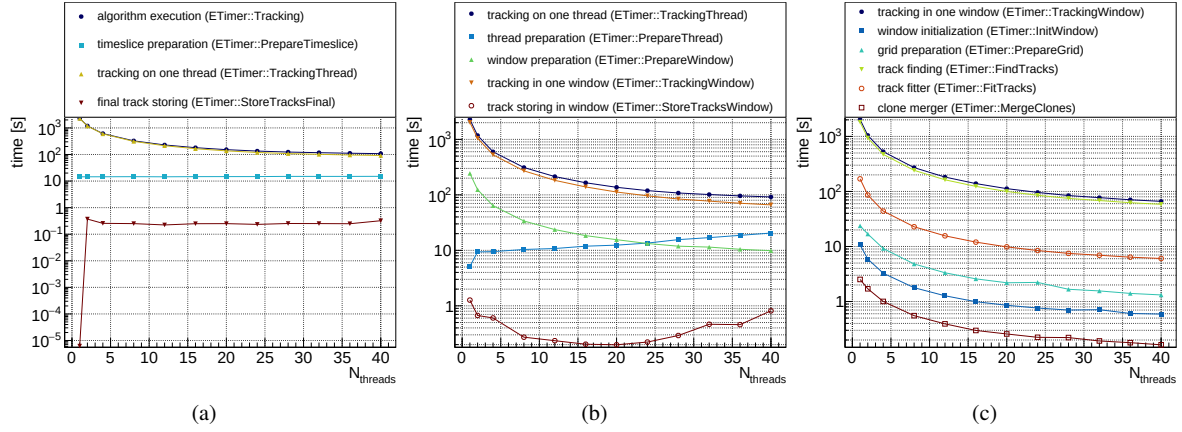


Figure 7: Time of different CA tracking steps execution vs. number of threads: (a) tracking algorithm execution scope, (b) one thread execution scope, (c) time window execution scope.

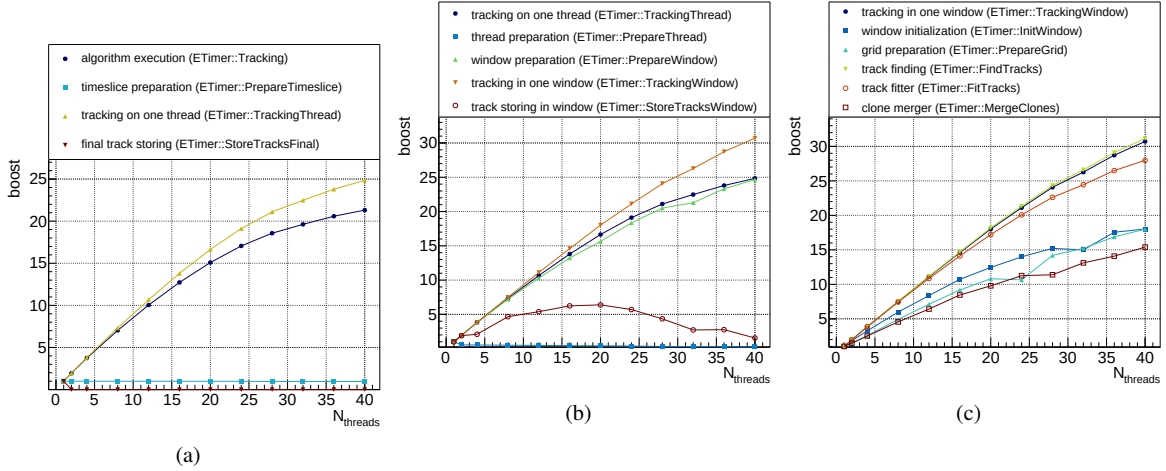


Figure 8: Boost of different CA tracking steps execution vs. number of threads in comparison with the one-thread run: (a) tracking algorithm execution scope, (b) one thread execution scope, (c) time window execution scope.

Figure 8 shows the boost of each tracking step relative to a single-threaded running mode. The one-window tracking and the full tracking algorithm execution boost linearly as $0.9N_{\text{threads}}$ and $0.75N_{\text{threads}}$ respectively, however at $N_{\text{threads}} > 20$ the boost slows down. The spread of the number of tracks does not exceed 0.1% and is caused by re-using some hits shared between two neighboring time windows processed by different threads. In the future, this discrepancy at the thread borders will be fixed by using the same no-merging algorithm that is currently used for the time window borders within one thread.

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Metric learning based triplets in the CA track finder

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Charged particle reconstruction (tracking) takes up, by far, the most computing resources in the CBM experiment. The 4D Cellular Automaton (CA) track finder algorithm has been shown to achieve high speed and efficiency for tracking in the Silicon Tracking System (STS) [1]. Inspired by the recent successes of neural networks for diverse problems, we are developing a new neural network based algorithm for tracking in the STS. This note briefly discusses our progress.

The CA track finder algorithm can be divided into two parts. Firstly, short track segments of three hits on adjacent STS stations, called triplets, are created. A Kalman Filter (KF) is used in fitting the triplets. Since most particles originate from the primary vertex (PV), the initial direction of the track is set by connecting the first hit of the triplet with the PV. Using the magnetic field, the particle trajectory is extrapolated to the next station to create a region of interest. Hits from the region of interest are connected to the first hit to create doublets. Track parameters are updated for each of the doublets. Further extrapolation to the next station adds the third hit to create a triplet. Close to 90% of the time for reconstruction is spent in this triplet finding stage. In the second part of CA track finder, the triplets are treated as cells and the cellular automaton is used to collect the longest and best fitting tracks.

Since the KF approach uses the PV for finding triplets, it is not suited to find secondary particles. This can be clearly seen in the track reconstruction efficiencies where primary high- p particles have a 97% efficiency whereas secondary low- p particles have only a 66% efficiency [1]. We propose a new neural network based approach, called metric learning, which overcomes this limitations and finds a complementary way to find triplets.

In the metric learning approach, a Multi-Layer Perceptron (MLP) is trained to learn a new coordinate system (embedding space) where hits belonging to the same particle are closer together but hits from different particles are farther apart when measured by Euclidean distance. After the embedding, every hit is connected to a certain number of its Euclidean distance nearest neighbours on the next station to form doublets. These doublets are then extrapolated to the next station using the KF to create triplets. Finally these triplets are passed to the CA algorithm to find tracks exactly as in the original CA track finder.

The MLP is trained using the following hinge loss,

where the true/fake summation is over pairs of hits (on adjacent stations) from the same/different particle, d^2 is the square of the Euclidean distance in the embedding space and λ is a hyper-parameter called margin. During training the total loss is minimized using gradient descent. $\mathcal{L}_{true}$ ‘pulls’ hits from the same particle closer while $\mathcal{L}_{fake}$ ‘pushes’ hits from different particles away to outside the margin.

This metric learning approach to triplet finding was implemented in the stand-alone CA track finder in event mode. Fig. 1 shows the event display for one event with 32 tracks. The metric learning approach finds all the tracks with 92% of the hits in the tracks being matched correctly on average. The CA track finder finds in this event only 30 tracks. The ghost and clone rates are similar for both approaches. The pulls distribution for all track parameters are unbiased.

The metric learning based triplet finder is modular and can be easily integrated into the CA track finder as a new iteration. The MLP used is written entirely in C++ and is completely independent of external libraries like PyTorch [2]. We aim to replace the secondary track iterations of the CA track finder with our new approach. We also plan to investigate neural networks that will allow us to directly find triplets instead of first finding a doublet and extrapolating it with the KF. The KF fit then need only be performed once.

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$$\mathcal{L} = \frac{1}{n_{true}} \sum_{true} d_{true}^2 + \frac{1}{n_{fake}} \sum_{fake} \max(\lambda - d_{fake}^2, 0)$$

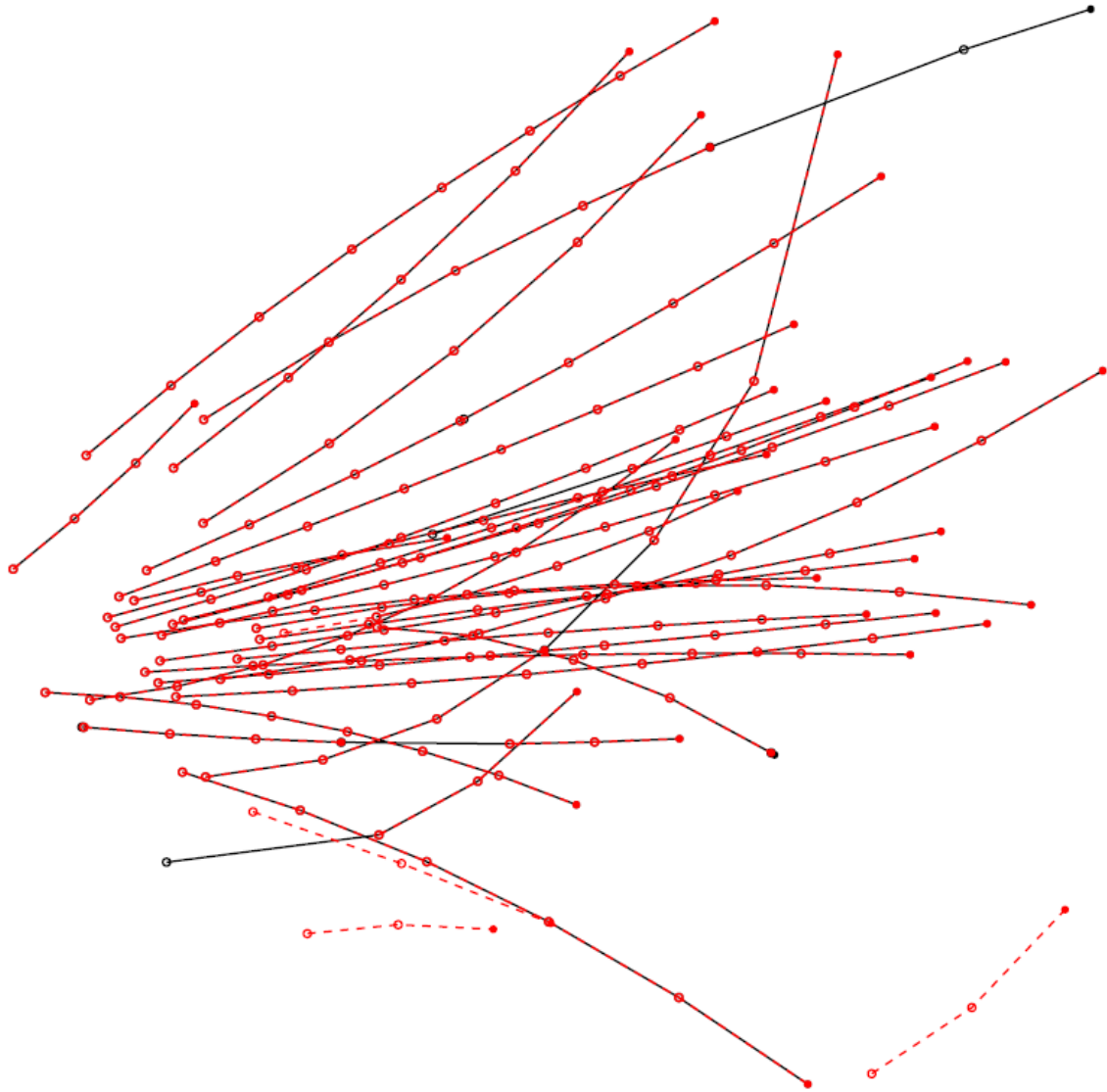


Figure 1: Red and black curves are reconstructed and MC tracks, respectively. A reconstructed track with $\geq 70\%$ hits coming from an MC track is said to be matched with it. Red dashed lines are ghost tracks without a black counterpart.

A brute-force minimization approach for detector alignment

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Introduction

For heavy-ion experiments at high interaction rates like CBM, precise detector alignment is essential. The purpose of track-based software alignment is to automatically determine the alignment parameters $\vec{p}$ which are usually small corrections in position of individual components by way of translation vectors and rotation matrices. These parameters may be calculated using χ^2 minimization [1]. One of the major challenges in the minimization process is to avoid so-called weak modes. Weak modes describe parameter changes that are not reflected in the weight function and can lead to incorrect results. To suppress this effect, suitable constraints must be found and defined within the minimization strategy. One of the generic software packages available for alignment is Millepede-II, which was developed at the University of Hamburg and is maintained at DESY [2]. Initial attempts to use Millepede-II in the context of CBM were made in the past, see Ref. [3]. The software analytically determines the global minimum, which requires the provision of all partial derivatives of the function with respect to the alignment parameters. This and the limited range of applicable constraints motivated the design of an additional alternative alignment strategy, based on brute-force χ^2 minimization.

Concept

Minimization

The brute-force alignment approach follows a trial-and-error strategy. As a requirement, the χ^2 must be defined as a function of the alignment parameters $\vec{p}$, and a validity interval in the parameter space must be provided. The minimization procedure iterates over the parameters, applies minimal changes within the respective validity range and evaluates the weight function at every step. The changes in $\vec{p}$ are kept if they result in an improvement of the χ^2 value but otherwise discarded (cp. Fig.1). This leads to convergence towards the minimum along the χ^2 gradient. As evaluation of the weight function is computationally intensive, it is calculated in parallel. Furthermore, a reduction in the number of necessary iterations is desirable. In order to achieve this, the gradual brute-force procedure was supplemented by further optimization methods that can be applied iteratively to individual parameters or parameter groups: 1-dimensional quadratic approximation, gradient descent and the conjugate gradient method. These extensions allow the convergence to be accelerated in the first phase of the minimization process.

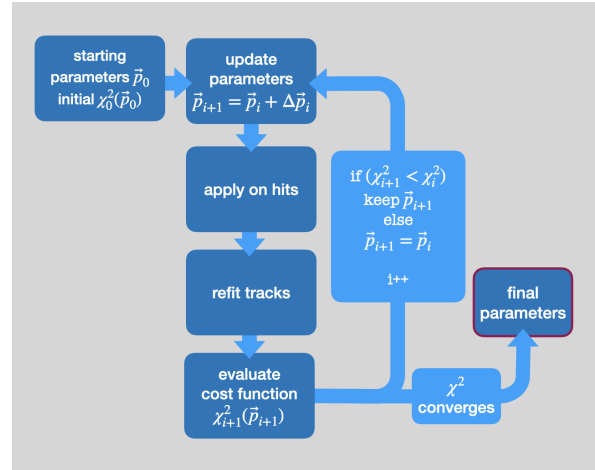


Figure 1: The brute-force Alignment Procedure

Constraints

As mentioned above, constraints are of great importance for the alignment, as they limit the multidimensional minimum of the χ^2 function and thus make the required accuracy possible in the first place.

It is always possible to formulate constraints as part of the weight function with a corresponding penalty factor. This has the disadvantage that a corresponding weighting is sometimes difficult to define. In addition to this approach, there are two other obvious ways of integrating constraints within the iterative brute-force minimization:

- only allow $\vec{p}$ that are in agreement with all constraints
- allow $\vec{p}$ that violate constraints but apply a "repair function" in order to recover the constraints at particular iteration steps

Two constraints were implemented as a proof-of-concept prototypes using these approaches:

- **Adding a distance measurement to the alignment procedure.** The distance from a specific point on an alignable detector element with known local coordinates to a given reference point can be included into the iterative alignment process. The local coordinates are locked with the global measurement and only parameters $\vec{p}_i$ that correspond to this locking within the respective measurement error are permitted in the trial-and-error minimization. This is a highly desirable functionality, as distance measurements are

comparatively easy to perform and the flexible inclusion of such measurable variables in purely analytical alignment approaches is not readily possible.

- **Demanding that the sum of the translations of all detector components in one dimension equals zero.** This is a simple linear equality constraint that prevents large simultaneous shifts of all detector elements. In the brute-force process, after each completed iteration cycle, all corresponding parameters are jointly corrected so that they have an overall minimum distance to the corresponding axis. Such constraints can also be introduced relatively easily in other approaches such as Millepede-II.

Integration into CbmRoot

The described functionalities have been successfully tested on a very basic and restricted 3D toy detector test scenario, which ignores most non-linear effects such as magnetic field or multiple scattering.

In the context of the CbmRoot software framework, a prototype implementation of the outlined brute-force method is available as an external library¹. For initial tests a highly simplified scenario was used on simulation data for the Silicon Tracking System: From 100 UrQMD events (Au-Au, central collisions at 10 GeV), up to 5000 tracks were selected. The selection criteria where: Hits in all STS stations and a minimum momentum of 1 GeV. A virtual misalignment of up to 1 cm (shifts only) was then introduced to six of the eight STS stations on hit basis (the first and the last station where fixed). In each iteration $\vec{p}$ was applied as correction terms to the individual hit coordinates. For χ^2 evaluation the tracks were refitted and the track- χ^2 was summed over the entire track sample.

In this setting, the brute-force minimization was able to determine x- and y- displacements of the STS stations with an accuracy in the order of 4-5 μm and displacements on the z-axis with an accuracy of approximately 20 μm in first test runs. However, more detailed systematic testing is still pending.

Outlook

The most obvious next step towards the necessary fine-tuning of the individual detector sensors and more robust test scenarios is to integrate a root geometry management into the alignment procedure. This will allow the expansion of brute-force prototype library with the functionalities that have been tested for the toy detector, such as additional optimization methods or generic ways of setting measurement constraints. Furthermore, an iterative, hierarchical organization of the alignment process is necessary so that a realistic alignment of not only the active but also the passive detector elements can be achieved.

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¹<https://git.cbm.gsi.de/se.gorbunov/bba>

Neural-Network-based competition for short-lived particle candidates

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The Kalman Filter (KF) Particle Finder [1] contains a wide range of algorithms for particle and decay reconstruction. During reconstruction of short-lived particles, the KF Particle Finder identifies and creates all potential mother particle candidates. While this approach ensures that none of the possibly existing particles are rejected, it also leads to an increase in the reconstructed background. To decrease this produced background, KF Particle Finder offers an optional particle competition that allows to let pairs of particles compete against each other based on their mass-distance to their PDG mass, rejecting the losing candidate and, therefore, remove the likely false mother particle candidate from the list of reconstructed particles.

Previous work [2] has already shown that a neural network is capable of solving the competition-problem by classifying the particles based on their properties. This approach was tested for the particle decays

$$K_S^0 \rightarrow \pi^+ \pi^- \text{ and} \quad (1)$$

$$\Lambda \rightarrow p \pi^-. \quad (2)$$

We have implemented a more complex model into the KF Particle Finder to solve the competition for these particle decays, using the Artificial Neural Network for First Level Event Selection (ANN4FLES) [3] package.

Input features	Reconstructed mass and PDG mass of each candidate
Hidden layers	3 layers with 8 neurons each, LeakyReLU activation
Output features	2, for K_S^0 and Λ classification, with Softmax activation
Loss	Categorical cross-entropy
Optimizer	Adam [4]

Table 1: Hyperparameters of the model used for particle classification of K_S^0 and Λ .

The raw classification performance of the neural network shows an accuracy of almost 99% on the test set for Au+Au central collisions at 10 AGeV, generated with the UrQMD model [5]. The training and testing was based on 12,000 events (80:20 ratio split), whereas for the final evaluation in the KF Particle Finder 13,000 other events were used. Integrated into the KF Particle Finder, the neural-network-based results were comparable to the existing competition but exhibited slight improvements in reducing combinatorial background (see Fig. 1) while retaining nearly all meaningful signal (for details, please refer to [6]).

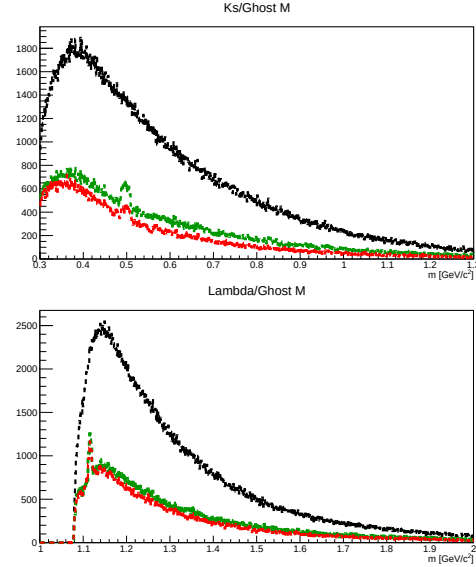


Figure 1: Histogram for reconstructed ghosts for K_S^0 (top) and Λ (bottom). Black: no competition, green: default competition, red: neural-network-based competition.

Rejecting this combinatorial background is crucial as it lacks physical significance and its removal enhances the quality of physics analysis.

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ANN-based approach for optimization of Λ signal to background ratio in CBM

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The Kalman Filter (KF) Particle Finder [1] serves to identify and reconstruct short-lived particles. Throughout the reconstruction phase, upon detecting a decay, it generates all conceivable mother particle candidates. This approach ensures that potential signals from particles are not mistakenly dismissed due to incorrect particle hypotheses. This generates background, which significantly impedes physical analyses, especially in the context of combinatorial background. To improve the signal/background ratio, and thus, to reject the background produced by falsely reconstructed particles, without rejecting too many signal particles, we implemented a neural-network-based approach which classifies the Λ particles into signal or background [2].

The default approach of the KF Particle Finder uses hard-coded statistical cuts for the reconstruction of short-lived particles. Our approach uses a Multi-Layer Perceptron (MLP), created with the Artificial Neural Network (ANN) for First Level Event Selection (ANN4FLES) [3] package. This MLP is used after the Λ particles have been reconstructed. For this, the hard-coded cuts have to be loosened, to give the MLP enough space for reconstructing Λ particles that would not have been reconstructed using the default cuts. Therefore, we changed χ^2_{prim} from $\chi^2_{prim} > 18.42$ to $\chi^2_{prim} > 4.605$, χ^2_{geo} from $\chi^2_{geo} < 3$ to $\chi^2_{geo} < 6$ and $l/\Delta l$ from $l/\Delta l > 3$ to $l/\Delta l > 2$.

Input features	Mass m , transverse momentum p_T , χ^2_{geo} , χ^2_{prim} , χ^2_{topo} and $l/\Delta l$ of the reconstructed Λ p_T and χ^2_{prim} of the positive and negative daughter particles
Hidden layers	4 layers with 64 neurons each, LeakyReLU activation
Output features	2, Signal and Background with Softmax activation
Loss	Cross-entropy
Optimizer	Adam [4]

Table 1: Hyperparameters of the model used for Signal-Background classification of Λ .

The MLP (see Table 1) achieves an accuracy of almost 99% on the validation set. We utilized a dataset comprising 787,000 Λ particles from simulated events (UrQMD, Au+Au, 10 AGeV, central collisions) for training and validation. The dataset was balanced to ensure a 50% representation of both signal and background particles, with

a split of 80:20 for training and validation respectively. For the final evaluation of the MLP approach in the KF Particle Finder package, we used 46,000 new events and compared the MLP approach with the default approach on the same data. In the mass range of 1.06 GeV/c² to 1.2 GeV/c², our approach rejects a factor of 24.6 more background than the default approach, in particular the combinatorial background (ghosts) was reduced by a high factor of 34.33. Therefore, our approach generates 95.94% less total background than the default approach, while it reconstructs a negligible factor of 1.36% less true Λ particles in the mass range from 1.1 GeV/c² to 1.135 GeV/c² than the default approach.

	S/B Ratio	Significance
Default	3.49	11.38
ANN4FLES	38.28	12.95
Improvement factor	10.97	1.14

Table 2: Summary of the results of signal/background ratio and significance, including the factor of improvement.

For calculating the signal/background ratio and significance, the total amount of reconstructed Λ particles in the mass range of 1.06 GeV/c² to 1.2 GeV/c² is fitted by the sum of a Gaussian function (signal) and a 2nd order polynomial (background). Afterwards, the signal is calculated by the integral in the range of $\pm 3\sigma$ of the Gaussian fit that represents the signal, whereas the background is calculated using the integral of the 2nd order polynomial in the range of $\pm 6\sigma$ around the mean of 1.115 GeV/c². The final results can be seen in Table 2.

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Particle identification for dielectron analysis in CBM using machine learning

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Introduction

Because of the high abundance of hadrons in heavy-ion collisions, excellent particle identification (PID) is essential for di-electron analysis to effectively reduce the combinatorial background from non-electron tracks. For this reason, the CBM detector contains two subsystems which are mainly dedicated to the identification of electrons, namely the Ring Imaging Cherenkov (RICH) detector and the Transition Radiation Detector (TRD). Additionally, information from other subsystems such as the Silicon Tracking System (STS) or the Time-of-Flight System (TOF) is used in order to further enhance the identification capabilities of CBM. Conventionally, the electron identification is achieved by implementing several subsequent box cuts, each using information from only one subsystem at a time. Conversely, when using machine learning (ML) techniques, classifiers can be trained which can utilize the data from all subsystems simultaneously. In the course of his master thesis, Henrik Schiller created a framework to generate and test such ML classifiers for PID in CBM [1]. The result was a successful proof of principle, which now was expanded and tested with a larger data set directly in cbmroot.

Used ML Classifier

The used classifier was based on boosted decision trees implemented with the *eXtreme Gradient Boosting* (XGBoost) library¹. In total, 21 track parameters were chosen as input variables:

- p, ϕ, θ : Momentum, radial and azimuth angle of track
- 8 RICH ring parameters: Distance to track, length of axes, etc. For a list of all parameters see Ref. [1].
- E_1, E_2, E_3, E_4 , Nr. of TRDHits: Energy loss in different TRD layers, number of layers hit
- $\Delta\beta_{\text{Electron}}$: Difference between β measured by TOF and β for an electron
- Nr. of MVDHits, Nr. of STSHits, E_{STS} : Number of layers hit in both tracking stations, energy loss in STS

From these input parameters, the classifier outputs a number between 0 (not an electron) and 1 (electron) on the basis of which a PID cut can be implemented. The hyperparameters were optimized in order to maximize the area

under the receiver operating characteristic (ROC) curve using bayesian optimization.

Results

The trained classifier was ported into cbmroot, and its performance in di-electron analysis was evaluated using two million Au+Au collisions simulated using UrQMD with additional e^+e^- originating from decays simulated by PLUTO. After various base cuts on track quality, a PID cut on basis of the classifier output was implemented. This was compared with the conventional method of using three subsequent cuts on RICH, TRD and TOF information respectively and the efficiency of the ML cut was chosen to match the efficiency of the conventional cut for the electrons embedded with PLUTO. A comparison of the amount of tracks per event for different particle species is shown in Fig. 1.

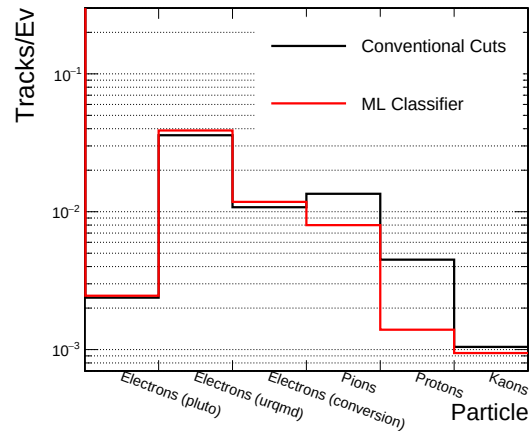


Figure 1: Amount of tracks per event of different particle species.

We find the ML approach to significantly improve the hadron rejection. The additional suppression relative the one obtained with the conventional, cut-based method is 41% for pions, 69% for protons and 10% for kaons at a similar electron efficiency.

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¹<https://github.com/dmlc/xgboost>

A review of changes to technical and simulation subsystem geometries

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It has been two years since the authors last wrote a joint report on the status of the engineering and the simulation geometries for subsystems of the future CBM experiment [1]. Much has happened in that time, with definite setbacks when viewed on a monthly or even semi-annual basis, however on the longer time-frame of two years, we are pleased to report clear, definite, and impressive progress to the realisation of our experiment. It is now well established that CBM is in the “First Science plus” priority list for FAIR, with our home called the “CBM cave” built and ready to be populated with auxiliary wiring and equipment, which will place us on a determinable track for first beam in late 2028. The authors are hopeful that with a lot of work by our detector and subsystem working groups, that all subsystems can be properly represented from day one of the experiment. As before, simulation geometries are available in the online repository¹ and more recently, in order to better share geometries within the collaboration, CAD files for CBM subsystems in STEP format may be accessed from a similarly styled repository². In this report, we document some of the progress and changes that has occurred over the last two years.

Noteworthy Updates

The major event that led to serious negative technical, scientific, financial and personal impact on the CBM experiment and CBM collaboration was the Russian war on the Ukraine and measures taken by Western governments as a consequence. There were many losses to the collaboration in terms of personnel and institutional members from Russia and a serious destruction and needless complications for Ukrainian people and colleagues. The impact was so consequential that the next six subsections are dominated by having to address the significant issues directly related to this event which needed to be overcome before more routine development could resume.

PSD

At the time of our last report, the PSD looked to be progressing nicely towards day one with the executive summary [2] stating “The PSD project is ready for the Production Readiness Review”. However, the PSD subsystem was managed, maintained and developed by our former Russian colleagues and therefore, their efforts are, for all intensive purposes, unobtainable. Consequently, there were

¹https://git.cbm.gsi.de/CbmSoft/cbmroot_geometry

²https://git.cbm.gsi.de/p.dahm/cad_step

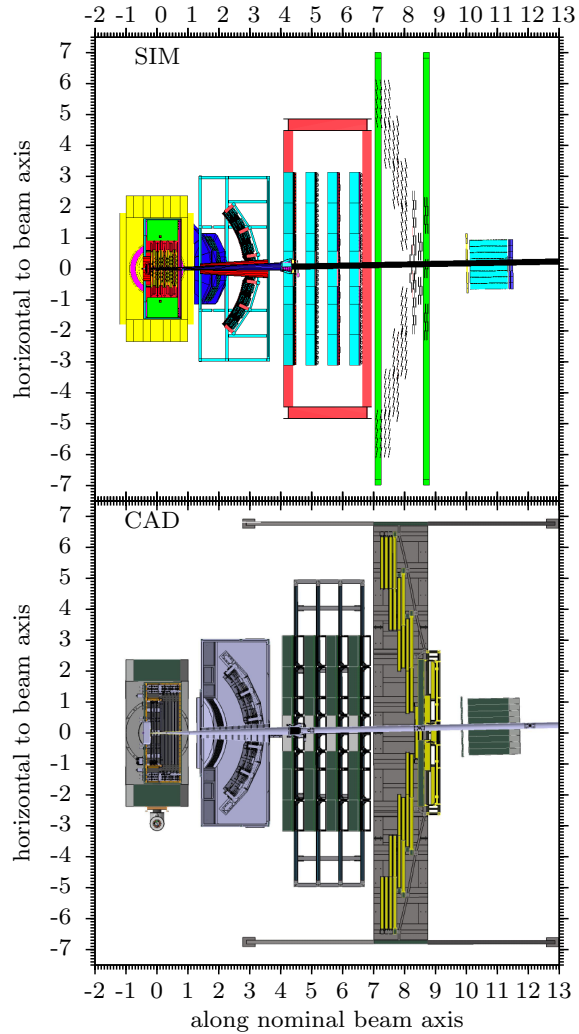


Figure 1: The CBM experiment in its electron setup configuration for 10 AGeV fully-stripped gold ion beam. Birds’ eye view with platform and material above the horizontal beam plane being removed.

no further updates added to CAD files, but the simulation geometry was maintained by the first author, to fix bugs and to provide desired functionality to physics working groups (PWG). One aspect of the PSD which will survive and remain in CBM is its manipulator frame, which was already built and is waiting in storage at GSI. This will likely be mounted to provide support for, among others, the downstream beampipe. Absence of the PSD without redress,

would lead to the CBM experiment having no designated detector for determination of the event plane of collisions.

FSD

With the realisation that the PSD would not be available, a new way to determine the event plane of collisions was investigated and a proposal from our Czech colleagues for a “Forward Spectator Detector” [3], to be placed in the former position of the PSD subsystem, and which could utilise the PSD manipulator frame, was suggested. Performance studies and radiation flux investigation were conducted and reported on at the last collaboration meeting in Bucharest Romania. Although huge strides were completed during the last two years, several efforts including granularity studies as well as completion of a first CAD model are ongoing. The FSD is fully integrated into the `cbmroot` environment with GEANT geometries tested and available in our geometry repository¹, however currently there is only a mockup representing the proposal in CAD. This mockup was created by the second author by simply shortening the models of the PSD modules and placing them in the appropriate positions in the manipulator frame, whilst the first author converted the existing simulation geometry which focused on the sensitive parts of the FSD directly into a CAD STEP format. An actual CAD geometry is to be delivered by the FSD group shortly.

Magnet

At our last report, the simulation and CAD geometry for the magnet were definitely finalised with even a photograph in Ref. [4] of the already manufactured and blue-painted yoke as it appeared in its factory in St. Petersburg, Russia. Unfortunately due to the aforementioned geopolitical events of 2022 and 2023, receipt of this magnet was deemed extremely unlikely. A full new tender for a new magnet was required. In light of these changes, a slight redesign was requested by the STS group (see below) which enlarged the aperture of the magnet by 30 mm in height and 300 mm in width (cp. Ref. [5]). A simulation geometry for the magnet with wider aperture was created by modification of the existing magnet geometry by the first author to allow the simulation validation of the STS design to continue. At the time of writing this progress report, the contract for the redesign and manufacture of the magnet yoke and cryo system has been awarded to the company Bilfinger Noell (BNG) from Würzburg, Germany. Requested changes to the previous design requirements have been discussed with detector groups and BNG with a Preliminary Design Report being planned for publication for the end of March 2024. The model that is currently used in the CAD setups is still a mockup using the adjuster stand, poles and cryostat from the previous design integrated into the preliminary design of the yoke with new dimensions. It was also created by the second author and will be replaced as soon as actual CAD models are available from BNG.

B-field With the changes in dimension of the opening and yoke, new magnetic field maps were required to be calculated to more accurately model the transport of charged particles and ions through the CBM cave and the detector subsystems. This is outlined in Ref. [6] which validated the change in the field compared to the previous magnet design. Unlike previously, when the magnet yoke was considered in isolation to other subsystems, the new magnetic field maps made a distinction between the magnet with field clamps “field.v22a”, the magnet without field clamps “field.v22b”, and the magnet with field clamps and the rich shielding box “field.v22c”. This has given greater contrast between the standard experimental setups with an especially more precise fringe field calculation. A study on ring detection in the RICH detector in the new magnetic field is contained in Ref. [7].

STS

A report on the effect of the Russian war on the Ukraine on the progress of the STS subsystem is contained in Ref. [8]. The STS concept went through a major re-envisioning going from the previous STS-8, meaning a STS with 8 stations, to the so-called STS-3+5, meaning an effective splitting of the STS detector into two separate subsystems, a 3-station STS to be placed upstream of a 5-station STS, see Ref. [9]. The primary espoused benefit is to allow upgradability of the STS detector with the possibility of swapping out the STS-3 for another detector subsystem after a few years of operation. The additional space requirement requires 4 cm more between the third and fourth station, i.e. between STS-3 and STS-5, as compared to the STS-8 design. Ref. [9] documents the development of the simulation geometries, “sts.v22c” implements the paradigm change and is comparable to the previous STS-8 (“sts.v21e”), while later the “sts.v22d” realises a more realistic material budget, in particular by adding considerable material due to wiring and cabling in the outskirts of the STS enclosure. The complete set of CAD files is also available in the SAP system at GSI and has been integrated into the published setups as of January 2024. An overview of the mechanical redesign can already be found in Ref. [10]

RICH

Early in 2022, the GEANT geometry for the RICH detector was rewritten in compiled code in `cbmroot`³ [11], which is a moving away from the traditional creation macro approach of other detector subsystems. This has both positive and negative consequences. There are definite drawbacks from adding complexity in the verification and validation standpoint, a somewhat unnecessary difference from the modus operandi from other detector subsystem, and a change in paradigm for versioning control. However, it may benefit from having code standards applied directly to the code base, and may allow direct compilation of detector geometries at startup of simulation, which was

expressed as a desired feature by some developers prior to this change being implemented. This seems unlikely to ever happen though. The produced version “rich.v22a” did not converge towards the CAD of the RICH, and very substantial differences persisted and increased between the GEANT and CAD geometries during this time.

During 2022, changes in other detector subsystems revealed issues with this v22a geometry. Namely, the beam pipe tunnel was not correctly defined so as to allow the addition of the beampipe through its centre without overlaps, and it was shown that the RICH geometry had been a participant in a material mixing issue which affected most subsystems. There had been some quick internal fixes inside the RICH geometry by the creation of a “fake” volume which hacked a desired order of loading of materials which temporarily alleviated but also hid the issue. The “rich.v23a” geometry along with other commits in `cbmroot`³ fixed these issues. Simulations on the effect of the changed magnetic field on the RICH detector using this geometry is documented in Ref. [7].

A report on differences between the CAD and GEANT geometries was conducted by the two authors and communicated in May 2023 privately to the RICH team which resulted in a plethora of issues to be tracked via Redmine⁴. Towards the end of 2023, a new simulation geometry which addressed many of the differences and very significantly converged to the present CAD appeared. A new CAD geometry implementing many of the changes discussed was also delivered in February 2024. However much work still remains outstanding, whereby some proposed changes to the technical design, which were already reported in Ref. [12], will still need completing during the current year.

MUCH

Since the entire mechanics system was being designed and developed by our Russian colleagues, this responsibility had to be shifted to the group in India after the geopolitical events of 2022. The major ongoing effort here is to understand design decisions that were taken in the past and verify their validity for the current planning, as well as finishing the routing of pipes and cables. All this has to be mostly finished before the delivery of a new CAD geometry is sensible and work on the integration into the setups can start anew. All in all, this project will take considerable effort to be delivered on time.

The simulation geometries for the MUCH needed several small changes during the last two years, in particular, small movements and cuts to the 5th station were required to make sufficient breadth to allow support of the bellows [13] of the beam pipe in the J/ψ setups.

In the last few months, a substantial effort was made by the MUCH team to make a more realistic representation of

the fine scale structure in the first two of the four GEM stations in the LMVM muon simulation geometry. Unfortunately, although the simulation showed good convergence to the CAD, the internal nodal structure and the method of shape definition within the geometry led to an unjustifiable increase in the computational load and thus this geometry could not be recommended as default geometry. The geometry is available in our repository and may be specified in custom setups with caution when required.

TRD

Recently, two new GEANT geometries were added to the geometry repository.

The first one refers to a day-one TRD configuration, which is to model a reduced TRD geometry in terms of size and acceptance coverage, and was motivated by budgetary requirements within the TRD group. A geometry for each setup is available with the tag “trd.v23a” in the repository.

A simulation geometry with a tag number from 2018 which provided some functionality of the TRD-2D detector design was being adhocly shared within the collaboration which became a topic of conversation at the CBM collaboration in TU Darmstadt during March 2023. There was a real desire to get the functionality of the TRD2D as a standard geometry in our shared repository¹. Happily this was achieved after a lot of effort and Ref. [14] of this report records some of this work. In addition to the geometry binary itself, there were significant changes to the procedure of generation of the geometry with the 2D chambers being created as compiled code within `CBMROOT`³, whilst the older section which were in common with the TRD1D still being generated by a creation macro. This simulation geometry was given the “trd.v23b” tag. It was requested by the TRD team that neither of these significantly improved geometries should be made default in the standard setups of the upcoming software release.

The representation of the TRD in CAD remains unchanged for now, as the mainframe is in place and work on the routing of cables is heavily dependent on the finalisation of detector modules and layouts. The last update on the mechanical superstructure can be found in Ref. [15].

TOF

In the time since the last progress report on this subject, the CAD model of the TOF has been reworked considerably and several iterations of its geometries have been delivered. Most of the changes stem from the static load calculations and mockups done in Heidelberg and are described in Refs. [16, 17]. They mainly concern the design and stiffness of the mainframe and its attachment to the rails in the CBM Cave and thus are mostly irrelevant for simulations.

³<https://git.cbm.gsi.de/computing/cbmroot>

⁴<https://redmine.cbm.gsi.de/issues/2786>

Compatible Geometries

Default setups

During the intervening two years there have been two software releases. Along with each release we try to compile the geometries into setups where we provide additional validation and verification to recommend a geometry set for simulation of one of the main CBM experimental configurations. We have for the last number of years distributed compatible geometries for the electron setup (see Fig. ??, the hadron setup, the J/ψ muon setup and the LMVM (low mass vector mesons) muon setup. In an effort to communicate as clearly as possible, tables were provided with a list of compatible geometries for APR20 in Ref. [18] and for the DEC21 release in Ref. [1]. Table. 1 shows the default geometries recommended for the four setups distributed with the FEB23 software release. As we write this report, a new release candidate (probably called FEB24) is nearing final validation checks. Due to the likelihood of changes, we decided against listing these new geometries in order to avoid errors and future confusion and instead we will rely on a future progress report for their documentation. In the meantime, for readers seeking this information, please consult the software release directly.

SUB	Electron	Hadron	J/ψ	LMVM
MAG	v22a	v22a	v22b	v22b
PIPE	v21d:v21i	v21d:v21i	v21d:v21i	v21d:v21i
MVD	v20d_tr	-	-	-
STS	v22c	v22c	v22c	v22c
RICH	v22a	-	-	-
MUCH	-	-	v22a*jpsi	v21c*lmvm
TRD	v20b_1e	v20c_1h	v20c_1m	v20c_1m
TOF	v21a_1e	v21a_1h	v21a_1m	v21a_1m
PSD	v22a	-	-	-
PLAT	v22b	v13a	v22b	v22b
FIELD	v22c	v22a	v22b	v22b

Table 1: Compatible and validated geometries defined as default in the FEB23 software release for simulation of the electron, hadron, J/ψ and low mass vector meson (LMVM) experimental setups. The '*' abbreviates 'sis100_1m'.

Distributed alternatives

Some of the additional geometries distributed with the latest software release will be candidates for default in the subsequent releases, others have specific testing purposes for internal investigation within subsystem groups or wider CBM-wide proposed changes. As mentioned above, two TRD geometries are distributed in the simulation geometry repository which can be easily swapped instead of the default. It was the desire of the TRD team, not to make these geometries default at this time. The RICH team provided a new geometry which significantly converged towards their CAD, although it appeared late enough before the software release that it was not possible to fulfil our full verification steps to recommend it as a default

this time. The MUCH team provided a geometry for the LMVM setup well in advance of the release, which can be used by anyone wishing to have a more accurate material budget representation of the first 2 GEM stations. The MUCH geometry was downgraded back to the previous default because of an unjustified increase of computational load which was not explainable by the added complexity in the geometry.

This completes our discussion on changes to the technical and simulation geometries during 2022 and 2023.

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Implementation of realistic detector components of GEM modules for Muon Chambers (MuCh)

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Introduction

The Muon chambers (MuCh) for the Compressed Baryonic Experiment (CBM) [1] will consist of four stations in total, each with a distinct number of modules per layer and size of detector modules. In addition, different technologies are used for the first two stations (GEM) and last two stations (RPC). Lastly, each detector module in itself consists of many intricate parts.

Several major components have already been modelled using the GEANT package for the purpose of preliminary simulation studies. However, several other important components were missing in the existing geometry since the geometry files were still evolving. One has to encode information for all the components of the detectors in GEANT and make the material budget as close as possible to the realistic geometry. In this report, we discuss the different geometrical modifications made to the geometry file of the first two stations (see Fig. 1).

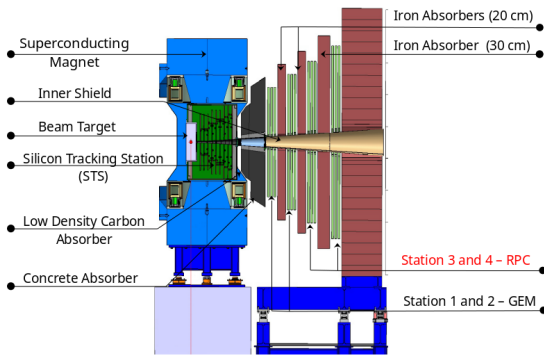


Figure 1: Side view CAD image of the CBM experiment in its dimuon setup with 2 GEM and 2 RPC stations and 5 absorbers.

Geometry Corrections

The following geometrical modifications have been implemented:

- **Active Area:** The active region, passive regions and foils of GEM modules are supposed to be like a sector. However, in previous versions the active area was

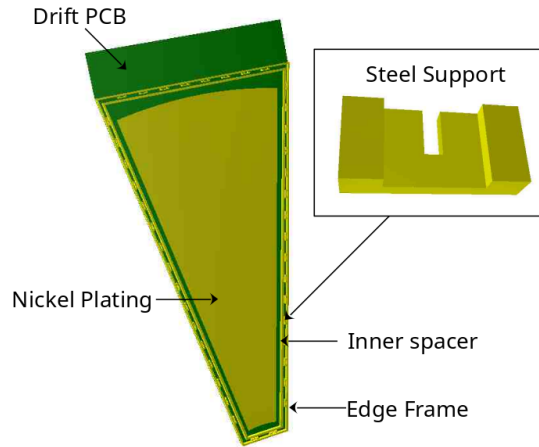


Figure 2: Image of Steel supports, inner spacers and outer spacers on Readout PCB rendered using GEANT

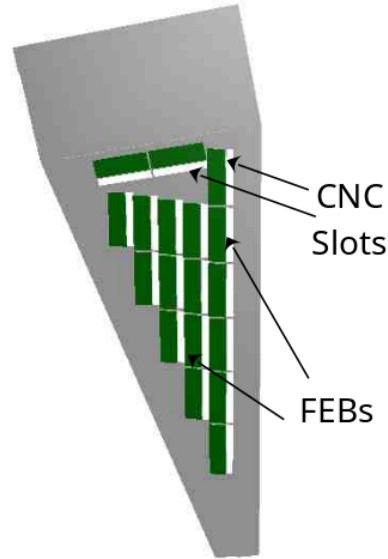


Figure 3: FEBS (green) beside CNC slots (white) in aluminium support/cooling plate

made in the shape of a trapezoid. The acceptance region has now been corrected in version v23a for shape and dimension while maintaining the 2π coverage (see

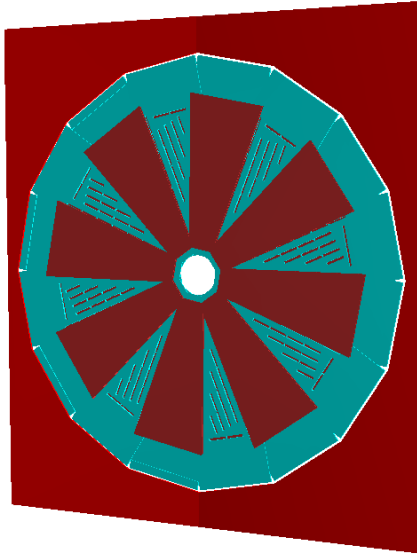


Figure 4: Module layer with support (Cyan) and C-plate (Red)

Fig. 5).

- Inner components of GEM Module: To hold the triple GEM foils in place multiple inner spacers are required. These spacers maintain a 3-2-2-2 mm gap between GEM Foils. Additionally, to tighten these foils, several steel supports are fixed on the PCB which are then screwed to the inner spacer (NS-2 technique). Finally an edge frame is used to make the whole assembly airtight. These three components with their respective material and approximate dimensions are added to the revised geometry (see fig. 2).
- Nickel Plating: Both the GEM readout and drift PCBs have a 5 micron nickel plating on top. This plating has also been included in the latest update.
- Aluminium support/cooling plate: To hold the GEM modules in place as well as to provide water cooling to the electronics, we have designed a trapezoidal aluminium plate with a thickness of 12 mm (see Fig. 5). This aluminium support plate also has dedicated slots for mounting the Front-end Electronics Boards (FEBs) directly onto the cooling surface. In addition, the FEBs also have 1 mm copper coating which couples to the aluminium surface for better thermal bonding. The plate also has a network of aluminium pipes inside, which carry cold water. The entire plate (barring the internal water pipes), CNC slots and FEBs are modelled in the updated geometry.
- C-Plate: Each aluminium cooling plate of the layers of station 1 and 2 are coupled to a 12 mm thick plate on the outer side referred to as C-Plate (see Fig. 4).

This C-Plate has been appropriately included in the geometry as well.

Dimensions of most of these components were taken from the engineering drawing. In addition, small components like steel support, inner spacers etc. were physically measured and subsequently implemented in GEANT. Appropriate precautions were taken to ensure that no overlaps exist between any two geometrical volumes.

Results

Station 1 and 2 of geometry (tag v23a) is now reasonably close to the planned CBM geometry. The geometry also resembles the engineering designs made using CATIA. In earlier versions the inner radius started from 20.5 cm but now it starts from 18.41 cm. The shape of acceptance region is now in accordance with the plan (see Fig 5) making it the geometry of choice for physics simulation. We have already observed an improved signal-to-background in dimuon simulation using this geometry.

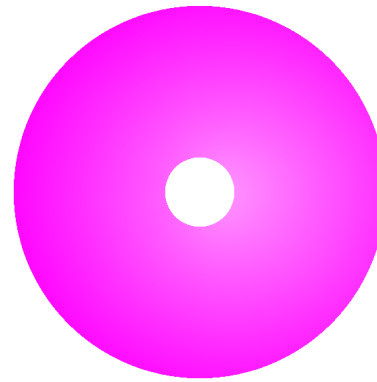


Figure 5: Corrected shape of active area with 2π coverage.

Further studies

With addition of new materials described above, a slowdown of $\sim 200\%$ was observed in CPU run time. Multiple boolean operations while performing physics calculations is chief reason behind this delay. We have already made a lightweight substitute of the geometry which has all the good features of this geometry while making it faster during simulation. As part of future plans, we wish to commit the lightweight geometry file to the cbmroot repository after thorough testing.

References

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Simulation comparison study of GEANT-3 and GEANT-4

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Introduction

The GEANT (Geometry and Tracking) software toolkit is widely used for detector physics simulation in High Energy Physics, Heavy-Ion Physics, Nuclear Physics, Medical Physics, and Space Science experiments. GEANT-4 is the successor of GEANT-3. GEANT-4 was redesigned for better physics simulation and improvement in performance. It includes improved physics and features for a complex geometry simulation [1]. In this report, we discuss the comparison of GEANT-3 and GEANT-4 for the Compressed Baryonic Matter (CBM) experiment setup.

Simulation Setup and Computation Time

We used CBM's SIS-100 electron setup with the default settings defined for GEANT in the CBM-ROOT framework. Table 1 describes the different detector geometries used during the simulation.

Simulation geometry	
Detector system	Geometry tag
MVD	v20d_tr
STS	v22d
RICH	v23a
TRD	v20b.1e
TOF	v21a.1e
PSD	v23a
Platform	v22b
Beam pipe	v21d:v21i
Magnet	v22a
Magnetic field map	field_v22c
Magnetic field	1 T

Table 1: Simulation geometry setup: SIS-100 electron.

For the simulation, the scenario we have studied used 12 AGeV/c Au-Au collision of minimum-bias UrQMD model-based events. Figure 1 shows that CPU time taken by GEANT-4 is 6.7 times that of GEANT-3. This could be related to the different hadronic model implementations being used to process the hadronic processes of particle interaction with matter in GEANT-4.

Results

Figure 2 shows the different particle species originating from the source. Since the source supplied to the GEANT versions is the same, their ratios are confirmed being unity.

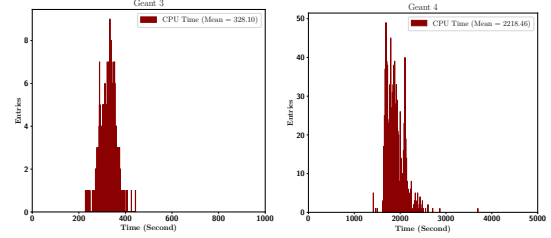


Figure 1: Computation time: GEANT-3 (l), GEANT-4 (r).

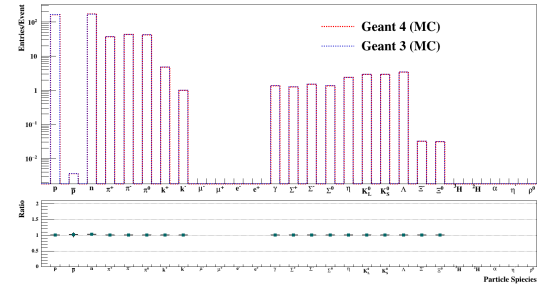


Figure 2: Primary tracks and their ratios; GEANT-3 and 4.

Figure 3 represents the different processes that happen while the transported events pass through matter. Some of the hadronic processes are not involved in GEANT-3 while some of the electromagnetic processes are not seen which could be due to the step limit and energy threshold setting default used in the CBM-ROOT framework.

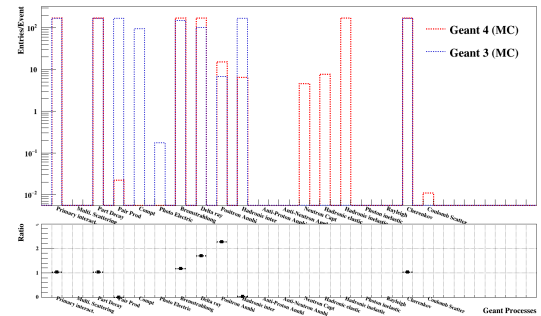


Figure 3: GEANT-3,4 physics processes and their ratios.

Figures 4 and 5 show the secondary particles produced. Neutral and back-scattered particles ($P_z < 0$) are neglected. An increase of secondary particles by 66% in GEANT-4 w.r.t. GEANT-3 can be inferred from the entries.

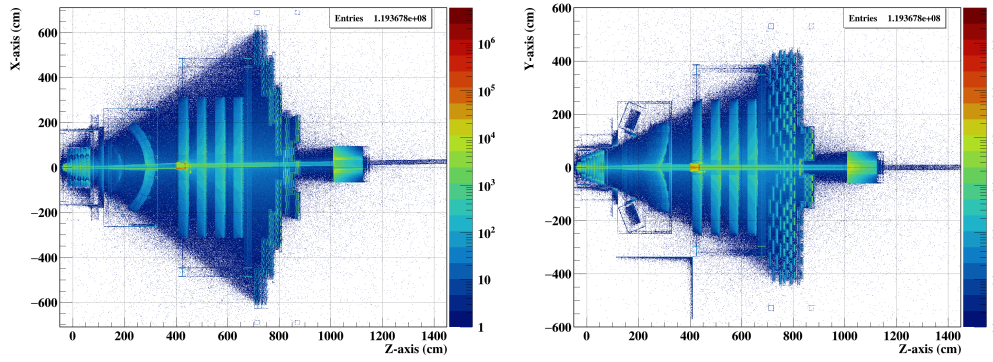


Figure 4: Geant 3: X-Z and YZ distribution of secondary particles produced.

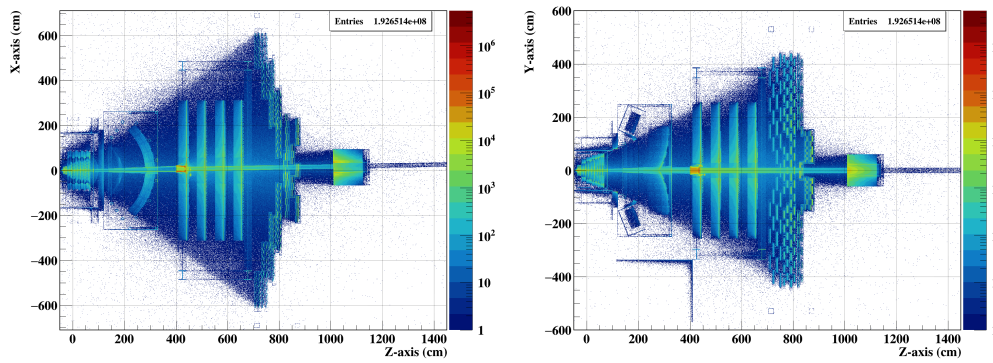


Figure 5: Geant 4: X-Z and YZ distribution of secondary particles produced.

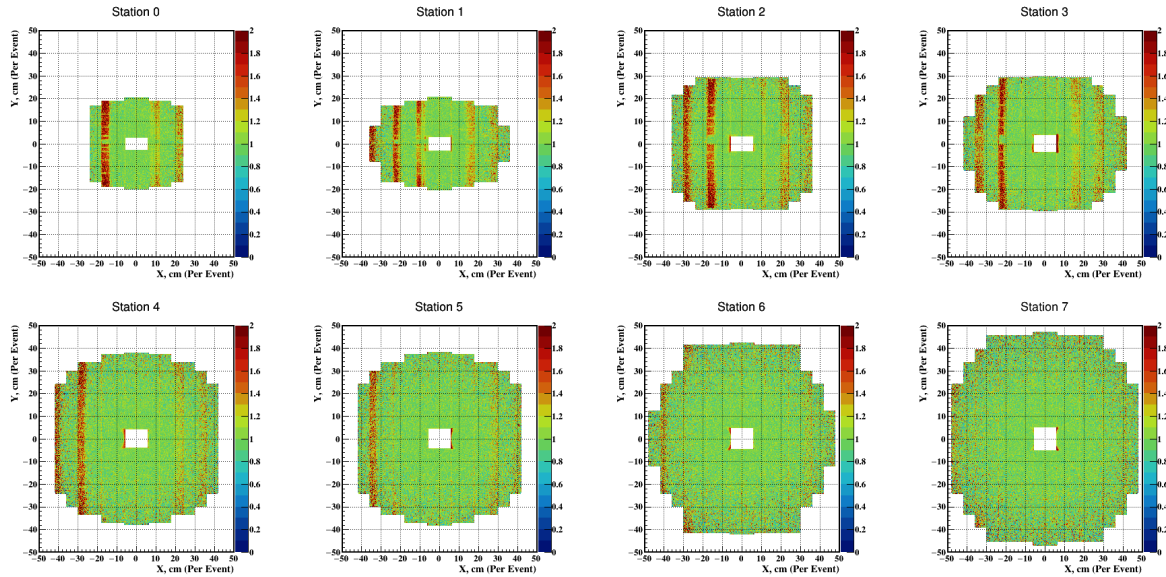


Figure 6: Ratios for MC points between GEANT 4 and GEANT 3 for the different STS stations.

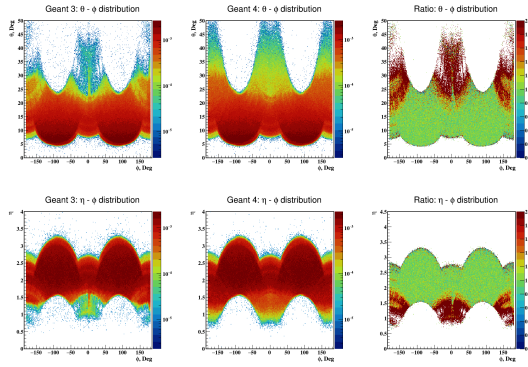


Figure 7: Theta-Phi (above) and Eta-Phi distribution (below) for the reconstructed tracks.

The ratio of the MC point distributions in the STS stations (Fig. 6) shows that the increased production of secondaries is located around the position of the peripheral ladders. This is also seen in Fig. 7, the ratio of the reconstructed particle increased on the cornered area of the STS acceptance. This is due to the magnetic field model used in different GEANT versions. By default GEANT-3 uses the Runge-Kutta method - Nystroem algorithm (second order), and GEANT-4 Dormand and Prince Runge-Kutta (5th order). There is also an angular cut used in GEANT-3 while in GEANT-4 there is only a step and precision limit [2].

Figure 8 shows the energy loss distribution of all particles in different GEANT versions. There is a kink appearing in the case of GEANT-3. As a default setting QGSP BERT EMV+optical, stepLimiter is being used while it needs to be QGSP BERT EMV+optical, specialCuts+stepLimiter and also the energy cuts need to be checked to produce the similar energy loss for GEANT-3 [3]. Figure 9 shows the beta vs. momentum and mass² vs. momentum distributions for fully reconstructed particle tracks (STS hits ≥ 7 , TRD hits ≥ 3 and TOF hits ≥ 1). Comparing GEANT-3 (left) to GEANT-4 (middle), with the help of the ratio (right), it is clear that different particle yield with the two transport engines arises from low momentum region (below 1.5 GeV/c) for all particle species.

Summary

Significant differences are found in the yield of secondary particles with GEANT-3 and GEANT-4, partly due to the energy thresholds, partly to the step limit, and partly to the different magnetic field models. Further investigations are ongoing [2].

References

- [1] <https://geant4.web.cern.ch/>
- [2] <https://redmine.cbm.gsi.de/issues/3138>
- [3] <https://redmine.cbm.gsi.de/issues/2466>

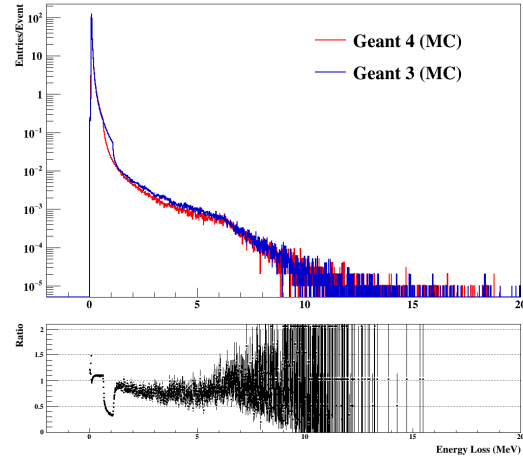


Figure 8: Energy loss of the all particles in STS.

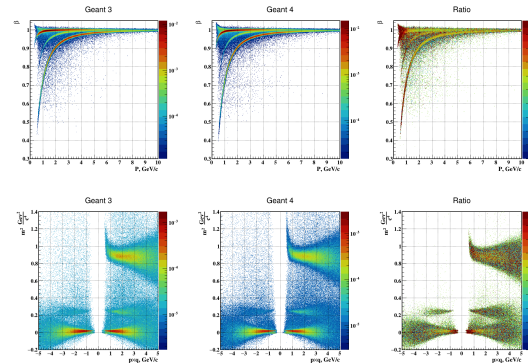


Figure 9: Beta vs. momentum (above) and mass square vs. momentum sign (below) for the reconstructed tracks.

Comparison of GEANT3 vs. GEANT4 for the CBM-RICH simulation

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Introduction

The Compressed Baryonic Matter (CBM) experiment at FAIR aims to study the QCD phase diagram at high net baryon densities. Comprehensive Monte Carlo simulations with the CBM detector setup are being carried out in order to understand the experiment response, evaluate sensitivity for different physics cases, optimize the detector performance, and tune the reconstruction algorithms. The CBM detector geometry description is based on Virtual Monte Carlo, VMC, principally allowing to use different transport engines, in particular GEANT3 and GEANT4. In the past, most simulations were performed using GEANT3, mainly for performance reasons. However, the active maintenance of GEANT3 will be discontinued in a few years from now. Moreover, within CBM, GEANT4 is more and more becoming the standard transport engine. In this report, we compare the simulation performance and obtained results of GEANT3 and GEANT4, with particular emphasis put on the RICH performance results in terms of ring reconstruction and photon hit yield.

The geometries used in the simulation setup are:

- Magnet geometry v22a
- Beam pipe geometry v21d and v21i
- MVD geometry v20d.tr
- STS geometry v22c
- RICH geometry v21a
- TRD geometry v20b.1e
- TOF geometry v21a.1e
- PSD geometry v22a
- Platform geometry v22b.

The particle input for this study is generated by a box generator. We performed 100 runs with 100 events each for GEANT3 and GEANT4 setups. Each event contains seven electrons and three positrons. From now on, we will refer to electrons both for electrons and positrons. The particles are generated with $p_T < 3$ GeV and the standard angular acceptance. The momentum distribution is shown in Fig. 1. Additionally, the figure shows the ratio of the entries in each bin of the GEANT 3 and GEANT4 simulations.

The differences between GEANT3 and GEANT4 are caused by random fluctuation because the box generator was independently run for both simulations.

Comparing GEANT3 and GEANT4

The distribution of the momentum of the primary electrons which are identified as electron by the RICH detec-

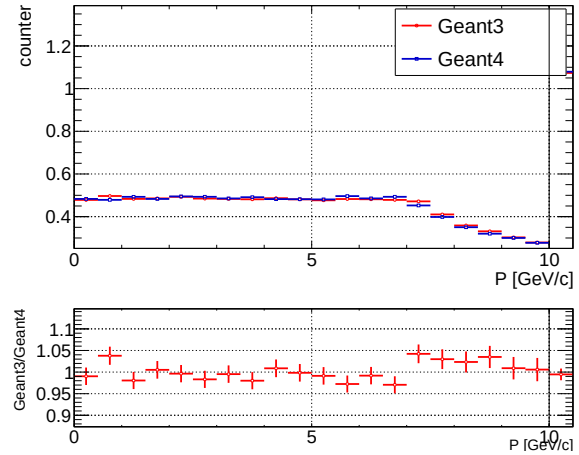


Figure 1: Momentum distribution of the total number of primary electrons normalized to the total number of events for GEANT3 and GEANT4 (top) and the GEANT3/GEANT4 ratio (bottom). The last bin is an overflow bin which contains all electrons with a momentum larger than 10 GeV/c.

tor in GEANT3 and GEANT4 simulations, as well as the GEANT3/GEANT4 ratio are shown in Fig. 2.

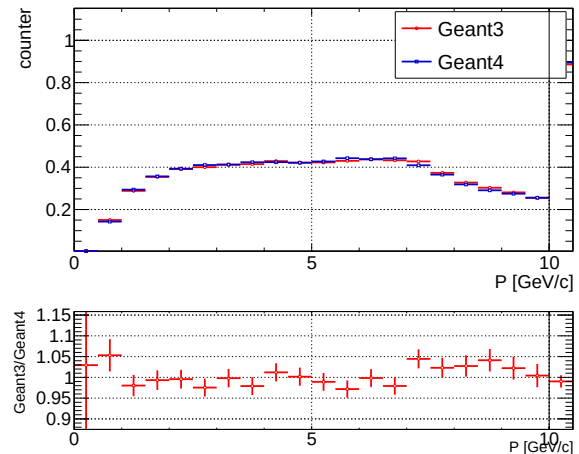


Figure 2: Momentum distribution of the primary electrons which are identified by the RICH detector as electrons (top) and the GEANT3/GEANT4 ratio (bottom). The last bin is an overflow bin which contains all electrons with a momentum larger than 10 GeV/c.

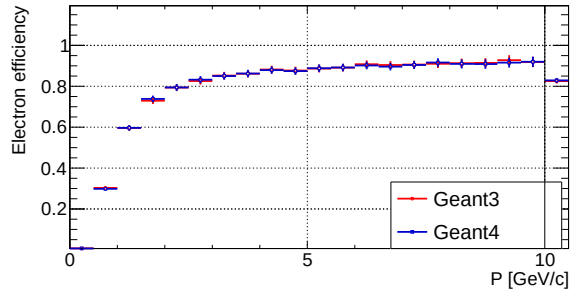


Figure 3: Electron detection efficiency for primary electrons as a function of the momentum for GEANT3 and GEANT4 simulations. The last bin is an overflow bin which contains all electrons with a momentum larger than 10 GeV/c.

The differences between the GEANT3 and the GEANT4 samples are negligible and again explainable by the random fluctuation of the distribution of the electrons caused by running the box generator twice.

As was expected from the plots in Figs. 1 and 2, the electron reconstruction efficiency shown in Fig. 3 does not show significant differences between the simulations with GEANT3 and with GEANT4.

The number of Cherenkov rings found in the RICH detector by the standard ring finder is shown in Fig. 4 together with the number of hits in the RICH detector of each ring.

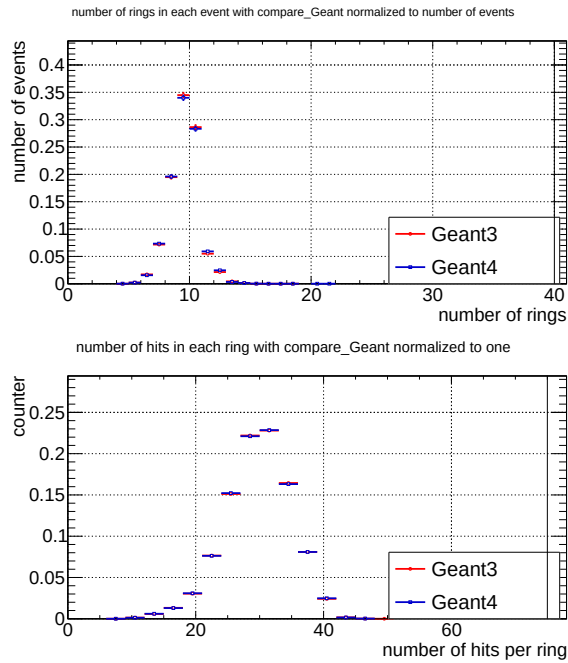


Figure 4: Histograms of the number of rings in the RICH detector (top) and the number of hits per ring (bottom). The last bin in both plots is an overflow.

Again, the differences between the GEANT3 and GEANT4 simulation results are negligible.

The runtime for the transport step of the simulation using full CBM geometry increase for running with GEANT4 with respect to GEANT3 by a factor of two for simulations with box generated electrons and a factor of three for simulations with Urqmd samples.

Summary

The comparison between GEANT3 and GEANT4 based simulations shows no significant differences with respect to the RICH detector performance. The photon yield and electron efficiency are comparable for both transport frameworks.

Acknowledgments

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Modelling of simulation geometries using Tessellated Shapes with the Vectorized Geometry (VecGeom) package

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Introduction

Accurate simulation of a particle physics experiment like CBM, requires a detailed description of the matter, its shape and position. Several software toolkits, including CERN-ROOT¹ and GEANT², provide the capability to describe detectors' shape, placement and composite makeup of the geometries for simulation purposes. However, accurately representing the intricate details of detector geometry, as provided in CAD models used for engineering purposes, poses a challenge within the current software toolkits. To address this challenge, advancements have been made in describing complex geometry through the conversion of CAD models to the Geometry Description Markup Language (GDML)³, utilising tessellated solids/shapes⁴. This report documents some of the ongoing investigations into the usefulness of these methods for CBM.

CAD to GDML Conversion

Numerous software toolkits, such as FreeCAD, SolidWorks, and FAST-RAD, offer direct conversion of the STEP file which is a portable format of CAD into GDML format³, which is a XML-schema for describing elements, materials, positions, volumes, and shapes including tessellated shapes. For our specific case, we utilised FreeCAD to convert the STEP files into GDML format. This conversion process was applied to convert the CAD for the c-frame and ladder cut-outs of the Silicon Tracking System (STS) as shown in Fig. 1, and for the support structure of the Transition Radiation Detector (TRD) as can be seen in Fig. 2. Both these figures are visualised using CERN-ROOT which demonstrates successful conversion. This approach allows an accurate representation of complex geometrical shapes within the simulation framework which would be hard-to-impossible to achieve using the traditional TGeoVolume⁵ approach.

¹<https://root.cern.ch>

²<https://geant4.web.cern.ch/>

³https://root.cern.ch/doc/v614/group__Geometry_gdml.html

⁴https://root.cern/doc/master/TGeoTessellated_8cxx_source.html

⁵<https://root.cern.ch/doc/master/classTGeoVolume.html>

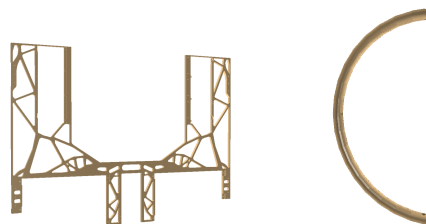


Figure 1: Proposed C-frame for the different station and Ladder cut-out for the central ladders for the STS.

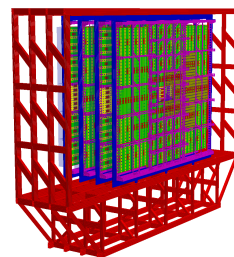


Figure 2: Support structure for the TRD.

Results

After application to the c-frames and ladders of the STS geometry and to the support structures of the TRD geometry, they were checked by a random ray method as illustrated in Fig. 3 for the STS example and in Fig. 4 for the TRD example. A discrepancy was observed that when employing random rays to volumes made of tessellated shapes for the STS c-frames and for the Kanya profile of the TRD main support frame, whereby the TGeoNavigator of CERN-ROOT failed to accurately trace out the true shape, and boundaries when the random rays should enter and exit the tessellated shape. This limitation arises because the current implementation of the TGeoTessellated class⁴ lacks navigation functionality. Consequently, these tessellated solids behave as simple boxes, following the characteristics of their parent class, TGeoBox⁶. However, it is noteworthy that ROOT does support navigation functionality for tessellated solids when compiled with the VecGeom package⁷ and utilising the VecGeom converter during the modelling and simulation processes, see Ref. [1].

⁶https://root.cern/doc/master/TGeoBBox_8cxx.html

⁷<https://gitlab.cern.ch/VecGeom/VecGeom>

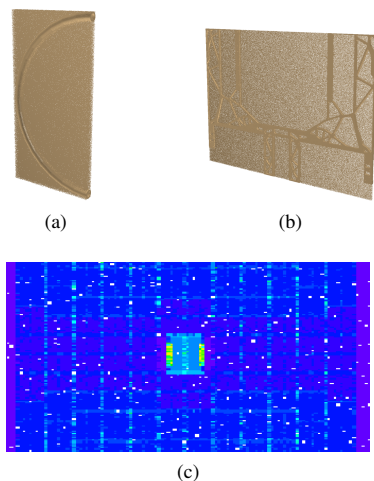


Figure 3: STS geometry volumes without VecGeom (a) Ladder cut-out (b) C-Frame (c) Ladder cutout in a material budget map

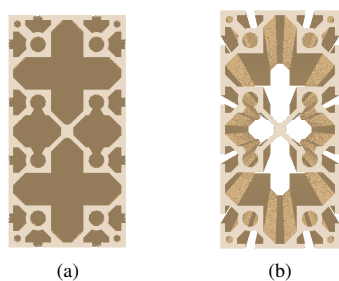


Figure 4: TRD geometry volumes (a) Kanya profile of main support structure without VecGeom (b) Kanya profile of main support structure with VecGeom

The *VecGeom* package provides a converter that essentially transforms all the shapes in each *TGeoVolume* (including Tessellated) into *VGShapes* as defined within the CERN-ROOT, *TGeoVGShape* class⁸. This integration facilitates improved navigation capabilities for the tessellated shapes within the ROOT framework.

We can observe as illustrated in Fig. 5, after compilation of the *VecGeom* package functionality in CERN-ROOT along with FAIRSOFT and FAIRROOT packages, the shapes in a material budget map of both STS and TRD examples, appear as one would expect from a successful conversion from CAD and a successful simulation of material budget.

Conclusion

The direct conversion from CAD to GDML allows the modelling of complex parts and structures, which would

⁸https://root.cern/doc/master/dir_f659b5a9ca37b079a242c72a02a19916.html

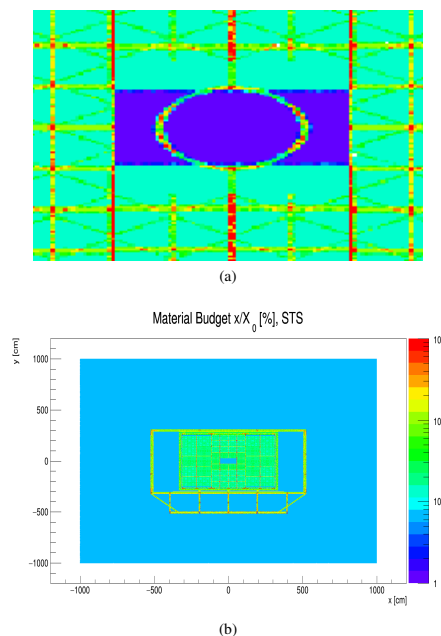


Figure 5: Material budget map after implementation of *VecGeom* (a) Ladder cut-outs in STS (b) Support structure for the TRD

be extremely tedious to implement using the traditional approach⁵. ROOT may be compiled to allow navigation functionality for volumes made of tessellated shapes through the *VecGeom* package⁷. Recently some particle physics experiments[2, 3] have experimented integrating the *VecGeom* package approach in their simulations and studied how the simulation runtime varies using different navigators like *TGeoNav*, *G4(VG Solids)*, *G4* and *VecGeomNav*. In their work, *VecGeom* navigator shows a speedup in runtime which depends on geometry complexity. Here, implemented and conducted the first tests of these approaches for subsystems of the CBM experiment.

Acknowledgement

We are grateful to Andrei Gheata, working at CERN in the SFT group on R&D projects, for his kind help and guidance in the work we have discussed in this report.

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- [2] S. Wenzel, J. Apostolakis, and G. Cosmo, “A *VecGeom* navigator plugin for *Geant4*”, EPJ Web Conferences 245, 02024 (2020).
- [3] E. G. Stan and A. Gheata, “GPU-friendly boundary representation geometry model for simulation” CERN Students Note 177 (2023)

Applying TGeoArbN based tessellation in the CBM geometry description

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Introduction

Optimizing the design and geometry of a large particle detector like CBM is done in many individual iterations and incremental steps, where changes in the CAD mechanical design and modifications in the GEANT detector description used for detector simulation are often decoupled. In the standard approach, the GEANT detector description is based on assemblies (and boolean operations) of simple geometrical shapes, like boxes, spheres or tubes, owed to the necessity of fast particle propagation in the simulation process. In CAD, complex geometries are often obtained by extruding 2d shapes. These different approaches make it difficult to transfer CAD geometries directly into GEANT, usually requiring independent geometry modeling for CAD and GEANT. Often, this results in discrepancies between CAD design and simulation model, and slows down the iterative design process.

A promising alternative to this classical approach is the use of tessellation for describing objects in GEANT. Tessellated surface meshes of 3d geometries can be directly exported from most CAD programs, e.g. via STL file export ("Standard Tessellation Language"). Usage of these tessellated objects in GEANT allows for a much easier and less error prone geometry transfer from CAD to GEANT, allowing for more rapid iteration cycles in geometry optimization. An obvious disadvantage of using tessellation in GEANT detector simulation is the much higher complexity in particle tracking: finding the next object boundary in a given direction involves a much higher degree of complexity compared to the existing algorithms for simple object geometries, and involves comprehensive loops over the different facets of the geometry surface. Tessellation therefore can certainly not serve as a general tool for the full detector description. But for description of few, particular complex geometries, which are difficult to accurately model otherwise, or as intermediate step in the iterative design cycle of a geometry, tessellation can be of great benefit.

This report summarizes first applications of tessellation in CBM geometry description using TGeoArbN. TGeoArbN is a software tool developed by the PANDA Group at the University of Bonn as part of the work package 9 of the NRW-FAIR network activities, and is already actively used in the standard PANDA detector MonteCarlo geometry description. TGeoArbN comes with an own set of routines for boundary detection and particle propagation and is independent from G4TessellatedSolid in GEANT4 and from TGeoTessellated within ROOT. As huge benefit, it can be easily integrated in the VirtualMonteCarlo ap-



Figure 1: TGeoArbN-based geometry consisting of a simple iron plate with complex cut-outs (letters), directly extracted from the CAD model.

proach applied within CBM, allowing the usage of both GEANT3 and GEANT4 transport engines with the same geometry file.

Workflow and technical implementation within CBMROOT Framework

In order to use TGeoArbN based tessellated volumes within CBMROOT simulations, the class descriptions of TGeoArbN have to be added to the CBMROOT framework by adding to the CMakeList and loading the classes with include statements. Once this is done, TGeoArbN-based geometries can be included in the simulation just like any other, classical geometry.

All necessary steps to create a TGeoVolume from an ASCII-STL file using TGeoArbN can be contained in one function call. Input parameters are only the path to the ASCII-STL input file, the material of which the volume should consist of, and optionally a name for the volume. The returned TGeoVolume can then be used for geometry assembly like every other TGeoVolume, and many individual STL-based TGeoVolumes can be combined. A single material is assigned to each TGeoArbN geometry object, and complex geometries, made out of more than one material, have to be broken down to individual STL files for geometries of same material. In theory it should be possible to automatize the creation of geometries with tessellated parts from different step files.

First test with simple geometry

A first simple test was conducted to test whether the TGeoArbN based tessellation (directly exported from CAD) works within the CBMROOT framework, and if it

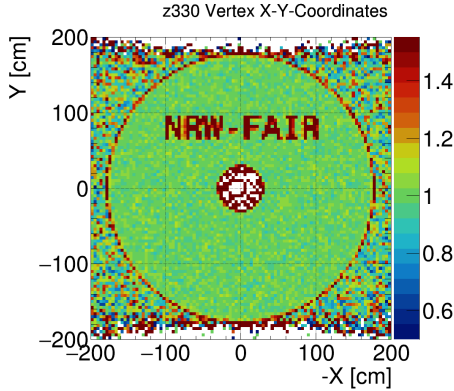


Figure 2: Ratio of XY-distributions of the photon conversion vertices at the position of the plate for the tessellation-based geometry, and the TGeoBox based geometry with same outer shape but without cut-outs.

yields the same results as the same geometry, implemented using the classical approach. A $5.8\text{ m} \times 4.14\text{ m} \times 0.04\text{ m}$ iron plate with a number of complex cut-outs as shown in Fig. 1, is added behind the RICH (using geometry version v21a). Simulation results were compared to a second geometry, where a similar metal plate (only without the cut-outs) was implemented as TGeoBox object using the standard approach. Both simulations used box-generated photons for same angular- and energy range, and the number of photon-conversion vertices is compared.

Figure 2 shows the ratio of secondary vertices in xy projection produced at the position of the plate for both simulated geometry variants. The circular shape is caused by the maximum emission angle of the box-generated photons. The ratio is very close to 1 (except the cut-outs), confirming same material budget (and same particle propagation) in both geometry variants. The results of this test confirm that TGeoArbN based tessellation within the CBMROOT framework produces the expected results.

First use case

As a first realistic use case of TGeoArbN based tessellation within CBM, two different geometry variants of beam pipe support structures, as currently discussed within the CBM beampipe working group, were extracted directly from CAD designs using TGeoArbN. A first variant consists of a large carbon composite cross structure, mounted inside the RICH radiator vessel, providing extended stability to the RICH for attaching the beampipe support to the RICH exit wall. The second variant consists of a large pillar-frame structure, placed directly behind the RICH, in front of the TRD detector, also made of carbon fiber. This second solution would allow a complete mechanical decoupling from the RICH detector. Both tessellated geometries are shown in Fig. 3. The beamcross, the left geometry in the figure, is created as a single TGeoVolume. The pil-

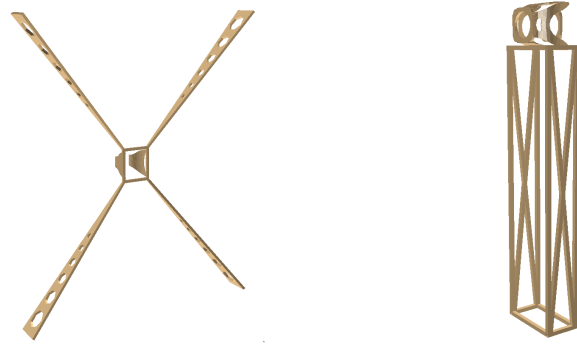


Figure 3: Two different designs for a beampipe support structure behind the RICH. Both geometries are implemented using TGeoArbN based tessellation.

lar structure, the right geometry in the figure, is created as two TGeoVolumes which are both subvolumes of the same TGeoVolume. Alternatively, it would be also possible to create this geometry as one TGeoVolume.

Both geometries are currently investigated in detailed Monte Carlo simulations to obtain first ideas on the amount of generated secondary particles (seen in TRD and backward detectors) and to estimate the possible influence of asymmetric material structures like the pillar solution on the event plane determination accuracy.

Summary

Tessellation of CAD geometries for direct use within GEANT simulations is an interesting approach to speed up the design iteration cycle, and to improve accuracy of Monte Carlo geometries in regions where this is critical. The technical solution described here, TGeoArbN, comes with the advantage of being independent of GEANT4, allowing seamless integration in the CBM VMC simulation framework, using both GEANT3 and GEANT4 transport engines alternatively. First test with simple geometries yield comparable results to the classical geometry definition approach, more complex geometries are currently investigated.

Acknowledgments

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. TGeoArbN is a development of the PANDA group at university Bonn, made available to us as part of the joint NRW-FAIR network activities.

Designing a Proof-of-Useful-Work (PoUW) blockchain for CBM

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Introduction

CBM, like other HEP experiments, relies on Monte Carlo simulations to model complex particle interactions and detector responses with statistical accuracy. This not only helps us with R&D of new detector components but will also make interpretation of real-world experimental data possible. Depending on accuracy requirements, running MC simulations can be computationally expensive, and the past few years in HEP (e.g. start of Run3 at ALICE) have shown once again that as luminosity and collision energies are increased, the complexity of particle interactions also rises, which creates the need for even higher simulation accuracy requirements to predict the outcome of these events.

In order to satisfy the rising need for computing power, the goal of my project is to explore distributed computing approaches that allow people from around the world to donate spare computing resources to support scientific experiments. Volunteer computing is not a new idea. In fact, CERN's BOINC project LHC@home started in 2004 and even today is still popular with more than 5000 active volunteers [1]. The novelty of my work is trying to combine ideas from volunteer computing with a blockchain-based approach to provide volunteers with additional incentives to participate.

Transition from hash-based PoW to simulation-based PoUW

In traditional Proof-of-Work, miners are brute-forcing hash function inputs to get an output smaller than a given number (target difficulty). This has helpful properties:

- **Non Re-usability**

The hash of the previous block has to be part of the hash function input. This makes it impossible to re-use previous solutions.

- **Adjustable Hardness**

Target difficulty can be dynamically adjusted to increase or decrease the problem hardness. Forcing miners to find hashes with more leading zeroes exponentially increases the difficulty of the block problem with every additional zero digit.

- **Fast Verification**

If a node claims to have solved the problem it is trivial to verify the claim. Calculating a single hash output of e.g. SHA256 takes less than a millisecond on modern hardware.

- **Parallelizability**

The block problem can be parallelized trivially if multiple CPU cores or hash engines are available.

For more in-depth information on how these properties can be retained in PoUW, refer to [2].

While hash-based PoW is able to secure the underlying blockchain, it also leads to a massive consumption of energy. According to the Cambridge Bitcoin Electricity Consumption Index, the estimated energy consumption of Bitcoin in 2021 was ~ 104 TWh, which is more than the total estimated energy consumption of the Philippines in that year. For this reason, a blockchain in which hash-based block problems are replaced with running MC simulations in a HEP environment is being developed so that energy is not wasted, but instead used to generate value outside the blockchain network by providing experiments with valuable simulation data.

Work in Progress

The blockchain reported here is from the start designed for this purpose. It is actively being developed in Golang and is expected to be completed and open-sourced by the end of 2024. It makes use of the libp2p networking stack, which was initially developed as part of IPFS, for its networking and transport capabilities.

Currently implemented blockchain features are:

- Rendezvous + Kademlia for peer discovery through NAT,
- PubSub message distribution,
- execution of well-defined simulation tasks in the CBM environment,
- transaction support,
- various sync protocols with support for full/light nodes.

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Open Science for CBM computing tasks

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Introduction

“Open Science” is the umbrella term that encompasses the multifaceted topics aimed at increasing access to and freedom to engage in scientific research with as few barriers as possible. These concepts are espoused by recognised international and national bodies including the United Nations through the UNESCO Recommendation on Open Science¹, by the European Union through the European Open Science Cloud, and the German DFG through a positioning statement². Distinct topics of open science, as far as GSI/FAIR is concerned, are delimited in six key objectives as shown around the info wheel (cf. Fig. 1).

Conceptually, ‘Open Science’ is a simple idea that can be broadly understood by contemplation of the list of topics positioned around the wheels in Fig. 1 whilst the complexity of the subject is driven by the abstraction of these topics and hopefully when addressed correctly, the possible removal or attempted removal of complexity and barriers to present inhomogeneous information homogeneously.

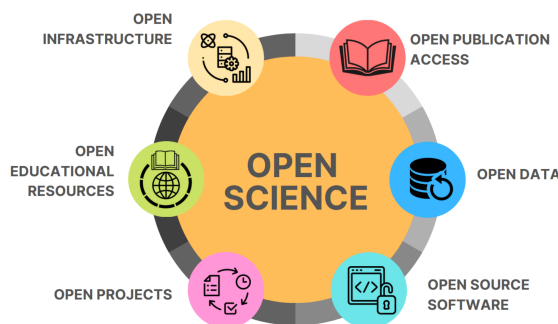


Figure 1: Logo showing the pillars of Open Science.

At GSI/FAIR, a working group of diverse experts was formed to consider and formulate our open science strategy, which met six times during 2023 and culminated in the successful 1st workshop on Open Science at GSI/FAIR on the 19th/20th October 2023³. In part, this report summarises a presentation [1] given at that workshop. Further information on open science at GSI/FAIR, the open science working group, as well as contact details are available

online⁴. In the next two sections, we address two important open science topics as they relate to non-hardware related CBM computing, namely access to our software in the guise of “Open Software” and access to our data in the guise of “Open Data” once the experiment is up and running. We will learn in the open data section below that the prototype experiment mCBM provides an exciting testbed for our open data policy ideas.

Open Software

Everybody working in programming has a personal understanding of what “open” software means, which, although often share similarities, are unfortunately rarely equivalent. For the purposes here, we simply mean software that has open-access to its source code, and possibly in a manner that is mostly barrier free, i.e. publication in a findable, free-to-download, and online searchable repository. Here, the F.A.I.R. principles⁵ are useful mnemonic to keep in mind [2]. Copyright through explicit declaration or implied in national laws always restrict the end user from using the software in some predefined ways. Although these may differ for commercial reasons especially in larger corporations, many everyday software developers or those engaged in research are more interested in firstly, preventing the possibility of being sued because of unintentional bugs or the lack of suitability of their code for a certain task, and preventing development without sharing back to the original author, which surprisingly could even block the originator developing obvious additional functionality into their already published code.

The CBM collaboration, and the CBM software framework, is an interesting case study and may provide a blueprint for implementation of open science and open software principles to similar international scientific collaborations. Although CBM is due to conduct its experiments in the FAIR research facility in Germany, it is important to appreciate that it comprises of many research institutes distributed worldwide (see Fig. 2), many of which are neither based in Germany nor Europe, and are funded by national and international funding agencies, which do have differences in copyright, licensing, and legal requirements. As highlighted in Tab. 1, the CBM collaboration is truly global being more Hessian than Darmstädter being more

⁴<https://www.gsi.de/work/forschung/open-science>

⁵ F.A.I.R. stands for F - Findability; A - Accessibility; I - Interoperability; R - Reusability. This should not to be confused with the acronym FAIR, which means the Facility for Anti-Proton and Ion Research in Europe GmbH.

¹<https://www.unesco.org/en/open-science/about>

²<https://zenodo.org/records/7194537>

³<https://indico.gsi.de/event/17498/timetable/>

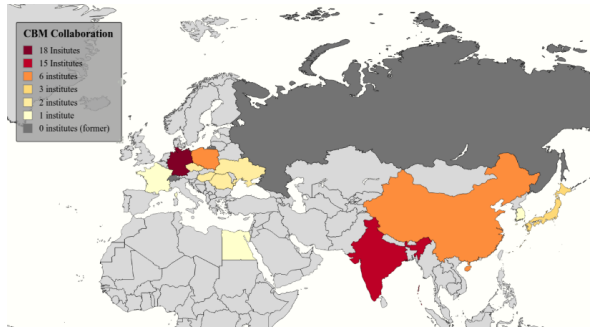


Figure 2: Visualisation of data from the CBM collaboration database⁷. Graphic shows distribution of member institutes worldwide and prevalence per country.

German than Hessian, being more European than German, and being more Global than European based. To make matters more complex, CBMROOT⁶, which is our bespoke software framework, was developed over the space of more than a decade by many authors based worldwide in academic and research institutes, many of whom are no longer personally or institutionally members of the collaboration, with contributions without copyright consideration or declaration. Some classes of our code base had copyright declaration notices included ad-hocly and often, the original authors were no longer contactable having left their participating institutes and left the particle physics community and/or programming fields.

In order to pursue an open science policy in relation to our software, it was first necessary to determine who owned and held copyright of existing work. It was reasoned that the original authors held originator rights, and the body/institute paying the wage to the developer for the development of code held the copyright, although this was complicated somewhat by many authors having multiple affiliations. It was also very important to determine other major contributors to a piece of code. Originator and authorship information was determined from the git repository (after 2020) and the SVN repository (before 2020) for each file, which often contains a single OOP class in our repository. The original submitter of the file and code was determined to be the originator, and their institute was deemed to hold the copyright. Other authors of the code were determined by having lines of code in the current file with the order of authorship in the authors' list determined by the number of these lines. Once the copyright holder of each piece of code was determined, permission to publish the work under an agreed copyright was needed. For this, it was needed for each institute to agree to a common approach via signing a memorandum of understanding by each institutes' representative in the collaboration board. The distribution of institutes is shown in Fig. 2. Transfer of copyright to the CBM collaboration was not possible as it is not a legal entity such that it could hold copyright of itself.

⁶<https://git.cbm.gsi.de/computing/cbmroot>

Darmstadt	3
Hessen (excl. Darmstadt)	4
Germany (excl. Hessen)	11
Europe (excl. Germany)	13
World (excl. Europe)	28

Table 1: Distribution of full (47) and associated (11) institutional members of the CBM collaboration.

As recommended by computing board members, the GNU Public license version 3 (GPLv3) was proposed to the collaboration board and was agreed by them as owners of the code produced in the past. In addition, as future owners of new contributions to our code base going forward, it was determined that all software intended for CBM should be released “open source”. The rights and obligations on recipients of our code is abbreviated in Tab. 2. As outlined in the table, the full text from the GPLv3 was included in the base directory of our source code. Installation instructions had already been included. To every C++ files, all root macros, and all bash scripts a 3-line header at the top of each file explicitly declaring the GPLv3 release license was prepended.

```
1 /* Copyright (C) {Year}[-{LastEditedYear}] {
   CBM Institute}, {city}
2 SPDX-License-Identifier: GPL-3.0-only
3 Authors: Contributor_1, Contributor_2 [
   committer], Contributor_3 */
```

The first line contains the word “copyright” and its ASCII symbol “(C)”; the year of the original submission, and if changed over more then the year, then followed by the last edited year, followed by the institutional copyright holder with city location. In the cases where the original author had more than one affiliation, the institutes in acronym form were extracted from the CBM Collaboration Database⁷ in May 2021 to be used for listing the institutes like “Institute_1/Institute_2, City_1/City_2”. The second line contains a machine and human readable reference to the GPLv3 license. The third line contains a list of authors, in order of the number of lines of code to the file. The identifier “[committer]” is appended to the name of the original author as this determines the institutional copyright holder. This same header was appended to all .cxx, .h, and .C files in our repository. Bash scripts had a slightly different variant which followed the same principles. All source code with licence information is made openly available via our GitLab based online repository⁶ which is easily findable via any of the standard search engine searches.

Although, by these approaches, the F.A.I.R. principles are loosely satisfied [3], we could and should look to increase the ‘FAIRness’ of the software by, for example, assigning a persistent identifier (such as a Digital Object Identifier (DOI)), publishing the code with machine readable metadata (see codemeta), and onboarding the software to a dedicated curation community, such as the ESCAPE

⁷<https://www-cbm.gsi.de/cbmcd/main.cgi>



Permission	Forbidden	Obligated
Commercial Use	Sublicense	Include Original
Modify	Hold Liable	State Changes
Distribute		Disclose Source
Place Warranty		Include Licence and Copyright
Use Patent Claims		Include Install Instructions

Table 2: Above: Logo for GNU general public license Version 3, 29 June 2007 Copyright (C) 2007 Free Software Foundation, Inc. <https://fsf.org/>. Below: Table summarises limitations, permissions, and obligations on the non-original developer of a piece of code released under this license.

Open Source Software Repository (OSSR)[4]. The authors of this manuscript are involved in the formulation of a set of “GSI/FAIR Research Software Guidelines”, whose recommendations are in part drawn from experiences in CBM, which is expected to be published by GSI in early 2024. Consultation of that document is encouraged when developing code for CBM collaboration tasks, although strict compliance with these guidelines is not required due in part to the special nature of CBM as an international structure.

Open Data

Data is the life blood of our experiment as well as collaboration. Everything we do as experimental physicists is geared towards the effort of collecting data to investigate the nature of compressed baryonic matter. Even from purely computing considerations, the main technological hurdles to overcome are how to handle the huge data rates from our detectors (1TB/s [5]), how to process this data in realtime and aftertime, and how to store a massive quantity of data to share it within our collaboration (and externally?). It is natural that particle physicist in the analysis working groups of our collaboration who wait to analyse the CBM data wish to have a privileged first access to the data after it has been validated by our technical teams. The sheer importance of data to us cannot be understated, and therefore any policy on data will be controversial, and will be contested between all members and interest groups of the collaboration robustly. The only reason that spirited voices have been quiet on these issues to date is due to the timeframe. There are many critical problems to overcome in CBM which could prevent us from setting up our experiment, and any problem related to data policy will seem quite distant compared to these, especially until at least the first data starts to arrive (maybe 2028) after the detectors are fully installed and the first beam taking data runs are completed. Even then, some are of the opinion, that there may be a number of years before the data is fully validated from a technical standpoint and thus is in a reliable state which can be shared. It is perhaps only due to the workshop

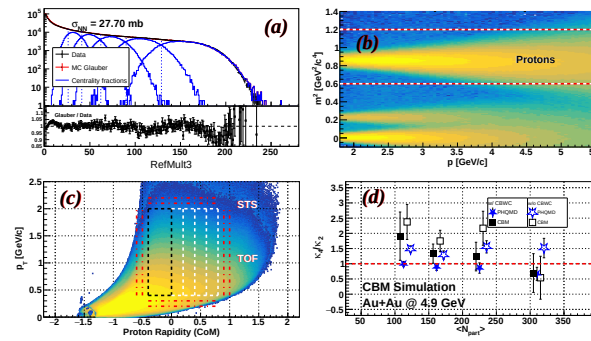
on “Open Science” held at GSI in October 2023³, which changed minds and one heard the first rumblings that the formulation of our data policy and consideration of an open data policy on CBM data may be required well before time. In this sense the workshop was a huge success in starting the conversation.

Despite still being an experiment in preparation and it being a long while before the true data flows, CBM of today is already a real particle physics experiment with real experimental data in the form of a prototype, called mini-CBM (mCBM), which has participation of all detector sub-systems of the future CBM experiment and which collects particle physics data from collision at SIS18 beam energies. The usefulness of this prototype is manifold, including testing detector electronics, readouts, sensor sensitivity and radiation hardness, on-line and off-line event building and reconstruction, and for the purposes of this manuscript, it may be used for providing proof-of-concept for an open data policy for full CBM of the future. Adding this real data to a multitude of other data from full scale simulations of the experiment, to specific data used for setting correct parameters for our algorithms, CBM should have sufficient data for the testing of a CBM data policy. In this regard, some initial investigations were already conducted by us (see [6]) by testing the integration of the CBM data flow chain with a datalake infrastructure from the ESCAPE project. This informed us on the capability of utilising datalake infrastructure on simulated data at the transport, digitisation and reconstruction level, as well as real experiment data from mCBM being replayed at realtime rates to storage, with immediate sharing of data utilising the ESCAPE datalake infrastructure. To advocate for an “open data” policy for CBM, proof that we have a workable and useful vision is crucial if we are to convince the decision makers in the computing, management and collaboration boards as well as the wider members of the CBM collaboration. To have a robustly convincing argument, we will need to showcase our vision using mCBM during a real data run in the very near future.

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Physics Performance



A study of the correlation between reconstructed and generated protons of the PHQMD model using AnalysisTree

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The newly developed Parton-Hadron-Quantum-Molecular-Dynamics (PHQMD) model has been suggested to be used as an event generator for studies related to the physics of the Compressed Baryonic Matter (CBM) experiment. The PHQMD model [1] is a powerful theoretical framework at the intersection of nuclear and particle physics which plays a vital role in exploring the complex dynamics of heavy-ion collisions, where matter undergoes a transformative journey from the high-energy QGP phase to the more familiar hadronic phase. The microscopic n-body-transport approach allows a dynamic cluster formation due to the interactions between baryons.

This report explores the correlation between reconstructed and generated protons in the PHQMD model using AnalysisTree in CBM. AnalysisTree in CBM, simplifies data management by providing tools for storage, analysis, and visualization, facilitating access to CbmRoot output, and enhancing data with analysis-specific details, fostering a user-friendly analysis environment.

Particle identification techniques is the necessary step to determine the types of particles produced. Finally, physics observables are studied using the simulated and reconstructed data. Protons have to be identified with greater accuracy for studying event-by-event fluctuations of the net proton number which is an observable to serve as the signal of the QCD critical end-point. Simulated protons contain both protons from the event generator (primary) and those which were produced during the propagation through the detector with GEANT (e.g. decay products or particles produced in inelastic processes). The reconstructed protons are those identified within the active area of the detector, meeting both event and track quality criteria. Correlating reconstructed to generated protons validates detector accuracy and efficiency in representing high-energy collision events, ensuring reliable measurements and precise insights into fundamental physics. It is crucial for validating detector performance and obtaining accurate experimental results.

Fig. 1 shows the correlation between reconstructed and generated protons. The simulation was carried out using a PHQMD input file for Au+Au at $\sqrt{s_{NN}} = 4.9$ AGeV minimum bias, with the geometry FEB23_NEW_DEFAULT_SETUP. For purpose of the analysis, 100k events were considered. We have observed an anomalous pattern in the correlation plot, necessitating further investigation into its distinctive nature. To investigate nature of the anomaly, we studied the proton number correlation in the following three different ways: i) for different rapidity intervals, ii) for different centrality intervals and

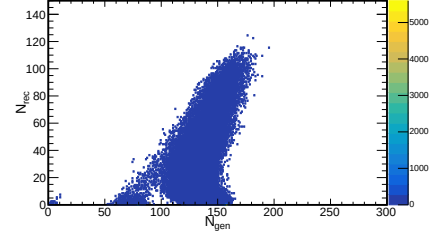


Figure 1: Correlation between the reconstructed (N_{rec}) and the generated (N_{gen}) number of protons

iii) for different transverse momentum regions.

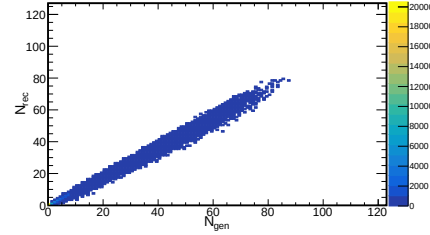


Figure 2: Correlation between the reconstructed (N_{rec}) and the generated (N_{gen}) number of protons using CBM rapidity range, $1.08 < y < 2.08$

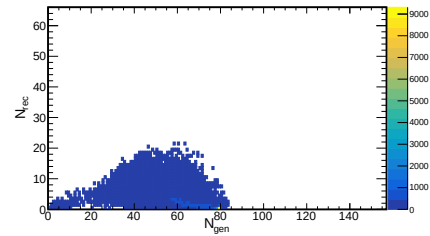


Figure 3: Correlation between the reconstructed (N_{rec}) and the generated (N_{gen}) number of protons within rapidity range $-1 < y < 1$

At first we have investigated for different rapidity intervals. Fig.2 and Fig.3 show the correlation plot of protons for the CBM rapidity acceptance, $1.08 < y < 2.08$, and for the rapidity acceptance $-1 < y < 1$, respectively.

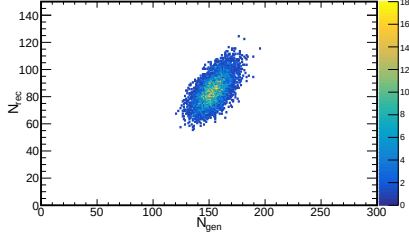


Figure 4: Correlation between the reconstructed (N_{rec}) and the generated (N_{gen}) number of protons for 0-5% centrality

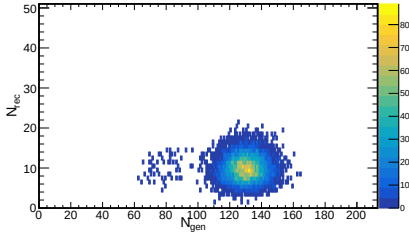


Figure 5: Correlation between the reconstructed (N_{rec}) and the generated (N_{gen}) number of protons for 50-60% centrality

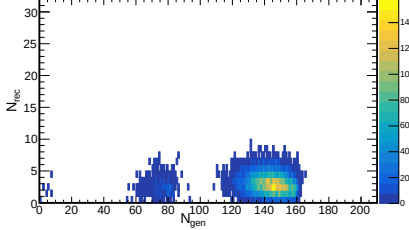


Figure 6: Correlation between the reconstructed (N_{rec}) and the generated (N_{gen}) number of protons for 70-80% centrality

Centrality dependent correlation plots are shown in Fig. 4 (0-5%), Fig. 5 (50-60%) and Fig. 6 (70-80%).

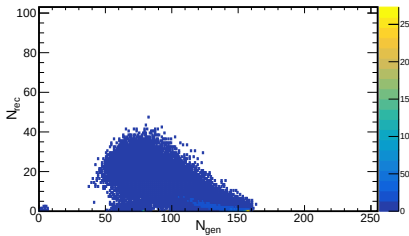


Figure 7: Correlation between the reconstructed (N_{rec}) and the generated (N_{gen}) number of protons in the p_T range 0-0.5 GeV/c

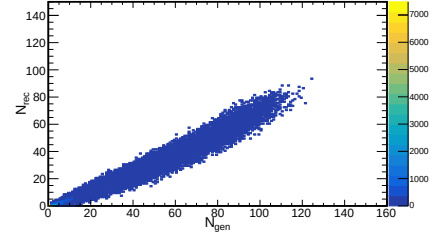


Figure 8: Correlation between the reconstructed (N_{rec}) and the generated (N_{gen}) number of protons in the p_T range 0.5-8 GeV/c

The study of the dependence on transverse momentum is presented in Fig. 7 and Fig. 8, where the range of p_T is chosen from 0–0.5 GeV/c and 0.5–8.0 GeV/c, respectively.

We observe a nice correlation of the number of reconstructed and simulated protons above p_T value 0.5 GeV/c and considering the CBM rapidity acceptance. The centrality study shows a better correlation between reconstructed and generated protons for the most central events (0–5%), whereas with increasing centrality, the correlation gets worse as the contribution from the spectator protons dominates in the peripheral events. We can conclude that the anomalous nature of the correlation plot (Fig. 1) is due to the lower p_T spectator protons. This study will help us choose the proper parameter range to accurately identify protons for further physics analysis.

Acknowledgements

The authors would like to thank Oleksii Lubynets for his help on using AnalysisTree and Dr. Anjali Sharma and Dr. Sanchari Thakur for the helpful discussion. Rudrapriya Das wants to express her gratitude to the Inspire Fellowship research grant [DST/INSPIRE Fellowship/2020/IF200305].

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CBM Performance for Λ Yield Analysis using Machine Learning Techniques

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To investigate the CBM performance for the reconstruction of the Λ^0 hyperon, a procedure was developed to extract its yield per event at different rapidities y . The current analysis is done on simulated data for UrQMD Au-Au collisions at 12 AGeV/c transported through the CBM detector setup using GEANT4. The investigated decay mode is $p\pi \rightarrow \Lambda$ and reconstructed by combining all positively and negatively charged tracks within an event using the KFParticle based package PFSimple[1].

Machine Learning Model

For the selection of the signal candidates, an XGBoost model is trained which utilizes 5 topological variables of the Λ^0 decay and additionally the m_p^2 and m_π^2 information obtained by the TOF detector, if available. The topological variables are $\chi_{\text{prim-}\pi}^2$, $\chi_{\text{prim-p}}^2$, $L/\Delta L$, χ_{geo}^2 and DCA, ordered by their importance for the prediction determined by SHAP[2]. These values are computed directly by the PFSimple package for each Λ candidate. The training of the model in the final experiment is planned to be done with DCM-QGSM-SMM generated Λ candidates with a mass in the 5σ region around $m_\Lambda = 1115.7 \text{ GeV}/c^2$ as signal candidates and real measured data outside the 5σ region as background candidates, since background is hard to model. For this feasibility study, UrQMD data is used as a proxy for the real data. After training with this data, the model outputs a BDT score which is the probability of a Λ candidate being signal. A cut has to be applied on this value to classify the candidates as signal or background, which in this work is set such that the p_T -integrated model efficiency is at $\eta_{\text{int}} = 0.9$.

Data Processing

To conduct this study with very high statistics, the 2M UrQMD events are processed on GSI's virgo cluster. The commonly generated events are stored in the lustre file system in AnalysisTree file format. They are used as input to PFSimple, which is configured to use only very loose cuts to reject unphysical candidates. The inference of the BDT probability of the candidates is done by a specially developed tool which processes PFSimple output analysis trees and adds a field to each candidate for the BDT probability. It uses the Open Neural Network Exchange (ONNX) runtime to compute this value in C++ for the XGBoost model, which has to be converted to the ONNX format for this purpose. It again outputs the candidates in AnalysisTree file format, which are then further processed using Anal-

ysisTreeQA on the cluster to apply the BDT cut and plot their physical properties. The output files are merged and ready for post-processing on the local computer (rebinning and fitting invariant mass distributions).

Yield Extraction

After candidate selection by XGBoost, in the inv. mass spectrum there is still combinatoric background, which needs to be estimated and subtracted. The fit routine developed by S. Khan[3] is utilized to fit the Λ peak using a double-sided Crystal Ball (DSCB) function. Compared to gaussian and double-gaussian functions the DSCB showed best results when comparing the raw Λ yield (integral of DSCB) with the raw MC yield (counting of true-positive candidates). The fit routine is applied in different $p_T - y$ intervals and consists of 3 steps:

1. **Obtain tail parameters** On simulated DCM-QGSM-SMM signal-only data a DSCB function is fitted in 3σ region around m_Λ to obtain the 4 parameters of the DSCB power-law tails.
2. **Initial background fit** On the data-like UrQMD events, the signal region is excluded and a polynomial is fitted on the remaining background. The polynomial's degree is iteratively increased to $N = 4$ while using the fit parameters of $\text{pol}(n)$ as start parameters for $\text{pol}(n + 1)$.
3. **Perform final fit** The final fit is performed using a superposition of the DSCB function with a 4th order polynomial. The tail parameters of the DSCB are fixed to the values obtained in step 1 and the $\text{pol}(4)$ is initialized with the parameter values from step 2.

Fig. 1 shows an example of the fit for a p_T - y interval. The extracted raw yield is in good agreement with raw MC yield ($Y_{\text{raw}}/Y_{\text{raw,MC}} = 1.001 \pm 0.007$) and the fit function describes the data well.

Yield Correction

To take into account the limited acceptance and reconstruction efficiency of CBM combined with the branching ratio of the investigated decay mode, the raw yield is corrected by a number $\text{Acc} \times \epsilon_{\text{comb}}$ which is calculated for each $p_T - y$ interval using MC data (UrQMD). Additionally, the efficiency η_{ML} of the XGBoost model has to be corrected for, which is also calculated for each $p_T - y$ interval separately. Finally, the corrected yields are plotted

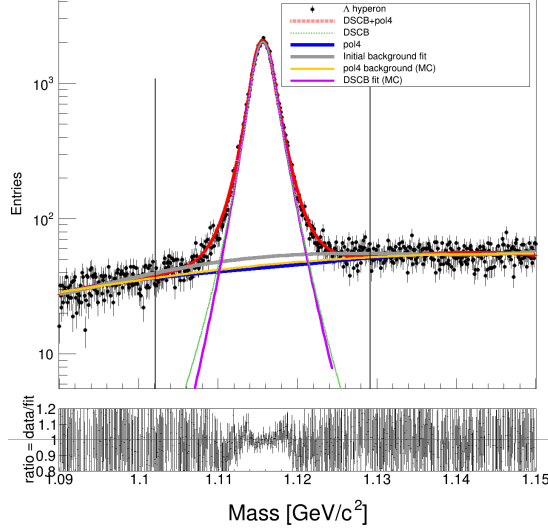


Figure 1: Application of the 3-step DSCB+pol4 fit routine to XGBoost Λ signal candidates in $1 < y < 1.5$, $0.75 \text{ GeV/c} < p_T < 0.85 \text{ GeV/c}$. Additionally plotted are the pol4 fit of the MC-true background (yellow) and the DSCB fit of the MC-true signal (violet), which are both in good agreement with their corresponding function parts of the final fit function.

as p_T spectra (Fig. 2) and fitted using blast-wave functions. This allows to extrapolate the measurement towards low- p_T regions where CBM has no acceptance. Integrating these blast-wave functions and normalizing by the number of events gives the desired Λ yield as function of rapidity y . The result is plotted in Fig. 3 along with MC-truth yield. There is a good agreement between the reconstructed yield and MC truth, the remaining difference may originate primarily from the blast wave fits. The fit allows to extrapolate the measurement towards lower rapidities which are out of CBMs acceptance. Integration of this spectrum gives the total Λ yield, which can be used as ingredient in statistical hadronization model fits or for estimating the needed statistics for further studies (e.g. flow).

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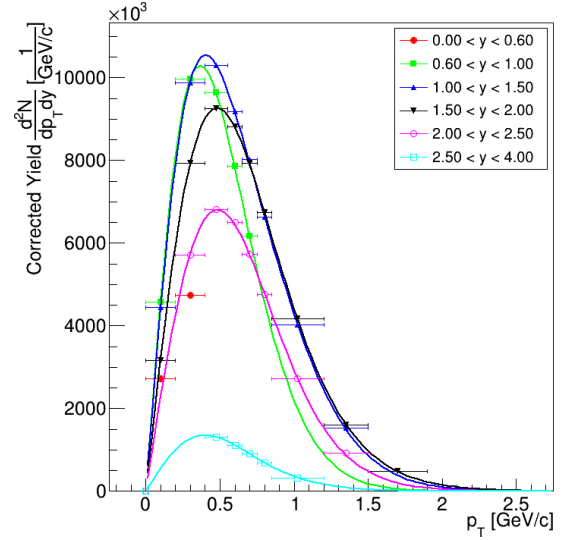


Figure 2: p_T spectra of Λ yield in 2M UrQMD AuAu collisions at 12 AGeV/c beam momentum corrected by $\text{Acc} \times \epsilon_{\text{comb}} \times \eta_{\text{ML}}$ for different rapidity intervals. Blast-wave fits are used for extrapolating the yield towards higher and lower p_T .

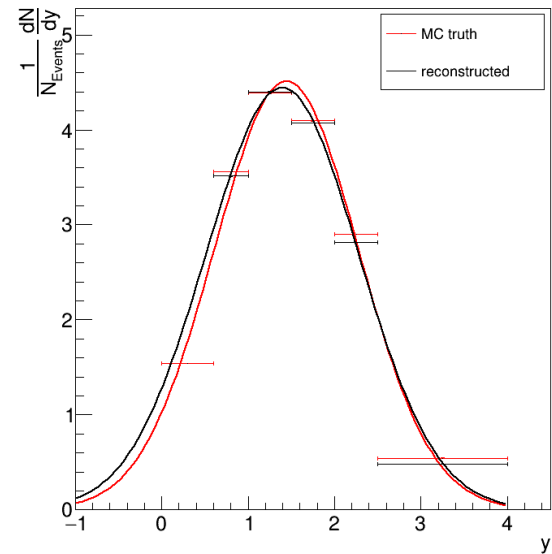


Figure 3: Reconstructed Λ yield (black) at 12 AGeV/c beam momentum compared to MC-truth yield. The applied fit allows extrapolation of the yield to lower rapidities.

Reconstruction of hypernuclei with CBM

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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] – even very rare double hypernuclei, like ${}^6_{\Lambda\Lambda}\text{He}$, are expected to be measured with sizeable statistics. In this performance study the ${}^3_{\Lambda}\text{H} \rightarrow \text{d} + \text{p} + \pi^-$ (BR: 40.1 % [2]) is probed as a case study for the 3-body-decay of ${}^5_{\Lambda}\text{He}$ and ${}^6_{\Lambda\Lambda}\text{He}$ and to evaluate the experimental sensitivity to properties of hypernuclei, such as their lifetime.

To study the CBM detector performance with respect to the reconstruction of hypernuclei, 10^6 central events at $\sqrt{s} = 4.9$ GeV were generated with the PHQMD model [3], a n-body microscopic transport approach which includes the dynamic formation of nuclei and hypernuclei. The PFSimple package [4], a software which is based on the KF Particle Finder [5], was used for the reconstruction of the 3-body-decay as well as the Pid framework [6] for the particle identification with the $\text{TOF-mass}^2/Z^2$ -measurement. Also, to increase the reconstruction efficiency, tracks with no TOF PID were identified by the TRD- dE/dx .

To reconstruct the rapidity spectrum of ${}^3_{\Lambda}\text{H}$, the extrapolation to unmeasured p_T -regions was done with Blast-Wave model fits [7] for each rapidity-bin. The reconstructed y -spectrum (Fig. 1, left) describes well the simulated data within the error bars for $-0.5 < y < 0.5$. At rapidities $|y| > 0.5$ large systematic effects of the extrapolation with the given statistics contribute to the reconstructed points. The total number of reconstructed hypertritons is 1284 in 10^6 events. The estimated ${}^3_{\Lambda}\text{H}$ lifetime $\tau = 236.74 \pm 28.6$ ps (Fig. 1, right) reproduces the simulated lifetime $\tau = 237.0$ ps (world average [8]) well within the error. The statistical error for only 10^6 events is already at the same range as the latest ALICE error. The estimated uncertainty for 90 days of data taking at 0.5 MHz interaction rate is $\sigma_{\text{stat}} = \pm 0.05$ ps only. The systematic error will be estimated as a next step.

The reconstruction efficiency can be improved further by applying a machine learning approach to optimize the applied cut values. With the XBoost model [9] a boosted decision tree maps a cut value vector of a candidate to the probability of being a signal candidate (BDT score). The training was performed with the Hipe4ML python package and the Optuna [10] package was used for hyperparameter optimization. The mass spectrum can be reconstructed with a very good signal-to-background ratio (Fig. 2, left) and

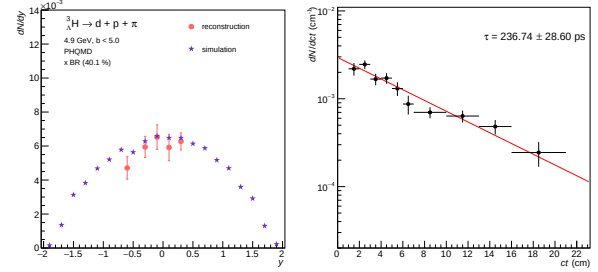


Figure 1: Reconstructed rapidity spectrum (left) and the decay length distribution ct (right) for the ${}^3_{\Lambda}\text{H}$ -3-body-decay (branching ratio = 40.1 %).

the efficiencies for accepted particles (Fig. 2, right) can be increased from 43 % (no ML) to 54 %.

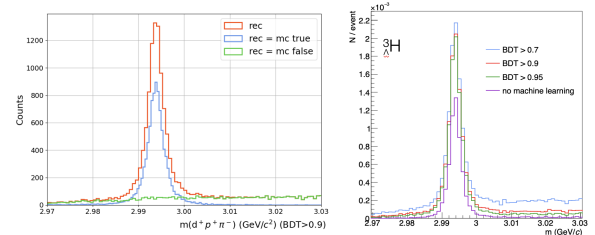


Figure 2: Reconstructed mass spectra for BDT > 0.9 (left) and for different BDT values compared to cut optimization without machine learning (right). Candidate selection is based on MC-PID here.

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Hypertriton reconstruction using TMVA machine learning tool

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Introduction

A reconstruction of short-lived particles decaying into a pair of two charged hadrons is usually performed using a set of cuts imposed on variables appearing in the context of decay topology [1]. With an advent of machine learning techniques, it becomes of interest to verify if some of their classifiers offer better signal recognition than rectangular selections.

In this manuscript, we report a study on the performance of recognition in CBM of hypertritons (${}^3_\Lambda\text{H}$) decaying into ${}^3\text{He} + \pi^-$ with help of TMVA package [2] of the ROOT platform. Hypertritons, produced by a Thermal model, were embedded in 1000 PHQMD events of central Au+Au collisions at the beam energy of 10 AGeV, with proportionally 10 such particles per event. It was then processed by the usual CBM analysis chain and the reconstructed tracks were translated to the `AnalysisTree` format [4]. ${}^3\text{He}$ and π^- we combined into pairs by the `PFSimple` package, and treated as candidates for hypertriton decay products. The algorithm links the reconstructed tracks with true particles traced by the simulation, thus allowing to separate the sample into true hypertritons and into background tracks.

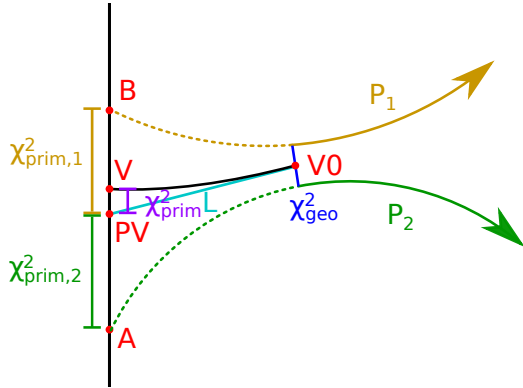


Figure 1: Sketch of topology of decay of a particle into two charged products. *PV* and *V0* depict, respectively, the vertex of production (in target) and decay of parent particle. For explanation of further relevant symbols, see text.

Due to hypertriton's lifetime of $\sim 2.5 \times 10^{-10}$ s [6], an average distance between decay and reaction vertices is about 17.5 cm for midrapidity emission from collision at 10 AGeV. Therefore, the V-topology approach seems relevant to this case. It is sketched in Fig. 1. The following quantities were treated as input to the neural network-based

classifier:

- χ^2_{geo} , distance between ${}^3\text{He}$ and π^- tracks divided on its uncertainty in terms of σ assuming the Gaussian distribution
- χ^2_{topo} , sum of the above and distance of the reconstructed hypertriton track candidate to the reaction vertex (PV)
- $\chi^2_{prim,1}$, $\chi^2_{prim,2}$ distance between track of 1st (2nd) decay product to reaction vertex normalized on their error
- L , distance between decay and reaction vertex
- $L/\Delta L$, above distance divided on its uncertainty, shows how far the candidate is constructed from the primary vertex in terms of σ assuming the Gaussian distribution

Note that χ^2 's and $L/\Delta L$ are calculated by `KFParticle.cxx` routine, whereas PV and its errors are calculated by `CbmKFPrimaryVertexFinder.cxx`.

For the classification method, we chose the multilayer perceptron (MLP) neural network [2]. As for many of such methods, for a given input it generates a classifier value between 0 (if input is identified as a pure background) and 1 (pure signal). For every tested scenario, two measures of strength of signal (*S*) with respect to background (*B*) were chosen: *S/B* and significance, $S/\sqrt{S+B}$. At the training and testing stages, where clear distinction between *S* and *B* is possible, *S* was found by fitting the Gaussian function to the signal histogram, and integrating it within in $\pm 3\sigma$ range around centroid. *B* was calculated by finding the area of background histogram within the same range. MLP offers a flexible number of hidden layers and nodes per layer. However, we found that choosing more than 1 layer does not improve the recognition significantly. Therefore, we chose 1 hidden layer and varied No. of nodes therein, within {1,6} range.

Figures 2 and 3 show the values of, respectively, *S/B* and significance as function of number of nodes of the hidden layer and the minimal accepted value of the MLP classifier, the latter called "cut-off". In both cases, a rising trend with cut-off is observed, as expected. The *S/B* measure rises steadily throughout all the domain, whereas significance reaches maximum around cut-off = 0.85 - 0.97 (depending on the number of nodes used), but at higher values it drops due to vanishing signal strength. It seems that neither *S/B* nor significance changes monotonously with number

of nodes. Judging by maximum of significance obtained for some wider range of *cut-off* values, the variant of network with 5 nodes achieves the best performance.

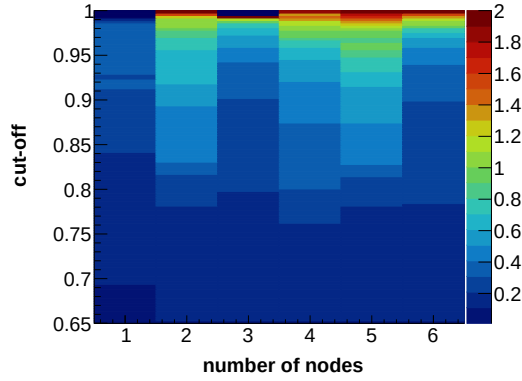


Figure 2: Hypertriton signal over background from uncorrelated ${}^3\text{He} + \pi^-$ pairs as function of number of nodes of a MLP hidden layer and minimal accepted value of MLP classifier

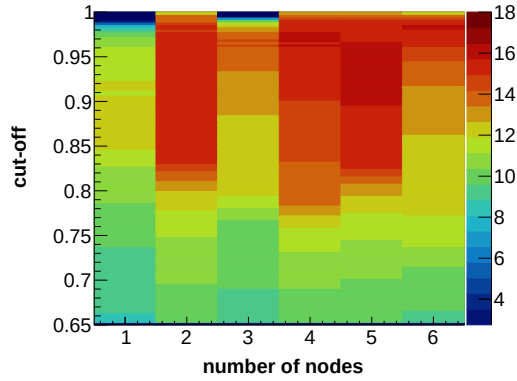


Figure 3: Significance of hypertriton signal reconstruction from ${}^3\text{He} + \pi^-$ pairs as function of number of nodes of a MLP hidden layer and minimal accepted value of MLP classifier

An important characteristics of the performance of the algorithm is the ROC (receiver operating characteristics) curve. Figure 4 shows the set of ROC curves for different number of nodes of MLP's hidden layer drawn on the plane of (relative) hypertriton signal efficiency versus rejection of background from uncorrelated ${}^3\text{He} + \pi^-$ pairs. In general, all the tested variants fare similarly, although the 5- and 6-node networks rank with a minor advantage. At relative signal strength of 80% the background rejection is at quite high level of $> 95\%$. At values of signal strength above 90%, the variants with 5 and 6 nodes take the lead. At values of strength below 60%, the level of background rejection is optically indistinguishable between variants, with exception of the "1 node" scenario, which fares a bit worse than the rest. A dot on this plot shows for reference the

result for the default set of strict cuts on the V-topology variables. Apparently, the MLP method allows the user to flexibly control the balance between the signal strength and the background rejection.

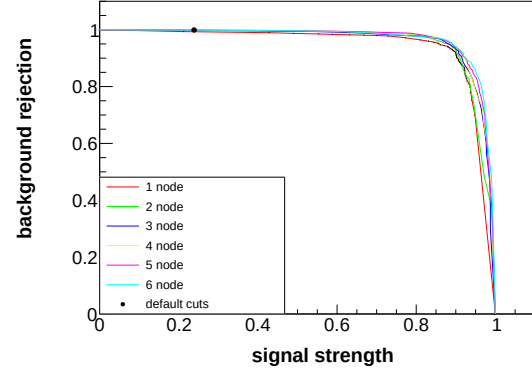


Figure 4: ROC curve on the plane of hypertriton signal efficiency (horizontal axis) versus rejection of background from uncorrelated ${}^3\text{He} + \pi^-$ pairs (vertical axis) for 6 variants of number of nodes of MLP hidden layer. Dot shows the performance of the 'historical' (pre-MLP) set of cuts.

In summary, we tested the performance of recognition of hypertriton decays into ${}^3\text{He} + \pi^-$ by the multilayer perceptron implemented in TMVA. Hypertritons were embedded in the events of Au+Au collisions at 10 AGeV, simulated by PHQMD transport model. We found that adding the second hidden layer does not improve the performance significantly. Overall, the signal over background (S/B) and significance rises with the classifier values, however significance reaches maximum around 0.85 - 0.97 (depending on number of nodes) and then drops. Judging by the height and stability of maximum of significance, the best performance is reached by the network with 5 nodes. From the perspective of ROC curve, all the variants fare similarly. Whereas at relative signal strengths above 90% the variants with 5 and 6 nodes appear to take the lead, for the signal strengths below 60% all the variants except "1 node" scenario fare nearly the same. The developed method of Hypertriton reconstruction using TMVA machine learning tool is a necessary step to approve it with high statistic timebased PHQMD heavy-ion collision simulations with the CBM detector.

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Implementation of fast simulation techniques to simulate enhanced background for low-mass di-electrons

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Introduction

In CBM, the analysis of di-electron simulations [1] is currently limited in statistics, i.e. limited to 5×10^6 events for UrQMD particles and 1×10^6 events for PLUTO particles. In the invariant mass spectrum for the low-mass vector meson (LMVM) analysis, this proves to be not sufficient in statistics, which becomes noticeable in strongly fluctuating spectra and even lack of data at higher mass regions. Thus, *Fast Simulation* techniques were implemented to generate large amounts of artificial events to enhance background statistics.

Fast Simulations is a rather loose term that describes procedures that use e.g. simplifications of detector geometries, approximations of models or parametrisations of analysis output in simulations. The advantage of its use is the much shorter computing time and less disk space occupancy while showing only small (often negligible) deviations from the output of "slow", i.e. full UrQMD+PLUTO simulations when implemented properly.

Procedure

Here, *Fast Simulation* techniques were implemented by using four values per charge, namely *multiplicity* and *3D momentum*, from slow simulations as basis to construct high statistics background by means of randomly generated events.

To generate these random events, the *multiplicity* and *3D momentum* distributions of each positive and negative particles of the common ("slow") simulations are stored separately in histograms after transport, digitization, reconstruction and electron identification. In a next step, these *multiplicity* and *momentum* distributions are used as probability distributions to create artificial positive and negative particles in large numbers (by means of the `GetRandom()` function of TH1 and THnBase). After this, all possible unlike sign pairs from randomly generated electrons and positrons are formed and their invariant mass m_{inv} is calculated by the momenta of both particles and their opening angle. Each m_{inv} value is filled into a histogram which then is normalized to the number of random events.

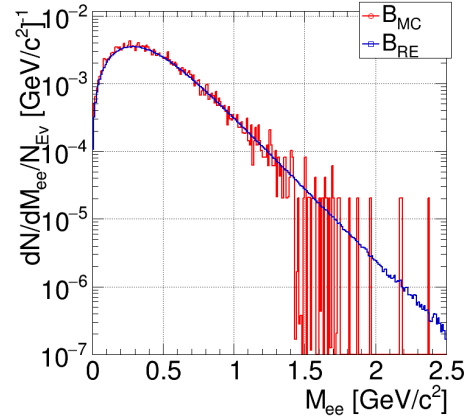


Figure 1: MC-true background (red) with a statistics of 5×10^6 UrQMD events compared to the background obtained by generating large numbers of random events (blue) with a statistics of 20×10^9 events. While the MC-true background has large fluctuations and many empty bins in the higher mass regions, the background generated with *Fast Simulation* techniques (B_{RE}) proceeds smooth and contains no empty bins.

Results

The resulting background yield B_{RE} is shown in Fig. 1 (blue curve) for a statistics of 20×10^9 events and compared to the MC-true background B_{MC} with a statistics of 5×10^6 events (red). Unlike the low statistics background, the fluctuations of B_{RE} are much smaller and no empty bins occur.

To obtain the LMVM signal, the calculated combinatorial background CB_{calc} is subtracted from the sum of random event background B_{RE} and MC-true Cocktail. This MC-true Cocktail is composed of all known di-electron sources, i.e. γ -conversions, π^0 -, η - and ω -Dalitz decays, as well as the vector mesons ρ , ω and ϕ , using an *in medium* shape for the ρ meson and adding QGP radiation. The combinatorial background is calculated combining same event like-sign pairs for masses below $400 \text{ MeV}/c^2$ and mixed events above. Spectra are normalized to each other typically in the range of $(400-700) \text{ MeV}/c^2$. In order to account for differences in the acceptance of reconstruction of different charges, the so-called k-factor is calculated and used [2]. The result of subtracting this background from all same

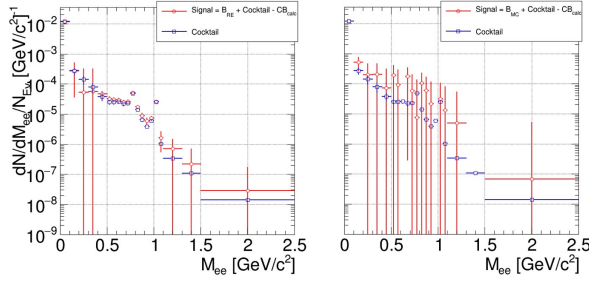


Figure 2: Left: Di-electron signal obtained by means of random event techniques (red) compared to according MC input (blue). Right: Signal obtained by conventional method, i.e., without the usage of *Fast Simulations*.

event unlike-sign pairs is shown in Fig. 2. On the left side, the obtained result (red) is drawn along with the MC-true Cocktail (blue). For comparison, on the right side the signal is shown that is obtained with the conventional method, i.e., without the *Fast Simulation* techniques, but with the low statistics MC-true background.

Errors and Problems

Though the agreement between calculated signal and MC-true Cocktail is on a high level, the result is accompanied by relatively large errors. This results from the fact that two large numbers had been subtracted. To

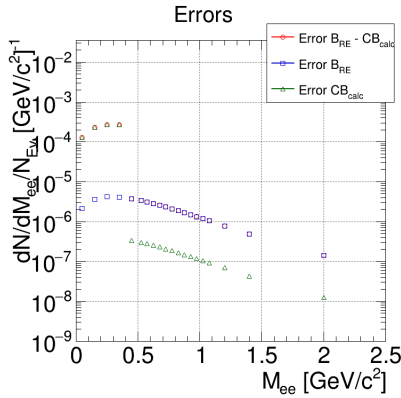


Figure 3: Error values for B_{RE} (blue), CB_{calc} (green) and signal error obtained by the subtraction $B_{RE} - CB_{calc}$ (red). At low invariant masses the error is dominated by the same event statistics of CB_{calc} , whereas at higher masses the error is dominated by the B_{RE} error due to its statistics and a low signal-to-background ratio.

understand dominating contributions in the errors, in Fig. 3 the errors of B_{RE} and CB_{calc} and the error for the subtraction $B_{RE} - CB_{calc}$ (calculated with error propagation) are shown. In the low mass region the error is dominated by the statistics of CB_{calc} . In CB_{calc} , from 400 MeV/ c^2 on same-event like-sign yields are replaced

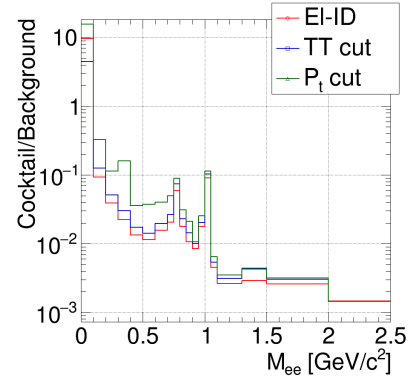


Figure 4: The signal-to-background ratio for different analysis steps.

by normalized mixed-event like-sign yields (mixing depth: 50 000 events). Hence, a sharp drop of the error curve occurs in this region. The main reasons for the large error in the higher mass region are the limited statistics of events and the low signal-to-background ratio (see Fig. 4). In the higher mass region ($m_{inv} > 1.2$ GeV/ c^2) the signal-to-background ratio is about 1/200. As can be seen, even for the full statistics of 20×10^9 events the remaining error is five to ten times larger than the signal itself.

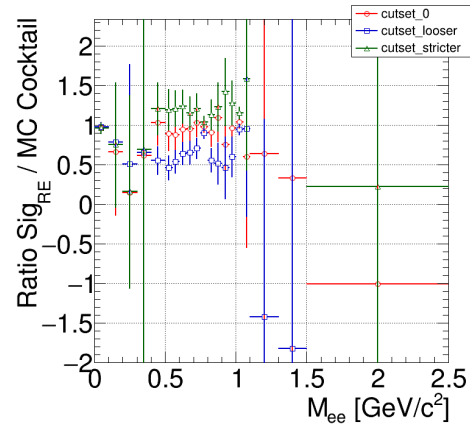


Figure 5: Ratio of calculated Signal (S_{RE}) over MC Cocktail for different electron-ID cut sets. The systematic error regarding the variation of the cuts amounts to about 50 %.

An obstacle of the calculation of the signal is its sensitivity to variations of parameters like electron-ID cuts or the chosen range to normalize mixed event yields to same event yields. Depending on ID-cuts the agreement of the signal to the MC-true Cocktail varies in the range of about 50 % (Fig. 5). Hence it is of great importance to further reduce the background in order reduce the ratio between the

signal error and the signal itself.

Temperature Measurement

Nevertheless, first attempts to measure the medium temperature T with these results were made.

If $M \gg T$, the emission rate dN/dM can be approximated by $dN/dM \propto (MT)^{3/2} \exp(-M/T)$ [3]. Hence, the slope of dN/dM is dependent on the temperature.

In Fig. 6 the MC Cocktail yield is shown for the initially created particles (MC) and the yield left after electron-ID (Elid), each along with a fit of the previous mentioned emission rate function to the data. The temperatures obtained by the fit of both data curves agree within errors to each other. Thus no bias is added by the detector acceptance and efficiencies. The lower limit of the fit is chosen to be 1.15 GeV/c^2 to exclude contributions from the phi meson.

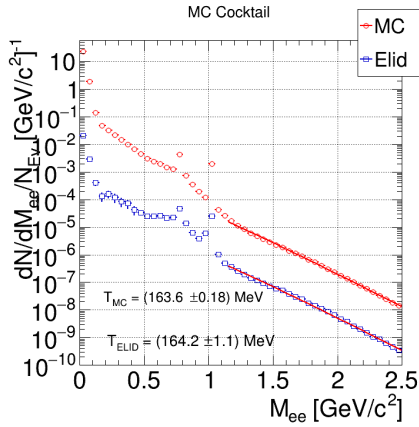


Figure 6: MC Cocktail yield for the analysis steps MC and electron-ID with temperature fits. No bias is posed by acceptance and electron-ID efficiency.

In the future experiment, the yield of known sources will be subtracted from the obtained signal in order to keep only contributions from the in-medium rho ($\rho_{i.m.}$) and QGP. These known sources are electrons from π^0 , η_D , ω , ω_D and φ decays (index 'D' for 'Dalitz').

In Fig. 7 the such reduced signal is shown along with the temperature fit. Due to small statistics bin sizes are large for high masses, this fact still needs to be taken into account in the fit.

Technical Issues

The generation of these random events is based on histograms that were filled after the electron-ID step which is applied prior to pair cuts in the LMVM analysis. Hence, the effect of pair cuts is not considered here yet, but will be investigated in a next step.

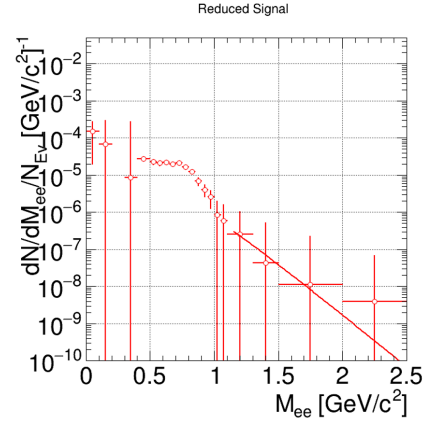


Figure 7: Reduced Signal after electron-ID with temperature fit.

In a first step, the input histograms were supplied separately not only regarding the charge, but also regarding particle species. As it turned out, the random backgrounds generated with both procedures differ only in the range of statistical errors from each other.

The 3D momentum histograms are implemented with a bin precision of 5000 bins per axis to assure a random background calculation with high precision. They are implemented as THnSparse histograms which allocate memory only for bins with non-zero content. Since large parts of bins in the higher momentum regions are empty, this histogram type is a great advantage over TH3D histograms regarding disk space occupancy and run time.

As standard random event statistics a number of 20×10^9 events is chosen, which is a realistic number for the future CBM experiment in the first years. The computing time for the generation of this amount of random events is about 10 minutes with parallelized jobs on the batch farm.

This *Fast Simulation* procedure is implemented in separate classes and macros so that it easily can be used also for other analyses. The only input needed are *multiplicity* and 3D momentum histograms separately for positive and negative particles (and, if favored, additionally also for separate particles).

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Performance of new MuCh geometry v23a for muon simulations in CBM

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Introduction

The Muon Chamber (MuCh) of the CBM experiment will be used to measure di-muons produced in energetic nuclear collisions, and is to be placed downstream of the STS at the position of the RICH detector, when not installed. MuCh consists of segmented absorbers, and the triplet of the detector layers will be placed in between these absorbers[1]. This novel scheme allows identification of momentum-dependent muons. The detectors within station 1 of MuCh are arranged in staggered manner on 12 mm Al-plate. This was implemented in v21c version of the MuCh geometry and various simulations were performed in the past which considered this as the default version available in CBM geometry repository. However there were issues related to detector acceptance, digitization, absence of realistic material budget, etc. The major challenges in development of the MuCh geometry is the selection of materials for its absorbers and detectors which maximise the signal to background ratio. In order to address this, a new MuCh geometry was created, with the tag v23, a for these more realistic simulations. In this report, we discuss simulation results with the v23a geometry and compare them with the previous MuCh default.

Detector Geometry

MuCh is built-up of constituent parts like absorbers, detector modules, cooling and support plates, etc. The detector part also comprises several small components like supports, Frontend boards (FEBs), etc., which amounts to significant material budget when considered cumulatively. The following modifications were included in the new geometry (v23a):

- 1.) Steel support, inner spacers and edge frames have been added in GEM modules.
- 2.) 18 FEBs have been added over the cooling and support plate. Additional copper plate has been introduced with the PCB which will be used to couple the cooling with PCB.
- 3.) C-Plate have been implemented. It is used to mount cooling plates to the overhead support.
- 4.) Dimensions of PCBs have been fixed and correctly implemented. An extension of PCB board to hold optocoupler based electronics is introduced.
- 5.) Class CbmMuchSectorRadial has been changed, so that it can now allow for odd number of pads.

We report that most of the major material have been taken into account.

Simulation and Analysis

Using the two geometries (tagged v23a & v21c), we have attempted to reconstruct omega ω meson along with combinatorial background estimated using super event(SE) technique. Background of Central Au-Au collisions at 8 AGeV was generated using UrQMD event generator, whereas for ω signal PLUTO event generator was used. Single ω decaying into $\mu^+ + \mu^-$ was embedded into each background event. The charge deposited is converted to digital signals (digis), which when clustered give hits. Hits from different detectors are used for reconstruction of global tracks. Muon track candidates are identified by applying selection cuts on global tracks based on associated number of hits in STS, MuCh and TRD detectors, χ^2 of the track segments in STS and MuCh and extrapolated to the primary vertex and reconstructed track momentum and mass based on time registered in ToF detector. Oppositely charged muon track candidates are then used for calculation of dimuon invariant mass spectra. A sample of 10^5 central Au+Au collisions are analyzed in event by event mode.

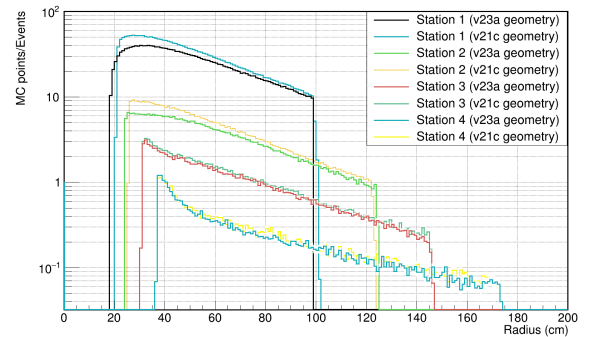


Figure 1: Radial distribution of Monte Carlo (MC) points/events of Station 1,2,3,4 of MuCh system for two geometries(tagged v23a & v21c) for 8AGeV Au-Au central collisions

Fig. 1 shows the radial distribution of Monte-carlo (MC) points for station 1-4 of MuCh system. The reduction in MC points for station 1 & station 2 is due to effect of material budget added whereas there is no reduction in MC points for station 3 & station 4 because no material was added in the new geometry. Sector and channel distribution of digis for v23a and v21c geometries can be seen in Fig. 2. There are 23 sectors and 97 channels in GEM mod-

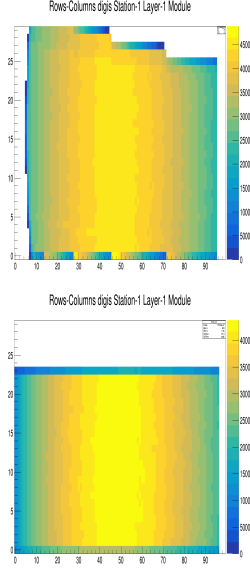


Figure 2: Sector and channel distribution of digis for v21c(left) and v23a(right)

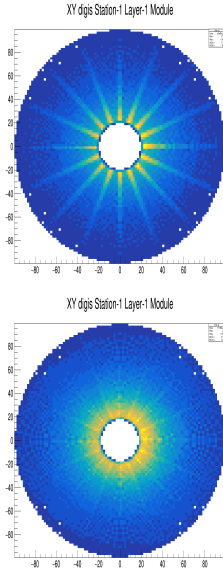


Figure 3: XY distribution of digis for v21c(left) and v23a(right)

ules, for v21c geometry, we were getting wrong numbers of sectors but this is resolved for the v23a geometry. Fig.3 shows XY distribution of digis for v23a and v21c geometries. The spoke-like structures was visible for v21c geometry which may be due to the issue with the incorrect numbers of sectors. Fig.4 and Fig.5 shows QA plots (Residuals & Pulls respectively). Much χ^2 of reconstructed track for v23a & v21c geometries can be seen in Fig.6. Finally we compare the dimuon detection performance of

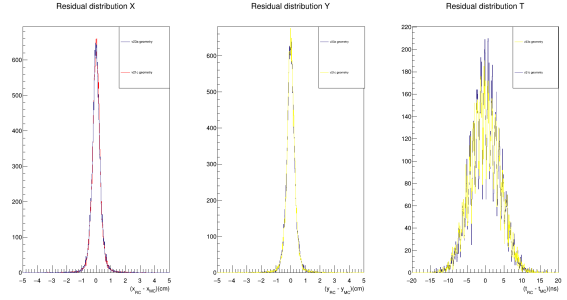


Figure 4: Residual X (left), Residual Y (middle) and Residual T (right) for v23a and v21c geometries

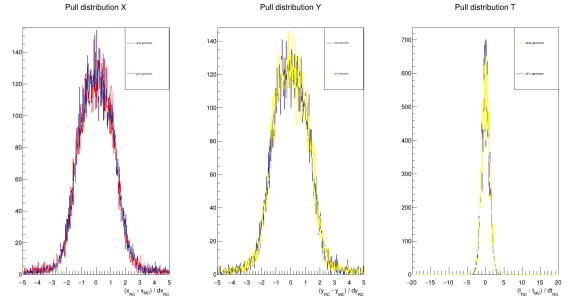


Figure 5: Pull X (left), Pull Y (middle) and Pull T (right) for v23a and v21c geometries

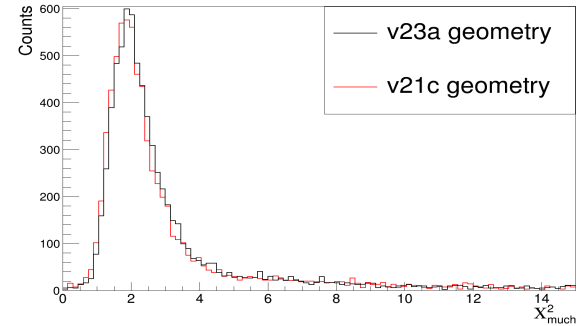


Figure 6: Much χ^2 of reconstructed track for v23a (green) & v21c geometries (black)

the two geometry versions in terms of reconstruction of omega mesons (Fig.7). The following cuts have been used for omega reconstruction: $MUCH_{hits} \geq 11$, $STShits \geq 7$, $TRDhits \geq 1$, $TOFhits \geq 1$, $MUCH \chi^2 \leq 3$, $STS \chi^2 \leq 2$, $Vertex \chi^2 \leq 3$, $\sigma_{TOFCut} = 2$. The efficiency and S/B ratio are comparable for the two geometries.

The geometry is now close to the planned geometry and simulation results are comparable for two geometries (v23a and v21c).

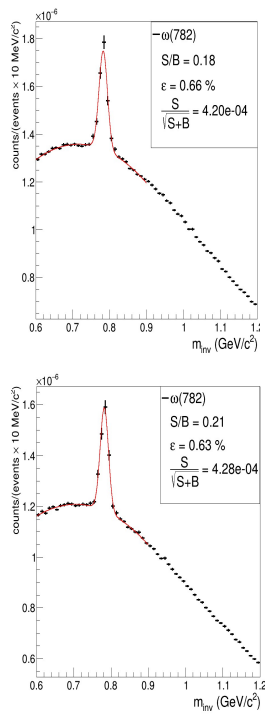


Figure 7: Invariant mass spectra of ω meson for v21c(left) and v23a(right)

References

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Sensitivity of di-muon reconstruction performance on realistic digitization parameters of MuCh

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In this report we examine the physics performance of the Muon Chamber detector setup, employing realistic digitization parameters used to simulate the response of GEM and RPC detectors. For this purpose reconstruction of omega mesons in central Au-Au collisions at an 8 AGeV beam energy ($\omega \rightarrow \mu^+ \mu^-$) has been used. The Muon Chamber detector (MuCh) system is specifically designed for detection of muon pairs produced in energetic nuclear collisions at FAIR SIS100. Within CBMROOT framework, Background particle generation is facilitated by the UrQMD event generator, while the Pluto event generator simulates the decay of omega signals into $\mu^+ \mu^-$. The aim of this study is to evaluate the performance of the MuCh detector with more realistic digitization parameters, and estimate the resulting Efficiency, Signal to Background ratio, and significance for omega meson reconstruction as obtained at different digitization parameters.

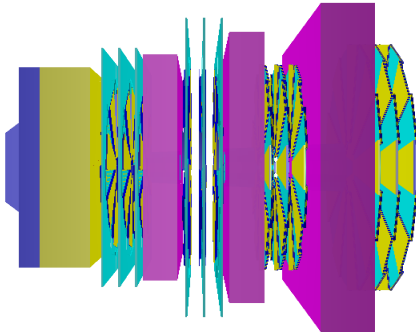


Figure 1: A schematic of the realistic MuCh Setup.

For transport simulation, the CBM experiment's geometric setup, named *SIS100_muon_lmvm*, is used. The chosen geometry version for the MuCh detector is *much.v23a*, representing a more realistic configuration compared to the previous versions of MuCh geometries available in the repository. The MuCh geometric setup incorporates GEM technology for the first two stations, where particle rates are notably high, and RPC technology for the subsequent two stations, where particle rates are comparatively lower. Hadron absorbers are placed between the detector stations, with the first absorber composed of carbon and concrete, while the remaining absorbers are made of iron. Pad readout is used for technologies with projective pad segmentation with azimuthal angle 1 degree for GEM and 2 degree for RPC. The digitization param-

eters default as well as more realistic values of GEM and RPC are outlined in Table 1.

Digitization Parameters				
	Default values		Realistic values	
Parameters	GEM	RPC	GEM	RPC
$Q_{\text{threshold}}$	2 fc	30 fc	6 fc	15 fc
Q_{max}	80 fc	130 fc	80 fc	250 fc
Spot Radius	500 μm	2mm	500 μm	1.25cm
Mean Gas Gain	5000	30000	5000	30000

Table 1: Digitization Parameters for MuCh Detector.

The parameters for both GEM and RPC detectors, comparing the default digitization with the more realistic one are given Table 1. Changes have been made to the GEM detector, adjusting the charge threshold to 6fc from the default value of 2fc. Similarly, for the RPC detector, the charge threshold has been lowered to 15fc from 30fc, with the charge avalanche saturation increased to 250fc from 130fc. Additionally, the spot radius of the RPC has been adjusted to 1.25cm from the Default value of 2mm. These modifications were recommended by the hardware team to ensure more realistic parameters for the Muon Chamber Detector.

For this study, various configurations of digitization parameters were prepared. After incorporating the necessary adjustments in the *CbmMuchDigitizeGem* class, data were generated for all the different setup configurations as outlined in Table 2.

For a comparative analysis, statistics were collected for 100 k events for each digitization configuration setup. The manual cuts selection employed for identification of muon

Setup No.	Different Digitization Configuration
Setup 1	All Default Digitization Parameters
Setup 2	All Default digitization parameters except 6fc $Q_{\text{threshold}}$ GEM
Setup 3	All Default digitization parameters except 15fc $Q_{\text{threshold}}$ RPC
Setup 4	All Default digitization parameters except 250fc Q_{max} RPC
Setup 5	All Default digitization parameters except 1.25cm Spot Radius RPC
Setup 6	All Default Realistic Parameters

Table 2: Different Setups of Digitization parameters.

Parameters	Manual Cuts
No. of STS hits	7
No. of MuCh hits	11
No. of TRD hits	1
No. of TOF hits	1
χ^2 Vertex	2.5
χ^2 STS	2.0
χ^2 MuCh	3.0

Table 3: Manual Cuts used to separate the signal and Background.

track candidates from the pool of reconstructed global tracks are provided in Table 3. Oppositely charged muon track candidates are then combined for calculation of the invariant mass spectra. Super Event technique is used to generate the dimuon combinatorial background. Figure 2 illustrates the invariant mass of omega mesons along with combinatorial background for different configuration setups of digitization parameters.

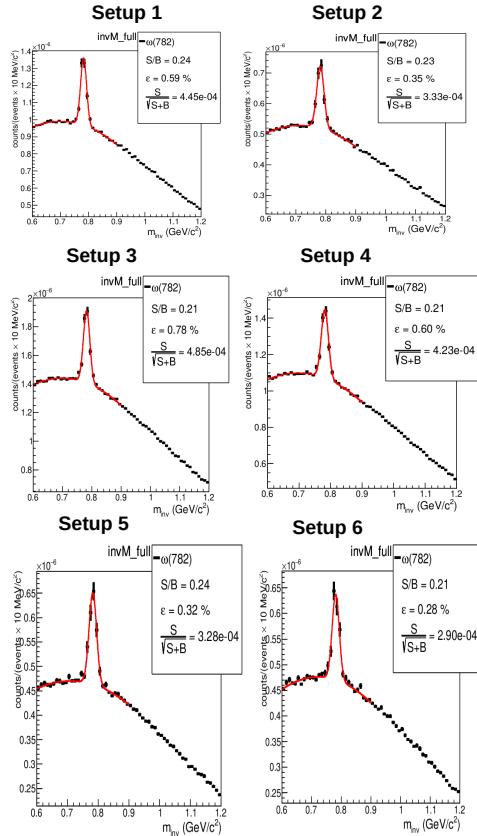


Figure 2: Invariant mass spectra of omega meson for different digitization configuration setup.

The impact of digitization parameters on Efficiency, Signal to Background ratio, and Significance value for each

configuration setup has been evaluated. Additionally, normalized significance values were calculated and are presented in Table 4. A reduction of approximately 5% in significance value was observed due to the change in charge saturation value from 130 fC to 250 fC while keeping all other parameters constant. Conversely, there was an increase in significance value of about 8% resulting from the adjustment of the charge threshold to 15 fC instead of 30 fC for the RPC detector, with all other parameters unchanged.

Significant changes in efficiency for omega meson reconstruction were noted due to the 6 fC charge threshold of the GEM and the 1.25 cm spot radius of the RPC. Specifically, a reduction of 26% in significance value was attributed to the 6 fC charge threshold instead of 2 fC for the GEM detector, and a 27% decrease in significance value was observed when using a spot radius of 1.25 cm instead of 2mm for the RPC detector. A notable decrease in significance value of approximately 34% was observed when employing all realistic parameters together.

Setup No.	Efficiency	S/B	Significance	Normalized Significance
Setup 1	0.59	0.24	4.45e-04	1.00
Setup 2	0.35	0.23	3.33e-04	0.74
Setup 3	0.78	0.21	4.85e-04	1.08
Setup 4	0.60	0.21	4.23e-04	0.95
Setup 5	0.32	0.24	3.28e-04	0.73
Setup 6	0.28	0.21	2.90e-04	0.65

Table 4: Comparison of Efficiency, S/B and Significance of various digitization parameters setup.

A comparative analysis of digitization parameters is required, wherein one realistic parameter remains constant while the others are varied. Additionally, investigations are necessary to ascertain the enhanced gas gain for GEM as the charge threshold increases.

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Reconstruction of omega (ω) meson using Machine Learning methods

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This report depicts the reconstruction of omega mesons in central Au+Au collisions at a beam energy of 8 AGeV for 100 k events, employing diverse machine learning algorithms, and compares the outcomes with traditional dimuon analysis. The SIS-100 accelerator ring at FAIR generates accelerated beams, reaching energies up to 30 AGeV for protons and 12 AGeV for heavy ions. Identifying muon pairs produced through vector meson decay is a crucial physics observable for characterizing the hot and dense matter formed in these collisions. The Muon Chamber detector (MuCh) system is designed to identify these muon pairs. The background particle generation is facilitated by the UrQMD event generator, while the Pluto event generator is utilized to model the omega signal decaying into $\mu^+\mu^-$. The objective of this endeavour is to assess the performance of various machine learning algorithms to enhance $\omega \rightarrow \mu^+\mu^-$ reconstruction efficiency while maintaining a favorable Signal to Background(S/B) ratio. The analysis utilizes the APR21 release of CBMROOT software.

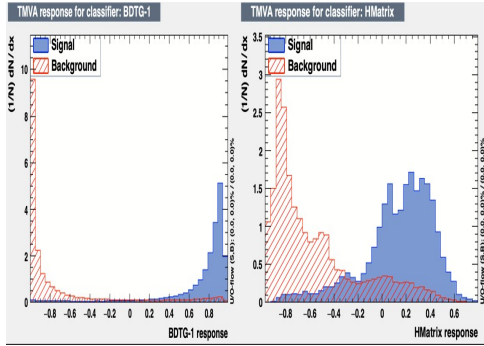


Figure 1: Separation of signal and background muon tracks from BDTG (left) and Hmatrix (right) of ML model.

Various machine learning algorithms such as Gradient Boosted Decision Trees (BDTG), k-Nearest Neighbors (kNN) and HMatrix from the TMultiVariable Analysis class are employed to distinguish between signal and background muons. Traditional cut methods typically utilise single-dimensional boundaries to separate data, but in reality, boundaries can be more intricate. Decision trees facilitate the separation of data across multiple dimensions, enabling the identification of more precise boundaries between signal and background. kNN compares an observed event with reference events from a training dataset. HMatrix discriminates between classes (e.g., signal and background) of a feature vector, utilising Gaussian-distributed

Parameters	Manual Cuts	Soft Cuts
No. of STS hits	7	5
No. of MuCh hits	11	8
No. of TRD hits	1	1
No. of TOF hits	1	1
χ^2 Vertex	2.5	20.0
χ^2 STS	2.0	20.0
χ^2 MuCh	3.0	20.0
TOF mass cut	2σ	2σ

Table 1: Parameters for separating background and signal.

correlated elements, with the inverse being the HMatrix.

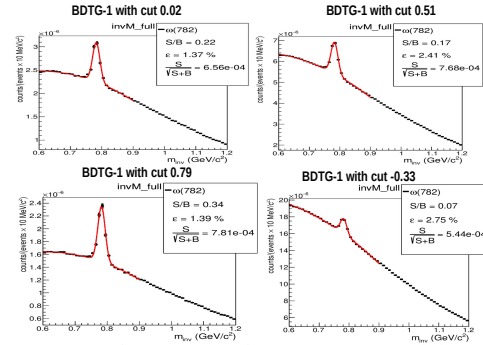


Figure 2: Invariant mass using BDTG-1 model at various values of the ML cut.

Manual cuts are used in traditional dimuon analysis software. Soft cuts are employed in ML techniques for selection of muon track candidates. The ML models are trained using parameters with softer cuts such as Mass, Momentum, Number of STS hits, Number of MuCh hits, Number of TRD hits, Number of TOF hits, χ^2 Vertex, χ^2 STS and χ^2 MuCh track segment and 2σ TOF mass cut as given in Table.1. After training the ML models with soft cuts on the different parameters mentioned, single output variable is obtained for each model as shown in figure 1. Then select the desired cut value with this plot as a reference. It is observed that there is an increase in efficiency without compromising the S/B ratio as the cut value of models is varied as displayed in Fig.3.

TMVA methods are widely employed in the High Energy Physics (HEP) community to assess physics performances and enhance the efficiency of detector systems. Using the various machine learning algorithm, the efficiency for reconstructing omega mesons is observed to increase without compromising the (S/B) ratio compared to conventional method.

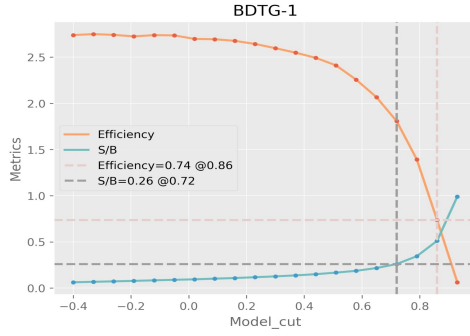


Figure 3: Variation of Efficiency and S/B with BDTG-1 model cut showing pair reconstruction efficiency (orange line) and S/B (green line).

Additionally, the coverage of the Y-Pt phase space is evaluated for the optimal cut values of BDTG-1 as shown in Fig.4. It is observed that applying the most efficient cuts leads to an increased Y-Pt phase space coverage of ω meson considered leading to increase pair reconstruction efficiency.

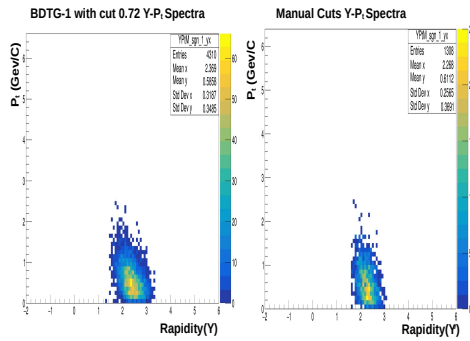


Figure 4: Transverse Momentum(P_t) and Rapidity(Y) phase space distribution of omega mesons in 8 A GeV central Au+Au collisions using BDTG-1 ML algorithm (left) and manual selection cut (right).

After testing multiple models, the BDTG-1 model emerges as the best performer in distinguishing between background and signal muons. The BDTG-1 model demonstrates nearly a three-fold increase in efficiency without compromising the Signal to Background ratio compared to manual cut method as seen in Fig.5. Additionally, other models such as kNN, and HMatrix also exhibit improved performance, demonstrating a notable increase in efficiency while maintaining the same S/B ratio as achieved through manual cuts method. These improvements are quantified and presented in Table 2.

A comparative analysis of the performance of different machine learning algorithms has been conducted as described previously in this report. Future studies will focus on investigating the reconstruction of various other resonances to generate a complete dimuon cocktail in the low mass sector and J/ψ in the high mass region.

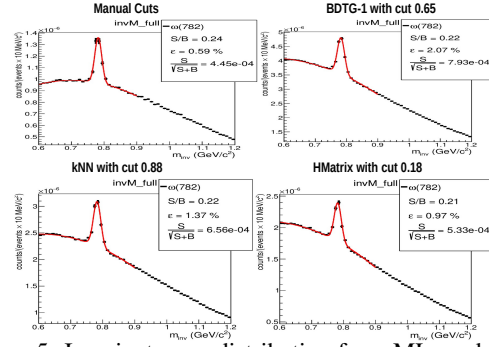


Figure 5: Invariant mass distribution from ML model with best cut values.

Method Name	Best cut value	Efficiency	S/B
Usual Cuts	-	0.59	0.24
BDTG-1	0.65	2.07	0.22
kNN	0.88	1.37	0.22
HMatrix	0.18	0.97	0.21

Table 2: Efficiency and S/B for ML models with best cut values

Acknowledgements

The authors would like to thank Dr. Anna Senger and Prof. Tetyana Galatyuk for their valuable discussions in the course of this study.

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Reconstruction of di-muon cocktail using machine learning techniques in CBM experiment at FAIR

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Introduction

The CBM experiment at FAIR-SIS100 will investigate strongly interacting matter at high baryon density and moderate temperature. One of the proposed key observable is the measurement of the low mass vector mesons, which can be detected via their di-lepton decay channel. As the decayed leptons leave the dense and hot fireball without further interactions, they can provide unscathed information about the fireball produced in energetic nuclear collisions.[1].

In this report, we discuss the reconstruction of di-muon continuum spectra for central Au-Au, 8 AGeV collisions using machine learning techniques for selection of muon track candidates. We compared the results from various Machine learning models and with older manual selection cuts for omega (ω), eta(η), phi(ϕ), rho (ρ) mesons and for full di-muon cocktail spectra.

Simulation

Using the latest version of realistic muon chamber (MuCh) detector geometry(tagged v23a), we have attempted to reconstruct LMVM (ω, η, ϕ, ρ) in the event by event mode following standard reconstruction software. Background of central Au-Au collisions at 8 AGeV was generated using UrQMD event generator, whereas for low mass vector mesons signals PLUTO event generator was used. Single LMVM decaying into $\mu^+ + \mu^-$ was embedded into each background event. The particles are then transported through the upgraded detector setup using the GEANT3 transport engine. The charge deposited is converted to digital signals (digis), which when clustered give hits. The full freeze-out dimuon cocktail spectra include the di-muon decay channel of ω, η, ρ, ϕ and dalitz decay of omega ($\omega \rightarrow \mu^+ + \mu^- + \pi^0$), eta ($\eta \rightarrow \mu^+ + \mu^- + \gamma$) leading to continuum in pair mass distribution[2].

Machine learning techniques

The motivation behind using Machine learning(ML) is to improve the di-muon performance over the existing procedure based on manual selection cuts. ML can be a very useful tool for identifying muon tracks coming through decay of LMVMs. Various ML algorithms like Gradient boosted decision trees (BDTG), KNN, MLP, HMatrix etc. from the TMVA class have been employed for the present study as shown in fig.1. These ML models are trained using variables such as number of MuCh Hits, number of STS

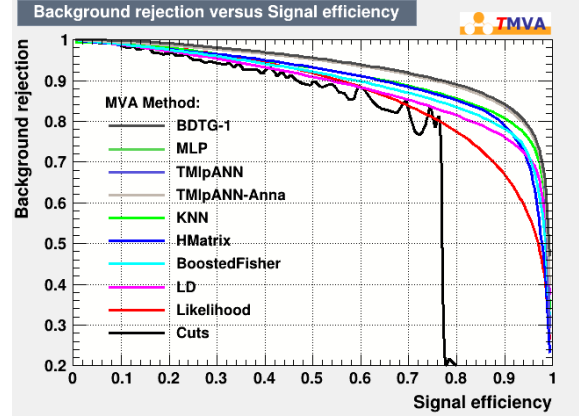


Figure 1: Performance of various ML models.

Hits, number of ToF Hits, number of TRD Hits, χ^2_{MuCh} , χ^2_{Vertex} , χ^2_{STS} , momentum and ToF mass of muon tracks candidates. Out of these models, BDTG performed well for separation of signal and background [fig.2].

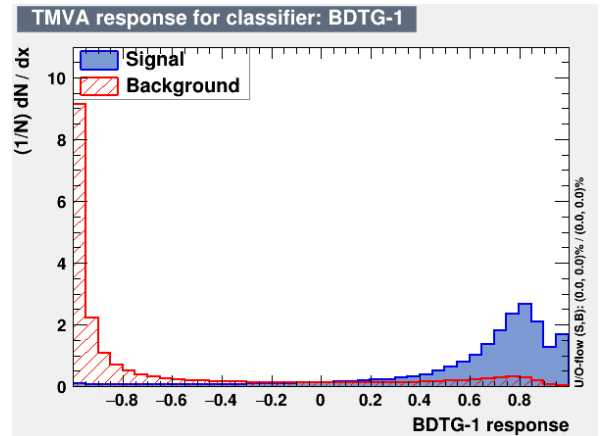


Figure 2: Separation of signal & background using BDTG model for cocktail data

Result and Analysis

Traditionally the following single muon manual selection cuts are used for calculation of di-muon invariant mass distribution: Number of MUCH hits ≥ 11 , number of STS hits ≥ 7 , number of TRD hits ≥ 1 , number of TOF hits ≥ 1 , $\chi^2_{MuCh} \leq 3$, $\chi^2_{STS} \leq 2$, $\chi^2_{Vertex} \leq 3$, sigmaTOF-

Cut = 2, applied in sequence. So, instead of these cuts we have used a single cut on ML output variable of BDTG model to obtain dimuon invariant mass spectra for the two body decay of resonances. For each case the combinatorial background is calculated using super event(SE) analysis.

Omega reconstruction ($\omega \rightarrow \mu^+ + \mu^-$)

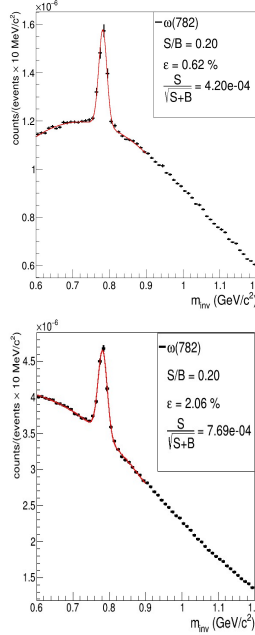


Figure 3: Invariant mass spectra of ω meson using manual cuts(left) and using BDTG model with cut at 0.7 (right)

Eta reconstruction ($\eta \rightarrow \mu^+ + \mu^-$)

Phi reconstruction ($\phi \rightarrow \mu^+ + \mu^-$)

Particle	method	S/B ratio	Efficiency (%)	Normalized Significance
ω	manual cuts	0.20	0.62	1
ω	BDTG@0.7	0.20	2.07	1.83
η	manual cuts	0.01	0.26	1
η	BDTG@0.7	0.01	1.20	2.12
ϕ	manual cuts	0.01	2.53	1
ϕ	BDTG@0.5	0.01	6.44	1.52
ϕ	manual cuts	0.01	2.53	1
ϕ	BDTG@0.84	0.02	2.37	1.29

Table 1: Comparison of ML with manual cuts for LMVMs.

Fig.3,4,5 shows the invariant mass spectra of ω , η , ϕ reconstruction respectively, using manual cuts and using BDTG model. The improvement in di-muon performance using ML algorithm can be seen from above table and figures. For comparable S/B ratio, the pair reconstruction effi-

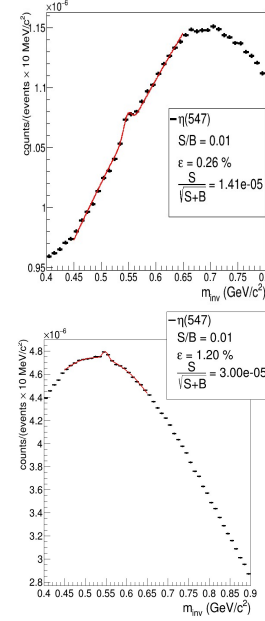


Figure 4: Invariant mass spectra of η meson using manual cuts(left) and using BDTG model with cut at 0.7 (right)

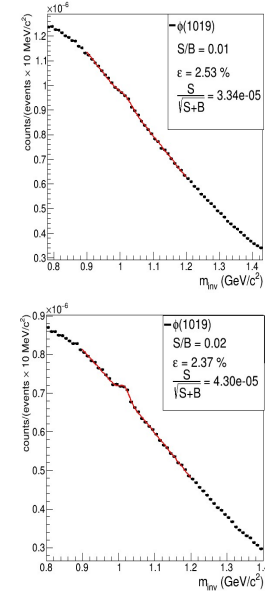


Figure 5: Invariant mass spectra of ϕ meson using manual cuts(left) and using BDTG model with cut at 0.84 (right)

ciency and significance is seen to be increased significantly for ω , η , ϕ mesons. Alternatively by varying the ML cut parameter value, we have seen that for efficiencies comparable to manual cuts, the S/B increases by around a factor of 2 for ϕ meson[table 1].

Work is under progress for further optimization of the ML procedure for reconstruction of the di-muon continuum contributions both from freeze-out cocktail and the thermal

radiations from a hot and dense fireball.

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Thermal and non-thermal production of J/ψ from 30 AGeV p+A collision at CBM

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In relativistic nuclear collisions, hadrons containing charm quarks are produced in the initial stage of the collisions and thus offer the possibility to probe the entire evolution of the collision. Depending on the interaction with the medium, CBM experiment at FAIR-SIS100, charm quarks and anti-quarks can hadronize into D meson, charmed baryon (like Λ_c) or charmonium (J/ψ , ψ'). In CBM experiment at FAIR-SIS100 charm production will be studied close to the kinematic production. In these low energy collisions as will be available from SIS100, the formation time of J/ψ mesons is small compared to the recation volume. The kinematic coverage of CBM experiment is uniquely suitable to study the interaction between the fully formed J/ψ mesons and the dense nuclear medium. Systematic measurement of J/ψ production in proton-nucleus ($p + A$) collisions with varying mass number (A) of the target nucleus at proton beam energies up to 30 GeV will shed light on the inelastic interaction and dissociation of the J/ψ mesons in the cold nuclear medium. To study feasibility of such measurements in CBM, we have been doing physics simulations to study $J/\psi \rightarrow \mu^+ \mu^-$ reconstruction in 30 GeV $p + Au$ collisions, with the CBM-MuCh setup. So far, in these studies the phase space (transverse momentum (p_T) and rapidity (y)) distributions of J/ψ mesons are obtained from PLUTO event generator. PLUTO generates the J/ψ mesons following a thermal fireball model with thermal $m_T (= \sqrt{m^2 + p_T^2})$ and Gaussian rapidity distributions [1]. However validity of such thermal distributions for J/ψ in low energy collisions is questionable. Therefore, in the present study we use PYTHIA event generator to sample non-thermal J/ψ phase space distribution at the FAIR energy range. In PYTHIA, J/ψ s are produced by fragmentation of stretched strings following a LUND string fragmentation formalism [2].

In this article we use PLUTO and PYTHIA generators to compare thermal and non-thermal J/ψ production in p+A collisions at FAIR with proton beam at 30 GeV. For PYTHIA, we however, generate pp collisions because at such low energy pp and p+A will be very much similar because a proton at the most will interact with a single nucleon of the target nucleus. Figure 1 shows transverse momentum and rapidity distributions of J/ψ at 30 AGeV generated from PYTHIA (blue line) and PLUTO (red line) at the generator level. It seems from Fig. 1 that the width of both transverse momentum and rapidity distributions are wider for PLUTO than PYTHIA.

At present, this study is only performed at the generator level. Next we plan to perform full CBM physics simulation, incorporating detector effects, taking input distribu-

tion from PLUTO and PYTHIA. Our final objective is to check whether efficiency, signal-over-background, significance, etc are different for thermal and non-thermal phase space distributions obtained from PLUTO and PYTHIA, respectively.

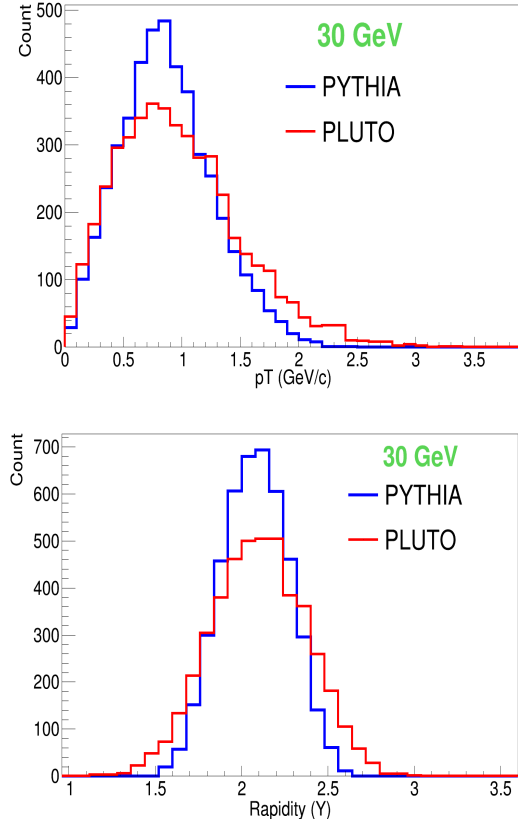


Figure 1: Transverse momentum (top) and rapidity (bottom) distributions of J/ψ at 30 AGeV generated from PYTHIA (blue line) and PLUTO (red line)

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Prospects towards proton structure studies via charm production in proton-proton interactions with the Compressed Baryonic Matter experiment

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This report discusses prospects of charm-production studies with a proton beam by the Schwerionensynchrotron 100 (SIS100) impinging on a fixed proton target and using the Compressed Baryonic Matter (CBM) experiment at the Facility for Anti-proton and Ion Research (FAIR). The charm-nucleon interaction can be experimentally studied exploiting the reaction $pp \rightarrow ppJ/\psi$ whereby the J/ψ is identified via its dileptonic decay $J/\psi \rightarrow ee, \mu\mu$ with branching fractions of about 6% each. Hereby, it is expected that the exchange between the protons and the J/ψ s are purely based on gluonic nature enabling the possibility to determine and access the gluonic gravitational form factors (GFFs) [1] based on hadroproduction. In these studies, we assume a liquid hydrogen (LH₂) target with a thickness of 5 cm. The reachable maximum proton momentum is 30 GeV/c corresponding to a center-of-mass energy of $\sqrt{s} = 7.6$ GeV. The CBM detector is a suitable site for the reconstruction of exclusive final state events. Thus, the proton-proton program can be seen as an extension of the heavy-ion program with CBM at FAIR. Assuming the J/ψ production cross section to be ~ 1 nb and 10^{10} to 10^{11} protons-on-target (POT) per 10 seconds (spill), the expected production rate with CBM is about 1100 to 11000 events per day. Figure 1 represents the signal efficiency using the geometrical acceptance of the CBM detector versus the proton lab momentum based on fast simulations (PANDAROOT-FastSim package).

The fast simulation results presented in Fig. 1 are com-

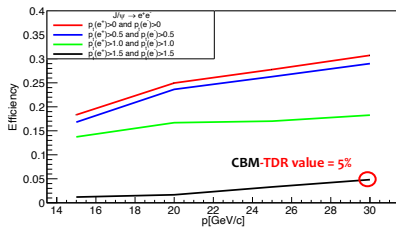


Figure 1: Signal reconstruction efficiency using CBM acceptance for the channel $pp \rightarrow ppJ/\psi$ for $J/\psi \rightarrow ee, \mu\mu$ decays as a function of the lab momentum for the CBM detector using fast simulations. The different colors represent different p_t cuts i.e. cuts on the transverse momentum applied separately on the electrons and positrons.

patible with earlier studies that were done with a full simulation using CBMROOT [2] and reported in [3]. For the heavy-ion feasibility studies, an explicit cut on p_t was used resulting to a total efficiency of 5 % (Fig. 1 red circle). To

validate our fast simulation results, we studied the effect of the reconstruction efficiency for proton collisions on LH₂ target with different p_t cuts. It turns out that the independent simulation method based on fast simulations is in agreement when looking at a lab momentum of 30 GeV/c and using a p_t cut applied separately on the electrons and positrons at 1.5 GeV/c. For the proposed proton-proton studies, it will be possible to exclude an explicit p_t cut leading to an efficiency gain by a factor of almost ~ 6 to 30 % (red line, no p_t cut). Besides the efficiency studies, we also studied the background yield and evaluated the maximum statistical significance one will be able to obtain. The main background source will be due to the pionic channel via e.g. $pp \rightarrow pp\pi^+\pi^-$ with a cross section of about 1 mb. Taking into account the expected capabilities of CBM and by making use of kinematic constraints (energy-momentum conservation), we expect to be able to reach a high signal-to-background ratio of about $s/\sqrt{s+b} \sim 100$ within 1 month of beam time (30 days) with 10^{11} POT. Figure 2 illustrates the corresponding invariant-mass spectrum of the dilepton pair under these conditions using a product of duty cycle and reconstruction efficiency to be 10 %. In conclu-

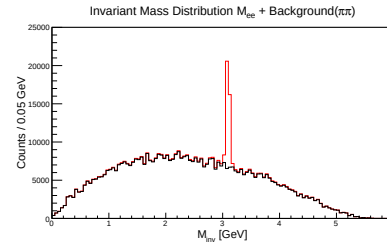


Figure 2: Invariant mass distribution of $M_{inv}(J/\psi \rightarrow ee) + M_{inv}(\pi^+\pi^-)$ (red) versus $M_{inv}(\pi^+\pi^-)$ (black).

sion, the proton beam foreseen with SIS100 in combination with the CBM detector opens a window towards accessing the $p - J/\psi$ final state interaction strength. Cross section measurements near the hidden-charm production threshold are linked to various key topics in the field of strong QCD, namely the intrinsic charm component of the proton, the mass radius of the proton, GFFs and the emergent hadron mass puzzle.

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Elliptic and triangular flow of charged hadrons in $^{197}\text{Au}+^{197}\text{Au}$ collisions at $E_{\text{lab}} = 10A$ and $20A$ GeV in the AMPT model

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We present some results on second and third harmonics of the azimuthal angle (ϕ) distribution of charged hadrons emitted from Au+Au collision events generated by a multiphase transport (AMPT) model [1], in its default (Def) and string melting (SM) version, at incident beam energies $E_{\text{lab}} = 10A$ and $20A$ GeV. The anisotropy in ϕ -distribution can be Fourier decomposed as [2],

$$\frac{dN_{ch}}{d\phi} \propto \left[1 + 2 \sum_{n=1}^{\infty} v_n \cos \{n(\phi - \Psi_R)\} \right] \quad (1)$$

The n -th order flow coefficient (v_n) is then given by,

$$v_n = \langle \cos[n(\phi - \Psi_R)] \rangle \quad (2)$$

where Ψ_R is the azimuthal angle of the reaction plane, a plane subtended by the impact parameter (b) of the collision and the incident beam axis. $\langle \rangle$ denotes an averaging over all particles and all events. The second and third harmonic coefficients, respectively known as the elliptic (v_2) and triangular (v_3) flow parameters, are of particular interest. They allow us to study the early stage evolution of a nucleus-nucleus (AB) collision [3, 4]. In real experiments the direction of impact parameter can not be determined. An alternative way to determine the flow parameters is to use the n^{th} order participant plane angle ψ_n given by,

$$\psi_n = \frac{1}{n} \left[\arctan \left(\frac{\langle r^n \sin n\varphi \rangle}{\langle r^n \cos n\varphi \rangle} \right) + \pi \right] \quad (3)$$

where (r, φ) denote the polar coordinates of the nucleons directly participating in a collision. Corresponding geometrical anisotropy of the overlapping part of the colliding nuclei is measured by an eccentricity parameter [4],

$$\varepsilon_n = \frac{\sqrt{\langle r^2 \cos n\varphi \rangle^2 + \langle r^2 \sin n\varphi \rangle^2}}{\langle r^2 \rangle} \quad (4)$$

In Figure 1 we present the centrality dependence of v_2 and v_3 for charged hadrons with transverse momentum $p_T > 0.2$ GeV/c falling within the central pseudorapidity region $|\eta - \eta_0| < 1.0$. Collision centralities are determined by the reference multiplicity (N_{ref}) method that takes care of the auto-correlation effect [5]. We use the multiplicity of charged hadrons in the $|\eta - \eta_0| > 1.0$ region as N_{ref} . A bell shaped pattern of the centrality dependence is seen in the simulated v_2 -values irrespective of the beam energy and model used. This observation can be explained in terms of the initial geometry and pressure gradient developed

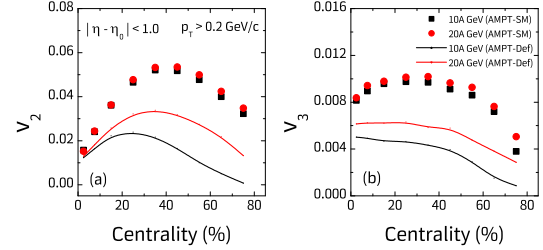


Figure 1: Centrality dependence of v_2 and v_3 in Au+Au events at $E_{\text{lab}} = 10A$ and $20A$ GeV in the AMPT-SM and AMPT-Def models.

thereof in early stages of the collision. In central collisions overlapping part of the colliding nuclei is almost symmetric, and enough pressure gradient is not generated that results in lower v_2 -values. In peripheral initial asymmetry of the overlapping region is maximum, but not enough particles are present to carry the effect of pressure gradient to the final state. In mid-central collisions enough particles as well as spatial asymmetry are present, which lead to a maximum in the v_2 -distribution. We get significantly lower v_2 -values in AMPT-Def than in AMPT-SM, a feature also observed at the top RHIC energies [6]. This feature can be ascribed to the absence of partonic interactions in the AMPT-Def model. In the AMPT-SM v_2 -values hardly change from $10A$ to $20A$ GeV. However, in the AMPT-Def a higher E_{lab} shows significantly higher v_2 . Except in a few extreme peripheral classes we do not observe any significant difference in the v_3 -values between $10A$ and $20A$ GeV obtained in the AMPT-SM. Once again those obtained from AMPT-Def show a clear energy ordering. In comparison with v_2 , the v_3 -values are always at least an order less in magnitude. The reason is, v_3 arises only due to fluctuations of the initial state. There is no role of pressure gradient whatsoever.

Figure 2 shows the p_T -dependence of v_2 and v_3 for charged hadrons emitted within $|\eta - \eta_0| < 1.0$ for the (30 – 40)% central events. In both AMPT-Def and AMPT-SM v_2 and v_3 increase almost linearly with p_T . It implies that particles with higher p_T can more efficiently carry the signal of initial spatial asymmetry to the azimuthal momentum anisotropy in the final state. We do not see any significant energy dependence in the differential p_T -distributions of v_2 and v_3 obtained from the AMPT-SM, whereas a clear energy ordering is present in the AMPT-Def model. Just like the integrated v_2 and v_3 -values, their differential p_T -distributions in the

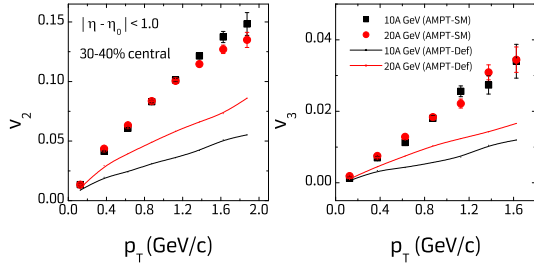


Figure 2: Transverse momentum dependence of v_2 (left) and v_3 (right) in (30 – 40)% central Au+Au events at $E_{\text{lab}} = 10A$ and $20A$ GeV in the AMPT-SM and AMPT-Def models.

AMPT-Def mode lie lower than the AMPT-SM.

In order to study the effects of initial asymmetry of the overlapping part of the colliding nuclei on the flow parameters, we determine the correlation functions $C(\varepsilon_n, v_n)$ defined as [7],

$$C(\varepsilon_n, v_n) = \left\langle \frac{(\varepsilon_n - \langle \varepsilon_n \rangle_{\text{av}}) \cdot (v_n - \langle v_n \rangle_{\text{av}})}{\sigma_{\varepsilon_n} \sigma_{v_n}} \right\rangle_{\text{av}} \quad (5)$$

Here σ_{ε_n} and σ_{v_n} are the standard deviation of the quantities ε_n and v_n respectively. $\langle \rangle_{\text{av}}$ denotes an averaging over all events belonging to the same centrality class. In Figure 3 we plot the centrality dependence of $C(\varepsilon_n, v_n)$ for $n = 2$ and 3 . For $n = 2$ one can see peaks in the distributions in central collisions. On the other hand for $n = 3$ the correlation coefficients monotonically decrease from central to peripheral collisions. At each centrality $C(\varepsilon_3, v_3)$ is always significantly smaller than

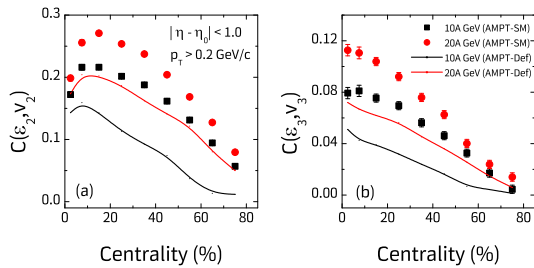


Figure 3: Centrality dependence of (a) $C(\varepsilon_2, v_2)$ and (b) $C(\varepsilon_3, v_3)$ in Au+Au events at $E_{\text{lab}} = 10A$ and $20A$ GeV in the AMPT-SM and AMPT-Def models.

$C(\varepsilon_2, v_2)$, which suggests that eccentricity (ε_2) of the overlapping part plays a stronger role to develop v_2 than what triangularity (ε_3) does to v_3 . Initial fluctuations of the participating nucleons are more responsible to develop v_3 . In the AMPT framework a higher E_{lab} always generates a higher correlation. Correlation strength in the AMPT-Def mode is consistently weaker than that observed in the AMPT-SM mode.

Even within a particular centrality class the v_n -values can fluctuate on an event-by-event (e-by-e) basis. Such fluctu-

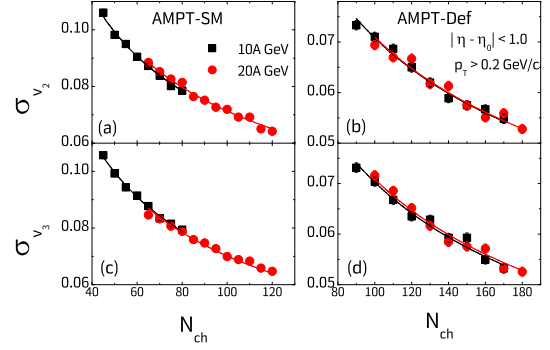


Figure 4: Multiplicity dependence of σ_{v_2} and σ_{v_3} in Au+Au collisions at $E_{\text{lab}} = 10A$ and $20A$ GeV in the AMPT-SM and AMPT-Def models. Continuous curves represent $1/\sqrt{N_{ch}}$ scaling.

ations are statistical and dynamical in nature. In order to study the flow fluctuations we first calculate the standard deviations ($\sigma_{v_n} : n = 2, 3$) of the e-by-e v_n distributions at a fixed multiplicity (N_{ch}) in the centrality classes where v_n is maximum i.e. $dv_n/db = 0$. In this way we eliminate the contributions coming from the impact parameter and multiplicity fluctuations. In Figure 2, we plot (σ_{v_n}) against N_{ch} . We find that in all cases σ_{v_2} and σ_{v_3} nicely scale like $1/\sqrt{N_{ch}}$, which suggests that the e-by-e flow fluctuations at this energy range are due to statistical reasons [8], and are almost energy independent. However, significant dynamical contributions to flow fluctuations are reported in the STAR experiment and corresponding AMPT-SM simulation at $\sqrt{s_{NN}} = 200$ GeV [9]. This simulation study may act as a baseline prediction for the upcoming compressed baryonic matter experiment to be held at the facility for anti-proton and ion research.

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Development of an algorithm for fitting correlation functions

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Introduction

Femtoscopia is a technique used in experimental physics to measure the size of the source that emits particles [1]. The measured correlation function (CF) is defined as the ratio of correlated pairs (numerator N) to the uncorrelated pairs (D denominator). The denominator is usually calculated by mixing particles from mixed pairs. The ratio is calculated as a function of momentum difference q (1).

$$C(q) = N(q)/D(q) \quad (1)$$

There is also another formula for the theoretical correlation function:

$$C(q) = \int S(\Delta r) |\Psi(q, \Delta r)|^2 d\Delta r \quad (2)$$

In the Eq. (2) above, the S is the source function, Δr is the relative distance between the emission points of two particles, and Ψ is a two-particle wave function. Whilst the equation can be solved analytically for a limited number of cases, determination numerically is the usual approach [2]. The calculations usually need the pairs from the model/data as input because such generation requires a lot of computing time. Usually, pairs are generated once and later reused. Generally, even calculating a single theoretical correlation function requires a significant amount of time; in the case of fitting, this problem is even larger because we have to calculate many such functions.

In the CBM experiment, protons will be one of the most abundant particles. Understanding the spatio-temporal nature of their source will be key to understanding the dynamics of the processes during collisions. Now, many algorithms allow the fitting of the one-dimensional proton-proton correlation functions. Unfortunately, no algorithm allows for three-dimensional functions of the proton pair to be fitted, due in the main part, to the enormous computational time needed for such an operation.

The ROCO

The standard approach calculates each theoretical CF used in the fit procedure separately. The problem is that the data for calculations must be read each time, and for each pair, the two-particle wave function must be calculated. The data is read once in the ROCO (Read Once, Calculate Once) procedure. Also, the two-particle wave function is calculated once. It makes the ROCO procedure much faster as compared to a classical approach.

The ROCO algorithm was successfully implemented into

the HAL framework (software used for femtosopic measurements in CBM) for the calculation of one-dimensional correlation functions. In 2023, the ROCO procedure was implemented to calculate the three-dimensional correlation function of protons. Implementation of the ROCO algorithm required several changes:

- The ROCO calculates all theoretical CFs simultaneously. Unfortunately, this would require a huge amount of memory. Therefore, the algorithm calculates only one bin of the theoretical CF (another bin might be calculated in another computing node)
- Further reduction of memory consumption was possible using the Spherical Harmonics representation of the CF [3] (one large 3-dimensional histogram that represents the function was replaced by a few one-dimensional histograms).
- The structure of the file with pairs (used to calculate the CF) was modified. Now, data is sorted to avoid unnecessary I/O operations.
- The new way of writing the theoretical CF's was developed, as it was mentioned before - it's impossible to store all calculated theoretical CF's simultaneously. Now, the ROOT trees are used, and thanks to this, only a small part of the data is loaded into memory.
- Due to the fact that despite optimizations, calculations still require huge resources, the ROCO was modified and now supports using a batch system (each bin of CF can be calculated on a separate node).
- Each node calculates only the fraction of theoretical functions; a special application for merging that data into one output file was developed. This algorithm merges data in two steps. In the first step, data is merged in one file but not compressed (e.g., the numerator and denominator of CF are stored); in the second step, data is compressed (this makes the fitting procedure faster).

Validation

The results of the calculations were validated by comparing data obtained from ROCO with analytical calculations for non-interacting identical fermions. Comparison is shown on . A V-tune profiler was used to test the new algorithms ¹. Proton-proton correlation functions with a

¹<https://www.intel.com/content/www/us/en/developer/tools/oneapi/vtune-profiler.html>

Gaussian source were tested for $N=1000$ (a thousand theoretical correlation functions). The most significant benefit of ROCO was related to the fact that I/O operations (pair reading) are performed once. The speed-up of the algorithm was estimated in the analyzed case to be around 800. It can be seen on . The red and yellow areas are used in ROCO once, whereas, in the standard approach, they are called N times.

Figure 1: Comparison of C_0^2 component of correlation function. The points show the results of analytical calculations, and the red line shows the output of the ROCO algorithm.

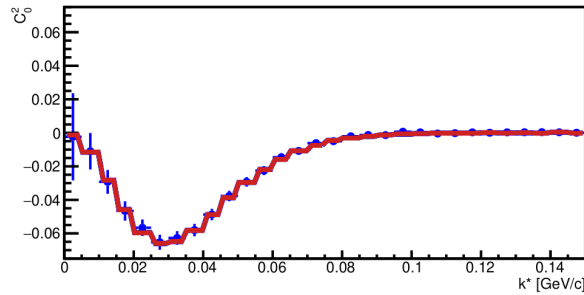
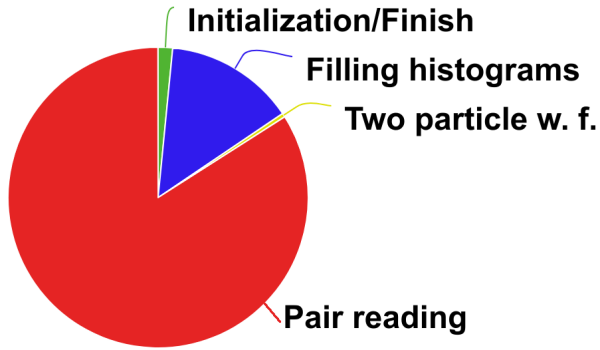


Figure 2: Results of profiling with V-tune.



Plans

The implementation of the ROCO procedure was successful. The method initially developed for a one-dimensional correlation function significantly reduced the computing time needed for three-dimensional CFs calculations. Now, there are plans to implement this algorithm for different shapes of the source that emit particles and extend calculations to the cartesian representation of three-dimensional correlation functions.

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Femtoscopia studies with iHKM

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iHKM model

Integrated HydroKinetic Model (iHKM) [1] is a complete algorithm incorporates the following stages:

- generation of the initial states: (MC Glaub & CGC);
- thermalization of initially non-thermal matter;
- viscous chemically equilibrated hydrodynamic expansion;
- particlization of expanding medium at the hadronization area;
- a switch to UrQMD cascade with near equilibrium hadron gas as input;
- simulation of observables.

Model description includes:

- Initial State:
 - Generation of initial state using GLISSANDO;
 - Nucleon positions in colliding nuclei;
 - Transverse positions of sources and RDSs;
 - Calculation of physical quantities and output file;
- Pre-thermal Stage:
 - Initial energy density configuration with GLISSANDO;
 - Thermalization process with relaxation model;
- Matter Evolution:
 - Thermal and Chemical Near-Equilibrated Zone;
 - Evolution with relativistic viscous hydrodynamics after $\tau = 1$ fm/c;
 - Numerical solution using vHLLE code;
 - Expansion of superdense matter near local equilibria;
- Particlization:
 - Continuous process in iHKM;
 - Gradual escape of particles forming non-equilibrium Wigner function;
 - Input for UrQMD hadronic cascade;
 - Switch to particle cascade at $T = 165$ MeV;
 - Switching surface defined by Cornelius routine;

- Hadronic Cascade:

Generated hadrons fed into UrQMD cascade;

Particle propagation backward in time;

Interaction allowed at particlization hypersurface;

Application of Laine-Schroeder EoS;

Decay of heavy resonances not in UrQMD list;

Particle propagation stops at Cartesian time 400 fm/c;

Events stored in ROOT trees and files;

Special script-codes for predicting experimental observables.

Femtoscopia

Femtoscopia is a method of extraction of information about the space-time structure of the source that emits particles, and it is used to measure the size of a fireball created during a heavy-ion collision. Thus, it is possible to explore the dynamics of a such collision [2].

Femtoscopia uses two-particle correlations to measure the size of the source. The main tool femtoscopia uses is the correlation function (CF) defined in the case of the experiment by eq. 1, where, q is the difference between the four-momentum of two particles ($q = p_1 - p_2$). The N (the numerator of CF) is a distribution of correlated pairs, whereas D (denominator) is a distribution of uncorrelated pairs. The mixing technique creates uncorrelated pairs - particles in such pairs belong to different events.

$$C(q) = \frac{N(q)}{D(q)} \quad (1)$$

It is worth stressing that there is also another (theory) definition of the correlation function 2

$$C(q) = \int \rho(\Delta r^*, q) |\psi(\Delta r^*, q)|^2 d\Delta r^* \quad (2)$$

In this definition, r^* is the difference between the emission points of two particles. The shape of the correlation function depends on the size of the source ρ and the type of the particles. The particle's species defines the influence of the quantum statistic and interactions between particles described by $|\psi(\Delta r^*, q)|^2$ term.

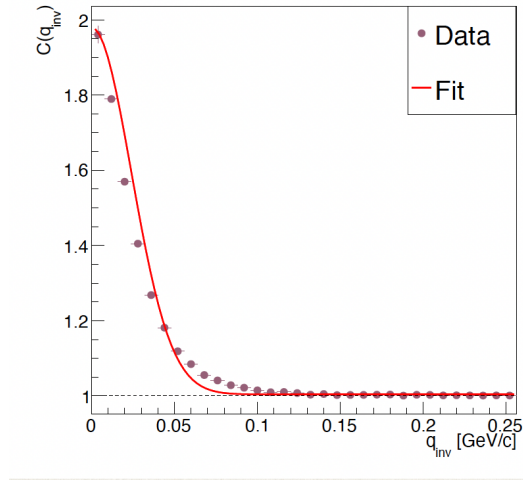


Figure 1: The result of 1-dimensional correlation function [4].

Two-pion measurements

One of the criteria to validate the iHKM model adaptation for the CBM experiment is to use two-particle correlations based on charged pions. For this purpose, the data generated from the iHKM model for the collision energy $\sqrt{s_{NN}}=4.5$ GeV using Au+Au collisions were used. Figure 1 shows the result of the one-dimensional correlation function for pairs of negative pions together with the theoretical fit described by the eq. 3.

$$C(q) = 1 + \lambda e^{-q^2 R^2} \quad (3)$$

where λ is the chaoticity parameter, and R describes the source size in a one-dimensional scenario. The correlation function is calculated for the Longitudinal Co-Moving System where q is denoted by the $q_{inv} = \sqrt{(p_1 - p_2)^2 - (E_1 - E_2)^2}$. Figure 2 shows the three-dimensional correlation function presented in the Bertsch-Pratt parametrization [3]. The left column shows the projections of the correlation function for *out*, *side*, and *long* directions, where the first column shows the fit described by eq. 4 and the second column by eq. 5. They all show results for the transverse momentum of the pair $k_T \in [0.1, 0.3]$ GeV/c.

$$C(q) = 1 + \lambda e^{-q_o^2 R_o^2 - q_s^2 R_s^2 - q_l^2 R_l^2} \quad (4)$$

$$C(q) = 1 + \lambda e^{-q_o^2 R_o^2 - q_s^2 R_s^2 - q_l^2 R_l^2 - q_o - l^2 R_o R_l} \quad (5)$$

Figure 3 compares iHKM predictions to the STAR data [5] of the femtoscopic parameters for various transverse masses $m_T = \sqrt{k_T^2 + m^2}$.

Figure 4 compares the iHKM predictions for $\sqrt{s_{NN}} = 4.5$ GeV to various World's results.

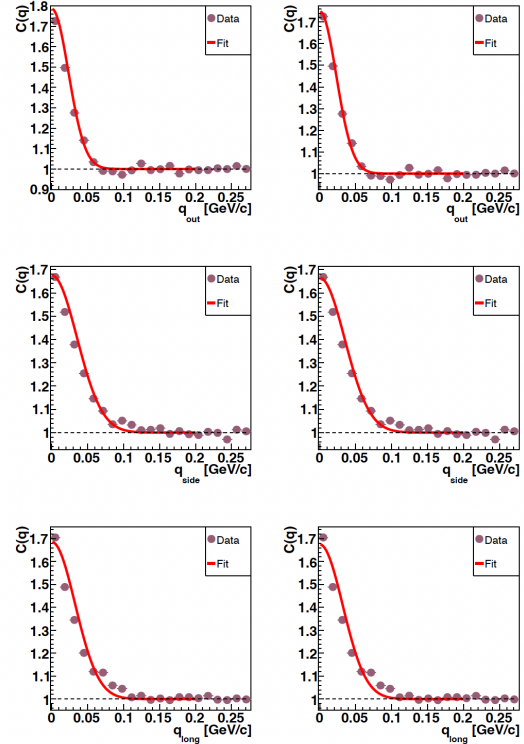


Figure 2: The result of 3-dimensional correlation function [4].

Summary

The iHKM model for the collision energy of $\sqrt{s_{NN}} = 4.5$ GeV is in progress. For future considerations, the following steps are considered: distinguishing various EoS, checking the impact of the collectivity, and considering observables other than femtoscopic to validate the model parameters.

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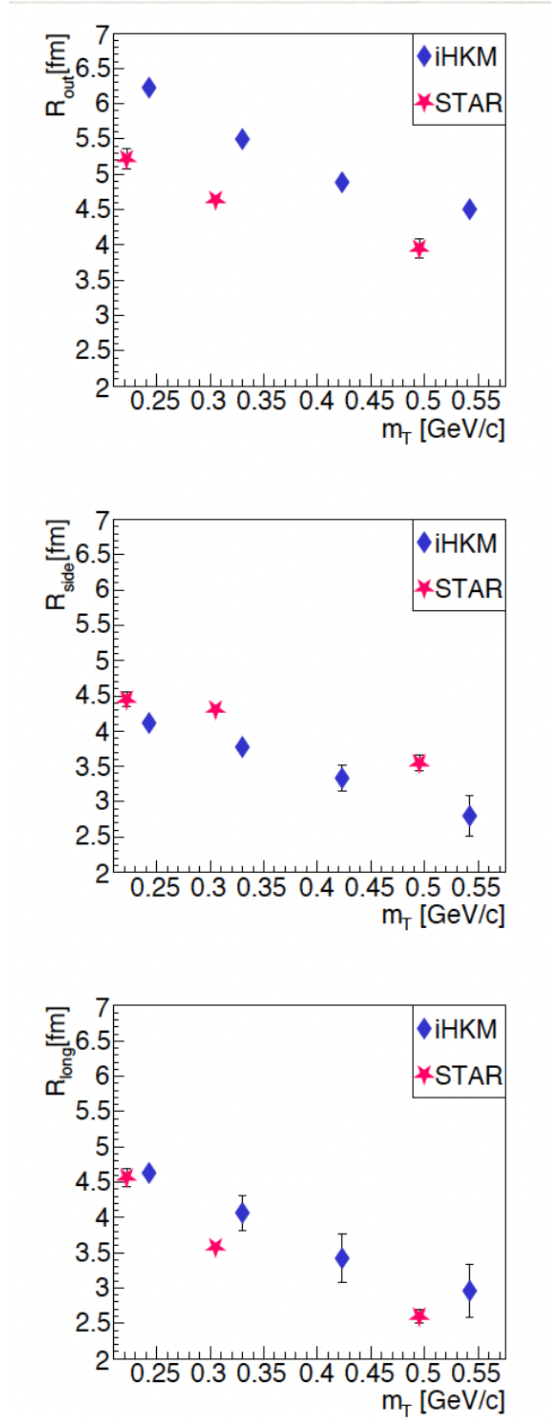


Figure 3: The result of the 3-dimensional correlation function for various intervals of the transverse mass [4].

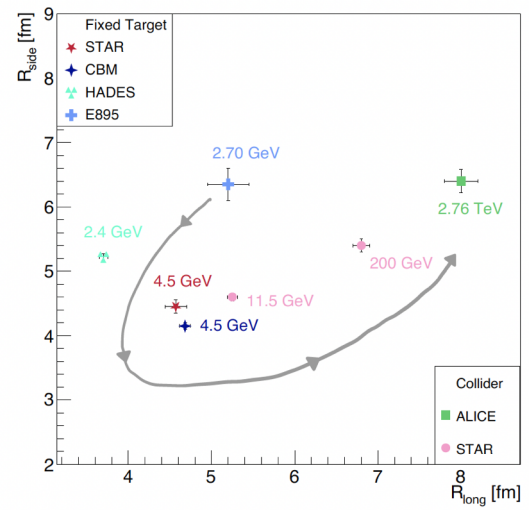


Figure 4: Sideward and longitudinal source sizes for various experimental results and the predictions from iHKM model [4].

Realizing dynamical fluctuations in AMPT generated Monte-Carlo (MC) data

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Introduction

One of the primary objectives of relativistic heavy-ion collisions is to investigate the Quantum Chromodynamics (QCD) phase diagram and phase boundary. Finite temperature Lattice QCD simulations indicate a crossover from hadronic phase to Quark Gluon Plasma (QGP) phase at vanishing baryon chemical potential $\mu_B = 0$ and a QCD-based model “*Two Color QCD*” suggest that the transition might be first-order at large μ_B [1, 2]. The first-order phase transition terminates at what is known as the critical end-point (CEP). Efforts, both theoretical and experimental, are being made to locate the CEP by studying the non-monotonic behaviors in the fluctuations of conserved quantities. Multiplicity or density fluctuations that follow intermittency behavior arise from the linked fractal geometry of QCD matter, in analogy to the critical opalescence seen in conventional matter around critical point. Rigorous studies have already been done by various researchers and research groups using experimental data. Power-law behavior in Si+Si collisions at 158 AGeV has been seen in the NA49 experiment [3]. The scaling exponent derived from the intermittency index in the initial analysis of the STAR experiment indicates a minimum in central Au+Au collisions at $\sqrt{s_{NN}} = 20\text{-}30$ GeV [4]. Meanwhile, simulations involving hadronic potentials and the self-similar feature indicate that the intermittency behavior could be seen in Au+Au collisions at RHIC energy. Similar investigations for lower beam energies is crucial. According to hydrodynamical calculations, it is expected that there might be a first order phase transition from hadronic matter to exotic nuclear matter at the highest SIS100 energies [5]. It is also anticipated that a critical point may exist at such a region of QCD phase diagram. Around the critical point, the thermodynamical variables are extremely sensitive to a slight change in order parameter. A search for physical observables related to thermodynamical parameters may be important to study.

Multiplicity fluctuation is one of the important observables to provide information about particle production mechanism in heavy-ion collisions. The fluctuation of multiplicity affects intermittency, and there is a correlation between these two. Intermittency measurement in relativistic heavy-ion collisions is a helpful probe of density fluctuations associated with the events. The Scaled Factorial Moment (SFM) technique is one of the most successful methods and is used to extract dynamical fluctuations from a mixture of statistical and dynamical fluctuations. In this study, an attempt has been made to study the dynamical fluctuation with SFM technique using generated data from the default mode of A Multi-Phase Transport model (AMPT) [6].

ical fluctuation with SFM technique using generated data from the default mode of A Multi-Phase Transport model (AMPT) [6].

Results and discussion

We commenced our analysis by generating 3×10^4 AMPT events. To minimise the projection effect, if any, the analyses of AMPT data using the SFM technique are being carried out for identified protons in the two dimensional $(p_x - p_y)$ space. The initial shape dependency of the two dimensional distribution spectrum is removed by converting the $(p_x - p_y)$ space to a cumulant variable $\chi(p_x - p_y)$ [1]. Fig. 1 represents the $\chi(p_x)$ vs $\chi(p_y)$ distribution for identified protons only. The figure shows that the $\chi(p_x - p_y)$ is perfectly flat, which indicates the initial shape dependency is removed.

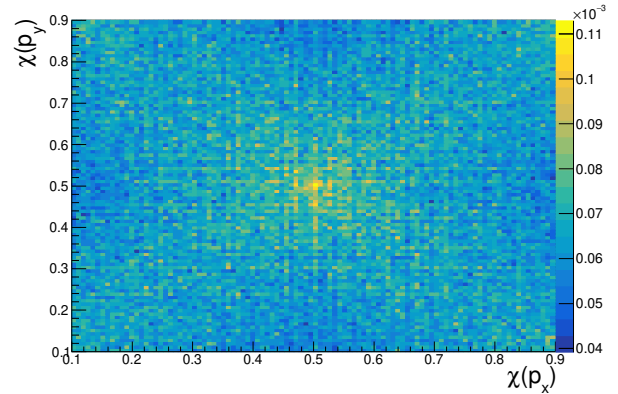


Figure 1: Distribution of two-dimensional cumulant variable in p_x and p_y space.

After converting the spaces measured the SFM using the following mathematical technique [1, 7].

$$\langle F_q \rangle = \frac{1}{N_{ev}} \sum_{i=1}^{N_{ev}} M^{q-1} \sum_{m=1}^M \frac{n_m(n_m-1)\dots(n_m-q+1)}{\langle n \rangle^q} \quad (1)$$

To estimate the scaled factorial moment in two dimensional $\chi(p_x - p_y)$ space using the above formula as stated in Eq. 1. The two dimensional horizontally averaged scaled factorial moments $\langle F_q \rangle$ of order of moments $q = 2\text{--}6$ are then estimated for two-dimensional χ space with AMPT generated data and the values of $\ln \langle F_q \rangle$ are plotted

against $\ln M^2$ in Fig. 2. From this plot, a clear signature of power-law behaviour of the form $\langle F_q \rangle \propto M^{\alpha_q}$ for the estimated values of $\langle F_q \rangle$ with the increasing number of phase space bin M^2 could confirm the presence of intermittency in AMPT default data. The exponent α_q is known as intermittency index. The variation of intermittency against order of moment is shown in Fig. 3. The plot implies that the intermittency indices are order dependent. The error bars shown in these two plots are estimated by considering them as independent statistical errors only.

The anomalous fractal dimension (d_q) is related to intermittency indices by the following mathematical relation:

$$d_q = \frac{\alpha_q}{q-1} \quad (2)$$

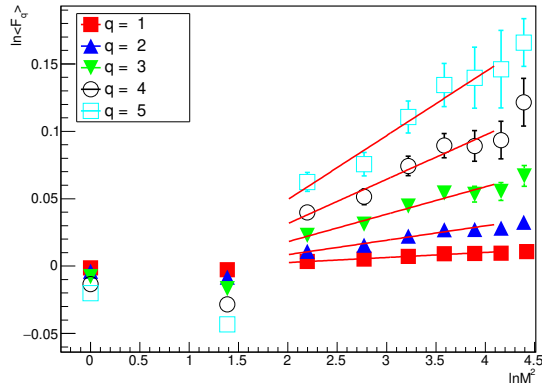


Figure 2: $\ln \langle F_q \rangle$ vs $\ln M^2$ plot in 2D $\chi(p_x-p_y)$ space for identified protons produced in Au+Au collision at 10 AGeV energy.

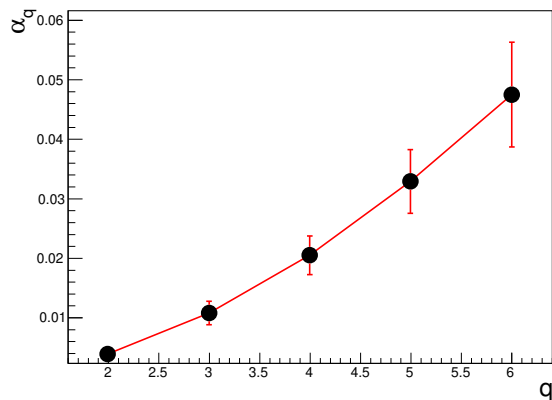


Figure 3: Intermittency indices against order of moment

The variation of d_q with q is shown in Fig. 4. It is found that the value of d_q increases monotonically with the increase of order of moment. A strong q dependence of d_q

is suggestive of particle production via self-similar cascading mechanism indicating about multifractal nature of the particle spectra.

This work is motivated by experimental searches for the critical point of the strongly interacting matter in heavy-ion collisions. AMPT data shows the power-law behaviour for two-particle, three-particle, four-particle, five-particle, and six-particle correlation.

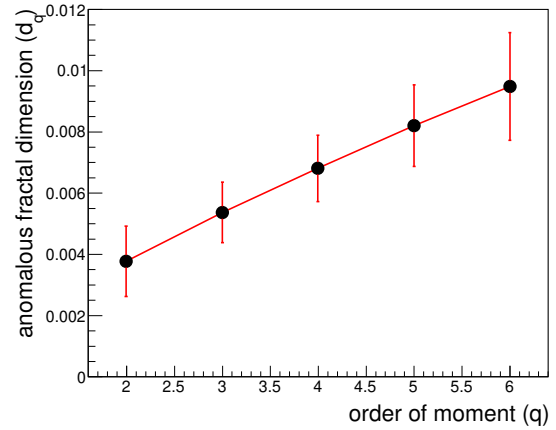


Figure 4: The plot of order dependent anomalous fractal dimension.

The presence of large dynamical fluctuation is one of the key signatures of existence of phase transition. From the present study, it can be concluded that dynamical fluctuation existed in AMPT generated data for 10 AGeV Au+Au collision.

Acknowledgement

The authors would like to acknowledge the Department of Science and Technology (DST) and Department of Atomic Energy, Government of India, for providing the computing facility, through the Project No. SR/MF/PS-02/2010 (E-6133) Dated 08/10/2021. This facility is used to generate the Monte Carlo (MC) data required for this work.

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Proton Number Cumulants in 4.9 GeV Au+Au Collisions

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Motivation

Non-monotonic energy dependence of the high moments of (net-)proton number distribution, which is related to the correlation length and susceptibilities of the system created in high-energy nuclear collisions, is suggested as a signature for the QCD critical point.

The STAR experiment has already published the results on net-proton cumulants from $\sqrt{s_{NN}} = 7.7 - 200$ GeV (collider mode) and 3 GeV (fixed target mode FXT) Au+Au collisions [4]. STAR's FXT program and the forthcoming CBM experiment are intending to fill the gap in the center of mass energy between 3 and 7.7 GeV and complete the measurements of collision energy dependence of high moments of proton number distributions. In this paper, we report a feasibility study of proton number cumulants from 4.9 GeV Au+Au collisions. The simulated events are generated using the PHQMD model.

High Moments of Protons Number Distribution in $\sqrt{s_{NN}} = 4.9$ GeV Au+Au Collisions

The PHQMD model [1] (Parton-Hadron Quantum Molecular Dynamics) is a microscopic n-body transport approach which describes the heavy-ion dynamics and dynamical cluster formation from low to ultra-relativistic energies. It follows Quantum Molecular Dynamics (QMD) approach to describe the propagation of baryons allowing the formation of clusters due to the attractive n-body forces and applies Minimum Spanning Tree (MST) algorithm to identify clusters. It incorporates the collision integrals of Parton-Hadron-String-Dynamics (PHSD) transport approach, the Quark-Gluon-Plasma formation and parton dynamics are also included.

In this study, about 2 million minimum-biased PHQMD events are generated. These events are further transported through the current CBM experimental setup [2] with GEANT [3]. Fig. 1 (a) shows the 'measured' charged particles (excluding protons) multiplicity distributions (referred to as RefMult3). After fitting the so obtained multiplicity distribution with that from the MC Glauber simulations, collision centrality is defined as illustrated by the vertical dashed lines in the plot. The blue histograms represent the corresponding centrality range as deduced from the number of participant nucleons (N_{part}). The bottom panel shows the ratio of the Glauber fit to the measured RefMult3. Fig. 1 (b) shows the particle identifications with

the time-of-flight detector: bands of positively charged pions, kaons and protons are clearly visible. Fig. 1 (c) represents the proton acceptance in p_T versus rapidity.

In Fig. 1, plot (d) shows the cumulant ratio κ_4/κ_2 of proton number distribution as a function of collision centrality in 4.9 GeV Au+Au collisions. Protons are selected in the kinematic region: $0.4 < p_T < 2.0$ GeV/c and $-0.4 < y < 0.0$. Red dashed line indicated the Possionian limit. Blue stars are the generator-level results from PHQMD. Black squares are the efficiency corrected ratios of the reconstructed protons. For solid symbols, the CBWC procedure is applied, to both model calculations and measurements [5]. On the other hand, the open markers represent calculations without CBWC. Within statistical uncertainties, both centrality dependencies are consistent.

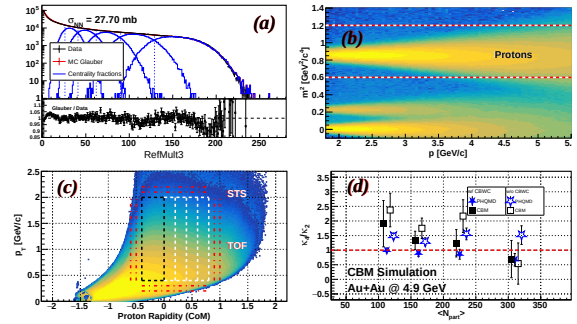


Figure 1: (a) centrality selection, (b) particle identification, (c) kinematic acceptance, (d) κ_4/κ_2 as a function of centrality.

Conclusions and outlook

Using the PHQMD event generator and the CBM experimental setup in GEANT, we have developed a realistic analysis procedure for extracting cumulants of proton number distributions. This is an important and necessary step for the QCD critical point search at the high net-baryon density region of the QCD phase diagram. In the future, we will refine the procedure with the high statistics simulations. Furthermore, we will study the collision energy dependence within the range of 3 - 4.5 GeV Au+Au collisions, which will serve as a non-critical baseline.

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Net-proton number fluctuations in CBM using UrQMD model

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Introduction

The main motivation for the proposed Compressed Baryonic Matter (CBM) experiment at the Facility for Antiproton and Ion Research (FAIR) in Darmstadt, Germany is to shed light on the nature of high density quantum chromodynamics (QCD) matter created there by investigating it using different diagnostic probes, which have never been done earlier in the energy range of FAIR, where the highest net-baryon densities are expected to be created [1]. The matter governed by QCD exhibits at least two discernible phases: the hadronic phase, characterized by the hadronic degrees of freedom, and the quark-gluon plasma (QGP) phase, where the quarks and gluons become deconfined. CBM has the unique opportunity to study the model predicted 1st order phase transition from hadronic matter to QGP with very high precision as the very high intensity beams from FAIR will result in collision rates much higher compared to any such previous experiments. A novel observable has been introduced to serve as an indicator of the QCD critical endpoint, focusing on the event-by-event fluctuation of the net proton number, representing the difference between the numbers of protons and antiprotons observed. This investigation is rooted in the divergence of the baryon number susceptibility at the critical endpoint. This susceptibility is closely linked to the average magnitude of fluctuation in the baryon number. While the baryon number susceptibility exhibits a divergent behavior, the isospin number susceptibility remains negligible in its singular parts [2]. However, the challenge in experiments lies in the detection and measurement of all emitted baryons, particularly neutrons, which are not easily detected. Various moments, including σ^2 , skewness S , and kurtosis κ , have been found to be proportional to powers of the correlation length (ξ), specifically ξ^2 , $\xi^{4.5}$, and ξ^7 , respectively [3]. Higher-order susceptibilities are related to cumulants (C_n) as $\chi^{(n)} = C_n/V T^3$, where V and T represent the system's volume and temperature. To mitigate volume dependence, moment products such as $S\sigma$ and $\kappa\sigma^2$, as well as the ratio σ^2/M (M is the mean) have been constructed. Within the energy range of the CBM experiment, there is a hopeful anticipation of discovering the QCD critical point. The investigation aims to identify critical point induced signals by simulating net-proton C4/C2 (equivalent to $\kappa\sigma^2$) in Au+Au collisions across the CBM energy spectrum as enhanced critical signals are expected with higher-order cumulants.

Results and discussion

In our initial phase, we study the physics observables within the UrQMD model and subsequently present our findings in this article. These results stem from the utilization of the UrQMD model as our primary data source.

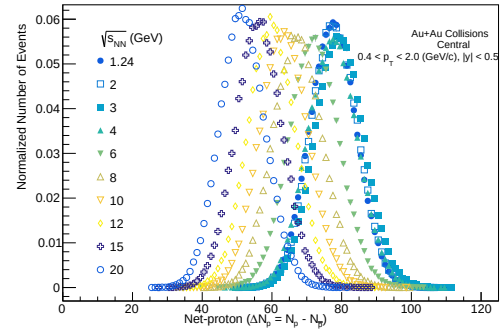


Figure 1: Event-by-event net-proton number distribution for head-on (0%) Au+Au collisions by using UrQMD

Fig. 1 shows net-proton multiplicity distributions for 0% collision centrality for Au+Au collisions at different collision energies from 1.24 GeV to 20 GeV considering Solenoidal Tracker at Relativistic Heavy Ion Collider (STAR) acceptance ($|y| < 0.5$, $0.2 < p_T < 2.0$, where y is the rapidity and p_T is the transverse momentum [4]).

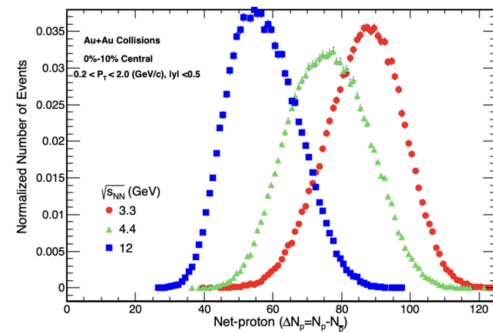


Figure 2: Net-proton distribution considering STAR acceptance

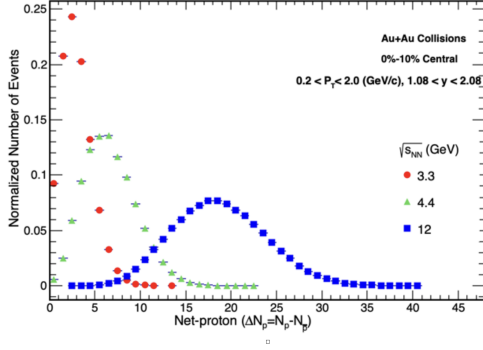


Figure 3: Net-proton distribution considering CBM acceptance

Fig. 2 shows the net proton distribution for 0-10% centrality. With increasing energy, proton number as well as net-proton number also decrease because the net baryon number tends to be zero at higher collision energies. In the Fig. 3, where we have used the CBM acceptance ($1.08 < y < 2.08$, $0.2 < p_T < 2.0$), shows the net proton number increases with increasing energy. The nature is opposite of the nature shown in Fig. 2 (where mid-rapidity acceptance is used), because of choosing forward rapidity acceptance as CBM is a fixed target experiment and the detectors will be placed in the forward rapidity region.

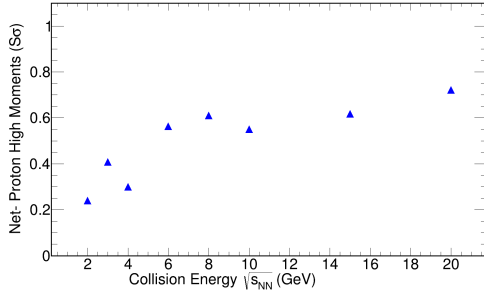


Figure 4: $S\sigma$ vs Collision energy for STAR acceptance

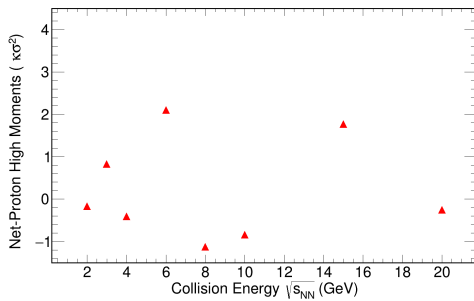


Figure 5: $\kappa\sigma^2$ vs Collision Energy for STAR acceptance

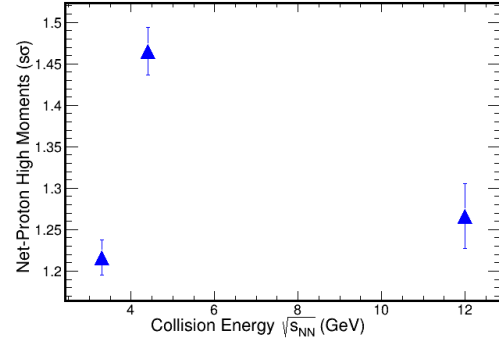


Figure 6: $S\sigma$ vs Collision energy for CBM acceptance

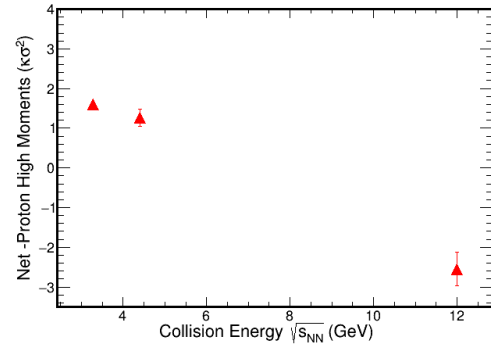


Figure 7: $\kappa\sigma^2$ vs Collision Energy for CBM acceptance

Net-proton higher moments have been shown; for STAR acceptance (Fig. 4 & 5) and CBM acceptance (Fig. 6 & 7). The delta theorem method [5] has been used to calculate the error in cumulants in Fig. 6 & 7 whereas error has not been shown in the Fig. 4 & 5. We have used the simulated events of 0-10% centrality and pure central events in our analysis. Our aim is to look for the non-monotonic behaviours of net-proton cumulant ratio in the CBM energy range. We will employ the output from the UrQMD event generator as input for our simulation. Following the transport of generated particles through the detector geometry, we will carry out successive processes encompassing digitization, clustering, and hit identification. Ultimately, after the successful identification of tracks and their fitting, we will proceed with the identification of track candidates. We will use the AnalysisTree and Particle Identification framework for further investigation.

In conclusion, measurements of net-proton $C3/C2$ and $C4/C2$ for UrQMD model have shown in Au+Au collisions over a collision energies up-to 12 GeV for uncorrected simulated data. The simulated data are presented for pure central (0%) and 0-10% collision centralities. Noted that anti-proton numbers are very less in the lower energy range. We have to further investigate to compare our results with the previous results of 0-5% central UrQMD simulated data.

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FAIR Phase-0 Activities

Next steps with mCBM towards CBM

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The mCBM experiment ("mini CBM"), a CBM demonstrator and full-system test-setup, was constructed 2017/18 at the experimental area Cave D (target station HTD) of the SIS18 facility of GSI/FAIR [1], taking C- up to U-beams at various kinetic projectile energy of 1 - 2 AGeV since 2019

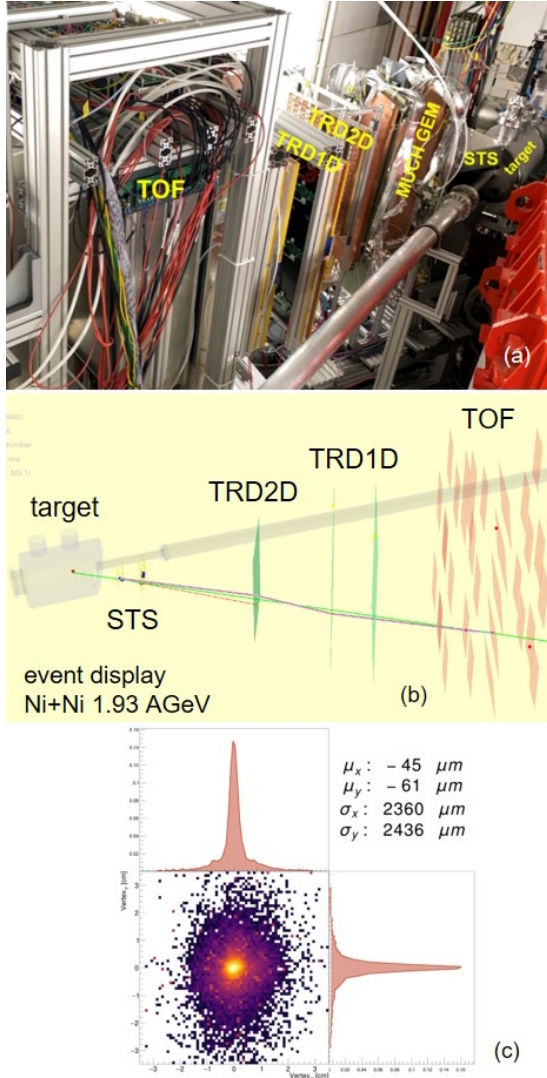


Figure 1: Photograph of the mCBM setup in 2022 (a), event display (b) and vertex reconstruction with mCBM (c). The CBM CA (Cellular Automaton) track reconstruction algorithm was applied to the mCBM 2022 data. Tracks were formed from hits in STS, TRD (TRD2D and TRD1D) and TOF.

within the FAIR Phase-0 program. With the data taken in 2022, rare Λ baryons were reconstructed with the mCBM experiment in Ni + Ni collisions at 1.93 AGeV[2],[3], proving the free-streaming data acquisition concept of CBM as well as demonstrating the rare probe capability involving the full CBM data chain.

In 2023, the focus was placed on (1.) developing the CBM online system for real-time reconstruction and selection in a computer farm, (2.) designing and performing major upgrades of the detector subsystems for mCBM experiments in 2024 and (3.) optimizing the CBM offline data analysis chain in terms of calibration, alignment, hit finding and track reconstruction. For the latter, Fig. 1 (b) shows an event display of a track found by the CBM CA (Cellular Automaton) track reconstruction algorithm [7] which was applied to mCBM 2022 data, taken in Ni+Ni collisions at 1.93 AGeV kinetic bombarding energy. Tracks were formed from hits in the Silicon Tracking System (STS), the Transition Radiation Detector (TRD1D and -2D) and the Time-of-Flight wall (TOF). The primary interaction vertex was reconstructed from the intersection of the track projection with the target plane, shown in Fig. 1 (c) [10]. Performance tests and further optimizations of the CA track reconstruction algorithm as well as the alignment approach are ongoing.

Detector performance studies Since CBM will cope with unprecedented collision rates up to 10 MHz, systematic rate capability studies of the detector subsystem are an essential part of the mCBM program. Here, a distinct micro-spill structure of the slow-extracted SIS18 beam was observed within the 2022 data resulting to intensities peaked by a factor about 10 (and above). At average collision rates in the MHz-range, the front-end ASICs were partially driven into saturation and thus suffered data loss, which significantly challenge the investigation on saturation effects of the detector systems. Hence, further rate scans up to highest collision rates will be performed during the 2024 beam campaign. First beam tests dedicated for the TOF detector system were carried out in December 2023 during the machine engineering run, the data analysis is ongoing. Furthermore, a spill-smoothing cavity installed within SIS18 as well as a beam feedback-system might significantly reduce the micro-spill structure of the slow-extracted SIS18 beam. Both systems were successfully tested during the machine engineering run in November/December 2023.

Examples for results on detector performance studies are depicted in Fig. 2. The data were taken in U + Au collisions at 1.06 AGeV (a),(b) in March 2022 and (c) in Ni + Ni col-

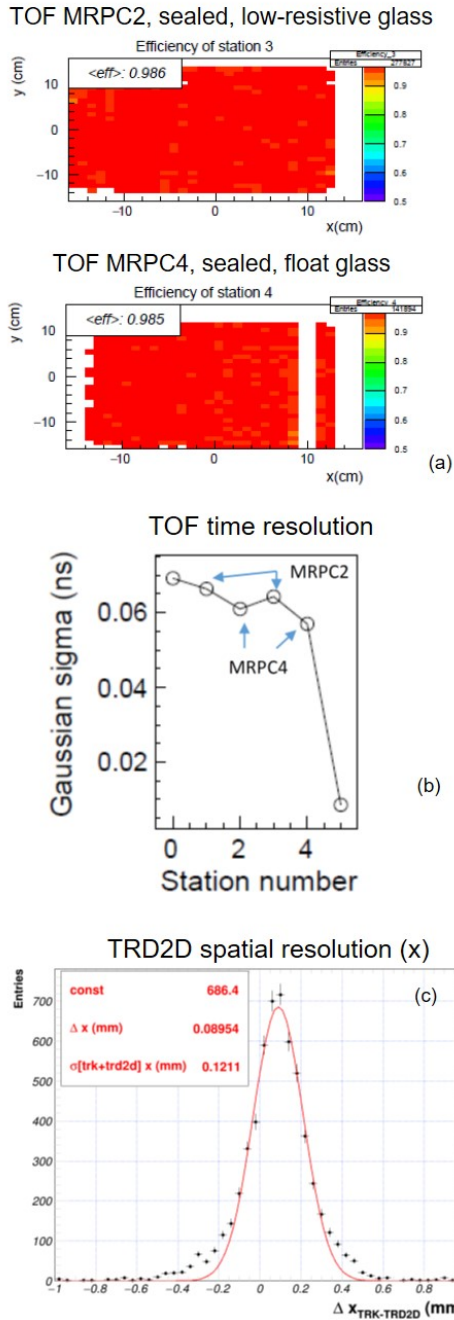


Figure 2: Results on detector performance: detection efficiency (a) and time resolution (b) of TOF RPC modules as well as spatial resolution of the TRD2D detector (c).

lisions at 1.93 AGeV kinetic projectile energy (May 2022). Both were measured at moderate collision rates of about 400 to 500 kHz (averaged). The TOF RPC modules show detection efficiencies of about 0.98 (a) with a time resolution of approx. 60 ps (b). Additionally, the spatial resolution of the TOF RPC modules were determined to

2.5 mm across and 3.5 mm along strips. The spatial resolution of the TRD2D detector station, a MWPC equipped with triangular-shaped read-out pads for 2-dimensional position measurement, was determined to approx. 100 μm , see Fig. 2 (c). The obtained results are in good agreement with the design specifications of the corresponding CBM detector systems.

Preparation for the 2024 campaign Major upgrades of the detector systems have been launched for upcoming mCBM experiments in 2024. The STS has been additionally equipped with a third station (station-0) positioned upstream, see Fig. 3 (a) [9]. The new STS station comprises a $6 \times 6 \text{ cm}^2$ Si-strip sensor read out by a FEB8-5 front-end board (Fig. 3 (b)), which provides a 5-times higher bandwidth. For the MUCH system, 2x new (station-1) GEM modules were constructed which will replace the present detectors, mounted in an optimized mechanics enabling higher charged particle fluxes. The first station of the TRD detector system (TRD2D) will be fully equipped with pre-series read-out electronics [12],[13], while the two TRD1D stations (type-8, 768 channels each) will be substituted by stations with significantly enhanced granularity (type-5, 3456 channels each) [11]. Furthermore, a second RPC wall will extend the TOF system. In the new TOF configu-

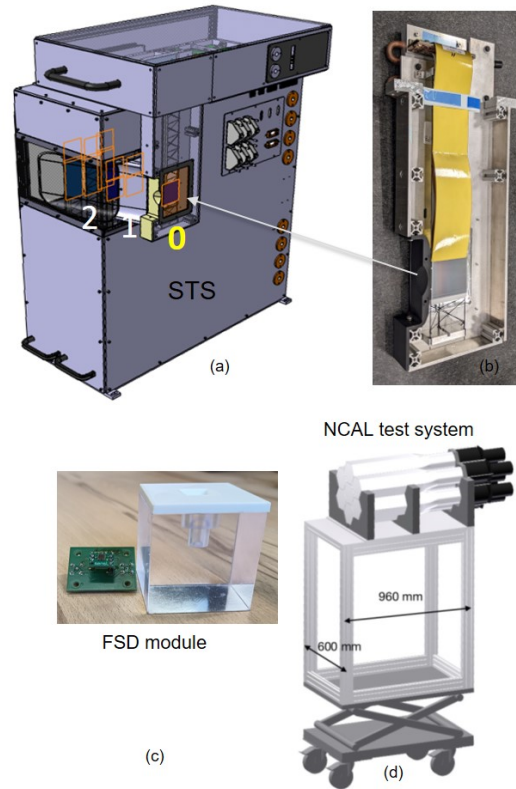


Figure 3: Upgrade of detector systems for mCBM experiments in 2024.

ration, all RPC modules of the double wall are aligned horizontally as foreseen for the CBM TOF wall. Two new test systems are being installed consisting of prototype modules for the Forward Spectator Detector (FSD), see Fig. 3 (c), as well as of the (Jülich) Neutron Calorimeter (NCAL), see Fig. 3 (d) [16]. The mobile test systems (see Fig. 3 d) will be positioned under 25° downstream the TOF system as well as under 0° close to the beam dump. Furthermore, essential development steps have been made towards a CBM Experiment Control System (ECS) [8] and, hence, are in preparation to be applied within the upcoming mCBM experiments in 2024.

One central task for the mCBM experiments in 2024 is to test a prototype online system for CBM. Hence, two stages of online reconstruction and selection are being prepared for the 2024 campaign. The first involves unpacking of the detector system data, followed by event building based on a time-cluster search within the time-stamped hit messages (DigiEvent building). As a second stage, optimized hit reconstruction algorithms for STS [5], TRD and TOF [6] are applied as well as track reconstruction by the CA algorithm [7]. Furthermore, events are selected containing a Λ baryon candidate. The online system prototype was tested and further optimized within dedicated data challenges, based on a real-time replay of 2022 data [4]. Additional data challenges are foreseen until the 2024 experiments start.

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Investigations of event vertex reconstruction in mCBM as application of CA tracking and alignment

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A realistic test of various data processing algorithms prepared for CBM is performed by analyzing the data collected at mCBM [1]. A hybrid approach of event identification in the trigger-less data stream of mCBM was successfully applied [2]. Using such filter, the data analysis can be performed using standard tools developed for CBM, the detectors' reconstruction procedures and Cellular Automaton (CA) tracking [3]. The filtered data are used to determine a realistic track model, align a significant set of detectors and hint at vertices reconstruction quality.

Event filtering efficiency

The reconstruction and tracking yield can be summarized as in Fig. 1. In the top picture, the quality of event filtering, quantified by CA, shows that only $\approx 3\%$ of the selected data are noise (no tracks) while the typical mCBM event has 3 tracks.

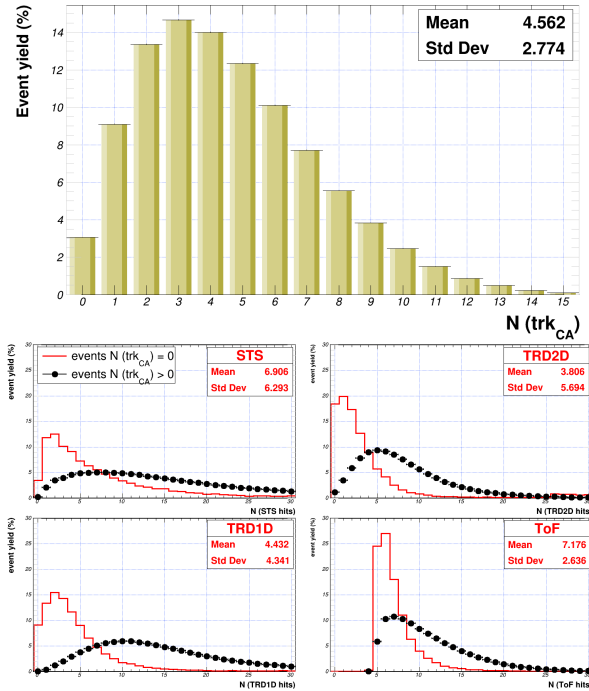


Figure 1: Data yields for CA (top) and the four tracking detectors, STS, TRD2D, TRD1D and ToF (bottom panel), wrt. the event selection.

In the bottom panel of Fig. 1 the reconstruction yield per event for the tracking detectors, STS, TRD and ToF is

presented for two cases: noise (N) selection (red) and mean bias (MB) interactions (black). A simple scaling would be $N_{hit}^{MB} = N_{trk} \times N_{ly} + N_{hit}^N$ where N_{hit} represent a statistics (e.g. mean, MPV) from the distributions in the bottom panel, N_{trk} same statistics from top figure and N_{ly} the no of tracking stations for each system. For the e.g. *mean values*, the TRD detectors follow closely the above relation, with the ratio $\epsilon = N_{th}/N_{exp}$ being $\epsilon_{TRD2D} = -3\%$ and $\epsilon_{TRD1D} = 1\%$ while for STS and ToF a more complex approach should be applied.

The track model

The partial output of the CA filtering is the generation of *sets of hits*, linearly correlated, as track trace candidates. The track model defined on this set is *the pair of two independent first order polynomials* defined by hits' projected positions on the **x-z** and respectively **y-z** planes, and their estimated uncertainty.

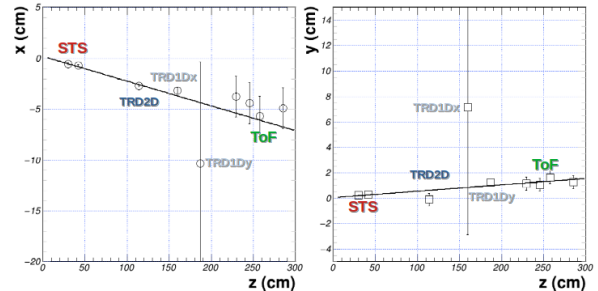


Figure 2: Simple track model of two independent first order polynomials, corresponding to the **x-z** (left) and **y-z** hit projected positions respectively (right).

In Fig. 2 an example track is shown on which the three elements of the model are shown: the hits (markers), the uncertainties (error bars) and the estimated trace (line), independently for **x-z** and **y-z** projections. Uncertainty estimations are especially important as they provide the pull strength of each hit and have to account for the following effects: reconstruction uncertainties, [incomplete] calibration, [incomplete] alignment, [fake] hit attachment, track definition, multiple-scattering, etc; a too strong pull (small uncertainty) may deflect the trace while a too weak one may render the hit irrelevant for trace definition. A pragmatic approach for uncertainty estimation is by simultaneously aligning the distribution of normalized residuals

(pulls) defined in Eq. 1 to the normal Gauss distribution.

$$pull_i(x) = \frac{x_{hit}(i) - f_x^i(z_{hit}(i))}{\sqrt{\sigma^2(x_{hit}(i)) + \sigma^2(f_x^i)}} \quad (1)$$

where i represents a tracking station, which contribute the track with the hit projection (x_{hit}, z_{hit}) . The f_x^i and its uncertainty $\sigma(f_x^i)$ represents the linear regression through the set of hits and their uncertainties **except** for the i^{th} hit. A similar expression to Eq. 1 is independently used for the **y-z** projection.

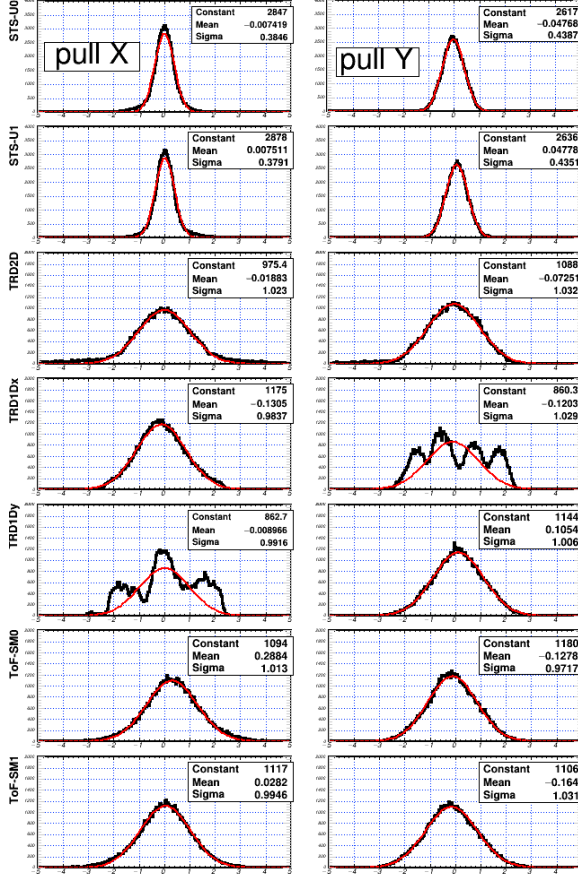


Figure 3: Distribution of pulls (Eq. 1) for the **x-z** (left) and **y-z** (right) projections and 7 tracking stations.

The convergence of the 7-fold coupled Eq. 1 for both **x-z** and **y-z** projections was defined by the condition $\sigma_i(pull) < 3\%$ for any tracking station i , as shown in Fig. 3. The values for detector uncertainties are shown in Tab. 1. There are two observations:

- The tracking stations TRD1Dx and TRD1Dy are not position sensitive in the **y-z** respectively **x-z** plane and therefore the pulls are not following a Gauss distribution.
- The setup is such that $\sigma(f_x^i) \gg \sigma(x_{hit})$ for the tracking stations with the highest position sensitivity, STS-U0 and respectively STS-U1. Therefore only upper limits were estimated in these cases.

layer	$\sigma(x_{hit})$ [mm]	$\sigma(y_{hit})$ [mm]
STS-U0	< 0.1	< 0.1
STS-U1	< 0.1	< 0.1
TRD2D	0.75	3.4
TRD1Dx	2.10	34.0
TRD1Dy	30.00	8.0
ToF SM0	6.70	10.8
ToF SM1	8.00	11.2

Table 1: Detector uncertainties obtained as solution to the coupled Eq. 1 by converging the distributions from Fig. 3.

Alignment

The track model described previously can be used to align the detectors by finding the deviations from the geometric description of the setup used during reconstruction. The solution is searched by finding the convergence of *Mean* values from Fig. 3 to 0. In practice, since data are affected by various systematic effects, a more differential approach has to be followed. We will assume, for simplicity, that the tracking stations *STS-U0/1* and *TRD2D/1D* are already aligned [4]. The ToF detector has been already calibrated [5] and thus residuals of the form:

$$\Delta_i(x) = x_{tof}(i) - f_x^i(z_{tof}(i)) \quad (2)$$

can be estimate. Here, f_x^i is similarly defined as in Eq. 1, by STS and TRD, and extrapolated to the z_{tof} . An example, of the final convergent stage, for ToF SM1 (type 0) is shown in Fig. 4

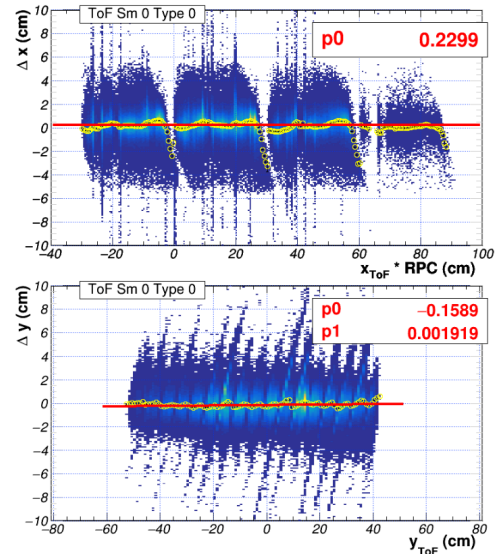


Figure 4: Residuals of type Eq. 2 for ToF Sm 0 (type 0), for the **x** (top) and **y** (bottom) coordinates as function of ToF position and detection unit (RPC).

Distributions of the type shown in Fig. 4 can be constructed for all 5 tracking stations (Sm 0-3 of type 0 and

Sm 0 of type 2) in the mCBM setup [1]. The data are averaged first as function of ToF coordinate (yellow markers) and finally over the station. The two step averaging smoothen the systematic deviations which are due to other than alignment effects. In particular, the y_{tof} value, being least affected by calibrations, is used also to determine downstream alignment by registering the global slope ($p1$ parameter in Fig. 4 bottom). The solution to ToF alignment expressed as residual misalignments is given in Tab. .

ToF station	δx [mm]	δy [mm]	δz [mm]
Sm0-Type0	2.30	-1.59	4.35
Sm1-Type0	-0.22	-2.07	2.94
Sm0-Type2	-0.52	0.03	1.90
Sm2-Type0	-0.04	-1.30	1.23
Sm3-Type0	-8.08	-0.09	1.78

Table 2: The values of the residual misalignments for all ToF stations in the global data taking [1] as determined wrt the STS-TRD system.

The addition of ToF hits to the the STS-TRD system improves the pointing resolution by significantly increasing the lever arm.

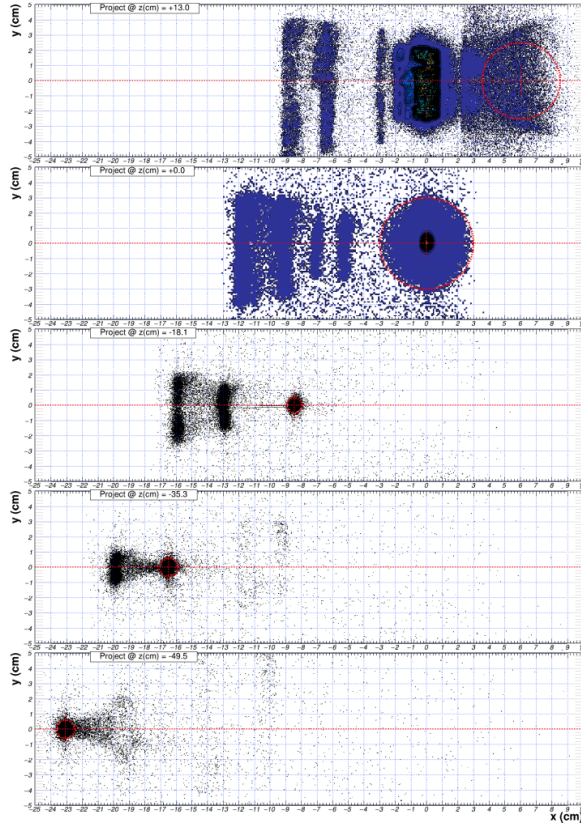


Figure 5: Track projections, at various distances downstream and upstream from the target, showing the correlation (red circles) with various constructive elements of the target chamber, indicative of their vertex.

A simple quality test for the procedure is to reconstruct the material budget around the target. We have selected five x - y plans relative to the target, correlated with physical structures around it, in order to check the alignment as detailed in Tab. 3. The Distribution of track projec-

ΔL (cm) beam direction	Description
+15.8	Downstream window of the target chamber, beam pipe
0.0	Target
-20.0	Bmon detector
-38.0 (- 1)	Upstream window of the target chamber
-50.5 (- 4.1)	Window of the beam diagnostic chamber.

Table 3: Selected planes upstream of the mCBM setup used to identify material budget around target by track projection clusterization.

tions in the five planes is shown in Fig. 5. For each plane, the physical structure on which the projection is focused is marked by a red circle. As the focus plane is moved upstream of mCBM, track vertices which are already identified, are removed from subsequent planes. Starting from the top figure from Fig. 5 the window and the wall of the target chamber downstream ox - y plane of the target are identified (for $\approx x > 2$ cm). Further down, the target and all secondaries are identified within an area of $r = 3$ cm. In the third distribution, after removing all tracks related to the target production, we can identify the Bmon detector in an area of $r \approx 0.5$ cm at 20 cm from the target center, along the beam direction. Two, further upstream, regions can be also identified linked to separation windows on the beam, as detailed in Tab. 3. Their position along the beam pipe, as determined by track focusing, is shifted more upstream wrt. the design values which need investigation on the geometry.

Vertexing

Having a self-consistent track model and reasonably aligned and calibrated detectors the next step is to use the track pointing resolution to determine primary and secondary vertices. The vertex reconstruction is based on following a minimum set of conditions adapted to the setup geometry :

- vertex candidates are defined by the point (x_0, y_0) of intersection in the x - y plane, of a pair of tracks;
- candidates are selected based on evaluating $\Delta z = D(z_x^1, z_x^2, z_y^1, z_y^2)$ where z_x coordinates are derived from the following equality $f_x^i(z_x) = x_0$; f_x the track model for track index i ;
- vertex filtering is done based on the following concurrent conditions: largest distance to the target, smallest value of the D expression from all candidates up to a maximum of

$$\Delta z = 3.5 \text{ cm};$$

- solitary tracks can be absorbed in existing vertices if they fulfill $DCA < 1 \text{ cm}$ in the **x-y** plane.

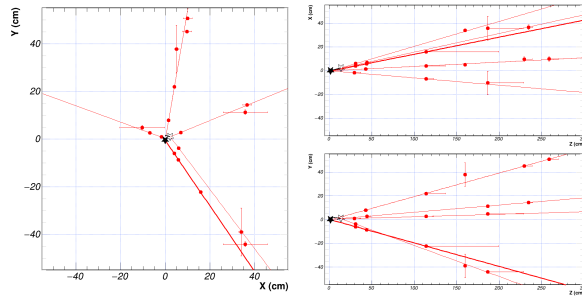


Figure 6: An example of reconstructing the primary and a secondary vertices (stars) as seen by projecting tracks in the **x-y** plane (left) and, the **x-z** and **y-z** planes respectively (right).

In Fig. 6 an example of vertex reconstruction is provided for an event with track multiplicity 5; a rather typical event with more than 12 % abundance according to Fig. 1 (top). The secondary vertex (open star symbol) is defined by two tracks while the primary one (filled star symbol) by three detected tracks and the mother of the secondary vertex, so a track multiplicity of 4. The relative distance to the secondary vertex is $d = 12.4 \text{ cm}$, a topology compatible with a Λ decay [5].

Conclusions

The official CA tracking mechanism developed for CBM was applied successfully to the data collected by the mCBM. A set of algorithms were developed specifically for this case to account for systematic effects observed in data. A self-consistent set of uncertainty estimations and alignment parameters were found for a set of detectors including STS, TRD and ToF stations. The results were tested against material budget distributions in the setup and pointing performance with satisfactory results.

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Hypernuclei reconstructions with eTOF in Au+Au collisions at $\sqrt{s_{NN}} = 3.5$ GeV with the STAR detector

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By studying how hypernuclei form in the high-density region of the QCD phase diagram at BES-II, along with measuring their lifetimes and decay patterns, one can unlock valuable insights into hyperon-nucleon interactions. This knowledge is crucial for understanding the equation of state for dense nuclear matter, which ultimately holds the key to unraveling the properties of neutron stars structure.

The high statistics data from fixed-target Au+Au collisions at $\sqrt{s_{NN}} = 3.5$ GeV, taken in 2020 by the STAR detector is very suitable to study light hypernuclei. 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 ^3He , ^4He , ^6He , ^6Li and ^7Li are shown. The dE/dx provided by TPC were used to identify charged particles and heavy fragments such as ^3He and ^4He .

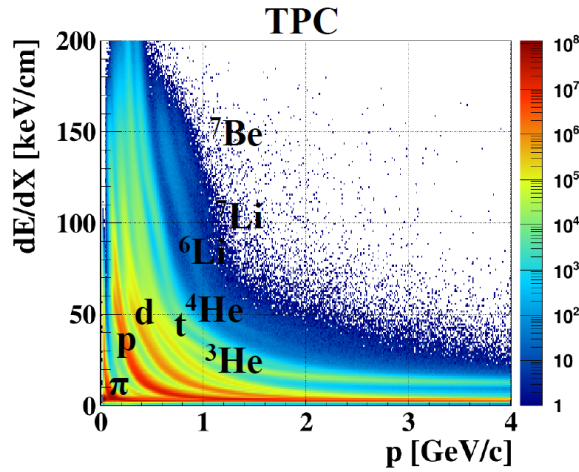


Figure 1: Distribution of dE/dx as a function of momentum p for electrons, $\pi^\pm$, $K^\pm$, p , $\bar{p}$, $d^\pm$ and $t^\pm$ and heavy fragments such as ^3He and up to ^7Li . The units of dE/dx and momentum p are keV/cm and GeV/c, respectively. The particle locuses follow a corresponding Bichsel's prediction. dE/dx splitting for high ionization region due to secondary and pileup tracks.

In order to improve particle identification, especially in the high momentum region, BTOF or eTOF information is used. The merged hit from BTOF or eTOF to the reconstructed TPC track allows calculate the mass of the particle. We require corresponding mass range for all deuterons and tritons, and for high momentum ^3He and ^4He particles. The eTOF significantly extend PID capabilities at forward

rapidity as it shown in Fig. 2.

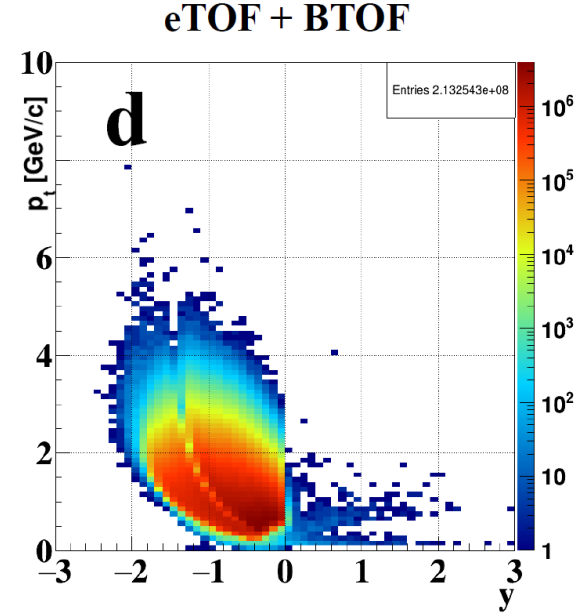


Figure 2: 2D distribution of identified deuterons as a function of rapidity and p_t . Two zones corresponds to BTOF and eTOF coverage.

Together with 2-body channels, decays with three daughters in the final state allow to measure hypernuclei 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 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 here for the offline analysis [2].

A detailed description of the experimental setup and sub-detectors for tracking, particle identification, etc. can be found in [3].

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. 3. 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.

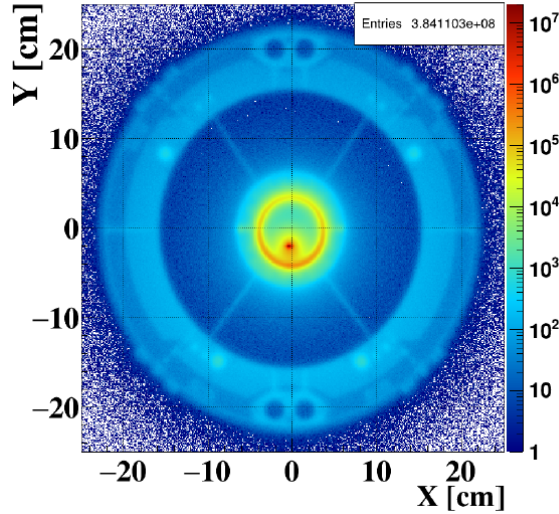


Figure 3: 2D XY distribution of primary vertices for Au+Au fixed-target collisions at 3.5 GeV with a clearly visible gold target edge located at $y = -2$ cm.

Reliable CA tracking combined with excellent particle identification provided by TPC, BTOF, and eTOF allows the reconstruction of complex light hypernuclear decay topologies on- and offline 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. 4 the reconstructed invariant mass spectra of ${}^3_{\Lambda}\text{H} \rightarrow {}^3\text{He}\pi$, ${}^3_{\Lambda}\text{H} \rightarrow \text{dp}\pi$, ${}^4_{\Lambda}\text{H} \rightarrow {}^4\text{He}\pi$, ${}^4_{\Lambda}\text{H} \rightarrow \text{tp}\pi$, ${}^5_{\Lambda}\text{He} \rightarrow {}^3\text{He}\pi$ 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. Typical mass resolution is about 1.5 MeV/c^2 . Due to extended PID capabilities by eTOF at forward rapidity region the collected statistics are sufficient to measure the yield, lifetime, p_t , and rapidity spectra of ${}^3_{\Lambda}\text{H}$, ${}^4_{\Lambda}\text{H}$ and ${}^5_{\Lambda}\text{He}$ hypernuclei.

In order to reconstruct ${}^4_{\Lambda}\text{He}$ seen by eTOF, ${}^4\text{He}$ track was combined with soft secondary pion. The obtained invariant mass is shown in Fig. 5. An excellent 1.94 signal to background ratio is 2.5 times higher than in the corresponding invariant mass plot obtained with combined TPC or eTOF or BTOF ${}^4\text{He}$ particle identification procedure.

In conclusion, a high quality dE/dx TPC measurement for particles up to heavy fragments together with eTOF

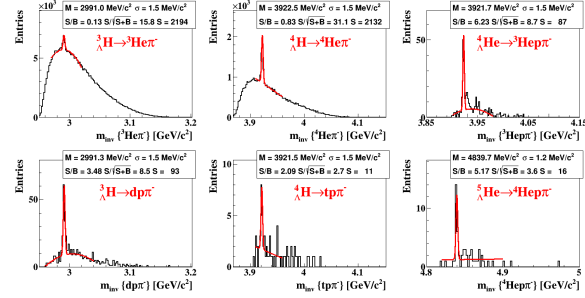


Figure 4: Reconstructed hypernuclei in Au+Au collisions at $\sqrt{s_{NN}} = 3.5$ GeV.

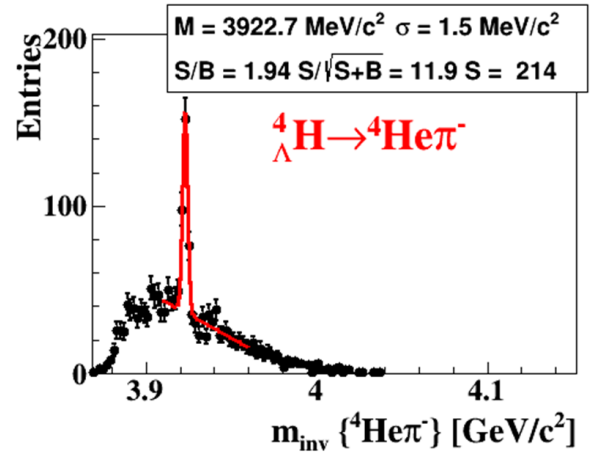


Figure 5: Reconstructed invariant mass spectrum of ${}^4_{\Lambda}\text{H}$ with ${}^4\text{He}$ identified by eTOF.

and BTOF measurements allows to reconstruct hypernuclei signals with high significance. The eTOF significantly extend PID capabilities at forward rapidity region, allows to reduce background for all two body decays and measure clean signals with an excellent signal to background ratio.

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