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Exploring baryon-rich QCD matter with CBM at FAIR: Status and prospects

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Abstract. The Compressed Baryonic Matter (CBM) experiment is under construction at the Facility for Antiproton and Ion Research (FAIR) in Darmstadt, Germany. It aims to explore the phase structure and microscopic properties of strongly interacting matter at large net-baryon densities and moderate temperature using heavy-ion collisions in the energy range $\sqrt{s_{NN}}$=2.9 - 4.9 GeV. This contribution provides an overview of CBM's progress in detector development, current production status, and performance studies.

1 Introduction - CBM physics goals

The Compressed Baryonic Matter (CBM) experiment is a next-generation heavy-ion experiment under development at the Facility for Antiproton and Ion Research (FAIR) in Darmstadt, Germany. Its main scientific mission is to explore the properties of strongly interacting matter at high net-baryon densities with a previously unreachable precision. The CBM experiment aims to perform high-precision, multi-differential measurements to address key open questions such as: How are the properties of hadrons modified in dense matter? What is the phase structure of QCD matter and its equation of state (EoS)? Can we observe critical phenomena associated with the expected transition between a predicted first-order and a cross-over phase transition? To address these questions, the CBM detector is designed to fully exploit the capabilities of the SIS100 accelerator. It will be able to measure even very rare probes with unprecedented statistical precision, made possible by collision rates of up to 10 MHz.

Event-by-event fluctuations of conserved charges are excellent probes for studying the QCD phase diagram, including the search for the predicted existence of first-order phase transitions and a critical point. Recent STAR results on net-proton cumulants indicate a possible deviation from the non-critical baseline around $\sqrt{s_{NN}}$=20 GeV. Precise measurements of higher-order cumulants in the CBM energy region will be crucial both for investigating the properties of the phase transition and to establish reliable baseline measurements in the non-critical region. Within three years, CBM plans to measure the excitation function of $\kappa_4(E)$ for protons and to obtain first results on $\kappa_6(E)$. It will also extend these studies to strangeness fluctuations by measuring κ_4 of Λ baryons.

Production of strange particles is a sensitive probe to the properties of dense baryonic matter. CBM will use a combination of a silicon tracking system, online event reconstruction together with excellent particle PID, and a Kalman filter-based algorithm package to identify complex decay topologies. This will enable unprecedented precision of multi-differential studies of multi-strange hyperons and single- and double-Λ hypernuclei. For example, based

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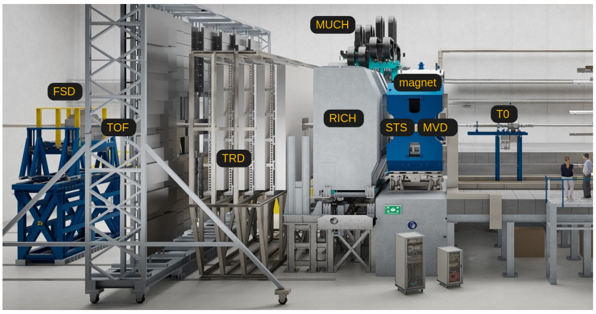

Figure 1. Schematics of the CBM experimental setup (© GSI/FAIR, Zeitrausch).

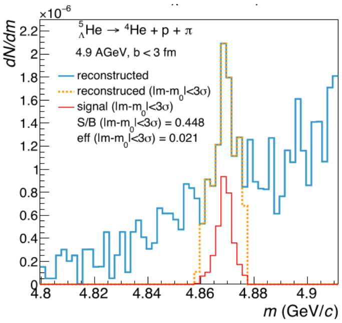

Figure 2. Simulated reconstruction of $^{5}_{\Lambda}$He mass spectrum.

on performance simulation in Fig. 2, yield of about 2×10^5 of $^{5}_{\Lambda}$He is expected to be reconstructed within a first year of running at 100 kHz collision rate.

Thanks to its variable configuration, CBM will be able to perform high-precision measurements with di-electron and di-muon pairs within the same detector acceptance. It is expected that the statistics from the first year of running will be sufficient to obtain the excitation function of di-electron spectra for determining the temperature of the system. The excess yield in the low-mass region will provide information on the system's lifetime and the properties of the phase transition. In addition, the measured spectra are expected to be sensitive to potential signatures of chiral symmetry restoration.

While the physics topics above have been extensively discussed before, a new hadron-physics program called "QCD at FAIR" was recently initiated. It aims to bring together experts in hadron, nuclear, and heavy-ion physics for cross-community research on QCD topics utilizing the proton beams of SIS100. Since 2023, a strong community has been working to identify flagship topics. As a result, a community white paper on "Hadron Physics Opportunities at FAIR" is being finalized for publication in 2025, outlining a new world-class set of physics goals to be pursued at CBM. These include detailed studies of hyperon production and structure, as well as charm production near threshold, including searches for exotic states such as hidden-charm pentaquark-like candidates[1].

2 Detector status

The layout of the CBM detector with its various subsystems is shown in Fig. 1. CBM is a modular fixed-target forward spectrometer with full azimuthal coverage within the polar angle acceptance of $2.5^\circ < \theta < 25^\circ$. It can be configured in different setups optimized for measuring observables that require either hadrons, electrons, or muons. This flexibility allows CBM to deliver the necessary spatial, momentum, and timing resolution at the high event rates required for a wide range of rare observables. As of 2025, the realization of FAIR and CBM has advanced significantly. The installation of SIS100 accelerator components and of the technical infrastructure is ongoing, and the CBM collaboration is progressing towards the goal of being ready for beam at the end of 2028. All major CBM subsystems are currently in various stages of component series production, detector assembly, and testing.

At CBM, tracking and vertexing are performed by two silicon detectors: the Micro-Vertex Detector (MVD) and the Silicon Tracking System (STS), both placed inside the 1 Tm superconducting dipole magnet. The magnet project has successfully completed the first stage of its Final Design Review and has now entered the production phase. Currently, the manufacturing of the yoke and coil is ongoing, while the magnet support has already successfully passed the on-site Factory Acceptance Test.

The MVD is a high-precision silicon vertexing detector consisting of four stations with 288 MIMOSIS monolithic active pixel sensors specifically developed for the CBM experiment. With pixel size of $27 \times 30\ \mu m^2$ and time resolution of $5\ \mu s$ it allows precise reconstruction of secondary decay vertices with $50\ \mu m$ resolution in event rates up to 100 kHz. Three prototype chips (MIMOSIS-1, -2, and -2.1) were developed and tested at the CERN SPS [2]. Work is now advancing towards the Production Readiness Review of MIMOSIS-3, with the submission of the final chip design foreseen by the end of 2025.

The STS is composed of eight tracking stations with double-sided 320 μm thick silicon micro-strip modules, with a material budget of only 0.3% to 1.4% X_0 per station. With a dead time per channel of approximately 300 ns and a timing resolution of 5 ns, the STS provides tracking and momentum measurements of charged particles in the high-multiplicity environment of nucleus–nucleus collisions at top SIS100 collision rates. Currently, about 70% of modules have been completed at GSI and KIT Karlsruhe, with around 15% of ladders already assembled. Preparations are underway for the first half-unit integration [3].

Particle identification is provided by downstream detectors. Here, either the Ring Imaging Cherenkov Counter (RICH) or the MUon CHambers (MUCH) detector can be installed, depending on whether high-purity electron identification or muon detection is required. The RICH system is designed to identify electrons with momenta up to 8 GeV/c, achieving a pion suppression factor of about 5×10^3. It employs a 1.7 m long CO_2 radiator with a pion Cherenkov threshold of ~ 4.65 GeV/c. The produced photons are reflected by UV-reflective lightweight mirrors and detected by 1100 multi-anode photomultipliers (MAPMT) coated with a wavelength-shifting film to enhance their sensitivity to UV photons. The RICH has successfully deployed and tested its MAPMT sensors within the HADES experiment [4] and is now focusing on the design and production readiness of its camera system and mirror wall.

MUCH identifies muons originating from vector meson and charmonium decays. It consists of several tracking stations interleaved with iron and carbon absorbers. The first two stations use triple-GEM (Gas Electron Multiplier) detectors for high spatial resolution and rate capability, while the last two employ Resistive Plate Chambers (RPCs) for operation at lower fluxes. MUCH is currently preparing for review to launch the series production of its Station 1 chambers.

The Transition Radiation Detector (TRD) extends electron identification to higher momenta. It consists of four layers of multi-wire proportional chambers (MWPCs) equipped with polyethylene foam radiators. The TRD achieves an electron detection efficiency of about 98.5%, with a spatial resolution of ~300 μm in x and ~5 mm in the y direction. Its electronics design enables dead-time-free operation with a time resolution better than 80 ps. To enhance spatial resolution and low-p_T tracking, a two-dimensional (2D) MWPC readout concept with a resolution of 150 μm in x and 850 μm in y was conceived. At this time, the TRD has successfully passed the Production Readiness Review for the outer chambers and is moving to the production stage. The technical design of the inner chambers is under review.

The last large downstream detector is the Time-of-Flight (ToF) system, which provides identification of pions, kaons, and protons up to 4 GeV/c. It comprises a 120 m^2 detector wall with ~230 modules and 1400 MRPCs, corresponding to about 90,000 readout channels. Beam and cosmic-ray tests confirmed a ~50 ps single-counter resolution and stable operation at high rates. Moreover, the detector system was successfully tested when part of it was deployed as the eTOF detector at the STAR experiment at BNL as part of the Beam Energy Scan II program. The ToF system is currently in the stage of mass production of MRPCs, with approximately 40% of all counters already assembled.

3 Towards detector commissioning

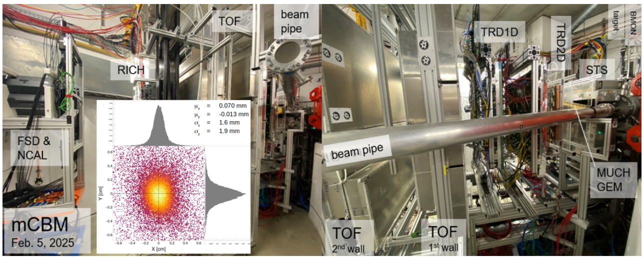

Figure 3. mCBM detector test setup at SIS18. Inlay shows event-by-event reconstruction of primary vertex at mCBM using STS tracks[5].

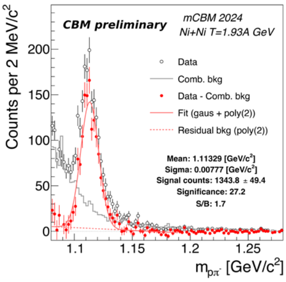

Figure 4. Signal of Λ baryon reconstructed by mCBM.

In order to prepare for the start of the CBM detector, a test setup called mCBM@SIS18 (see Fig. 3) was constructed at SIS18 of GSI/FAIR, taking data since 2019 within the FAIR Phase-0 program at GSI. It consists of pre-series version components of all CBM subdetectors, using the free-streaming data acquisition system and a demonstrator setup of the online data analysis chain. The high-rate capabilities of the complex system of hardware and online/offline software have been successfully demonstrated under realistic conditions of the high-intensity SIS18 beams with collision rates up to 10 MHz (averaged). As an example, recent studies [5] demonstrate excellent operational performance of the STS tracking detector within mCBM, achieving a hit reconstruction efficiency of 98%, a spatial resolution of 25 μm, and a timing resolution of about 5 ns. The functionality of the complete system running in self-triggered mode, together with the DAQ chain, calibration, and event reconstruction, was further demonstrated by reconstructing Λ baryons (see Fig. 4) from $\sim 10^9$ Ni+Ni collisions at $E_{\mathrm{kin}} = 1.93\,A\,\mathrm{GeV}$, recorded during 2.5 hours at an average collision rate of 200 kHz. This verifies the CBM readout concept in a setup scalable towards the full CBM experiment.

In summary, the CBM collaboration is making significant progress in both detector construction and software development in order to be beam-ready by 2028.

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