THE COMPRESSED BARYONIC MATTER EXPERIMENT AT FAIR

J. M. Heuser[1] and the CBM Collaboration[2]

[1] *GSI Helmholtz Center for Heavy Ion Research GmbH, Darmstadt, Germany*
[2] *www-cbm.gsi.de*

The Compressed Baryonic Matter (CBM) experiment is being planned at the international research center FAIR, under realization next to the GSI laboratory in Darmstadt, Germany. Its physics programme addresses the QCD phase diagram in the region of highest net baryon densities. Of particular interest are the expected first order phase transition from partonic to hadronic matter, ending in a critical point, and modifications of hadron properties in the dense medium as a signal of chiral symmetry restoration. Laid out as a fixed-target experiment at the heavy-ion synchrotron SIS-300, the detector will record both proton-nucleus up to 89 GeV and nucleus-nucleus collisions at beam energies between 10 and 45*A* GeV. Hadronic, leptonic and photonic observables have to be measured with large acceptance. The interaction rates will reach 10 MHz in order to measure extremely rare probes like charm near threshold. Two versions of the experiment are being studied, optimized for either electron-hadron or muon identification, combined with silicon detector based charged-particle tracking and micro-vertex detection. The CBM physics requires the development of novel detector systems, trigger and data acquisition concepts as well as innovative real-time reconstruction techniques. A initial version of the CBM detector together with the HADES experiment will be used to start the physics programme in FAIR construction phase A at the SIS-100 synchrotron. The full set of CBM observables can only be investigated with the completed detector at SIS-300 energies. Progress with feasibility studies of the CBM experiment and the development of its detector systems are reported.

1. The CBM physics programme

The CBM experiment will conduct a comprehensive research programme on nucleus-nucleus collisions at FAIR [1, 2]. The aim of the CBM project is to investigate the largely unexplored QCD phase diagram at highest net baryon densities and moderate temperatures, complementary to the heavy ion programmes at RHIC and at LHC that address the physics of the early universe at low densities and high temperatures. With projectile energies between 10 and 45 *A* GeV SIS-300 will provide intense beams in the range where the highest net baryon densities are predicted to reach about 10 times that of ground state nuclear matter. This will enable the CBM programme to focus on signatures of the expected first order phase transition from partonic to hadronic matter, ending in a critical point, and on modifications of hadron properties, e.g. their masses, in the dense nuclear medium as a signal of chiral symmetry restoration. The research programme will be started at the SIS-100 synchrotron, to be realized first within the FAIR construction phase A [3] and planned to be operational in the year 2018. The SIS-100 will provide ion beams with energies between 2 and 11*A* GeV, and protons up to 29 GeV on nuclear targets to the HADES detector [4] and an initial version of the CBM experiment. Recently proposed other programmes in this beam energy range at RHIC/BNL and NICA/ JINR will be complementary to the CBM programme as they are limited in interaction rates and will focus on bulk particle production. The full exploration including rare probes will be the task of the CBM experiment at the future SIS-300 synchrotron.

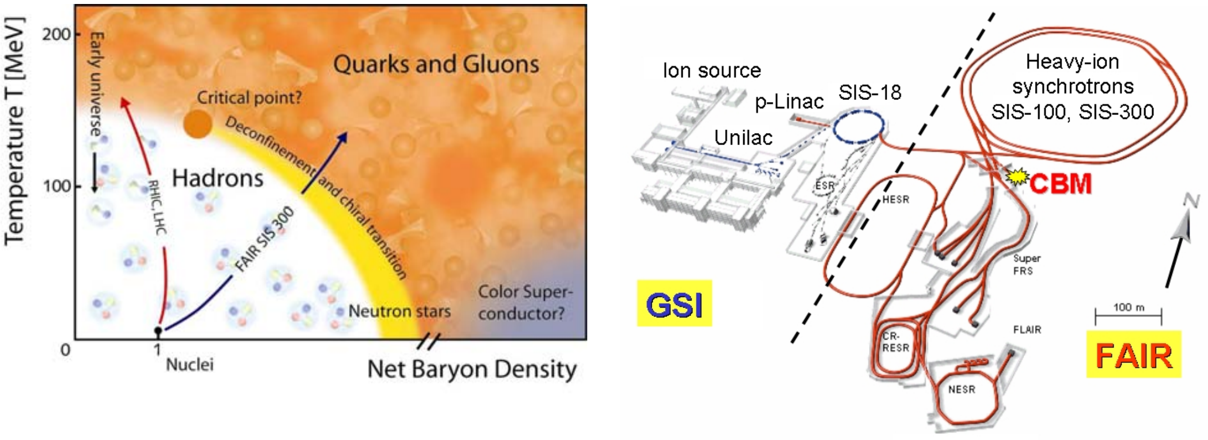

Fig. 1. Cartoon of the QCD phase diagram to be explored by the CBM experiment (*l*eft).
The FAIR complex with the CBM experiment at the SIS-100 and SIS-300 synchrotrons (*right*).

2. The CBM detector

Two configurations of the CBM detector are being evaluated for electron-hadron and muon-hadron measurements. Both may be realized at different stages. They have in common low-mass silicon tracking system (STS), the central detector to perform charged-particle tracking and high-resolution momentum measurement with radiation tolerant silicon microstrip and pixel detectors. Combined with an ultra-thin micro-vertex detector (MVD) based on monolithic active pixel sensors, it will be installed in the gap of a dipole magnet in short distance downstream of the target, typically a gold foil of 250 μm thickness corresponding to 1 % nuclear interaction length. In the electron-hadron configuration, the CBM experiment comprises a ring imaging Cherenkov (RICH) detector downstream of the magnet to identify electron pairs from vector meson decays. Transition radiation detectors (TRDs) provide charged particle tracking and the identification of high energy electrons. Hadron identification will be realized in a time-of-flight (TOF) system built from resistive plate chambers (RPC). An electromagnetic calorimeter (ECAL) will be used for detecting direct photons. The projectile spectator detector (PSD) is a calorimeter that determines centrality and reaction plane of the collisions. In the muon-hadron configuration of the experiment, the RICH detector system is replaced by a compact active absorber system (MUCH). Vector mesons are detected via their decays into muon pairs. Hadrons can be measured with the absorbers moved out.

A particular feature of the experiment is its data acquisition and trigger concept, imposed by the physics programme with rare probes, e.g. charm production near threshold, and the necessity for interaction rates between 0.1 and 10 MHz. It is based exclusively on self-triggering front-end electronics to time-stamp and to ship the detector signals to a fast computing farm for event building and high-level trigger generation.

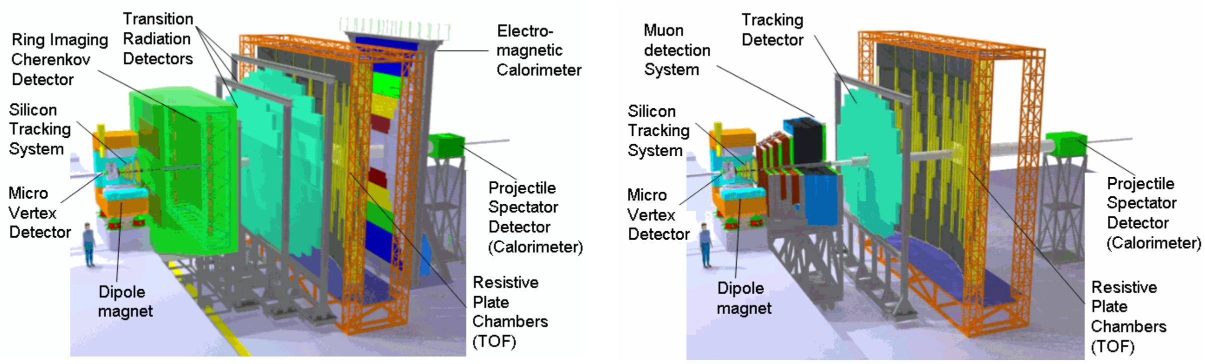

Fig. 2. The CBM detector in electron-hadron (*left*) and in muon configuration (*right*).

3. Physics performance studies and detector development

Progress with the preparation of the experiment has been achieved with detailed physics performance simulations, based on increasingly realistic implementations of the CBM detector systems. This includes feed-back from the beginning detector developments and the evaluation of first demonstrator systems in test-beam experiments [5].

3.1. Charged particle tracking

The high multiplicity of up to 700 charged particles per central nuclear collision is reconstructed with the Silicon Tracking System [6, 7]. The measurement of essentially all CBM observables depends on the high performance of the STS. Currently 8 tracking stations are considered in a 1 T dipole magnetic field based on radiation tolerant silicon micro-strip sensors mounted on a light-weight carbon fiber support structure. The material budget may be less then 1 % radiation length per station. In central 25*A* GeV Au + Au events, generated with UrQMD, tracks pointing to the primary vertex are reconstructed with 96 % efficiency above momenta of 1 GeV/c using Cellular Automaton and Kalman Filter algorithms. The material budget is such that a momentum resolution of 1.3 % is obtained.

3.2. Di-lepton spectroscopy

Electron identification is performed using a Ring Imaging Cherenkov Detector and a Transition Radiation Detector system. The RICH system uses a CO_2 radiator of 1.5 m length, providing a pion separation threshold momentum of 4.65 GeV/c. Mirrors of 12 m^2 area project electron ring images of about 6 cm diameter onto the 2.4 m^2 photo detection plane. The ring finding efficiency, evaluated in simulations with several reconstruction algorithms, is in excess of 95 % for electrons embedded into central Au + Au collisions at 25*A* GeV beam energy. The detector R&D for the RICH system focuses on the evaluation of thin spherical glass mirrors of 3 m radius with Al + MgF_2 coating and multi-anode photo multiplier tubes coupled to self-triggering readout electronics. For the TRD detector, innovative multi-wire proportional chambers with double-sided pad readout coupled to a foil radiator are being developed, capable of high counting rates. The combined electron identification efficiency of RICH and TRD is 85 % at a pion suppression factor of 10^4. The remaining background is dominated by π^0 Dalitz decays [8]. Muon identification is performed with a segmented hadron absorber and a tracking system downstream of the STS. The MUCH system is divided into two regions addressing low-mass muon pairs (vector mesons) and high-mass pairs (J/ψ). Five iron discs of 20 cm to 35 cm thickness, with a total thickness of 7.5 nuclear interaction lengths, are interleaved with 5 gaps of GEM detector layers and serve the measurement of the low-mass vector mesons. After another 1 m of iron and total 13.5 nuclear interaction lengths, the J/ψ pair candidates are detected. The particle multiplicity is reduced such that after 1.25 m iron 0.25 identified muons are obtained in 25*A* GeV Au + Au with the dominant background coming from π and K decays at 0.13 muons per event [8]. Spectra and phase-space coverage of reconstructed di-leptons are shown in Figs. 3 and 4.

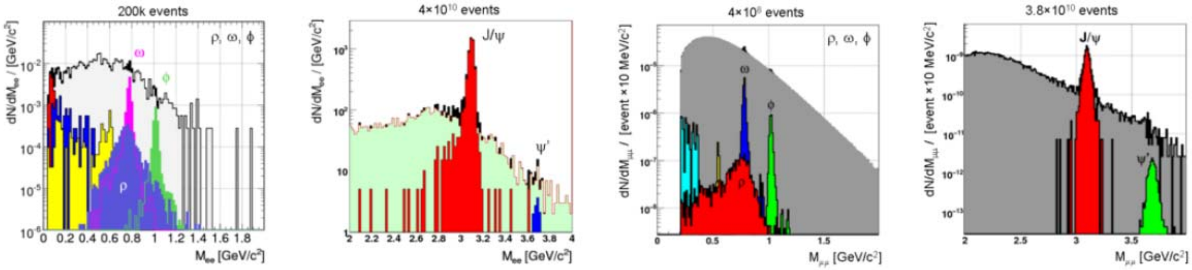

Fig. 3. Di-lepton spectra for low-mass vector mesons and charmonium, together with combinatorial background. The left two plots are for the di-electron experiment, the right two plots for the di-muon case.

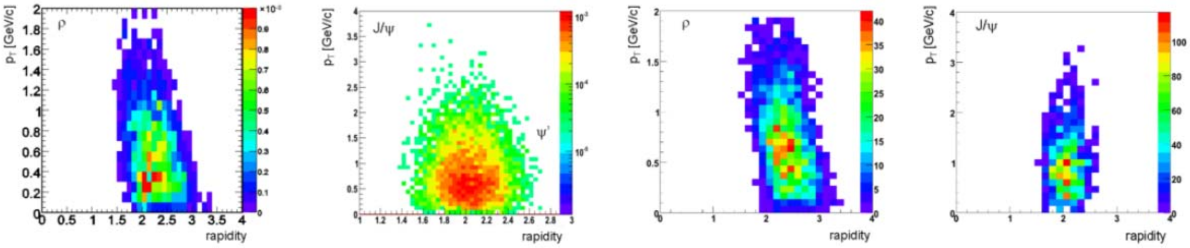

Fig. 4. Di-lepton phase space coverage for the electron configuration (*left two plots*) and the muon configuration of the CBM experiment (*right two plots*).

3.3. Hadron measurement

Hadrons are identified via time-of-flight measurement with a detector system based on resistive plate chambers. Different RPC technologies are being explored, including ultra-thin glass pad RPC, ceramic RPC, and differential RPC based on semi-conductive glass. High counting rate capability up to 25 kHz has to be achieved with a time resolution of 80 ps [9]. The "global" track reconstruction efficiency obtained with the simulated STS, TRD and TOF systems is 85 %.

3.4. Open charm detection

The efficient separation of primary and short-lived decay vertices for open charm detection requires a z-vertex resolution of the order of 50 μm r.m.s. This is planned to be realized with a two-station micro vertex detector in front of the silicon tracker, built from Monolithic Active Pixel Sensors [10]. The stations must be ultra-thin. Two MVD stations with a material budget of 0.3 and 0.5 % radiation lengths have been studied at 5 cm and 10 cm downstream of the target. No K and p identification is performed but proton rejection via TOF. The interaction rate is limited to 10^5/s - 10^6/s as imposed by the probably maximum readout speed of the monolithic pixel detectors. With this MVD system the estimate of the yield [11] is 16k (87k) D^0 + 46k (251) $\overline{D}^0$ and 26k (52k) D^+ + 49k (98k) D^- according to the HSD (SHM) model in 10^{12} minimum bias events, corresponding to about 2 – 20 weeks of full-time data taking with efficiencies as shown in Fig. 5.

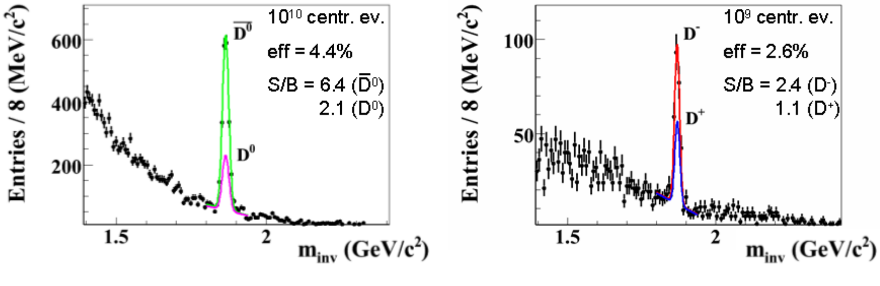

Fig. 5. Invariant mass spectra of D mesons in central Au + Au collisions at 25*A* GeV.

3.5. Development of detectors, data acquisition system and on-line event selection

Further developments comprise self-triggering front-end electronics for the STS, RICH and MUCH systems, a readout chip for the TOF system with 25 ps time resolution, a data acquisition system with 500 MB/s/node throughput, and fast on-line event selection and track reconstruction. For the on-line computing many-core architectures and parallelized reconstruction code are explored [12]. A starting point is the application of commercial high-end graphics cards assembled into a GPU farm. The maximum archiving rate will be 25 kHz. High-level trigger strategies are being developed for different physics cases, including: (a) Open charm: full event reconstruction; limited by MVD to 10^5 - 10^6 events/s; (b) J/ψ, ω,φ → $\mu^+\mu^-$: event pre-selection by MUCH ($\times 10^{-3}$) and (c) J/ψ → e^+e^-: trigger based on TRD and STS (minimum bias events).

3.6. Physics with HADES and pre-CBM at SIS-100

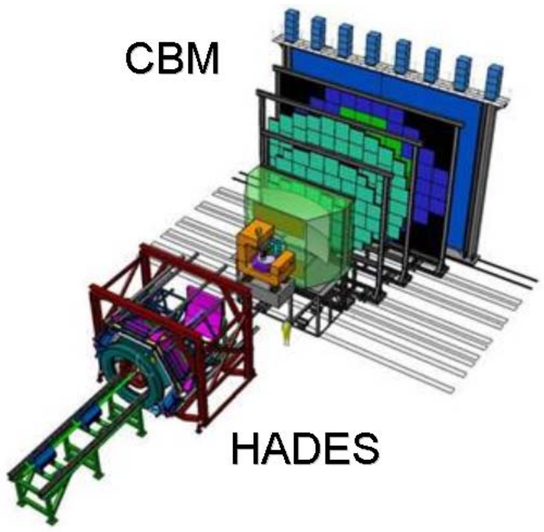

Fig. 6. Illustration of the HADES and CBM detectors in the experimental hall at SIS-100.

In the initial phase of FAIR the beams available from the SIS-100 synchrotron allow starting the investigation of nuclear matter in the vicinity of the expected deconfinement phase transition. The currently operating fixed-target experiment HADES at the SIS-18 synchrotron will be moved into the CBM experimental hall and installed in front of a partial configuration of the CBM experiment. The set-up is illustrated in Fig. 6. The combination of the HADES detector, capable of hadron, electron and photon measurement, and the pre-CBM detector with silicon tracking, decay vertex identification, hadron identification and muon detection capabilities, will allow for investigating in separate HADES/CBM data taking runs several observables. These include the excitation function of multi-strange particles (Fig. 7) and lepton pairs (HADES: electrons, CBM: muons) in heavy-ion collisions, open-charm production at threshold in p + C collisions up to 29 GeV (CBM configuration: STS and MVD in dipole magnet, TOF) as well as charmonium production (CBM: STS and reduced muon detector) (Fig. 8). Cold nuclear matter effects can be studied as reference data for later A + A collisions at SIS-300.

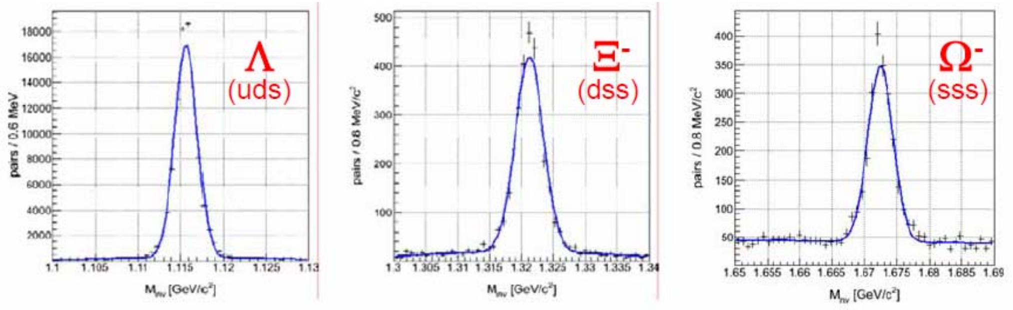

Fig. 7. Invariant mass spectra of hyperons obtained through reconstruction of their decay topology in the silicon tracking system

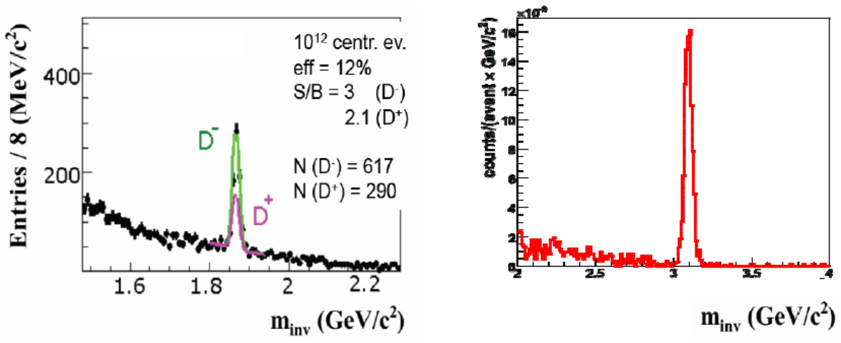

Fig. 8. Charm production in p+C collisions of 29 GeV:
Open charm from $D^\pm$ +X, $D^\pm \rightarrow K\pi\pi$ (*left*) and charmonium from J/ψ +X, J/ψ→$\mu^+\mu^-$ (*right*).

Acknowledgments

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