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The Compressed Baryonic Matter (CBM) experiment at FAIR

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The CBM experiment will investigate highly compressed baryonic matter created in A+A collisions at the new FAIR accelerator. With a beam energy range up to 11 AGeV for the heaviest nuclei at the SIS 100 accelerator, CBM will investigate the QCD phase diagram in the intermediate range, i.e. at moderate temperatures but high net-baryon densities. This research program is thus complementary to the studies performed at the high-energy accelerators LHC and RHIC and is of particular interest because, compared to the high energy case, the strongly interacting matter created here is expected to have very different characteristics due to the high net-baryon densities. Different to the crossover between partonic and hadronic matter seen at low net-baryon densities, a first order phase transition ending in a critical point and possibly new high-density phases of strongly interacting matter are expected.

In this range of the QCD phase diagram only exploratory measurements have been performed so far. CBM, as a second generation, high-luminosity experiment, will substantially improve our knowledge of matter created in this region of the QCD phase diagram and characterize its properties by measuring rare probes such as multi-strange hyperons, dileptons or charm, but also with event-by-event fluctuations of conserved quantities, and collective flow of identified particles. Due to the unprecedented reaction rates CBM has a high discovery potential. The experimental preparations in terms of detector development, feasibility studies and fast track reconstruction are progressing well such that CBM will be ready with the FAIR start. Several detector components will even be used in other heavy-ion components prior to FAIR start substantially enhancing their physics potential.

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1. Mapping the QCD phase diagram with heavy-ion experiments

The QCD phase diagram is of fundamental interest for understanding the strong interaction and strongly interacting matter in particular in the non-perturbative regime. Figure 1 (left) shows the conjectured QCD phase diagram in dependence on temperature and baryon chemical potential μ_B [1]. Besides phases where the known hadrons (hadronic phase) and quarks and gluons (Quark-Gluon Plasma, QGP) are the relevant degrees of freedom, more exotic phases have been predicted in particular in the high baryon density range. Most prominently the so called quarkyonic matter [2] which has properties of both, high density baryonic matter and chirally symmetric and deconfined matter. At very high baryon densities but low temperatures color superconducting phases are expected. Heavy-ion collisions in the laboratory allow to investigate the QCD phase diagram; depending on collision energy a fireball of varying temperature and baryon density is created. For $\mu_B = 0$ lattice QCD calculations predict a phase transition (crossover) from partonic to hadronic matter at temperatures around 160 MeV which is driven by the energy density [3]. As critical energy density values of about 1 GeV/fm^3 are derived. LHC and RHIC experiments at highest collision energies explore this range of the phase diagram measuring indeed a crossover between partonic and hadronic matter. They successfully set out for characterizing the created matter in terms of gluon density, viscosity etc. At large baryon densities, however, the phase structure is uncharted territory as lattice QCD calculations are not applicable and cannot give firm predictions, and as no high-precision data are available but only rather limited information from the former AGS experiments. Effective models, on the other hand, predict structures such as a first order phase transition and a critical point, see e.g. [4], and exotic phases like the above introduced quarkyonic phase. The experimental discovery of such landmarks of the QCD phase diagram would be a breakthrough of our understanding of the strong interaction in the non-perturbative regime and thus has triggered a number of experimental campaigns worldwide.

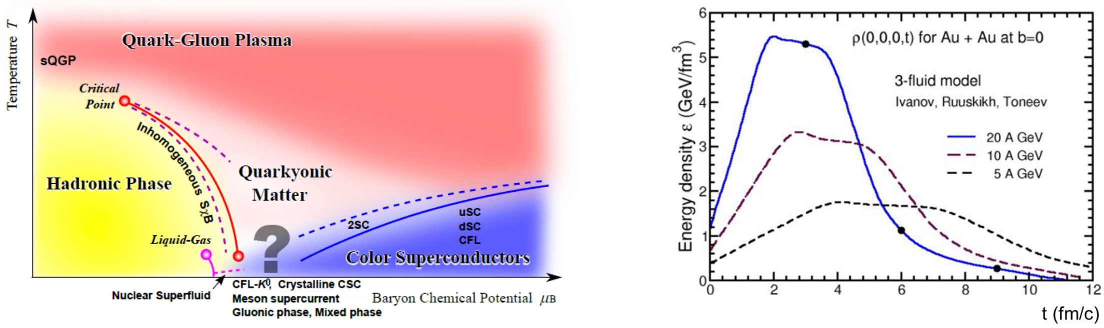

Figure 1: Left: Conjectured QCD phase diagram [1]. Right: Energy density versus time in the central cell of Au+Au collisions at various energies from a 3-fluid model [5].

The SIS100 accelerator at FAIR will offer heavy-ion beams with energies up to 11 AGeV for Au ions at intensities up to 10^9 ions/s. Model calculations predict that at these collision energies matter with high net-baryon densities reaching up to 10 times normal nuclear matter density ρ_0 will be created [5]. At the same time substantial energy densities are reached in the fireball, in the center exceeding the critical density of 1 GeV/fm^3, see figure 1 (right). The unprecedented beam intensity in a beam energy range most relevant for the exploration of high-baryon density matter is the prerequisite for CBM becoming a unique heavy-ion experiment with large discovery potential, see see [6] and [7] for more details than can be discussed here. Figure 2 (left) highlights this unique feature of CBM showing interaction rates of running and future heavy-ion experiments which share the ambition to unravel the intermediate range of the QCD phase diagram. The interaction rates achieved in the CBM experiment open up new possibilities: CBM will provide high precision data and systematic studies on hadronic observables including multistrange particles and D-mesons (depending on energy). Results of these measurements will answer the long standing question on strangeness equilibration at freeze-out of the dense matter into a hadron gas. Beyond the investigation of phase space abundancies, the exploration of flow, correlations and fluctuations of conserved quantities will give further insight into the created matter allowing to determine e.g. the equation of state, a first order phase transition or the critical point. Driven by the high baryon densities more exotic hadrons like kaonic clusters and hypernuclei may be created. A completely new territory at CBM energies will be the investigation of dileptons. This observable is particularly promising because once created dileptons leave the strongly interacting matter undisturbed and allow to look into the fireball. A multidifferential analysis of dileptons over the whole range of invariant masses will give access to early fireball temperatures (photons) or in-medium properties of the ρ-meson. The most important measurement however may be the dilepton yield beyond invariant masses of 1 GeV/c^2 as this allows to directly access the fireball temperature. Fig. 2 (right) illustrates the discovery potential connected to this measurement because depending on the nature and location of the phase transition a caloric curve may be the result.

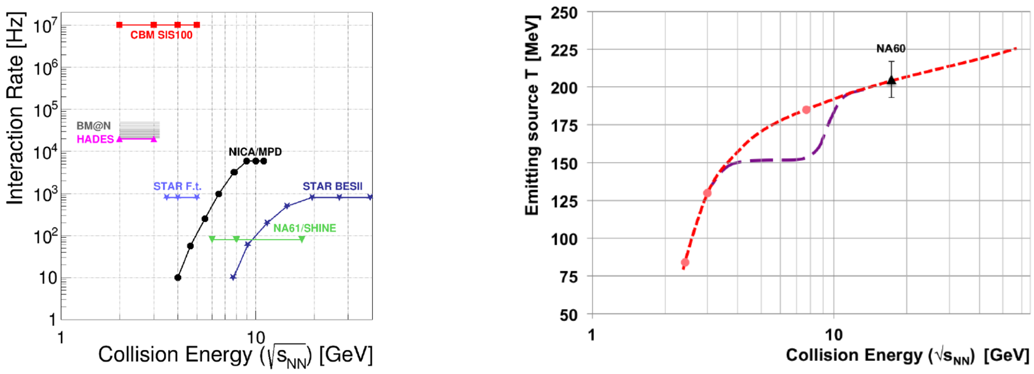

Figure 2: Left: Interaction rates achieved by existing and planned heavy-ion experiments as a function of center-of-mass energy [7]. "STAR F.t." denotes the fixed-target operation of STAR. Right: Model calculation (dashed red curve) of the excitation function of the fireball temperature measured with dileptons and speculated shape (violet) with a first order phase transition in the SIS 100 energy range [8].

2. The CBM experiment

The CBM detector has been designed to measure the whole range of hadronic and leptonic probes in a wide phase space acceptance. Figure 3 (left) presents the layout of the full detector system: Heart of CBM will be a fast and radiation hard tracking detector consisting of 8 layers of double sided silicon micro-strip sensors (STS) inside the magnetic dipole field. For highest tracking and vertex reconstruction resolution close to the event vertex four layers of silicon monolithic active pixel sensors (MVD) will be added. Following this high precision tracking system particle identification is added to the CBM setup: In order to identify electrons and hadrons a RICH detector, a few layers of transition radiation detectors (TRD) and a time-of-flight (TOF) wall using Multi-Gap Resistive Plate Chambers (MRPC) are positioned downstream. For muon identification the RICH will be exchanged with a Muon Chamber system (MuCh) consisting of alternating layers of absorbers and gaseous micropattern tracking chambers. In all cases the setup is completed by a compact calorimeter for a position resolved detection of the projectile spectators (PSD) in order to characterize the events in terms of centrality and reaction plane. For all detectors except MVD and TRD technical design reports have been approved by FAIR, the missing detectors will follow soon. Construction phase of most of the detectors has already been started.

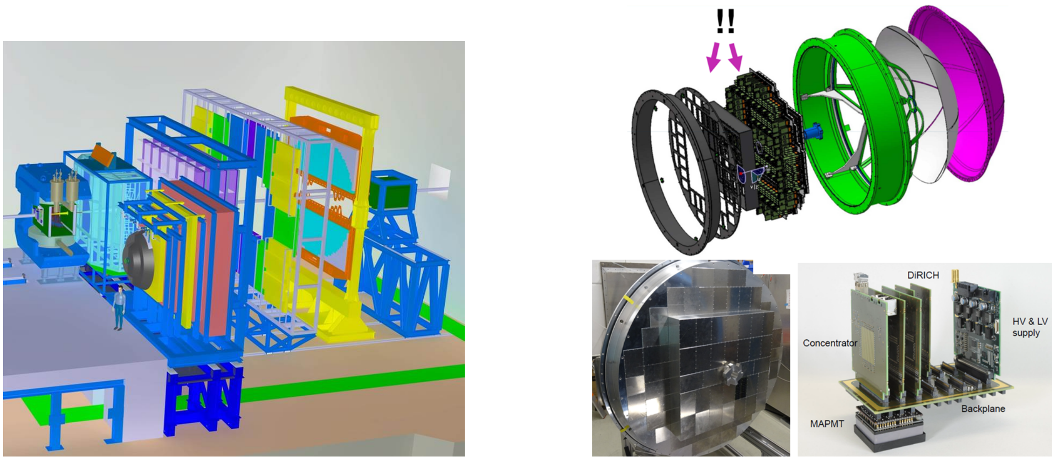

Figure 3: Left: Setup of the CBM experiment at SIS 100. Beam is entering from left, the sequence of the detectors is: tracking system consisting of silicon pixel (MVD) and micro-strip detectors (STS) in the superconducting dipole magnet, RICH detector, some layers of TRD, TOF, ECAL and a calorimeter for event caracterization (PSD). The muon detector (MuCh) is shown here in the parking position. Right: Exploded view of the HADES RICH detector showing the photon detector replaced by CBM MAPMTs (top). New HADES-RICH photodetector frame with first 2x3 MAPMT module installed (lower left) and first assembly of a 2x3 MAPMT module with readout and power supply.

A CBM specific challenge poses the need to run at event rates of 100 kHz up to 10 MHz in order to access the desired rare observables [9]. The data acquisition of all detectors will thus be based on self-triggered front-end electronics sending a data-stream with precise time-stamps to a high performance computing farm in the GSI GreenIT cube. A high speed first level event selection (FLES) system [10] will deliver online event reconstruction and selection including secondary vertex finding in real-time [11]. Only this effort will allow to filter out the rare events with, e.g., weakly decaying multi-strange hyperons or D-mesons. In order to cope with the high rates and time-stamped data format, the track reconstruction routines will add time as a fourth dimension in order to disentangle the different events [12]. Reconstructed tracks are then clustered in groups representing the original events (figure 4). As the FLES system is an integral and highly important part of CBM, a technical design report is being prepared also for this CBM component.

All observables being relevant for CBM have been and still are investigated in detailed feasibility studies adding more and more details on detector response and the complexity of the 4d-tracking

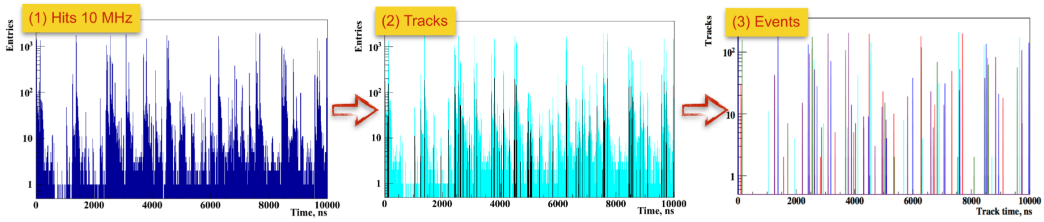

Figure 4: Part of a time-slice with 100 minimum bias Au+Au collisions at 25 AGeV beam energy [12]. Left: time distribution of hits in the selected time-slice. Middle: reconstructed tracks (black) within the time distribution of hits. Right: reconstructed tracks clustered into event groups.

algorithms. All simulations are performed within the CbmRoot framework [13] using GEANT 3 [14] for the detector simulations. Results are sound and convincing for all probes, see e.g. [15] and [16] for recent studies. In central Au+Au collisions at 8 AGeV, e.g, about 500,000 Ω-baryons will be measured within one week assuming a storage rate of 100 kHz. High statistics within a short time for one selection of centrality and energy is the prerequisite to perform systematic measurements in dependence on energy and centrality allowing also for multidifferential analysis including not only phase space yields but also flow, correlations and fluctuations.

The current FAIR schedule foresees first beams being delivered 2022 with CBM being the first-day experiment. CBM will be ready till then, even more, several detector components will be ready substantially earlier in time. Therefore, CBM detector components will be installed prior to the usage at FAIR in existing heavy-ion experiments at other laboratories. This so called "FAIR phase 0" program has many benefits: The CBM detector components will substantially improve the detector performance of the experiments, the CBM detectors and their readout chain will be thoroughly tested and calibrated being fully operational and well understood for the start of CBM at FAIR, and members of the CBM collaboration will participate in data taking and physics analysis in the field of heavy ion physics. In this context several projects are carried out. Approximately 40% of the H12700 Hamamatsu MAPMTs for the CBM RICH detector will be used in order to replace the gaseous photon detector of the RICH detector in the HADES experiment. This project is far advanced, see figure 3 (right) for an exploded view of the HADES-RICH and photos from the new photon-detector and readout during first test assembly. The upgrade will be ready for the intermediate research program at GSI starting 2018 and will boost the dilepton pair efficiency of HADES in particular at small opening angles. Other projects are in brief: About 10% of the TOF-MRPC modules will be installed at the STAR detector at BNL in order to substantially enhance the hadron identification capability at forward rapidities for the second beam energy scan in 2019/2020. Four prototype stations of the STS will be installed in the future fixed-target experiment BM@N at the Nuclotron at JINR in Dubna. PSD components are tested at the NA61/SHINE experiment at CERN which also employs a hadron calorimeter which is very similar in design to the CBM PSD. At the SIS18 at GSI a "mini-CBM" setup will be installed using full-size CBM prototypes which will focus on commissioning the full readout-chain and online event reconstruction in the GreenIT cube at GSI. This endeavour should substantially reduce commissioning time for CBM at SIS100.

3. Summary

The CBM experiment at FAIR is part of a world-wide endeavour to experimentally map the QCD phase diagram and characterize strongly interacting matter in dependence on temperature and baryon density. The CBM experiment will be unique for the exploration at high-net baryon densities because CBM will operate at interaction rates a few orders of magnitude higher than anywhere else. CBM will thus be able to systematically explore matter at high baryon densities with systematic high-precision measurements of rare observables like multistrange particles, dileptons and charm. This offers the chance to resolve many open fundamental physics questions related to baryon-dense matter such as for the nuclear matter equation of state, phase transitions and possible new phases or in-medium modifications of hadrons. CBM thus has a substantially discovery potential. The CBM detector development is well advanced and several of the detector components can even be used in other heavy-ion experiments prior to FAIR start substantially enhancing their physics potential.

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