The technological concept of the Compressed Baryonic Matter (CBM) experiment

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Abstract. The Compressed Baryonic Matter (CBM) experiment is to explore the properties of strongly interacting matter in the regime of highest net baryon densities. It aims to find experimental evidence for numerous predicted effects like a first order phase transition between hadronic and partonic matter, the existence of a critical endpoint of this phase transition and the expected onset of chiral symmetry restoration. The 8-45 AGeV heavy ion beam needed to create the hot and dense matter in the fixed target experiment will be provided by the SIS100 and the SIS300 synchrotron of the future FAIR facility in Darmstadt, Germany. The paper provides an introduction into the measurement challenges and the technological concept of CBM-experiment from an instrumentalist’s point of view.

1. The phase diagram of nuclear matter
A sketch of the phase diagram of strongly interacting matter is displayed in Figure 1. This phase diagram shows the state of matter as a function of the temperature and the baryo-chemical potential ($\mu_B$). The temperature ($T$) is defined via the energy of the particles per

Figure 1. Simplified view of the phase diagram of hadronic matter. From [1].

Figure 2. Evolution of a nuclear collision. The thin lines refer to the evolution prior to thermalization, the thick lines to an evolution in “thermal equilibrium”. From [3].
degree of freedom and can be determined by measuring their kinetic energy spectrum. The $\mu_b$ is the energy needed to add one baryon to the volume ($V$) of the system. Although both are connected, it should not be confused with the (net) baryon density $\rho_B = B/V$. The baryon number $B = 1/3 (n_q - n_{\bar{q}})$ of a system with $n_q$ quarks and $n_{\bar{q}}$ anti-quarks is conserved during heavy ion collisions.

The phase diagram is divided into two major regimes\(^1\), the confined hadronic matter and the postulated deconfined quark gluon plasma (QGP). In simple terms, QGP is created if individual hadrons start to overlap and the previously confined quarks may travel within the common potential. The necessary particle density may be created by compression of existing hadrons (low $T$, high $\mu_b$) or by an excessive thermal generation of particles (high $T$, low $\mu_b$). The phase transition between the hadronic matter and the QGP is considered to be of first order in the region of high baryonic densities. A critical endpoint separates this regime from the crossover studied by ALICE and STAR in the regimes of highest temperatures and lowest baryonic densities. The existence and position of the first order phase transition and the endpoint are debated controversially as nowadays theoretical predictions underlie substantial uncertainties\(^2\) and as no experimental observation was reported so far.

Experimentally, the extremely hot and dense nuclear matter needed for exploring the phase diagram is generated in heavy ion collisions. In a simplified picture, a heavy ion collision starts with head-on collisions of the nuclei, which may create particles of highest mass. Hereafter, the system reaches a kind of thermal equilibrium while its temperature and pressure increase further and QGP may be formed. After reaching the maximum density and $T$, the fireball expands and cools down. A phase transition from QGP to hadronic matter, the so-called hadronization, occurs. Once $T$ turns too low for thermal particle formation, the chemical equilibrium breaks and the relative number of particles remains constant except for usual particle decays. If the density shrinks too far to force frequent elastic collisions, the thermal equilibrium breaks and the kinetic properties of the particles stay unmodified. Both processes are referred to as chemical and thermal freeze out. They fix the $T$ and $\mu_b$ observed when interpreting the properties of the decay products of the collision by means of statistical thermodynamics. The $T$ derived from the chemical composition is named $T_{\text{chem}}$, the $T$ taken from the kinetic properties is called $T_{\text{kin}}$.

Note that some of the hadrons/quarks formed in head-on collisions may be too heavy to join the chemical equilibrium. Moreover, some heavy particles might leave this equilibrium slightly earlier than light ones.

The $\mu_b$ and $\rho_b$ increase when colliding heavier ions. Model calculations like the one displayed in Figure 2 suggest that an increased beam energy turns into a higher maximum $T$ and $\mu_b$ during the collision. However, the system tends to pass the phase border already before reaching thermal equilibrium. As a phase is defined only in equilibrium, a transition in the strict term occurs only during expansion. The $T$ and $\mu_b$ needed for observing a first order phase transition during expansion is found at intermediate beam energies, which motivates the choice of the CBM beam energy. Note that the detailed numbers of the evolution of the collision are model dependent, a compilation of different results is found in\(^4\).

The “thermal” expansion of the fireball has a strong impact on the chemical composition and kinetic properties of its strongly interacting particles. The decay products of the fireball show therefore in first order the $T$ and $\mu_b$ reached in the moment of freeze-out. To study the earlier evolution of the collision, one has to identify so-called diagnostic probes, which conserve information through the expansion of the fireball.

Numerous probes were proposed for CBM\(^5\). A non-conclusive list includes leptons and photons, which are not subject to the strong interaction and leave the fireball mostly

\(^1\) Discussing the additional potential phases shown in Figure 1, e.g. the quarkyonic matter, is beyond the scope of this work. A related review is found in [1].
undisturbed. Moreover, particles containing the heavy charm quarks are suited as those quarks are created only in the early collisions and hardly destroyed during expansion. The collective properties of the fireball, e.g. its pressure distribution during the collision, may be probed by assessing the collective motion (flow) of all particles relative to the so-called collision plane. This plane is spanned by the beam direction and the impact parameter of the colliding hadrons.

A common feature of all probes is the difficulty to interpret the encoded information. Light vector mesons decaying into lepton pairs within the fireball may for example provide information about possible modifications of the meson mass in the medium. However, to name only one trivial complication, one has hard times to distinguish, at which time of the collision the meson was formed and decaying. Instead, one integrates over the full evolution of the fireball.

The data is interpreted by comparing the observations with results from theoretical models, which are to reproduce the evolution of the collision. This method is limited as the heavy ion collision itself is not accessible to observation while the decay products observed in the detectors provide only reduced information. This gives room for numerous theoretical concepts, which differ substantially concerning their physics content but predict, within the uncertainties of available experimental data, similar decay products. In the CBM energy range, this room is particularly wide as most existing data was taken with elder experiments, which were technologically restricted to the measurement of only few of the potential probes and observables.

2. The concept of CBM

Accounting for the above mentioned complication and profiting from the rapid progresses of sensor and computer technology during the last two decades, CBM aims to measure as many different probes as accessible to nowadays most powerful detector technologies. The results will constrain the degrees of freedom in nowadays theoretical models. This will hopefully allow for rejecting a substantial number of models and assumptions, which would sharpen our understanding of the physics of hot and dense nuclear matter quite substantially.

CBM will measure e.g. strange and multi-strange hadrons, open charm$^2$ and prompt gamma rays. The particularly interesting light vector mesons and charmonium will be observed via both, the $e^+/e^-$ and $\mu^+ / \mu^-$ decay channels. This is as the $e^+/e^-$ channel appears better suited for light vector mesons while the $\mu^+ / \mu^-$ channel seems more appropriate to observe charmonium.

$^2$ Open charm particles combine one charm quark with light quarks, charmonium contains a $c/\bar{c}$-pair.
Moreover, the interpretation of di-lepton spectra requires a particularly good quantitative understanding of the background. Accessing the same physics in the same acceptance but with two independent measurements will ease to spot potential systematic errors in the background subtraction and such increase the reliability of the data and its interpretation.

As many of the probes are rare (e.g. few $10^{-6}$ $D^0 \rightarrow K^- + \pi^+$ decays per central Au-Au collision), CBM is designed as a dedicated high rate experiment. It will operate at the SIS100 and the SIS300 synchrotron of the future FAIR facility, which will both provide slowly extracted spills of 10-100s with a beam intensity of ($\gtrsim 10^9$/s). The design goal of CBM is to obtain a rate of $\sim 10^7$ heavy ion collisions per second by means of a 1% target. The wish to handle this collision rate and the need to reach the instrumental sensitivity required for identifying rare probes determine the layout of the experiment call for a design at the edge of nowadays technologies. Intense and fruitful R&D had to be carried out to transform the ambitious plans to a working device. Today, numerous technical details are still under (cost-)optimization. However, the global detector concept has converged.

As shown in Figure 3 and 4, CBM is designed as a facility integrating a hadron-, an electron-, a $\gamma$- and a muon-spectrometer. All systems are extensions of a central detector, the Silicon Tracking System (STS)[7, 8]. This silicon strip detector is located in an 1 Tm magnetic field which bends the trajectories of charged particles by means of the Lorentz force. The STS measures the impact points of the particles in 8 consecutive sensing layers, reconstructs the trajectory and determines the particle momentum $p$ from the bending radius. Its only 300 $\mu$m thin, double sided sensors have a very fine (58 $\mu$m) strip pitch and a stereo angle of $8^\circ$. The sensors are connected via ultra-thin capton cables with readout chips located outside the detector acceptance. This solution allows for a measurement accuracy of $\Delta p/p \approx 1\%$.

The ability to identify hadrons is of particular interest when reconstructing strange and open charm particles from their decay products. To do so, the velocity ($v$) of the hadrons is determined by measuring their time of flight while passing a known distance. Knowing $v$ and $p$, the rest mass of the particles can be determined. The Time Of Flight (TOF) system of CBM [9] will be composed from a diamond detector serving as start counter. The stop counter will rely on Resistive Plate Chambers (RPC) with enhanced rate capability. Both detectors together reach a time resolution of 80 ps, which should allow to identify protons. Moreover, it should separate pions and kaons up to $p \approx 6$ GeV/c. Above this value, both particles are highly relativistic and their difference in $v$ becomes marginal.

Strange and open charm particles decay before reaching a detector and must be reconstructed from their daughter particles. To distinguish those from other decay products of the fireball, one separates their decay point (secondary vertex, SV) from the decay point of the fireball (primary vertex, PV). This is done with a Micro Vertex Detector (MVD) [10], which helps to extrapolate the measured particle trajectories back to the vicinity of the target and to search for intersection points. Those points are interpreted as decay vertex. If besides a PV, a SV is found, one concludes on the decay of a short lived particle. To separate the PV and the SV of the short lifed open charm particles, one needs a vertex resolution of $\sim 50 \mu$m along the beam axis. To reach it, the MVD has to show a very good spatial resolution ($\lesssim 5 \mu$m). Moreover, it must be very light. Otherwise it would scatter the impinging particles and loose its accuracy for track extrapolation.

The MVD will consist of 3-4 layers, each equipped with the 50 $\mu$m thick CMOS Monolithic Active Pixel Sensors [11]. It will operate in the vacuum of the target chamber of CBM and its heat is evacuated with a cooling support made from CVD diamond. The material budget of the crucial first station including cables and support will be $\sim 0.3\% X_0$ only. As it is exposed to

3 This work focuses on the full CBM-setup as foreseen for SIS300. A reduced start version will be used for early experiments at SIS100. This setup and the related physics cases are discussed in Ref. [6].

4 A radiation length ($X_0$) of material forces ultra relativistic $e^-$ penetrating it to emit but $1/e$ of their energy as
extreme track densities, the MVD is limited to $\sim 10^5$ coll./s for the startup of CBM, which is sufficient for open charm measurements.

The $e^+/e^-$ spectrometer is to reconstruct charmonium and light vector mesons by computing the invariant mass of $e^+/e^-$ pairs. To control the background, one has to distinguish the electrons very precisely from pions. To reach the ambitioned pion suppression factor of $10^{-4}$, a complementary Ring Imaging Cherenkov Detector (RICH) \cite{12} and Transition Radiation Detectors (TRD) \cite{13} are used.

The RICH identifies highly relativistic particles via the production of Cherenkov light. This light is emitted in a cone, if the speed of a charged particle exceeds the speed of light in a medium, which was chosen as CO$_2$ for CBM. The photons are focused with a concave glass mirror and the $\sim 20$ photons of the light rings obtained are observed with a camera made from Multi Anode Photomultiplier Tubes (MAPMT). The RICH of CBM allows to reject pions with $p \lesssim 8$ GeV. For $p > 4.65$ GeV, the velocity dependence of the ring radius is exploited.

Highly relativistic charged particles emit photons like X-rays when passing the interface between materials with high and low refraction index. The TRDs of CBM recognize those fast particles (namely electrons with $p > 1.5$ GeV) by detecting this so-called transition radiation. The TRDs of CBM are formed from radiators like for example stacks of plastic foils, which create a high number of interfaces in the path of flight of the particles. The X-rays created are detected with a gas detector, which is also sensitive to the particle itself. One separates slow and fast particles by measuring the energy deposit in its gas volume, which varies in the presence or absence of the photon. Different energy deposit turns into different pulse highes and shapes in the output signal of the detector. As the creation and absorption of the X-ray is somewhat statistic, about 10 consecutive TRD-layers are needed to obtain significant results. To match the requirements in speed (250 ns charge collection time), no or only few cm drift distance in the gas detector is foreseen. The technical details of the TRD are not yet fixed as several alternative concepts were tested successfully.

The muon detector (MUCH) \cite{14} of CBM is to reconstruct light vector mesons and charmonium via their $\mu^+ / \mu^-$ decays. It will profit from the ability of the muons to penetrate thick materials and identify them by stopping all other particles with 6 iron absorbers with a total thickness of 225 cm. They are interrupted by up to 6 sensor planes made from three layers of triple GEM \cite{15} detectors with pad readout. Those are to measure the tracks of identified muons and to match them back to the related track found in the STS. The MUCH is put into the place of the RICH (1.20m from the target) by means of a rail system. This hampers CBM from measuring $\mu^+ / \mu^-$-decays simultaneously with other decays but suppresses efficiently the background from secondary muons generated in $\pi^+/\pi^- + \nu_{\mu}$ decays.

The electro-magnetic calorimeter (E-Cal) of CBM \cite{16} is to measure direct photons and reconstruct the $\pi^0$ and $\eta$ - decays needed for normalizing the $e^+/e^-$ spectra. It will be a sampling calorimeter composed from 1 mm thick lead absorbers and 1 mm scintillator sensors. The absorbers force $\gamma$ and $e^\pm$ to produce showers of secondary particles. The scintillators located between the absorbers record the energy of the secondary particles and the sum of all secondaries scales with the energy of the initial particle. The spatial segmentation of $3 \times 3$ cm$^2$, $6 \times 6$ cm$^2$ and $12 \times 12$ cm$^2$ will provide a good spatial resolution. The ambitioned energy resolution is $\sigma(E)/E = 4 - 6\%/\sqrt{E/\text{GeV}}$.

The second calorimeter of CBM is the segmented projectile spectator detector (PSD) \cite{16}. The PSD is to measure nuclear fragments produced in the collision and such to determine the related event plane. Moreover, the energy deposit will allow determining the number of nuclei, which did not participate in the collision, which is crucial for the study of event-to-event fluctuations. The PSD comprises 44 individual modules each consisting of 60 lead/scintillator bremsstrahlung. The related multiple scattering angle is determined by the material thickness devided by $X_0$.\textsuperscript{5}
layers with a surface of $20 \times 20 \text{ cm}^2$. Its energy resolution will be $\sigma(E)/E = 56.1\%/\sqrt{E}$.

CBM aims to combine high collision rates with complex trigger signatures like displaced decay vertices in the case of open charm. In traditional trigger concepts, high rates call for fast trigger decisions while searching for the vertices needs substantial reconstruction efforts and thus sizable computing time. To solve this issue, a self triggered readout is used. The latter consists of FEE-chips, which autonomously recognize particle hits, add time information and send them to a central DAQ in the data push mode. The data is received and sorted by a concentrator and event building network. Hereafter, information related to a defined period in time is send to a CPU, which buffers it in its RAM during processing. Such, complicated radiation tolerant data buffers in the sensors are replaced by custom of the shelf PC-RAM.

However, this concept requires an unusually high network bandwidth of $\sim 1\text{TB/s}$ and the estimated computing power of several $10^4$ computing cores for real time event reconstruction[17]. To address this issue, a first prototype computer named LOEWE-CSC was built and equipped with 2 PFlops computing power based on 20900 cores and 778 GPGPUs. This allowed reaching rank 22 in the worldwide list of supercomputers. Reconstruction algorithms profiting from modern multi-core and GPGPU environments were written and tested off-line with simulated data. The simulation and data analysis framework of CBM (CBMRoot) is to be extended to control the real time algorithms at least off-line. This will allow to compare measurement results with simulated data interpreted by the identical reconstruction algorithms and further improve the reliability of the CBM results.

3. Summary and Conclusion
The CBM-experiment will explore the phase diagram of nuclear matter at beam energies of 8-40 AGeV. This region should allow for observing the predicted first order phase transition between hadronic matter and QGP. Moreover, the critical endpoint of this phase transition might be observed. CBM integrates an electron-, hadron-, $\gamma$- and $\mu$-spectrometer in order to constrain theoretical models with a maximum amount of experimental probes. The technological concept of the experiment has been developed and demonstrated with various demonstrators.

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