STATUS OF THE COMPRESSED BARYONIC MATTER EXPERIMENT AT FAIR AND ITS SILICON TRACKING SYSTEM*

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The Compressed Baryonic Matter (CBM) experiment will carry out systematic research on the properties of nuclear matter under extreme conditions, in particular, at highest net baryon densities. These conditions will be met by colliding beams of heavy ions on targets in the energy range from 2 to 14, eventually 45 GeV/nucleon, as they will be provided with highest intensities by the heavy-ion synchrotron SIS-100, and in a future stage by the SIS-300 machine of the Facility for Antiproton and Ion Research (FAIR) at GSI, Darmstadt, Germany. The paper summarizes the CBM physics case and observables, and updates on the status of the experimental preparations. The development of CBM's central detector, the Silicon Tracking System for charged particle reconstruction and momentum measurement, is described in more detail. Synergies with the commissioning of the tracker's components in the stationary target experiment BM@N, under preparation at an extraction beamline of JINR's Nuclotron, are addressed.

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1. Introduction

The Compressed Baryonic Matter (CBM) experiment aims at realizing an experimental facility for a systematic exploration of the phase diagram of strongly interacting, or QCD, matter [1]. In the diagram's representation using the variables temperature *vs.* baryon chemical potential, different phases and transition regions are predicted. At highest collision ener-

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gies and lowest baryon chemical potentials, the number of baryons approximately equals that of anti-baryons. The situation is similar to the early universe. Lattice-QCD calculations find a cross-over transition from the hadronic phase of matter, where nucleons are bound in hadrons, to a deconfined system where quarks and gluons move freely. Experiments at RHIC and the LHC have observed such strongly interacting Quark–Gluon Plasma (sQGP). At lower-collision energies, the number of baryons exceeds significantly that of anti-baryons. For such not-vanishing, even highest baryon chemical potentials, matter densities are reached as high as in the cores of neutron stars. Lattice-QCD calculations are not applicable here. Models predict a first-order phase transition from hadronic matter to Quark–Gluon Plasma, including quark–hadron mixed or exotic phases as *e.g.* quarkyonic matter. Experiments are carried out in the beam-energy scan program at RHIC and by NA61 at the CERN-SPS. They are limited in collision rates either due to the accelerators not being optimally suited at those lower energies, or by the detector systems' data rate capabilities. New dedicated experimental programs are under preparation, specifically projected to allow for high-statistics measurements of observables: the CBM experiment at FAIR in Darmstadt, Germany, and experiments at NICA in JINR, Dubna, Russia.

2. CBM physics case, observables and experimental challenges

The beam conditions at FAIR's SIS-100 accelerator will allow creating nuclear collision systems with baryon densities significantly higher than in stable nuclei, ρ_0. Various model calculations yield that in central Au+Au collisions, net baryonic densities of about $5 \times \rho_0$ (5 GeV/nucleon) and $8 \times \rho_0$ (10 GeV/nucleon) are reached with a maximum of $12 \times \rho_0$ at projectile energies of around 35 GeV/nucleon. The densities are established for time scales of few to several fm/c and allow the system to evolve from the phase of confinement through coexistence to deconfined nuclear matter, and finally back. The CBM physics program addresses the following topics and observables for their exploration; this is further expanded in [2]:

— Nuclear matter equation-of-state at neutron star core densities: collective flow of hadrons (driven by pressure); particle production at threshold energies (in particular multi-strange hyperons).

— Onset of chiral symmetry restoration at high baryonic densities: in-medium modifications of hadrons ($\rho, \omega, \Phi \to e^+e^-(\mu^+\mu^-)$); dileptons at intermediate invariant masses (ρ-a1 chiral mixing).

— New phases of strongly-interacting matter: excitation function and flow of lepton pair production; excitation function and flow of strangeness ($K, \Lambda, \Sigma, \Xi, \Omega$).

— Deconfinement phase transition at high baryonic densities: excitation function and flow of charm ($J/\Psi, \Psi', D_0, D^{\pm}, \Lambda_c$); anomalous charmonium suppression.

— Strange matter: (double-) Λ hypernuclei; strange meta-stable objects (*e.g.* strange dibaryons).

With CBM operating initially at SIS-100, providing nuclear beams with energies between 2 and 14 GeV/nucleon on target, messengers from the dense fireball are dilepton pairs from ρ decays as well as anti-particle and particle production including strangeness, through all the density stages. The experimental challenge comes from the fact that the respective particle yields span many orders of magnitude, as illustrated in Fig. 1 (a). Only the most abundantly produced particles have been measured so far in the high net-baryon density region, by experiments at AGS, Brookhaven. Detecting the rare probes calls for the application of novel detectors, data taking and on-line event reconstruction techniques. They will be consequently applied in the CBM experiment (Fig. 1 (b)) realizing:

— rate capability for 10^5–10^7 Au+Au reactions/sec;

— efficient reconstruction of charged particles, high-resolution momentum measurement;

— determination of vertices from short-lived decays;

— identification of leptons and hadrons;

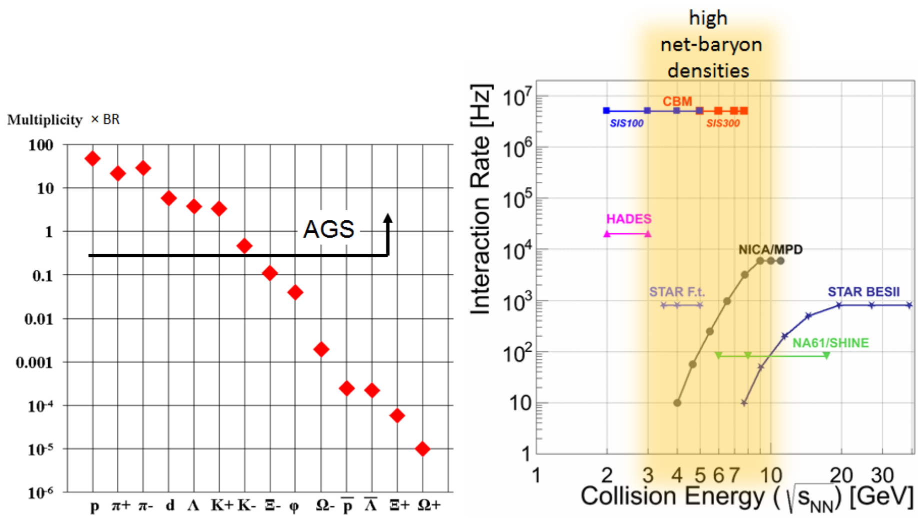
— fast and radiation hard detectors;

— free-streaming readout electronics;

— high speed data acquisition;

— high performance computing farm for on-line event selection;

— 4-dimensional event reconstruction.



(a) (b)

Fig. 1. (a) Particle yields in central Au+Au collisions at 4 GeV/nucleon projectile energy. (b) Experiments exploring dense QCD matter and their interaction rate limits.

3. The CBM experiment

The CBM experiment with its detector systems configured for operation at SIS-100 is shown in Fig. 2 as it will be set up in its underground hall at FAIR. The target region, surrounded by the superconducting dipole magnet, will be instrumented with two silicon detector systems, the Micro Vertex Detector (MVD), an ultra-thin pixel detector, and the Silicon Tracking System (STS), the central detector for charged-particle identification and momentum measurement. The time-of-flight detector (TOF), based on resistive plate chamber technology, will perform hadron identification. Event centrality will be determined by the Projectile Spectator Detector (PSD), a calorimeter. Further detectors will enable the measurement of leptons. The Ring Imaging Cherenkov Detector (RICH) together with a partly instrumented Transition Radiation Detector (TRD) will serve electron detection. It can be exchanged against the Muon Detector (MUCH) for studies of muon decay channels. The detectors are equipped with self-triggering front-end electronics that ships time-stamped data via data concentrator electronics (DAQ) to the computing farm (FLES) outside the experimental area where event determination and analysis will be performed on-line. The technical development of the CBM sub-systems is advanced. Technical design reports have been approved for the Magnet, STS, RICH, TOF, MUCH, and the PSD. Those of MVD, DAQ/FLES, TRD and ECAL are in preparation.

The teams of the project groups work towards realizing final prototypes of the detectors and prepare for production readiness of the components. Most systems plan completion of commissioning without beam by 2021.

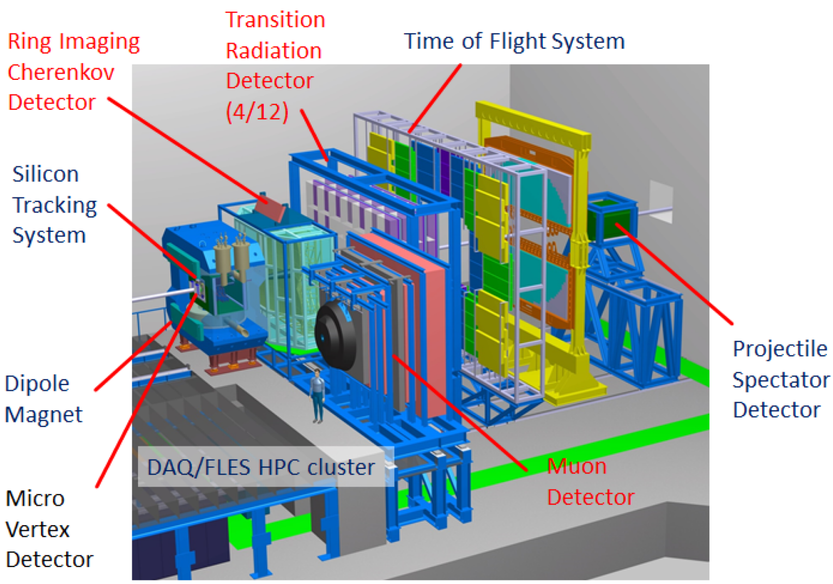


Fig. 2. The CBM experiment in SIS-100 configuration.

4. The CBM Silicon Tracking System

As the central detector system for charged particle detection and momentum measurement in the CBM experiment, the Silicon Tracking System [3] shall be introduced in some detail together with overviewing progress made with its development. The detector will consist of 8 tracking stations located in the aperture of a 1 T dipole magnet between 30 and 100 cm distance downstream of the target. The stations employ double-sided silicon microstrip sensors to cover the polar angles between 2.5° and 25° and have a total active area of about 4.2 m^2. The structure of the STS is shown in Fig. 3. The beam pipe intersects the detector at small polar angles, starting at the upstream target vacuum that includes also a further silicon detector system, the Micro Vertex Detector. The stations will be operated in a thermal enclosure at -5°C in order to reduce sensor leakage current and irradiation effects. Every station is composed of ladders which, in turn, carry several detector modules. The ladders will be mounted on 18 mechanical "half-units", C-shaped frames equipped with cooling plates for the front-end electronics. The detector modules are the basic functional parts of the STS. Their design is driven by the requirement for minimum material budget, leaving essentially only the silicon sensors in the physics aperture. Front-end electronics and cooling infrastructure are placed outside of the detector acceptance at the periphery of the stations. Only few other lightweight materials are introduced, in particular micro-cables as signal bridges between sensors and electronics, and carbon-fiber support structures.

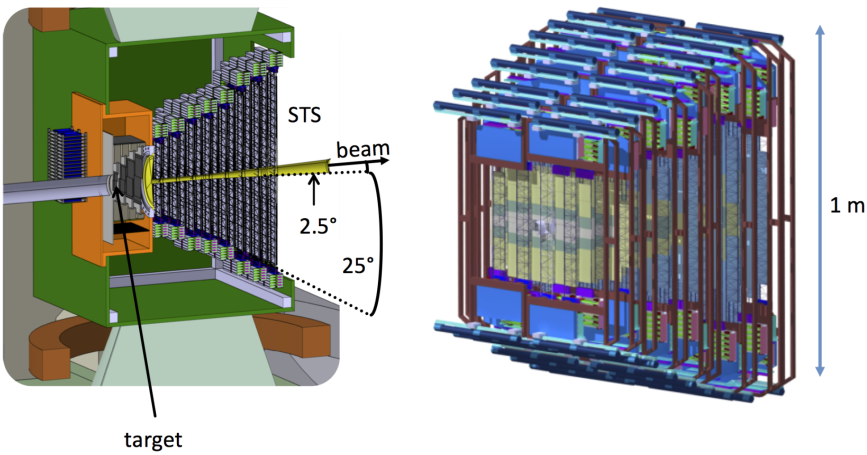


Fig. 3. Engineering views of the Silicon Tracking System.

4.1. Microstrip sensors

Final prototypes of double-sided silicon microstrip sensors with about 300 μm thickness have been produced in cooperation with two vendors, CiS (Germany) and Hamamatsu (Japan) [4]. The sensors feature four discrete sizes (62 mm width and 22, 42, 62 and 124 mm height). The wafer material is of n-type. The sensor layout has been optimized for the attachment of microcables by *tab* bonding for read-out and bias connections, minimum trace resistance and inter-strip capacitance. The sensors are segmented into 1024 strips per side at a strip pitch of 58 μm. The strips are read out through integrated *AC* coupling. The p-strips are arranged under a stereo angle of 7.5° with respect to the n-strips. The short corner strips are interconnected using a second metal layer in order to enable full readout of the p-side from one sensor edge only, like with the simpler topology of the n-side. Samples of sensors have been tested under the anticipated thermal operation conditions and were shown to be radiation tolerant up to twice the nominal lifetime fluence in the experiment, 2×10^{14} 1-MeV $\mathrm{n_{eq}cm^{-2}}$.

4.2. Microcables

The microcables are implemented as a stack of two signal layers per side with aluminum traces on a polyimide substrate with spacers in between and additional shielding layers on the outside. One stack is designed to read out 128 channels on each side of the sensor, thus 16 microcable stacks are required for the full readout of a sensor. The microcable structure aims at balancing the trace capacitance and series resistance based on the contribution to the total noise seen by the preamplifier. A signal layer comprises 64 Al lines at 116 μm pitch, twice the strip pitch on the sensor. Two signal layers are stacked to match the read-out pitch. The thickness of aluminum and polyimide is 14 μm and 10 μm, respectively. Such a cable structure corresponds to 0.23% X_0 equivalent to 213 μm of silicon. The cables are produced in lengths up to 55 cm. The current pre-series production of microcables aims at maximizing yields [5].

4.3. Read-out chip

The read-out chip STS-XYTER has been developed specifically for the STS. It is a mixed signal ASIC with data driven architecture [6]. Each channel has a fast lane for time stamp generation with less than 5 ns resolution, and a slow branch for amplitude measurement. The chip provides 128 independent channels with switchable signal polarity and two gain settings that makes it suitable for use with the STS and a further CBM sub-system, the muon detetector with its GEM chambers. For silicon detector read-out, the dynamic range of the integrated 5-bit ADC is 12 fC, which can be switched to 100 fC for the gaseous detectors. The design goal with STS-XYTER is to achieve a noise performance of 1000 e^- with a power consumption that is estimated to be < 10 mW/channel. This will ensure matching with the STS detector module structure where significant noise contributions are expected from capacitance and series resistance of the microcable signal traces and sensor strips. The noise performance is addressed in the chip architecture using the double-threshold technique, where triggers generated by the fast branch are vetoed if no coinciding signal peak was detected. The chip is currently under production in its second version, compatible with the CERN GBT read-out protocol, using a 180 nm CMOS process.

4.4. Module assembly

The module assembly steps have been developed and dedicated tooling and machinery established at the assembly sites at GSI and JINR. Several module mock-ups have been assembled proving the module integration concept with double-sided processing [7, 8]. It applies *tab* bonding of the microcables to the read-out chips after which they can be tested. The so assembled "chip cables" are then subsequently attached to the silicon sensor by *tab* bonding as well, one side at a time. Further steps include installation of the chips to the front-end board and their connection to the circuitry by wire bonding. Assembled dummy modules with sensors of different sizes are shown in Fig. 4.

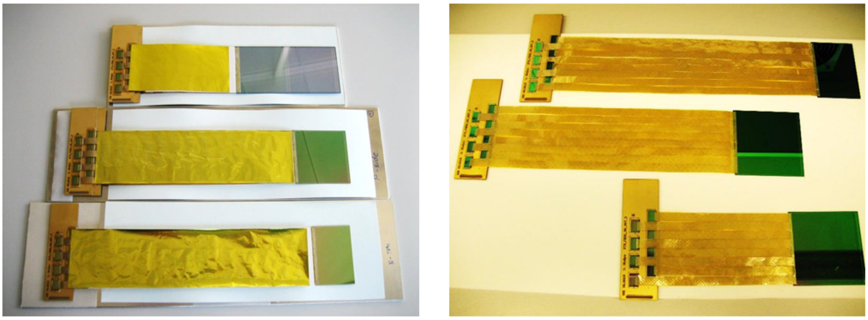


Fig. 4. Module demonstrators assembled at GSI (left) and JINR (right).

4.5. Construction of the CBM-STS

The detailed structure of the tracking stations including cable routing and design of the cooling plates for the electronics is a matter of ongoing engineering activities [9]. Production readiness is expected in 2017 followed by the construction of module and ladder components at the CBM-STS assembly sites GSI and KIT in Germany, and JINR in Dubna. The STS system integration at GSI and the detector commissioning shall be achieved until 2021.

5. CBM-like STS in the BM@N experiment at Nuclotron

The BM@N (Baryonic Matter at Nuclotron) [10] experiment is a stationary target detector at a Nuclotron beam extraction line, a precursor experiment for NICA experiments currently under construction. It's physics ambition addresses strangeness production at threshold, hadron production in elementary reactions and "cold" nuclear matter in $p+p$, $p+n$, $p+A$ collisions. Au beams will be provided up to 4.5 GeV/nucleon. Simulation studies show clearly enhanced observables in the BM@N tracker, *e.g.* Λ decaying into p and π^-, when some of its GEM stations are augmented with CBM-like STS tracking stations. There is mutual interest by CBM groups from Germany and Russia to install, commission and use several CBM-like Silicon Tracking Stations in the BM@N experiment in 2018–2021, starting with a partial set-up in 2018. A memorandum of understanding is under preparation that foresees CBM-STS detector ladders for deployment in the BM@N tracker, provided that the technical and funding conditions will enable that project in addition to the completion of the CBM-STS detector.

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