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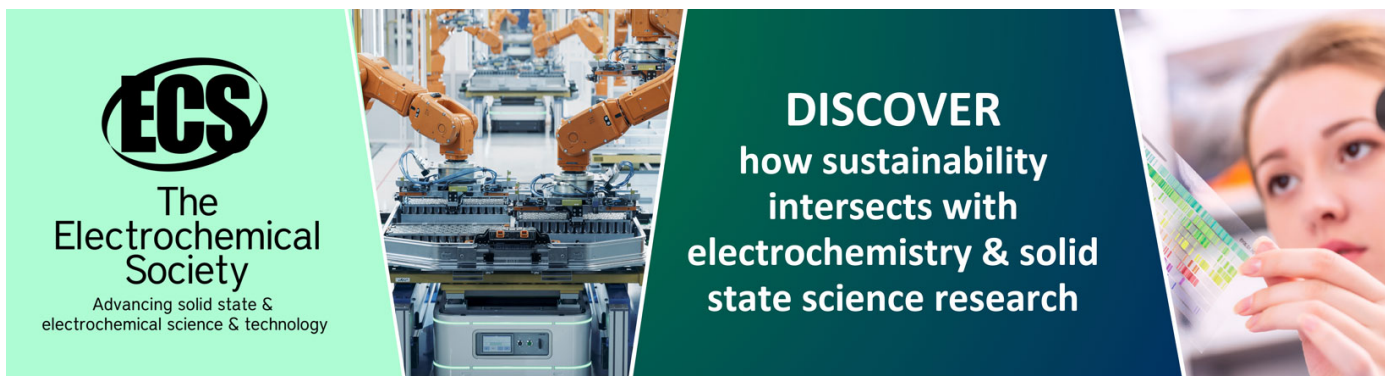
Physics of compressed baryonic matter

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Physics of compressed baryonic matter

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Abstract. The experimental investigation of the QCD phase diagram with heavy ion collisions is an ongoing intense research topic at international accelerator facilities since the 80's and recently got new boost with the first results from the LHC experiments. Together with results from the top RHIC energies they investigate partonic matter in every detail at high temperatures but very low net-baryon densities. Complementary to these studies, the planned Compressed Baryonic Matter (CBM) experiment at FAIR will allow for a detailed investigation of nuclear matter at moderate temperatures but very high net-baryon densities this way completing our knowledge on the phase diagram. In this region of the QCD phase diagram structures such as a first order phase transition between hadronic and partonic matter or further phases such as quarkyonic matter have been predicted. CBM will allow to study these topics with rare probes being sensitive to the medium, i.e. with the measurement of charm production and di-leptons. In this presentation, an overview on the motivation for CBM, its experimental program and status of preparations will be given.

1. Introduction

1.1. The QCD phase diagram

Strongly interacting matter is expected to be existent in different phases, depending on temperature and pressure or baryon density. Figure 1 shows a representation of the QCD phase diagram from Ref. [1] in which also a newly postulated phase at high baryon density [2], the so called quarkyonic matter, is included. The expected different phases triggered investigations of the QCD phase diagram by means of heavy ion collisions at various accelerator facilities worldwide since the early 80's. Figure 2 shows the QCD phase diagram in which freeze-out points from a statistical model analysis of the particle ratios measured in these heavy ion collisions at different center of mass energies are included [3]. Moreover, recent lattice QCD calculations [4] are shown: They point to the existence of a crossover between partonic and hadronic matter at low baryochemical potential and a critical endpoint from which on the phase transition would be of first order. The latter is very much under debate, see e.g. Ref. [5]. Recent lattice calculations mostly converge to finding a crossover phase transition at $\mu_B=0$ [6] at a critical temperature T_C of about 160 MeV [7].

Experimental findings can be summarized basically in three items: The freeze-out conditions for hadrons produced in A+A collisions all line up on a freeze-out curve as depicted in Fig. 2: The higher the center of mass energy in the collision, the higher temperatures and lower baryochemical potentials are reached. For illustration, also lines with constant energy or baryon density are drawn which obviously do not catch the experimentally observed freeze-out conditions. At $\mu_B=0$ the freeze-out temperature is around 160 MeV in accordance with T_C from lattice calculations. This is one of many observations pointing to the fact that at high

temperatures partonic matter is created in the course of heavy-ion collisions, see e.g. Ref. [8] for recent data collections and discussions. The precision data from high-energy A+A collisions at the RHIC and LHC accelerator facilities finally allow to characterize the matter created at high temperatures and low baryochemical potential in terms of initial temperature, viscosity-to-entropy ratio, gluon density etc. Furthermore, the combination of various measurements strongly support the interpretation that in collisions exceeding $\sqrt{s_{NN}} = 8$ GeV partonic (deconfined) matter is created throughout the fireball evolution, see e.g. [9] for a summary. New results from the beam energy scan at RHIC support this interpretation as it seems hadronic degrees of freedom start to become dominant below $\sqrt{s_{NN}} = 11$ GeV [10].

In this context, it is very intriguing to have a look at a different view of the QCD phase diagram as presented in Ref. [11], see Fig. 3. Here, the above discussed freeze-out curve is shown in dependence on the net-baryon density instead of baryochemical potential. In this representation A+A collisions at $\sqrt{s_{NN}} = 8$ GeV stick out in addition to the above mentioned onset of deconfinement: They emerge as the turning point where the maximum net-baryon density is reached. At this point the matter created in the collision also changes between being baryon dominated (lower temperatures) and being meson dominated (higher temperatures) [12].

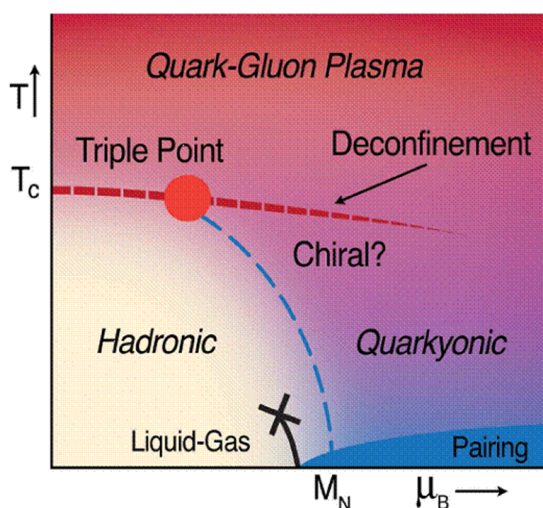


Figure 1. Sketch of the QCD phase diagram indicating different phases, taken from [1].

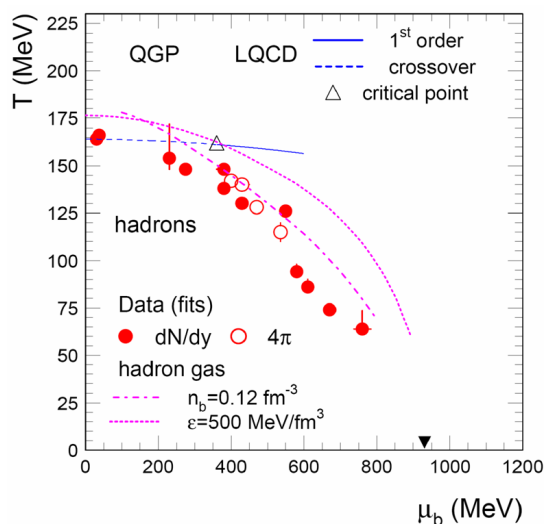


Figure 2. QCD phase diagram with freeze-out points from a statistical analysis of experimental data, taken from [3].

1.2. Experimental results and future prospects

Detailed information and a characterization of the matter created at lower collision energies, i.e. higher baryon densities is still lacking. This, as well as the possible existence of structures and new phases in the phase diagram, is the main motivation for current and future heavy-ion experiments investigating dense baryonic matter. The different campaigns and their main characteristics, such as energy range and reaction rates are listed in Table 1. While all experiments are suited to measure bulk observables and fluctuations, their limited collision rates hampers them to access rare probes such as di-leptons and charm. However, with the planned second beam energy scan at RHIC (BES II) after upgrading the accelerator, di-leptons might become accessible also at lower RHIC energies. The CBM experiment at FAIR is the first experiment designed to explicitly access these rare observables at high net baryon densities as listed in Table 2. In summary, the different energy scans beautifully complement each other and

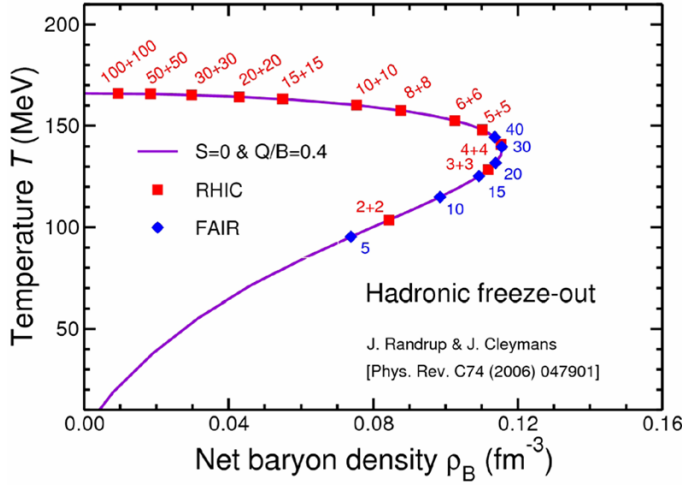


Figure 3. Freeze-out curve from a statistical model analysis in the temperature versus net-baryon density plane, taken from [11]. Red and blue points show the region available by experiments at RHIC and FAIR, respectively, depending on the collision energy.

combining them all will add lots of new information on the QCD phase diagram from low to medium high temperatures.

Table 1. Energy ranges and reaction rates of current (STAR, PHENIX, NA61) and future experiments (MPD, HADES@FAIR, CBM) on dense baryonic matter.

Experiment	Energy range (Au/Pb beams)	Reaction rates (Hz)
PHENIX & STAR @RHIC, BNL	$\sqrt{s_{NN}} = 7 - 200$ GeV	1 – 800 (limitation by luminosity)
NA61@SPS CERN	$E_{kin} = 20 - 160A$ GeV $\sqrt{s_{NN}} = 6.4 - 17.4$ GeV	80 (limitation by detector)
MPD@NICA Dubna	$\sqrt{s_{NN}} = 4 - 11$ GeV	1000 (design lumin. of $10^{27} cm^{-2} s^{-1}$ for HI)
CBM & HADES @FAIR, Darmstadt	$E_{kin} = 2 - 35A$ GeV $\sqrt{s_{NN}} = 2.7 - 8.3$ GeV	$10^5 - 10^7$ (limitation by detector)

Rare probes such as low-mass di-leptons, charmonium and open charm will open the possibility to characterize the medium in much more detail as has ever been done before at high net-baryon densities. Namely, the ratio of J/ψ to open charm is expected to be very sensitive to the medium: Depending on whether charm quarks propagate as quarks in a partonic phase or directly form hadrons in a confined phase, a very different ratio and energy dependence is expected, see Figure 4. Similarly, but on a very different energy scale, low-mass di-leptons probe the medium. In particular the ρ -meson with a (vacuum) lifetime of 1.3 fm/c only decays to a large fraction inside the medium. Measuring the rare decay into a di-lepton pair thus gives access to a penetrating probe carrying undistorted information of the ρ -meson properties in the medium. Also, di-leptons are proposed to be a possible tool to address the predicted existence of quarkyonic matter. So far, no data in the rang between 2A GeV (HADES, see Ref. [15]) and 40A GeV (CERES, see Ref. [16]) are available.

Besides the rare probes, other observables promise additional insight into the production mechanism and properties of the created medium. Two probes of particular interest shall be

Table 2. Observables (to be) measured in current and future experiments on dense baryonic matter.

Experiment	Observables for beam energies at about $\sqrt{s_{NN}} = 8$ GeV (high baryon density region)			
	hadrons	correlations, fluctuations	di-leptons	charm
PHENIX & STAR @RHIC, BNL	yes	yes	no (yes in BES II?)	no
NA61@SPS CERN	yes	yes	no	no
MPD@NICA Dubna	yes	yes	no	no
CBM & HADES @FAIR, Darmstadt	yes	yes	yes	yes

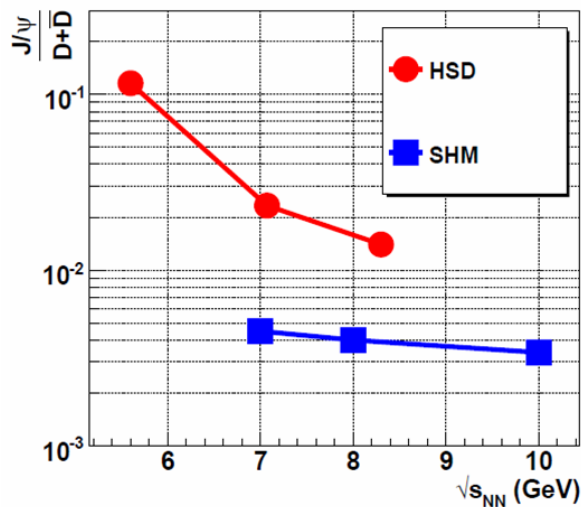


Figure 4. Expected J/ψ to open charm ratios for a partonic (blue, SHM [14]) and a hadronic (red, HSD [17]) scenario; taken from [13].

discussed here. So far, both could not be measured in the AGS energy range due to the required high statistics and/or appropriate detector setup: the production of multi-strange particles and (particle ratio) fluctuations.

The new data from the beam energy scan at RHIC [18, 19] confirm nicely the previously published measurements from NA49 [20] on strangeness and Ξ -production. Results on Ω -production are still expected verifying the earlier NA49 measurement [21]. So far, the data are very well described by a statistical hadronization model assuming strangeness to be in equilibrium [14]. It has been argued in Ref. [22, 23] that such a feature is intimately connected to freeze-out and hadronization at a phase boundary. Recent data from the HADES experiment on subthreshold Ξ -production [24] show that at very low energies hadrons carrying strangeness are not in equilibrium anymore. To answer the question when this feature breaks down and whether this is related with a phase boundary, high precision data on multi-strange particle production below beam energies of 40 A GeV are required.

For many years, the measurement of non-statistical fluctuations is a very popular but challenging topic. They are appealing because large fluctuations are expected to be related to either a critical point or a first order phase transition line. The NA49 collaboration measured a strong increase of K/π -ratio fluctuations towards low energies [25] and more recently also of K/p -ratio fluctuations which even show a sign change [26]. The STAR collaboration is working on crosschecking these data [28]. However open issues remain concerning e.g. the dependence on the acceptance or the particle number in the acceptance [27]. More important, however, is the fact, that no measurements at all exist for energies below the SPS energy range. Those are of course absolutely necessary before any conclusions on non-monotonous behavior can be drawn.

2. The CBM experiment at FAIR

The CBM experiment will explore highly compressed baryonic matter in heavy-ion collisions from 8 – 45A GeV beam energy at the future FAIR accelerator at Darmstadt [13]. The lower energy range from 2 – 8A GeV beam energy, which starts from the top energy of the present SIS18 at GSI, will be covered by the recently upgraded HADES experiment. The construction of FAIR has started 2011. The accelerator complex as depicted in Figure 5 will be completed in various stages; the first stage being the SIS100 ring including the experimental cave for the HADES and CBM experiments. Current plans foresee to have first beams in 2018. CBM will start its physics program at SIS100 with a reduced detector setup to be completed finally for running at SIS300.

The CBM experiment will measure hadronic and leptonic probes with a wide phase space acceptance. The proposed full detector system is shown schematically in figure 6. The core of CBM will be a silicon tracking system (STS) in a magnetic dipole field for tracking and momentum information. In order to investigate open charm production, an additional micro-vertex detector (MVD) is placed 5 cm behind the target. This setup is followed by detectors for particle identification: a RICH and a transition radiation detector (TRD) for electron identification, a time-of-flight (TOF) wall for hadron identification, and an electromagnetic calorimeter (ECAL) for the measurement of direct photons in selected regions of phase space. Di-muon measurements will be possible by using an active absorber for muon identification (MuCh), which is interchangeable with the RICH. This way CBM will have the opportunity for an independent measurement of both detection channels for penetrating probes.

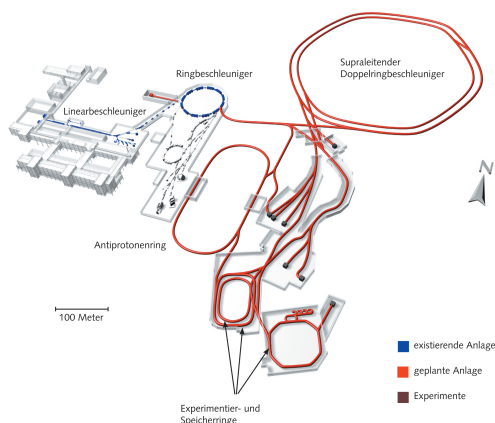


Figure 5. Layout of the FAIR accelerator complex (full version).

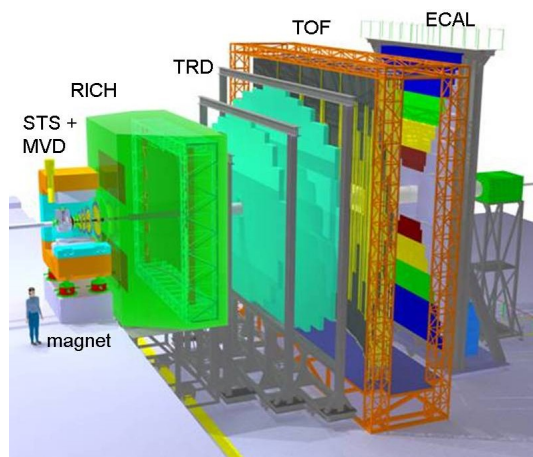


Figure 6. Layout of the CBM experiment with detectors for electron identification.

Experimental challenges for CBM mainly arise from two demanding requirements: open

charm reconstruction which requires a secondary vertex resolution of about 50 μm and the ability to run at up to 10 MHz in order to access charmonium production. This requires fast and radiation hard detectors with high resolution as well as a fast readout and trigger concept. In CBM, the latter is based on self-triggered readout electronics shipping all data to a computer farm on which trigger decisions are taken in due time. In particular for the reconstruction of open charm decays this requires a high precision of online tracking and secondary vertex finding.

2.1. CBM physics program at SIS100

At SIS100 proton and ion beams will be accelerated up to maximum energies as listed in Table 3. This offers CBM the possibility to start its physics program by investigating dense baryonic matter at rather low temperatures. Those measurements form a first and essential step to obtain a complete insight into the properties of compressed baryonic matter in the FAIR energy range. A detailed study of hadronic properties in this energy range may reveal whether chiral symmetry is restored and if there is an additional phase transition to quarkyonic matter as proposed in Ref. [1, 2] and shown in Fig. 1. If strangeness can also exist in heavy, meta-stable objects such as di-baryons, CBM will be perfectly able to detect them. Charm production in p+p and p+A collisions can be studied close to threshold and propagation of charm in cold nuclear matter will be investigated. Both measurements have a value of their own. Moreover, they also lay the basis for further charm investigations in A+A collisions at SIS300.

The minimum start-up version of the CBM detector will consist of the dipole magnet, the silicon tracking system and time-of-flight wall. This setup already allows for reconstruction of hadrons including multi-strange hadrons or even exotic objects like strange di-baryons. Adding the RICH detector at an early stage will allow to directly connect to the HADES measurements in the di-electron channel. A startup version of the muon absorber will allow a very clean measurement of charmonium production, see Fig. 8.

Table 3. Overview on accessible maximum beam energies at SIS100.

Beam	$p_{lab,max}$	$\sqrt{s_{NN,max}}$
heavy ions (Au)	11A GeV/c	4.7 GeV
light ions ($Z/A = 0.5$)	14A GeV/c	5.3 GeV
protons	29 GeV/c	7.5 GeV

2.2. CBM physics program at SIS300

With the SIS300 accelerator becoming available at FAIR at a later stage, the CBM physics program will come to full glory covering the complete region of high net-baryon densities at moderate temperatures. SIS300 will provide Au-beams up to 35A GeV and beams of lighter ions ($Z/A = 0.5$) up to 45A GeV. This energy range allows for the full physics program as outlined above. In short, it can be summarized in four main pillars: The investigation of the equation-of-state at high μ_B , the search for and study of the deconfinement phase transition at high μ_B , the search for a critical endpoint and the investigation of the possible onset of chiral symmetry restoration at high μ_B . Main observables are the collective flow of hadrons, particle production at threshold energies (open charm), excitation functions and flow of strange and charmed particles, possible charmonium suppression and in-medium modification of hadrons measured by the reconstruction of penetrating probes. Overall, CBM aims for precision measurements of the widest possible range of probes, including rare probes. The experimental program will cover

systematic investigations of these observables at different energies, centralities and system sizes including also p+p and p+A reactions. For a detailed overview the reader is referred to the *CBM Physics Book* [13].

2.3. Feasibility studies

All observables being relevant for the CBM physics program at SIS100 and SIS300 are studied in detail with the simulation framework CBMROOT [29]. Detector response is implemented as realistically as possible and is continuously improved with the results from prototype measurements becoming available more and more. Complete event reconstruction with track reconstruction, secondary vertex finding and particle identification routines are implemented. Examples for recent simulation studies for SIS100 and SIS300 are shown in Figs. 7, 8, 9 and 10.

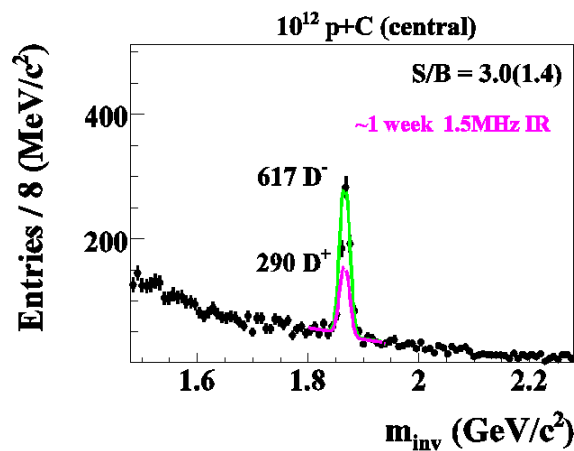


Figure 7. Feasibility study of an open charm measurement (green D^- , magenta D^+ -mesons) in p+C collisions at 30 GeV (SIS100); the spectrum corresponds to 10^{12} central (b=0) events.

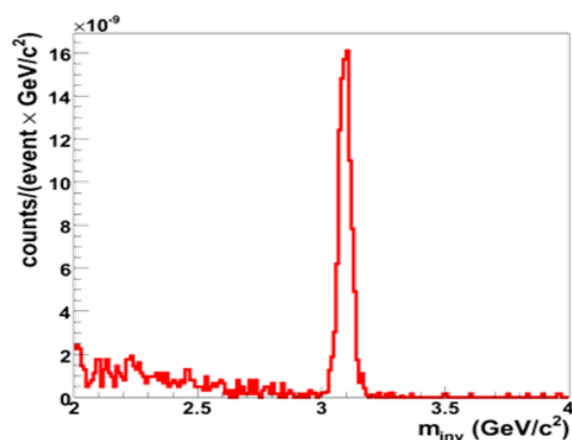


Figure 8. Feasibility study of a charmonium measurement in p+C collisions at 30 GeV in the di-muon channel (SIS100). Six J/ψ would be measurable in 10^{10} events.

A lot of effort is going towards the development of a high speed first level event selection (FLES) package [30] in order to meet the specific challenges in computing issues [31]. Those mainly arise from the quest of having high level trigger decisions including secondary vertex finding at reaction rates of $10^5 - 10^7$ Hz. In CBM, the self-triggered readout electronics will deliver a stream of time-stamped data which has to be analyzed on fast and large computer farms in order to deliver trigger decisions in due time [32]. All tracking codes developed so far have been ported to modern multi- and manycore machines and full use is made of parallel computing. A standalone FLES package has been established that is portable, efficient, SIMDized (Single Instruction, Multiple Data), and fully parallelized. Its scalability has successfully been tested up to 80 cores. Currently, with this package tracking in the STS and secondary vertex finding takes only 8 ms/core for minimum bias and 62 ms/core for central Au+Au collisions at 25.4 GeV beam energy.

2.4. Detector development

For all CBM detector components prototype construction and in-beam tests are ongoing in order to prepare Technical Design Reports for 2013/2014. In this article, three detector developments shall be introduced in some more detail:

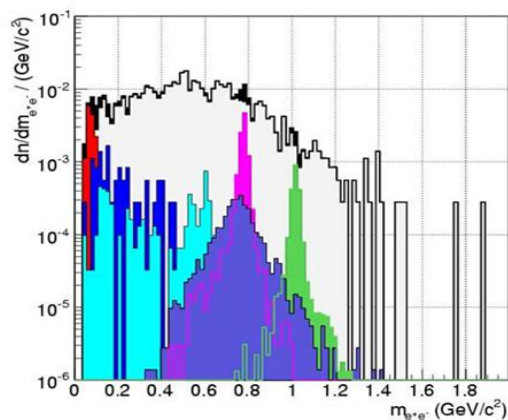


Figure 9. Feasibility study of a measurement of low-mass vector mesons (di-electron channel) in central Au+Au collisions at 25.4 GeV (SIS300). This spectrum corresponds to 200k events only, i.e. just a few seconds beamtime. Shown sources from left to right are: π^0 - (red), ω - (blue) and η -Dalitz (light blue) decays, ρ - (violet), ω (magenta) and ϕ -mesons (green).

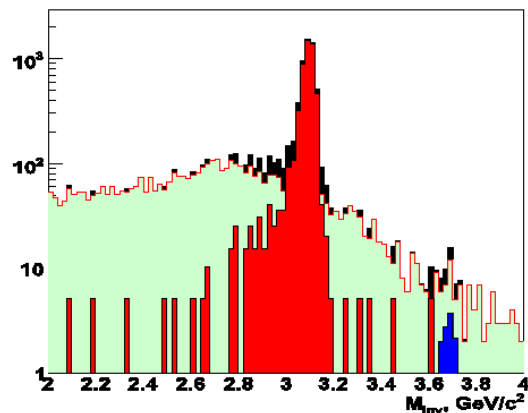


Figure 10. Feasibility study of a charmonium measurement (J/ψ in red, ψ' in blue) in central Au+Au collisions at 25.4 GeV in the di-electron channel (SIS300); $4 \cdot 10^{10}$ events are shown in the spectrum. As for low-mass vector mesons, electrons from γ -conversion (0.1% Au-target used) and π^0 -Dalitz decay dominate the background; the pion suppression factor is about 10^4 .

For the silicon tracking system, radiation hard, double-sided silicon microstrip detectors with 7.5° stereo angle and $58 \mu\text{m}$ pitch are being developed. They shall be $300 \mu\text{m}$ thick and will be bonded to ultra-thin micro cables for readout at the periphery of the system. All components are under development and are tested in dedicated testbeam activities. Fig. 11 shows for example a teststation with a double-sided microstrip sensor which is read out by self-triggering n-XYTER chips [34]. A picture of the beamspot from 2.4 GeV protons at an in-beam test at COSY, Jülich, in January 2012 is shown in Fig. 12. The next major step will be the test of a complete system combining sensor, cables, and the newly designed readout chip STS-XYTER. For more details see e.g. Ref. [33].

Highest and unambiguous track resolution close to the vertex for open charm reconstruction will be achieved by ultra-thin Si-pixel detectors. The development in CBM concentrates on using Monolithic Active Pixel Sensors (MAPS). Those sensors are routinely thinned down to $50 \mu\text{m}$ and offer single point resolution of a few μm only. However, on account of having a rather long readout time and moderate radiation hardness. The latter could be improved considerably in the past years, as for example reported in Ref. [35]. Readout times of about $100 \mu\text{s}$ will be compensated by running at about 100 kHz interaction rate which is sufficient for open charm reconstruction. The current compromise for CBM at SIS100 offers a time resolution of about $110 \mu\text{s}$, a radiation hardness of more than $10^{13} n_{eq}$ for non-ionizing particles at a single point resolution of $4 \mu\text{m}$ and a material budget of about $0.05\% X_0$. Including a support structure and cooling plate the first MVD station will have a material budget of about $300 \mu\text{m}$ Si-equivalent only. Current prototype developments aim at running a part of an MVD station in 2012/2013 in a testbeam experiment, see pictures in Figs. 13 and 14.

The RICH detector of CBM will serve for identifying electrons with $p < 8 \text{ GeV}/c$ in order to reconstruct the di-electron decay channel of low-mass vector mesons and charmonium [36].

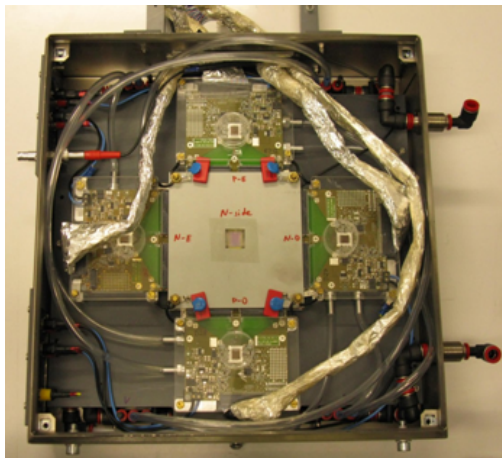


Figure 11. STS teststation with double-sided Si-strip sensor and n-XYTER read-out.

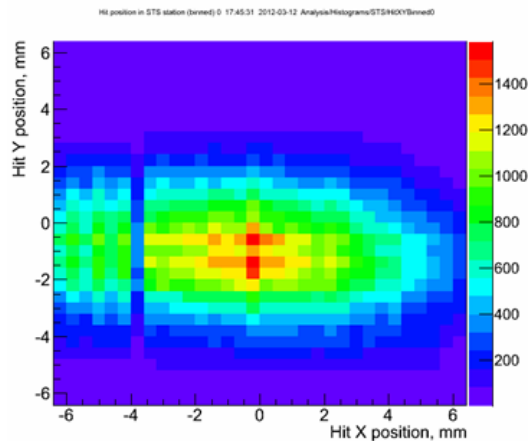


Figure 12. Beamspot in the STS teststation (see left) in a 2.4 GeV proton beam at COSY.

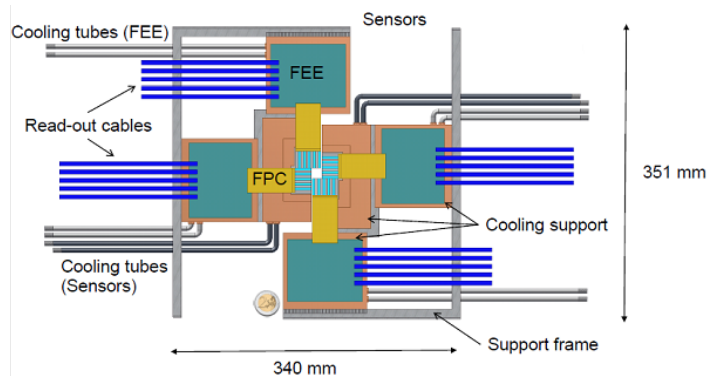


Figure 13. Schematic layout of the first MVD station.

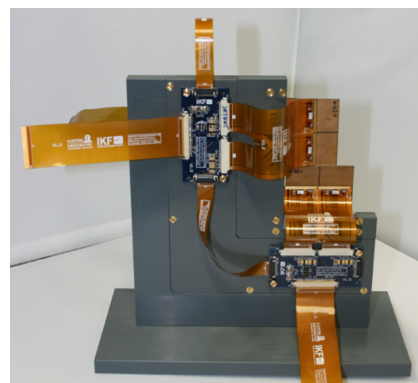


Figure 14. Mockup of a prototype for the first MVD station to be tested in-beam in 2012/ 2013.

The RICH and the TRD are being designed to obtain a combined pion-misidentification factor of about 10^4 . This level is required in order to suppress the background from misidentification and to be dominated by physical sources, mainly electrons created by γ -conversion and π^0 -Dalitz decays. In the RICH detector development, a complete prototype being full size along its important direction (length) could be tested in a beam of negatively charged particles at CERN in October 2011. The radiator length was 1.7 m and CO_2 was used as radiator gas. Fig. 15 (upper row) shows the two main elements, mirror and photodetector plane. The lower row shows first results from this beam test: A typical event display of an electron ring with about 20 measured photons at a noise level of about 10 Hz per channel only. Ring finding routines [37] were implemented for online reconstruction and could be finally tested with data. In the momentum scan shown in Fig. 15 (lower right), pion rings rising in size above the Cherenkov threshold of $p = 4.65 \text{ GeV}/c$ are clearly seen and well separated from electron rings up to $8 \text{ GeV}/c$ ($> 7\sigma_\pi$). In a next in-beam test in 2012, different photomultipliers and a prototype of the finally anticipated readout electronics will be tested.

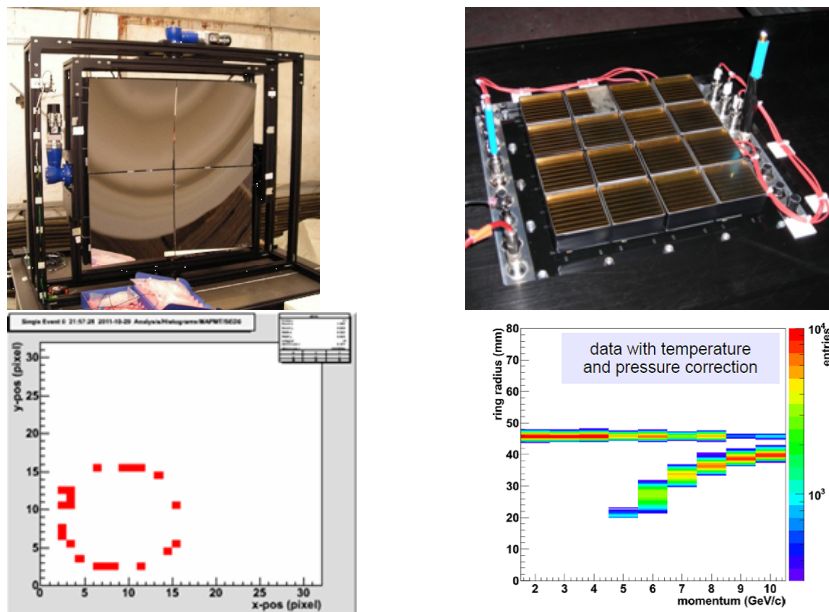


Figure 15. Pictures of the main RICH prototype components (upper row): 2×2 mirror plane, 4×4 photodetector plane with Hamamatsu H8500 MAPMTs. Results from an in-beam test in October 2011 at CERN (lower row): Typical event display for an electron ring (left) and ring radius vs. momentum from a momentum scan (right).

In the same testbeam campaign at CERN, several TRD prototypes with a wide variety of chamber types with and without drift region and different distances were tested. Those chambers were then combined with various radiator types made of fibers or foil stacks. The collected data will be used for finalizing the overall TRD design. Currently, a real dimension prototype of $60 \times 60 \text{ cm}^2$ is being constructed for a test in 2012.

3. Summary

The exploration of the QCD phase diagram with heavy-ion collisions has advanced from more qualitative investigations to a quantitative characterization of the created matter in the high-energy experiments at RHIC and LHC. The same quality of data will be achieved with the future heavy-ion experiments in the high-baryon density regime, in particular with the CBM experiment at the future accelerator complex FAIR. Amongst other significant probes, CBM has the unique feature that the beam intensities at FAIR together with the experimental apparatus of CBM will allow the measurement of rare probes such as di-leptons and charm. Together with the upgraded HADES detector, a beam energy range from 2 – 45 A GeV will be investigated covering the low temperature but high net-baryon density regime. Preparation of the CBM experiment in terms of software and detector development is proceeding well aiming at a start-up version of the detector in 2018 for the first beam at SIS100.

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