PERSPECTIVES FOR HEAVY-ION COLLISIONS AT FUTURE FACILITIES*

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Starting from the next decade, new accelerator facilities will become available for the investigation of the QCD phase diagram at high net-baryon densities. We discuss and compare the current status of these projects, the opportunities they will offer for the research with nuclear collision experiments, and the mid-term prospects for experimental access to observables characterising dense QCD matter and the features of the QCD phase diagram.

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1. Introduction

The contemporary experimental investigation of QCD matter at extreme conditions can, to a certain extent, be separated into the study of the properties of deconfined matter at the highest available energies at the LHC and the exploration of the QCD phase diagram at high net-baryon densities with moderate collision energies. The aim of the latter is to understand features of the QCD phase diagram like the transition from confined to deconfined matter, the restoration of chiral symmetry, the critical point, and possible exotic phases such as quarkyonic matter or colour super-conductivity [1]. At moderate energies, several experimental programmes are under way at GSI-SIS18, CERN-SPS and BNL-RHIC. In the near and mid-term future, new accelerator facilities will become available which will significantly extend the coverage of present experiments in terms of energy range and observables: the FAIR research centre in Darmstadt and the NICA facility at JINR Dubna. In the following, we give an overview on these new facilities and the opportunities they will offer for heavy-ion research, putting emphasis on FAIR since NICA is covered by a separate contribution to these proceedings. We conclude with a synopsis of the experimental prospects with these new facilities in the context of running experimental programmes.

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2. FAIR

The Facility for Anti-proton and Ion Research (FAIR) is currently under construction in Darmstadt, Germany [2]. It is a complex accelerator system serving a variety of physics communities with beams of ions, anti-protons and rare isotopes (Fig. 1). FAIR is organised as an international research facility, currently involving about 3,000 scientists from all over the world, the biggest fractions being from Germany, Russia and India.

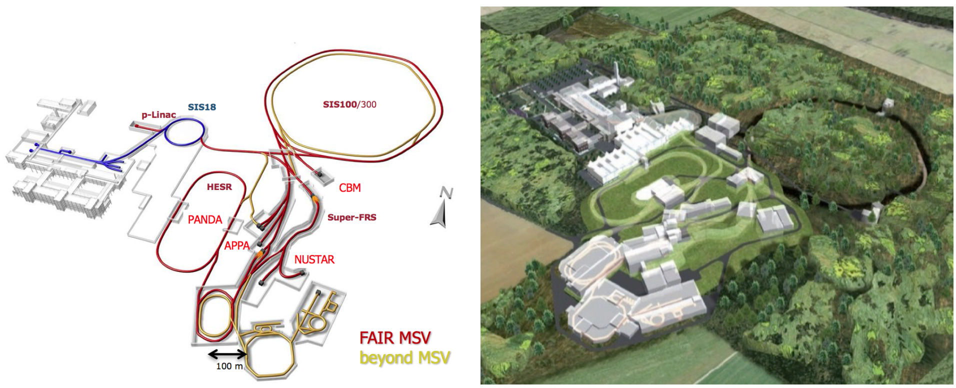

Fig. 1. (Color online) Left: schematic view of the FAIR accelerator complex. The existing GSI facilities are shown on the left side. Components marked in black/red constitute the "Modularised Start Version" (see the text); those in gray/yellow are components beyond MSV. Right: artistic view of the FAIR complex after completion.

The backbone of the accelerator complex is a synchrotron with a circumference of 1,100 m and 100 TM bending power (SIS-100). At a later stage, this will be accomplished by a second, booster synchrotron (SIS-300). For the research on QCD matter, FAIR in its first phase will deliver external, fully stripped heavy-ion beams in slow extraction at energies from 2 A to 11 A GeV. In a second phase, ion beams with energies up to 45 A GeV will become available from SIS-300.

The nuclear collision physics programme at FAIR will be carried out by the HADES and the CBM experiments. The HADES detector will be moved from its current location at GSI to the CBM cave. It will perform measurements of lepton pairs and hadrons in collisions induced by proton and medium-mass ion beams in the lower SIS-100 energy range (up to 4 A GeV), thus extending its current physics programme at the GSI SIS-18 accelerator. CBM (Compressed Baryonic Matter) is a next-generation heavy-ion experiment designed to investigate proton- and ion-induced reactions over the entire FAIR energy range [3]. The physics programme of CBM comprises the measurements of hadrons, leptons and charm. Peculiar for CBM is the ambitious aim to achieve very high interaction rates (up to 10^7 collisions per second) in order to be sensitive to extremely rare probes like multi-strange anti-hyperons or charmed hadrons.

After several years of conceptual studies, technical and financial planning, and formation of the project within a consortium of international partners, the realisation of the FAIR project was decisively shaped in 2015. Based on the recommendations of a project review team, the FAIR council decided in September 2015 that the construction of the first phase of FAIR, the Modularised Start Version (MSV), shall start as early as possible and be completed latest by 2025. The MSV comprises the SIS-100 synchrotron and the experimental hall for CBM (Fig. 1, left). The realisation of the MSV will be done stepwise such as to ensure the start of experiments as early as possible. The current, conservative planning schedules the completion of buildings for 2022 and first beams from the SIS-100 into the CBM cave in 2024.

The FAIR council in September 2015 also confirmed its goal to realise to full FAIR facility as laid down in the FAIR Convention. Although the efforts and resources in the next years will clearly be concentrated on the realisation of the MSV, a strategy for FAIR beyond MSV continues to be developed. Of high relevance for QCD matter physics is the second synchrotron SIS-300, which will increase the maximal beam energy for CBM to 35 A GeV for heavy ions and to 45 A GeV for symmetric nuclei. The synchrotron tunnel will be built sufficiently large to host a booster ring on top of the SIS-100 at a later stage. Details of the realisation of "beyond-MSV" will be refined when MSV is closer to completion.

With the "green light" from the FAIR council, the construction of the facility is now in progress. The planning for the SIS-100 tunnel is complete, and the application for the construction permit to the civil authorities was submitted end of 2015. Tendering for civil construction will start in September 2016, and site works are expected to begin in 2017. Series production of the magnets for the SIS-100 and their delivery to FAIR has already started. The completion of the delivery of the 46 dipole and 84 quadrupole magnets is expected for mid-2017.

3. NICA

NICA (Nuclotron-based Ion Collider Facility) is the flagship project in high-energy physics at JINR Dubna [4]. Its physics motivations are the exploration of dense QCD matter and the investigation of the nuclear spin structure. The NICA facility will use the existing Nuclotron, after upgrades, as injector to a booster ring and a collider, enabling heavy-ion collisions in the energy range of $\sqrt{s_{NN}} = 2\,A$–$11\,A$ GeV. The ambitious goal is to reach a luminosity of $10^{27}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$. The nuclear collision programme at NICA will be carried out by the MPD experiment, being designed to measure hadronic and leptonic probes. Contrary to fixed-target experiments like CBM, the limits for the interactions rate are defined by the accelerator; a rate of 7 kHz is expected at the higher energies, decreasing to about 10 Hz at the lowest energy. MPD is scheduled to start physics in 2019 with a start-up configuration and reach its full capacity in 2023 after an upgrade with inner and end-cap trackers.

Earlier than the MPD, a fixed-target nuclear collision programme will be pursued by the BM@N experiment, using extracted beams from the upgraded Nuclotron in the energy range 1 A–4.5 A GeV. The detector system, comprising a tracking system of GEM and drift-chambers and a time-of-flight system, will be able to measure hadrons, in particular hyperons from 2017 on. At a later stage, an upgrade with a silicon-based vertex detector and an electro-magnetic calorimeter is foreseen. The interaction rates with BM@N are limited by the readout system, which uses a conventional, triggered concept, to about 50 kHz.

A more detailed report on NICA and its current status is given elsewhere in these proceedings [5].

4. Physics prospects

Figure 2 summarises the experimental landscape for the research on dense QCD matter in terms of collision energy and interaction rate. The currently running programmes nicely cover the entire energy range from AGS

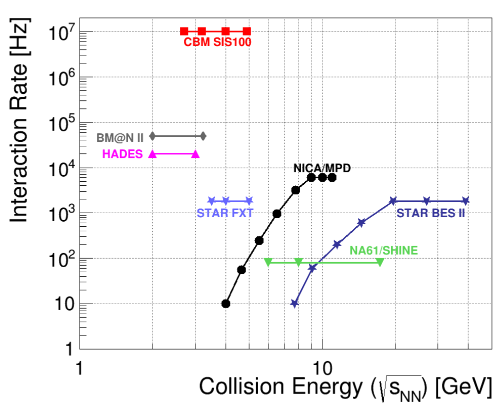

Fig. 2. Landscape for heavy-ion experiments investigating baryon-dense QCD matter in terms of collision energy and interaction rate. Shown are experiments either already running or approved (from [3]). Not included are proposed experiments at SPS [6] and J-PARC [7], which are still in a conceptual stage.

to RHIC, but are limited to moderate interaction rates either by the accelerator or by the read-out. They will deliver data on bulk probes like flow of identified particles, strangeness, and event-by-event fluctuations, which do not require high-statistics measurements. Both BM@N and HADES at SIS-100 will be able to go to higher rates, but are restricted to low collision energies.

CBM and MPD provide complementary approaches to decisively extend the range of energies and observables accessible by current experiments. While MPD, as a collider experiment, is able to cover a broader energy range, it is restricted in rate, but will still exceed in statistics by about an order of magnitude compared to STAR-BES and NA61. CBM, on the other hand, is not rate-limited by the accelerator and has a most ambitious goal in terms of interaction rate, but is, in its first years of operation, limited to the energy range of SIS-100. Both CBM and MPD will provide measurements of low-mass lepton pairs; the intermediate mass range, which requires substantially higher statistics, will be accessible only by CBM. The same holds for anti-hyperons, which in the low-energy range are extremely rare probes.

The experimentally most challenging probes are charmed hadrons. At higher energies ($80\,A$–$160\,A$ GeV), NA61 after an upgrade with a micro-vertex detector will have an access to open charm probes with limited statistics. CBM comes with both detectors capable of detecting open charm and charmonium and with the required rate capacity, but is restricted at SIS-100 to measurements very close to or even below the elementary production threshold. This situation will change once the FAIR energy range is extended by a booster ring; such an extension is thus a prerequisite for the systematic study of charm production at highest net-baryon densities.

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