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Status and physics perspectives of FAIR

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Summary. — The Facility for Antiproton and Ion Research (FAIR) in Darmstadt, which is being built close to the GSI Helmholtzzentrum für Schwerionenforschung in Darmstadt, makes significant progress in its mission to provide unique opportunities for a rich and multidisciplinary research program. The mission of FAIR comprises the investigation of QCD-matter and QCD-phase diagram at high baryon densities; nuclear structure and nuclear astrophysics investigations with nuclei far off stability; QCD studies with cooled, high-intensity antiproton beams; precision studies on fundamental interactions and symmetries; high-density plasma physics; atomic and material science studies; radio-biological investigations and other application oriented research.

1. – Introduction

The Facility of Antiproton and Ion Research (FAIR), which is currently being built together with international partners close to the GSI campus, will offer unique research opportunities on the fields of strongly interacting matter under extreme conditions, hadron physics, nuclear structure and reaction dynamics, nuclear astrophysics, atomic and plasma physics, symmetries and fundamental interactions, and application-related science employing nuclear physics tools like materials and biophysics research using accelerated high-intensity and high-energy ion beams.

The shareholders of FAIR are Finland, France, Germany, India, Poland, Russia, Romania, Slovenia, and Sweden. United Kingdom is associated and Czech Republic aspirant partner. Research at FAIR is structured along four pillars: APPA (Atomic Physis, Plasma physics, materials research, biophysics and Applied science), CBM (Compressed Baryonic Matter), NUSTAR (NUclear STructure And Reactions physics), and PANDA (antiProton ANnihilation at DArmstadt). More than 2500 scientists representing over 200 institutions in 53 countries are participating in the various collaborations.

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FAIR is designed as a multipurpose accelerator facility providing stable and unstable beams of all ion types as well as antiproton beams with unprecedented high intensities and qualities. The layout of the FAIR facility is shown in fig. 1. The centerpiece of FAIR is the fast-ramping, superconducting SIS100 synchrotron with a circumference of 1100 m and a rigidity of 100 Tm. The synchrotron is installed in a 20 m deep tunnel. SIS100 allows the acceleration of ion beams ranging from hydrogen to uranium. Protons with intensities up to 4×10^{13} particles/cycle can be accelerated to 29 GeV, and up to 5×10^{11}uranium ions (U^{28+}) to 2.7 GeV/u. The beam in SIS100 can be extracted either as a short pulse (< 100 ns) for injection into storage rings or plasma physics experiments, or in a long spill with duration of several seconds for fixed target experiments. SIS100 beams can be directly used for fixed target experiments for the CBM and APPA pillars or be directed to the two production targets for rare isotopes or antiprotons.

SIS100 is supplemented by a fragment separator, Super-FRS, providing secondary beams by in-flight fragmentation or fission with subsequent identification and separation of the exotic nuclei. The Super-FRS will have a rigidity of 20 Tm and a large acceptance, which will provide intensities up to two orders of magnitude higher than at the fragment separator FRS situated at the GSI facility. The Super-FRS will serve three experimental branches, the Low and High Energy Branches (LEB and HEB) and a branch to the storage ring complex.

Two storage-cooler rings (CR and HESR) for ions and antiprotons will complete the facility. The production mechanisms of secondary particles lead to large momentum spreads and phase space distributions, thus in storage rings the beam quality needs to improved by stochastic and electron cooling.

The GSI accelerators, UNILAC and SIS18, will serve as injectors for FAIR. The linear accelerator UNILAC accelerates all ions up to 11.4 MeV/u, whereas the SIS18 accelerates ions up to to 2 GeV/u (carbon) or 1 GeV/u (uranium) and protons up to 4 GeV. In order to match the intensity requirements for FAIR operation, an extended upgrade program for the GSI accelerators including a modernization of the legacy control system has been initiated several years ago. Recently, a new record uranium intensity has been achieved; 8 mA U^{28+} could be accelerated in the linear accelerator UNILAC and transferred to SIS18. Already now, the level of intensity reached in SIS18 would result into 2×10^{11} ions in a SIS100 cycle. Protons of high intensities will be provided by a separate linear accelerator, the proton-linac. Pion beams available at SIS18 are produced in collisions of protons, carbon, or nitrogen ions (at energies between 1.6 and 3.5 GeV for protons, and 1.2 and 2 GeV/u for heavy ions) on a thick beryllium target. The pion beam is used by the HADES experiment in particular, but is also available for detector tests.

For financial and scheduling reasons FAIR will be realized in successive steps, each of them offering unique science opportunities by itself. But it is clear that the full science potential could only be realized once the whole suite of accelerators, storage rings and experimental facilities will become available. During the Early Science (ES) phase, direct beams from the SIS18 will be transported to the Super-FRS for commissioning of the fragment separator and performing experiments in the NUSTAR high high-energy cave, where the R3B experiment will be situated. Once the installation of SIS100 is completed, the First Science (FS) phase will start: beams of SIS100 will be used for the production of exotic nuclei. The combination of upgraded GSI accelerator chain, SIS100 and Super-FRS could enhance the intensities for exotic beams up to 3 orders of magnitude compared to the intensities available today. Under the condition of sufficient funding, the CBM cave will be taken into operation with SIS100 beam (FS+) and the APPA cave together with the low-energy branch of the Super-FRS will be completed (next steps). The realization

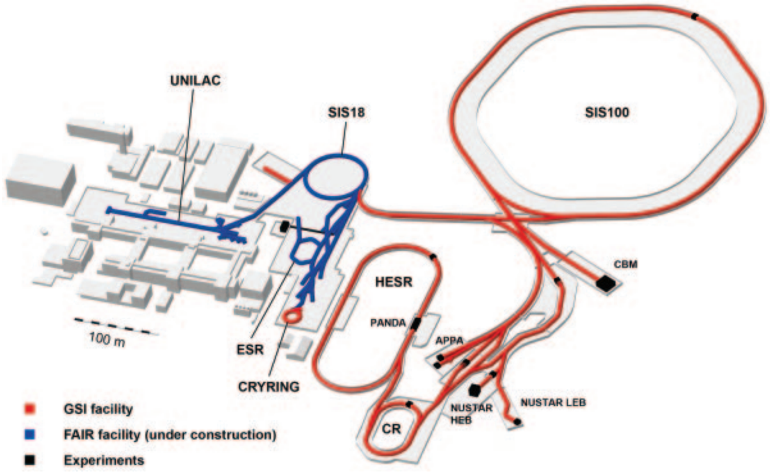

Fig. 1. – Sketch of the GSI and FAIR facilities.

of the full facility comprising in addition the proton-linac and the storage rings CR and HESR (Modularized Start Version MSV) will require substantial additional financial contributions from the shareholders. It is important to note that the completion of the MSV is the declared goal of all shareholders.

According to the current planning, Super-FRS and the SIS100 synchrotron will become available in 2027 and 2028, respectively. Until the start of FAIR operation, GSI is pursuing an intermediate FAIR Phase-0 program by exploiting the upgraded GSI accelerators and novel FAIR instrumentation. Though limited to approximately three months user beamtime per year, FAIR Phase-0 ensures an important environment for accelerator and detector tests, but also enables scientific experiments in preparation of FAIR research. FAIR Phase-0 is of great importance for the scientific community of FAIR to maintain and enhance its international visibility, to train early career researchers and to attract new groups to FAIR.

2. – Scientific perspectives at FAIR

FAIR research will focus on the structure and evolution of matter on all length scales by employing heavy-ion accelerators, novel detector technologies and advanced analysis tools. One of the main thrusts of FAIR science is to establish a connection between multi-messenger astrophysics and laboratory experiments. The four international collaborations will address different topics.

The APPA pillar covers a broad range of highly interdisciplinary research fields: atomic and precision physics with trapped and stored highly charged ions (SPARC), physics of dense plasmas (HED), materials research and biophysics (BIOMAT) [1].

The SPARC Collaboration will make use of the combination of trapping and storage facilities available at FAIR, which will cover energies in the eV-regime (HITRAP) up to several GeV/u (HESR). SPARC focuses on the study of atomic matter under extreme electromagnetic fields as well as atomic processes mediated by ultrafast electromagnetic interaction. A prominent example are the high-Z one-electron ions where the K-shell electrons are exposed to a high electric field (*e.g.*, 10^{16} V/cm in U^{91+}). By employing different experimental techniques (1s lamb shift, 1s hyperfine-structure, bound-stage g-factors, etc.), precision tests of QED are possible.

The BIOMAT Collaboration combines biophysics and materials research to explore new frontiers in radiotherapy with high-energy heavy ions, the effects of galactic cosmic rays on human cells and electronic equipment during long-term space missions, response of materials exposed to extreme radiation hard conditions, and the application of ion beams in astro-chemistry, mineralogy, nanostructures and other topics. An example are irradiation experiments with simultaneous application of extreme pressure and temperatures by using high-pressure cells to investigate the effects on compressed and heated minerals of Earth's interior. Another example of research topic is the development of new imaging technologies for radiation therapy. An extensively used method in heavy-ion therapy is PET. Image-guided therapy could be improved by using β^+-emitters as beams, which could be used both for treatment and imaging (*e.g.*, ^{11}C).

Matter at huge energy densities can be created by using bunched FAIR heavy-ion beams of high intensity, which can be investigated in novel experiments employing the diagnostic capabilities of high-power lasers, *e.g.*, the PHELIX laser which is available at GSI. Matter exposed to energetic and intense heavy-ion beams experiences similar extremes of temperature and pressure as those existing in the interior of stars, brown dwarfs and giant planets.

The CBM [2] experiment will address the characteristics of bulk properties of strongly interacting matter and possible phase transitions. The center piece of CBM is a superconducting dipole magnet with a tracking system based on monolithic active pixel sensors (MAPS) and double-sided silicon strip sensors which are supplemented by time-of-flight detectors, Ring Imaging Cherenkov detectors and transition radiation detectors for electron identification and tracking, an electromagnetic calorimeter, and a projectile spectator detector. The main characteristics of the CBM set-up is the high rate capability which will allow event rates from 100 kHz up to 10 MHz. The CBM data acquisition will be free streaming, hence, full events have to be reconstructed online by fast algorithms running on a high-performance compute farm hosted in the Green-IT cube of GSI.

HADES [3] will be the second experiment in the CBM cave at FAIR. HADES is a high-acceptance electron spectrometer for studies of di-electrons stemming from rare decays of hadrons. Thus the design of HADES aims to detect electrons with high precision. A toroidal magnet deflects charged particles in the polar angle region of 20 to 85°. Four planes of drift chambers provide the tracking of particles before and after the momentum kick. Directly behind the target in a field free region a Ring Imaging Cherenkov detector is installed, which provides the electron identification. The setup is augmented by time-of-flight detectors and calorimetry for charged particle measurements. HADES is in operation at SIS18 and will be moved into the CBM cave at FAIR, once the CBM detector has been installed.

QCD matter at rather low densities has been extensively studied at LHC and its properties have been established. The experimental observations are consistent with a smooth crossover transition between a hadronic system and a quark gluon plasma. No signals of a phase transition have been observed. At large net-baryon densities the picture might change. Lattic QCD calculations predict a first-order phase transition at high net-baryon densities and a critical end point. A sketch of the QCD phase diagram is shown in fig. 2. The region of a potential phase transition with a critical end point (marked with an orange circle) is indicated including the range in temperatures and densities which will be accessible at FAIR regions. The STAR Collaboration studied this region already in beam energy scans at the RHIC accelerator at the Brookhaven National Laboratory.

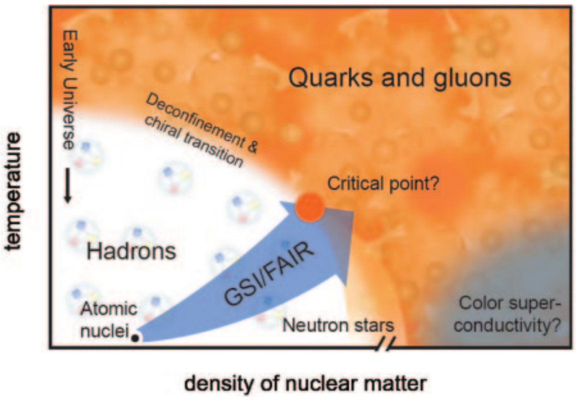

Fig. 2. – Sketch of the QCD phase diagram as a function of temperature *vs.* density.

Fluctuation observables show a rise towards lower energies, which would signal a phase transition [4], but the existence of a critical end point still needs to be confirmed. Here, the CBM experiment will provide novel high statistics data. By employing the high-rate capabilities of the detector, it will be possible to measure rare probes, which might give access to possible phase transitions. In particular, di-leptons as penetrating probes are a promising observable which will be addressed by CBM.

The interaction of strange quarks with normal nuclear matter at high densities has direct implications for the understanding of objects like neutron stars. Depending on the type of interaction it is conceivable that the interior of neutron stars is made out of hyperon matter. Hyperons could be stable in dense neutron matter and will effect the characteristics of dense QCD matter. Theoretical models predict that the existence of hyperons would soften the neutron matter equation of state and would make heavy neutron stars unstable. However heavy neutron stars ($> 2M_{solar}$) have been observed [5], which might be explained by repulsive $\mathrm{NN}\Lambda(\Lambda)$ interactions in dense matter. Therefore, another goal of the CBM Collaboration is the search for hyper-nuclei in particular double Λ nuclei produced in heavy-ion collisions.

High-intensity radioactive beams produced with the Super-FRS will give access to the characteristics of exotic nuclei far off the stability region. The NUSTAR Collaboration will investigate the properties of such nuclei and study reactions which are of astrophysical relevance, *e.g.*, during the nucleosynthesis in neutron star mergers or supernova explosions by a several complementary detector setups. The high intensities available at FAIR will give access to the structure of nuclei at or beyond the neutron dripline. The 3rd r-process peak will be investigated by means of comprehensive measurements of masses, lifetimes, beta-delayed neutrons, dipole strengths, and level structures. Exotic states with multiple neutrons like the tetraneutron, which has been first measured at RIKEN [6], will be investigated at the R3B set-up at FAIR.

R3B is a setup (shown in fig. 3) for the investigation of reactions with radioactive relativistic beams [7]. It allows for kinematically complete measurements of reactions with heavy-ion beams with energies at around 1 GeV/u. The facility comprises full tracking of incoming projectiles and outgoing fragments including light charged particles and emitted photons. The projectile residues are identified and momentum analyzed by reconstructing trajectories through the field of the superconducting large-acceptance

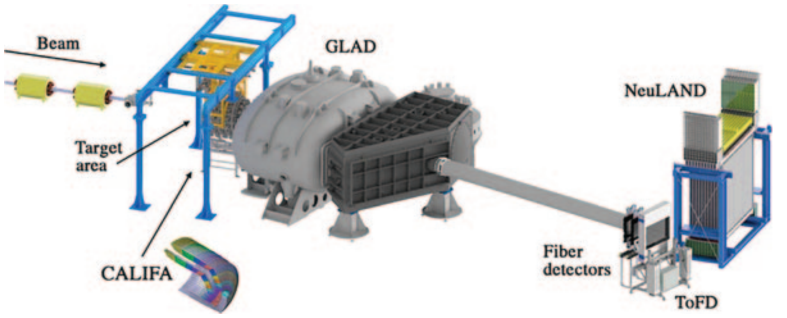

Fig. 3. – Schematic drawing of the R3B setup consisting out of large acceptance dipole, various tracking detectors, a calorimeter surrounding the target and a highly efficient highly granular neutron detector from [8] (CC BY 4.0).

dipole magnet GLAD by employing fiber detectors placed in vacuum. The target is surrounded by a gamma calorimeter and light charged particle detectors. Neutrons emitted from excited projectiles are detected with the large area ($250 \times 250\,\text{cm}^2$) neutron detector NeuLAND. One of the scientific goals of the R3B Collaboration is to study the density dependence of the symmetry energy, which is one of the ingredients to the nuclear matter equation of state and of high relevance for the understanding of the characteristics of dense astrophysical objects like neutron stars and the evolution of neutron star mergers. By measuring the dipole polarizability of a very neutron rich nucleus, one could deduce the size of its neutron halo and thus obtain the slope of the symmetry energy at ground state densities.

Other NUSTAR experiments are the HISPEC or DESPEC setups. DESPEC is designed to study the nuclear structure by decay spectroscopy, where the radioactive nucleus is implanted into an active stopper. A key element of DESPEC@FAIR is the Advanced Implantation Detector Array (AIDA), which acts as an active stopper. AIDA is surrounded by an arrangement of high-purity germanium detectors and fast timing detectors for γ-rays and/or particles from β-decays. HISPEC stands for high resolution in flight spectroscopy, with the goal to measure γ-rays arising from nuclear states excited in the course of secondary reactions of radioactive beams. The outgoing particles are identified event-by-event and γ-ray detection is done with the AGATA (Advanced Gamma Tracking Array). With the DESPEC setup, the collaboration will study the evolution of the shell structure and nuclear shapes, transition probabilities, spin structure, and single particle structures. With decay spectroscopy half-lives, spins, nuclear moments, GT strength, isomer decay, beta decay, beta delayed neutron emission and exotic decays involving two protons will be investigated. Hence, the physics case of HISPEC/DESPEC concentrates on nuclear structure, nuclear reactions and related questions in nuclear astrophysics.

The fragment separator (Super-)FRS can in parts be used as a spectrometer, by placing a target in its middle focal plane. Heavy, fast forward moving fragments produced in nucleus-nucleus collisions will be identified by the 2nd half of the fragment separator with high precision, whereas light particles can be measured with a detector surrounding the target. Such a set-up was realized for the first time, by installing the WASA (Wide Angle Shower Array) detector in the middle focal plane of the FRS. WASA is a close to 4π detector for light charged and neutral particles. Such a set-up allows to reconstruct hyper-nuclei with high precision: one is able to measure the kaon produced in association with the Λ-hyperon, the decay pion of the formed hyper-nucleus, and the forward moving heavy decay particle.

The GSI storage ring ESR is designed to accumulate, store and cool heavy ions up to uranium with energies up to 500 MeV/u and down to several MeV/u. The ESR can be directly served by SIS18, the FRS or via a stripper target, where highly charged ions are produced. The circulating beams are and will be used for a large variety of experiments by the SPARC and ILIMA Collaborations, *e.g.*, mass and lifetime measurements as well as the study of reactions with astrophysical relevance. High luminosity is achieved with thin gas targets due to the large circulation frequencies up to 2 MHz. The CRYRING@ESR is a second storage ring which is designed for slowing radioactive nuclei down to the keV region, which allows to study nuclear reactions at energies which are relevant in astrophysical processes.

The PANDA (antiProton ANnihilation at DArmstadt) experiment at the High-Energy Storage Ring HESR will study collisions between protons and antiprotons in a wide momentum range. PANDA will address a broad scientific program. Therefore, the detector covers the full phase space and is composed of two spectrometers. A target spectrometer in a solenoid magnet and a forward spectrometer with a dipole magnet. PANDA is aiming to improve our understanding of the strong interaction and the hadron structure and the experiments will address a multitude of scientific topics. The PANDA Collaboration will among others study gluonic excitations and search for glueballs and other exotics, and will investigate charmonium states and study form factors.

3. – Recent highlights from FAIR Phase-0

The FAIR Phase-0 program started in 2018 with the goal to employ detectors built for FAIR and the upgraded GSI accelerators to start a stepwise approach towards FAIR science, to train and educate early career researchers and to enhance the visibility of FAIR on the international scientific landscape. Some exemplary highlights are reported in the following.

Laser spectroscopy of hyperfine structures (HFS) of highly charged heavy ions provides a unique opportunity to test quantum electron dynamics in the presence of strong fields. In a measurement campaign at the storage-ring ESR it was possible to measure the hyperfine splitting in hydrogen and lithium-like bismuth ions ($^{209}\mathrm{Bi}^{82+}$ and $^{209}\mathrm{Bi}^{84+}$), which showed a large deviation from state-of-the-art QED calculations. This puzzle was resolved by re-measuring the magnetic moment of $^{209}\mathrm{Bi}$ and improved calculations.

Materials under extreme conditions of pressure, temperature, and radiation may undergo dramatic structural changes which are not observed with the application of only pressure or temperature. Such studies are now possible at the high-pressure set-up of the Materials Research Collaboration at SIS18. A material sample is pressurized in a diamond anvil cell and irradiated from the side using a well collimated heavy-ion beam. The structural changes of the material are observed by Raman Spectroscopy, which can be done through the diamond crystals. In a first series of experiments, benzene, CO, CO_2, Bi, and Sb have been irradiated.

Cosmic radiation is one of the main risks for human exploration of space. During long travels astronauts are exposed to substantial amounts of radiation, which are threatening their life quality and the success of the mission. However, the knowledge on the biological effects of cosmic rays is sparse. During the last years the European Space Agency (ESA) has established a program to study the effects of cosmic radiation not only on humans, but also on electronics and supported research on shielding materials. Scientists at GSI have developed a novel technology to create a broad spectrum of galactic cosmic rays by using 3d printed range modulators. By using only an iron beam at three different energies it is possible to generate a cosmic ray field which is similar to the one in outer space. With the higher energies available at FAIR it will be possible to create a nearly complete cosmic ray spectrum for irradiation studies [9].

Nuclear decays, which employ the atomic electron cloud (such as orbital electron capture, internal conversion etc.), show different properties for an atom with its electron cloud or a bare nucleus. For instance, first excited 0+ states in even-even nuclei are known to be long lived due to angular momentum conservation. These states decay by electron conversion (or by electron-positron pair creation if the excitation energy is high enough $> 1.022\,\mathrm{MeV}$). If the nucleus is fully stripped, electron conversion becomes impossible and the only open decay channel is two-photon decay. In an ESR experiment bare ^{72}Ge nuclei were stored. The first excited 0+ state could be identified and its decay rate was measured, which is a factor 10 larger than expected from theory [10].

The ^{205}Pb nucleus may serve as a cosmochronometer for the early Solar System due to its unique position among astrophysically "short lived" radioisotopes ($T_{1/2} = 1.73 \times 10^7\,\mathrm{y}$), because it is produced only via the s-process. The abundance of ^{205}Pb relative to the stable reference isotope ^{204}Pb would constrain nucleosynthesis activity prior to the formation of the Sun and the Solar System. In a harsh stellar environment, the lifetime of ^{205}Pb is reduced substantially by excitation into its 1st excited state, from which electron capture decay into ^{205}Tl is substantially faster than from the ground state. On the other hand, ^{205}Pb is produced by the bound state beta-decay of fully ionized ^{205}Tl as it is existing under astrophysical conditions. In order to shed light on the complex ^{205}Pb production process, the decay rate of bare $^{205}\mathrm{Tl}^{81+}$ was measured at the ESR. The result of 291^{+33}_{-27} days is substantially longer than theoretically predicted. The new decay rate of $^{205}\mathrm{Tl}^{81+}$ allows to predict how much ^{205}Pb has been produced in AGB stars and was present in the primordal gas cloud which formed the Sun. By comparing with the amount of ^{205}Pb found in meteorites, one is able to deduce that the formation of the Sun from the progenitor molecular gas cloud took about 10 to 12 million years [11].

HADES succeeded to identify $^{3}_{\Lambda}\mathrm{H}$ and $^{4}_{\Lambda}\mathrm{He}$ hypernuclei by their weak decay topology in Ag+Ag collisions in sufficient amounts to reconstruct phase space distributions. Thermal model calculations predict that the maximum yield for hypernuclei production will actually be reached at FAIR energies [12]. At CBM with a moderate interaction rate of 500 kHz it will be possible to detect 100 $^{6}_{\Lambda\Lambda}\mathrm{He}$ nuclei per week. The discovery of new (double-) Λ hypernuclei and the determination of their lifetimes will provide information on NΛ and $\Lambda\Lambda$ interactions.

4. – Summary and outlook

According to the current planning for FAIR, the Super-FRS fragment separator using SIS18 beams and the SIS100 synchrotron will become available in 2027 and 2028, respectively. Therefore, a comprehensive FAIR Phase-0 program will continue with operating and exploiting the existing research infrastructures at GSI and the newly built detector setups for FAIR. Once FAIR starts to become operational, it will be an international flagship for fundamental science. Already with Super-FRS and SIS100 operational, FAIR will open up unprecedented research opportunities in hadron physics with proton beams at CBM, nuclear physics with high-energy exotic beams delivered from the Super-FRS and high-intensity heavy-ion beams at CBM as well as in associated applied science. Atomic physics as well as nuclear physics experiments will continue at the storage rings ESR and CRYRING and the HITRAP trapping facility at GSI, where the detector technologies are continuously pushed forward. The PHELIX Laser will be further upgraded and user operation will be continued. HADES will continue operation at SIS18 for some more years, employing the unique opportunities of the high-energy and high-intensity pion beam.

Already during the first operation phases of FAIR, when SIS100, Super-FRS and the CBM cave are operational, novel information will be obtained on how complexity arises from the fundamental building blocks and the interaction among them: the higher intensities at FAIR will give access to heavier halo nuclei and to unbound nuclei close to or beyond the neutron dripline and will advance the understanding of nuclei relevant for the 3rd r-process peak. The combination of high-intensity beams of heavy nuclei and the high-rate experiment CBM will provide unique conditions to study the QCD phase diagram in the region of high baryon-chemical potentials. Research on space radiation protection will greatly benefit from the high-energy beams at FAIR, as well as irradiation studies under high-pressure conditions in the context of materials research.

The next steps would be the completion of the APPA cave and the installation of the Low-Energy Branch (LEB) of the Super-FRS. In the LEB it will be possible to study radioactive nuclei at energies between 0 and 300 MeV/u. For efficient stopping of the highly energetic exotic beams a Cryogenic Stopping Cell will be used, which is under development at GSI.

FAIR will be a flagship infrastructure offering a broad spectrum of research opportunities for basic science focusing on the understanding of matter and materials.

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