

FAIR - Cosmic Matter in the Laboratory

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Abstract. To explore cosmic matter in the laboratory - this fascinating research prospect becomes available at the Facility for Antiproton and Ion Research, FAIR. The new facility is being constructed within the next five years adjacent to the existing accelerator complex of the GSI Helmholtz Centre for Heavy Ion Research at Darmstadt/Germany, expanding the research goals and technical possibilities substantially. This includes new insights into the dynamics of supernovae depending on the properties of short-lived neutron-rich nuclei which will be investigated with intense rare isotope beams. New insights will be provided into the interior of stars by exploring dense plasmas with intense heavy-ion beams combined with a high-performance laser - or into neutron star cores by probing the highest baryon densities in relativistic nucleus-nucleus collisions at unprecedented collision rates. To the latter, the properties of hadrons play an important part which will be systematically studied by high precision hadron spectroscopy with antiproton beams at unmatched intensities. The worldwide unique accelerator and experimental facilities of FAIR will open the way for a broad spectrum of unprecedented fore-front research supplying a large variety of experiments in hadron, nuclear, atomic and plasma physics as well as biomedical and material science which will be briefly described in this article. This article is based on the FAIR Green Paper [4] and gives an update of former publications [5] - [12].

1. Introduction

The new international facility FAIR (Facility for Antiproton and Ion Research in Europe [1]-[3]) is being constructed adjacent to the site of the GSI Helmholtz Centre for Heavy Ion Research at Darmstadt, Germany (see Fig. 1). It will substantially expand research goals by providing worldwide unique accelerator and detector facilities for a large variety of unprecedented fore-front science. The main thrust of FAIR research focuses on the structure and evolution of cosmic matter on a microscopic scale. This will deepen our understanding of fundamental questions such as:

- How does the complex structure of matter at all levels arise from the basic constituents and the fundamental interactions ?



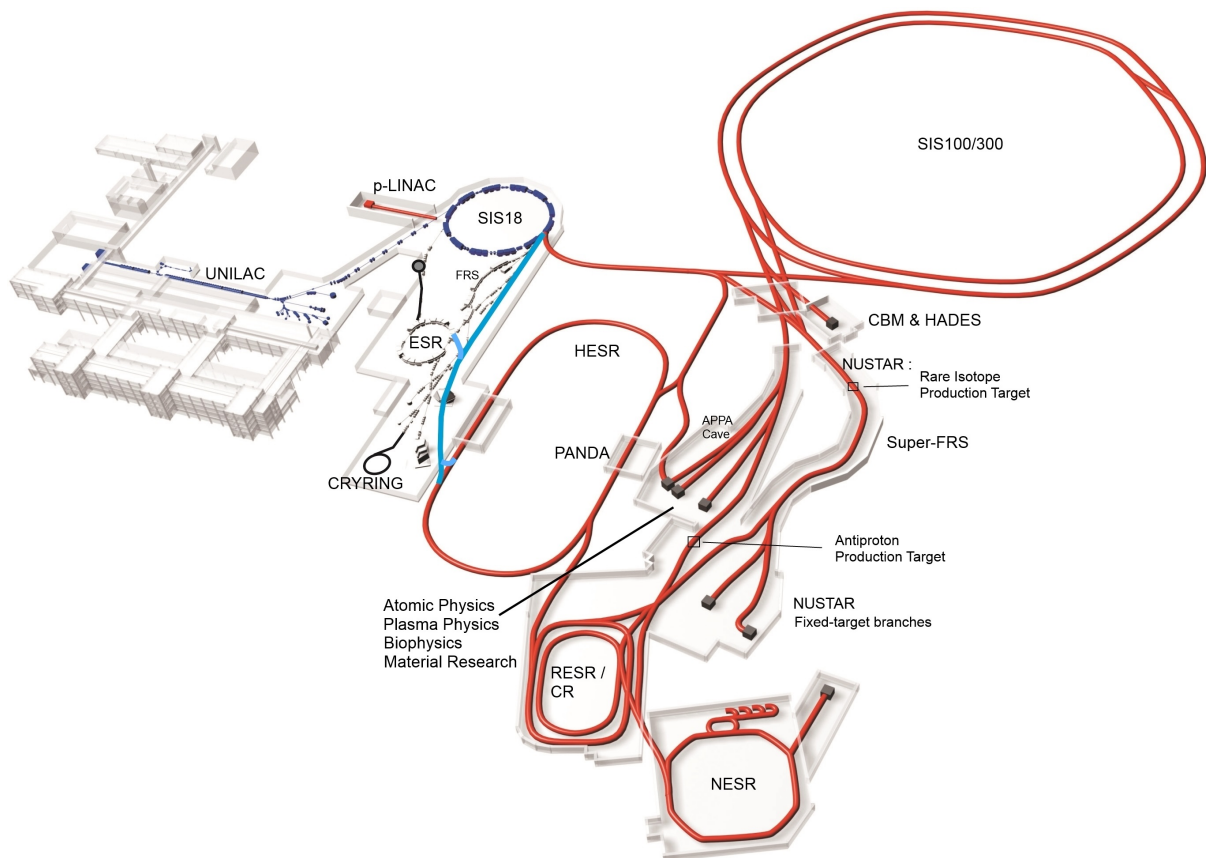


Figure 1. The existing GSI facility is shown on the left, in dark-blue the existing GSI accelerator facilities and ion sources. On the right the new FAIR complex is displayed in red with its 100 and 300 Tm super conducting double-ring synchrotrons SIS100 and SIS300, detector areas (i) for atomic and plasma physics, biomedical and material sciences (APPA), (ii) for the relativistic nucleus-nucleus collision experiments CBM and HADES, (iii) for the radioactive beam facility (NUSTAR), the and (iv) for the hadron physics detector system PANDA as well as the rare-isotope and antiproton production targets with storage rings. Proposed beamlines for transport of protons and ions from SIS18 directly to the High Energy Storage Ring HESR [13] and of antiprotons and exotic ions from HESR to the ESR/CRYRING are shown in addition (light blue). After the start phase the facility will be completed by the experimental storage rings NESR (New Experimental Storage Ring) and RESR (Recuperated Experimental Storage Ring) enhancing capabilities of secondary beams and by the superconducting synchrotron SIS300 providing true parallel operation of experimental programs as well as particle energies twenty-fold higher compared to those achieved so far at GSI [4].

- How can the structure of hadronic matter be deduced from the strong interaction ? In particular, what is the origin of hadron masses ?
- What is the structure of matter under the extreme conditions of temperature and density found in astrophysical objects ?
- What was the evolution and the composition of matter in the early Universe ?
- What is the origin of the elements in the Universe ?

To address these fundamental questions FAIR will provide an extensive range of particle beams from protons and their antimatter partners, antiprotons to ion beams of all chemical elements up to the heaviest (stable) one, uranium, with world record intensities. As a joint effort of more than 50 countries the new facility builds, and substantially expands, on the present accelerator system at GSI Helmholtz Centre for Heavy Ion Research, both in its research goals and its technical possibilities. Compared to the present GSI facility, the beam intensities will increase by a factor of 100 for primary beams and up to a factor of 10000 for secondary radioactive beams with an excellent beam brilliance of primary as well as secondary beams. This will be achieved through innovative beam handling techniques, many aspects of which have been developed at GSI over recent years with the present accelerator complex. This includes in particular stochastic, and electron-beam cooling of high-energy, high-charge state ion beams in storage rings and bunch compression techniques. Even laser cooling has been demonstrated to be powerful tool for certain ion species. To realize parallel operation of the research programs the design of FAIR includes the superconducting double-ring synchrotrons SIS100 and SIS300. Both have a circumference of 1100 meters each and a magnetic rigidity of 100 and 300 Tm, respectively. Since a key feature of the new facility will be the generation of intense, high-quality secondary beams, the facility design contains a system of associated storage rings for beam collection, cooling, phase space optimization and experimentation (see Fig. 1).

The *Modularized Start Version* (MSV) [3, 4] of FAIR consists of the superconducting synchrotron SIS100 which feeds primary beams for fixed-target experiments and production targets for secondary beams of rare isotopes and antiprotons with the two cooler-storage rings HESR (High Energy Storage Ring) and CR (Collector Ring). Detector areas for all scientific pillars are included. Following an upgrade for high intensities, the existing GSI accelerators UNILAC and SIS18 will serve as injectors. The facility will be completed by experimental storage rings enhancing capabilities of secondary beams and by the superconducting synchrotron SIS300 providing parallel operation of experimental programs as well as particle energies twenty-fold higher compared to those achieved so far at GSI.

To increase even further the flexibility in beam handling and operation, currently detailed investigations of short additional beamline sections are getting pursued (light blue colored in Fig. 1) [13]. These beamlines will allow to transport stable as well as exotic ions from SIS18 (as well as from ESR or FRS) directly to the High Energy Storage Ring HESR and of antiprotons and exotic ions from HESR to the ESR.

2. The Experimental Program of FAIR

The approved FAIR research program embraces 14 experiments. These form the four scientific pillars of FAIR and offer a large variety of unprecedented forefront research in hadron, nuclear, atomic and plasma physics as well as applied sciences. Already today, over 2500 scientists and engineers are involved in the design and preparation of the FAIR experiments. The four scientific pillars are named

- APPA – Atomic Physics, Plasma Physics and Applications,
- CBM and HADES – Compressed Baryonic Matter,
- NUSTAR – Nuclear Structure, Astrophysics and Reactions,
- PANDA – AntiProton ANnihilation in DArmstadt .

2.1. APPA – A look into the interior of giant planets and stars

In the Universe at large, matter exists predominantly either as hot dense plasma in the interior of stars or in stellar atmospheres, as medium- or low-temperature dense plasma in the interior of giant planets, or as hot plasma of very low density in interstellar space. In particular the regime of dense plasmas is so far only scarcely explored, since it is difficult to approach experimentally.

Intense heavy-ion beams provide an efficient tool to create large samples of this high-energy-density matter with volumes of the order of a few mm^3 or even cm^3 and lifetimes of the order of several tenths of nanoseconds by isochoric and uniform heating of solid matter. The uniform physical conditions and comparatively long life times facilitate application of a broad spectrum of the diagnostic tools for studying these states of matter. For Plasma physics the availability of high-energy, high-intensity ion-beams in unique combination with a petawatt-laser enables the investigation of high energy density matter in regimes of temperature, density and pressure not accessible so far [16]. It will allow probing new areas in the phase diagram and long-standing open questions of basic equation-of-state research can be addressed. The efficient generation of these states in macroscopic amounts will be boosted by the implementation of new, efficient time and space resolved diagnostics methods based on high-energy proton microscopy and intense lasers. Around these topics, two plasma physics collaborations were built: the High Energy Density Matter generate with intense Heavy Ion Beams (HEDgeHOB) [16] and the Warm Dense Matter (WDM).

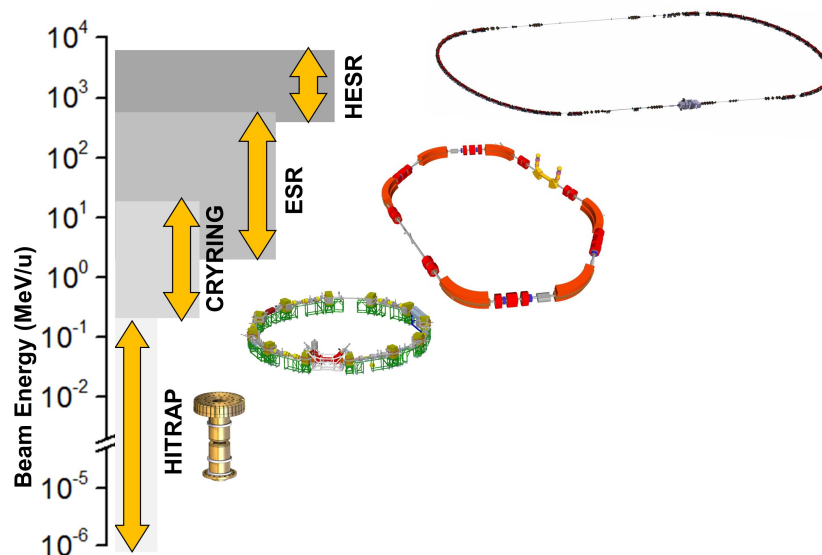


Figure 2. Portfolio of storage and trapping facilities at FAIR. These facilities cover continuously a kinetic beam-energy range of more than 10 orders of magnitude, ranging from rest in the laboratory up to large γ values.

Atomic physics at FAIR [14, 15, 17] will focus on the exploration of matter in extreme electromagnetic fields by exploiting the storage and trapping facilities. The unrivaled combination of storage and trapping facilities for antiprotons and heavy ions are a further unique feature that distinguish FAIR from all other particle accelerator facilities worldwide (planned or in operation). As depicted in Fig. 2, these facilities cover a kinetic beam-energy range of more than 10 orders of magnitude, ranging from rest in the laboratory up to large γ values. For atomic physics, FLAIR [17] will exploit these research opportunities for experiments with low-energy anti-protons whereas SPARC [14, 15] will pursue experiments with stable and exotic nuclei at high atomic charge-states over the whole beam-energy range available. This will allow the extension of atomic-physics research across virtually the full range of atomic matter, i.e. concerning the accessible ionic charge states as well as beam energies.

In SPARC experiments two major research areas are planned: collision dynamics in strong electromagnetic fields and fundamental interactions between electrons and heavy nuclei up to bare uranium. In the first area we will use the relativistic heavy ions for a wide range of collision studies. In the extremely short, relativistically enhanced field pulses, the critical field limit (Schwinger limit) for lepton-pair production can be surpassed by orders of magnitudes and breakdowns of perturbative approximations for pair production are expected. The detection methods of reaction microscopes will give the momentum of all fragments when atoms or molecules are disintegrating in strong field pulses of the ions. This allows exploring regimes of multi-photon processes not accessible by other means. In particular, the storage ring HESR will be exploited for collision studies and fundamental atomic processes will be investigated for cooled heavy-ions at well-defined charge states interacting with photons, electrons and atoms. One may note, that the HESR can store cooled beams at energies of up to a few GeV/u and can thus enable unique precision experiments with cooled relativistic energies (γ values ranging from 2 to 6).

For SPARC, the experiments in the high energy regime will be complemented by the CRYRING at ESR (see Fig. 1) [18]. Here, at the low-beam energies (between 1 and 14 MeV/u) atomic interactions for highly-charged ions are governed by strong perturbations and quasi-molecular effects. The other class of experiments will focus on the determination of properties of stable and unstable nuclei by atomic physics techniques on the one hand, and precision tests of quantum electrodynamics (QED) and fundamental interactions in extremely strong electromagnetic fields on the other hand. A further important scenario for this class of experiments will be the slowing-down, trapping and cooling of particles in the ion trap facility HITRAP [19]. This scenario will enable high-accuracy experiments in the realm of atomic and nuclear physics, as well as the determination of fundamental constants or even highly-sensitive tests of the Standard Model.

Variants of civil construction sequences are presently investigated to enable an earlier start of the scientific program of FAIR, among which we would like to note the direct coupling of SIS18 to HESR and of HESR to ESR and CRYRING [13]. Both are outside of the Modularized Start Version of FAIR, but both APPA and the low-energy antiproton and Ion (Flair) community see this as a cost-effective model for an early start of the science of module 5 as outlined in the Green Paper of FAIR [4].

Applied research benefits from the large range of beam energies and intensities for various activities, in particular in biophysics and material science. The biophysics research has two main topics: space radiation effects on humans (astronauts) and spacecraft instrumentation (microelectronics); and particle therapy using high-energy protons and heavy ions for cancer and non-cancer diseases. Research in material science is dedicated to heavy-ion induced modifications in solids under extreme conditions such as short ion pulses, high fluences, and the simultaneous application of pressure and temperature. A multipurpose irradiation facility, able to uniformly scan large targets and equipped with various instrumentations for in-situ and on-line monitoring, has been designed. This facility will be built and exploited by the BIOMAT collaboration consisting of international collaborations on heavy-ion biophysics (BIO) and material science (MAT).

2.2. CBM and HADES – A look into the interior of neutron stars

The stability of neutron stars is guaranteed by the Pauli principle of nucleons together with the repulsive part of the nucleon-nucleon interaction. Therefore the structure of a neutron star is dictated by the strong interaction with the nuclear equation-of-state as key ingredient. The transition from the outer to the inner core of a neutron star is specified by the appearance of exotic phases, e.g. matter containing additional particles species carrying strangeness such as hyperons, pion or kaon condensed matter or deconfined quark matter. The question whether

the interior of a neutron star is already in a (superconducting) quark phase is an active field of research. To explore nuclear matter densities beyond saturation density in the laboratory nucleus-nucleus reactions provide the only possibility.

The mission of high-energy nucleus-nucleus collision experiments worldwide is to investigate the properties of strongly interacting matter under these extreme conditions. At very high collision energies, as available at RHIC and LHC, the measurements concentrate on the study of the properties of deconfined QCD matter at very high temperatures and almost zero net baryon densities. Results from lattice QCD indicate that the transition from confined to deconfined matter at vanishing net baryon density is a smooth crossover, whereas in the region of high net baryon densities, accessible with heavy-ion reactions at lower beam energies, a first-order phase transition is expected [20]. Its experimental confirmation would be a substantial progress in the understanding of the properties of strongly interacting matter.

Complementary to high-energy nucleus-nucleus collision experiments at RHIC and LHC, the CBM experiment [21, 22, 23] as well as HADES [25] - [30] at SIS100/300 will explore the QCD phase diagram in the region of very high baryon densities and moderate temperatures by investigating heavy-ion collision in the beam energy range 2 - 44 AGeV. This approach includes the study of the nuclear matter equation-of-state, the search for new forms of matter, the search for the predicted first order phase transition to the deconfinement phase at high baryon densities, the QCD critical endpoint, and the chiral phase transition, which is related to the origin of hadron masses.

In the case of the predicted first order phase transition, basically one has to search for non-monotonic behavior of observables as function of collision energy and system size. The CBM experiment at FAIR is being designed to perform this search with a large range of observables, including very rare probes at these energy regime like charmed hadrons. Produced near threshold, their measurement might be well suited to discriminate hadronic from partonic production scenarios. The former requires pairwise creation of charmed hadrons, the latter the recombination of c-quarks created in first chance collisions of the nucleus-nucleus reaction. Ratios of hadrons containing charm quarks as a function of the available energy may provide direct evidence for a deconfinement phase.

The properties of hadrons are expected to be modified in a dense hadronic environment which is eventually linked to the onset of chiral symmetry restoration at high baryon densities and/or high temperatures. The experimental verification of this theoretical prediction is one of the most challenging questions in modern strongly interacting matter physics. The dileptonic decays of light vector mesons (ρ, ω, ϕ) provide the tool to study such modifications since the lepton daughters do not undergo strong interactions and can therefore leave the dense hadronic medium essentially undistorted by final-state interaction. For these investigations the ρ meson plays an important role since it has a short lifetime and through this a large probability to decay inside the reaction zone when created in a nucleus-nucleus collision. As a detector system dedicated to high-precision di-electron spectroscopy at beam energies of 1 - 2 AGeV, the modified HADES detector at SIS100 will measure e^+e^- decay channels as well as hadrons [28, 29, 30] in collisions of light nuclei up to 10 AGeV beam energy. In addition and complementary, the CBM experiment will cover the complete FAIR energy range by measuring both the e^+e^- and the $\mu^+\mu^-$ decay channels.

Most of the rare probes like lepton pairs, multi-strange hyperons and charm will be measured for the first time in the FAIR energy range. The goal of the CBM experiment as well as HADES is to study rare and bulk particles including their phase-space distributions, correlations and fluctuations with unprecedented precision and statistics. These measurements will be performed in nucleus-nucleus, proton-nucleus, and proton-proton collisions at various beam energies. The unprecedented beam intensities will allow to study extremely rare probes with high precision which have not been accessible by previous nucleus-nucleus experiments at the AGS, SPS and

the beam energy scan program (BES) at RHIC.

Complementary to the CBM program at FAIR and at about the same time as FAIR the Nuclotron-based Ion Collider facility NICA will come into operation at the Joint Institute for Nuclear Research (JINR) in Dubna [24]. The main goal of the project is to study hot and dense strongly interacting matter in nucleus-nucleus collisions at center-of-mass energies $\sqrt{s_{NN}} = 4$ -11 GeV with the Multi-Purpose Detector (MPD). As a collider, NICA achieves higher collision energies while CBM will perform experiments with up to 4 orders of magnitude higher collision rates.

2.3. NUSTAR – Rapid nuclear processes in supernovae and the elemental abundances in the universe

Reactions between nuclei play a decisive role in many astrophysical processes in the universe. Nuclear structure effects and the dynamics of nuclear reactions are directly reflected in the various evolutionary stages of stars, in the light curves of stellar explosions, and in the elemental abundance distributions in the Universe. Unstable nuclei, far away from stability, are involved and their properties determine the fate of the relevant astrophysical processes. The radioactive beam facility at FAIR offers world-wide unique experimental opportunities for this area of research.

The main scientific thrusts in the study of nuclei far from stability are aimed at three areas of research: (i) the structure of nuclei, the quantal many-body systems built by protons and neutrons and governed by the strong force, towards the limits of stability, where nuclei become unbound, (ii) nuclear astrophysics delineating the detailed paths of element formation in stars and explosive nucleosynthesis that involve short-lived nuclei, (iii) and the study of fundamental interactions and symmetries exploiting the properties of specific radioactive nuclei.

The central part of the NUSTAR programme at FAIR [31, 32] is the high acceptance Super-FRS with its multi-stage separation that will provide high intensity mono-isotopic radioactive ion beams of bare and highly-ionized exotic nuclei at and close to the driplines. This separator, in conjunction with high intensity primary beams with energies up to 1.5 AGeV, is the keystone for a competitive NUSTAR physics programme. This opens the unique opportunity to study the evolution of nuclear structure into the yet unexplored territory of the nuclear chart and to determine the properties of many short-lived nuclei which are produced in explosive astrophysical events and crucially influence their dynamics and associated nucleosynthesis processes.

2.4. PANDA – The structure of hadrons and the generation of mass in the visible universe

In the evolution of the universe, microseconds after the big bang, a coalescence of quarks and gluons to hadrons occurred associated with the generation of hadron masses. The elementary light quarks, the up and down quarks that make up the nucleon, have very small masses amounting to only a few percent of the total mass of the nucleon. Most of the baryon's masses, and hence of the visible universe stems from the QCD interaction. The generation of mass is thus associated with the confinement of quarks and the spontaneous breaking of chiral symmetry, one of the fundamental symmetries of QCD in the limit of massless quarks.

The big challenge in hadron physics is to achieve a quantitative understanding of strongly interacting complex systems at the level of quarks and gluons. In $p\bar{p}$ -annihilation, particles with gluonic degrees of freedom as well as particle-antiparticle pairs are copiously produced, allowing spectroscopic studies with unprecedented statistics and precision. The PANDA experiment at FAIR [33, 34, 35] will bring new fundamental knowledge in hadron physics by pushing the precision barrier towards new limits. The charmonium ($c\bar{c}$) spectroscopy will take advantage of high-precision measurements of mass, width and decay branches. Particular emphasis is placed on mesons with open and hidden charm, which extends ongoing studies in the light quark sector to heavy quarks, and adds information on contributions of the gluon dynamics to hadron

masses. The search for exotic hadronic matter such as hybrid mesons or heavy glueballs will profit by precise scanning of resonance curves of narrow states as well. Additionally, the precision gamma-ray spectroscopy of single and double hypernuclei will allow extracting information on their structure and on the hyperon-nucleon and hyperon-hyperon interaction.

Recently, much attention has been attracted by the observation at electron-positron colliders of the so-called X, Y and Z states with masses around 4 GeV as measured by experiments e.g. Belle at KEKB [36], BESIII at BEPC [37] and others. These heavy mesons show very unusual properties, whose theoretical interpretation is entirely open.

An extension of the FAIR antiproton facility to a $\bar{p}p$ -collider with a maximum center-of-mass energy $\sqrt{s}^{max} = 30$ GeV [39] and luminosities of about $3 \cdot 10^{30} cm^{-2} s^{-1}$ [38] would allow to analyze these exotic objects and their beauty complements at quantal states not accessible to electron-positron colliders. FAIR would thus open the way to a rich spectrum of Beauty Physics by formation of beauty baryon-antibaryon pairs with a large variety of beauty, charm, strange and light quarks, as well as beauty mesons with spin $\neq 1$. Technically, the antiproton and proton beam would be stored and accelerated in opposite directions inside the HESR which would require a second injection point as well as a second electron cooler. Furthermore the PANDA detector can serve as the mid-rapidity detector system. This fascinating opportunity will enrich the PANDA physics program into new, unprecedented realms and will push the physics program of the High Energy Storage Ring HESR for decades to come.

3. Summary

After the official launch of the project in 2007, nine countries (in alphabetical order: Finland, France, Germany, India, Poland, Romania, Russia, Slovenia and Sweden) signed the international agreement on the construction of the Facility for Antiproton and Ion Research, FAIR, on October 4th, 2010. The construction has started in 2013, so that the first beams will be delivered by the super conducting synchrotron SIS100 in 2019. The scientific program of FAIR cover

- the investigation of bulk matter in the dense and hot plasma state, atomic physics of ultra-high electro-magnetic fields, material and biological research using intense, highly-stripped ions and high-intensity laser fields (APPA);
- the exploration of the QCD phase-diagram and the phase transition to the deconfinement phase at high baryon densities in high-intensity nucleus-nucleus collisions (CBM and HADES);
- the investigation of the nuclear chart and nuclear structure far from stability and of nuclear astrophysics with radio-active beams (NUSTAR);
- the exploration of the hadron structure, QCD vacuum, and the nature of the strong force in the non-perturbative regime of quantum-chromo-dynamics with high-energy beams of antiprotons (PANDA),

forming together the four scientific pillars. The design of FAIR includes the superconducting double-ring synchrotrons SIS100 and SIS300 to realize parallel operation of the research programs. Since a key feature of the new facility will be the generation of intense, high-quality secondary beams, the facility design contains a system of associated storage rings for beam collection, cooling, phase space optimization and experimentation.

The first phase of the FAIR project comprises the superconducting synchrotron SIS100 as well as experimental areas to perform experiments for all research pillars. It will allow to carry out an outstanding and world-leading research program in hadron, nuclear, atomic and plasma physics as well as applied sciences. Due to the high luminosity which exceeds current facilities by orders of magnitude, experiments will be feasible that could not be done elsewhere. FAIR will expand the knowledge in various scientific fields beyond current frontiers. Moreover, exciting

synergy effects between the various research fields and instruments at FAIR in five parallel and crossed operation modes will prove what has been the basic idea of the FAIR communities: *four* scientific pillars with *one* machine.

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