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THE FACILITY FOR ANTIPROTON AND ION RESEARCH, FAIR

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Adjacent to the existing accelerator complex of the GSI Helmholtz Centre for Heavy Ion Research at Darmstadt (Germany) the Facility for Antiproton and Ion Research (FAIR) substantially expands research goals and technical possibilities. It will provide worldwide unique accelerator and experimental facilities allowing for a large variety of unprecedented forefront research in hadron, nuclear, and atomic and plasma physics as well as applied sciences which will be described in this article briefly. The civil-construction work will start in 2012 and first beams will be delivered in 2018.

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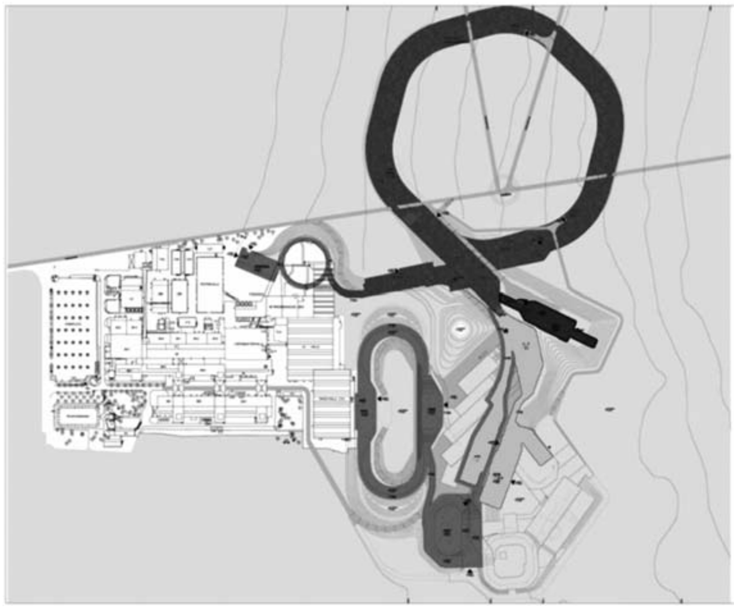
INTRODUCTION

The GSI laboratory at Darmstadt (Germany) was founded 40 years ago through the efforts of scientists from the nearby universities. The goal of the founding fathers was to combine efforts and resources, and to create a forefront research facility for nuclear physics and related areas. They proposed the construction of a novel heavy-ion accelerator that would exceed the technical capabilities of a single university. The success of the concept and the strong involvement from universities, first from Germany, but soon from most of Europe and worldwide, widened the scope of the facility. Together with a significant energy upgrade about 20 years ago, the facility has evolved into a major international research centre using beams of heavy ions.

The Facility for Antiproton and Ion Research, FAIR [1–3], builds on this tradition. It 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 one, uranium, with in many respects world record intensities. As a joint effort of 16 countries[2], the new facility builds, and substantially expands, on the present accelerator system at GSI, both in its research goals and in its technical possibilities. Compared to the present GSI facility, an increase of a factor of 100 in primary beam intensities, and up to a factor of 10000 in secondary radioactive beam intensities, will be a technical property of the new facility. Other characteristics will be excellent beam qualities of both primary and secondary beams. This will be achieved

[1] Invited talk.
[2] In alphabetical order: Austria, China, Finland, France, Germany, Greece, India, Italy, Poland, Romania, Russia, Slovenia, Slovakia, Spain, Sweden, and the United Kingdom.



On the left-hand side, the existing GSI facility is shown. Colored displayed is the so-called Modularized Start Version of FAIR including modules 0, 1, 2, and 3. Coloring: the 100 Tm super conducting synchrotron SIS100 (module 0) — green; the experimental area for CBM/HADES (module 1) — red; the NuSTAR facility including the Super-FRS (module 2) — yellow; The antiproton facility including the PANDA experiment (module 3) — orange. Not shown is the additional experimental area above ground for the APPA community (module 1). These colored parts are financed within the presently available firm funding commitments of the 16 partner countries

through innovative beam handling techniques, many aspects of which have been developed at GSI over recent years with the present system. This includes in particular electron-beam cooling of high-energy, high-charge state ion beams in storage rings and bunch compression techniques.

After the official launch of the project on November 7th, 2007, the FAIR scientific community is eager to see FAIR materialized. Because of the long lead times for civil-construction planning civil work for the first buildings of FAIR will start in 2012 and first beams will be delivered in 2018. The start version of FAIR, the so-called *Modularized Start Version* [4, 5], includes a basic accelerator SIS100 (module 0) as well as three experimental modules (modules 1–3) as it is colored illustrated in the Figure. The superconducting synchrotron SIS100 with a circumference of 1100 m and a magnetic rigidity of 100 $\mathrm{T \cdot m}$ is at the heart of the FAIR accelerator facility. Following an upgrade for high intensities, the existing GSI accelerators UNILAC and SIS18 will serve as an injector. Adjacent to the SIS100 synchrotron are two storage-cooler rings and experiment stations, including a superconducting nuclear fragment separator (Super-FRS) and an antiproton production target. The Modularized Start Version secures a swift start of FAIR with outstanding science potential for all scientific pillars of FAIR within the current funding commitments. Moreover, after the start phase the facility will be upgraded by experimental storage rings enhancing capabilities of secondary beams and by the SIS300 providing particle energies 20-fold higher compared to those achieved so far at GSI as additional funds become available.

THE EXPERIMENTAL PROGRAMME OF FAIR

The main thrust of FAIR research focuses on the structure and evolution of matter both on a microscopic and on a cosmic scale –2̆013 deepening our understanding of fundamental questions like: How does the complex structure of matter at all levels arise from the basic constituents and the fundamental interactions? 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?

The approved FAIR research programme embraces 14 experiments, which form the four scientific pillars of FAIR and offers a large variety of unprecedented forefront research in hadron, nuclear, atomic and plasma physics, and applied sciences. Already today, over 2500 scientists and engineers are involved in the design and preparation of the FAIR experiments. They are organized in the experimental collaborations APPA, CBM, NuSTAR, and PANDA.

APPA — Atomic Physics, Plasma Physics, and Applications. Atomic physics with highly charged ions [6] will concentrate on two central research themes: a) the correlated electron dynamics in strong, ultra-short electromagnetic fields including the production of electron–positron pairs and b) fundamental interactions between electrons and heavy nuclei 2̆013 in particular the interactions described by Quantum ElectroDynamics, QED. Here bound-state QED in critical and supercritical fields is the focus of the research programme. In addition, atomic physics techniques will be used to determine properties of stable and unstable nuclei and to perform tests of predictions of fundamental theories besides QED.

For Plasma physics the availability of high-energy, high-intensity ion-beams enables the investigation of High-Energy Density Matter in regimes of temperature, density and pressure not accessible so far [7]. 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 biological effectiveness of high-energy and high-intensity beams was never studied in the past. It will afford to investigate the radiation damage induced by cosmic rays and protection issues for the Moon and Mars missions. Furthermore, the intense ion-matter interactions with projectiles of energies above 1 GeV/u will endorse systematic studies of material modifications.

CBM/HADES — Compressed Baryonic Matter. Violent collisions between heavy nuclei promise insight into an unusual state in nature, that of highly compressed nuclear matter. In addition to its relevance for understanding fundamental aspects of the strong interaction, this form of matter may exist in various so far unexplored phases in the interior of neutron stars and in the core of supernovae. 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.

Complementarily, HADES [8–10] and CBM [11, 12] at SIS100/300 will explore the QCD phase diagram in the region of very high baryon densities and moderate temperatures. 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 between hadronic and partonic matter, the QCD critical endpoint, and the chiral phase transition, which is related to the origin of hadron masses. Vector mesons decaying into di-lepton pairs, strangeness and charm are promising diagnostic tools. It is intended to perform comprehensive measurements of hadrons, electrons, muons and photons created in collisions of heavy nuclei. Most of the rare probes like lepton pairs, multistrange hyperons, and charm will be measured for the first time in the FAIR energy range. The goal of the CBM/HADES experiment 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 different beam energies.

NuSTAR — Nuclear Structure, Astrophysics, and Reactions. 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 [13,14] is the high-acceptance Super-FRS with its multistage separation that will provide high intensity monoisotopic 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 $1.5A$ GeV, 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.

PANDA — AntiProton ANnihilation in DArmstadt. 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 [15, 16] 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 by precision measurements of mass, width, decay branches of all charmonium states. 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 gains enormously by precise scanning of resonance curves of narrow states as well. Recently, this field has attracted much attention with the surprise observation at electron–positron colliders of the new X, Y, and Z states with masses around 4 GeV. These heavy particles show very unusual properties, whose theoretical interpretation is entirely open. 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.

CONCLUSIONS

All research pillars will carry out an outstanding and world-leading research programme. FAIR will allow forefront research addressing

• the investigation of the properties and the role of the strong (nuclear) force in shaping basic building block of the visible world around us and of its role in the evolution of the Universe;

• tests of symmetries and predictions of the Standard Model and search for physics beyond in the electroweak sector and in the domain of the strong interaction;

• the properties of matter under extreme conditions, both at the subatomic as well as at the macroscopic scale of matter and applications of high-intensity, high-quality ion and antiproton beams in research areas that provide the basis for, or directly address, issues of applied sciences and technology.

Due to the high luminosity which exceeds current facilities by up to a factor of 10000, experiments will be feasible that could not be done elsewhere. FAIR will expand the knowledge in the various scientific fields beyond current frontiers. Moreover, there exist strong cross-topical synergies which can be exploited and promise novel insights.

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