Megaprojects: 2
Facility for Antiproton and Ion Research*

Universe in the Laboratory

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The second article of the series on megaprojects presents FAIR prospects for seamless experimentation across the nuclear landscape, and more; FAIR offers facilities to explore exotic plasma, nuclei and materials!

Details of the scientific programme, technological challenges, present status and future plans of FAIR are presented. India's role as the third largest contributing country in FAIR GmbH is highlighted. Outreach activities and avenues to work in FAIR are discussed in detail.

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Introduction

The Facility for Antiproton and Ion Research (FAIR) coming up at Darmstadt in Germany is one of the largest upcoming basic science projects in the world. Gesellschaft für Schwerionenforschung (GSI), a German nuclear physics laboratory, acts as the host laboratory of FAIR. GSI has made pioneering contributions in the field of nuclear physics over decades. Among the most well-known results are the discovery of six new elements with proton numbers from 107 to 112 and the development of cancer therapy exploiting carbon beams.

On 4th October 2010, the FAIR–GmbH was formed by nine international partners with India as the third largest contributor after Germany and Russia. It is expected to be used by about 3000 researchers the world over. The main accelerator ring of FAIR is a synchrotron, housed in a 1.1 km circumference, 60 m wide tunnel and having 100 Tm (Tesla meter) magnetic rigidity. A few major features of this facility are (a) provision to provide ion beams

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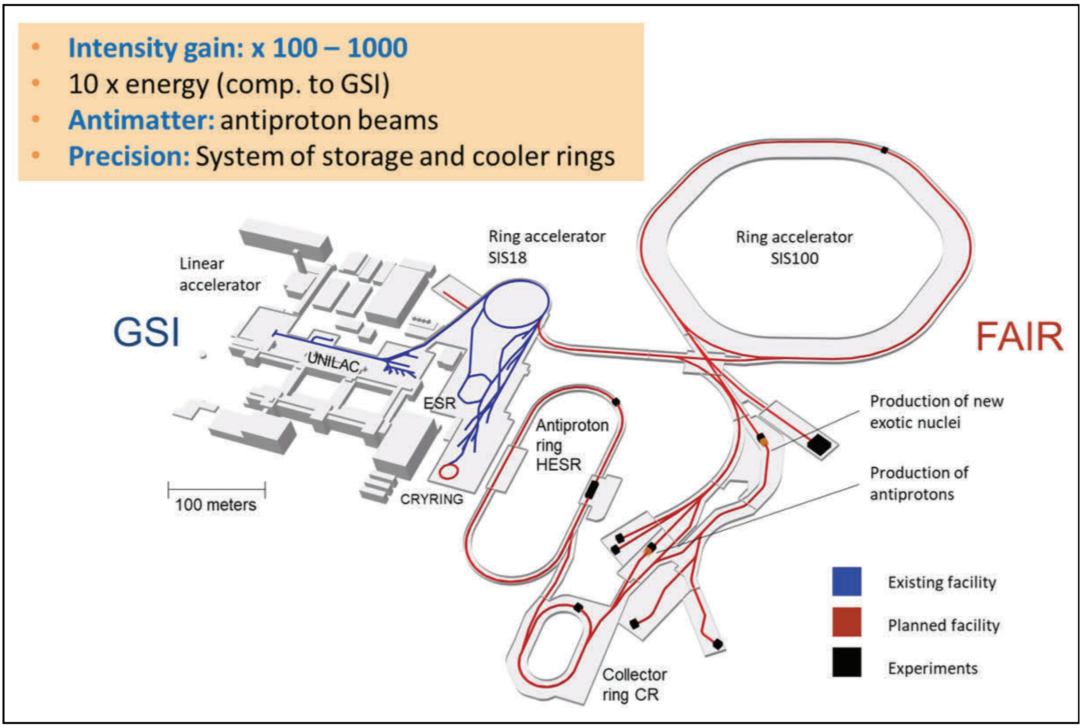

Figure 1. Schematic view of the FAIR facility. GSI is shown on the left. Beams from GSI will be injected to the main SIS100 ring and after acceleration will cater to four scientific pillars. The switching building after SIS100 is crucial in delivering the beams to different research facilities in parallel.

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concurrently for research and innovation in four major fields of physics (b) high intensity beams for both stable as well as rare-ion species with intensity for rare ion beams 10000 times higher than the existing availability at GSI (c) acceleration of ions of all elements up to uranium, rare isotopes and antiprotons (d) ion energies reaching up to a few MeV/A to 45 GeV/A, varying with ion species (e) production and storage of beams of exotic ions and antiprotons.

A schematic view of the FAIR facility, showing the existing GSI facility (blue lines) and extension to the new FAIR facility (red lines) is presented in *Figure* 1.

Unlike many such large projects with highly specific science goals, FAIR is planned to serve the interests of four major research communities – high energy nuclear physics, nuclear structure, nuclear reactions and astrophysics, atomic and plasma physics and

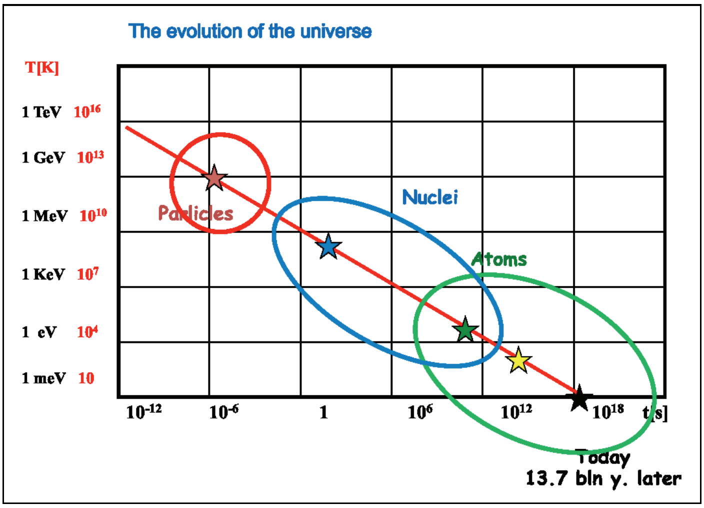

Figure 2. Regimes in the evolution of the universe that are to be explored at FAIR – high energy nuclear physics will explore the microsecond old universe, nuclear physics about a second after the Big Bang and atomic physics at the later phases as marked in the figure.

hadron physics using antiprotons. In particular, this broad scientific scope – when compared to many other large research infrastructures and projects – makes FAIR attractive to a large international community, including many Indian researchers from a number of different institutions.

Figure 2 shows schematically the different regimes in the evolution of the universe that the FAIR physics programme will explore.

The project has made significant progress so far, particularly in civil construction and the development of accelearator components and experimental facilities. *Figure* 3 is a snapshot of the ongoing civil construction showing the construction of the SIS100 tunnel.

Some of the main features of the accelerator setup are as follows:

1. 60-meter wide tunnel.
2. 1.1 km ring of SIS100.
3. Rapid-cycling superconducting magnets with large aperture and unique, cryogenically cooled chambers.

Figure 3. Aerial view of the FAIR construction site showing the excavations for the SIS100 tunnel.

4. Dynamic vacuum control.

5. High energy electron cooling.

6. Ultra-stable power converters.

7. Dedicated service tunnel for faster maintenance and changeover.

Physics Programme of FAIR

Some of the major science questions hoped to be answered by FAIR are the following:

- Why do we not observe individual quarks, the basic building blocks of strongly interacting matter?
- What is the origin of the masses of strongly interacting particles called hadrons? (The Higgs mechanism cannot explain the masses of hadrons and, therefore, of most of the matter around us.)
- What is the origin of the elements?

- What is the structure of neutron stars?
- Can we ignite the solar fire on earth?
- Does matter differ from antimatter?

Brief descriptions are given below of each of the experiments covering the four physics pillars of FAIR

The precursor of FAIR is a well-known nuclear physics facility credited with the discovery of several of the elements of the periodic table.

(a) NUclear STructure Astrophysics and Reaction (NUSTAR): GSI, the precursor of FAIR is a well-known nuclear physics facility credited with the discovery of several of the elements of the periodic table. The nuclear physics setup at FAIR facilitated mainly by the Super FRagment Separator (Super-FRS) uses rare ion beams (RIB) to explore the formation of nuclei and their structures. The astrophysical site as well as the detailed processes leading to the formation of heavy elements in the universe still belong to the big questions of physics. One of the objectives of FAIR is to shed light on this problem by studying the properties and reactions of nuclei far from stability and their relation to the formation of heavy elements in stars, star explosions and neutron star mergers. The observation of a gravitational wave signal by LIGO/VIRGO in 2017, together with detections across the electromagnetic spectrum by other telescopes, has given further push to this research topic as it confirms the theoretical prediction that neutron star mergers are the astrophysical sites of the formation of very heavy elements like Pt, Au and beyond. Major experimental setups like R3B, DESPEC/HISPEC, Mats and LaSpec as well as the storage ring experiments ILIMA and EXL will be installed to study short-lived nuclei and their reactions.

The PANDA collaboration will do basic physics research on various topics around the weak and strong forces, exotic states of matter and the structure of hadrons.

(b) Antiproton Annihilation at Darmstadt (PANDA): The PANDA collaboration will do basic physics research on various topics around the weak and strong forces, exotic states of matter and the structure of hadrons. The experiments will use antiproton beams to bombard various targets and produce short-lived states that will decay to reveal various features of hadron structures. The production and exploration of, theoretically predicted but so-far unobserved states like glueballs and multiquark states are also aimed at, among others. The uniqueness of the PANDA experiment is that it makes use of high-resolution beam particles to create and study resonance states, for understanding the internal structure of hadrons. The setup uses advanced detectors and makes use of energy-resolved beams with excellent energy resolution.

The experiment for studying compressed baryonic matter will produce a medium with a density similar to that expected at the cores of neutron stars.

(c) Compressed Baryonic Matter (CBM): The experiment for studying compressed baryonic matter will produce a medium with a density similar to that expected at the cores of neutron stars. At such high densities, nuclear matter is thought to undergo a transition to a phase consisting of quarks and gluons, the basic constituents of strongly interacting matter. In this experiment, the medium created in the collisions of accelerated ions with various targets are to be studied using a set of observables, to test the production of such a state of quarks and gluons. A particular strength of the CBM experimental setup is the use of specific detector systems that can detect particles coming out of the initial as well as the evolving states of the collision, along with an extremely high-rate capability, allowing the study of very rare events. Such rare and penetrating probes help to make unambiguous studies of the system. The observables to study the properties of the medium include collectivity, equation of state, viscosity and de-confinement among others.

Beams from GSI, and then, FAIR will be used to develop innovative modalities for the treatment of cancer and various other medical indications. GSI has pioneered ion beam therapy to destroy tumor cells without affecting healthy tissue. It can also be used for localized irradiation to destroy dysfunctional “pacemaker" areas.

(d) Atomic, Plasma Physics and Applications (APPA): This setup studies atomic physics and plasma physics at FAIR. Beams of ions with extreme electric field, like Uranium ions with only one electron left orbiting, are examples of the testing grounds for quantum electrodynamics (QED) at extreme conditions. High power lasers are used to perform spectroscopy of warm dense matter. Another area of research at FAIR is the study of matter under conditions like those in the interiors of the Earth and of large planets. High-intensity beams, when stopped in a thick cylindrical target produce ionic plasma of high density, which can then be studied. Questions that are being addressed are (i) does hydrogen go into a metallic state under the extreme conditions of pressure and temperature on and inside Jupiter? (ii) how does hydrogen separate from helium? (iii) are there diamond layers in Uranus and Neptune? On the application front, in collaboration with the European space agency, FAIR beams can be used to simulate radiation effects in space among other things. Moreover, beams from GSI, and then, FAIR will be used to develop innovative modalities for the treatment of cancer and various other medical indications. GSI has pioneered ion beam therapy to destroy tumor cells without affecting healthy tissue. It can also be used for localized irradiation to destroy dysfunctional “pacemaker" areas.

The uniqueness of FAIR is the high intensity of its beams compared to other accelerators. Due to the high intensity, a larger number of interactions take place within a short time, permitting the study of even rarely produced particles in a reasonable time period of operation. FAIR accelerates almost all elements in the periodic table and also their rare isotopes. The large variety of beam particles helps to vary the interactions and study different aspects of atomic physics, nuclear physics and high energy physics.

India’s Role at FAIR

India is a founding member of FAIR, committed to contribute about 3% of the construction cost of the megaproject. India’s contribution is mostly in terms of providing accelerator equipment and detectors, as in-kind contributions. The equipment that have been identified so far to be built in India for FAIR are described below.

1. Power Converters: A large fraction of magnets (room temperature and superconducting) that will be used in the FAIR accelerator will be powered by the power converters being built by ECIL-Hyderabad, India. These devices will give the required voltage with sufficient power to energize the magnets. In total, about 750 power converters will be designed and built in India. A prominent feature of these devices is voltage and current stability of the order of 100 ppm. After several rounds of R&D in collaboration with FAIR engineers, ECIL has got clearances to ship 67 power

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Figure 4. Photograph of a set of power converters at ECIL-Hyderabad ready to be shipped.

converters. *Figure* 4 shows a part of the set of these power converters ready to be shipped. The procurement and production for the next sets of power converters is under way.

2. Ultra-high Vacuum Chamber: About 70 vacuum chambers will be provided as Indian contribution. These thin-walled chambers, to be installed in FAIR beamlines, will house the beam-diagnostic equipment. These chambers are to maintain a vacuum level of 10^{-9} millibar pressure. Production of these chambers presents several challenging features: special quality of steel is to be used as material, welding and other manufacturing processes require special handling, multistep cleaning is required to ensure vacuum quality etc. A major challenge is to weld up to 7 cylindrical ports on a barrel, which, when completed, should maintain mechanical tolerances at the level of tens of microns. The technology demands extremes of care and quality control.

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3. Beam Stoppers: The uniqueness of FAIR is the availability of high-intensity, pulsed beams of different species up to U-238. The nuclear physics research programme requires rare ion beams that are produced by bombarding high energy Uranium ion beams on a thick target. The products and the primary beam are stopped except the selected beam particles. The stopping of the primary and secondary products requires special techniques of cooling and also materials to withstand the large power absorption. A team from the Central Mechanical Engineering Research Institute

(CSIR-CMERI), Durgapur has completed the design work of this special device which has been cleared by the FAIR team. Efforts from Indian manufacturers are under way to build such a device from this design. The need to operate in and hence withstand high radiation, high temperature and high vacuum environments makes the device very complex and unique.

The center-piece of FAIR is the fast-cycling superconducting synchrotron SIS100, exploiting superconducting magnets of various sizes and strengths.

4. Superconducting Magnets: The center-piece of FAIR is the fast-cycling superconducting synchrotron SIS100, exploiting superconducting magnets of various sizes and strengths. Indian designers have completed the engineering design of a set of large aperture, superconducting dipole magnets each of about 90-ton weight. These magnets are to be installed in the low-energy branch of the Super-FRS for nuclear physics research. The design has been cleared by FAIR and has been credited to the Indian team.

5. Power Cable: Indian industry is working to produce about 180 km long co-axial cables to be used to connect the magnets with the power converters over an extended network of accelerators and beamlines. Samples built by Indian industry are cleared by FAIR.

Apart from accelerator equipment, Indian researchers are also involved in building advanced detectors for the FAIR experiments. About 40 groups expressed interest in performing experiments at FAIR covering all four science pillars. At present, Indian researchers are working on detector development primarily for two physics pillars i.e., Compressed Baryonic Matter (CBM) and Nuclear structure, astrophysics and reactions (NUSTAR).

CBM experiment explores the strongly interacting matter at high net-baryon density created in heavy ion collisions at FAIR energy. The debris from these collisions are to be detected for making inferences about the details of the medium created.

CBM experiment explores the strongly interacting matter at high net-baryon density created in heavy ion collisions at FAIR energy. The debris from these collisions are to be detected for making inferences about the details of the medium created. The main emphasis of the CBM setup is to detect the particles created at the beginning of the collision. These particles will carry information on the initial state of the medium. One of the most interesting physics goals of CBM is to study the creation/modification of the masses of hadrons. This can be studied by detecting particles that remain unaltered through the evolution of the collision zone. One such probe is muon-pairs that remain unaffected by the surrounding medium. Indian researchers are involved in the development and production of detectors for muon-pairs. These detectors work on the principle of using a thick absorber segmented into several slices with a detector medium like gas/silicon placed in between the slices. Muons being weakly interacting charged particles pass through the absorber slices and give signals from detectors while passing through them. Other particles like pions that are strongly interacting interact with absorber material and stop at an intermediate stage. The paths of the penetrating muons, curved by the magnetic field in which they are moving, will help to obtain their momenta. One challenge for such detectors is to cope with the very high interaction rate due to the high intensity of the beams. The detector and readout electronics, therefore, need to be radiation hard along with having the capacity to handle high particle rates. Indians are working on a type of gaseous detector called Gas Electron Multiplier (GEM). These wire-less gaseous detectors built by Indian researchers (*Figure* 5) have been found to handle particle rates up to 3 MHz/cm^2. Recently, data was taken using two large size (80 cm $\times$ 40 cm) sector-shaped GEM chambers in the phase-0 programme of FAIR.

Indian researchers are involved in building neutron and gamma-ray detectors for the DESPEC setup. The high-resolution setup will make use of precision mechanical setups for holding the crystals for gamma ray spectroscopy.

NUSTAR experiment aims to study nuclear physics far from the stability line i.e., study nuclei that have large asymmetry in proton and neutron number (high N/Z ratio). These rare beams can be used to perform experiments producing exotic states and explain the production of different types of nuclei. In this setup, spectroscopy of the decay products from the compound formed by the collision of the beam with target nuclei (DESPEC) is done; the other option being to perform in-beam spectroscopy with high-intensity beams (HISPEC). Indian researchers are involved in building neutron and gamma-ray detectors for the DESPEC setup. The high-resolution setup will make use of precision mechanical setups for holding the crystals for gamma ray spectroscopy. For neutron detectors, specially designed liquid scintillators are used to capture neutrons and discriminate them from gamma-rays. Sev-

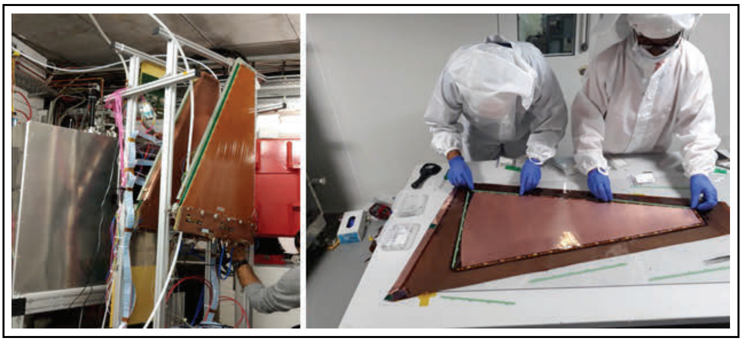

Figure 5. (Left) Two GEM chambers installed and ready for operation at GSI-Germany. (Right) a GEM chamber being assembled at VECC-Kolkata.

eral prototypes have been successfully developed.

Industry Involvement in FAIR

FAIR is a marvel of technology and will use most advanced technologies in various fields like power conversion, superconductivity, computing with low power consumption, high-speed data acquisition and transfer, online data processing and ASIC (Application-Specific Integrated Circuit) development among others. Indian industries are involved in the production of several challenging technological products as mentioned earlier. Several industry meets were held to have discussions with industry partners on various accelerator equipment. Presently, all industrial activities are being performed in collaboration with FAIR engineers; the synergy helps to improve product quality control.

Human Resource Development

There are two types of HRD in this project; one is the training of technologists capable of handling front-ranking products for FAIR, and the other, getting science students trained and involved in front-ranking research, detector technology and discovery science. In India, about 40 groups have shown interest in FAIR science and several students have obtained their PhD degree even in the present development phase of FAIR.

Public Outreach at FAIR

Vigyan Samagam showcases FAIR activities in general and Indian participation at FAIR in particular.

FAIR at Darmstadt and the IFCC (Indo-FAIR Coordination Centre) at Bose Institute are involved in comprehensive outreach programmes to attract and involve students and young, talented researchers and others. To achieve this, the "Get-Involved" programme was established. The programme seeks students and young researchers eager to be involved in FAIR science and invites applications from all over the world. The students, who join this short-term programme, get trained in physics, engineering, computing and such other activities. Apart from this, GSI-FAIR organises regular summer courses to train young researchers. Similar programmes are being held by the IFCC, like training programmes on computing, electronics and physics among others. The FAIR pavilion in *Vigyan Samagam* showcases FAIR activities in general and Indian participation at FAIR in particular. In the programmes that are held at each of the venues, several trained volunteers from various colleges and universities from nearby areas, explain the posters and exhibits. During the FAIR week, presentations are given on accelerator, detector, and neutron-star physics and the like. Interactive sessions are held in which students participate in quizzes and discussions.

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Suggested Reading

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[3] **[3] https://indico.cern.ch/event/660622/contributions/2774021/attachments/1569701/2475489/NUSTAR_ISOLDE_WS_2017_Herlert_final.pdf**