STATUS OF THE FAIR FACILITY

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Abstract

The unique facility for Antiproton and Ion Research – FAIR will deliver stable and rare isotope beams covering a huge range of intensities and beam energies. In addition, the beams for the experiments will have highest beam quality for a cutting edge physics program. Therefore a unique accelerator facility using cutting edge technology will be built until 2018. The challenges are heavy ion synchrotrons for highest intensities, antiproton and rare isotope production stations, high resolution separators and several storage rings where beam cooling can be applied. Here new kind of superconducting magnets, rf-systems, injection and extraction systems and beam diagnostics will be applied. As the construction of the FAIR facility and procurement has started, an overview of the designs, procurements status and infrastructure preparation will be provided.

INTRODUCTION

FAIR – the Facility for Antiproton and Ion Research in Europe – constructed at GSI Helmholtzzentrum für Schwerionenforschung GmbH in Darmstadt comprises an international centre of heavy ion accelerators that will drive heavy ion and antimatter research [1]. FAIR will provide worldwide unique accelerator and experimental facilities allowing a large variety of fore-front research in physics and applied science. FAIR will deliver antiproton and ion beams of unprecedented intensities and qualities. The main part of the FAIR facility is a sophisticated accelerator system, which delivers beams to different experiments of the FAIR experimental collaborations – APPA, NuSTAR, CBM and PANDA – in parallel. The accelerated primary beams will then be employed to create new, often highly exotic particles in a series of experimental programs.

The corresponding four pillars of FAIR physics comprise experiments studying exotic particles that will explore fundamental processes which are thought to have happened in the early phases and still happen in the on-going evolution of the universe. These processes produced the basic constituents of matter and overall structure we see now in the universe. In addition, a range of experiments will be possible in which different forms of matter are compressed. The experiments will simulate conditions in the early Universe, in ultra-dense stars and at the cores of giant planets like Jupiter. FAIR will explore, in a unique way, the properties of fundamental particles and how they combine into more complex forms of matter under a wide range of astrophysical conditions. Base on the committed funding FAIR Member States, a Modularized Start Version (MSV) (Fig. 1) has been agreed upon. This version provides for outstanding and world-leading research programmes in all four scientific areas of FAIR. It provides also a unique scientific and technological environment for educating the next generations of students.

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THE MODULARIZED START VERSION

Based on 2005 cost estimates and the firm commitments on funding of the FAIR Member States a Modularized Start Version (MSV) has been determined that provides for an outstanding and world-leading research programmes in all four scientific areas. More than 2500 scientists are involved in setting up and exploiting the Modularized Start Version [2]. It provides also a unique scientific and technological environment for educating the next generations of students. This modular approach takes into account the following FAIR objectives. It allows for setting up single, relatively independent construction of the modules. It provides the flexibility to realize FAIR according to available funding. The modules we are talking about are:

- Module 0: Heavy-Ion Synchrotron SIS100 – driver accelerator of FAIR and required for all science programmes.
- Module 1: CBM/HADES cave, experimental hall for APPA and detector calibrations
- Module 2: Super-FRS for NuSTAR
- Module 3: Antiproton facility for PANDA, providing further options also for NuSTAR ring physics

UPGRADE OF THE EXISTING FACILITY

The FAIR accelerators will be supplied with ion beams by the GSI accelerator facilities, which presently undergo an upgrade program that addresses all major technical systems from the ions sources towards the SIS18 synchrotron extraction (Fig. 2). The existing GSI accelerator facility comprises the linear accelerator UNILAC, in operation since 1975, capable to accelerate all ions from p to U to variable energy. The ions are delivered from three different ion source stations (two terminals are available for operation of Penning sources and for the high current sources MEVVA and MUCIS, and a 14 GHz ECR-source is available at the high-charge injector HLI). The heavy ion synchrotron SIS18, in operation since 1990, has a maximum magnetic rigidity of 18 Tm. In addition GSI accelerator facility comprises the ESR (Experimental Storage ring) as well, which is in operation since 1990 and has a maximum magnetic rigidity of 10 Tm.

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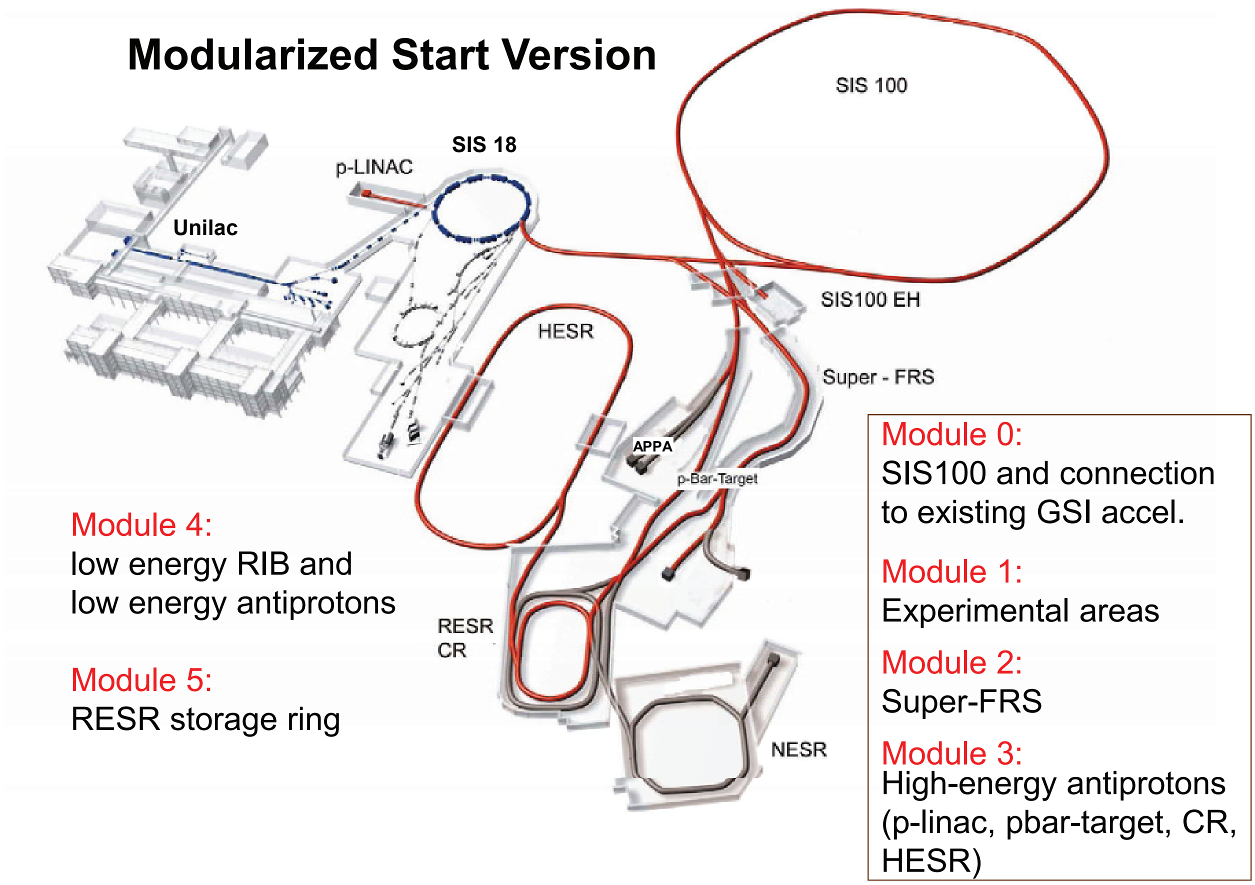

Figure 1: Overview of the FAIR accelerator facility and the modules 0-5 of the different accelerator and experiment sections. Modules 0-3 represent the modularized start version, which will be realized.

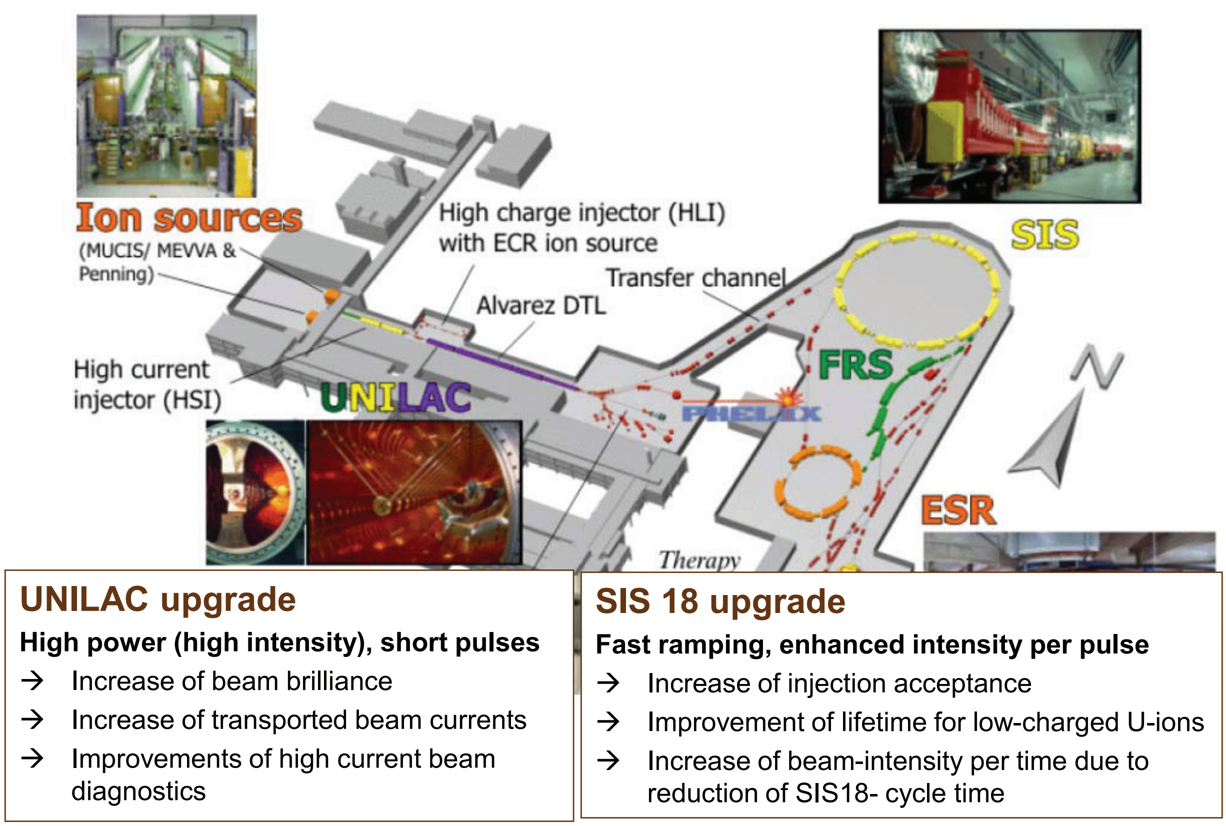

Figure 2: Overview of the GSI accelerator facility and the upgrade program of the UNILAC and the SIS18.

The requirements for FAIR define the main beam parameter for the existing facility, especially for SIS18, which is the direct FAIR injector system. Acceleration and extraction of all ion species, but especially heavy ions to FAIR with a maximum intensity and beam quality, which is defined by the space charge limit of SIS18 and by the SIS 100 acceptances is required. For heavy ions U^{28+} has been defined as the 'reference' ion. In addition, the acceleration and extraction of an intense proton-beam, which will be injected to SIS18 from a new proton-Linac (p-Linac) is a major tasks. Therefore the reduction of the SIS18 cycle time in order to get a maximum beam intensity per second is one main goal on the upgrade program. The SIS18 beam is delivered to the SIS100 via fast extraction or 'bunch to bucket'-transfer. That means 4 times 2 for bunches for heavy ions or 4 times 1 for proton bunches with maximum repetition rate. The main design parameters for SIS18 are:

- Uranium - charge state: 28+
- extraction U^{28+}-intensity: $1.5 \cdot 10^{11}$ ions/pulse
- extraction energy 200 MeV/u
- Max. repetition rate 2.7 Hz

There is no stripping in the transfer channel to SIS18 in order to enhance the space charge limit in SIS18 by a factor of 7 compared to the U^{73+} charge state. Besides the low-charged U-ions also U^{73+} ions at a maximum intensity of $2 \cdot 10^{10}$ particles/pulse should be accelerated in SIS18 and transferred to FAIR. For the delivery of protons the new p-Linac will deliver a max. 70 mA p-beam with an energy of 70 MeV to SIS18. A maximum intensity of $2 \cdot 10^{13}$ particles/pulse is expected, which can be accelerated to 4 GeV and transferred to FAIR.

The upgrade program at the UNILAC concentrates on the increase of the transmission and on the beam brilliance. Modifications of the existing LEBT and a new compact LEBT are planned in order to inject beams with higher brilliance into the IH-RFQ [3]. In 2009 the 36 MHz RFQ accelerator was upgraded by exchange of the mini vanes which provide a modified transverse acceptance and phase advance and therewith an improved beam transmission. The SIS18 upgrade program focus on the increase of the injection acceptance, the improvement of the lifetime of medium charged heavy ions and on a faster ramp rate. Beam losses generated by the dynamic vacuum effect are by far dominating the loss process. It begins significantly earlier as space charge and current depending effects. The reduction of the initial beam loss has the highest importance for the dynamic vacuum and the FAIR booster operation. Initial beam loss originates in initial pressure bumps, which dominate the vacuum pressure and ionization beam loss in the machine cycle. Therefore, the reduction and control of the beam loss at multi turn injection was a major issue of the development program.

Presently the UNILAC as well as the SIS18 have reached full performance, which has to be confirmed in upcoming machine development beam times. The missing intensity factor for FAIR of roughly 2.5 can be gained by the planned straight LEBT and new ion source terminal. The SIS18 performance will be increased by the introduction of the powerful h=2 cavities and the 2.7 Hz cycle frequency.

STATUS OF THE FAIR ACCELERATORS

Many questions cannot be addressed with the present accelerator facilities and therefore more sophisticated accelerators are required to address cutting edge physics. The FAIR facility consists of a carefully designed configuration of accelerators for generation of high-quality primary beams, and for creating secondary particles by colliding or bombarding the beams on especially tailored targets. An overview of the final FAIR/GSI accelerator complex is shown in Fig. 1. The full FAIR facility will consist of eight circular accelerators, of two linear accelerators and of about 3.5 kilometer beam lines. The Research Centre Jülich will build the HESR - High Energy Storage Ring - for the research with high-energy antiprotons using the PANDA detector. GSI is in charge of the design of the other machines which are constructed in consortia with international partners.

The driver accelerator of FAIR is the fast ramping, superconducting heavy ion synchrotron - SIS100 - that allows the acceleration of the most intense beams of stable elements from Protons (30 GeV) to Uranium (10 AGeV). SIS100 is installed in a 20 m deep tunnel, which is designed for the installation of the SIS300 synchrotron in a later stage of the project. The CBM- Plasma- and Biomat-experiments are directly supplied with primary beams from the SIS100. Two target stations for the generation of secondary beams (antiprotons and RIBs) allow the conversion of primary ions. The intensities of secondary beams will increase by a factor of 1,000-10,000 as compared to presently available beams. The secondary beams may be stopped in gas cells or accumulated in the FAIR storage rings for use in precision experiments.

In the full extension of FAIR, the storage rings CR and RESR will accumulate the secondary beams and improve their quality by stochastic and electron cooling. The production mechanism of secondary particle beams leads to large momentum spreads and phase space distributions. High beam quality is essential for the performance of precision experiments, hence active phase space cooling in transverse and longitudinal direction of the beams in the storage rings (CR, RESR, HESR and NESR) will be performed. The storage rings HESR and NESR host a large fraction of the experiment platforms with a variety of different experiments. The product of both, high beam intensity and excellent beam quality, of the FAIR accelerators is unique.

SIS100 Driver Accelerator

The synchrotron SIS100, as the main new driver accelerator of the FAIR project accelerates heavy ion beams with much higher intensities to higher energies as

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it is presently possible with SIS18. Higher beam energies are specifically required for the production of antiprotons by bombarding Nickel-targets with Proton beams. The final energy of the ions in SIS100 is chosen such that, both radioactive ions and antiprotons, are produced with highest efficiency in the targets. A short acceleration cycle of just 2 seconds is required to obtain a sufficiently high average intensity. Due to the fast ramping with 4 Tesla per second, the magnets and their vacuum chambers are subject to heating by eddy currents. The eddy current heating was a real challenge for the development of appropriate superconducting magnets and the according vacuum chambers with wall thicknesses of only 0.3 mm. The vacuum chambers are used as a huge system of cryogenic pumps and contribute significantly to the required extremely low vacuum pressure. Beam losses by stripping via collisions of the ions with atoms of residual gases are sufficiently reduced at a residual gas pressure below 10^{-11} mbar.

An essential prerequisite for all beam scenarios is the rapid acceleration of the ions that requires high acceleration voltages. A dedicated Rf-system is needed to compress the beam after acceleration in a two-step process into a short pulse. Due to the low resonance frequency of ring resonators and the strict space limitation in all rings, the compact design of these cavities is mandatory and requires modern magnetic alloy (MA)-ring-core cavities [4]. Short beam pulses are mandatory for the production of secondary beams with maximum efficiency.

The FAIR Targets and Separators

The multi-stage superconducting fragment separator (Super-FRS) is the work horse of the NuSTAR experiment program. The Super-FRS will be the most powerful in-flight separator for exotic nuclei up to relativistic energies [5]. Rare isotopes of all elements up to Uranium can be produced and spatially separated. Very short-lived nuclei can be studied as the produced fragment beams consist of a very wide variety of different isotopes from the entire area of the nuclear chart. The layout of the Super-FRS consists of magnets with $B_{\rho max}$ of 20 Tm. Approximately 10% of the primary beams provided by the SIS100 will be converted in a rotating wheel target into exotic isotopes. In the production process of such exotic beams the kinetic energy is approximately preserved. The remaining 90% of the primary beam are selectively dumped in special beam catchers made of graphite and iron. The in-flight production provides secondary beams with high kinetic energies. Nevertheless, their large phase space volume requires huge magnets with enormous apertures and high field gradients. Ultimately, this demands the use of massive, superferric magnets.

The lay-out of the Super-FRS is shown in Fig. 3. The operating principle of the Super-FRS is based on a combination of magnetic field analysis and element-dependent energy loss in specially shaped degraders. Super-FRS has three branches which are the links to the different experimental stations and the collector ring (CR) with the "ring branch". At the "high energy branch" (HEB) kinematically complete reaction studies are carried out using highest beam intensities at relativistic energies. The "low energy branch" (LEB) will employ a gas stopping cell which allows low energy experiments with the rare isotopes. In the gas cell, the exotic isotopes are slowed down and then provided to the experiments for spectroscopic studies at beam energies in the keV range.

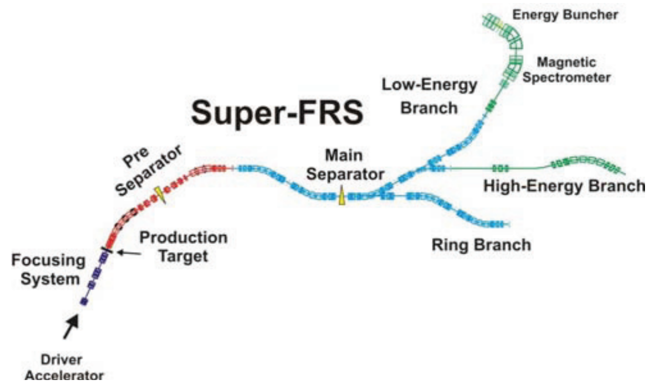

Figure 3: Lay-out of the Super-FRS of the FAIR facility.

With beams of antiprotons, a variety of experiments is planned at FAIR. Antiprotons are produced in high-energy collisions of nuclei. The common technique uses a set of 10 cm long nickel rods, which are bombarded with proton beams. SIS100 will deliver proton beams with 29 GeV to the target. At 29 GeV beam energy, one out of ten-thousand protons will produce an antiproton. About 10^8 antiprotons per spill are expected. The antiprotons must be separated with high efficiency from the background particles as well as from the remains of the primary beam. The concept for the production of antiproton beams at FAIR is basically determined by the luminosity requirement for experiments with cooled antiproton beams in the HESR. In the PANDA experiment, collision of the antiproton beam with the internal hydrogen gas-target will be possible.

The FAIR Storage Rings

One of the most important rings for the preparation of secondary particle beams is the Collector Ring CR [6]. The CR is a high acceptance ring with full aperture injection and extraction kickers, RF cavities for bunch rotation, adiabatic de-bunching and re-bunching, and a dedicated stochastic cooling system. The CR will collect and cool secondary particle beams that emerge from the production targets and have a large spread in beam energy and a huge spatial extension. The injection kicker design guarantees that the full ring acceptance is available for the incoming hot secondary beams. The beam coming from the production targets are not be suitable for precision experiments. The use of beam cooling improves the quality of the secondary beams by several orders of magnitude and the well prepared beams can be then transported into subsequent storage rings for use in experiments. The stochastic cooling system of the CR can be used for antiprotons and radioactive beams as well. In addition, the CR allows mass measurements of short-lived radioactive ions using the isochronous mode. The CR has to perform stochastic precooling of secondary beams at a fixed kinetic energy of 740 MeV/u for radioactive isotopes and 3 GeV for. A special procedure is applied in case of the longitudinal phase space. Since bunches emerging from the production target are very short (<50 ns) but show a significant large momentum spread, phase space rotation with subsequent adiabatic de-bunching will be applied.

In the HESR, antiprotons can be collected using the barrier bucket injection and stochastic cooling. While already injected particles are cooled, a coasting beam is formed. Using barrier buckets, a gap is opened that additional particles can be injected. The subsequent cooling reduces the transverse momentum of the injected particle and generates space for further injections. This accumulation scenario has been demonstrated for the first time in the ESR of GSI [7].

Testing of SC-magnets

For any machine using superconducting technology the test of the superconducting devises requires thorough attention. An infrastructure to conduct the test of the accelerator and separator magnets is mandatory. All the tests are best split in three packages, which are:

- For safe operation all tests, which ensure that the superconducting magnet will not be destroyed by any incident, are requried. Tests in that category are for example the test of the insulation.
- Check on specifications covers all tests which show that the magnet is built as expected. These test demonstrate that the magnet can achieve the required current and thus required field (including the training quenches if required).
- Parameters for operation are inquired by all tests which provide data needed for installing or operating of the magnet (transfer function of the magnet for instance).

The testing of superconducting magnets, however, require that these are installed on dedicated test benches, which typically involves more mechanical work, as many connections have to be soldered or welded and the cryostat and shield has to be assembled. Further the magnet has to be cooled down and warmed up. Therefore dedicated test facilities are required for testing the superconducting magnets. This infrastructure consists of the building, the crane or other transportation means, the cryogenic supply and distribution, the feedboxes, power converters, high voltage and instrumentation test equipment. The GSI test site for the prototype magnets is depicted in Fig. 4.

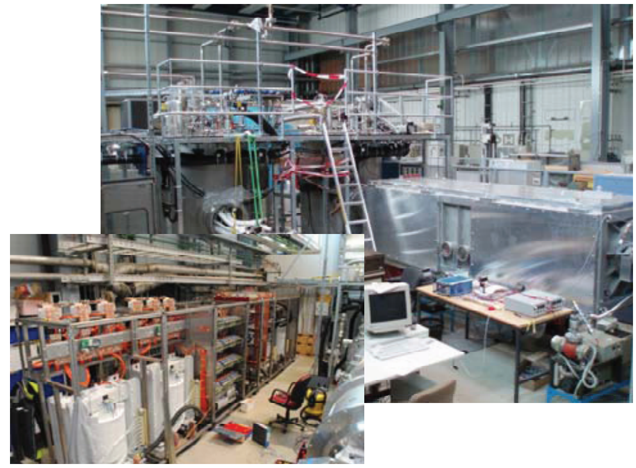

Figure 4: Magnet test facility at GSI including the new 20 kA pulse power supply.

The GSI facility will be used to test the SIS100 dipole modules and all prototype magnets of SIS100. For the massive super-ferric magnets of the Super-FRS, a dedicated facility is established at CERN hall 180. The SIS100 quadrupole units will be built and tested in Dubna.

ACKNOWLEDGMENT

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