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FAIR COMPLETION OF CONSTRUCTION WORKS, TOWARDS COMMISSIONING AND FIRST SCIENCE

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Abstract

The international accelerator facility FAIR, one of the largest science projects worldwide, is being built in Darmstadt, Germany. At FAIR, matter that usually only exists in the depth of space will be produced in a lab for research. With the planned experiments scientists will be able to gain new insights into the structure of matter and the evolution of the universe from the Big Bang to the present. The existing GSI linac and heavy-ion synchrotron, UNILAC and SIS18 will become part of FAIR and will serve as first acceleration stage. The construction of the tunnels and buildings including the technical building infrastructure for the first project stage, including the SIS100 synchrotron and the Super-FRS (SFRS) fragment separator will be completed at the end of the year 2025. Component manufacturing, testing and delivery for the FAIR accelerator facility is progressing. Numerous components are completed, delivered and stored ready for installation. A clear plan is in place to address the replacement of the Russian in-kind contributions following the international sanctions due to the Ukraine war. Installation of accelerator components in the buildings will start at the beginning of the year 2024. Recent highlights are, for example, the progressing SIS100 string test and the successful Super-FRS magnet tests at CERN. A multi-stage strategy towards commissioning is under development aiming at the FAIR startup in the year 2028 with early science.

THE FAIR ACCELERATOR FACILITY

The FAIR science program [1] will address many of the open questions in nuclear physics and closely related fields. The science at FAIR has been divided into four pillars, each of which has a large collaboration of scientific users working to develop the instruments needed to carry out their science. The broad areas of physics covered by the pillars are: atomic and applied physics—APPA; high energy-density nuclear matter—CBM; nuclear structure and astrophysics—NUSTAR; and the structure of exotic states of QCD—PANDA. In order to enable a world-leading science program for all four pillars the FAIR facility will add five new machines to the existing GSI accelerators (see Table 1 and Figure 1). In addition, a new proton injector linac for the existing SIS-18 heavy ion synchrotron is foreseen. The new SIS100 will increase the available intensity for energetic heavy-ion beams used as primary ions for the production of exotic nuclei by an order of magnitude. In addition it will provide the required proton and heavy-ion energies for the PANDA and CBM programs. The new Super-FRS (SFRS) will enable highest separation efficiency for in-flight produced exotic nuclei up to relativistic energies. The Super-FRS is characterized by a large phase-space acceptance employing large-aperture superconducting magnets. The main task of the new Collector Ring (CR) ring is the efficient collection and fast stochastic cooling of hot intense secondary beams coming from the SFRS or from the antiproton separator. It can be used as a high resolution mass spectrometer for exotic nuclei. Finally, the High Energy Storage Ring (HESR) will enable experiments with cooled antiprotons and stable ions at high energies.

Figure 2 gives a schematic overview of the FAIR accelerator complex. The colors indicate which accelerators and beam lines are intended for the beam production for the FAIR experiments NUSTAR (blue), CBM (red), PANDA (orange), and APPA (violet for Atomic Physics and Applications and green for Plasma Physics).

Following the recommendation of a recent scientific review and the subsequent decisions by the FAIR council a stepwise approach for the completion of FAIR will be pursued, bringing the facility progressively into operation. As a first stage experiments using the Super-FRS with primary beams from the SIS18 will be possible from 2028 on (Early Science: ES). Afterwards the SIS100 will enable higher intensity beams for NUSTAR as well as atomic physics (APPA) experiments (First Science: FS), before beams will be extracted to the new CBM cave (First Science Plus: FS+). In the following we will describe the main features and the present status of the Super-FRS and the SIS100.

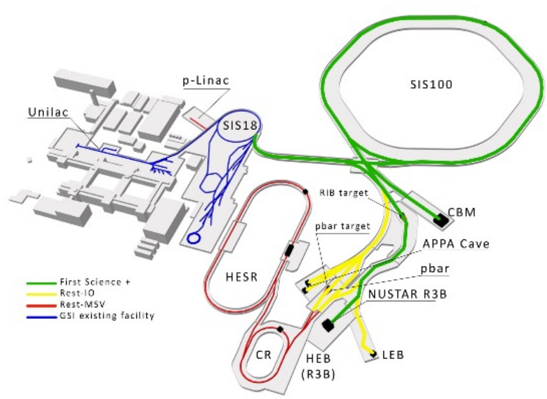

Figure 1: Layout of FAIR with the different realization stages.

THE SIS100 HEAVY-ION SYNCHROTRON

The superconducting, heavy ion synchrotron SIS100 [3] is the core of the new FAIR facility at GSI, Darmstadt, Germany. Its unique design is dedicated to the acceleration of high intensity beams of intermediate charge state heavy ions. Several new technical approaches ensure the stabilization

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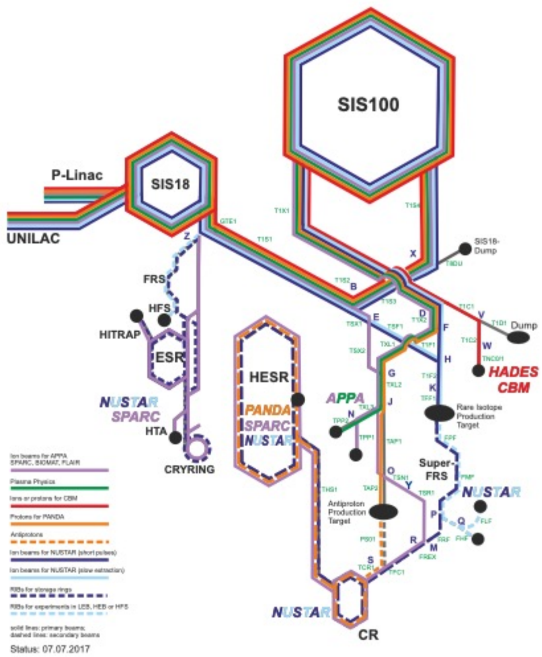
Table 1: The FAIR Machines

Machine	Length	Rigidity	Specific features
SIS100	1084 m	18-100 Tm	Fast ramping heavy-ion synchrotron. Fast extraction of single short bunches (50 ns) or slow extraction for dc-like beams.
Super-FRS	176-204 m	2-20 Tm	Large acceptance fragment separator for in-flight produced short lived isotopes.
CR	212 m	13 Tm	Large acceptance storage ring. Stochastic cooling. Isochronous mass spectrometer mode.
HESR	574 m	50 Tm	High energy antiproton and ion storage ring. Stochastic cooling.



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of the vacuum dynamics and the minimization of charge related beam loss. Beside high intensity heavy ions, SIS100 will accelerate all ions from Protons to Uranium with intensities up to the space charge limit, determined at injection energy. In spite of the fact that superconducting magnets are used, SIS100 will be as flexible in ramping and cycling as a normal conducting synchrotron. An example cycle for the production of exotic nuclei is shown in Figure 3. The beams from the SIS18 are accumulated over 1 s in SIS100 before acceleration. Afterwards slow extraction results in a dc-like beam on the production target (over 2 s in the chosen example case). The reference primary beam intensites from the SIS100 for selected ion species are given in Table 2.

SIS100 makes use of superferric, iron dominated magnets (see Figure 4). The coil of the magnets consists of a Nuclotron cable, which is operated with currents of up to 17 kA in the dipoles and ramp rates of up to 28 kA/s, which

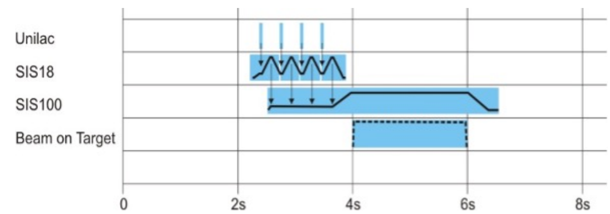

Figure 3: Example machine cycle for NUSTAR.

corresponds to a field ramp of 4 T/s. The peak field in the dipole magnets is 1.9 T and the maximum gradient of the quadrupole magnet is 27T/m. The series production of the 108 dipole magnets has been successfully completed, while series production of the 166 superconducting quadrupole units is still ongoing.

The quadrupole units manufactured at JINR, Russia before the Ukraine crisis, served for the integration of 13 series quadrupole modules. Beside the quadrupole units, the quadrupole modules contain a number of other components provided by GSI, such as elliptical thin wall and LHe cooled magnet chambers, the cryogenic beam position monitors and the cryogenic ion catchers. After integration the modules have been successfully cold and power tested at the GSI series test facility and in the INFN test facility Thor in Salerno.

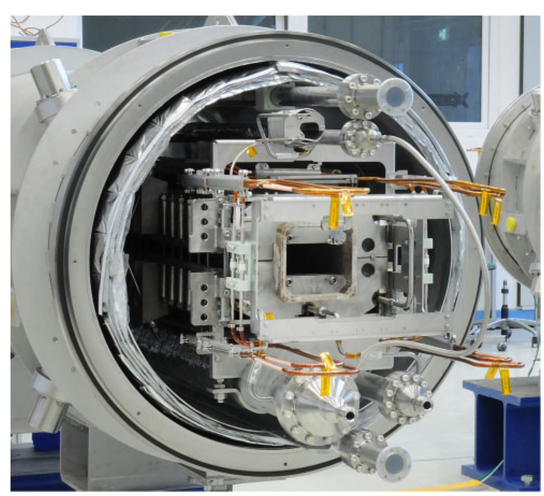

Figure 4: SIS100 dipole magnet.

The SIS100 lattice has been optimized with respect to the loss distribution of intermediate charge state heavy ions (e.g. U^{28+}) lost by ionization during collisions with residual gas atoms. A so-called charge separator lattice provides a

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Table 2: Reference FAIR Beam Parameters for Selected Primary Ions and Research Areas

Research area	Energy	Ions/cycle	Cycle time	Extracted beam: time structure
NUSTAR	U: 0.4-2.7 GeV/u	up to $5 \cdot 10^{11}$	2 s	single (50 ns) bunch or dc-like
CBM	Au: 11 GeV/u	10^{10}	10 s	dc-like
APPA	U: 0.1-10 GeV/u	10^{9}	2 s	dc-like
PANDA	p: 27 GeV/u	$2 \cdot 10^{13}$	5 s	single (50 ns) bunch

theoretically 100% catching efficiency for singly ionized Uranium projectiles (U^{28+} to U^{29+}) by the dedicated ion catcher system. The ion catchers are installed in each lattice cell of the six arcs. The main reason for the design choice of a superconducting synchrotron is the cryopumping by the cold beam pipe, which further improves the beam lifetime. Besides the superconducting magnets themselves, there is a number of devices making use of the liquid helium (LHe) as coolant. All magnet chambers are actively cooled with LHe. Even during fast ramping and corresponding inductive heating by the changing magnetic field, their surface temperature has to be kept at 10 K. In order to minimize the heat load and also the field degradation by induced eddy currents, the dipole- and quadrupole chamber are rib reinforced, thin wall chambers with a wall thickness of 0.3 mm (see Figure 5).

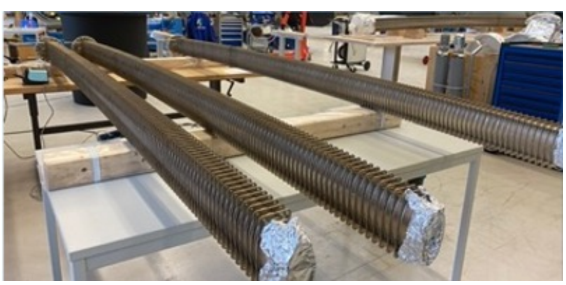

Figure 5: SIS100 dipole vacuum chamber.

The SIS100 synchrotron should be operated at the "space charge limit" for light- and heavy-ion beams. Beam losses due to space-charge-induced resonance crossing should not exceed a few percent during a full cycle. The recent advances in the performance of particle tracking tools with self-consistent solvers for the 3D space charge forces allowed to reliably identify low-loss areas in tune space, considering the full SIS100 accumulation plateau of one second (160'000 turns) duration [4]. The magnet error model, extracted from the bench measurements of the SIS100 main dipole and quadrupole magnets, is included in the simulations. The simulations allowed to identify a low-loss working point region in SIS100 for the design FAIR beam parameters, as shown in Figure 6. Several countermeasures to space charge are proposed to enlarge the low-loss area and to further increase the space charge limit.

THE SUPER FRAGMENT SEPARATOR (SFRS)

The superconducting fragment separator Super-FRS [5,6] is going to be the core facility for the NUSTAR pillar at the

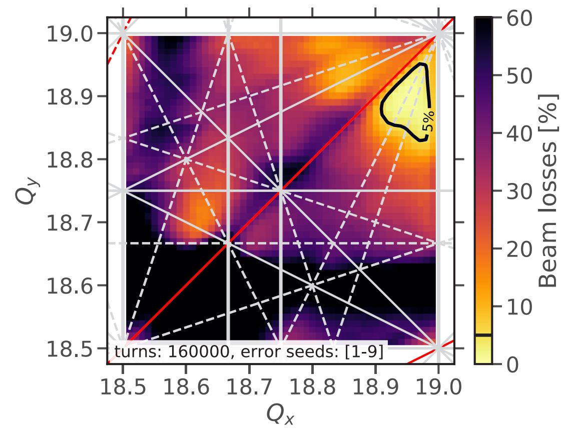

Figure 6: Tune diagram showing the predicted beam loss due to space charge and magnet errors at injection energy in SIS100 [4].

FAIR facility. The NUSTAR collaboration comprises a set of specially tailored experimental setups aiming at different studies of nuclear physics, astrophysics and reaction properties, and is organized in dedicated sub-collaborations [7]. The Super-FRS serves as a world-wide very competitive intense source for exotic isotopes, provided at relativistic beam velocities. It makes use of intense primary beams to be provided first by SIS-18, and in the following by the SIS-100 synchrotron, which will eventually allow to achieve full performance of the production facility. The whole system is dedicated to experiments, requiring clean and intense beams of unstable, short-lived nuclei that exhibit special properties very far from the valley of β-stability. The high beam energies allow in particular to benefit from clean nuclear reaction channels – e.g. for the study of short-range correlations, to be able to coulomb excite nuclei across the giant dipole resonance, to excite the Δ resonance, to produce eta-mesic states, and to be able to populate hyper-nuclei in reactions with rare isotope beams. Key parameters of the separator are listed in Table 3, the acceptance and resolution of the ion-optical system are optimized [8] to make maximum use of the secondary beams stemming from fragmentation and fission reactions in thick production targets of several g/cm².

The three main groups comprising technological challenges of SFRS are: a superconducting magnet system [9] allowing for large apertures, including their power converters and the quench detection and protection system, a target area suitable to withstand the high primary beam intensities [10] provided by the SIS-100 synchrotron, and the diagnostic systems with high rate capability [11]. The superconducting

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Table 3: Key parameters of the superconducting fragment separator Super-FRS. For details, see text.

Parameter	Value
Magnetic rigidity range	2-20 Tm
Momentum acceptance dp/p	$\pm$ 2.5 %
Horizontal angular acceptance	$\pm$ 40 mrad
Vertical angular acceptance	$\pm$ 20 mrad
Momentum resolution	1500

magnet system of SFRS comprises 24 dipoles and 175 multipoles, grouped in 30 multiplets. Three out of the 24 dipoles have a special design to allow a branching of the separator towards the three different experimental areas, shown in Figure 7: low energy branch LEB, high energy branch HEB and ring branch RB. The Early Science phase comprises the HEB, operated with SIS18 beams. During the First Science phase, SIS100 beams will become also available.

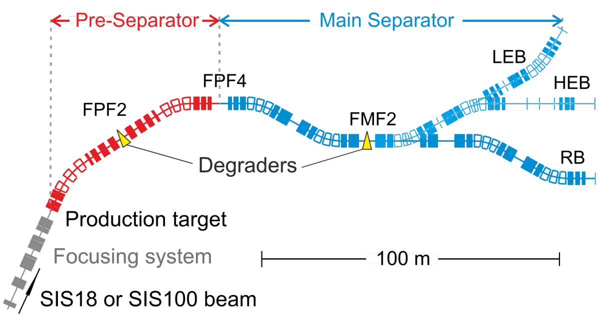

Figure 7: Schematic view of the Super-FRS layout. The first of two $B\rho - \Delta E - B\rho$ separation stages, preseparator (red), and the main separator (blue) with its three branches: (LEB) the low energy branch, using slowed down isotopes in conjunction with an energy buncher spectrometer for stopped beam experiments, that will be also independently usable as a high resolution magnetic spectrometer. (HEB) The high energy branch, providing the secondary beam to the R3B experimental setup, and (RB) the ring branch, where intensive bunched beams will be transported towards the collector ring (CR) for bunch rotation and stochastic cooling. Dipole magnets are shown with trapezoid frames; the multipole magnets are shown as filled rectangles. The energy degraders, placed in the main dispersive focal planes FPF2 and FMF2 are shown as yellow triangles.

Each of the 30 SFRS multiplet units contains several multipole magnets, embedded in a unique vessel and refrigerated as one piece with a weight of several tens of tons. These multiplets are currently in an advanced production phase: all short multiplets (7+1 spare) and 5 out of 13 long multiplets needed for the early-science phase have been manufactured and went through the FAT procedure. The series manufacturing of the superconducting dipoles has also been started. The dedicated magnet test facility [12, 13] shown in Figure 8 with forefront state-of-the-art cryogenic technologies which was built at CERN for performing the cold tests and magnetic measurements of the superconducting magnets, could demonstrate the parallel operation last year and is running the series measurements phase. With the conclusion of testing FAIR magnets, the facility will be made available for the entire scientific community.

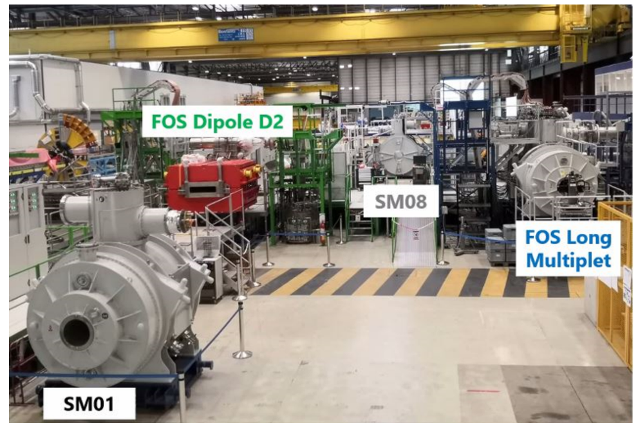

Figure 8: Magnet test facility at CERN. All three branches are operating in parallel with the first-of-series (FoS) dipole D2 being warmed up, the short multiplet SM08 being cooled down and FoS long multiplet undergoing magnetic measurements.

Integral and local magnetic field distributions, displacements of individual magnets centres from the common multiplet axis and cross-talk behaviour are measured within the test program at CERN in order to maintain the required good ion-optical properties. Mechanical tolerances for the magnet axis and alignment range in the 1/10 mm region while sizeable cross talk is expected and requires stringent monitoring due to the extended apertures of the magnets. For several magnets these tests could successfully carried out and magnets where delivered to GSI and placed in a storage area following the final pre-assembly for tunnel readiness and site reception entrance tests. The demanding local cryogenic system, aiming at controlling a phase mixture of liquid helium and distributing it at a few Kelvin absolute temperature over several hundred meter distance towards the magnets, is finalizing its conceptual design phase and tendering the blueprint production. [14]. A set of dedicated bipolar power converters including the quench detection system, are currently being tendered.

The target area faces a particular technological challenge due to the special constrains imposed by the highly radioactive environment [10]. All components will be hosted in a narrow tunnel, built of iron and concrete, and acting as radiation shield. There will be only a few centimetres clearance between the components and the sidewalls to limit air activation in this tunnel. Hence, for performing operations on highly activated components, it is foreseen to transport them in a shielding flask into the so-called hot cell with connected storage place [15, 16]. The iron shielding of the target area encloses the target chamber with a graphite rotating target, three radiation-hard normal conducting dipoles, three quadrupoles and two sextupoles, and three chambers hosting a beam catcher system with removable plugs. All

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components including the three 90-ton dipoles are operated and aligned to sub-millimetre precision via sophisticated remote controls. After a forefront R&D phase, all components in the target area except for radiation-hard magnets are in the production phase. The prototype radiation-hard dipole, which was built at BINP, Russia, in 2010, is available for installation. The other two dipoles, which were in production in Russia, had to be re-tendered. The awarding is expected in summer 2023. The 5 radiation-hard multipoles are in the end of the design phase and their production is expected to start in a few months.

All along the Super-FRS, vanguard detecting-system and radiation resistant electronics with very high rate capabilities of several MHz are being used [11]. The detector and degrader systems are hosted in special vacuum chambers (called diagnostic chambers), located in each focal plane. The diagnostic chambers (that were being produced in Russia) are being tendered. Two FoS chambers were re-tendered, produced, and successfully tested. The will be used for the testing of the detectors. For all detectors, the R&D phase was finished, for some of detectors the design phase was also concluded and some are already being produced.

The components of SFRS along the beamline will be brought into the tunnel from few entering introducing constraints on the installation sequence. Due to limited space in the tunnel, the beamline components will be pre-assembled in so called assembly units, tested, and installed as one. The installation and commissioning schedule, which is required for optimal and collision-free work of subsystem teams, is currently being finalized.

CONCLUSIONS

The realization of the FAIR project's first stage is progressing, with the goal to enable first physics experiments in the new SFRS in 2028. Primary, intense heavy-ion beams will be delivered to the Super-FRS production target from the existing, upgraded UNILAC/SIS18 complex and later from the new SIS100. Construction as well as component manufacturing and testing are progressing as planned towards this goal. Recent highlights are the completion of the SIS100 dipole magnet series production and the start of the string tests, including a first quadrupole module. Full-scale beam simulation studies using the latest magnet error model have been completed, confirming the required low-loss operation for the design beam intensities at the space charge limit. The Super-FRS magnets are in the production phase. First successful cold tests and magnetic field measurements at the dedicated facility at CERN were successfully carried out and the respective magnets where delivered to GSI. In parallel, based on the incoming data from the magnet measurements, a detailed ion optical model of the SRFS is being developed to support the later commissioning.

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