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# The FAIR Heavy Ion Synchrotron SIS100

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Abstract: The superconducting, heavy ion synchrotron SIS100 is the core of the new FAIR facility at GSI, Darmstadt, Germany. Its unique design is dedicated to the acceleration of intermediate charge state heavy ions. Several new technical approaches assure the stabilization 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, and in spite of the fact that superconducting magnets are used, SIS100 shall be as flexible in ramping and cycling as a normal conducting synchrotron.

Keywords: Accelerator Subsystems and Technologies; Acceleration cavities and superconducting magnets (high-temperature superconductor; radiation hardened magnets; normal-conducting; permanent magnet devices; wigglers and undulators); Accelerator modelling and simulations (multi-particle dynamics; single-particle dynamics); Beam Optics

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## Contents





## 1 General features

The FAIR [1] SIS100 [2] is a new type of synchrotron explicitly designed for acceleration of intermediate charge state heavy ions. The operation with high intensities of such ions is the motivation for significant technical differences between SIS100 and typical Proton synchrotrons. Since the FAIR accelerator facility is serving a broad spectrum of user requirements, SIS100 does also provide high flexibility in cycling by means of fast ramped superferric magnets [3]. This flexibility enables the operation with pure triangular cycles for fast extraction with a cycle length of about 1 s and cycles with long injection plateaus for stacking or long extraction plateaus for slow extraction with a spill length of up to 100 s. Like the existing GSI accelerator facilities, SIS100 is supposed to accelerate all ions from Protons to Uranium. By means of various stripper stations, the GSI injector facility provides the flexibility to change the charge states for all ions over a wide range, such that each SIS100 operation can be optimized with respect to the requested beam energy and intensity. To name some extreme cases, the maximum energy and intensity are for Protons 29 GeV with $2.5 \times 10^{13}$ Protons/cycle, while for Uranium ions those values depend on the charge state and vary from 2.7 GeV/u for $U^{28+}$ ions with $5 \times 10^{11}$ ions/cycle to 10 GeV/u for $U^{92+}$ ions with $4 \times 10^{10}$ ions/cycle. The SIS100 focusing structure consists of a doublet configuration powered by three independent quadrupole circuits. Several different operation modes can be realized with different optical settings and different working points. There are four reference working points, two for operation with heavy ions, one for fast and one for slow extraction, and two for operation with high intensities of Protons using fast extraction. The working point for fast extraction of intermediate charge state heavy ions is the main driver for the basic lattice design and is explicitly described in the following section. The two different optics for Proton operation provide two options to mitigate the issue with beam loss at crossing the transition energy. The reference option is to shift the transition energy by means of an asymmetric horizontal focusing to very high values, such that crossing transition during acceleration is avoided. This is achieved by splitting the F-quadrupoles into two families. Optionally, a conventional concept for transition crossing can be applied by means of a set of $\gamma_T$-jump quadrupole magnets. In case of cycles with final bunch compression, the dispersion function in the arcs can be kept well below 2 m. The phase advance in the arcs can be set such that the straights are free of dispersion and no longitudinal-transverse coupling occurs in the Rf cavities. The SIS100 Rf system consists of 14 ferrite loaded acceleration cavities ($V_{\text{total}} = 280\,\text{kV}$), 9 Rf cavities for final bunch compression ($V_{\text{total}} = 360\,\text{kV}$), and 4 broad-band cavities for the generation of barrier buckets and longitudinal feed-back (each $V_0 = 15\,\text{kV}$), [4]. This equipment enables flexibility in longitudinal manipulations, such as bunch merging, batch compression, pre-compression in barrier buckets and final compression by means of fast phase space rotation. By means of an injection kicker system, the ion beam accelerated in the SIS18 booster synchrotron is stacked in SIS100 longitudinally. SIS18 will be operated at a repetition rate of 2.7 Hz and four ion batches will be stacked over the one-second injection plateau of SIS100. The bipolar and ramped SIS100 extraction kicker system provides the possibility for fast and emergency extraction in any phase of the cycle. The fast extraction takes place in vertical direction. In case of emergency extraction, the beam is dumped on an internal beam dump underneath the last magnetic septum. The slow extraction system uses a third integer resonance, in which the particles are driven by means of a fast quadrupole or a transverse knock-out exciter. The excitation of resonant particles is generated in the horizontal plane and a Lambertson septum provides the vertical deflection into the same extraction channel as for fast extraction. There are three major mechanism resulting in systematic beam loss in SIS100: a) For intermediate charge state heavy ions, electron loss produced by collision of beam ions with residual gas particles leads to loss of affected particles in dispersive regions of the lattice. This loss mechanism will be covered in detail in the next sections. b) Resonance driven diffusion over the one-second injection plateau during operation at the space charge limit [5], with an incoherent tune spread of about $dQ_v = -0.25$, leads to halo formation and beam loss if the acceptance of the machine is exceeded. c) During slow extraction, systematic and unavoidable beam loss of up to 5% of the overall beam intensity is created due to the interaction of beam particles with the wires of the electrostatic septum. In order to control the second and third types of beam loss, SIS100 is equipped with two multi-state halo collimation systems, the design of which is dictated by the specific properties of intermediate charge state heavy ions in contrast to fully stripped heavy ions or Protons. Due to the requirement of allowing alternating sequences of cycles with different ion species, some components of the halo collimation systems require fast actuators for adapting their positions from cycle to cycle. The systematic beam loss during slow extraction has consequences for other accelerator components as well. The high specific energy deposition of heavy ions in the septum wires creates specific demands for the technology of the septum. Moreover, two of the superconducting lattice quadrupole magnets had to be replaced by radiation-hard normal-conducting quadrupole magnets. Beside lots of new technical features and technical concepts which are described in later sections, in order to enable an operation with high intensities of intermediate charge state heavy ions, a new type of synchrotron lattice has been introduced.



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## 2 Charge separator lattice

The SIS100 lattice has been optimized with respect to the distribution of intermediate charge state heavy ions (e.g. $U^{28+}$) lost by ionization during collisions with residual gas atoms. The invented and so-called charge separator lattice (figure 1) [6] provides 100% catching efficiency for singly ionized Uranium projectiles ($U^{28+} > U^{29+}$) by the dedicated ion catcher system. The ion catchers are installed in each lattice cell of the six arcs. In the design phase of SIS100, several lattice configurations (e.g. FODO, triplet, doublet etc.) have been compared with respect to catching efficiency and impact on machine acceptance. The chosen doublet lattice with focusing structure DF shows the highest control of ionized projectiles without any negative effect on the machine acceptance. A disadvantages of the chosen, strong focusing structure is its high natural chromaticity, which prevents full chromaticity correction in all operational modes except for the transition jump mode due to a prohibitively strong reduction of dynamic aperture. The specially developed, cryogenic ion catchers, which are installed at the peaks of the loss distribution, in the middle of the arc quadrupole modules, capture ionized beam particles in a controlled manner. The goal of this controlled ion capture is to minimize ion induced gas desorption and to inhibit desorbed gas from interaction with the revolving beam.

## 3 Dynamic vacuum and projectile ionization

During operation with intermediate charge state heavy ions, the main intensity limitation is given by charge exchange process at collisions with residual gas atoms and molecules. Beam loss originated in such processes starts to dominate the overall loss budget significantly earlier than any space charge or current dominated phaenomena. The cross section for ionization of intermediate charge state heavy ions in the energy range of SIS100, is about a factor of Hundred higher than for highly charged heavy ions. The issue with charge exchange driven loss becomes significant and develops into an instability as the residual gas pressure in the machine is any longer not static but becomes strongly dynamic with local variations of up to two orders of magnitude. The main driver for the vacuum dynamics is the beam itself. Systematic processes (e.g. injection/extraction processes, Rf capture losses etc.) and, especially in case of intermediate charge state heavy ion operation, charge exchange processes, are the initiators of a strong residual gas pressure dynamics. A single ion, impacting the surface of an accelerator component is able to release up to $10^4$ bound atoms and molecules. The released particles create a local pressure bump which itself enhances the beam loss by ionization (figure 1) [7].

Beyond a certain threshold, which is dominated by the machine layout and the beam intensity and if not controlled, this mechanism creates a self-amplification and develops into an instability with dramatic beam loss in short time. Originated in a locally enhanced beam loss and pressure bump, the ionization loss and pressure increase moves from one cell to the next until the overall machine pressure is significantly increased. In order to be able to conduct self-consistent simulations of the spatial and time resolved development of the pressure evolution in circular accelerators, the STRAHLSIM code has been developed. STRAHLSIM accounts for the following features: the machine lattice, the machine cycles, the atomic physics cross sections for projectile ionization and capture, the cross sections for target ionization, the properties of the conventional UHV system,

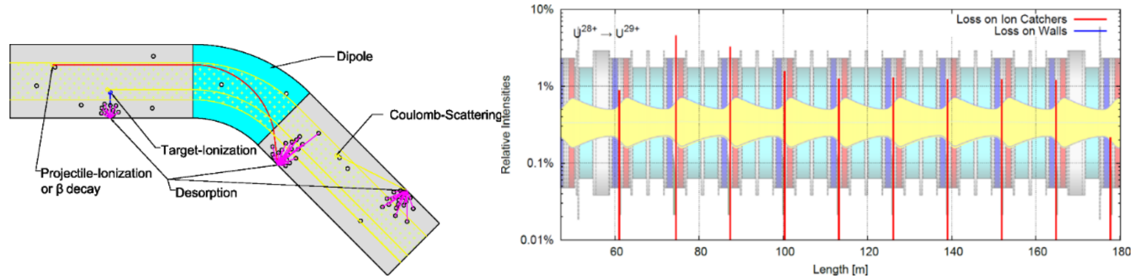


**Figure 1**. Left: the major beam loss during operation with intermediate charge state heavy ions is driven by change exchange processes at collisions with residual gas particles. At the impact of projectiles which underwent an ionization process, local pressure bumps are generated which themselves amplify the ionization process. Right: the SIS100 charge separator lattice provides a peaked loss distribution of ionized projectiles with peaks in the middle of each doublet group (red lines). This loss distribution enables a control of the desorbed gases.

the desorption yields of different materials, and the pumping properties of NEG and cryogenic surfaces. The results of this unique code are benchmarked in machine studies in the existing heavy ion synchrotron SIS18 and are used to predict the efficiency of technical measures in SIS18 and SIS100 dedicated to this special issue. The control and stabilization of the dynamic vacuum and the minimization of beam loss by charge exchange processes, are key developments for the FAIR synchrotrons SIS18 and SIS100. For its future booster operation with intermediate charge state heavy ions, SIS18 has experienced a major technical upgrade. After implementation of various technical features, the number of accelerated intermediate charge state heavy ions could be significantly enhanced. However, for reaching the FAIR intensity goals and stable operation at a repetition rate of 2.7 Hz, further measures for increased pumping power need to be implemented [8]. Therefore, several options for implementing cryogenic inserts are considered. Also in SIS100, the main technical approach for stabilizing the dynamic vacuum is the application of cryopumping. The usage of superconducting magnets in SIS100 is mostly driven by the need for a cryogenic UHV system which acts as a super-pump and stabilizes the dynamics of the residual gas pressure.

## 4 Super-pumping concept and technologies

In order to enable extensive usage of cryopumping, SIS100 has become a superconducting synchrotron. 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 (figure 2).

The magnet chambers are made of a special steel (Böhler steel) which maintains its low permeability up to cryogenic temperatures. The chambers are cooled via separate process lines, connected to an individual auxiliary supply heater. The decoupling of the UHV system cooling from the magnet cooling enables independent thermal cycles, e.g. to recover the UHV system from condensed and adsorbed gases. In addition to the cryogenic magnet chambers and with the

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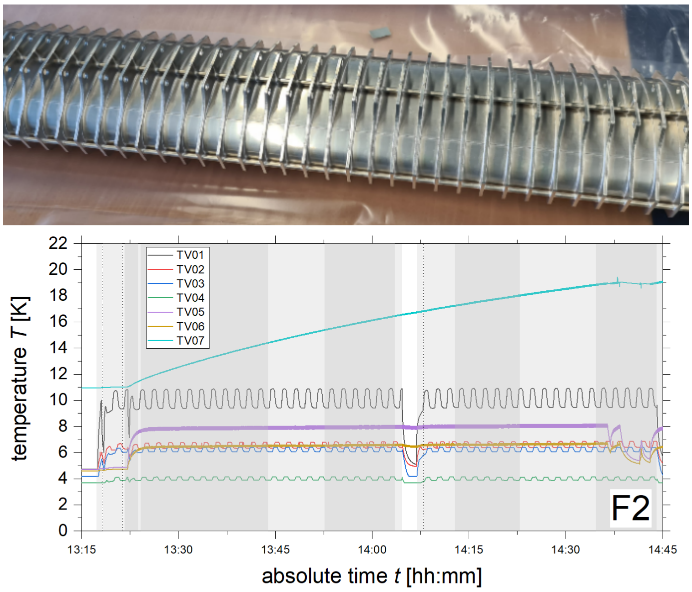


**Figure 2**. Top: thin wall, rib reinforced, LHe cooled quadrupole chamber. Bottom: temperature measurement at different position on the quadrupole chamber at fast cycling of the quadrupole magnets.

**Figure 3**. Cryosorption pump using charcoal for H pumping.

purpose to provide sufficient pumping power for light atoms, e.g. for H and He, a large number of cryosorption pumps is foreseen (figure 3). The cryosorption pumps are installed in between each dipole pair in the arcs and in the quadrupole modules in the straight sections. The cryosorption pump uses a LHe cooled charcoal to provide large pumping power for light residual gas atoms. In order to minimize and control the pressure bump generated at the main loss positions for ionized projectiles, special cryo-ion catchers have been developed [9] (figure 4). The cryocatchers contain a block which dumps the ionized projectiles outside the machine acceptance, surrounded by a cryogenic surface. To minimize the release of particles, the Cu-blocks have a low desorption yield Au-coating. The block is kept on an intermediate temperature by means of its connection to the shield cooling system. This assures that the block itself does not act as a cryopump and no residual gas molecules stick to

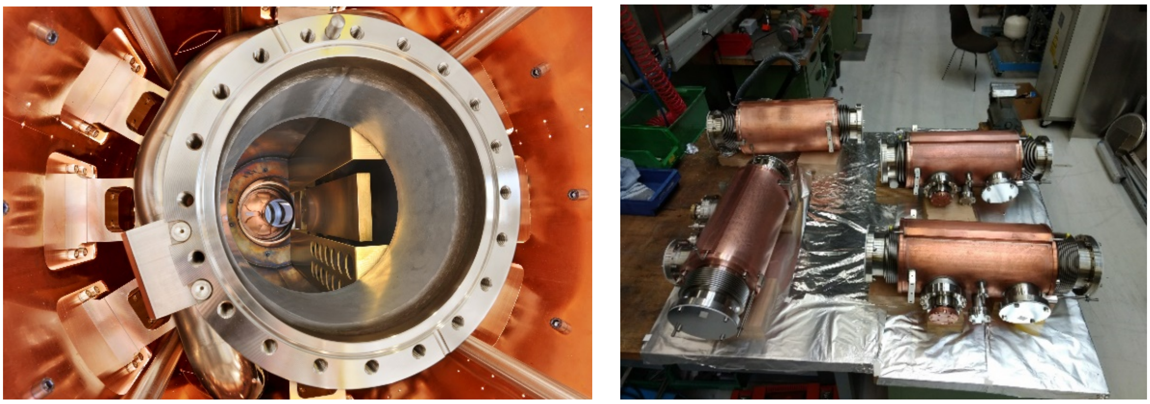

**Figure 4**. Left: prototype cryogenic ion catcher with low desorption beam absorber. Right: series devices of SIS100 cryogenic ion catcher system.

its surface. The surrounding vacuum vessel provides a cryogenic surface with a stable temperature of 4.5 K free from inductive heating by the field of the neighbouring quadrupole magnets.

The design and acceptance of each room-temperature device, is strictly followed and dominated by the demand of providing a static residual gas pressure below $10^{-11}$ mbar. All components are baked-out at a temperature of 300 °C and a large amount of conventional pumps, NEG pumps and NEG coating is used to assure excellent UHV properties also in the critical warm components.

## 5 Technical challenges

SIS100 makes use of superferric, iron dominated magnets. The magnet technology is based on the technology developed for the Nuclotron accelerator at JINR. 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 corresponds to a field ramp of 4 T/s. The cable consists of a CuNi tube with the superconducting NbTi strands wrapped around. The superconducting strands are efficiently cooled from the inside by the LHe at 4.5 K. The peak field in the dipole magnets is 1.9 T and the maximum gradient of the quadrupole magnet is 27 T/m. In a joint collaboration between GSI and JINR, the magnet technology has been further improved over a decade towards lower dynamic loss and improved field quality. While the arcs comprise a closed cryomagnetic system, the straights consist of room temperature devices interrupted by stand-alone superconducting quadrupole modules. The room temperature sections of SIS100 are bridged by cryogenic bypass lines which, in contrast to usual cryogenic transfer lines, contain the bus bar systems for the four superconducting electrical magnet circuits (figure 5).

There are three feed boxes and three quench protection systems equally distributed over the circumference. Since SIS100 is operated with very different magnet cycles, the heat load to the cryogenic system varies over a large range. In a pure triangular cycle, the heat load is dominated by the AC loss in the magnets and the vacuum chambers, while in cycles with slow extraction the heat load is significantly lower and dominated by the static heat load of the cryomagnetic system. Since SIS100 shall be operated similar to a normal conducting synchrotron, special concepts had to be developed to assure a stable cooling of the magnet string and an efficient operation of the

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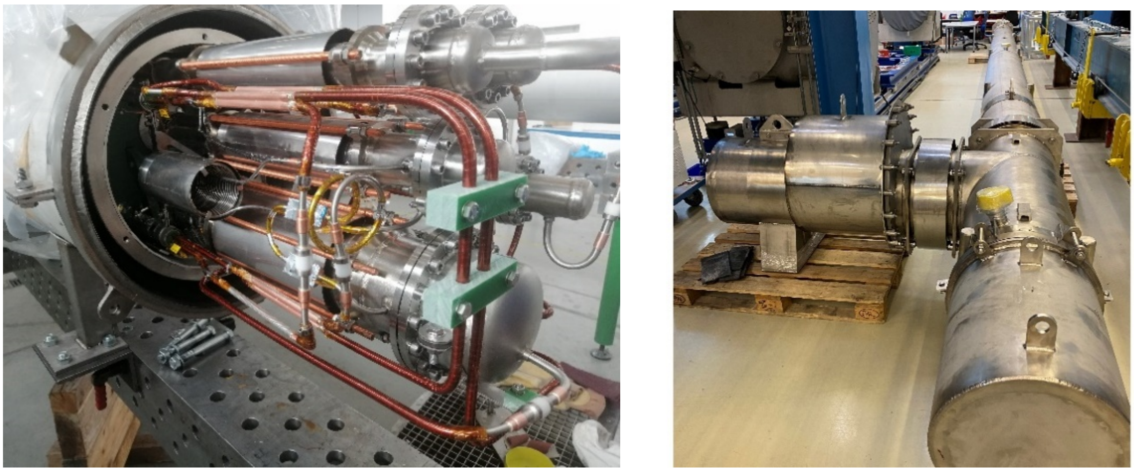

**Figure 5**. Cryogenic bypass line carrying the LHe process lines and the bus bar systems of the four main magnet circuits.

central cryogenic facility. The individual and parallel magnet cooling circuits are hydraulically adjusted to each other by means of mass flow restrictors with reference to a selected high load cycle. Nevertheless, due to operation with quite different cycles and the fact, that each quadrupole circuits is in general performing a different ramp, the goal of reaching 100% of gaseous He in the return header cannot always be reached. Therefore, in order to maintain an efficient operation of the cryogenic system, liquid Helium pumps are foreseen in the feed boxes to pump remaining liquid from the return header to the supply line. Furthermore, each of the parallel hydraulic magnet circuits is equipped with heaters, which may act as valves and provide auxiliary heat to the cryogenic system in low loss cycles or during transition phases.

## 6 Laser cooling facility

As first synchrotron world-wide, the SIS100 will be equipped with a unique laser cooling facility [10]. Several ion-charge state combinations (for $Z \leq 54$) have been identified as candidates suitable for laser cooling at relativistic energies. Besides serving as an internal experiment for the SPARC collaboration (Stored Particles Atomics Physics Research Collaboration), laser cooling will also provide very short ion bunches at final energy for operation with fast extraction. The laser lab, which will host 3 laser systems (1 cw and two pulsed systems), will be situated in the parallel supply tunnel. The laser beams will be guided from the laser lab, through a dedicated (evacuated) laser beamline consisting of high-reflectivity UV mirrors, to the accelerator tunnel where a special vacuum chamber will be used to couple-in the laser light. Once inside the accelerator vacuum, the laser beams will be overlapped with the ion beam, using two sets of scrapers. To enable a long interaction region, a horizontal closed orbit distortion is generated, which tilts the beam axis over almost a full straight section of SIS100.

The principle of laser cooling is as follows (see figure 6): the 'classical´ laser force results from the scattering (i.e. absorption and subsequent emission) of laser photons from an ion via a fast atomic transition, which is typically a fast electric dipole ($E1$) transition. The absorbed laser photons, and

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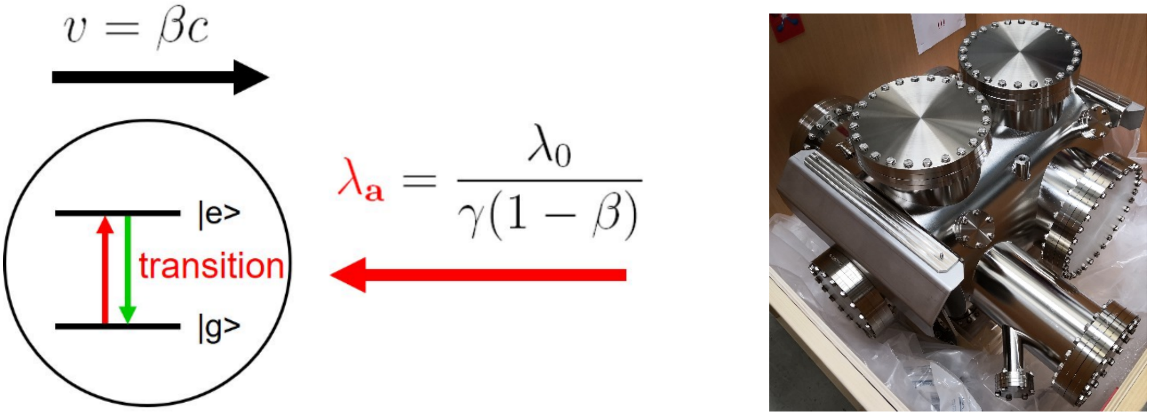


**Figure 6**. Left: principle of laser cooling of relativistic projectiles. Right: laser chamber used to transfer the laser beam into the SIS100 UHV beam pipe for overlapping with the ion beam.

thus their momentum, always come from a single direction and their wavelength must match the Doppler-shifted cooling transition in the ion. Fluorescence emission, and thus recoil, occurs in all directions and averages out to zero, leaving a net cooling force in the direction of the laser light. In this anti-collinear geometry, the required laser wavelength scales extremely favourable with the Lorentz factor ($g$). However, to achieve cooling, there must also be a 'counteracting´ force to the laser force. This is provided by the Rf-bucket force, which comes from bunching the ion beam. Due to the bunching, the ions will also perform synchrotron motions inside the Rf-bucket, having different amplitudes depending on the relative velocities of the ions. By detuning the laser wavelength to the red side of the spectrum, i.e. to slightly lower photon energies, only ions that are a bit too fast will feel the laser force and will be slightly decelerated. By using two different (broadband) laser pulses and a scanning cw laser beam, even ion beams with a initially large momentum spread ($dp/p \sim 10^{-3}$) can be captured by the laser light and be cooled down to $dp/p \sim 10^{-7}$ within only a few seconds. Thereby, also very short ion bunches are being created, which could, after extraction from the SIS100, be used for e.g. plasma physics or even heavy-ion fusion experiments.

## 7 Civil construction

The official ground breaking for the FAIR civil construction took place in the year 2017. At first, the excavation of the SIS100 tunnel pit has been conducted, which required a significant lowering of the ground water in the whole construction area previously. The shell construction of the SIS100 tunnel is progressing well aiming at completion of concrete works for the shell in 2021. The construction, which covers the underground accelerator tunnel, a parallel supply tunnel and up to three floors up to ground level, is completed to about 60% [11] (see figure 7) in Oct. 2020. Furthermore, connected buildings in the southern part of SIS100, the main crossing building, and the CBM (compressed baryonic matter) cave, the connection to the GSI accelerator facilities and the central supply building are under construction. Within the year 2020 the tendering of the technical building infrastructure for the whole construction field North and part of construction field South has been launched. According to the recent lean construction management plan, start of installation of the SIS100 accelerator components is foreseen in the year 2022.

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**Figure 7**. Top: SIS100 open pit tunnel construction including the shell construction of the crossing building (right) and the connecting tunnel to SIS18. Bottom: completed section of the SIS100 accelerator tunnel from the inside.

## 8 Accelerator status

The series production of the 110 superferric dipole magnets made at Bilfinger Noell, Würzburg Germany is completed (see figure 8). All magnets have been cold tested at the GSI series test facility (STF). The mechanical precision of the inner aperture, which is measured by means of a high precision capacitive pick-up has been maintained over the full series within $\pm 50\,\mu\mathrm{m}$ leading to extremely small random field errors. The manufacturing of the series of the superconducting quadrupole units at JINR, Russia, comprising the superconducting quadrupole magnets and chromaticity correction sextupoles (both superferric magnets), as well as the combined horizontal and vertical steerer magnets and the nested multipole correctors (both cos-theta magnets), has been launched. About half of the quadrupole yokes and the yokes of all corrector magnets have been manufactured. The goal is to complete the series production of the quadrupole units by the end of 2023. With the completion of a dedicated NICA-FAIR superconducting magnet test facility at JINR in the year 2016, all preparation for testing the series units have been finished [12].

The overall design of the quadruple modules (see figure 9) has been conducted together with industrial partners. The tendering of manufacturing and integration, which is one of the biggest technical efforts for the FAIR accelerators, has been successfully closed in February 2018. In parallel, possibilities for cold testing of the integrated modules have been evaluated. In an early

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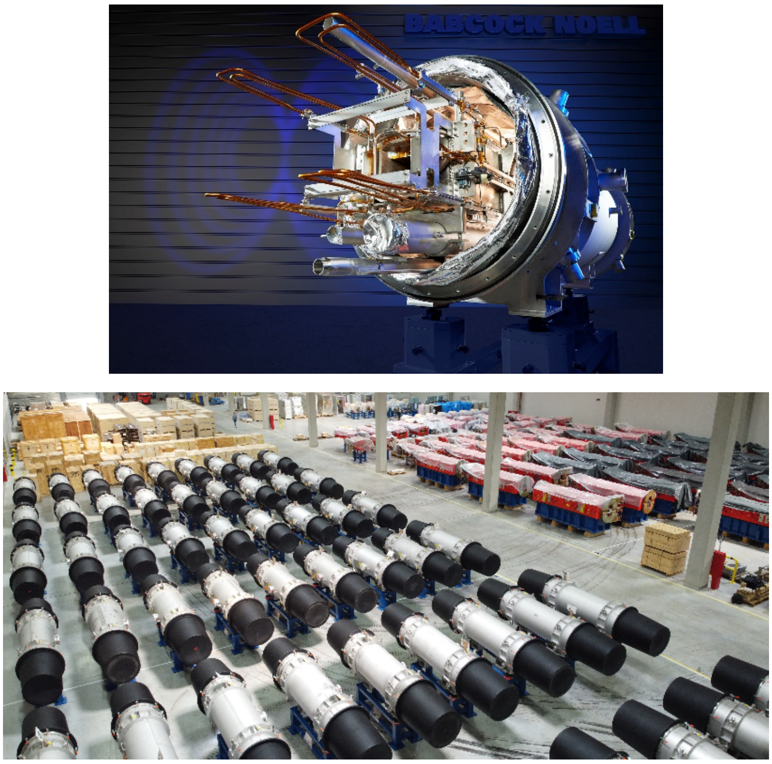


**Figure 8**. Top: extremities of the SIS100 superferric dipole magnet with yoke and connecting loops for the four bus bar systems. Bottom: SIS100 superconducting dipole magnets in storage areas at GSI

phase of the FAIR project a facility has been prepared for the cold testing of future SIS300 magnets at INFN Salerno. This facility is presently modified for testing of the integrated SIS100 quadrupole modules. The FOS quadrupole module, integrated at Bilfinger Noell, has been cold tested over many thermal cycles, at GSI. No major issues have been observed during cold testing and no design changes are required. With delivery of the series units from JINR, the series integration of the quadrupole modules will start in Q4 2020. Besides the superconducting magnet units, the production of several other components has to be synchronized for integration. Main provisions for the integration of the quadrupole modules are the thin wall quadrupole chambers, the cryogenic BPM system with signal cables, cold terminals and interceptions for the local current leads of the corrector magnets and the UHV system cold-warm transitions. For all parts, the series production has been launched.

The status of manufacturing of the main Rf systems, for acceleration (see figure 10) and compression of the beam is well advanced. The series production of all 14 acceleration cavities and all 9 bunch compression cavities is completed. Based on a completed design study, a FOS broad-band cavity for barrier bucket generation, will be tendered still in Q4 2020.

The procurement of several other SIS100 components has been launched. The tendering of the main power converters for the dipole- and quadrupole magnets is presently running. The power converters shall not only provide controlled, high precision and flexible fast ramping but also serve the extreme precision requirements of $dI/I = 10^{-6}$ for slow extraction. The goal is to complete the procurement according to functional sections. All major components of the injection system, the injections kicker modules and the injection septum magnets [13] have been tendered,

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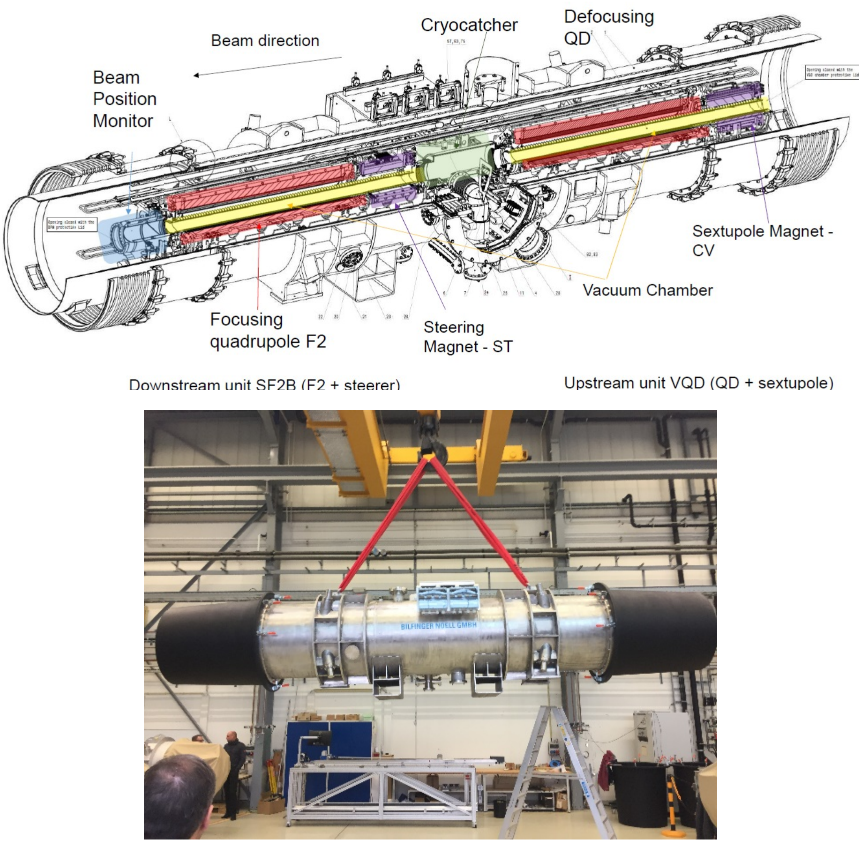


**Figure 9**. SIS100 quadrupole module. Top: sketch of the integrated module with two quadrupole units consisting of quadrupole magnets and corrector magnets, the cryogenic ion catcher system, beam position monitor and common girder. Bottom: First of Series (FOS) quadrupole module at GSI test facility.

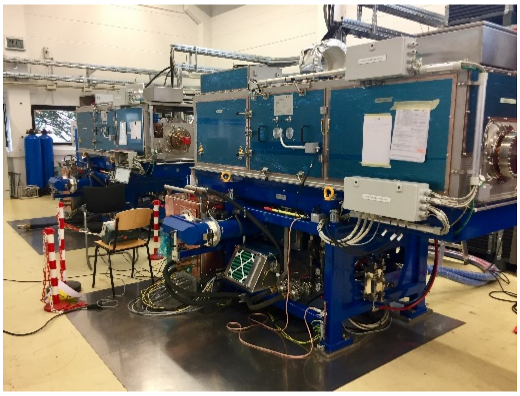

**Figure 10**. Series production of SIS100 acceleration cavities and factory acceptance tests.

awarded and are under construction. As next large system, the components of the extraction system will be procured, starting with the electrostatic extraction septum and the radiation hard quadrupole magnets, followed by the technically challenging three magnetic septa. The so-called local cryogenics system is one of the most complex and unique technical systems of SIS100.

Especially the bypass lines, bridging the warm sections of SIS100, are demanding and differ from conventional cryogenic transfer lines. The series production of the bypass lines has been launched and first devices have been delivered to GSI/FAIR. In parallel to the bypass lines, the design of the overall local cryogenics system, including the end boxes, current feed boxes and feed-in boxes is under completion at WUST (Wroclaw University of Technology and Science).

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