THE SUPERCONDUCTING SIS100 SYNCHROTRON FOR HIGH INTENSITY PROTON AND HEAVY ION BEAMS

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Introduction

In order to achieve the goals of the FAIR project, the intensities of heavy ion beams have to be increased by two orders of magnitude compared to the present intensity levels. Space charge limits and significant beam loss in stripper stages disable a continuation of the present high charge state operation. Thus, the FAIR intensities can only be reached by lowering the charge states, e.g., with acceleration of U^{28+}-ions instead of U^{73+}-ions. However, in the energy range of SIS18 and SIS100 [1], the intermediate charge state 28+, which is produced in the first stripper stage of the UNILAC, is typically below the equilibrium charge state. Thus at low charge state heavy ion operation, ionisation processes due to collisions with rest gas atoms become the main issue with respect to potential beam loss in the FAIR synchrotrons. Therefore, a new synchrotron design concept had to be developed with the goal to minimization the beam-rest gas interaction and consequently the beam loss by charge change: SIS100 is the first synchrotron which has been optimised for the acceleration of high intensity, intermediate charge state, heavy ion operation [2]. Ionisation beam loss, desorption processes and pressure stabilization were the driving issues for the chosen general system layout and for several technological approaches. However, it is expected, that SIS100, in combination with the upgraded heavy ion synchrotron SIS18 [3], allows acceleration of beams of all ions from Protons to Uranium. Therefore, the SIS100 lattice has to provide sufficient flexibility to accommodate for acceleration of high intensity light ion and Proton beams as well. According to the needs of the different experiments, these beams must be extracted with appropriate time structures. A sophisticated extraction system layout, matching the tight constraints given by SIS300, enables fast and slow extraction and emergency dumping during any time of the acceleration process.

Design Parameters

The highest heavy ion beam intensity will be achieved by means of lowering the charge states of heavy ions. Presently, SIS18 is being operated with highly charged heavy ions, e.g., U^{73+}. This charge state is produced by means of two stripper stages; the first stage is situated behind the UNILAC high current injector, the second stage behind the UNILAC ALVAREZ section, just before injection into SIS18. At each heavy ion stripping process, a large fraction of the particle current is lost due to the charge state distribution generated in the stripper system, e.g., at stripping from U^{28+} to U^{73+} typically about 85 % of the initial particle current is lost. In order to reach the design goals, the transfer channel stripper will be not used for the FAIR high intensity operation. Thereby, part of the total stripping loss is being eliminated and furthermore the space charge tune shift after injection into SIS18 and SIS100 is reduced.

Table 1: Design beam parameters for the lightest and heaviest ions in SIS100

SIS100	Protons	Uranium U^{28+}
Number of injections	4	4
Injection method	long. stacking	long. stacking
Number of ions per cycle	2.5×10^{13}	5×10^{11}
Maximum energy	29 GeV	2.7 GeV/u
Ramp rate	4 T/s	4 T/s
Beam pulse length after compression	50 ns	90 - 30 ns
Extraction mode	Fast and slow	Fast and slow
Repetition frequency	0.4 Hz	0.7 Hz

System Design and Design Constraints

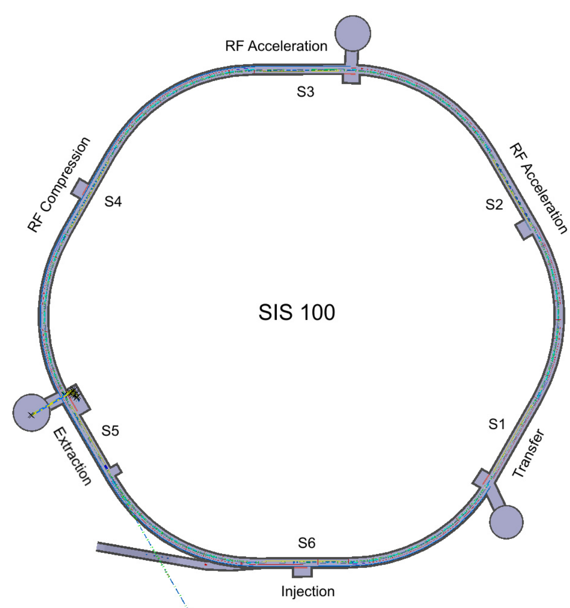

Figure 1: SIS100 with sixfold symmetry and the distribution of the main technical systems.

Various geometrical structures have been considered for SIS100 and SIS300. The finally chosen sixfold super-symmetry matches the following design criteria:

- Sufficiently long, warm straight sections for the technical subsystems
- Reasonable line density in the resonance diagram for large tune shift operation

- Good geometrical matching to the overall beam line topology

In order to enable an installation of SIS300 on top of SIS100 in a common ring tunnel, the geometry of both synchrotrons SIS100 and SIS300 with their different lattice structures and different magnet technologies had to be matched carefully. The ratio of the straight section length and the arc length at a fixed circumference of five time the circumference of SIS18, has been defined by the required length of warm straight sections in SIS100, e.g., the systems for fast-, slow- and emergency extraction have to fit into one of these sections. The following constraints had to be fulfilled for the layout of the extraction systems:

- The extraction point has to be situated precisely at the same position as the extraction point of SIS300
- The angles of the fast and slow extracted beams have to be the same as the angles of the beams of SIS300
- The SIS100 and SIS300 beams have to continue with a constant distance in the transport lines.
- The vertically extracted SIS100 beam has to bypass the arc of SIS300.

The finally chosen layout of the different extraction- and transfer systems had to be based on device specifications at the limit of technical feasibility.

Charge Separator Lattice

The SIS100 doublet lattice structure as described in the FAIR Baseline Technical Report (FBTR) [4] is based on superferric, straight dipole- and quadrupole magnets. The lattice structure has been optimised with respect to the efficiency of a charge scraper system, consisting of six times eleven scrapers situated in the arcs of SIS100. Each lattice cell acts as a charge separator providing a peaked distribution of ionisation beam loss along the circumference. The peaked loss distribution enables the control of ionisation beam loss by means of a specially designed scraper system. A large number of different lattice structures have been investigated with respect to the fraction of ions controlled by the scrapers and the scraper distance from the beam edge. The final doublet structure assures an almost hundred percent control of single ionised beam ions without effecting the synchrotron acceptance.

In addition, the lattice has to accommodate for different beam manipulations, e.g., for the generation of a single compressed bunch or for the acceleration of protons without crossing the transition energy.

For the acceleration of proton beams to 29 GeV with a final γ=32, a dedicated quadrupole setting will be used shifting the transition energy to a very high value (e.g., γ=44). The gamma transition shift is enabled by means of three independent quadrupole families (two F and one D quadrupoles). The chosen doublet structure provides the following general properties:

- Peaked distribution and highly efficient collimation system for ionization beam loss
- Maximum transverse acceptance (minimum 3x emittance at injection) at limited magnet apertures (with restricted total pulse power and AC loss)
- Vanishing dispersion in the straight sections for high dp/p operation during compression
- Low dispersion in the arcs for high dp/p operation during compression
- Sufficient dispersion in the straight section for slow extraction with Hardt condition
- Variable transition energy (three quadrupole bus bars) for Proton operation
- Sufficient space and efficient use of space for the accommodation of all components
- Accommodation of slow, fast and emergency extraction and transfer within one straight.

Magnets

Although, the lattice itself as described in the "Technical Report" has basically not been changed, some major properties of the main dipole- and quadrupole magnets needed to be reconsidered and optimised [Table 2]. In order to provide a reasonable acceptance for the large emittance heavy ion beams (at minimum three times the KV emittance), quite large apertures were required especially for straight dipole magnets. Consequently, the AC loss, which was substantially reduced by the magnet R&D, did not meat the original design goals anymore. Due to the increasing sagitta and beam displacement in the fringe fields, an elongation of the straight dipole magnet could not be considered. Moreover, the required field strength of 2.1 T resulted in a significant increase of the stored energy with consequences for the quench protection system. Due to the high dipole field strength and also quadrupole gradient the field quality in both magnet types was considered to be marginal. Therefore, it was decided to reduce the apertures and the maximum field strength and to focus the magnet R&D on an elongated, curved dipole magnet. Making use of a curved magnet instead of a straight enables an increased length without affecting the beam acceptance. After reviewing the available warm straight section length, the length of the quadruple could also be increased by 10% and in accordance the maximum gradient could be reduced.

In SIS100, superferric magnets as developed for the NUKLOTRON synchrotron [5] will be used. Based on this technology, an R&D program aiming for a further improvement of the properties of these magnets has been conducted together with the Joint Institute of Nuclear Research in Dubna. The major goals of the R&D program were:

- Reduction of the AC loss during ramping with 4 T/s
- Improvement of the 2D and 3D field quality
- Long term mechanical stability over 2×10^8 cycles

The experimental part of the R&D program has been conducted to a large extend at JINR, using a number of available magnets for modifications. The design goal of 13 W/m for the AC has almost been reached by re-designing the yoke, especially the lamination on both ends, the coil loop, the brackets and endplates.

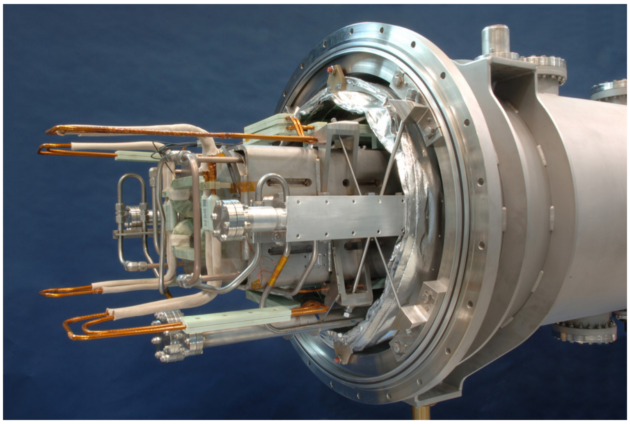

Figure 2: Full length, straight SIS100 model dipole built by BNN, Würzburg, Germany.

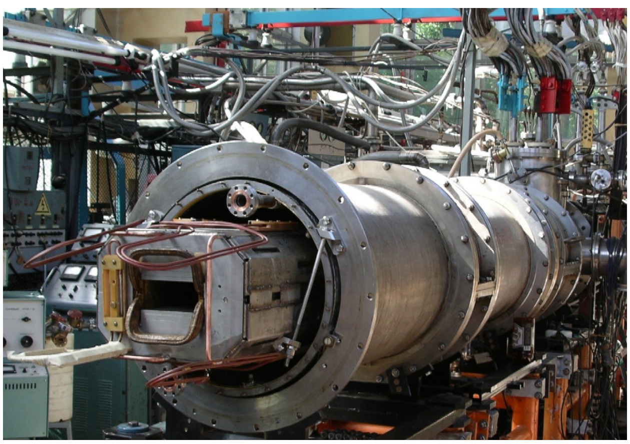

Figure 3: Full length, straight SIS100 model dipole at cold test built by JINR, Dubna, Russia.

Meanwhile, two straight full length dipole magnets according to the original lattice structure have been manufactured. Both magnets will be delivered including the cryostats and the thin wall (0.3mm) vacuum chambers. One straight dipole with large aperture has been built by BNN in Würzburg (Figure 1) and delivered to GSI beginning of 2008, Germany. For the production of the full length dipole magnet, BNG has taken over and has modified a cable winding machine from the LHC magnet production. Thus, a second source for production and delivery of the NUKLOTRON type cable has been established. The second straight dipole has been recently completed in JINR in Dubna (Figure 3), Russia and a curved dipole is under production in BINP, Novosibirsk, Russia. Transportation of the curved dipole to GSI is still planned for 2008.

The large hydraulic resistance of the two layer coil built in all prototype dipoles does not provide the cooling power for operation with pure triangular cycles. Triangular cycles are considered as fall-back option in case problems occur on the long injection flat-top of the reference cycles (e.g., unacceptable beam loss induced by resonance trapping drives to strong rest gas dynamics and consequently ionisation beam loss). The Nuklotron-type coils are made of a s.c. cable consisting of a too long He-pipe with a too small cross section. Therefore, the first pre-series magnet will be equipped with a new single layer coil with slightly increased cable cross section and a high current conductor (13 kA instead of 7 kA).

Table 2: Comparison of the modified (TDR) and FBTR main magnet parameters

	Straight dipole (FBTR)	Curved dipole (TDR)
B x L_{eff} [Tm]	5.818	5.818
B [T]	2.11	1.9
L_{eff} [m]	2.756	3.062
Estimated L_{yoke} [m]	2.696	3.002
Bending angle[deg]	3 1/3	3 1/3
Radius of curvature [m]	47.368	52.632
Aperture (h x v) [mm]	130 x 60	115 x 60
Ramp rate [T/s]	4	4
	Quadrupole (FBTR)	Quadrupole elongated (TDR)
B' x L_{eff} [T]	35	35
B' [T/m]	32	27
L_{eff} [m]	1.1	1.3
Estimated L_{yoke} [m]	1	1.2
Aperture (h x v) [mm]	135 x 65	135 x 65
Ramp rate [T/ m s]	67.5	57

After the decision to elongate the main quadrupole magnets by 20 % and to reduce the maximum field gradient correspondingly, the magnet has been re-designed for the accommodation of a six turn coil. A full length model quadrupole is presently being produced in the frame of an EU FP6 design study in JINR.

Power Converters

A 11 kA power converter making use of a silicon controlled rectifier (SCR) and a switch mode parallel active filter has been built for the s.c. magnet test stand at GSI. The hardware, firmware and software for the digital control of dynamic high precision power converters has been developed and is in practical use in the power converters of the therapy accelerator of HICAT in Heidelberg. Because of the demanding quench protection system of the SIS100 dipole magnets, an electronic 8 kA DC circuit breaker has been developed. A prototype DC circuit breaker is under construction in TU-Darmstadt.

Rf Systems

In collaboration with the BINP, Novosibirsk a technical design study has been conducted and meanwhile completed for the ferrite loaded acceleration cavities [6]. The collaboration has been continued with an engineering study with the goal to prepare the tendering process for a prototype production. The same acceleration cavities as developed for SIS100 will be used in SIS300 and similar cavities are in operation in SIS18. No R&D has been started for the bunch compression systems, assuming that the recently completed bunch compression cavity project for SIS18 provides sufficient information for a direct call for tender. For the completed SIS18 bunch compressor project, GSI has conducted an extensive survey on commercially available magnetic alloy core materials.

Table 3: SIS100 Rf Systems

	Harm./ Voltage	f /MHz	Numb.	Cavity Technology
Acceleration System	h=10/ 400 kV	1.1–2.7	20	Ferrite loaded, “narrow” band cavities
Compression System	h=2/ 640 kV	0.395-0.485	16	Magnetic alloy loaded, broad band (low duty cycle) cavities
Barrier Bucket System	/15kV	2	2	Magnetic alloy loaded, broad band (low duty cycle) cavities

Injection-Extraction Systems

The ion optical design of the extraction system for slow, fast and emergency extraction has been further optimized [7]. For slow extraction, a combined horizontal and vertical scheme has been developed which makes use of a third order resonance in the horizontal plane and a Lambertson septum magnet for deflection and extraction in vertical direction. Such a scheme allows the combination of devices for slow, fast and emergency extraction in one (short) straight section. According to the ion optical layout, the injection- and extraction devices have been specified and design studies were started for the bipolar kicker system. In parallel, experimental investigations were conducted with pulse forming networks in collaboration with the Technical University of Darmstadt. HV pseudo spark switches as possible replacement for thyratron switches are under development in cooperation with the University of Erlangen. Specific problems arise during the slow extraction process of high intensity, intermediate charge state heavy ion beams:

- In spite of a thickness of only 0.1 mm, due to the high specific energy loss of heavy ions, the temperature of the septum wires (tungsten) is increased considerably
- By the interaction with the septum wires, the beam ions are further ionized and consequently lost in the following quadrupole module.

Calculations have indicated that a further reduction of the septum wire thickness may prevent the septum wires from melting or loss of mechanical strength respectively. However, a septum test in the focus of the present GSI plasma physics cave, where presently the highest beam densities can be achieved, is planned. The total power deposited by the beam ions lost in the quadrupole doublet following the electrostatic septum is in the order of several kW. Since a safe removal of the deposited beam energy, preventing the superconducting quadrupoles from quenching, seams to be impossible, the whole cryo-magnetic unit must be replaced by two warm-iron radiation hard magnets.

Dynamic Vacuum

For the simulation of dynamic vacuum effects and beam loss due to a charge change of the projectiles, the program STRAHLSIM has been developed [8]. The accuracy of the predictions for ionization beam loss in the energy range of SIS100 could be further improved. The GSI atomic physics group and their collaborators could meanwhile extend the models for calculation of charge change cross section to relativistic energies [9]. The new cross sections, as well as a new scaling law for the desorption yield according to the specific energy deposition $(dE/dx)^2$ [10] were implemented in STRAHLSIM. However, experimental studies are still missing, supporting the extrapolations to high energies.

Furthermore, the beam scrubbing effect and the dependence of the pumping speed of NEG-coated and cryogenic surfaces as a function of the number of mono-layers adsorbed gases are accounted. Thereby, long term simulations and predictions on the ionization beam loss and dynamic pressure have been enabled.

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