# ION OPTICAL DESIGN OF THE HEAVY ION SYNCHROTRON SIS100

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*Abstract*

We present the ion optical design of SIS100, which is the main synchrotron of the FAIR project. The purpose of SIS100 is the acceleration of high intensity heavy ion and proton beams and the generation of short compressed single bunches for the production of secondary beams. Since ionization in the residual gas is the main loss mechanism, a new lattice design concept had to be developed, especially for the operation with intermediate charge state heavy ions. The lattice was optimized to generate a peaked loss distribution in charge separator like lattice cells. Thereby it enables the control of generated desorption gases in special catchers. For bunch compression, the lattice provides dispersion free straight sections and a low dispersion in the arcs. A special difficulty is the optical design for fast and slow extraction, and the emergency dumping of the high rigidity ions within the same short straight section.

## INTRODUCTION

The synchrotron SIS100 is the primary accelerator in the FAIR project [1]. It is designed for a magnetic rigidity of B=100 Tm. SIS100 accelerates high intensity and high energy proton and ion beams. The FAIR research program defines the following key parameters:

- For the radioactive beam program, acceleration of about $3\cdot 10^{11}$ $U^{28+}$- ions per second or $5\cdot10^{11}$ ions per pulse to energies from 400 to 2700 MeV/u, either with a long duty cycle or in a single bunch with a pulse length in the range from 50 to 100 ns.
- For the antiproton production, acceleration of $4 \cdot 10^{13}$ protons per pulse to a maximum energy of 29 GeV with one machine cycle every 5 seconds.
- For plasma physics research, acceleration of at least $5 \cdot 10^{11}$ $U^{28+}$-ions in a single short bunch (50 to 100 ns) to energies from 400 to 2700 MeV/u.
- For the research program with high energy heavy ion beams $2 \cdot 10^{10}$ $U^{92+}$-ions per cycle.

However, beside the reference ions uranium and proton, acceleration of all other ions species is foreseen.

The incoherent space charge limit for synchrotron acceleration scales with the factor $A/q^2$. The use of intermediate charge state $U^{28+}$-ions for acceleration of high intensity uranium beams will increase the maximum beam intensity per synchrotron pulse by the factor 6.8 compared to the presently used $U^{73+}$-ions. In addition, a short synchrotron cycle time of $T < 1.6$ s is required to achieve an average beam intensity of $N > 3\cdot 10^{11}$ uranium ions per second. In order to fulfill these requirements new technical features are necessary for the SIS100 design:

- Operation at a very low base pressure of $p = 1\cdot10^{-12}$ mbar in the XHV range.
- Careful control of beam loss, especially beam losses due to charge exchange from charge state 28+ to charge state 29+ after collisions with residual gas molecules, by implementation of a well designed scraper system.
- Superconducting synchrotron magnet operation with a ramp rate of 4 T/s.
- An Rf compression system for the generation of a single short bunch of high intensity proton and uranium beams for the production and storage of secondary beams.

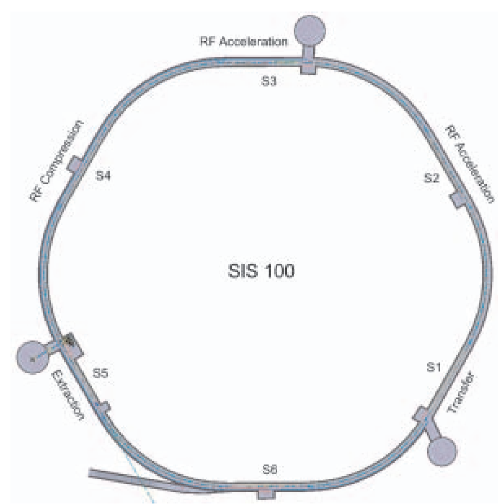


Figure 1: Distribution of the injection-, extraction-, transfer- and Rf-system (beam acceleration and bunch compression) in the six straight sections of SIS100.

## CONCEPT AND OPTICAL DESIGN

The SIS100 lattice was designed to fulfill the following requirements:

- Large horizontal and vertical machine acceptance.

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- Adequate free space in the six straight sections.
- Variable dispersion setting in the straight sections with the option to set zero dispersion for the fast extraction of bunches with large momentum spread and to generate sufficient dispersion required for the Hardt condition [2] at slow extraction.
- High collimation efficiency in the six magnet arcs for local control of $U^{29+}$-ions produced by charge exchange.
- Low dispersion in the arcs to allow the operation with high momentum spread.

The circumference of the SIS100 is 1083.60 m, i.e. five times the circumference of the existing injector synchrotron SIS18. The new synchrotron has six long straight sections (six fold symmetry) to provide adequate space for the different injection and extraction systems and also for the large Rf systems in SIS100 (see Figure 1).

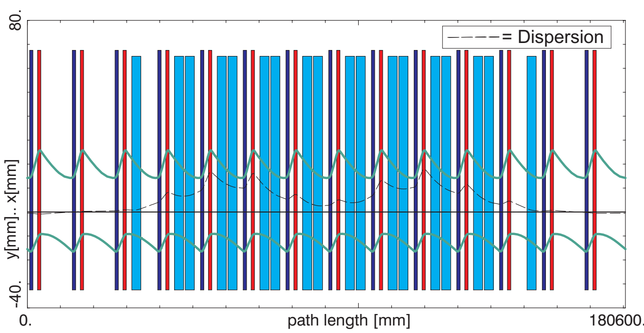


Figure 2: SIS100 lattice with the basic layout of one full sector or sextant with 14 lattice cells. The beam envelopes are shown for a beam emittance of $e_h$ = 34 mm mrad in the horizontal phase plane and $e_v$ = 14 mm mrad in the vertical phase plane respectively. The dispersion function is plotted for a momentum deviation of dp/p=1 % and the ion optical functions for the tune setting $Q_h$=18.84 and $Q_v$=18.73.

It has been shown that beam losses due to charge exchange processes, i.e. $U^{28+}$ to $^{29+}$, can be controlled to a large extent (about 99.5 %) by the installation of a system of beam collimators in each arc in combination with a peaked loss distribution [3, 4]. To achieve such a distribution a synchrotron lattice design with DF doublet focusing was chosen. Figure 2 shows the layout of one sextant.

Another important parameter is the high ramping rate of SIS100, which is required for fast repetition with 0.75 - 1 Hz. The magnets in SIS100 will be fast pulsed, super ferric synchrotron magnets, which are similar in design to the Nuklotron magnets used in the JINR in Dubna. Table 1 summarizes the basic lattice parameters.

In every regular lattice cell two dipole magnets, each 2.76 m long, and two quadrupole magnets, each 1 m long, are arranged in a doublet focusing scheme D, F, BM, BM.

Table 1: Basic machine parameters of SIS100. Bracketed values for proton operation.

| | |
|---|---|
| Machine circumference (m) | 1083.6 |
| Magnetic rigidity B$\rho$ (Tm) | 90 (100) |
| Magnet field B (T) | 1.9 (2.1) |
| Bending radius R (m) | 47.36 |
| Number of lattice cells $N_f$ | $6 \cdot 14$ |
| Length of lattice cell $L_f$ (m) | 12.90 |
| Number of dipole magnets | 108 |
| Number of quadrupole magnets | 168 |
| Dipole bending angle | $3\,\frac{1}{3}^\circ$ |
| Sagitta in straight dipole magnet $s \approx R \cdot (a/2)^2$ (mm) | 20.1 |
| Dipole magnets per sextant | 8·2 + 2·1 |
| Straight sections | $4 \cdot L_f$ |

Five meter free space can be used for installation of steering magnets, sextupole magnets, multipole corrector magnets and beam position monitors. Doublet focusing in the scheme DF provides sufficient transverse acceptance. In the straight sections a very small dispersion in the range of 0.2 to 0.4 m depending on the precise tune setting, is achieved. This should be adequate even for machine operation in the bunch compressor mode with a maximum momentum spread of dp/p= 1% and a resulting beam broadening of 2-4 mm in the straight sections. Table 2 summarizes the ion optical parameters for three different tune settings in the SIS100 lattice [5]. It is proposed to use the tune setting at working point WP1 for standard operation with ion beams and fast extraction. The lower working point WP2 was introduced for slow extraction to provide the necessary momentum dispersion for fullfilling the Hardt condition [2]. The third working point WP3 will be used for proton acceleration to high energies.

Two families of sextupole magnets are foreseen for chromaticity adjustment. Each family comprises 24 sextupole magnets in the arcs alternating in front of the D and F quadrupole. For correction of the closed orbit distortion one pair of combined steerer magnets for horizontal and vertical correction has to be installed in each of the 84 lattice cells. In addition, in each of the six magnet arcs two sets of correction systems are foreseen, which combine skew quadrupole magnets, sextupole magnets, and octupole magnets. These twelve unit sets will be installed in the twelve end cells of the six arcs (see [6] for details on the correction system). Twelve warm extraction sextupoles are installed in the straight sections.

## INJECTION AND EXTRACTION

The transfer line from SIS18 to SIS100 synchrotron has to transfer the beam from ground level to about 12.5 m underground. The sloped section of the transfer is placed near by SIS100. At the end of the transfer line the horizontal ion beam is directed towards the SIS100 with an angle of about

Table 2: Ion optical parameters for three working points.

| Workingpoint<br>Tunes (h/v) | WP2<br>17.42 / 17.36 | WP1<br>18.84 / 18.73 | WP3<br>20.84 / 20.73 |
|---|---|---|---|
| Mode of SIS100 operation | Ions,<br>slow extraction | Ions,<br>fast extraction | Protons,<br>high energy |
| Max. $\beta$-function (h/v) (m) | 19.1 / 19.3 | 19.0 / 19.1 | 19.3 / 19.6 |
| Dispersion function<br>Maximum $\alpha_p$ (m)<br>Minimum $\alpha_p$ (m) | <br>1.57<br>-1.13 | <br>1.76<br>-0.09 | <br>1.30<br>-0.33 |
| Phase advance per lattice cell (deg) | 75 / 74 | 81 / 80 | 89 / 89 |
| Transition energy | 14.47 | 15.63 | 17.58 |
| Natural chromaticity $\xi_{nat}$/Q (h/v) | -1.16 / -1.16 | -1.19 / -1.2 | -1.26 / -1.26 |
| Transverse acceptance (h/v) (mm mrad) | 234 / 54 | 234 / 54 | 231 / 53 |

4.30 or 75 mrad. Figure 3 shows the corresponding part of the transfer line. In front of the inflector septum mag-

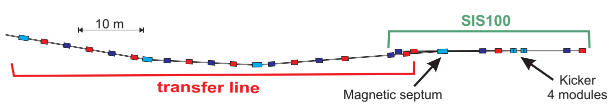


Figure 3: Schematic view of the transfer line and part of the SIS100 with injection elements. The diameter of the magnets is about the size of the cryostat.

nets the two SIS100 quadrupole magnets of the injection beam line are arranged with a lateral displacement of about 500 mm with respect to the two quadrupole magnets of the SIS100 ring in a combined cryostat module. The inflector septum magnet is placed in the first free sector of the injector straight section and the kicker modules are placed in the second section.

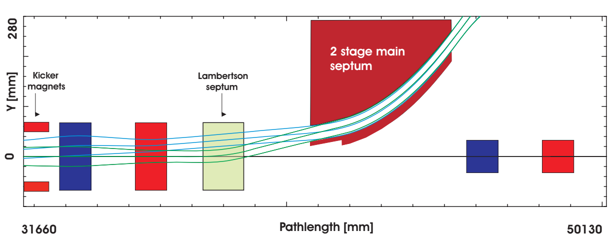


Figure 4: Detail of the extraction area. Slow (light) and fast (darker) extracted beams fit into the same aperture of the extraction septum. The depicted beams comprise twice the emittance of the extracted beam in order to define the aperture of the septa.

SIS100 extracts the beam vertically. The vertical extraction allows to transport the beam directly to the surface where the experiments are located. The machine beam dump of SIS100 and SIS300 is situated half way to the surface. Slow and fast extraction and the emergency beam dump are placed in the same straight section. Slow extraction is performed in two stages: a) horizontal excitation of the beam and deflection of the excited particles by a horizontal electrostatic septum, b) horizontal transport into a Lambertson septum and vertical deflection towards the main septum magnets. 'KO'-extraction will be used as standard extraction method. Fast extraction is performed by means of a set of fast kicker magnets used to deflect the beam upwards. Emergency extraction will be performed using the same kicker magnets (bipolar operation) but deflecting the beam downwards onto an internal beam dump.

## CONCLUSION AND OUTLOOK

We present a lattice layout which can fulfill the basic design requirements. The dynamic vacuum effects caused by the operation with intermediate charge states can be controlled by the dedicated lattice layout. A solution was found that slow and fast extraction, as well as the emergency dump are placed in one straight section. A correction system concept has been established. In future the correction of resonances and higher order effects will be studied in detail to minimize beam loss at high current operation.

## REFERENCES


[1] An international accelerator facility for beams of ions and antiprotons. http://www.gsi.de/GSI- Future/cdr/, 2004. Conceptual Design Report.

[2] W. Hardt. Ultra slow extraction out of lear. Ps/dl/lear internal note 81-6, CERN, 1981.

[3] P. Spiller. Accelerator plans at gsi and plasma physics applications. In *Proceedings of the HIF*, Princeton, 2004.

[4] P. Spiller, K. Blasche, B. Franczak, J. Stadlmann, and C. Omet. Optimization of the SIS100 Lattice and a Dedicated Collimation System for Ionization Losses. In *High Intensity and High Brightness Hadron Beams*, number 773 in AIP Conference Proceedings, pages 40–44. American Institute of Physics, 10 2004.

[5] G. Franchetti et. al. Considerations for the high-intensity working points of the sis100. In *these proceedings*, GSI, 2006.

[6] V. Mikhaylov et. al. Basic aspects of the sis100 correction system design. In *these proceedings*, JINR, 2006.