SIS100/300 Conceptual Design Studies

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1. Introduction

The main accelerator system of the proposed research facility FAIR is the two stage synchrotron complex SIS100/300, consisting of two separate synchrotron accelerators with equal circumferences. SIS100/300 shall provide beams of protons and heavy ions with high intensities and high energies. The existing GSI accelerators UNILAC and SIS18 shall serve as injector for SIS100/300.

SIS100 will be designed for the acceleration of heavy ion beams, e.g. for U^{28+}-ions with an intensity of up to $1 \cdot 10^{12}$, an energy range from 400 to 2715 MeV/u and one machine cycle every second. These beams of heavy and also of lighter ions will be used for the production of secondary beams of radioactive ions. SIS100 shall also accelerate high intensity proton beams with $2.8 \cdot 10^{13}$ protons per second for the production of intense antiproton beams.

SIS300 will be used for the acceleration of fully ionized uranium ions (U^{92+}) to very high energies up to 34 GeV/u. This energy has been raised above the CDR [1] value of 23.3GeV/u in the course of discussions with the scientific community, who prepares studies of condensed baryon matter (CBM). Hence the design value for the magnet bending power had to be increased from 200Tm to 300Tm at an unchanged circumference of 1083m. SIS300 will also be operated as a stretcher ring for high intensity heavy ion beams to provide almost 100% duty cycle during slow extraction.

2. Layout of the Synchrotron Complex SIS100/300

The layout of the SIS100/300 magnet lattices presented in the CDR was determined by the following design considerations: (a) six straight sections to provide sufficient space for beam injection, extraction and transfer between both synchrotrons and also for the extended rf systems required for fast acceleration and bunch compression, (b) triplet focusing for SIS100 to provide the transverse acceptances for the low-energy injection at about 100MeV/u from the SIS18, (c) missing magnet periods between the arcs and the straight sections to minimize the dispersion in the arcs and to achieve dispersion free straight sections, (d) dynamic variation of the ion optical setting to stay below the transition energy even for the acceleration of protons to the maximum energy of 30GeV, and (e) identical dipole magnet lattices for the SIS100 and the SIS300 to secure the alignment of both rings on top of each other.

Meanwhile, additional aspects and alternative lattice structures have been studied. It is important to control carefully beam losses due to charge exchange processes. Theoretical studies have shown that a large part of the losses due to the charge exchange $U^{28+} \rightarrow U^{29+}$ can be localized and controlled by the insertion of thirteen collimators per arc, mainly behind each pair of dipole magnets. The collimation efficiency and the number of needed collimators depend significantly on the lattice structure and must be optimized for each case.

Studies were made about the detailed lattice layout for SIS100:

(a) Comparison of different focusing structures. Triplet focusing could be replaced by doublet or singlet focusing with only two instead of four dipole magnets between each quadrupole group. However, a small beta-function in both planes is one main optimization criterion.
(b) Dispersion suppression for an operation with up to $dp/p = \pm 1\%$ by an arc with a compact dipole structure (no missing dipole concept) but a phase advance of 4π.
(c) Layouts for the matching of the six straight sections to the arcs and options for the optimum focusing structures providing the best conditions for injection and extraction systems.
(d) Dynamic aperture studies for SIS100 and calibration experiments in the SIS18.

3. Beam Dynamics Studies for High Intensity Beams

A two-harmonic rf cycle (h=10/20) for SIS100, leading to flattened bunch profiles and a higher space charge limit, has been studied in detail. As a preliminary result, based on analytic as well as large scale numeric simulation studies, we obtained the required rf parameters and could determine the Landau damping in bunches affected by space charge. The simulations indicate that in the presence of space charge, a longitudinal broadband feedback system will be required for damping of bunched beam modes. The stability of bunches with a flat-top or 'hollow' distribution, as a possible alternative to the distribution created by a second harmonic rf system, is presently being studied.

Using a 3D particle tracking code, the dynamic aperture due to the nonlinear field components of the SIS100 magnets was obtained as a function of the working point. Simulation results for emittance growth and beam losses induced by the combined effect of nonlinear magnet fields and 'frozen' space charge were successfully compared with experiments in the CERN PS [2]. Code development efforts in close collaboration with partners from BNL and LBNL concentrate on 3D self-consistent particle tracking studies required e.g. for fast compression in SIS100.

4. Injection and Extraction Systems

The planned operation of SIS100/300 requires the following injection and extraction channels:

(a) injection and longitudinal stacking of SIS18 bunches in SIS100
(b) fast extraction of the beam after and during acceleration towards the experimental area from SIS100 or the external beam dump from SIS100 and SIS300
(c) slow extraction from SIS100 and SIS300 towards the experimental areas
(d) injection of antiproton beams through the extraction channel of SIS100
(e) fast vertical extraction and injection for the transfer between SIS100 to SIS300

The ion-optical layout of the injection- and extraction systems depends strongly on the technical design parameters of the electric and magnetic deflectors like electrostatic septa, magnetic septa, magnetic kickers etc. R&D work has been started to raise the maximum values for the electric field strength and for the magnetic kicker fields beyond the present operation parameters in SIS18.

5. Magnets and Power Supplies

The superferric dipole magnet used in the Nuclotron synchrotron of the JINR (Dubna) has been improved considerably in cooperation with the JINR for its application in SIS100 [3].

In the course of these developments several model magnets with a length of 1.4m were built and carefully studied. The ac losses could be reduced considerably from 38Watt/m to 14Watt/m, as measured in a triangular magnet field cycle with a ramp rate of 4T/s up to a field of 2T. Hence, the total loss for the 120 dipole magnets of the SIS100 ($L=2\pi\cdot 50$m) will reach about 4.5kW for the triangular magnet field cycle or about 2.5kW in a more realistic operation cycle.

The mechanical structure of the yoke and of the superconducting coils was improved to achieve the necessary stability for more than 500 million field cycles during the SIS100 life time. In addition, the field quality has been improved by a new design of the yoke cross section.

In SIS300, superconducting magnets with two-layer $\cos\theta$ coils have to be used to reach the desired magnetic field of 6T. Meanwhile, in collaboration with BNL [4], it could be demonstrated that in a one layer model coil, the ac losses can be reduced to 7Watt/m for operation at the design ramp rate of 1T/s in a triangular test cycle up to 4.3T.

The power supplies for the dipole magnets of SIS100 and SIS300 were designed. Each power supply uses three sub-units, which are connected in series and located at three positions around the ring tunnel. These sub-units have the following components: (a) one 12 pulse SCR unit with free-wheeling thyristors, (b) each with smoothing inductor and active parallel transistor unit, and (c) two quench protection units, the first one with fast IGBT switch, dump resistor, and free-wheeling thyristor, and a second auxiliary unit with fast IGBT switch and dump resistor to limit the maximum quench voltage. The design concept was applied to the power supply unit for the magnet test stand and was successfully commissioned.

6. RF-Systems for Acceleration and Bunch Compression

In SIS100 two different RF systems are required: the first one is used for acceleration of high intensity heavy ion and proton beams with a fast ramp rate of 4T/s and the second system is required to generate a short single bunch by a two step process of merging and compression.

The rf cycle in SIS100 includes the following steps:

a) bunch-to-bucket transfer of four SIS18 cycles, each cycle containing two bunches which are injected into eight of ten buckets in the SIS100,

b) acceleration at harmonic number h=10 with a total acceleration voltage of 400kV compared to 300kV as listed in the CDR or acceleration in a two-harmonic mode (h=10 and h=20) with 400kV at h=10 and 160kV at h=20,

c) fast bunch merging of the accelerated eight bunches to one long bunch using appropriate schemes which are not yet defined, and

d) fast phase space rotation to produce a short bunch with a pulse length of 50ns (at 1GeV/u) using the bunch compressor system with a maximum voltage of 1MV. Careful studies are necessary to design an optimized rf system, which could be based either on MA cores or on ferrite cores. It could be shown that a ferrite based cavity may reach 25kV per gap in a high duty cycle operation.

The bunch compressor system has to provide a maximum voltage of 1MV in the low frequency range of 465±70kHz only for a rather short pulse duration, while the acceleration system has to be designed for a broader frequency range from 1.14 to 2.67MHz (h=10) for operation with a high duty cycle of the order of 50%.

Therefore, it is planned to realize the bunch compressor system with magnetic alloy cores. At present, a prototype MA loaded compression system is in the final stage of development for SIS18. In order to reach the maximum voltage amplitude at acceptable driver power, small MA test cores from different manufactures were investigated at GSI. Both, amorphous and nano-crystalline materials will be checked in the prototype cavity at a high voltage amplitude of at least 40 kV.

Further studies are under way to achieve an optimized layout for the large rf systems in the SIS100. It is not yet clear, if two separate systems for acceleration and bunch compression or a combined system will be preferred.

7. Vacuum Systems

For both synchrotrons, SIS100 and SIS300 a careful design of the vacuum system is essential for the successful operation with an intermediate charge state, high intensity heavy ion beams.

Experiments in SIS18 have demonstrated that an ion beam with $1\cdot 10^{10}$ U^{28+}-ions can induce a strong dynamic pressure rise, leading to extreme beam losses due to charge changing processes. At present, this effect limits the maximum intensity of U^{28+}-beams to about $3\cdot 10^{9}$ ions per cycle. On the other side, due to the lower ionization cross section, more than $1\cdot 10^{11}$ Ar^{10+} ions [5] could be accelerated without significant losses.

The vacuum systems in the SIS100/300 shall be designed for a static base pressure of $1\cdot 10^{-12}$ mbar and for a stable dynamic pressure below $<1\cdot 10^{-11}$ mbar during operation with high intensity ion beams. Since the installation of warm beam tubes with the necessary bake out systems had to be excluded for technical reasons, the arcs of both synchrotrons will be equipped completely with cold beam tubes. On the other side the straight sections shall be designed with warm beam tubes, respecting the installation of rf systems and injection and extraction components.

In the cold as well as in the room temperature sectors, a very high pumping speed of the order of 1000 to 10000 ltr./s·m beam tube is required to achieve the low base pressure and to keep the dynamic pressure in the allowed range even at strong gas desorption. The cold beam tube surfaces, which act as cryopumps, provide the necessary high pumping speed. In the room temperature sectors discrete pumps cannot yield the required pumping speed. Therefore, in order to achieve a distributed and high pumping speed, NEG coating will be applied in all beam tubes.

8. References

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[4] P. Wanderer et.al., Proc. of PAC03, Portland (2003)
[5] SIS Status Report, this GSI report