BASIC ASPECTS OF THE SIS100 CORRECTION SYSTEM DESIGN

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Abstract

The basic concept and the main design features of the superconducting SIS100 correction system are presented. The system comprises 84 steerer magnets consisting of two orthogonal dipole windings each for correction of the beam close orbit in vertical and horizontal planes, 48 normal sextupole windings connected in two families with opposite polarities for chromaticity correction and 12 units containing skew quadrupoles, normal and skew sextupoles and octupoles as well. The correction system should operate in a pulse mode corresponding to the accelerator cycle, i.e. up to 0.6 Hz. The main magnetic, geometrical and electrical parameters of the corrector magnets were specified. They are based on a beam dynamic analysis within the frames of the chosen DF-type SIS100 lattice at different betatron tune numbers and tolerable alignment and manufacturing errors of the main lattice dipole and quadrupole magnets. The problem of reasonable unification of the corrector modules is discussed also, including their geometrical sizes, maximum supply current and cooling at 4.5 K. The concept of the SIS100 corrector magnets is based on the pulsed correctors designed for the Nuclotron and used in this accelerator.

INTRODUCTION

The heavy ion superconducting synchrotron SIS100 with circumference of 1083.6 m is the unique accelerator of the designed Facility for Antiproton and Ion Research (FAIR) at GSI [1]. The rapid cycling superferric magnets with field up to 2 T and ramp rate up to 4 T/s [2] have been considered as lattice dipoles. The main goals, specified for the SIS100 beams, are the following:

- 3×10^{11} U^{28+} ions per pulse with energy up to 2.7 GeV/u, for the radioactive beam program and plasma physics research;
- 4×10^{13} protons per pulse up to 29 GeV, for the antiproton production;
- 2×10^{10} of U^{92+} ions per pulse, for the research program with high energy heavy ions.

Acceleration of the other heavy ion species is supposed also. High intensity requires minimization of heavy ion losses during all stages of the accelerator cycle. The reasons of the particle losses are the following: 1) space and time imperfections of the magnetic and electrical fields; 2) space charge instabilities; 3) charge exchange of the ions at the residual gas molecules; 4) particle losses at slow extraction. The incoherent shifts of the betatron tunes due to four-pulsed injection from SIS18 to SIS100 and compression of the accelerated ion bunches to short (~ 50 ns) single ones make the problem of minimization the particle losses much more complicated.

In this paper we consider the possibilities of the magnetic field correction and technical realization of the correctors based on the concept of the Nuclotron superconducting correction system. The analysis was performed for the lattice version presented in [3], neglecting space charge effects.

LATTICE & CORRECTION SCHEME

The chosen six fold symmetry SIS100 lattice consists of 84 regular DF cells. The arc includes 8 standard cells with two dipoles in each, two cells with one missing dipole and four cells without dipole magnets within straight section. Note, several different DF lattice versions and correction schemes were analysed earlier. The presented one includes 84 (14×6) combined (horizontal & vertical) steering magnets placed alternately near defocusing (DF) or focusing (QF) quadrupoles, 84 combined multipole corrector magnets (normal or skew quadrupole, sextupole and octupole) installed in each regular cell. The beam position monitors (BPM) are used also in each cell. Layout of the system is shown in Fig. 1.

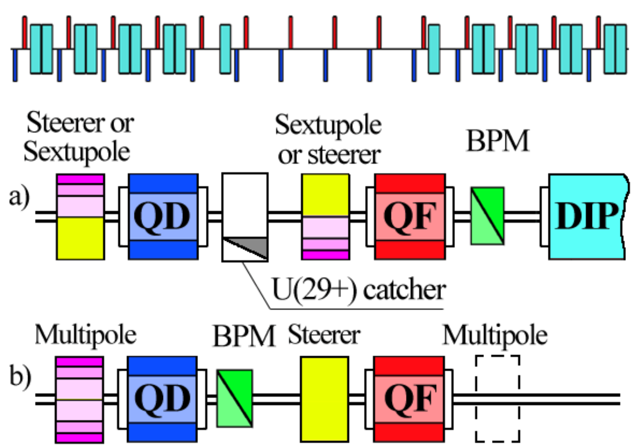

Figure 1: The SIS100 lattice superperiod and layout of the correction system units: a) in the arcs, b) in the straights.

There is some difference between positions of the elements in the arcs and in the straight sections motivated by installation of the catchers behind the QD in the arcs. Two different positions of the multipoles in the straights are possible, namely: before the QD and after the QF.

The presented results correspond to maximum magnetic rigidity of 100 T·m, betatron tunes near 18.75 and a beam emittance of $\varepsilon_x = 50\ \pi$ mm·mrad, $\varepsilon_y = 20\ \pi$ mm·mrad at injection. The data (Fig. 2) from the Nuclotron dipole measurements [4] recalculated for the specified SIS100 dipoles effective length of 2.756 m were used.

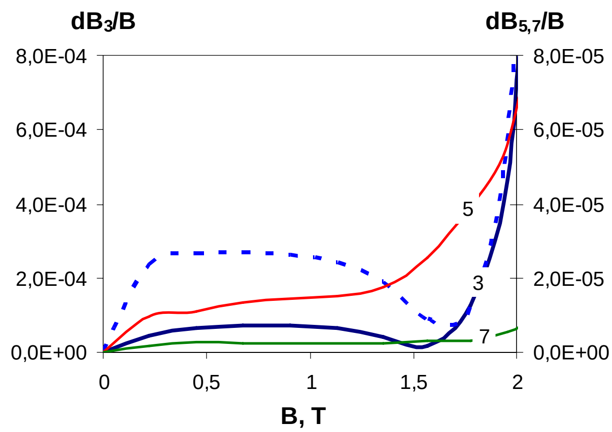

Figure 2: The systematic harmonics amplitudes of the dipole magnetic field at the radius r = 25 mm. (Dash line is the amplitude of the third harmonic in the Nuclotron dipoles).

CLOSED ORBIT CORRECTION

Two approaches were investigated: 1) sorting of the dipoles [5] and 2) active correction with the steerers.

Dipole Sorting

The correction quality depends mainly on the number of dipoles included in the optimization. Assuming that all 108 lattice dipoles are measured and their integral magnetic lengths (ΔB / B) are distributed by the normal law with r.m.s. < ΔB / B > = 5×10^{-4}, it was found, the initial close orbit distortions could be reduced by a factor of 10 - 17. The basis for that is just minimization of the averaged spread of integral dipole fields along the orbit by combining of the dipoles in pairs and their optimal positioning in the ring.

Active Correction

The MICADO algorithm was used for the close orbit (c.o.) minimization strategy. The simulations of c.o. correction have been performed with a full set $N_{cor} = N_{BPM} = 84$ to reduce maximum of the needed corrector kick. The correction goal was to obtain the remnant distortions not exceed of $<x>_{r.m.s} = <y>_{r.m.s.} = 0.5$ mm. The alignment tolerances of $<x,y>_{r.m.s.} = 0.2$ mm and $\Delta\theta = 0.5$ mrad were supposed. The results are shown in Table 1.

Table 1: Closed orbit distortion statistics.

C.o. distortions	x-plane	y-plane
Maximum before correction	26.7 mm	16.6 mm
R.m.s. before correction	13.4 mm	7.8 mm
Maximum after correction	1.9 mm	1.9 mm
R.m.s. after correction	0.5 mm	0.5 mm

The needed maximum steerer field is equal of 0.12 T for the steerer effective magnetic length of 0.5 m.

BETATRON TUNE AND CHROMATICITY CORRECTION

It is planned to supply the lattice dipole focusing and defocusing quadrupoles by three independent currents. To keep the tunes within$|\Delta Q_{x,y}| \leq 0.01$ during all acceleration cycle the deviation from the established value should not exceed $|\Delta G/G|_{f,d} \leq 3\times10^{-4}$ for the following lattice ratios: $\partial Q_{x,y}/(\partial G/G)_{f,d} = 34.05$ and $\partial Q_{x,y}/(\partial G/G)_{d,f} = -12.46$.

The chromaticity correction $Q'_{x,y} = -23.4$ is realized by two families of the sextupoles: 4 + 4 in each arc with strengths of 222 T/m^2, and – 474 T/m^2 respectively. It was found, compensation of the chromaticity decreases the accelerator dynamic aperture (DA), by a factor of about 3 and increases the amplitude dependent tune shifts up to $\Delta Q_x = 0.14$ in the horizontal plane (in the case of 100 % compensation). The both values are unacceptable. A partial (50 %) chromaticity compensation of up to –13 allow to reduce an amplitude detuning to $\Delta Q_x = 0.04$ and DA decreasing factor to 1.5. The needed sextupole field strengths goes down to S_f = 122 T/m^2, S_d = -252 T/m^2 respectively. It is possible to reduce the tune spread placing octupole corrector windings in the multipoles. The needed maximum octupole strength is of 3600 T/m^3. The tune shift values as a function of the betatron amplitudes are presented in Fig. 3.

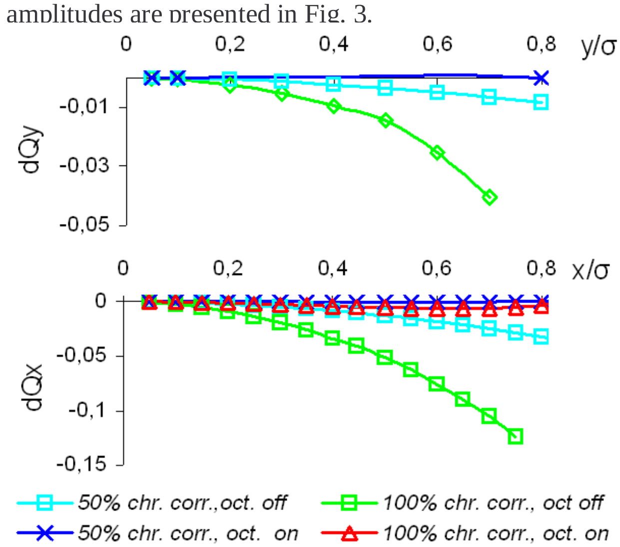

Figure 3: Amplitude dependent tune shift for the cases of 50 % and 100 % chromaticity corrections.

The problem of the dynamic acceptance increase should be solved by proper correction of the resonances.

RESONANCE CORRECTION

Similar to the close orbit correction, both as quadrupoles sorting [5] and active correction were simulated.

Quadrupole Sorting

The proper arrangement of structural quadrupoles in the ring make it possible to minimize the influence of the four or two half integer resonances nearest to the operating point. The Nuclotron magnetic measurements data [4] were used to generate the distribution of the random integral gradient errors. The field errors with the average Gaussian values $K_1L = 0$ and r.m.s. $< K_1L > = 0.0020$ m^{-1} define the corresponding resonance stopband widths of $<p>_x = 0.11$ in the horizontal plane and of $<p>_y = 0.063$ in the vertical plane. To reach simultaneous correction of the mentioned four resonances the function $F = (\sum <p>^2)^{1/2}$ should be minimized. It was found, the value of F = 0.177 is correspond to arbitrary initial combination of the quadrupoles in the ring. The strategy of the resonance correction consists in the choice of the most optimal quadrupole and its position at each iteration step. The iteration cycles go through all 168 quadrupoles. The obtained result of the F-function minimization is the following: the corresponding minimized widths are $<p>_x = 0.04$, $<p>_y = 0.02$, and F = 0.067. Thus, the simultaneous correction of the 4 resonances reduce the resonance bandwidth by a factor of 3.

Nevertheless, in the case of high intensity beams in SIS100, special attention should be paid to half integer resonances $2Q_{x,y} = 37$. Their crossing is really expected due to incoherent space charge tune shift. It is possible to redistribute the minimization function weights and reach the increased suppression that resonances. Such a special procedure gives the bandwidth reduction by a factor of 5.

Betatron Resonances

For a single particle model the SIS100 correcting system can be taken similar to the Nuclotron one. The recalculated field strength for the SIS100 correctors are presented in Table 2.

Table 2: Number of coils and field strengths of the multipole correctors.

Winding type	**Number of windings**		**Field strength**
	normal	**skew**	
quadrupole	4×4	4	1 T/m
sextupole	4×2	4×2	200 T/m^2
octupole	4×2	4×2	3000 T/m^3

This set provide correction of the resonances up to the forth order. Nevertheless, the requirement of very small relative losses of the particles during all acceleration cycle suppose additional studies taking the incoherent tune shift into account.

CORRECTOR AND STEERER DESIGN

It is suppose to use the design approach of the Nuclotron superconducting pulsed correctors [6] in the SIS100 case. The corrector (steerer or multipole) is connected mechanically to the neighbouring quadrupole. The photograph of the Nuclotron quadrupole/corrector cryostat module (from the corrector side) is shown in Fig. 4.

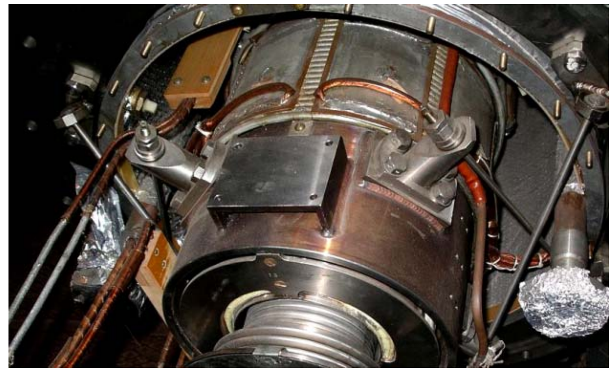

Figure 4: View of the Nuclotron corrector module.

The design of the corrector windings is in progress. A set of calculations of the windings parameters and magnetic fields, both as 2D and 3D, was performed. The steerer is consists of two single-layer coils each, the sextupole for chromaticity correction should have three-layers winding, while a normal or skew multipoles are produced by the sextupole or octupole symmetry coils bu means of a single- or double-layers windings. Except of the steerer, the angular length of each multipole winding is equal to 60 °/n ("n" is the main harmonic number). The most careful design and tests are necessary in the case of the chromaticity correction sextupole. The three-layer coil is made from 0.7 mm diameter NbTi wire. The total number of the coil turns is 114. Operation current of 350 A is needed to reach the sextupole strength of 400 T/m^2. The corrector coil is cooled indirectly through thermal contact with cooling tube. Construction and test of the sextupole corrector model is scheduled for this year. The main research goal is experimental tests of the dynamic characteristics, cooling conditions and the integral magnetic field quality.

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