

OPTIMIZATION OF THE SIS100 NONLINEAR MAGNET SCHEME FOR SLOW EXTRACTION

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Abstract

The SIS100 superconducting synchrotron was initially planned mainly for fast extraction of protons and heavy ions. Due to the delay of the construction of the SIS300 synchrotron, SIS100 has to be able to provide slowly extracted heavy ion beams to the experiments. To improve the robustness of the slow extraction from SIS100, a lattice review was performed, resulting in an optimization of the nonlinear magnet scheme. In the original scheme the Hardt condition cannot be established due to a collapse of the dynamic aperture caused by the chromatic sextupoles. In the optimized scheme the positions of the chromatic sextupoles are modified and octupoles are employed to compensate the second order effects of these sextupoles. In addition, the number of resonance sextupole magnets is reduced. With the new scheme, the Hardt condition can be established, leading to higher extraction efficiency. The separatrix can be freely adjusted and closed orbit control is improved.

INTRODUCTION

The FAIR facility, soon to be constructed close to the site of the existing GSI facility, will serve experiments from a variety of fields with slowly extracted heavy ion beams at unprecedentedly high intensities. Since the synchrotron SIS300 will not be constructed as part of the modularized start version of FAIR, the synchrotron SIS100 has to produce the slowly extracted beams. Thus, the performance of SIS100 for slow extraction is of crucial importance for the success of the scientific program of FAIR.

However, the lattice of SIS100 has a number of design constraints [1] which are hard to satisfy simultaneously. In particular, the lattice has been optimized for operation with intermediate charge state heavy ions, resulting in a comparatively strong focusing to achieve efficient capture of ionized beam particles by means of a dedicated ion catcher system [2][3].

The strong focusing entails large natural chromaticities $C_{h/v}$ and a small horizontal dispersion D_h (see Table 1). Thus, establishing the Hardt condition [4] to minimize losses at the septum requires strong sextupoles for chromaticity correction. Under these conditions, the perturbative theory of slow extraction [5] is no longer valid. Instead, the separatrices become bent and islands emerge. In the original lattice, setting up the Hardt condition would have caused a collapse of the dynamic aperture. Therefore, the strength of the chromaticity sextupoles was reduced to achieve an acceptable compromise between extraction efficiency and dynamic aperture [6].

Given the importance, the slow extraction from SIS100 was recently surveyed again, with the focus being on improving the robustness and flexibility of the solution under operational conditions. As shown below, the slow extraction can be optimized in these respects by rearranging the sextupoles of the lattice and employing the existing octupoles to compensate second order effects. The dynamics is then much closer to the perturbative model, implying the flexibility to adjust size and angle of the separatrix freely. Also, the Hardt condition can be established, resulting in an increase of the extraction efficiency from 95% to 99%. Finally, the tolerance against orbit distortions is improved in the new scheme.

Table 1: Comparison of slow extraction parameters for the optimized and the original SIS100 lattice

Parameter	Optimized	Original
Q_h / Q_v	17.31 / 17.80	
C_h / C_v (nat.)	-20.6 / -21.4	
D_h (max.)	1.5 m	
C_h / C_v (corr.)	-1.0 / -27.2	-5.2 / -39.4
$K2L_{ch}$	-0.48 m ⁻²	-0.40 m ⁻²
$K2L_{cv}$	0.00 m ⁻²	-0.40 m ⁻²
$K2L_{sr}$	0.80 m ⁻²	0.15 m ⁻²
$K3L$	4.9 m ⁻³	0.0 m ⁻³
Bump	-6.0 mm	0.0 mm

LATTICE MODIFICATIONS

A review of the SIS100 lattice showed that the original slow extraction scheme, while working in principle, can be optimized in several respects: The optimized scheme allows establishing the Hardt condition; the size of the separatrix can be freely adjusted while keeping spiral step and entrance angle to the septum constant; moderate orbit distortions do not lead to beam loss on the aperture. These requirements, which are important when imperfections of the real machine and operational needs are taken into account, can be met by implementing the following modifications to the original scheme.

First of all, five of the original eleven resonance sextupoles can be eliminated, which is possible owing to the small ratio β_x/β_y of beta functions at their location. This change has little impact on the dynamics, but leads to a considerable space and cost saving.

Next, the horizontal chromaticity sextupoles shall be relocated from a position upstream of the focusing quadrupole to a position downstream, where the ratio β_x/β_y is significantly larger. The separation of planes being much better, the vertical chromaticity sextupoles are then no longer required to achieve the chromaticity correction for slow extraction (see Table 1).

Then, the order of horizontal and vertical chromaticity sextupoles shall be rearranged, with the aim of creating a more favorable phase advance between pairs of horizontal and vertical chromaticity sextupoles, respectively. With the new order, this phase advance corresponds to about 150° in both planes, compared to 75° (horizontally) and 225° (vertically) in the original lattice.

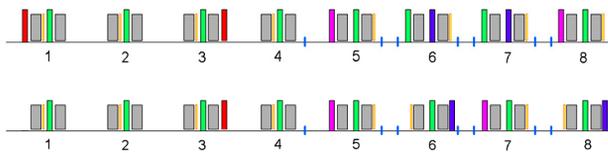


Figure 1: Location of sextupoles in the original (top) and the optimized (bottom) lattice. Resonance sextupoles, horizontal and vertical chromaticity sextupoles are colored red, blue, and pink, respectively. The green elements are orbit correctors, the yellow ones BPMs.

Apart from these rearrangements of the sextupoles, two more modifications shall be applied: Firstly, octupoles shall be used to compensate second order effects from the strong chromatic sextupoles (see next section).

Secondly, a horizontal local orbit bump at the electrostatic septum shall be introduced. This leads to a reduction of the amplitude of the resonant particles in the horizontal plane, thus increasing the distance to the aperture and hence the tolerance against closed orbit distortions.

COMPENSATION OF SECOND ORDER EFFECTS USING OCTUPOLES

Even with the indicated modifications to the SIS100 lattice, the sextupoles for chromaticity correction are still too strong for the perturbative model of slow extraction to be valid: The separatrices close upon each other forming islands, particles which would be unstable without chromaticity correction become stable.

These effects are caused by second order contributions of the chromaticity sextupoles, which manifest themselves mainly in a large amplitude dependent tune shift. Since octupoles create amplitude dependent tune shifts, they can be used to compensate the second order effects to a large extent.

Figure 2 demonstrates the effect of increasing octupole strength on the trajectories of particles with different horizontal amplitudes in horizontal phase space. The chromaticity sextupoles are always set to satisfy the Hardt condition. For the diagrams 1 to 4, the octupole strength corresponds, respectively, to zero, 1.5, 3.0, and 4.5 m^{-3} .

Note that for sufficiently large octupole strength the trajectories of the outermost particles become unstable again. Also, the tracks of the unstable particles approach more and more straight lines parallel to the edges of the stable triangular trajectories.

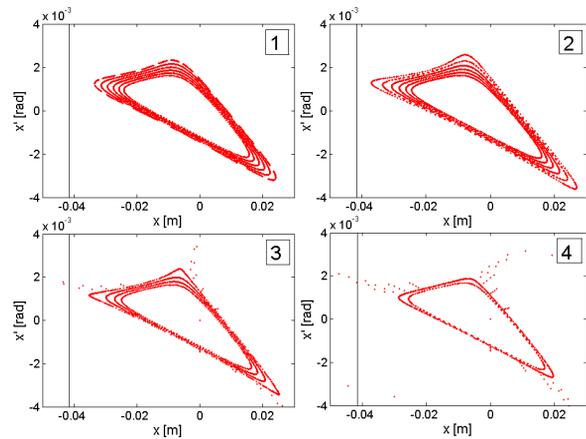


Figure 2: Trajectories in horizontal phase space as a function of octupole strength. The chromaticity is set to satisfy the Hardt condition. For details refer to the text.

This is even more evident from Figure 3, which displays separatrices with three different sizes for the nominal values of chromaticity sextupoles and octupoles (see Table 1). Note that the entrance angle at the septum as well as the spiral step is kept constant in the process. The different sizes have been obtained by varying the horizontal tune Q_h and the strength amplitude $K2L_{sr}$ of the distribution of the six resonance sextupoles, while the angle of the separatrices has been adjusted by changing the phase of this distribution. Thus, in contrast to the original slow extraction scheme, size and angle of the separatrix can be adjusted freely. This gain in freedom is of considerable advantage when the slow extraction has to be set up in the real machine, where imperfections usually necessitate corrections to the theory values.

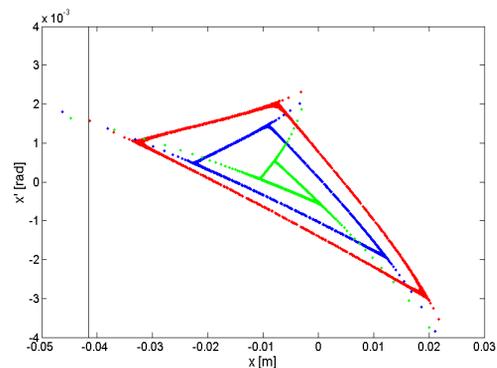


Figure 3: Separatrices of different sizes with identical spiral step and entrance angle at the septum.

An important advantage of the new slow extraction scheme is that the Hardt condition can be established without a collapse of the dynamic aperture. This is evident from Figure 4, which shows the dynamic aperture with the chromaticity corrected to satisfy the Hardt condition. The geometrical apertures of dipoles and quadrupoles have been added for comparison (grey curves). All colored curves but the blue one show the dynamic aperture for zero resonance strength, each curve corresponding to a different value of the octupole strength. Evidently, the dynamic aperture remains large enough in both planes even for octupole strengths larger than the nominal value of 4.9 m^{-3} . The dark blue curve represents the dynamic aperture with nominal extraction settings, i.e. with the resonance excited. In this case, the dynamic aperture is obviously limited in the horizontal plane by the boundaries of the separatrix.

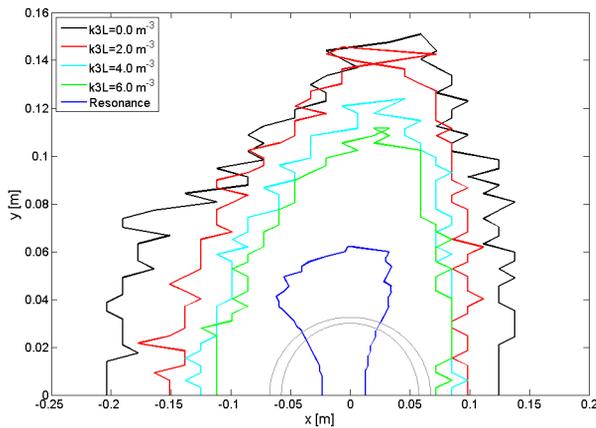


Figure 4: Dynamic aperture as a function of octupole and resonance strength. The chromaticity is corrected to satisfy the Hardt condition. For details refer to the text.

IMPROVED CLOSED ORBIT CONTROL

The modifications to the SIS100 lattice have the beneficial side effect of improving the control of the closed orbit. This is a consequence of the relocation of the combined horizontal and vertical correctors to positions between the two quadrupoles of each doublet.

To compare the efficiency of closed orbit corrections in the modified and the original lattice, the following lattice imperfections leading to closed orbit distortions were considered:

- Transverse shifts of the quadrupoles with a magnitude of 1 mm (RMS)
- Dipole tilts of 1.4 mrad (RMS)

For both imperfections, the errors were distributed according to a Gaussian distribution truncated at 2σ . The correction was done for two thousand different error seeds using the simulation code MADX.

As can be seen from Figure 5, the residual closed orbit distortions are reduced by a factor of about 2 and 1.5 in the horizontal and vertical planes, respectively. In addition, the necessary corrector strengths are significantly reduced in the horizontal plane.

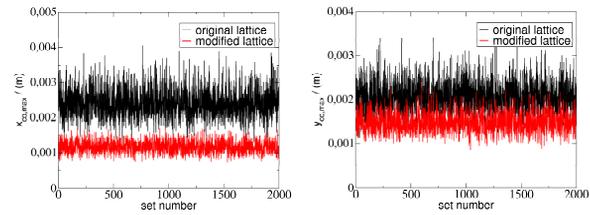


Figure 5: Residual orbit distortions in the horizontal and vertical plane for the original and the modified lattice.

CONCLUSIONS

An optimized nonlinear magnet scheme for the slow extraction from SIS100 was presented, in which octupoles are employed to compensate second order effects of the chromaticity sextupoles. The Hardt condition can be satisfied and the separatrix freely adjusted. Residual orbit distortions are reduced, while a local orbit bump increases the tolerance against closed orbit distortions.

While these results have been verified by independent tracking calculations, in the next step an analytical model for slow extraction with octupole compensation shall be developed.

Further studies are under way to systematically investigate the influence of machine imperfections (closed orbit distortions and field errors) as well as collective effects (space charge) on the performance of slow extraction with the new scheme.

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