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STATUS OF SIS100 SLOW EXTRACTION DESIGN INCLUDING EFFECTS OF MEASURED MAGNETIC FIELD ERRORS

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Abstract

The synchrotron SIS100 at FAIR, currently under construction in Darmstadt, Germany, will deliver slow extracted proton and ion beams up to 100 Tm employing resonant extraction. Its compact super-ferric dipole and quadrupole magnets allow fast ramping of magnetic field up to 4 T/s and 57 (T/m)/s, respectively. Recently, field errors have been measured for the dipole magnets and the first batch of quadrupole magnets. Higher order multipoles may interfere with resonant extraction, changing the geometry of the separatrix and conditions for resonant particles. The latter are affected most during their last turns and in the extraction channel owing to their large amplitudes, which amplify the effect of higher order multipoles. SIS100 comprises a set of corrector magnets up to octupole order, which can be used for compensating the impact of magnetic field errors. In this contribution, we report on the status of slow extraction simulation studies including field errors. Furthermore, we present alternative working points for the slow extraction, which are necessary to avoid the transition energy for some of beams required by the FAIR experiments.

INTRODUCTION

The synchrotron SIS100 is the core accelerator of the FAIR facility [1], designed to deliver high intensity heavy ion beams from protons up to uranium with a maximum rigidity of 100 Tm using slow extraction with a spill length in the order of a few seconds. The baseline scheme is transverse knock-out extraction (KO extraction) on a third-order resonance. Given the large emittances of heavy ion beams up to 30 µm, it has the advantage of minimizing losses by creating a very stable extracted beam with small angular spread at the electrostatic septum.

This scheme requires correction of horizontal chromaticity from the natural value of $\xi_x \approx -18$, including the systematic sextupole component of the dipoles, to a value close to zero. Since horizontal dispersion is small, $|D_x| \lesssim 1.5$ m, the chromaticity sextupoles are strongly excited, creating amplitude-dependent tune shift (ADTS) in second order of the sextupole strengths. This ADTS must be compensated using octupole correctors to obtain a useful separatrix shape [2]. Thus, already in the design scheme for slow extraction, SIS100 relies on the compensation of higher-order effects.

Meanwhile, measurements of the multipole errors of dipole and quadrupole magnets are available. Both magnet types have additional systematic multipole components large enough to influence slow extraction performance by distorting the separatrix, requiring an adapted compensation scheme to restore design performance. The adapted scheme has also been checked for robustness against the influence of random magnet errors.

Furthermore, some of the FAIR experiments require slow extraction at an energy very close to the transition energy of the lattice, albeit with low intensities. This energy regime cannot be reached with the standard working point, Q_x, Q_y = 17.3, 17.4. Therefore, alternative working points with distinct horizontal tunes have been devised.

MAGNETIC FIELD ERRORS

Compensation of Systematic Multipoles

The original slow extraction design for SIS100 did not consider any systematic multipole errors except systematic sextupole components of the dipoles [2]. Recently, measurements of the multipole errors of all dipole magnets [3] and the first batch of about 20 quadrupole magnets [4] became available. As expected, non-zero systematic multipole errors are essentially only present for the allowed components ($B_{d,3}$, $B_{d,5}$, and $B_{d,7}$ for dipoles, $B_{q,6}$ and $B_{q,10}$ for quadrupoles). While $B_{d,7}$ and $B_{q,10}$ can be neglected, $B_{d,5}$ and $B_{q,6}$ have a significant impact on the separatrix due to ADTS created by normal multipoles of order $2n$, which leads to a bending of the the outgoing branches of the separatrix.

Unlike the ADTS created in second order of chromaticity sextupole strengths, ADTS from $B_{q,6}$ cannot be compensated for all particle amplitudes and independent of the tune distance from the resonance due to the lack of corresponding correctors in SIS100. However, compensation at the amplitude corresponding to the location of the electrostatic septum is still possible using octupole correctors by adjusting their strengths as a function of tune distance or, equivalently, separatrix size. Compensation of $B_{q,6}$ works even in the presence of finite momentum spread, as long as the chromatic tune spread $\xi_x \delta$ is reasonably small.

While the odd multipole $B_{d,5}$ does not create ADTS by itself, it induces a non-negligible B_4-component through dispersive offsets in the dipoles. The resulting momentum-dependent ADTS leads to varying curvature of the separatrix as a function of δ, increasing losses at the electrostatic septum through a wider angular spread. For KO extraction, the impact of $B_{d,5}$ can be minimized by choosing a larger size of the separatrix, making the dynamics less sensitive to ADTS owing to the larger tune distance from the resonance. This is demonstrated in Fig. 1 for two nominal sizes of the separatrix, corresponding to tune differences from the resonance of $\delta Q_x = 0.013$ (left) and $\delta Q_x = 0.0055$ (right): the former has an angular spread at the electrostatic septum

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of $\Delta x' = 0.22$ mrad, and the latter $\Delta x' = 0.46$ mrad, which is already at the limit of the geometric acceptance of the extraction channel.

The influence of $B_{d,5}$ will, however, prevent quadrupole-driven extraction, originally foreseen in SIS100 as a fall-back mode, without need for a KO-exciter, due to the vanishing tune distance from the resonance intrinsic to this scheme. Fortunately, it appears that the recently developed COSE extraction scheme [5], which works by ramping all magnets in proportion to a momentum-change, sweeping over the longitudinal beam distribution, can be applied in SIS100 even in the presence of $B_{d,5}$. COSE gives a monotonous relation between horizontal emittance of an extracted particle and its momentum deviation. If the separatrices for different momenta are aligned at the electrostatic septum, the extracted beam has a very small angular spread. In SIS100, these conditions can be established by adjusting the horizontal chromaticity to an adequate value. Further studies are required to investigate this promising option in more detail.

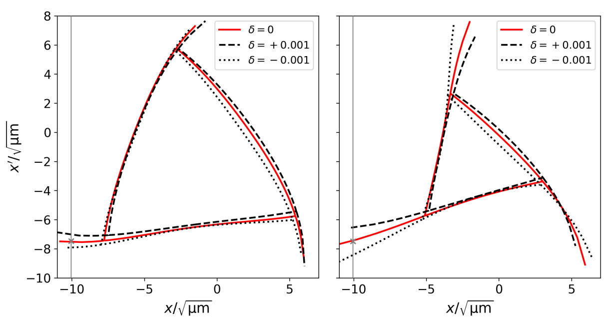

Figure 1: Separatrices for beams with emittances ε_x = 30 µm (left) and ε_x = 10 µm (right). Grey line and cross mark position and angle of the electrostatic septum respectively (see text for details).

Particle Loss Simulations

Operation of SIS100 requires a low level of beam loss. In order to explore the loss levels from different effects, multi-particle tracking simulations of slow extraction using MADX have been performed. 10000 test particles were tracked for 25000 turns. This corresponds to about 125 ms, which is shorter than typical extraction times but sufficient for determining losses. Results presented here correspond to extraction of uranium at the lowest energy of 400 MeV/u, using a stable phase space area corresponding to an emittance of 27 µm.

In the first step, particle losses due to magnet errors were studied for the standard working point. Starting with simulations including only systematic magnet errors, relative particle losses were found to be $P_{\mathrm{loss,ES}} = 3.4$ % at the electrostatic septum and $P_{\mathrm{loss,ring}} = 0.04$ % at other apertures around the ring, in the following referred to as ring losses.

For the subsequent simulations with random magnet errors, samples of multipole errors were generated based on the averaged multipoles and their rms deviations of the measured

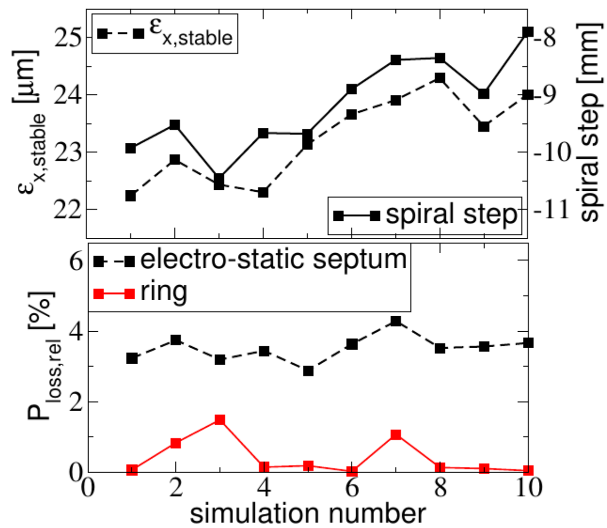

Figure 2: Upper graph: Emittances of the horizontal stable phase space areas and spiral steps found in the simulations. Lower graph: Corresponding relative particle losses.

field multipoles. The rms spread of the main quadrupoles' focusing strengths was estimated separately [6].

The obtained emittances of the separatrix, spiral steps, and relative particle losses are shown in Fig. 2. Losses at the septum are similar to those obtained with systematic errors only. Ring losses up to 2% are found, where $P_{\mathrm{loss,ring}} \ll 1$% for seven out of ten samples. The ring losses are not correlated with the separatrix areas and spiral steps: e.g. simulations 7 and 8 resulted in similar separatrix areas and spiral steps, but the corresponding ring losses differ by an order of magnitude. An analysis revealed that a major part of the ring loss occurred at magnetic extraction septa which limit the beam vertically. Particle loss due to vertical beam growth can be explained by the influence of the third order sum resonance $Q_x + 2Q_y = 52$, which is close to the standard working point (see Fig. 3). That resonance is systematically excited by the sextupoles used to create the extraction resonance $3Q_x = 52$ and modified by the actual sample of sextupole errors, which leads to different particle losses.

The influence of the coupling resonance depends on the working point, which was studied in the second step. For that purpose, tracking simulations were performed for varying Q_y, regarding systematic magnet errors only. The resulting losses are shown in Fig. 3, with a maximum at $Q_y = 17.35$. Since the resonance condition for $Q_x = 17.32$ is fulfilled for $Q_y = 17.34$, this is a strong hint at the coupling resonance as source of particle losses. Vertical losses can be avoided, thus, by staying sufficiently far away from the coupling resonance. For high intensities, the impact of space charge tune shift may be significant, especially for lower extraction energies, which will be considered in future simulation studies.

One should also note that the excitation strength of the coupling resonance depends on both horizontal and vertical phase advance between the resonance sextupoles [7],

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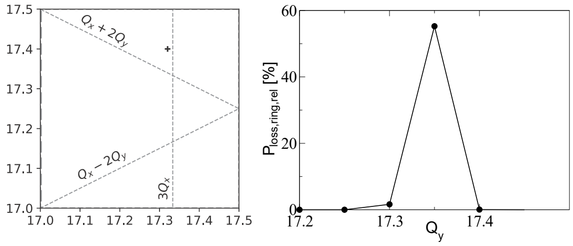

Figure 3: Left: Normal resonance lines up to 3rd order around the standard working point. Right: Relative ring loss as a function of the vertical tune.

i.e. the choice of vertical tune will influence the strength. Following [7] to denote by h_{3000} and h_{1020} the strengths of the extraction and of the coupling resonance respectively, one finds that the ratio h_{1020}/h_{3000} is 0.93 for $Q_y = 17.4$, 1.25 for $Q_y = 17.2$, and 0.04 for $Q_y = 17.8$. The working point $Q_x, Q_y = 17.3, 17.8$, proposed earlier [2], would therefore be favourable for minimising the excitation of the coupling resonance. Unfortunately, this working point is not suitable for beam accumulation at injection due to strong losses caused by the high density of systematic resonances in this area [8].

ALTERNATIVE WORKING POINTS

Some of the experiments carried out at FAIR rely on the availability of the highest possible particle energies from SIS100, up to 100 Tm rigidity. The present standard working point for slow extraction, $Q_x, Q_y = 17.3, 17.4$, has a transition energy of 12.3 GeV/u, corresponding to a gamma transition $\gamma_{tr} = 14.2$. Acceleration to, and slow extraction at, an energy close to transition is not possible due to instabilities. Thus, with the standard working point some ions cannot be extracted at the energies required by experiments since it would be too close to transition, such as Ar at 12.6 GeV/u and Ag at 12.3 GeV/u.

It was therefore necessary to devise alternative working points with different transition energies, either high enough for the extraction to take place below transition, or sufficiently low to allow for extraction above transition. Acceleration through transition, if necessary, is possible at moderate intensities of about 10^{10} particles per cycle sufficient for the relevant experiments. The working points for slow extraction considered and corresponding transition energies are summarized in Table 1.

Table 1: Transition Energies and Corresponding Forbidden Energy Ranges for Slow Extraction

Q_x	γ_{tr}	T_{tr} [GeV/u]	forbidden range, T [GeV/u]
16.7	13.5	11.7	10.7 – 12.6
17.3	14.2	12.3	11.4 – 13.2
18.7	15.3	13.3	12.4 – 14.2

The present extraction geometry in SIS100 is optimised for the standard working point and is limited by the fixed position of the Lambertson septum (LS) and the fixed distance between the electrostatic septum (ES) and LS.

Positions and angles of the split ES can be changed compared to their standard settings, making it possible to accommodate the changes in the focusing of the quadrupoles between ES and LS for different working points.

This is illustrated in Fig. 4 for two different cases. The change of the ES positions will also lead to a restriction of the aperture when moved closer to the beam center. For $Q_x = 18.7$, the acceptance is 73 µm compared to 100 µm with the standard working point. This is still acceptable due to the smaller size of fully stripped ion beams used for the highest possible energies, compared to e.g. uranium with intermediate charge state used for the highest intensities.

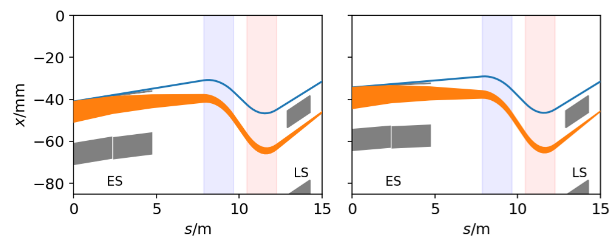

Figure 4: Extraction region and extracted beam envelope horizontally for $Q_x = 17.3$ (left) and $Q_x = 18.7$ (right), showing the difference in ES position.

Modified working points will also lead to a change in the particle trajectories during the last turns before extraction. To avoid particles being intercepted by cryo-catchers [9], some of them had to be moved to larger distances from the beam axis to enable such changes in the optics [10].

CONCLUSION

The impact of magnetic field errors of the dipole and quadrupole magnets on slow extraction has been studied. Both magnet types have additional systematic multipole components large enough to distort the separatrix, requiring an adapted compensation scheme to restore design performance of KO extraction, avoiding increased losses at the electrostatic septum. COSE has been identified as a promising candidate for a fall-back solution for tune-sweep extraction without KO-exciter, and will be studied in more detail.

Multi-particle simulations show that the lattice design is relatively robust to random errors. The influence of a nearby third order coupling resonance excited by the resonance sextupoles requires careful choice of the vertical tune to avoid vertical blow-up and associated losses. Further studies are needed to investigate the influence of space charge.

Alternative working points for different transition energies allowing a wider range of ions at the highest possible energy have been selected, and cryo-catcher positions modified to adapt to these changes. Acceleration through transition, if required, is possible at moderate intensities. As the electrostatic septum is movable, the change in phase advance can be accommodated, but will restrict the aperture for larger horizontal tune values.

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