

SIS100/300 EXTRACTION SYSTEM DESIGN BEAM DYNAMICS AND TECHNOLOGICAL CHALLENGES*

N. Pyka, U. Blell, C. Mühle, A. Saa-Hernandez, P. Spiller and J. Stadlmann,
GSI, Darmstadt, Germany

Abstract

The FAIR heavy ion synchrotrons SIS100/300 will provide heavy ion and proton beams with variable time structure. The design of the extraction systems has to allow fast extraction of compressed single bunches from SIS100, fast beam transfer between SIS100 and SIS300 and slow extraction from SIS100 and SIS300. High average beam intensities and the generation of an uninterrupted linac-like beam are enabled by combining both heavy ion synchrotrons in different operation modes (fast acceleration and stretcher operation). In order to reduce beam loss at slow extraction of intense heavy ion beams and to minimize the beam load in subsequent accelerator structures, dedicated ion optical settings of the basic lattice functions and higher order corrections will be applied. However, the tight geometrical constraints in the rather short straight sections and the need to extract from both synchrotrons, fast and slow, at the same position and in parallel to the beam transport system, require operation parameters of the extraction devices close to the limits of technical feasibility. Higher order beam dynamics simulations and technical developments on the magnetic septa will be presented.

ION OPTICAL BOUNDARY CONDITIONS

For slow extraction in SIS100 [1] and SIS300 [2] a third order resonance is generated with sextupole magnets installed in each of the six straight sections of the synchrotrons. Two families of sextupole magnets for the distinct correction of the horizontal and vertical chromaticity are placed in the six arc sections [3].

At slow extraction, a quite large fraction of the heavy ions interacting with the wires of the electrostatic septum are lost because of stripping in the septum wires. The next quadrupole lens downstream the septum defocuses the particles with the corresponding large deviation from the reference rigidity against the beam pipe.

The large number of ions lost in the quadrupole module deposits a considerable amount of energy in the involved components. An effective measure to minimize these losses is to remove the momentum dependence of the separatrix by applying special ion optical conditions (Hardt condition) [4]. In this case the separatrix where particles are moved into the electrostatic septum is overlapping in phase space for each momentum. Hence, all particles have the same angle at the electrostatic septum. In the following chapter the special ion optical settings at slow extraction from SIS100/300, in particular

considering the role of the dynamic aperture are described.

DYNAMIC APERTURE

SIS100

Ion optical calculations for SIS100 with the aim to fulfill the Hardt condition lead to a strong excitation of the sextupole magnets and a chromaticity close to zero in horizontal plane. Taking into account the unavoidable multipole components in the dipole magnets, in particular the sextupole component, the dynamic aperture (DA) which is large for $y=0$, became rapidly smaller for $y>0$. Switching off the chromatic sextupoles removes this effect completely.

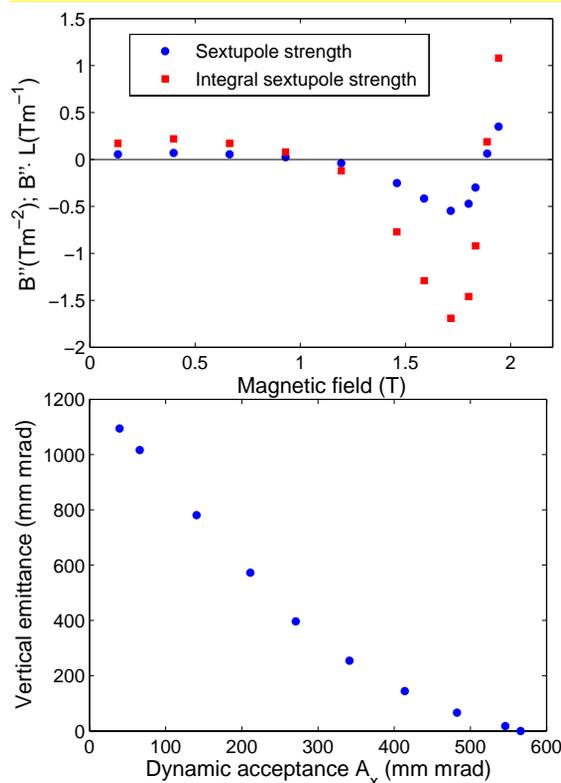


Figure 1: (Top) Intrinsic sextupole error of the SIS100 dipole magnets. (Bottom) Dynamic aperture at slow extraction. Chromatic sextupole magnets are set at $B''xL=36 \text{ Tm}^{-1}$ to correct for intrinsic sextupole errors of dipoles at $B''xL=-1.5 \text{ Tm}^{-1}$.

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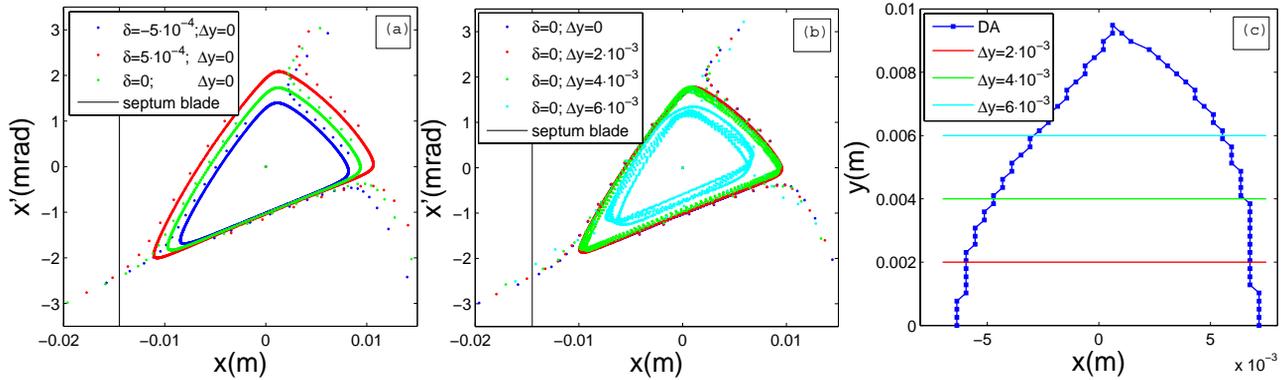


Figure 2: Slow extraction tracking simulations with Hardt condition for the working point Q_x/Q_y : 13.32/9.27 after implementing the optimization code results: (a) for $\Delta y=0$ overlapping of the separatrices heading towards the septum for different momenta $\delta=\Delta p/p$; (b) particles with $\Delta y \neq 0$; (c) as projected in (b).

Hence, the influence of different settings of the chromatic sextupole magnets on the DA and the necessary number of sextupoles was studied and the resonance extraction was optimized to the DA. Stable operating conditions for slow extraction were obtained if the different families of chromaticity sextupoles are set equally and at a much lower strength ($B''xL=39 \text{ Tm}^{-1}$) as proposed for the Hardt condition (max. 140 Tm^{-1}). The remaining divergence at the electrostatic septum is 0.2 mrad. Under these conditions there is still space for wider extraction parameter variations with respect to the DA. The number of 48 chromatic sextupole magnets leads to stable operation conditions with reasonable low magnet strengths. A further reduction would increase the necessary magnet strength accompanied again by a reduction of DA.

The sextupole components of the 108 dipole magnets which will be installed in SIS100, contribute to the horizontal machine chromaticity (see figure 1 top). The sextupole terms have been derived by 2D calculation of the magnetic field. Not included are sextupole terms due to eddy current effects at ramping and sextupole terms due to 3D end fields. Fine adjustment of the chromatic sextupole magnets to correct for these errors will be performed during commissioning. At low magnetic dipole fields the sextupole term is positive, which is due to a laterally increasing magnet field. In the field range between $B=1 \text{ T}$ and $B=1.8 \text{ T}$, the sextupole terms show negative signs, i.e. the magnetic field decreases with the distance from the magnet centre. This effect is created by the shimming of the yoke geometry. At very high field levels in the range of 1.9 T the sign of the sextupole terms turn again positive, which may be caused by saturation effects in the iron yoke.

The sextupole terms of the dipole magnets were taken into account by a reduction of the strength of the chromatic sextupoles to a global value of $B''xL=36 \text{ Tm}^{-1}$ which leads to the design value of chromaticity of $\xi_h = -0.3$ (natural machine chromaticity is $\xi_h = -1.17$; chromaticity is divided by the tune). With this setting a rather large DA is obtained for all $y > 0$ values (figure 1

bottom) providing sufficient safety at slow extraction. The sextupole magnets generating the resonance are almost not affected by the sextupolar components of the dipole magnets. The slight rotation of the separatrix is compensated by a modification of the phase angle for the sine wave excitation curve.

SIS300

Contrary to the doublet structure of SIS100, the SIS300 lattice is designed as a FODO structure [5] with 24 chromatic sextupole magnets in two families and 12 resonant sextupole magnets. The transverse nonlinearities induced by the sextupole magnets excite not only the third integer resonance, $3Q_x = 1$ but other undesired higher order resonances. Another effect caused by the sextupole magnets is the amplitude dependent tune or detuning. Both effects contribute to the reduction of the dynamic aperture and cause a larger beam loss than in SIS100.

These effects have been simulated, finding that at the initially planned settings of the machine [6, 7], the DA was too small for particles with vertical amplitudes, $\Delta y \neq 0$. An optimization code has been developed to determine appropriate extraction conditions and settings for a low-loss, resonant slow extraction. Proper conditions could be generated by minimizing the detuning coupling coefficient, α_{xy} , and the first order resonant terms $2Q_y + Q_x = 1$ and $2Q_y - Q_x = 1$ driven by the sextupoles, while keeping the excitation of the third integer resonance unchanged. Due to the geometrical constraints given by the transfer line to SIS300, and the common extraction channel, it was not possible to place the sextupole magnets at more suitable places (larger dispersions, decoupled betas). Exploitation of the phase advances between the sextupoles, aiming for higher symmetries and periodicities for a cancellation of the nonlinearities would have been preferable.

The resonance sextupole magnets introduce the dominant field nonlinearity. The chromaticity sextupole magnets in contrast, have relatively small sextupole strengths and the magnets are positioned such that their contributions nearly cancel. For this reason the

optimization parameters of the code are mainly the strengths of the 12 resonant sextupoles. The method has been applied for three potential working points. An example is given in figure 2. Stable triangles are aligned on the extraction separatrix for different momenta of the particles (figure 2 left). For amplitudes $y > 0$ the separatrix starts to shrink (figure 2 middle). The right figure summarises the DA for $y > 0$. Particles are stable within the calculated 2000 turns. The calculated DA of the synchrotron with chromatic sextupoles correcting for the Hardt condition (chromaticity at $\xi_{\eta} = -0.25$) and resonance sextupoles off, exceeds the beam tube diameter. In a next step, the tracking code will be extended to misalignments, and magnet errors disturbing the periodicity and symmetry in order to assure the robustness of the solution.

HIGH POWER MAGNETIC SEPTA

The high magnetic rigidity of both synchrotrons, leads to a small separation between extracted and circulating beam at the entrance of the magnetic septa [1]. Consequently, the blades of the septa have to be kept rather thin to minimize the impact on the machine acceptance. With the large operation currents needed to reach the high magnetic fields (0.35 T – 1.85 T), a large amount of heat has to be dissipated from the septum blade. In case of the SIS100 extraction septa the heat density is up to 160 Wcm^{-2} which exceeds typical values of septa.

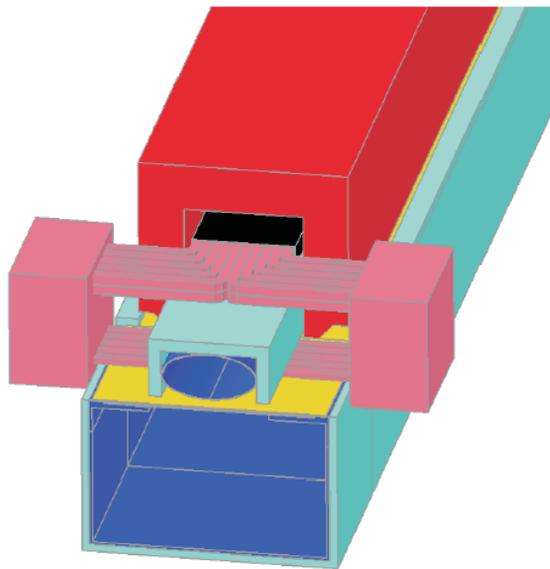


Figure 3: Sketch of the coil entrance/exit section of the magnetic septum. The electric conductors (purple) start/end in the electrical and cooling support structure (indicated by the purple blocks), main vacuum chamber (bottom, blue) for the circulating beam, magnetic shielding plate (yellow), the vacuum chamber of the extracted beam (top, blue), the yoke (red), and baking jackets (green).

This problem applies to a certain extent to all of the injection, extraction and transfer magnetic septa of SIS100. The normal conducting SIS300 magnetic septa have similar challenging parameter, and one SIS300 extraction septum had even to be designed superconducting.

Figure 3 shows the design of the normal conducting vertical septum which will be used in SIS100 for extraction into the high energy beam transport system and the transfer to SIS300. Single layer conductors, which are separately cooled and powered are used as the inner septum blade. At the end of the septum, each conductor is split into two conductors with larger diameter which guide the cooling water back to the septum entrance.

A test assembly of one single copper conductor proved that for a straight section of a septum it is even possible to remove a heat dissipation of twice the maximum demanded amount with a still reasonable pressure of 9.5 bar and 14.4 ms^{-1} water flow in a copper tube of $\text{Ø}5 \text{ mm}$ with inner $\text{Ø}4 \text{ mm}$. In practice, these parameters may be increased up to 20 bar and 20 ms^{-1} . Serious constraints are set by the geometry of the conductor outlet of the septum where the conductors are bent several times to save space. The temperature increase is non-linear in this area and the temperature difference to the maximum operating temperature is small. As counter measure, the heat transmission coefficient is increased via a tailored surface roughness in this section. The maximum outlet temperature of 80 deg Celsius has been chosen in order to assure a long lifetime of the epoxy matrix and to keep the structure sufficiently rigid. In addition this temperature regime is beyond the production of bubbles due to water boiling.

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