# SLOW EXTRACTION FROM THE SUPERCONDUCTING SYNCHROTRON SIS300 AT FAIR: LATTICE OPTIMIZATION AND COMPENSATION OF FIELD ERRORS

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*Abstract*

In order to increase the slow extraction efficiency, the SIS300 lattice has been redesigned. With this aim, a code has been developed for optimizing the sextupoles strengths, minimizing the excitation of undesired resonances and correcting the chromaticity to fulfill the Hardt condition. Additionally, the optimization allows the compensation of the $b_3$ field components, steady or time dependent, on the SIS300 dipoles. Based on tracking simulations, tolerances are given for both, allowed and non-allowed field errors, with and without compensation.

## INTRODUCTION

The two superconducting synchrotrons, SIS100 and SIS300, will be the core of the new Facility for Antiproton and Ion Research (FAIR) at GSI-Darmstadt [1]. SIS300 is planned to be a versatile machine, which by means of a low-energy stretcher-mode or a high-energy pulsed-mode (with a ramping rate of 1 T/s) will provide slow extracted heavy ion beams towards the experimental areas. Thus, SIS300 will become the first superconducting synchrotron worldwide providing slow extracted beams. Since both synchrotrons will be installed in the same tunnel, the dipole layout of SIS300 cannot be freely chosen. Compromises concerning the positions and phase advances between the optical elements have to be accepted. Thus, a standard lattice cannot be applied. Following the analytical description of slow extraction from Pullia [2], and the work on hamiltonian modes and resonances excitation from Bengtsson [3], a program for the optimization of the lattice under the given boundary conditions has been developed. This program is used to perform a numerical optimization of the operating parameters. The final goal of the lattice optimization is a higher efficiency at slow extraction. The results are evaluated by means of tracking simulations performed with the code *Elegant* [4]. In the first section of this report the SIS300 lattice is optimized with respect to the lattice described in [1]. In the second section, estimations for the field quality of the superconducting dipoles are presented. The optimization code is, at this stage, used to generate the steady or time dependent settings of the sextupoles, aiming for a compensation of the effect of the $b_3$ field component during slow extraction. The tolerances for the field errors are determined with the use of beam dynamics simulations.

## OPTIMIZATION OF THE SIS300 LATTICE

The installation of SIS300 on top of SIS100 results in a non-standard dipole layout. As a consequence of this dipole structure, non-standard phase advances per FODO cell are necessary to generate straight sections with a zero dispersion function at SIS300. Dispersion-free straight sections are preferable in a machine providing slow extraction where the sextupoles are used for two antagonistic tasks: $i)$ the excitation of a $3^{rd}$ integer resonance, creating unstable separatrices which guide the particles to the septum and $ii)$ the correction of the chromaticities to fulfill the Hardt condition. By means of the Hardt condition the angle of the particles at the entrance of the septum is independent from their relative momenta.

### *Working Point and Sextupole Positions*

A working point (WP) of $Q_x = 9.32$, $Q_y = 9.14$ corresponding to a phase advance per FODO cell of $\psi_x = 79.9°, \psi_y = 78.3°$ turns out to be an acceptable compromise. It generates a dispersion function very close to zero along the straight sections, as shown in figure 1. The contribution to the chromaticity of the resonant sextupoles situated in the straight sections is almost canceled. The chromatic sextupoles of each family had to be repositioned in the arc and were separated by two FODO cells. The new positions resulted in a phase advance of 160°, not far from the optimal 180° which would avoid the excitation of any resonance.

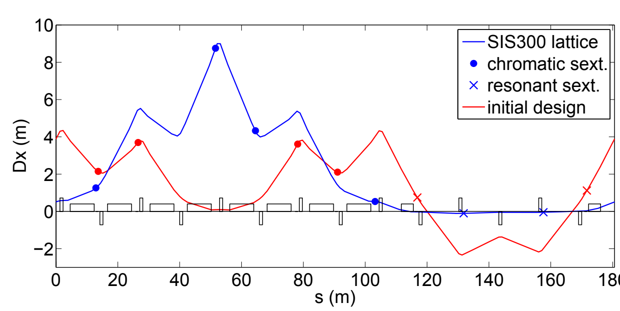


Figure 1: Dispersion functions of the modified and the initially proposed SIS300 lattice (WP = 13.31, 9.27), plotted for 1 sector of the ring. Dipoles and quadrupoles are depicted in the figure while the chromatic and resonant sextupoles are indicated along the dispersion functions.

### *Sextupoles Strengths*

Unless a careful optimization of the sextupoles strengths of the different families is performed, the excitation of unwanted resonances may eventually lead to coupling of the horizontal and vertical planes, reduction of the dynamic aperture (DA) and overall particle loss. The excitation of these resonances together with the amplitude-dependent tune-shift coupling coefficient ($\alpha_{xy}$), can be quantified and conveniently minimized by resorting to an adequate optimization function. The optimization, described in eqs. (1), (2) combines two functions which are minimized iteratively until convergence is found. The strengths of the chromatic and resonant sextupoles are the optimization variables, grouped in 2 and 6 families: $\vec{k}_{2,chrom} = (k_{2ch}, k_{2cv})$, $\vec{k}_{2res} = (k_{2r1}, k_{2r2}, k_{2r3}, k_{2r4}, k_{2r5}, k_{2r6})$.

$$\begin{aligned} f_{chrom}(\vec{k}_{2,chrom}) &= |\xi_x - \xi_{hardt}| \\ f_{res}(\vec{k}_{2,res}) &= w_1|h_{30000} - 2A| + w_2|\alpha_{xy}| + \\ &+ w_3|x' - x'_s| + \sum_{i,unwanted} w_i|h_i| \end{aligned} \tag{1}$$

The optimization pursues the following goals:

- Correction of the horizontal chromaticity to fulfill the Hardt condition, in this case $\xi_{hardt}$ = -0.0121.
- Excitation of the $3^{rd}$ integer resonance, $3Q_x$, driven by the $h_{30000}$ mode for slow extraction. The excitation is determined by the desired size of the stable triangular area $A = |\frac{\epsilon}{3\pi\varepsilon_x/4\sqrt{3}}|$, which depends on the tune distance from the resonance $\epsilon$, and on the beam emittance $\varepsilon_x$.
- Minimization of the coupling term, $\alpha_{xy}$, of the amplitude-dependent tune-shift.
- Orientation of the separatrices, described in [2], to match the entrance angle x'$_s$ = -1.4 mrad at the septum position $x_s$ = -15 mm.
- Minimization of the unwanted resonances $Q_x$, $Q_x + 2Q_y$, $Q_x - 2Q_y$ which correspond to the $1^{st}$ order hamiltonian modes as described by [3], $h_i \equiv h_{21000}$, $h_{10110}$, $h_{10200}$ and $h_{10020}$.

For normalization every term is multiplied by a factor ($w$). The factor is also used to weight the term according to the needs, e.g to fully cancel the excitation of a given unwanted resonance for a WP placed very close.
Tracking simulations performed for the optimized lattice show an increase of the short-term DA by more than one order of magnitude in the vertical direction. Thus, contrary to the initial design, the extraction of all particles, independently from their vertical amplitude, is possible. The extraction efficiency of a uniformly distributed beam with an emittance of $\xi_x = 2$, $\xi_y = 1$ mm·mrad reaches a value of 96.2%.

## INFLUENCE OF THE DIPOLE FIELD ERRORS ON THE SLOW EXTRACTION

The first dipole prototype for SIS300 will be delivered at the the end of 2010. Due to the lack of field quality measurements, a combination of calculations and data measured for similar magnets is used to estimate the errors, suggest possible cures and set limits to the tolerances. The allowed components up to $b_{15}$ are calculated using ROXIE [5] and plotted vs. the current in the magnet (figure 2). The values of the non-allowed components up to $a_{10}$ are taken from measurements on RHIC dipoles of a similar type [6]. The total magnetic field is a sum of field sources of different nature and characteristics. For low currents, the main contribution to the field components are the persistent currents (pc). The pc flow through the superconducting filaments and decay when the current remains constant. The pc are therefore supposed to be time-dependent. The stretcher mode is planned for this low-field region since the extraction will take place at 1 T or, equivalently, a magnetic rigidity of 64 Tm. For high currents the dominating source of the field is the iron saturation, which is steady. The high-energy mode is foreseen for this region (at 4.5 T or 300 Tm), where the contribution of the pc amounts only to 0.2 units. Thus their decay is a negligible effect.

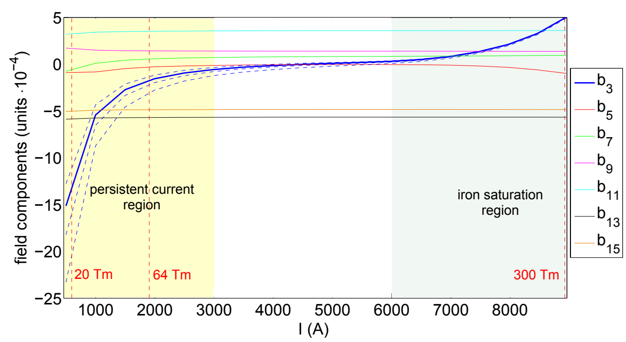


Figure 2: ROXIE simulations for the allowed field components of the SIS300 dipoles up to $b_{15}$. The field component $b_3$ is plotted in blue for different filament diameters (2, 2.5, 3.5 and 4 $\mu$m). The absolute value of $b_3$ increases with the thickness of the filaments at low fields. The thick blue line is used as a reference value (2.5 $\mu$m) in the text.

### *Compensation of the Sextupole Component*

Because of its sextupolar nature the $b_3$ component is the most dangerous of the allowed components of the dipoles. It contributes to the resonance excitation and especially to the chromaticity. For the nominal value of $b_3$ in the high-energy mode, its contribution to the chromaticity is 2 times bigger than the one of the chromatic sextupoles. Since the Hardt condition is no longer fulfilled, a big broadening of the separatrices and a 10 times bigger spread on the entrance angle at the septum is generated (figure 3). The effect of the $b_3$ components can be described by the analytical models used in the optimization code. Furthermore,

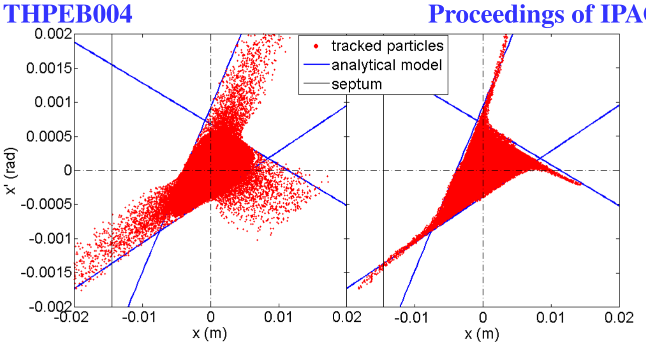


Figure 3: Phase-space plots of 1000 particles tracked for 100 turns. The left figure shows the particles before and the right one after the compensation by means of a new set of optimized strengths for the 2+6 families of sextupoles.

$b_3$ can be compensated by calculating new settings for the strengths of the chromatic and resonant sextupoles. The tolerances are set to the limit where the compensation is no longer possible.

In the first attempt to determine the limits for the tolerances, a steady field component was assumed. Limits were set to the mean value of the field component in all the the magnets ('systematic component'), and also to its variability from magnet to magnet, i.e. the standard deviation ('random component'). A scan from 0 to 20 units was performed for the systematic $b_3$ vs. the random $b_3$. Two assumptions were compared: $i$) the systematic and random components are known and can be compensated, which implies all dipoles were measured cold prior to their installation in the tunnel, and $ii$) only the systematic component is known and compensated. The values found for both situations are compiled in table (1). In case of known and compensated errors the limits can be more relaxed.

To anticipate the decay on the SIS300 dipoles is a difficult issue since it does not only depend on the magnets parameters but also on their powering history. There is no analytical model which provides a full description. Instead, an experimental fitting-function, a sum of 2 exponentials expressed in terms of the decay amplitude and the decay rate, was proposed in [7]. The fit has been applied to decay measurements performed for the RHIC dipoles [8] and the resulting decay rate was used for the SIS300 dipoles. The decay amplitude implemented on the SIS300 dipoles corresponds to the full pc contribution for the low energy mode from the ROXIE calculations. To compensate the time-dependent pc decay, new strengths for the different families of sextupoles were calculated using the optimization program. For slow decay rates, a ramping of the sextupoles is proposed as a dynamic compensation on the current plateau (figure 4). Slow decay rates are obtained from the fit to data for RHIC ($\tau = 52$s), LHC ($\tau = 189$s [7]) and TEVATRON ($\tau = 537$s [9]). In case of fast decay rates ($\tau = 4.9$s to $\tau = 9.6$s for HERA [10], depending on the dipole powering history), a waiting period before injection would be the easiest applicable solution to the SIS300 stretcher mode.

Other field components different from $b_3$, are dominated by the geometric field source, which is constant. These components cannot be compensated by setting new strengths on the sextupoles. Thus, no correction is attempted and the tolerances set in table (1) are based on the slow extraction efficiency of the tracking simulations.

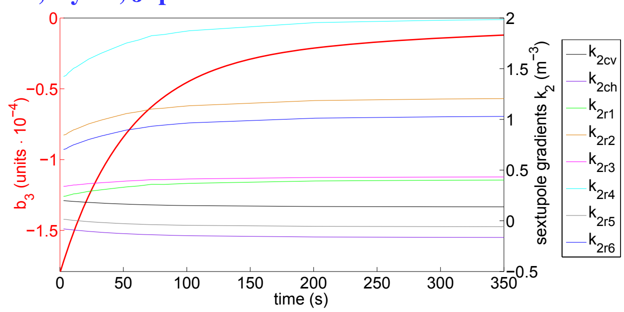


Figure 4: Estimated $b_3$ decay together with the dynamic sextupoles strengths proposed for its compensation.

Table 1: Tolerances for the Field Components (units$\cdot 10^{-4}$)

| | $b_3$ systematic | $b_3$ random |
|---|---|---|
| high-energy mode | 15 / 11[a] | 9 / 6 |
| low-energy mode | 9 / 5 | 6 / 4 |

| systematic | $b_5$ to $b_{15}$ | $a_2$ | $a_3$ | $a_4$ | $a_5$ to $a_9$ |
|---|---|---|---|---|---|
| both modes | -[b] | $\leq$1 | 4 | 2 | -[b] |

[a] systematic and random compensation / only systematic compensation.
[b] upper limit was not found within $\times$ 10 their nominal value.

## CONCLUSIONS

The changes suggested for the working point and the sextupoles positions of the SIS300 lattice, together with the optimized sextupole strengths increase the dynamic aperture and the extraction efficiency. Tolerances were set to the limit where the compensation of the systematic and random $b_3$ components is no longer possible. The decay of $b_3$ was estimated and could be compensated by ramping the sextupoles during the current plateau. Tolerances were also set for other field components, finding relaxed limits, except for the skew quadrupole, which couples the transversal planes, and has to be strongly constrained.

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