

# BEAM LOSS SIMULATIONS WITH SPACE CHARGE AND OCTUPOLES FOR THE SIS100 MAGNET QUALITY ASSESSMENT

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## Abstract

The components of the SIS100 synchrotron [1] (FAIR facility [2]) are presently under installation in the accelerator tunnel. The superconducting dipole magnets have been produced and the magnet field errors up to 7th order have been measured for all magnets. The superconducting quadrupole magnets are under production, the field error data for a part of the magnets is available. As a part of the magnet quality assessment, the particle tracking simulations are used to study the beam losses during the 1 sec beam accumulation at the injection energy. The tune settings for the slow extraction operation are considered. Direct space-charge effects and the Landau damping octupole magnets, which dominate the incoherent tune distribution, are included. In order to reduce the computational load and to increase the parameter resolution, a machine learning based optimizer is used in the accelerator and beam parameter studies.

## SIS100 MAIN MAGNETS

Due to inevitable deviations from a pure dipole and quadrupole structure, the magnetic field of the main magnets contain field errors. The resulting magnetic field can be represented as a sum of the harmonic coefficients  $B_n$ ,  $A_n$ ,

$$B_y + iB_x = (B_n + iA_n) \left( \frac{x + iy}{r_0} \right)^{n-1}, \quad (1)$$

where  $r_0$  the reference radius,  $B_n$  are the normal components,  $A_n$  are the skew components.  $B_1$  is the dipole component,  $B_2$  is the quadrupole component, etc. The relative field error components for a dipole magnet are defined as  $b_n = \int B_n ds / \int B_1 ds$  and  $a_n = \int A_n ds / \int B_1 ds$ . For a quadrupole magnets, the definition is corresponding, with the leading component  $B_2$  which is used in the denominator.

Since the available magnet data is not complete, we construct a statistic model for the main magnets. Each multipole  $b_n$  and  $a_n$  is described by a “systematic” component, which is the mean of the distribution, and by a “stochastic” component. The latter corresponds to the standard deviation of the Gaussian distribution, which is used to randomly assign each magnet with its individual component. It is assumed that only the geometrically allowed harmonics (for dipoles  $B_3, B_5, B_7$ , for quadrupoles  $B_6$ ) provide the systematic components.

The SIS100 focusing system includes 166 superconducting quadrupole magnets and 2 normal-conducting quadrupole magnets for the extraction section. The superferric superconducting magnets have the length 1.3 m

while the normal-conducting ones 1.76 m. The resulting focusing perturbation is assumed to be compensated by the lattice settings [3]. The manufactured superconducting quadrupole magnets are measured with a rotating coil magnetometer [4, 5]. The data from 51 magnets is available now, the resulting field error model is shown in Fig. 1.

The 108 SIS100 dipole magnets [6, 7] are superferric superconducting magnets. All the SIS100 dipole magnets have been manufactured, delivered and measured with a rotating coil system [4, 8] in the cold (superconducting) condition. The quality assessment of the dipole magnets, including the beam loss studies using the particle tracking simulations [9] have demonstrated a high field quality which is required for high-intensity, low loss operation. Due to a good quality of the magnets, it has been decided to refrain from the magnet sorting. The process of the dipole magnet installation into the accelerator tunnel is presently under progress, and the exact position of each magnet in the lattice is not specified so far. Therefore, similar to the quadrupole magnet case, we use the statistic model for the field error harmonics  $b_n$ ,  $a_n$ , with the systematic and stochastic components, see Fig. 2.

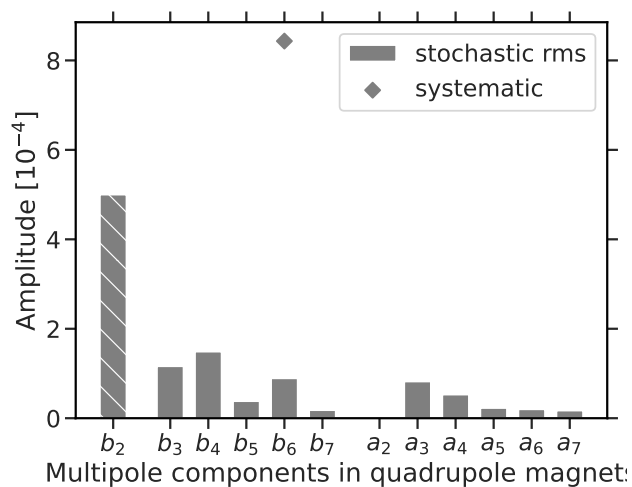


Figure 1: The model for the magnet field errors ( $b_n$ ,  $a_n$ ) in the SIS100 main quadrupole magnets.

## BEAM CONDITIONS IN SIS100

Beam accumulation for 1 sec at the injection energy is a challenging phase of the SIS100 cycle. Low-loss, below 6%, is required under conditions of high-intensity. The  $U^{28+}$  reference beam parameters considered here correspond to [3, 9]. In addition, we take into account the octupole magnets which

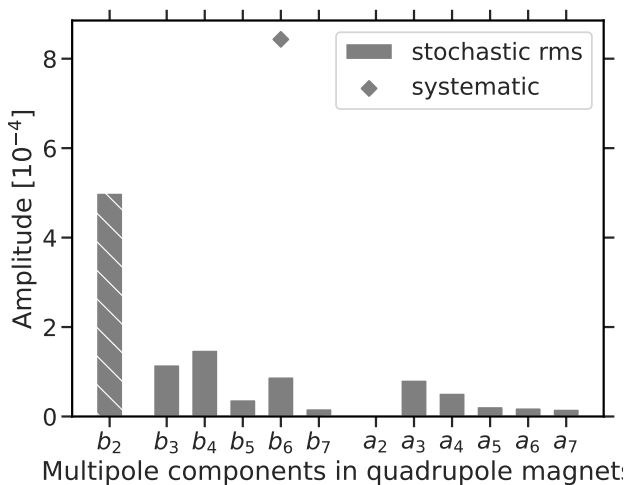


Figure 2: The model for the magnet field errors ( $b_n, a_n$ ) in the SIS100 main dipole magnets.

will be used to suppress the transverse collective instabilities but can reduce the dynamic aperture and cause beam losses [10, 11]. For a comparison with the effect of octupoles, Table 1 summarizes the relevant tune shifts.

The focus of the SIS100 operation in the first years will be the slow extraction mode. After the beam acceleration to the final energy the tune will be placed close to  $Q_x = 17.33, Q_y = 17.4$  for the resonance-driven slow extraction. During the injection energy phase the tune will be chosen close to this location with the objective of the low-loss operation. In this work we examine the corresponding tune quadrant.

Table 1: Transverse Tune Shifts Conditions

Space charge	max shift	$x$	-0.2
Space charge	max shift	$y$	-0.3
Chromaticity	rms spread	both	0.01
$K_3 = 50 \text{ m}^{-4}$	max span	$x$	0.039
$K_3 = 50 \text{ m}^{-4}$	max span	$y$	0.043

## SEARCH FOR THE SAFE TUNES

The particle tracking simulations are performed using the 6D symplectic single-particle tracking library SixTrackLib [3, 12]. The complete SIS100 lattice is modelled with the thin-lens representation of the long magnets, the fringe field effects are also included. A 6D Gaussian bunch distribution with the  $2\sigma$  truncation is used. The corresponding transverse nonlinear space-charge interaction is applied to every particle continuously in the frozen method [3].

The first method of the search for the safe tune areas is the tune scan. Figure 3 shows the results of a tune scan with the tune step  $\Delta Q_x = \Delta Q_y = 0.025$ . Beam loss after 160 thousand turns, which corresponds to 1 sec, is shown with the color for each tune value. For both  $Q_x$  and  $Q_y$ , 16 values are considered, resulting in 256 simulation runs for this scan.

The black line in Fig. 3 shows the contour of the beam loss of 6%, the area within this line is  $S_Q = 0.0129$ . The best tune found is  $Q_x = 17.12, Q_y = 17.27$  with the beam loss of 0.1%.

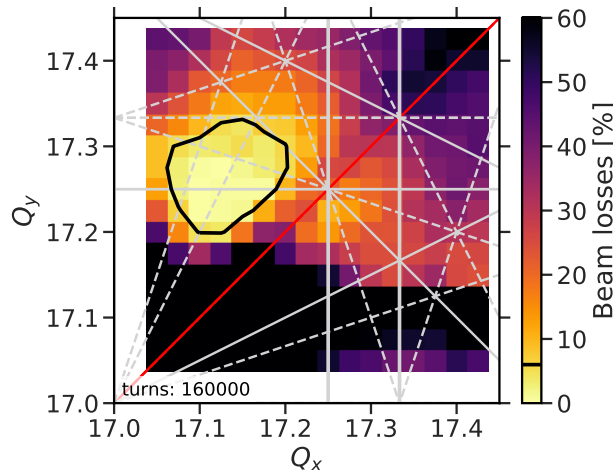


Figure 3: Beam losses from the simulation runs in a tune scan. The black line is the contour of the 6% beam loss.

The second method is a Bayesian Optimization using a Gaussian process to propose the tune values. The "AX" software [13, 14] has been used, with the "Log Noisy Expected Improvement" method [15]. In this example an iterations consists of a set of 20 tune values. Simulations are performed for a tune set, the algorithm analyzes the results of the simulation runs and provides the next set of 20 tunes. Figure 4 demonstrates the progress of the Bayesian Optimization with four consecutive tunes sets. The resulting beam loss contours are shown in Fig. 5. The area of tunes with low losses around  $Q_x = 17.12, Q_y = 17.27$  is found in the second iteration. During the following iterations, only a few tunes are chosen close to the safe tune, while the rest are used to explore other tune areas. The contour of the 6% beam loss nearly does not change after the second iteration. The best tune with zero losses has been found already in the third iteration for  $Q_x = 17.115, Q_y = 17.239$ . In the fourth iteration two tunes with zero losses were determined.

## SIMULATIONS WITH OCTUPOLES AND CONCLUSIONS

For our study of the effect of Landau damping octupoles on the beam losses, we consider the scenario with all the SIS100 octupoles powered by  $K_3 = \pm 50 \text{ m}^{-4}$ , with the effective field length  $L = 0.75 \text{ m}$ . The case  $K_3 = \pm 100 \text{ m}^{-4}$  corresponds to the maximum magnet power. The results are summarized in Table 2.

The octupole magnets increase the beam losses and reduce the safe tune area. Figure 6 shows the results of a tune scan with octupoles  $K_3 = 50 \text{ m}^{-4}$ . The minimal beam loss found is 6.9% and the contour line in Fig. 6 is for the beam loss of 9%. The opposite polarity, Fig. 7, provides a slightly different beam loss pattern, but the safe tune area is similar. With

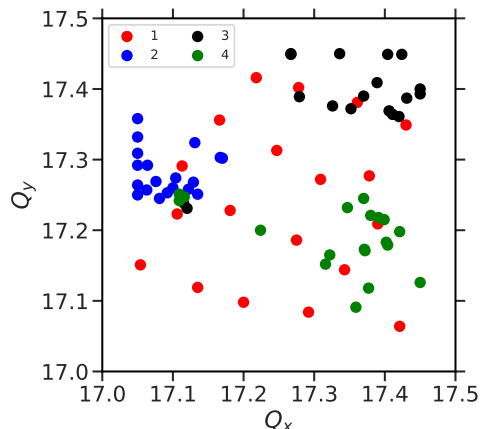


Figure 4: Four iterations in the Bayesian Optimization with 20 tune sets.

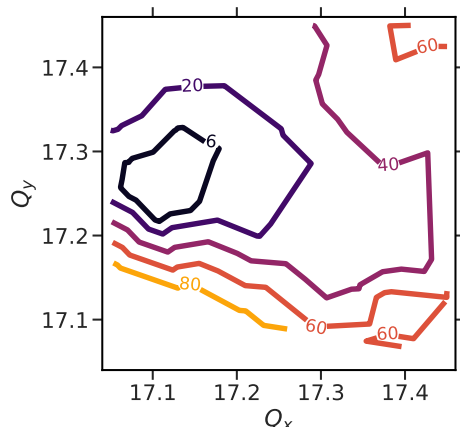


Figure 5: Contour lines of the beam losses (given in percent) from the simulation runs in a Bayesian Optimization.

Table 2: Results of the Beam Loss Simulations

Method	$K_3, \text{m}^{-4}$	$S_Q, 10^{-3}$	Min. Loss
Scan	0	12.9 for 6%	0.1%
BO	0	7.8 for 6%	0
Scan	50	13.2 for 9%	6.9%
Scan	-50	21 for 9%	5.6%
BO	50	24 for 9%	6.6%
Scan	100	5.6 for 22%	18.6%
Scan	-100	0.7 for 22%	18.6%
BO	100	4.8 for 22%	18.5%

the octupoles powered to the maximum  $K_3 = \pm 100 \text{ m}^{-4}$ , the minimal beam loss of around 19% has been found.

The simulations with octupoles using the Bayesian Optimization method provide similar safe tune areas, Table 2. Again, iterations with sets of 20 tunes have been used, the safe tune area has been determined after third iteration.

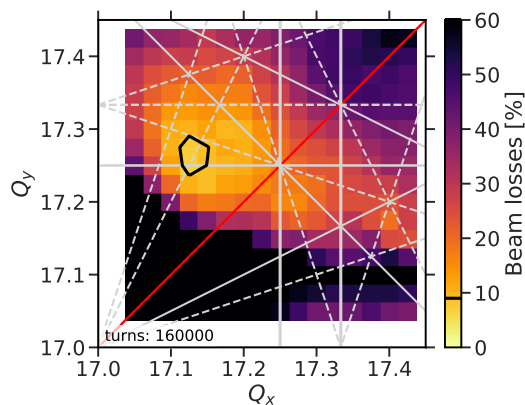


Figure 6: Beam losses from a tune scan with the octupole magnets  $K_3 = 50 \text{ m}^{-4}$ . The black line is for 9%.

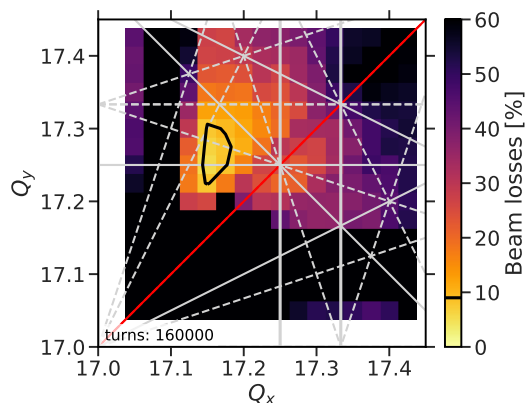


Figure 7: Beam losses from a tune scan with the octupole magnets  $K_3 = -50 \text{ m}^{-4}$ . The black line is for 9%.

In conclusion, our particle tracking simulations with space charge indicate reliable safe tune areas (Figs. 3, 5), which suggests a sufficient main magnet quality for the low-loss SIS100 operation. A Bayesian Optimization for the search of the safe tunes has been implemented. In the present example, this method requires 60 simulation runs, in a comparison to 256 runs during a tune scan for similar results. The BO can be used for extensive beam and machine parameter studies and optimizations.

The octupole magnets will be used in SIS100 to suppress the transverse collective instabilities. For the reference  $U^{28+}$  beam conditions and the tune considered in this work, it is estimated that  $K_3 \approx 50 \text{ m}^{-4}$  will be needed to stabilize the coupled-bunch instability [16]. Our simulations indicate that this octupole power is marginally acceptable to obtain a  $\approx 6\%$  beam loss operation. The octupole magnet polarities and power setups within the two octupole magnet groups in SIS100 can be optimized. We observed that the octupoles with  $K_3 = \pm 100 \text{ m}^{-4}$  produce intolerable beam losses. For a safety margin during the SIS100 operation with the octupoles, the usage of a feedback system is advisable. It will allow to balance the octupole power with the beam loss and the beam stability.

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