

STUDIES OF SLOW EXTRACTION FROM SIS100 IN THE PRESENCE OF MAGNET IMPERFECTIONS

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Abstract

The synchrotron SIS100 at FAIR, under construction in Darmstadt, Germany, will deliver slow-extracted proton and ion beams up to 100 Tm using resonant extraction. The baseline method is transverse knock-out (KO) extraction, while the COSE (Constant Optics Slow Extraction) scheme has emerged as a promising alternative to quadrupole-driven extraction. This is particularly relevant for experiments requiring short extraction times, which are challenging to attain with KO extraction due to the power limitations of the KO exciter. Higher-order multipoles from the fast-ramping super-ferric dipole and quadrupole magnets deform the separatrix and increase the angular spread of particles with different momenta at the electrostatic septum, leading to enhanced losses. In this contribution, we present the status of SIS100 slow-extraction simulations for different extraction schemes, including the effects of systematic and random magnetic-field errors.

INTRODUCTION

The core accelerator of the FAIR facility is the synchrotron SIS100 [1], designed to deliver high-intensity heavy-ion beams from protons up to uranium at a maximum rigidity of 100 Tm. Slow extraction with spill lengths of the order of seconds is essential to the experimental program of FAIR (NUSTAR, CBM, and APPA). The NUSTAR experiments at the Super-FRS impose particularly stringent demands: for the reference ion U^{28+} , the design intensity is $5 \cdot 10^{11}$ particles per cycle, or up to $1.5 \cdot 10^{11}$ particles per second. At these intensities radiation and machine protection requirements limit the tolerable beam loss to a few per cent, generally requiring an extraction efficiency exceeding 95 %.

Magnetic measurements of the main dipoles and quadrupoles have revealed systematic multipole components large enough to distort the separatrix and thereby degrade extraction efficiency. Recently, the design of the corrector magnets has been modified to include decapole corrector magnets [2], enabling compensation of the decapole error in the dipoles.

The baseline extraction scheme in SIS100 is transverse knock-out (KO) extraction [3], with constant optics slow extraction (COSE) [4] and quadrupole driven extraction as fallback options. In the present report, we use the standard working point for slow extraction, around $Q_x, Q_y = 17.32, 17.45$, utilizing the third order resonance at $Q_x = 52/3$ for extraction. In certain cases, for high-energy beams, alternative working points are considered to avoid the transition en-

ergy [5]. However, the overall influence of field errors is similar and the following discussion remains valid.

MAGNETIC FIELD ERRORS

All the 110 super-ferric main dipoles of SIS100 have been magnetically measured [6] and the resulting data analyzed. Systematic mean values appear for the allowed components b_3 (sextupole) and b_5 (decapole).

The super-ferric main quadrupoles are still under manufacturing and magnetic field data are presently available for 53 of the 166 magnets [2]. Among the multipole errors, the allowed components b_6 (dodecapole) and b_{10} (20-pole) show significant systematic mean values, with b_6 being particularly prominent and inspection of the data confirms that both components originate predominantly from the magnet ends. Although only one third of the magnet data is available, the distribution and mean values of the field harmonics are assumed to be representative.

MULTI-PARTICLE TRACKING

Systematic Field Errors

Systematic magnetic field errors in dipoles (b_5) and quadrupoles (b_6) introduce amplitude-dependent tune shift (ADTS), which affects slow extraction performance in SIS100. While the b_6 component of the quadrupoles generates ADTS directly, the b_5 component of the dipoles contributes indirectly via dispersion-induced feed-down, producing a momentum-dependent octupole term. This results in a momentum-dependent ADTS, leading to an angular spread of the separatrices and increased losses at the electrostatic septum (ES) and the Lambertson septum (LS).

Representative slow extraction scenarios have been defined for different extraction modes and beam emittances. For each case, machine settings were optimized assuming an ideal lattice without random errors. The relevant systematic multipole components from dipoles (b_3, b_5) and quadrupoles (b_6) were included using mean values from measured field data. The systematic b_{10} component of the quadrupoles was set to zero, since its contribution would partially compensate the effect of b_6 . This choice represents a conservative scenario, requiring full compensation of b_6 by dedicated correction schemes.

Multi-particle tracking simulations were performed using Elegant [7] to study the loss performance. The initial transverse beam distribution was a 4D waterbag distribution, matched to the separatrix area of each case, while the longitudinal distribution was Gaussian in $\delta = \Delta p/p$, with a standard deviation of $\sigma_\delta = 5 \cdot 10^{-4}$, truncated at $2\sigma_\delta$. 5000 particles were tracked over 30000 turns.

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For KO extraction, two separatrix sizes were considered, $28\pi\mu\text{m}$ and $8\pi\mu\text{m}$, adapted to U^{28+} beams at 0.4 GeV/u and 1.5 GeV/u , respectively, see Fig. 1. KO extraction requires horizontal chromaticity correction close to zero. The strong sextupoles needed for this correction introduce significant second-order ADTS, which has to be compensated by octupole correctors. Due to the momentum-dependent ADTS from the dipole b_5 component, the Hardt condition cannot be fulfilled exactly, resulting in correlations between particle coordinates and momentum deviation, as seen in Fig. 2. Losses at the ES remain low for KO, amounting to 2.2 % for the large and 1.8 % for the small separatrix. The slightly higher losses for the larger separatrix are attributed to an increased particle density at the ES wires, despite a smaller angular spread, indicating that loss estimates cannot rely on angular spread alone.

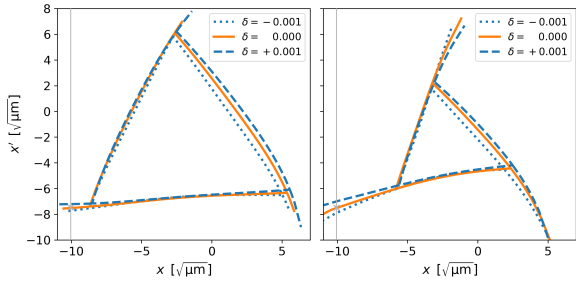


Figure 1: Separatrices for KO extraction with stable area $28\pi\mu\text{m}$ (left) and $8\pi\mu\text{m}$ (right) in normalized phase space. The grey line and cross mark the position and angle of the ES.

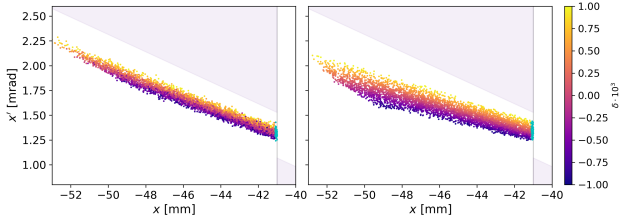


Figure 2: Horizontal phase space distribution of extracted particles at the ES for KO extraction with $28\pi\mu\text{m}$ (left) and $8\pi\mu\text{m}$ (right), color-coded by δ . Particles lost at the ES or LS are marked in cyan.

For COSE, the reference momentum is varied during extraction such that all magnet strengths are scaled in proportion to $B\rho$ while maintaining constant optics. In SIS100, the presence of the dipole b_5 component actually improves the overlap of separatrices by partially compensating chromatic effects, Fig. 3, thereby reducing the angular spread at the ES. This is advantageous compared to quadrupole-driven extraction, where varying the tune by ramping quadrupoles changes the separatrix properties and increases the angular spread at the ES.

Simulations for COSE were carried out for separatrix areas of $28\pi\mu\text{m}$ and $10\pi\mu\text{m}$, Fig. 3. The extracted phase space distributions, Fig. 4, show reduced correlation between angle and momentum compared to KO-extraction.

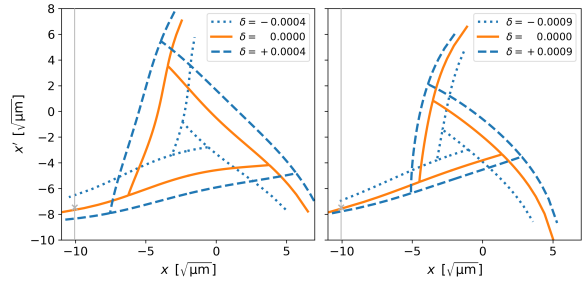


Figure 3: Separatrices for COSE with $28\pi\mu\text{m}$ (left) and $10\pi\mu\text{m}$ (right) stable area in normalized phase space. The grey line and cross mark the position and angle of the ES.

The simulated losses are 2.1 % for small and 3.5 % for large separatrix cases, with an additional 0.2 % loss at the LS in the latter case. The losses at the LS can, however, be mitigated by increasing the ES deflection angle from its nominal value, since the large separatrix is only required for lower extraction energies. A practical limitation of COSE is the requirement to ramp all main magnets simultaneously over a relatively small magnet field range, making the resolution of the current control of the power converters critical for a smooth spill structure

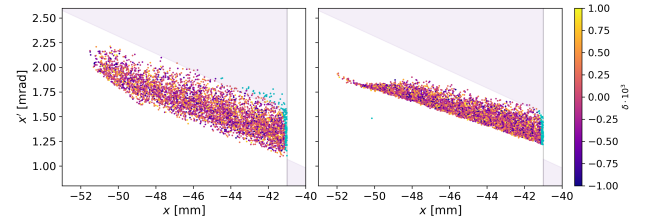


Figure 4: Horizontal phase space distribution of extracted particles at the ES for COSE with $28\pi\mu\text{m}$ (left) and $10\pi\mu\text{m}$ (right) separatrix, color-coded by δ . Lost particles in cyan.

Initial studies incorporating b_5 corrector magnets have been carried out for quadrupole-driven extraction, showing that losses, particularly in the extraction channel at the LS, can be reduced by compensating the dipole b_5 component. The correctors may also be beneficial for COSE by deliberately increasing the effective b_5 component, improving the overlap of the separatrices at the ES and thereby reducing losses.

The simulations demonstrate that systematic multipole errors play a key role in slow extraction, but that suitable settings can recover design performance. KO extraction provides the lowest losses at the ES, while COSE is a viable alternative benefiting from partial compensation of chromatic effects by the dipole b_5 component, which reduces angular spread at the ES as compared to quadrupole-driven extraction. The total losses for different cases are summarized in Table 1 (left column).

Random Magnet Errors

Multi-particle tracking simulations using MAD-X [8] were performed to study the influence of random magnet errors on slow extraction. In addition to the systematic mul-

Table 1: Losses of KO and COSE From Multi-Particle Simulations for Systematic Field Errors, and Random Field and Alignment Errors Respectively

Extraction mode	Loss (systematic)	Loss (random)
KO, $8\pi\mu\text{m}$	1.8 %	2.4 %
KO, $28\pi\mu\text{m}$	2.2 %	2.2 %
COSE, $10\pi\mu\text{m}$	2.1 %	4.2 %
COSE, $28\pi\mu\text{m}$	4.0 %	5.7 %

tipoles, the errors included variations in the integral strength of dipoles and quadrupoles, random multipole errors (normal and skew) of order 2 to 7 for the dipoles and of order 3 to 10 for the quadrupoles, as well as alignment errors. The values for the integral strength variations and random multipole errors were extracted from measurement data [9]. The magnet alignment errors were modeled using truncated Gaussian distributions with a cutoff at 2σ . The applied errors include dipole rolls with $\sigma_\theta = 4\text{ mrad}$, random quadrupole transverse offsets with $\sigma_{x,y} = 1\text{ mm}$, and quadrupole rolls with $\sigma_\theta = 1\text{ mrad}$.

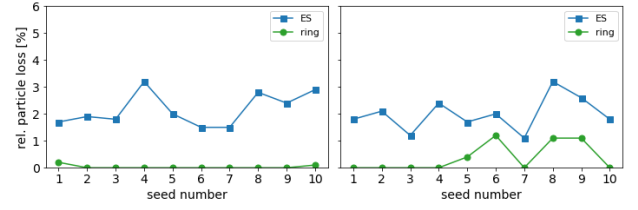
The initial transverse beam distribution was a 4D Gaussian with a cut-off at 2σ in each plane, where the boundary emittance corresponds to the nominal beam emittance. Longitudinally, a Gaussian distribution with $\sigma_\delta = 5 \cdot 10^{-4}$ truncated at $2\sigma_\delta$ was used, identical to the simulations with systematic errors only.

For each slow extraction case, ten random error realizations were generated using different seeds. For each seed, after applying the errors, the closed orbit was corrected using steering magnets, leaving a maximum residual closed orbit distortion of $\lesssim 3\text{ mm}$. An optimization step was then performed to recover a separatrix with characteristics similar to the systematic case, namely separatrix area, spiral step, and separatrix angle at the ES. The parameters varied in the optimization include tune distance to resonance, resonance sextupole amplitude and phase, octupole strengths, and ES orbit bump amplitude, with tunes and chromaticities matched at each step.

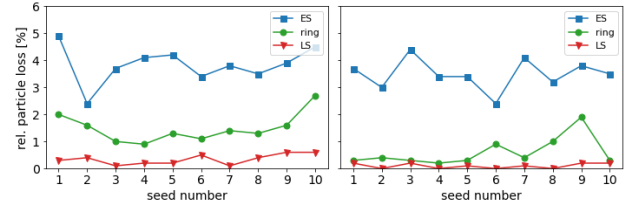
The particle losses were determined by multi-particle simulations, where 1000 particles were tracked for 25000 turns. Identical initial beam distributions were applied across all seeds for simplified comparison.

Simulations for KO extraction were carried out for two separatrix areas, $28\pi\mu\text{m}$ and $8\pi\mu\text{m}$, adapted to U^{28+} beams at 0.4 GeV/u and 1.5 GeV/u , respectively. The KO exciter was modeled as a thin dipole kick applying a band-limited pseudo-random noise signal generated via binary phase shift keying (BPSK). The losses for each seed are shown in Fig. 5. Losses occur predominantly at the ES, with additional ring losses for some seeds. For the large separatrix case, the average ES loss is 2.2% and for the small separatrix case, the average ES loss is 2.0% , with an additional 0.4% ring loss.

Simulations for COSE were carried out for separatrix areas of $28\pi\mu\text{m}$ and $10\pi\mu\text{m}$. The losses for each seed are displayed in Fig. 6. For the small separatrix case, the


 Figure 5: Losses for KO extraction for $28\pi\mu\text{m}$ (left) and $8\pi\mu\text{m}$ (right) separatrix cases for different random seeds.

average ES loss is 3.5% , with additional losses of 0.1% at the LS and 0.6% in the ring. For the large separatrix case, the average ES loss is 3.8% , with additional losses of 0.3% at the LS and 1.5% in the ring. For seed 4 in the large separatrix case, the spiral step was reduced to 9 mm to mitigate horizontal ring losses. Residual vertical ring losses appear for a few seeds, attributed to the skew third-order resonance $2Q_x + Q_y = 52$. These are expected to disappear with reduced initial momentum offset of the COSE sweep.


 Figure 6: Losses for COSE for $28\pi\mu\text{m}$ (left) and $10\pi\mu\text{m}$ (right) separatrix cases for different random seeds.

In summary, KO extraction yields the lowest losses, with ES losses comparable to the systematic-error case. COSE shows higher ES losses than the systematic case. Ring losses in the random-error simulations are higher than in the systematic case, but remain below 1% for most cases, which is expected to be tolerable from a machine protection perspective. An exception is the COSE large-separatrix case (1.5%), which can likely be reduced by local orbit bumps and optimization of the initial δ offset. A comparison of the total losses of different extraction modes is shown in Table 1.

CONCLUSION

The impact of dipole and quadrupole magnetic field errors on slow extraction has been studied. Both magnet types have systematic multipole components large enough to distort the separatrix, and require dedicated compensation schemes to control losses. KO extraction remains baseline extraction scheme, with COSE as a fallback option. Multi-particle simulations, including random field errors as well as alignment errors, indicate that the lattice is robust against the expected magnet imperfections and that both KO extraction and COSE can provide acceptable extraction efficiencies.

Further studies will assess the recently included b_5 corrector magnet. Improvements are expected primarily for quadrupole-driven extraction but also for COSE, giving improved alignment of separatrices for different momenta and thereby reduced losses.

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