SLOW EXTRACTION ISSUES OF SIS-100

S. Sorge

GSI Darmstadt

Introduction

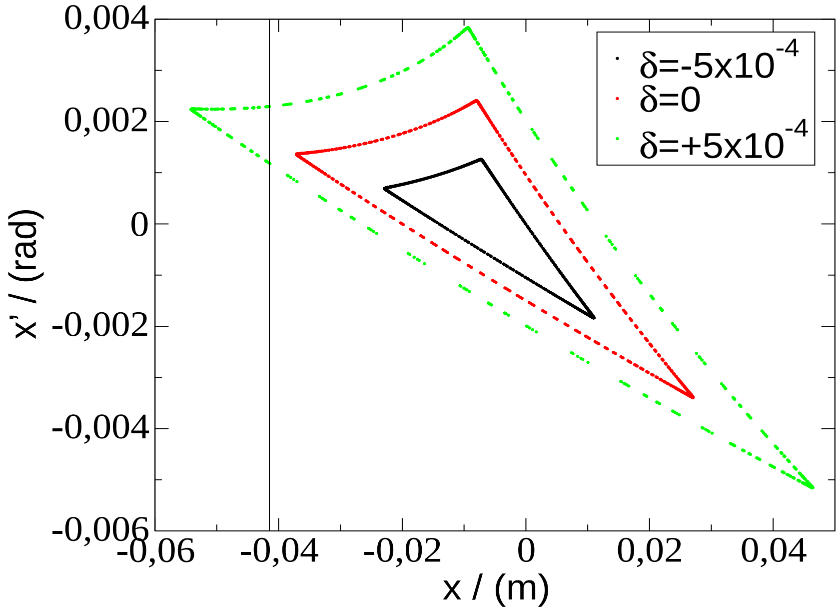
- SIS-100: heavy ion synchrotron of circumference $C = 1083.6$ m.
- Six period consisting of 14 cells each containing a quadrupole doublet.
- Acceleration of high intensity beam of many ion species' from Protons up to Uranium ions.
- Dominant mode: slow extraction of heavy ion beams.
  - Excitation of third integer resonance $3 \cdot Q_x = 52$ with 6 sextupoles $\rightarrow$ Working point: $Q_x = 17.31, Q_y = 17.45$.
  - Standard method: RF-KO extraction.
  - Reference ion: U^{28+}.
  - Extraction energies: $(0.4 - 2.7)$ GeV/u
  - Particle number up to $5 \cdot 10^{11}$ per cycle.

Goal of the studies

- Check settings for uncontrolled beam loss and modify them to minimise beam loss, where beam loss budget: $\sim\ 5\ \%$.
  $\rightarrow$ Particle tracking study.
- Starting point: Unperturbed lattice with settings provided by D. Ondreka.
- Extend model by magnet imperfections. Restrict to those of dipoles and quadrupoles.

Special details of SIS-100

Large natural chromaticities



Unnormalised natural horizontal chromaticity of unperturbed lattice: $\xi_{x,nat} = -20.9$

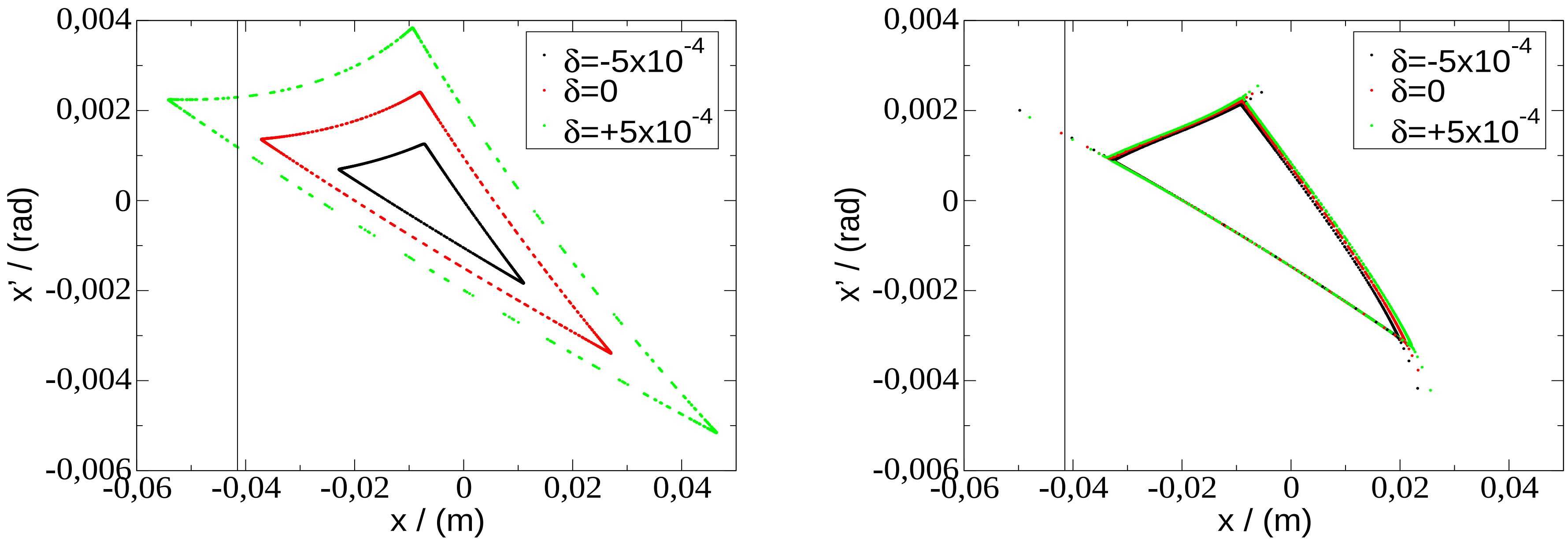
defined by

$$\Delta Q_z = \xi_z \delta, \quad z = x, y.$$

$\rightarrow$ Non-acceptable dependence of stable phase area and separatrix position on δ.

Special details of SIS-100

Horizontal chromaticity



Correct only horizontal chromaticity (D. Ondreka):

- Target value: $\xi_{x,corr} = -1.0$.
- Spread of separatrix phase space angles at ES septum $< 3.0 \cdot 10^{-5}$ rad for $\delta = \pm 0.001$.

Special details of SIS-100

Lattice with two normal-conducting quadrupoles

- Main magnets super-conducting. Exceptions:
  - Sextupoles for resonance excitation.
  - Quadrupoles in cell with ES septum (Cell 52).
- Normal-conducting quadrupoles with length $L = 1.76\ \mathrm{m}$ whereas all other quadrupoles super-conducting with length $L = 1.3\ \mathrm{m}$.
- Break slightly symmetry $\rightarrow$ beta beating.
- Minimisation for unperturbed lattice by properly setting their focusing strengths $k_1 L$ (D. Ondreka).
- Scheme for lattice with perturbations under construction (V. Chetvertkova).

Special details of SIS-100

Imperfections of dipoles and quadrupoles

- Misalignments → Closed orbit deformation.
- Random uncertainties in dipole bending angles and quadrupole focusing strengths.
  → modify closed orbit and lattice functions.
- Non-linear field errors given by multipole coefficients $k_n L, j_n L$ with systematic and random contributions.
  - in dipoles: measurement of first-of-series dipole.
  - in quadrupoles: field simulations.
  - modify resonance strength, chromaticities, and dynamic aperture.
- Magnets iron-dominated, largest field errors at maximum energies due to saturation.
  → At present simulations only for maximum energy.

Special details of SIS-100

Consequences of imperfections of dipoles and quadrupoles.

1. Change of horizontal chromaticity due to systematic sextupole errors.

- Contribution for present magnet data: $\xi_{x,errors} = -6.5 \pm 0.5$, (spread due to random errors).

- Resulting change of natural chromaticity:

$$\text{unperturbed lattice:} \quad \xi_{x,nat} = -20.9$$

$$\text{with magnet imperfections:} \quad \xi_{x,nat} = -27.5 \pm 0.5$$

- Need for stronger chromaticity correction sextupoles: 24 of strength

$$\text{unperturbed lattice:} \quad k_2L = -0.47\ \mathrm{m}^{-2}$$

$$\text{with magnet imperfections:} \quad k_2L = -0.6\ \mathrm{m}^{-2}$$

- On the other hand, 6 sextupoles for resonance excitation of strength $(k_2L)_{max} = 0.76\,\mathrm{m}^{-2}$.

  $\rightarrow$ non-linear optics part not dominated by resonance excitation sextupoles.

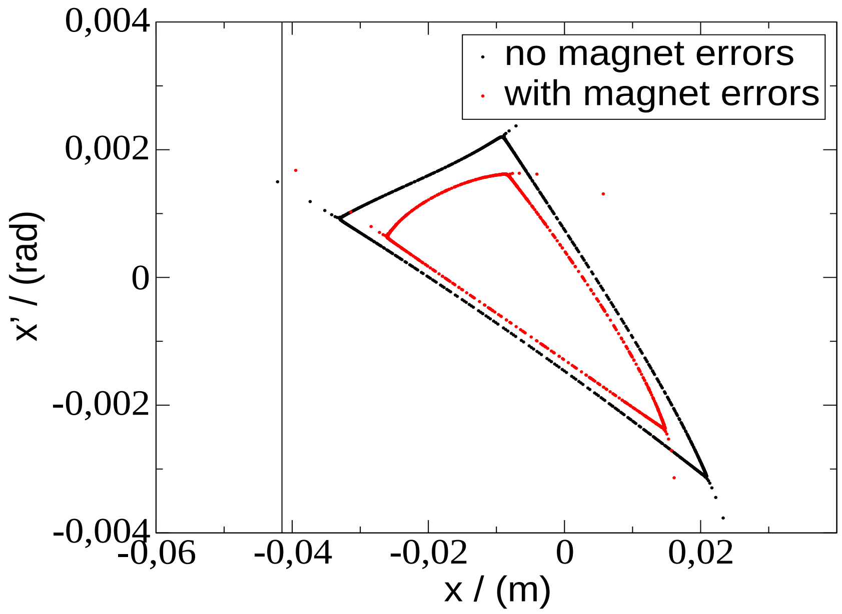
Special details of SIS-100

Consequences of imperfections of dipoles and quadrupoles.

2. Decrease of stable phase space area and increase of spiral step

Spiral step width at ES septum position:

- unperturbed lattice: $\Delta x_3 = 10$ mm
- lattice with errors: $\Delta x_3 = 20$ mm,



$\Downarrow$

Beam loss of ~ 10 % distributed around the ring, i.e. not at ES septum.

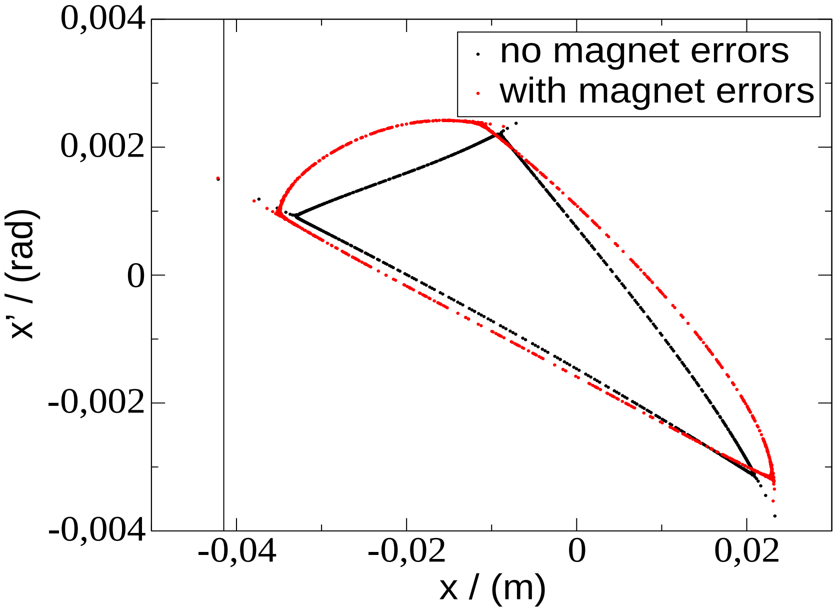
Magnet imperfections

Consequences of imperfections of dipoles and quadrupoles.

Cure:

Reducing strengths of resonance exciting sextupoles:

- original: $(k_2L)_{res,max} = 0.76\ \mathrm{m}^{-2}$
- final: $(k_2L)_{res,max} = 0.45\ \mathrm{m}^{-2}$



$\Downarrow$

- Stable phase space area and spiral step width restored.
- Separatrices no longer straight.

Final beam loss

Estimate particle loss with tracking simulations using MAD-X

- 10000 test particles
- 15000 turns which corresponds to $\Delta t \approx 0.05$ s
- KO extraction with artificially increased horizontal RF kick.
- Achieved beam loss of
  - $P_{loss} \approx 1\ \%$ at ES septum
  - $P_{loss} \approx 0.4\ \%$ distributed around the ring.

Remarks

Low beam loss is result of lattice optimisation in numerical model, where settings are entirely known.

Try to analyze how certain is information from simulations so that it can help to control settings in reality. Focus on

- Horizontal chromaticity
- Stable phase space area.

Horizontal chromaticity

Horizontal chromaticity ξ_x with uncertainties in lattice functions β_x, D_x

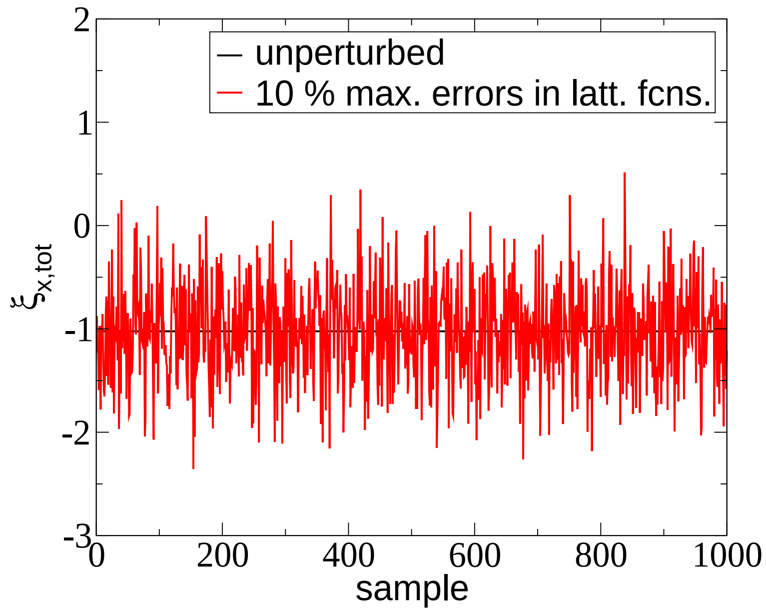
- Use formula to investigate robustness of chromaticity:

$$\xi_x = -\frac{1}{4\pi} \oint \mathrm{d}s\ \beta_x(s) \left[k_1(s) - D_x(s) k_2(s)\right]$$

- Add random deviations to β_x, D_x.

- RMS deviations of horizontal chromaticity, σ_{ξ_x}, for $\pm\ 10\ \%$ maximum deviations in lattice functions:

σ_{ξ_x}, main quads. and sexts.	σ_{ξ_x}, sextupole errors	σ_{ξ_x}, total
0.530	0.035	0.534



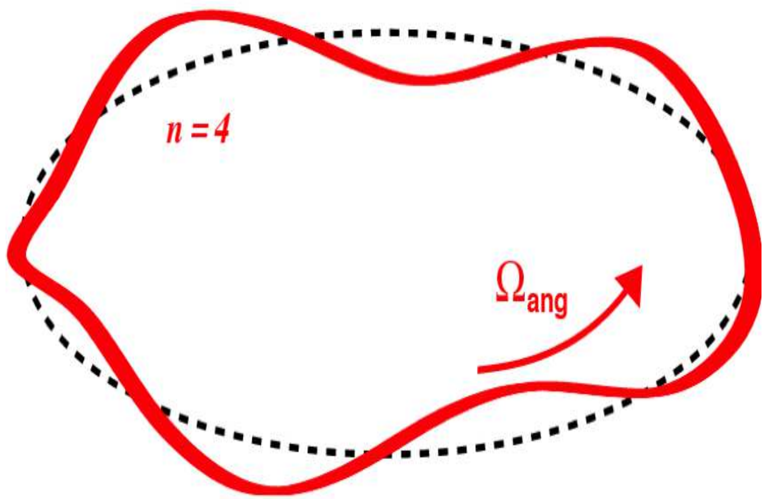
$\xi_x \pm 2\sigma_{\xi_x}$ exceeds slightly interval $[-2, 0] \rightarrow \Delta x'_{sep}(x_{ESS}) < 6.0 \cdot 10^{-5}$ for $\delta = \pm 0.001$.

Horizontal chromaticity

Spread in phase space angle of separatrix determines cross section of ES septum for particle collisions. Expect negligible increase for spread of $\Delta x'_{sep}(x_{ESS}) < 6.0 \cdot 10^{-5}$.

Possibly problem for high intensities for very small chromaticities:

- Coherent high intensity effects can drive beam instabilities $\rightarrow$ beam oscillation or destruction
- Large chromaticity inhibit growth of instabilities.
- Topic under discussion
  $\rightarrow$ possibly need for settings with larger ξ_x

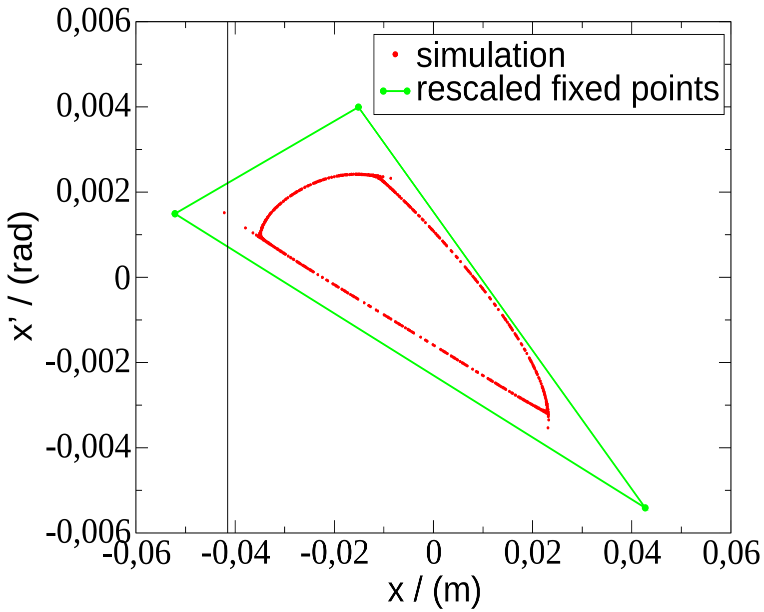


Courtesy: V. Kornilov

Stable phase space area

Size and orientation of stable phase space area determine spiral step and phase space angle of separatrix at ES septum position and, finally, beam loss.

Strong chromaticity correction and magnet errors: Strong sextupoles which do not contribute to virtual sextupole S_{virt}. Analytical expressions of linear theory of third integer resonance no longer valid.



Examples: modulus of unstable fixed points (UFP):

- Theory, S_{virt} with lattice functions from MAD-X:

$$|\vec{X}_{UFP}| = 8\pi \left| \frac{\Delta Q_x}{S_{virt}} \right| = 1.4 \cdot 10^{-2}\ \mathrm{m}^{1/2}$$

- Simulation: $|\vec{X}_{UFP}| = 0.8 \cdot 10^{-2}\ \mathrm{m}^{1/2}$.

  Also spiral step can not be analytically determined.

Stable phase space area

Consequence:

Sextupole settings which yield low beam loss were found by trial-and-error with simulations.

- Already generation of proper settings as input for multi-particle simulations is time consuming.
- In contrast to analytic formula, studying influence of lattice function uncertainties in sense of measurement errors can not be done independently of modifications of optics settings, e. g. quadrupole strengths.
- Nevertheless, such study is next proper step.

Summary

1. Simulation results suggest that settings can be found which provide acceptable particle loss.
2. The settings have to be validated.