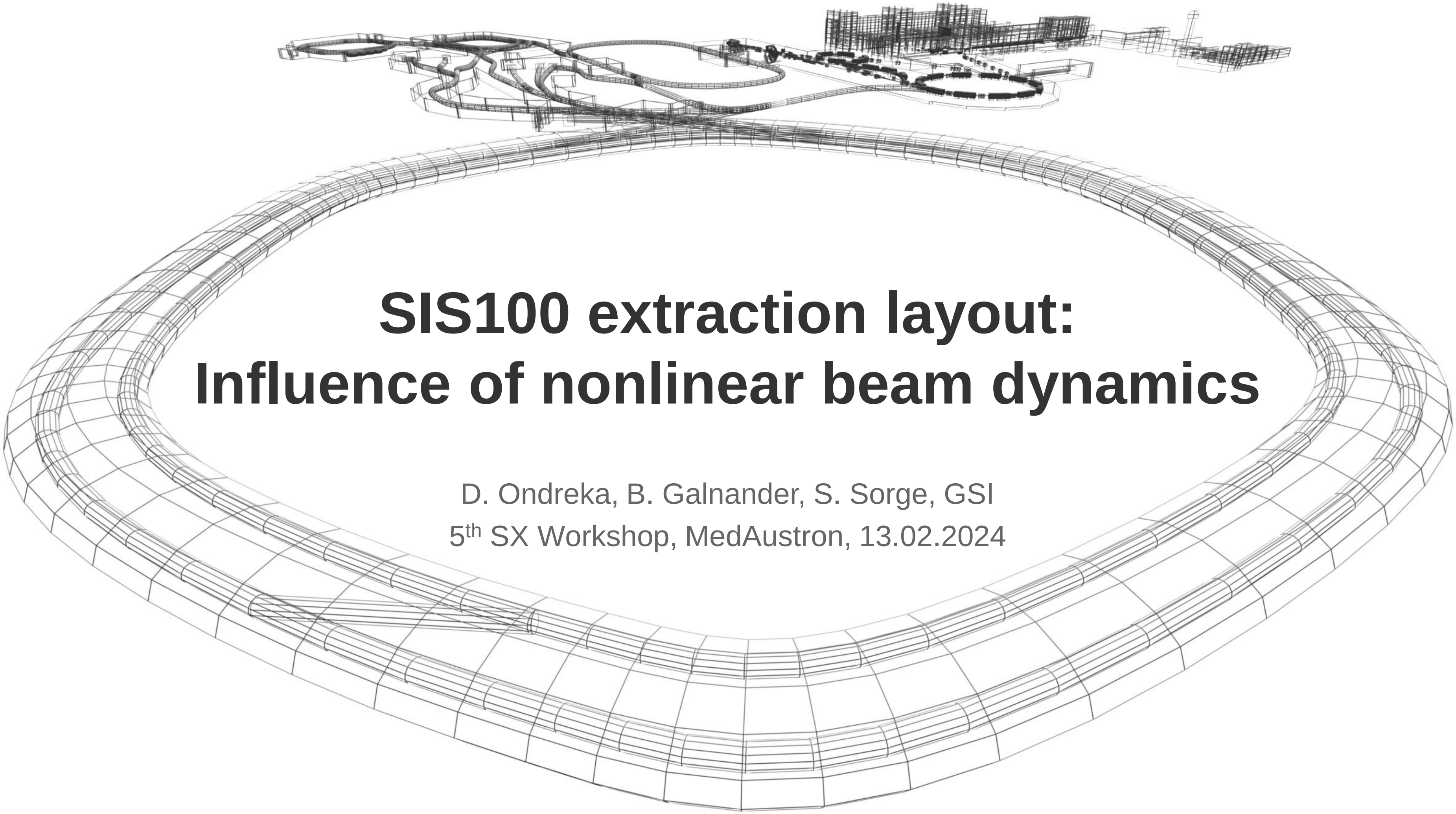


SIS100 extraction layout: Influence of nonlinear beam dynamics

D. Ondreka, B. Galnander, S. Sorge, GSI

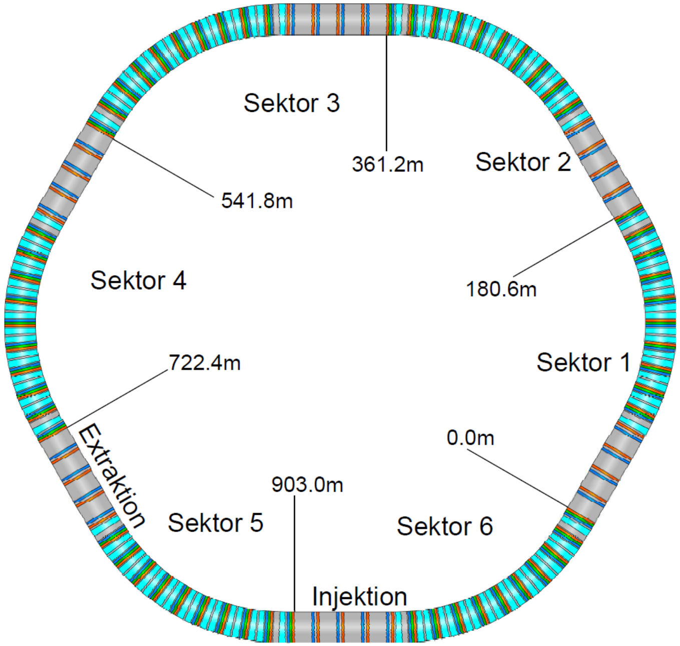
5th SX Workshop, MedAustron, 13.02.2024

Contents

- Lattice design criteria
- Constraints on SX
- Effect of nonlinearities on SX
- Impact of field errors
- SX schemes for SIS100
- Challenges for operation
- Summary and Outlook

SIS100: Overview

- Basic parameters
  - Circumference 1083m (= 5 x SIS18)
  - Max. magnetic rigidity 100Tm
  - Max. ramp rate 4T/s
  - Mostly super-ferric magnets
- Ion optical layout
  - Super-periodicity 6, 14 cells per period
  - DF focusing structure (charge separator lattice)
  - Optimized for operation with intermediate charge state ions
- Working modes
  - Batch injection from SIS18
  - Slow extraction to fixed targets
  - Fast extraction of compressed single bunches to fixed targets or storage rings



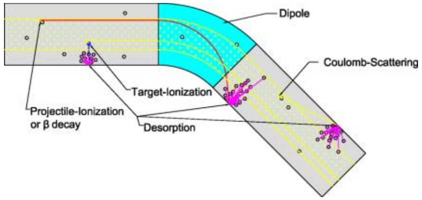
SIS100 optical parameters (SE)	
Q_h / Q_v	17.31 / 17.4
Q'_h / Q'_v	-20.3 / -20.6
α_p	0.005
γ_t	14.2

SIS100: Charge Separator Lattice

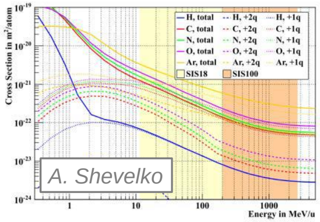
- Increased intensities due to low charge states
  - No stripping losses, lower space charge
  - FAIR design ion U^{28+} (instead of U^{73+})
  - Large transverse emittances in relation to rigidity
- Stable vacuum becomes critical issue
  - High electron loss cross section with residual gas
  - Lost particles create avalanche due to desorption
  - Tighter constraint than space charge
- SIS100 optimized for low charge states
  - DF doublet confining losses to well defined spots
  - Strong focusing to maximize catching efficiency
    - Tunes ~18, nat. chromaticities ~ -20
    - Challenging for SX due to large emittances
  - Cryo-catchers limit acceptance for SX

FAIR	SIS18	SIS100
Ion	U^{73+}	**U^{28+}**
Max. Energy	1 GeV/u	2.7 GeV/u
Max. Intensity	10^{10}/s	**10^{11}/s**

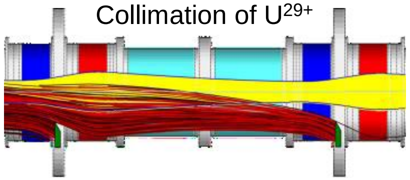
Vacuum instability by desorption



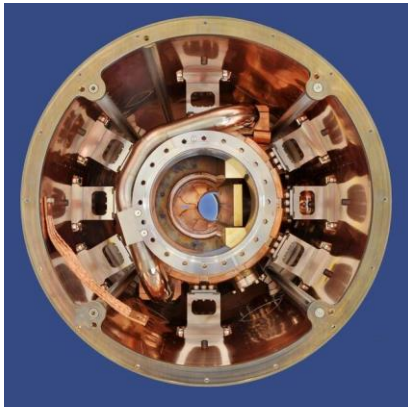
e-loss cross sections



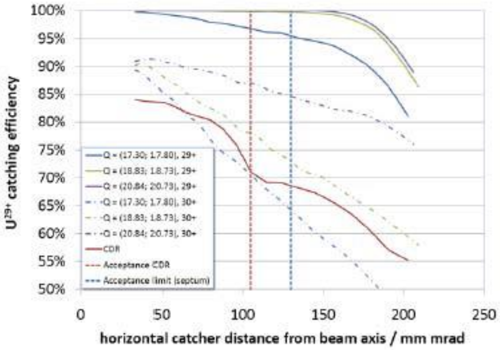
Collimation of U^{29+}



Cryo-catcher prototype



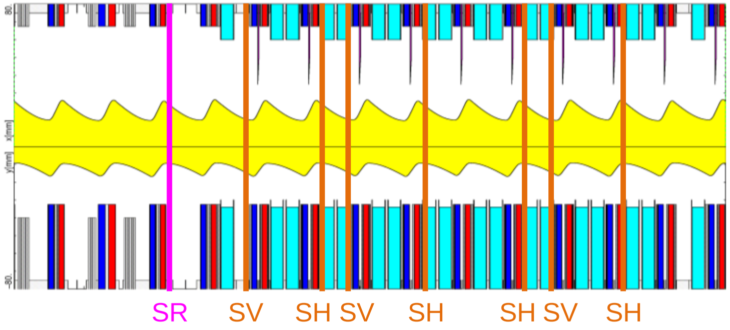
Catching efficiency for different tunes



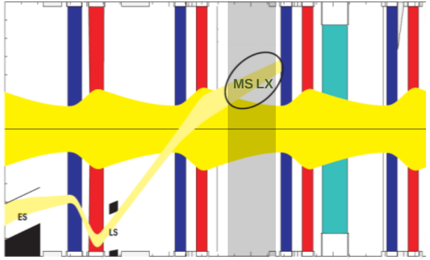
SIS100: Slow Extraction Layout

- Third order resonant extraction
  - Resonance tune $Q_r = 52/3$
  - Excited by six sextupoles with harmonic distribution
  - 42 additional chromaticity sextupoles
  - Large natural hor. chromaticity $Q'_x = -18$
- Extraction channel
  - 2 electrostatic wire septa (ES)
  - Vertical extraction through Lambertson septum (LS)
  - Single orbit bump at ES/LS
  - 3 magnetic septa (MS)
  - Lambertson steerer (LX) for hor. correction
- Slow extraction schemes
  - Baseline: Transverse RF KO extraction
  - Alternative: Tune ramp or similar
  - Reasons for alternative scheme
    - Uncertainties about micro-spill structure
    - Fall-back options for KO exciter failures

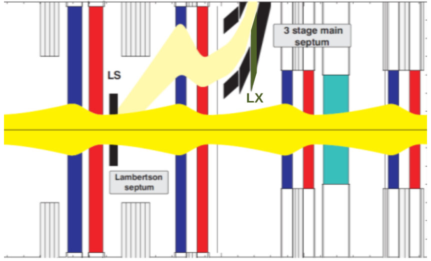
SIS100 slow extraction optic: envelopes



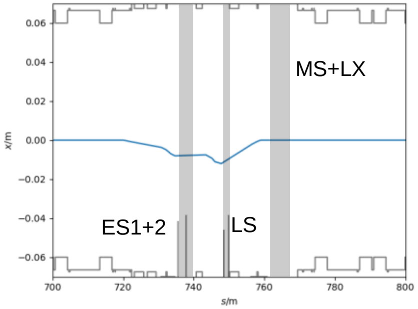
Extraction channel (H)



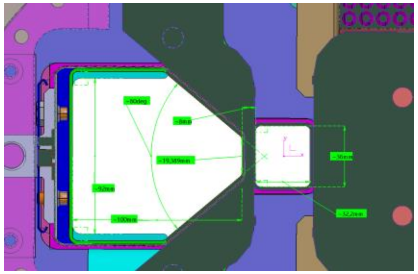
Extraction channel (V)



SIS100 extraction orbit



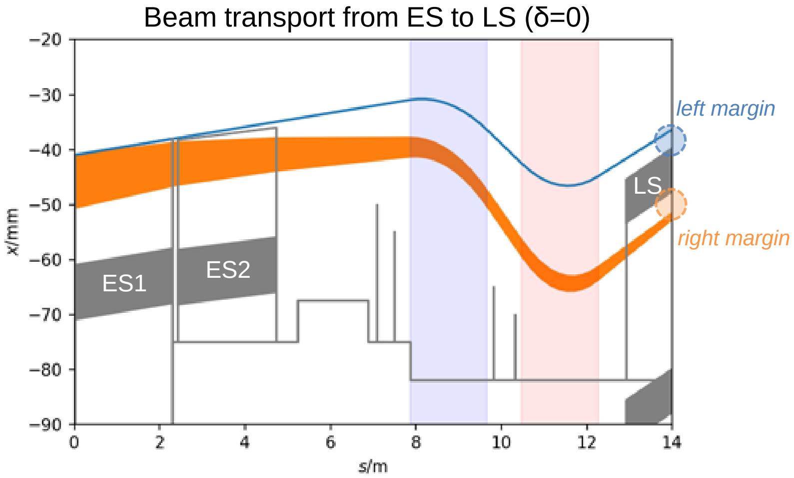
LS cross section

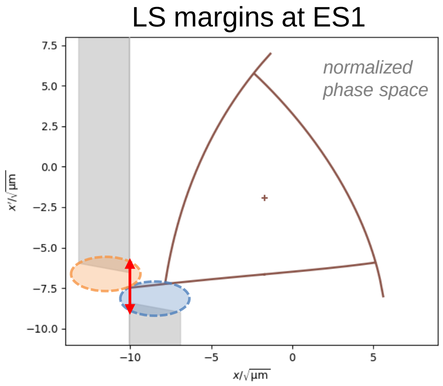


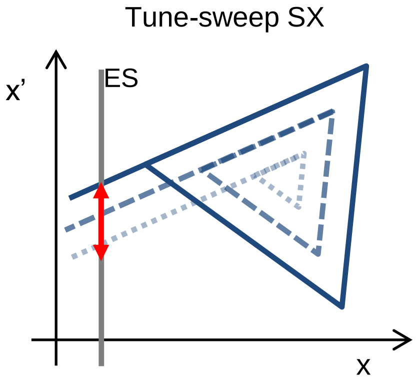
Constraints:
Extraction Channel

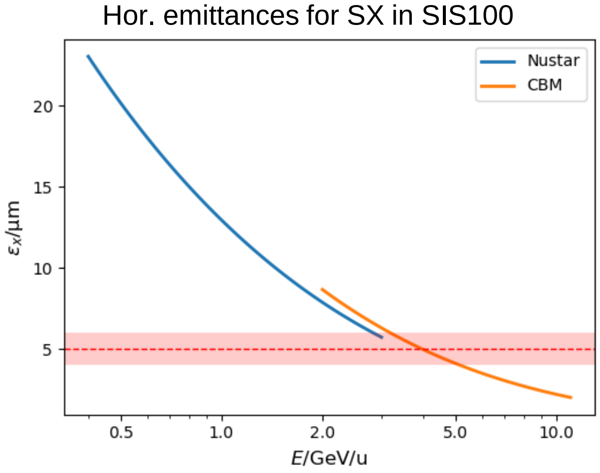
- Geometric constraints
  - ES kicks deliver 16mm separation at LS
  - Leaves design margin of ±4mm (for δ=0) at LS
  - Position response from ES1 to LS 15mm/mrad
  - Constrains SX separatrices
    - Permissible angular spread at ES1 ±0.25mrad
    - Spiral pitch at ES limited to |step/pitch| > 11.5 m/rad

- Consequences for SX schemes
  - Small angular spread despite large emittances
  - Curvature of separatrices must be limited
  - Limits simplest tune-sweep SX scheme to emittances below 5 mm*mrad


Beam transport from ES to LS (δ=0)


LS margins at ES1

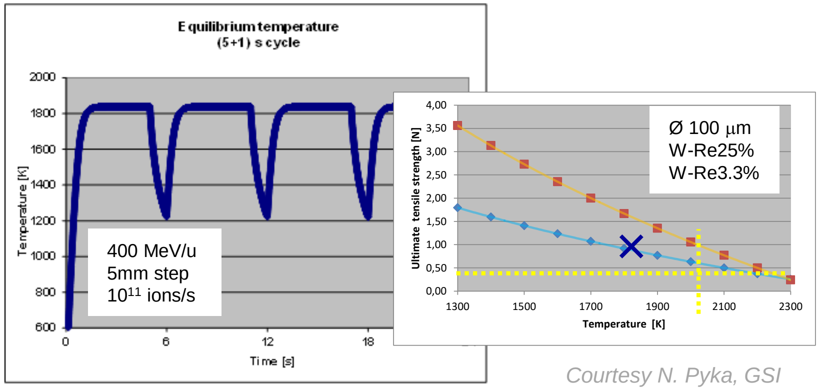

Tune-sweep SX


Hor. emittances for SX in SIS100

Constraints:
Spiral Step

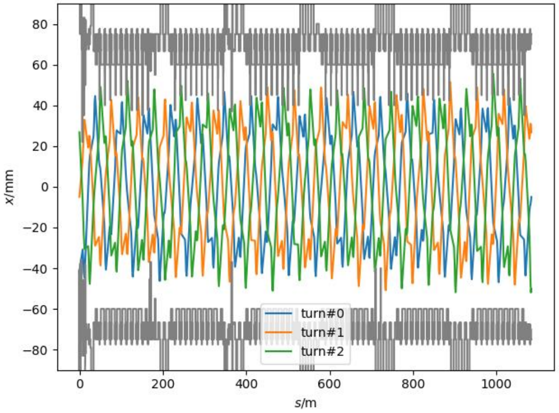
- Thermal load on ES wires
  - SIS100: 100µm W-Re25% wires at 1N tension
  - High dE/dx of heavy ions like U^{28+}
  - Temperatures critical for small spiral step
  - Spiral step must be at least 8 to 10mm
- Particle amplitudes over last three turns
  - Strongly constrained by cryo-catchers
  - Cryo-catcher distribution matched to amplitudes
  - Spiral step must not exceed 12 to 14mm

Thermal load on ES wires for U^{28+} design intensities

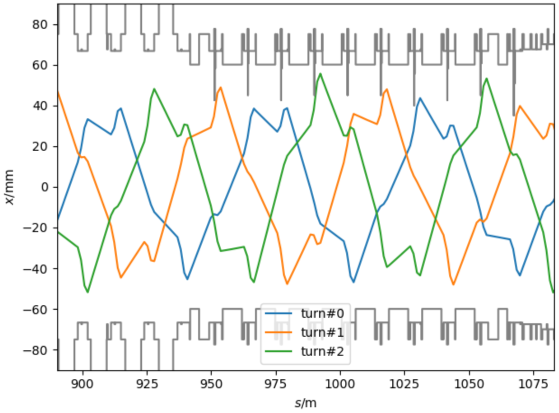


Courtesy N. Pyka, GSI

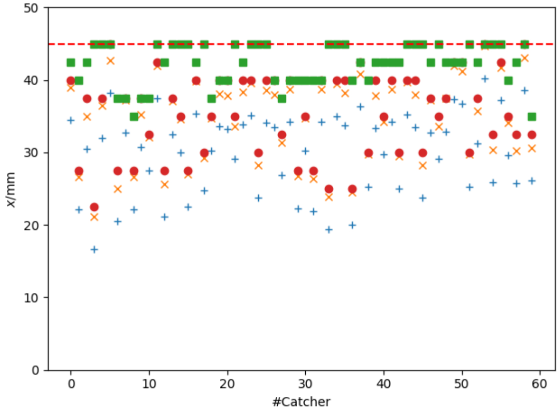
Amplitudes over the last three turns



Last three turns in sector 4



Matched acceptance at cryo-catchers



Nonlinearities in SX

- Simplest lattice for 3^{rd} order resonant SX
  - Sextupoles for resonance excitation only
  - No resonance but extraction resonance excited

- Additional nonlinearities in real SX lattices
  - Sextupoles for chromaticity correction
  - Quadrupole fringe fields (pseudo-octupole)
  - Higher multipoles from field errors of main magnets

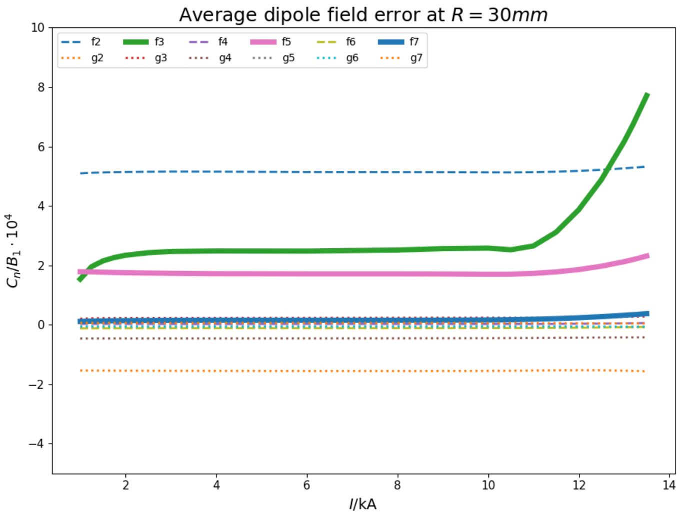
- Systematic effects relevant for SX design
  - Amplitude-dependent tune shift (ADTS)
  - Momentum-dependence beyond chromaticity
  - Parasitic resonances

- Random effects left for error studies

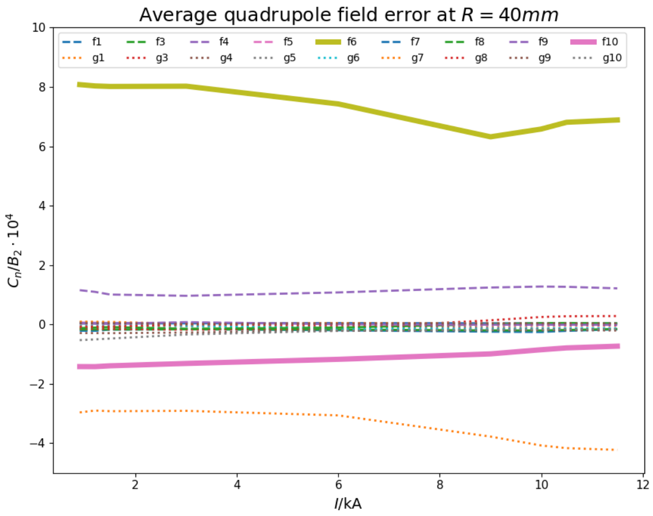
Type of NL	**Source**	**Effect**
Quadrupole fringe fields	Quadrupoles	ADTS in first order of the pseudo-octupole strengths
Even multipoles	Allowed errors of quadrupoles	ADTS in first order of the multipole strengths
Odd multipoles	Resonance sextupoles	ADTS in second order of the multipole strengths Momentum-dependent ADTS by feed-down from dispersion
	Chromaticity sextupoles	
	Allowed errors of dipoles	
Sextupoles	Resonance sextupoles	Excitation of unwanted resonances

Field Errors of Main Magnets

- General remarks on main magnets
  - Super-ferric magnets with small aperture
  - Field quality expected to be inferior to NC magnets
- Dipoles
  - All dipoles measured at GSI serial test facility
  - Multipole data available up to order 7
  - Average data based on 110 dipoles
  - B3 and B5 significant for SX
  - Allowed components included into SX design as systematic multipoles (B3, B5, B7)
  - Other components included in error studies
- Quadrupoles
  - Field measured by manufacturer
  - Presently ~20 magnets measured
  - Multipole data available up to order 10
  - B6 unexpectedly large
  - Allowed components included into SX design as systematic multipoles (B6, B10)
  - Other components included in error studies



n	$\|k_nL\| * m^{n-1}$
3	0.03 … 0.09
5	300 … 400
7	$7 \cdot 10^6$ … $2 \cdot 10^7$



n	$\|k_nL\| * m^{n-1}$
6	$7 \cdot 10^3$ … 10^4
10	10^{12} … $2 \cdot 10^{12}$

Systematic Field Errors: Geometric Effects

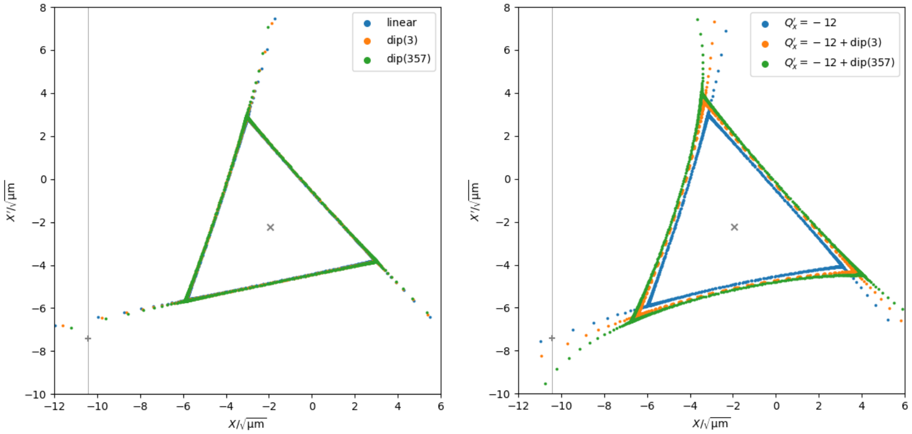
- Main dipoles
  - Significant effect of higher orders in combination with other nonlinearities, e.g. chromaticity correction
  - Caused by creation of ADTS in second order of odd multipole strengths (6-pole, 10-pole, …)

ADTS in second order of sextupole strength

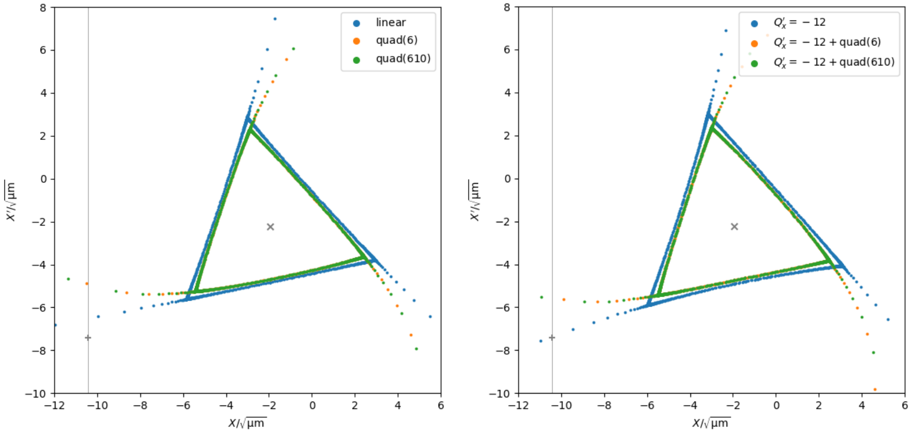
$$\frac{\partial \nu_x}{\partial J_x} = -\frac{1}{16\pi}\sum_{j=1}^{N}\sum_{k=1}^{N}(b_3L)_j(b_3L)_k\beta_{xj}^{3/2}\beta_{xk}^{3/2} \times\left[\frac{3\cos\left(|\mu_{j\to k,x}|-\pi\nu_x\right)}{\sin\left(\pi\nu_x\right)}+\frac{\cos\left(|3\mu_{j\to k,x}|-3\pi\nu_x\right)}{\sin\left(3\pi\nu_x\right)}\right]$$

- Main quadrupoles
  - Both B6 and B10 cause ADTS in first order of multipole strength
  - Effect independent of presence of other nonlinearities, e.g. chromaticity correction

Dipole errors without and with chromaticity correction



Quadrupole errors without and with chromaticity correction



Systematic Field Errors: Chromatic Effects

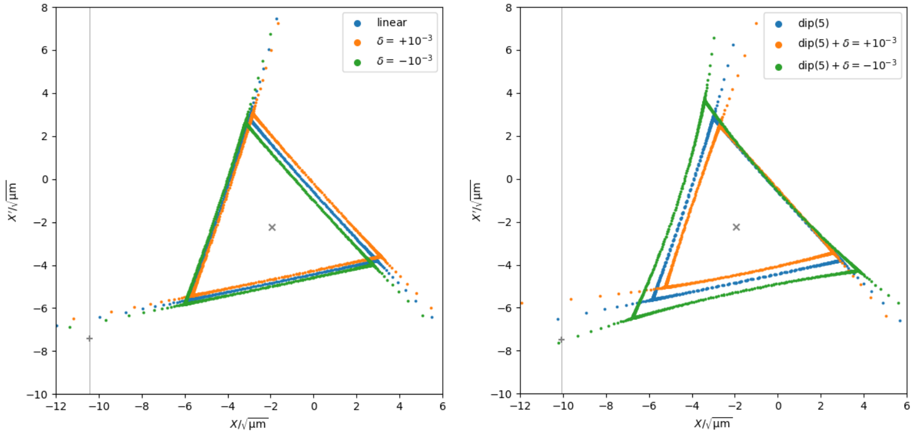
- Main dipoles
  - Create even multipoles (4-pole, 8-pole, …) by feed-down from dispersion
  - B3 (6-pole) reduces hor. chromaticity (tune-shift independent of amplitude)
  - Higher orders cause δ-dependent ADTS

δ-dependent ADTS from B5 (10-pole) error

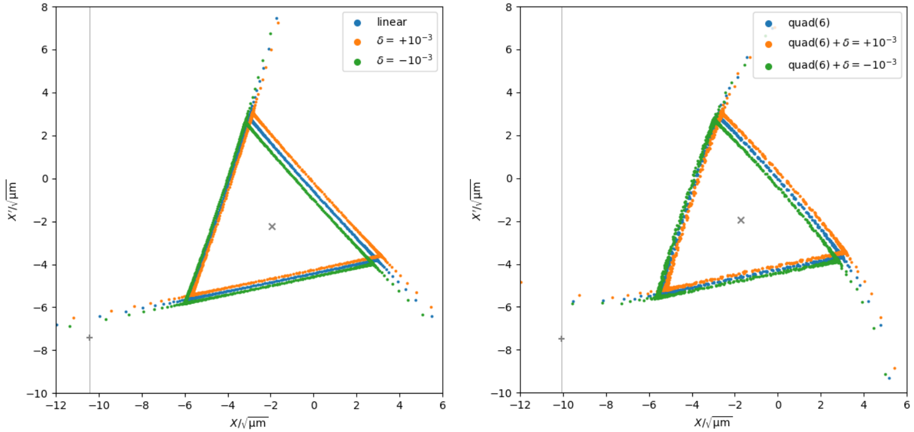
$$a_{xx} = \frac{\partial Q_x}{\partial J_x} = \delta \cdot \frac{1}{16\pi^2} \sum_i k_{5,i}\, \eta_i\, \beta_{x,i}^2$$

- Main quadrupoles
  - No significant effects beyond chromaticity itself

δ-dependence for same particle-tune without and with dipole B5



δ-dependence for same particle-tune without and with dipole B5



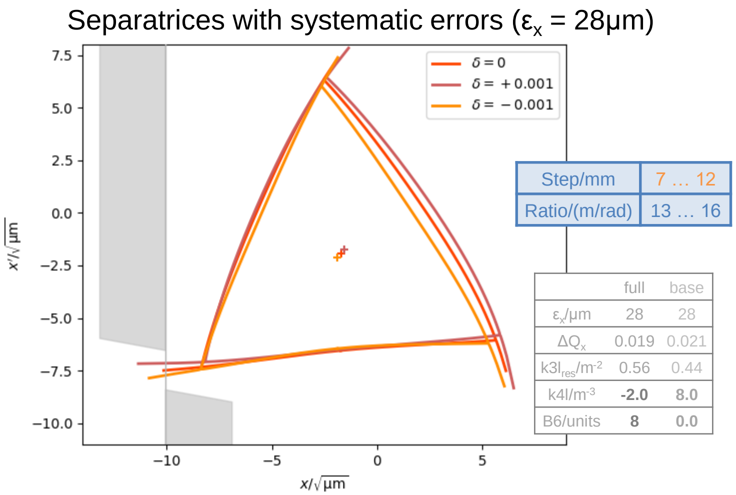
KO SX with Systematic Field Errors

- KO extraction with small chromaticity
    - Chromaticity correction minimizes δ-dependence
        - Separatrix size, angular spread at septum
    - Small separatrix size for high rigidities desired
        - Reduces power requirements on KO exciter

- Mitigation of geometric ADTS
    - Compensated by octupole correctors
        - 2^{nd}-order ADTS from strong chromaticity sextupoles
        - 1^{st}-order ADTS from quad B6 and B10
    - Settings may depend strongly on separatrix size

- Mitigation of chromatic ADTS
    - Dipole B5 like k3l ≈ 2 on octupoles for $\delta = 10^{-3}$!
    - Compensation impossible with SIS100 correctors
        - Requires 10-pole magnets in dispersive location
        - May be considered as future upgrade
    - Increases angular spread for small tune distances

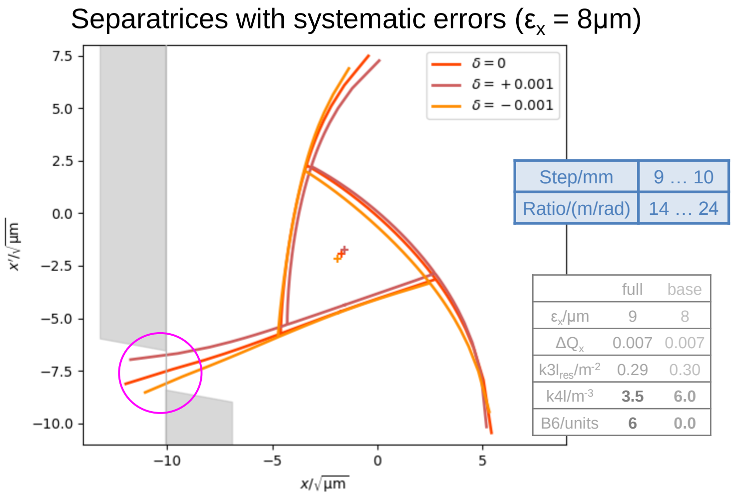
- No guarantee that acceptable settings can be found for any separatrix size



Separatrices with systematic errors (ε_x = 28μm)

Step/mm	7 … 12
Ratio/(m/rad)	13 … 16

	full	base
ε_x/μm	28	28
ΔQ_x	0.019	0.021
$k3l_{res}/m^{-2}$	0.56	0.44
$k4l/m^{-3}$	**-2.0**	**8.0**
B6/units	**8**	**0.0**



Separatrices with systematic errors (ε_x = 8μm)

Step/mm	9 … 10
Ratio/(m/rad)	14 … 24

	full	base
ε_x/μm	9	8
ΔQ_x	0.007	0.007
$k3l_{res}/m^{-2}$	0.29	0.30
$k4l/m^{-3}$	**3.5**	**6.0**
B6/units	**6**	**0.0**

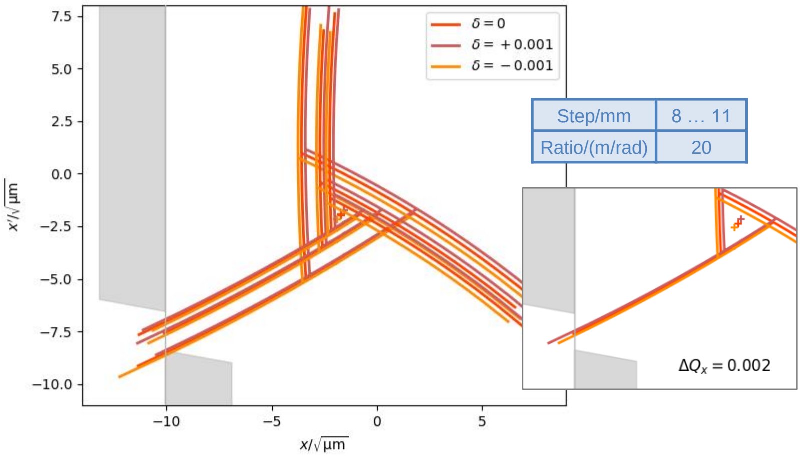
A simple commissioning scheme?

- KO SX in SIS100 requires precise control of many nonlinear effects
  - Hard to observe or verify in the machine
  - Settings may be sensitive to parameter mismatches

- Idea: start with simple scheme
  - Tune-sweep SX with natural chromacity
    - Avoid strong chromaticity sextupoles
  - Small emittance to keep angular spread low

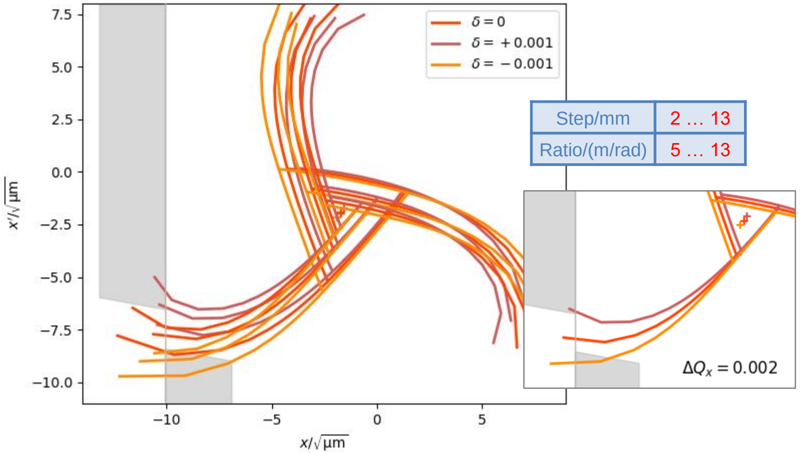
- Questionable in presence of field errors
  - Strong influence for small tune distances
  - Curvature caused by quadrupoles'
    B6 and B10 increases spiral pitch
  - Momentum-dependent curvature caused by dipoles'
    B5 increases angular spread
  - Perhaps for tiny emittance and momentum spread?

Tune-sweep SX with baseline lattice



Step/mm	8 … 11
Ratio/(m/rad)	20

Tune-sweep SX with systematic errors



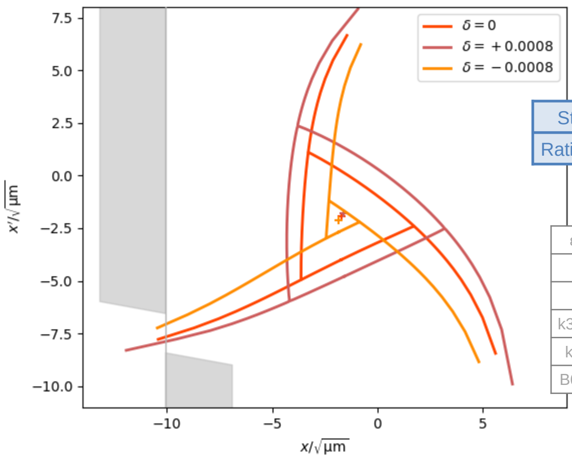
Step/mm	2 … 13
Ratio/(m/rad)	5 … 13

COSE as Alternative Scheme

- Constant Optics Slow Extraction (COSE)
  - Momentum-driven scheme developed at CERN
  - Extraction induced by rigidity ramp Bρ(t)
  - Requires sufficiently large chromaticity
  - Separatrix for single particle characterized by
    - fixed machine tune Q_x
    - time dependent $\delta(t) = 1 - B\rho(t)/(qp)$

- COSE for SIS100 looks promising
  - Sufficiently small angular spread reachable
  - Tentative settings with different chromaticity
    - Small chromaticity: amplitude selection
    - Large chromaticity: momentum selection
  - Further studies needed to confirm applicability

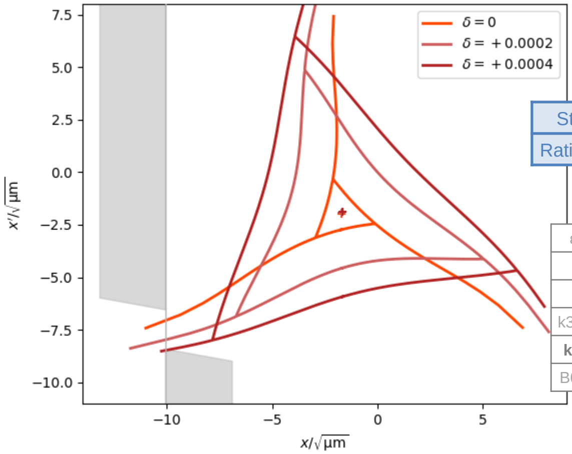
COSE separatrices for small emittance



Step/mm	7 … 10
Ratio/(m/rad)	16 ... 21

ε_x/µm	11
ΔQ_x	0.004
Q'_x	**-3.5**
$k3l_{res}/m^{-2}$	0.26
$k4l/m^{-3}$	1.5
B6/units	6

COSE separatrices for large emittance



Step/mm	7 … 9
Ratio/(m/rad)	16 … 18

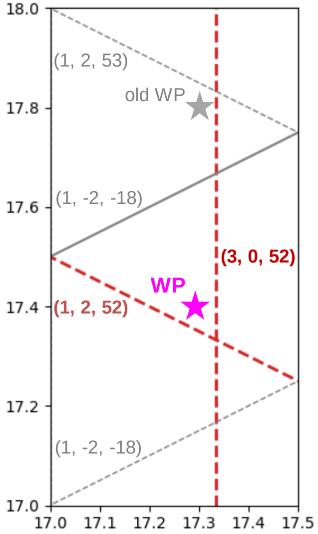
ε_x/µm	28
ΔQ_x	0.002
Q'_x	**-12**
$k3l_{res}/m^{-2}$	0.40
$k4l/m^{-3}$	**-12**
B6/units	8

Other NL Effects

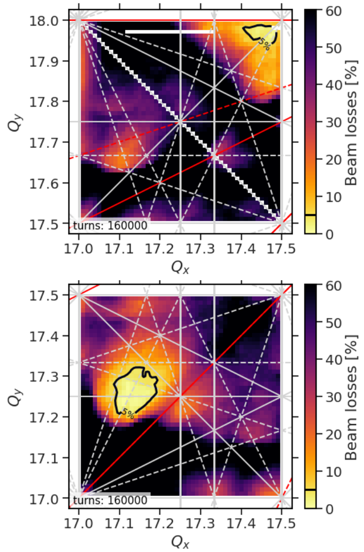
- Parasitic resonance constraining WP
  - Vertical tune had to be moved to Q_y=17.4
    - Original Q_y=17.8 not suitable for high intensities
  - Coupling resonance excited by sextupoles
    - Driving term for Q_x+2Q_y now about equal to $3Q_x$
    - No compensation with existing magnets
  - Luckily available space in Q_y appears sufficient

- Effect of random field errors
  - First error studies on KO SX performed
    - Orbit corrected for distortions by alignment errors
    - Error model for dipoles and quadrupoles based on spread of magnetic measurements
  - Design appears to be robust against errors

Normal sextupole lines

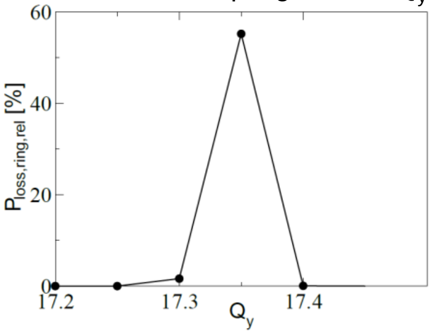


Low-loss injection regions

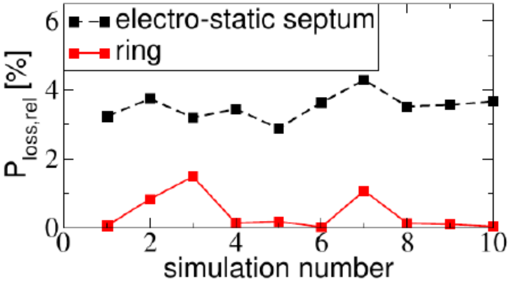


Courtesy A. Oeftiger, GSI

Losses on coupling res. vs. Q_y



Losses through random errors



S. Sorge, B. Galnander et al., TUPM099, IPAC23

Challenges for Operation

- Higher-order effects play important role for SX from SIS100
  - Increased complexity due to required compensation of nonlinearities

- Challenge: simplified model for defining optimal settings
  - Large parameter space for control of SX parameters
    - Tunes (2) and chromaticities (2)
    - Distribution of resonance (6) and chromaticity (7) sextupole strengths
    - Choice of octupole (2) strengths
  - Solution not uniquely defined by SX parameters
    - Spiral step e.g. depends on resonance strength, tune distance and ADTS
  - Present results mostly obtained by ‘educated tuning’ in tracking simulations
  - Can we find a computationally faster yet sufficiently predictive model?

- Challenge: control of parameters in real machine
  - Far fewer observables than in simulations
  - Ambiguity in source of deviations for critical parameters (step/pitch)
  - How to commission SX with the least number of degrees of freedom?
  - How to introduce complexity in small steps?

Summary and Outlook

- SIS100 has tight constraints for SX due to optimization for low charge-state ions
- Nonlinearities including systematic magnet errors affect the dynamics significantly due to ADTS
- Robust settings for KO SX in the presence of field errors have been found
- COSE SX has been identified as a promising alternative scheme

- Explore COSE option further including error and sensitivity studies
- Try to find simplified model to reduce dependence on tracking
- Devise a reasonable commissioning scheme
- Study upgrade options for installing higher-order multipole correctors

Thanks for your attention!


October 2023

Thanks to all who have contributed and continue to contribute to the development of slow extraction for FAIR.