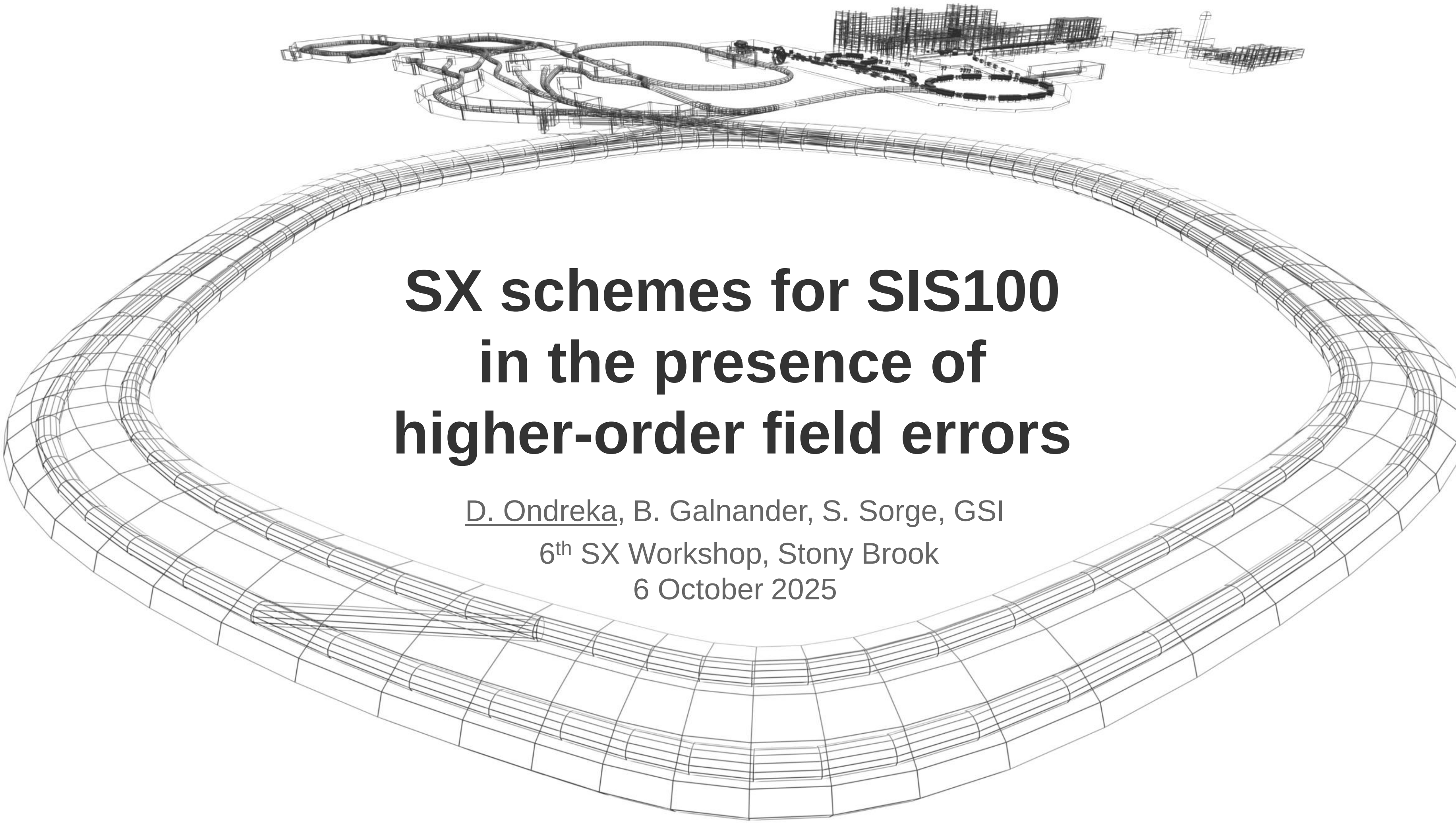

SX schemes for SIS100 in the presence of higher-order field errors

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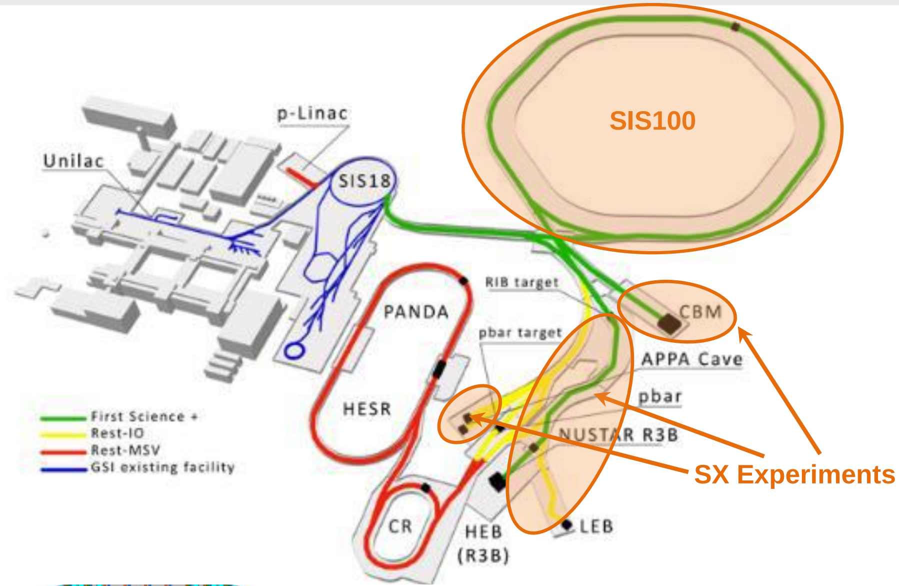
6th SX Workshop, Stony Brook
6 October 2025

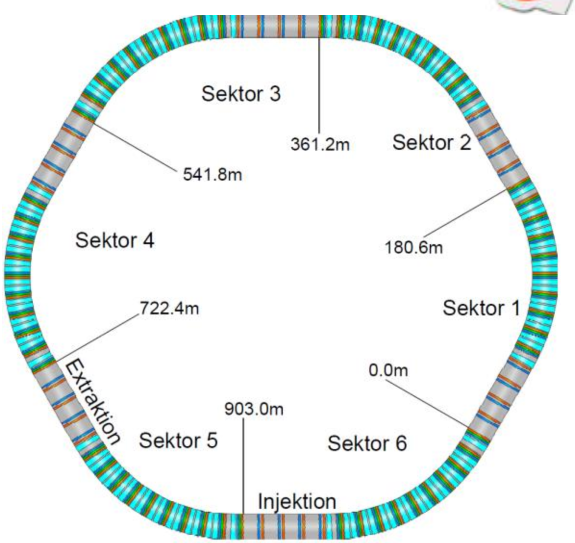
Contents

- Recap of status from last WS
  - Overview of SIS100
  - Magnetic field measurements
  - Effect of systematic errors
- Modified multipole correctors
- SX schemes with field errors
  - Modified SX design
  - Random error studies
- Next steps
- Summary

SIS100: Overview

- Workhorse of FAIR facility
  - Primary heavy ion beams
  - Factor 100 higher intensities than SIS18
- Basic parameters
  - Circumference 1083 m (= 5 x SIS18)
  - Max. magnetic rigidity 100 Tm
  - Max. ramp rate 4 T/s
  - Super-ferric main 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 to fixed targets or storage rings



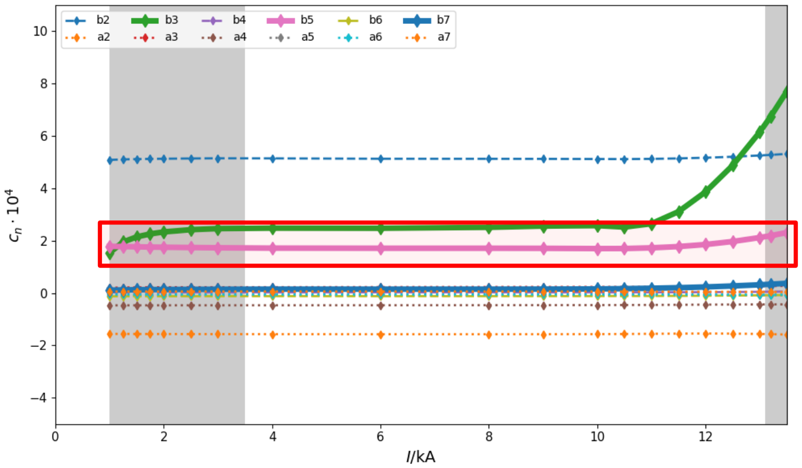


Optical parameters (SX)`	
Q_h / Q_v	17.31 / 17.4
Q'_h / Q'_v	-17.5 / -22.7
α_p	0.005
γ_t	14.2

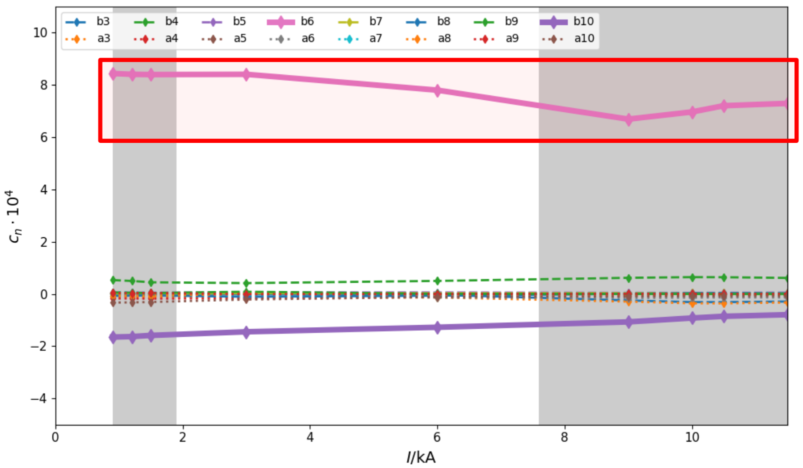
Magnetic Measurements: Field Errors

- Measurements of SF main magnets
  - Dipoles: all magnets measured (108 + 2)
  - Quadrupoles: data from 53 magnets available
- Analyzed data as function of current
  - Variation of integral field
  - Harmonics at R_{ref} (dipole: $n \leq 7$, quad: $n \leq 10$)
  - Unexpectedly large systematic components
    - Dipoles: decapole (b_5)
    - Quadrupoles: dodecapole (b_6)
- Systematic components influence SX strongly

Systematic field errors in dipoles

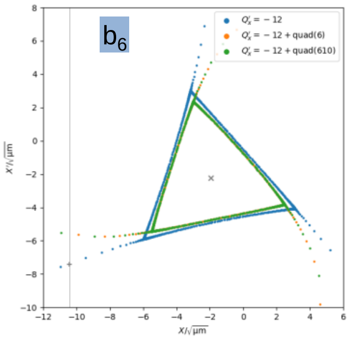


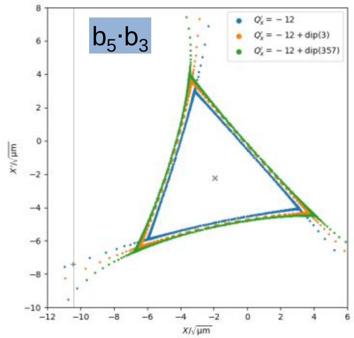
Systematic field errors in quadrupoles

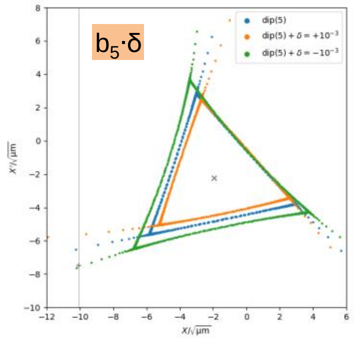


SX: Effect of Systematic Errors

- SX affected by ADTS bending separatrix
  - Effects independent of momentum
    - ADTS in first order of strengths: **b_6**
    - ADTS in second order of strengths:
      - $b_3 \cdot b_3$ (considered in baseline design)
      - **$b_5 \cdot b_3$** (coupling with sextupoles)
  - Effects depending on momentum
    - Momentum-dependent ADTS by feed-down from dispersion in first order of strength:: **$b_5 \cdot \delta$**



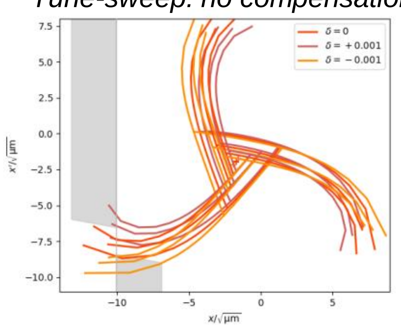




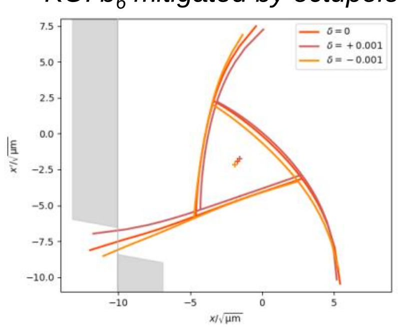
- Effects on SX in SIS100
  - Larger angular spread at ES through $b_5 \cdot \delta$
  - Strong bending by b_6, larger for small tune distance

- Compensation options in SIS100 (baseline)
  - No b_5 or b_6 corrector magnets
  - Two families of octupoles effecting ADTS by b_4
    - Baseline: compensate $b_3 \cdot b_3$ from chroma sextupoles
    - Can be used to mitigate effects of b_6 and $b_5 \cdot b_3$
  - No compensation of $b_5 \cdot \delta$ in baseline lattice

Tune-sweep: no compensation

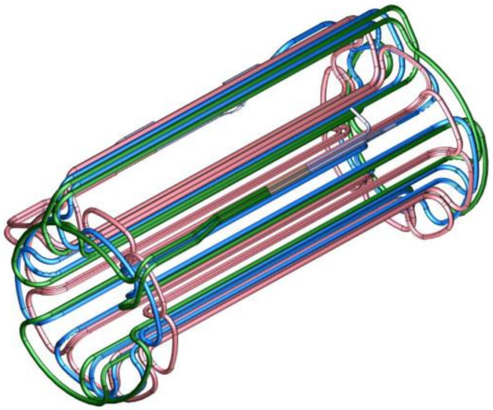


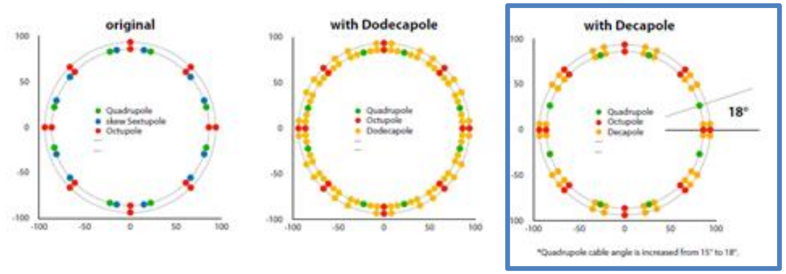
KO: b_6 mitigated by octupoles



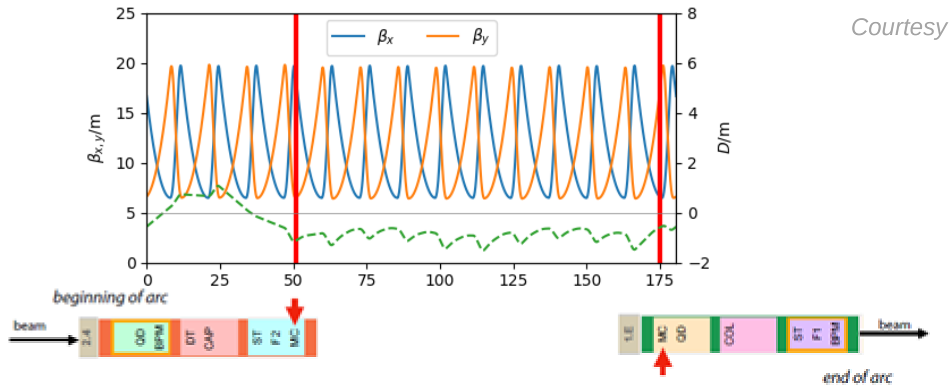
Multipole correctors

- Baseline corrector
  - Nested cos(θ) coils comprising b2, a3, b4
  - Two families, six each (large and small β_x / β_y)
  - Options for b5 and b6 coils studied
- Constraints on modified corrector
  - Only three types per magnet
  - b_5 corrector would need location with large $\beta_x \cdot D$
  - b_6 corrector would need location with large β_x
- Final decision:
  - Corrector with b5 at beginning of arc (b2, b4, **b5**)
  - Baseline corrector at end of arc (b2, a3, b4)
  - Mitigate b_6 using baseline octupoles





Courtesy K. Sugita



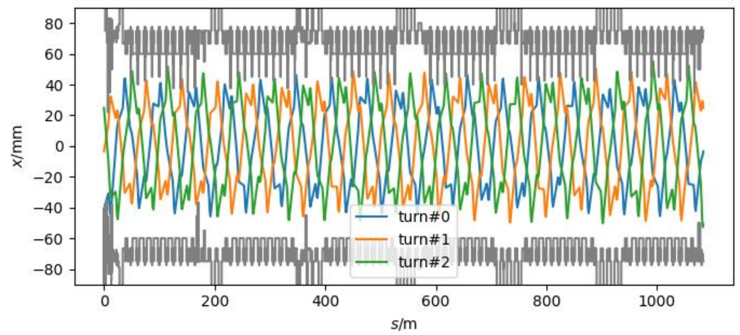
SX schemes with field errors

- Requirements
  - Separatrix sizes up to 25-30 um
  - Extraction efficiency > 95% (activation)
  - Losses on first wire ~ 1% (ES protection)
  - Robustness against random magnet imperfections
  - KO extraction plus one fallback scheme
  - Avoid b_5 compensation if possible (simplicity)

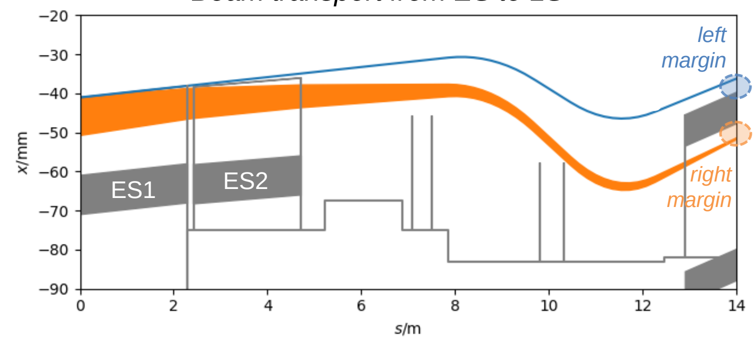
- Constraints
  - No major changes to lattice (under construction)
  - Acceptance of ring limited by cryo catchers
  - Small acceptance of extraction channel

- Challenge
  - Large emittance for separatrix shrinking schemes

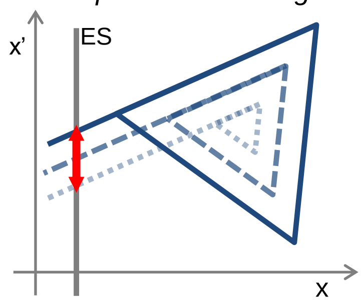
Particle trajectories over last three turns



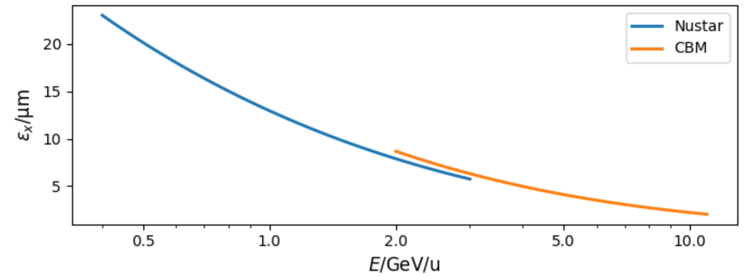
Beam transport from ES to LS



Separatrix shrinking



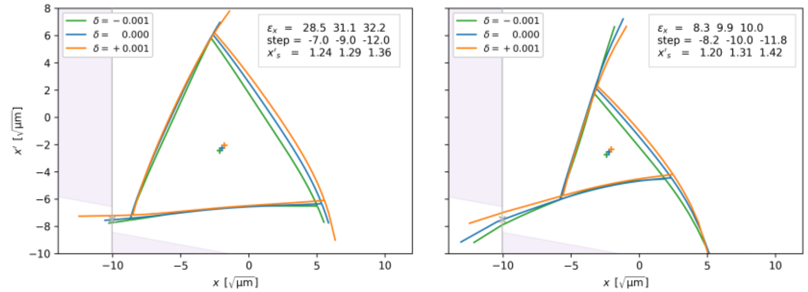
Design horizontal emittances on flattop

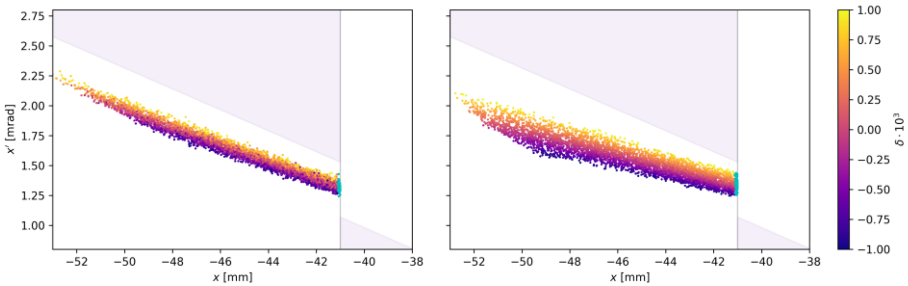


SX Schemes: KO

B. Galnander

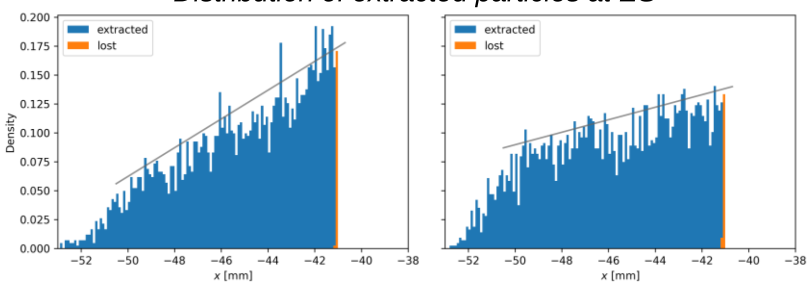
- Specific challenges
  - Small and large separatrix
    - Different ion species and energies
    - Power saving for KO exciter
- Characteristics
  - Small chromaticity for good separatrix overlap
  - Bending by b_6 mitigated with octupoles
  - Usage of b_5 correctors not necessary
    - Increased spread through $b_5 \cdot \delta$ acceptable
  - Total losses well within budget
  - First wire losses a bit higher than expected (~1%) due to non-uniform distribution





Sepratrix size	28 π·μm	8 π·μm
Hor. chromaticity	-3	-1
Sextupole amplitude	0.70 m^{-2}	0.45 m^{-2}
Octupole strength	-1.0 m^{-3}	1.9 m^{-3}
Total losses	2.2%	1.8%
Losses first wire	1.7%	1.5%

Distribution of extracted particles at ES

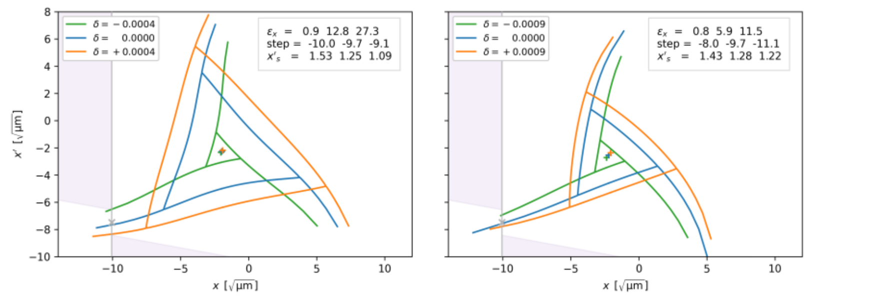


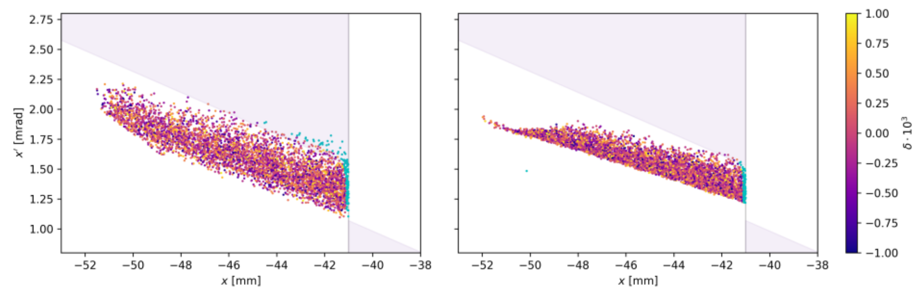
SX Schemes: COSE

B. Galnander

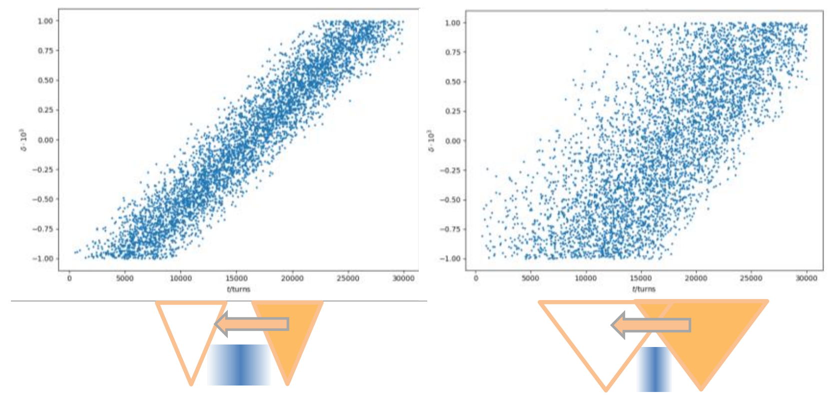
- Specific challenges
  - Large emittance difficult to handle
    - 'Linear' Hardt condition for $Q'_x \approx 0$
    - Small angular acceptance
- Characteristics
  - Usage of b_5 correctors not necessary
    - $b_5 \cdot \delta$ bending actually improves alignment
  - Large chroma preferred due to smaller ΔBρ
    - More δ selective → constant phase space at ES
  - Strong octupoles for larger chromaticity
    - ADTS cross-term a_{xy} must be removed
- Preferred fallback scheme

Sepratrix size	28 π·μm	10 π·μm
Hor. chromaticity	-10	-3.5
Sextupole amplitude	0.40 m^{-2}	0.32 m^{-2}
Octupole strength	-/+9.2 m^{-3}	1.5 m^{-3}
Total losses	3.5%	2.1%
Losses first wire	1.5%	1.5%





Momentum deviation vs. turn number

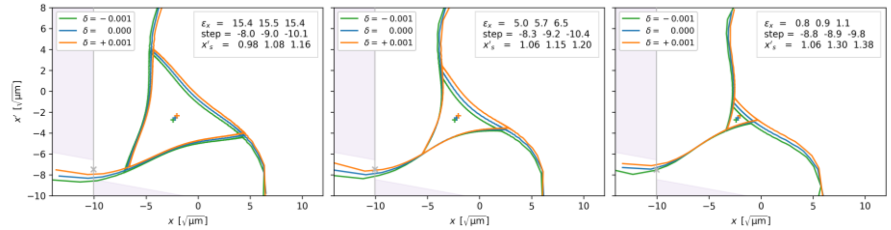


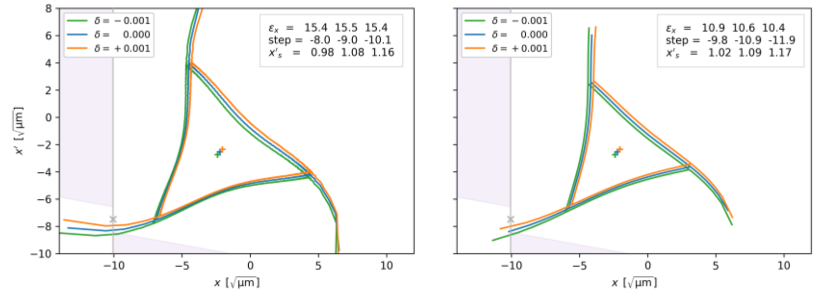
SX Schemes: Tune-Sweep

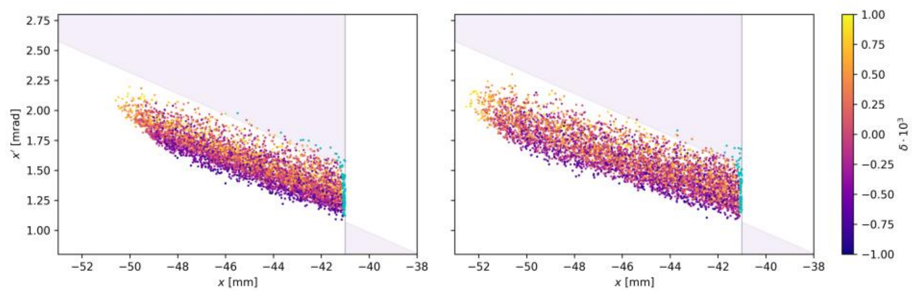
B. Galnander

- Specific challenges
  - Large emittance difficult to handle
  - Large angular spread favors b_5 compensation
- Characteristics
  - Chromaticity uncorrected
  - Very large octupole strengths required
    - ADTS cross-term a_{xy} must be removed
  - Large angular spread due to shrinking separatrix
  - Acceptable losses only for sepa size <= 15 π·um
  - Possibly useful as commissioning scheme

Shrinking separatrices for different momenta





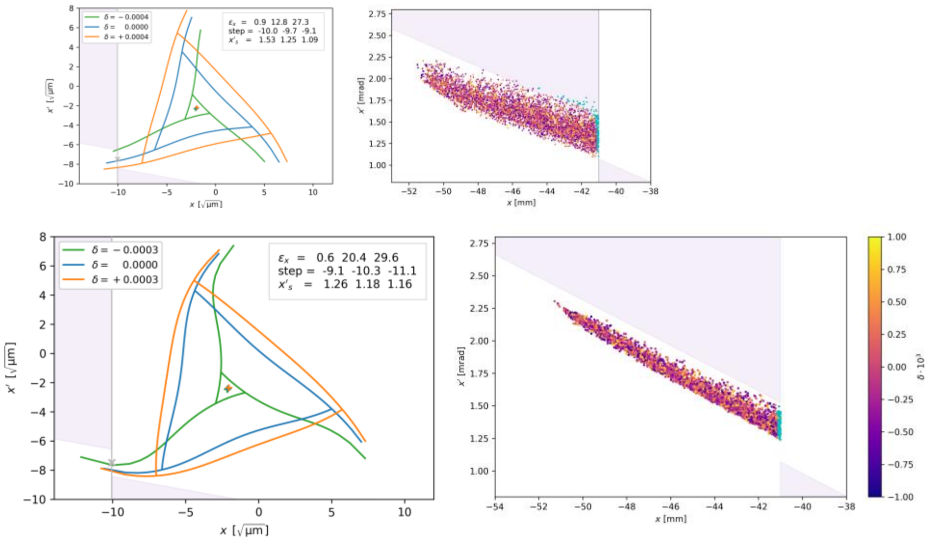


Sepratrix size	15 π·µm	10 π·µm
Hor. chromaticity	-17.5 (nat.)	-17.5 (nat.)
Res. sext. ampl.	0.33 m^{-2}	0.38 m^{-2}
Octupole strength	**-/+12.7 m^{-3}**	**-/+9.2 m^{-3}**
Total losses	3.9%	3.2%
Losses first wire	1.5%	1.2%

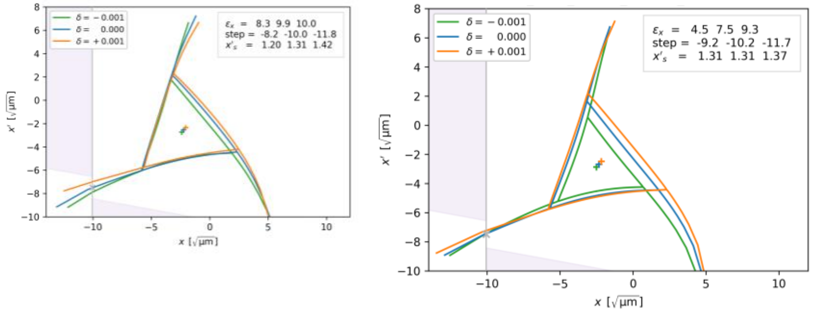
Options for employing b_5 correctors

- Goal: better separatrix alignment
- COSE: ‘anti-compensation’
  - Amplify effect of b_5 from dipoles
  - Increased $b_5 \cdot \delta$ bending improves overlap
  - Small losses (2.3%) even for large emittance
  - Robustness yet to be checked
- KO: limits for small separatrix
  - Compensation of b_5 not independent
  - Better overlap at price of stronger size dependence
  - Hard to get around acceptance limit at LS
- Benefits to be investigated in further studies

COSE without and with b5 ‘anti-compensation’



KO extraction without and with b5 compensation



SX with Magnet Imperfections: Random Error Studies

S. Sorge

- Goal: Verify robustness of SX schemes against magnet imperfections
  - Magnet alignment errors
  - Magnetic field errors (variations in integral field, harmonics)

- Simulation procedure per scenario
  - 10 random error seeds chosen from Gaussian distribution truncated at 2σ
  - Nelder-Mead optimizer to match separatrix
    - Target parameters: separatrix size, spiral step, crossing angle
    - Variables: tune distance, virtual sextupole, orbit bump, octupole strengths
  - Tracking of 1000 particles over 25000 turns with MAD-X to evaluate performance

- Preliminary results on SX without b_5 compensation
  - KO extraction and COSE robust against errors

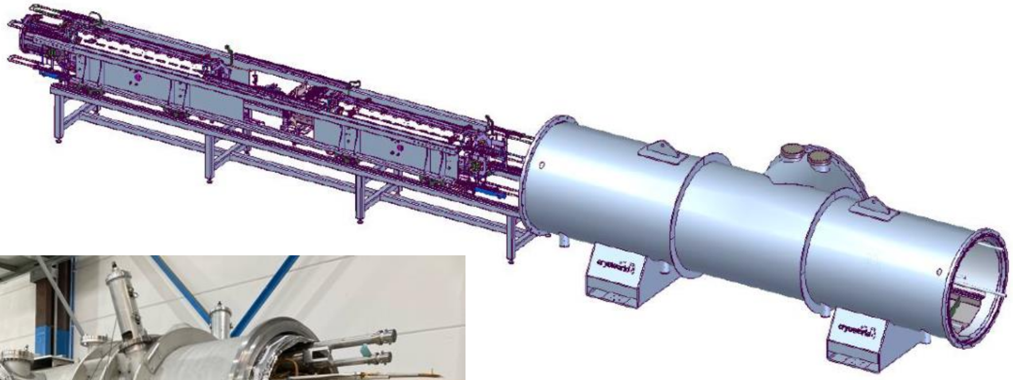
- Limitations
  - Optimistic distributions for quadrupoles' roll and variation of integral field
  - Matching of separatrix can lead to non-optimal settings due to ignorance of distributions
    - MAD-X tracking times not suitable for use of optimizer with multi-particle simulations

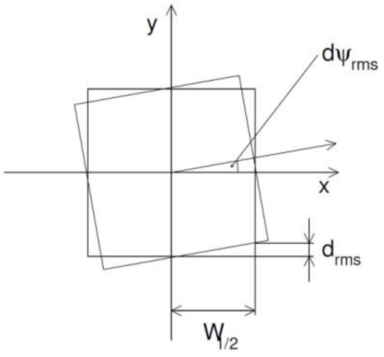
Magnet Imperfections:
Alignment Errors

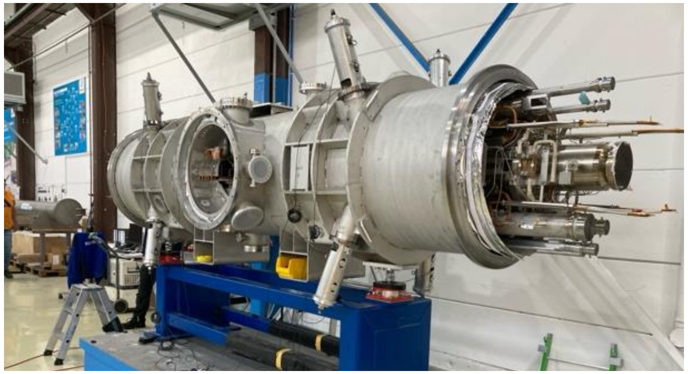
S. Sorge

- Sources of alignment errors for SF magnets
  - Mismatch between geometric and magnetic axis
  - Tolerance for positioning magnet on girder
  - Tolerance for positioning girder in cryostat
  - Motion during cool-down
  - Alignment tolerance of cryostat

- Conservative values in simulations
  - Lateral shifts of with σ = 1 mm
  - Roll estimated from mechanical tolerances





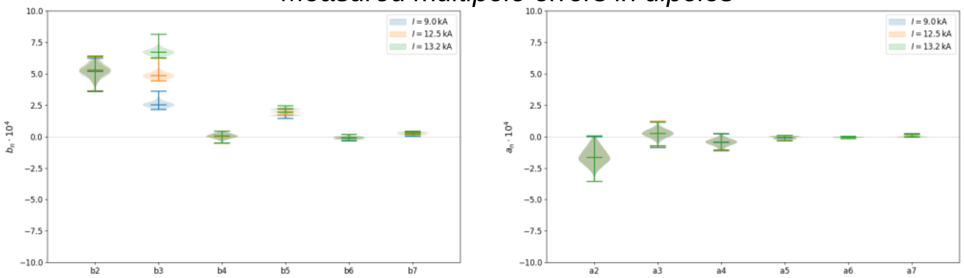


Magnet Imperfections: Model for Field Errors

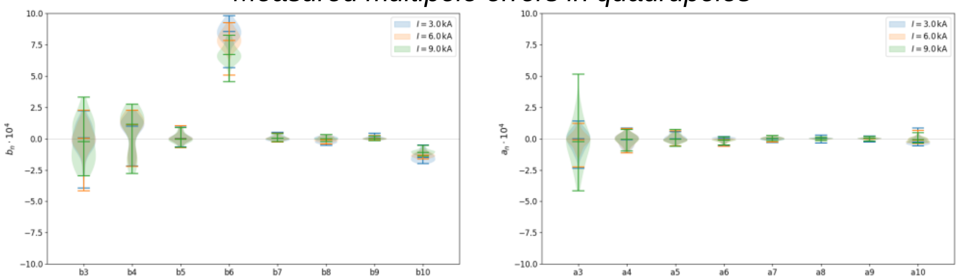
S. Sorge

- Dipoles
  - Systematic allowed components: b_3, **b_5**, b_7
  - Mean values of forbidden components discarded
    - b_2 artifact from measurement geometry
  - Random components: standard deviation used as σ
  - Integral field variation: $\sigma_{mod} = 4 \cdot 10^{-3} > \sigma_{meas} = 3 \cdot 10^{-4}$
    - Kept for comparison with previous studies
- Quadrupoles
  - Systematic allowed components: **b_6**, b_{10}
  - Mean values of forbidden components zero
  - Random components: standard deviation used as σ
  - Integral field variation: $\sigma_{mod} = 5 \cdot 10^{-4} < \sigma_{meas} > 7 \cdot 10^{-4}$
    - Kept for comparison with previous studies
- Calibration uncertainty for quadrupoles
  - Systematic offsets between magnetometers
  - Not fully removed by official cross-calibration
  - Factor 2 difference in expected beta beating

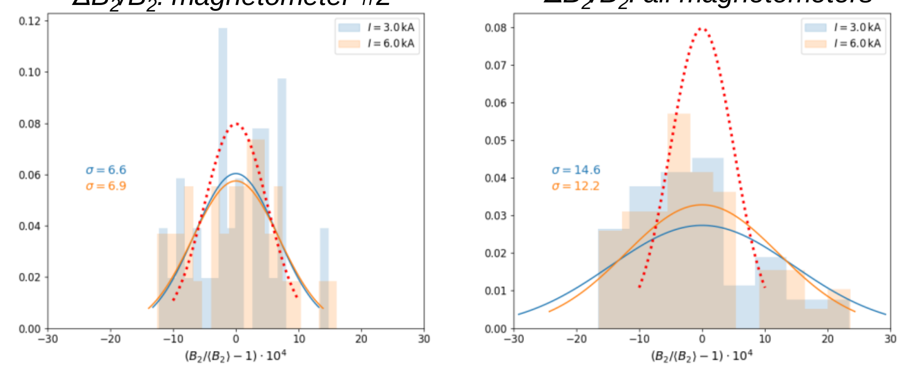
Measured multipole errors in dipoles



Measured multipole errors in quadrupoles



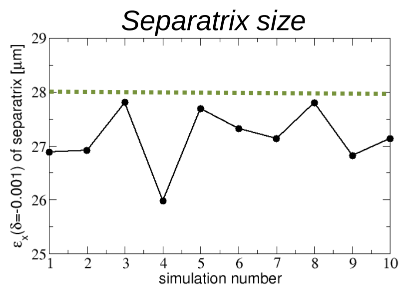
$\Delta B_2/B_2$: magnetometer #2 — *$\Delta B_2/B_2$: all magnetometers*

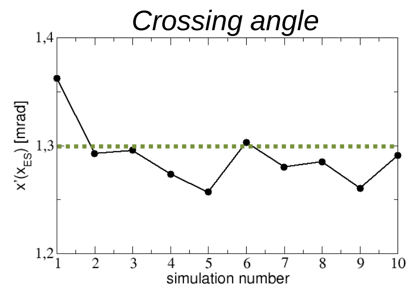


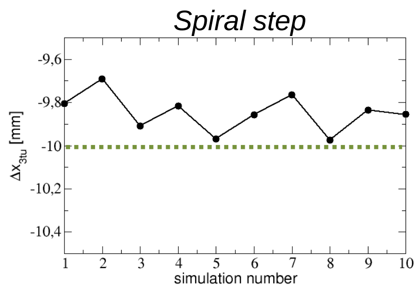
Random Error Studies:
KO Extraction (U28+, 400 MeV/u)

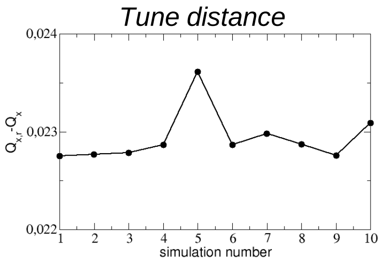
S. Sorge

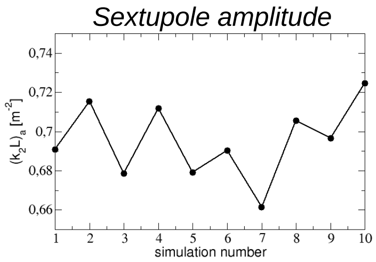
Target parameters	
Separatrix size	28 um
Spiral step	10 mm
Crossing angle	1.3 mrad

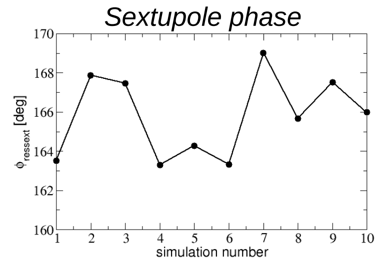


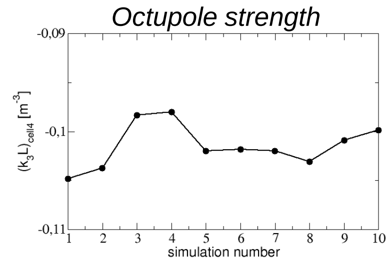




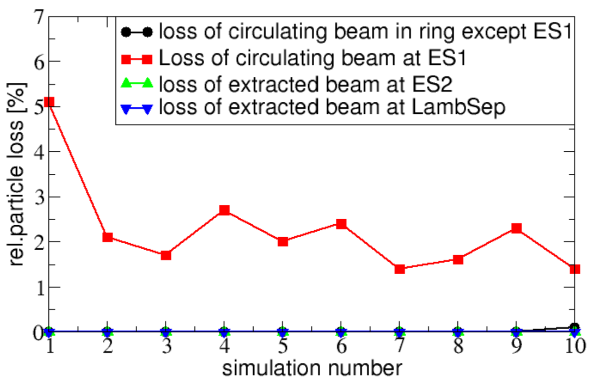


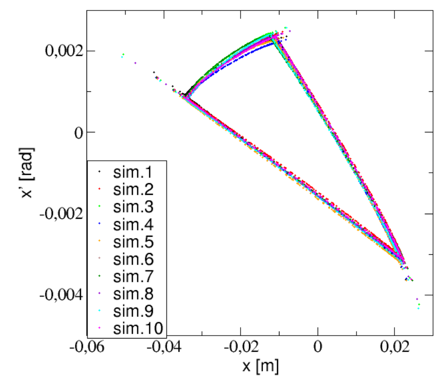






Performance (errors / ideal)	
Total losses	2.3% / 2.2%
Losses 1st wire	1.5% / 1.5%

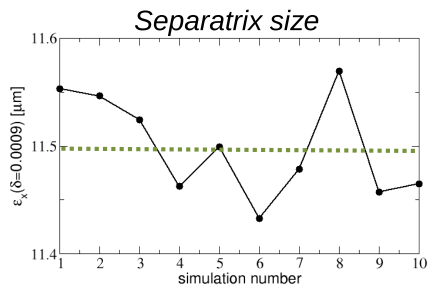


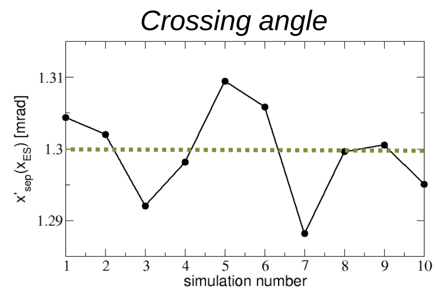


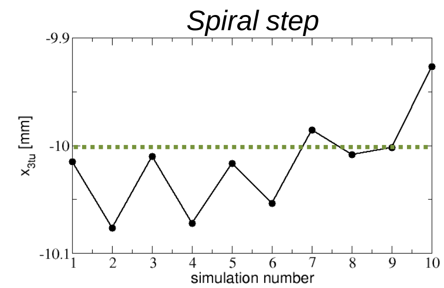
Random Error Studies:
COSE (U28+, 1.5 GeV/u)

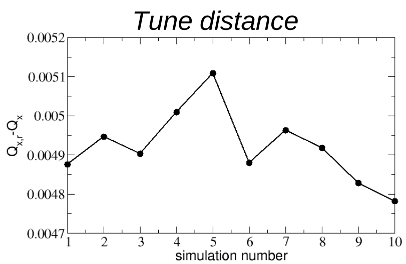
S. Sorge

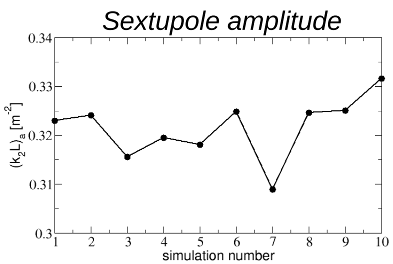
Target parameters	
Separatrix size	11.5 um
Spiral step	10 mm
Crossing angle	1.3 mrad

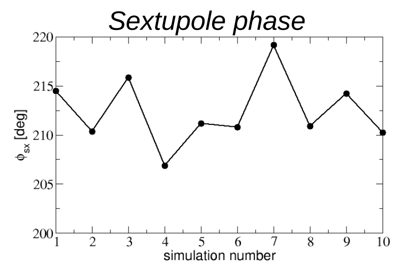


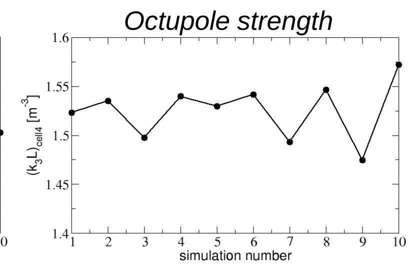






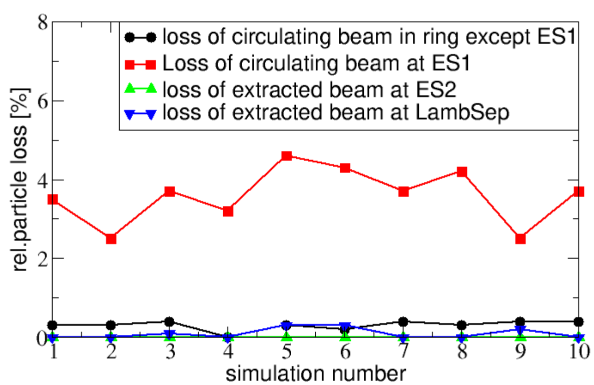


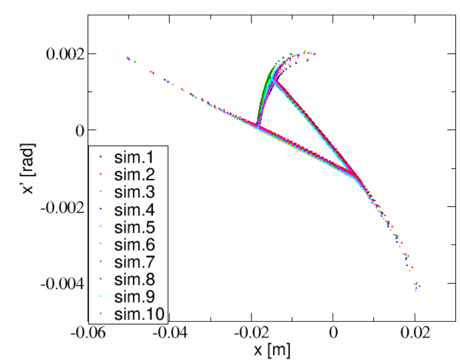




Performance (errors / ideal)	
Total losses	3.9% / 2.1%
Losses 1st wire	1.3% / 1.5%

artefact from matching issues





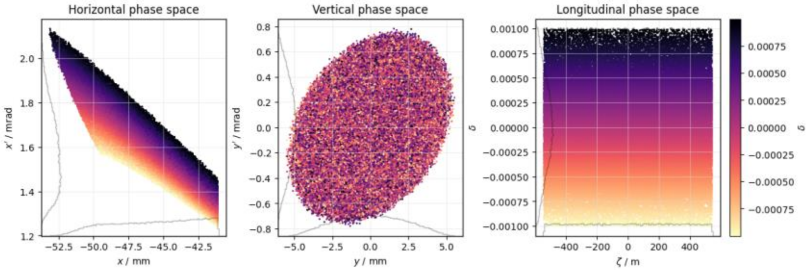
Next Steps

- Continuation of error studies
  - Schemes with b_5 compensation
  - Pessimistic quadrupole roll and field variation
  - More statistics (larger number of seeds)

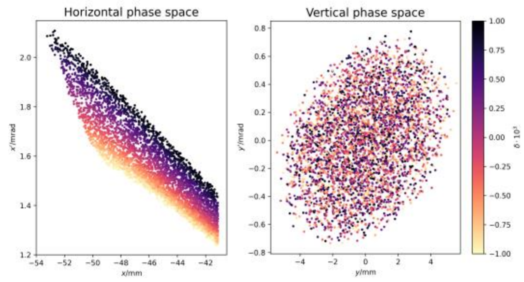
- Studies for commissioning and operation
  - Commissioning strategy
    - Robust settings for design schemes
    - Step-wise approach starting with simpler schemes
  - Models for tuning of SX in operation
    - ML for coupled, non-linear multi-parameter space
    - Optimizers for fast tuning

- Moving to Xsuite for faster tracking
  - On GPU farm: 0.1Mpart * 0.6Mturns in few hours
  - First runs (U^{28+}, 1.5 GeV/u) by Ph. Niedermayer
  - Benchmarked with Elegant for ideal machine

Phase space plots from Xsuite…



Courtesy Ph. Niedermayer



… and Elegant

Summary

- SX from SIS100 affected by systematic b_5 and b_6 errors from main magnets
- Multipole corrector family modified to include b_5 corrector
- SX design adapted to account for b_5 and b_6
  - KO SX and COSE work without b_5 corrector
  - Tune-sweep SX requires b_5 corrector, COSE and KO may profit from it
- Random error studies with MAD-X indicate robustness
  - Optimizer used to determine settings based on single-particle tracking
  - Some error estimates may be on the optimistic side, to be redone
- Further studies will be based on Xsuite for faster tracking times
  - Allows increased statistics and optimization using multi-particle simulations

Special thanks for their invaluable contributions go to:
B. Galnander , Ph. Niedermayer, S. Sorge, and K. Sugita

Thanks for your attention!

Impressions from the ongoing installation of SIS100






More info and media: https://www.gsi.de/en/researchaccelerators/fair/fair_civil_construction

Drone video of construction site: https://www.youtube.com/watch?v=tKuXUgJyirQ