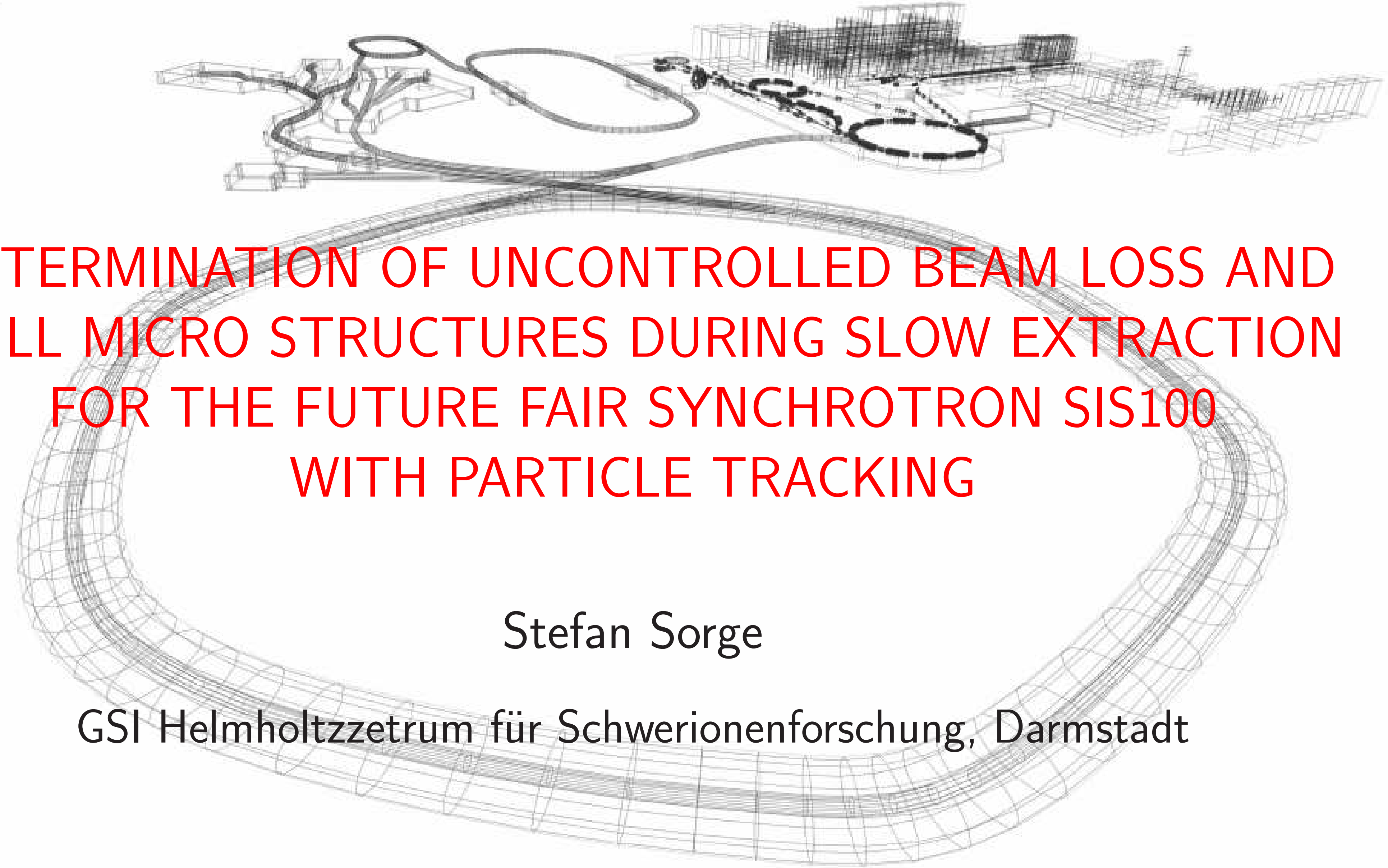


DETERMINATION OF UNCONTROLLED BEAM LOSS AND SPILL MICRO STRUCTURES DURING SLOW EXTRACTION FOR THE FUTURE FAIR SYNCHROTRON SIS100 WITH PARTICLE TRACKING

Stefan Sorge

GSI Helmholtzzetrum für Schwerionenforschung, Darmstadt

Motivation and content

- Simulations of slow extraction process mainly for two purposes.
  1. Estimation of uncontrolled particle loss.
  2. Description of spill structures, in particular spill micro structures.
- Computational requirements for both types of simulations are different.
- Show example of slow extraction in future heavy ion synchrotron SIS100 of FAIR project.

Heavy ion synchrotron SIS100

- Six fold symmetry, circumference: $C = 1083.6\ \mathrm{m}$:
  $5\ \times$ circumference of present GSI heavy ion synchrotron SIS18.
- Maximum rigidity: $(B\rho)_{\max} = 100\ \mathrm{Tm}$.
- Reference ion U^{28+} with maximum beam energy $E = 2.7\ \mathrm{GeV/u}$.
  → Example for this study.
- Many magnets with superconducting coils and iron yokes:
  108 main dipoles, 166 main quadrupoles (+ two normal conducting, which are radiation hard), 42 sextupoles for chromaticity correction. In addition, some super conducting corrector magnets. Consequences:
  - Magnets less radiation resistant because of possible quench.
  - Magnet imperfections due to misalignment and magnetic field errors with systematic components due to magnet design and random components.
- In addition, several normal conducting magnets, e.g. six sextupoles for 3rd integer resonance excitation.

Slow extraction

- Slow extraction based on excitation of 3rd integer resonance with sextupoles. SIS100: $Q_{x,\mathrm{r}} = 17.33333$.

- Formation of triangular stable phase space area, i.e. betatron motion stable inside and unstable outside, limited by straight separatrices.

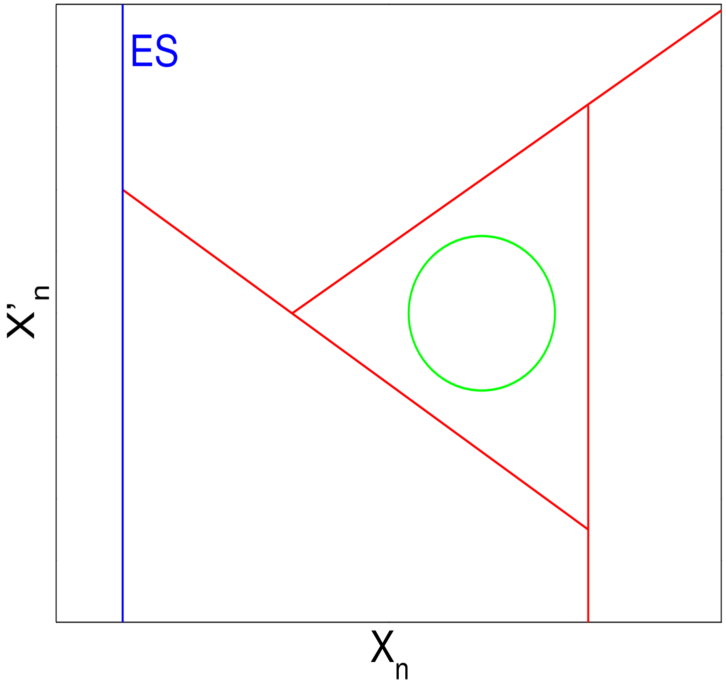
- Corners: unstable fixed points (UFPs) of betatron motion with modulus in normalised variables

$$\left|\vec{X}_{\mathrm{n,UFP}}\right| = 8\pi \left|\frac{Q_x - Q_{x,\mathrm{r}}}{S_{\mathrm{v}}}\right|$$

  with

  Phase space vector $\vec{X}_{\mathrm{n}} = (X_{\mathrm{n}}, X'_{\mathrm{n}})$, where $X_{\mathrm{n}} = \frac{x}{\sqrt{\beta_x}}$, $X'_{\mathrm{n}} = x'\sqrt{\beta_x} + \alpha_x \frac{x}{\sqrt{\beta_x}}$

  Virtual sextupole defined by $S_{\mathrm{v}} \mathrm{e}^{3\mathrm{i}\psi_{\mathrm{v}}} = \sum_m S_m \mathrm{e}^{3\mathrm{i}\psi_m}$



- Particles leave successively beam along separatrices when betatron motion exceeds stable phase space area.

Slow extraction in SIS100

Slow extraction techniques foreseen in SIS100:

1. KO extraction:
   Based on increasing horizontal beam width by beam excitation with horizontal rf field until each particle's emittance exceeds stable phase space area.
2. Constant Optics Slow Extraction (COSE) [1]:
   - Tune sweep technique, i.e. machine tune $Q_{x,\mathrm{m}} = Q_{x,\mathrm{m}}(t)$ moved across resonance tune resulting in slow shrinkage of stable phase space area.
   - Tune sweep can be performed with dedicated quadrupoles, e.g. SIS18.
   - COSE:
     - ALL magnets are changed such that their strengths correspond to time dependent momentum deviation $\delta_\mathrm{c}(t)$ which fulfils condition $Q_{x,\mathrm{m}}(t) = Q_{x,\mathrm{m}}(0) + \xi_x \delta_\mathrm{c}(t)$.
     - Result: all particles extracted with same lattice functions, i.e. "constant optics".
     - Simulation: Adding δ_c offset to all particles in each revolution instead of changing magnets.
     - Example in this presentation.

Beam loss simulations

Simulation requirements:

- Need sufficiently large particle number to resolve clearly tolerable uncontrolled particle loss $p_{\mathrm{loss,max}} \sim 1\ \%$ → requires particle number $N_{\mathrm{p}} \geq 1000$.
- Look only for accumulated number of lost particles
  → moderate simulation interval $N_{\mathrm{rev}} \sim 10000$ sufficient.
- Slow extraction: try to "loose" particles by passing through extraction septum and to avoid uncontrolled losses by hitting septum or other apertures.
  - Need for precise definition of lattice functions by the lattice model.
    → Thin lens tracking with slicing thick elements in sufficient thin elements.
  - Need for using lattice with all apertures.

Computational demands determined by lattice characteristics.

Beam loss simulations

Tracking with thin lens tracking module of MADX code. Apply several different samples of random magnet imperfections.

Step 1: Optimisation of sextupole settings according to sample of random magnet errors

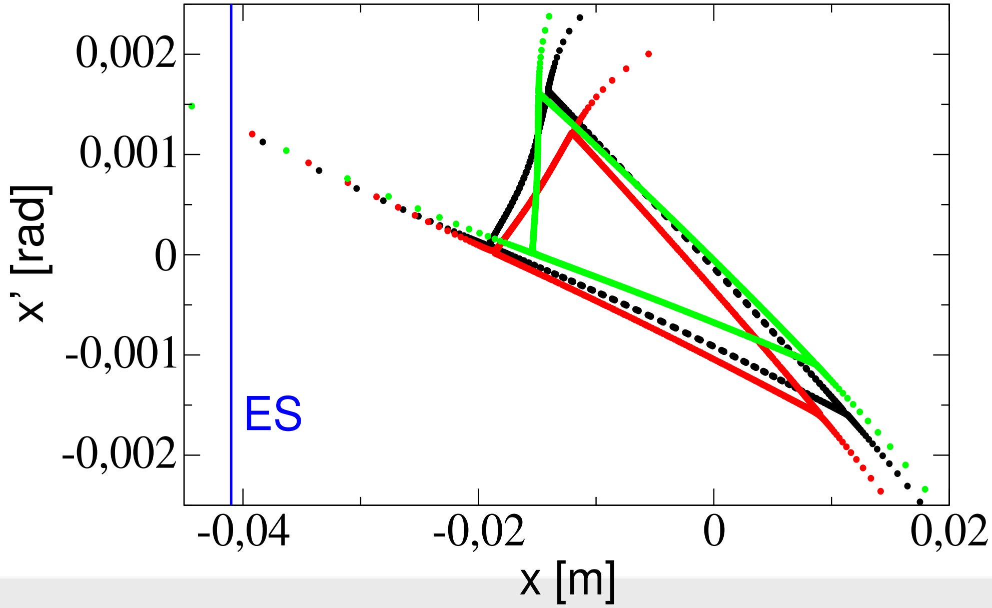
- Sextupol strengths defined by

$$(k_2L)_m = (k_2L)_a \sin\left[4\pi\frac{m-1}{6} + \phi_{sx}\right], \ m = 1, \ \dots, 6$$

- Optimise ϕ_{sx} to find optimal orientation of stable phase space area with trial and error procedure and single particle tracking.

Black:

No random imperfection.

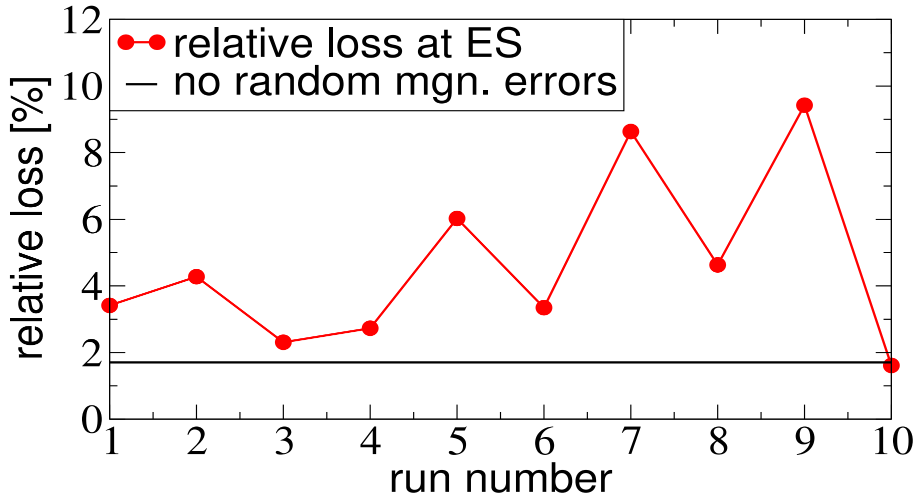


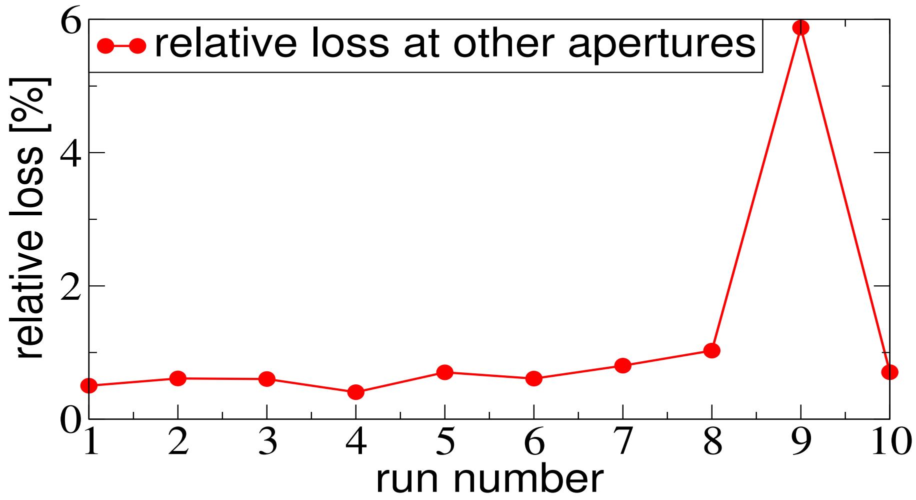
Beam loss simulations

Tracking with thin lens tracking module of MADX code. Apply several different samples of random magnet imperfections.

Step 2: Multi-particle tracking

- $N_\mathrm{p} = 1000$, $N_\mathrm{rev} = 31000$ (25000 for extraction, 6000 before for switching on sextupoles)
- 10 slices per quadrupole and dipole → in total 5156 thin elements (Twiss output). (Many elements thin before slicing, e.g. multipoles, markers, collimators etc.)





- Computational effort: Each simulation with duration $\approx 2\ \mathrm{h}$ on normal PC due to large lattice although particle and revolution numbers moderate. Hence, multi-variable optimisation with multi particle tracking (talk O. Kazinova) time consuming.

Spill structure simulations

Major aim: Determination of spill micro structures

- Structures usually generated by ripples in magnets from power supplies, in particular quadrupoles.
- Typical frequencies between $f_{\mathrm{min}} \sim 10\ \mathrm{Hz}$ and $f_{\mathrm{max}} \sim 10\ \mathrm{kHz}$.
  - Too high for correction with feedback system.
  - Much lower than revolution frequency.
- Requirements: resolution of time distribution of extracted particles.

Simulation requirements:

- Sufficient particle number to resolve ripples.
- Realistic simulation interval.

Spill structure simulations

Applied simulation conditions

- Extraction interval: $t_{\mathrm{ext}} = 150000 \text{ rev.} = 0.56 \text{ s}$.
- Total particle number: $N_{\mathrm{p}} = 100000$.
  Particle ensemble split into ten sub-ensembles of 10000 particles.
- Resulting extraction rate: $\dot{N}_{\mathrm{p}} = 1.8 \cdot 10^5 \text{ s}^{-1}$.
  Typical extraction rate in measurements at SIS18: $\dot{N}_{\mathrm{p}} = 10^6 \text{ s}^{-1}$.
  → Limit due to plastic scintillation counter which enables highest resolution.
- Spill recording in time bins of $t_{\mathrm{rec}} = 3\ t_{\mathrm{rev}} = 11.1\ \mu\mathrm{s}$.
  → actual sampling rate in measurements.
- Neglect random magnet errors.

Extraction interval and total particle number denote minimum requirement because

- Shortest slow extraction with duration $t = 0.5 \text{ s}$.
- Provides in average two particles per recording bin which is sufficient to distinguish between spill quality defined by extraction rate (Poisson limit) and “real” spill quality.

Spill structure simulations

Time dependent duty factor

$$F(t) = \frac{\langle N_\mathrm{p}(t)\rangle^2}{\langle N_\mathrm{p}^2(t)\rangle} = \frac{N_\mathrm{p,av}^2(t)}{N_\mathrm{p,av}^2(t) + \sigma_\mathrm{p}^2(t)}$$

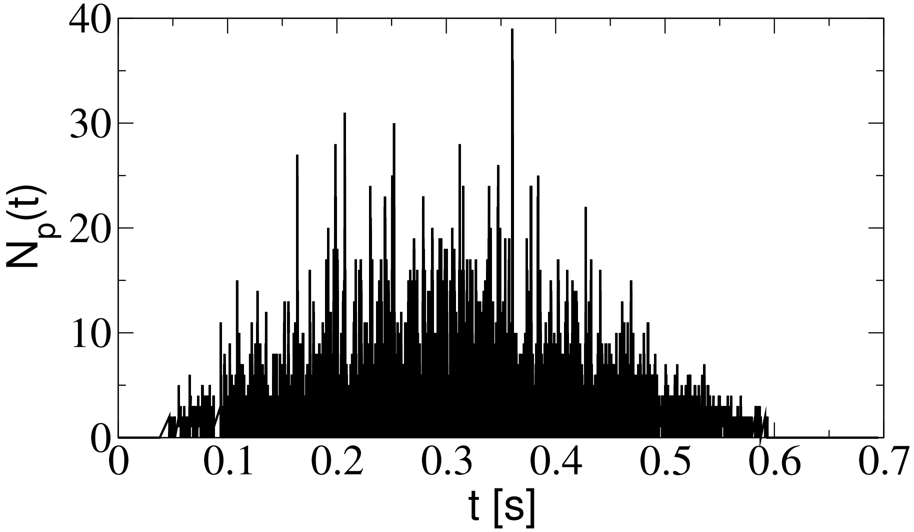
where $\langle x\rangle$ is average of variable x recorded in recording time bins $t_\mathrm{rec} = 11.1\ \mu\mathrm{s}$ in averaging time bins $t_\mathrm{ave} = 10\ \mathrm{ms}$.

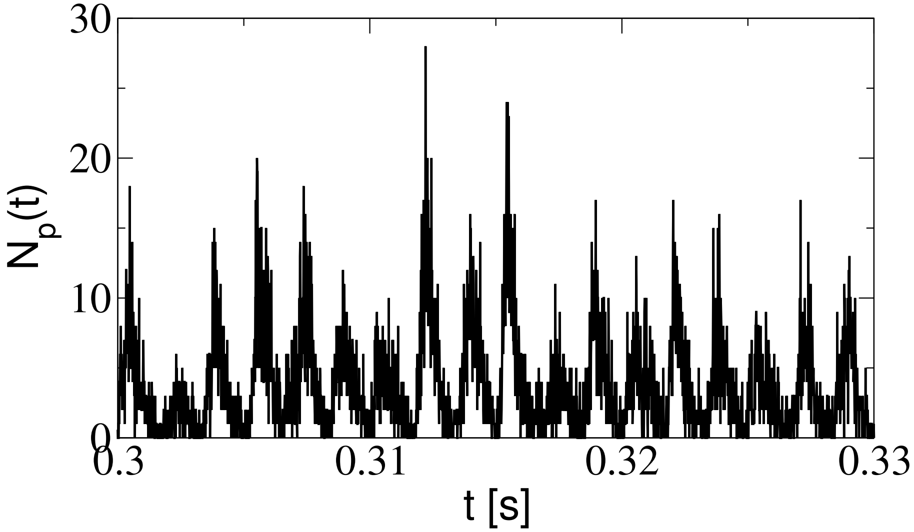
- F is measure for uniformity of particle number in recording bins.
- Counting particles due to low extraction rate and plastic scintillator enables determination of Poisson limit of F:

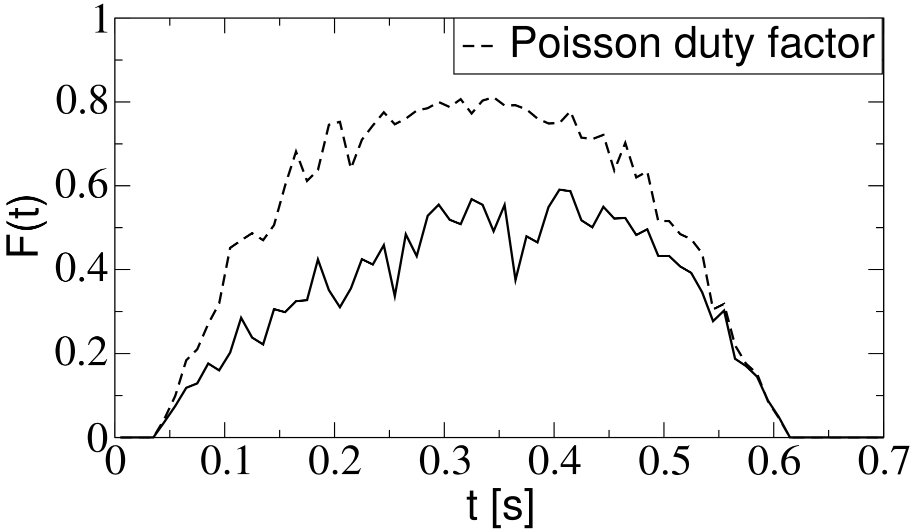
  $$F_\mathrm{P}(t) = \frac{N_\mathrm{p,av}(t)}{N_\mathrm{p,av}(t) + 1}$$

  - Limit of for random particle extraction within t_ave → maximum for realistic conditions.
  - Pure function of extraction rate $N_\mathrm{p,av}(t)$.

Spill structure simulations


Spill


Spill part


Time dependent duty factor

- Ripple on strengths of main quadrupoles: Sinusoidal component with $f = 600\ \mathrm{Hz}$ and white noise contribution with band width $f_{\mathrm{BW}} = 10\ \mathrm{kHz}$.
- $600\ \mathrm{Hz}$ signal well visible on spill.
- Non-uniform extraction rate reduce duty factor below Poisson limit.

Spill structure simulations

Computational effort:

- 1000 particles, $6000 + 25000$ revs.: $t_{\mathrm{sim}} = 1 : 54\ \mathrm{h}$.
- 1000 particles, $6000 + 150000$ revs.: $t_{\mathrm{sim}} = 10 : 10\ \mathrm{h}$.
  Spill simulation with 100000 particles would require 100 simulations: $t_{\mathrm{sim}} \approx 1000\ \mathrm{h}$.

Question: Are there ways to reduce simulation time?

Spill structure simulations

Computational effort:

- 1000 particles, $6000 + 25000$ revs.: $t_{\mathrm{sim}} = 1:54\ \mathrm{h}.$
- 1000 particles, $6000 + 150000$ revs.: $t_{\mathrm{sim}} = 10:10\ \mathrm{h}.$
  Spill simulation with 100000 particles would require 100 simulations: $t_{\mathrm{sim}} \approx 1000\ \mathrm{h}.$

Question: Are there ways to reduce simulation time?

Yes, because lower requirement to precision of lattice and losses only at ES.

- Reduce number of slices per thick element to 5: $t_{\mathrm{sim}} = 9:22\ \mathrm{h}.$
  100 simulations: $t_{\mathrm{sim}} \approx 930\ \mathrm{h}.$
- In addition, remove collimator elements: $t_{\mathrm{sim}} = 5:47\ \mathrm{h}.$
  100 simulations: $t_{\mathrm{sim}} \approx 580\ \mathrm{h}.$
- In addition, remove all apertures except ES: $t_{\mathrm{sim}} = 4:58\ \mathrm{h}.$
  100 simulations: $t_{\mathrm{sim}} \approx 500\ \mathrm{h}.$

In reality, spill simulations performed by tracking 10 times 10000 particles: $t_{\mathrm{sim}} \approx 30\ \mathrm{h}.$

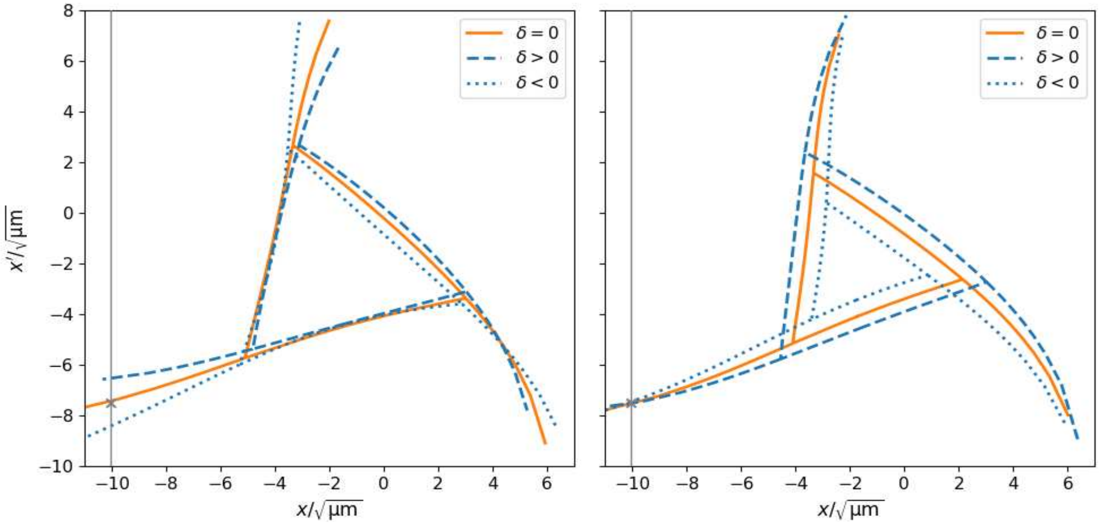
- 10 simulations: $t_{\mathrm{sim}} \approx 300\ \mathrm{h}.$

Summary

- Slow extraction simulations done mainly for two purposes: estimation of uncontrolled particle loss and description of spill structures, in particular spill micro structures, demonstrated with SIS100 example.
- Both purposes with different requirements to simulations leading to computational effort.
- Beam loss simulations: Long computing time due to comprehensive, large SIS100 lattice with many apertures in spite of moderate particle number and simulation interval.
- Spill structure simulations: particle number and time interval significantly larger than in beam loss simulations → Computing time significantly larger.
  - Acceptable computing time achieved by less precise lattice and removing apertures except electrostatic septum.
  - Requirement: marginal particle loss at other apertures.

Thank you for your attention.

COSE in SIS100



Courtesy: D Ondreka, GSI.

- Simultaneous extraction of particles with different δ.
- Separatrices for particles with different δ should cross ES at similar x' $\rightarrow$ low losses.
- Hardt condition: shifts of separatrix due to chromaticity and dispersion compensate each other.
- SIS100: Large systematic decapole component and dispersion in dipoles leads to δ dependent octupole by feed and bent separatrices.
  $\rightarrow$ Can be used for adjusting separatrices to the same x' at ES [2].
- COSE: Keep separatrices adjusted without complicated time dependent correction.

Hénon map simulation

Hénon map: motion of each particle in horizontal phase space determined by:

$$\begin{pmatrix} X_{n+1} \\ X'_{n+1} \end{pmatrix} = \begin{pmatrix} \cos\psi & \sin\psi \\ -\sin\psi & \cos\psi \end{pmatrix} \begin{pmatrix} X_n \\ X'_n + S_{\mathrm{virt}} X_n^2 \end{pmatrix}$$

with betatron phase advance per revolution $\psi = 2\pi(Q_{\mathrm{m}} + \xi\delta)$ and virtual sextupole S_{virt}.
Replace whole lattice with rotation matrix resulting in much faster simulation. But

- Vertical particle motion neglected.
- Works well if machine is linear, e.g. SIS18, CERN-SPS [3,4].
- SIS100:
  - Strong reduction of horizontal chromaticity $\xi_{x,\mathrm{nat}} = -27 \;\rightarrow\; \xi_x = -3$ with sextupoles which do not contribute to S_{virt} but reduce dynamic aperture.
  - Spiral steps modified with octupoles.
    Check carefully because size and number of steps from stable phase space area to extraction septum have strong influence on spill micro structures [5,6].

[1] V. Kain *et al.*, “Resonant slow extraction with constant for optics improved separatrix control at the extraction septum”, Phys. Rev. Accelerators and Beams **22**, 101001 (2019).

[2] D. Ondreka *et al.*, “SIS100 extraction layout: Influence of nonlinear beam dynamics”, Presentation during the 5th Slow Extraction Workshop, Wiener Neustadt, Austria, 2024.

[3] R. Muto, “Spill Structure with Newly Upgraded Main Magnet Power Supplies in J-PARC Main Ring”, Presentation during the 5th Slow Extraction Workshop, Wiener Neustadt, Austria, 2024.

[4] P. Arrutia *et al.*, “RF techniques for bunched/pulsed slow extractions from synchrotrons”, Presentation during the 5th Slow Extraction Workshop, Wiener Neustadt, Austria, 2024.

[5] S Sorge *et al*,“Measurements and Simulations of Spill Quality of Slowly Extracted Beams from the SIS-18 Synchrotron” 2018 *J. Phys.: Conf Ser.* **1067** 052003.

[6] R. Singh *et al.*, “Reducing Fluctuations in Slow-Extraction Beam Spill Using Transit-Time-Dependent Tune Modulation”, Phys. Rev. Applied **13**, 044076 (2020).