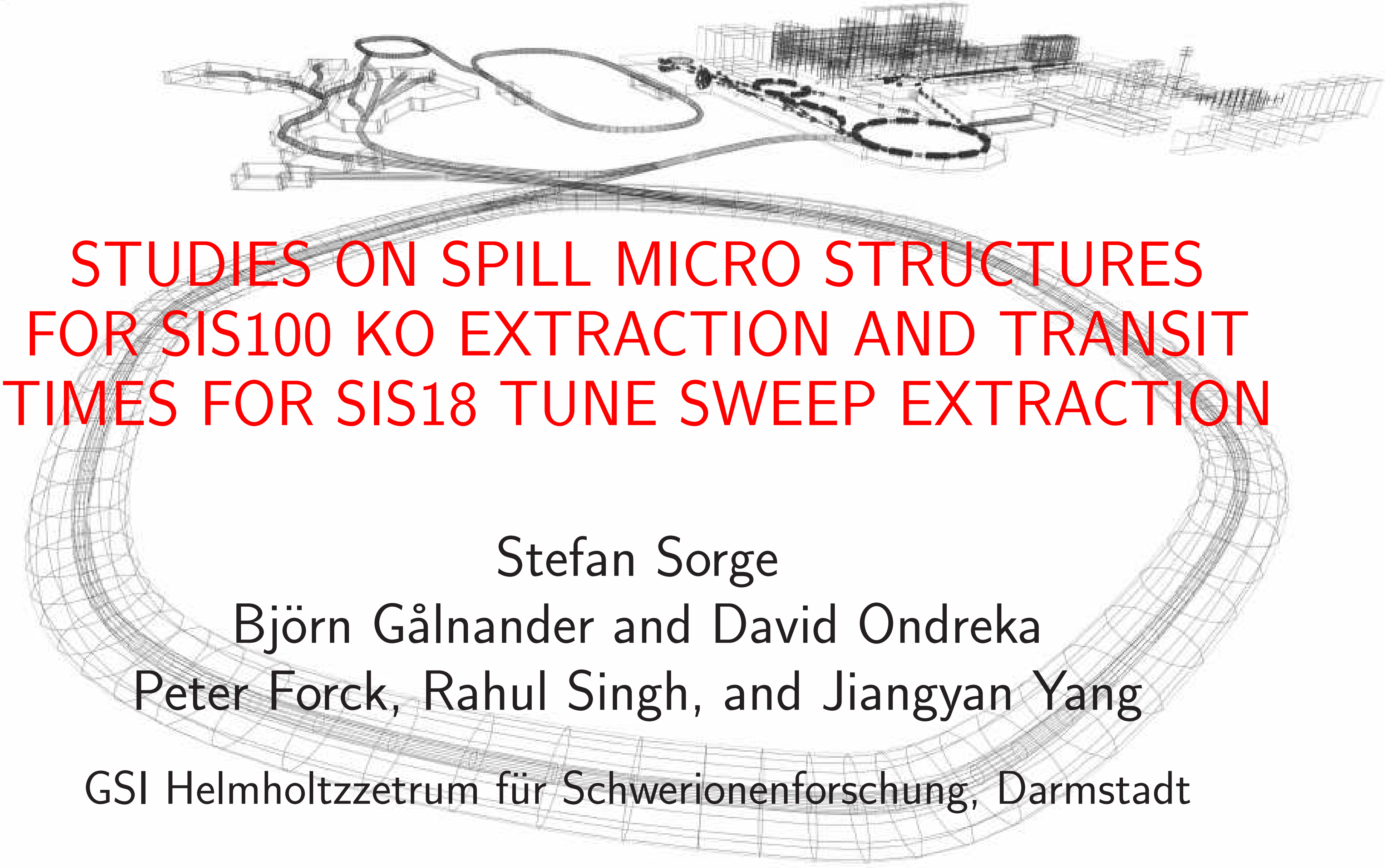

STUDIES ON SPILL MICRO STRUCTURES FOR SIS100 KO EXTRACTION AND TRANSIT TIMES FOR SIS18 TUNE SWEEP EXTRACTION

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Part I: SIS100 KO Extraction

Introduction to Part I on a simulation study on spill quality of SIS100 KO extraction

- SIS100 will be main synchrotron of future FAIR project.
  Circumference: $C = 1083.6\ \mathrm{m}$.
- Will deliver heavy ion beams to many fixed target experiments.
- Most experiments will require slow extraction.
  KO extraction is foreseen as standard slow extraction technique.
- Need for investigation of spill micro structures.
- Aim: Studying influence of some variables on spill quality:
  - Horizontal chromaticity.
  - Harmonic of the carrier frequency of the KO signal.
  - Time resolution of spill recording.

Part I: SIS100 KO Extraction

Some characteristics:

- Typical slow extraction working points near $Q_x = 17.32, Q_y = 17.4$.
- Chromaticities ξ_x, ξ_y according to definition

$$\Delta Q = \xi \; \delta$$

  Natural: $\xi_x = -20.1, \;\; \xi_y = -20.2$ changed to $\xi_x = -1 \; \ldots \; -3, \;\; \xi_y = -26.1$.

- Slow extraction energy range $E = (0.4, \; \ldots \; , 2.7)\ \mathrm{GeV/u}$ for reference ion U^{28+}.
  This presentation: only lowest energy $E = 0.4\ \mathrm{GeV/u}$.
  $\rightarrow$ Resulting revolution time: $t_{\mathrm{rev}} = 5.05\ \mu\mathrm{s}$.
- Simulations with MAD-X code.
  100000 particles tracked for 150000 revolutions $\rightarrow$ time interval $t_{\mathrm{ex}} = 0.75\ \mathrm{s}$.
- Spills recorded in time bins $t_{\mathrm{rec}} = 10.1\ \mu\mathrm{s} = 2\ t_{\mathrm{rev}}$:
  $\rightarrow$ not much longer than revolution time.
- KO signal: Random Binary Phase Shift Keying (RBPSK) signal.

Part I: SIS100 KO Extraction

Spill micro structures are created by quadrupole ripples and KO signal.

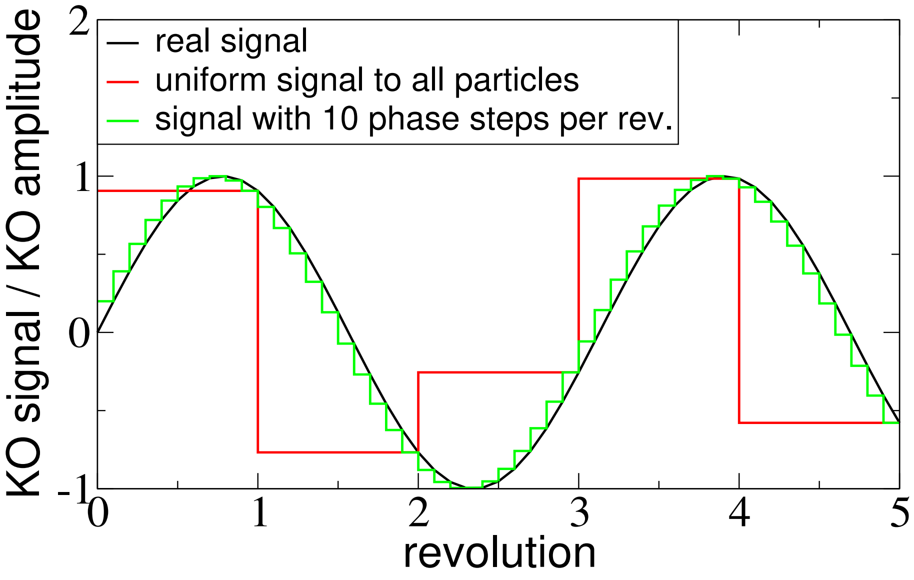
1. Quadrupole ripples:
   - Single frequency $f = 600\ \mathrm{Hz}$ with relative amplitude 10^{-5}.
   - Noise signal with band width limited to $f_{\mathrm{bw}} = 2\ \mathrm{kHz}$ and relative rms strength 10^{-5}.
   - Choice according to observations in present GSI synchrotron SIS18.
2. KO signal: Random binary phase shift keying (RBPSK) signal

$$\Delta x'(n_{\mathrm{rev}}) = \Delta x'_{\mathrm{a}} \sin\left(2\pi Q_{\mathrm{c}} n_{\mathrm{rev}} + \phi_{\mathrm{KO}} + \phi_{\mathrm{offset}}\right)$$

   - Constant KO amplitude $\Delta x'_{\mathrm{a}}$, set sufficiently large to extract all particles in simulation.
   - $f_{\mathrm{c}} = f_{\mathrm{rev}}\ Q_{\mathrm{c}}$: carrier frequency with “carrier tune” $Q_{\mathrm{c}} = h_{\mathrm{KO}} + 1/3 - \Delta Q_x/2$ and distance between horizontal machine and resonance tunes $\Delta Q_x \equiv 52/3 - Q_x$.
   - ϕ_{KO}: phase randomly shifted between values $\phi_{\mathrm{KO}} = 0, \pi$ with phase shift rate. Shifting ϕ_{KO} changes signal's sign → width $f_{\mathrm{w}} = f_{\mathrm{rev}}\ Q_{\mathrm{w}}$ of the power spectrum.
   - ϕ_{offset}: set of different fixed phase offsets applied to different fractions of particles.

Phase offsets ϕ_{offset}

- Simulations with MADX → KO signal is function of revolution.
- In reality, phase of KO signal changes within revolution.
  → Particles with different longitudinal positions receive KO signal of different phases.



Simple approximation:

- Split particle ensemble in $N_{\text{frac}} = 10$ fractions.
- Apply to each fraction signal modified by constant phase offset

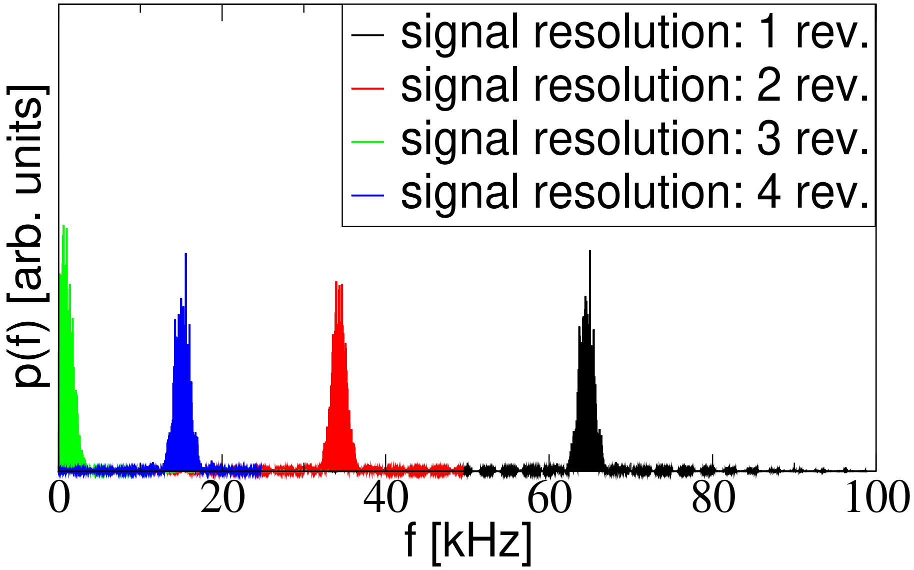
$$\phi_{\text{offset}} = 2\pi\ Q_c \frac{n_{\text{frac}} - 1}{N_{\text{frac}}}$$

with $n_{\text{frac}} = 1,\ \dots\ , N_{\text{frac}}$.

Effects due to phase slip factor neglected for coasting beam. Can be included with other code, e.g. XSuite. See presentation of Philipp Niedermayer.

Part I: SIS100 KO Extraction

Power spectrum of RBPSK signal recorded with several resolutions



$$p(f) \propto \left[\frac{\sin\left(\pi\frac{f-f_{\mathrm{cnt}}}{f_{\mathrm{w}}}\right)}{\frac{f-f_{\mathrm{cnt}}}{f_{\mathrm{w}}}}\right]^2$$

Half width defined by first minimum:

$$|f_{\mathrm{min}} - f_{\mathrm{cnt}}| = f_{\mathrm{w}}.$$

- Fractional phase advance per revolution and corresponding central frequency

  signal resolution 1 rev.: $\phi_{\mathrm{rev,cnt}}/(2\pi) = 1/3 - 0.0137/2 = 0.3265,\ f_{\mathrm{cnt}} = 64.7\ \mathrm{kHz}$

  signal resolution 2 rev.: $\phi_{\mathrm{rev,cnt}}/(2\pi) = 0.1735,\ f_{\mathrm{cnt}} = 34.4\ \mathrm{kHz}$

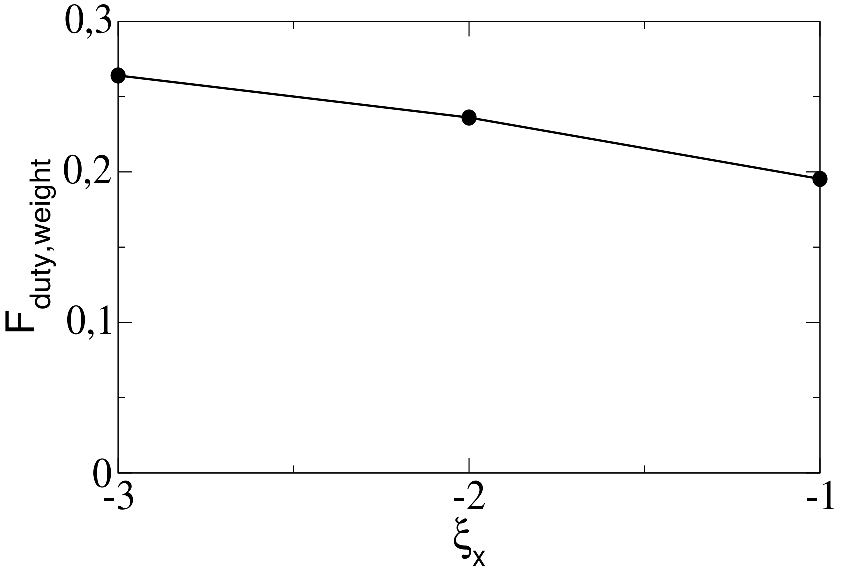
  signal resolution 3 rev.: $\phi_{\mathrm{rev,cnt}}/(2\pi) = 0.00685,\ f_{\mathrm{cnt}} = 1.36\ \mathrm{kHz}$

  signal resolution 4 rev.: $\phi_{\mathrm{rev,cnt}}/(2\pi) = 0.0765,\ f_{\mathrm{cnt}} = 15.1\ \mathrm{kHz}$

- Half width in all simulations to apply the same signal: $Q_{\mathrm{w}} = 0.0137, f_{\mathrm{w}} = 2.71\ \mathrm{kHz}$ sufficiently large to cover particle tunes and 3rd integer resonance for all chromaticities.

Part I: SIS100 KO Extraction

Influence of chromaticity, weighted duty factor for coasting beam



Higher spill quality denoted by larger weighted (or averaged) duty factor for horizontal chromaticity with larger modulus.

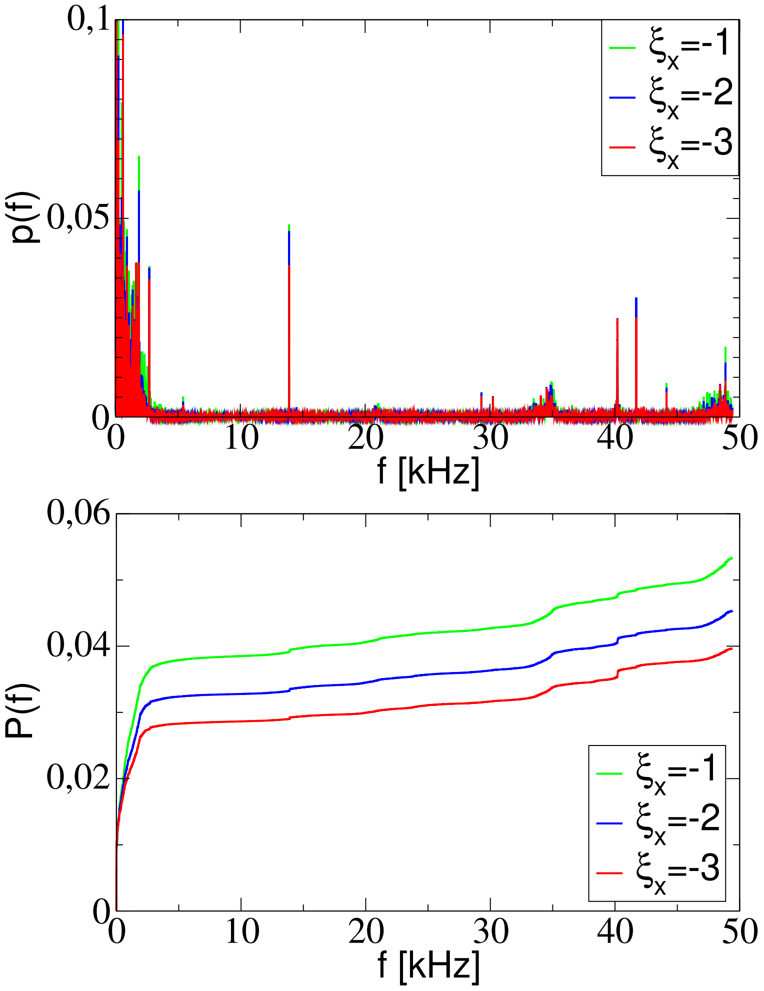
Weighted (or averaged) duty factor $F_{\text{duty,weighted}} = \dfrac{\int \mathrm{d}t\ F_{\text{duty}}(t)\dot{N}(t)}{\int \mathrm{d}t\ \dot{N}(t)} = \dfrac{\sum\limits_k\ F_{\text{duty}}(t_k)N(t_k)}{\sum\limits_k\ N(t_k)}$

with time dependent duty factor $F_{\text{duty}}(t_k) = \dfrac{\langle N\rangle^2(t_k)}{\langle N^2\rangle(t_k)}$.

$\langle x\rangle$: variable x recorded in time intervals $t_{\text{rec}} = 2\ t_{\text{rev}} \approx 10.1\ \mu\text{s}$ and averaged in averaging time intervals $t_{\text{ave}} = 1000\ t_{\text{rec}} \approx 10.1\ \text{ms}$.

Part I: SIS100 KO Extraction

Influence of chromaticity, spill spectra (only coasting beam)



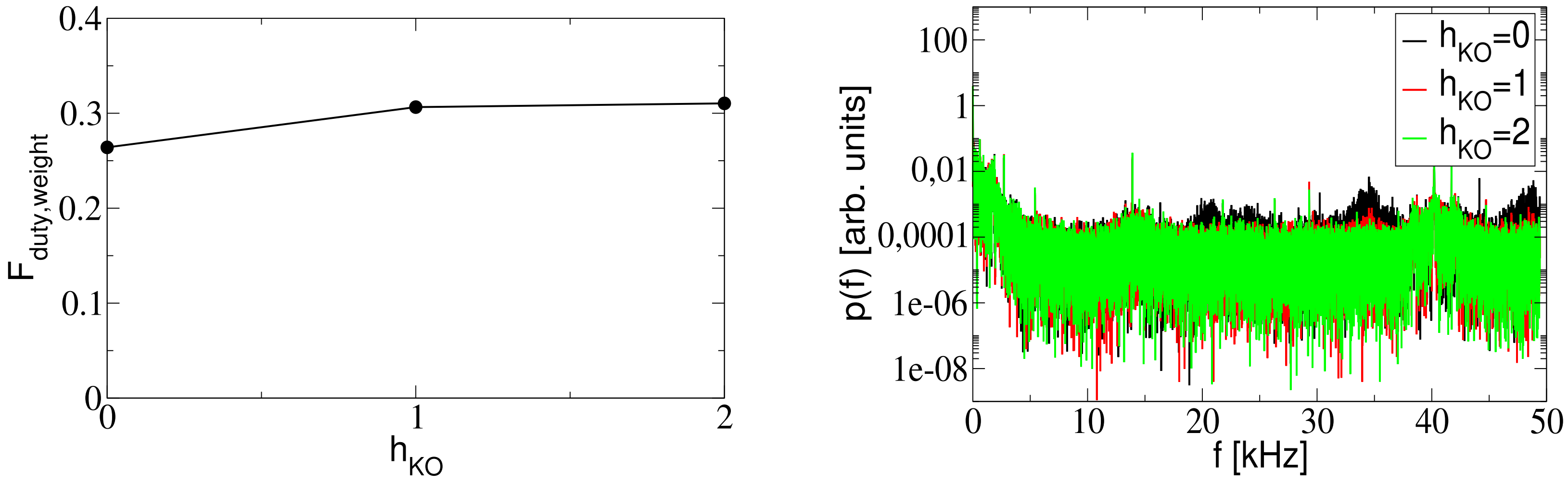
- Spectral power density $p(f)$ for different chromaticities similar.
- Difference better visible in integrated spectral power

$$P(f) = \int_0^f \mathrm{d}\bar{f}\; p(\bar{f})$$

- Chromaticity affects spill structure at low frequencies $f \leq 2\ \mathrm{kHz}$.
  $\rightarrow$ range of quadrupole ripple.

Part I: SIS100 KO Extraction

Influence of harmonic number of KO signal h_{KO}. Apply $\xi_x = -3$.



- Applying $h_{\mathrm{KO}} > 0$:
  - Increase of weighted duty factor.
  - Several structures on spectral power density at high frequencies disappear, in particular, peak near KO signal's central peak at $f = 34.4\ \mathrm{kHz}$.

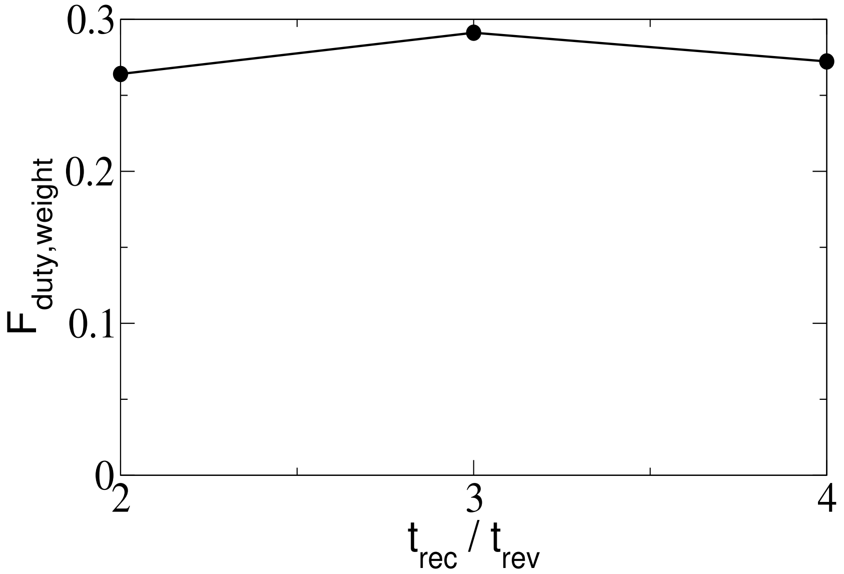
  Hypothesis: Binning provides average over KO signal values. The KO signal range in recording bin is increased for $h_{\mathrm{KO}} > 0$.

- Tiny difference between $h_{\mathrm{KO}} = 1$ and $h_{\mathrm{KO}} = 2$ → Possibly, need for more ϕ_{offset}.

Part I: SIS100 KO Extraction

Influence of recording time bin t_{rec}. Apply $\xi_x = -3$ and $h_{\mathrm{KO}} = 0$.

So far, recording bin lengths $t_{\mathrm{rec}} = (2, 3, 4)$ revolutions, where



- particle number kept constant.
- extraction time interval increased by factors 1.5 and 2 by reducing KO amplitude $\Delta x'_{\mathrm{a}}$ by factors $1/\sqrt{1.5}$ and $1/\sqrt{2}$, using relation

$$\frac{\mathrm{d}\epsilon_x}{\mathrm{d}t} \propto \Delta x'^{\,2}_{\mathrm{a}}$$

$$\Downarrow$$

Averaged number of particles in $t_{\mathrm{rec}}, t_{\mathrm{ave}}$, and Poisson duty factor kept.

Hypothesis: Increase of weighted duty factor because

1. Longer t_{rec} yields average over longer KO signal range which mitigates spill structures from KO signal.
2. $3\ Q_{\mathrm{c}} \approx \mathrm{integer}$, hence approximately average over full KO oscillations in $t_{\mathrm{rec}} = 3\ t_{\mathrm{rev}}$.

Part II: Transit Times SIS18 Tune Sweep Extraction

Motivation of Part II on the determination of transit times for SIS18 tune sweep extraction

- Work on transit times started at GSI 2017: Spread of the transit times was found to mitigate spill micro structures. High frequency spill structures more mitigated [1].
- Application developed for present GSI heavy ion synchrotron SIS18 [2]:
  Superposing low frequency tune ripple with high frequency tune modulation mitigates low frequency spill ripple. → "Tune wobble"
- Recent emergence of desire to measure transit times. Actual status:
  pre-studies with simulations and measurements done, where data evaluation still in progress.

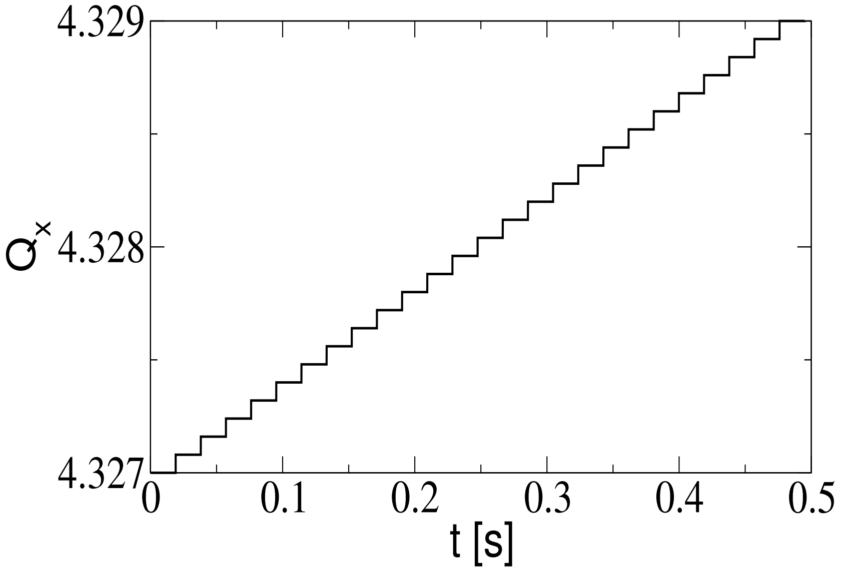
This presentation:

- Simulation study to introduce topic.
- Measurement details shown on poster of Jiangyan Yang.

Part II: Transit Times SIS18 Tune Sweep Extraction

Determination of transit times with simulations with tune sweep in steps

- SIS18 with circumference $C = 216.72\ \mathrm{m}$.
- Conditions of Ar^{18+} beam at $E = 500\ \mathrm{MeV/u}$ → Revolution time $t_{\mathrm{rev}} = 0.95\ \mu\mathrm{s}$.
- Simulation with simplified model which consists of rotation matrix and virtual sextupole.



- Horizontal tune sweep:
  $Q_{x,\mathrm{i}} = 4.327,\ Q_{x,\mathrm{f}} = 4.3362$.
- Height of tune step: $\Delta Q_x = 0.0008$.
- 115 steps of duration of 20000 revolutions.

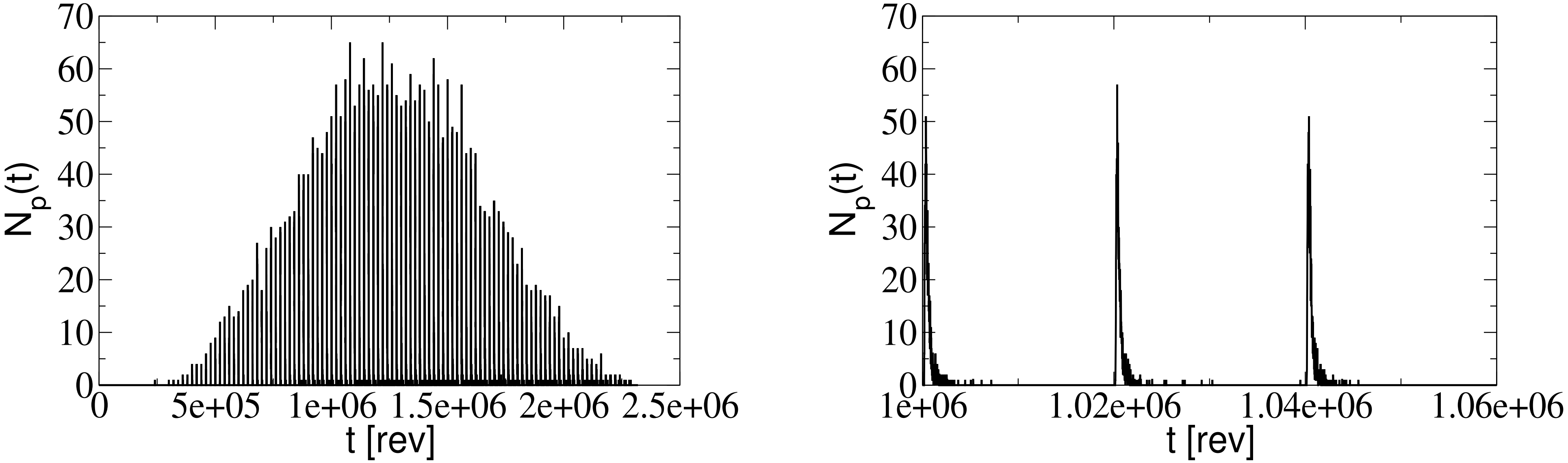
Idea:

Tune step provides that many particles leave stable phase space area at the defined instant.

Instant of step is start of the transit which is usually unknown.

Part II: Transit Times SIS18 Tune Sweep Extraction

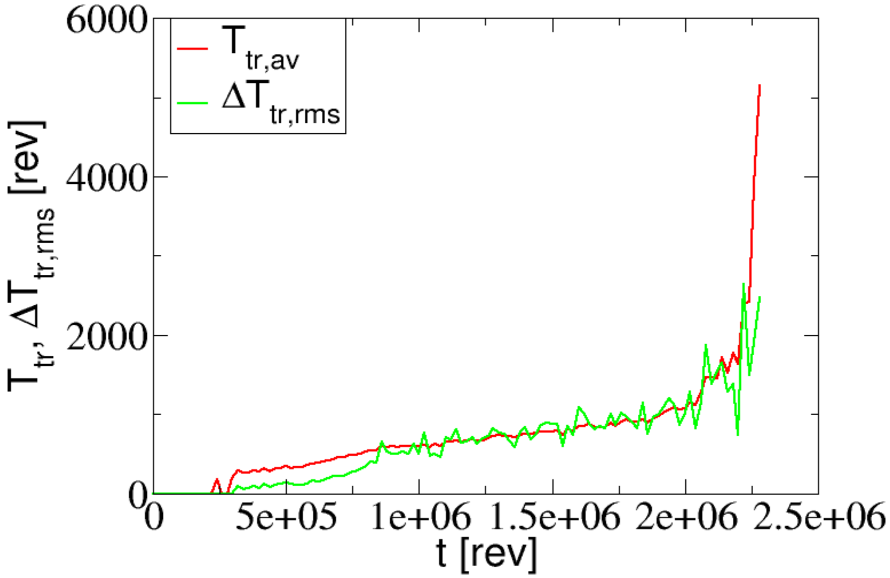
Ideal world: Simulation without quadrupole ripples.



- Spill is sequence of peaks shown in the right picture.
- Peaks are well separated. Hence, average and rms width of transit times can be determined.

Part II: Transit Times SIS18 Tune Sweep Extraction

Ideal: Simulation without quadrupole ripples.

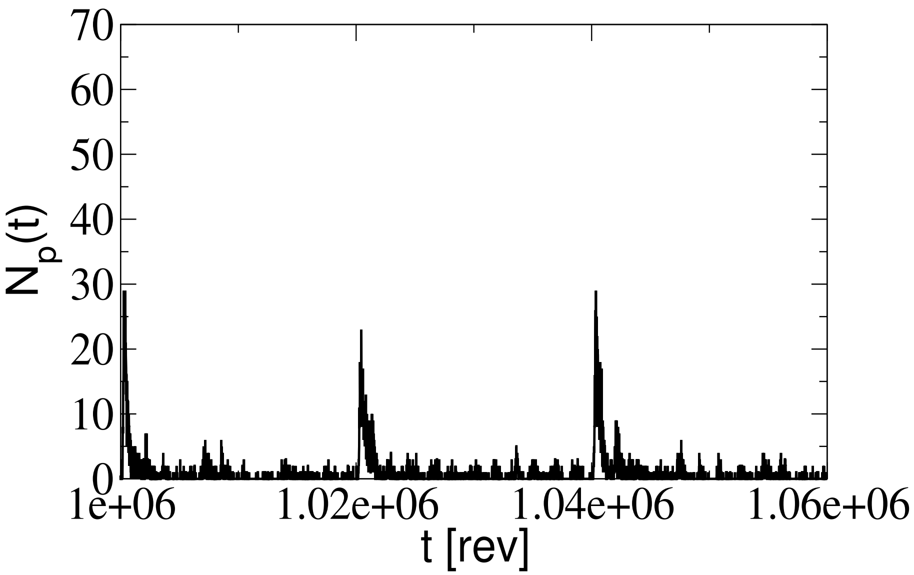


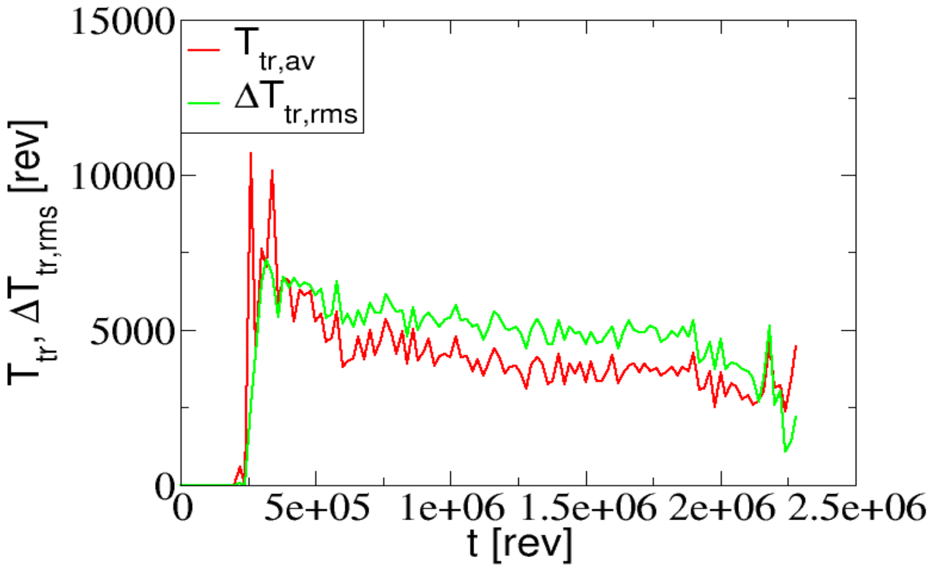
Time dependent average and rms spread of transit times

- Monotonic increase of $T_{\mathrm{tr,av}}$, $\Delta T_{\mathrm{tr,rms}}$ during the extraction because of increased number of particles which extracted near resonance towards spill end.
- Sign for increasing spill quality because larger average and spread of transit times results in lower spill micro structure level.
- Agreement with former observation of increasing spill quality towards the end of the spill.

Part II: Transit Times SIS18 Tune Sweep Extraction

More realistic model: Simulation with quadrupole ripples



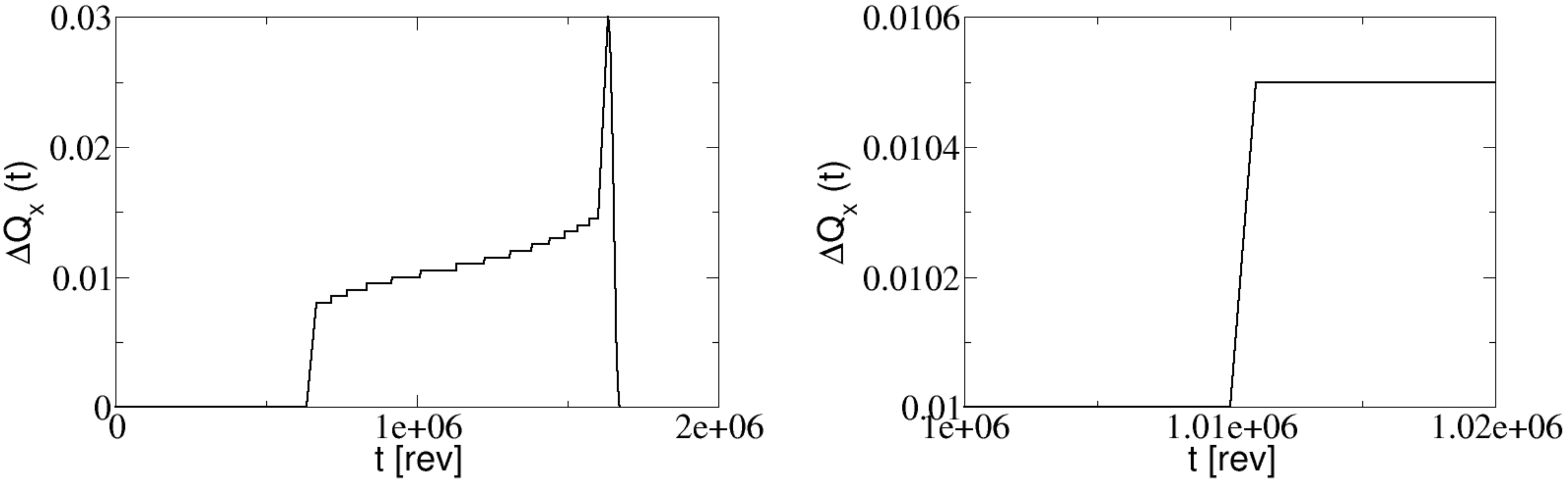


- Spill is sequence of peaks. Many particles extracted between peaks due to tune ripples. → Time span between particle arrival at detector and tune step not transit time anymore.
- Instead, average and rms spread of transit times determined by tune step duration of 20000 revolutions → larger than without quadrupole ripples and less time dependent.

Need for other way to determine average and spread of transit times.

Part II: Transit Times SIS18 Tune Sweep Extraction

Tune sweep with steps applied in measurement, U^{73+} beam at $E = 300\ \mathrm{MeV/u}$



- Applied step heights: $\Delta Q_x = 5 \cdot 10^{-5}, 10^{-4}, 2 \cdot 10^{-4}, 5 \cdot 10^{-4}, 10^{-3}$.
- Steps have finite rise time $\Delta t = 1000\ \mathrm{rev} \approx 1\ \mathrm{ms} \rightarrow$ further obstacle because requires distinction between similar contributions to peak duration of transit times and rise time.
- Rise time and tune ripple are points of data evaluation under discussion, see Poster of Jiangyan Yang.

Part I: SIS100 KO Extraction

Summary and conclusions

- The influence of some parameters to the spill quality of SIS100 KO extraction is investigated in particle tracking simulations done with MADX:
  horizontal chromaticity, harmonic number of the carrier tune of the KO signal, length of the recording bins.
- The last two are assumed to have an influence because the spills are recorded in bins which are not much longer than a revolution time.
- An increase of the spill quality is found by increasing each of the three parameters.
- Generally, duty factor is low.
- Possibly, inclusion of effects due to phase slip factor to additional spill smoothing, e.g. by particle to neighbouring recording time bins or change of KO phase due to longitudinal motion.

Part II: Transit Times SIS18 Tune Sweep Extraction

Summary

- An attempt to determine transit times for tune sweep slow extraction from SIS18 with particle tracking simulations using a simplified model is introduced. This study was a pre-study to measurements.
- The model consists of application of a tune sweep in sudden steps. Hence, the transit of the particles towards the extraction channel starts at a defined instant which is usually not known.
- The model seems to work well under ideal conditions, i.e. for sudden tune steps without tune ripples.
- The handling of tune steps with finite rise time and the presence of tune ripples is still under discussion.

References

[1] S Sorge, P Forck, and R Singh 2018 *J. Phys.: Conf. Series* **1067** 052003

[2] R. Singh, P. Forck, and S. Sorge, Phys. Rev. Applied **13**, 044076 (2020)