SLOW EXTRACTION AT FAIR: RECENT STUDIES ON SPILL STRUCTURE

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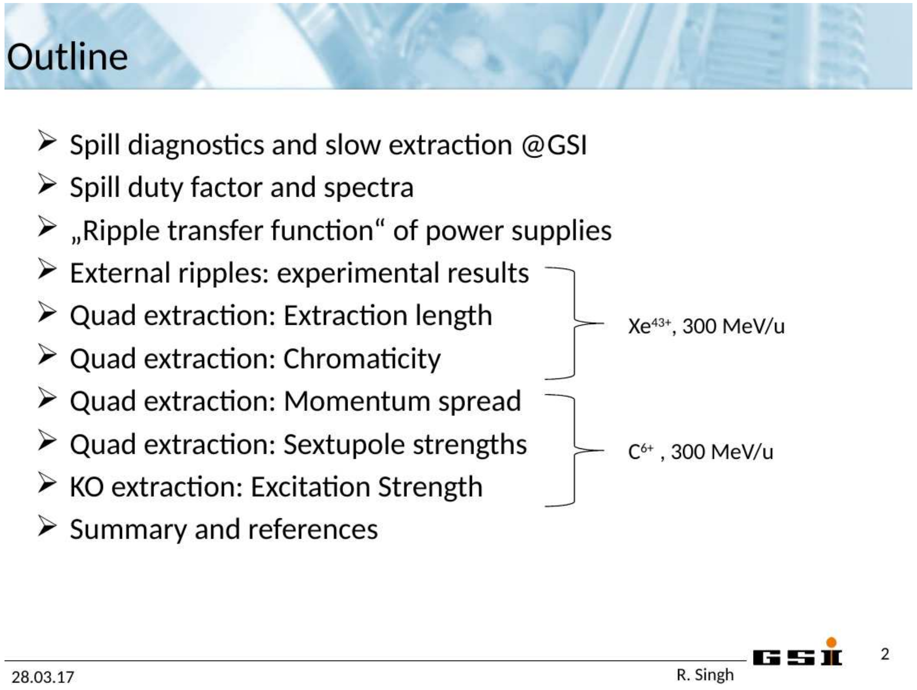
Content

- Spill of quadrupole driven extraction of unbunched beams from SIS-18: influence of sextupoles strength
- Spill of quadrupole driven extraction of bunched beams from SIS-18: influence of sextupole strength and synchrotron frequency
- Spill of KO extraction from SIS-18 and SIS-100

Introduction

Present studies motivated by SIS-18 experiments in 2016:

- Measurements done by R. Singh, P. Forck, P. Kowina, P. Schmid, A. Stafiniak, H. Welker, *et al.*
- Influence of several parameters on spill quality investigated.
- Strongest influence on spill structure found by
  - sextupole strength for unbunched beam extraction.
  - extraction of bunched beams.



Start of simulation studies in 2017 with investigation of dependence of spill quality on sextupole strength for quadrupole driven extraction.

- Simulations for C^{6+} beams at $E = 300\ \mathrm{MeV/u}$.
- Ripple in focusing strength of quadrupoles applied.

Introduction

- Continuation of simulation work this year:
  - Further studies on influence of sextupole strength.
  - Bunched beam extraction:
    1. Start with previous experimental conditions:
       rf voltage with amplitude $V_a = 2\,\mathrm{kV}$ and harmonic $h = 4$. →
    2. Possible influence of synchrotron motion for several cavity voltages.
  - KO extraction from SIS-18 and SIS-100.
- Beam times in December of 2018:
  - Experiments with Ar^{18+} at $E = 300\ \mathrm{MeV/u}$ and Ag^{45+} at $E = (600, 1580)\ \mathrm{MeV/u}$.
  - Repetition of variation of sextupole strength to verify recent results.
  - Measurements with varied rf voltage.
  - KO extraction with varied sextupole strengths.

Data not processed yet. Present only observations during measurements.

Introduction

Experiment conditions:

- Spill measurements with plastic scintillation counter.
- Limitation to extraction rate of $\mathrm{d}N/\mathrm{d}t \approx 10^6/\mathrm{s}$.
- Typical extraction duration: $T_{ex} = (1...2)\ \mathrm{s}$.
- Measurement resolution given by time bins $t_{bin} = 10\ \mu\mathrm{s}$.

Simulation conditions:

- Extraction duration: $T_{ex} = 500000$ **turns** $= 0.55\ \mathrm{s}$. Test particle number: $N = 100000$.
  $\rightarrow$ extraction rate $\mathrm{d}N/\mathrm{d}t = 1.8 \cdot 10^5/\mathrm{s}$
- Ripple applied to strengths of F and D quadrupoles: five sinusoidal ripple components

  frequencies: $f = (600, 1200, 1800, 2400, 3000)\ \mathrm{Hz}$

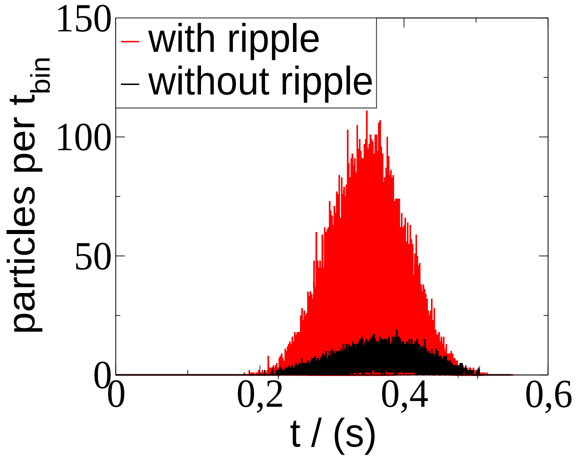
  motivated by strongest line at $600\ \mathrm{Hz}$ found in experiments 2016.

  ripple amplitude: $r_a = \dfrac{10^{-5}}{\sqrt{5}}$

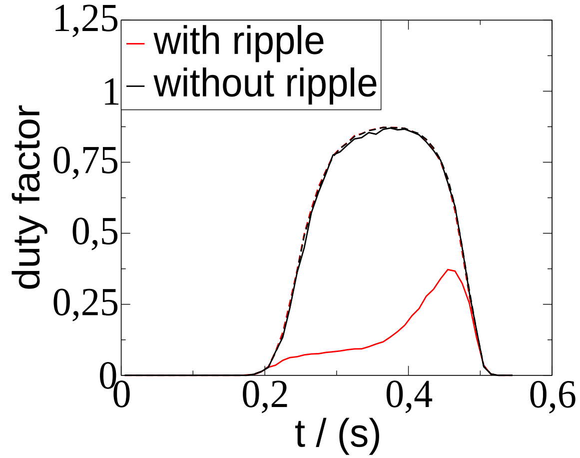
Spill characterisation

Example: Simulation with sextupole amplitude $(k_2 L)_a = 0.18\ \mathrm{m}^{-2}$

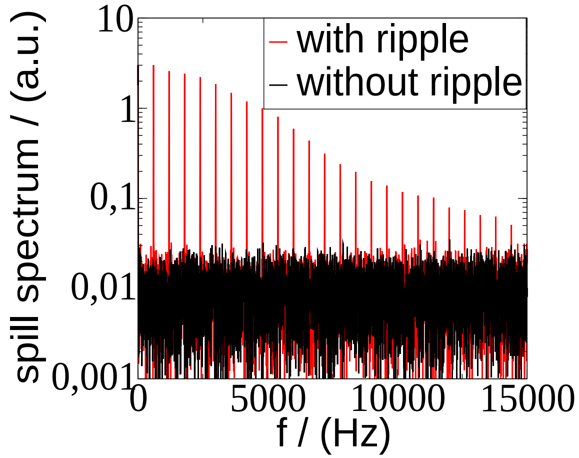
Spill



Duty factor



Spill spectrum



- Spills: both of same particle number. Higher spill intensity with ripple arises from spikes.
- Duty factor: time dependent due to average of $10\ \mu\mathrm{s}$ bins in $10\ \mathrm{ms}$ time intervals

$$F \equiv \frac{N_{av}^2}{N_{av}^2 + \sigma_N^2} = \frac{\langle N \rangle^2}{\langle N^2 \rangle} \quad \text{with Poisson limit} \quad F_{Poisson} = \frac{\langle N \rangle}{\langle N \rangle + 1}$$

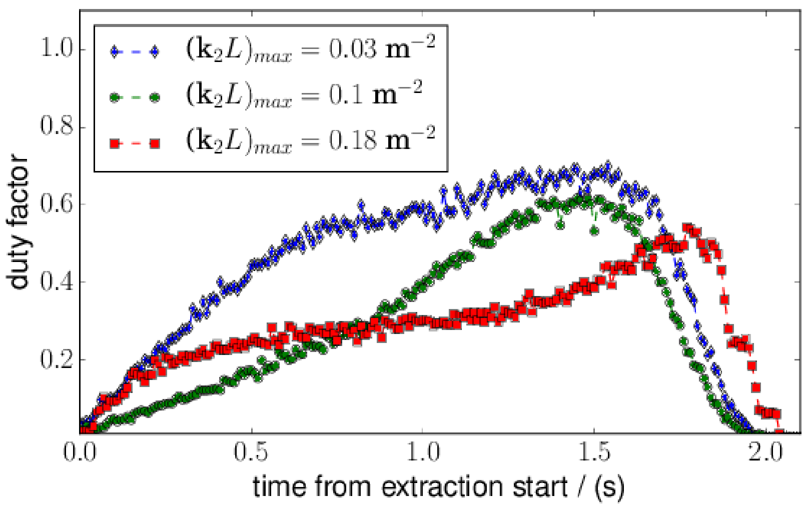
  $F_{Poisson}$ denotes limit of random spill. In centre figure given by dashed lines.

- Spill spectrum: line spectrum, damped for higher frequencies and ripple transfer beyond maximum excited frequency $f_{max} = 3000\ \mathrm{Hz}$.

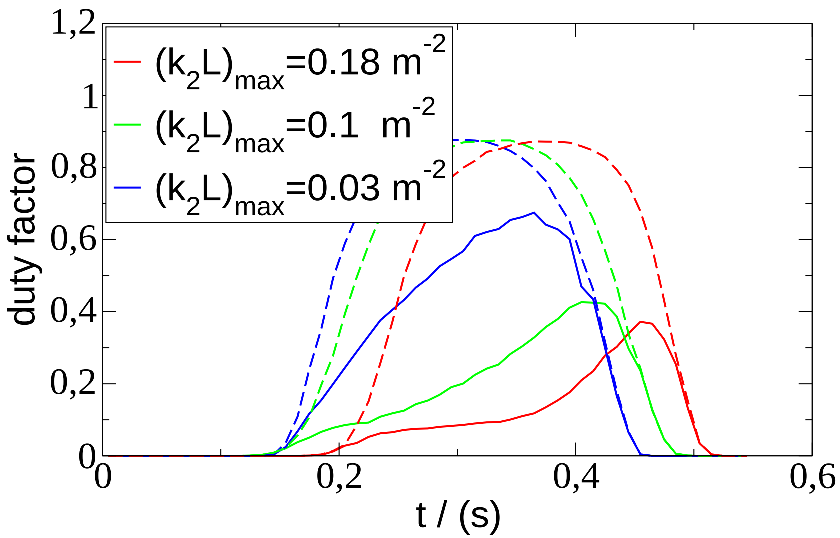
Influence of sextupole strength

Time dependent duty factor

experiment



simulation

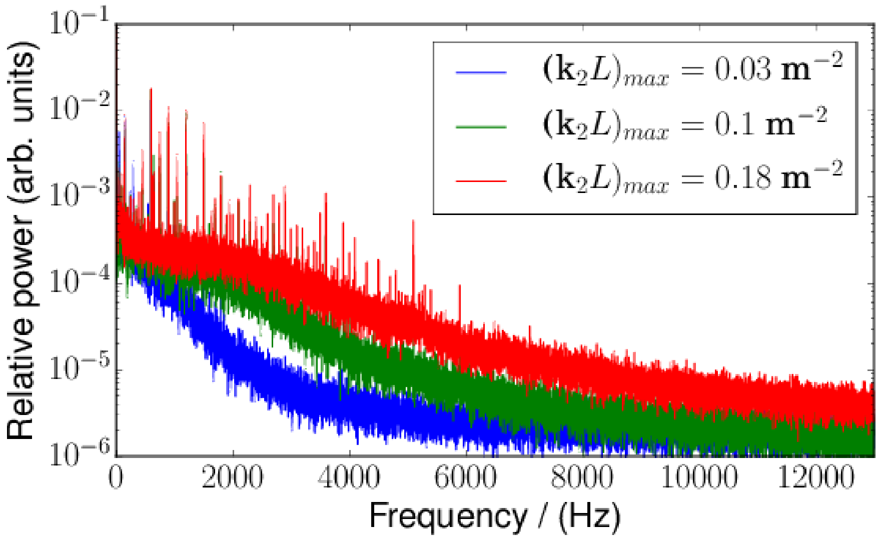


- Better spill quality found for weaker sextupoles and towards the end of the extraction indicated by larger duty factor increasing in time. → reproduced in simulations.
- Dashed lines in figure right:
  Poisson duty factor which denotes limit for random spill.

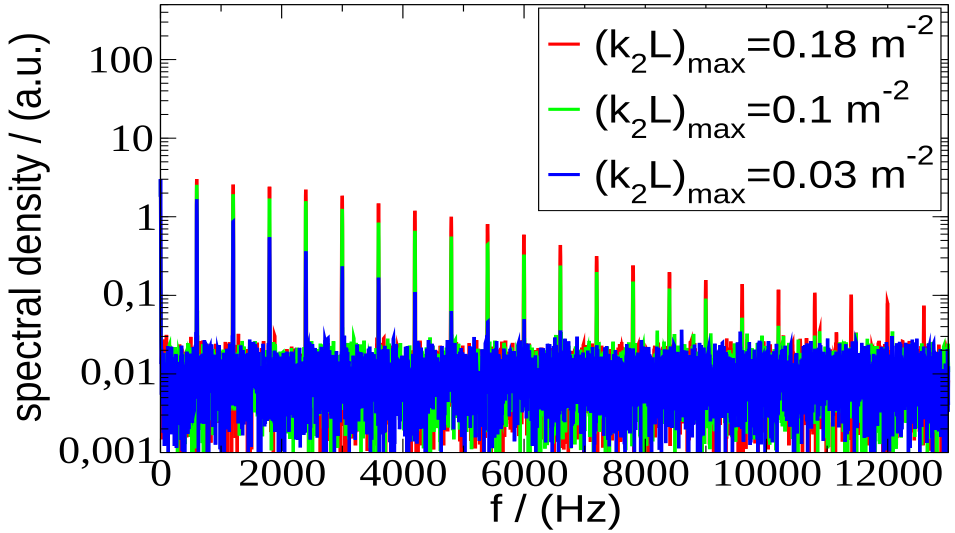
Influence of sextupole strength

Spill spectrum.

experiment



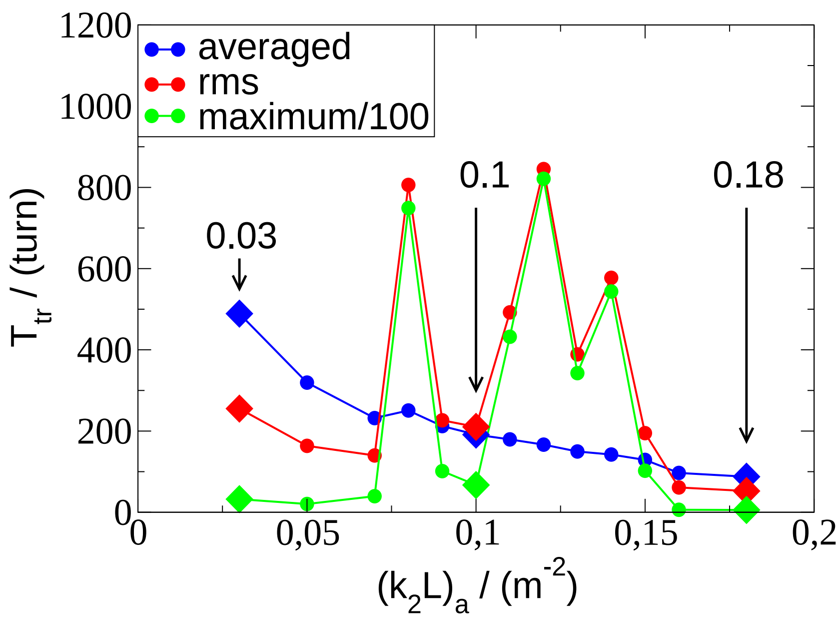
simulation



- Spill spectra drop at lower frequencies for weaker sextupoles. Indicates better spill quality.
- Spectra from simulations are without frequency dependent background. Open point.
- Hypothesis: Vanishing of spill components at high frequencies is due to spread of transit times T_{tr} which washes the high frequency components out. Spread ΔT_{tr} is larger for weaker sextupoles.

Influence of sextupole strength

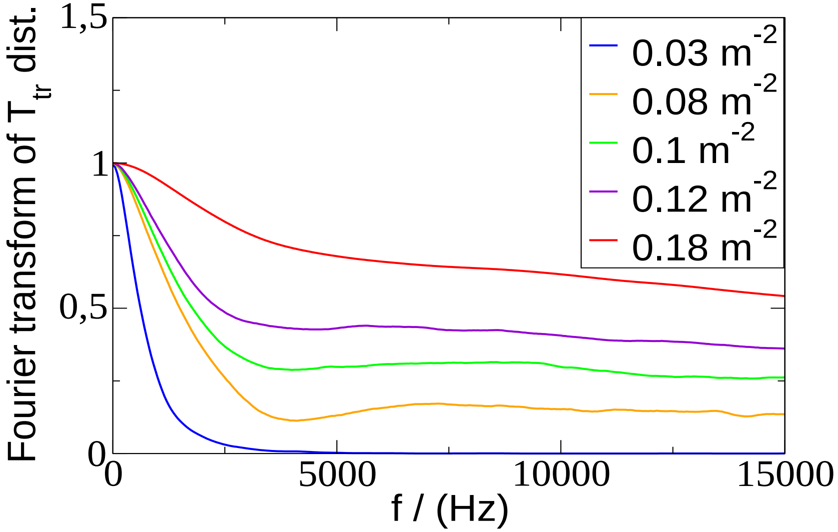
Average, rms spread, and maximum of transit times T_{tr} with simulations



- First attempt to confirm hypothesis by estimating rms spreads of transit times from simulations with several sextupole amplitudes.
- Generally, rms spread not proper because determined by few particles with very long T_{tr}.

Influence of sextupole strength

Instead width of Fourier transform of transit time distribution determined.



- Measure for relative ripple transfer by beam as function of frequency.
- Weaker sextupoles result in more narrow Fourier transform of transit time distribution
  $\rightarrow$ qualitative agreement with spill spectra.
- On the other hand: Narrow Fourier transform arises from broad transit time distribution, i. e. function with large transit time spread
  $\rightarrow$ supports hypothesis, more robust than rms transit time spread.

Influence of sextupole strength

Remarks on latest experimental results

- Beam times in December 2018 on spill quality of slow extraction and its dependence on sextupole strength with Ar^{18+} beams at $E = 300\ \mathrm{MeV/u}$ and Ag^{45+} beams at $E = (600, 1580)\ \mathrm{MeV/u}$.
- Spill measured with plastic scintillation counter. Extraction efficiency measured with ionisation chamber.
- Ar^{18+}:
  - For sextupole amplitudes $(k_2L)_a = (0.03, \ldots, 0.18)\ \mathrm{m}^{-2}$ old results confirmed, i.e. better spill quality for weaker sextupoles found. Good extraction efficiency: up to $90\ \%$ provided the correct calibration of the ionisation chamber used for measuring the extracted beam current.
  - Further reduction of sextupole strengths: significant reduction of extraction efficiency but no significant improvement of spill quality.

Influence of sextupole strength

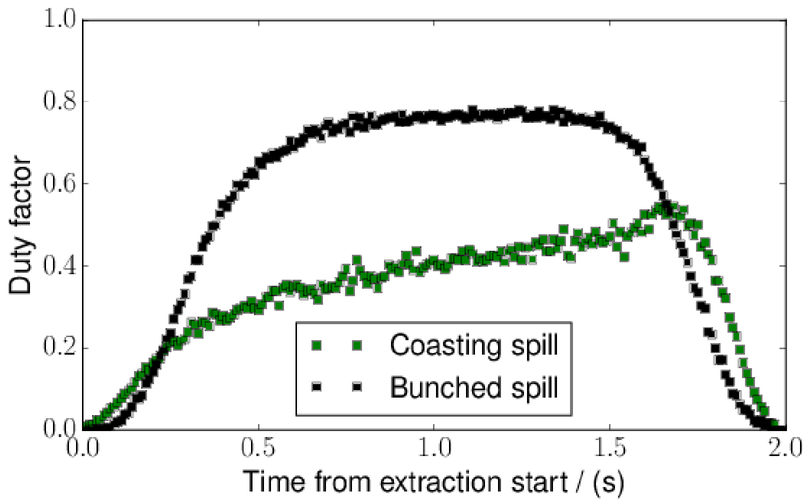
Remarks on latest experimental results

- Ag^{45+} at $E = 600\ \mathrm{MeV/u}$: results similar to those achieved with Argon, i.e. spill improvement if sextupole amplitude is reduced down to $(k_2L)_a = 0.03\ \mathrm{m}^{-2}$ and reduction of extraction efficiency for even weaker sextupoles.
- Ag^{45+} at $E = 1580\ \mathrm{MeV/u}$:
  - Deflection angle of electro-static septum not sufficient anymore resulting in reduction of extraction efficiency down to
    - $50\ \%$ for default sextupole strength $(k_2L)_a = 0.06\ \mathrm{m}^{-2}$ and
    - $10\ \%$ for $(k_2L)_a = 0.02\ \mathrm{m}^{-2}$
  - No significant spill improvement for $(k_2L)_a < 0.06\ \mathrm{m}^{-2}$

Consequence:
Sextupole amplitude in experiments should be reduced to $(k_2L)_a \approx 0.03\ \mathrm{m}^{-2}$ if the energy is sufficiently low.

Slow extraction with bunches from SIS-18

Extraction of bunched beam improves spill quality,
see duty factor from experimental campaign 2016



- Possible mechanism: particles cross separatrix faster while approaching the resonance tune due to synchrotron motion and, hence, are less affected by magnet ripple.
- Question: Does higher synchrotron frequency always lead to better spill?

Slow extraction with bunches from SIS-18

Simulation of bunched beam extraction

- Sextupole amplitudes as applied for coasting beam extraction: $(k_2L)_a = (0.03, 0.1, 0.18)\ \mathrm{m}^{-2}$.
- Rf voltage with $h = 4$ and amplitude up to $V_a = 20\ \mathrm{kV}$, where maximum achievable voltage in SIS-18 is $V_{a,max} \approx 12\ \mathrm{kV}$.

Synchrotron tunes Q_s, periods T_s, and frequencies f_s for C^{12+} beam at $E = 300\ \mathrm{MeV}$:

$V_a/(\mathrm{kV})$	Q_s	T_s	$f_s/(\mathrm{kHz})$
1.0	$0.57 \cdot 10^{-3}$	1752	0.52
2.0	$0.81 \cdot 10^{-3}$	1239	0.73
5.0	$1.3 \cdot 10^{-3}$	769	1.15
10.0	$1.8 \cdot 10^{-3}$	556	1.63
20.0	$2.6 \cdot 10^{-3}$	384	2.31

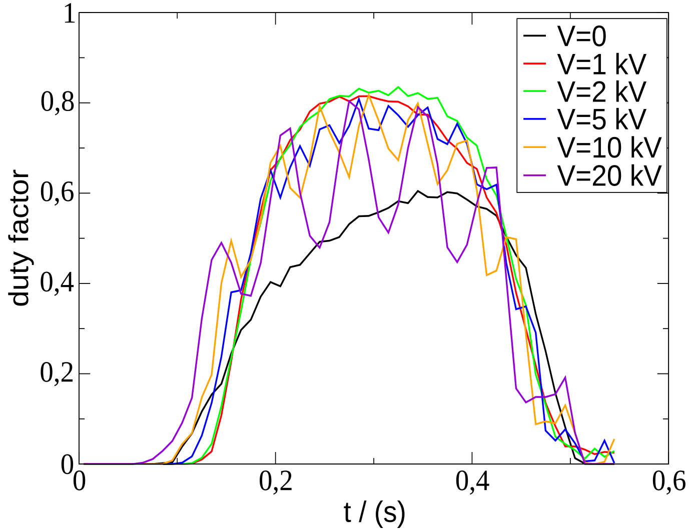
Averaged transit times for $(k_2L)_a = (0.03, 0.1, 0.18)\ \mathrm{m}^{-2}$: $T_{tr,av} = (255, 210, 52)$ turns.

- Synchrotron periods for weaker sextupoles approach transit times.
- Possibly stronger impact of tune ripple because particles re-enter stable phase space area.

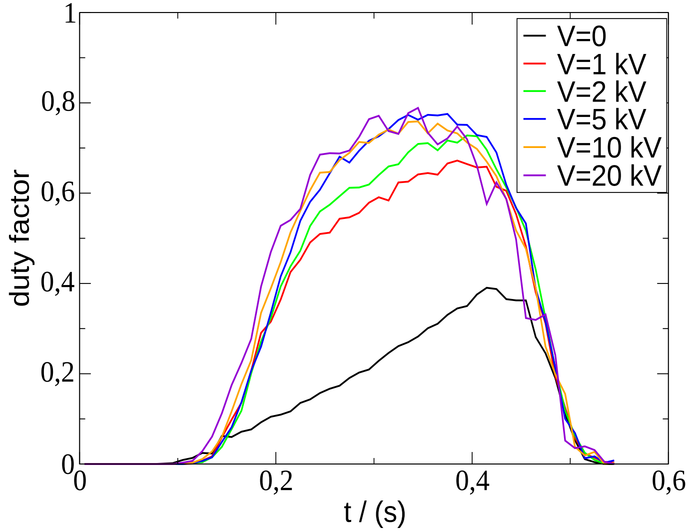
Slow extraction with bunches from SIS-18

Simulation for synchrotron frequencies corresponding up to rf voltage $V = 20\ \mathrm{kV}$ and $h = 4$. Beam energy $E = 300\ \mathrm{MeV/u}$.

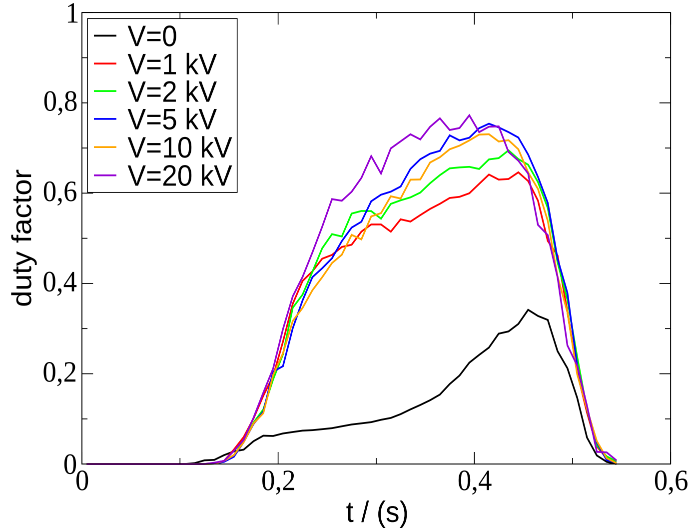
$(k_2L)_a = 0.03\ \mathrm{m}^{-2}$



$(k_2L)_a = 0.1\ \mathrm{m}^{-2}$



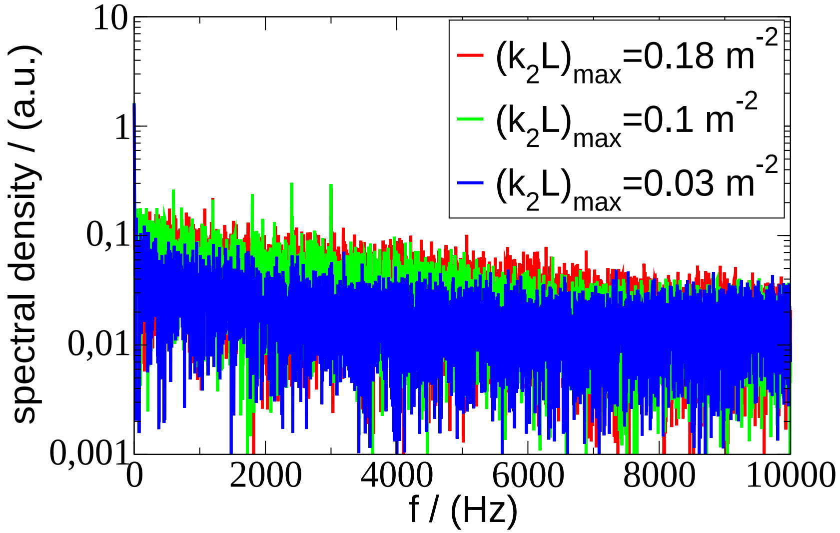
$(k_2L)_a = 0.18\ \mathrm{m}^{-2}$



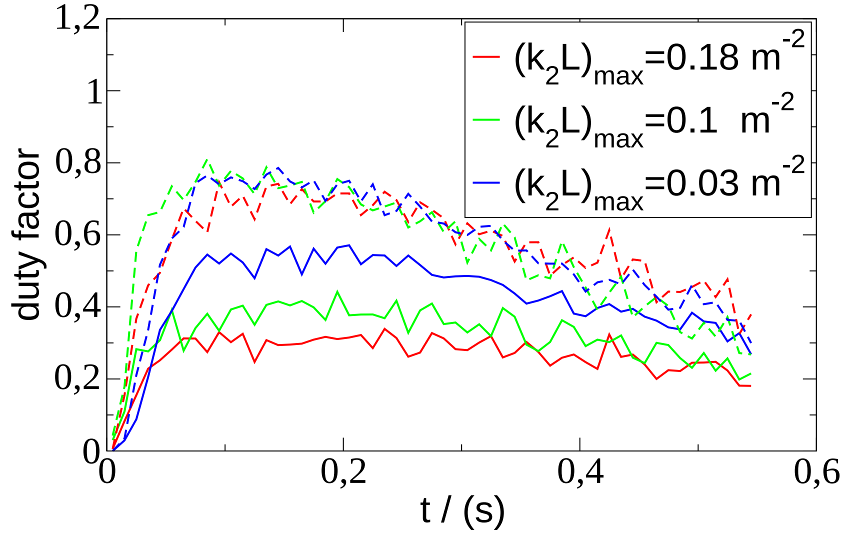
- Bunching leads to spill improvement
- It seems there is maximum frequency for spill improvement particularly for weaker sextupoles, i.e. new structures at duty factor for higher synchrotron frequencies.
- Measurements done, data not processed yet. First impression: spill more improved due to bunching for higher rf voltage until improvement not possible anymore.

SIS-18 KO extraction

Spill spectra



Duty factor, dashed lines: Poisson limit



- Simulation with ripple as before: sum of five sinusoidal ripples in F and D quadrupoles, and pseudo-random phase shift KO signal with constant amplitude.
  - Ripple spectrum much less visible. Instead frequency dependent background.
  - Duty factor relative to Poisson limit comparable to quadrupole extraction. Less dependent on sextupole strength.
- Measurements done. Data not processed yet. First impression: almost no dependence on sextupole strength, spill rather worse than for quadrupole extraction.

SIS-100 KO extraction with magnet ripple

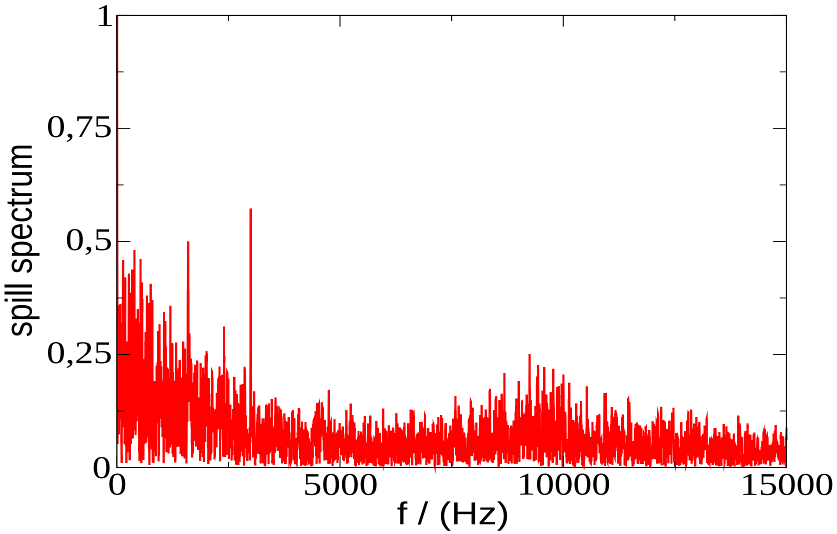
Simulation of KO extraction from SIS-100. Conditions:

- Consider U^{28+} beam at $E = 1.5$ GeV.
- Simulation with 100000 particles for time interval $T_{ex} = 200000$ **turns** $= 0.78$ s
- Standard settings:
  - Horizontal tune: $Q_x = 17.31$.
  - Non-normalised horizontal chromaticity $\xi_x = -1$ (Hardt condition).
  - Amplitude of resonance sextupoles: $(k_2 L)_a = 0.76\ \mathrm{m}^{-2}$.
- KO excitation with constant amplitude.
- Ripple in F and D quadrupoles:
  - Relative ripple amplitude 10^{-5}
  - Ripple with 5 and 50 components applied.
    Corresponding maximum ripple frequencies are 3 kHz and 30 kHz.

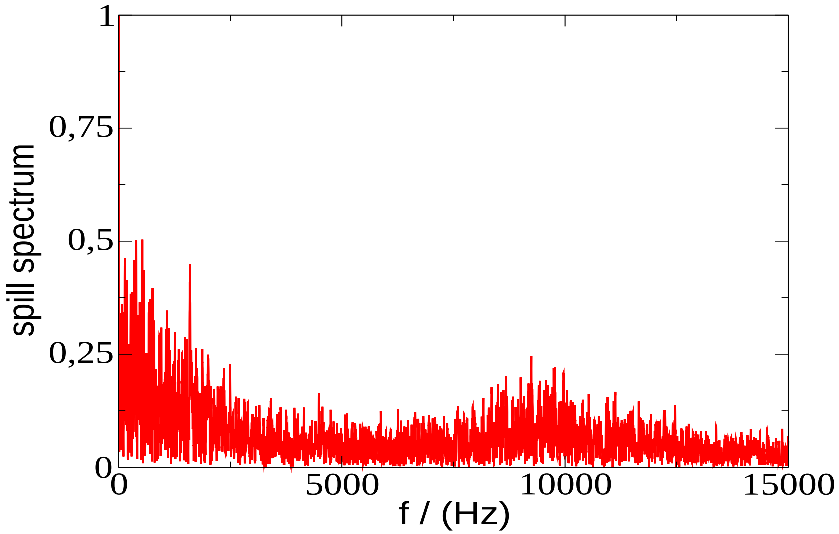
SIS-100 KO extraction with magnet ripple

Spill spectra with frequencies of quadrupole ripple up to $f = 3\ \mathrm{kHz}$ and without ripple

5 sinusoidal ripples



without ripple

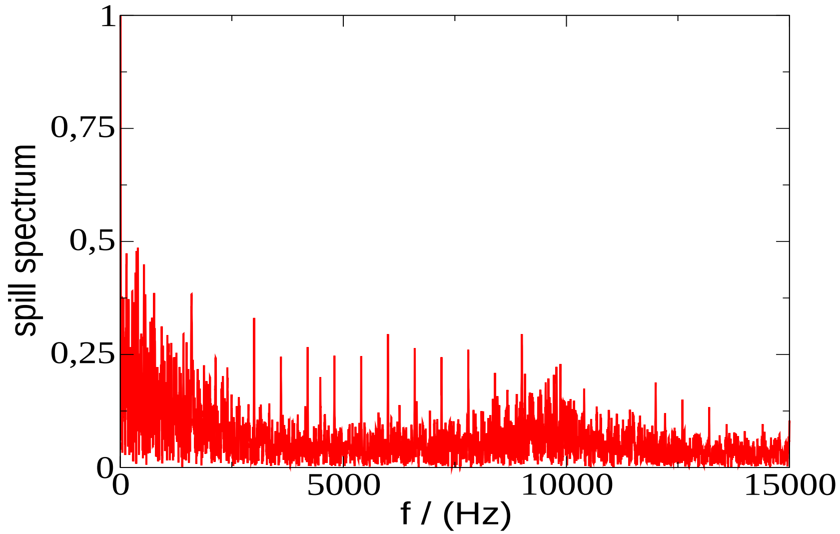


- Ripple spectrum almost invisible, only highest component at $f = 3000\ \mathrm{Hz}$ well visibly.
- Appearance of continuum dominated by KO spectrum:
  - KO signal: Pseudo-random phase shift keying signal with minimum of power spectrum for chosen conditions at $f = 4490\ \mathrm{Hz}$.
  - Frequency much lower than in SIS-18 because it scales with revolution frequency $f_0 = 256\ \mathrm{kHz}$ at $E = 1.5\ \mathrm{GeV/u}$. SIS-18 at $E = 300\ \mathrm{MeV/u}:\ f_0 = 910\ \mathrm{kHz}$.

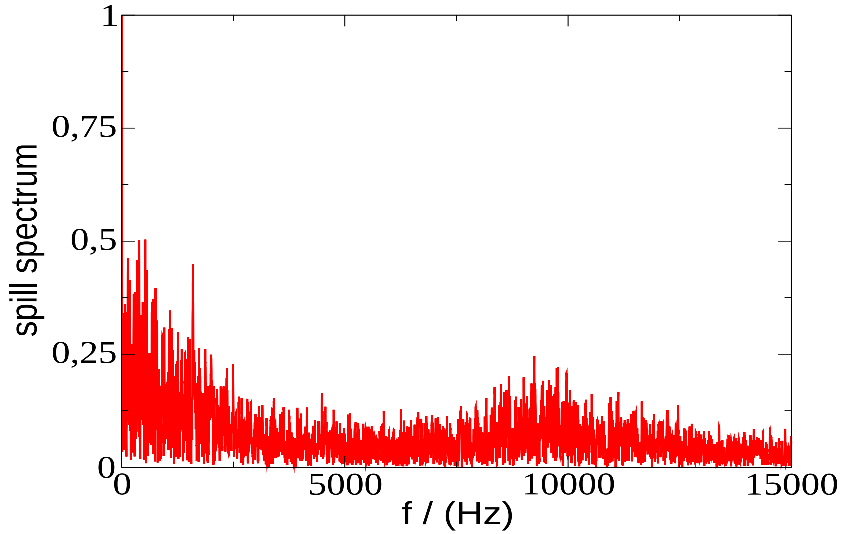
SIS-100 KO extraction with magnet ripple

Spill spectra with frequencies of quadrupole ripple up to $f = 30$ kHz and without ripple

50 sinusoidal ripples



without ripple

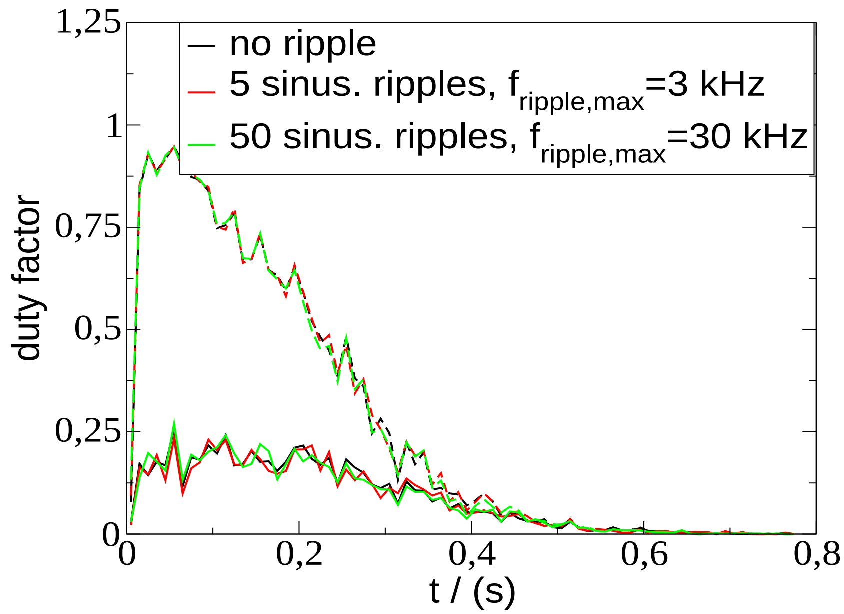


- Ripple with 50 sinusoidal components normalised so that total ripple power the same as that with 5 components.
- Ripple frequencies are visible for higher frequencies above main bump of KO spectrum.
- Spill spectrum drops above 12 kHz.

Generally, spill spectra rather dominated by KO spectrum than by field ripple.

SIS-100 KO extraction with magnet ripple

Duty factor, dashed lines denote Poisson limit

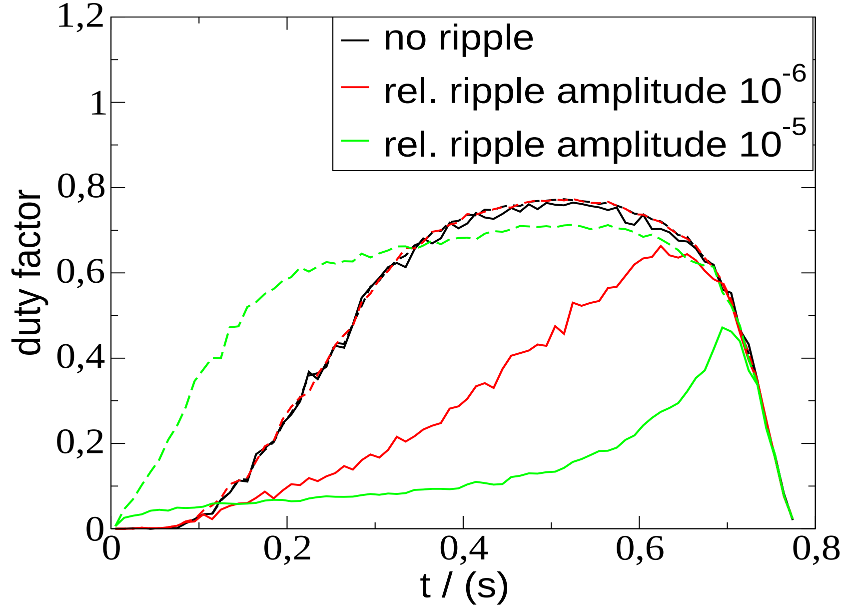


- Duty factor very low. Strong decrease towards end due to KO excitation with constant amplitude.
- Duty factor independent of ripple spectrum.

Possibly improvement by application of more proper KO signal.

SIS-100 quadrupole extraction

Example: Duty factor with quadrupole ripple as before: 50 ripple components up to $f = 30\ \mathrm{kHz}$, dashed lines denote Poisson limit



- Duty factor lower than for SIS-18. On the other hand settings not optimised at all yet.
- At least, significant dependence of spill quality on ripple amplitude.

Consequence:

If possible, quadrupole driven extraction should be kept as option.

Summary

- Spill quality can be improved by reducing sextupole strength during slow extraction, as long as the extraction conditions provide good extraction efficiency, e.g. beam energy not too high.
  - Relation between extraction efficiency and spill quality still open. Need for clarification.
- Spill improvement possible by extraction of bunched beam.
  - Dependence of spill quality on sextupole strength strongly reduced.
  - Simulation predicts optimum synchrotron frequency at least for weak sextupoles. Above that new time structures on duty factor.
  - The latter not seen in experiments. Need for clarification.
- Spill quality of KO extraction under present conditions is not better (SIS-18) or even worse (SIS-100) than spill quality of quadrupole driven extraction.
  - Almost no influence of magnet ripple. Instead spill quality dominated by KO signal.
  - Perhaps improvement due to application of other KO signal. Need of further studies.