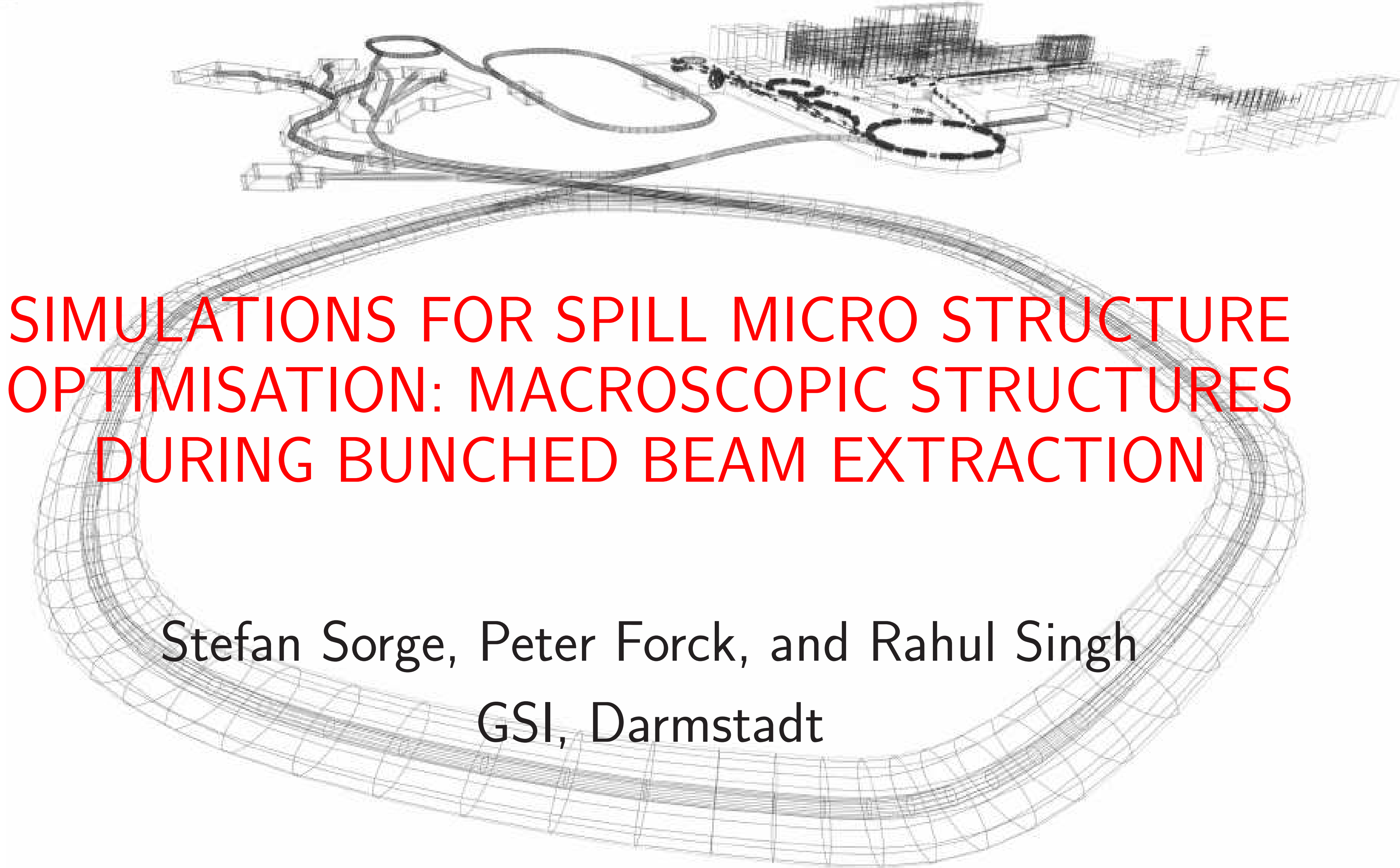


SIMULATIONS FOR SPILL MICRO STRUCTURE OPTIMISATION: MACROSCOPIC STRUCTURES DURING BUNCHED BEAM EXTRACTION

Stefan Sorge, Peter Forck, and Rahul Singh

GSI, Darmstadt

4th Slow Extraction Workshop, KEK/J-PARC, Japan, January 24-28, 2022.

Motivation

- Slow extraction of bunched beams widely used method to achieve reduction of spill micro structures.
- On the other hand, creation of structures due to bunches with frequency $f_{\rm rf}$ defined by the rf frequency. Typical in present GSI heavy ion synchrotron SIS18:
  - $f_{\rm rf} \approx (4 \ldots 5)$ MHz.
  - time span between subsequent bunch peaks defined by rf period $t_{\rm rf} \approx (200 \ldots 250)$ ns,
- FAIR experiment with detector HADES (High Acceptance Di-Electron Spectrometer) with integration time $t_{\rm int} = 140$ ns.
  - long dead times of detector due to integration during voids between bunches.
  - limitation to intensity and event rate.

Possible solution proposed by experimenters: increase rf frequency to $f_{\rm rf} \geq 40$ MHz, see presentation of Jerzy Pietraszko, "The HADES/CBM physics case requirements", during the 1st Slow Extraction Workshop, Darmstadt, June 2016.

Motivation

- Can be achieved by installation of cavity with such rf frequency.
- First step: Plan to install rf cavity with rf frequency $f_{\mathrm{rf}} = 80\ \mathrm{MHz}$ for test purpose, see presentation of Peter Schmid, "Planned measures for improving the SIS18 spill quality", during 2nd Slow Extraction Workshop, CERN, November 2017.
  - Use already existing Linac cavity for SIS18.
  - Hence, rf frequency is given.
- $f_{\mathrm{rf}} = 80\ \mathrm{MHz}$ corresponds in SIS18 to large harmonic number near $h = 80$, whereas typically used in present operation: $h = 4, 5$.
  Result: Synchrotron tune strongly increased.

$$Q_{\mathrm{s}} = \sqrt{\frac{Q_{\mathrm{ion}} h V_{\mathrm{rf}} |\cos\phi_s \eta|}{2\pi\beta^2 m_{\mathrm{ion}} c^2 \gamma}} \propto \sqrt{h}.$$

→ Initial motivation to study extraction with large synchrotron tune.

Slow extraction from SIS18

SIS18: present heavy ion synchrotron (SIS = “Schwerionensynchrotron”) at GSI.

- Maximum rigidity: $B\rho = 18\ \mathrm{Tm}$.
- Circumference: $C = 216.72\ \mathrm{m}$.
- Beams of ions from Hydrogen up to Uranium.
- Typical beam energies for heavy ions: $E \approx (100\ \mathrm{MeV/u}\ \ldots\ 2\ \mathrm{GeV/u})$.
- Typical revolution time: $t_{\mathrm{rev}} \approx 1\ \mu\mathrm{s}$.
- Standard slow extraction technique: quadrupole driven extraction, where horizontal tune is moved with two fast quadrupoles across third integer resonance at $Q_{x,\mathrm{res}} = 4.33333$.

$\rightarrow$ Restrict this presentation to this technique.

Spill simulation

- Simulations performed using MAD-X code.
- Motion of 10^5 test particles tracked for $5 \cdot 10^5$ revolutions corresponding to ≈ 0.5 s.
- Measurements: typical particle number of several 10^6 and slow extraction time interval $1 \dots 5$ s.
  - Higher than in simulations but comparable.
  - Slow extraction of higher particle number is possible. Limitation due to spill measurement with plastic scintillation counter.
- Tune changed with constant change rate.

Spill characterisation

Spill characterisation used in this presentation: time dependent duty factor:

$$F(t) = \frac{\langle N \rangle^2(t)}{\langle N^2 \rangle(t)} = \frac{N_{\text{av}}^2(t)}{N_{\text{av}}^2(t) + \sigma_N^2(t)},$$

where $\langle x \rangle = x_{\text{av}}$ is variable x measured in time intervals of $10\ \mu\text{s}$ and averaged in time intervals of $10\ \text{ms}$ duration. $\rightarrow$ Choice according to measurement conditions.

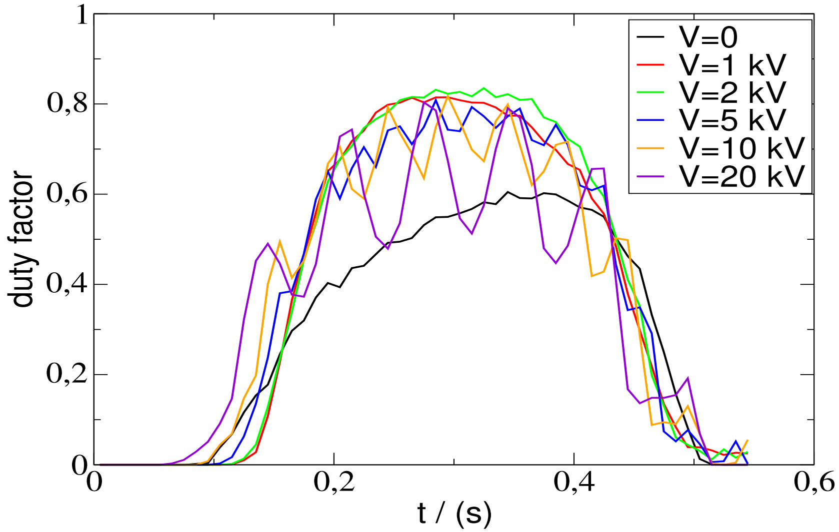
- Good spill with low spill micro structure level results in high duty factor.
- Realistic upper limit is stochastic spill with Poisson duty factor:

$$F_{\text{Poisson}}(t) = \frac{N_{\text{av}}(t)}{N_{\text{av}}(t) + 1}$$

$\rightarrow$ Function of spill intensity.

First simulation result

Time dependent duty factor from simulation for C^{6+} beam at $E = 300$ MeV/u in 2018



Start with simulations for present SIS18 conditions:

- rf harmonic number $h = 4$.
- rf voltage up to $V_{\mathrm{rf}} = 20$ kV.
  Is a little higher than maximum in reality: $V_{\mathrm{rf,max}} \approx 12$ kV.

$\rightarrow$ Result: Formation of macroscopic spill structures of time scale $t_{\mathrm{struct}} \sim 0.1$ s

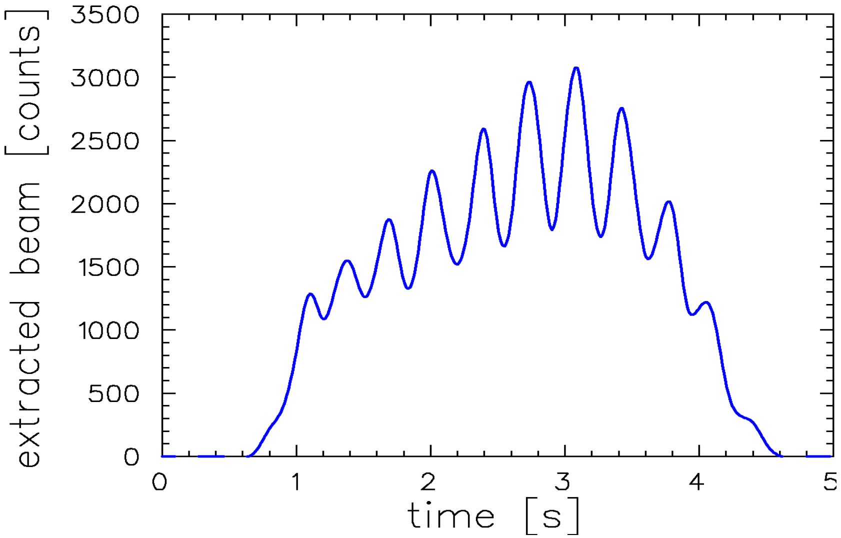
- Structures appear independently of tune ripple and spill micro structures.
- Arise from macroscopic spill intensity changes, instead.
- Structure length increased for higher rf voltage.

Question: Are structures real or artefact of simulation?

Further results

Findings with Ar^{18+} beam at $E = 500\ \mathrm{MeV/u}$

Measurement



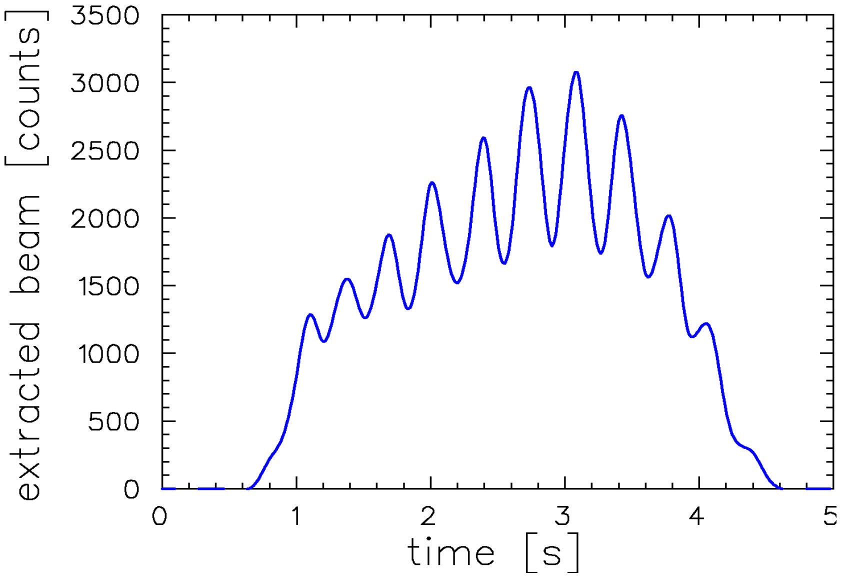
- Comprehensive measurement with Ar^{18+} beam by Peter Forck *et al.*
  Figure: $V_{\mathrm{rf}} = 12\ \mathrm{kV}, h = 5$.

Answer to question: Structures are real.

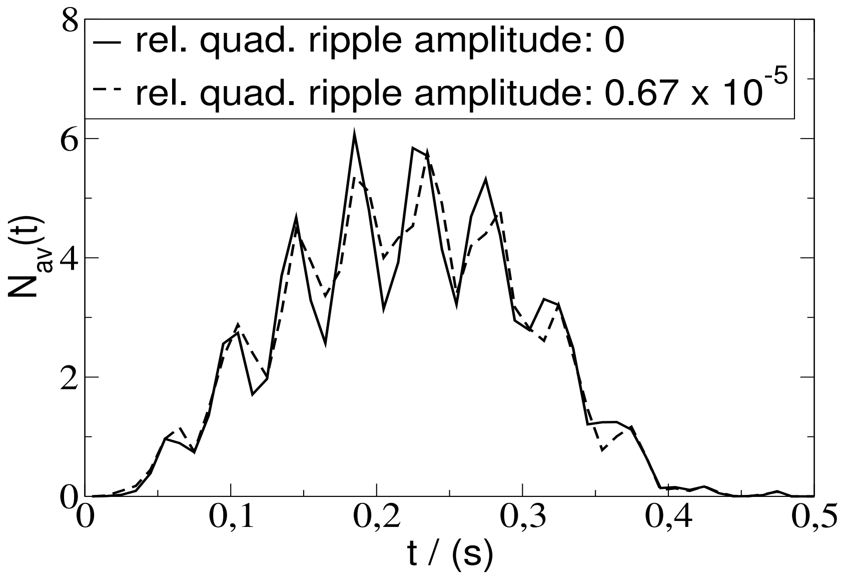
Further results

Findings with Ar^{18+} beam at $E = 500\ \mathrm{MeV/u}$

Measurement



Simulation



- Comprehensive measurement series with Ar^{18+} beam by Peter Forck *et al.*
  Figure: $V_{\mathrm{rf}} = 12\ \mathrm{kV}, h = 5$.
- Simulation for same rf voltage without and with quadrupole ripple.
  $\rightarrow$ quadrupole ripple diminishes macro structure formation.

Answer to question: Structures are real and can be reproduced. Unclear origin.

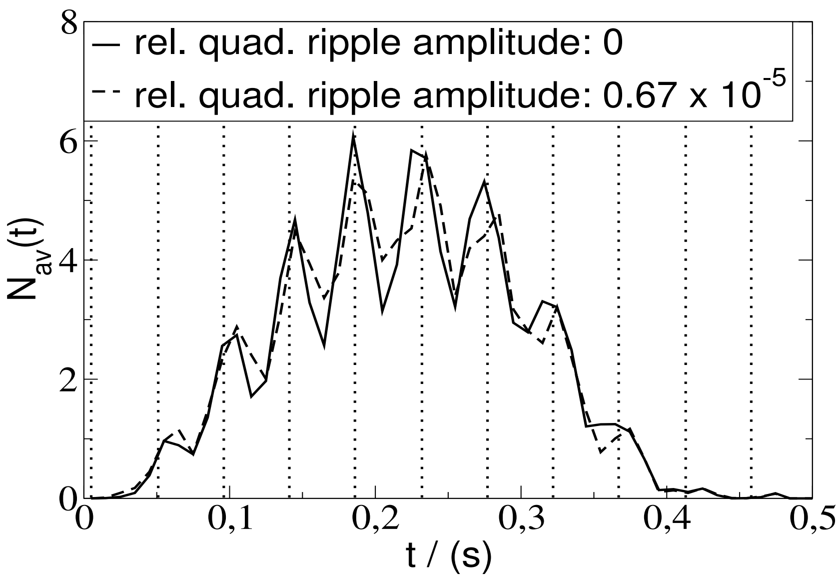
Synchro-betatron resonances

- Structure formation can be explained by excitation of synchro-betatron resonances defined by resonance condition [1]:

$$kQ_x + lQ_y + mQ_s = n$$

with integer numbers $k = 3, \; l = 0, \; n = 13$, and m defined by range of tune change, (quadrupole driven extraction!).

- Figure: Same spills from simulations as on previous page with times when resonance condition is fulfilled, marked with dotted lines.



$Q_s = 0.00143$

→ good agreement with structures.

[1]: A. Piwinski, "Synchro-betatron resonances", CERN, Geneva, Switzerland (1996).

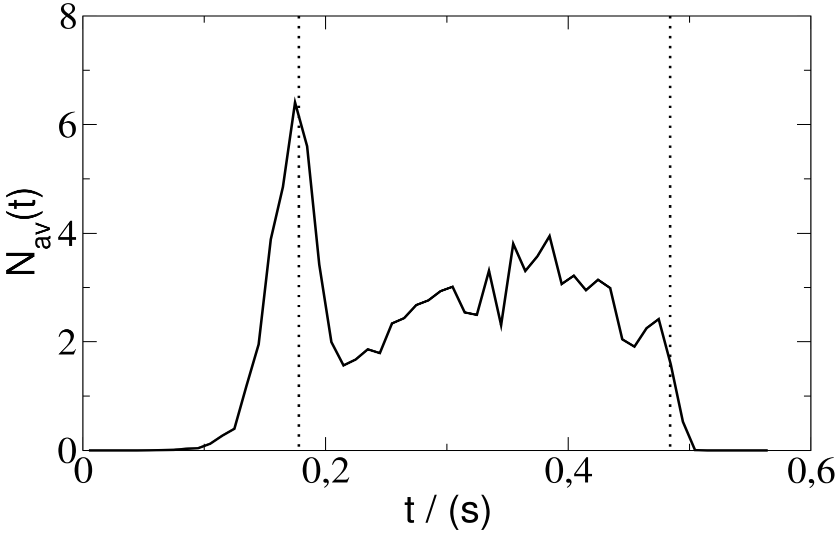
Synchro-betatron resonances

Remarks

- Resonances found in measurements as well as simulations for momentum width and transverse beam emittances lower than during usual SIS18 operation.
- Appearance of resonances depends on momentum width and horizontal beam emittance, the latter has stronger influence:
  Large momentum width and/or beam emittance results in larger resonance width such that they overlap and disappear.
- In most cases no important role under present SIS18 conditions, in particular rf fields with $h = 4, 5$.

High frequency rf cavity

Spill of Ar^{18+} beam at $E = 500$ MeV/u, $V_{rf} = 70$ kV, $h = 100$



$Q_s = 0.0154$

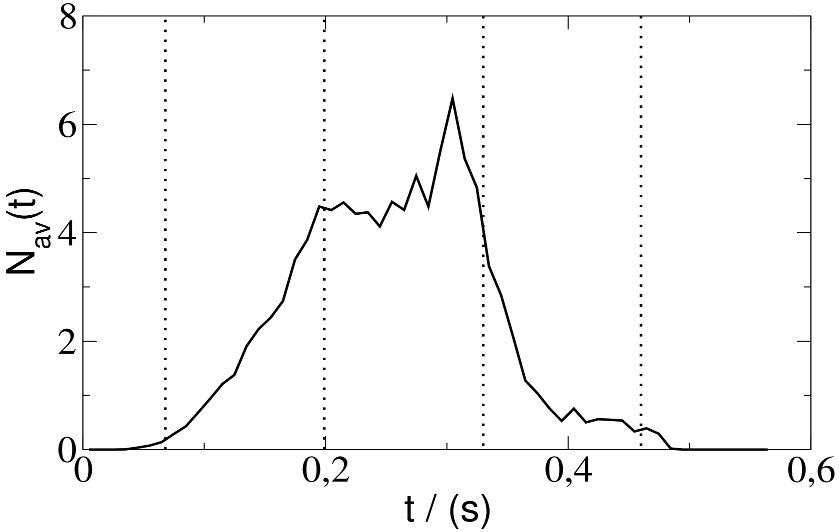
- Realistic momentum width and transverse beam emittance, i.e. not reduced. The latter according to machine acceptance entirely filled at injection energy and shrunk during acceleration.
- First step: choose highest foreseen voltage in order to ensure complete bunching.

Only single synchro-betatron resonance. Second resonance is third integer resonance.

- Strong intensity peak.
- Possibly, complete bunching not necessary. $\rightarrow$ Apply in next step lower rf voltage.

High frequency rf cavity

Spill of Ar^{18+} beam at $E = 500$ MeV/u, $V_{rf} = 5$ kV, $h = 100$



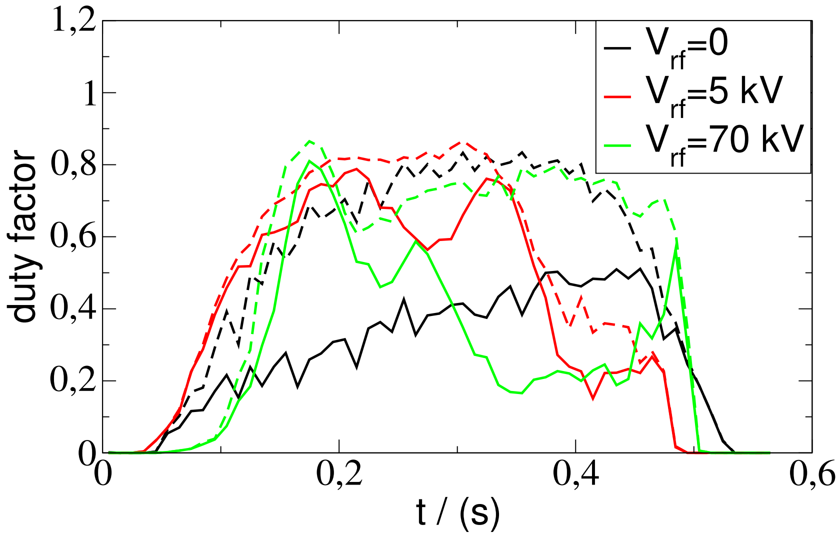
$Q_s = 0.00412$

- Spill follows mainly density in beam according to tune change linear in time.
- Macroscopic spill fluctuations visible but reduced. No gaps between resonance crossing times.

- Possibly, further spill smoothing possible with feed back system. Not aim of this study.
- Additional technical advantage of lower V_{rf}: lower requirement to dielectric properties of insulating material in cavity which becomes less insulating at such high frequency.

High frequency rf cavity

Time dependent duty factor of Ar^{18+} beam at $E = 500$ MeV/u, $h = 100$, several V_{rf}



Back to "original" topic: Goal of installation of cavity is reduction of spill micro structure.

- Figure: duty factors and corresponding Poisson limits (dashed lines).
- Comparison to unbunched beam extraction.

- High voltage case: Duty factor towards spill end lower than for unbunched beam extraction although Poisson duty factor high, i.e. limitation not due to low intensity.
- Low voltage case: Duty factor only towards spill end lower than for unbunched beam extraction. Limitation due to low extraction rate shown by low Poisson duty factor.
- Gain in spill micro structure reduction only with low rf voltage.

Summary

- Installation of rf cavity with high rf frequency $f_{\mathrm{rf}} = 80\ \mathrm{MHz}$ in GSI heavy ion synchrotron SIS18 planned for reduction of spill micro structures and avoiding spill structures at present $f_{\mathrm{rf}} \approx 4\ \mathrm{MHz}$ according to experimenters' request.
  $\rightarrow$ Motivation to study slow extraction with fast synchrotron motion.
- Result: Macroscopic spill structures on time scales $t_{\mathrm{struct}} \sim 0.1\ \mathrm{s}$ found for presently realistic extraction conditions in spill simulations and measurements, where rf voltage higher and momentum spread and transverse beam emittances lower than usually applied.
- Origin of macro structures: synchro-betatron coupling resonances.
  $\rightarrow$ Macroscopic structures appear more clearly for large synchrotron tune.
- Hence, significant impact to operation with planned cavity expected. But, spill quality improvement possible with low rf voltage: reduction of macro structure formation and of spill micro structure level below that of unbunched beam extraction found.
- Generally, macro structure formation denotes limitation to spill quality improvement by increase of rf voltage in order to achieve faster transition of particles across edge of stable phase space area.