SPILL QUALITY OF BUNCHED BEAM: SOME OBSERVATIONS WHEN TAKING INTO ACCOUNT SYNCHROTRON MOTION

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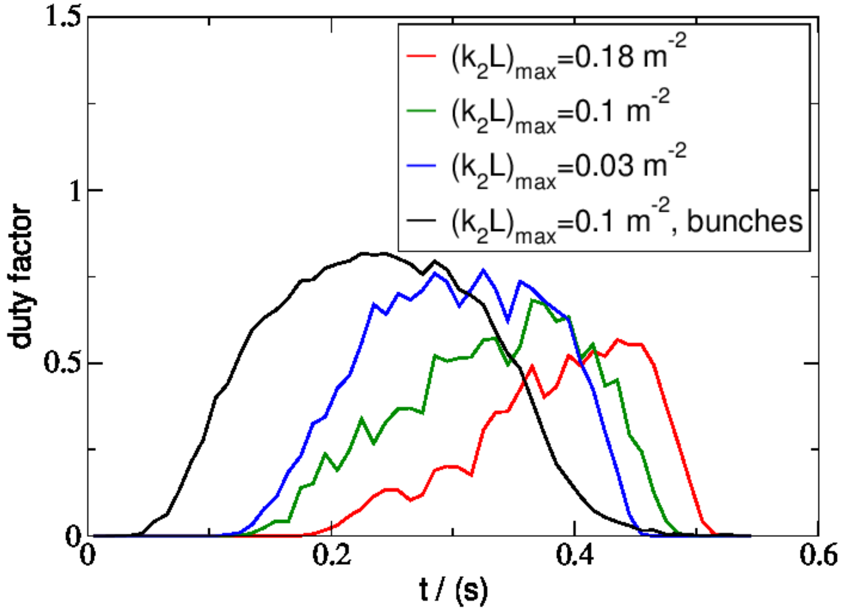
Introduction

- Synchrotron motion results in periodic tune oscillation.
- Particles cross separatrices faster when leaving stable phase space area resulting in shorter stay near separatrices and reduced influence of ripple of stable phase space area.



- Measure for spill quality: time dependent duty factor:

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

where $\langle \ldots \rangle$ is average of $10\ \mu\text{s}$ bins in $10\ \text{ms}$ bins.

- Larger duty factor with bunches. Denotes higher spill quality.

Figure from S. Sorge, P. Forck, and R. Singh, Proc. of IPAC 2018, Vancouver, Canada: Simulation of C^{6+} extraction for conditions of experiments of Beam Diagnostics Department from 2016, i.e. beam energy $E = 400\ \text{MeV/u}$ and rf voltage with $V = 2\ \text{kV},\ h = 4$.

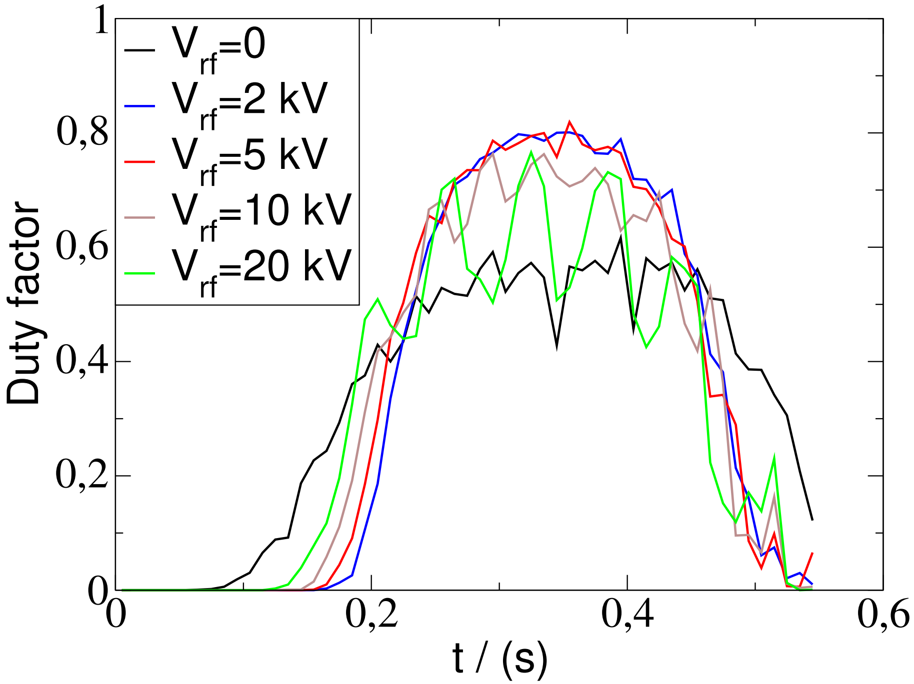
Naive conclusion: spill quality the more increased the faster synchrotron motion occurs.

Simulations

Main characteristics

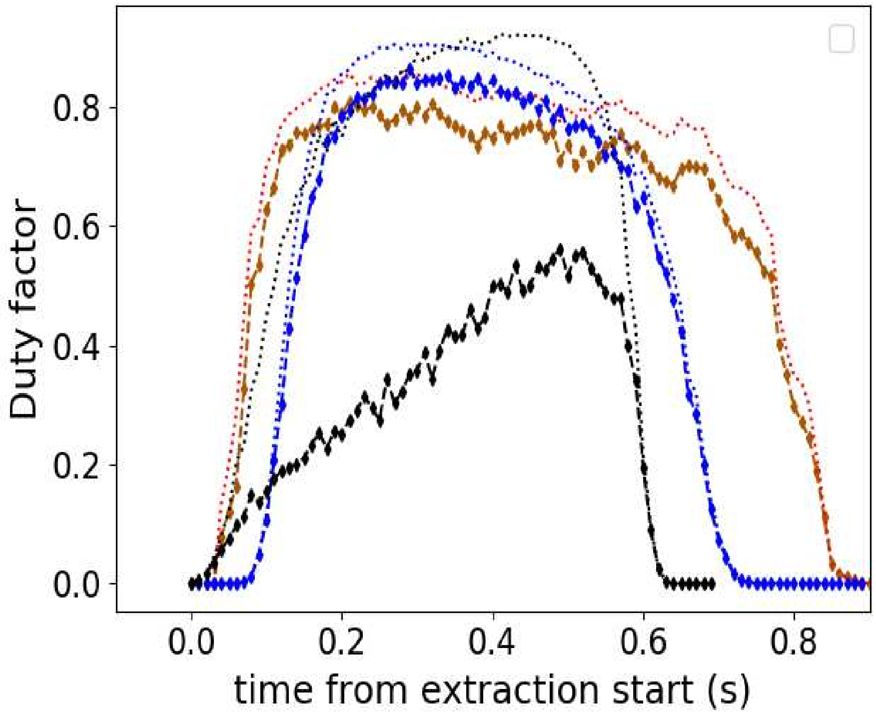
- Tracking simulations with 100000 particles for 500000 turns corresponding to $t = 0.55$ s.
- Beam like in new measurements: C^{6+} beam at $E = 300$ MeV/u.
- So far sextupole amplitudes $(k_2L)_a = (0.03,\ 0.06)\ \mathrm{m}^{-2}$.
- Extraction by tune ramp with initial and final horizontal machine tunes, $Q_{x,0}^{ini} = 4.326$ and $Q_{x,0}^{fin} = 4.334$. Constant vertical machine tune $Q_{y,0} = 3.29$.
  $\rightarrow$ $Q_{x,0}$ mostly below resonance tune $Q_r = 4.333333$.
- Natural chromaticity $\xi = \xi_{nat} < 0$.
- RF voltage with amplitudes $V = (2, 5, 10, 20)$ kV and harmonic number $h = 4$.
- Apply ripple to focusing strengths of F and D quadrupoles which consists of
  - single frequency component at $f = 600$ Hz and amplitude $r_a = 10^{-5} \cdot I_{quad}$.
  - broad band signal with bandwidth 9.1 kHz and rms signal strength $r_{rms} = 10^{-5} \cdot I_{quad}$.

Simulations



- Generally, beam quality for bunches better than for coasting beam.
- Worse for higher than for lower rf voltages.

Experiments



Courtesy: R. Singh

Curves: $V_{rf} = 0$ – black, $V_{rf} = 2$ kV – blue, $V_{rf} = 12$ kV – brown.

Similar behaviour:

- Better spill quality with bunches.
- Spill quality slightly worse for too high voltage. But effect less visible than in simulations.

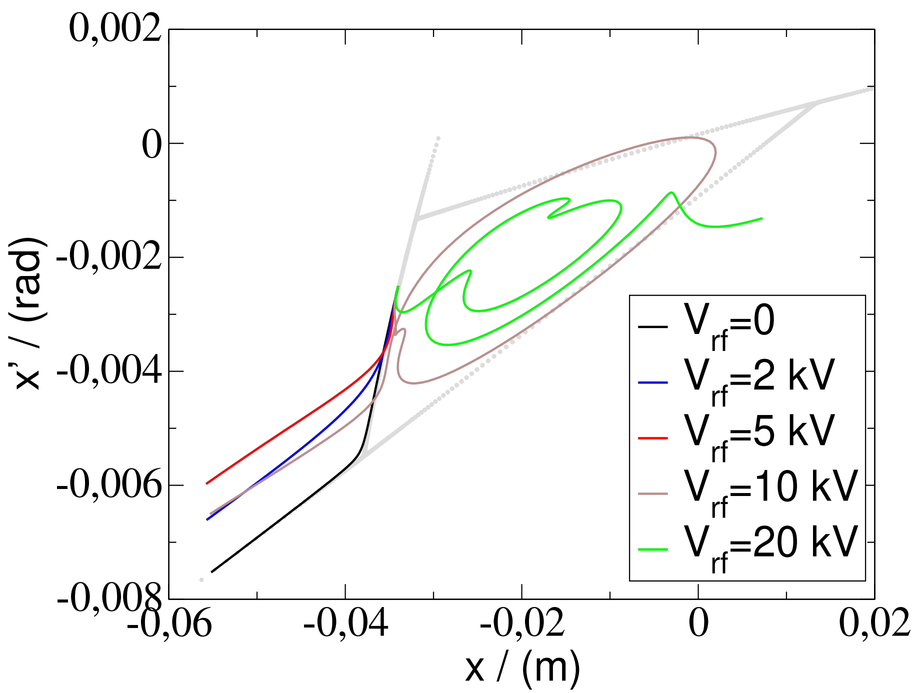
Discussion

Appearance of optimum rf voltage.

Investigation by single particle tracking with start position of particle:

- in longitudinal plane: $\delta = 0$ and decreasing, i.e. $Q_x = Q_{x,0} + \xi\delta$ approaches Q_r.
- in horizontal plane: slightly outside stable phase space area $\rightarrow$ initially unstable.

$\rightarrow$ particles move away from start point with different velocities.



- Lower voltages, $V_{rf} = (0, 2, 5)$ kV:
  Particle trajectories away from stable area.
- High voltages, $V_{rf} = (10, 20)$ kV:
  Particles re-enter stable area and stay long there.
  $\rightarrow$ re-capturing.

Re-capturing possible reason for worse spill quality.

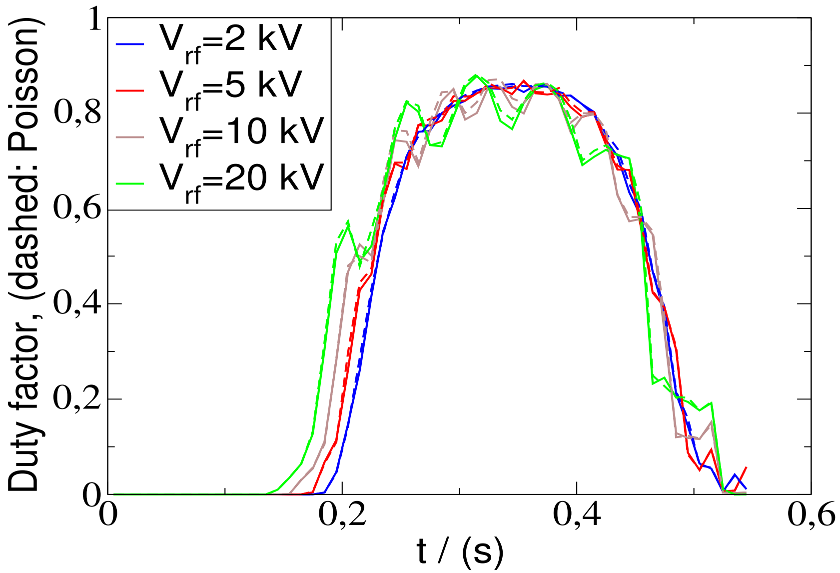
Discussion

- Lower voltages, $V_{rf} = (0, 2, 5)$ kV:
  Transit time with synchrotron motion shorter than without and shorter than synchrotron period.
- High voltages, $V_{rf} = (10, 20)$ kV:
  Transit time with synchrotron motion longer than without and longer than synchrotron period $\rightarrow$ probably reason for re-capturing.

Table: Transit times and synchrotron periods in turns

$V_{rf}/(\mathrm{kV})$	transit time/(turns)	synchrotron period/(turns)
0	342	–
2.0	171	1239
5.0	204	769
10.0	657	556
20.0	933	384

Simulation, no quadrupole ripple



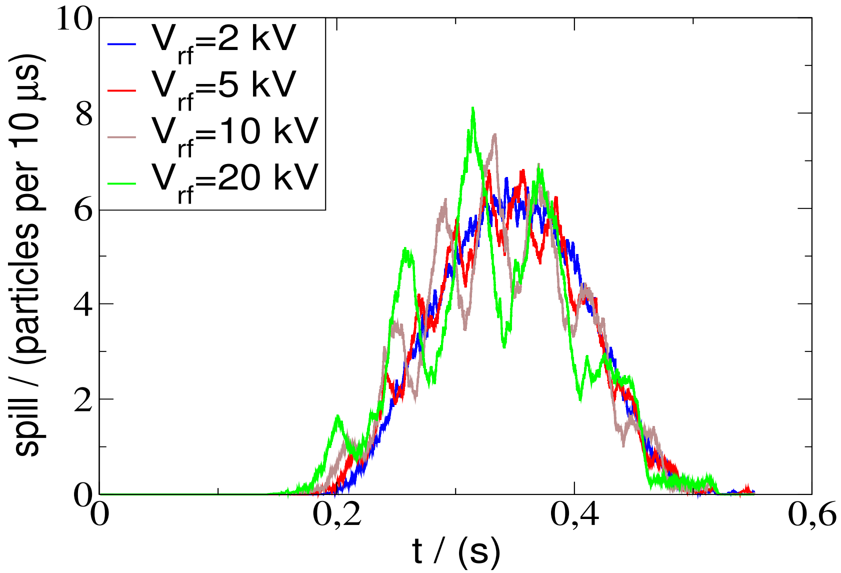


Figure left: Duty factor.

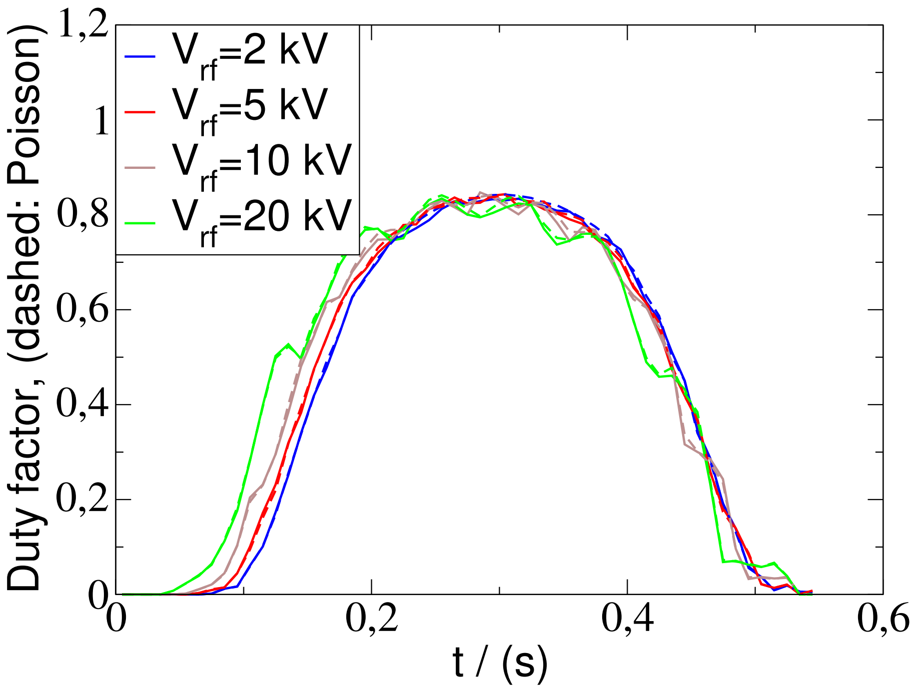
- No quadrupole ripple and, hence, no spill structures with frequencies above $100\ \mathrm{Hz}$.
  → Only statistical spill fluctuation. Duty factor (almost) equal to Poisson duty factor:

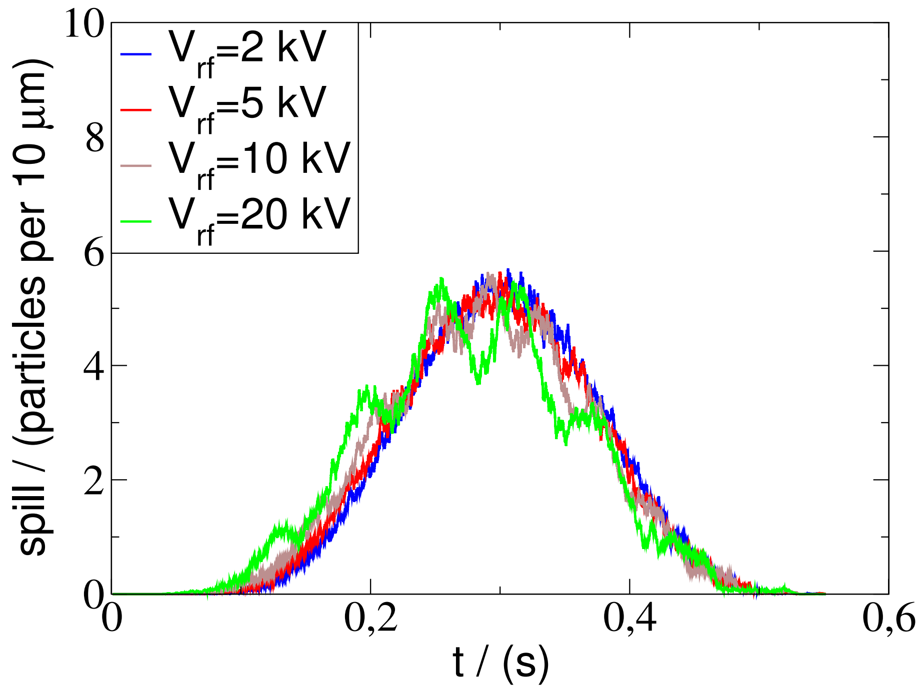
$$F_{Poisson} = \frac{\langle N \rangle}{\langle N \rangle + 1} \quad \rightarrow \quad \text{measure for extraction rate.}$$

- Instead, formation of macroscopic structures with duration $\sim 0.1\ \mathrm{s}$.

Figure right: spill, averaged over 200 consecutive data points. Macroscopic structures visible.

Simulation, no quadrupole ripple





- Larger sextupole amplitude $(k_2L)_a = 0.06 \text{ m}^{-2}$
- A little weaker formation of macroscopic structures, i.e. less sensitivity to fast synchrotron motion. $\rightarrow$ Reasonable because transit times shorter, reduced probability of re-capturing.

Nevertheless, origin of macroscopic structures not clear.

Summary

- Study on influence of synchrotron motion on spill quality for SIS-18 conditions.
- Common assumption: synchrotron motion improves spill quality because particle cross faster separatrices so that they feel possible ripple less.
- Limit to synchrotron frequency found for spill improvement in simulations and measurements. Effect is more visible in simulations.
- Results: if synchrotron frequency is above certain threshold then
  - Reduction of beam quality due to quadrupole ripple when increasing rf voltage. Can be explained by recapturing of particles so that they stay longer near border between stable and unstable motion and, hence, feel ripple stronger.
  - Formation of additional, macroscopic structures on extraction rate and duty factor even without quadrupole ripple. Origin not clear yet.
  - Less sensitivity of spill quality to fast synchrotron motion for stronger sextupoles. Probable reason: faster transit which reduces probability of re-capturing.