Investigation of Micro Spill in RF KO Extraction Using Tailored Excitation Signals

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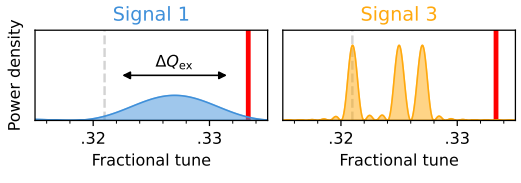
Radio Frequency Knock Out (RF KO) extraction is used to extract stored particle beams from synchrotrons through transverse excitation, delivering spills of particles for experiments and medical therapy. Minimizing the fluctuations of spill intensity is vital to prevent detector pile-up and interlocks while making most efficient use of the extracted beam. To improve the spill quality, different excitation signals with characteristic frequency spectra are explored. Results of experimental studies at the Heidelberg Ion Beam Therapy Center (HIT) are presented. These demonstrate the possible improvements by tuning multi-band spectra at different harmonics. Particle tracking simulations of the slow extraction process at HIT are used to understand how different excitation signals influence the spill quality.

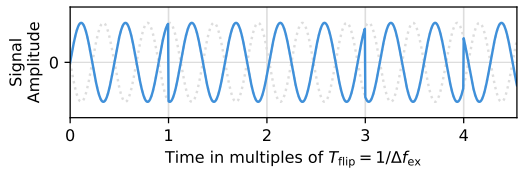
Excitation signals

- Random binary phase-shift keying (RBPSK)
  → Phase flipped sine yields broadened excitation signal
- Up to 3 parallel RBPSK signals available
- At betatron sidebands of different harmonics

No.	$Q_{\mathrm{ex},i}$	ΔQ_{ex}
1	0.327	0.009
2	0.321; 0.327; 1.327	0.009
3	0.321; 0.327; 1.325	0.001
4	2.321; 0.327; 1.325	0.001



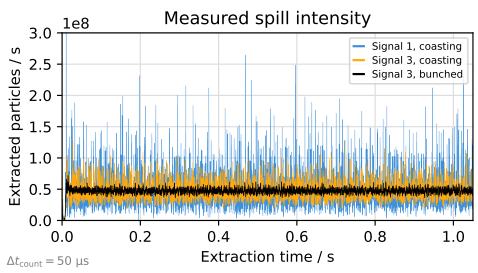
Spectra of excitation signals
Dashed line: $Q_x = 1.679\,02$
Red line: $5/3$ resonance



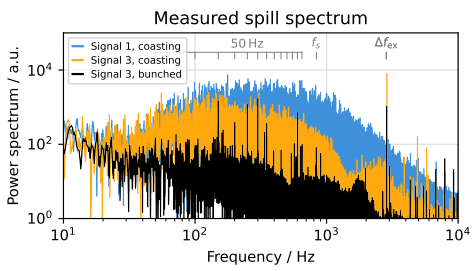
Principle of RBPSK phase flipping
(Bandwidth increased for illustrative prupose)

Experimental Studies

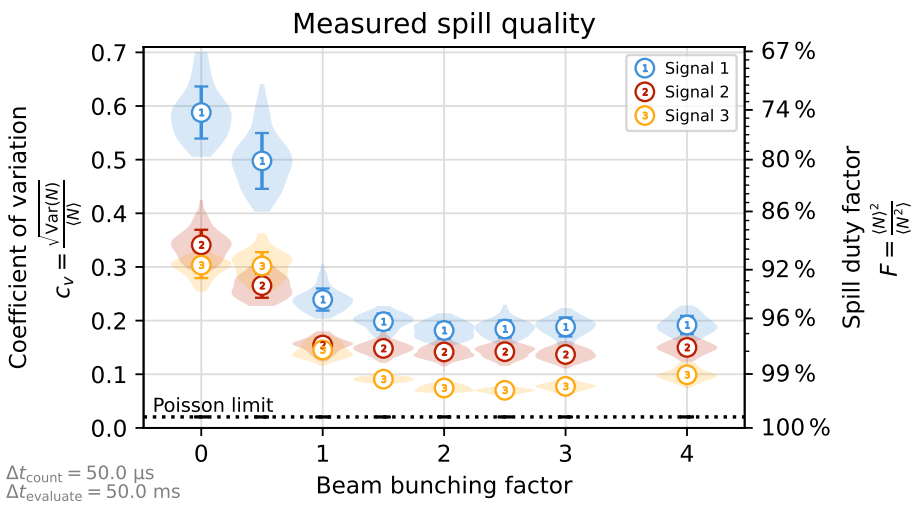
- Narrow multiband signals reduce fluctuations
  → Modulation at excitation bandwidth $\Delta f_{\mathrm{ex}} = \Delta Q_{\mathrm{ex}}\, f_{\mathrm{rev}}$
- Bunching reduces fluctuations further
- Remnant 50 Hz harmonics become visible



Spill intensity in time ...



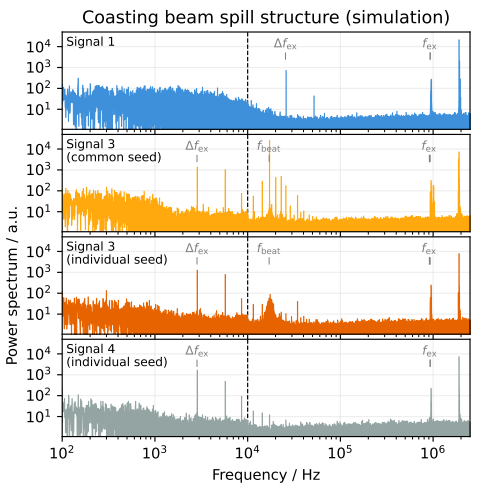
... and frequency domain



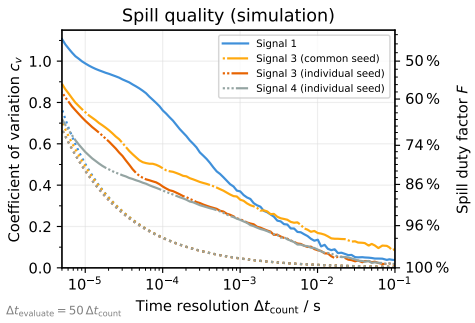
Spill quality for different excitation signals and bunching factors

Tracking Simulations with Xsuite

- Higher resolution reveals additional modulation effects
  → Excitation frequency $f_{\mathrm{ex},i} = Q_{\mathrm{ex},i}\, f_{\mathrm{rev}}$
  → Beating $f_{\mathrm{beat}} = |f_{\mathrm{ex},1} - f_{\mathrm{ex},2}|$
- Improve spill quality by supressing the beating
  → Decouple phase flipping (individual random seed)
  → Distribute frequency components across sidebands (signal 4)



Spill intensity in frequency domain



Spill quality for different signals
as function of detector resolution

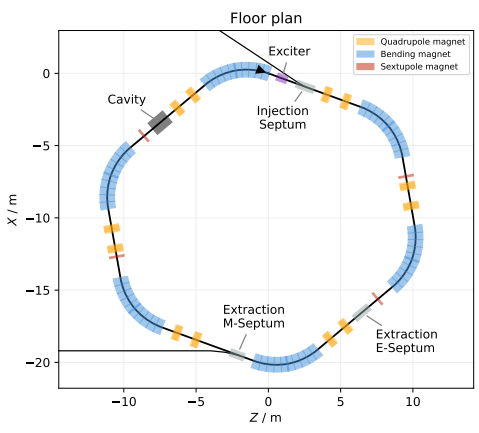
Simulation method:

xsuite.web.cern.ch

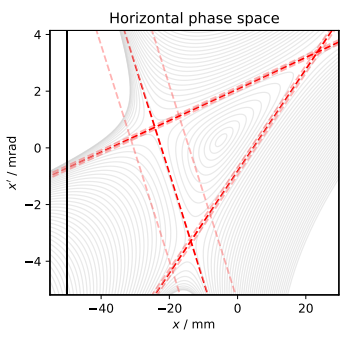
- Xsuite: GPU accelerated symplectic particle tracking code by CERN
- Contributed a new beam excitation element for arbitrary signals
- Tracking of 10^6 particles over 5×10^6 turns in 4 h using 8 GPUs
- Artificial power supply ripples and spill intensity feedback implemented

Slow Extraction at HIT

- RF KO extraction driven by transverse RF field in stripline exciter
- Spill measured with ionisation chamber (resolution 50 µs)
- Excitation amplitude controlled by spill intensity feedback



Layout of the HIT synchrotron



Phase space with separatrices
and septum blade at the E-Septum
(momentum error $\delta = 0$ and $\pm 10^{-3}$ shown)

Summary

- RF KO excitation waveforms determine spill spectrum
  → Excitation frequencies $f_{\mathrm{ex},i}$
  → Phase flipping frequency (bandwidth Δf_{ex})
  → Beating frequency f_{beat} of multi-band signals
  → Low frequency noise
- Optimized waveforms greatly improve spill quality
  → For coasting as well as bunched beams
- Synchrotron motion gives additional improvement

Outlook

- Simulations suggest newer optimal waveforms for better spill quality
- Next set of experiments planned with Software Defined Radio (SDR)

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