Tailored multi-band excitation to minimize fluctuations for Knock-Out extraction

6th Slow Extraction Workshop, 6. – 9.10.2025

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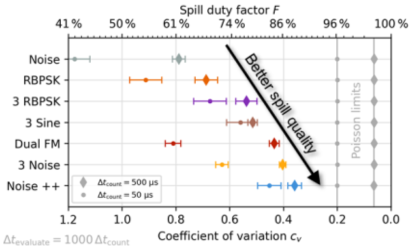
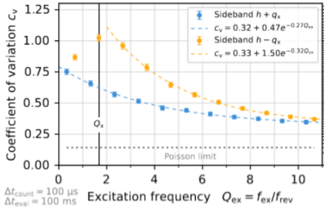
Rendering: GSI/FAIR, Zeitrausch

Outline

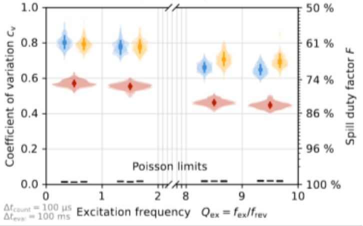
- Brief summary of previous studies
  - What signal types to use?
  - What is the ideal excitation frequency?



- Study of RF-KO at different sidebands
  - What sideband to choose?



- Multi-band RF-KO excitation methods
  - What is the best combination?



- Experimental hints and pile-up

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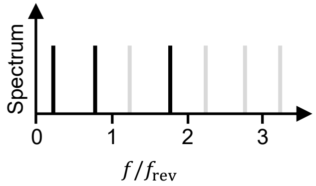
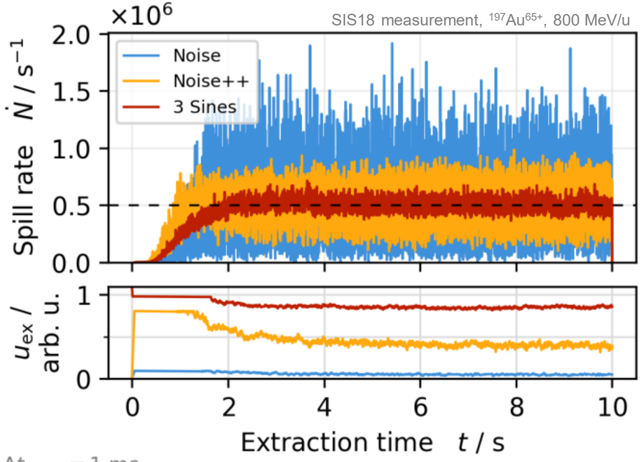
- Multi-Sine excitation signal
  - Multiple, distributed frequencies
  - For low rigidity beams / partial extraction
  - Best spill quality



- Noise++ excitation signals
  - Variable trade-off
  - Band-filtered noise → efficiency
  - Two sines → spill quality



Niedermayer, P., Singh, R. Excitation signal optimization for minimizing fluctuations in knock out slow extraction.
Sci Rep **14**, 10310 (2024). https://doi.org/p32w

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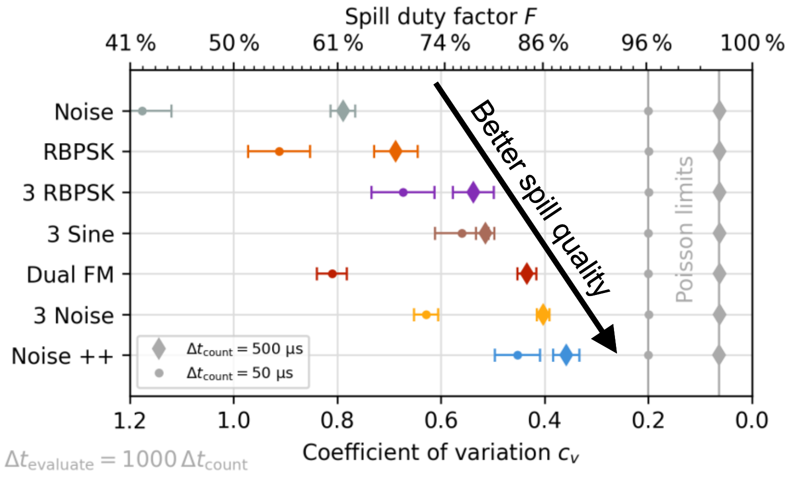
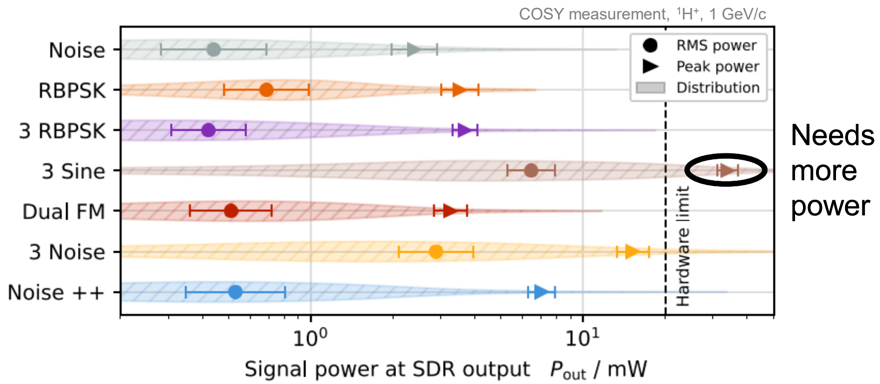
- Compared various excitation methods
  under identical beam conditions & optimized parameters





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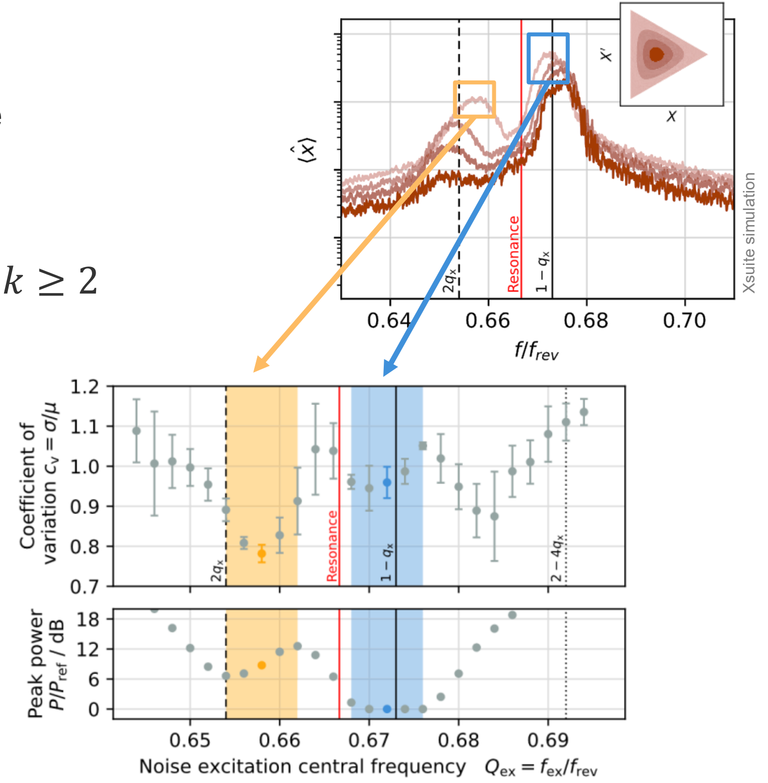
$$c_v = \frac{\sqrt{\mathrm{Var}\,N}}{\langle N \rangle} \qquad F = \frac{1}{1+c_v^2}$$

Excitation at 2nd order sidebands

- Discovered by "accident" at COSY
  - Optimizer converged to "wrong side" of resonance
- Nonlinear beam dynamics of KO machine
  → Betatron sidebands of higher order: $(h \pm k\, q_{\mathrm{x}})$ for $k \geq 2$
- Exciting them can drive extraction
  - Act mainly on particles near separatrix
  - Beam is "scraped", not "pushed"
  → More power required
  → Better spill quality

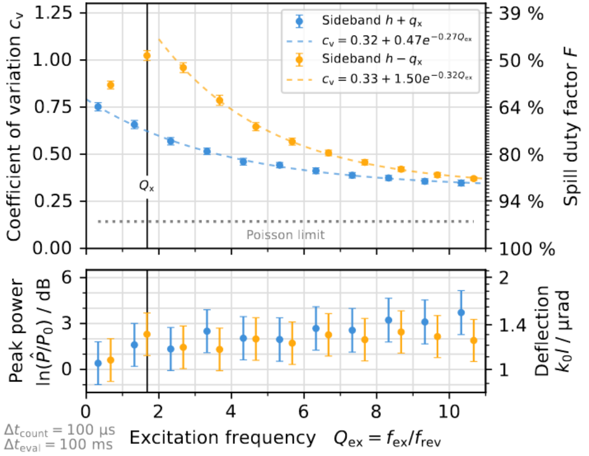


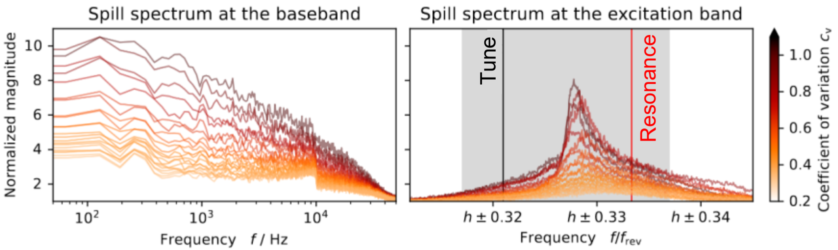
Niedermayer, P., Singh, R. Excitation of nonlinear second order betatron sidebands for knock-out slow extraction at the third-integer resonance. *Phys. Rev. Accel. Beams* **27**, 082801 (2024). https://doi.org/p32v

Does the choice of sideband matter?

Excitation at high harmonic sidebands

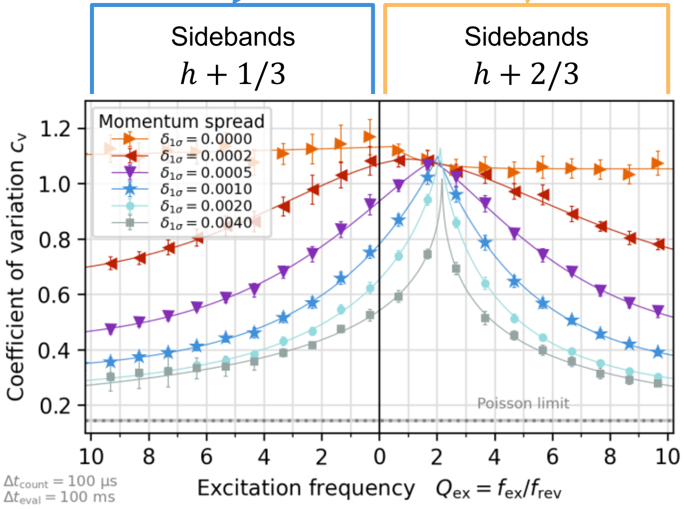
- Xsuite simulation study
  - HIT lattice with coasting beam
  - Feedback controlled RF-KO extraction
- Study “wideband” noise signals
  - Decouple from previous studies
  - Ensures efficient excitation (low power)
- Distinct behaviour at different sideband
  - Spill quality can be improved
  - Excitation imprint likewise reduced

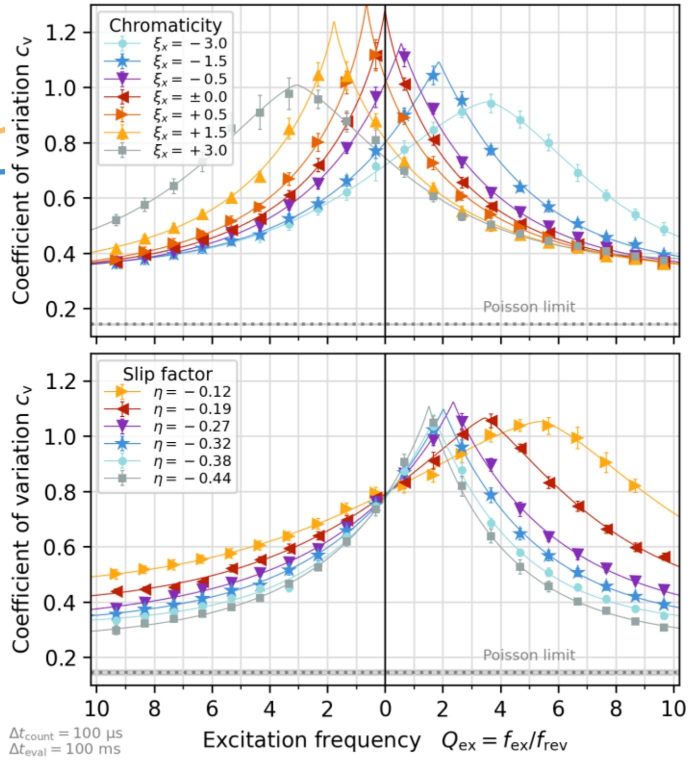




Excitation at high harmonic sidebands

- Depends on machine and beam parameters
  - E.g. chromaticity, slip factor, momentum spread
  - → Strong scaling with momentum spread

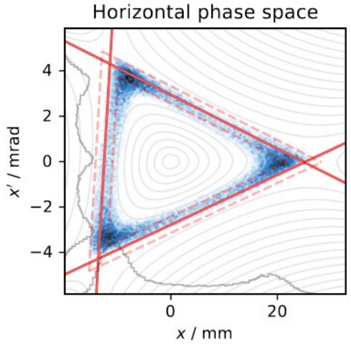


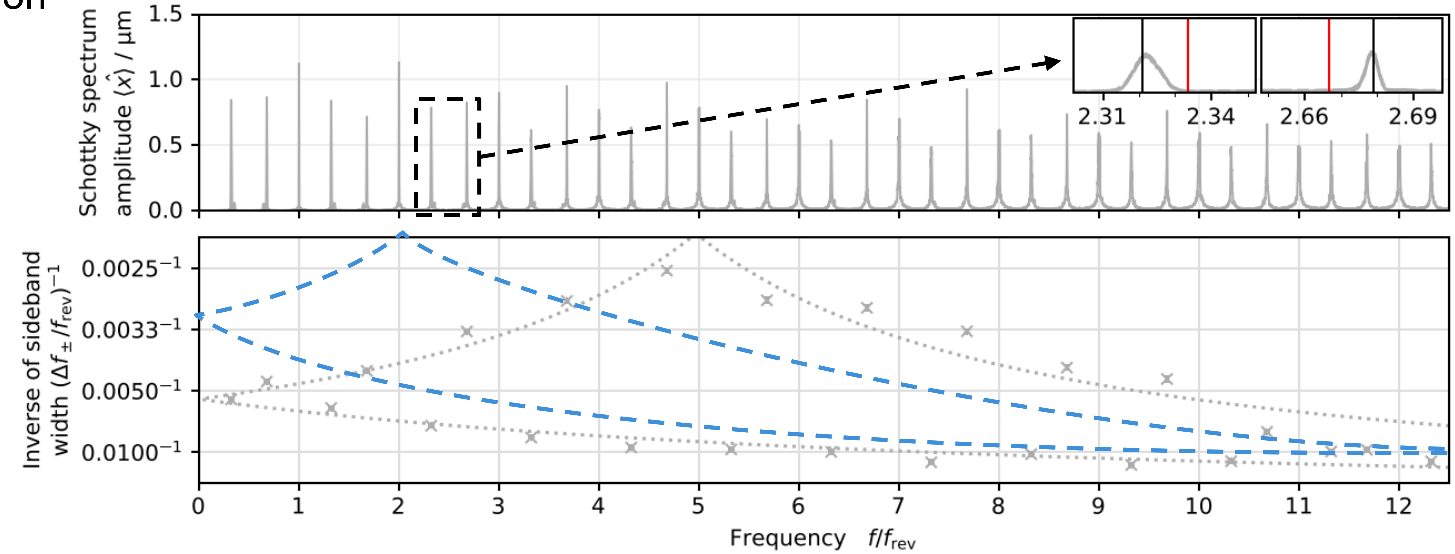


Beam spectrum

- Width of betatron sidebands
  - Additional nonlinear detuning term ν_{det} to approximate full beam spectrum
  - Slow extraction governed by hollow beam spectrum

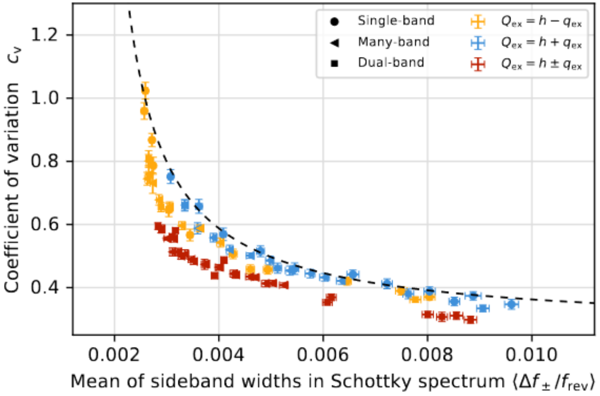
$$\underbrace{\frac{\Delta f_{\pm}}{f_{\text{rev}}} = \left|(h \pm q_{\text{x}})\eta \pm \xi_{\text{x}}\right| \frac{\Delta p}{p_{\text{ref}}}}_{\text{Linear theory}} + \nu_{\text{det}} + ?$$

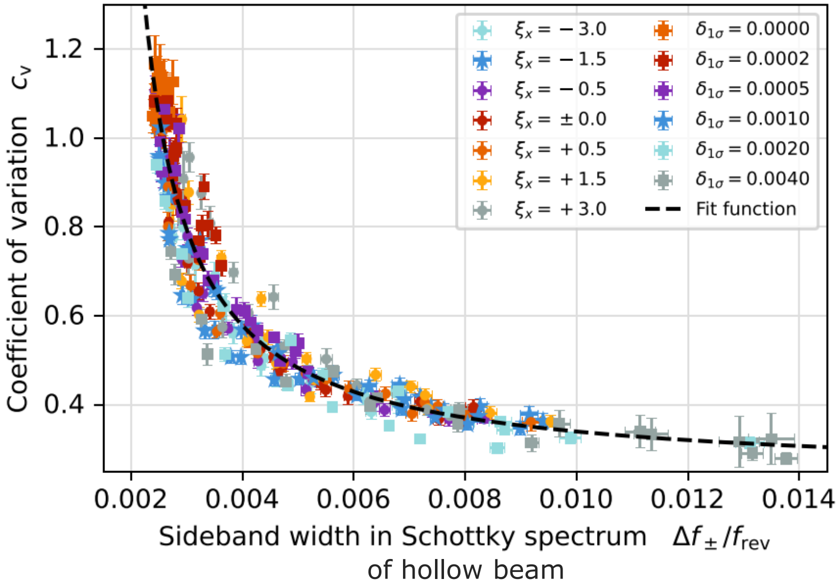




Beam spectrum

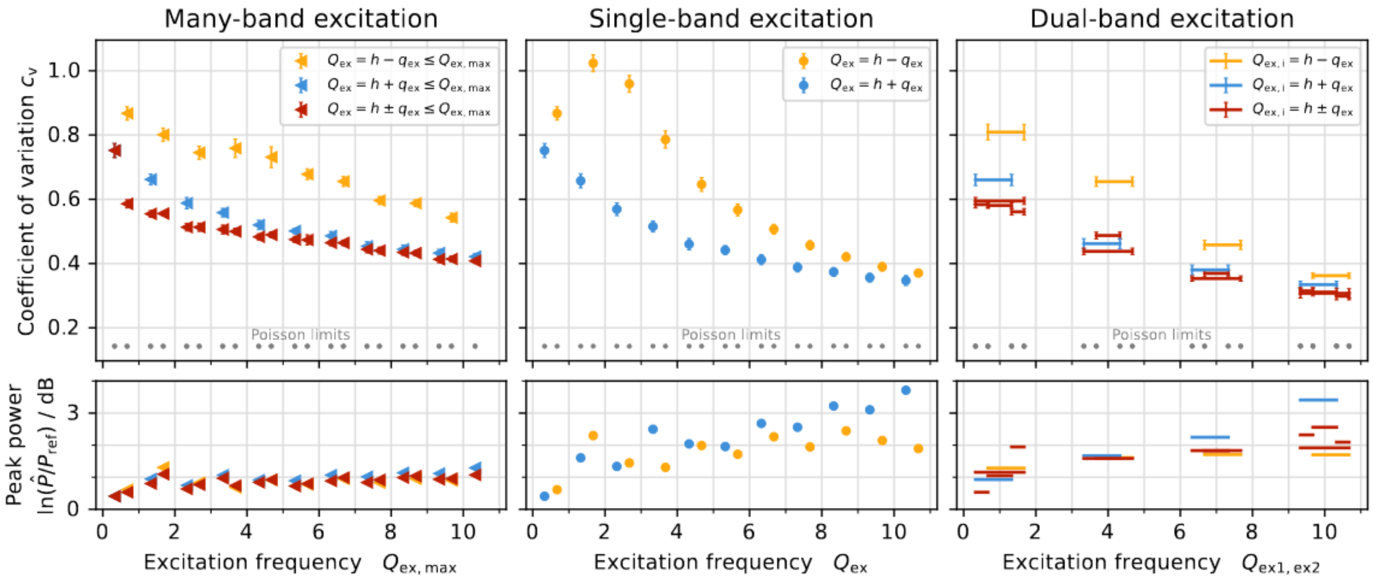
- Width of betatron sidebands for a hollow beam
  - → Correlates with spill quality
  - → Also for multi-band excitation (average width)





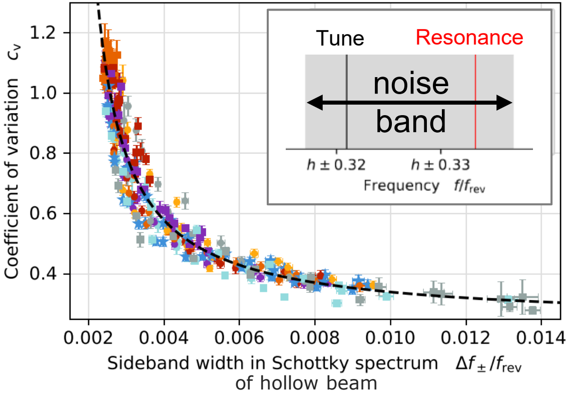
Excitation at multiple sidebands

- Many-band (all bands from 0 to $Q_{ex,max}$) → T. Yamaguchi et al. (WERC), doi.org/p4jc
- Dual-band (two bands) → E.C. Cortés García et al. (HIT), doi.org/p4jd



Interpretation of simulation results

- Low power noise signals ($\Delta Q_{\mathrm{ex}} \approx 0.02$)
- Excitation of wider sidebands improves spill quality
  - Better matching of wide excitation to particle spectrum
  - Less perturbation of particle motion before their extraction
  - Reduced imprint of excitation noise onto spill



→ Upper/lower sideband excitation make a difference at lower harmonics

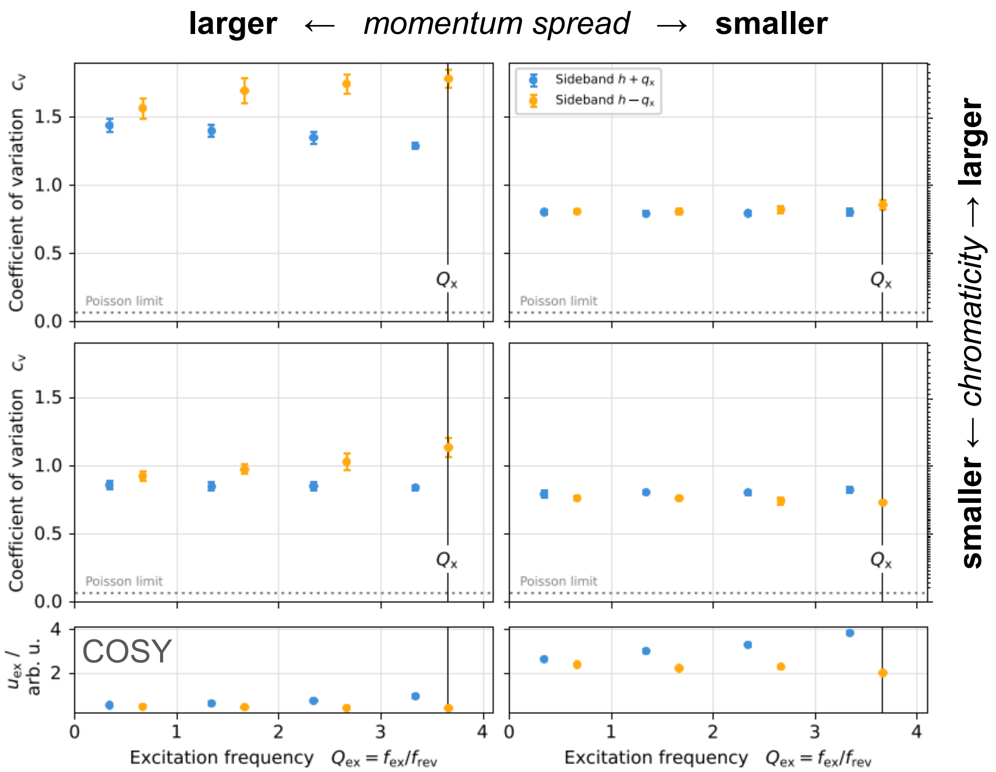
→ General improvement for higher harmonics

→ Depends on optics and beam parameters, strong scaling with momentum spread

- Dual-band excitation gives additional improvement

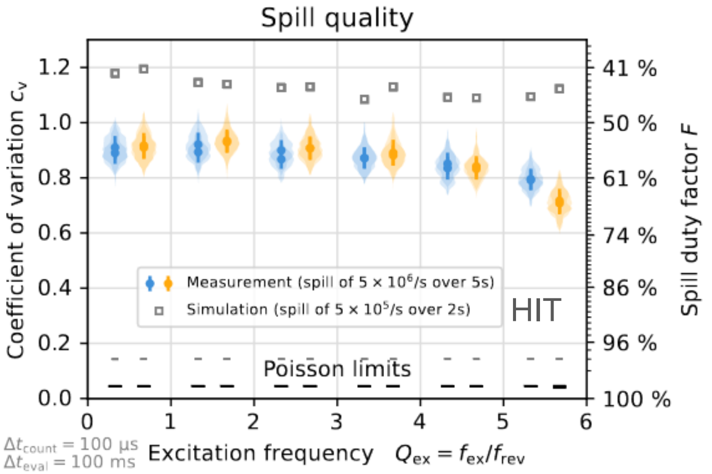
Experimental hints

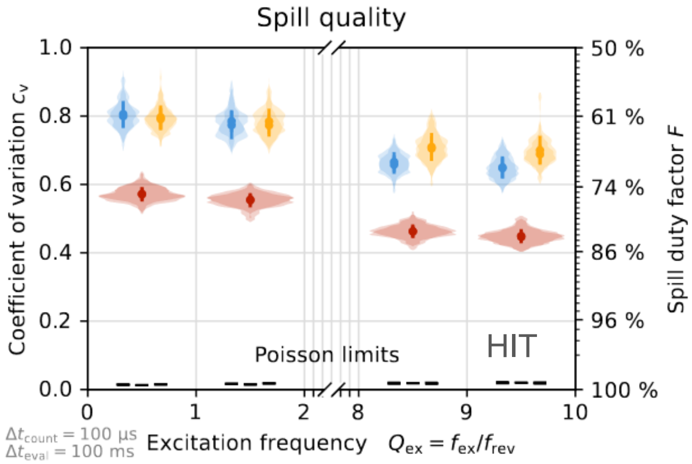
- Experiment at COSY Jülich (2023)
  - → Observed effect at low harmonics
  - → Dependence on chromaticity and momentum spread



Experimental hints

- Experiment at HIT Heidelberg (2024)
  - → Effect suppressed by low momentum spread $\delta_{1\sigma} \approx 7 \cdot 10^{-5}$
  - → Observed improvement at higher harmonics and for dual-band excitation

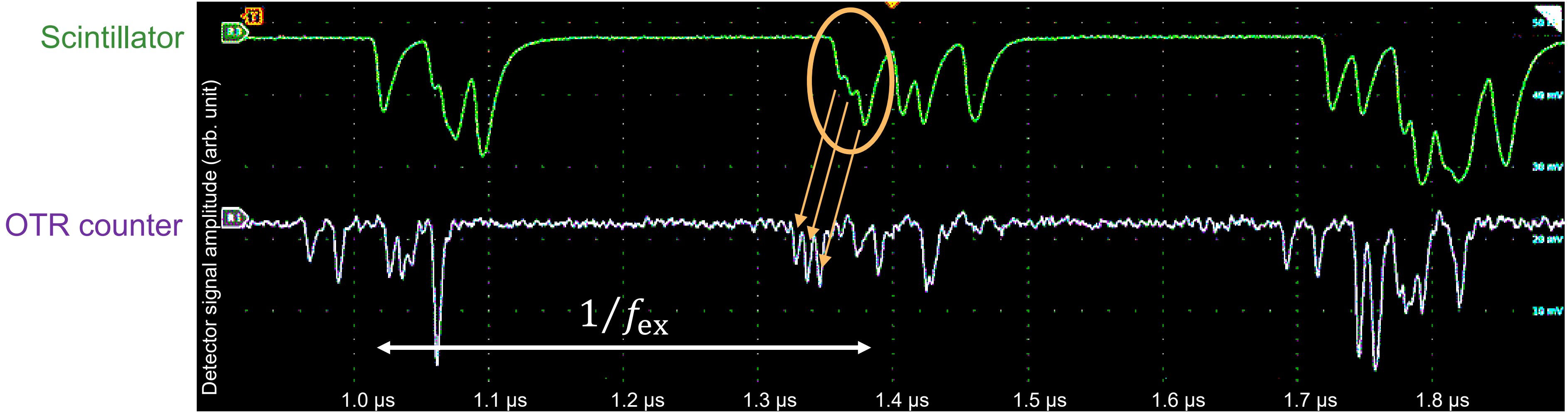




Pile-up

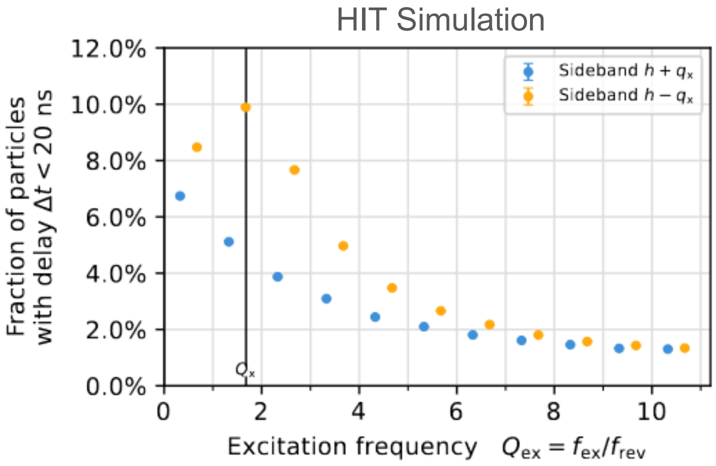
- Pile-up of overlapping single particle events
  → Optical Transition Radiation (OTR) based counter
    - Radiation-Hard (multiple 100 µm Aluminium foils)
    - Short pulses (time resolution of few ns) mitigates pile-up

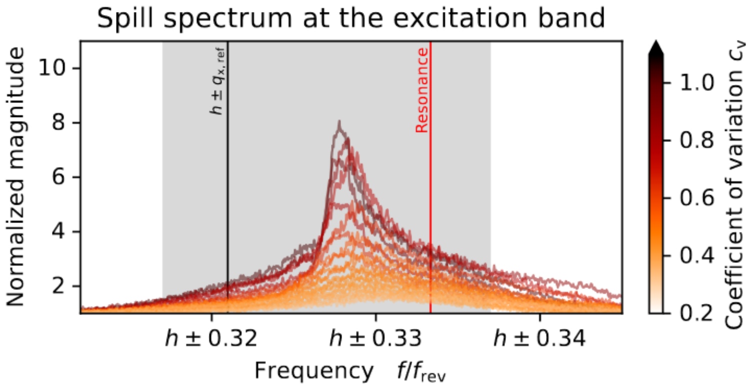
U^{73+} at 700 MeV/u and $f_{\mathrm{rev}} = 1.14$ MHz
Spill rate: $20 \cdot 10^6$ /s (GSI SIS18 2025)
Excitation at $f_{\mathrm{ex}} = 2.326 f_{\mathrm{rev}} =$ **2.6 MHz**
By **Rupesh Ghagi**, Rahul Singh et. al



Pile-up

- Pile-up reduction with high harmonic excitation
  - At large momentum spread → Reduction of excitation imprint avoids clustering

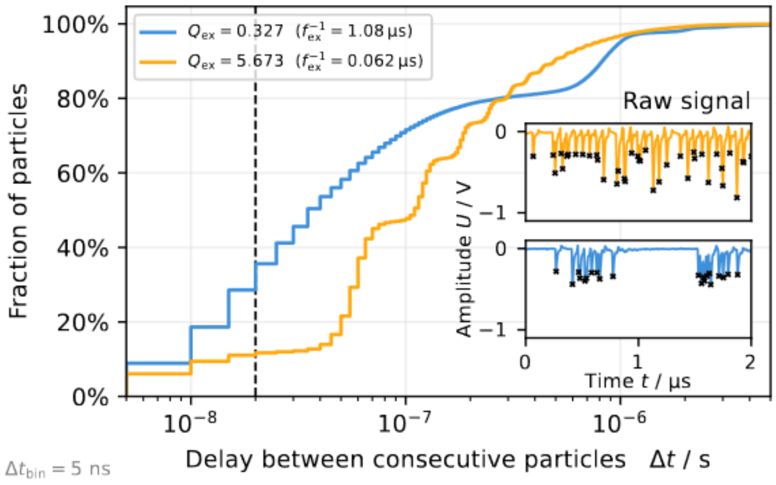


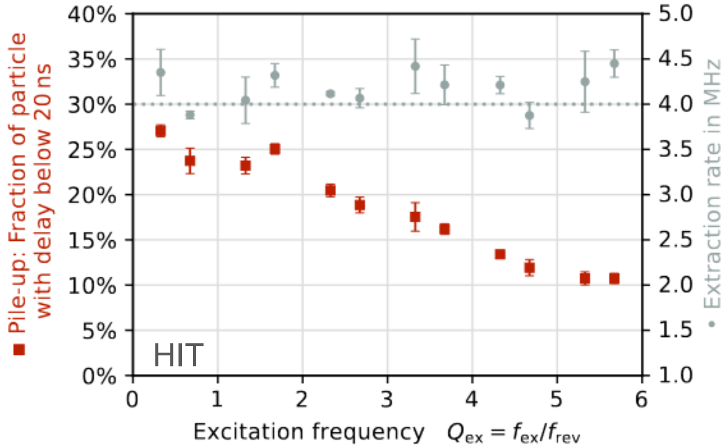


Pile-up

- Pile-up reduction with high harmonic excitation
  - At large momentum spread → Reduction of excitation imprint avoids clustering
  - At small momentum spread → De-clustering of spill structure with $f_{\mathrm{ex}} \geq \dot{N}_{\mathrm{spill}}$

Experiment at HIT Heidelberg (2024)



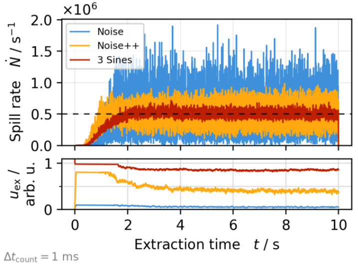


Summary

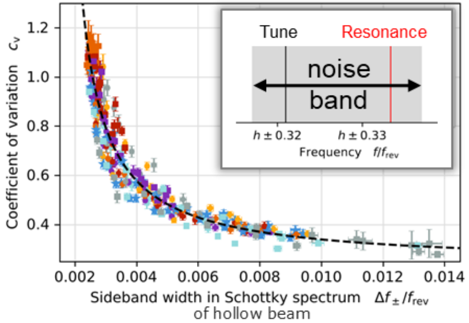
KO excitation signals to improve spill quality

- Multi-Sine and Noise++ signals
- Excitation at 2nd order sidebands

Higher excitation power required



- Sidebands of higher harmonics
  - Low power noise signals covering full tune range
  - Spill quality correlates with hollow beam spectrum
  - Best: excite dual bands at high frequencies
    - → Reduced imprint of excitation noise onto spill
    - → Mitigates pile-up (de-clustering for $f_{ex} \geq \dot{N}_{spill}$)



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