Spill Feedback and Optimization System for RF Knock Out and Quad-driven Extraction

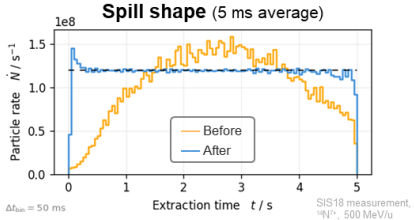
6th Slow Extraction Workshop, 6. – 9.10.2025

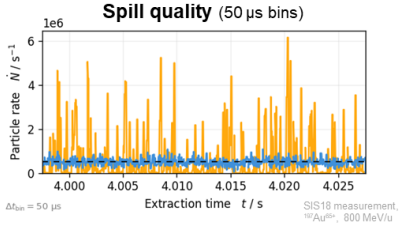
Philipp Niedermayer and Rahul Singh

Image: D. Fehrenz, GSI/FAIR, May 2025

Outline

- Slow extraction methods at GSI SIS18
- Spill Optimisation System (SOS)
- Feedback controlled extraction
- Spill quality improvement
  - Sine excitation
  - Tune wobbling



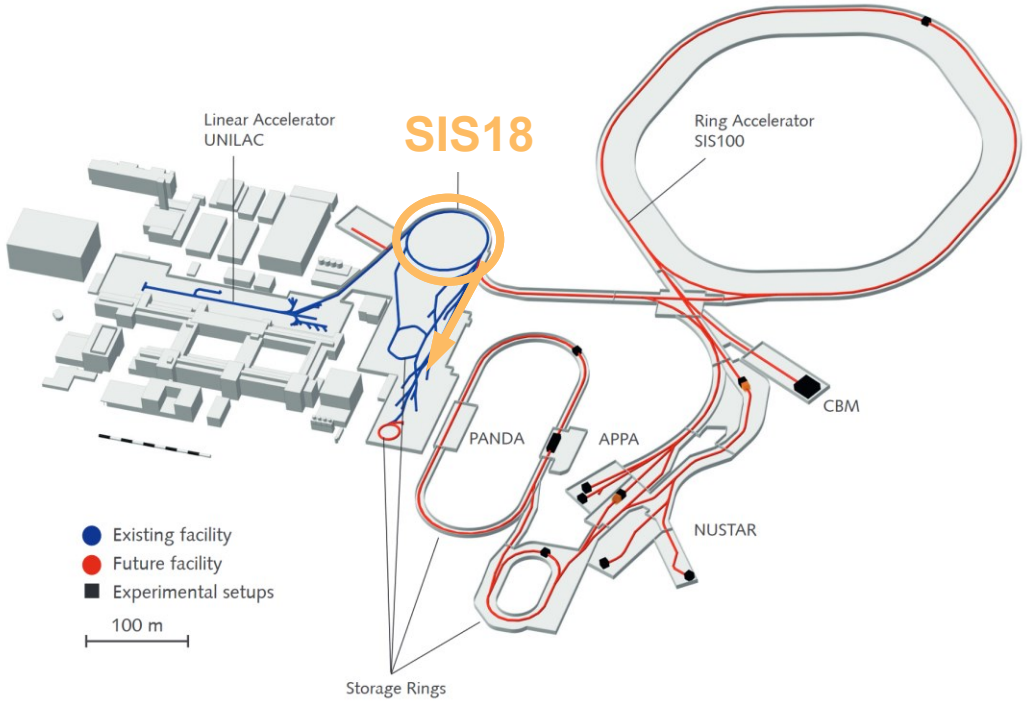


GSI Accelerators

- Slow extraction from SIS18
  - Main extraction scheme (94% of user beam time in 2024)
- Beam spills
  - Various Ions & Energies
  - Typically 10^6 to 10^9 ions/s
  - **1s to 20s spill length**

	Top Energy		Intensity	
	SIS18	SIS100	SIS18	SIS100
Protons	4.7 GeV	28.8 GeV	10^{11}	10^{13}
…				
Uranium	1.0 GeV/u (U^{73+})	2.7 GeV/u (U^{28+})	$4 \cdot 10^9$	$3 \cdot 10^{11}$

Source: https://indico.gsi.de/event/18184/contributions/76293

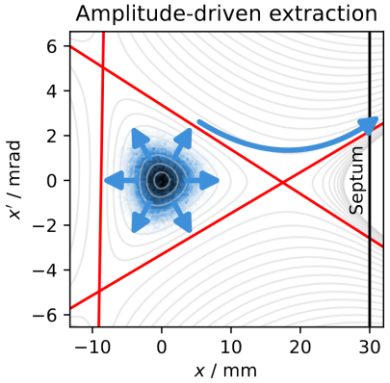


15 weeks slow, 1 week fast extraction in user beamtime 2024

Slow Extraction at GSI SIS18

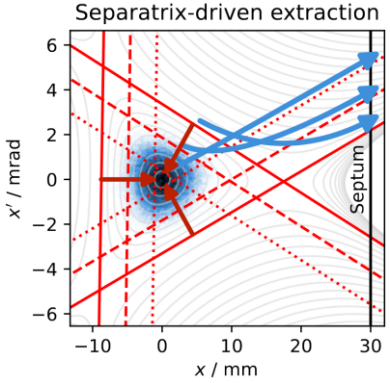
Third-order resonant extraction, two main schemes:

RF Knock Out extraction



- Extraction optics with chromaticity corrected
- Stripline exciter controls particle amplitude
- Beam-on-target fixed
- Momentum distribution preserved

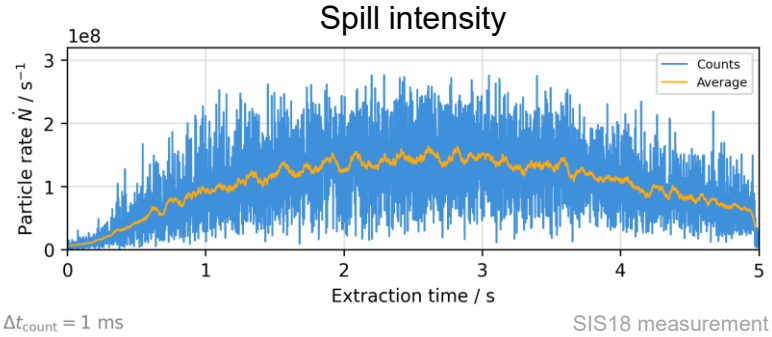
Quad-driven extraction



- Extraction optics with natural chromaticity
- Fast quadrupole to shrink separatrix
- Beam-on-target drifts
- Momentum drifts

Spill structure

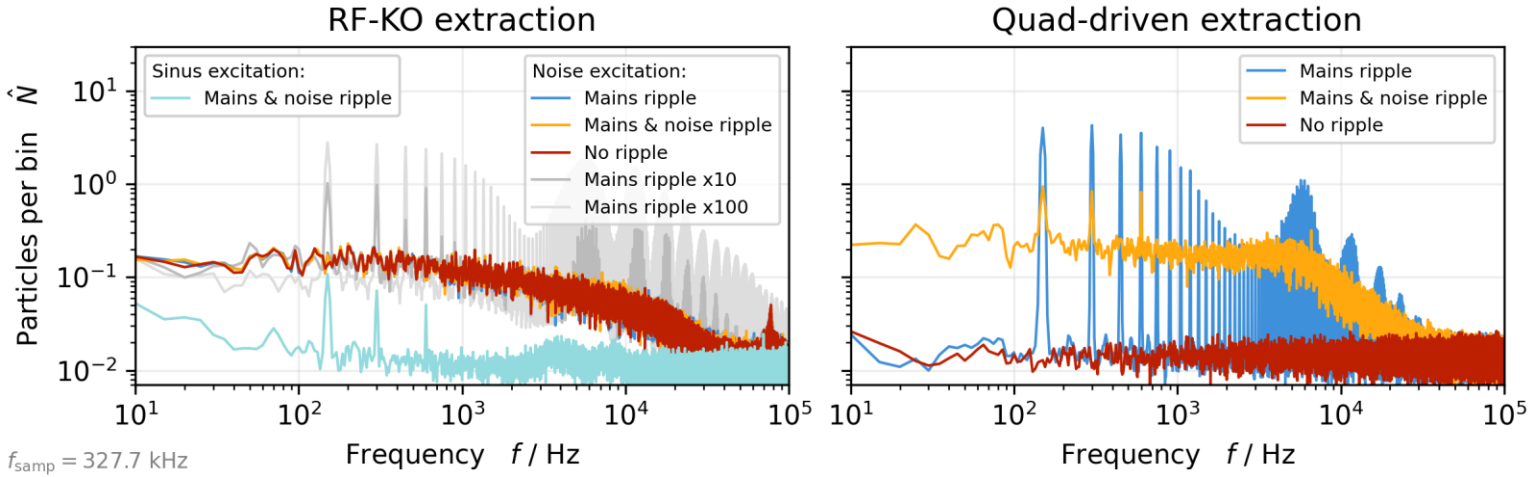
- Extraction is very sensitive
  - → Spill rate drifts ($t \gg \mathrm{ms}$)
    Spill shape
  - → Intensity fluctuates ($t \leq \mathrm{ms}$)
    Spill quality



- **Challenge: Minimize intensity fluctuations**
  - → Efficient beam usage (duty cycle, precise dose)
  - → Avoid pile-up and interlocks

Main Source of Spill Fluctuations

- Spill spectra from particle tracking simulation with Xsuite
  - → Extraction with/without ripples on quadrupole magnets (strength 10^{-5})



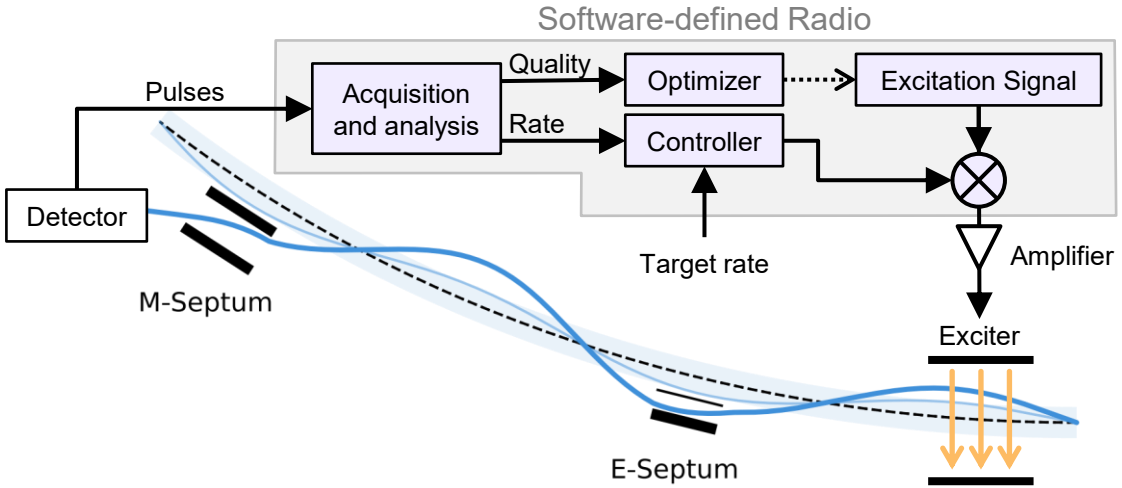
Spill fluctuations dominated **by excitation signal**

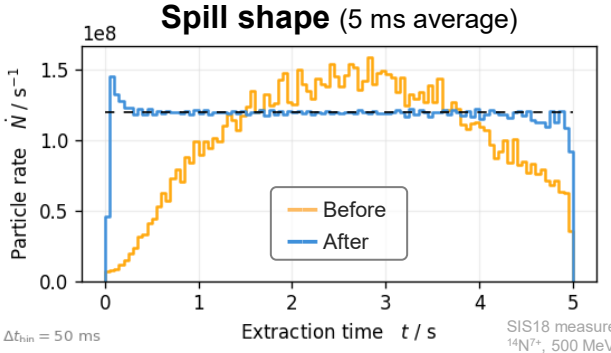
Spill fluctuations dominated **by quadrupole ripples**

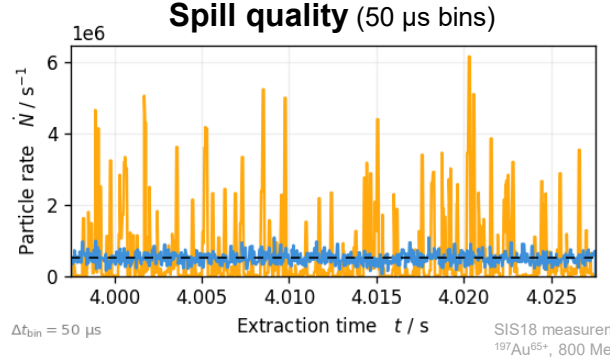
Mains ripple: 150, 300 and 600 Hz
Noise ripple: 0 to 10 kHz
Ripple magnitude: 10^{-5} [Singh et al., 2017]

Spill Optimization System (SOS)

- Developed to study excitation methods
  - Feedback controller for spill shape
  - Signal optimization for spill quality



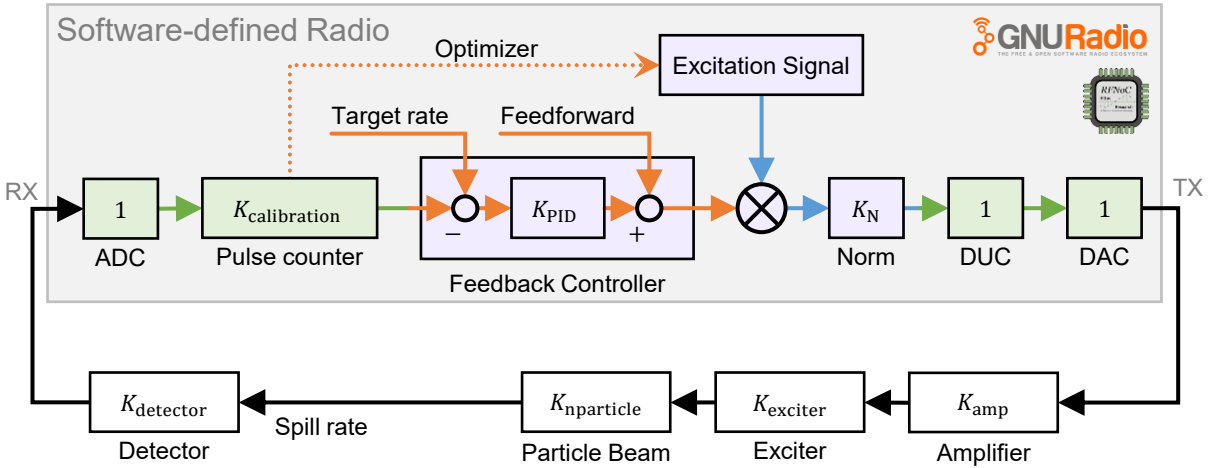




Spill Optimization System (SOS)

Published under GPLv3 at
git.gsi.de/p.niedermayer/exciter

- Implemented with Software-Defined Radio
  - Maintainable open source software and commercial hardware
  - Standalone all-in-one system
  - Flexible digital signal processing on CPU & FPGA



System parameters

- Latency: 1.5 ms (CPU)
  30 µs (FPGA)
- Bandwidth: 5 MHz
- Frequency: 0 .. 30 MHz

Process

- Latency: ~ 3 ms

Spill Optimization System (SOS)

- Implemented with Software-Defined Radio
  - Maintainable open source software and commercial hardware
  - Standalone all-in-one system

Published under GPLv3 at
git.gsi.de/p.niedermayer/exciter

Ettus USRP X310

Industrial PC

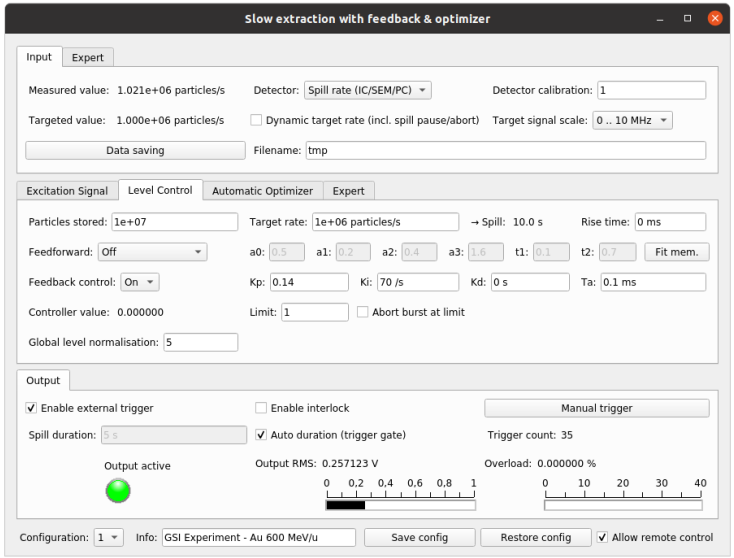
System interfaces

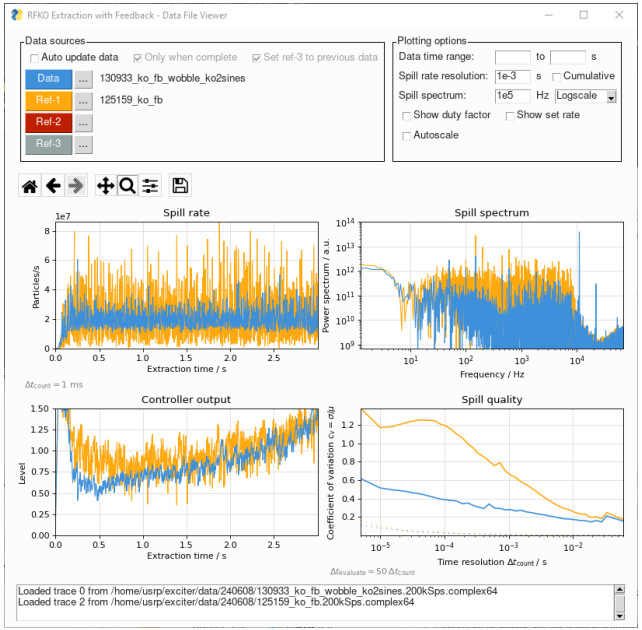
- Measured rate input: NIM (scaled)
- Dynamic rate control input: NIM
- Interlock and Trigger: TTL
- Output: 0 .. 30 MHz, 10 dBm
- Control: GUI, ZMQ API or FESA (ongoing)

Spill Optimization System (SOS)

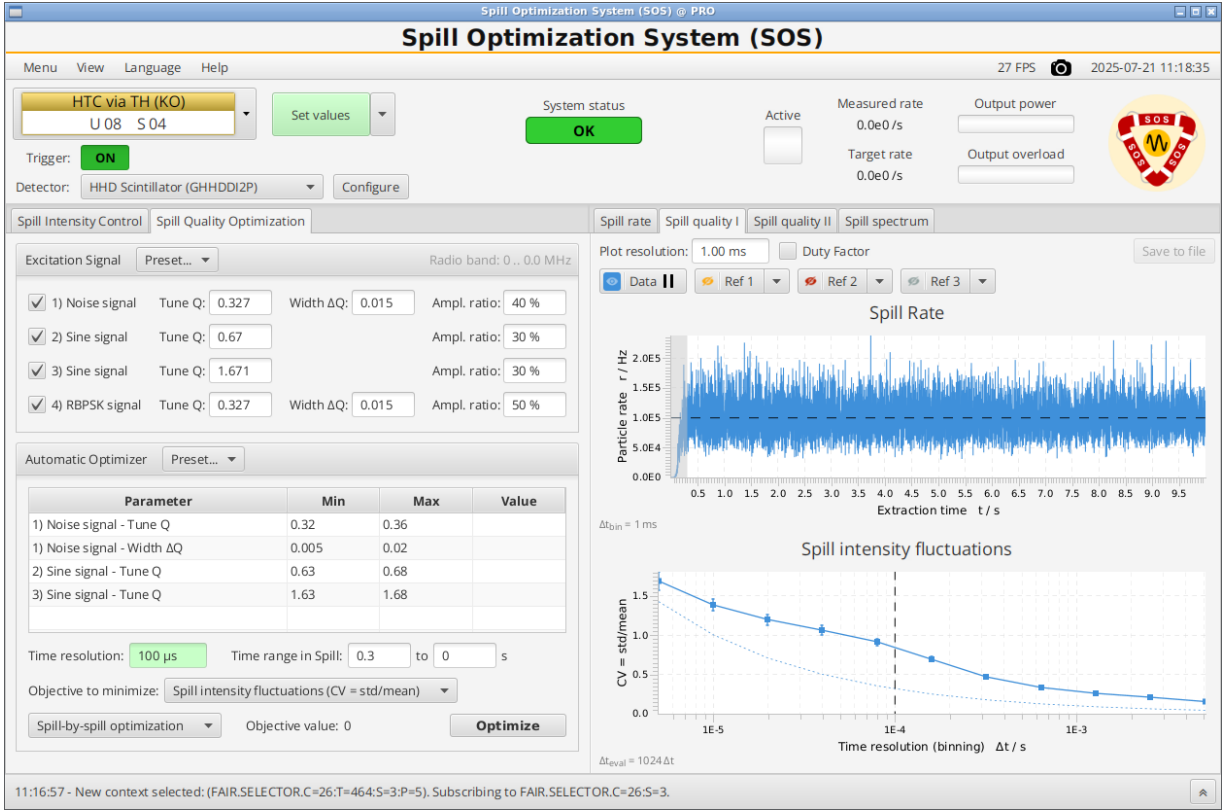
Published under GPLv3 at
git.gsi.de/p.niedermayer/exciter

- Implemented with Software-Defined Radio
  - Maintainable open source software and commercial hardware
  - Standalone all-in-one system



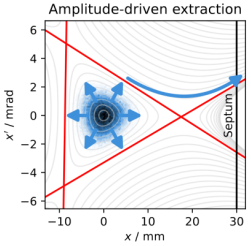


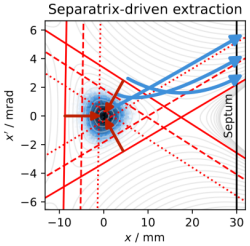
Spill Optimization System (SOS)

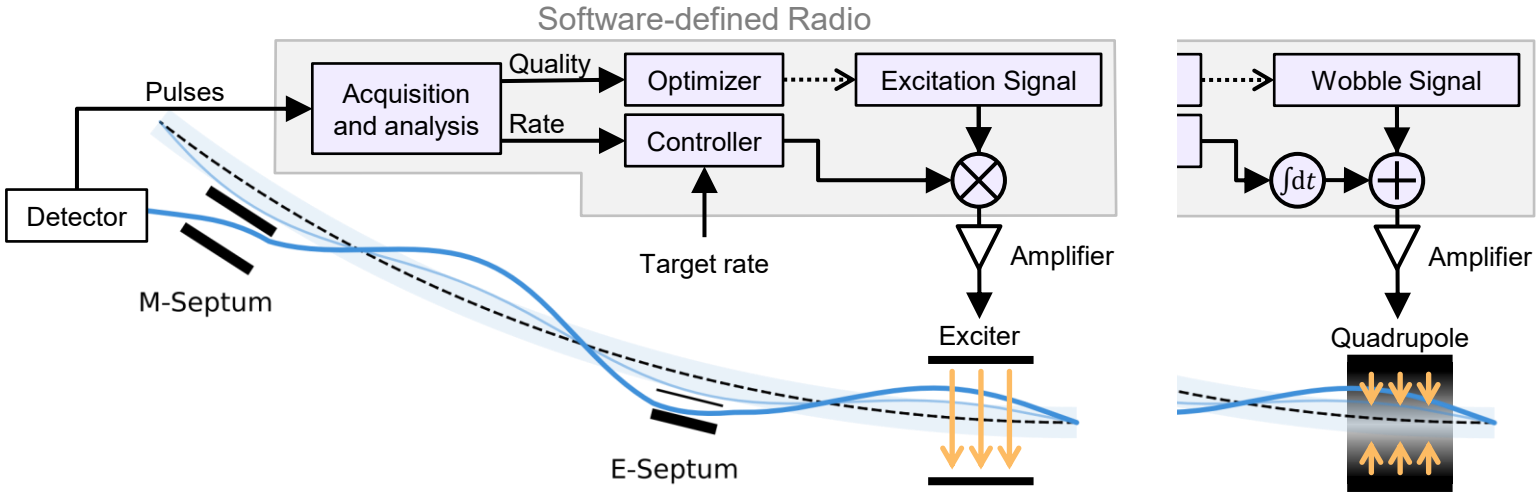


Spill Optimization System (SOS)

- Two similar systems
  - RF-KO (excitation signal): in regular user operation
  - Quad-driven (quadrupole set-point signal): demonstrated

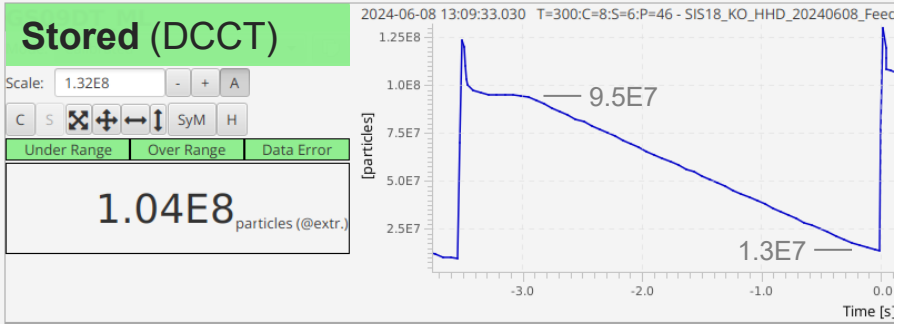




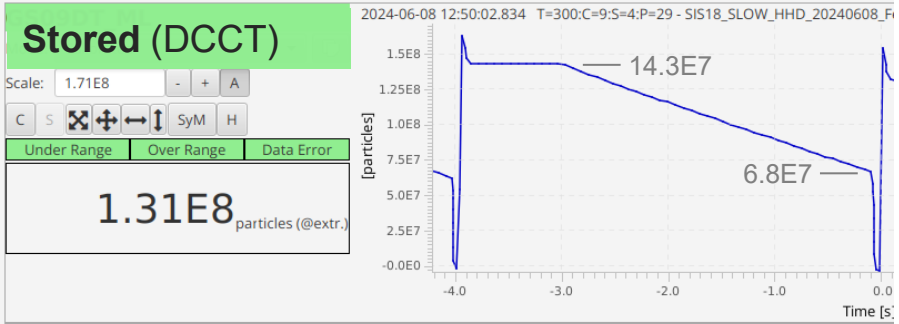


Feedback-Controlled Spill

RF Knock Out extraction



Quad-driven extraction

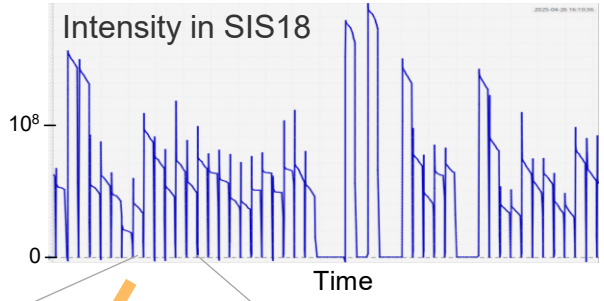


Measurement at SIS18, coasting $^{238}U^{73+}$ beam, $E_{\mathrm{kin}} = 500\ \mathrm{MeV/u}$, $p = 259\ \mathrm{GeV/c}$, $B\rho = 11.8\ \mathrm{T\,m}$

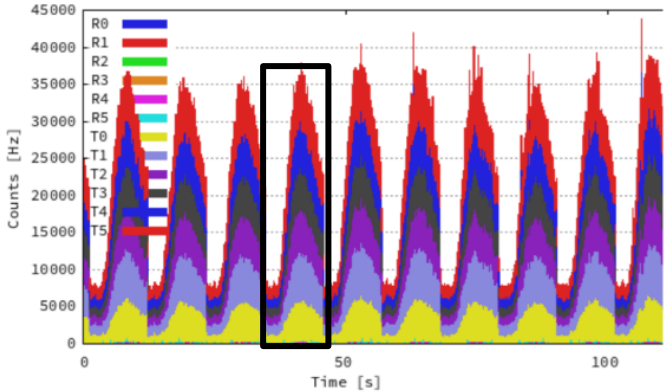
DCCT = DC Current Transformer
SEM = Secondary Electron Monitor

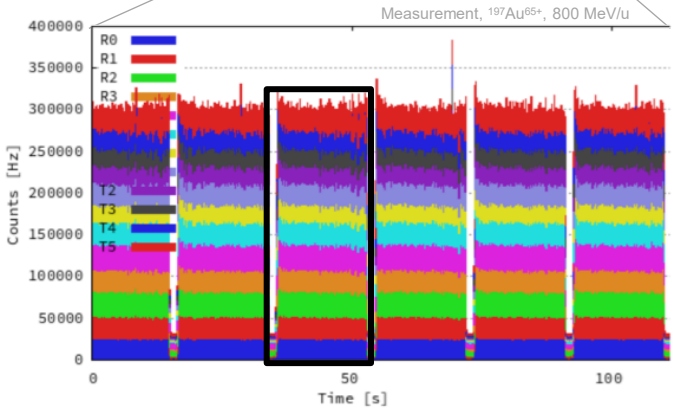
Feedback-Controlled Spill

- Stable “DC” beam: drifts ≥ 10 ms suppressed
  - → HADES: 40% more events
- Spill-to-spill reproducibility
  - → HADES: overall factor > 2 more events



Event rate of HADES detector

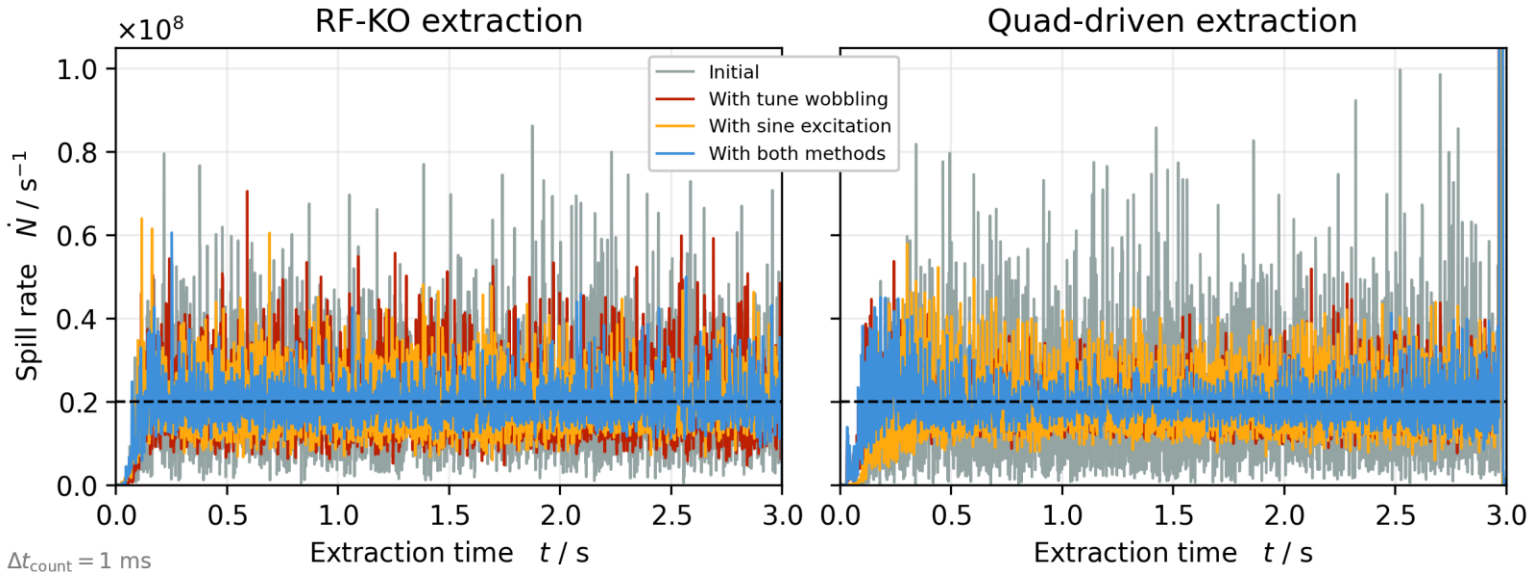




Images: M. Traxler / HADES Collaboration

Spill Quality Improvement

- Spill smoothing with tune wobbling[1] and sine excitation[2]
- Both reduce intensity fluctuations in either case



Measurement at SIS18, coasting $^{238}U^{73+}$ beam, $E_{\mathrm{kin}} = 500$ MeV/u

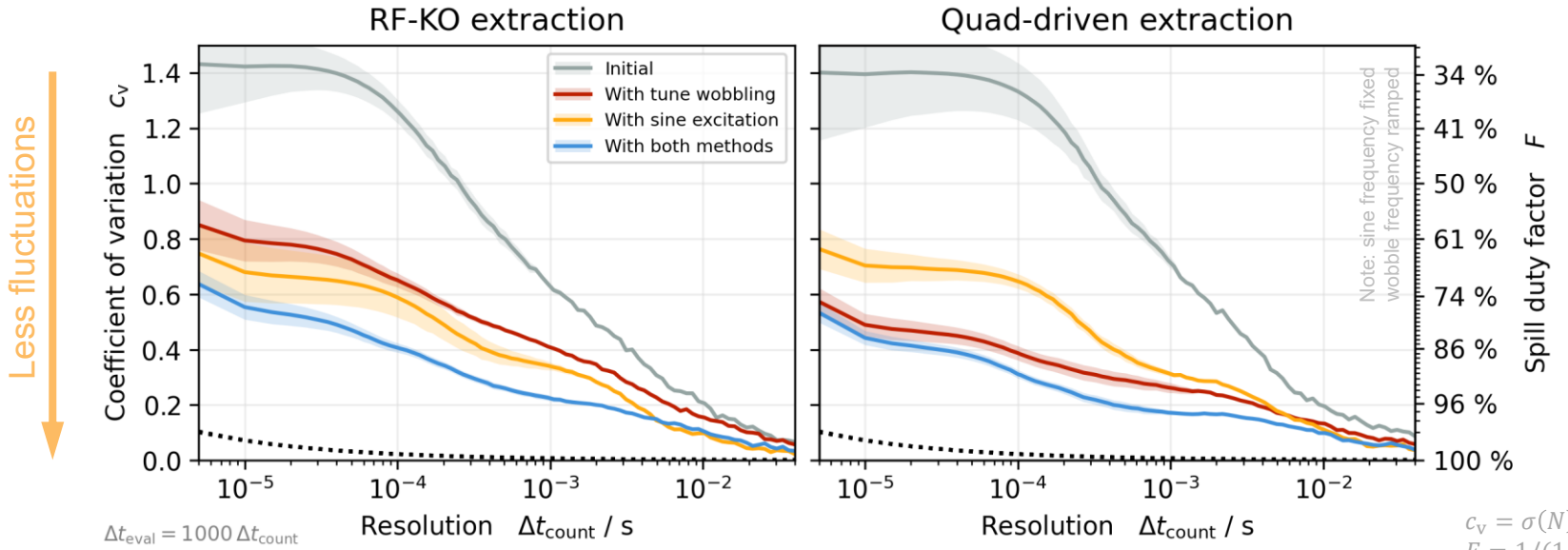
[1] doi.org/10.1103/PhysRevApplied.13.044076

[2] doi.org/10.1038/s41598-024-60966-y

Spill Quality Improvement

- Tune wobbling best for Quad-driven extraction
- Sine excitation best for RF Knock Out extraction

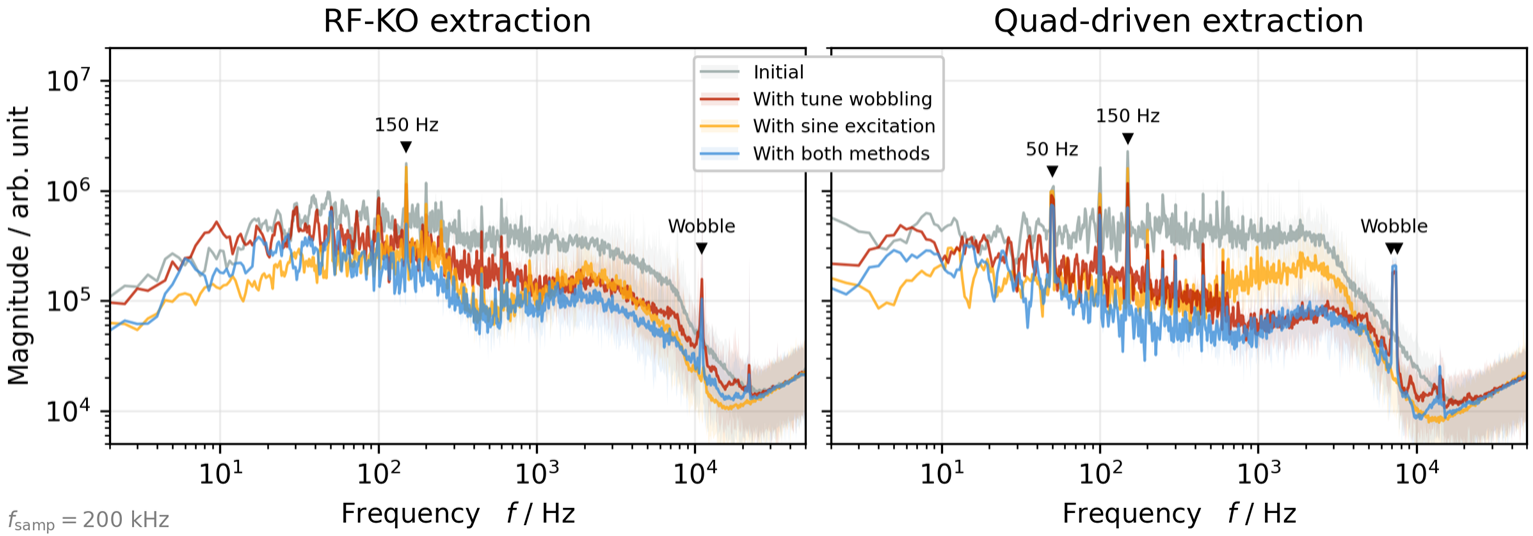
Acting on respective driving mechanism



Measurement at SIS18, coasting $^{238}U^{73+}$ beam, $E_{kin} = 500$ MeV/u

Spill Quality Improvement

- PS ripples stronger for Quad-driven extraction
- Feedback faster for RF Knock Out extraction



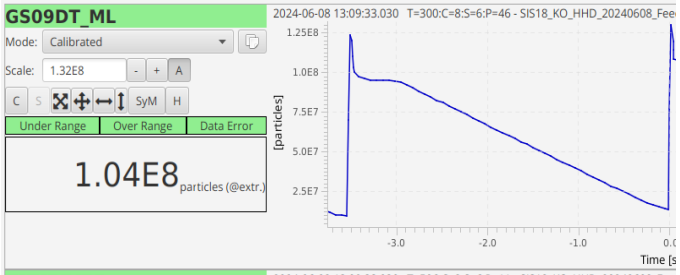
Measurement at SIS18, coasting $^{238}U^{73+}$ beam, $E_{kin} = 500$ MeV/u

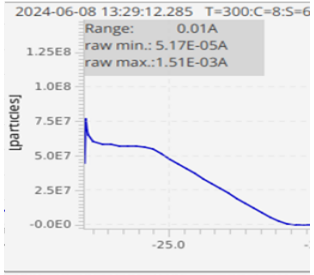
Spill Optimization System as “Toolbox”

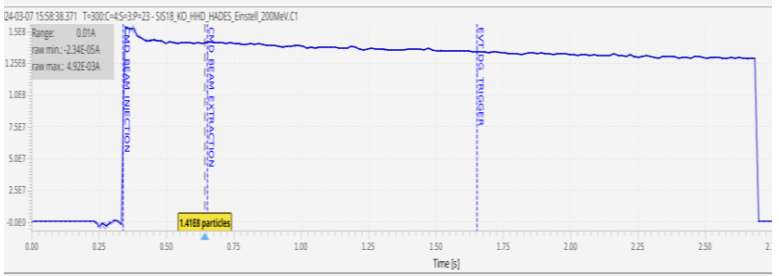
- Different operation modes (depending on user needs & beam energy/intensity)
  - E.g. “Full extraction and improved quality” at high energy/intensity
  - E.g. “Partial extraction and ultimate quality” at low energy/intensity (if power insufficient)
  - *In the future also: “Excitation at high harmonics” for better spill quality with low power*

Stored

Extracted



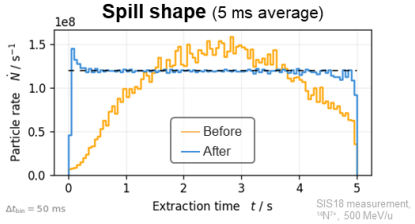


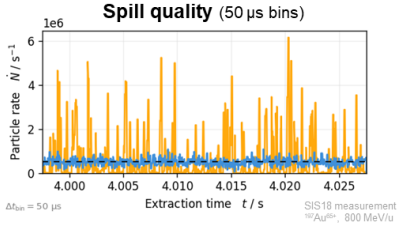


Summary

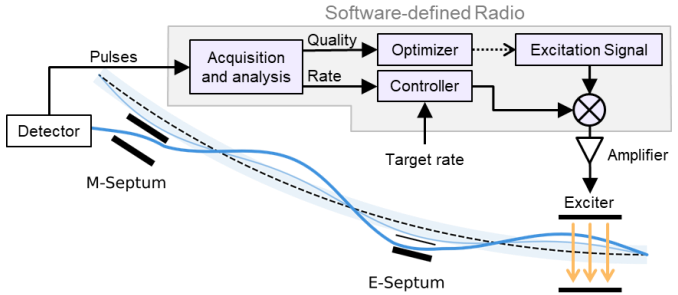
- Slow extraction at GSI: RF Knock Out and Quad-driven

- Spill Optimisation System (SOS)
  - Feedback → stable & reproducible spill rate
  - Optimizer → improved spill quality





- Software-defined radio module
  - Flexible digital open-source solution
  - Minimize time from machine study to daily operation
  - Interest to use it at your lab? Get into touch!



Published under GPLv3 at
git.gsi.de/p.niedermayer/exciter