Spill Optimization System (SOS)

7^{th} Beam Time Retreat, Kranichstein, 11.7.2024

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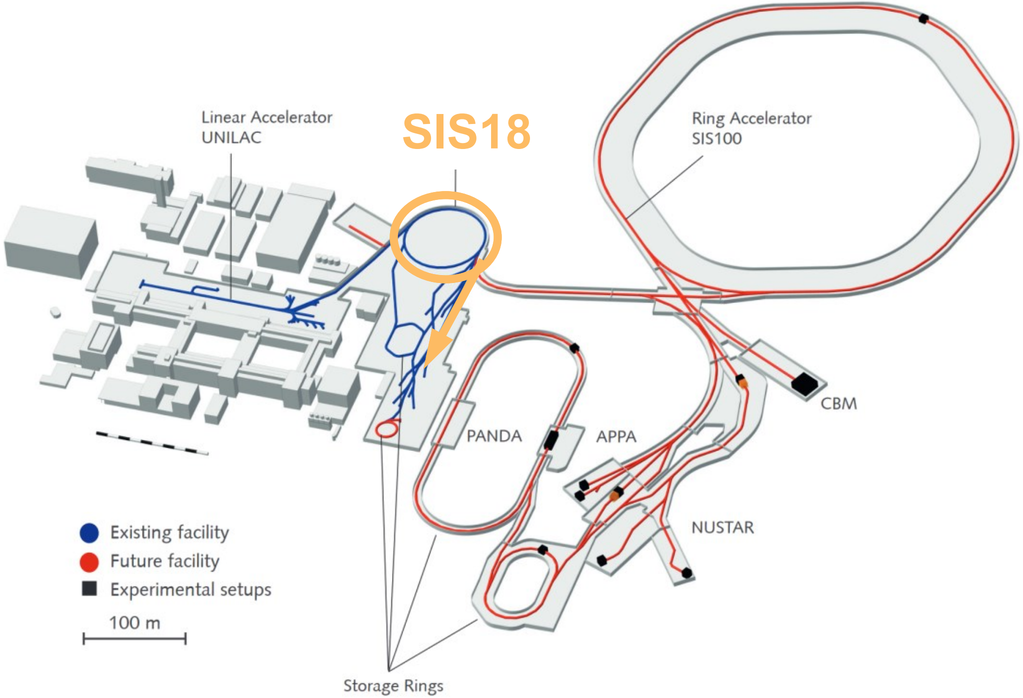
Bild: D. Fehrenz, GSI/FAIR, April 2024

Contents

GSI Accelerators

- Slow extraction from SIS18 and later SIS100
- Beam to many experiments
  - Various Ions & Energies
  - **1s to 20s spill length**

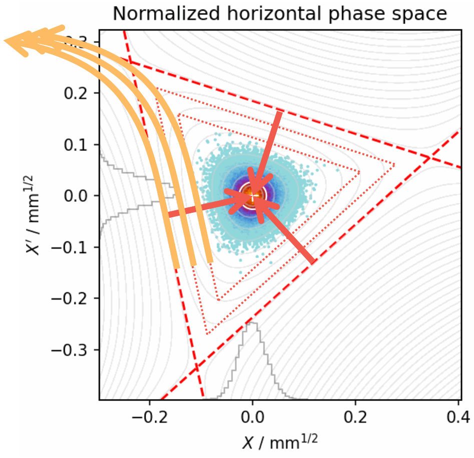


	Top Energy		Intensity	
	SIS18	SIS100	SIS18	SIS100
Protons	4.7 GeV	28.8 GeV	10^{11}	10^{13}
…				
Uranium	1.0 GeV/u (U^{73+})	2.7 GeV/u (U^{28+})	$4 \cdot 10^9$	$3 \cdot 10^{11}$

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

Slow Extraction from Synchrotrons

- Working point near sextupole driven 1/3 resonance
- Separatrix beyond which particles are unbound & extracted
- Methods to extract spill
  - **Quadrupole-driven** → Shrink separatix with tune change
    - Spill quality dominated by power supply ripples



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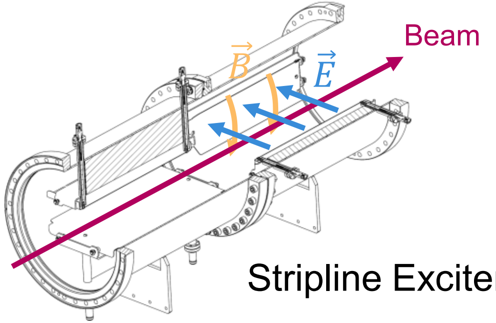
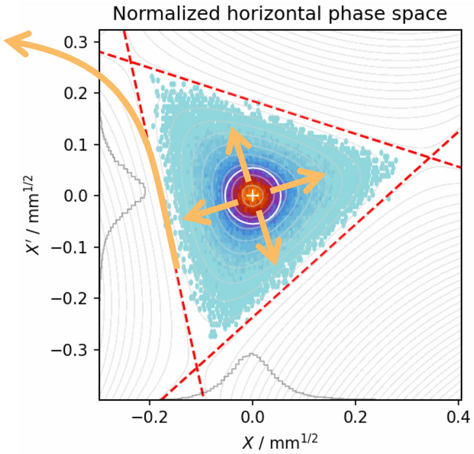
- Separatrix beyond which particles are unbound & extracted
- Methods to extract spill
  - **Quadrupole-driven** → Shrink separatix with tune change
    - Spill quality dominated by power supply ripples
  - **RF Knock Out** → Control particles with excitation
    - Spill quality dominated by RF signals



Stripline Exciter



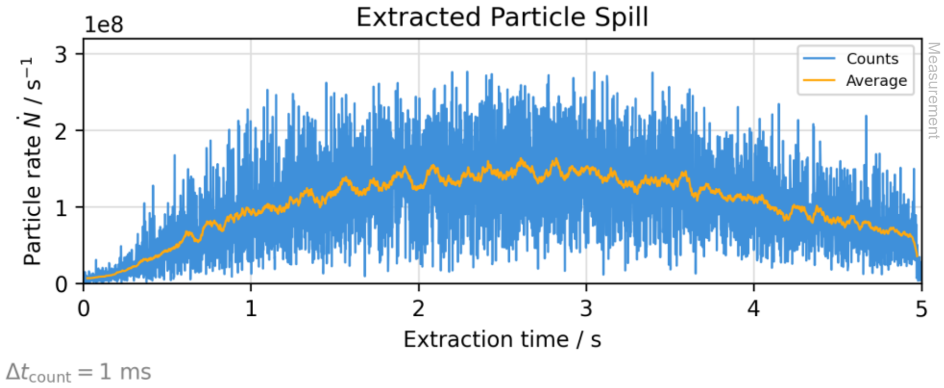
Technical drawing: P. Kowina / JHAASS

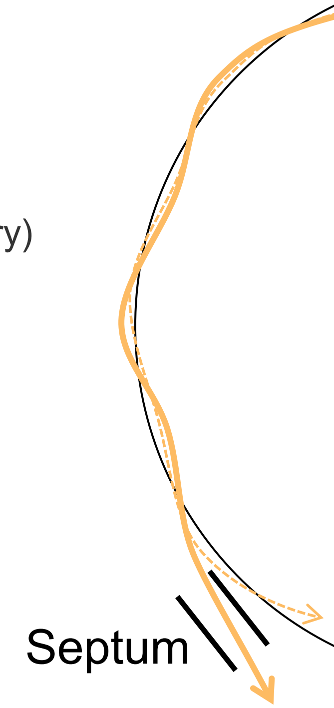
Slow Extraction from Synchrotrons

- Unbound particles enter septa and extraction beamline → Spill
- Challenge: Steady particle flux on all timescales

<u>Microscopic (μs to ms)</u>
For efficient detector usage
(minimize pileup and prevent interlocks)
→ **Micro-Spill Methods**

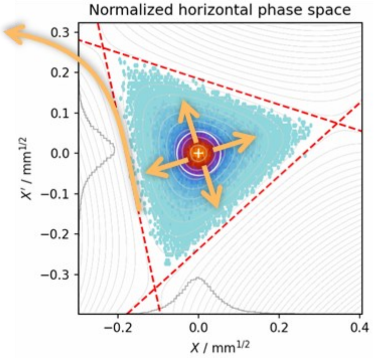
<u>Macroscopic (ms to s)</u>
For efficient beam usage
(maximize duty cycle, precise dose delivery)
→ **Feedback System**

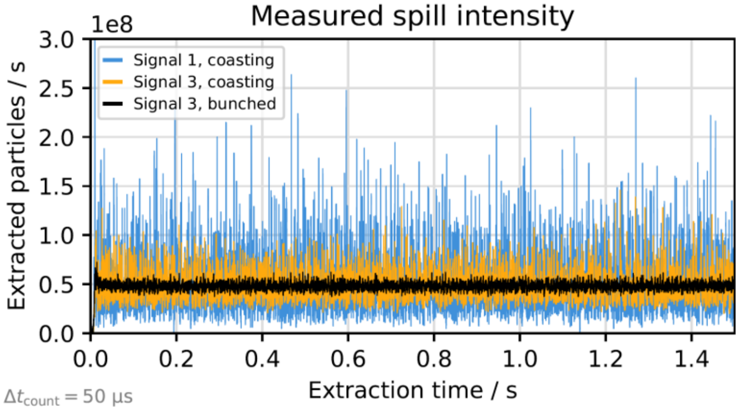


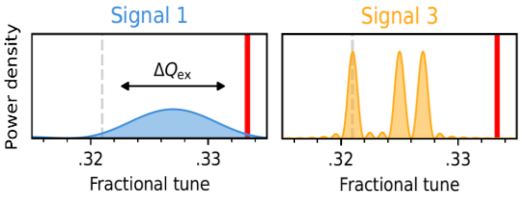


Tailored excitation signals

- Excitation signal controls RF-KO extraction process
  - Many different empirical signals are used
  - Recent progress with multi-narrowband signals at HIT (C. Cortés et. al.)
  - → **Huge potential for spill quality improvement**

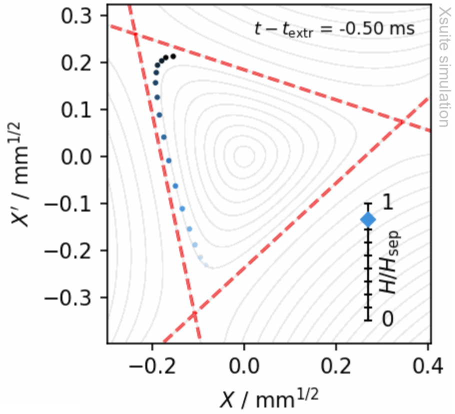




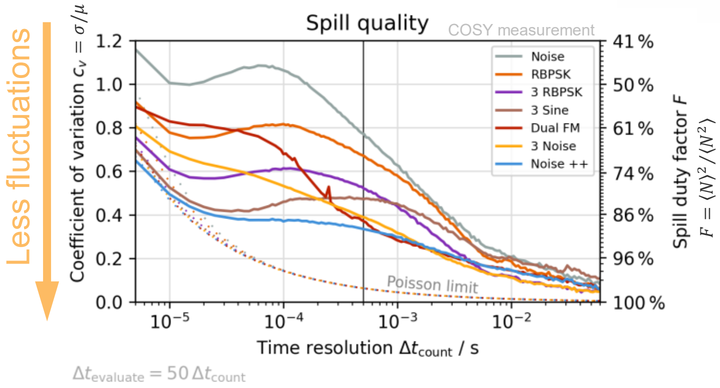


Tailored excitation signals

- Particle dynamics for RF-KO excitation
  - Simulations with Xsuite particle tracking
  - Sinusoidal excitation causes spiralling motion
  - → Faster separatrix crossing
  - → Supresses fluctuations introduced by magnet ripples and excitation band

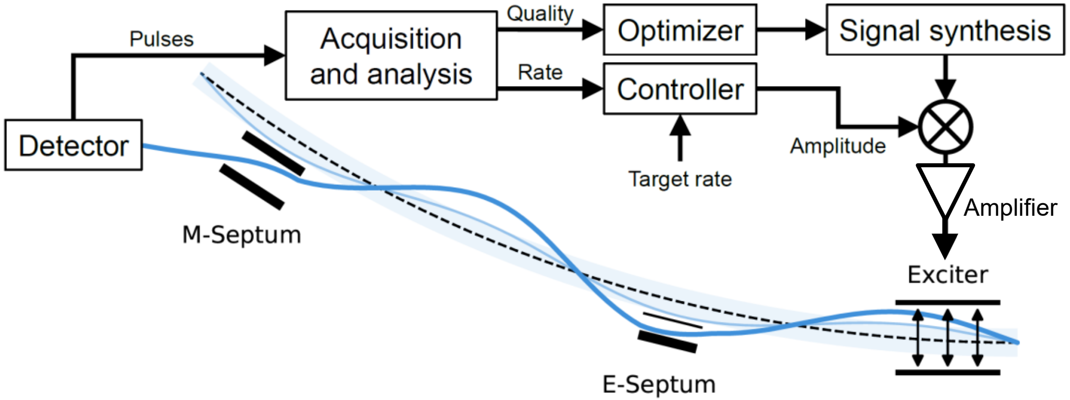


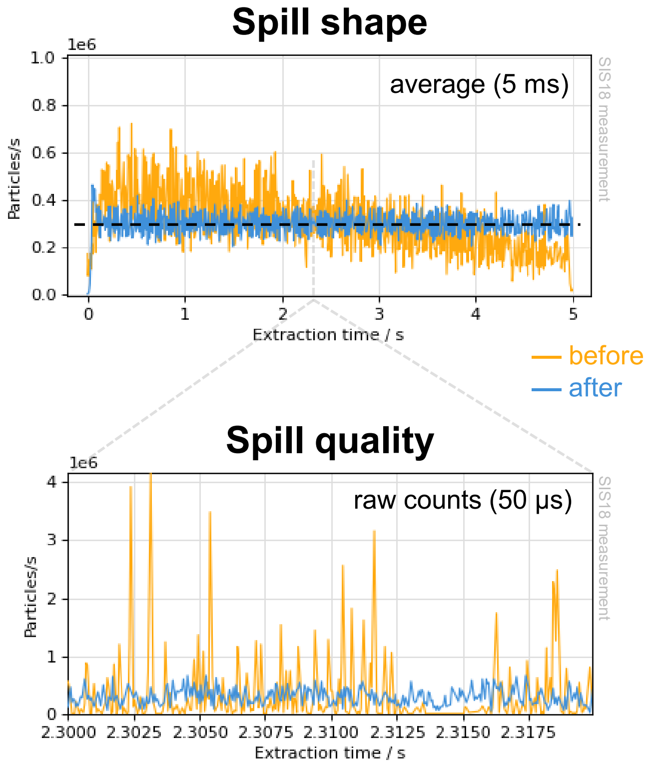
- Proposed Noise++ signal
  - Trade-off between 2 sines and noise (for efficiency)
  - Improvement confirmed in experiments at COSY Jülich



Spill Optimization System

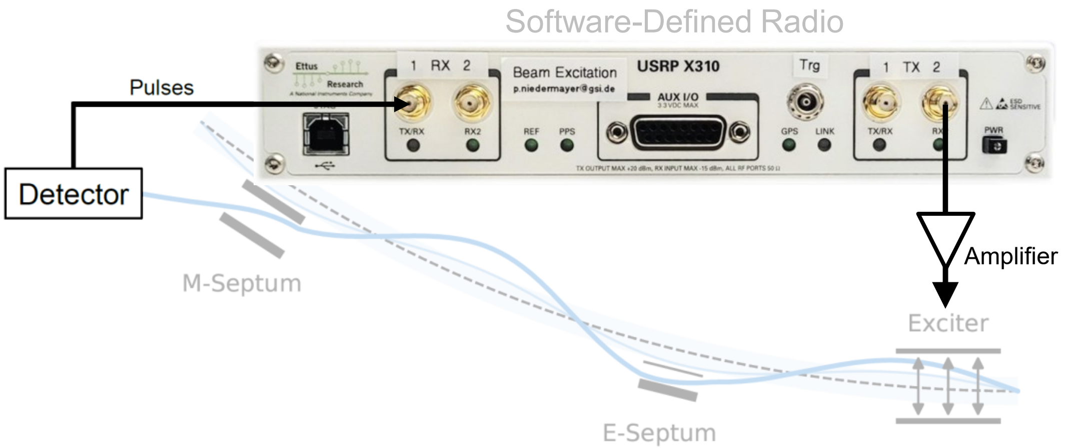
- Recent advances with Spill Optimization System
  - Feedback controller for macro-spill shape (ms to s)
  - Signal optimization for micro-spill quality (µs to ms)





Spill Optimization System

- Implemented with Software-Defined Radio (GNU Radio & RFNoC)
  - Digital signal processing on CPU & FPGA
  - Flexible, maintainable, open source, commercial hardware
  - Standalone all-in-one system



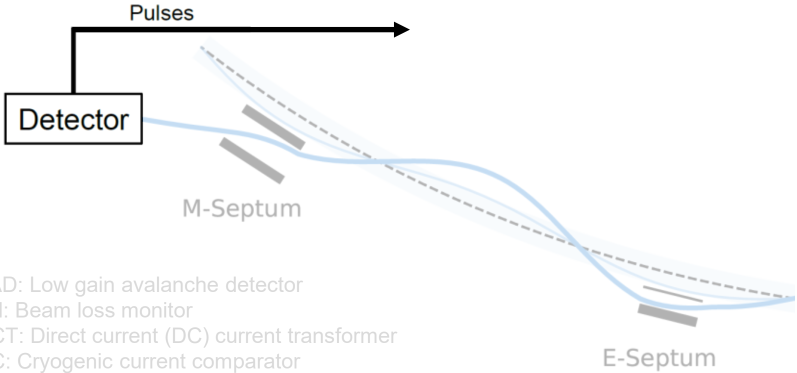
System Status:

- Commissioned at COSY Jülich
- Now used for GSI experiments
- Full control system integration and operator training planned

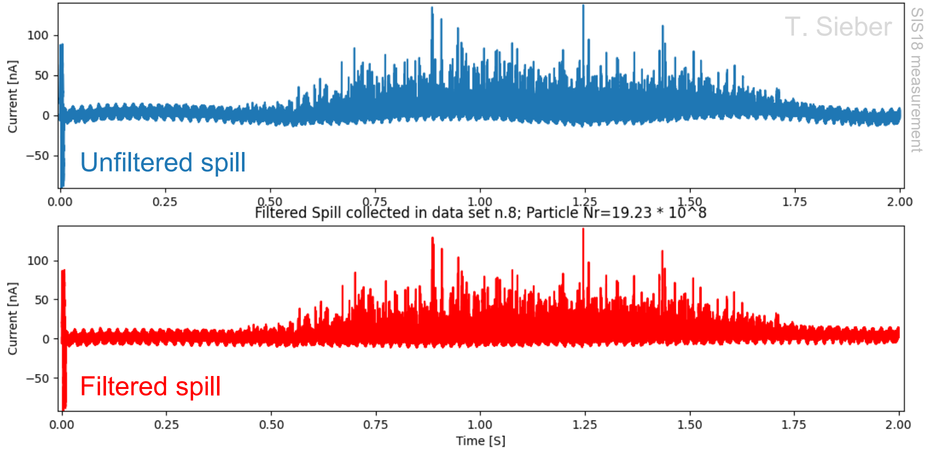
Published under GPLv3 at git.gsi.de/p.niedermayer/exciter

Spill Optimization System

- Different detector systems tested
  - Experiment detectors: LGAD, diamond, …
  - Non-destructive: BLM, DCCT, CCC
  - Destructive: IC, SEM, Scintillator
    - → to optimize & playback recorded signal



Cryogenic Current Comparator (CCC)



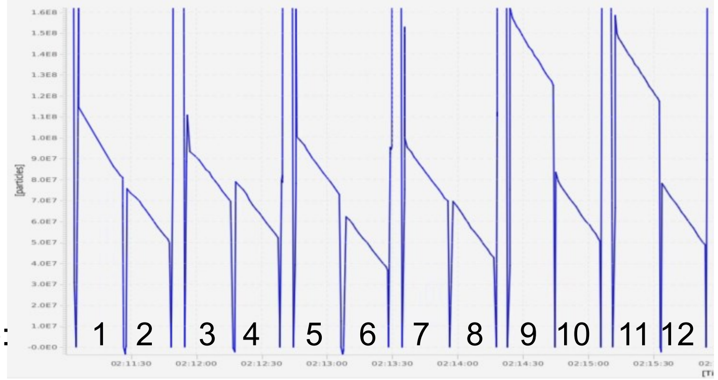
Plots: L. Crescimbeni & T. Sieber

LGAD: Low gain avalanche detector
BLM: Beam loss monitor
DCCT: Direct current (DC) current transformer
CCC: Cryogenic current comparator
IC: Ionisation chamber
SEM: Secondary electron monitor

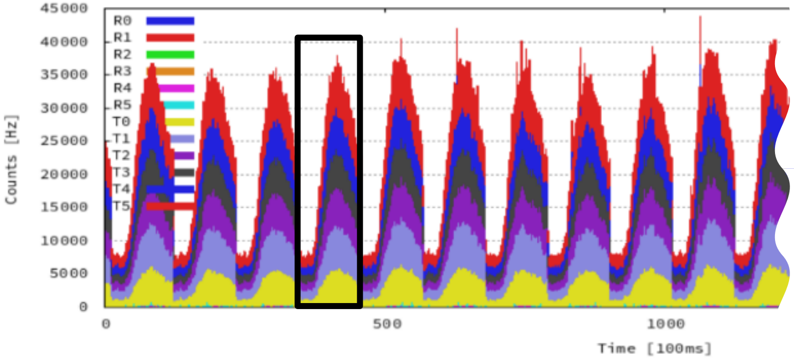
Improvements – Report from User

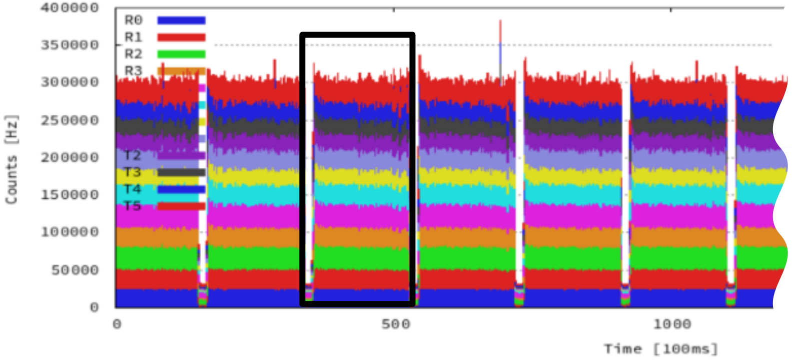
- HADES experiment reported
  - → Immediately **40% more statistics** due to “DC” beam (geometric factor)
  - → At least **factor 2 more statistics** due to absence of cycle-to-cycle fluctuations

Particle Number in SIS18



Data rate HADES detector





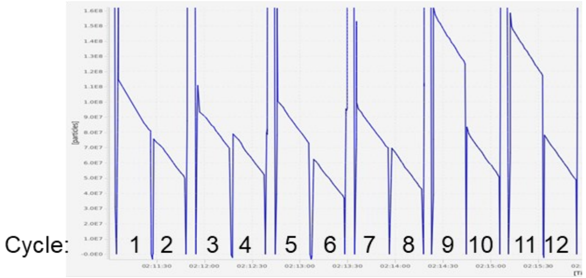
Plots: M. Traxler / HADES

Improvements – How does it help?

- Initial situation
  - Particle number from injector fluctuates
  - Maximum intensity limited by detectors / dose delivery
  - Safety factors reduce average rate
- **Macro-spill feedback**
  - → Delivers a stable "DC" beam
  - → Statistics outcome is maximized
- Machine protection (at high intensities)
  - Ring must be fully emptied
  - → Use dynamic extraction time or combination with quad-driven / fast extraction

    For fixed extraction time (accounting for peak intensity): gain in statistics "only" by geometric factor

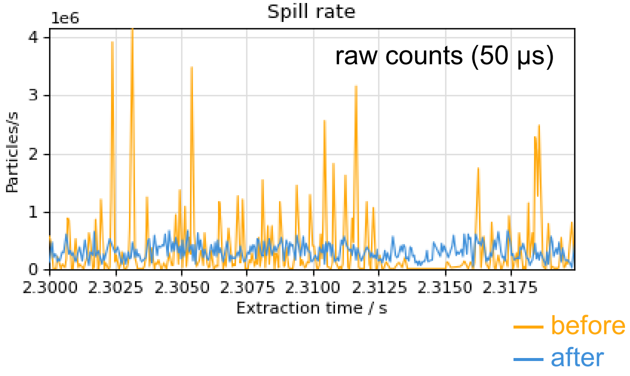
Particle Number in SIS18



$$\text{SPILL RATE} = \frac{\text{PARTICLE NUMBER}}{\text{EXTRACTION TIME}}$$

Improvements – How does it help?

- Initial situation
  - Intensity spikes lead to pile-up; gaps lead to idle times
  - Beam usage is inefficient
  - Precise dose delivery is difficult



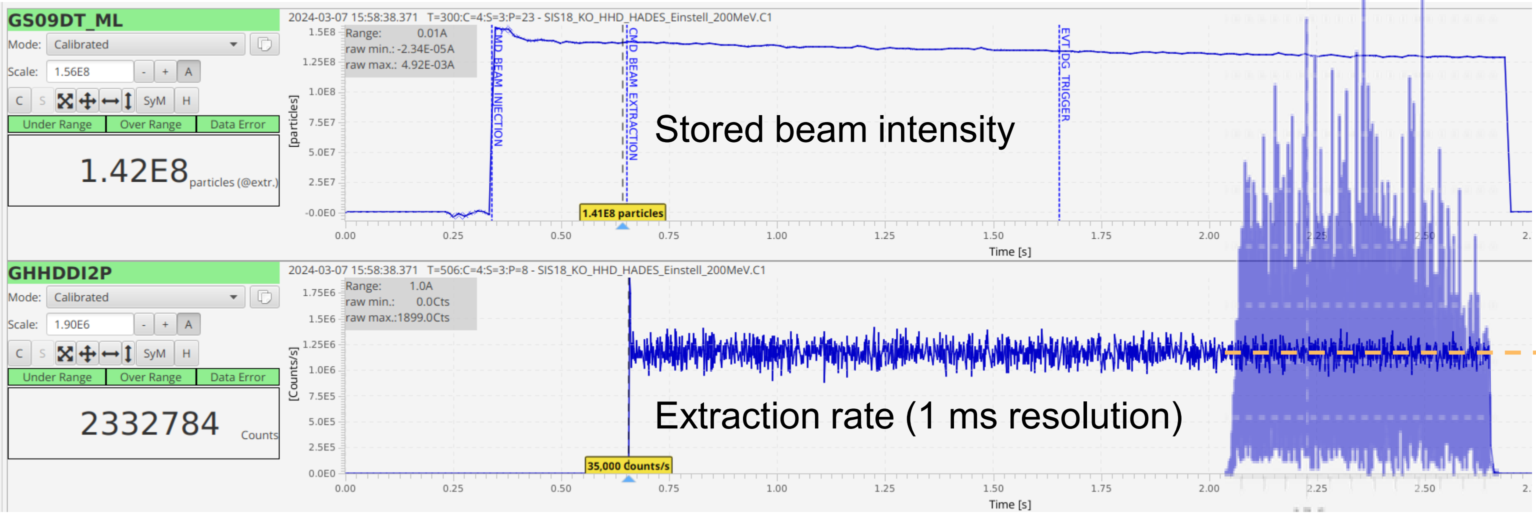
- **Micro-spill optimization**
  - → Delivers a spill with less spikes (better spill quality)
  - → Gain in statistics & predictable irradiation

- Trade-off (at high energies)
  - Improvement at cost of higher excitation power or lower efficiency
  - → Poisson-limited spill quality possible for low energy, low intensity beams

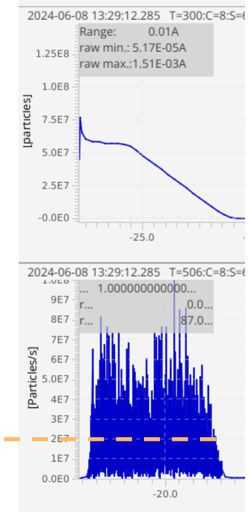
    For high energy, high intensity beams: gain in spill quality will be less (but still significant)

Improvements – Towards Poisson Limited Spills

- Experiment at SIS18 with $^{197}Au^{65+}$ at 200 MeV/u
  - 400 W amplifier extracts 1.6% of particles
  - Excitation signal: 3 sines with optimized frequencies



Regular spill to compare:



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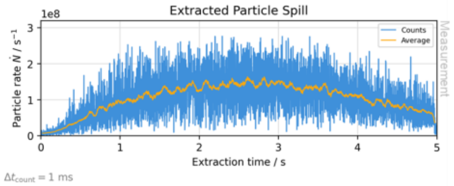
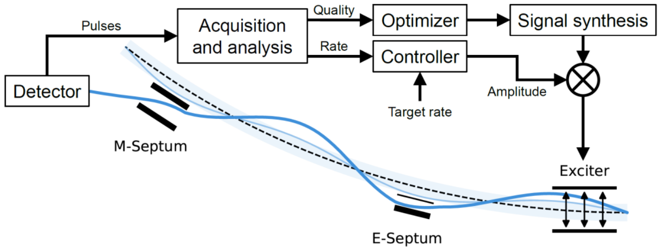
Summary

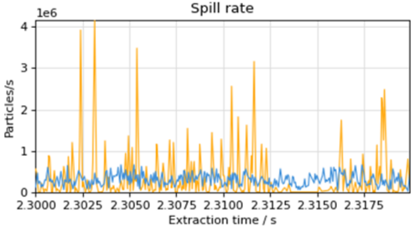
- Challenge of slow extraction
  - Steady particle flux
  - RF-KO excitation offers to improve the beam quality

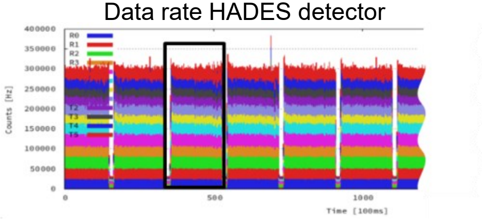


- Spill Optimization System
  - Feedback controller for macro-spill shape
  - Signal optimization for micro-spill quality
  - Implemented with Software-Defined Radio



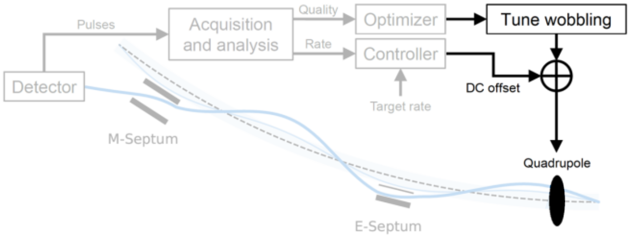
- Improvements
  - Gain in statistics
  - Precise dose delivery
  - Efficient beam usage

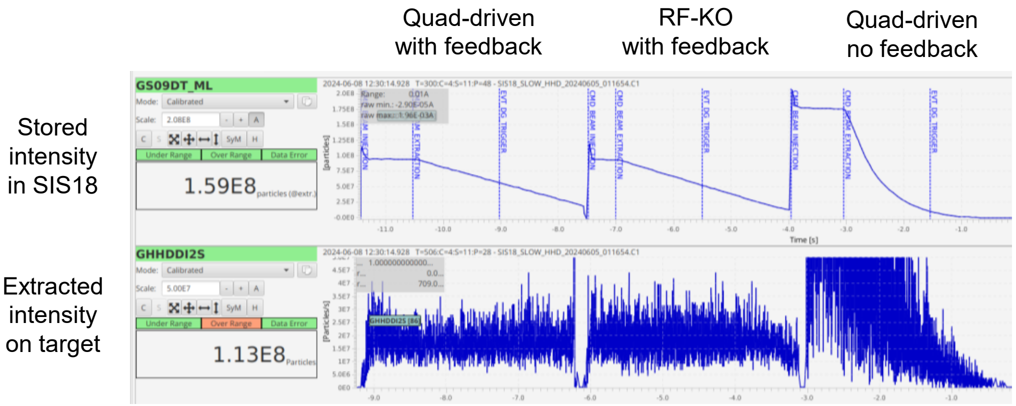




Outlook

- To maximize benefits while ensuring machine safety
  - → Use dynamic extraction time
  - → Combine with quad-driven or fast extraction
- Feedback for quad-driven slow extraction
  - System adopted and tune wobbling integrated
  - Proof of principle successful
- Integration into operating
  - Project plan written





Thanks to all supporting this work!

COSY Team; GSI Accelerator Physics, Accelerator Operations, Beam Instrumentation, Experiment Electronic, Ring RF, SIS 18/100; HADES Collaboration; Bastian Bloessl, Cristopher Cortés, Eike Feldmeier, Giuliano Franchetti, Ralf Gebel, René Geißler

Thank you!

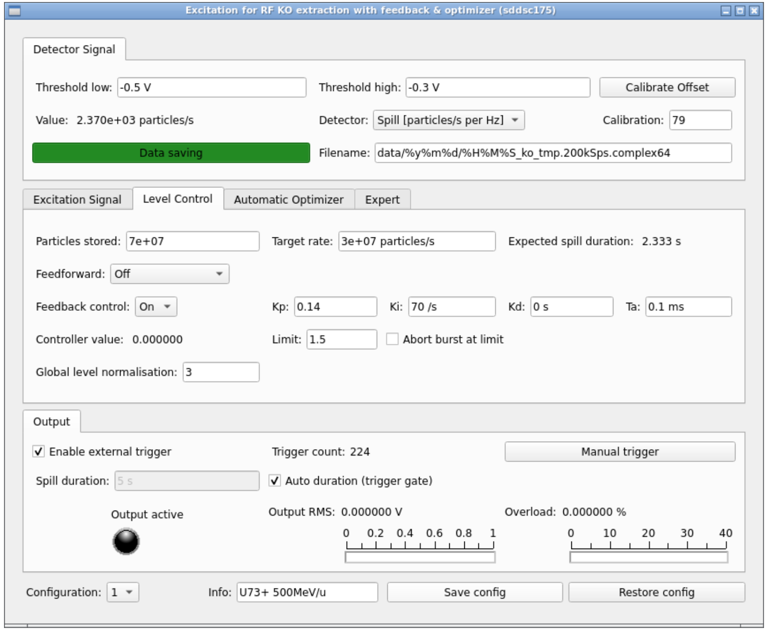
Backup Slides

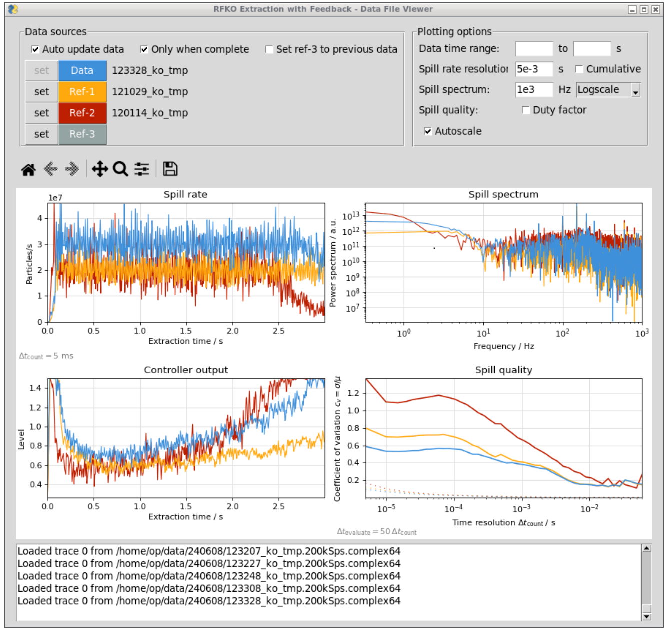
Project Plan: Spill Optimization System (SOS)

- Key milestones
  - Multiplexed operation (with multiple SDRs)
  - Dynamic intensity control (includes spill pause and abort)
  - Control system integration with FESA & LSA
  - Detector integration (Lassie) and failure checks
  - Commissioning with beam
  - Operator trainings & manuals

Spill Optimization System

- Documentation at git.gsi.de/p.niedermayer/exciter/-/wikis
- System available for operational use





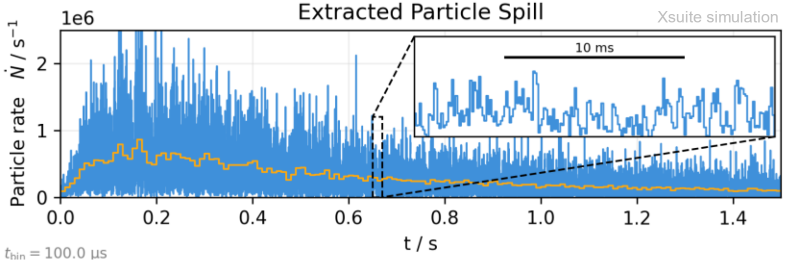
Spill Quality

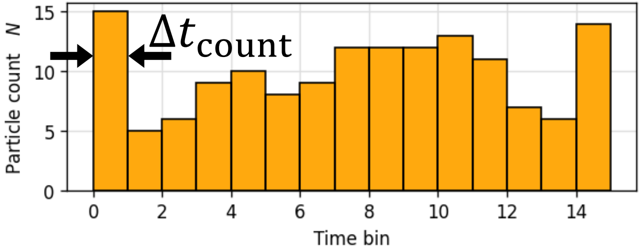
- Spill fluctuations
  - Define time bins Δt_{count} to count particles
  - Number of particles N per bin
  - Coefficient of variation

$$c_v = \frac{\sigma_N}{\mu_N} = \frac{\sqrt{\operatorname{Var} N}}{\langle N \rangle} \rightarrow \frac{1}{\sqrt{N}}$$

  - Spill duty factor

$$F = \frac{\langle N \rangle^2}{\langle N^2 \rangle} = \frac{\mu_N^2}{\mu_N^2 + \sigma_N^2} = \frac{1}{1 + c_v^2} \rightarrow \frac{\langle N \rangle}{\langle N \rangle + 1}$$

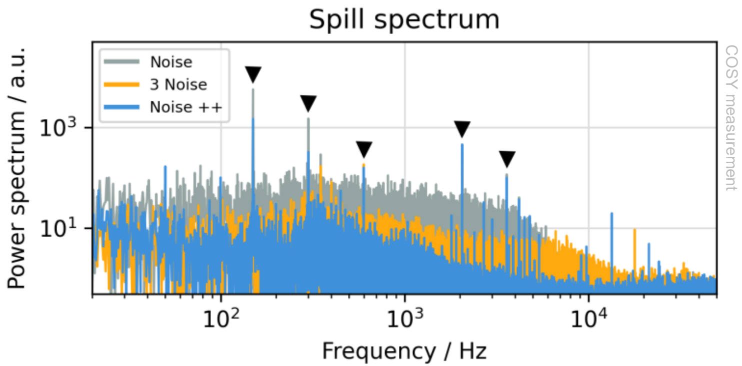


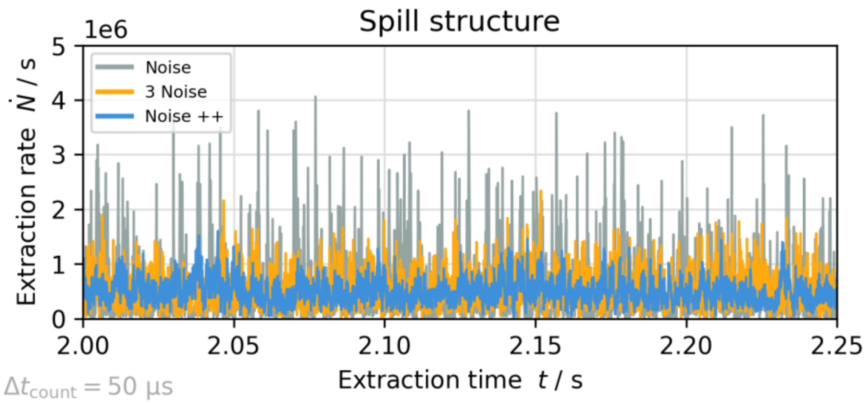


Poisson statistics: $\sigma_N = \sqrt{\langle N \rangle}$

Noise ++ excitation method

- Noise ++
  - Broadband noise signal
    - → Incoherent excitation & random walk
    - → Efficient power transfer to beam
    - → No artificial ripples induced
  - Mono-frequent sinusoidal
    - → Strong coherent excitation
    - → Fast separatrix crossing
    - → Reduce ripples & noise floor





Experiment: Comparison

- Excitation signals
  - Components distributed across sidebands
    → Mitigates beating
  - Parameters optimized at $\Delta t_{\mathrm{count}} = 500\ \mu s$
    → Comparing best cases each