Spill Optimization System (SOS)

Philipp Niedermayer, Operator School, 31 Oct 2025

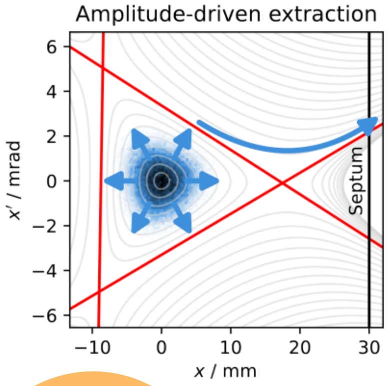
Image: SIS 18 Exciter
P. Niedermayer, GSI, 2024

Contents

- Overview and motivation
- Changes to hardware and software
- New dedicated GUI
- Operating practices
- Documentation

Slow Extraction from SIS18

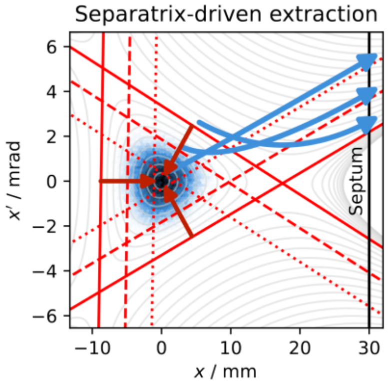
RF Knock Out (**KO**)



- Driven by RF excitation with stripline kicker
- Static optics, beam-on-target fixed
- Small chromaticity required & momentum distribution preserved

From 2026 on SOS

Quadrupole-driven (**SLOW**)



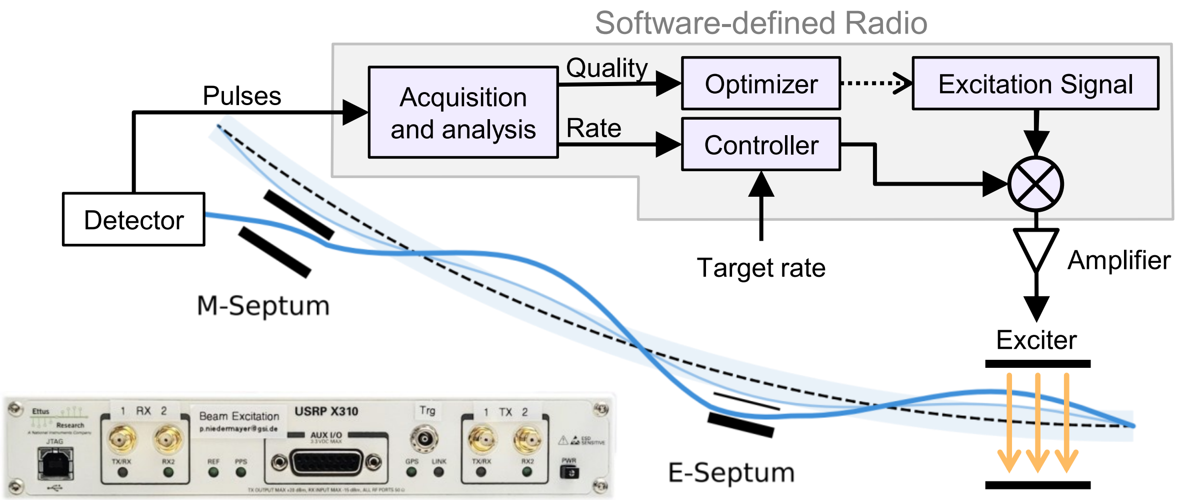
- Driven by tune ramp with fast quadrupole
- Dynamic optics, beam-on-target drifts
- Works also with large chromaticity, but then momentum drifts

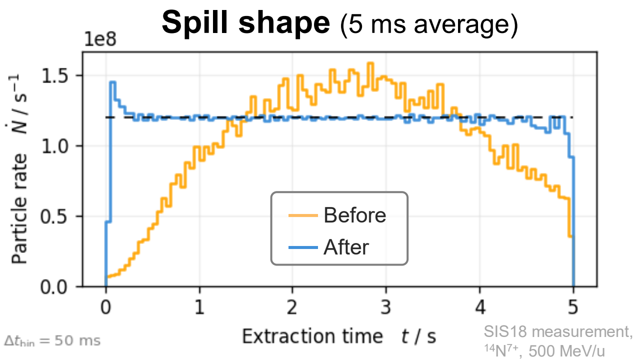
Reference-momentum-driven (**COSE**)

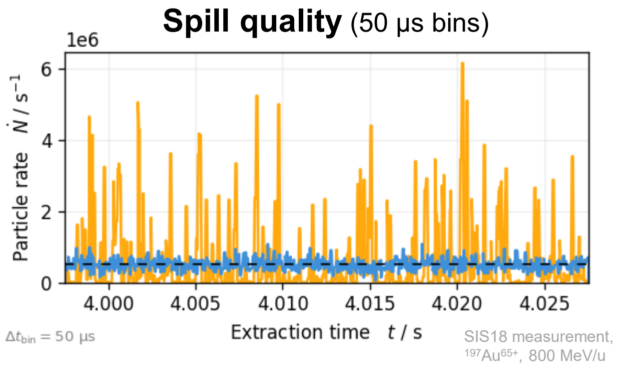
Not applicable to SOS

Spill Optimization System (SOS)

- Improved beam quality for slow extraction
  - Feedback controller for spill shape
  - Signal optimization for spill quality



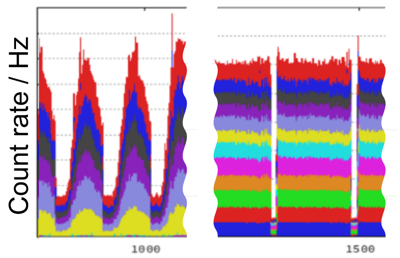




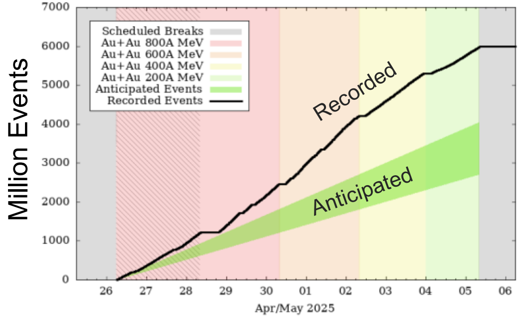
Improved beam quality for slow extraction

- Particle-Physics experiments
  - Increase duty cycle
  - Avoid intensity fluctuations and spikes
  - Experiments record more events
- Bio-Physics experiments
  - Dynamically controlled intensity
- Operational aspects
  - More stable spill shape control
  - Less interference in multiplexed operation

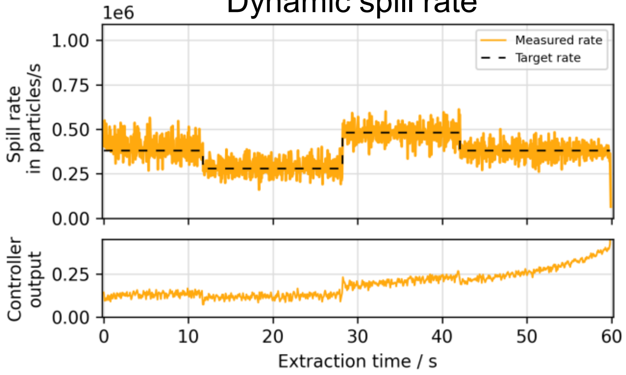
HADES event rate



HADES run statistics

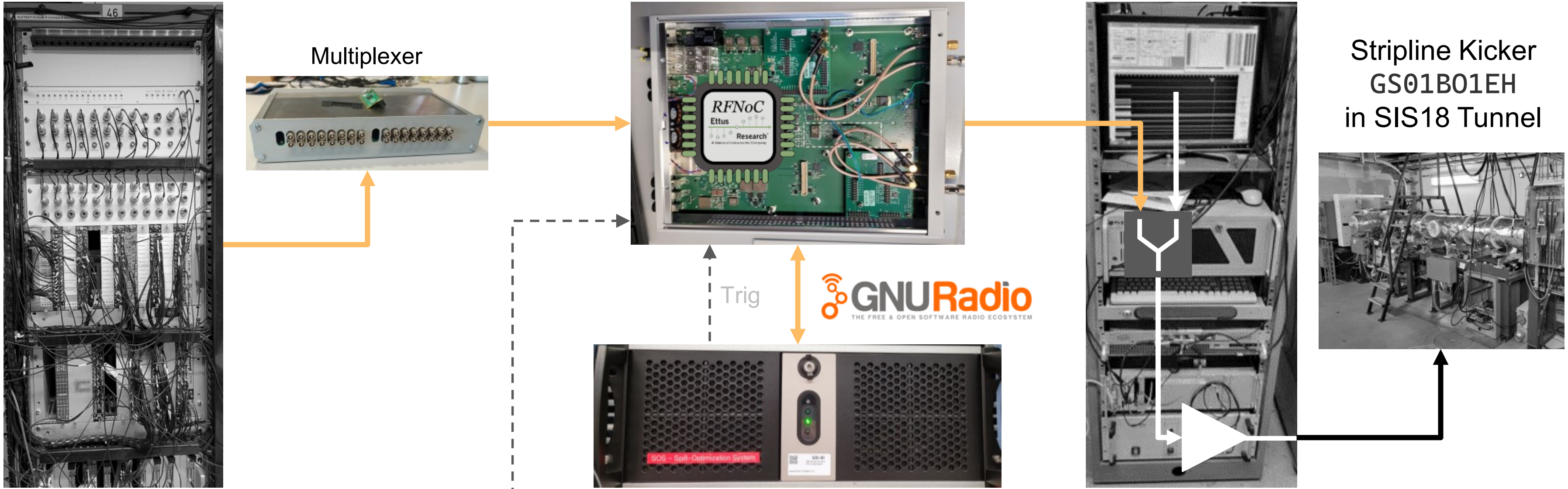


Dynamic spill rate



SOS: New Hardware

Detectors & Multiplexer	Software Radio	KO Exciter



BEA Electronics
in BG.2.009b

Spill abort
in BG.2.009

FEC: GNU Radio & FESA
in BG.2.009b

KO Amplifier
in BG.1.016

SOS: Selected Detectors

- Subset of *highly available* spill detectors for feedback
  - Beamline detectors for setup: TE1, TH1, HHD
  - Non-destructive detectors: DCCT, BLM
  - Experiment detectors: FRS, HHT, HFS, HAD, HTA, HTC, HTM, HTP
- Rate control signals
  - For dynamic intensity control, spill pause, etc. (Bio-Physics)
  - Experiment lines from caves

Port	Label	
1	Ring DCCT	GS09DT_ML
2	Septum BLM	GS04DL2I
3	Septum BLM	GS04DL3I
4	TE1 scintillator	GTE1DI1P
5	TE1 ion chamber	GTE1DI1I
6	TE1 SEM	GTE1DI1S
7	TH1 scintillator	GTH1DI4P
8	TH1 ion chamber	GTH1DI4I
9	TH1 SEM	GTH1DI4S
10	HHD scintillator	GHHDDI2P
11	HHD ion chamber	GHHDDI2I
12	HHD SEM	GHHDDI2S
13	HHD rad. hard	
14	FRS SEM	GTS1DI4S
15	HHT exp. detector	GHHTDIAE
16	HFS exp. detector	GTS4DIAE
17	HAD exp. detector	GHADDIAE
18	HTA exp. detector	GHTADIAE
19	HTC exp. detector	GHTCDIAE
20	HTM exp. detector	GHTMDIAE
21	HTP exp. detector	
22	Auxiliary 1	
23	Auxiliary 2	
24	Auxiliary 3	

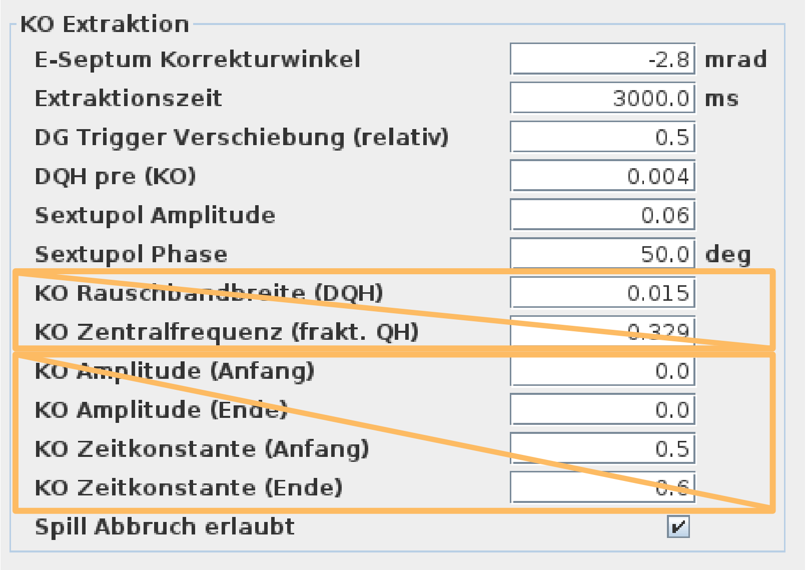
SOS: Changes to parameters

- KO excitation signal
  - Old: RBPSK frequency and width
  - → New noise and sine signals

- KO amplitude curve
  - Old: 4 parameters (amplitude, time constant)
  - → Online feedback
  - → Playback of recorded feedback
  - → 6 parameter curve (fit to feedback)

- More options
  - → enables spill tailored to experiment needs

ParamModi KO excitation signal



KO Extraktion

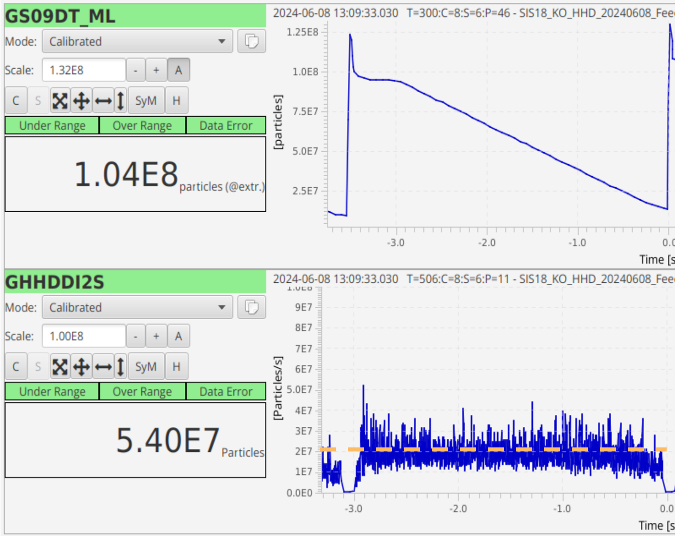
E-Septum Korrekturwinkel	-2.8	mrad
Extraktionszeit	3000.0	ms
DG Trigger Verschiebung (relativ)	0.5	
DQH pre (KO)	0.004	
Sextupol Amplitude	0.06	
Sextupol Phase	50.0	deg
KO Rauschbandbreite (DQH)	0.015	
KO Zentralfrequenz (frakt. QH)	0.329	
KO Amplitude (Anfang)	0.0	
KO Amplitude (Ende)	0.0	
KO Zeitkonstante (Anfang)	0.5	
KO Zeitkonstante (Ende)	0.6	
Spill Abbruch erlaubt	☑	

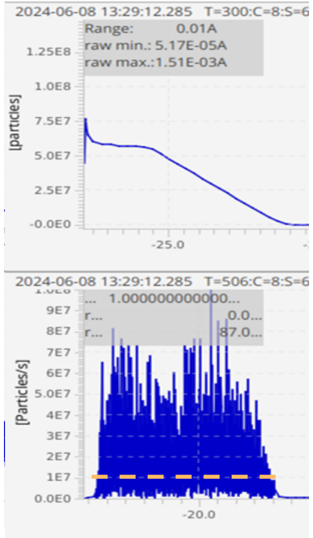
SOS as a "Toolbox"

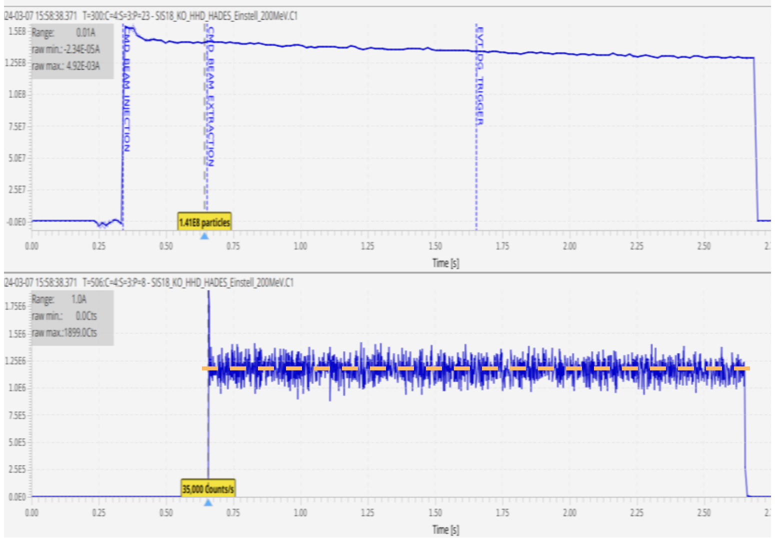
- Different operation modes (depending on user needs & beam energy/intensity)
  - E.g. "Full extraction and improved quality" at high energy/intensity
  - E.g. "Partial extraction and ultimate quality" at low energy and low intensity

DCCT

SEM

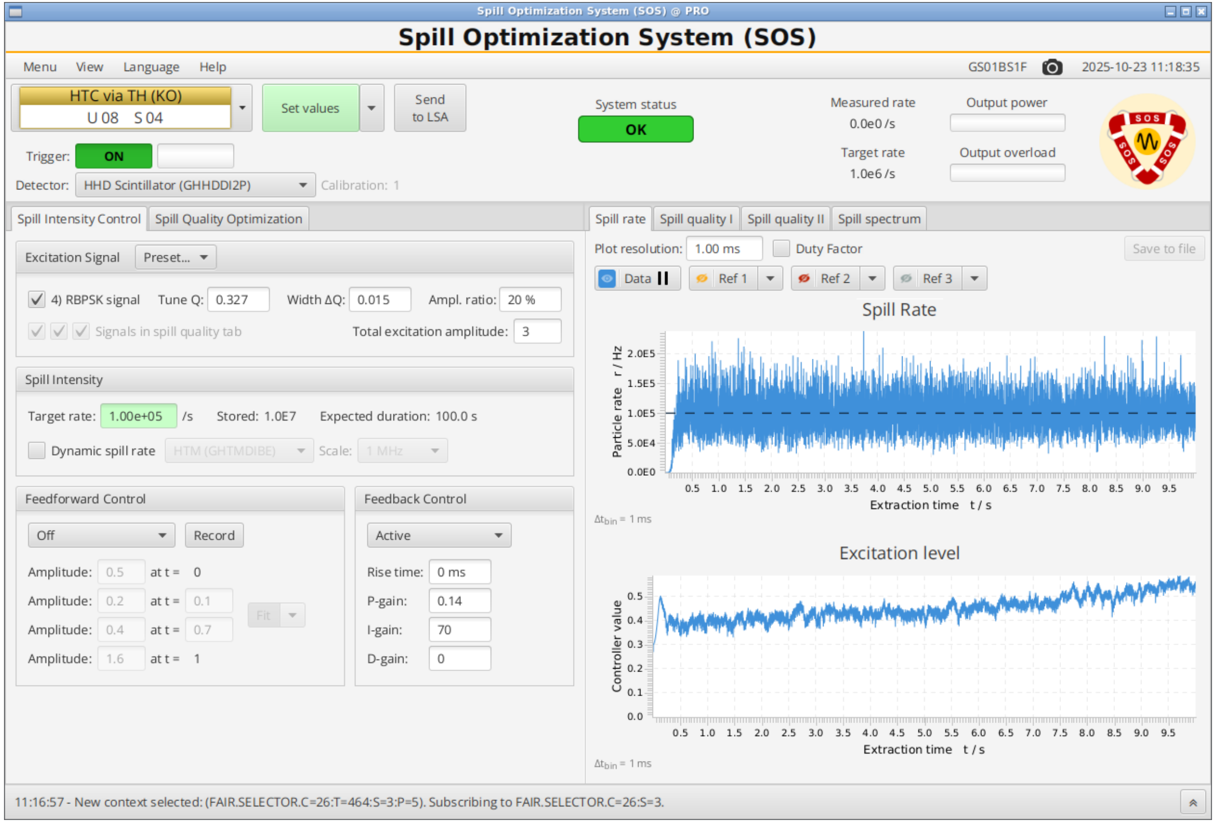






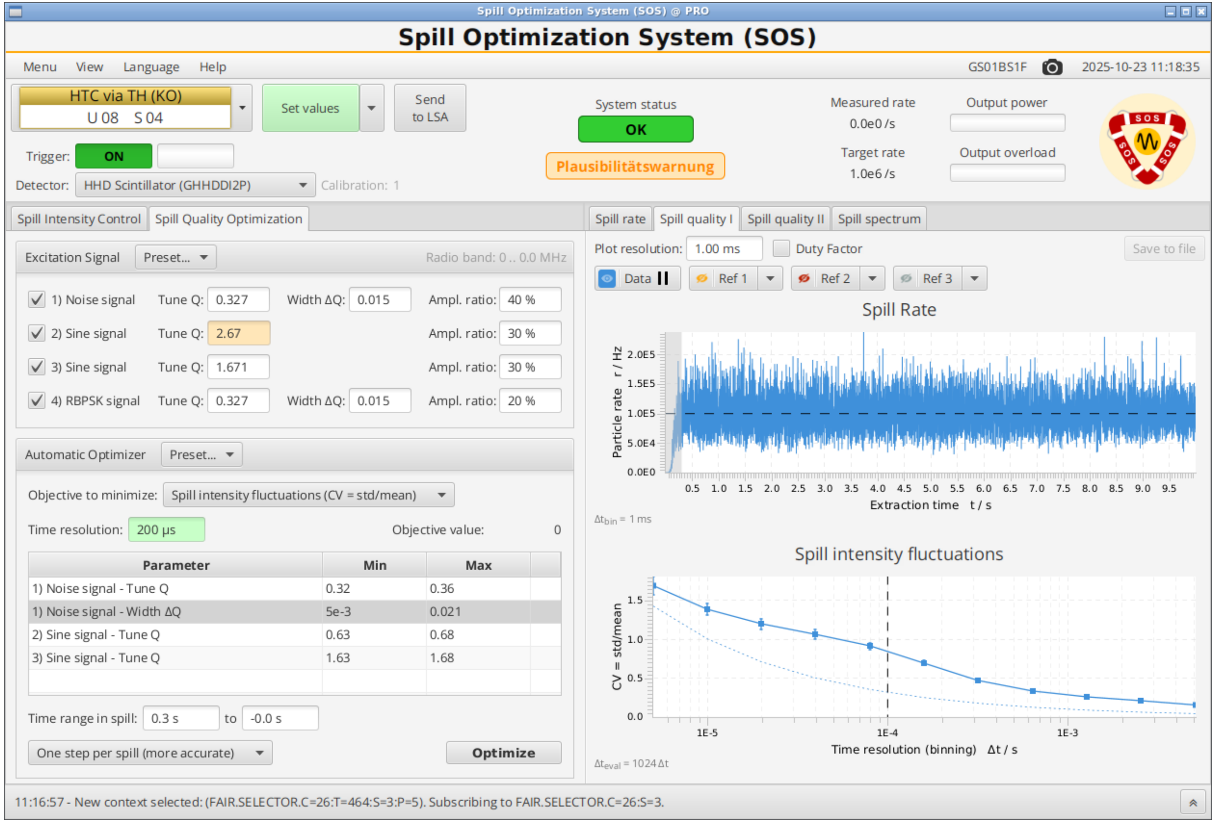
New dedicated SOS GUI

- Control & DAQ
  - → See what you optimize
- Presets for common scenarios
  - → To reduce complexity



New dedicated SOS GUI

- Control & DAQ
  → See what you optimize
- Presets for common scenarios
  → To reduce complexity
- Optimization algorithm
  → To improve spill quality
- Plausibility checks
  → Expert knowledge transfer



KO Setup with SOS

- Usual procedure, see Wiki and Talk by Jens
  - Set tune, correct orbit, correct hor. chromaticity (“-1”)
  - Set bucketfill, sextupole amplitude, **particle number**
  - Find resonance

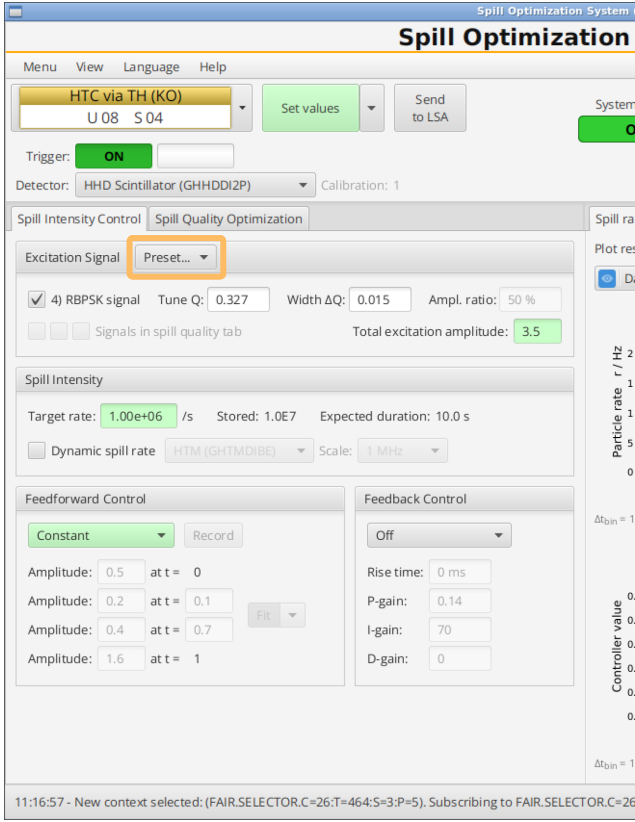
    Stored: 1.0E7 Expected duration: 10.0 s

    - Switch SOS OFF or set KO excitation amplitude to 0
    - Move tune as close to resonance as possible w/o extraction
  - SOS Spill Intensity: Preset “Initial Setup”
    - Set **target spill rate**
    - Adjust KO excitation amplitude, signal tune & bandwidth

KO Amplitude (Anfang)
KO Amplitude (Ende)
KO Rauschbreite (DQH)
KO Zentralfrequenz (frakt. QH)

Total excitation amplitude: 3.5

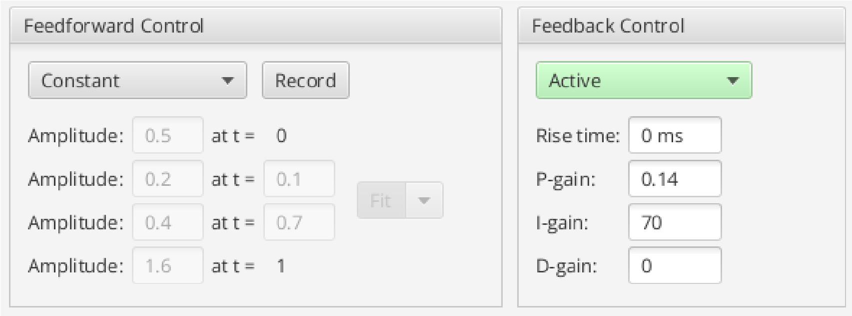
Tune Q: 0.327 Width ΔQ: 0.015

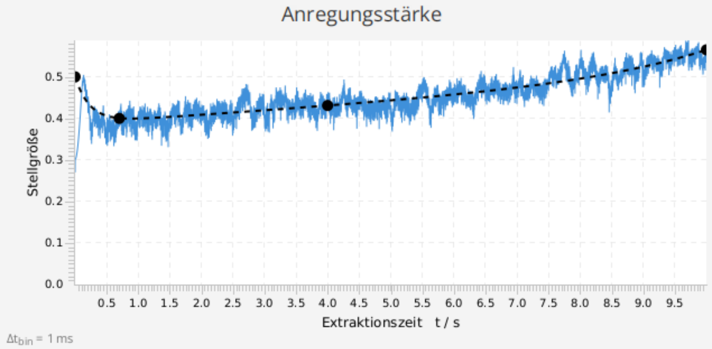


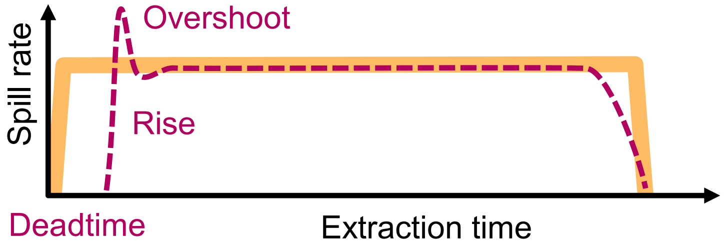
- Continue with **Feedback** and **Optimization**

Feedback Setup with SOS

- Wanted: **no deadtime**, steep rise & no overshoot
  - Optimal SIS KO optics setup very important
    → Correct chromaticity, smallest separatrix, etc.
  - Combination with feedforward
    → Provides a “head start”
  - Fine-tuning of feedback parameters
    → Rise-time and PID controller gains

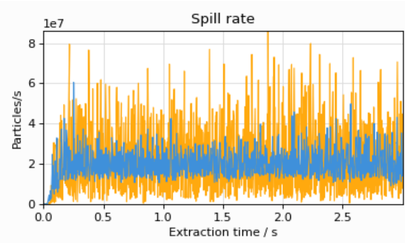


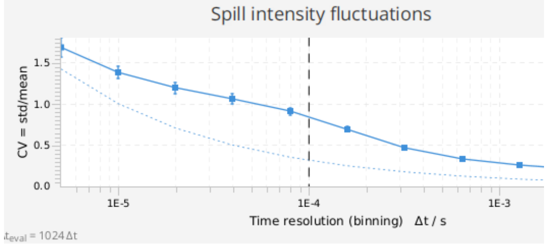


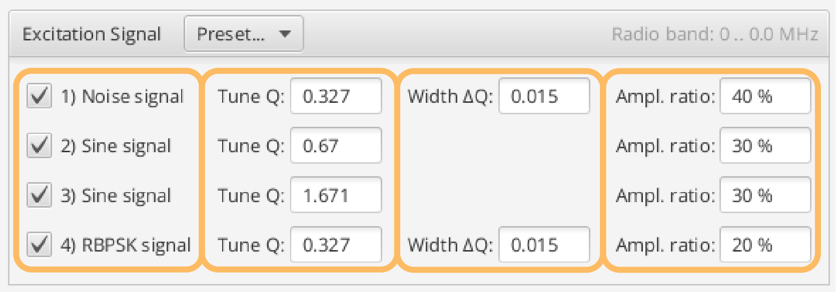


Spill Optimization with SOS

- Goal: reduce spill fluctuations
  - Minimize $c_v = \mathrm{std}/\mathrm{mean}$
- Tailored excitation signals
  - Noise for better efficiency
  - Sines for better quality
  - Noise++ or Multi-Sine
- Excitation frequencies: h ± 0.327
  - h → higher usually better (until saturation)
  - ± → select best upper/lower sideband
  - 0.327 → optimize fractional part with optimizer
- Excitation bandwidth → Optimizer







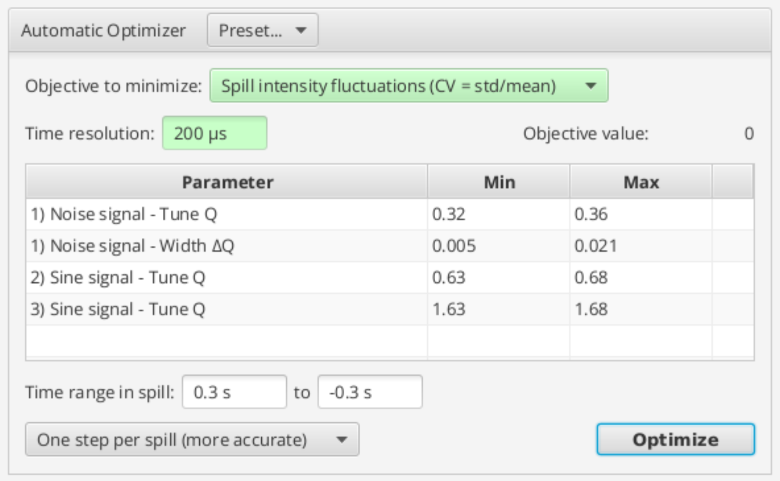
Noise++ = Noise + Sine + Sine
Multi-Sine = Sine + Sine + Zero-width RBPSK

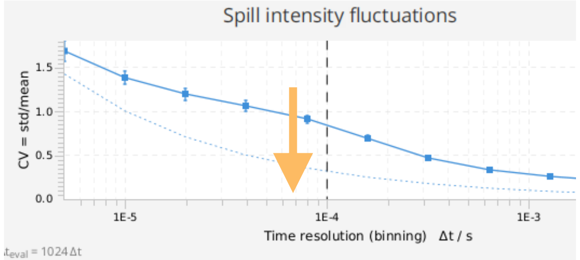
Spill Optimization with SOS

- Optimizer tool
  - Measure spill quality
  - Adjusts frequencies & bandwidths
  - Will affect spill shape → **use Feedback!**
- BOBYQA Optimization Algorithm
  - Intra-spill → find good settings quick
  - Spill-by-spill → find optimal settings

  → Builds a model and converges

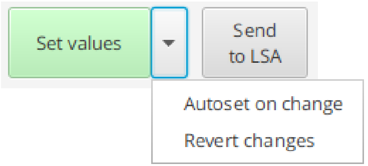
  → Generic tool: can also optimize
  – Feedback parameters,
  – Amplitude for macro-spill shape,
  – …

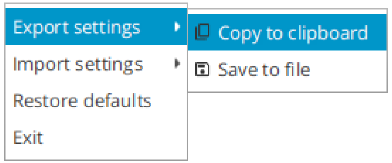


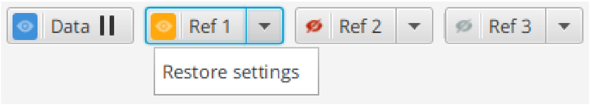


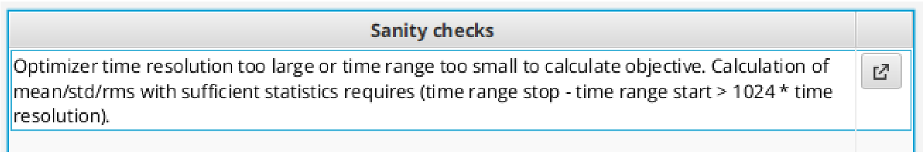
SOS GUI

- Utilities
  - Set values per button/hotkey or automatically on change
  - In-/decrement with arrow up/down and page up/down keys
  - Import & export settings from/to clipboard or file
  - References (incl. settings)
  - Dark mode
  - Screenshots
  - Plausibility checks



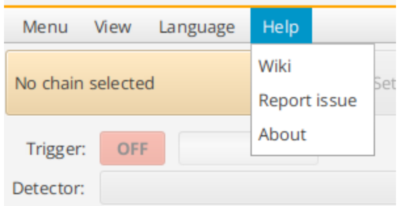






SOS Documentation

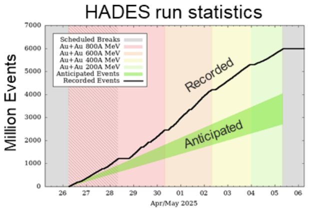
- Help-Menu in GUI
  - It actually works ;)
  - Form to report bugs and request features

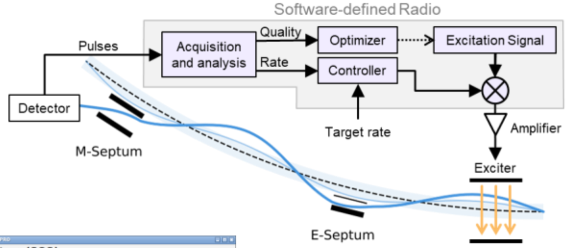


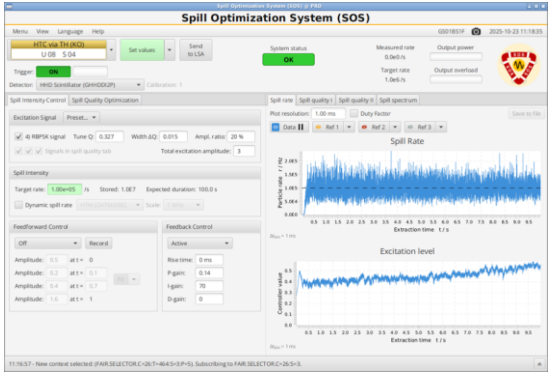
- SOS Wiki homepage
  - Information for experimentalists (e.g. feedback signal requirements)
  - Technical information (e.g. for call-in duty)
  - Link to OPE Wiki
- OPE Wiki
  - SIS18 Extraktion – revised
  - Einstellung SIS18 Extraktion KO – Basics as of 2021 still valid (screenshots outdated)
  - **Spill Optimization System – NEW: Setup-guides with background info and links**

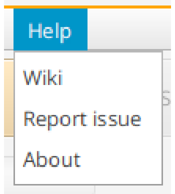
Summary

- Motivation: Improve beam quality
- New SDR-based System
- New dedicated GUI
- Operating practices
- Documentation









Next:

- Dry test & debugging in Jan/Feb run
- Hands-on training with beam
  in Sept 2026 before beamtime

Questions & Discussion

Fragen & Diskussion

Detectors

- Detektorliste okay ?

Port	Rate control signal
25	HHT (GHHTDIBE)
26	HFS (GTS4DIBE)
27	HAD (GHADDIBE)
28	HTA (GHTADIBE)
29	HTC (GHTCDIBE)
30	HTM (GHTMDIBE)
31	HTP (GHTPDIBE)
32	Auxiliary 1

Port	Detector		Port	Detector
1	Ring DCCT (GS09DT_ML)		13	HHD rad. hard
2	Septum BLM (GS04DL2I)		14	FRS SEM (GTS1DI4S)
3	Septum BLM (GS04DL3I)		15	HHT exp. detector (GHHTDIAE)
4	TE1 scintillator (GTE1DI1P)		16	HFS exp. detector (GTS4DIAE)
5	TE1 ion chamber (GTE1DI1I)		17	HAD exp. detector (GHADDIAE)
6	TE1 SEM (GTE1DI1S)		18	HTA exp. detector (GHTADIAE)
7	TH1 scintillator (GTH1DI4P)		19	HTC exp. detector (GHTCDIAE)
8	TH1 ion chamber (GTH1DI4I)		20	HTM exp. detector (GHTMDIAE)
9	TH1 SEM (GTH1DI4S)		21	HTP exp. detector (GHTPDIAE)
10	HHD scintillator (GHHDDI2P)		22	Auxiliary 1
11	HHD ion chamber (GHHDDI2I)		23	Auxiliary 2
12	HHD SEM (GHHDDI2S)		24	Auxiliary 3

ParamModi

- Teilchenzahl – bisher ungenutzt ? SIS18BEAM/NPARTICLES_S
  → Nutzung für PID-Normierung **NEU**

Strahlparameter

Ladung	7
Particle Symbol	14N
Teilchenzahl	5.0E10

- Chromatizität hinzufügen ?
  - Hor. Chromatizität (Flattop)
  - Hor. Chromatizität (Extr.)

- Neue SOS Parameter ?
  - SOS An/Aus (KO)
  - SOS Zielrate (KO)
  - *Alles andere in der SOS GUI*

Extraktion

Targetenergie	300.0	MeV/u
Extraktionssteifigkeit	[5.37251757, 5.	Tm
Extraktionsfrequenz	904.851	kHz
Hor. Arbeitspunkt QH (Flattop)	4.29	
Hor. Arbeitspunkt QH (Extr.)	4.3085	
Vert. Arbeitspunkt QV (Flattop)	3.295	
Vert. Arbeitspunkt QV (Extr.)	3.295	
Radiallage (Extraktion)	0.0	mm

Rampe und HF-Amplitude

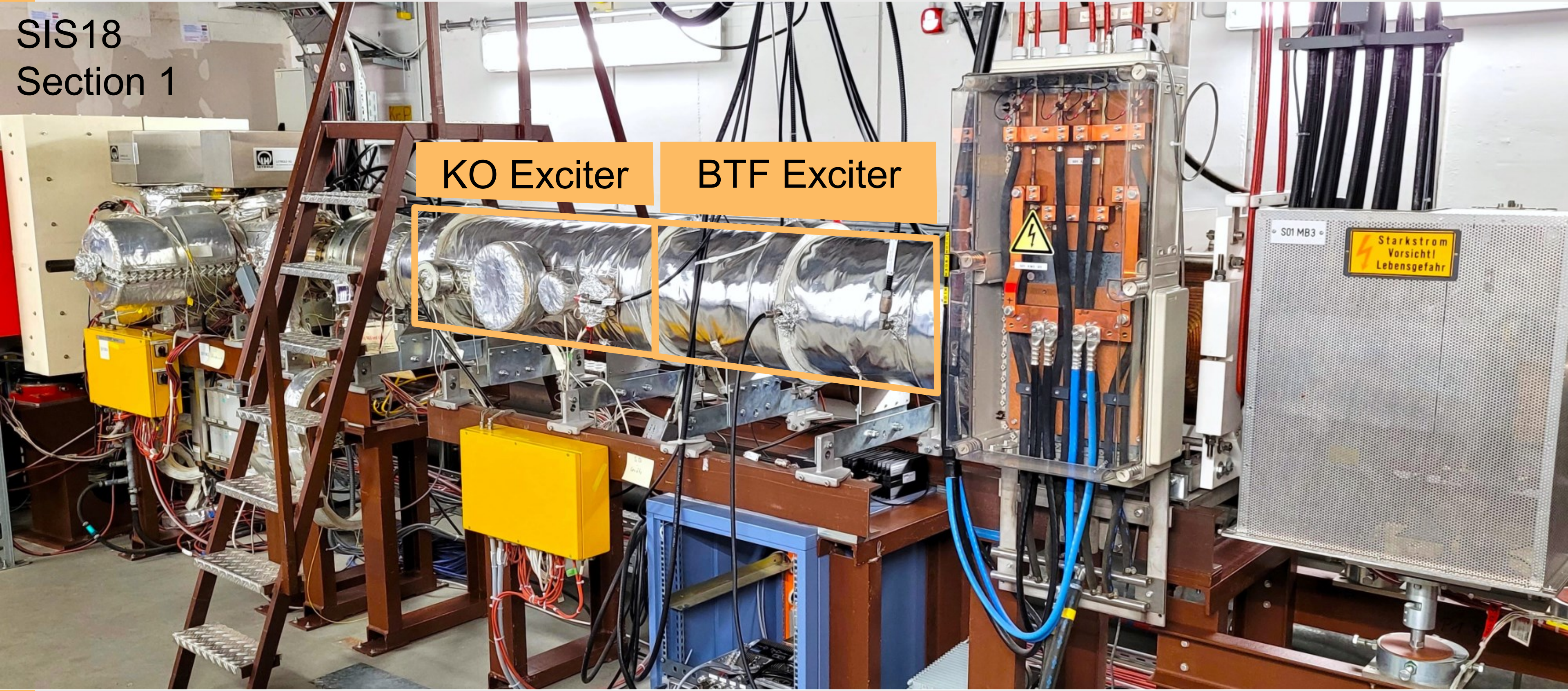
Verrundungszeit	[32.0, 32.0]	ms
Rampensteilheit	[3.0, 3.0]	T/s
Einfangzeit	16.0	ms
Impulsbreite (DC)	0.1	%
Bucketfill (Bunching)	[[0.0, 1.43]]	
Bucketfill (Ramp)	[[1.43, 1.43]]	
Bucketfill (Pre-Extraction)	[[1.43, 0.0]]	

KO Extraktion

E-Septum Korrekturwinkel	-2.9	mrad
Extraktionszeit	580.0	ms
DG Trigger Verschiebung (relativ)	0.2	
DQH pre (KO)	0.003	
Sextupol Amplitude	0.09	
Sextupol Phase	60.0	deg
Sextupol Offset	0.0	
~~KO Rauschbandbreite (DQH)~~	~~0.022~~	
~~KO Zentralfrequenz (frakt. QH)~~	~~0.329~~	
~~KO Amplitude (Anfang)~~	~~1.0~~	
~~KO Amplitude (Ende)~~	~~25.0~~	
~~KO Zeitkonstante (Anfang)~~	~~0.1~~	
~~KO Zeitkonstante (Ende)~~	~~1.2~~	
Spill Abbruch erlaubt	☐	

Backup

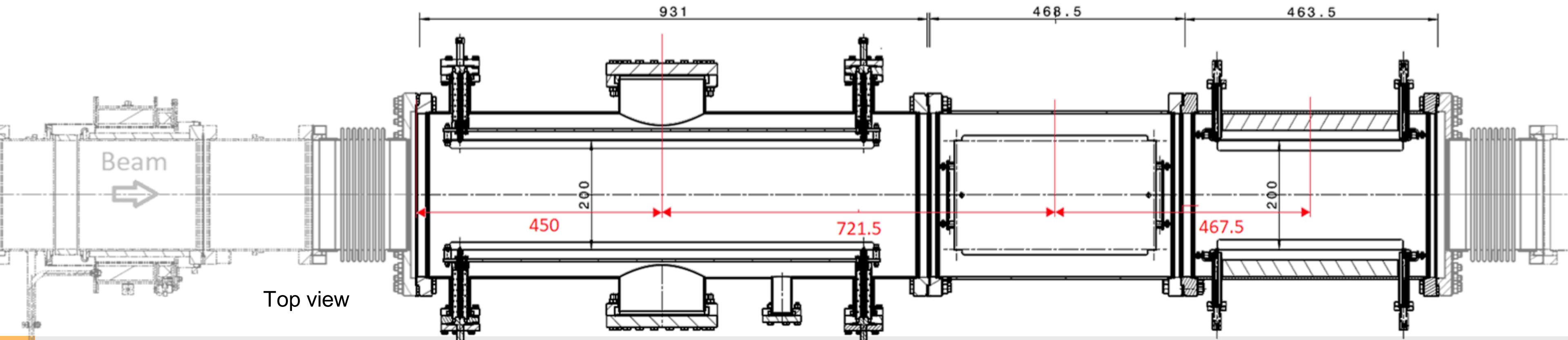
Exciters at GSI SIS18



Exciters at GSI SIS18

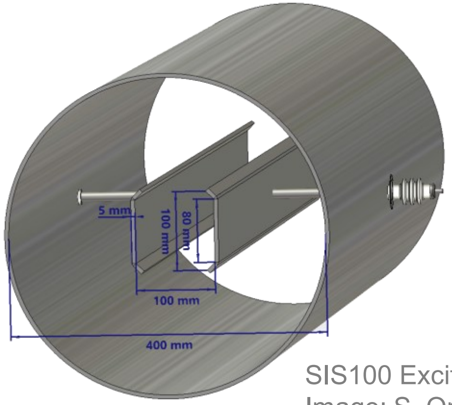
$^{12}C^{6+}$ at 6.3 T m

- KO Exciter for extraction
  - Horizontal `GS01BO1` l = 80 cm P_{max} = 400 W k_0l_{max} = 2.15 µrad
- BTF Exciter for diagnostics
  - Vertical `GS01DH1V` l = 37 cm P_{max} = 2×50 W k_0l_{max} = 0.66 µrad
  - Horizontal `GS01DH1H` l = 37 cm P_{max} = 2×50 W k_0l_{max} = 0.35 µrad

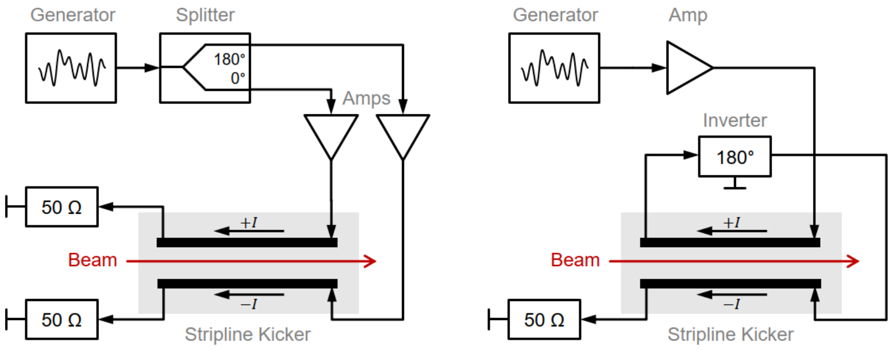


Exciters at GSI

- SIS18: Stripline Exciter
  - Parallel connection scheme (BTF exciter): better frequency response for $f \gg \mathrm{MHz}$
  - Series connection scheme (KO exciter): better wall plug efficiency
- SIS100: Capacitive Exciter
  - Design ongoing (Sebastian Orth, RRF)



SIS100 Exciter
Image: S. Orth

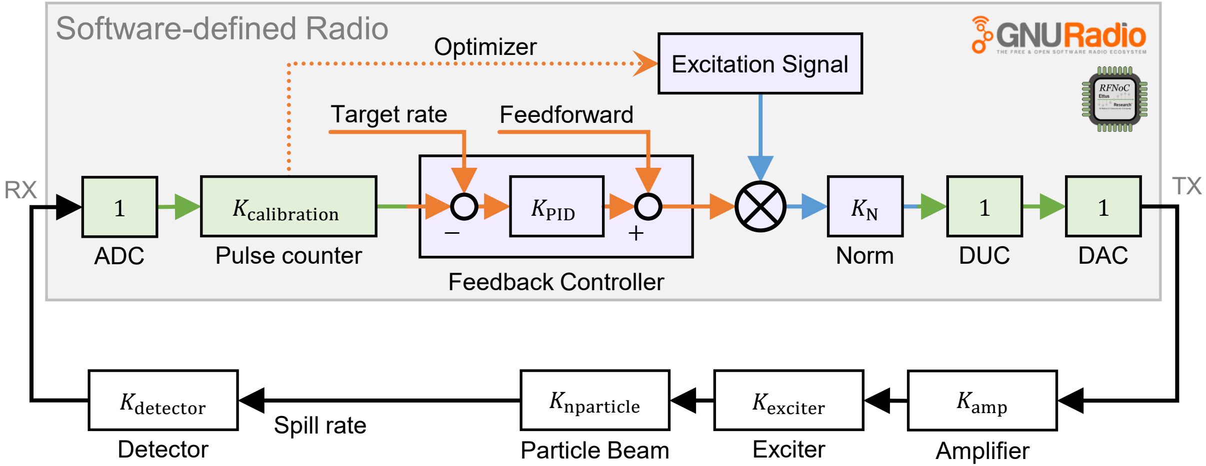


(a) Parallel connection scheme (b) Series connection scheme

Spill Optimization System (SOS)

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

- Implemented with Software-Defined Radio
  - Flexible digital signal processing on CPU & FPGA
  - Maintainable open source software and commercial hardware (USRP X310)
  - Standalone all-in-one system



System parameters

- Latency: 1.5 ± 0.1 ms
- Bandwidth: 5 MHz
- Frequency: 0 .. 30 MHz

Process

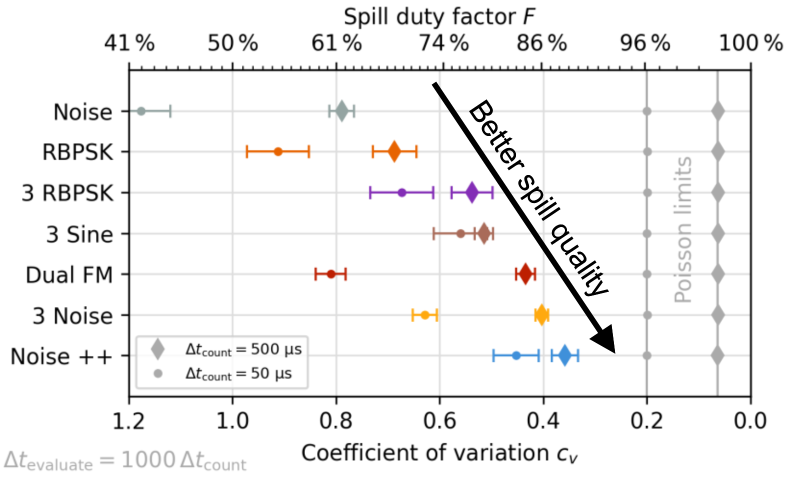
- Latency: ~ 3 ms

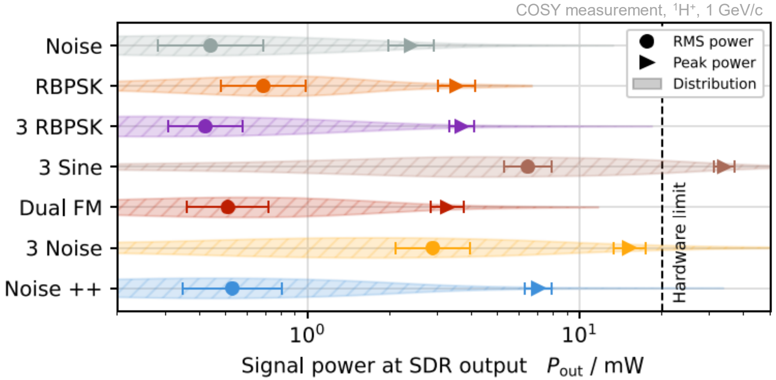
Comparison to other methods

- Compared various excitation signals
  - Dedicated experiment at COSY Jülich
  - Identical beam conditions & optimized parameters

$$c_v = \frac{\sqrt{\mathrm{Var}\,N}}{\langle N \rangle}$$

$$F = \frac{1}{1+c_v^2}$$



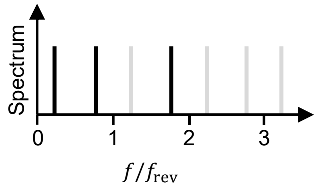


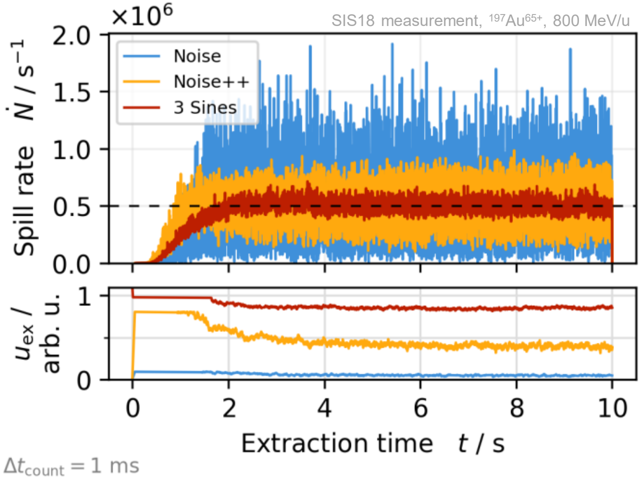
doi.org/10.1038/s41598-024-60966-y

Improved Excitation Signals

- 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

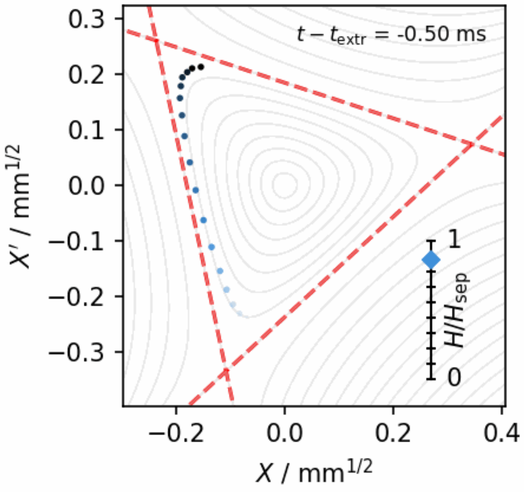


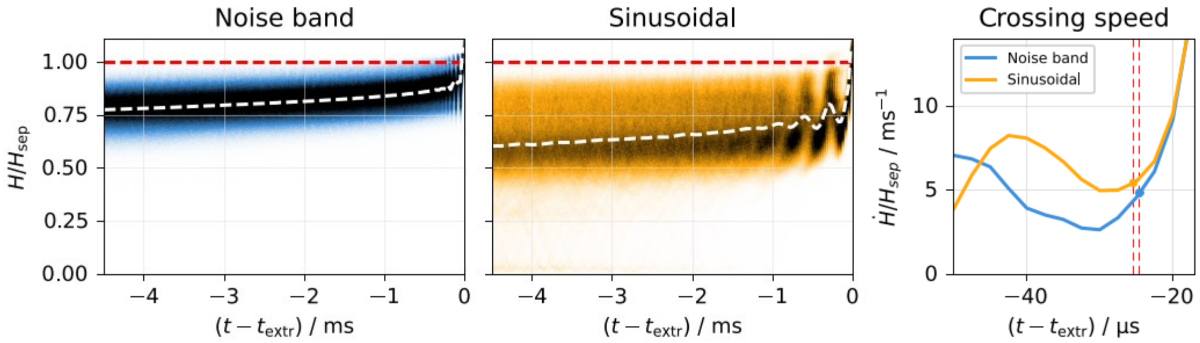


Spill Quality

- Simulation of nonlinear dynamics
  → Understand effect of excitations
- Example: sine excitation
  - Spiralling motion
  → Faster separatrix crossing
  → Avoids imprint of ripples and noise from excitation

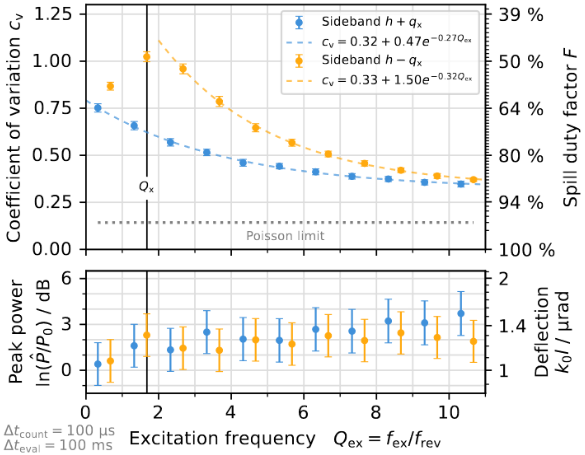
xsuite simulation

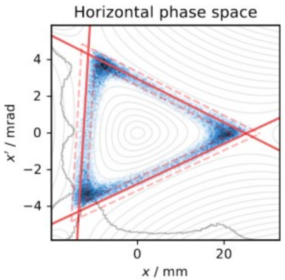


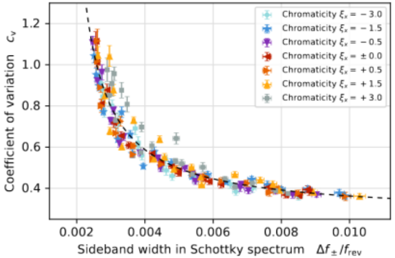


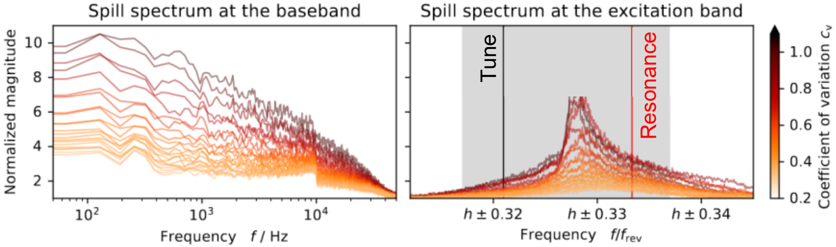
Excitation at high harmonics

- “Wideband” signals for better efficiency
  - Distinct behaviour for different sidebands $(h \pm k\, q_x)$
  - Reduced excitation imprint & better spill quality
  - Depends on machine and beam parameters
    - → Strong scaling with momentum spread
- Nonlinear beam dynamics of KO machine
  - Correlation with spectrum of particles near separatrix





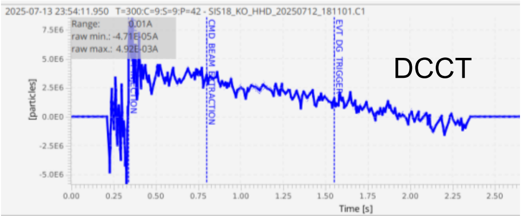


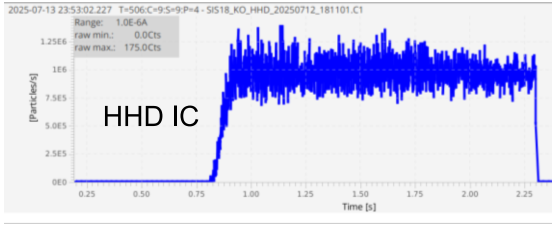


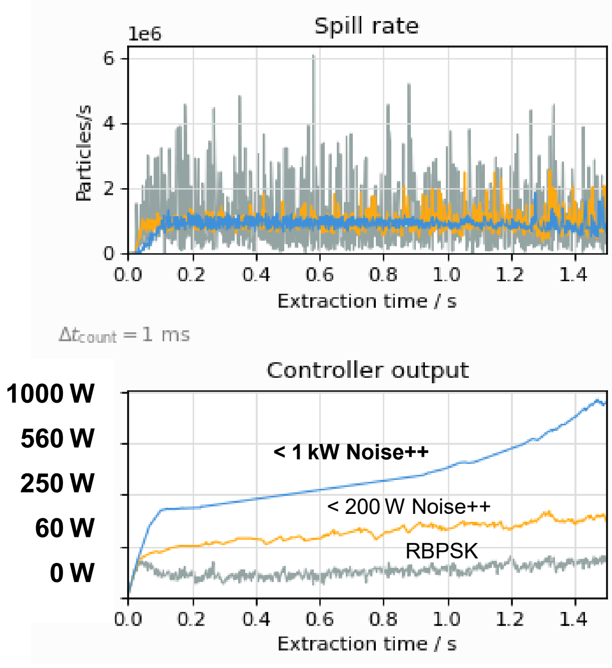
https://doi.org/10.48550/arXiv.2503.11285

Excitation Power

- High power beam test on 13.7.2025 (P. Kowina, U. Laier, P. Niedermayer, R. Singh, B. Zipfel)
  - 12 T m $^{238}U^{73+}$ beam, 1.5 s spill from SIS18 to HHD
  - 2 kW Barthels RF Amplifier from FZJ/IKP COSY inventory
  - 1.5 kW limit for safe operation (lab tests by P. Kowina)
  - 1 kW KO power used to **fully empty the SIS18**
  - Spill quality optimized with Noise++
    - Spill duty factor improved: 32% → 94%
    - Fluctuations reduced (c_v): 1.45 → 0.25

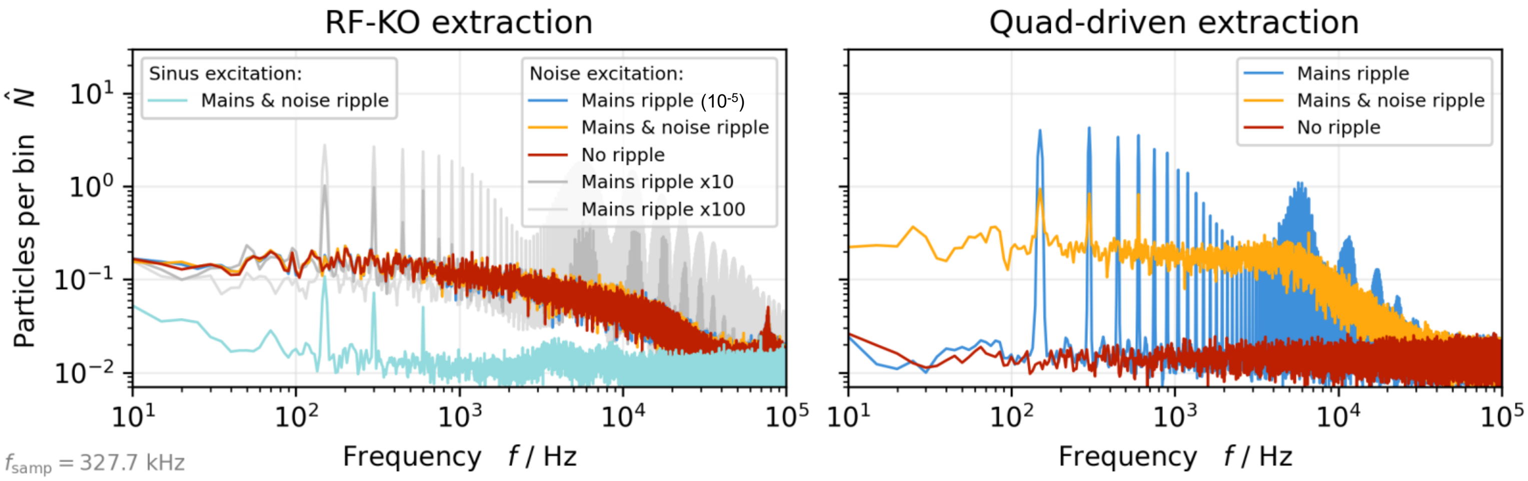






Main Source of Spill Fluctuations

- Spill spectra from particle tracking simulation with Xsuite
  → Model ideal case without ripples on quadrupole magnets



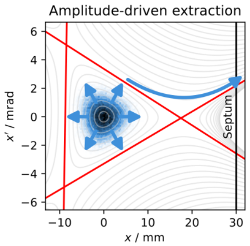
Spill fluctuations dominated **by excitation signal**

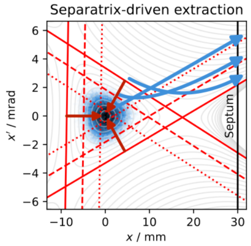
Spill fluctuations dominated **by quadrupole ripples**

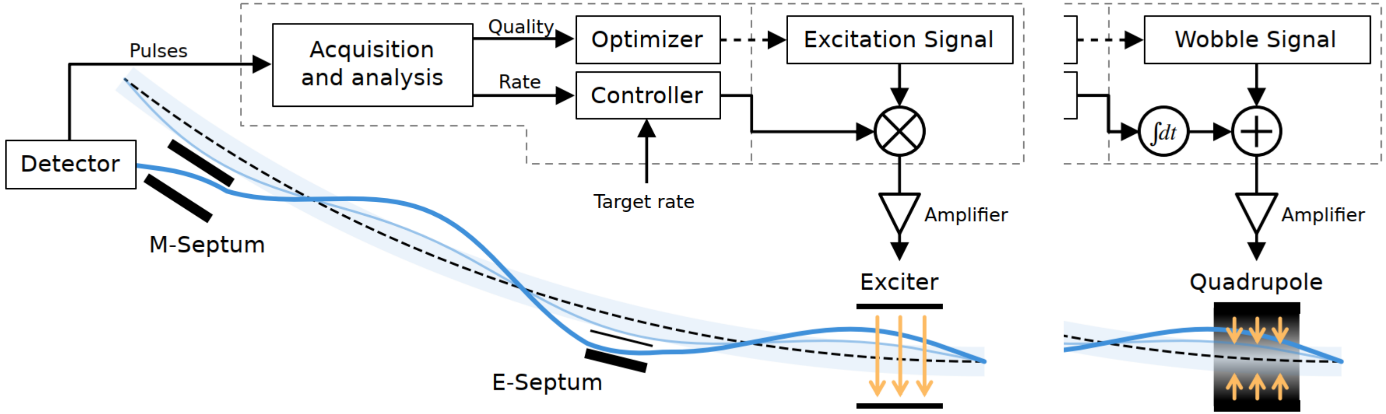
Mains ripple: 150, 300 and 600 Hz
Noise ripple: 0 to 10 kHz
Ripple magnitude: 10^{-5} [Singh et al., 2017]

Outlook: SOS for quad-driven extraction

- Future: systems for both extraction methods
  - **Knock-Out** → RF signal for KO exciter (`GS01BO1EH`)
  - **Quad-driven** → Set-point signal for fast quadrupole (`GS02KQ1E`)







Outlook: SOS for quad-driven extraction

- Future: systems for both extraction methods
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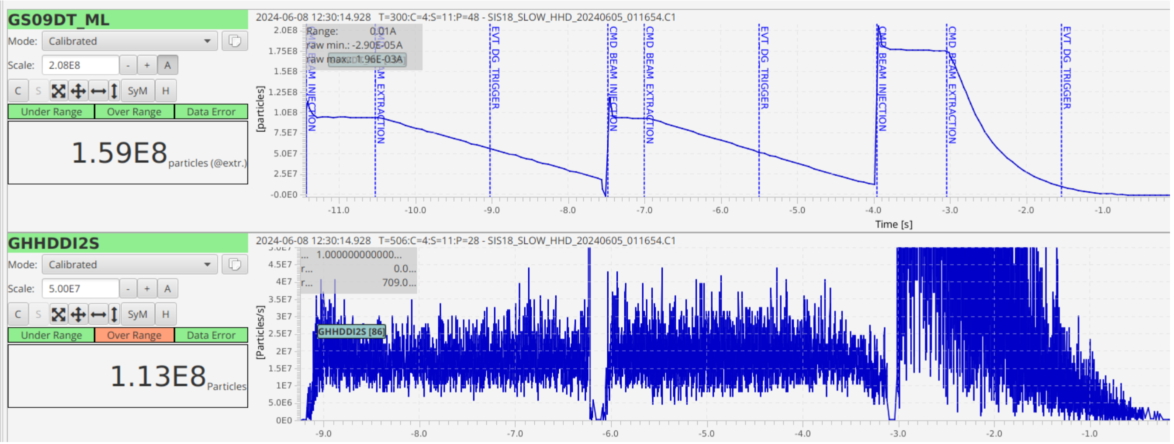
quad-driven with feedback

RF-KO with feedback

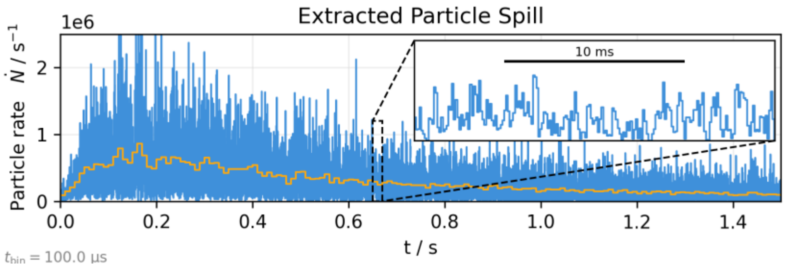
quad-driven no feedback

Stored intensity in SIS18

Extracted intensity on target

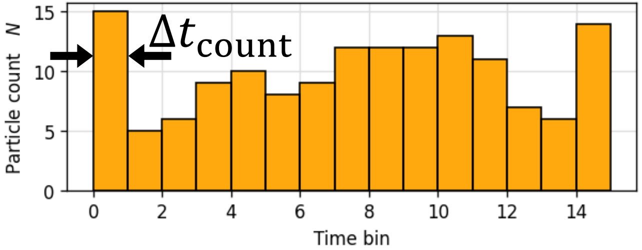


- Spill fluctuations
  - Define time bins $\Delta t_{\mathrm{count}}$ to count particles
  - Number of particles N per bin



  - Coefficient of variation

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



  - 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: $\sigma_N = \sqrt{\langle N \rangle}$

Spill Quality and Poisson Limit

- Poisson distribution

  $$P(N) = \frac{\lambda^N e^{-\lambda}}{N!}$$

  Mean: $\langle N \rangle = \lambda$

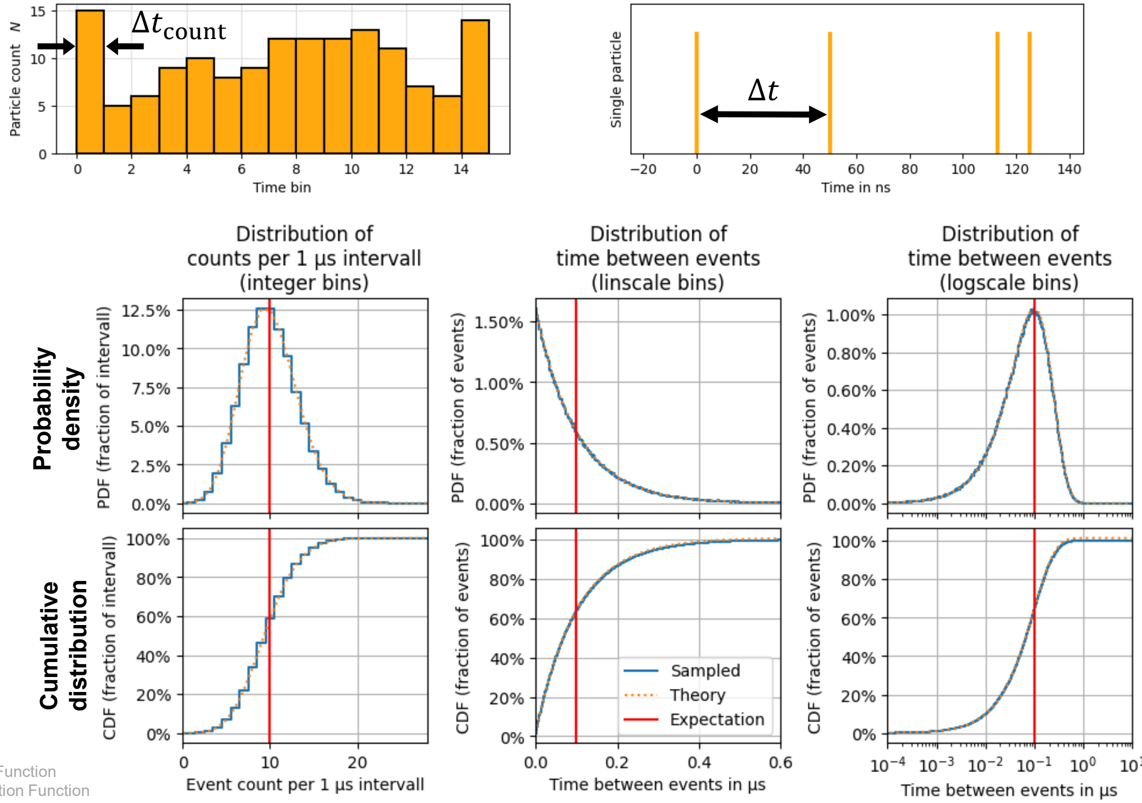
  Std: $\sqrt{\mathrm{Var}\,N} = \sqrt{\lambda}$

- Coefficient of variation

  $$c_v = \frac{\sigma_N}{\mu_N} = \frac{\sqrt{\mathrm{Var}\,N}}{\langle N \rangle} \to \frac{1}{\sqrt{N}}$$

- Poisson inter-particle delay

  $$P(\Delta t < t) = 1 - e^{-\langle \dot{N} \rangle t}$$



PDF = Probability Density Function
CDF = Cumulative Distribution Function