Spill Optimization: SIS18 Micro Spill Cavity

Beam Time Retreat

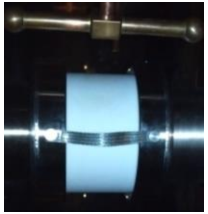
K. Groß, RRF

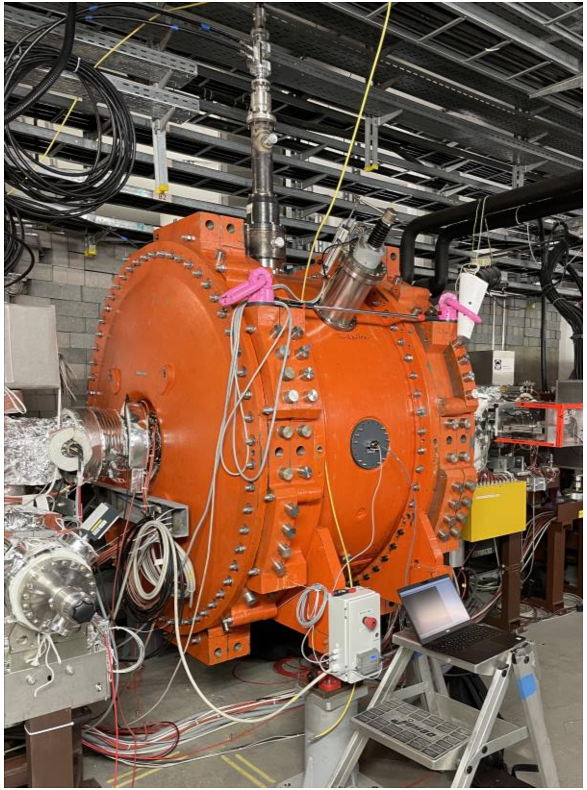
11.07.2024

Acknowledgments: **TRI, BAU, LRF, VAC, ARP, ATP, OPE, SIS100/SIS18, BEA, HADES, mCBM**

Current Status of Micro Spill Cavity in SIS18

- Cavity installed in SIS18 in July 2023
- Locally operated (BG 1.016)
- Access SIS18 required to remove short-circuit
- Impedance without shortcut about 500 kΩ
  $Q_0 \approx 5000$
- Frequency 80.3 to 81.6 MHz
  (sufficient for all energies
  with adjustment of harmonic number)
- Gap voltage amplitude 1.5 kV without
  conditioning & warmup (up to 25 kV in test setup)
- Conditioning required
  warming-up & cooling-down time





Experimental Results from Operation with Beam

- Dedicated MDE
  29.11.2023
  - Rev. freq. $f_0 = 904.8510$ kHz
  - h=4 $f_{RF} = 3.6194$ MHz
  - h=90 $f_{RF} = 81.4366$ MHz
  - Extraction: Quadrupole-driven
    8 seconds
  - Detector: HHD-CFD
- Outline:
  - **Duty Factor**
  - Spectrum
  - Arrival time with respect to RF

- (MDE / Parasitic Operation) HADES
  1. / 6.3.2024
  - Rev. freq. $f_0 = 1.1661$ MHz
  - h=4 $f_{RF} = 4.664$ MHz
  - h=70 $f_{RF} = 81.6283$ MHz
  - Extraction: RF Knock Out with SOS
    20 seconds
    (Noise / Noise++ / 3 Sines)
  - Detector: multiplicity signal derived from HADES / HHDDI2P

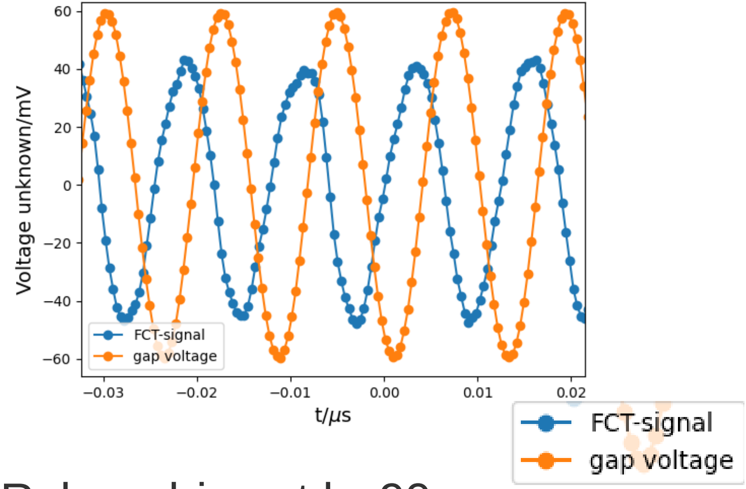
Evaluation based on code by P. Niedermayer, data recorded by T. Milosic and ideas from P. Forck, R. Singh, S. Sorge and J. Yang → Thanks to all!

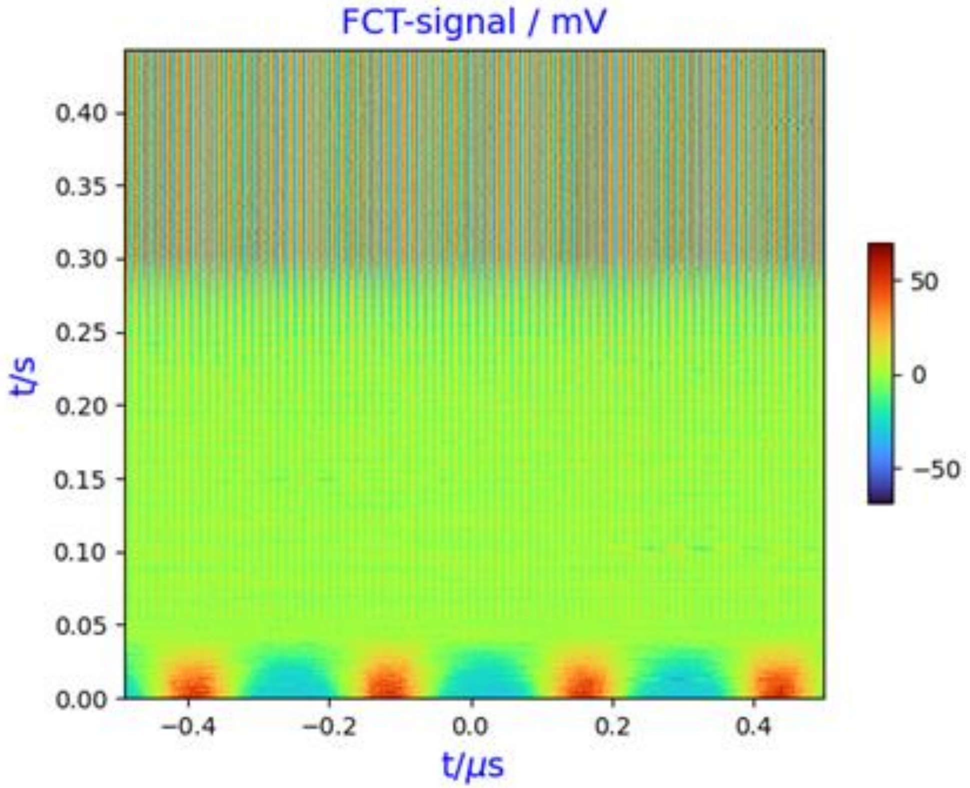
Dedicated MDE
29.11.2023

- Extraction: Quadrupole-driven (without SOS)
  8 seconds
- Detector: HHD-CFD

Experimental Results from Operation with Beam
Dedicated MDE 29.11.2023

- Bunched beam during extraction

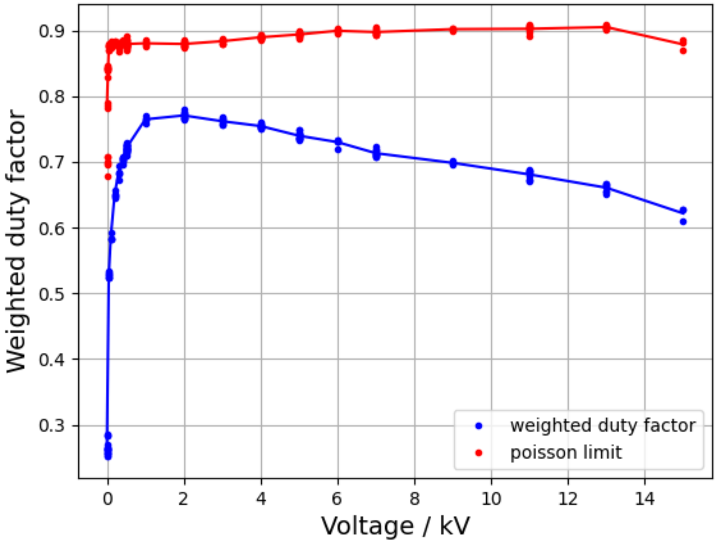




- Rebunching at h=90
- Debunching at h=4

Experimental Results from Operation with Beam
Dedicated MDE 29.11.2023

- Spill quality / weighted duty factor ($t_{\text{bin}} = 10$ μs, $t_{\text{av}} = 10$ ms)
- 167 spills, 16 voltages
- Valid for $t_{\text{bin}} < 1$ μs



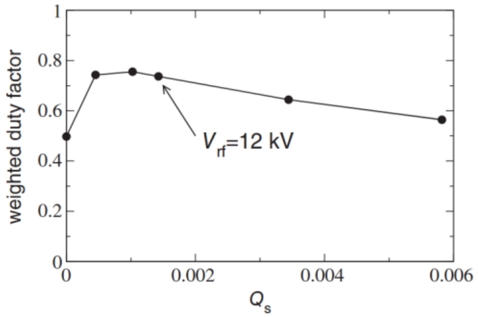
- $F_{\text{av}} = \frac{\sum_k N_k F_k}{\sum_k N_k}$ with $F = \frac{\mu^2}{\mu^2+\sigma^2} = \frac{\langle n \rangle^2}{\langle n^2 \rangle}$
  n in t_{bin}, N in t_{av}

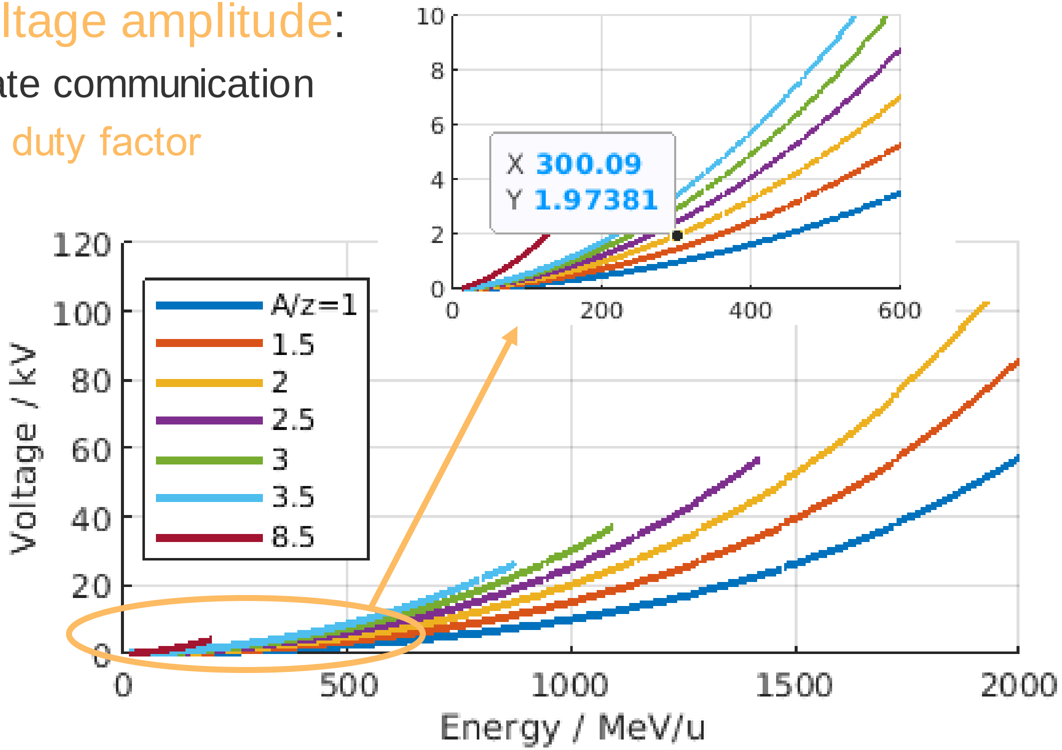
- Optimal voltage found at 2 kV is only valid for $^{14}N^{7+}$ @ 300 MeV/u
- Optimum synchrotron tune found at 2 kV is 0.0038
- Meaning of optimal synchrotron tune → next MDE / next slide

Experimental Results from Operation with Beam
Dedicated MDE 29.11.2023 - Outlook

- Next MDE – find optimal gap voltage amplitude:
  - Assumption based on [1] and private communication
  - Similar synchrotron tune → similar duty factor
  - Strongest impact
    - Transverse beam widths
    - Momentum width
    - Synchrotron tune

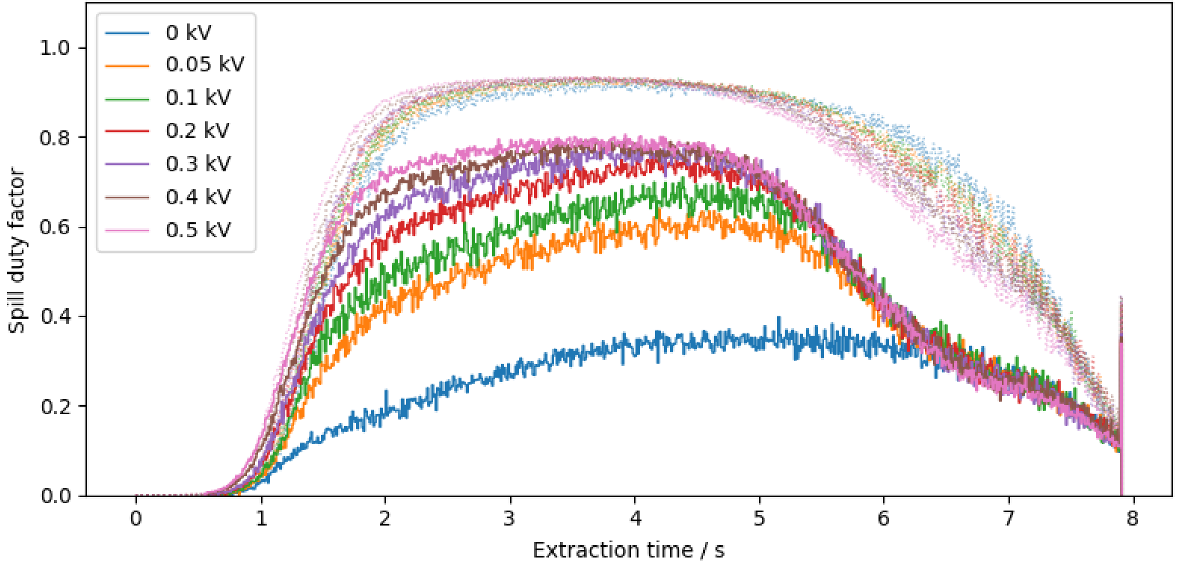
[1] S. Sorge et al, PR AB 26, 014402 (2023)





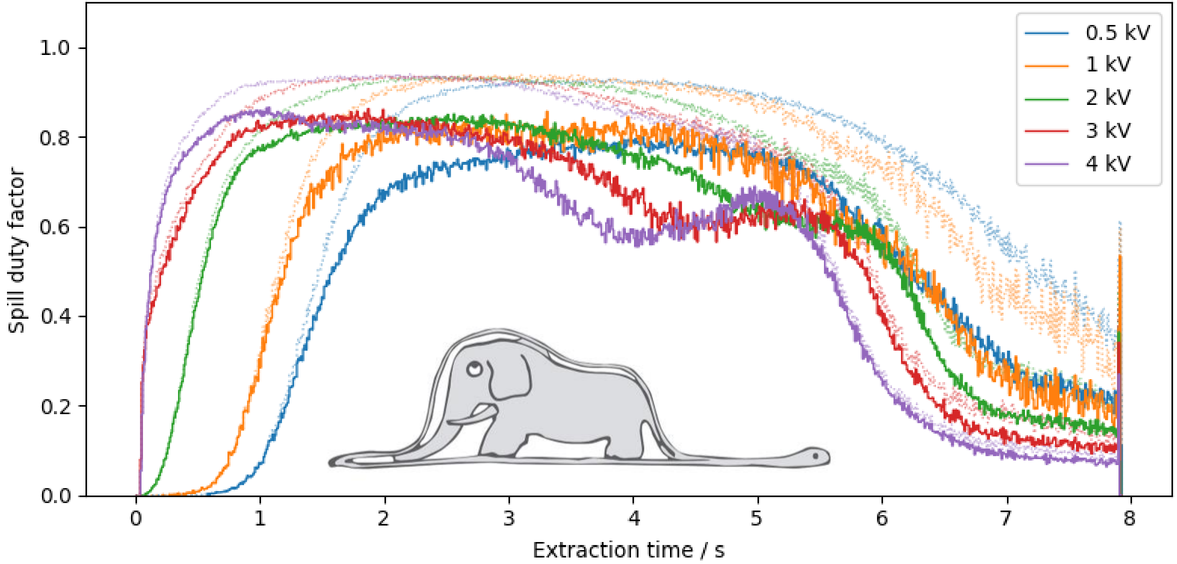
Experimental Results from Operation with Beam
Dedicated MDE 29.11.2023

- Spill duty factor over time – up to 500 V
- Spill duty factor increases with gap voltage



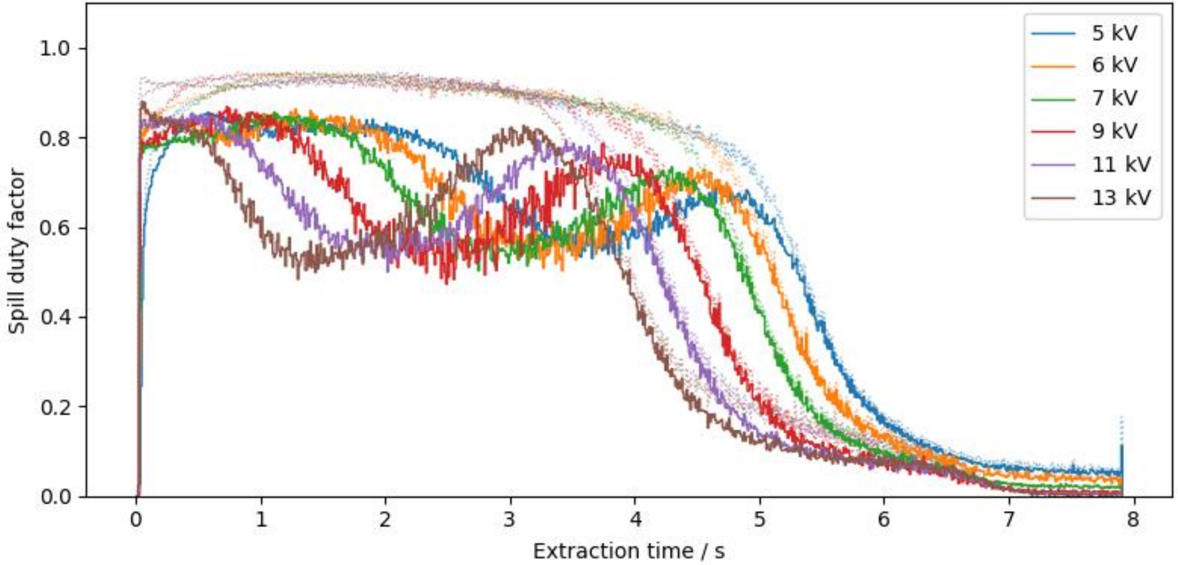
Experimental Results from Operation with Beam
Dedicated MDE 29.11.2023

- Spill duty factor over time – 500 V to 4 kV
- Optimum found at 2 kV
- Second local max. for gap voltage > 2 kV



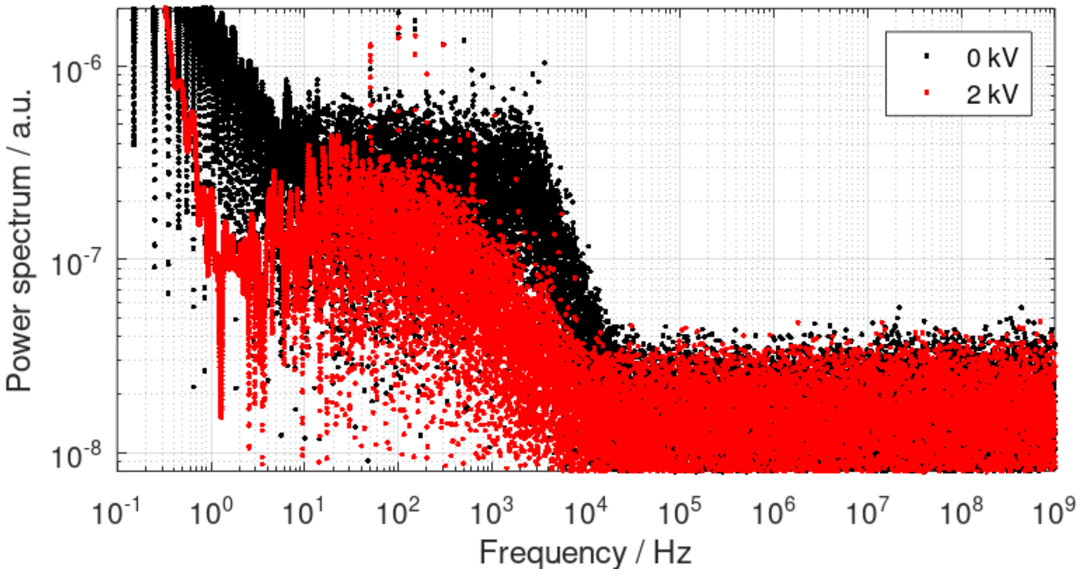
Experimental Results from Operation with Beam
Dedicated MDE 29.11.2023

- Spill duty factor over time – 5 to 13 kV
- Position of second local max. seems to depend on tune shift
- Further evaluation necessary



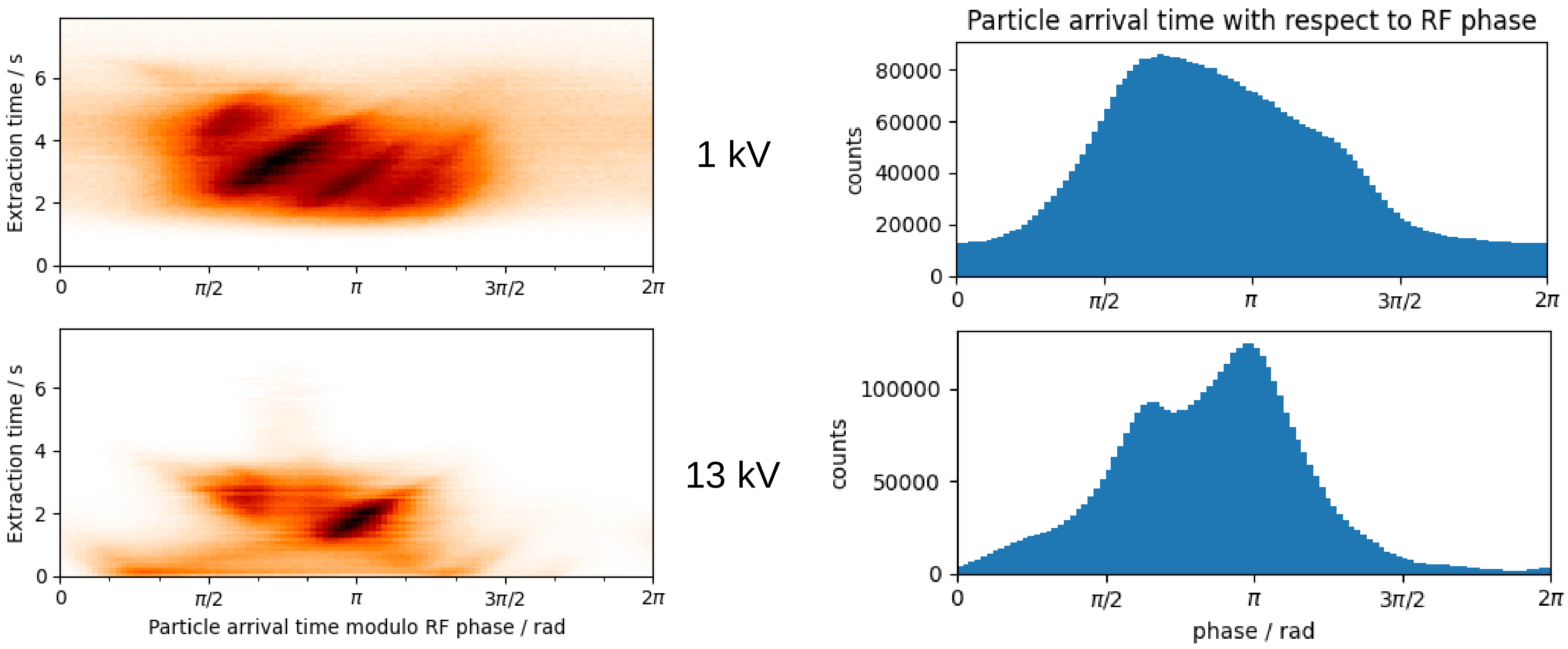
Experimental Results from Operation with Beam
Dedicated MDE 29.11.2023

- Spectrum of extracted beam
- Improvement for all frequencies



Experimental Results from Operation with Beam
Dedicated MDE 29.11.2023

- Arrival time with respect to RF phase (12.25 ns) - further evaluation needed

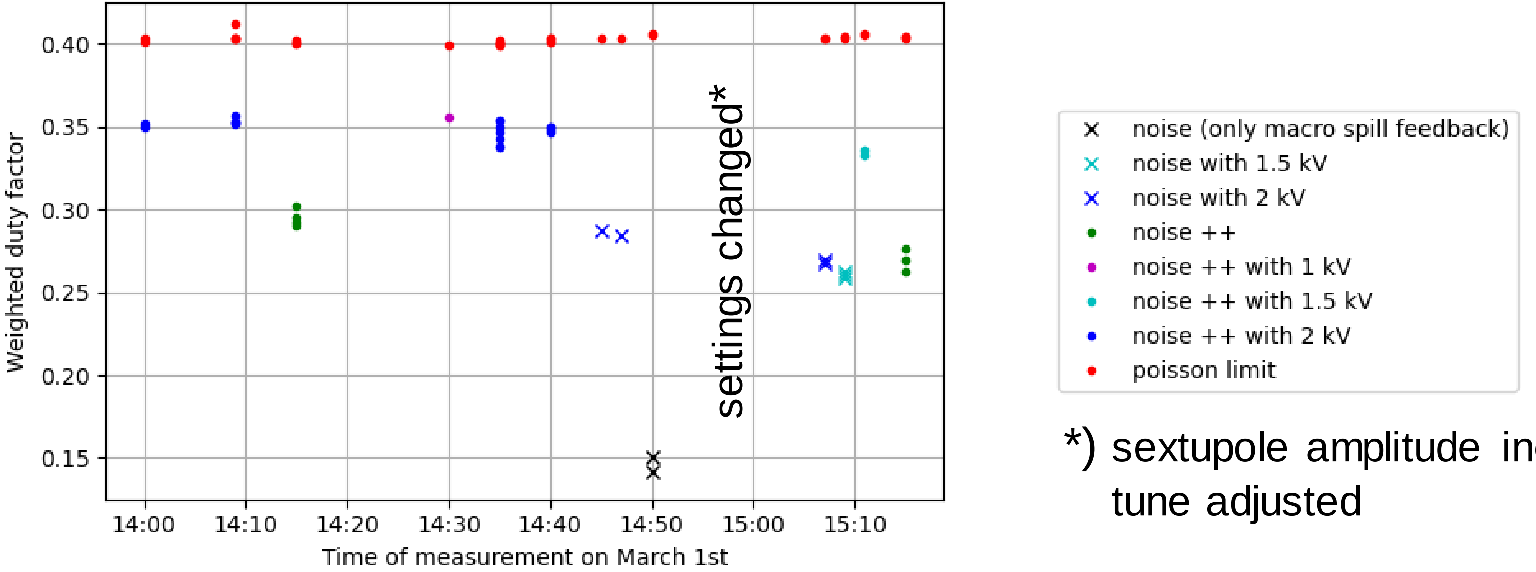


MDE - HADES
1.3.2024

- Extraction: RF Knock Out with SOS (Noise / Noise++)
  20 seconds
- Detector: multiplicity signal with a jitter of several ns
  derived from HADES

Experimental Results from Operation with Beam
Parasitic Operation HADES Beam Time

- Measurements performed by beam diagnostics department (BEA) on 1.3.2024

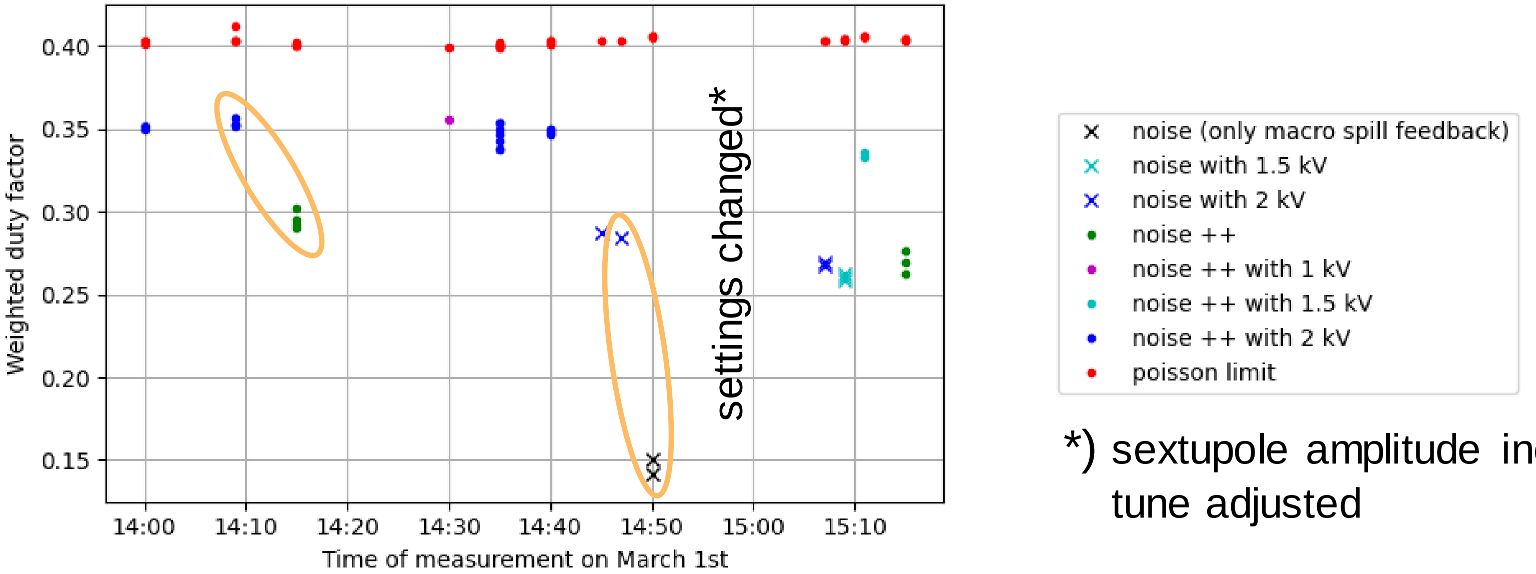


*) sextupole amplitude increased
tune adjusted

- Best results found with spill optimization system AND micro spill cavity on

Experimental Results from Operation with Beam
Parasitic Operation HADES Beam Time

- Measurements performed by beam diagnostics department (BEA) on 1.3.2024

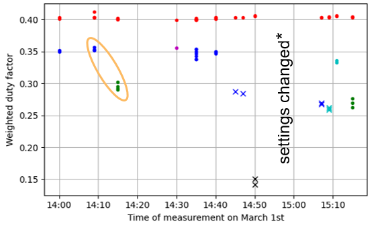


*) sextupole amplitude increased
tune adjusted

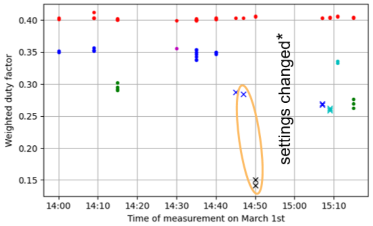
- Best results found with spill optimization system AND micro spill cavity on

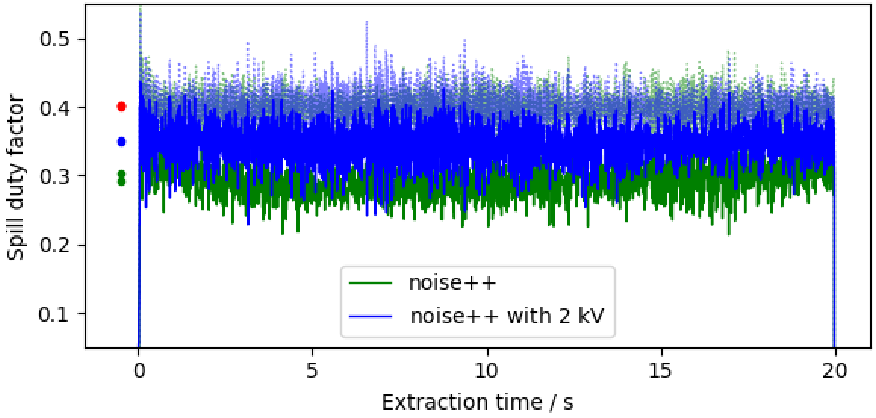
Experimental Results from Operation with Beam
Parasitic Operation HADES Beam Time

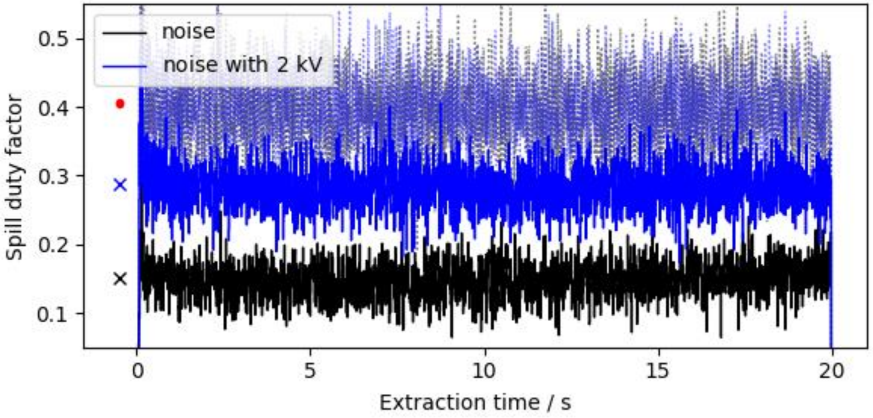
- Spill duty factor over time
- „noise++“ vs. „noise++ with 2 kV“



- „noise“ vs. „noise with 2 kV“



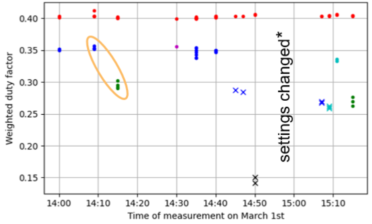




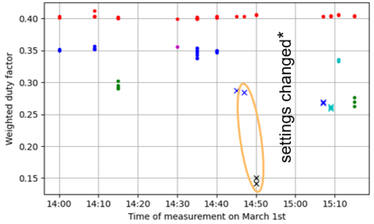
Experimental Results from Operation with Beam
Parasitic Operation HADES Beam Time

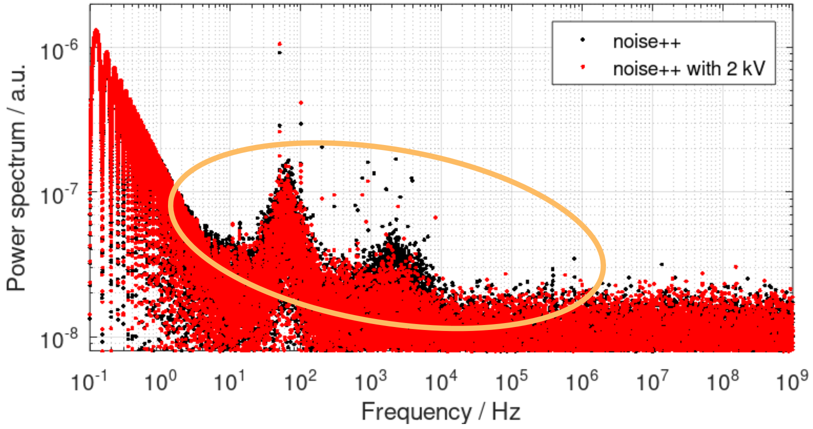
- Fourier series

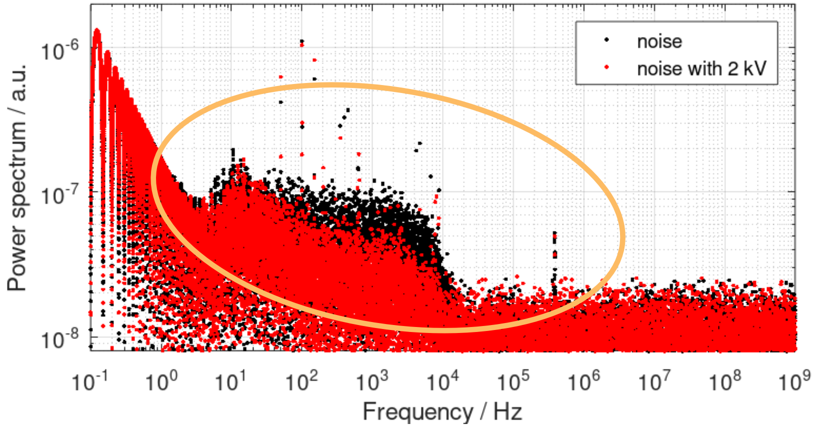
- „noise++“ vs. „noise++ with 2 kV“



- „noise“ vs. „noise with 2 kV“

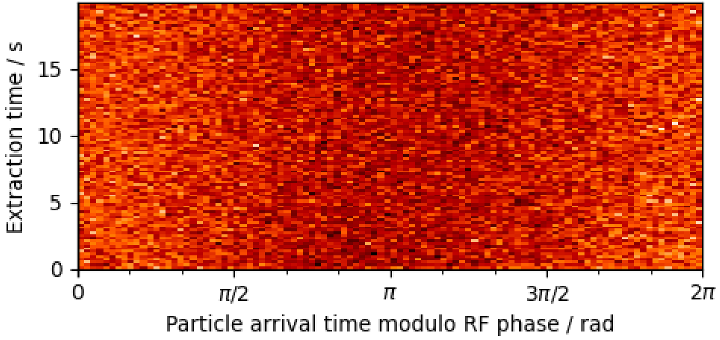


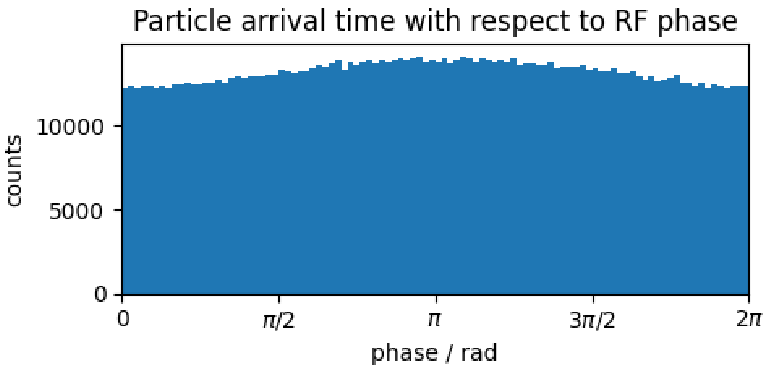




Experimental Results from Operation with Beam
Parasitic Operation HADES Beam Time

- Measurements performed on 1.3.2024
- “noise++ with 2 kV”





multiplicity signal → over time → not “structured”

→ Washed-out due to multiplicity signal with a jitter of several ns

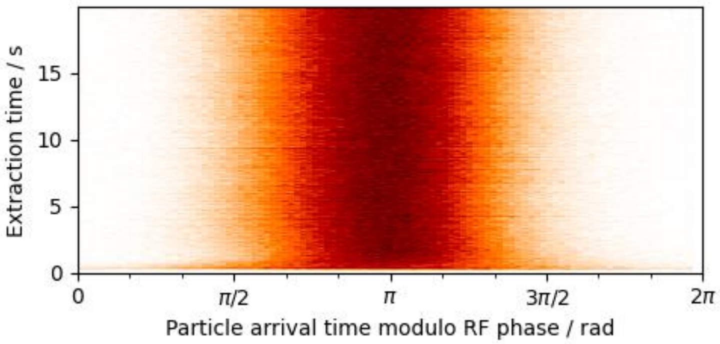
→ Structure (29.11.23) likely due to tune shift (quadrupole-driven extraction)

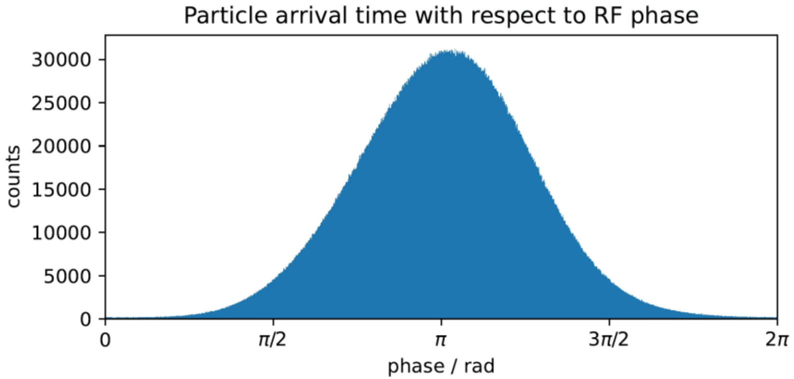
Parasitic Operation HADES
6.3.2024

- Extraction: RF Knock Out with SOS (3 Sines)
  20 seconds
- Detector: HHDDI2P

Experimental Results from Operation with Beam
Parasitic Operation HADES Beam Time

- Measurements performed by beam diagnostics group on 6.3.2024
- 3 Sines (“+++“) used instead of “noise++“ by SOS





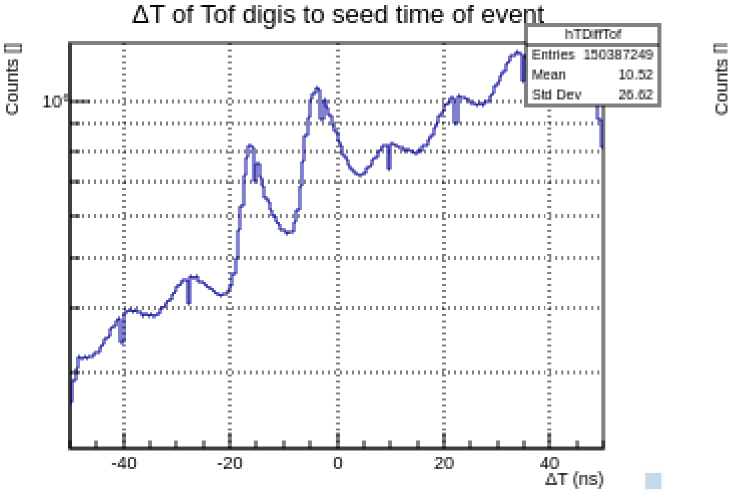
HHDDI2P

10^7 ions / (20 s · 81.63 MHz) = 0.006 ions

→ Structure (29.11.23) likely due to tune shift (quadrupole-driven extraction)

No further analysis due to different settings in the only measurement with cavity.

Experimental Results from Operation with Beam
Parasitic Operation HADES Beam Time (mCBM, Slow)



- The RF period of 12.25 ns could be measured at mCBM / HTD during quadrupole-driven slow extraction with cavity on at 1.5 kV

- time difference TOF-T0 (diamond)
- MQ based online analysis by Norbert Herrmann

multivariate systemof quadratic equations

Conclusion and Outlook

- Significant improvement in spill quality due to micro spill cavity
- Best results with combination of SOS and micro spill cavity

- Several further machine experiments necessary

- Work in progress to make the cavity usable with less RRF support
  - Step 1: set amplitude for selected pattern, frequency fixed, read status
  - Step 2: set frequency and amplitude, remote control (on, off, reset)
    remote short-circuit (if possible)
  - Step 3: LSA-model includes results from upcoming MDEs,
    optimal operational parameters are set automatically
  - Limited to 1.5 kV (2.25 W) for remote operation in all steps

Thanks

for your attention!

Questions?

Acknowledgements

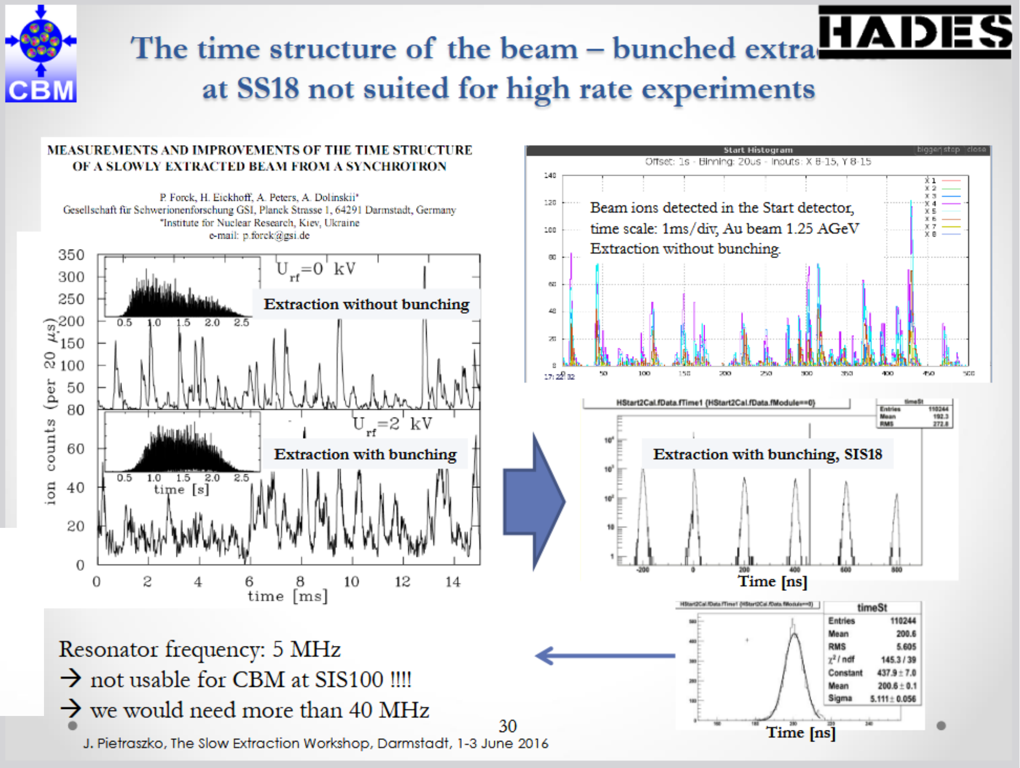
- Development and Commissioning: Accelerator Radiation Protection, Atomic, Quantum & Fundamental Physics, Construction (B. Benz, J. Kalenda), Linac RF (B. Schlitt, G. Schreiber, W. Vinzenz, J. Zappai et al.), Ring RF (R. Balß, B. Breitkreutz, C. Christoph, O. Disser, M. Hardieck, H. Klingbeil, H.G. König, U. Laier, D.E.M. Lens, S. Lux, S. Schäfer, C. Thielmann, T. Winnefeld, B. Zipfel et al.), SIS100/SIS18 (P. Spiller, J. Stadlmann), Transport and Installation (D. Acker, K. Lück, M. Grenz-Gustafson, M. Diebel, K. Kalaitzidis et al.), Vacuum Systems (M.C. Bellachioma, E. Renz, G. Savino)
- Spill Measurements: Accelerator Physics (S. Sorge), Beam Instrumentation (P. Boutachkov, O. Chorniy, P. Forck, T. Milosic, P. Niedermayer, R. Singh, J. Yang), SIS100/SIS18, HADES/mCBM (J. Pietraszko, C. Strum, M. Traxler)
- Machine Operating and Discussions: (Accelerator) Operation(s) (R. Aßmann, A. Bloch-Späth, C. Böhm, V. Kamerdzhiev, H. Kummerfeldt, F. Lorenz, S. Reimann, Y. Valdau)

Cavity Development, Operation and Upgrade

- Development
  - Requirement on Frequency
  - Gap Voltage Calibration
  - RF Frequency and Harmonic Number
- Operation
  - Conditioning
  - Temperature Development
  - Vacuum
  - High Beam Intensities
- Upgrade
  - Control System
  - Short-

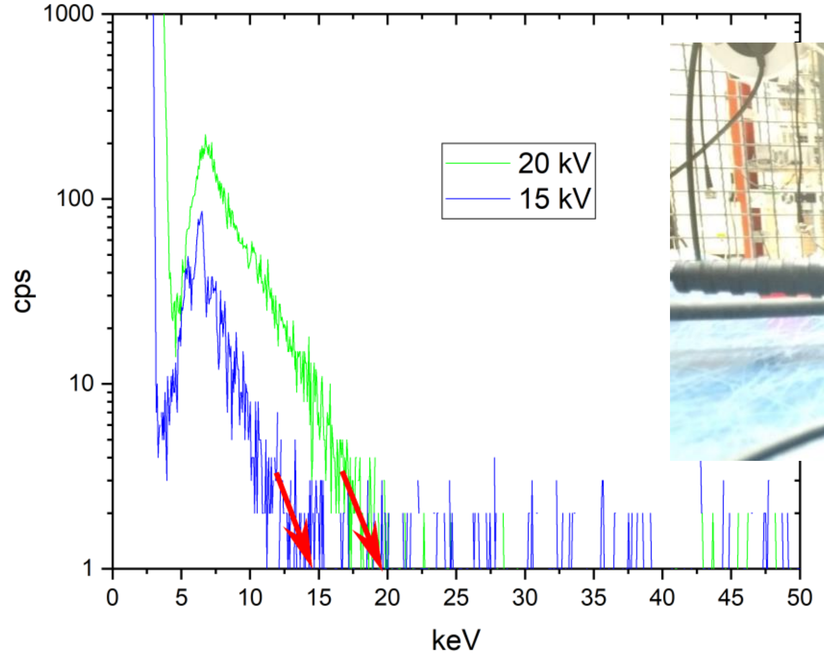
Requirement on Frequency

- J. Pietraszko,
  "The Hades/CBM physics case requirements",
  oral presentation at
  Slow Extraction Workshop, Darmstadt, Germany,
  June 2016.



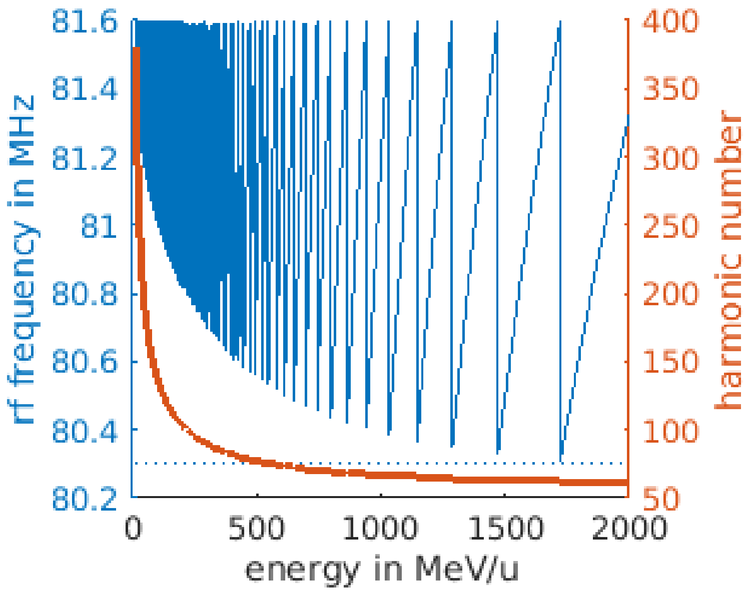
Resonator frequency: 5 MHz
→ not usable for CBM at SIS100 !!!!
→ we would need more than 40 MHz

Gap Voltage Calibration



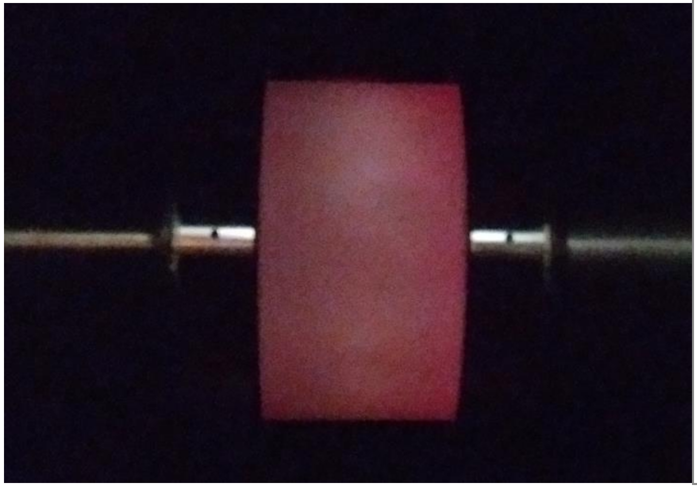
RF Frequency and Harmonic Number

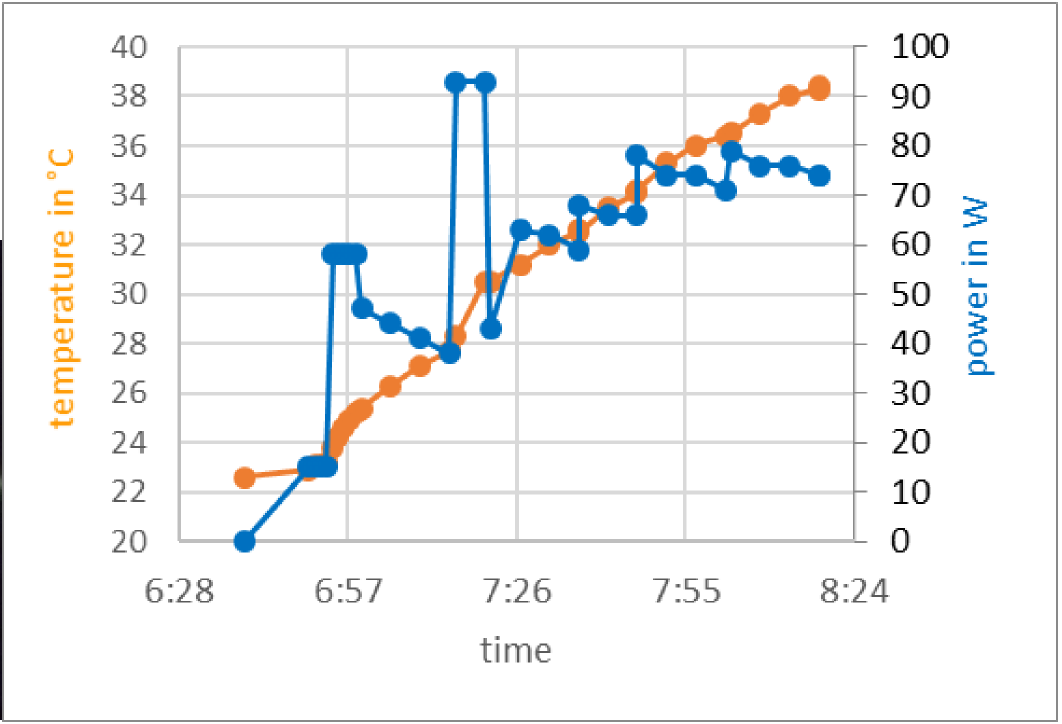
- One of several possibilities



Conditioning

- First conditioning in beam time can take 6 – 29 hours and require a power of up to 225 W (15 kV)



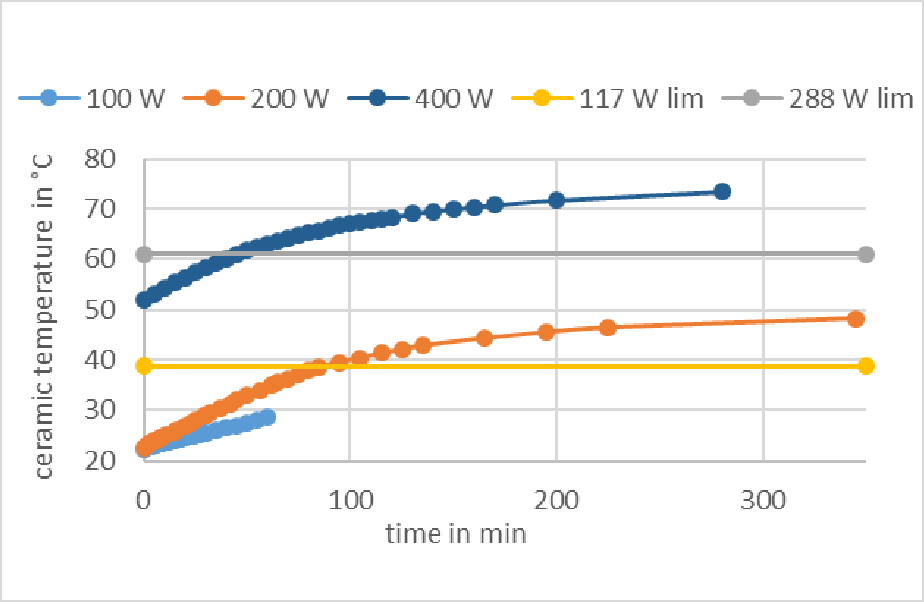


Temperature Development

$$\Delta\vartheta = \frac{\text{Energy}}{\text{m} \cdot 900\ \frac{\text{J}}{\text{kg K}}} = \frac{4\ \text{W}}{3.22\ \text{kg} \cdot 900\ \frac{\text{Ws}}{\text{kg K}}} = 0.08\ \frac{\text{K}}{\text{min}}$$

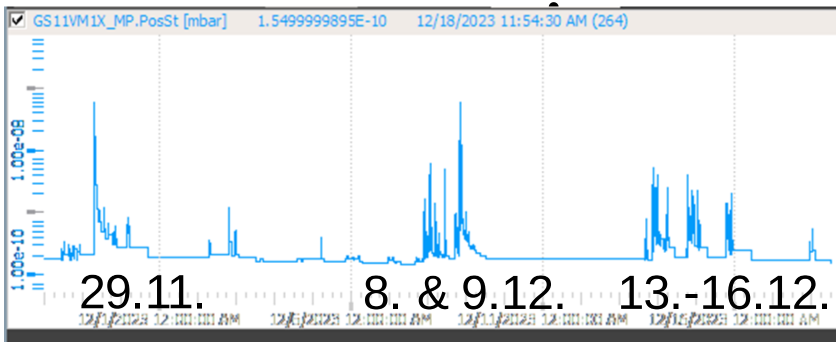
- Properties of the ceramic gap

Length	l	146 mm
Inner / outer Diameter	$2r_i$ / $2r_o$	170 / 190 mm
Mass	m_c	3.22 kg
Relative permittivity	ε_r	9.8
Dielectric loss tangent	$\tan(\delta)$	$3.8 \cdot 10^{-4}$
Specific heat capacity	c_c	$900\ \text{J kg}^{-1}\ \text{K}^{-1}$



Vacuum

- Worst case „ conditioning“ limited in time and similar to high current operation

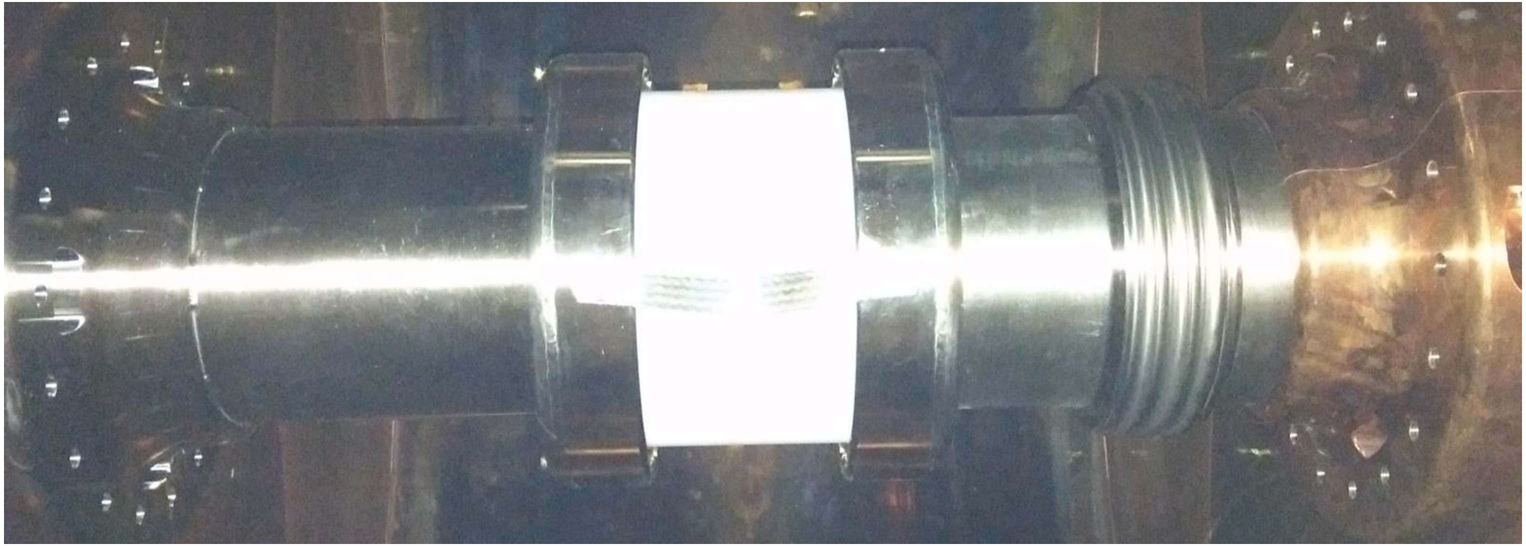


- Only necessary for MDEs with high voltage requirements
- Slow conditioning leady to lower peaks in the vacuum pressure

- Vacuum (GS11VM1X) $1.5 \cdot 10^{-10}$
- Beam pipe tested as any other beam pipe
- Heat out (up to now) limited to ceramic
- Vacuum not influenced by operation at 1.5 kV

Vacuum

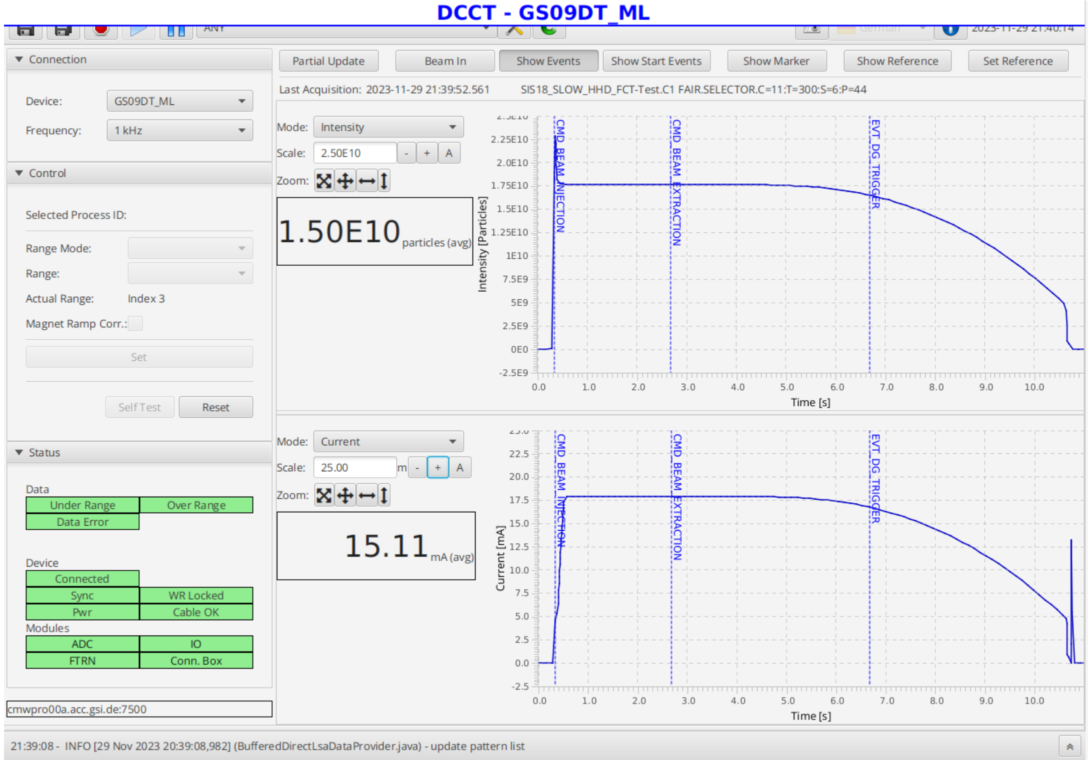
- Only the beam pipe is under vacuum



High Beam Intensities

Additional test:

- Successful acceleration of $1.5 \cdot 10^{10}$ particles, 15 mA
- Induced voltage was < 100 V

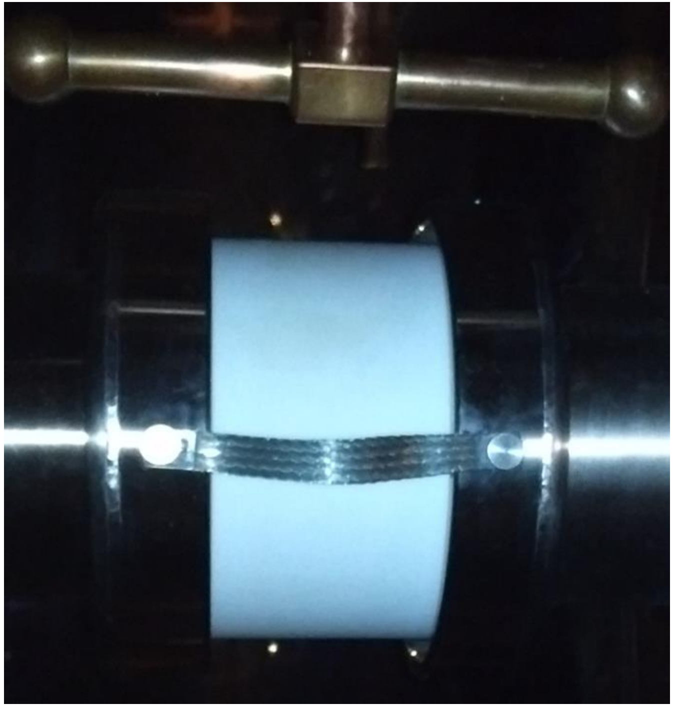


Steps towards Operation from Main Control Room

- Ramps and plunger control have to be integrated into control system
- PLC for interlock handling to be integrated in control system
- Limitation to 1.5 kV for standard operation without conditioning remains
- New output- and directional coupler for lower power
- Automatic short-circuit needed
  - not cycle to cycle (impedance applies to all running virt. accel.)
  - ambitious, evaluation of possibilities (new development of a plunger)

Short Circuit

- Construction of a new, small plunger



Research on Current Limitations

- Build up test environment / resonator to analyze the problems regarding …
  - Conditioning / plasma discharge:
    - Why was it not necessary in the test environment, but is necessary in SIS18?
    - How does this need depend on the vacuum / environment?
    - Coating, higher conductivity, better hided welds, …
  - Temperature rise in the ceramic / dielectric losses:
    - Measurement on Vacon-Temperature
    - Measurements on Ceramic Probes
- Decision on conditioning in SIS18

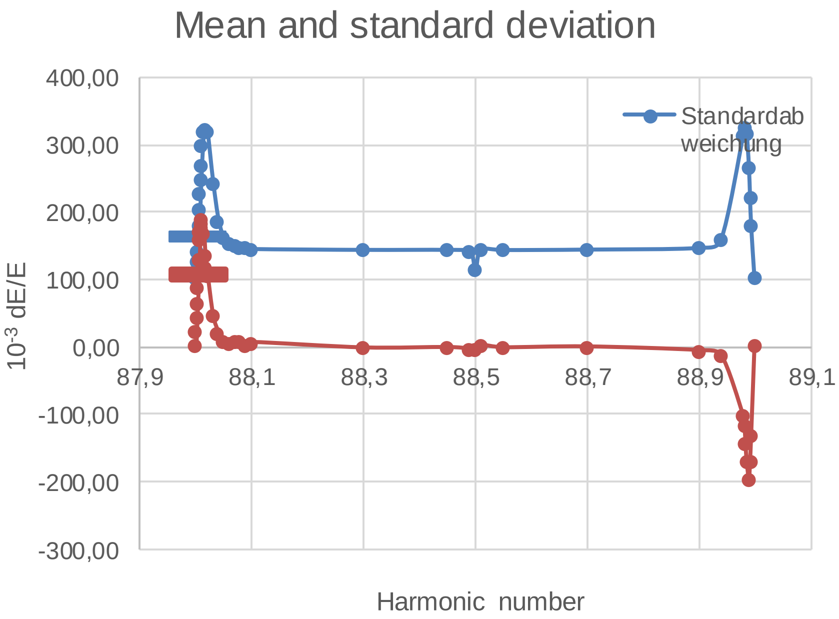
Experimental Results

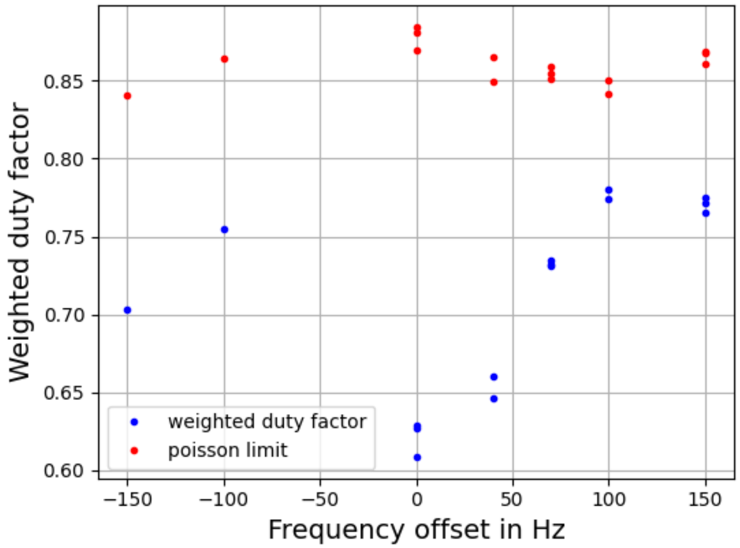
- Results not included in the presentation
  - RF frequency variation
  - Time structure of spill
  - Selected frequencies
  - Ions and energies
- Details of the results included in the presentation
  - Weighted duty factor for variation of t_{bin} and t_{av}
  - max / mean duty factor
  - Spectra
  - Changed settings

RF Frequency Variation

A shift of 100 Hz means a change in the harmonic number by 0.005

(marked with the bar in the figure – different setup simulation, calculation and measurement)

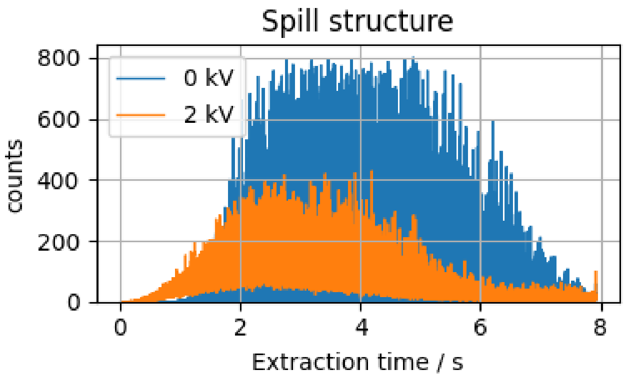


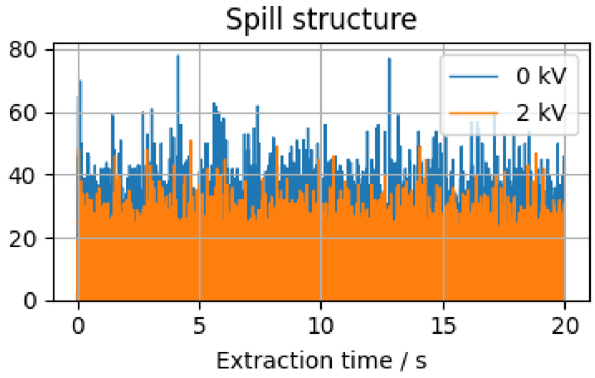


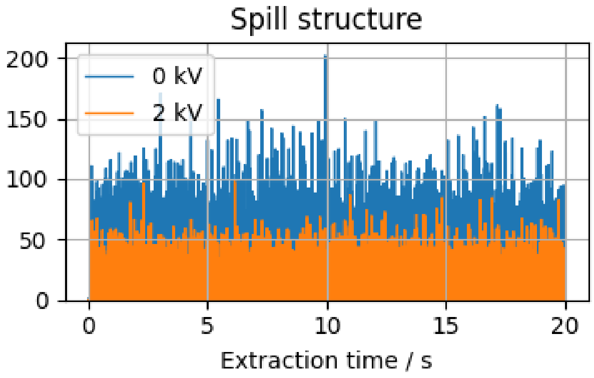
Experimental Results from Operation with Beam
Time Structure of Spill

- Spill structure – comparison between 0 kV and 2 kV ($t_{\text{bin}} = 100$ µs)

- Quadrupole-driven
- RF Knock Out with SOS
- „noise++“
- „noise”
  (macro-spill feedback)

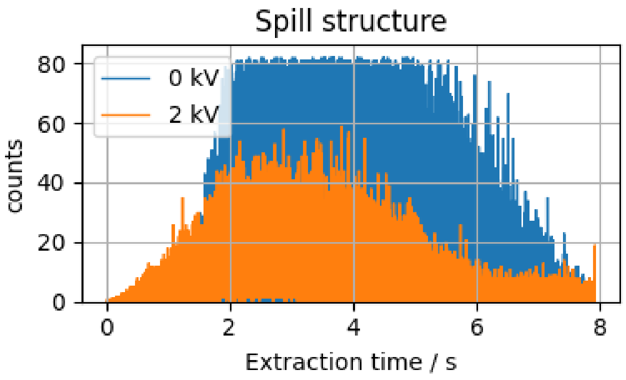


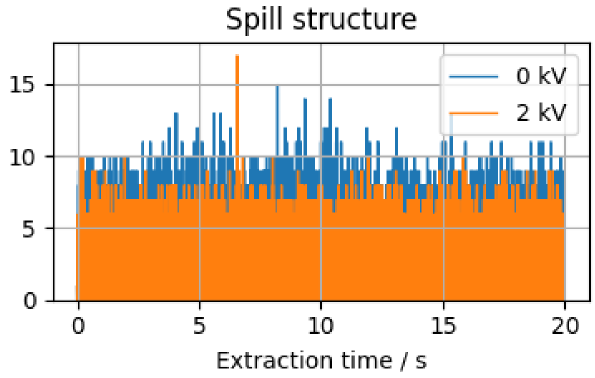


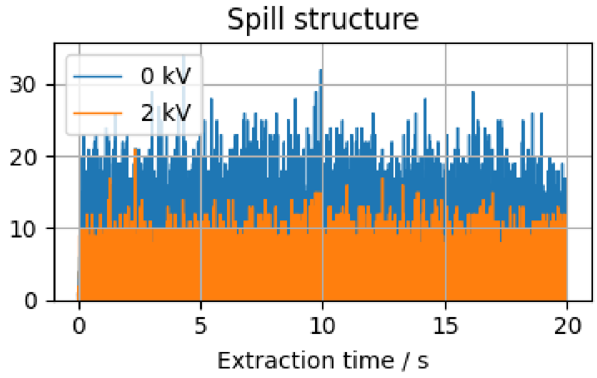


Experimental Results from Operation with Beam
Time Structure of Spill

- Spill structure – comparison between 0 kV and 2 kV ($t_{\mathrm{bin}} = 10\ \mu\mathrm{s}$)
- Quadrupole-driven
- RF Knock Out with SOS
- „noise++“
- „noise”
  (macro-spill feedback)

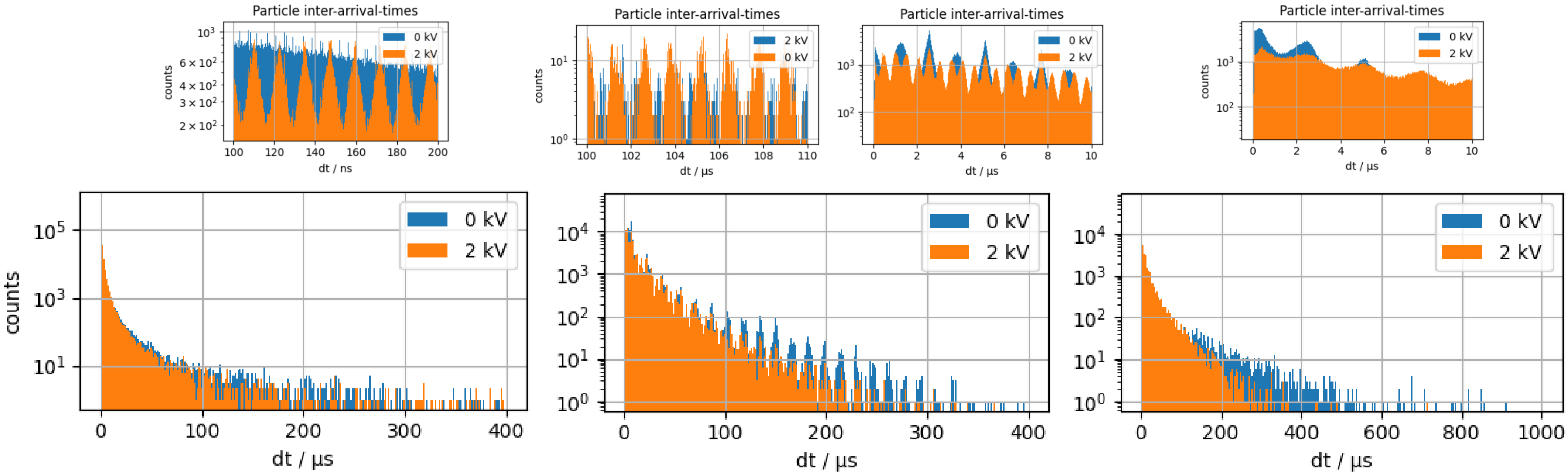






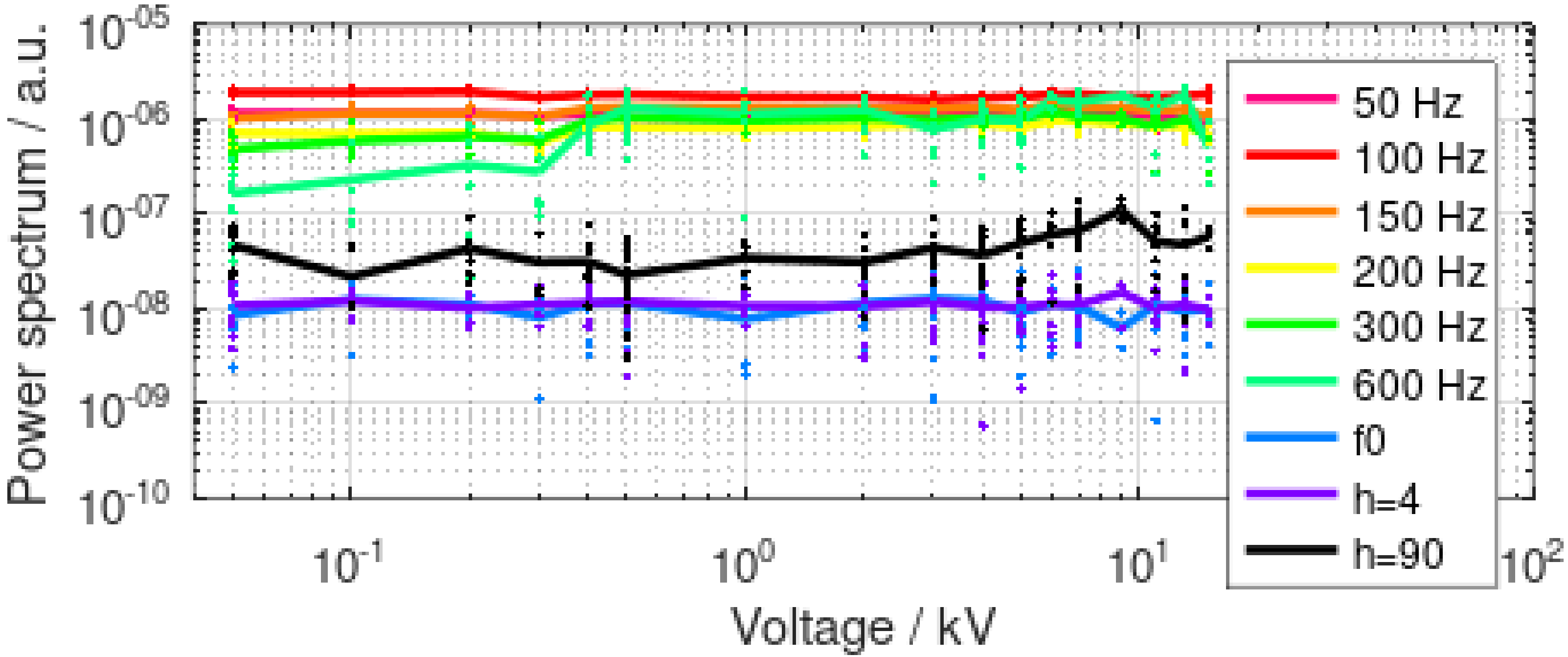
Experimental Results from Operation with Beam
Particle inter-arrival-times

- Particle inter-arrival-times – comparison between 0 kV and 2 kV
- Quadrupole-driven
  (80 MHz)
- RF Knock Out with SOS
- „noise++“ (**0.38**, 0.76, 1.9 kHz)
- „noise”
  (macro-spill feedback)



Experimental results from operation with beam
Dedicated MDE 29.11.2023 (2 shifts)

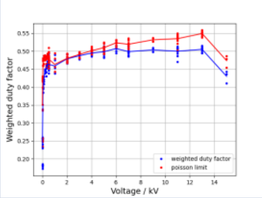
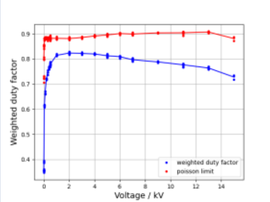
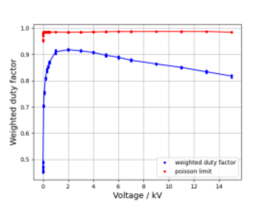
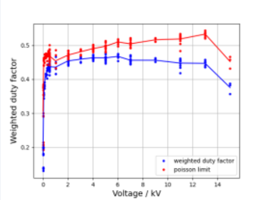
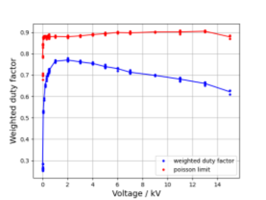
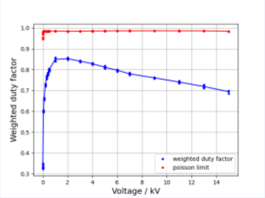
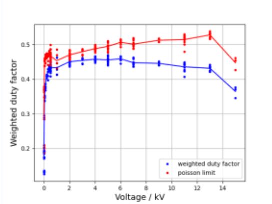
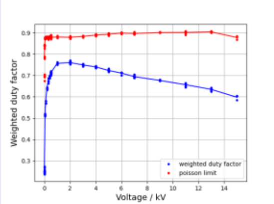
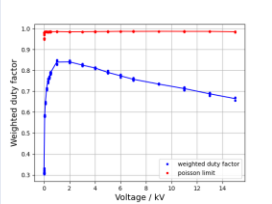
- No suppression of the dominant harmonics – rausnehmen!



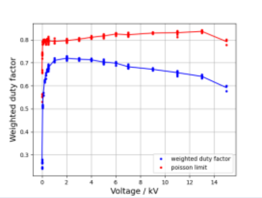
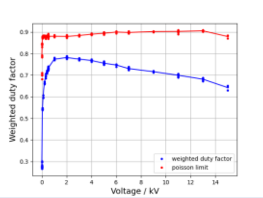
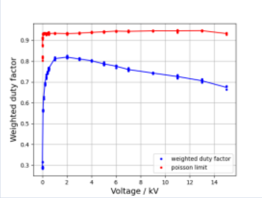
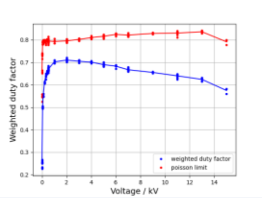
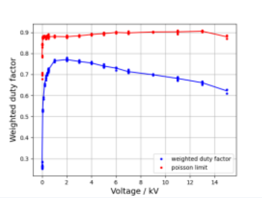
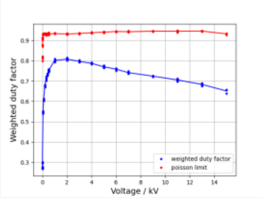
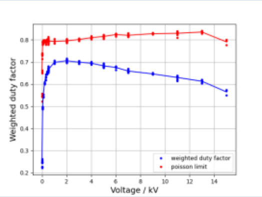
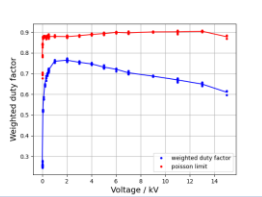
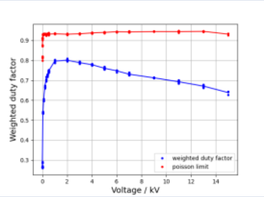
Ions and Energies

Date	Purpose	Ion	Energy MeV u^{-1}	h	f_0 kHz
11/29/23	1. PoP	$^{14}N^{7+}$	300	90	904.851
03/18/24	HADES	$^{197}Au^{65+}$	200	104	785.318
03/14/24			800	70	1166.12
03/17/24	mCBM	$^{197}Au^{68+}$	1200	65	1244.30
03/20/24		$^{197}Au^{65+}$	1130	66	1234.12

Dedicated MDE 29.11.2023
Spill quality / weighted duty factor ($^{14}N^{7+}$ @ 300 MeV/u)

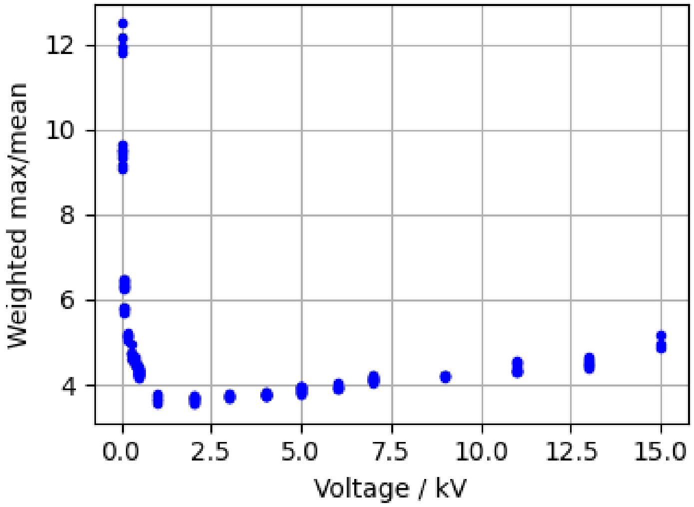
	t_{bin}=1 µs	t_{bin}=10 µs	t_{bin}=100 µs
t_{av}=1 ms			
t_{av}=10 ms			
t_{av}=100 ms			

Dedicated MDE 29.11.2023
Spill quality / weighted duty factor ($^{14}N^{7+}$ @ 300 MeV/u)

	t_{bin}=5 µs	t_{bin}=10 µs	t_{bin}=20 µs
t_{av}=5 ms			
t_{av}=10 ms			
t_{av}=20 ms			

Experimental Results from Operation with Beam Dedicated MDE 29.11.2023

- Spill quality / weighted duty factor ($t_{\text{bin}} = 10$ µs, $t_{\text{av}} = 10$ ms)
- 167 spills, 16 voltages
- Valid for $t_{\text{bin}} < 1$ µs



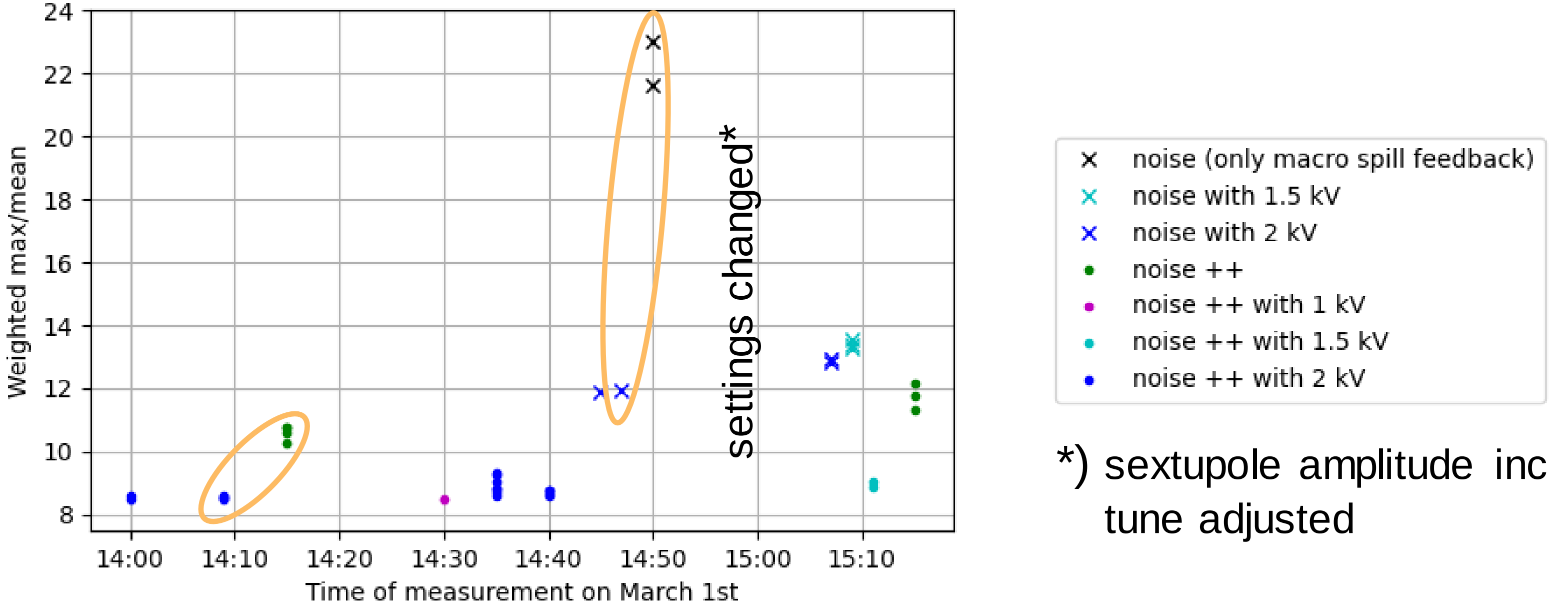
- $F_{\text{av}} = \frac{\sum_k N_k F_k}{\sum_k N_k}$ with $F = \frac{\max(n)}{\langle n \rangle}$

  n in t_{bin}, N in t_{av}

- Optimal voltage found at 2 kV is only valid for $^{14}N^{7+}$ @ 300 MeV/u
- Optimum synchrotron tune found at 2 kV is 0.0038

Experimental Results from Operation with Beam
Parasitic Operation HADES Beam Time

- Measurements performed by beam diagnostics department (BEA) on 1.3.2024

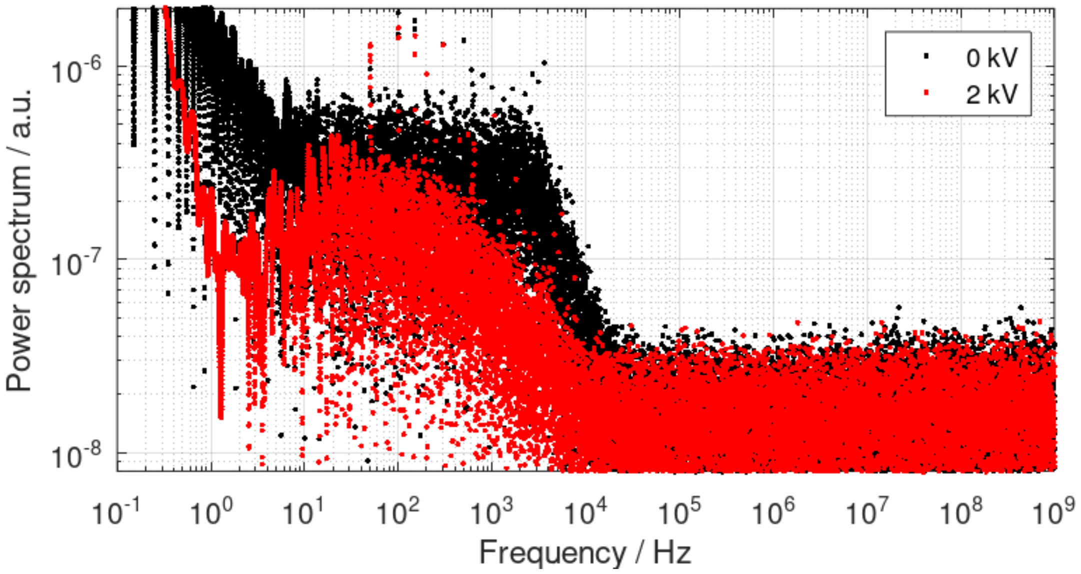


*) sextupole amplitude increased
tune adjusted

- Best results found with spill optimization system AND micro spill cavity on

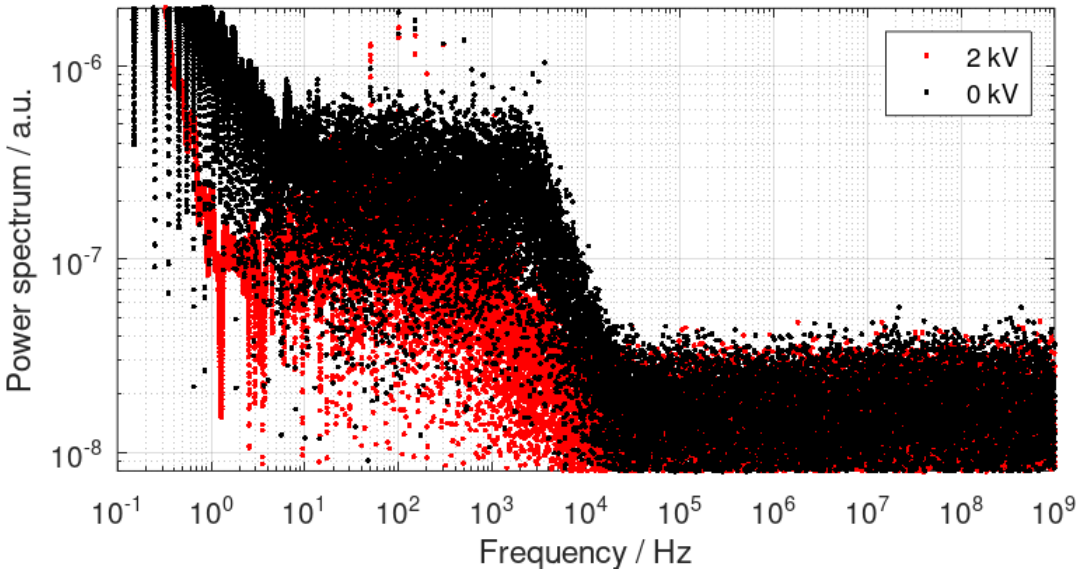
Experimental results from operation with beam
Dedicated MDE 29.11.2023

- Spectrum of extracted beam
- Improvement for all frequencies



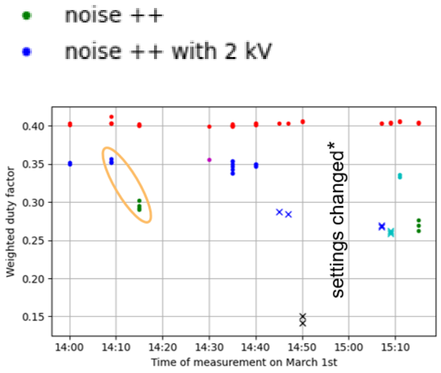
Experimental results from operation with beam
Dedicated MDE 29.11.2023

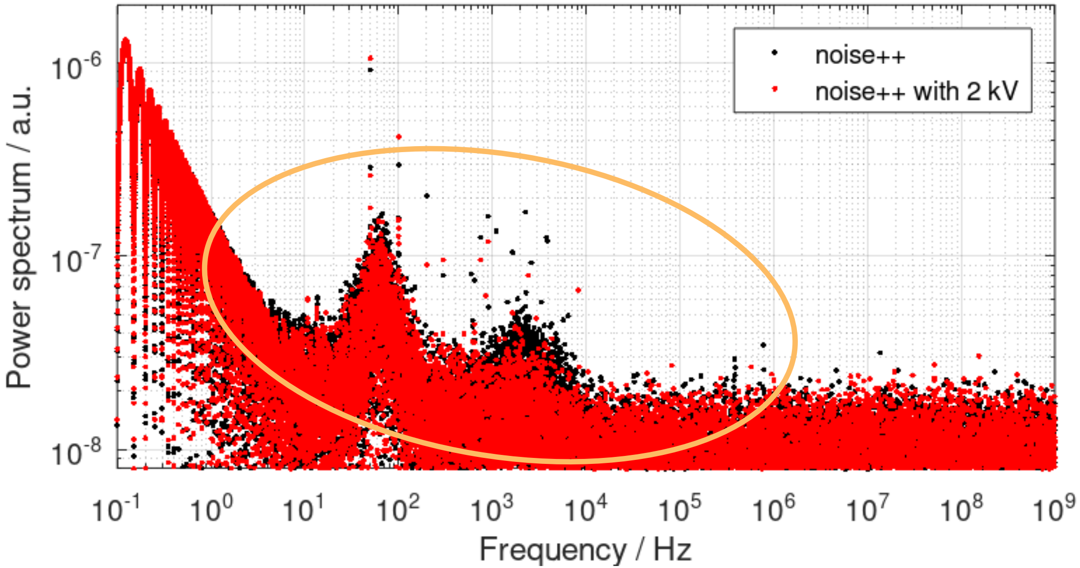
- Spectrum of extracted beam
- Improvement for all frequencies



Experimental results from operation with beam
Parasitic Operation HADES Beam Time

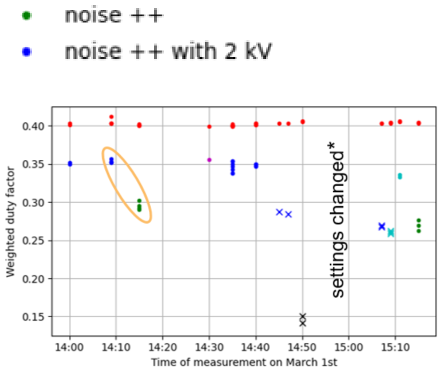
- Fourier series – „noise ++“ vs. „noise ++ with 2 kV“

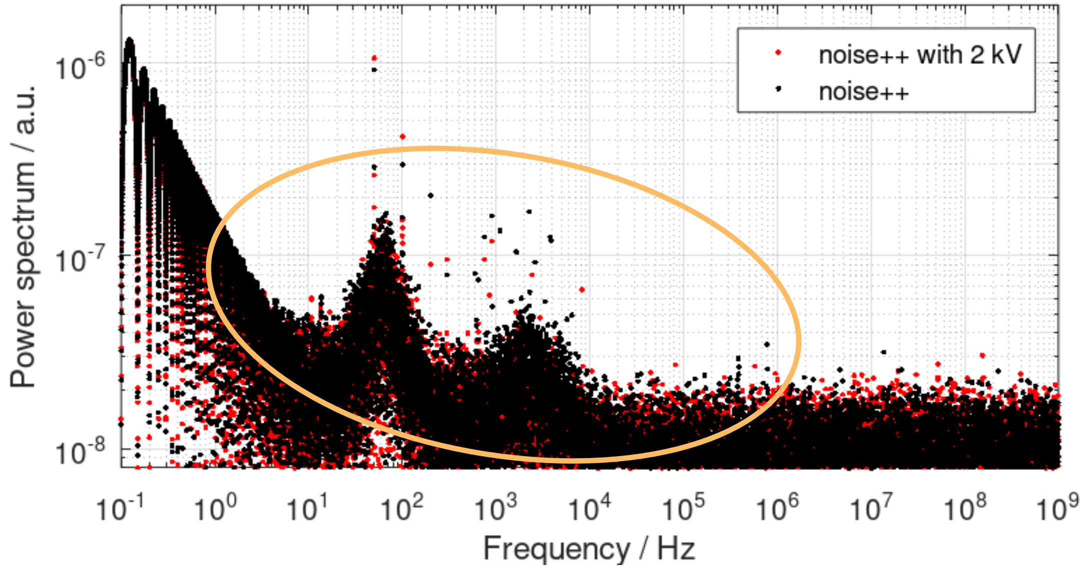




Experimental results from operation with beam
Parasitic Operation HADES Beam Time

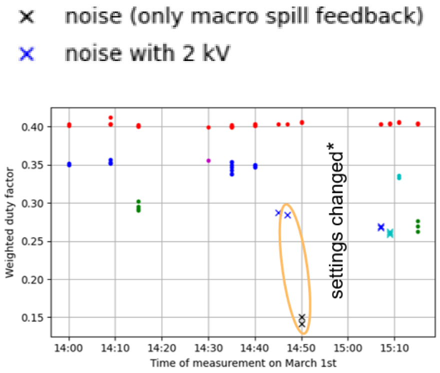
- Fourier series – „noise ++“ vs. „noise ++ with 2 kV“

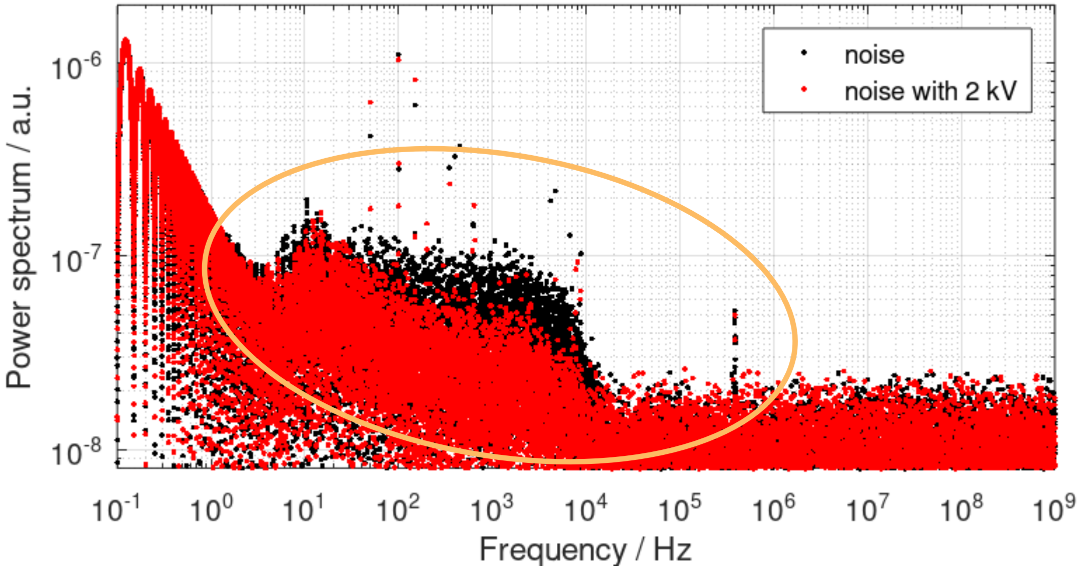




Experimental results from operation with beam
Parasitic Operation HADES Beam Time

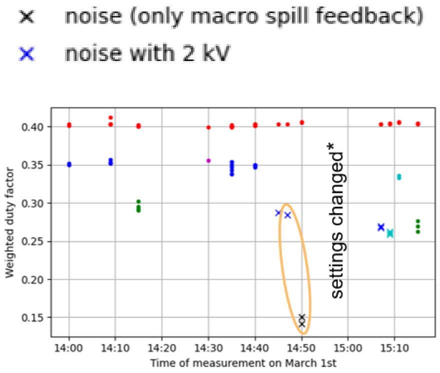
- Fourier series – „noise“ vs. „noise with 2 kV“

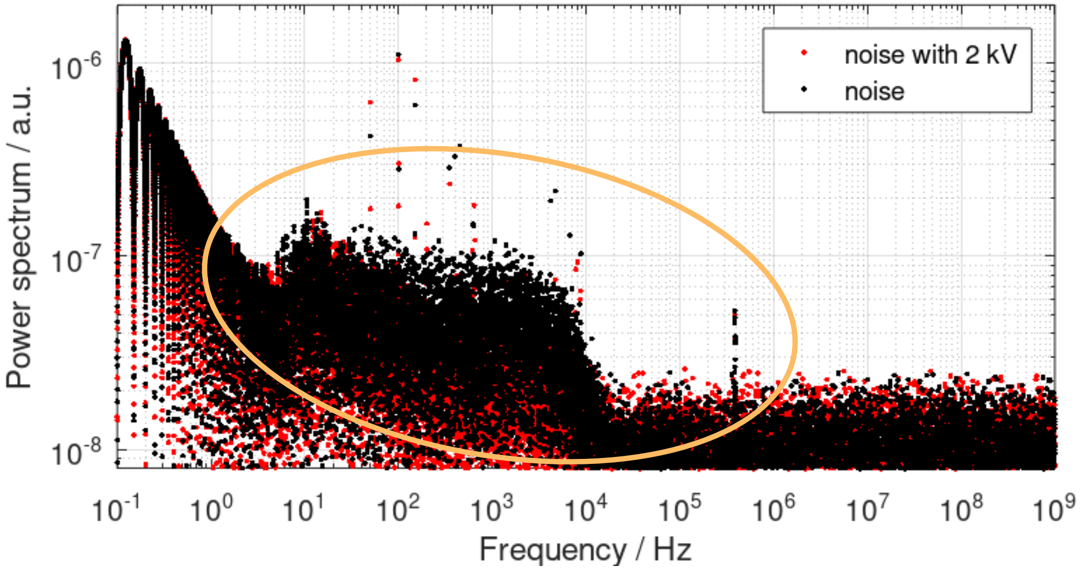




Experimental results from operation with beam
Parasitic Operation HADES Beam Time

- Fourier series – „noise“ vs. „noise with 2 kV“





Experimental results from operation with beam
Dedicated MDE 29.11.2023

- Different Settings

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]	
Langsame Extraktion		
E-Septum Korrekturwinkel	-2.5	mrad
Extraktionszeit	8000.0	ms
DG Trigger Verschiebung (relativ)	0.5	
Spillmitte	0.65	
Spillamplitude	0.8	
Spillform	0.0	
Sextupol Amplitude	0.04	
Sextupol Phase	40.0	deg
DQH total (Slow)	0.03	
DQH pre (Slow)	0.0054	
DQH spill (Slow)	0.0048	
Spill Abbruch erlaubt	✔	

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]	
Langsame Extraktion		
E-Septum Korrekturwinkel	-2.5	mrad
Extraktionszeit	8000.0	ms
DG Trigger Verschiebung (relativ)	0.5	
Spillmitte	0.65	
Spillamplitude	0.8	
Spillform	0.0	
Sextupol Amplitude	0.04	
Sextupol Phase	40.0	deg
DQH total (Slow)	0.03	
DQH pre (Slow)	0.0061	
DQH spill (Slow)	0.0065	
Spill Abbruch erlaubt	✔	