HCI analysis status

AEGIS Collaboration meeting May 2024

Fredrik PG

Highly Charged Ions (HCIs)

- HCIs are atoms stripped of most or all their electrons.
- Exhibit extreme electromagnetic properties:
  - Ideal for test of strong field QED
  - Enhanced sensitivity to nuclear structure (QCD)
- Radioactive HCIs have supressed decay:
  - Electron capture no longer possible (Weak interaction studies)

RESEARCH BRIEFINGS | 04 October 2023

Testing the limits of the standard model of particle physics with a heavy, highly charged ion

PAPER • OPEN ACCESS

Perspectives on testing fundamental physics with highly charged ions in Penning traps

K Blaum[1], S Eliseev[2,1] and S Sturm[1]

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Quantum Science and Technology, Volume 6, Number 1

Focus on Quantum Sensors for New-Physics Discoveries

Citation K Blaum *et al* 2021 *Quantum Sci. Technol.* **6** 014002

Article | Published: 29 January 2020

Coherent laser spectroscopy of highly charged ions using quantum logic

P. Micke, T. Leopold, S. A. King, E. Benkler, L. J. Spieß, L. Schmöger, M. Schwarz, J. R. Crespo López-Urrutia & P. O. Schmidt

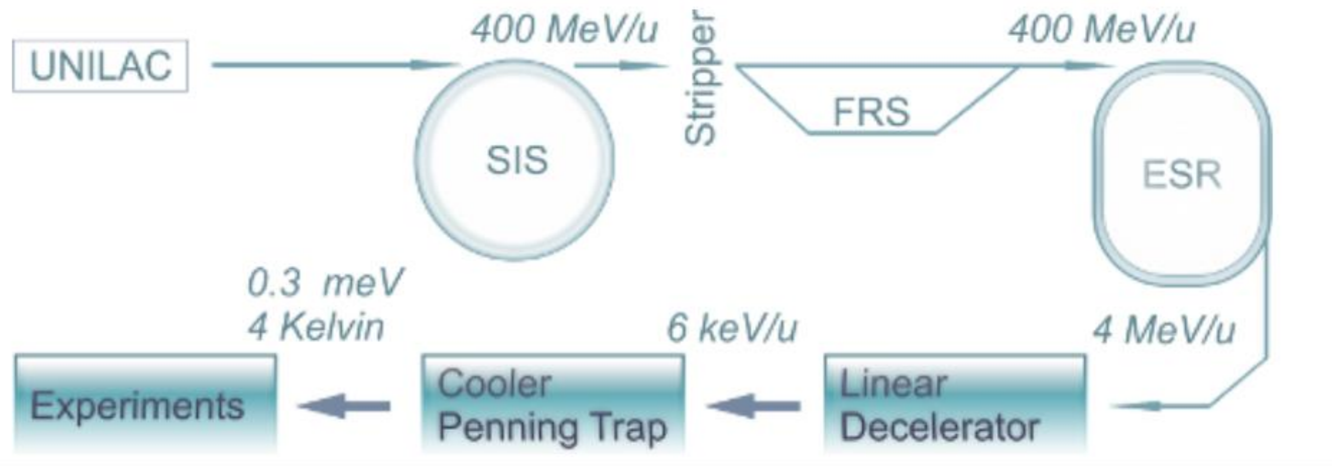
Nature **578**, 60–65 (2020) | Cite this article

Electroweak Decay Studies of Highly Charged Radioactive Ions with TITAN at TRIUMF

by Kyle G. Leach[1,*], Iris Dillmann[2], Renee Klawitter[2,3], Erich Leistenschneider[2,4], Annika Lennarz[2], Thomas Brunner[2,5], Dieter Frekers[6], Corina Andreoiu[7], Anna A. Kwiatkowski[2] and Jens Dilling[2]

Traditional HCI formation at radioactive beam facilities:

High energy beam through stripper foil:



Electron beam ionization:

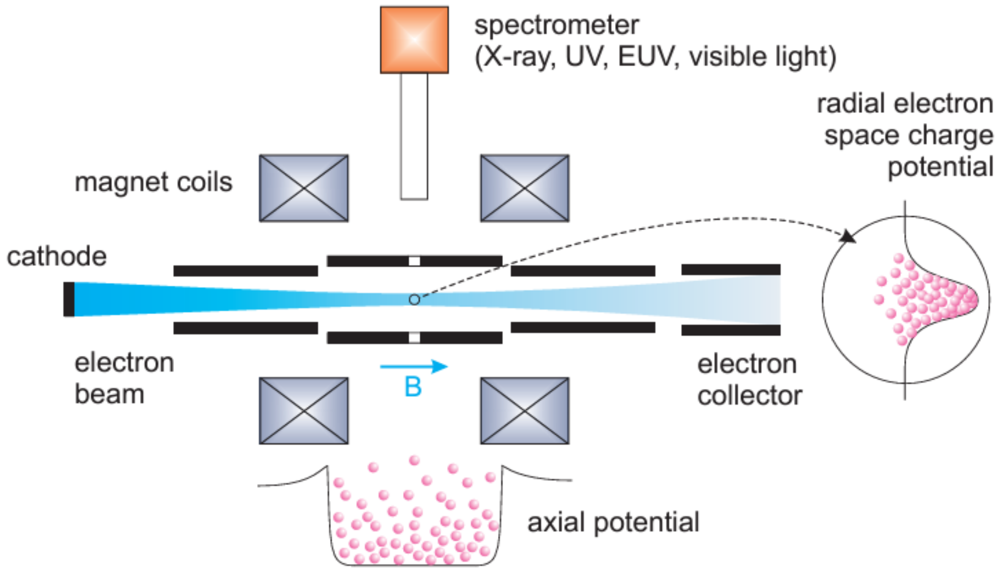


Fig. 2: Principle of operation of an EBIS

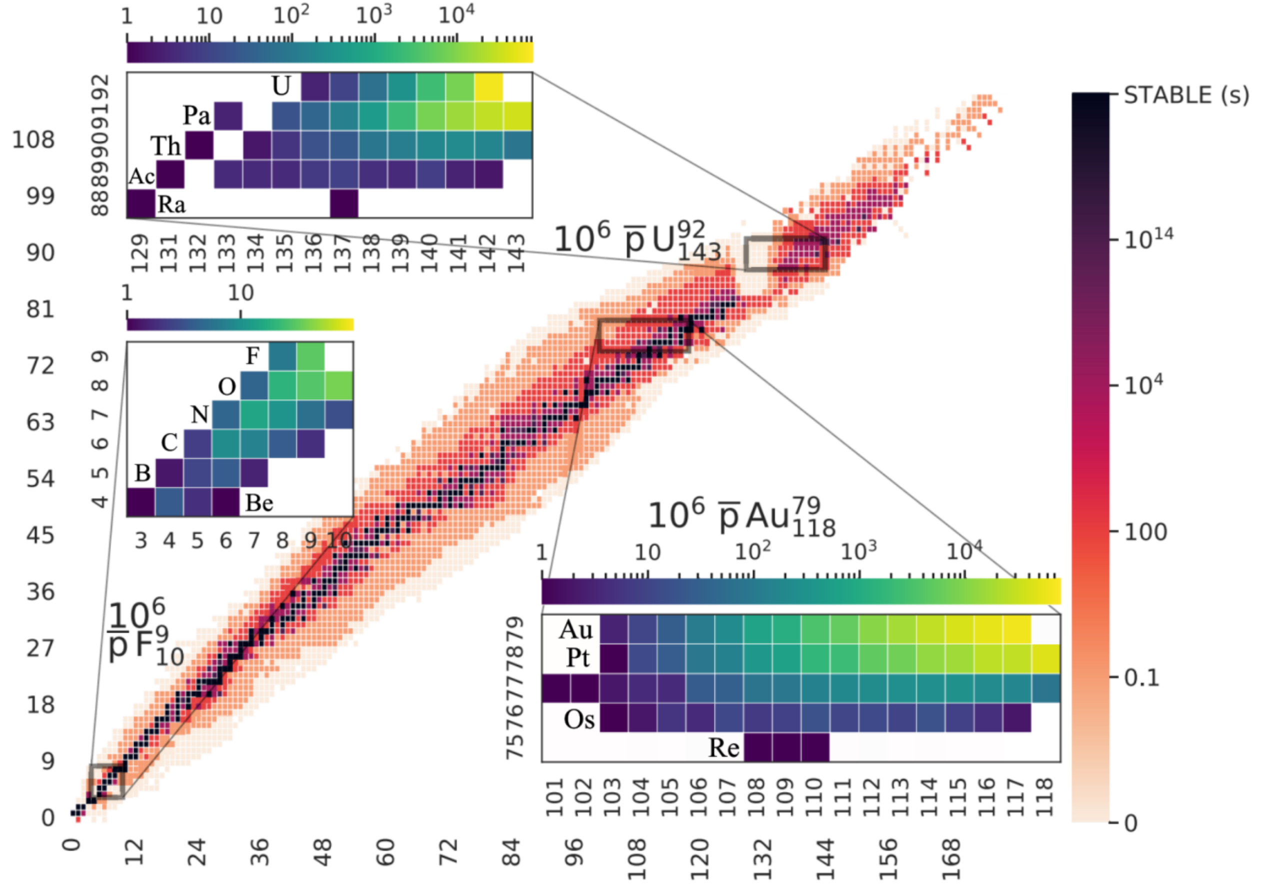
Zschornacka, G., M. Schmidt, and A. Thorn. "Electron beam ion

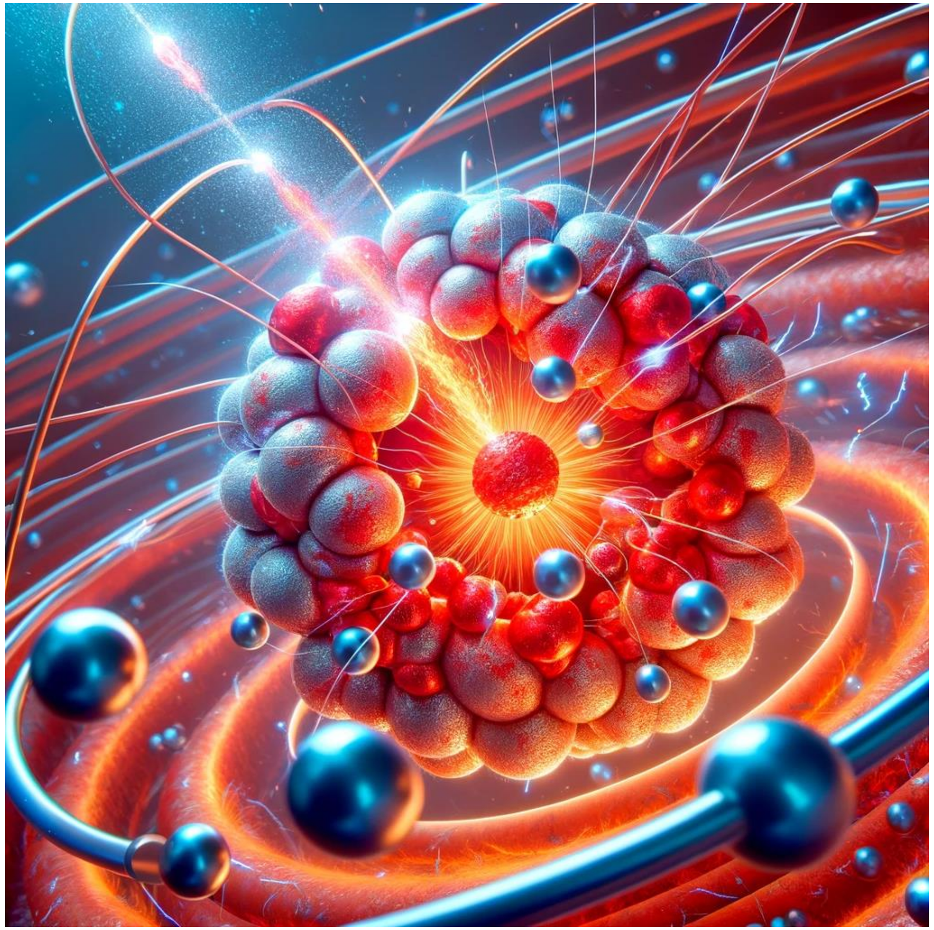
Radioactive HCI formation using antiprotons?

Synthesis of cold and trappable fully stripped highly charged ions via antiproton-induced nuclear fragmentation in traps

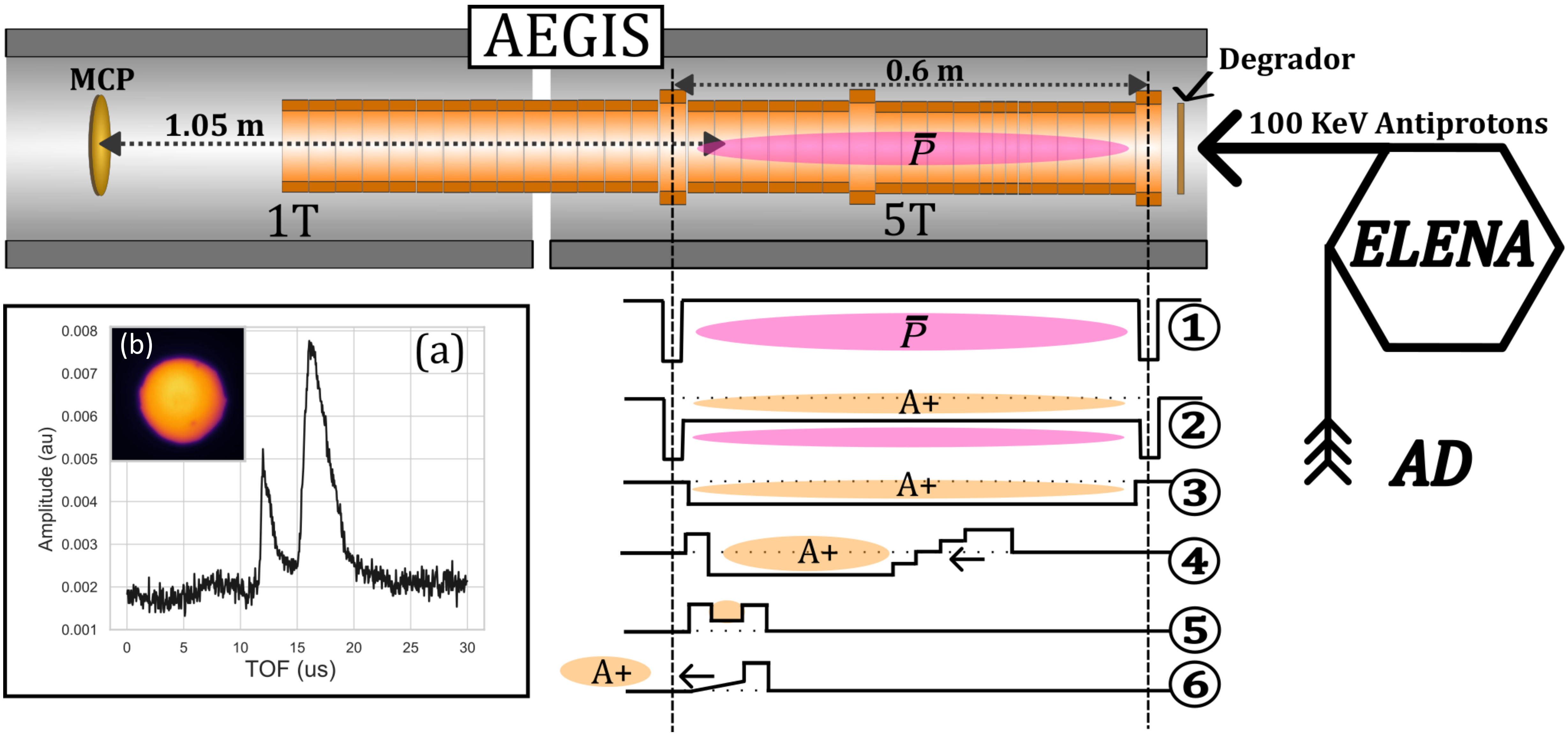
G. Korṅakov, G. Cerchiari, J. Zieliński, L. Lappo, G. Sadowski, and M. Doser

Phys. Rev. C **107**, 034314 – Published 23 March 2023





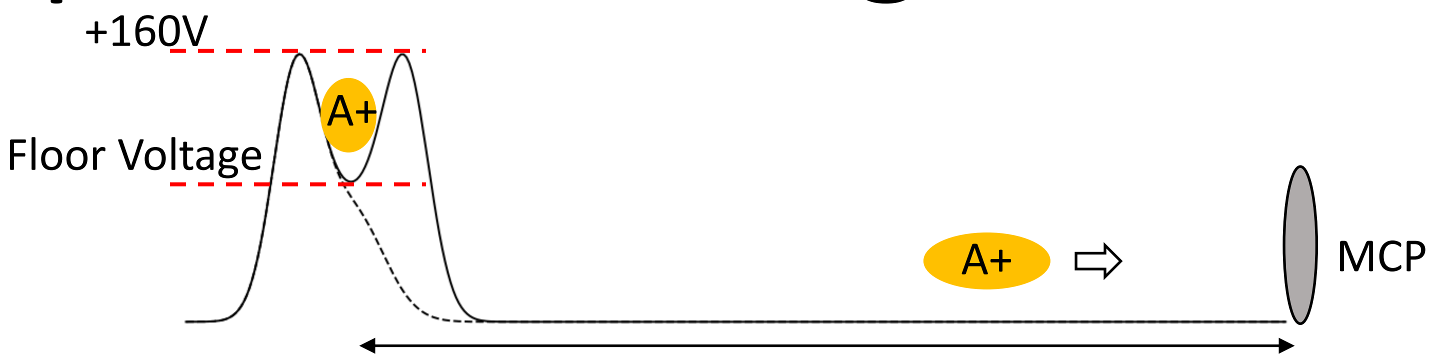
Overview of the fragment capture procedure

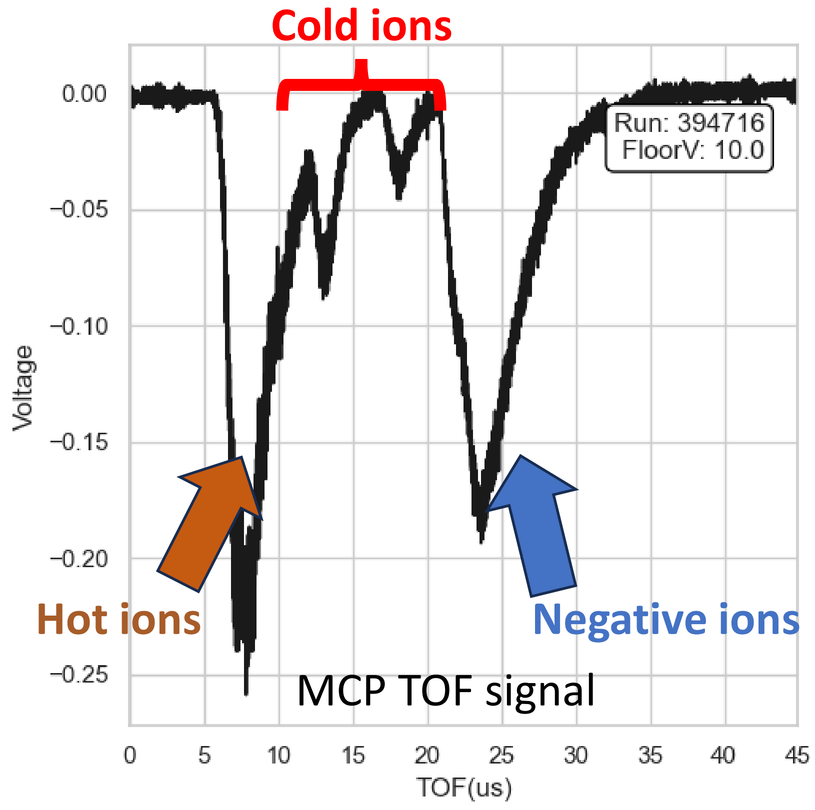


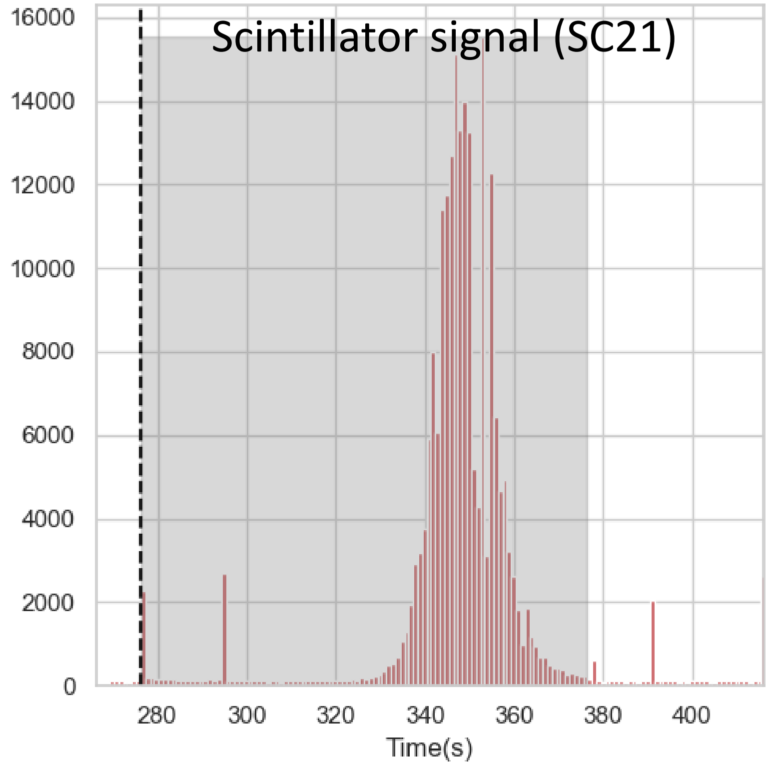
Overview of HCI campaigns in 2023

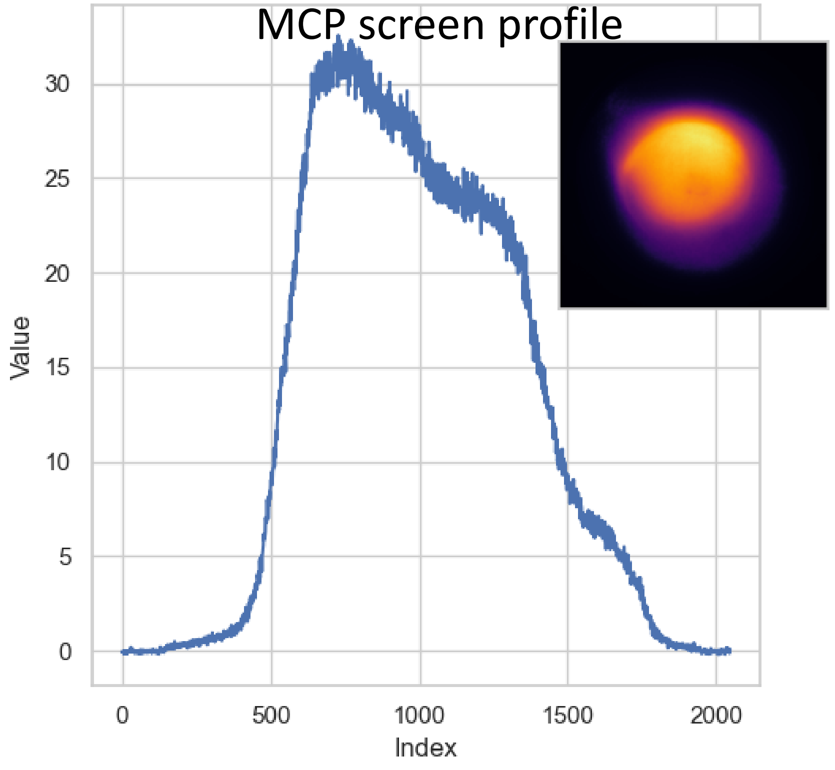
- **Air leak campaign: (3 weeks)**
  - First postive ion signal.
  - Techniques developed for manipulating trapped ions.
  - Barrier scan, Multi-step, MR-TOF procedure.
  - Identifying the energy of the TOF components.
- **Antiproton and electron calibration**:
  - Calibration of TOF spectra.
  - Confirming linearity with mass and energy.
- **Nitrogen campaign**: (36h):
  - Clean nitrogen environment.
  - Confirming HCI formation from nitrogen.

Sample data during air leak campaign

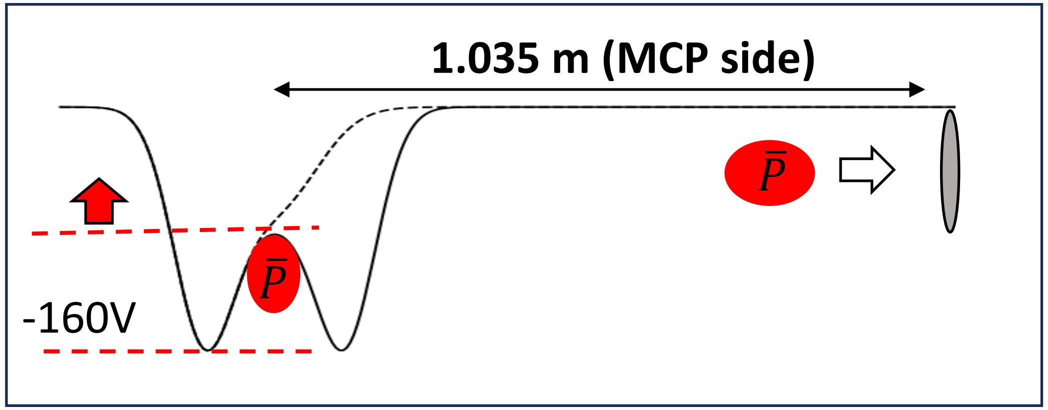


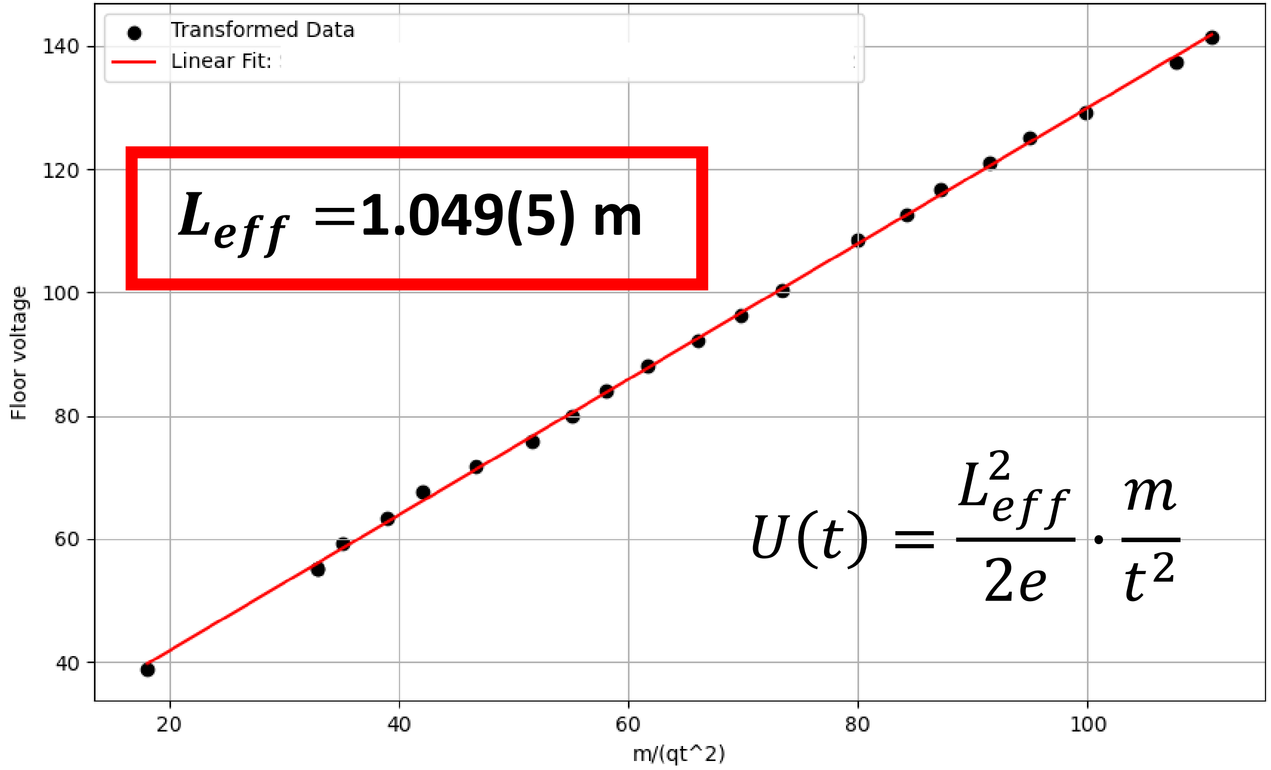


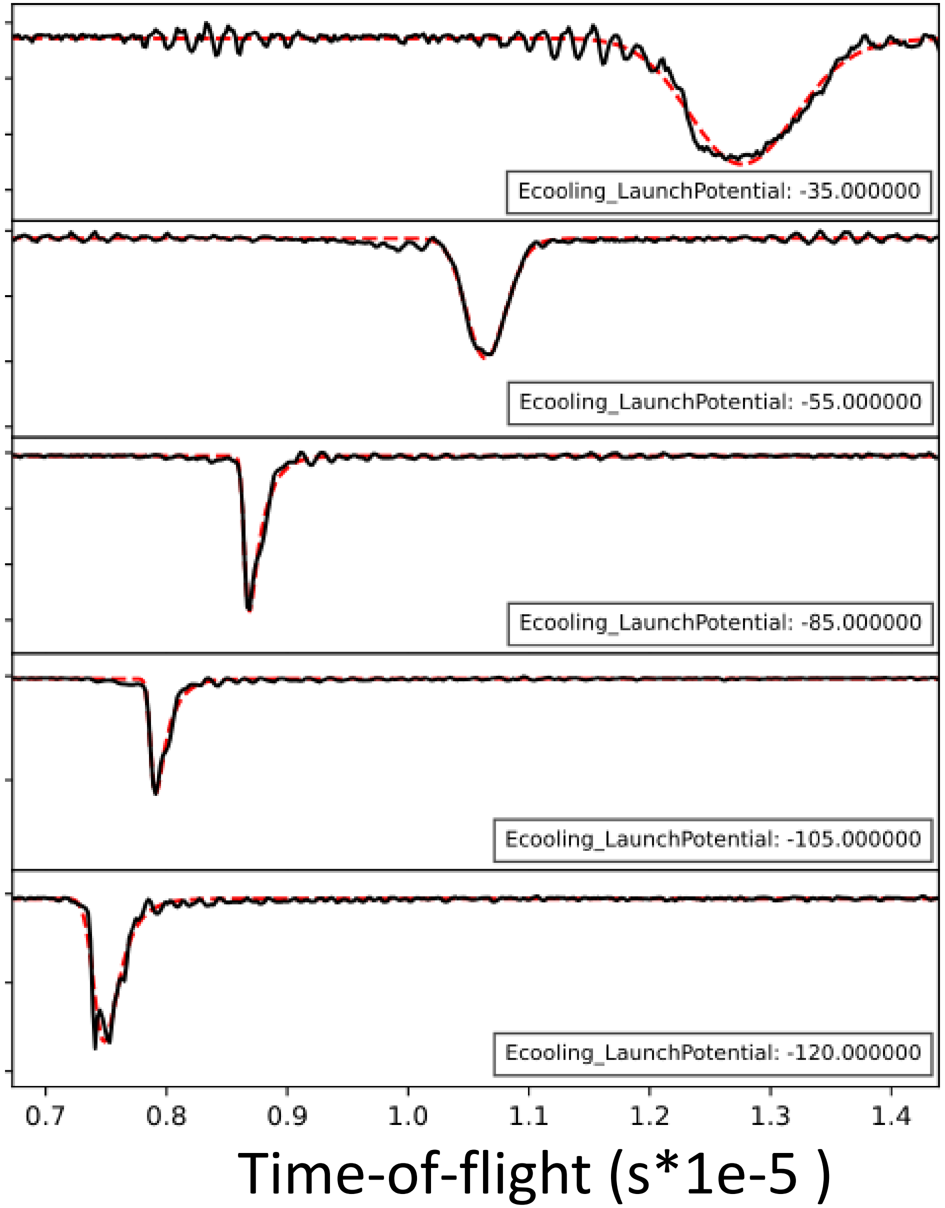




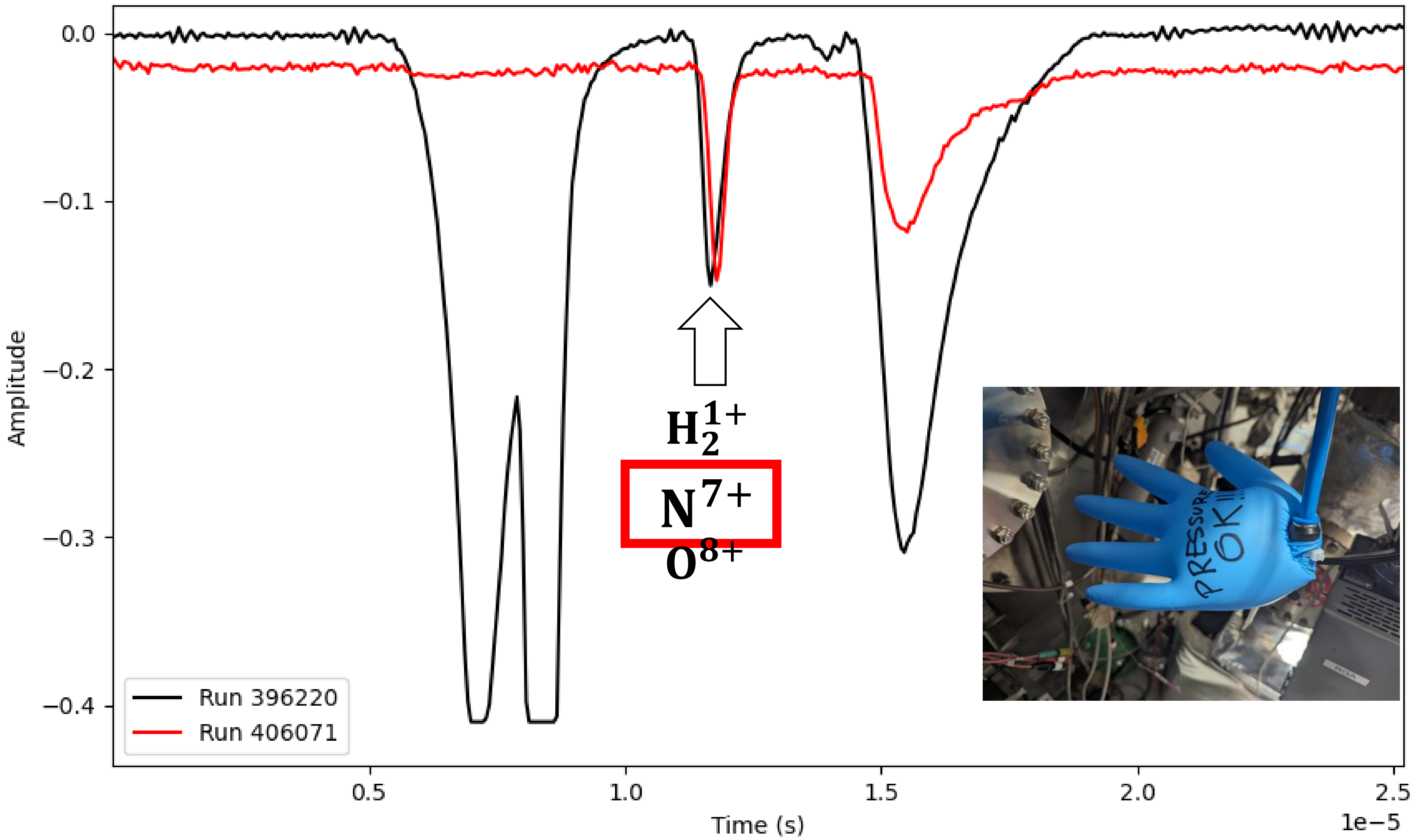
Time-of-flight calibration using Pbars



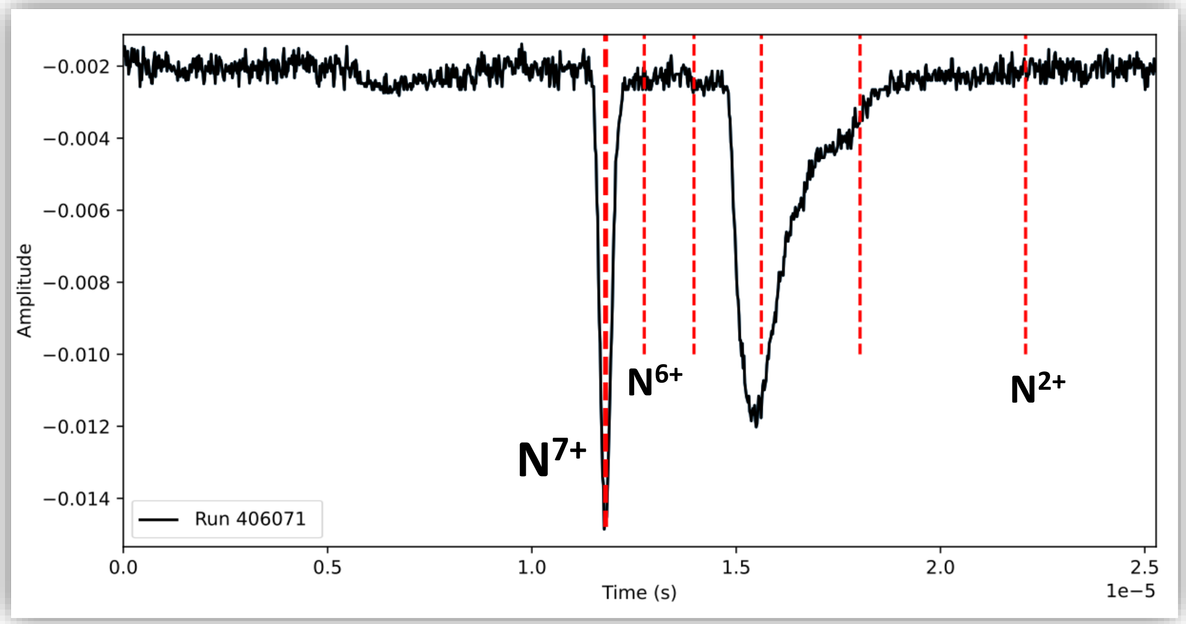


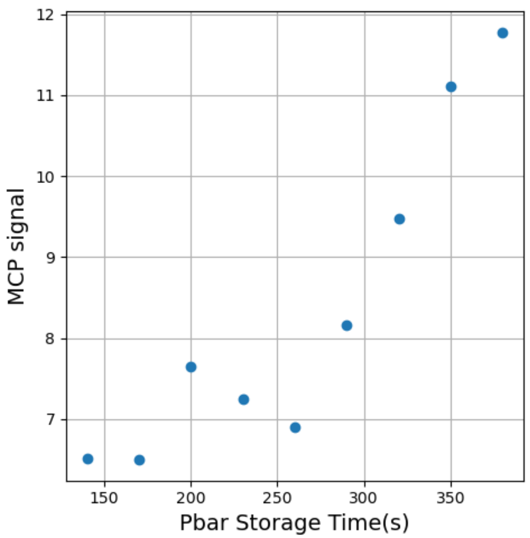


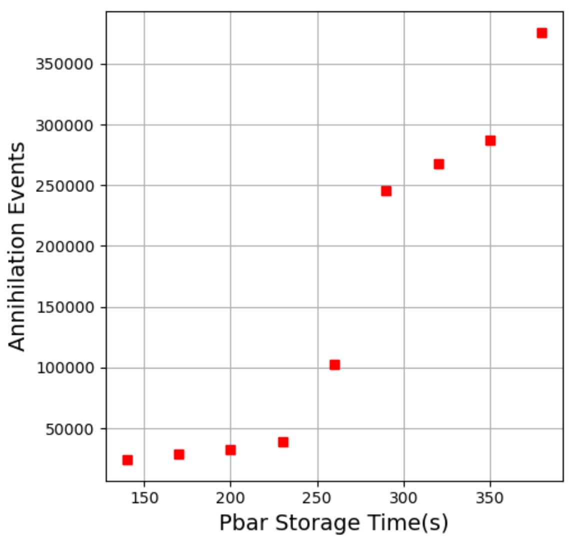
Peak at m/q=2
Fully stripped nitrogen identified?

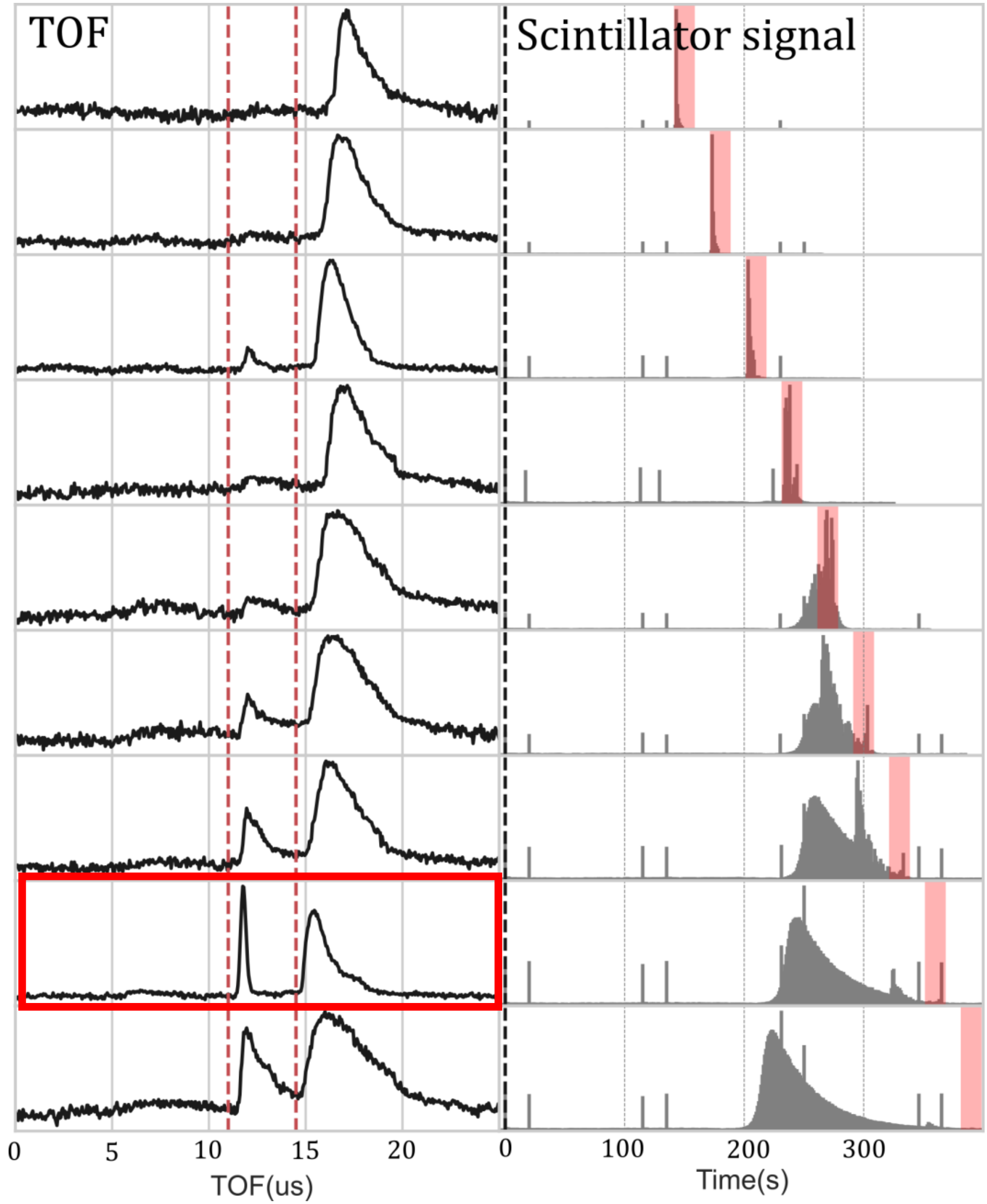


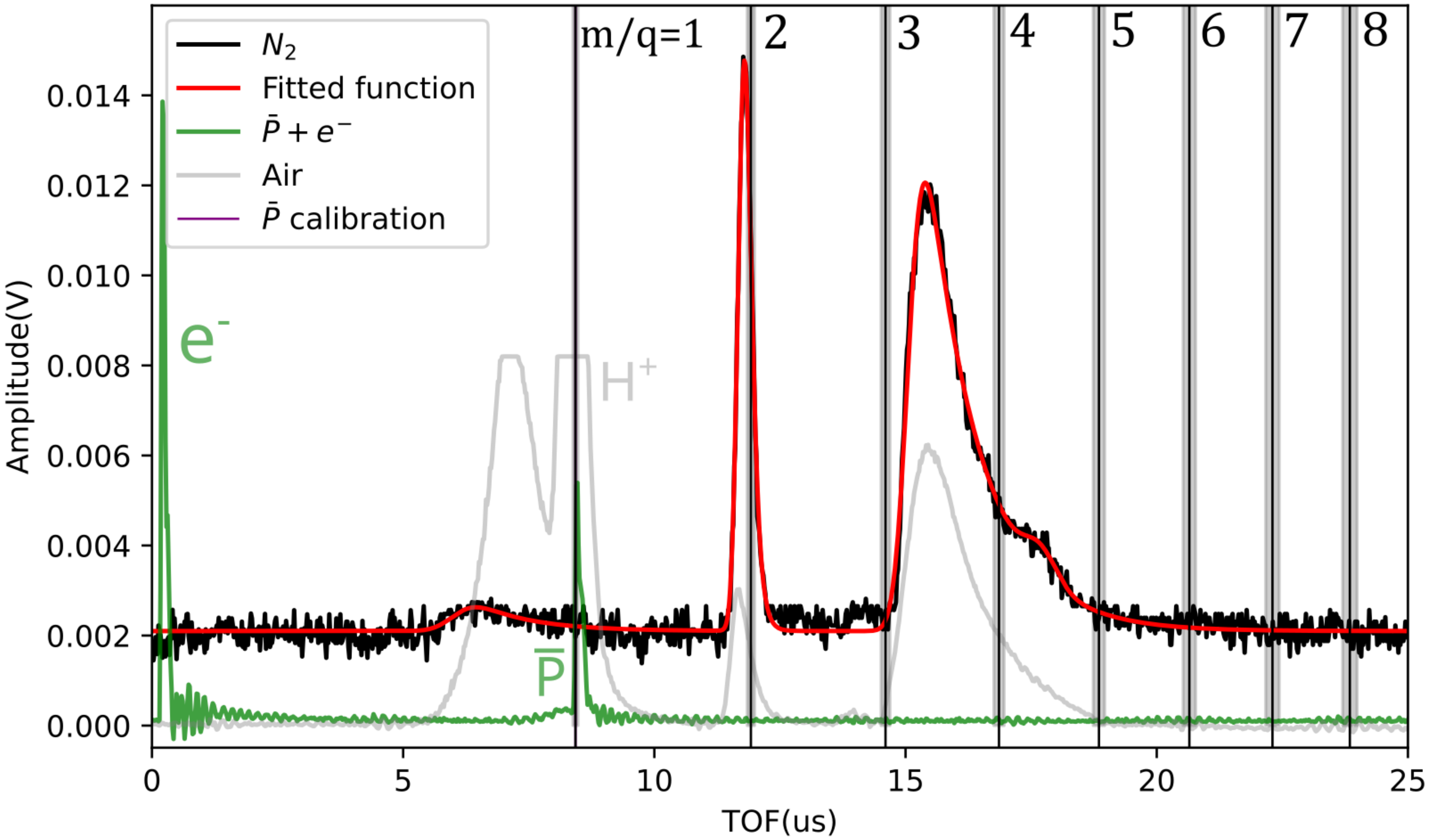
Evolution of formation







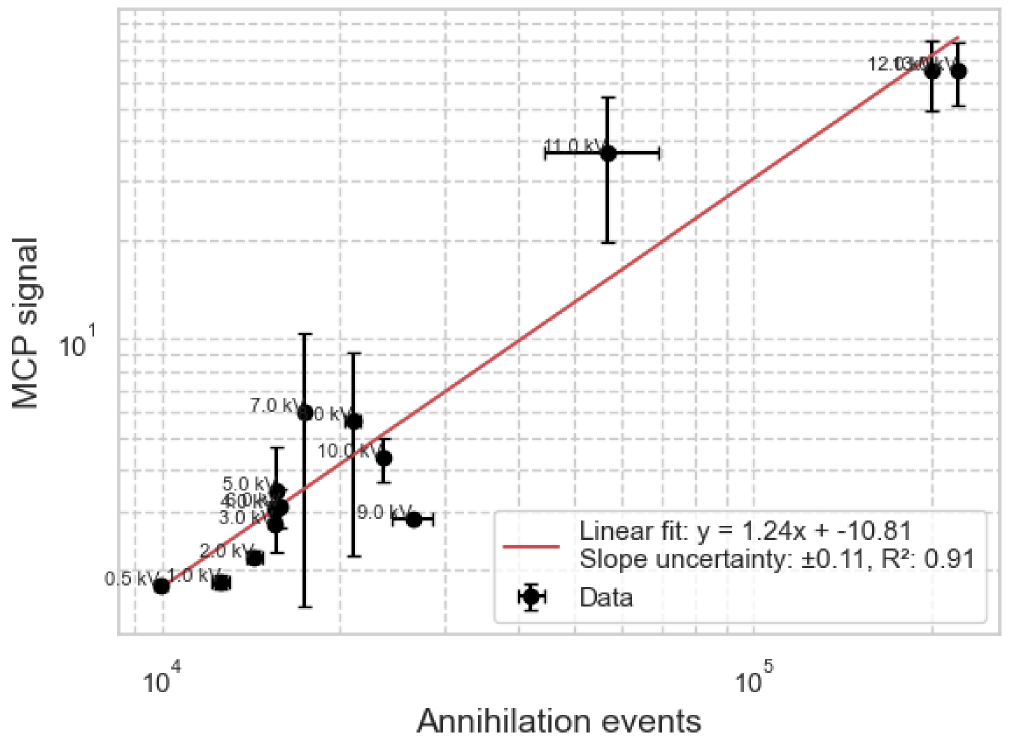


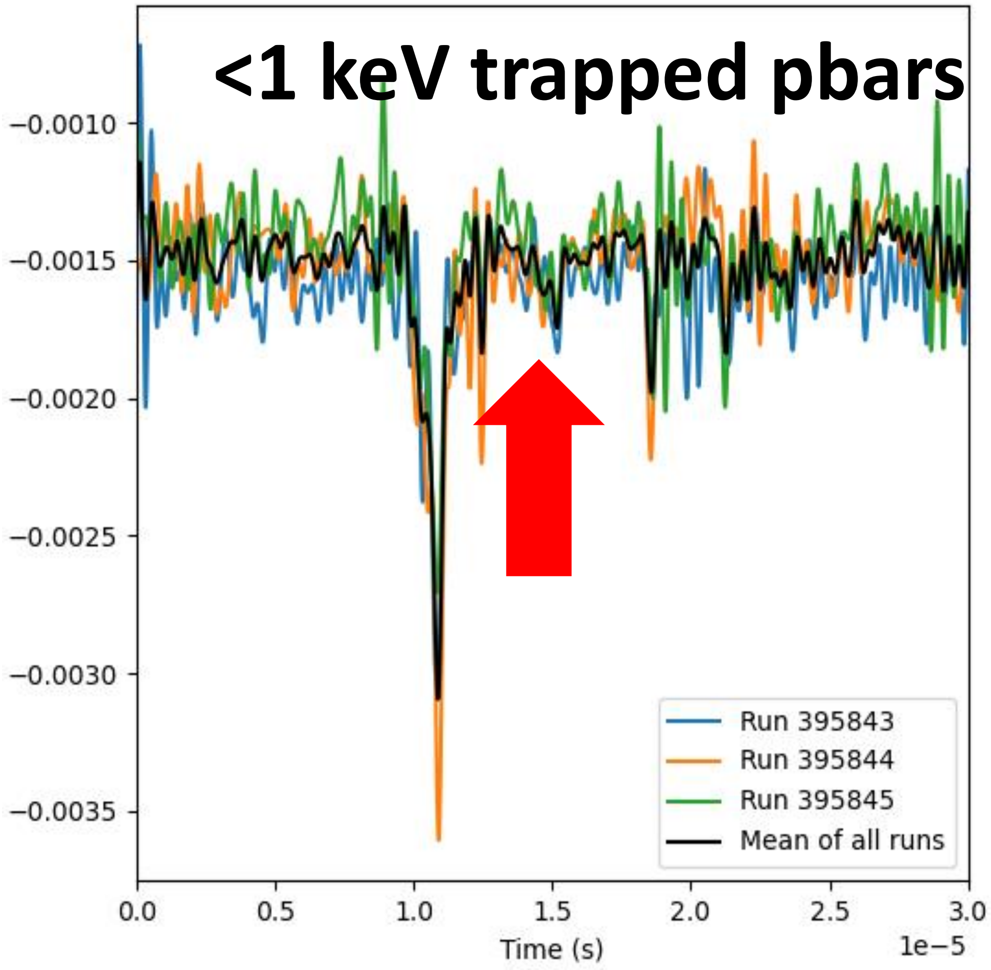


N2
Fitted function
P̄ + e⁻
Air
P̄ calibration
m/q=1
2
3
4
5
6
7
8
e-
H+
P̄
Amplitude(V)
0.000
0.002
0.004
0.006
0.008
0.010
0.012
0.014
0
5
10
15
20
25
TOF(us)

Low energy antiproton interactions

Signal of m/q=2 peak vs annihilation event:

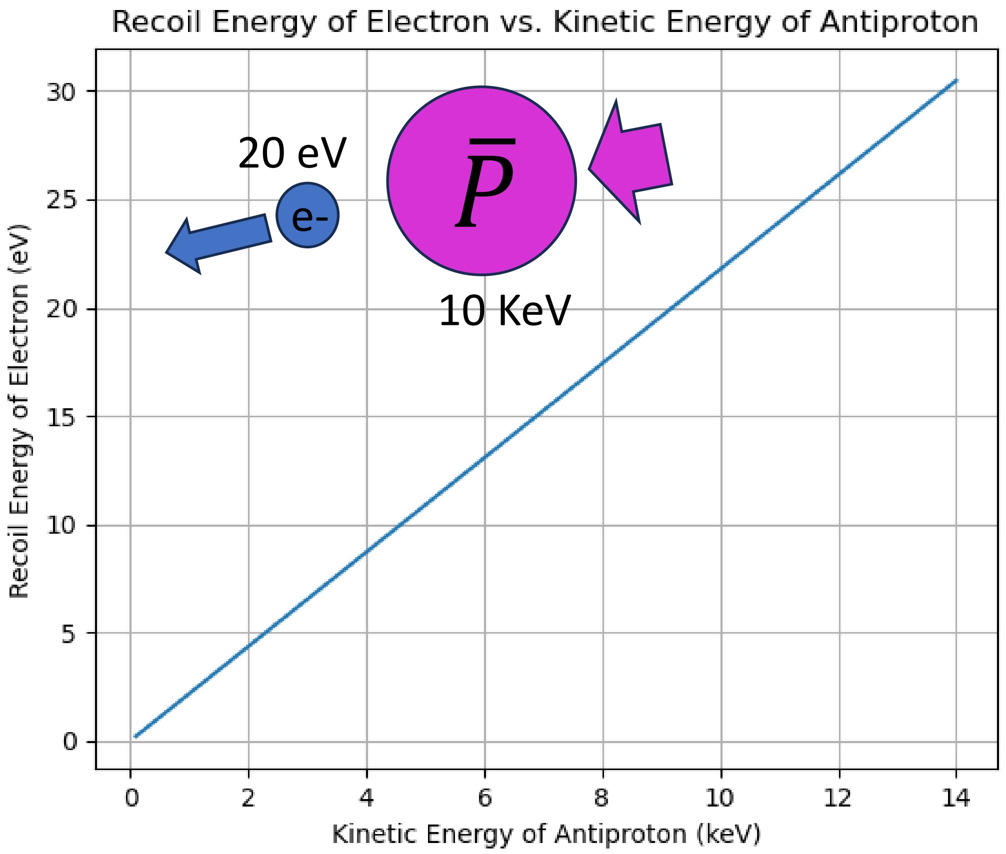


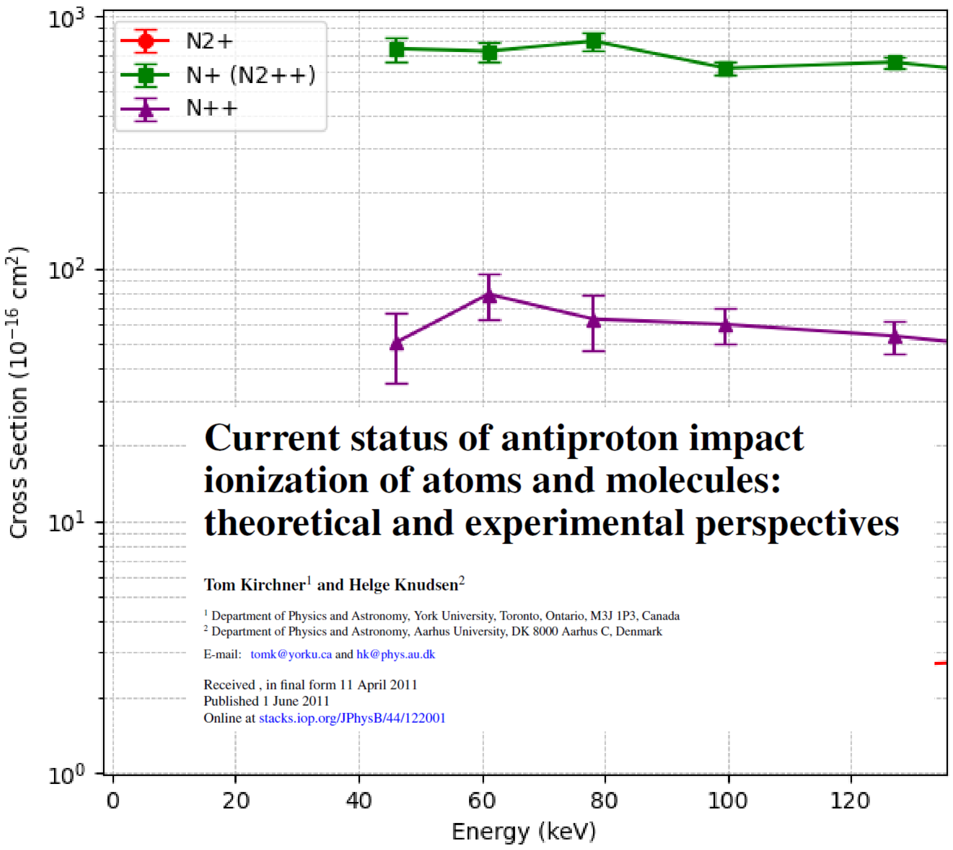


What could result in the formation of m/q=2 from nitrogen?

Collissional ionization with antiprotons?

3000 eV is required to form N^{7+} from the N_2 molecule

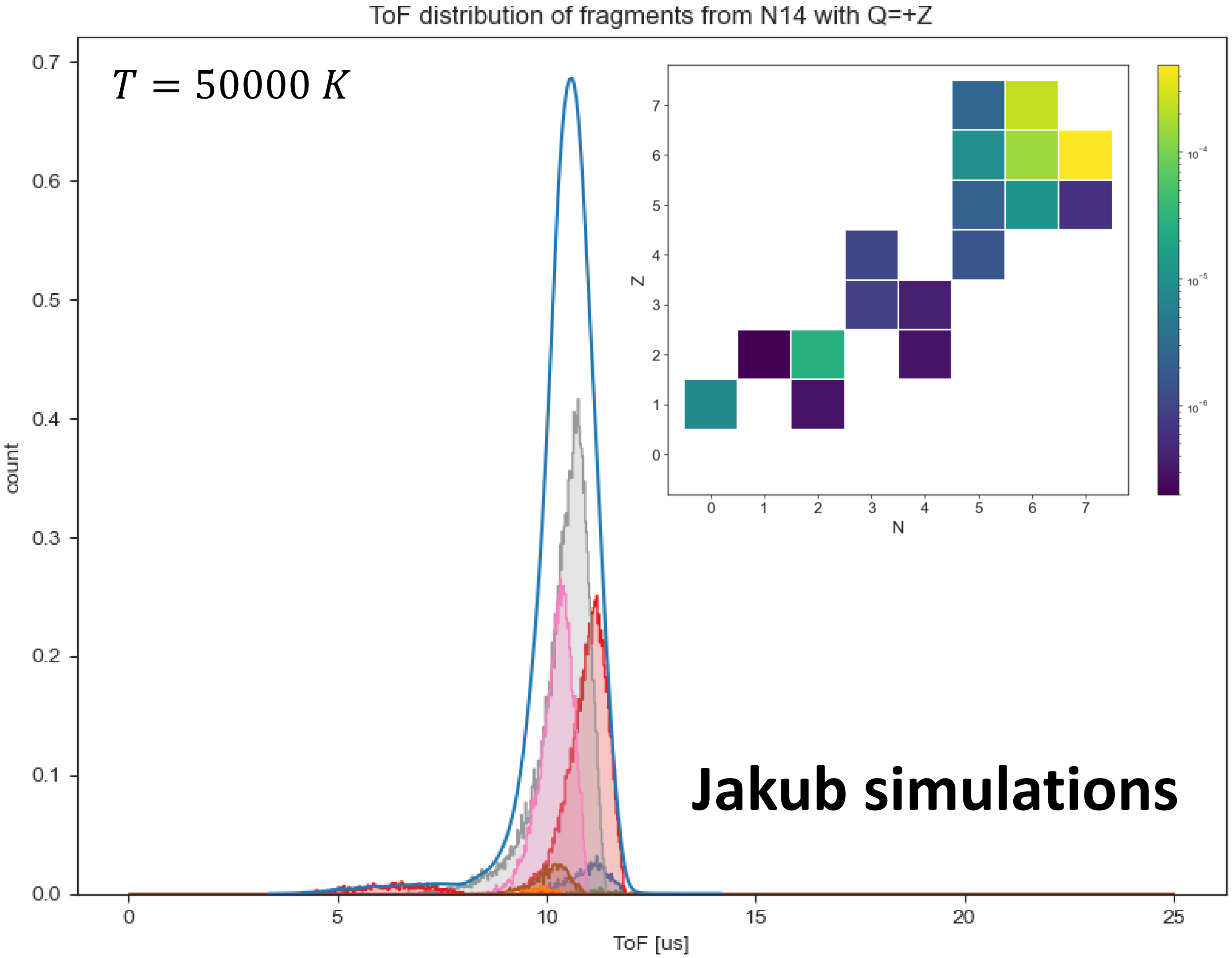


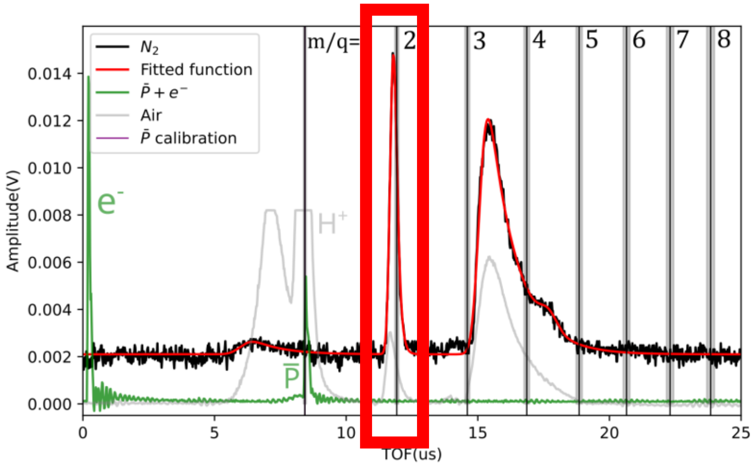


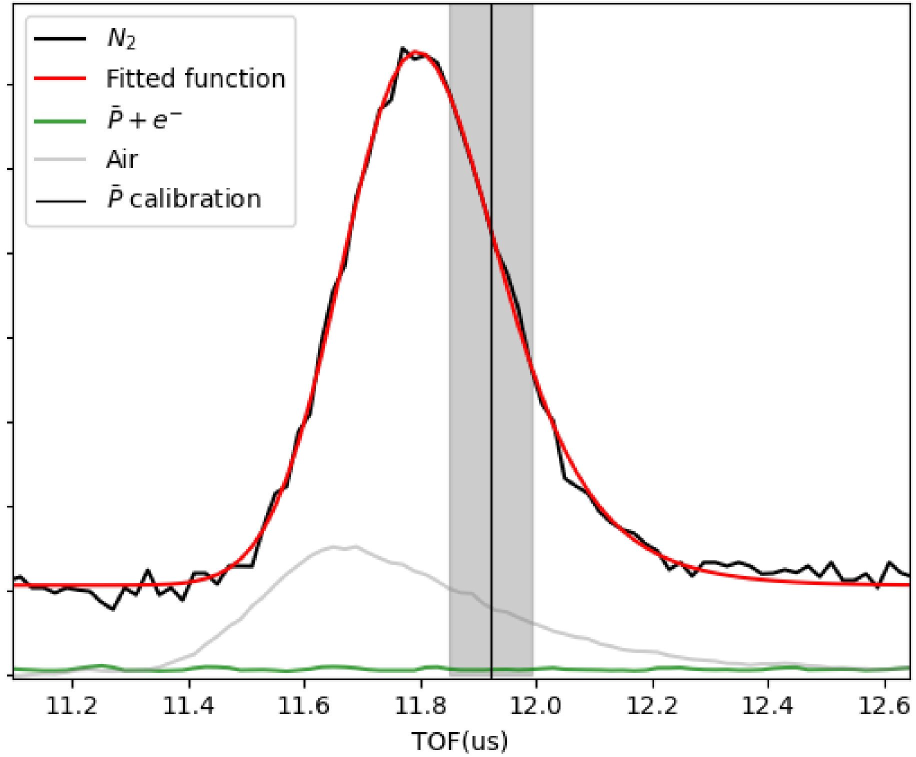
Could electrons accelerated by HV electrodes strip nitrogen?

Simulation by Bharat using CST in progress...

Nuclear fragments?





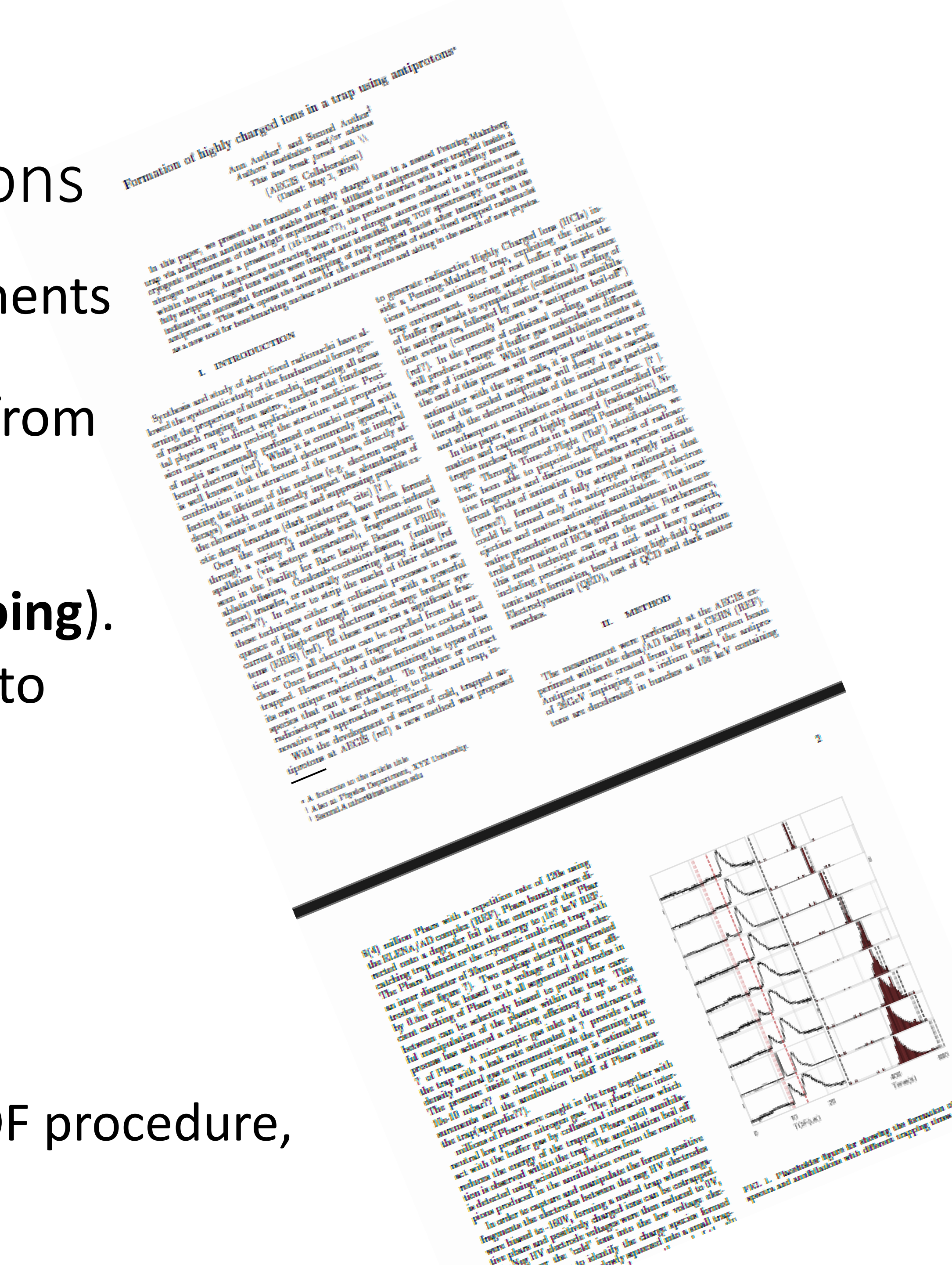


Could fully stripped fragments be formed from impact with high energy recoil fragments?

Proof-of-Principle paper:

Formation of HCIs in a trap with antiprotons

- Introducing possibilities of trapping nuclear fragments from annihilation.
- Presenting mechanism for trapping HCIs formed from Pbar annihilation with N_2 gas.
- Identification of TOF spectra.
- Discussing origins of formation (**Simulations ongoing**).
- Concluding with most likely origin. Opening door to community to investigate further.
- **Suggested Journals: PRL, Scientific reports..**

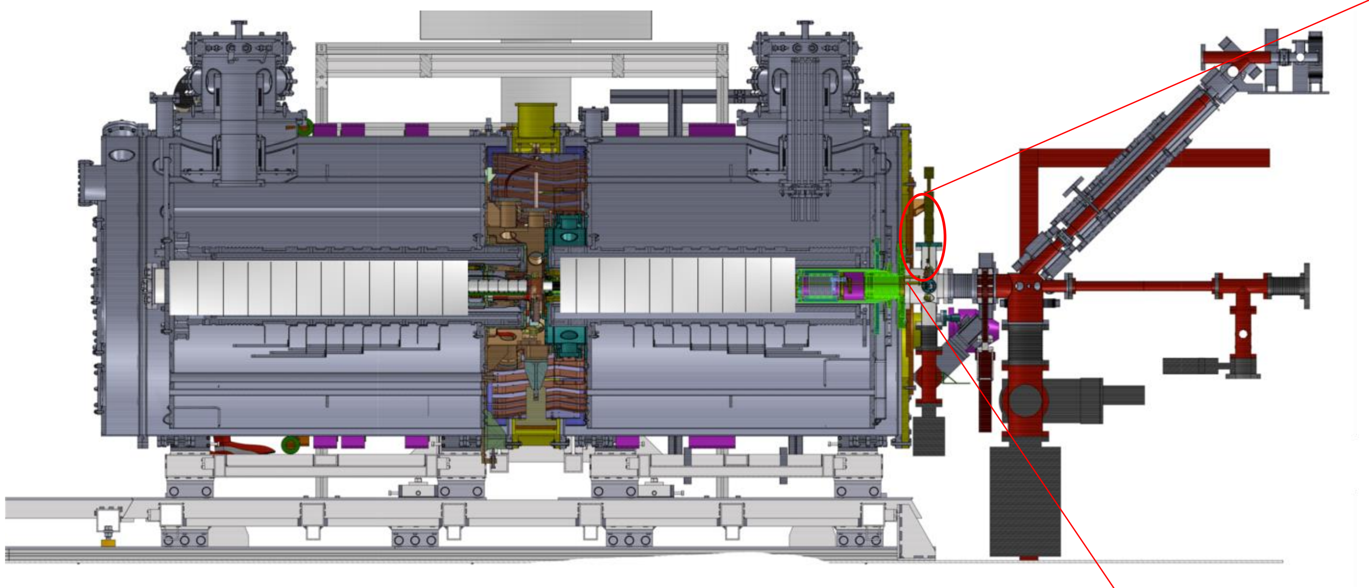


Technical paper:

- Detailed technical report.
- Nested trap procedure, Ion manipulation, MR-TOF procedure, future improvements.. **analysis ongoing..**

Outlook

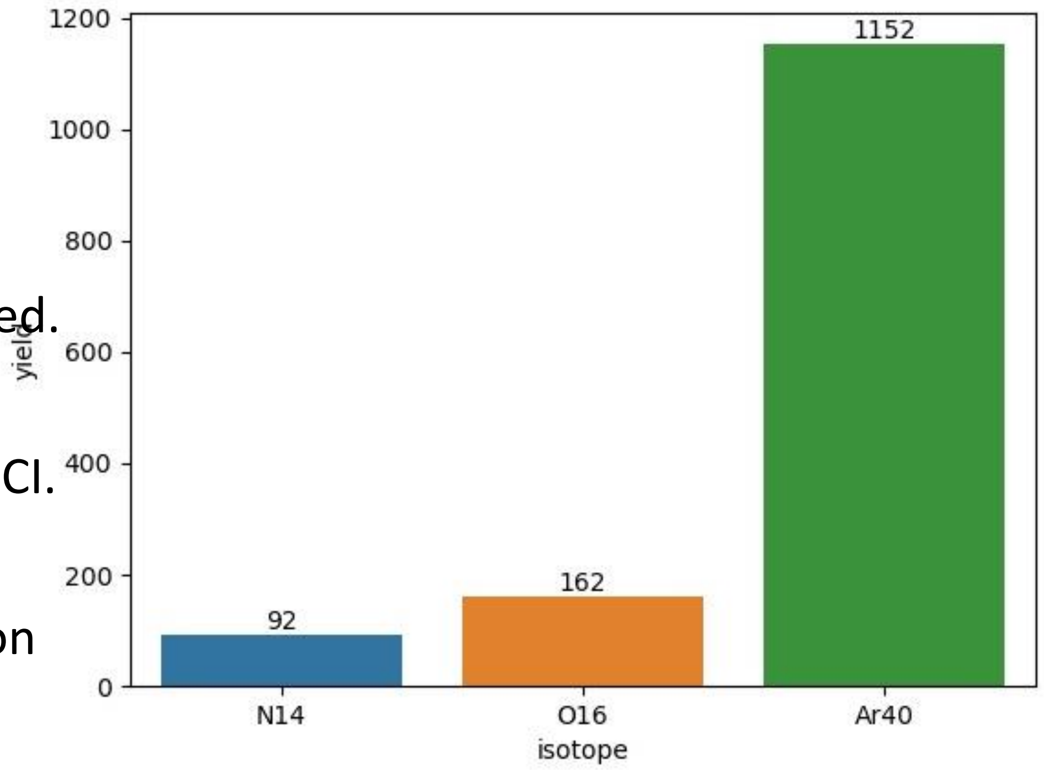
Gas injection valve installed



Controlled injection of gas into AEGIS

Suggested measurements for 2024

- **Argon (A=40):**
  - 10x capture yield fragment yield expected
  - Formation of 18+ very difficult with collissions.
- **Helium (A=4)**:
  - Reference where we expect minimal fragments trapped.
- **Krypton (A=83):**
  - Heaviest gas available, largest trappable fraction of HCI.
- **Nitrogen (A=14):**
  - For continued technical development, refine resolution and stability.



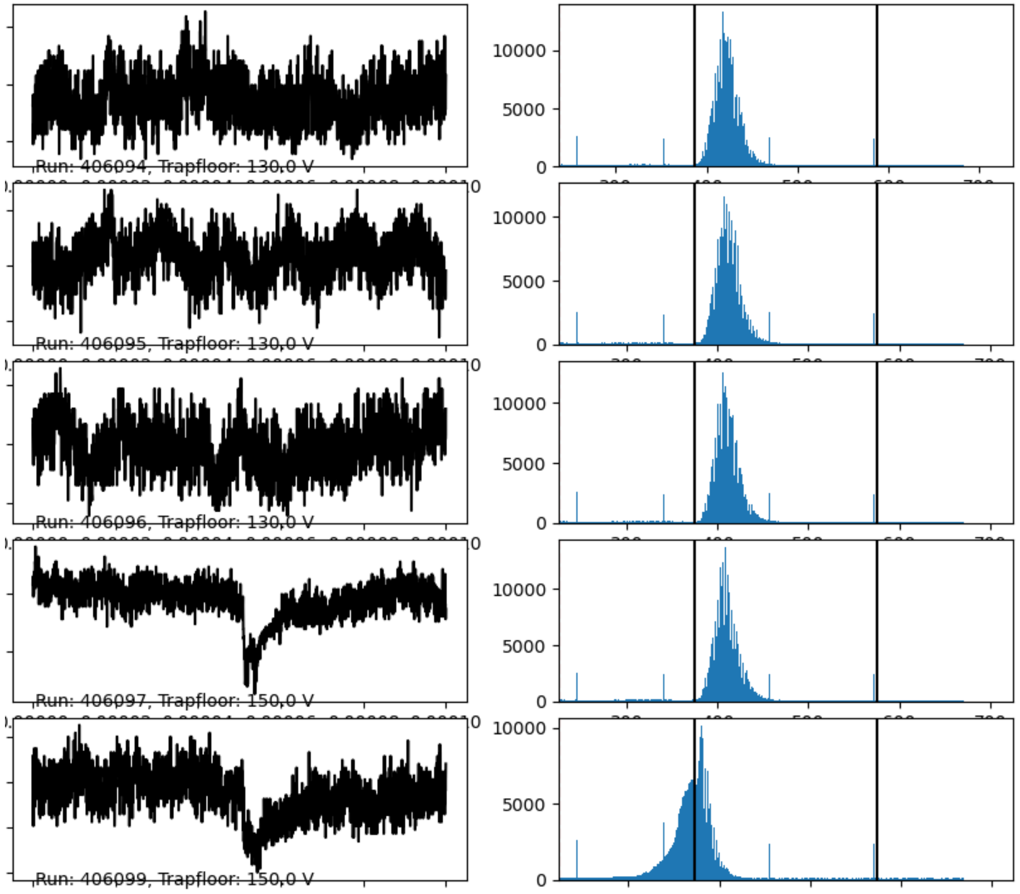
Antiprotonic atom spectroscopy at AEGIS

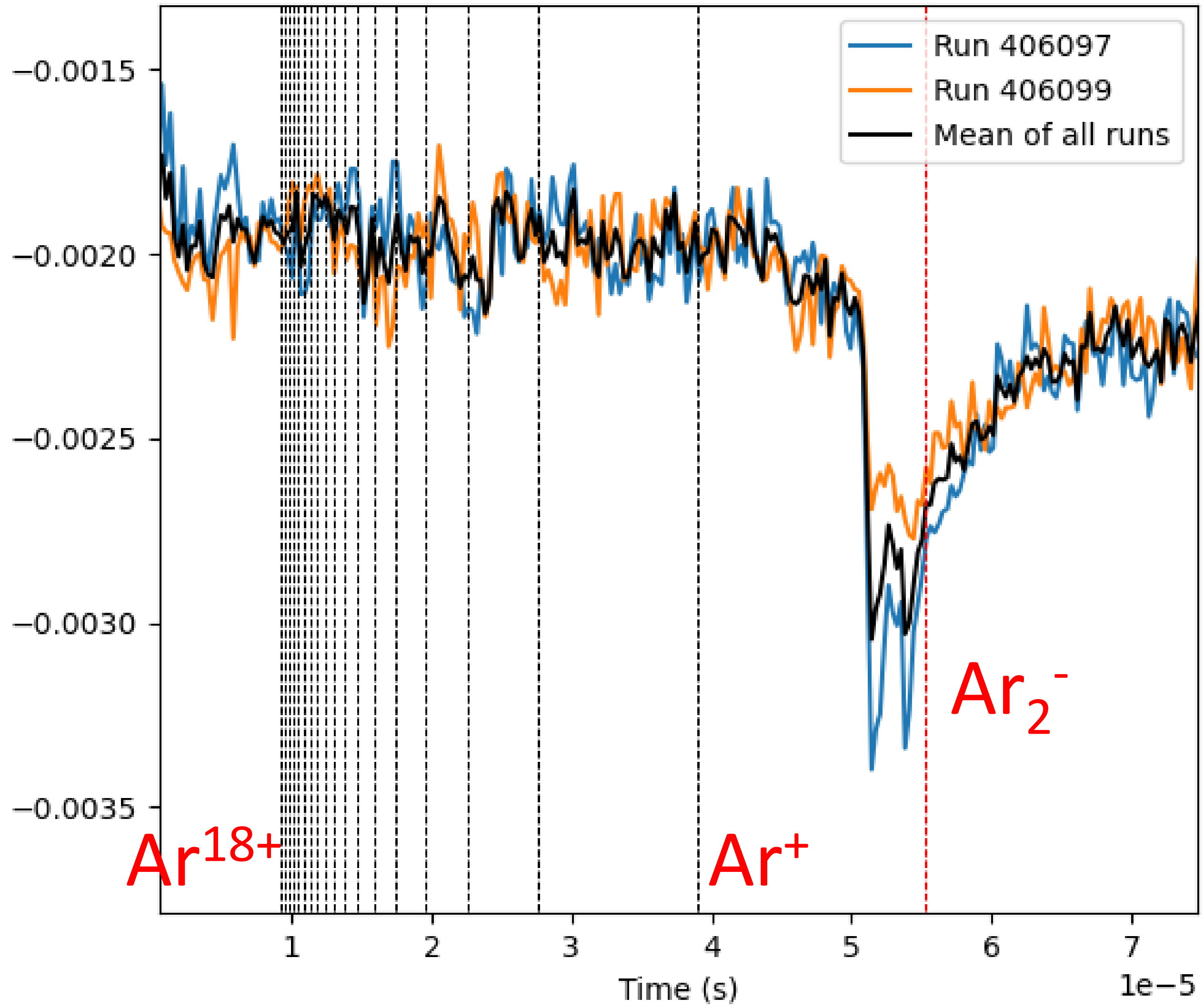
- Continuing LEAR era measurments: Plenty of physics cases!
- Teaching us the procedure for antiprotonic atom x-ray spectroscopy.

Argon run 2023

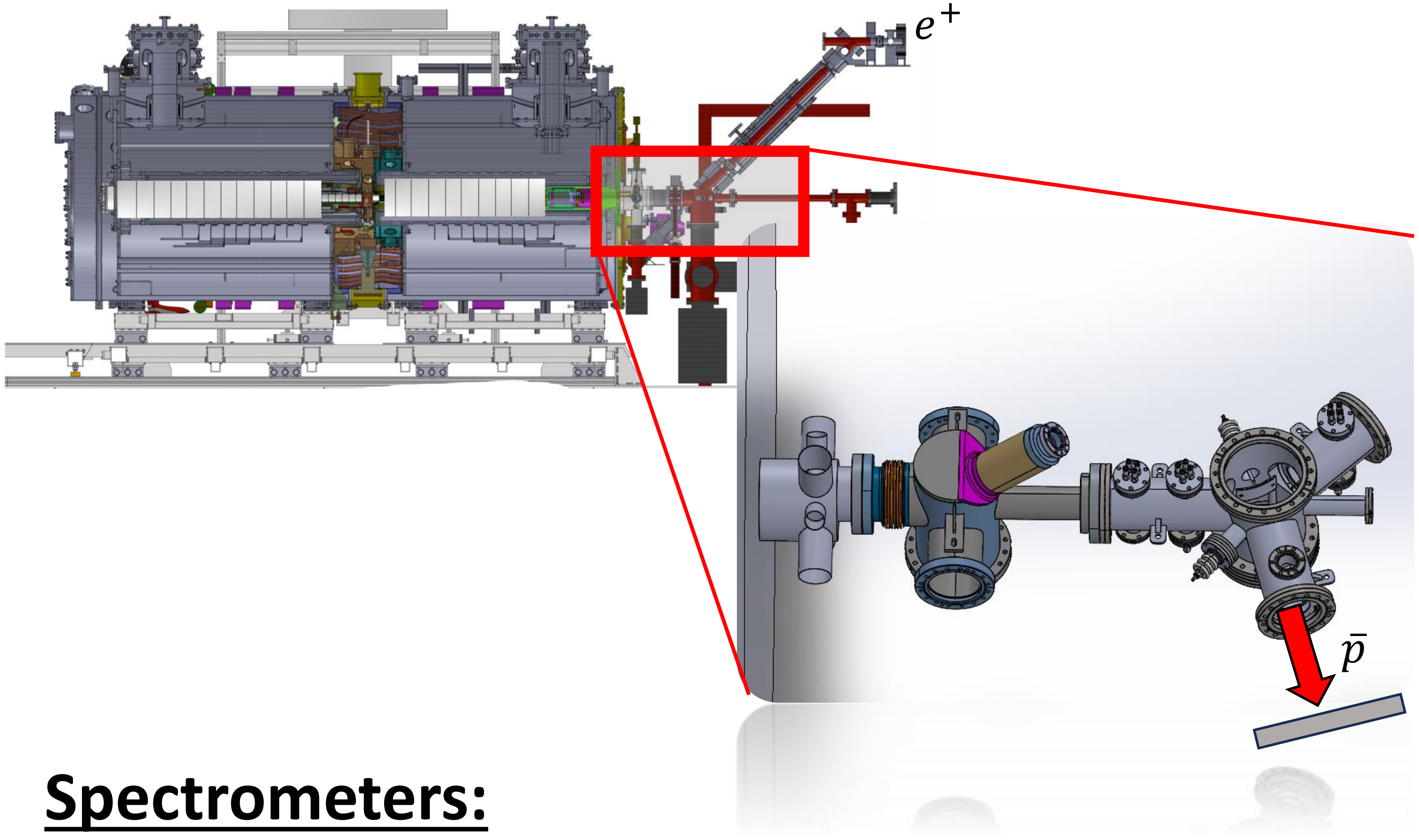
MCP signal

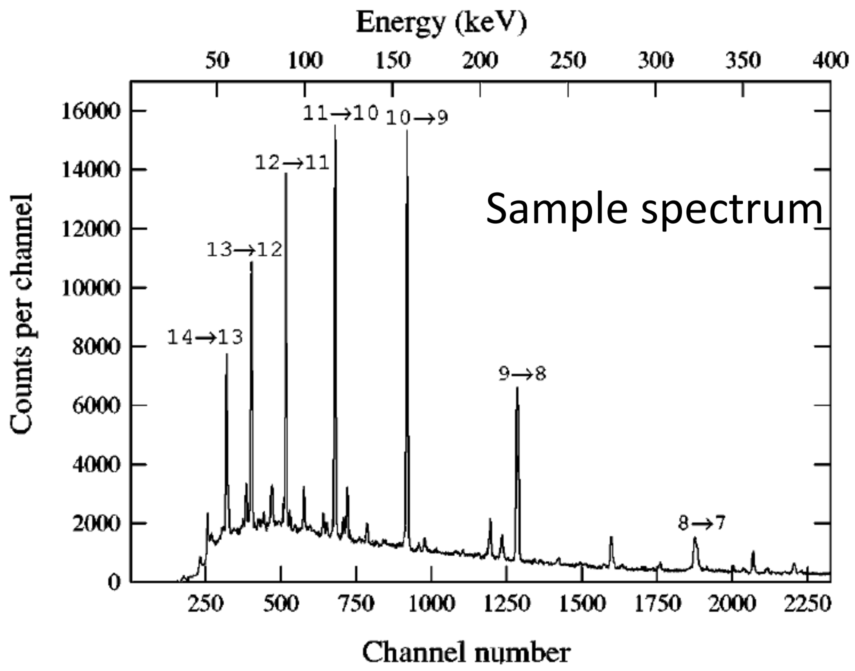
Scintillator signal





First x-ray spectroscopy at AEGIS



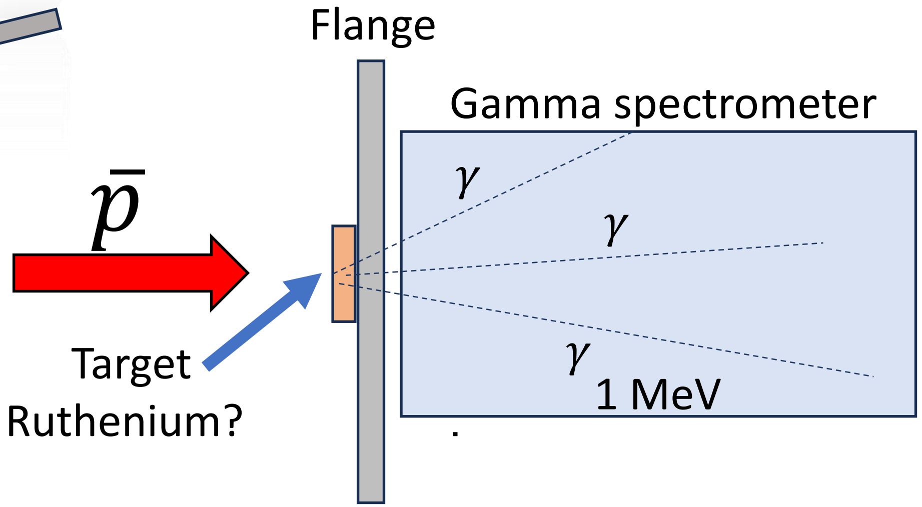


<u>Spectrometers:</u>

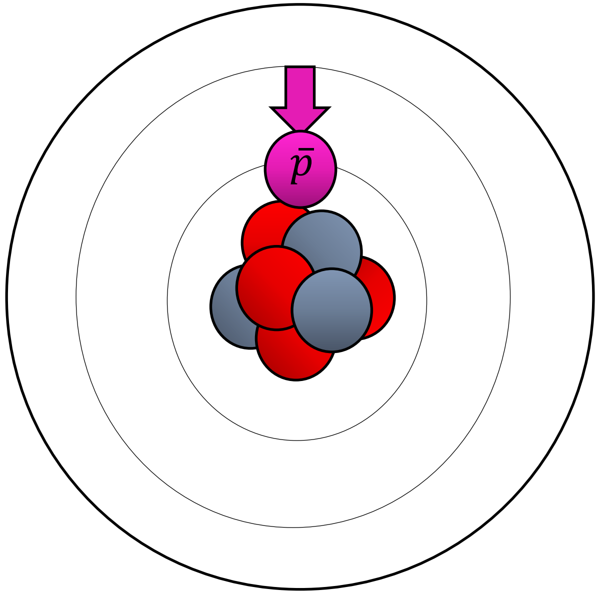
CsI (simple but low efficiency)

BGO detectors (Student project)

HPGe spectrometer (Requesting quote from Mirion)



Physics case: The spin-flip-induced quadrupole resonance effect in odd-A exotic atoms



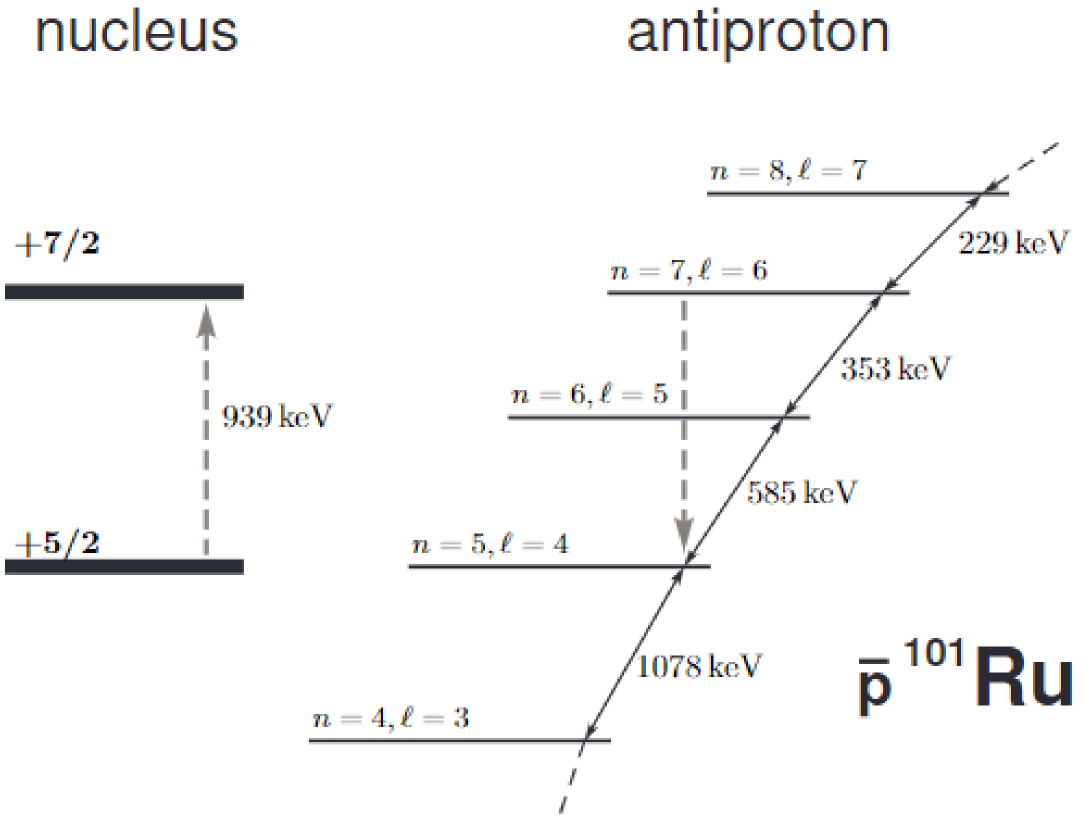


TABLE I. Examples of stable odd-A antiprotonic atoms where the spin-flip-induced quadrupole resonance is expected. clear transition energies were acquired from [42] and the antiproton transition energies were calculated from the Ham $\mathcal{H}_r$. In parenthesis, we indicate tentatively assigned nuclear spins of the excited states. The calculated coupling matrix $\langle\mathtt{fin}|\mathcal{H}_Q|\mathtt{ini}\rangle/\mathcal{Q}_0$ is presented for each scenario. Follow text for more details.

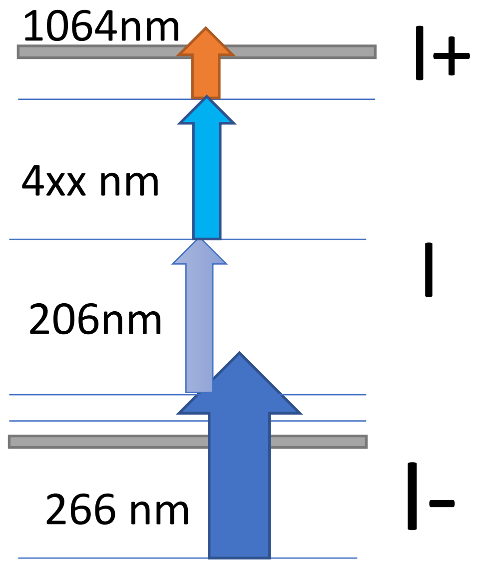
isotope	Z	N	nuclear spin ground	nuclear spin excited	ΔE_N (keV)	$\Delta E_{\bar{P}}$ (keV)	n initial	n final	$\langle\mathtt{fin}|\mathcal{H}_Q|\mathtt{ini}\rangle/\mathcal{Q}_0$ (eV b^{-1})
			NUCLEUS			ANTIPROTON			
^{101}Ru	44	57	5/2	(7/2)	938.65	939.40	7	5	159
^{111}Cd	48	63	1/2	3/2	1115.57	1119.20	7	5	92
^{123}Sb	51	72	7/2	(9/2)	1260.80	1264.81	7	5	258
^{165}Ho	67	98	7/2	(9/2)	2178.00	2189.96	7	5	584
^{169}Tm	69	100	1/2	(3/2)	2312.2	2323.38	7	5	275
^{183}W	74	109	1/2	(3/2)	2667.8	2667.47	7	5	339
^{203}Tl	81	122	1/2	(3/2)	1988.88	1987.73	8	6	159

Accepted in Physical Review C

New lasers for AEGIS

- **Goal: Laser triggered formation of antiprotonic atoms in AEGIS. (First case: Iodine)**

- Broad range (Versatility)
- High intensity (Non-resonant and weak transitions)
- Pulsed
- Resolution? Spectroscopy?
- OPO systems from EKSPLA..



Summary of outlook:

- Continued **development of trapping procedure and identification of HCI fragments** from antiproton-atom interaction using gas injection (the dirty method).

- **First x-ray spectroscopy of** antiprotonic atoms at AEGIS (initially on target). Characterizing background for spectroscopy inside the trap. Many ’simple’ physics cases.

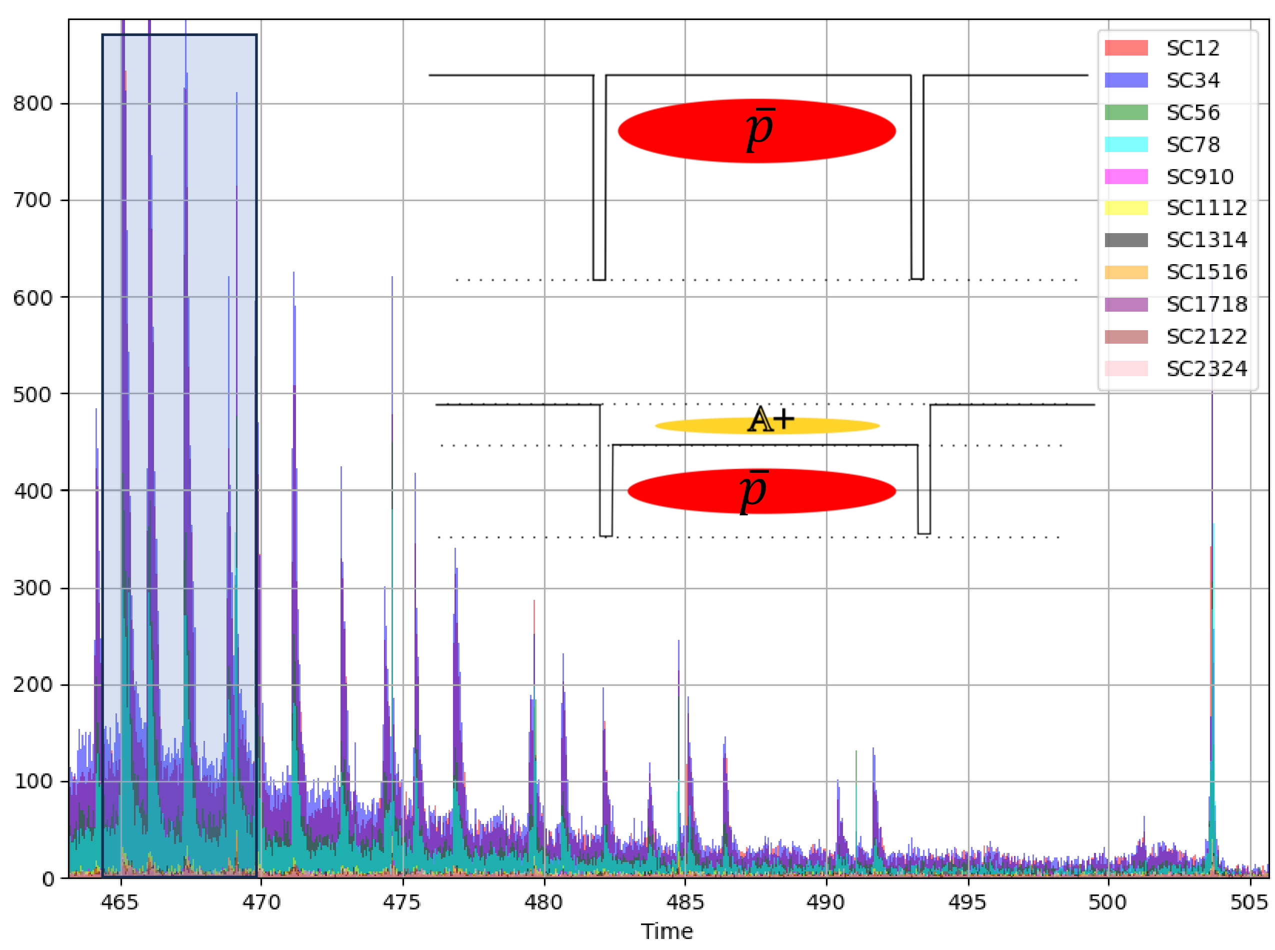
- **(Triggered formation of antiprotonic atoms** through target ablation near trapped cold antiprotons?)

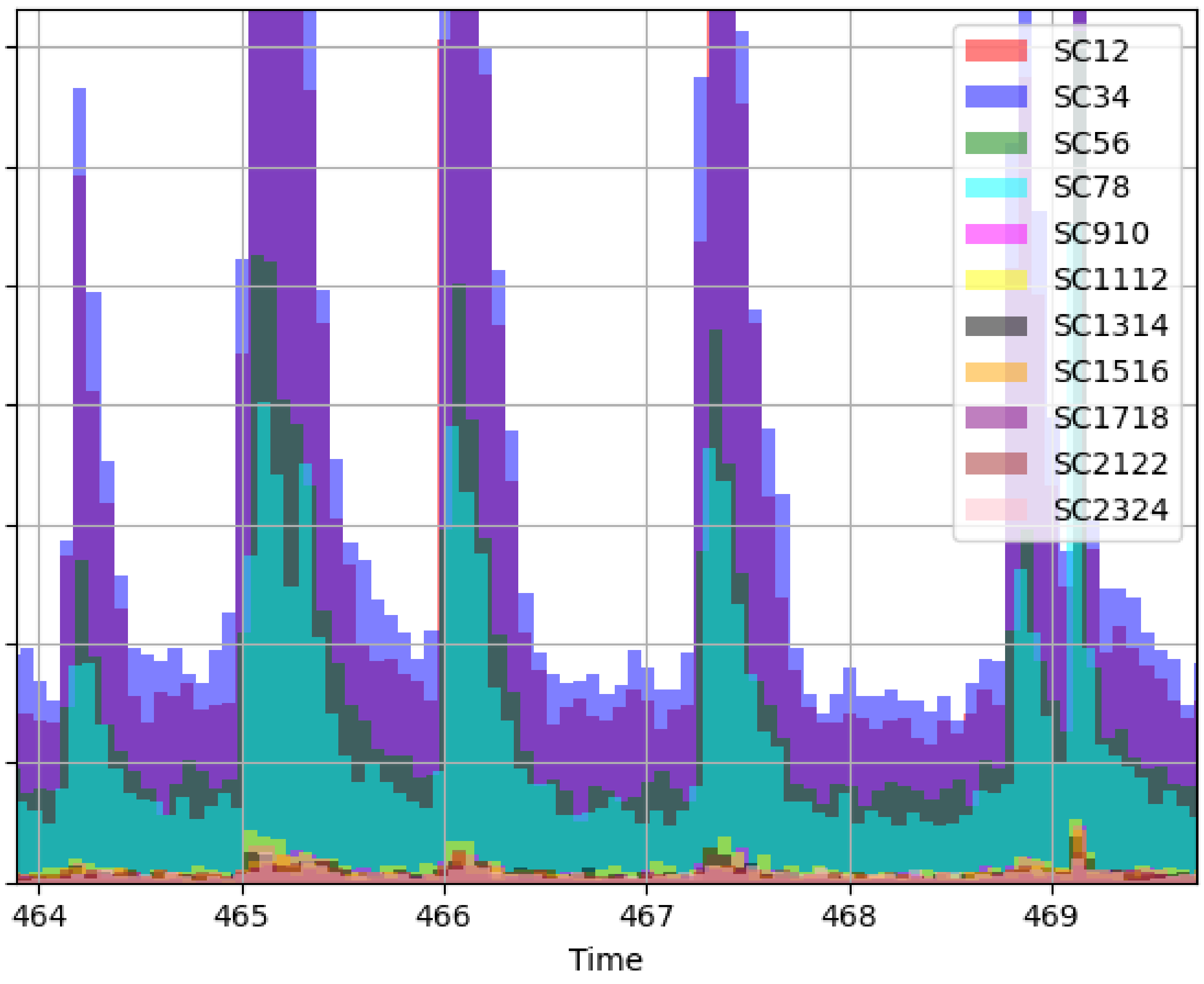
- **Purchase of laser systems** for photodetachment and Rydberg excititatation: Triggered formation of antiprotonic atoms with cotrapped anions.

Goal: Laser triggered formation of antiprotonic atoms (laser/x-ray/auger spectroscopy) and trapping and cooling of resulting HCI fragments.

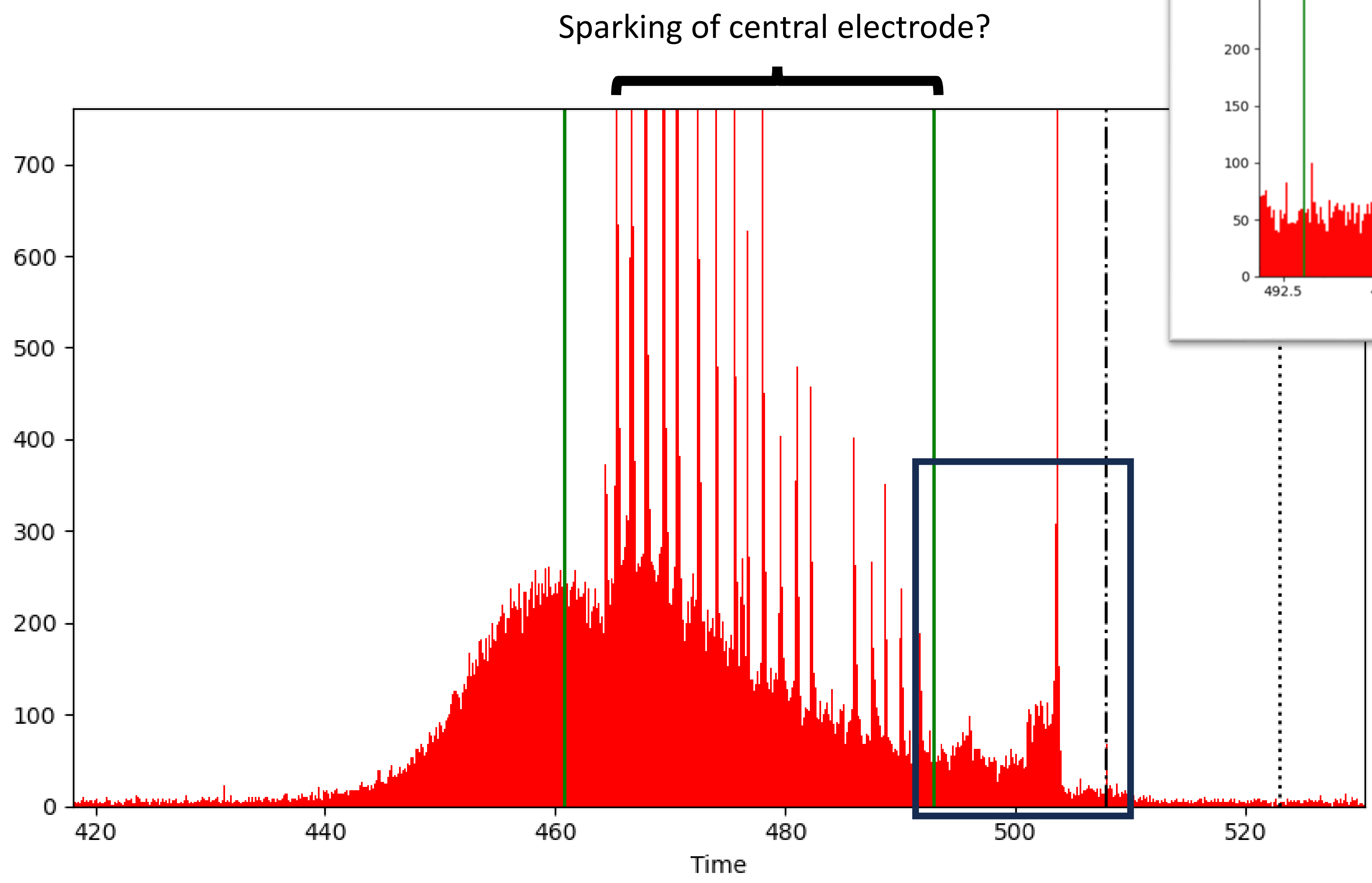
Quasi-periodic Pbar annihilation?

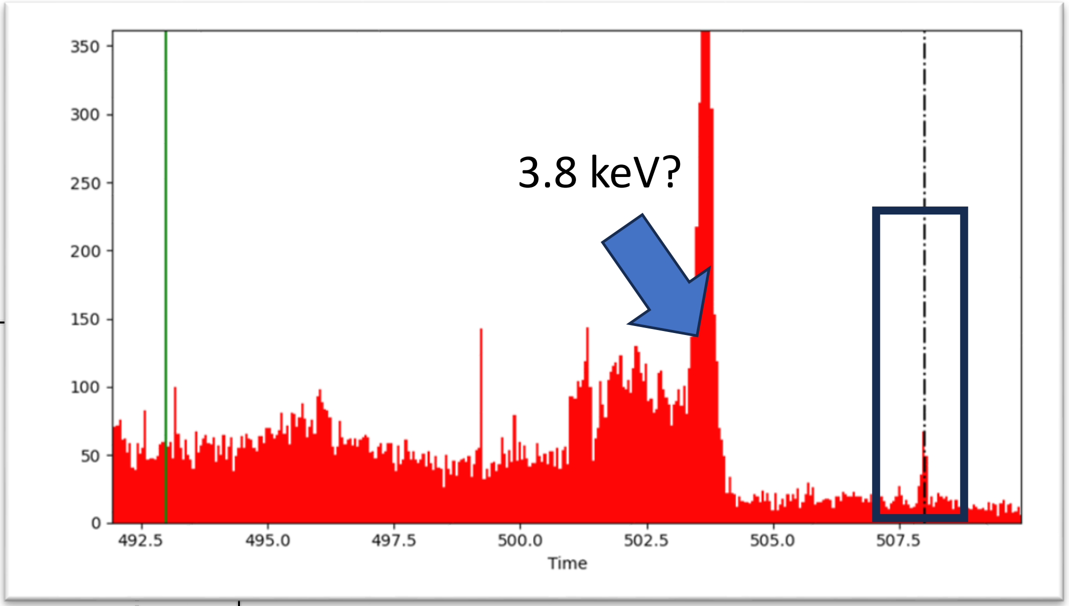
Floating electrode in 5T trap?

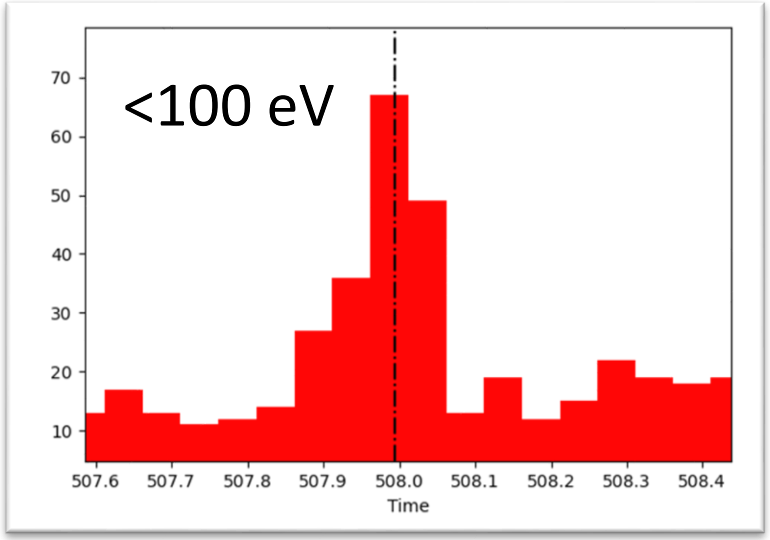




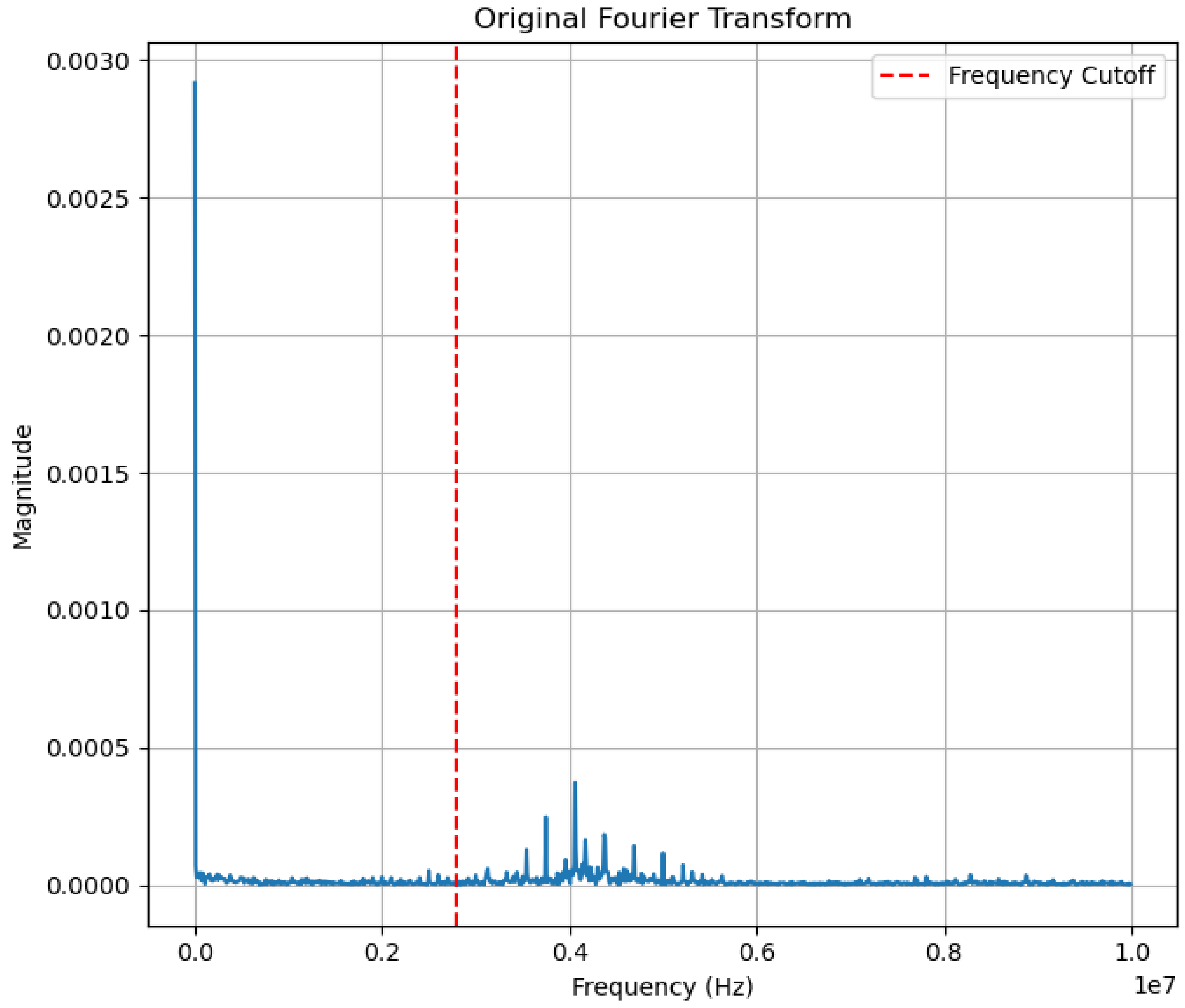
Annihilation peak

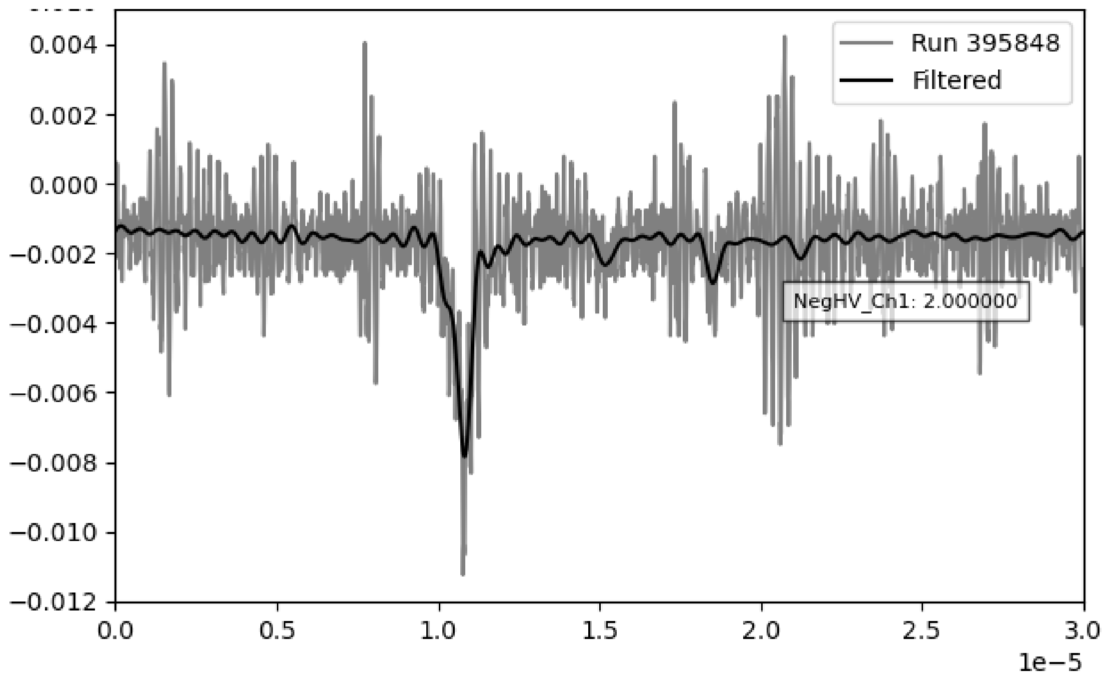




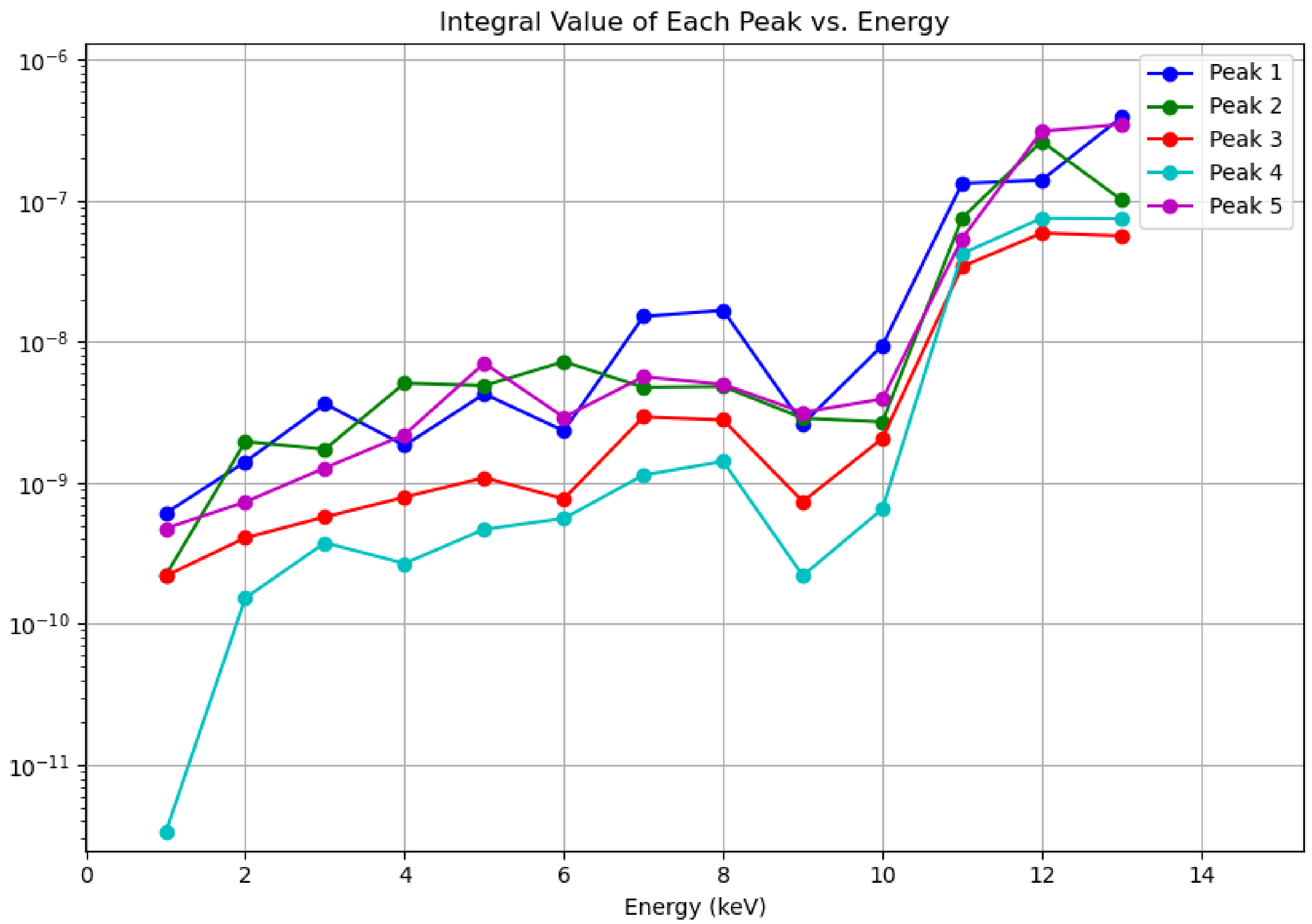


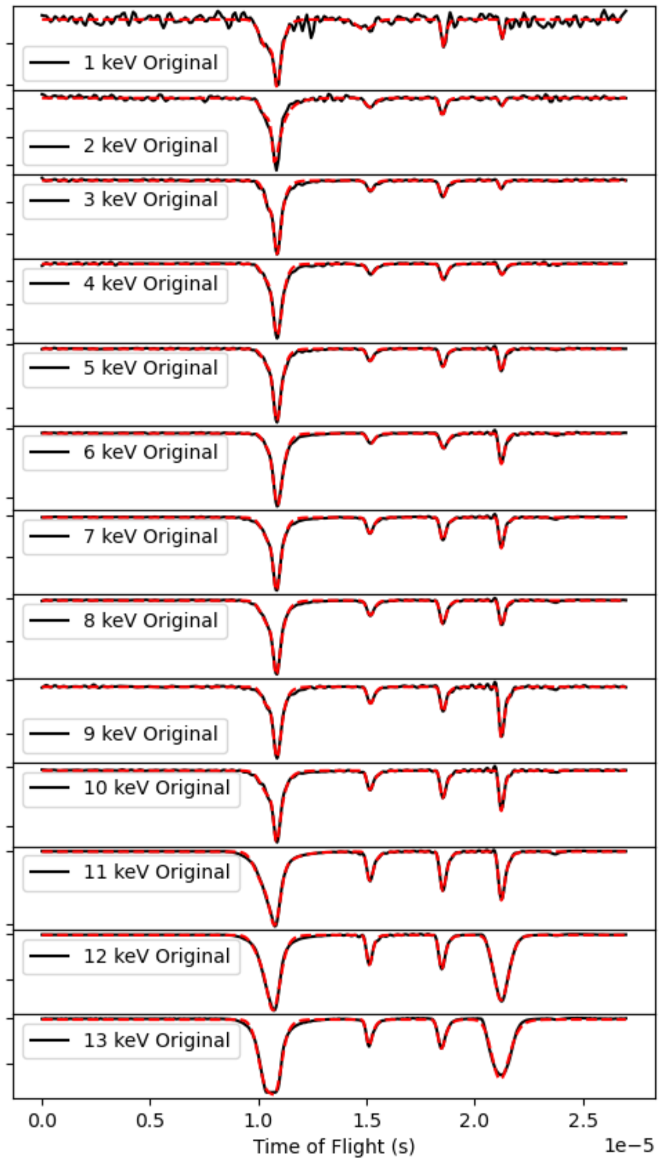
Noise filtering



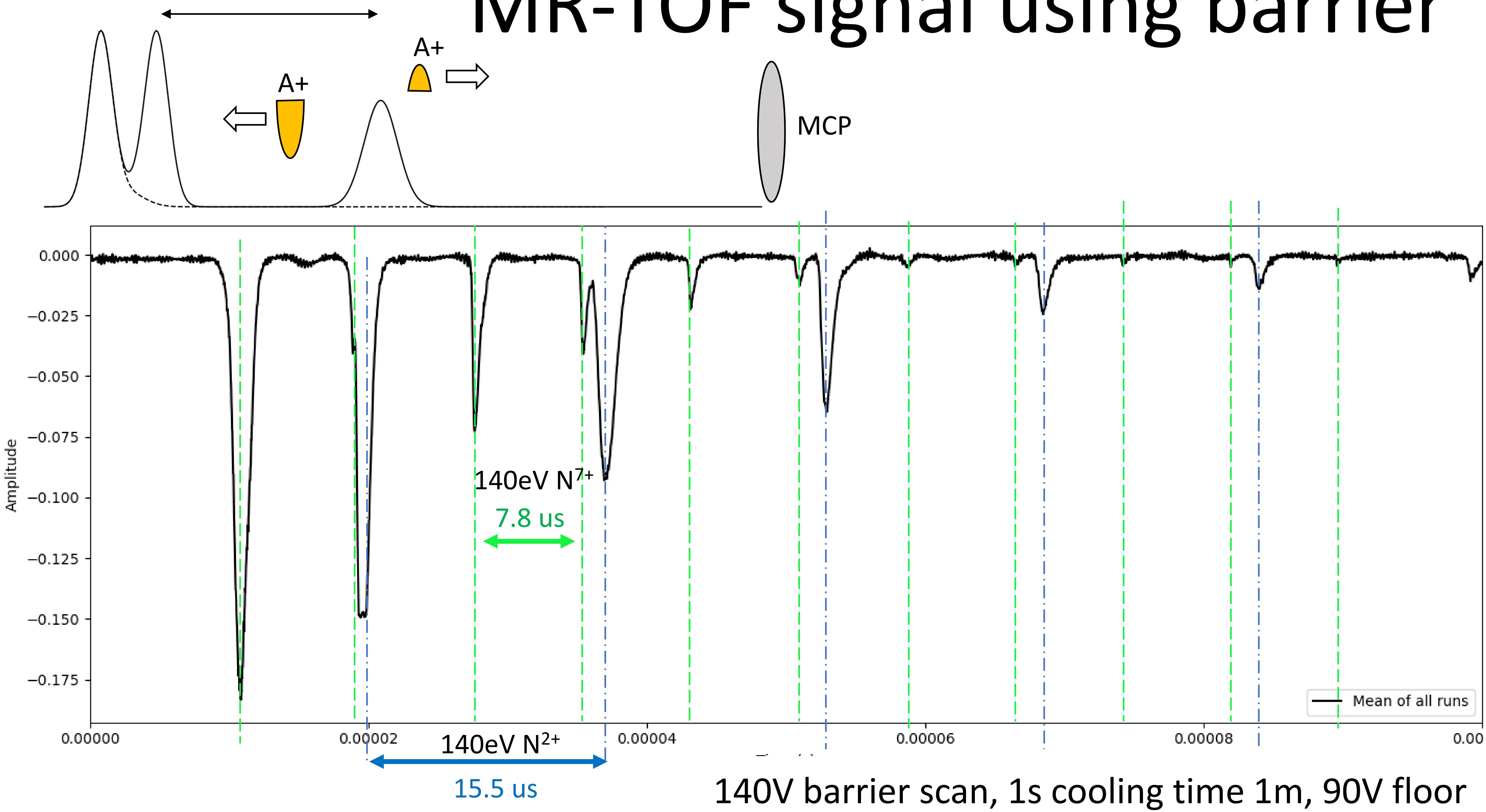


Pbar trapping voltage vs MCP signal





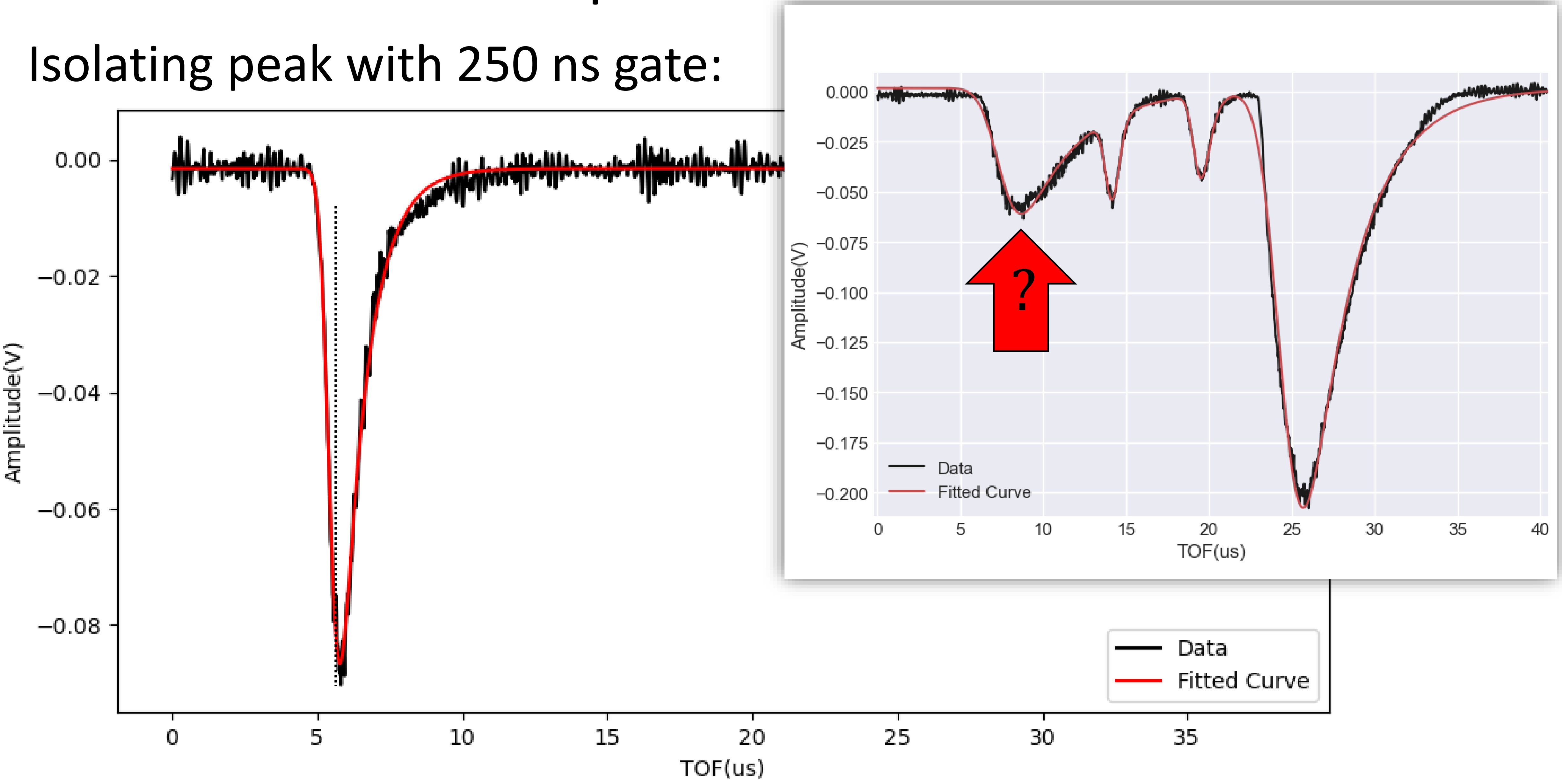
MR-TOF signal using barrier



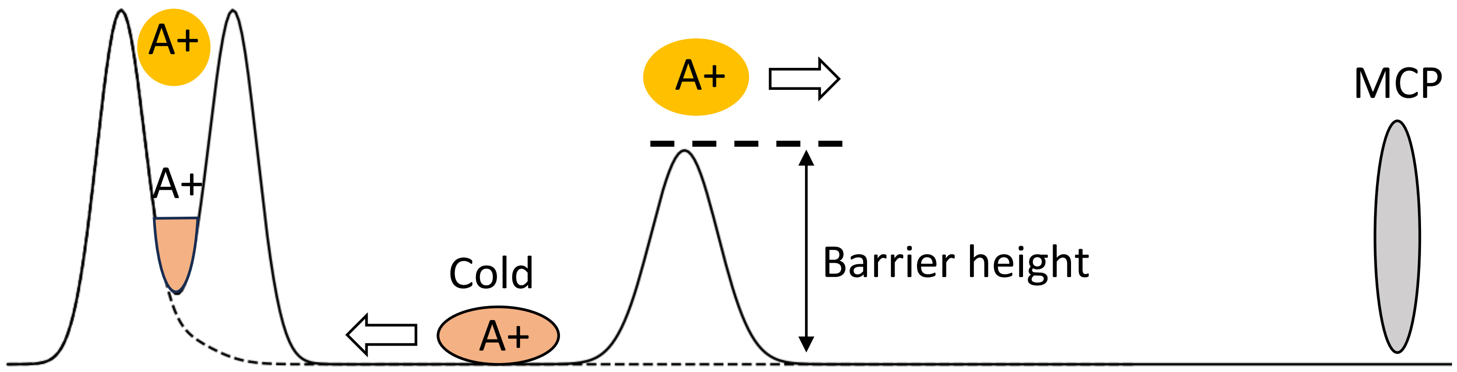
140V barrier scan, 1s cooling time 1m, 90V floor

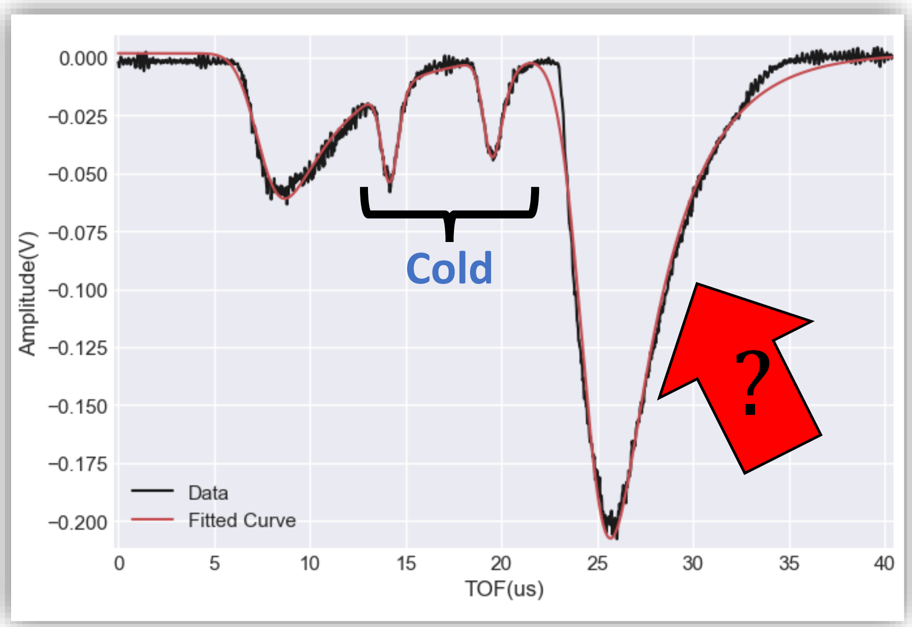
Fast TOF component?

Isolating peak with 250 ns gate:

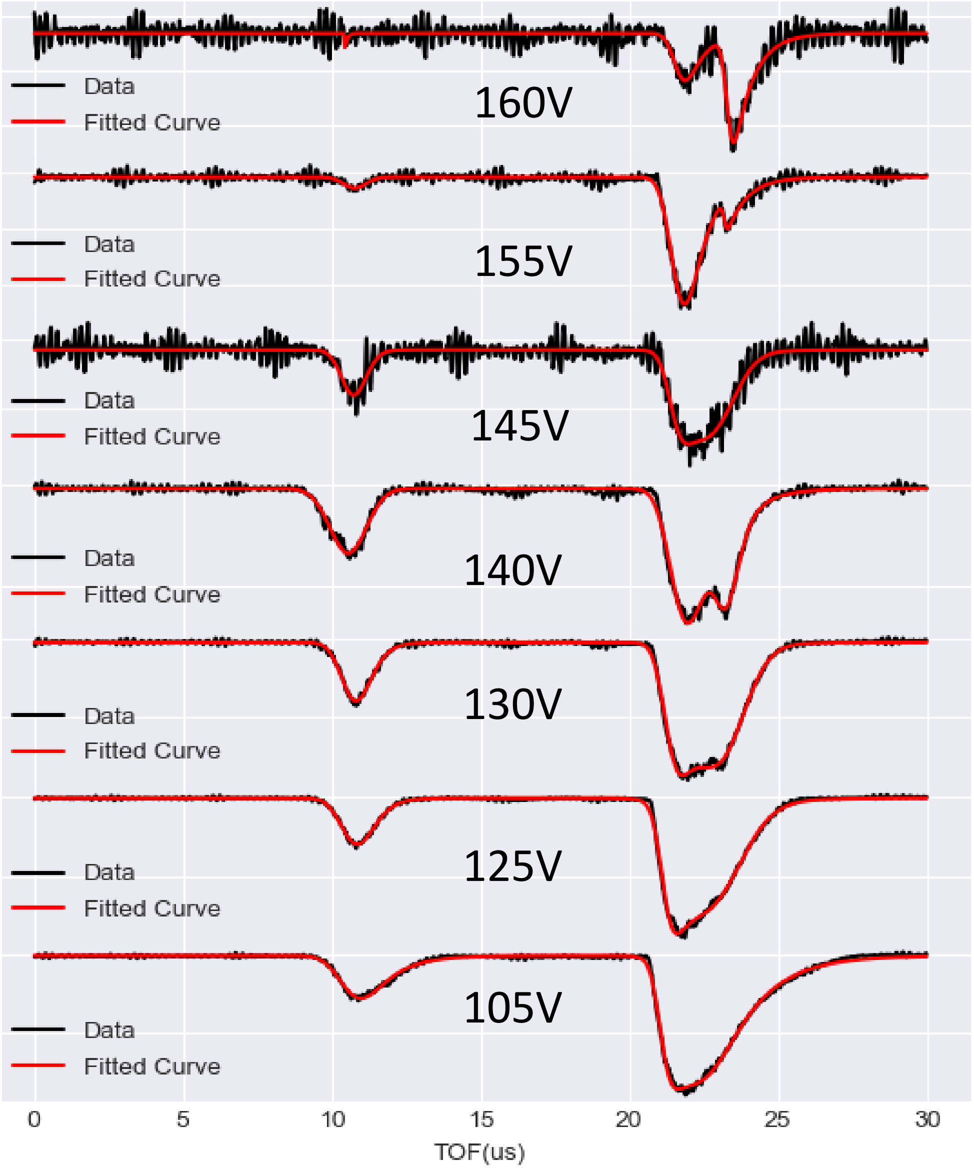


Barrier scan with 10 V floor voltage

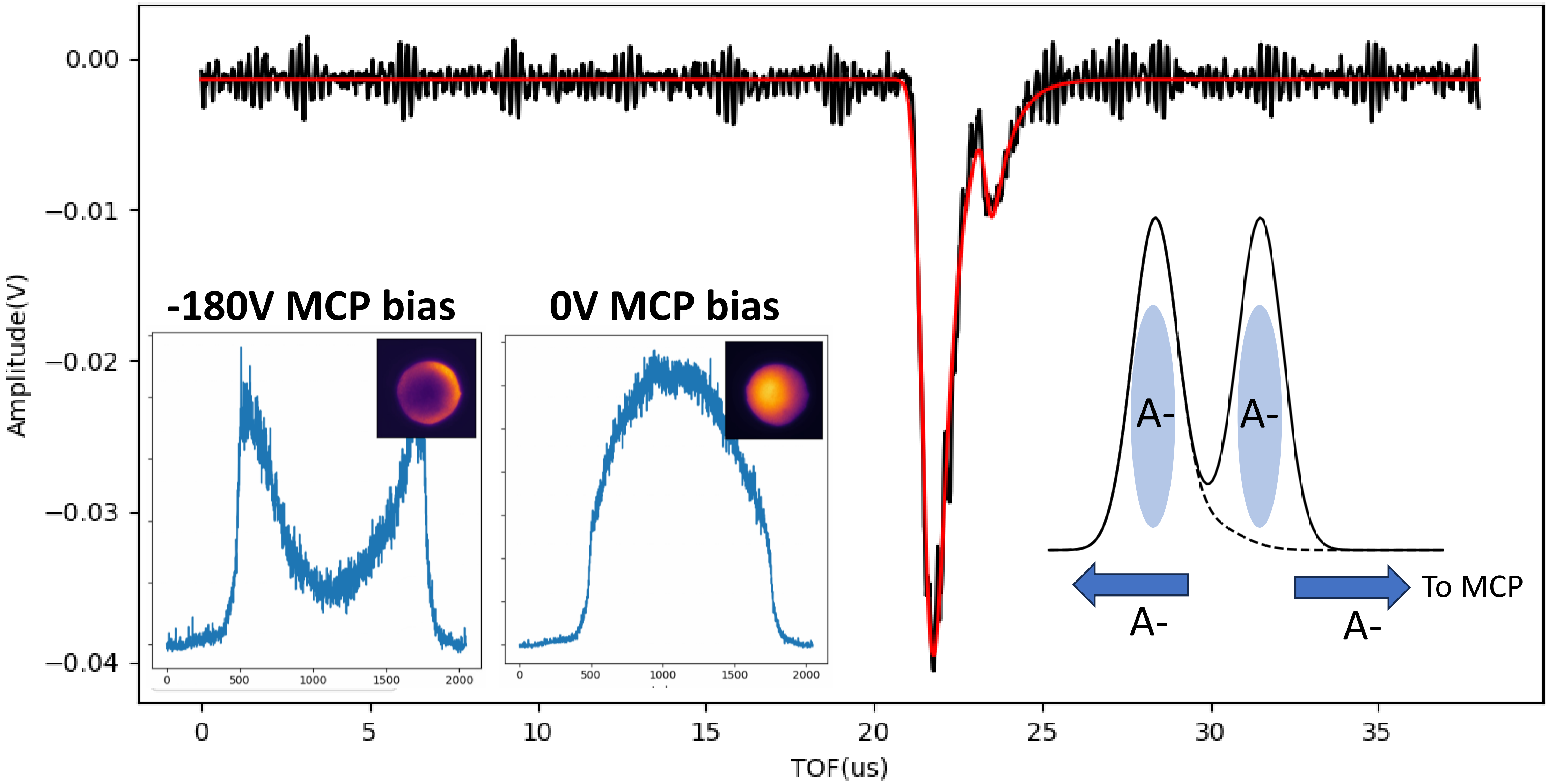




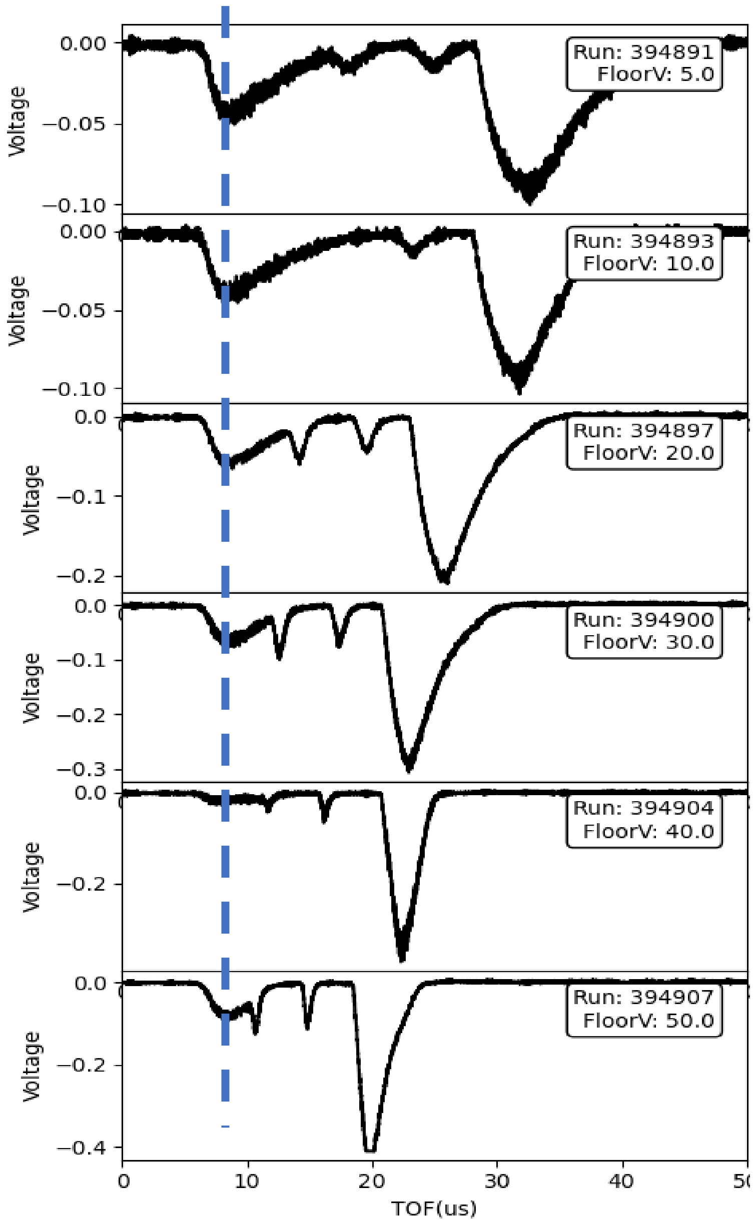
TOF vs Barrier height

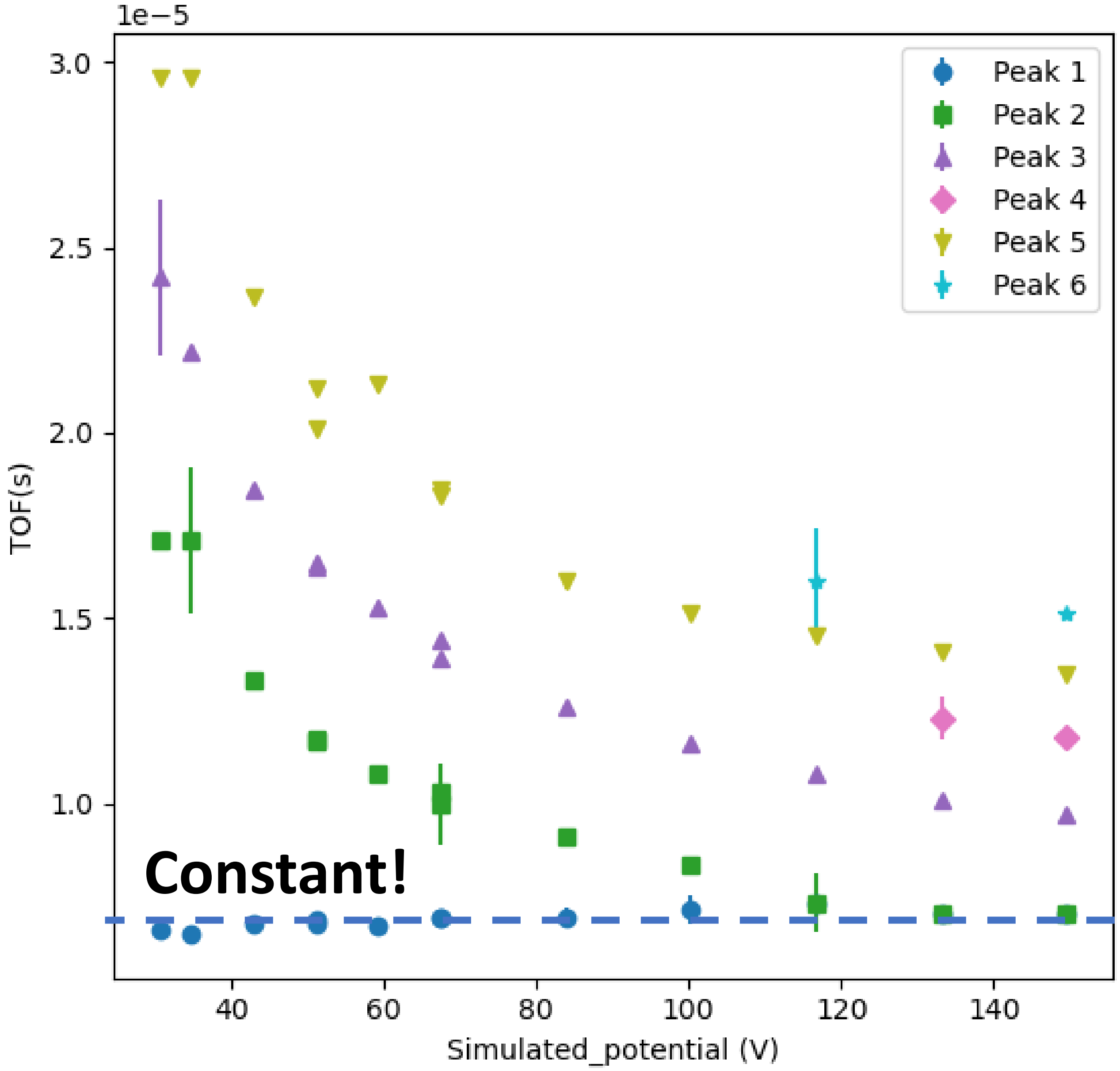


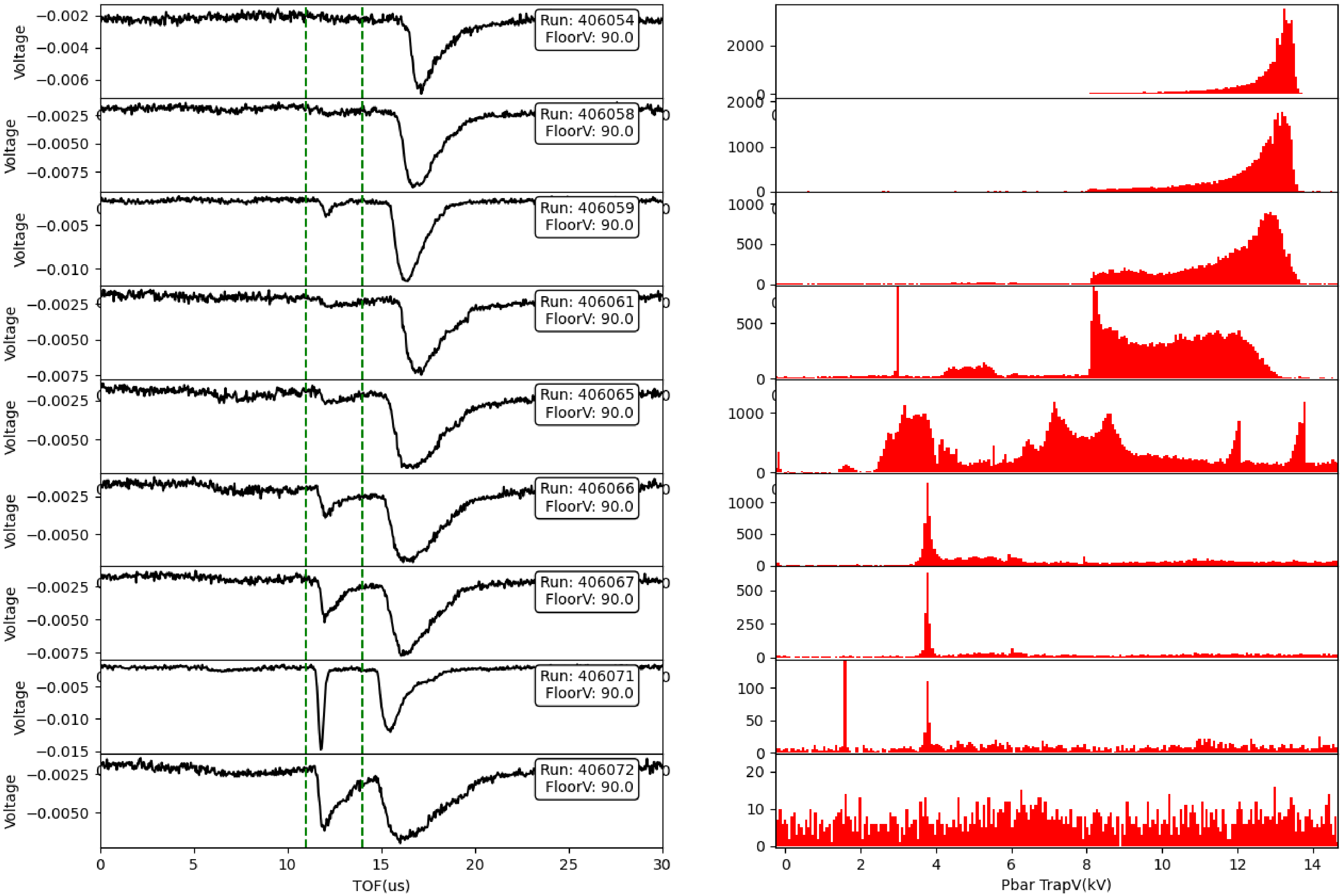
Isolating slow peak with 160 V Barrier



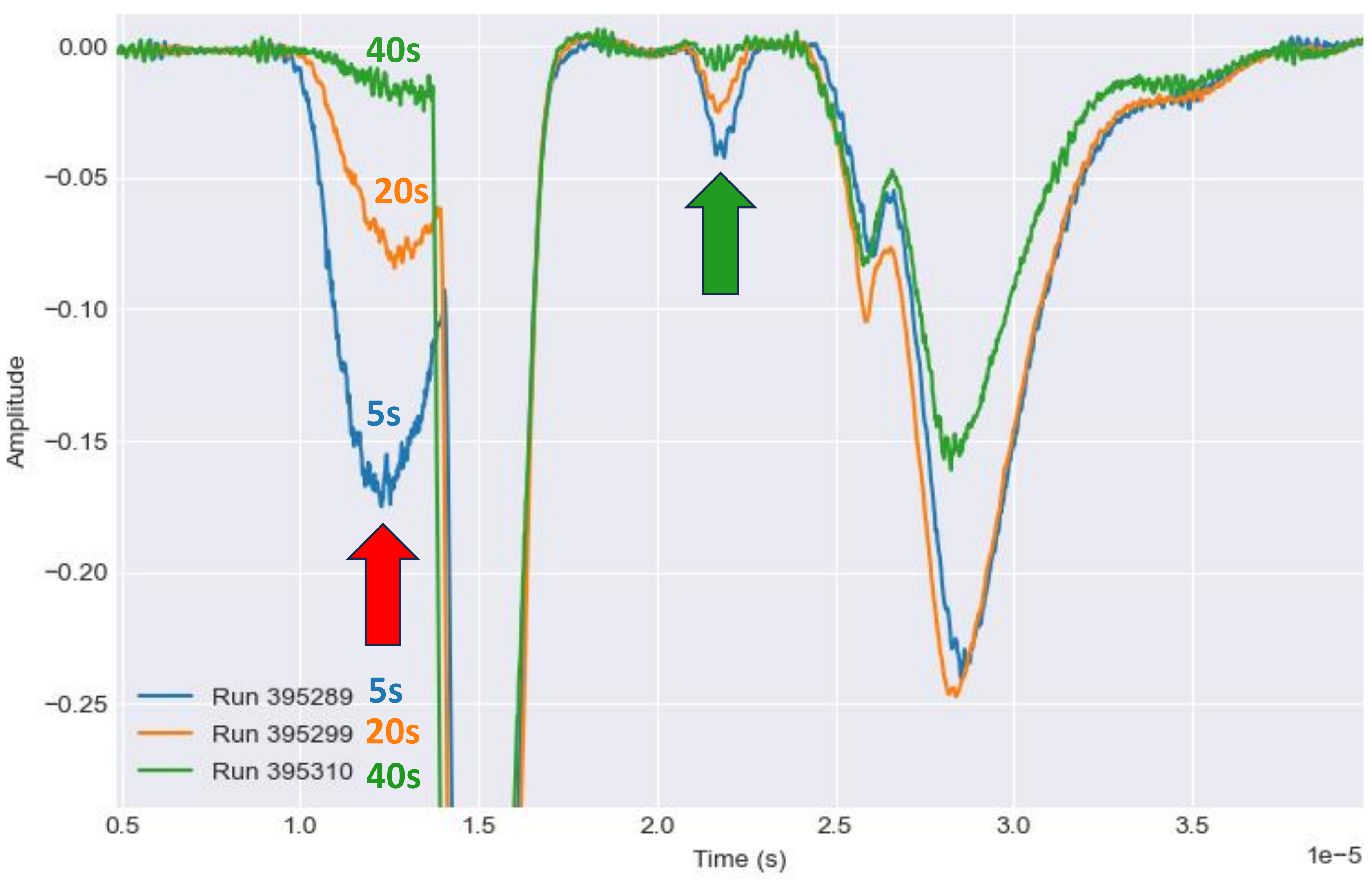
Floor voltage scan with release from MCP side

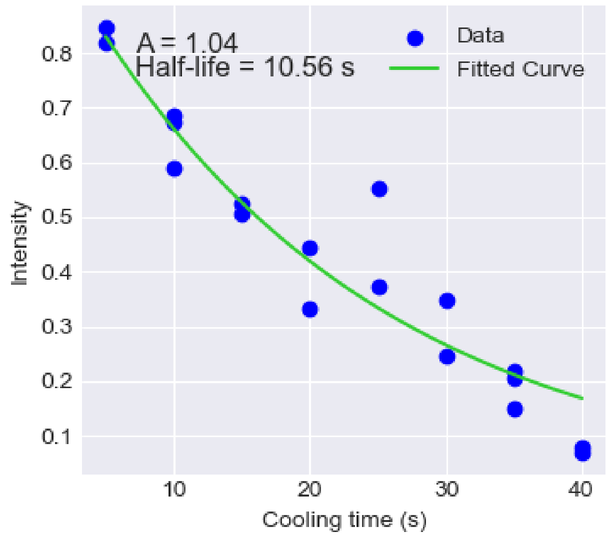


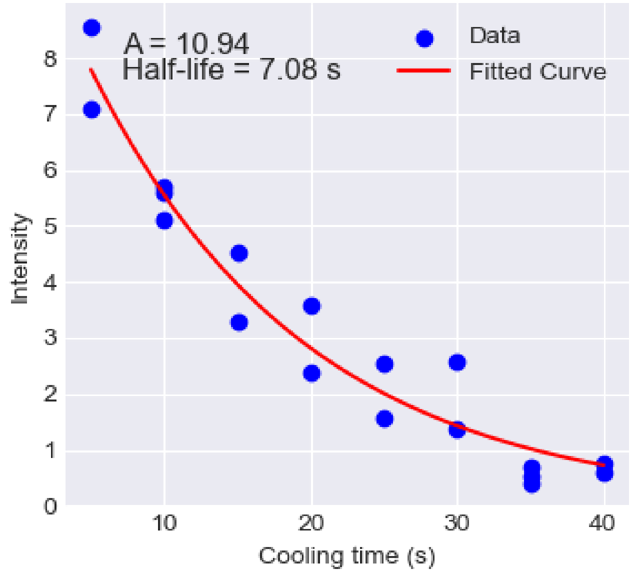



Run: 406054
FloorV: 90.0
Run: 406058
FloorV: 90.0
Run: 406059
FloorV: 90.0
Run: 406061
FloorV: 90.0
Run: 406065
FloorV: 90.0
Run: 406066
FloorV: 90.0
Run: 406067
FloorV: 90.0
Run: 406071
FloorV: 90.0
Run: 406072
FloorV: 90.0
Voltage
TOF(us)
Pbar TrapV(kV)

Ion time changes the 7+ population







The other peaks do not change significantly with time

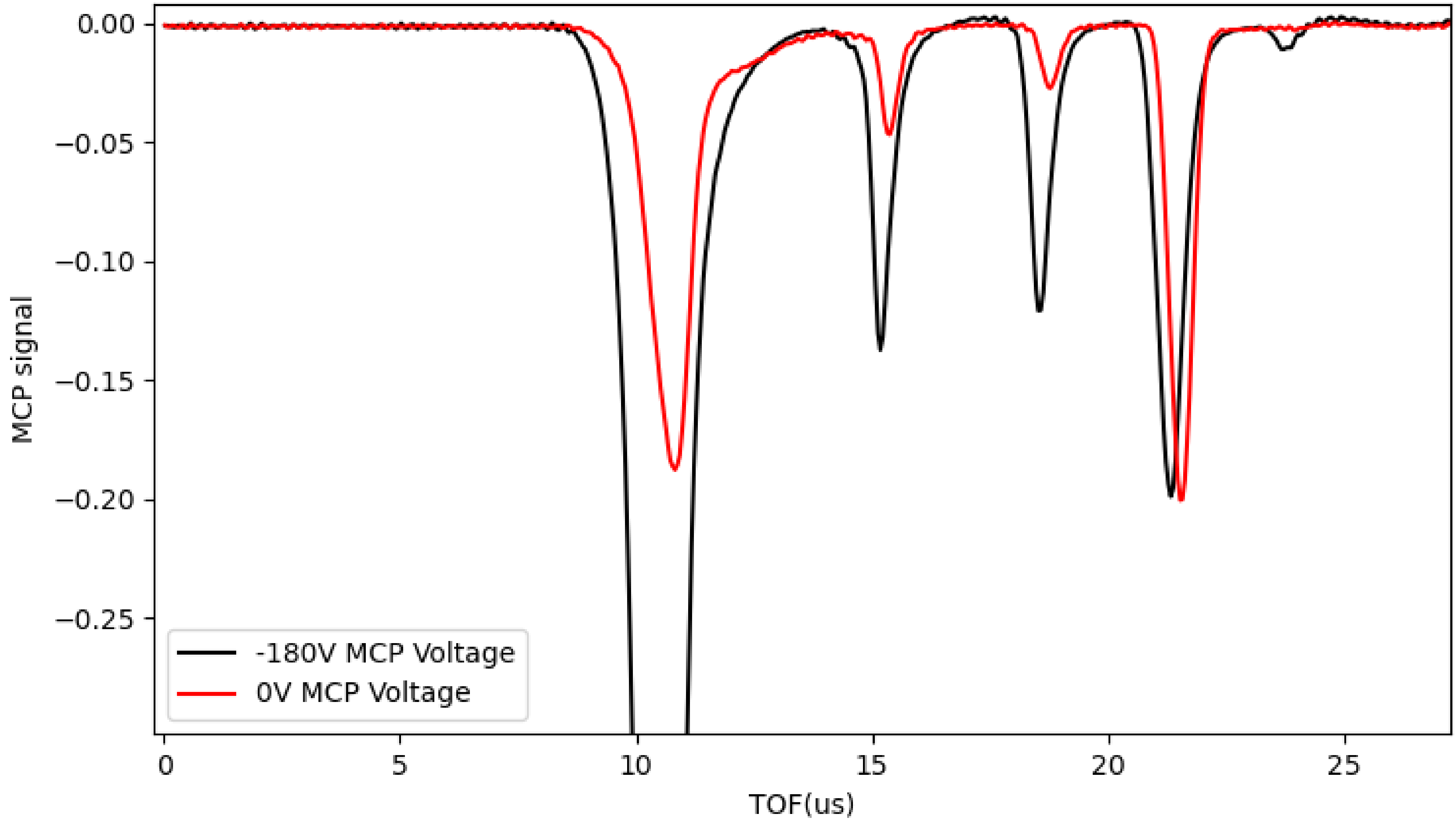

0.00
−0.05
−0.10
−0.15
−0.20
−0.25
MCP signal
0
5
10
15
20
25
TOF(us)
-180V MCP Voltage
0V MCP Voltage

Table 2: Ideal production conditions for ions of different isoelectronic sequences. Given are the ionization factor $j_e\tau$ (e^- cm^{-2}), the optimal electron beam energy (keV) and the required ionization time (ms or s) for an assumed ionization factor of $j_e\tau = 3 \times 10^{22}$ e^- cm^{-2}.

Sequence	Neon $Z = 10$	Argon $Z = 18$	Krypton $Z = 36$	Xenon $Z = 54$	Gold $Z = 79$	Uranium $Z = 92$
Atom	Ne^{10+}	Ar^{18+}	Kr^{36+}	Xe^{54+}	Au^{79+}	U^{92+}
fully	2×10^{21}	2×10^{21}	3×10^{22}	2×10^{23}	6×10^{23}	$2 \times 10^{24+}$
ionized	3	9	40	80	180	300
	7 ms	67 ms	1 s	7 s	20 s	67 s

Elena side measurment

$$K = \frac{\left(L_{eff} + L_{5Ttrap}\right)^2 k}{2e10^{12}} = 13000(75)$$