



# 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 suppressed decay:
  - Electron capture no longer possible (Weak interaction studies)

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



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

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<sup>1</sup> , S Eliseev<sup>2,1</sup>  and S Sturm<sup>1</sup>

Published 6 November 2020 • © 2020 The Author(s). Published by IOP Publishing Ltd

[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](#)

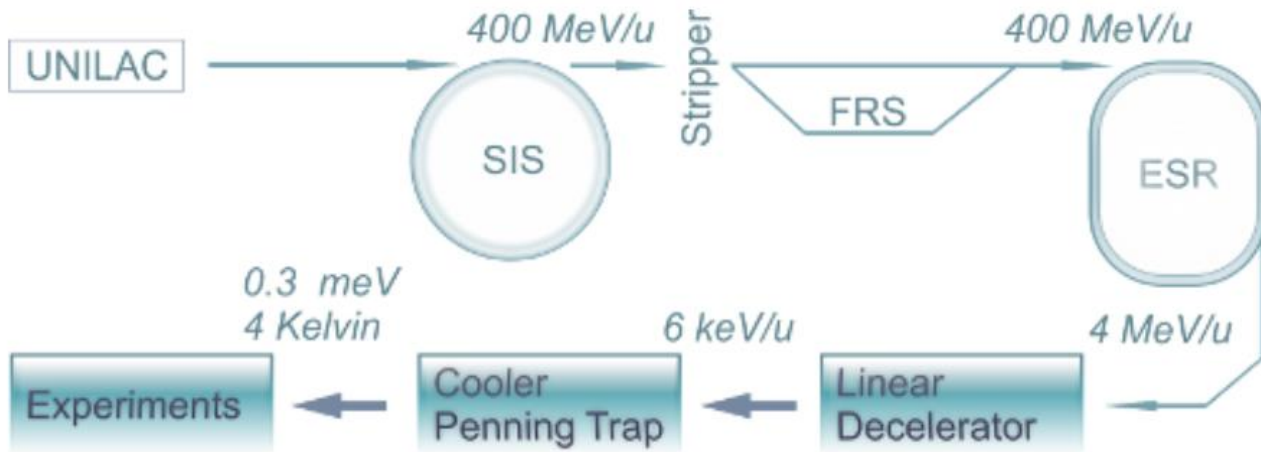
## Coherent laser spectroscopy of highly charged ions using quantum logic

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

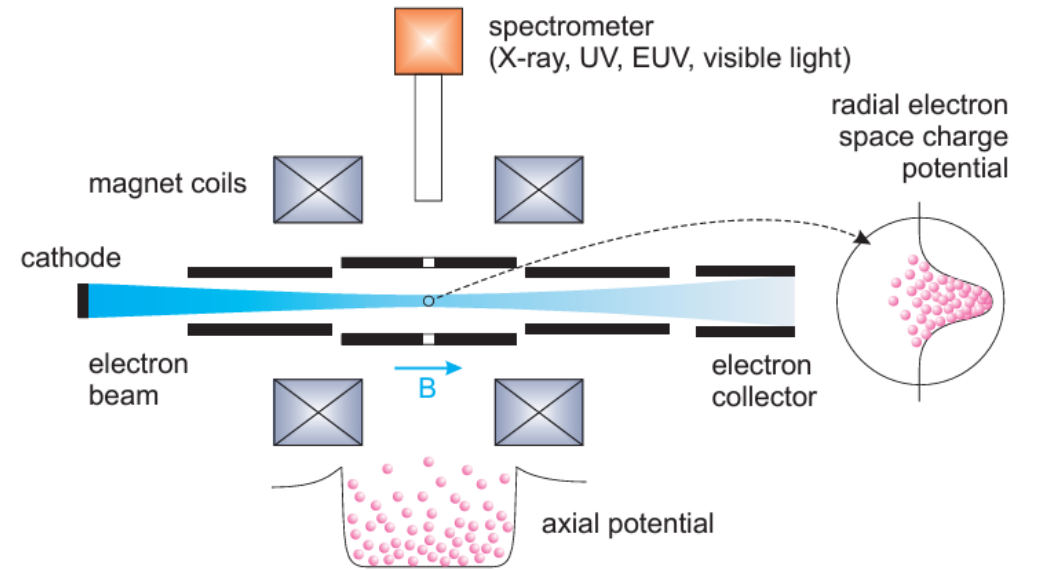
*Nature* **578**, 60–65 (2020) | [Cite this article](#)

# Traditional HCI formation at radioactive beam facilities:

High energy beam through stripper foil:



Electron beam ionization:

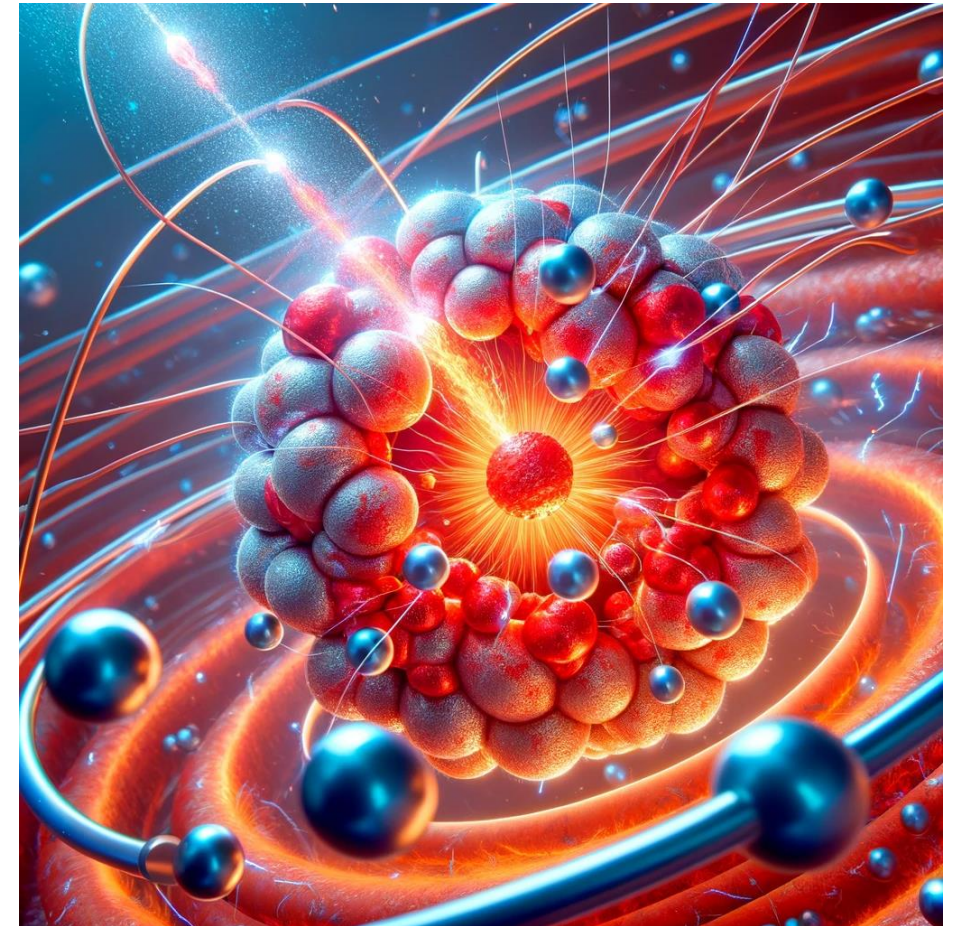
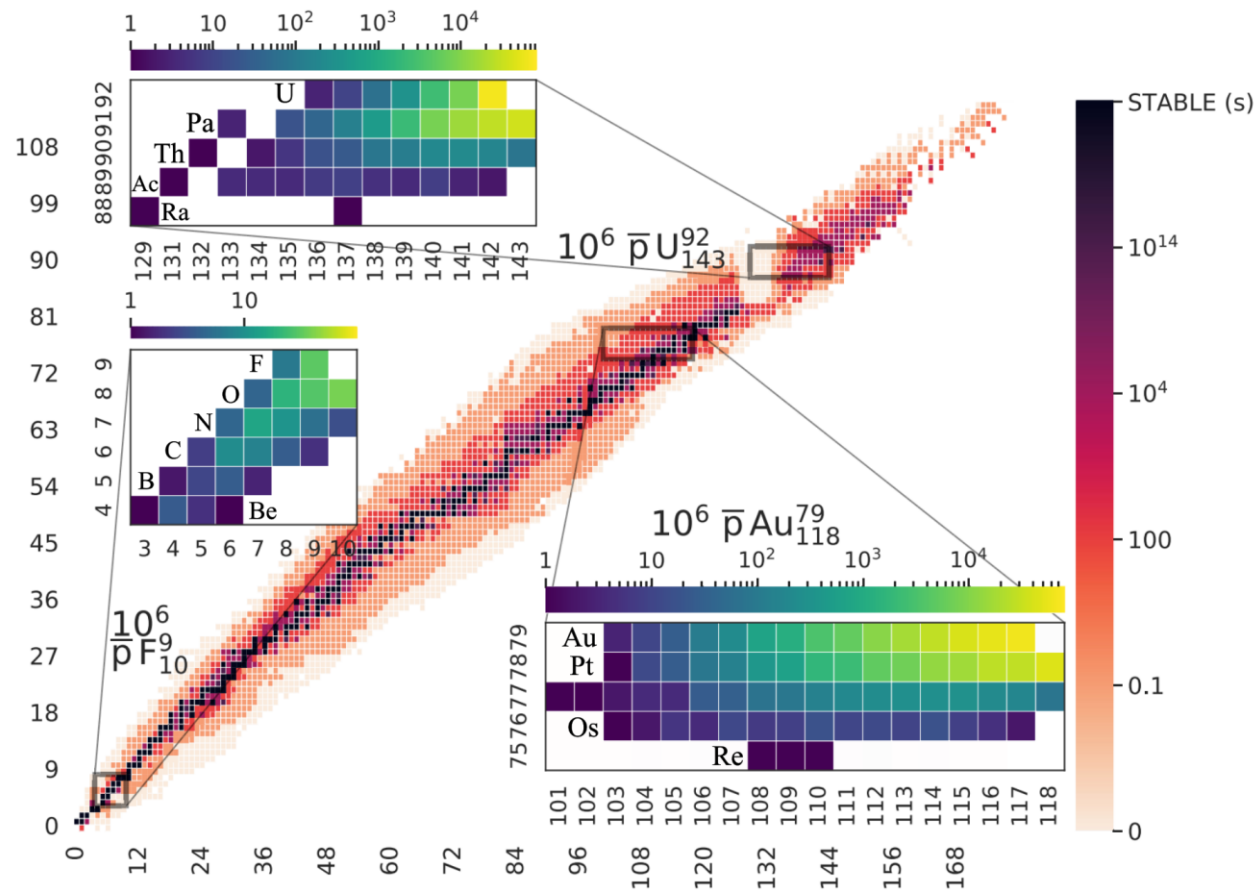


**Fig. 2:** Principle of operation of an EBIS

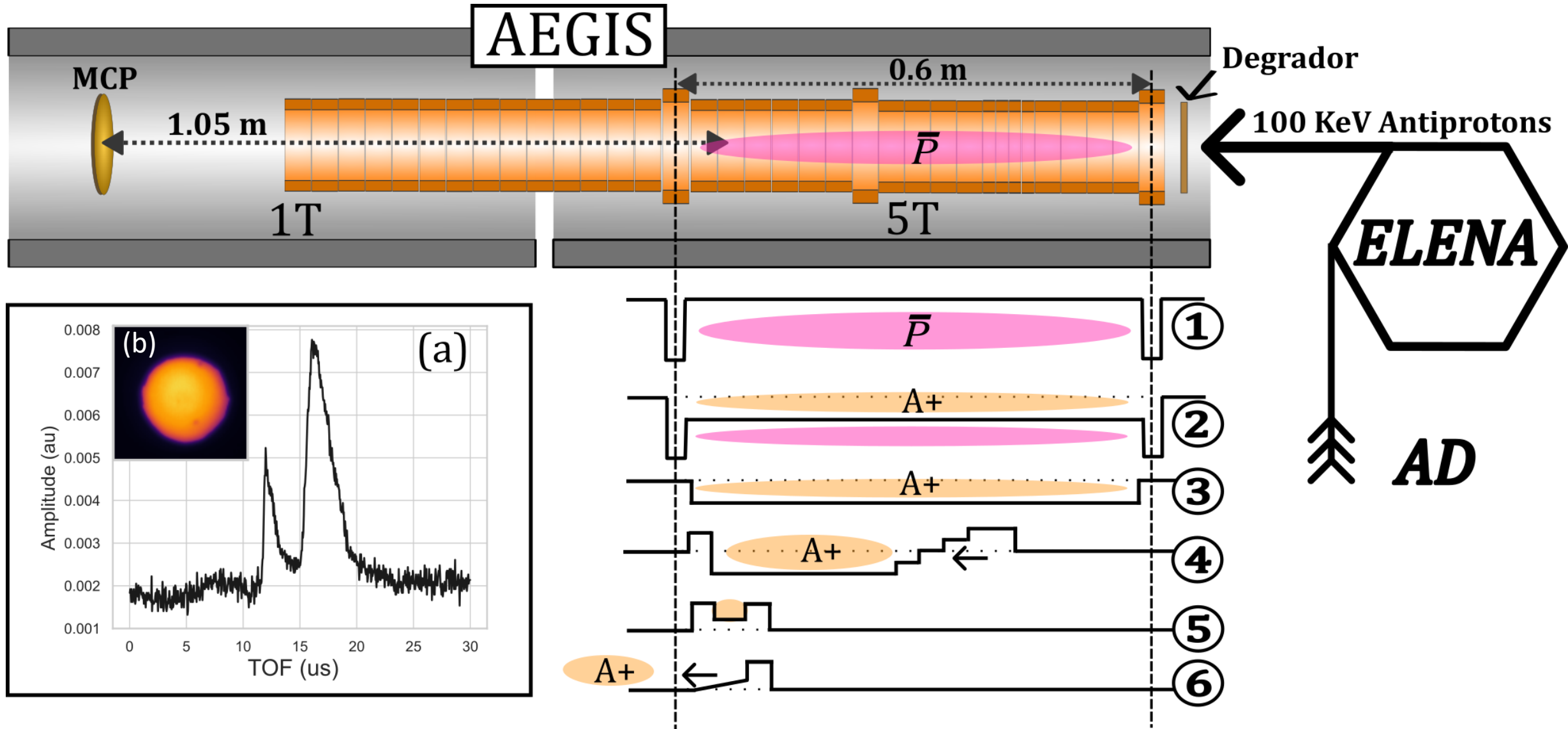
# Radioactive HCl formation using antiprotons?

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

G. Kornakov, 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 HCl campaigns in 2023

- **Air leak campaign: (3 weeks)**

- First positive ion signal.
- Techniques developed for manipulating trapped ions.
- Barrier scan, Multi-step, MR-TOF procedure.
- Identifying the energy of the TOF components.

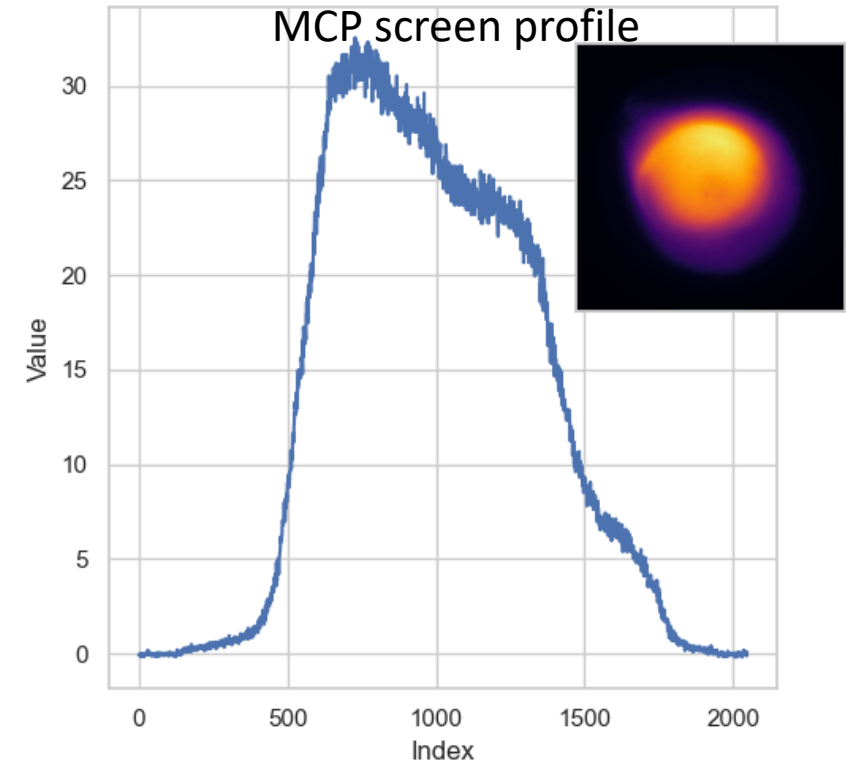
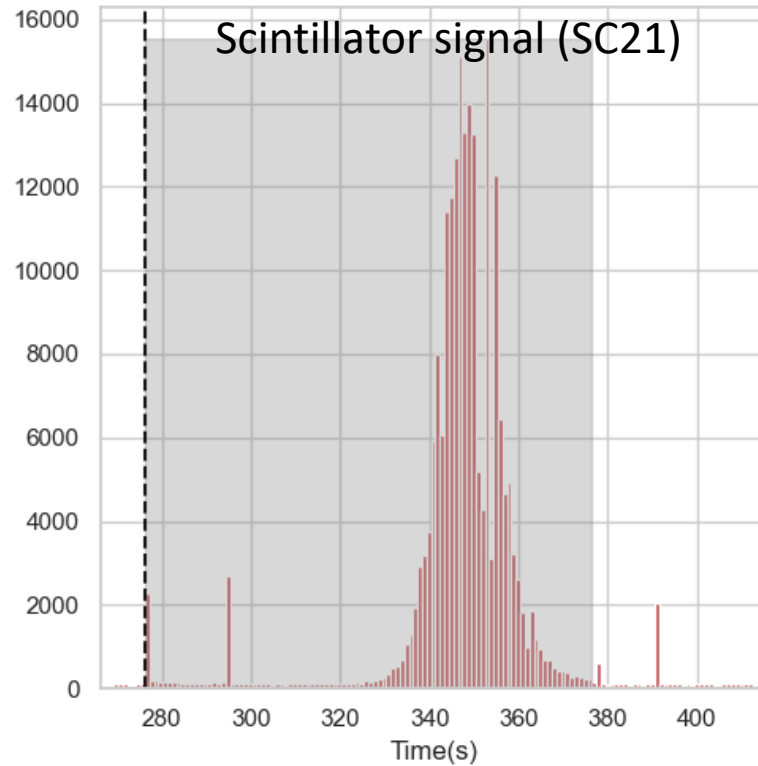
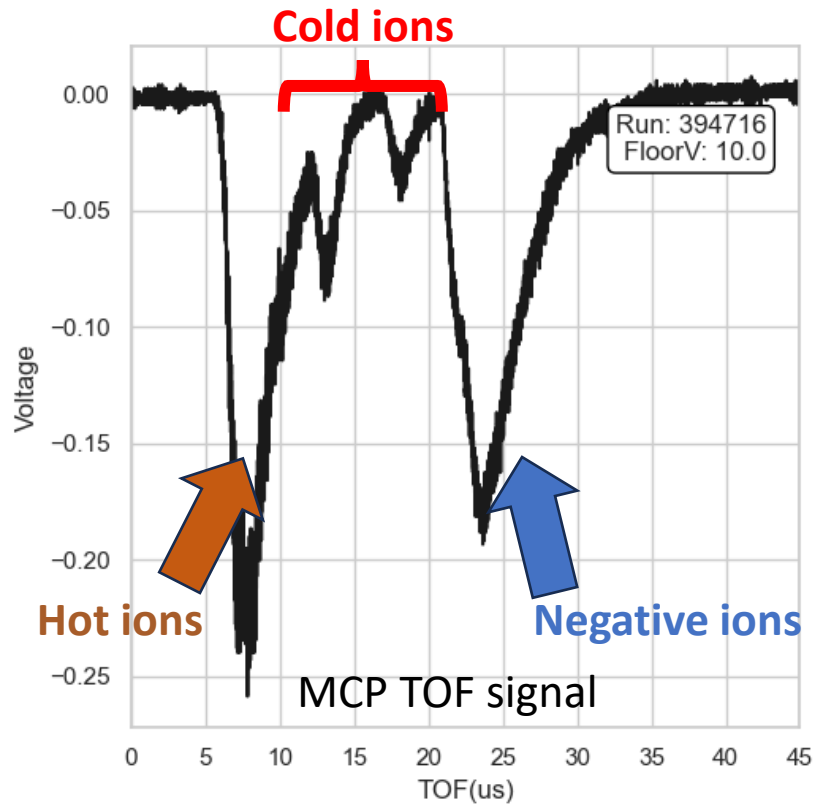
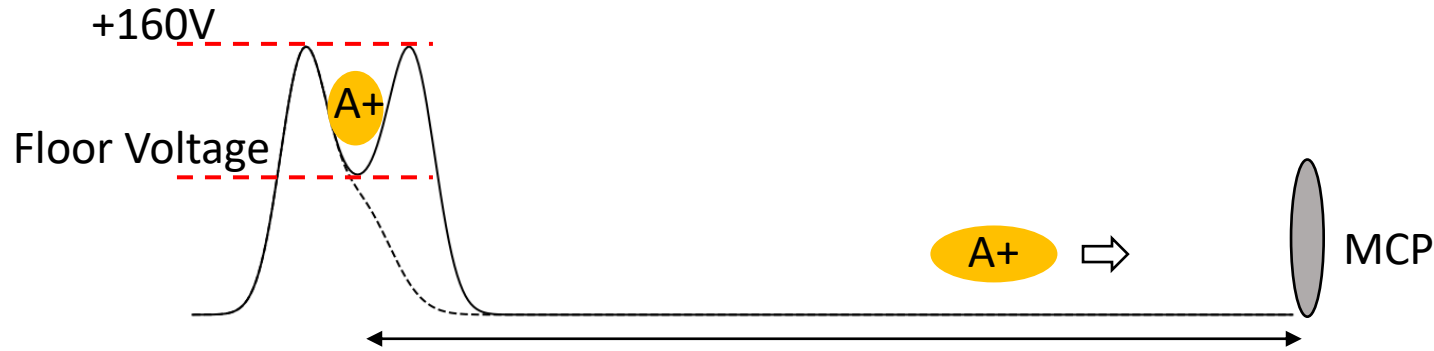
- **Antiproton and electron calibration:**

- Calibration of TOF spectra.
- Confirming linearity with mass and energy.

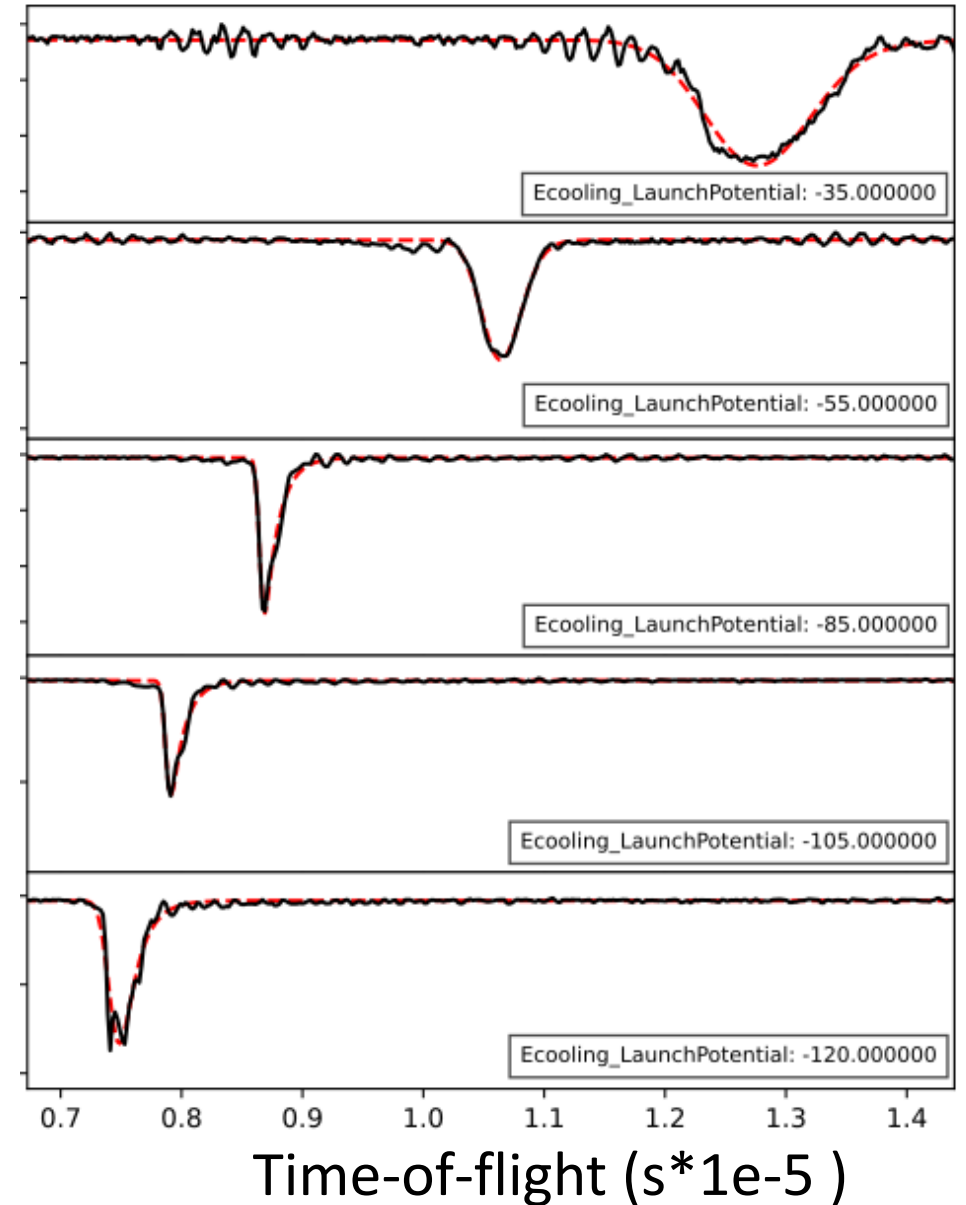
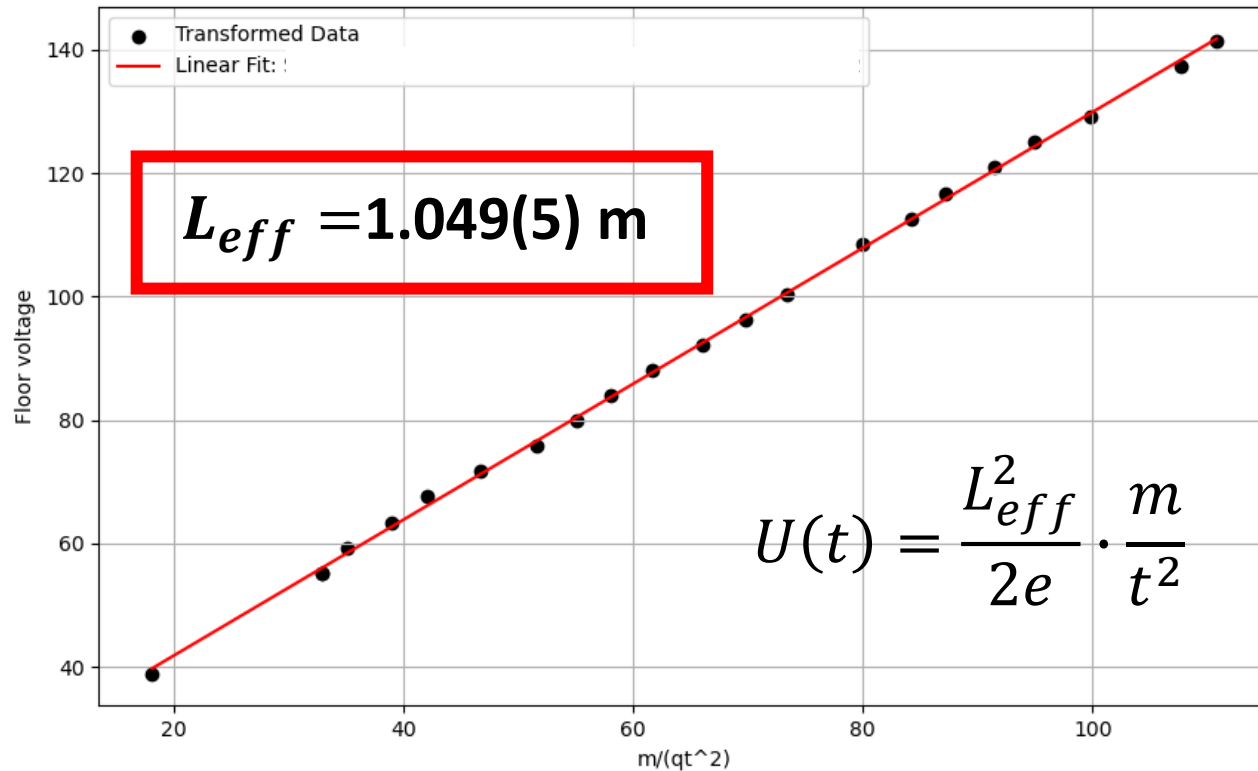
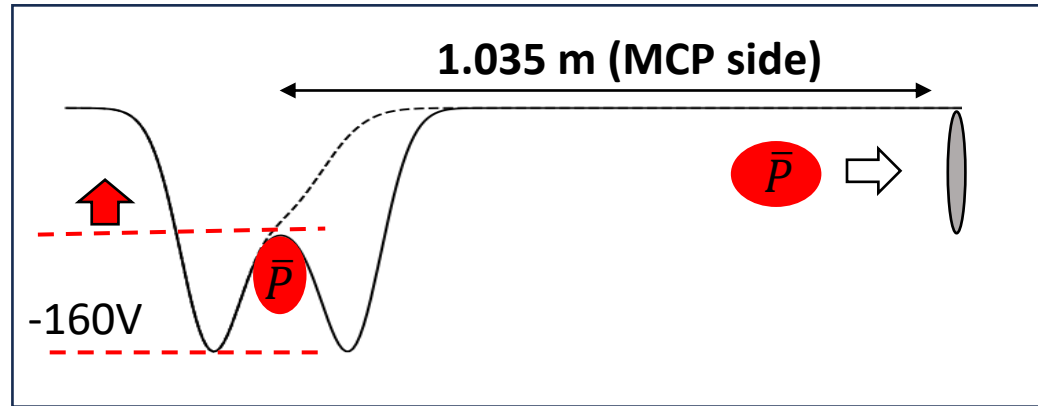
- **Nitrogen campaign: (36h):**

- Clean nitrogen environment.
- Confirming HCl formation from nitrogen.

# Sample data during air leak campaign



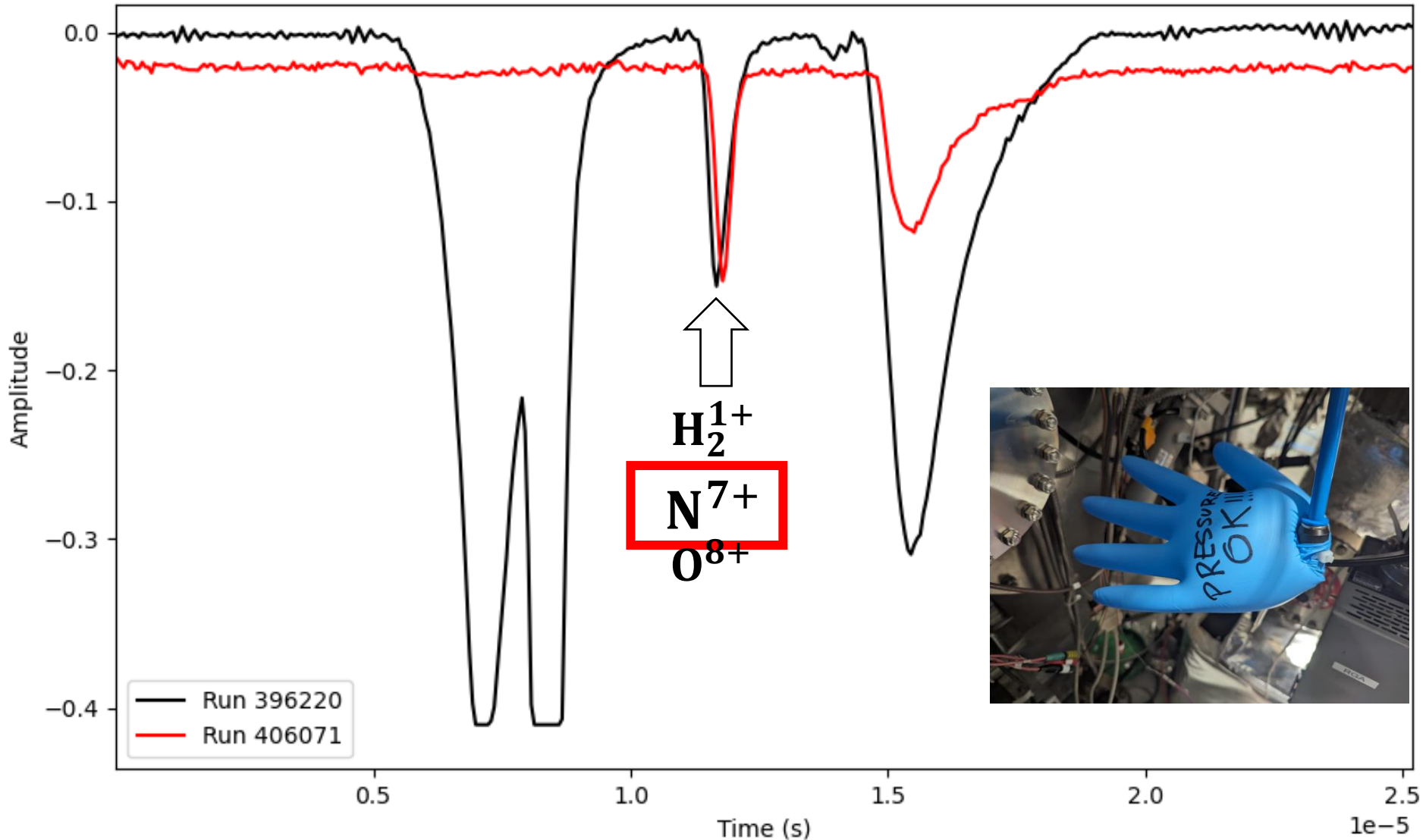
# Time-of-flight calibration using Pbars



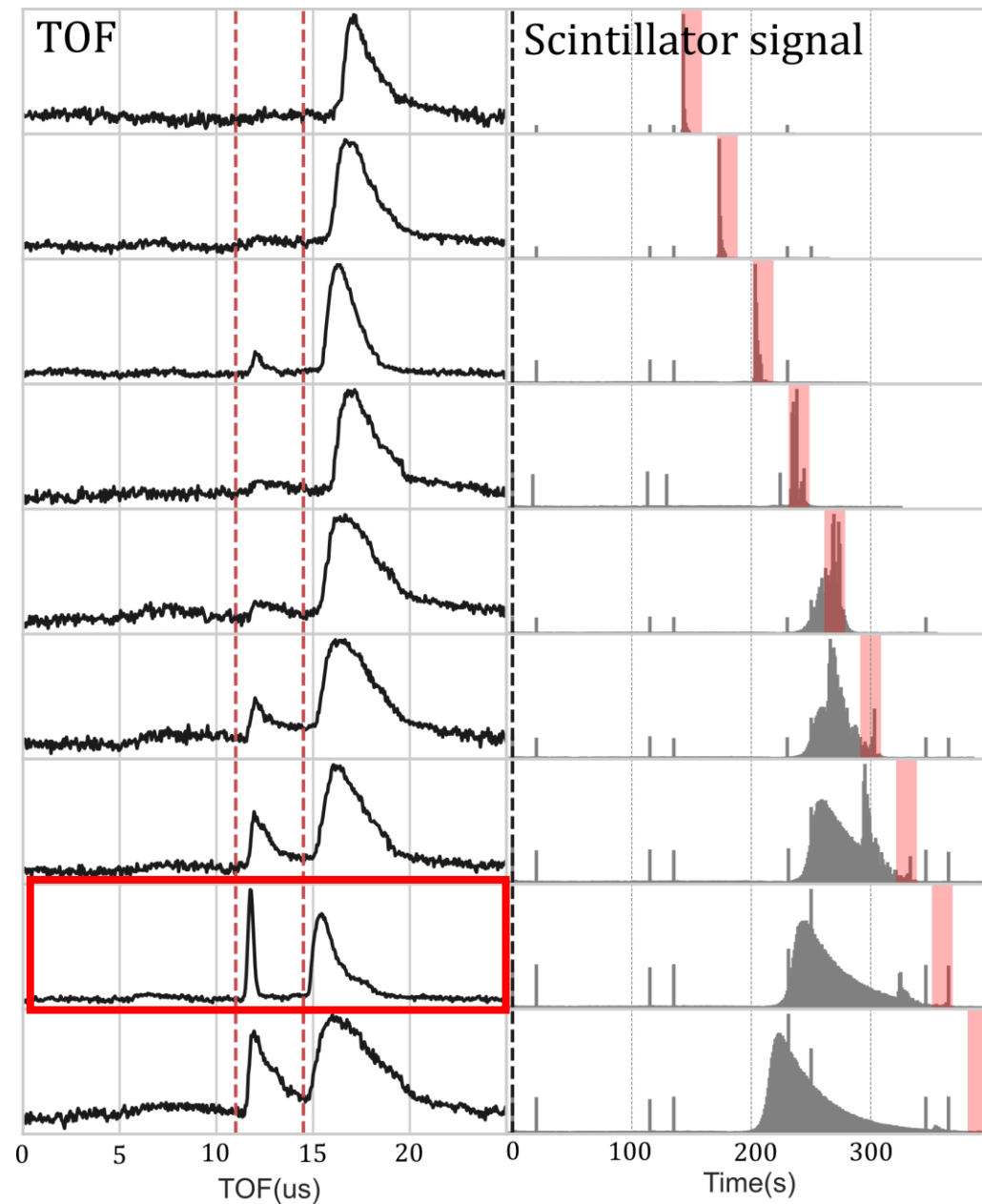
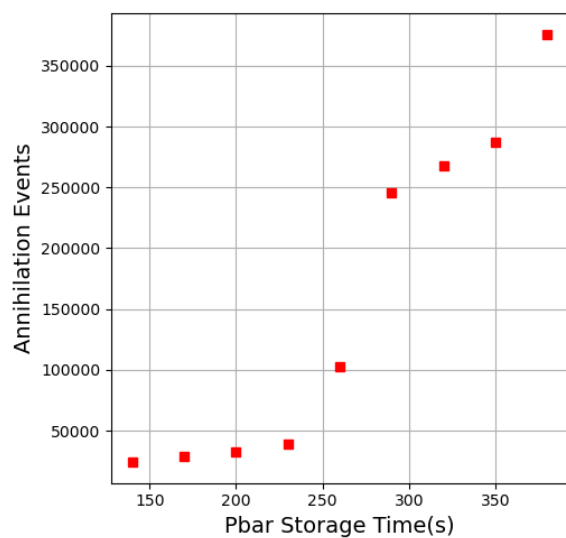
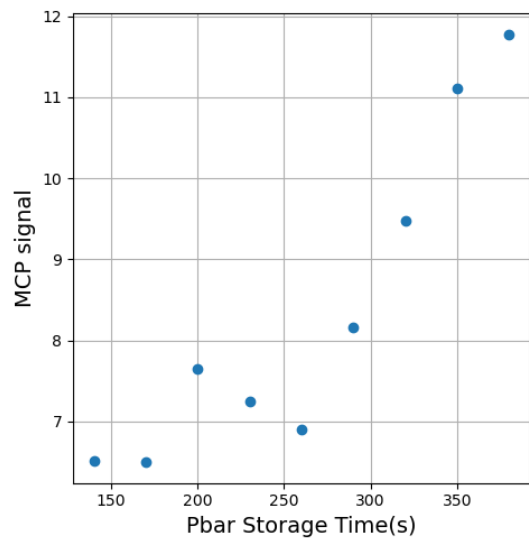
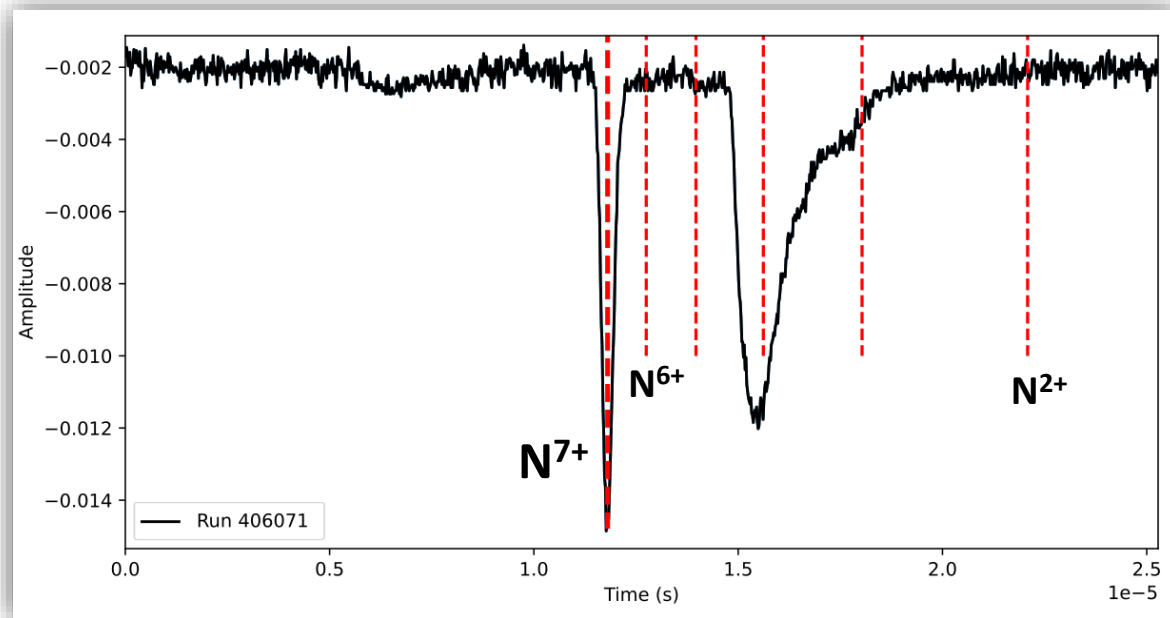


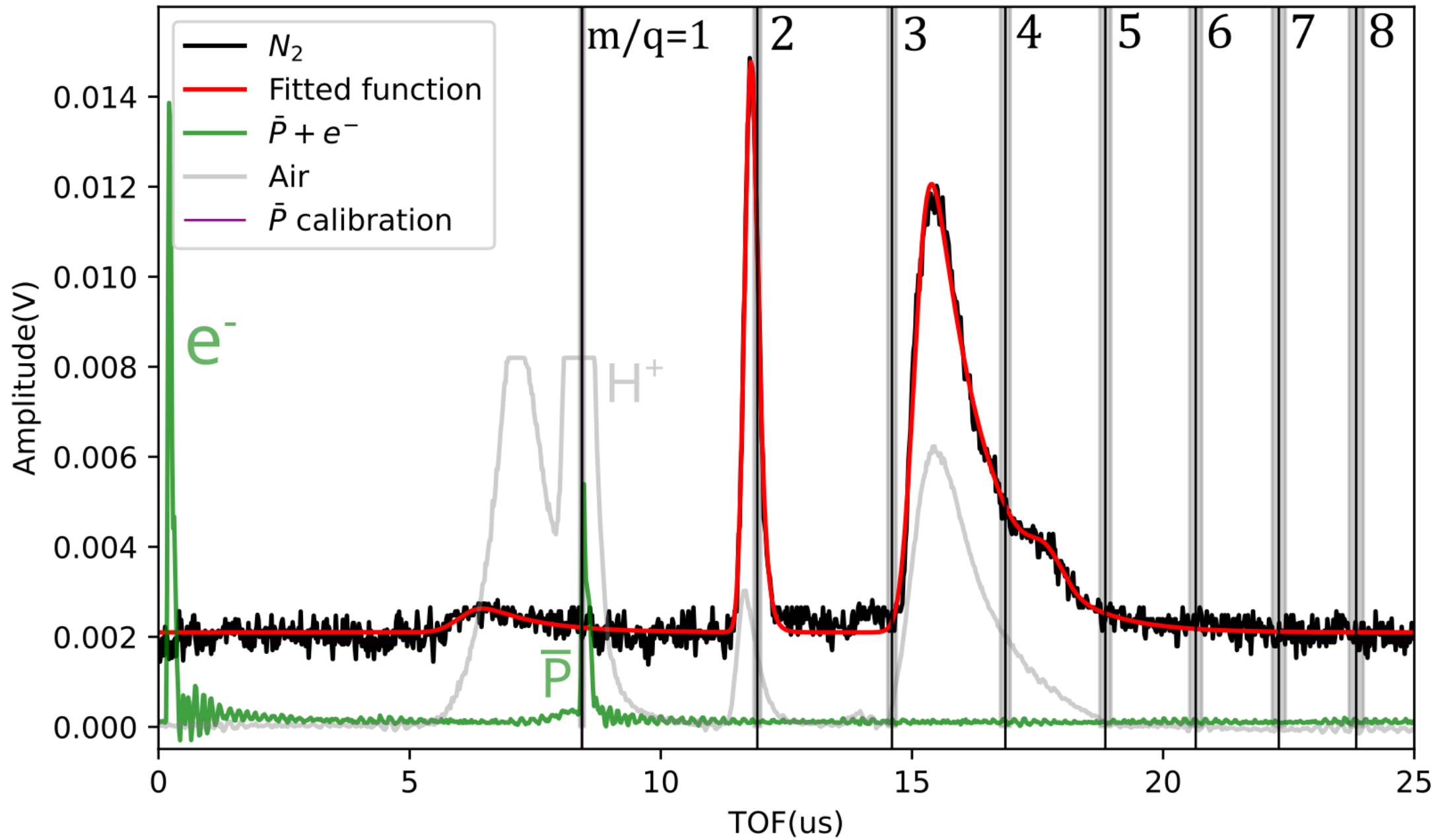
# Peak at $m/q=2$

## Fully stripped nitrogen identified?



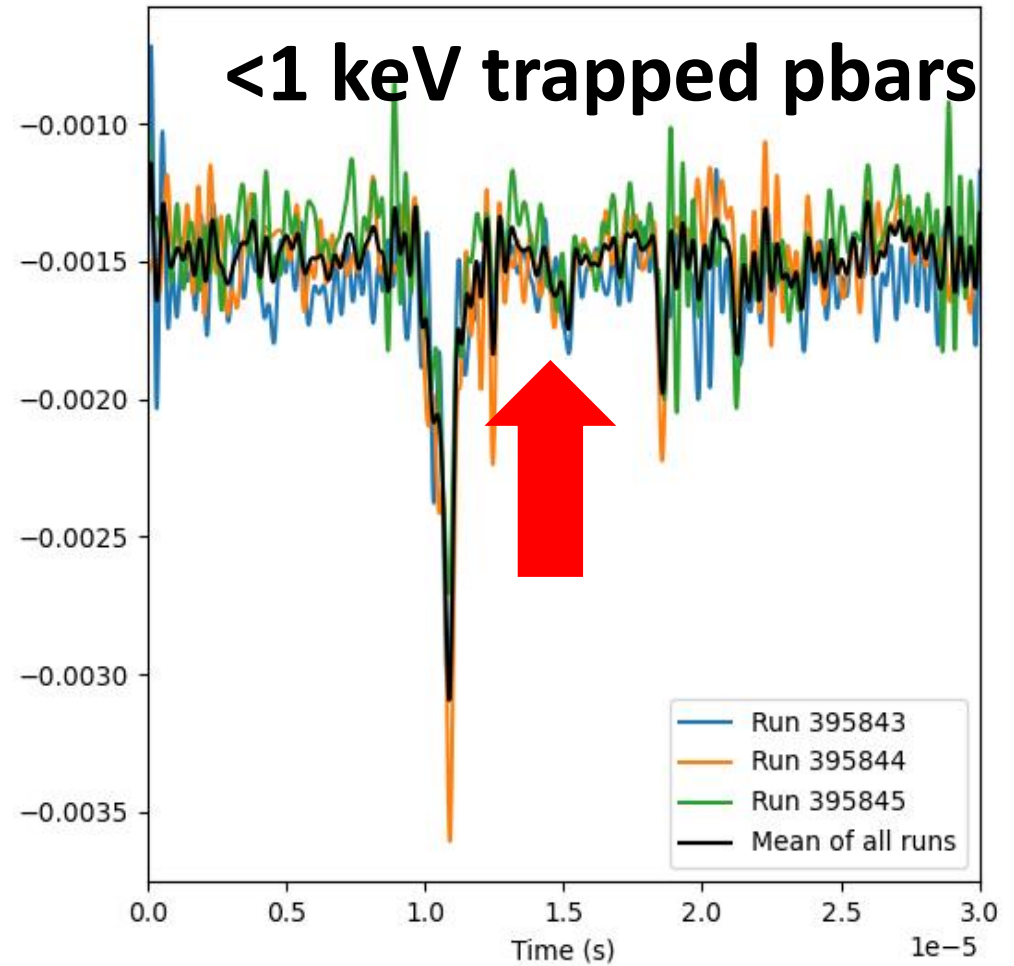
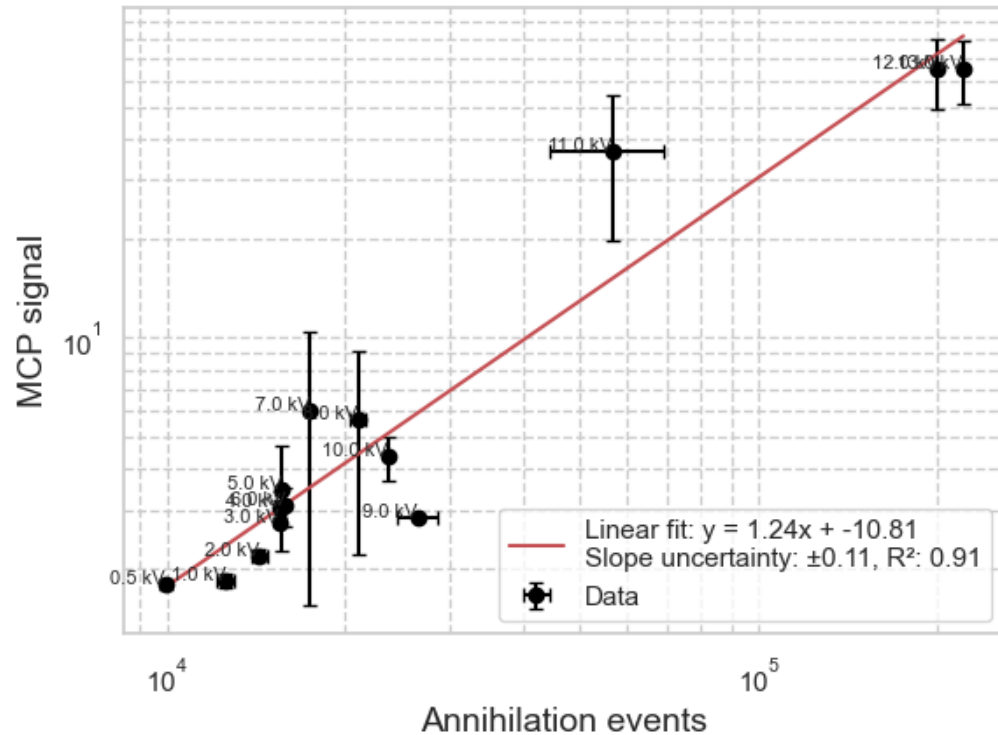
# Evolution of formation





# Low energy antiproton interactions

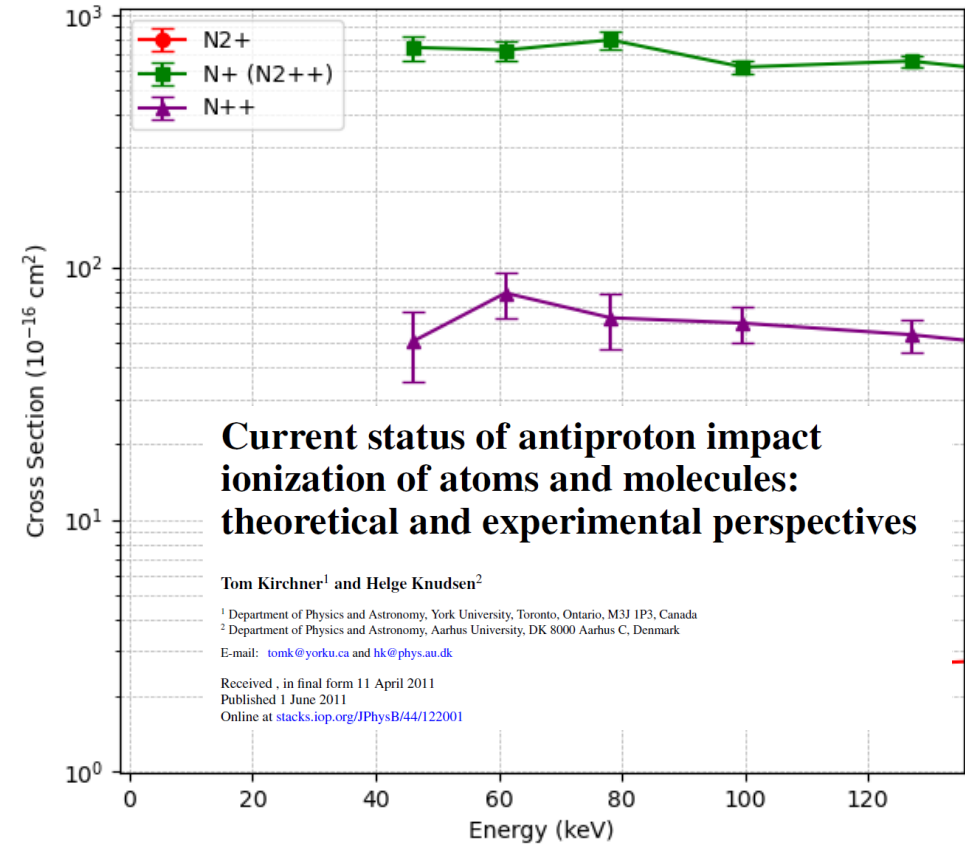
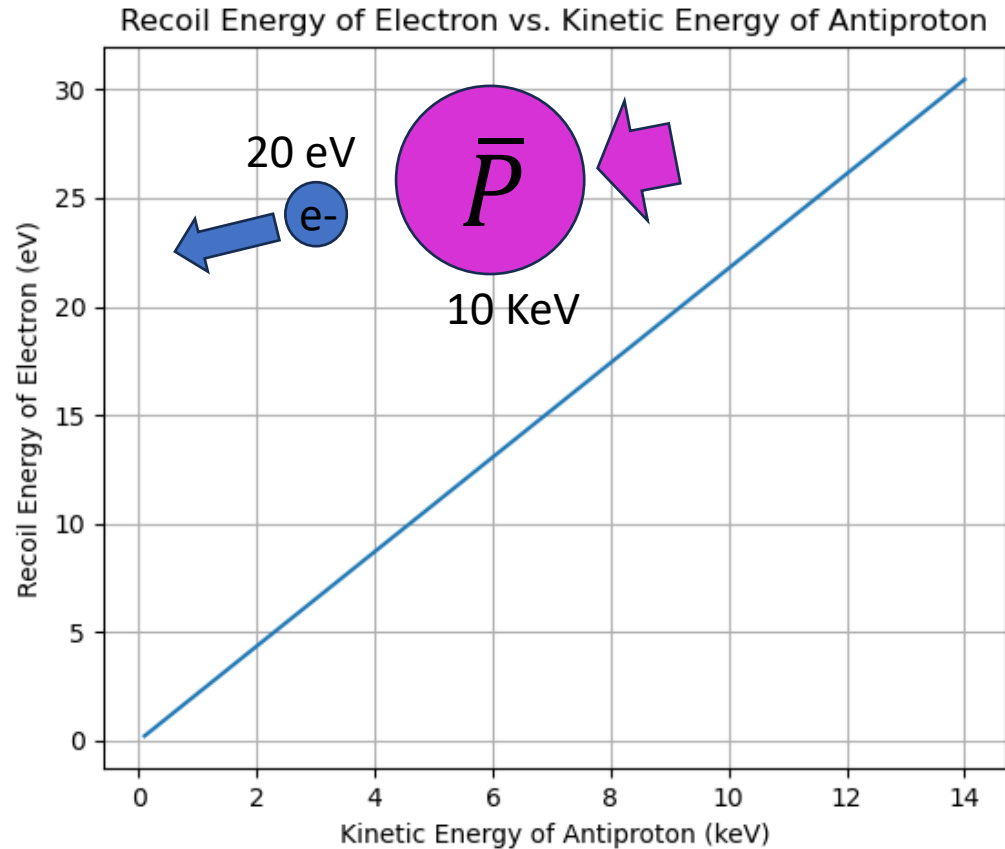
Signal of  $m/q=2$  peak vs annihilation event:



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

# Collisional ionization with antiprotons?

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

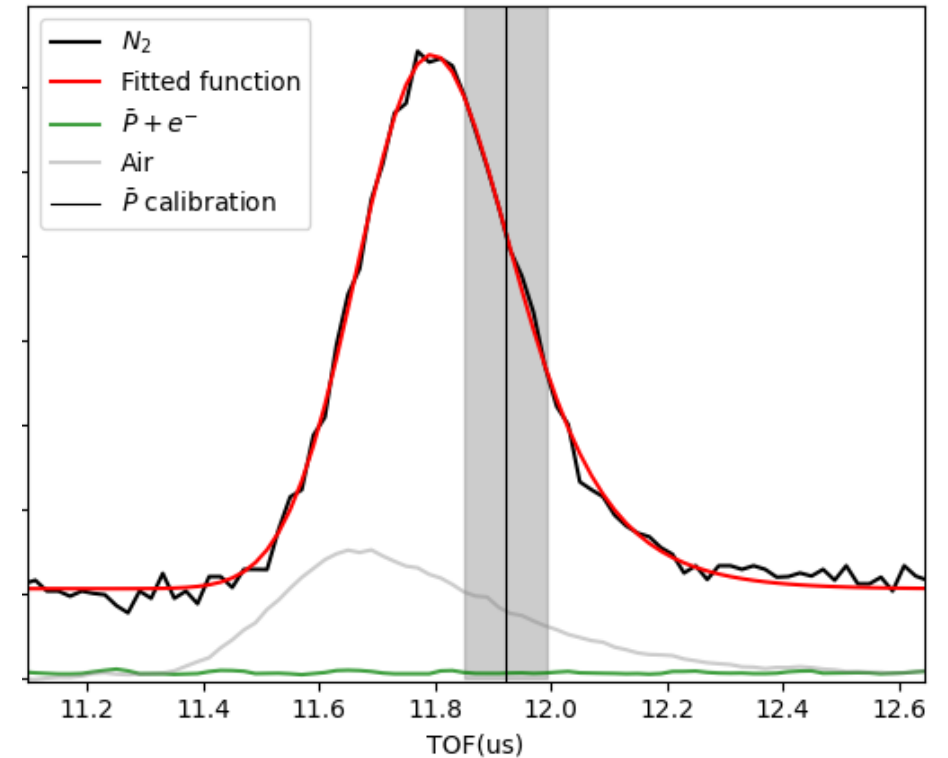
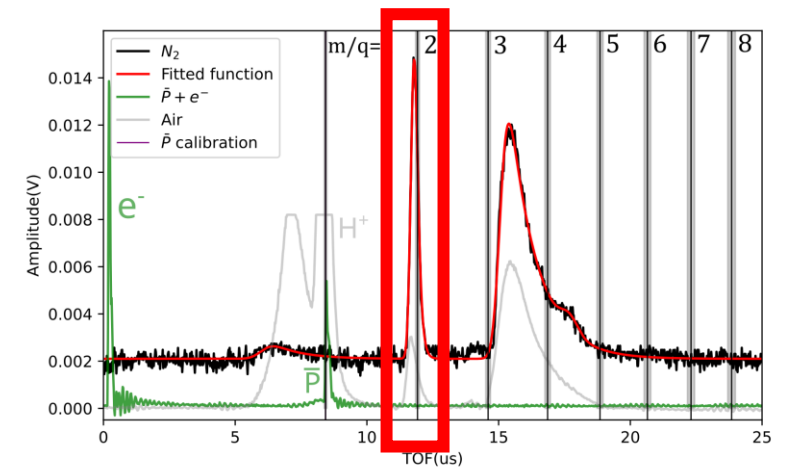
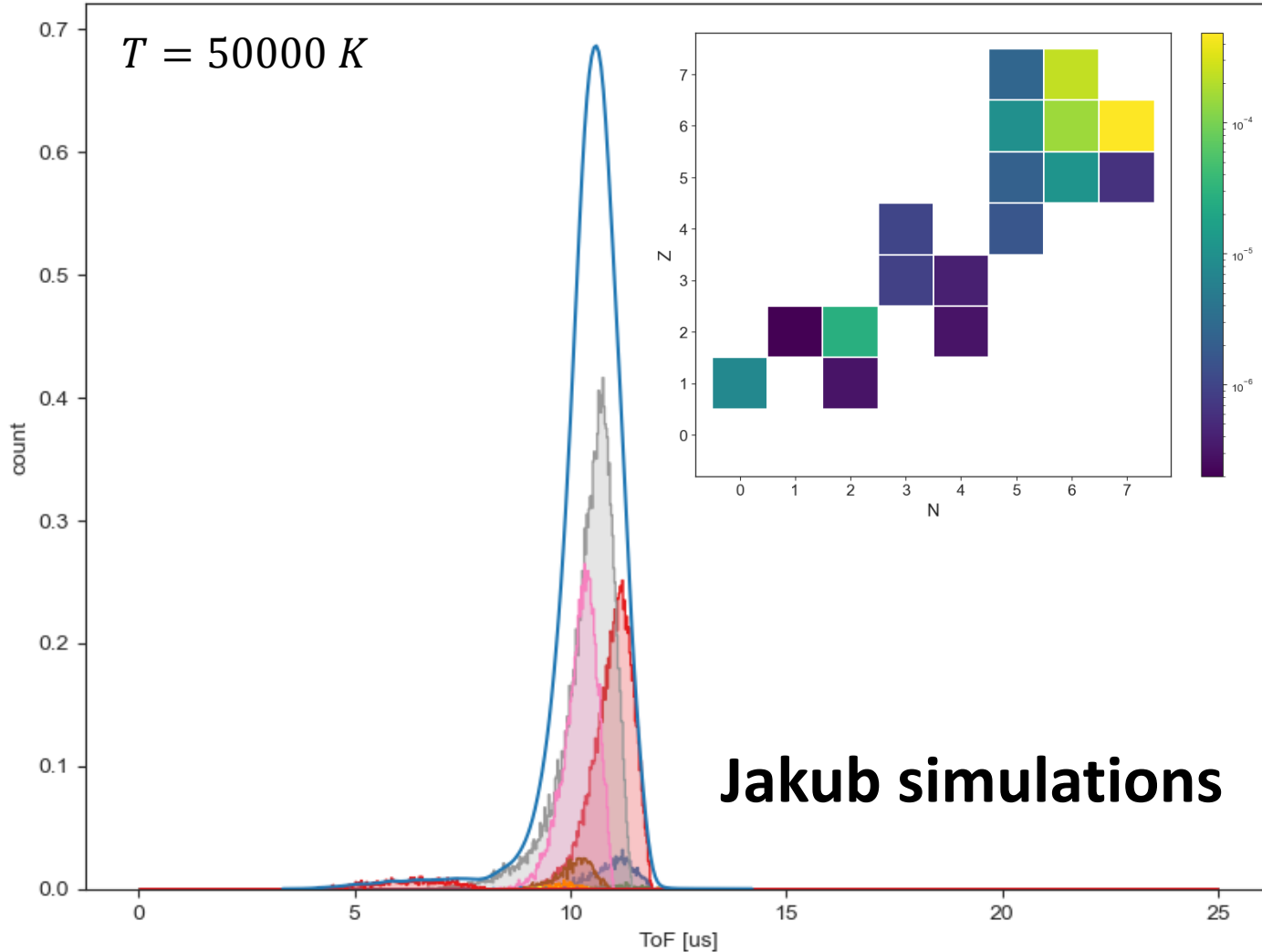


Could electrons accelerated by HV electrodes strip nitrogen?

Simulation by Bharat using CST in progress...

# Nuclear fragments?

ToF distribution of fragments from N14 with Q=+Z



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

# Proof-of-Principle paper:

## Formation of HCl<sub>s</sub> in a trap with antiprotons

- Introducing possibilities of trapping nuclear fragments from annihilation.
- Presenting mechanism for trapping HCl<sub>s</sub> formed from Pbar annihilation with N<sub>2</sub> 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..**

Formation of highly charged ions in a trap using antiprotons<sup>\*</sup>  
Ann Axness<sup>1</sup> and Søren Malmberg<sup>2</sup>  
Ann Axness<sup>1</sup> (mailto:axness@cern.ch)  
Søren Malmberg<sup>2</sup> (mailto:malmberg@cern.ch)  
(AUGUS Collaboration)  
(dated: May 2, 2014)

In this paper, we present the formation of highly charged ions in a nested Penning-Malmberg trap via antiproton annihilation on stable atoms. Millions of antiprotons were trapped inside a cryogenic micro-trap at the ALPHA experiment and allowed to interact with a positive ion charge state molecule as a precursor of (10<sup>10</sup> ions/m<sup>3</sup>), the protons were released in a positive ion while the trap. Antiprotons interacting with neutral atoms resulted in the formation of highly charged ions. The work opens the avenue for fully stripped atoms and also interaction with the antiprotons. The work opens the avenue for the study of short-lived trapped ions in the search of new physics.

### I. INTRODUCTION

Synthesis and study of short-lived radioactive have allowed the systematic study of the fundamental forces governing the properties of atomic nuclei, impacting all areas of research ranging from astrophysics to medicine. Precision measurements probing the structure and properties of nuclei are normally performed on nuclei composed of bound nucleons (n.b.). While it is commonly agreed, it is well known that the bound nucleons have a significant contribution to the structure of the nucleus (e.g. the distribution of the nucleons in the nucleus) [1]. In fact, the lifetime of one nucleon and its associated properties (e.g. the electric and magnetic moments) have been measured to a high degree of precision [2]. Over the century, radioisotopes have been used as tracers in a variety of fields such as geology, medicine, and nuclear physics (via isotopic separation), and in the study of their chemical properties (via isotopic substitution) [3]. In order to study the nuclear structure of these isotopes, one needs to know the type of ion (e.g. the charge state) and the type of ion (e.g. the mass) of the ion. One method, such as those mentioned above, is to use a mass spectrometer, which can be used to identify the ion. However, such a method is not suitable for the study of short-lived ions. The present work proposes a new approach to study the formation of short-lived ions. With the development of sources of cold, trapped antiprotons at ALPHA (n.b.) a new method was proposed.

### II. METHOD

The measurements were performed at the AUGUS or positronium within the ALPHA facility at CERN (HEP). Antiprotons were created from the positron beam using a 200 MeV antiproton target. The antiprotons are decelerated in bunches at 100 keV containing

<sup>\*</sup> A version to the article has been submitted to Physical Review Letters. <sup>†</sup> Søren Malmberg (mailto:malmberg@cern.ch)

8(4) million Pbars with a repetition rate of 100 using the ALPHA AD complex (HEP). Pbar bunches were directed into a degrader foil at the entrance of the Penning trap which reduces the energy to 100 keV. The Pbars then enter the cryogenic multi-ring trap with an inner diameter of 20 mm composed of segmented electrodes (see Fig. 1). Two output electrodes were placed by 0.1 m and biased to a voltage of 14 kV for efficient catching of Pbars within the trap. The distance between the electrodes is 1.5 cm. A low pressure ion source (LPI) provides a low pressure ion source. A microscopically small ion source provides a low pressure ion source. A microscopically small ion source provides a low pressure ion source. A microscopically small ion source provides a low pressure ion source.

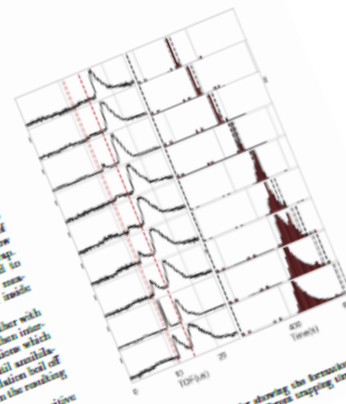
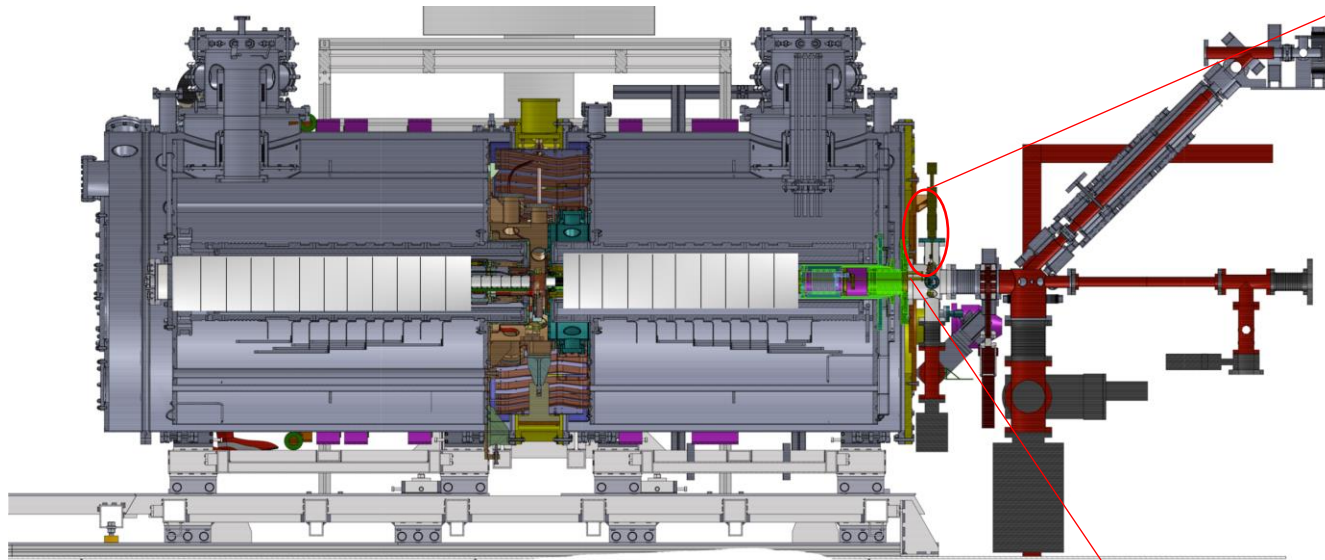


FIG. 1. Fluorescence signals for showing the formation of species and annihilation with different trapping times.

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 collisions.

- **Helium (A=4):**

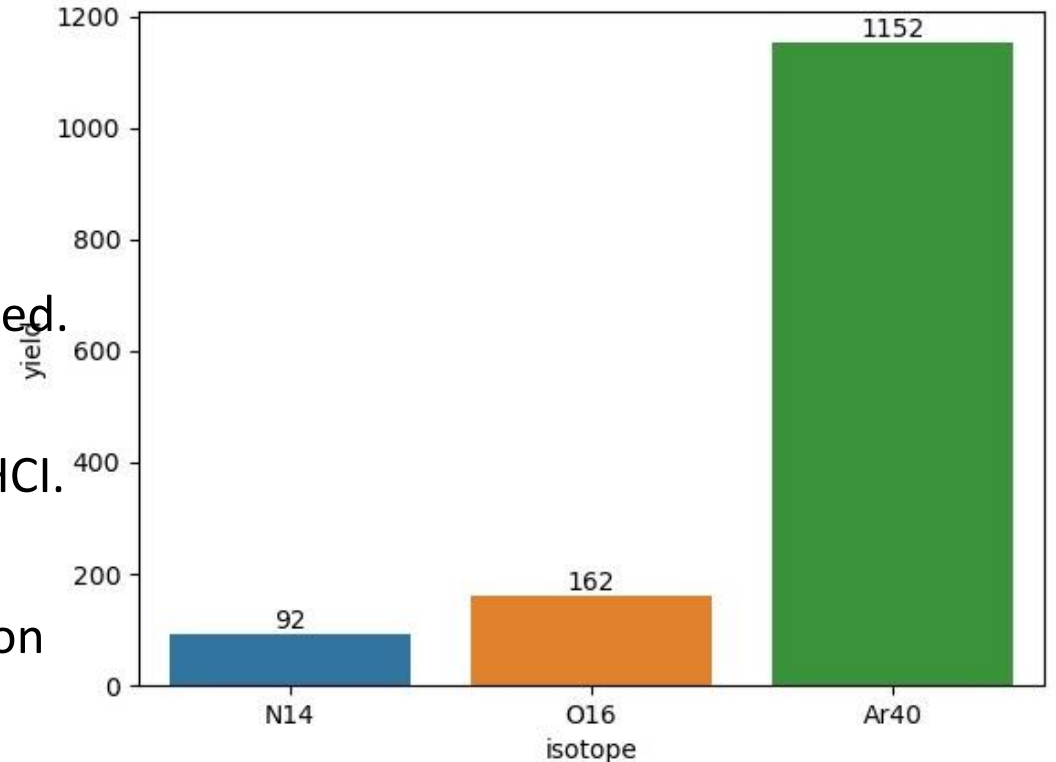
- Reference where we expect minimal fragments trapped.

- **Krypton (A=83):**

- Heaviest gas available, largest trappable fraction of HCl.

- **Nitrogen (A=14):**

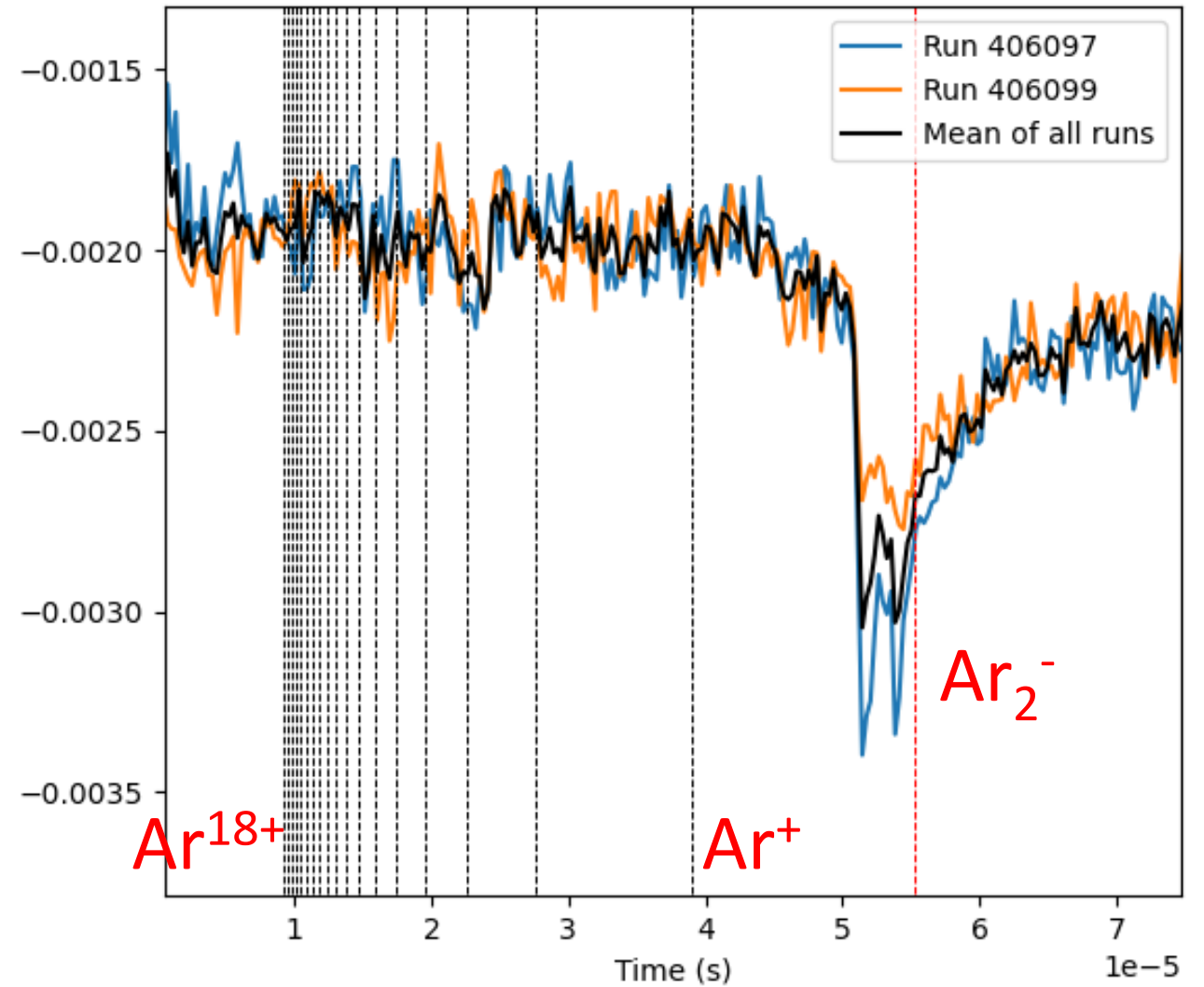
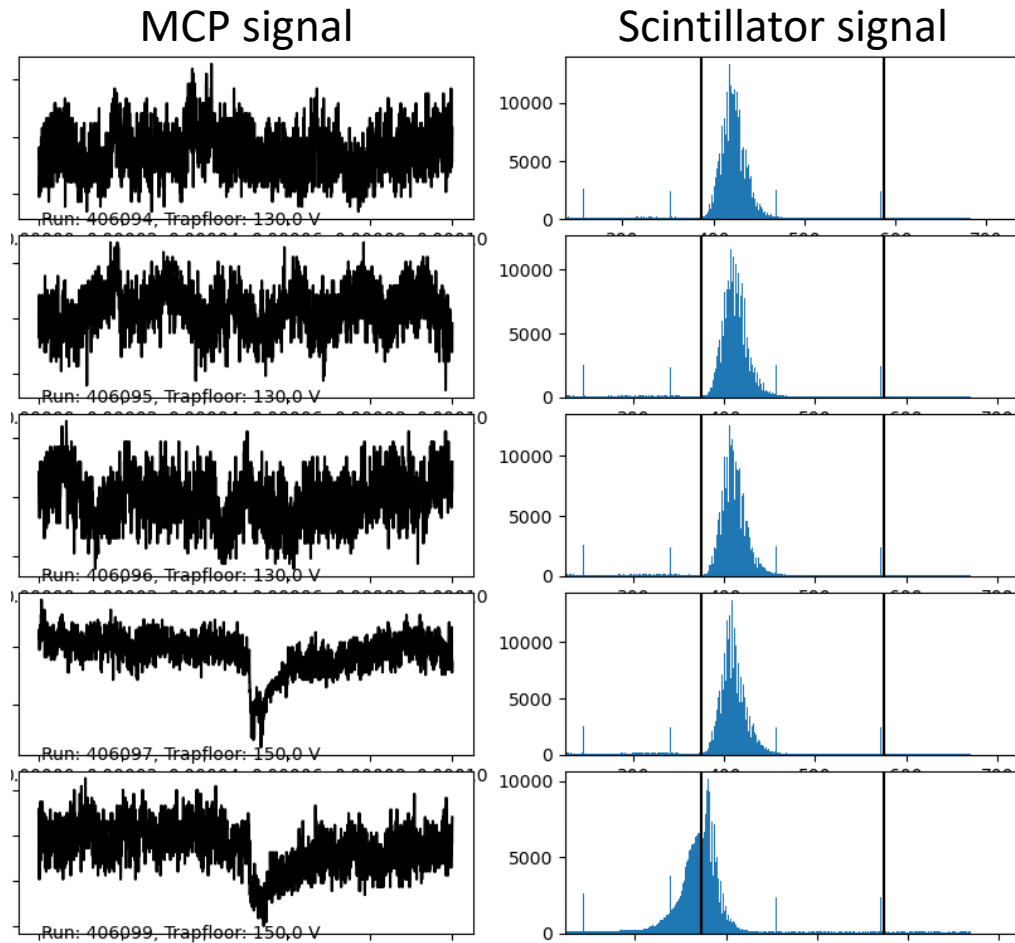
- For continued technical development, refine resolution and stability.



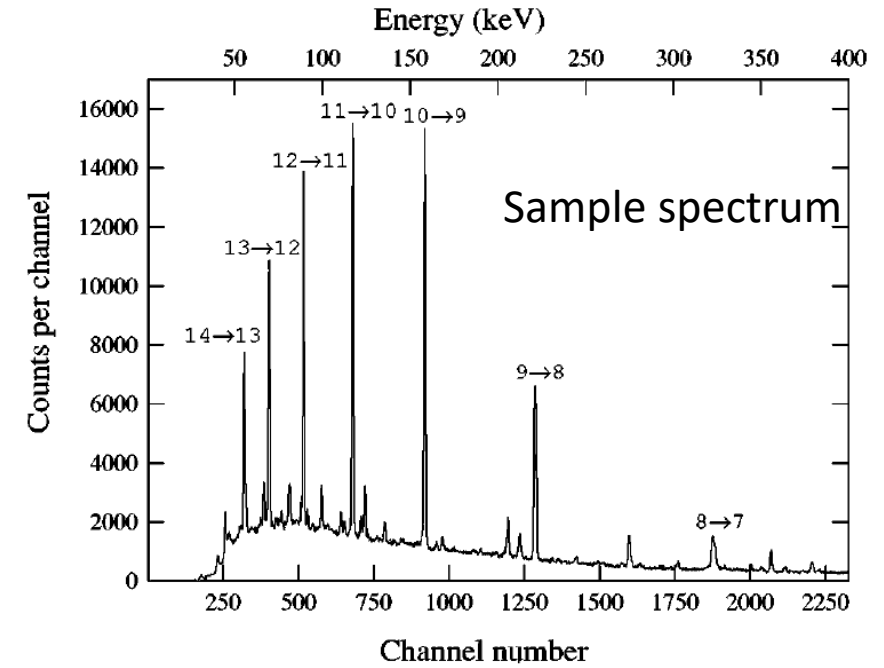
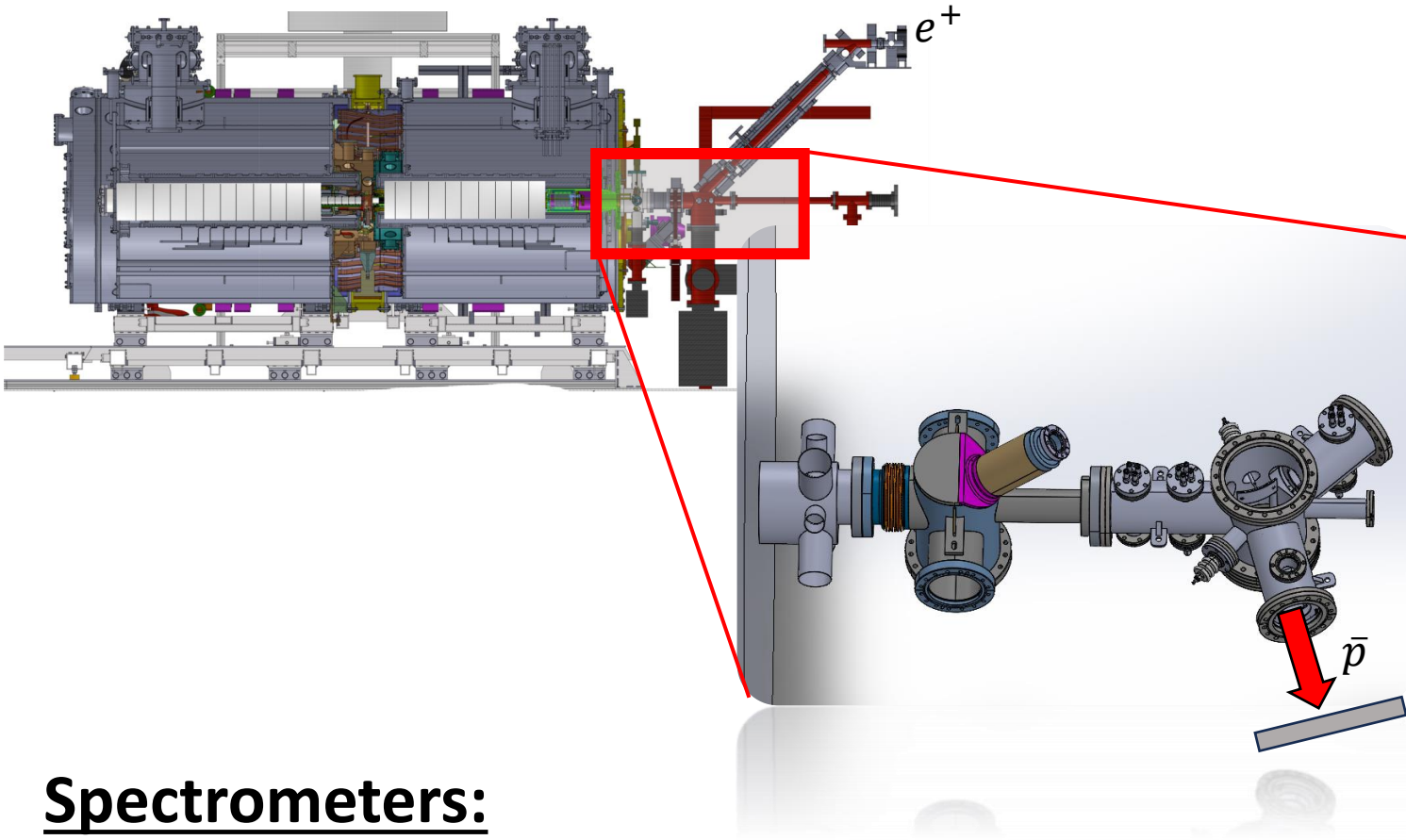
## Antiprotonic atom spectroscopy at AEGIS

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

# Argon run 2023



# First x-ray spectroscopy at AEGIS

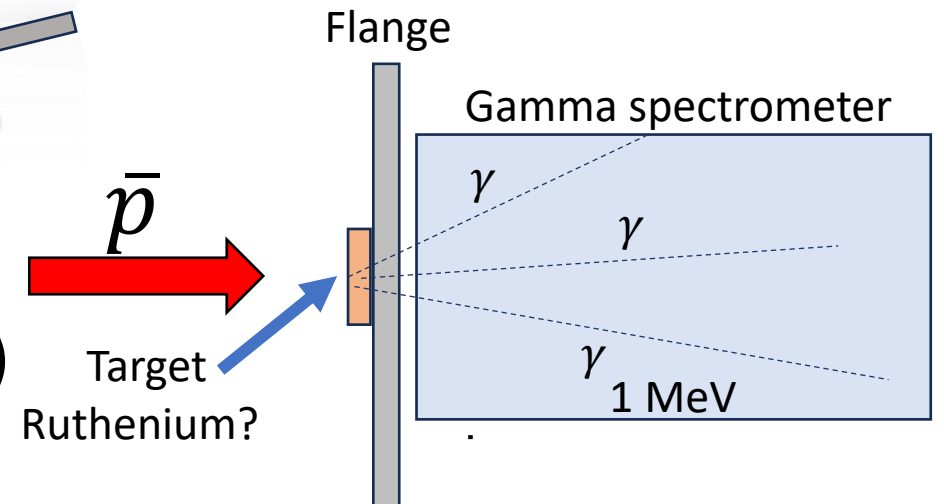


## Spectrometers:

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

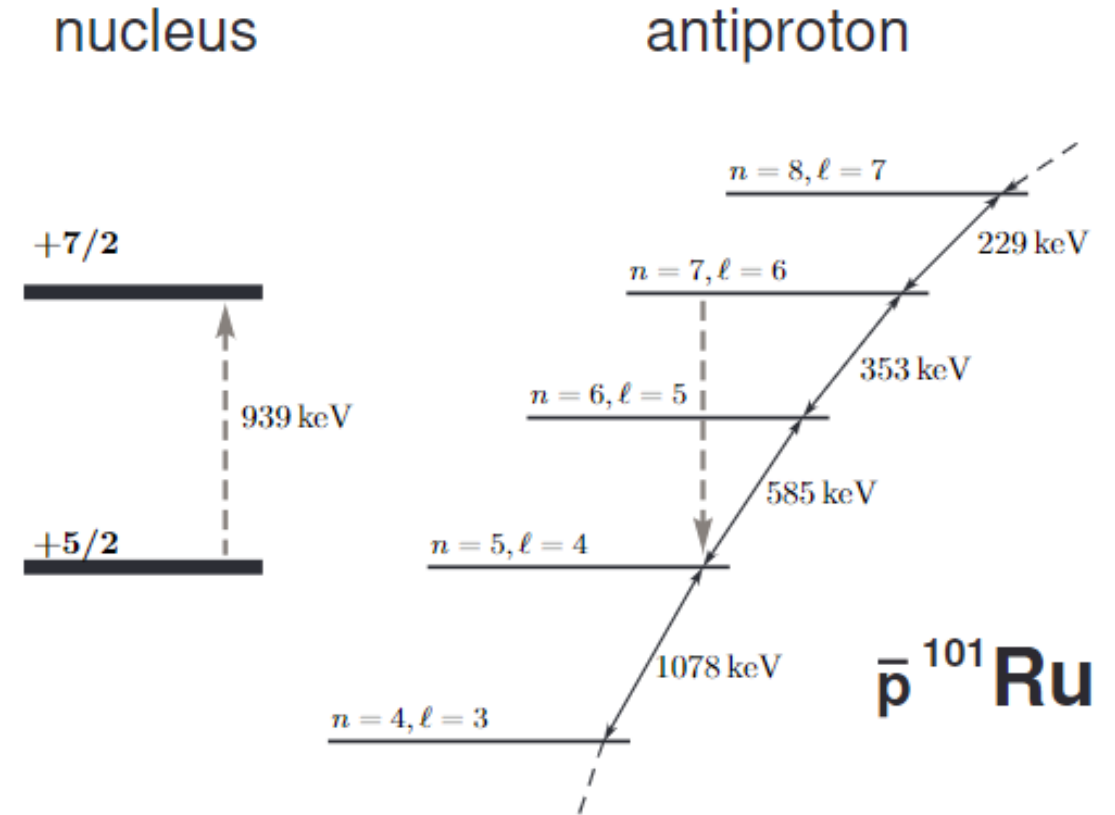
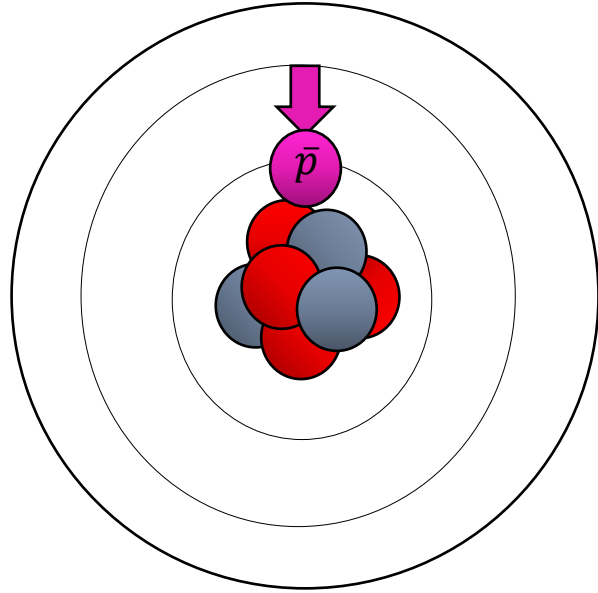


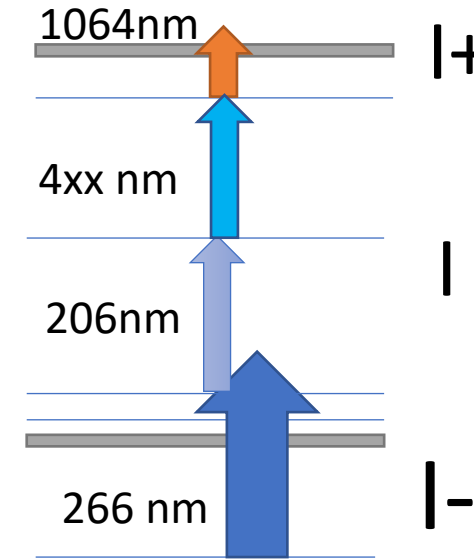
TABLE I. Examples of stable odd- $A$  antiprotonic atoms where the spin-flip-induced quadrupole resonance is expected. Clear transition energies were acquired from [42] and the antiproton transition energies were calculated from the Ham  $\mathcal{H}_r$ . In parenthesis, we indicate tentatively assigned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

isotope	Z	N	nuclear spin		$\Delta E_N$ (keV)	$\Delta E_{\bar{p}}$ (keV)	$n$		$\langle f_{in}   \mathcal{H}_Q   i_{in} \rangle / \mathcal{Q}_0$ ( $\text{eV b}^{-1}$ )
			ground	excited			initial	final	
			NUCLEUS			ANTIPROTON			
<sup>101</sup> Ru	44	57	5/2	(7/2)	938.65	939.40	7	5	159
<sup>111</sup> Cd	48	62	1/2	(3/2)	1115.57	1119.99	7	5	92
<sup>123</sup> Sb	51	72	7/2	(9/2)	1260.80	1264.81	7	5	258
<sup>165</sup> Ho	67	98	7/2	(9/2)	2178.00	2189.96	7	5	584
<sup>169</sup> Tm	69	100	1/2	(3/2)	2312.2	2323.38	7	5	275
<sup>183</sup> W	74	109	1/2	(3/2)	2667.8	2667.47	7	5	339
<sup>203</sup> 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..



Cond Tunable Wavelength Lasers

Nanosecond Lasers

## NT260 SERIES

Narrow Linewidth  
10 kHz Tunable  
Lasers



### FEATURES

- ▶ Two years warranty
- ▶ Clean air purging for long lifetime of optics
- ▶ Integrated monitoring of energy and wavelength
- ▶ Hands-free no gap wavelength tuning in 210 – 2600 nm range
- ▶ High repetition rate 10 kHz
- ▶ Narrow linewidth down to  $1.5 \text{ cm}^{-1}$
- ▶ Up to 0.7 W output
- ▶ Monolithic rugged frame
- ▶ Motorized output shutters
- ▶ Mixed Q-switched/ mode-locked operation
- ▶ Easy control via keypad or PC

### BENEFITS

- ▶ Super reliable
- ▶ Wide tuning range 210 – 2600 nm without gaps
- ▶ Output peak in VIS range (useful for popular applications, like LIF)
- ▶ Hands-free wavelength tuning – no need for physical intervention

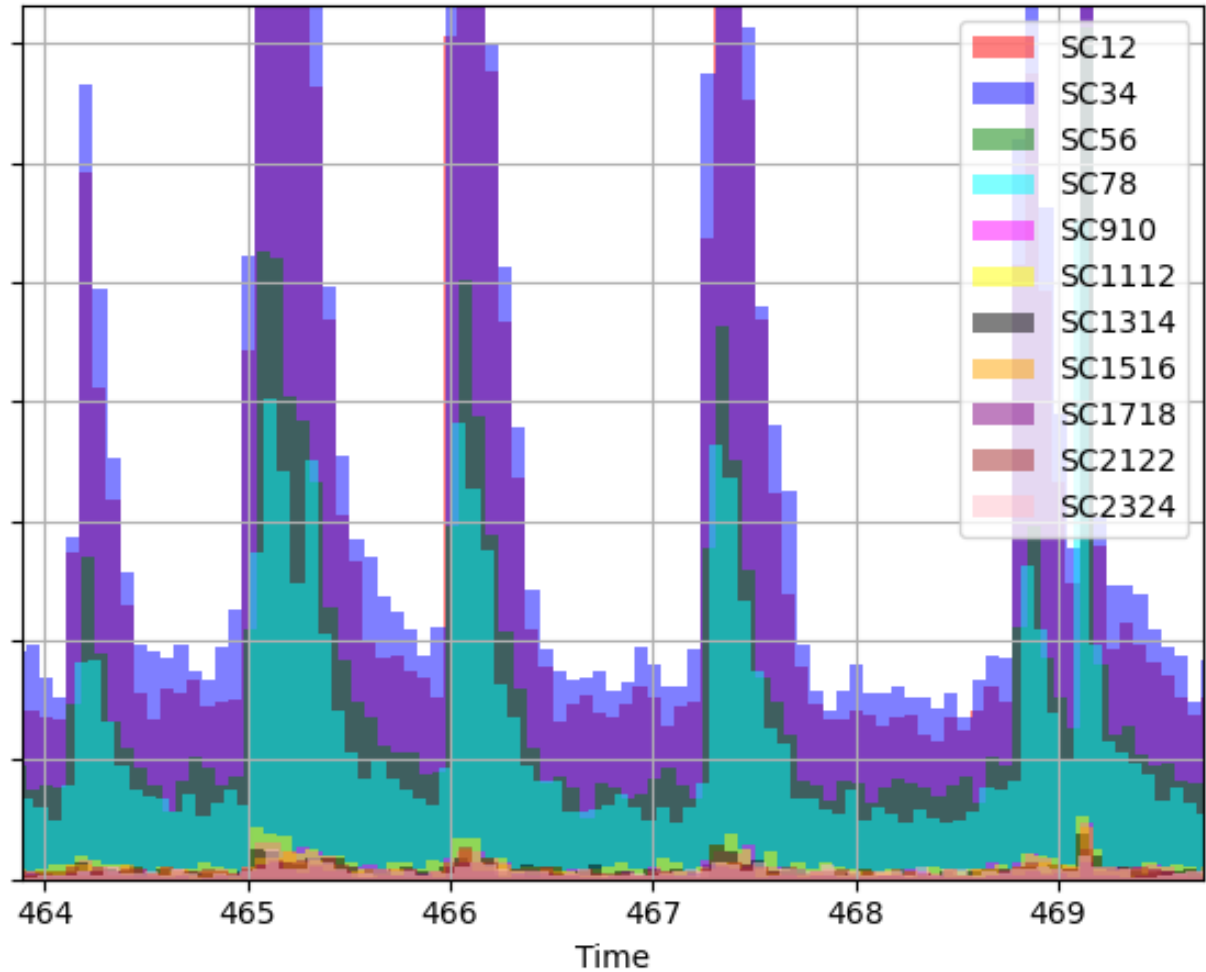
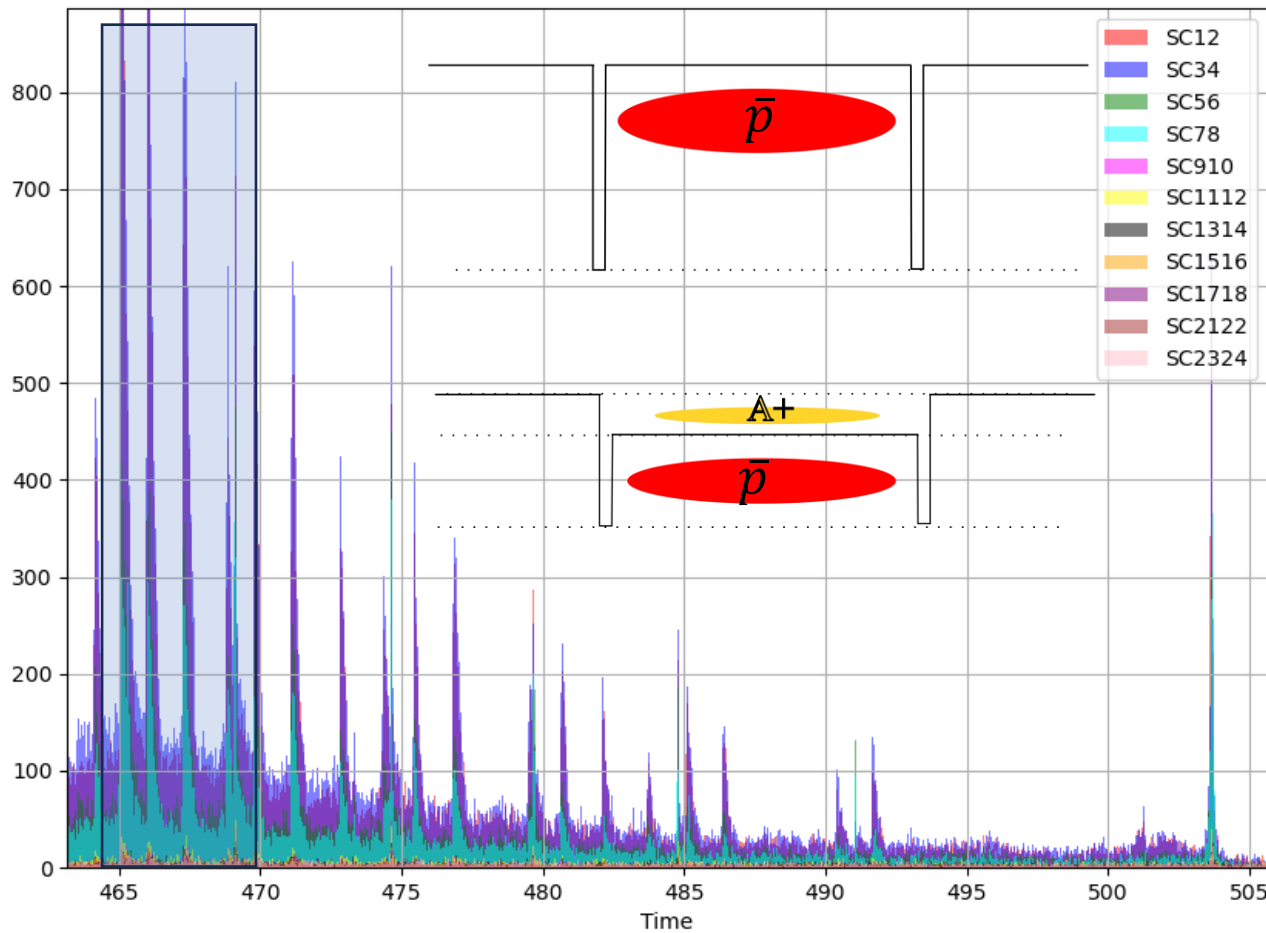
# Summary of outlook:

- Continued **development of trapping procedure and identification of HCl 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 excitation: Triggered formation of antiprotonic atoms with cotrapped anions.

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

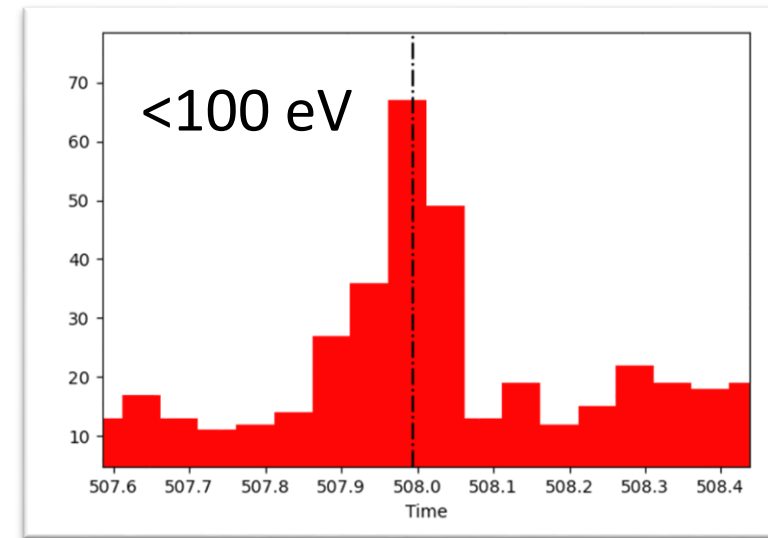
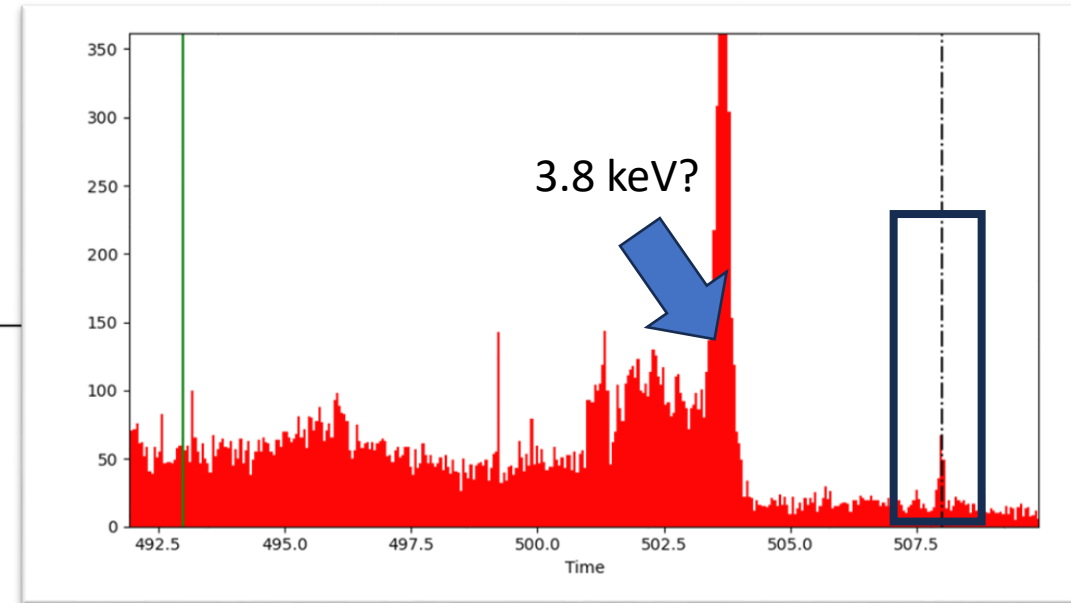
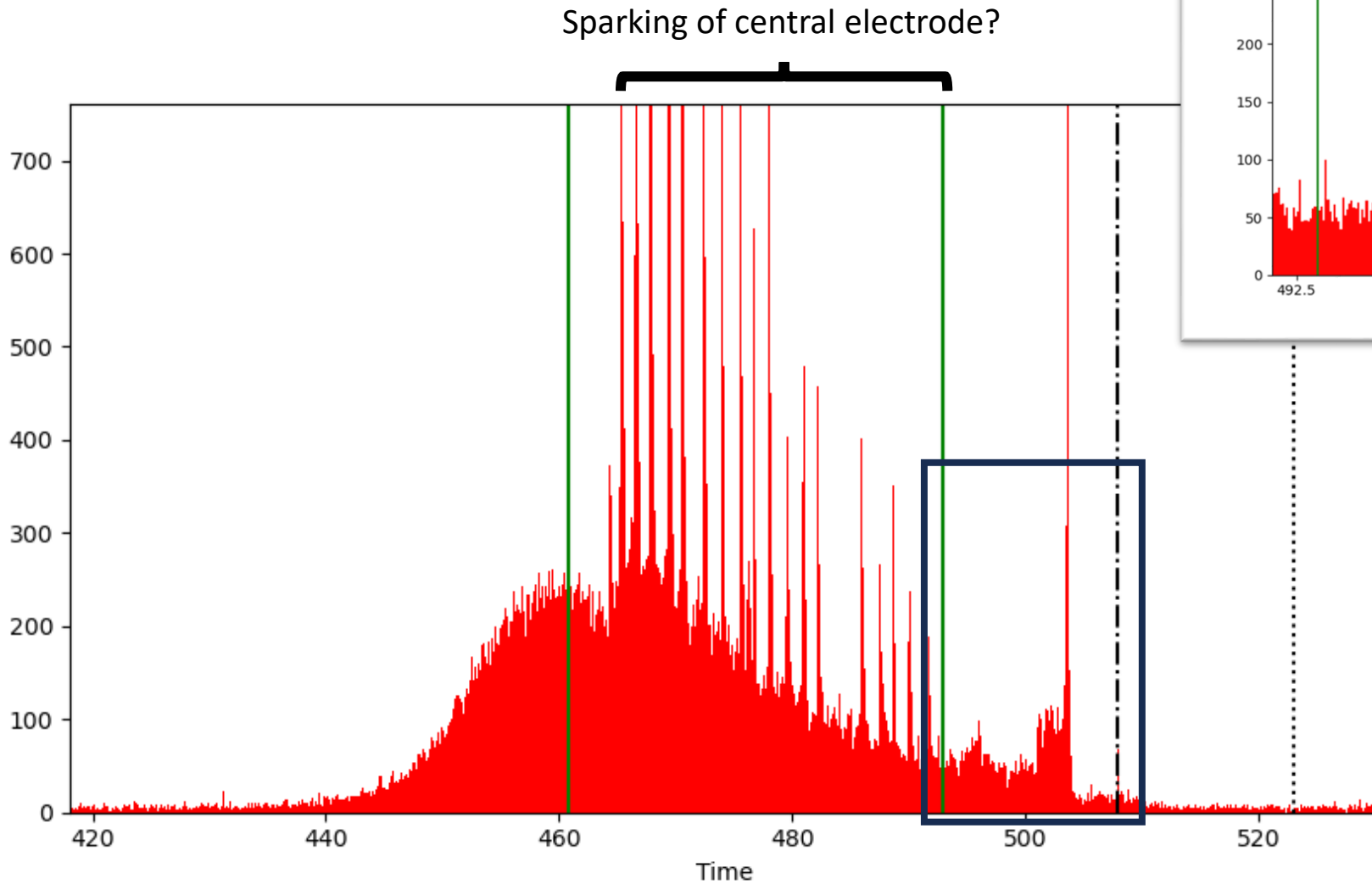
# Quasi-periodic Pbar annihilation?

Floating electrode in 5T trap?



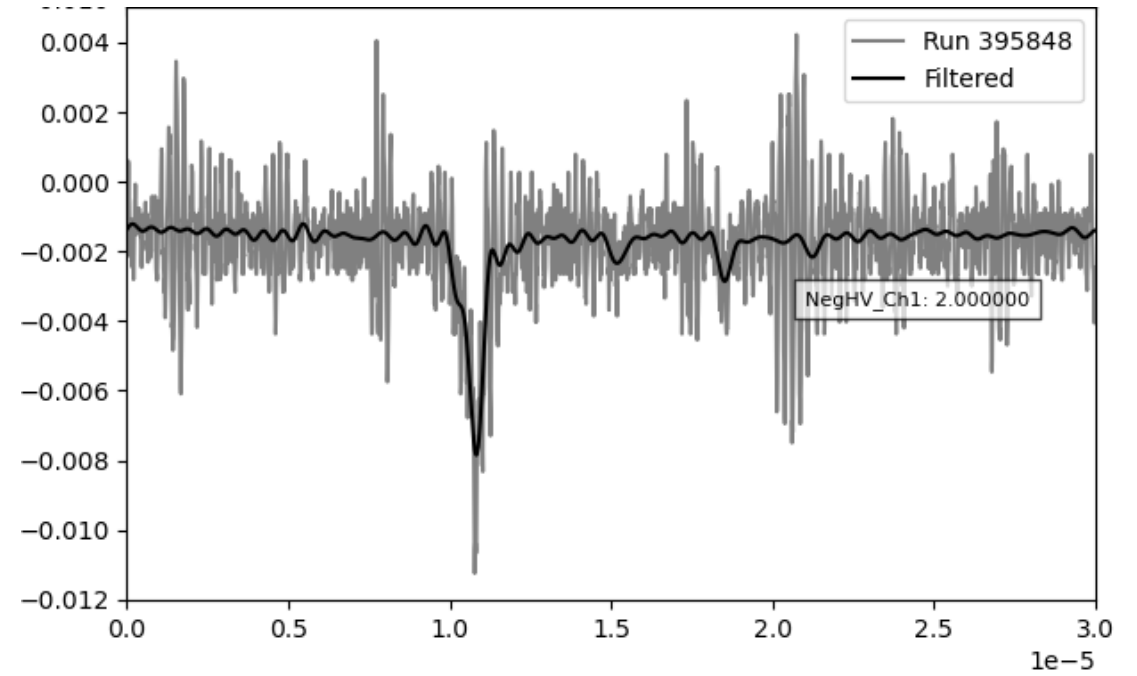
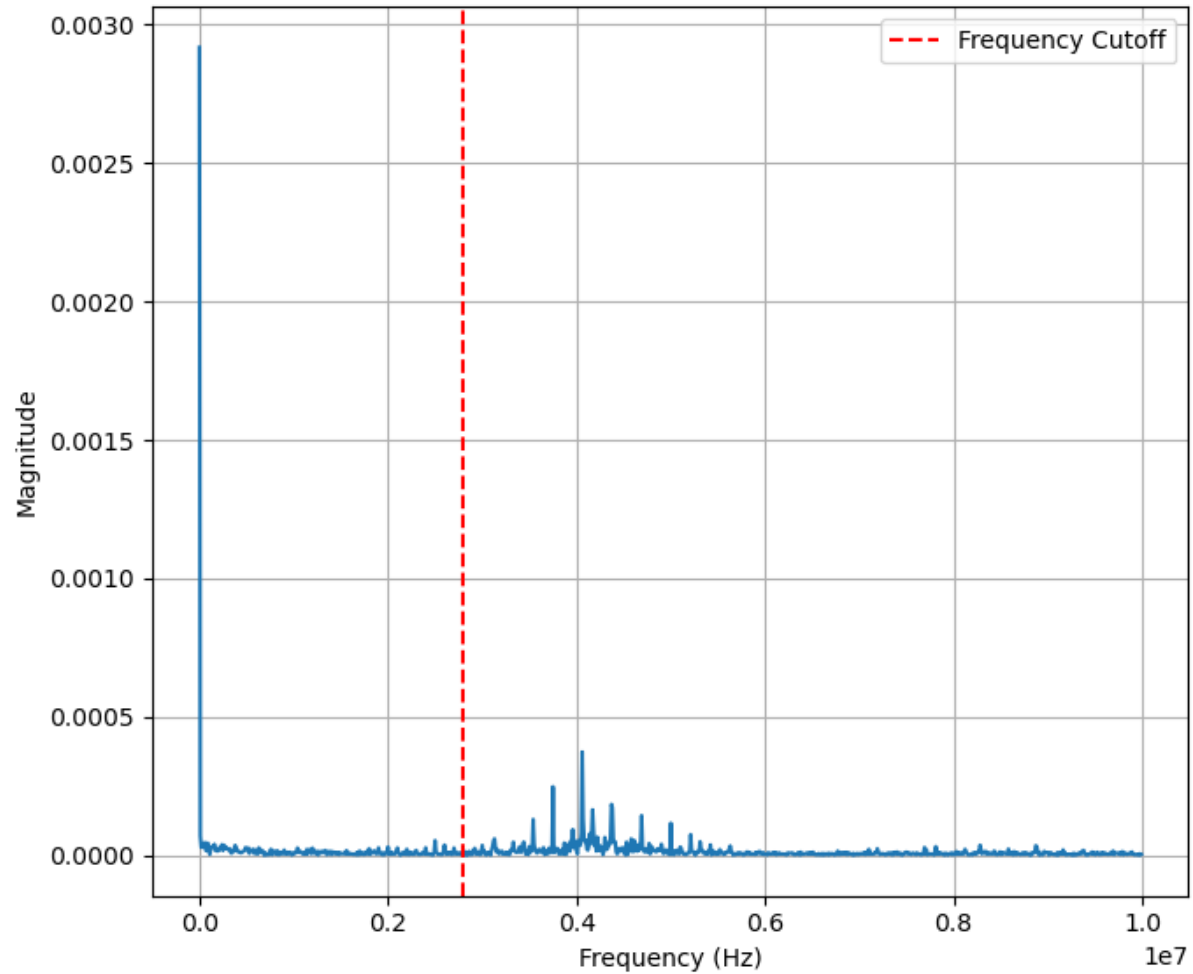


# Annihilation peak



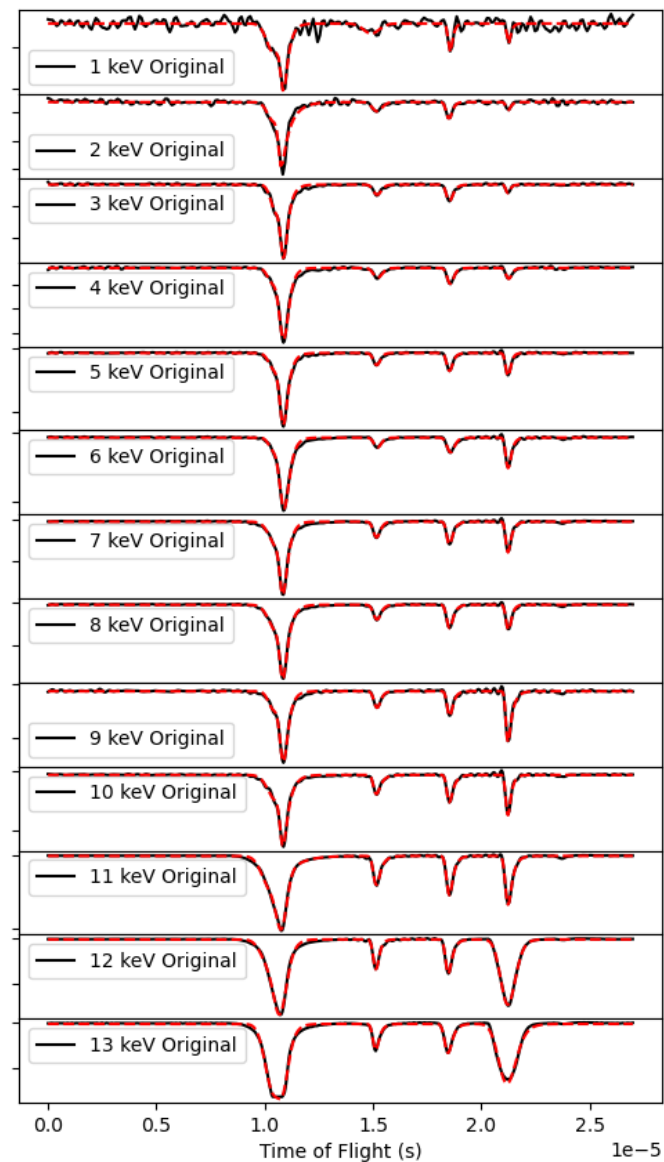
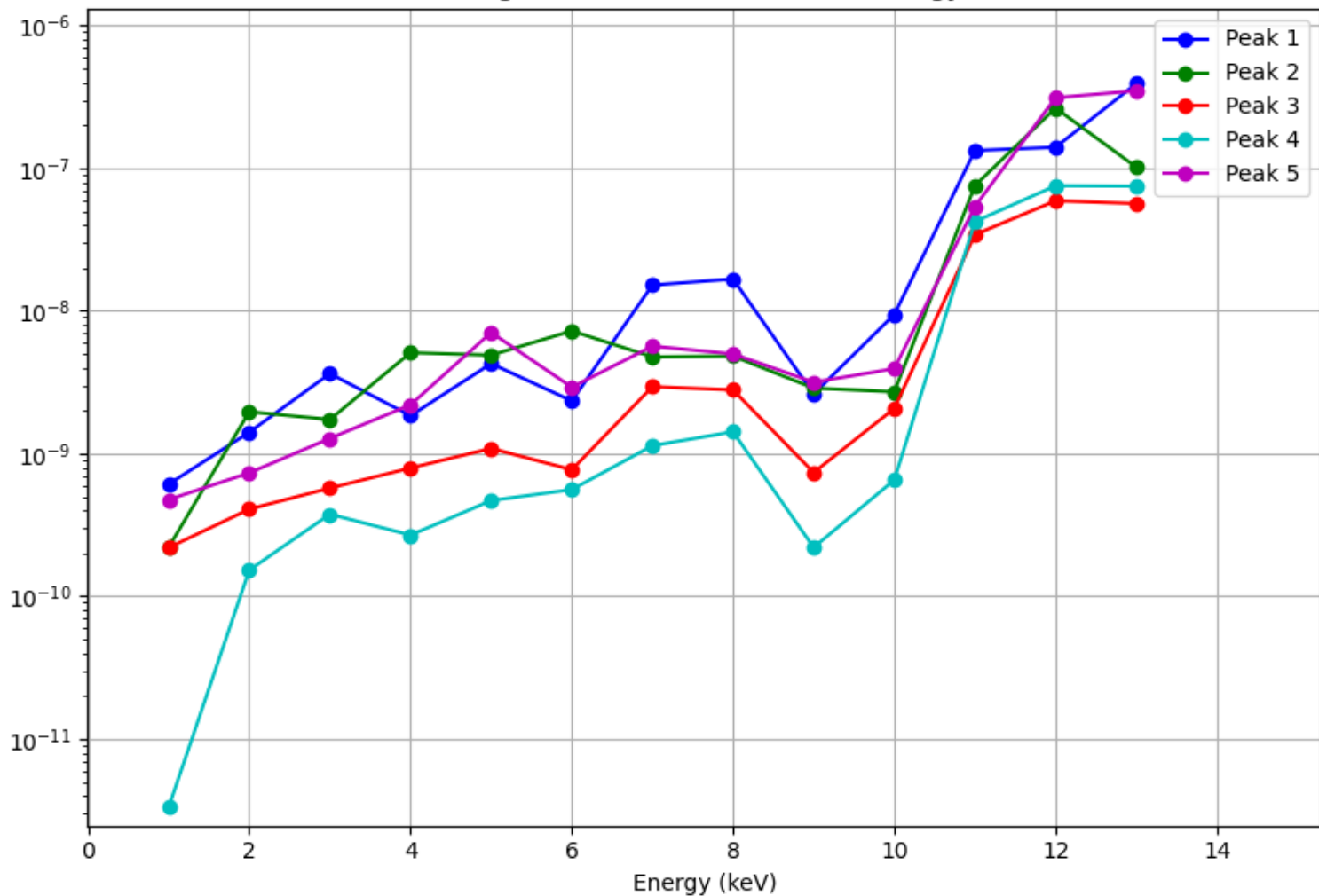
# Noise filtering

Original Fourier Transform

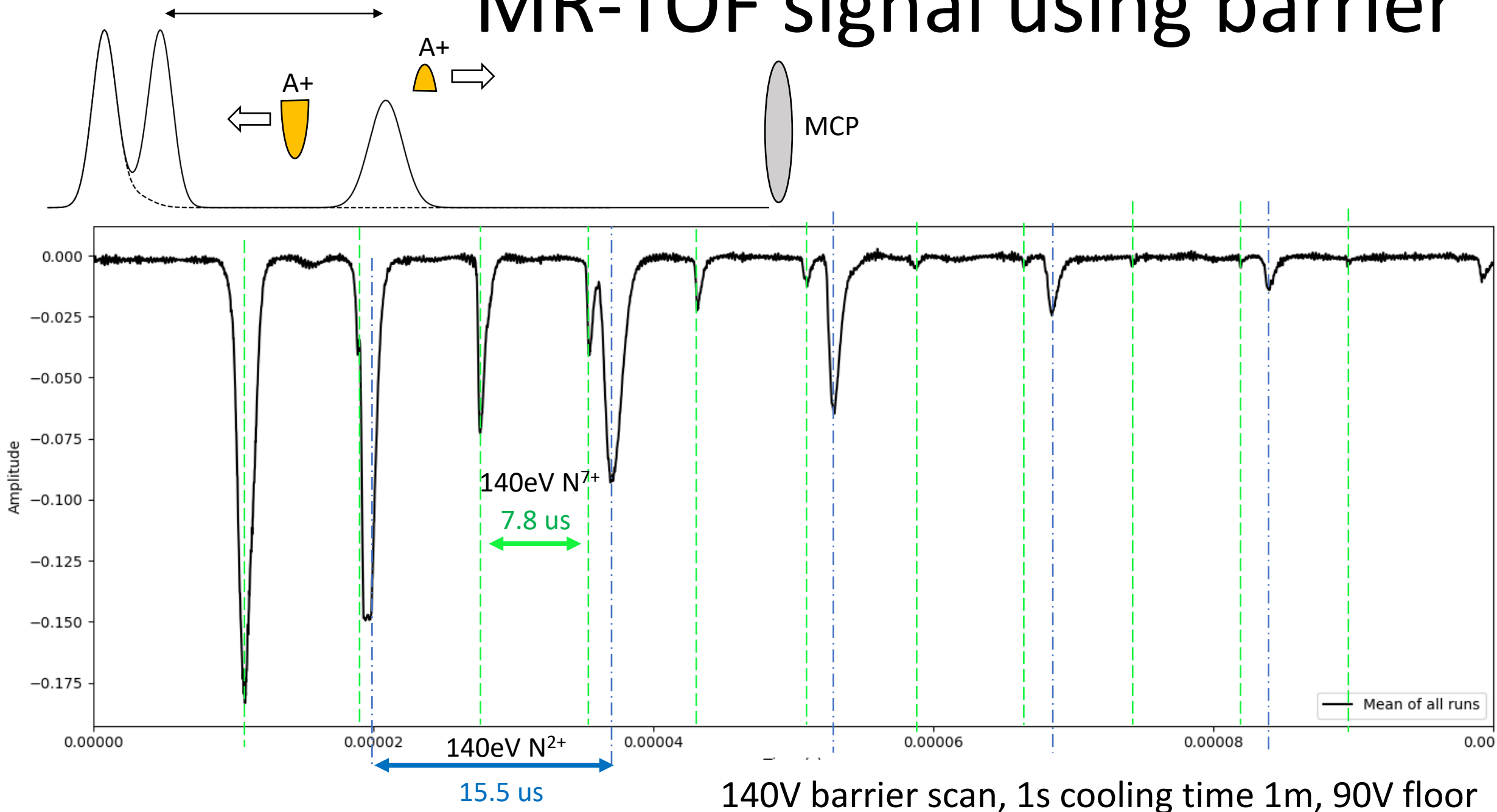


# Pbar trapping voltage vs MCP signal

Integral Value of Each Peak vs. Energy

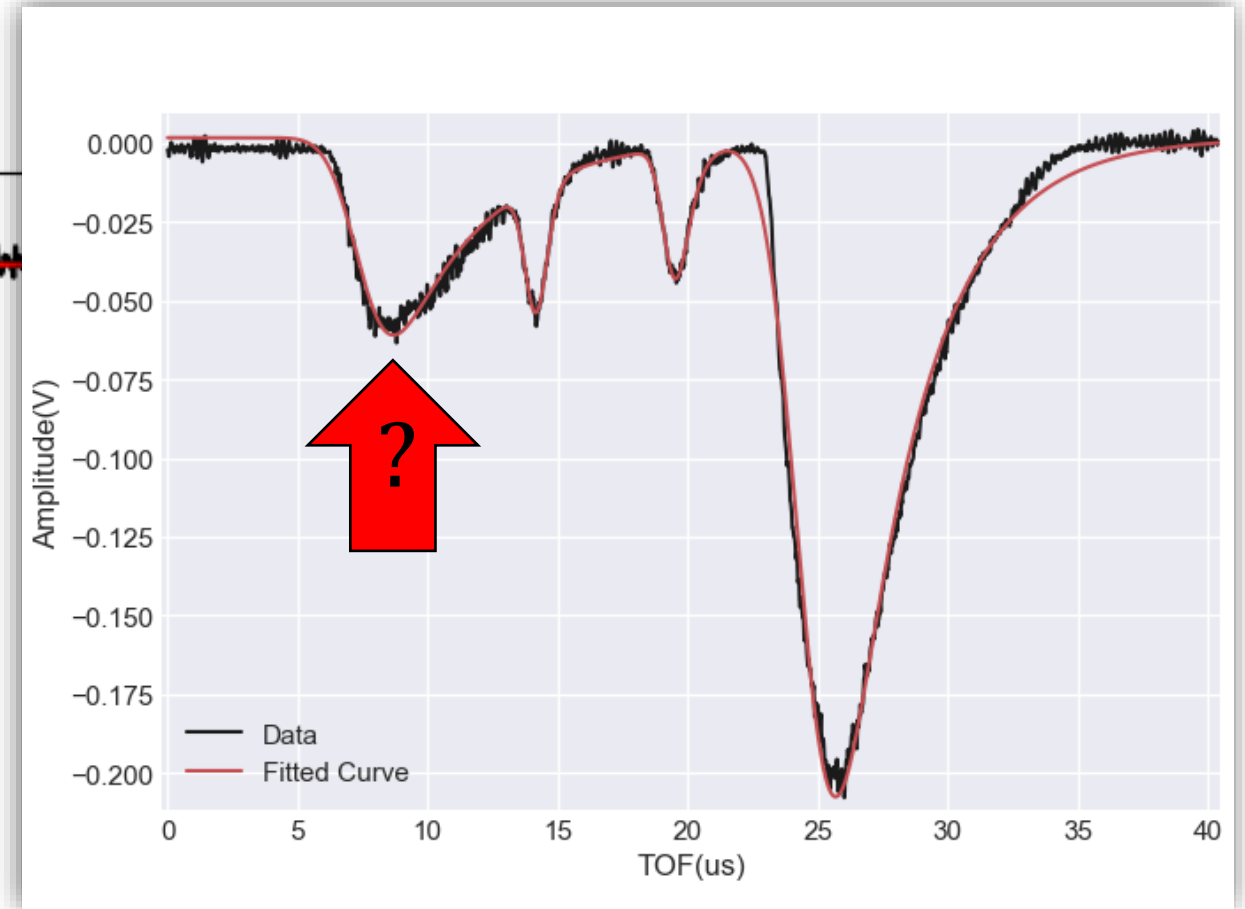
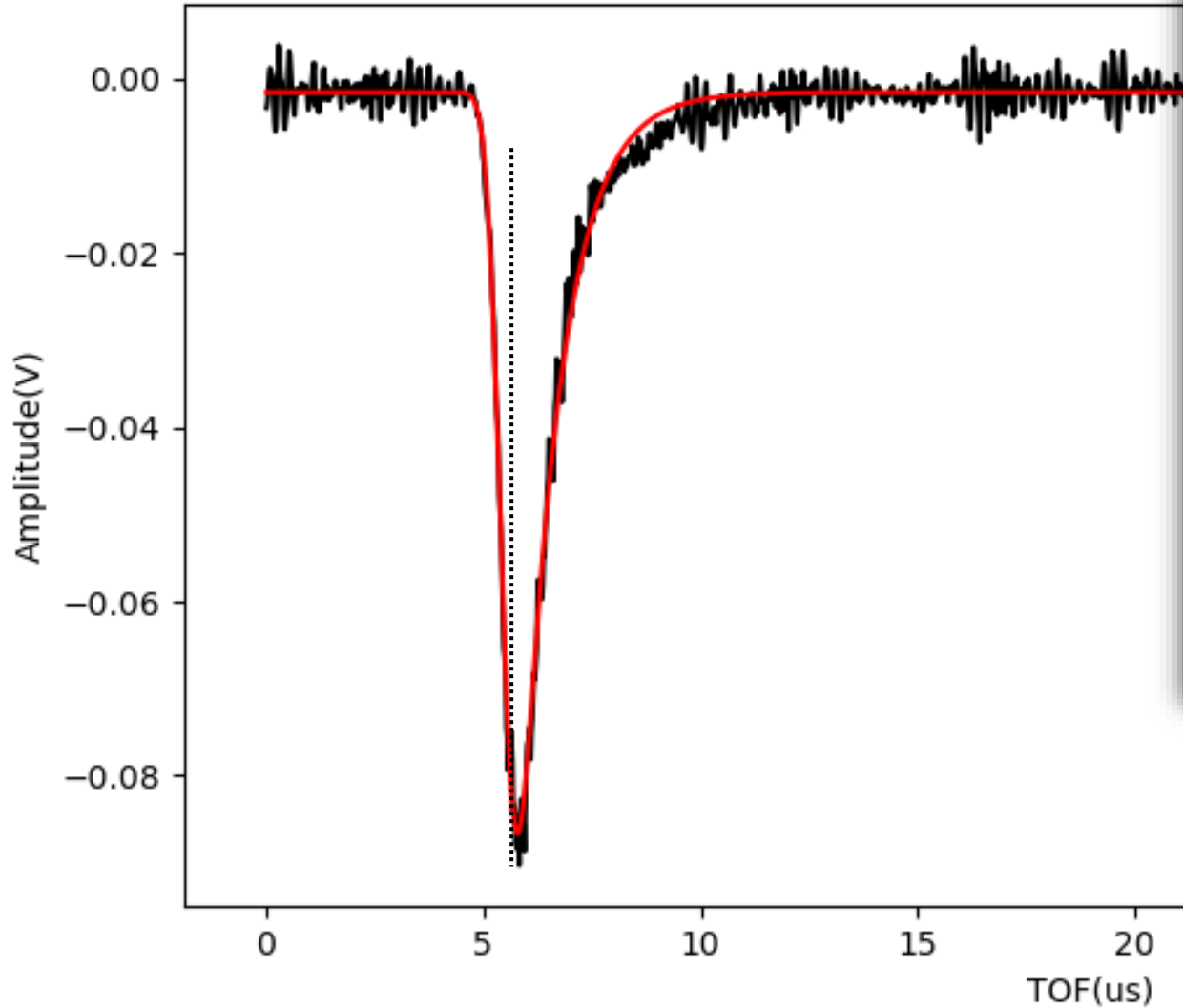


# MR-TOF signal using barrier

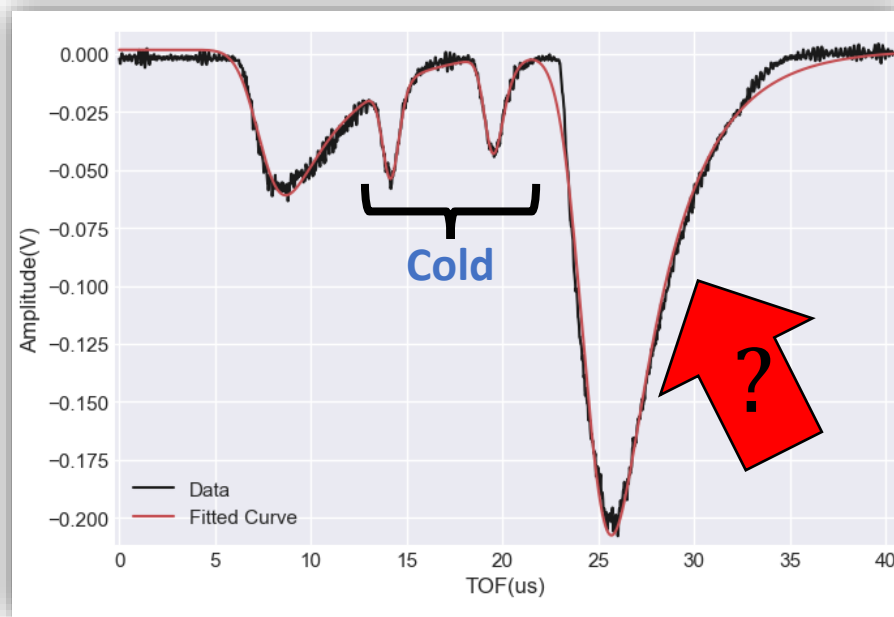
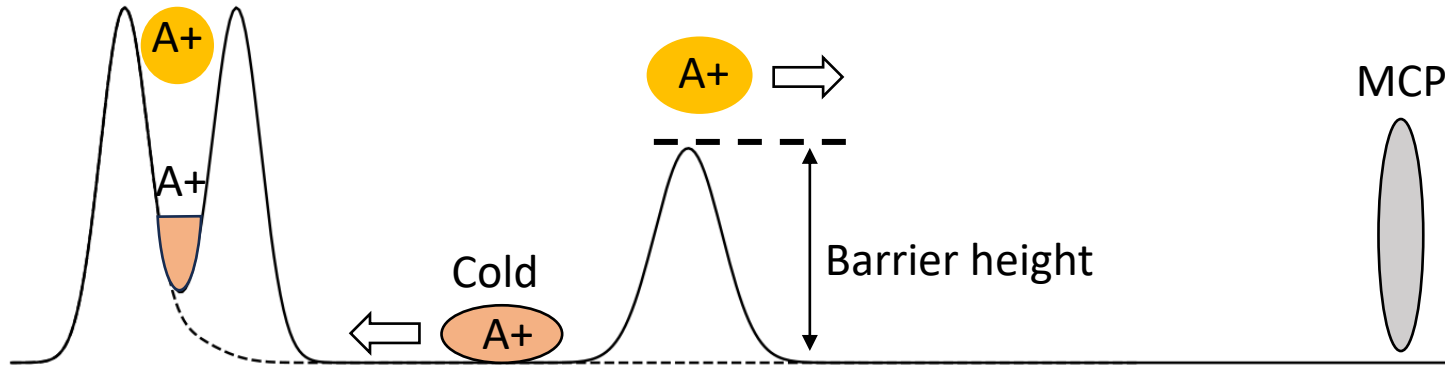


# Fast TOF component?

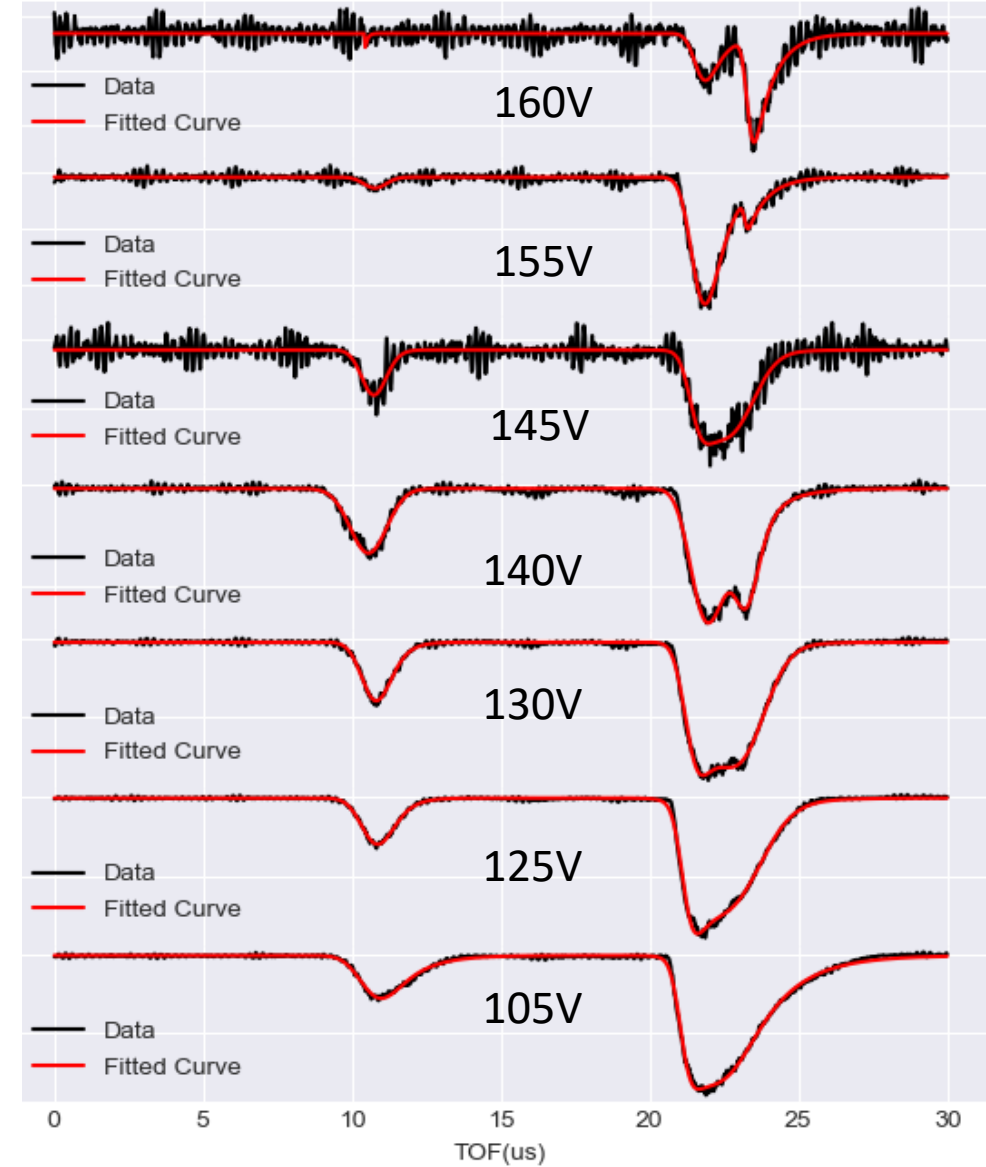
Isolating peak with 250 ns gate:



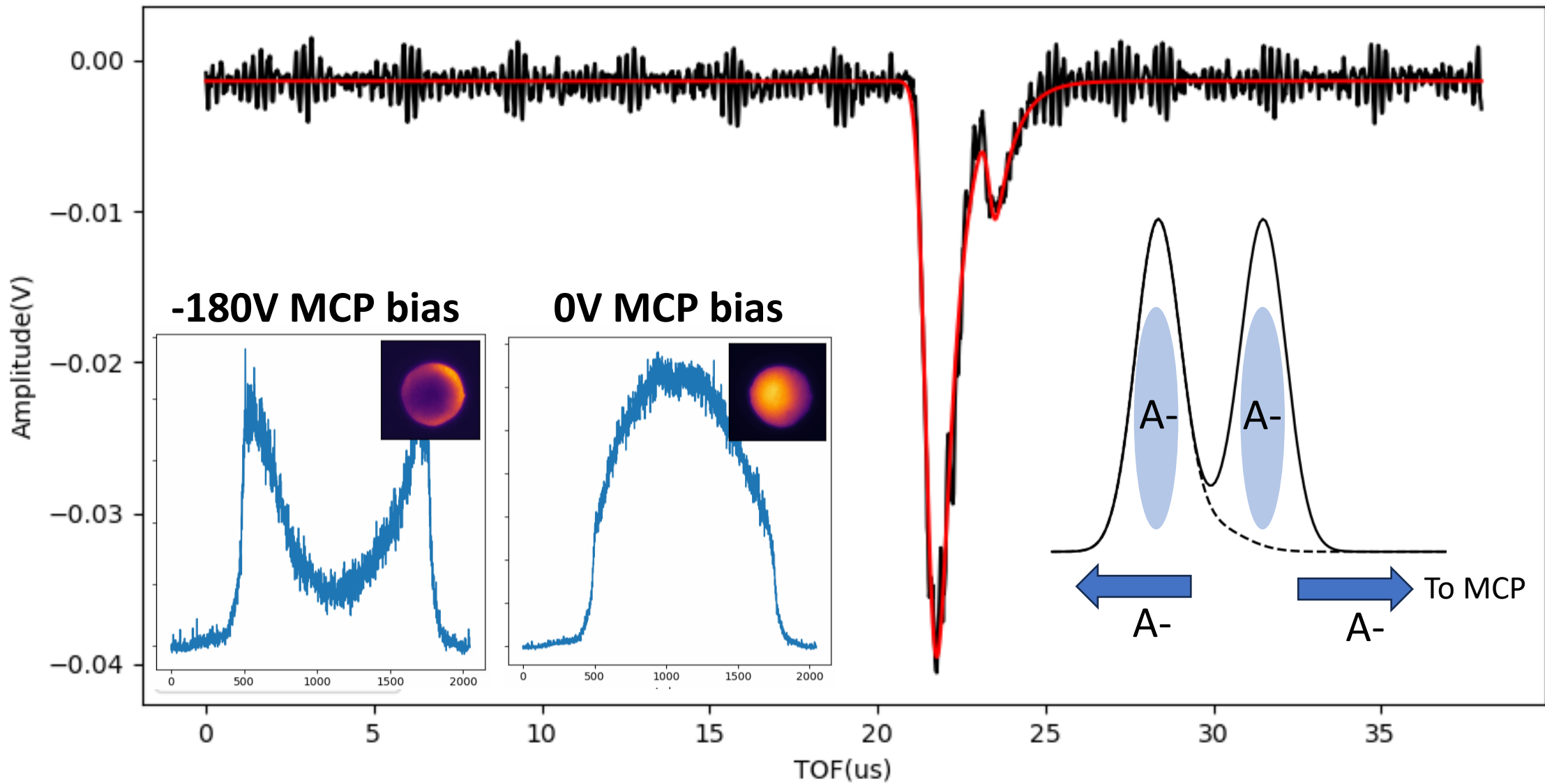
# Barrier scan with 10 V floor voltage



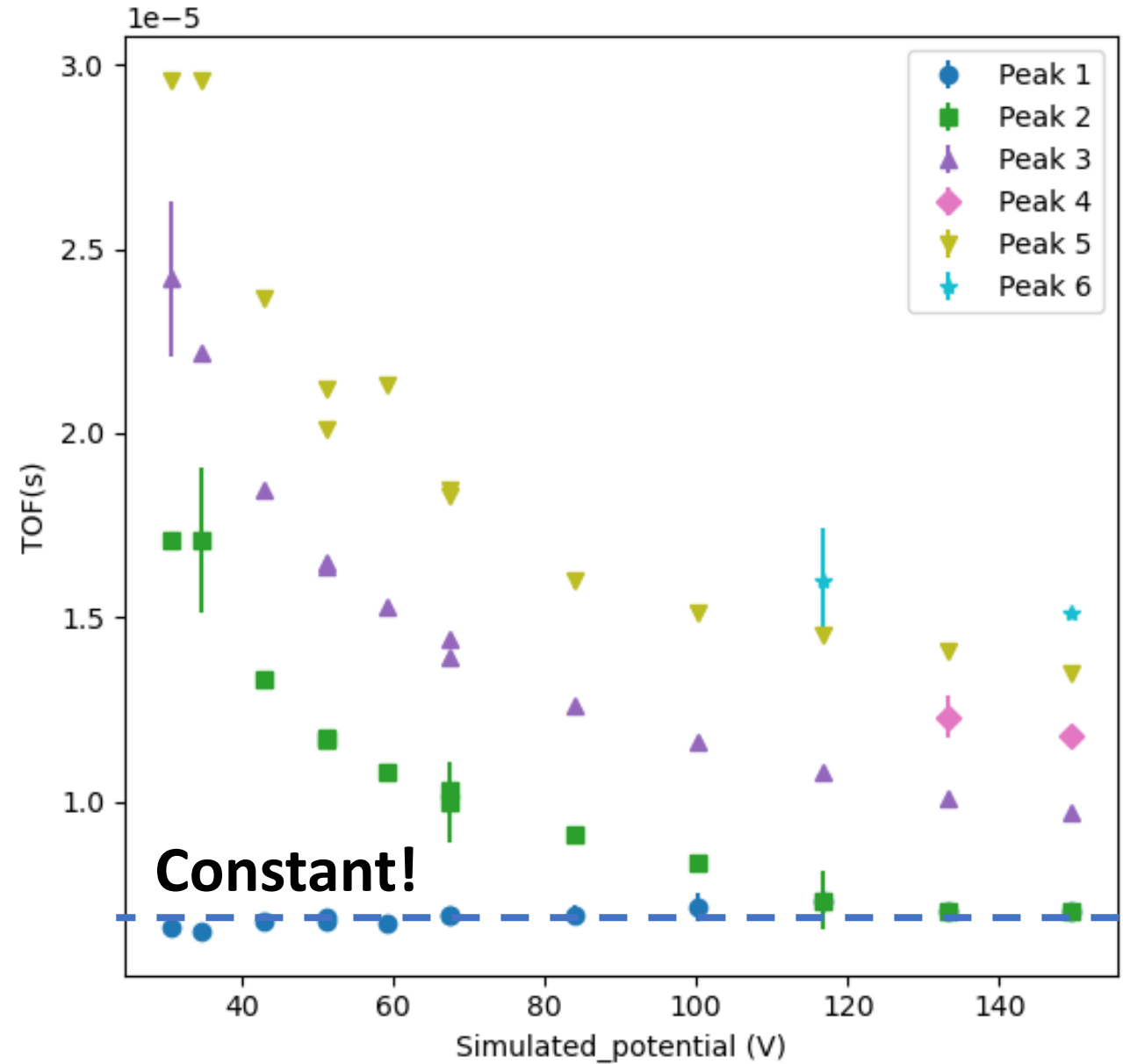
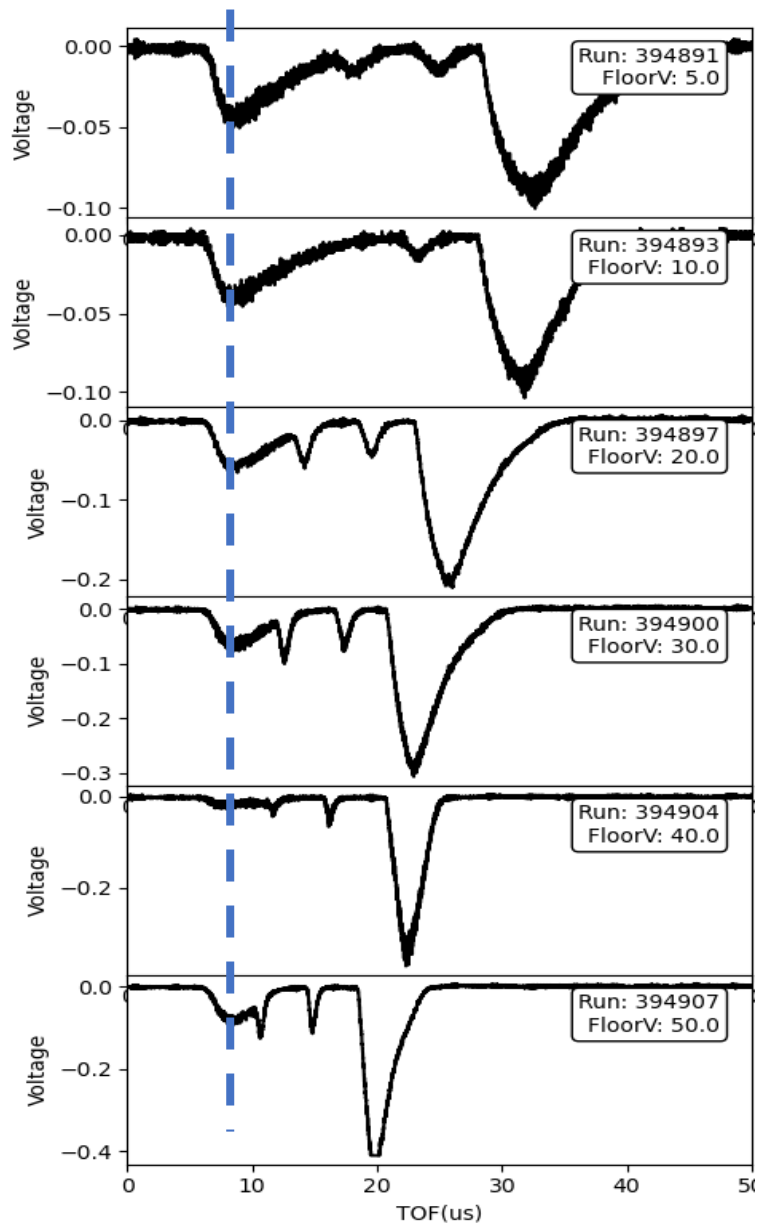
## TOF vs Barrier height



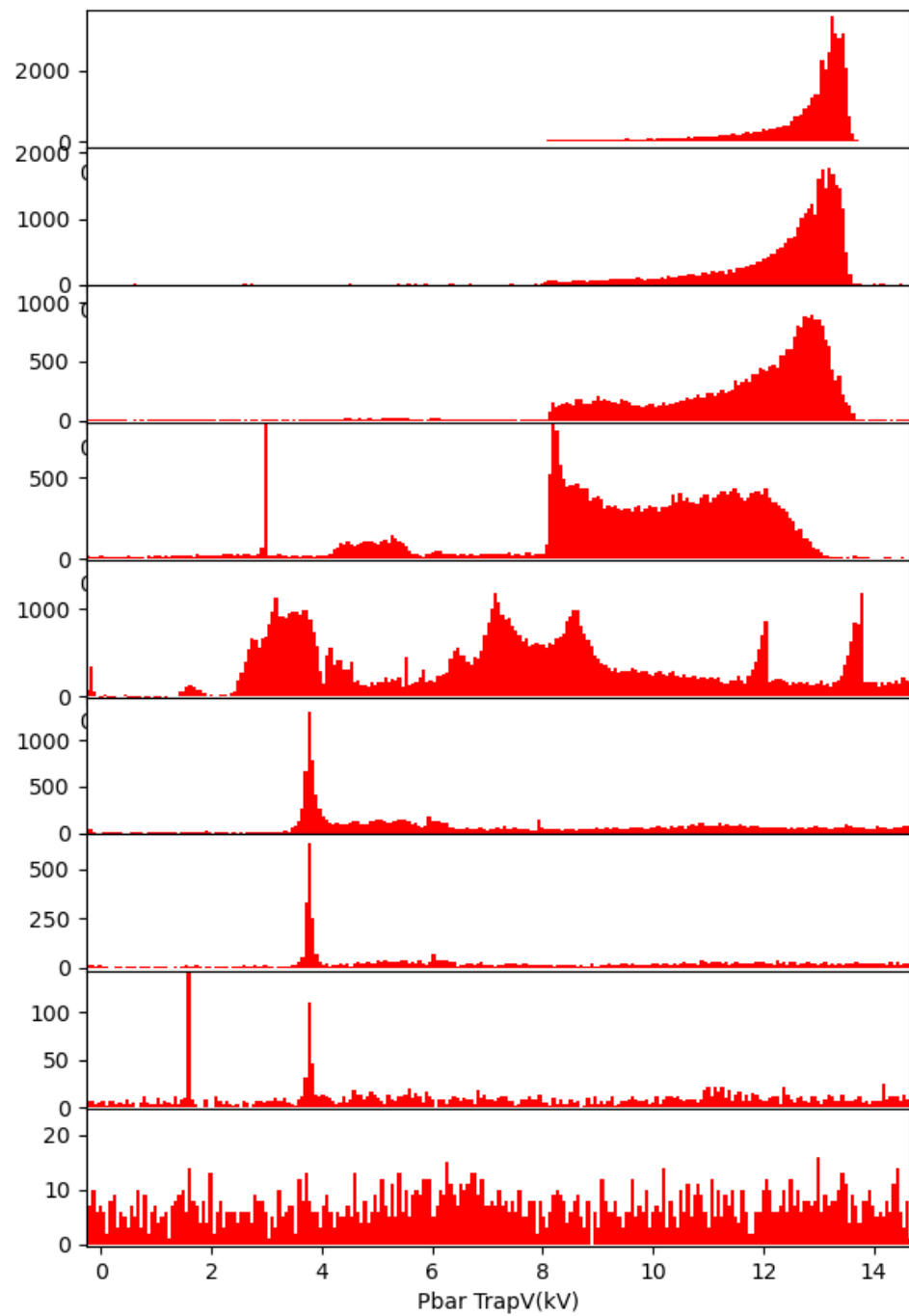
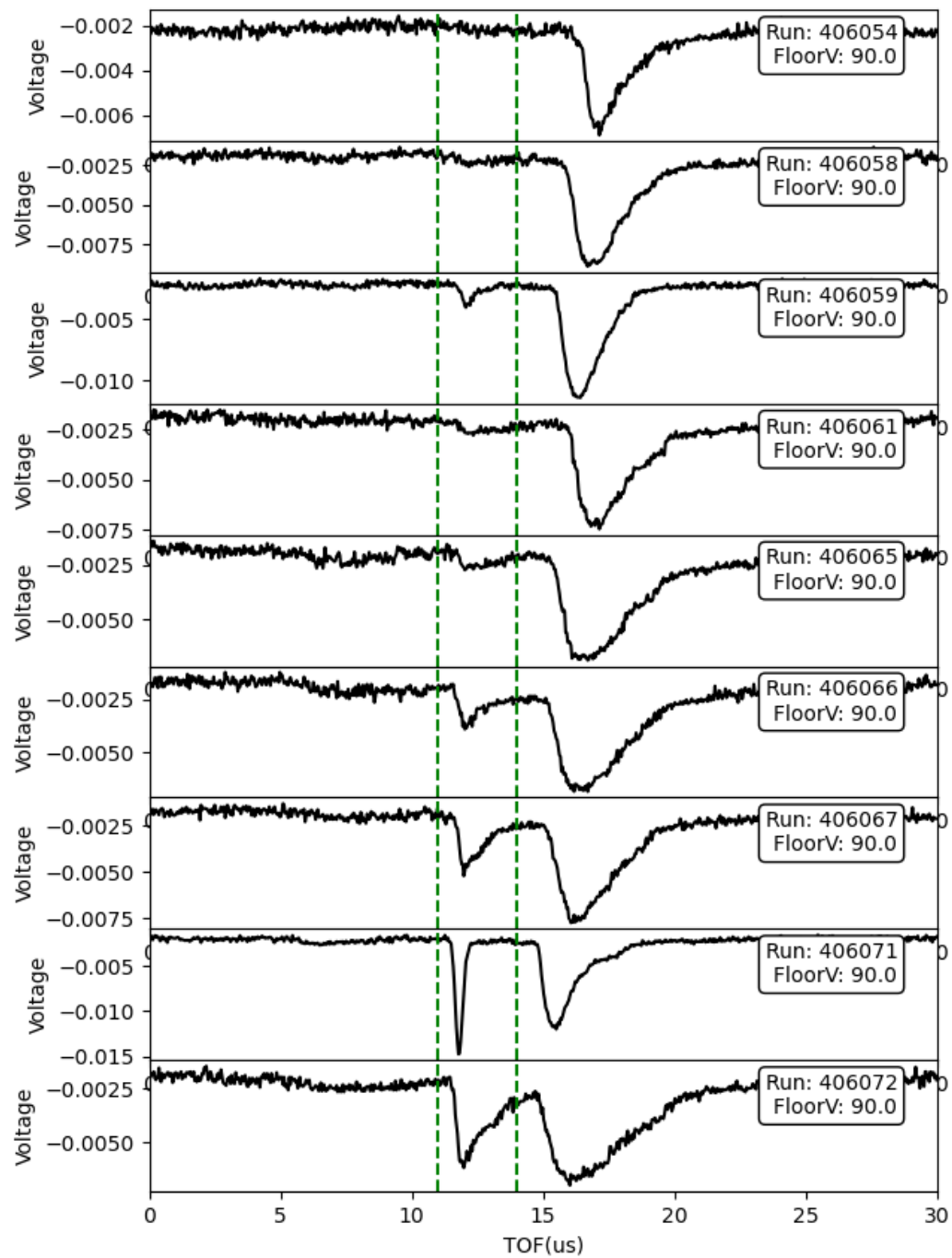
# Isolating slow peak with 160 V Barrier



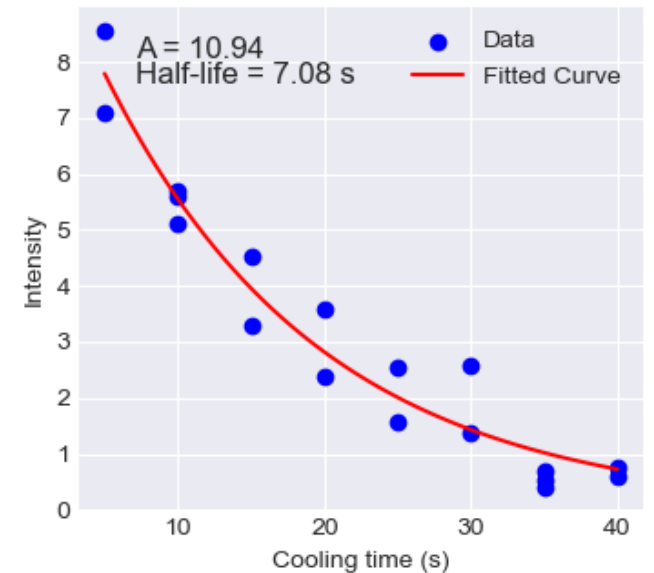
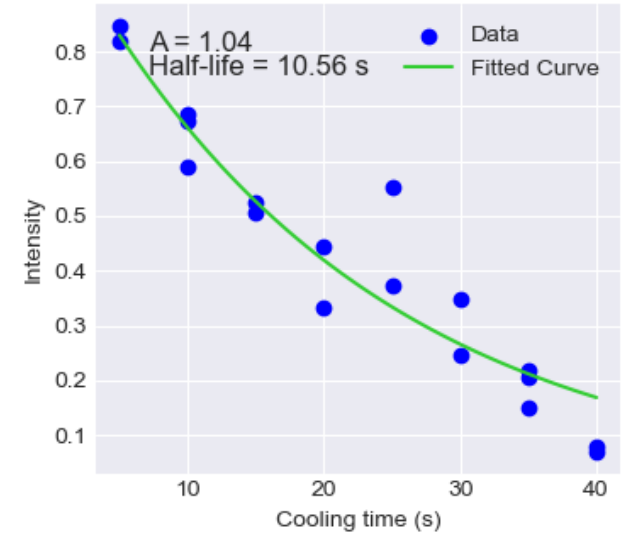
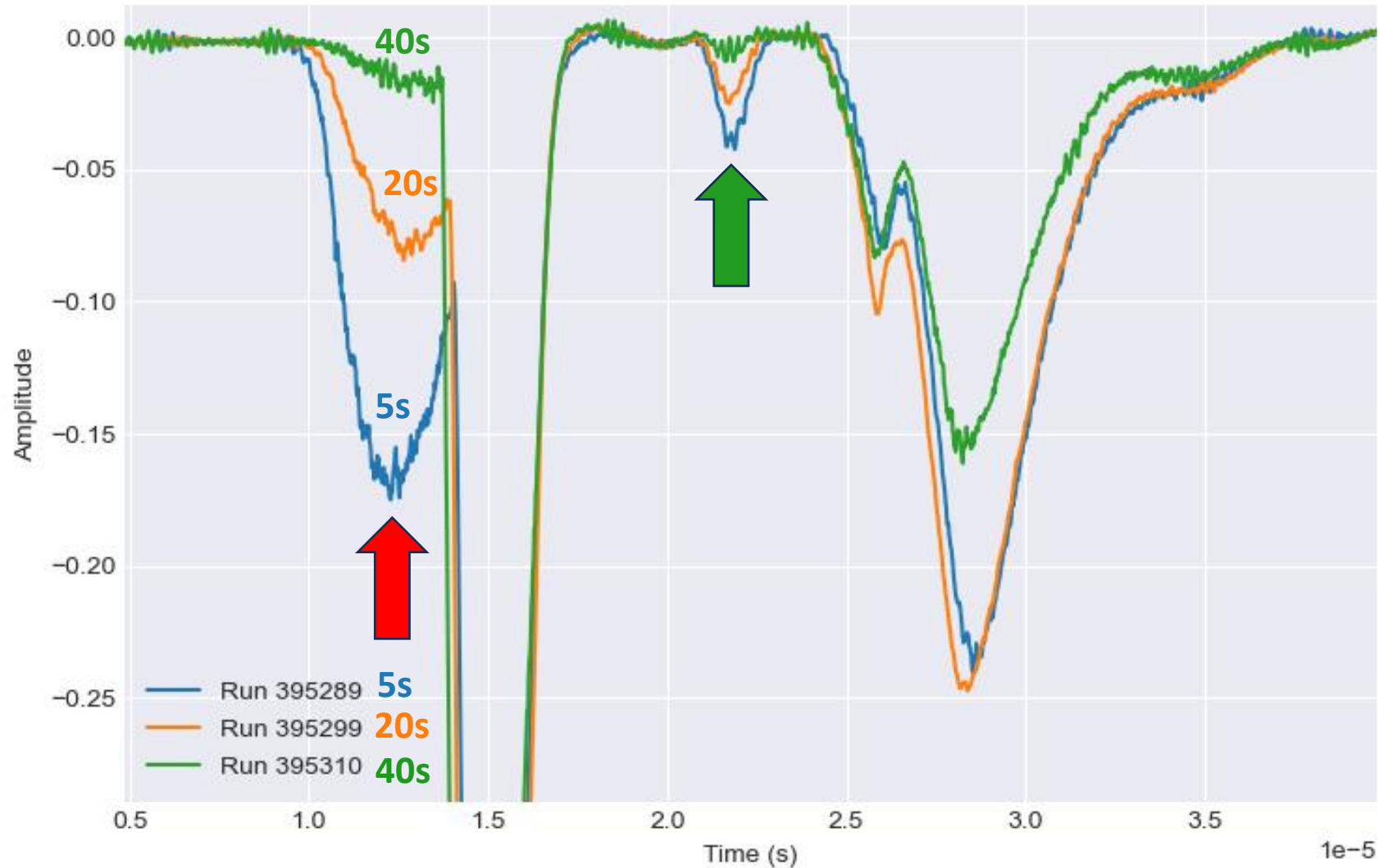
# Floor voltage scan with release from MCP side



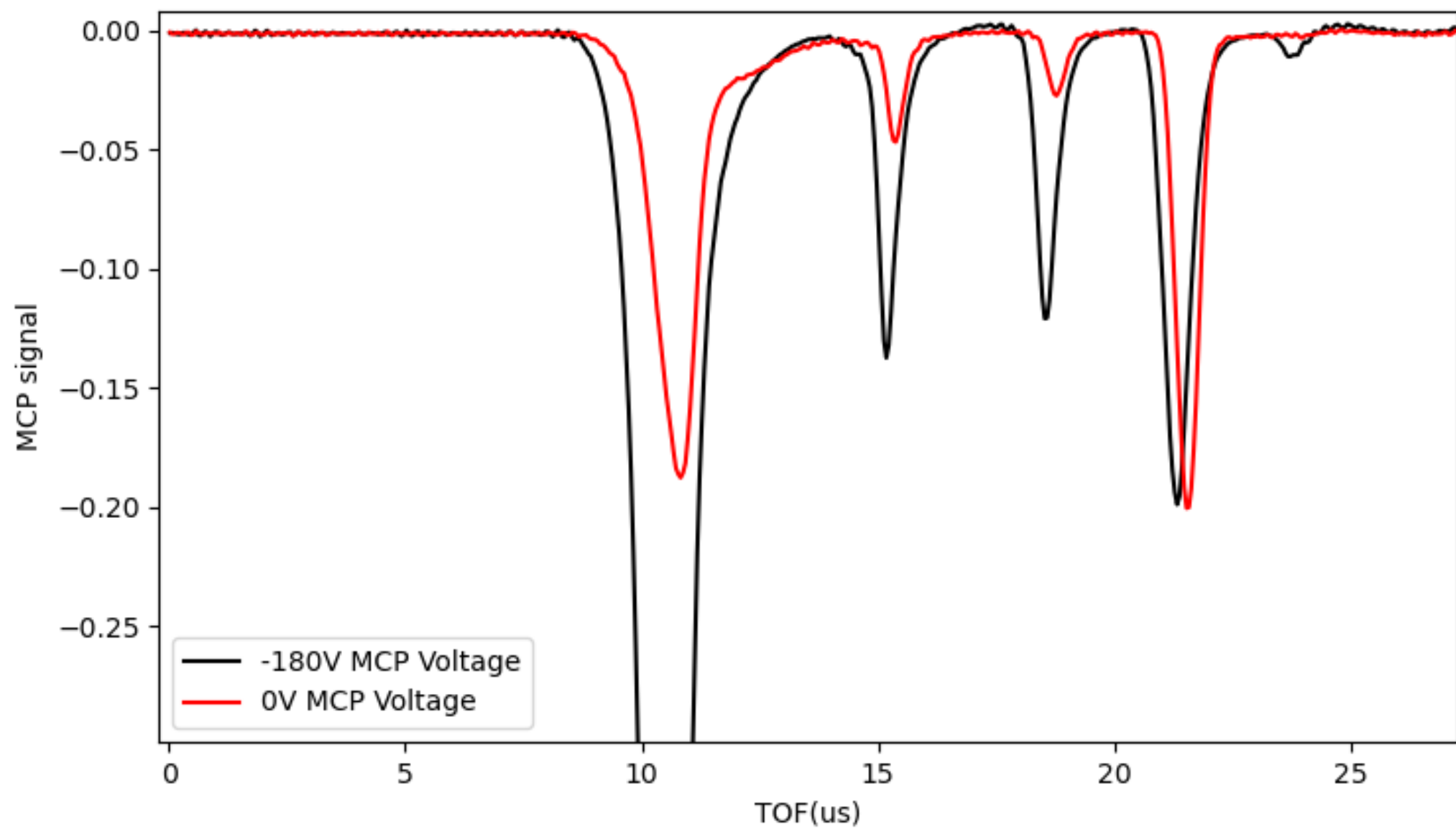




# Ion time changes the 7+ population



The other peaks do not change significantly with time



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

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

# Elena side measurement

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

