# Overview of HCI campaigns 2024

AEGIS Collaboration meeting December 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]

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

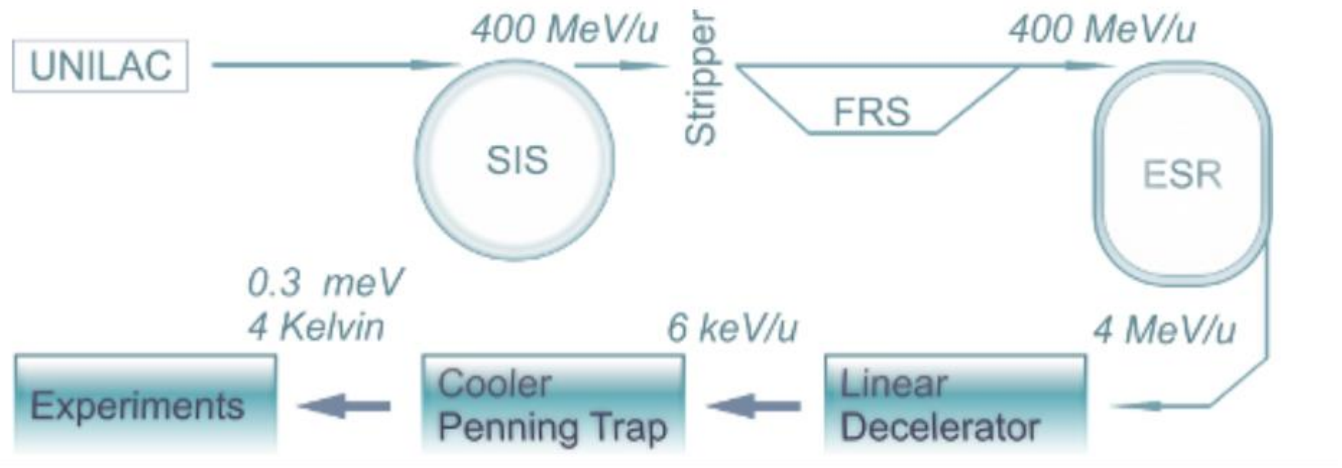
*Nature* **578**, 60–65 (2020) | Cite this article

**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:

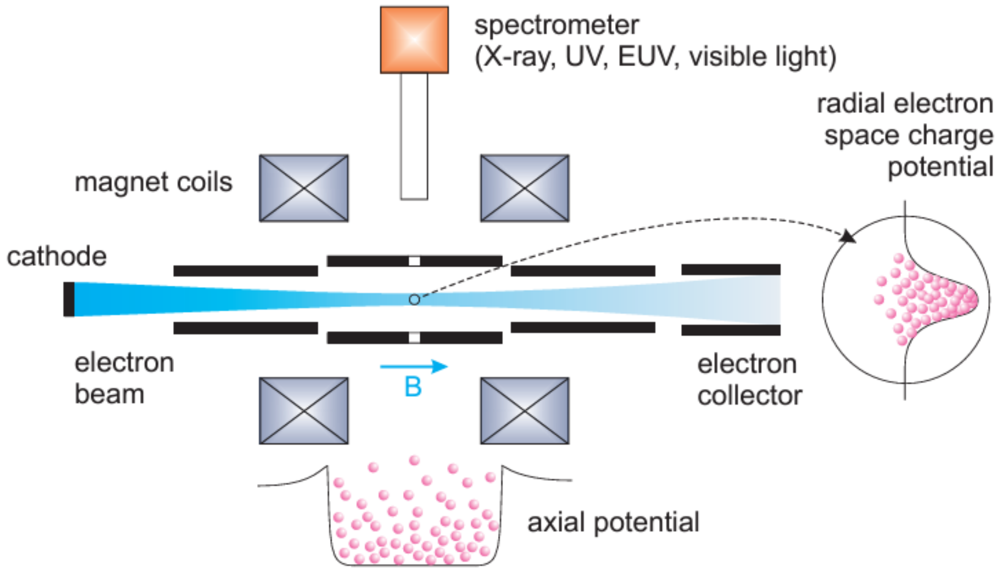
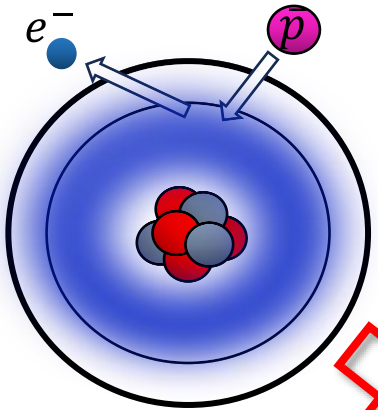


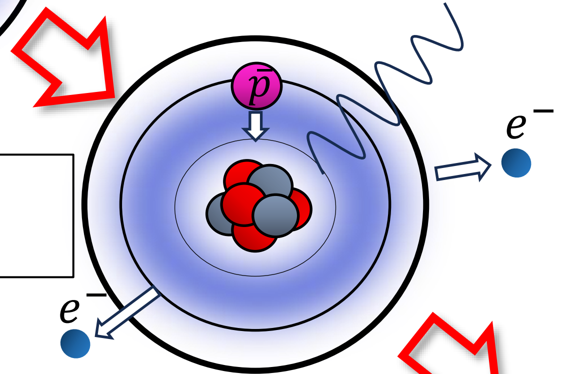

**Fig. 2:** Principle of operation of an EBIS

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

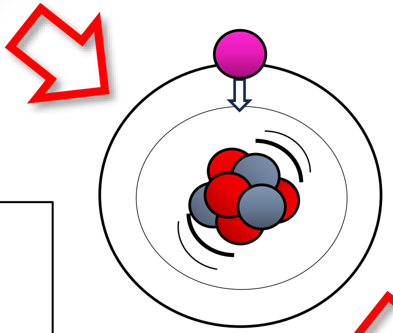
# The life of an antiprotonic atom



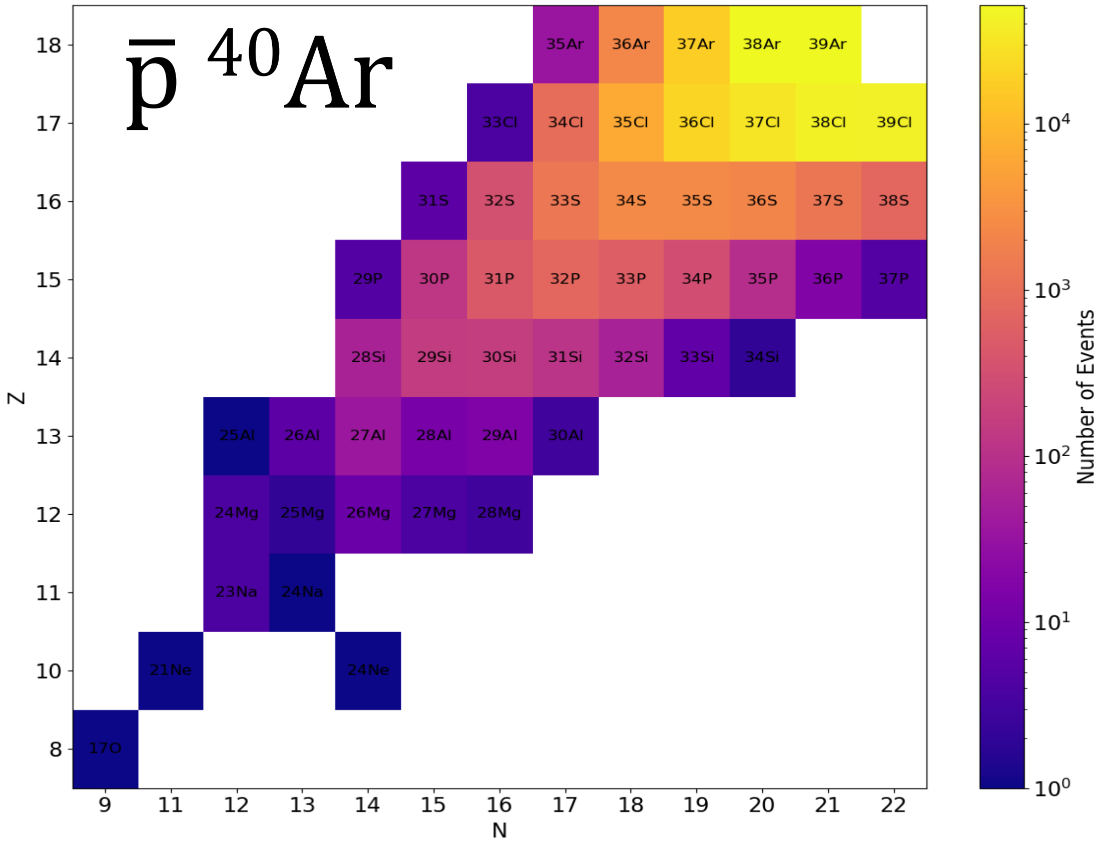

Capture of the antiproton in a **high-n Rydberg state.**

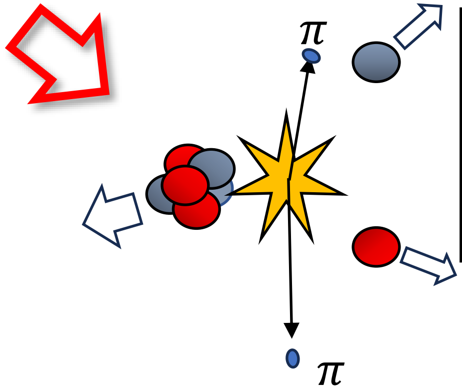



**Cascade** emitting x-rays and Auger electrons.



Antiproton approaching stripped nucleus, **strong interaction influences orbitals.**



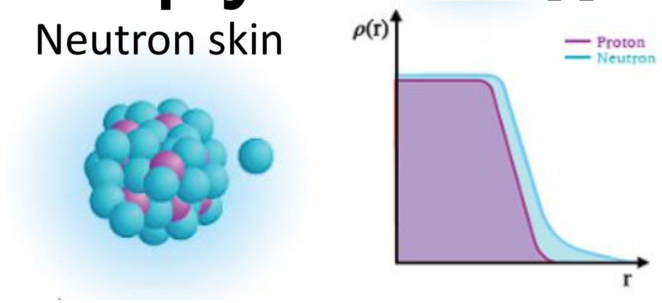




**Annihilation on nucleus results in the formation of Highly Charged (radioactive) Ions (HCIs)**

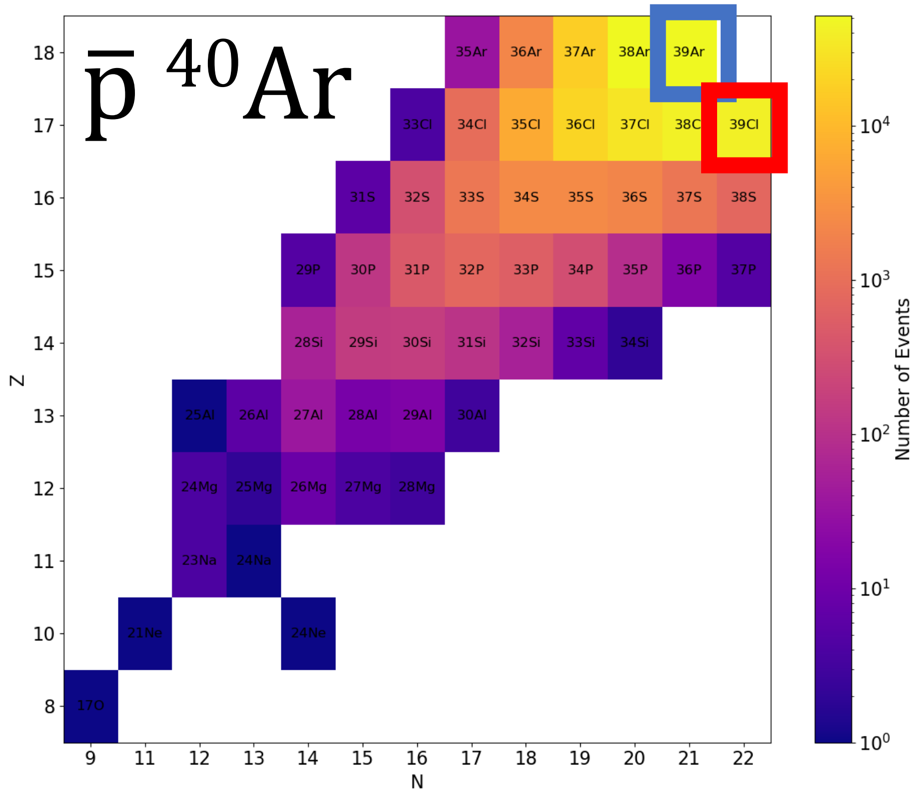
# Trapping and TOF spectroscopy of fragments

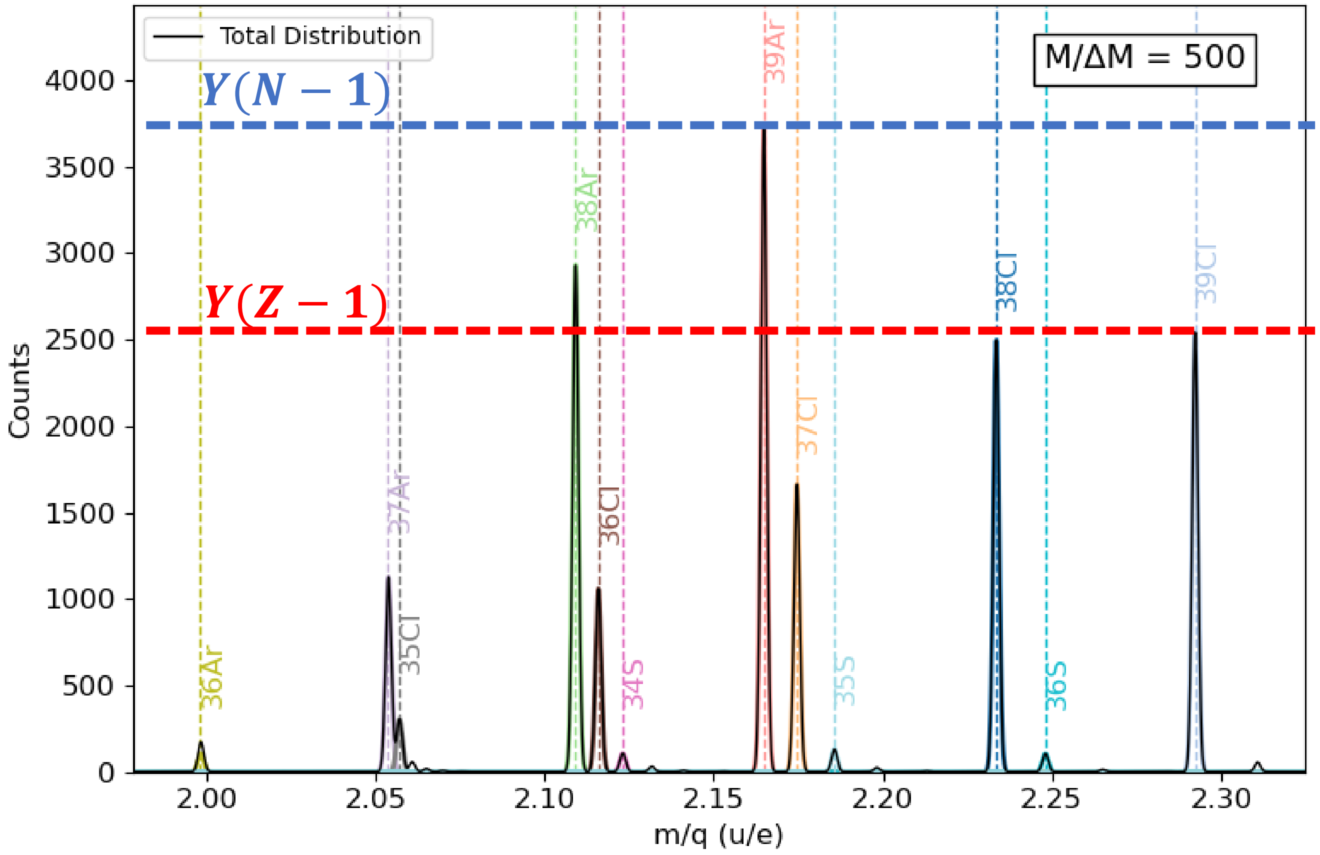
Trapped fragments


Neutron skin

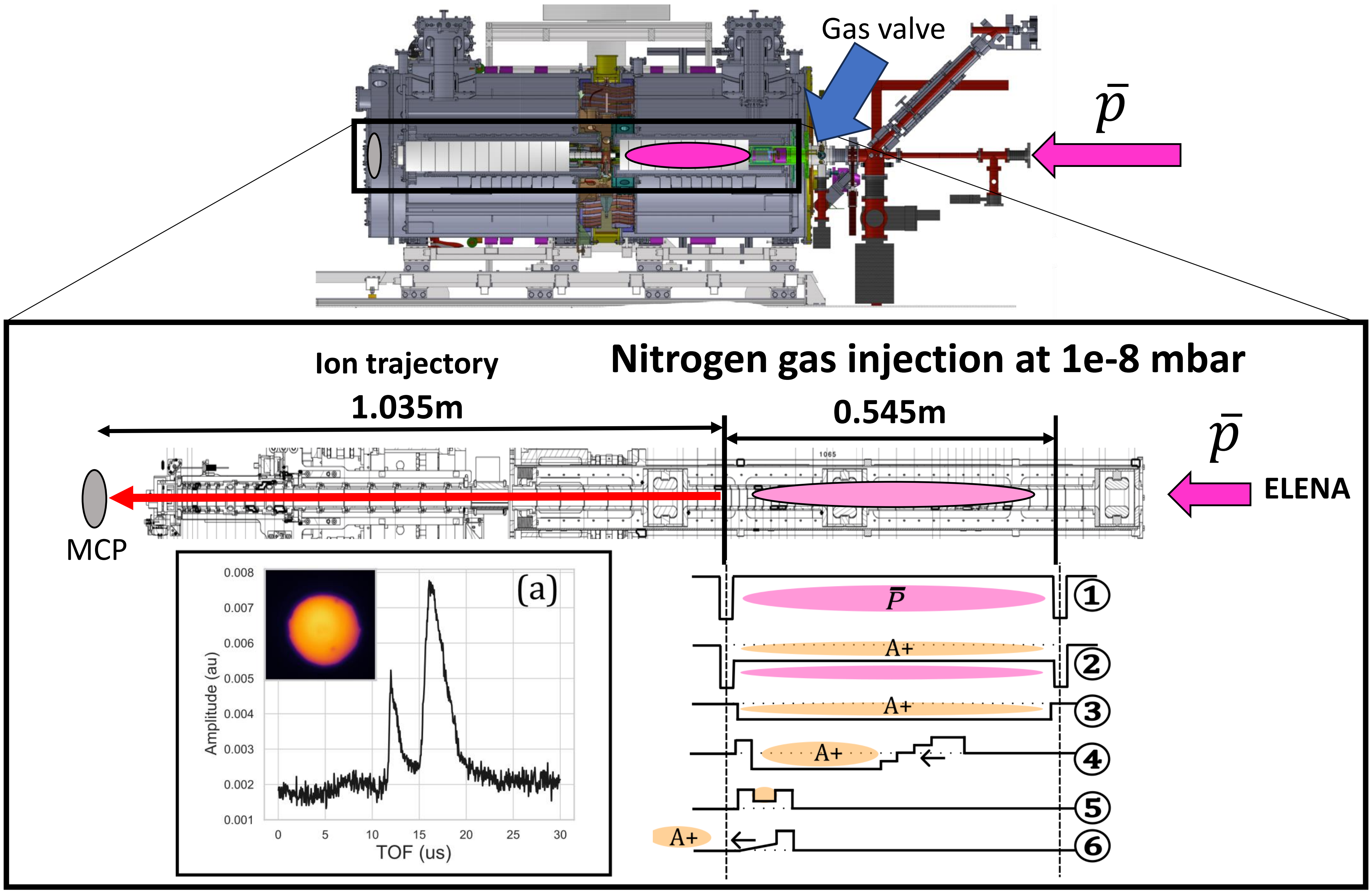



$$R_{np} = Y(N-1)/Y(Z-1)$$

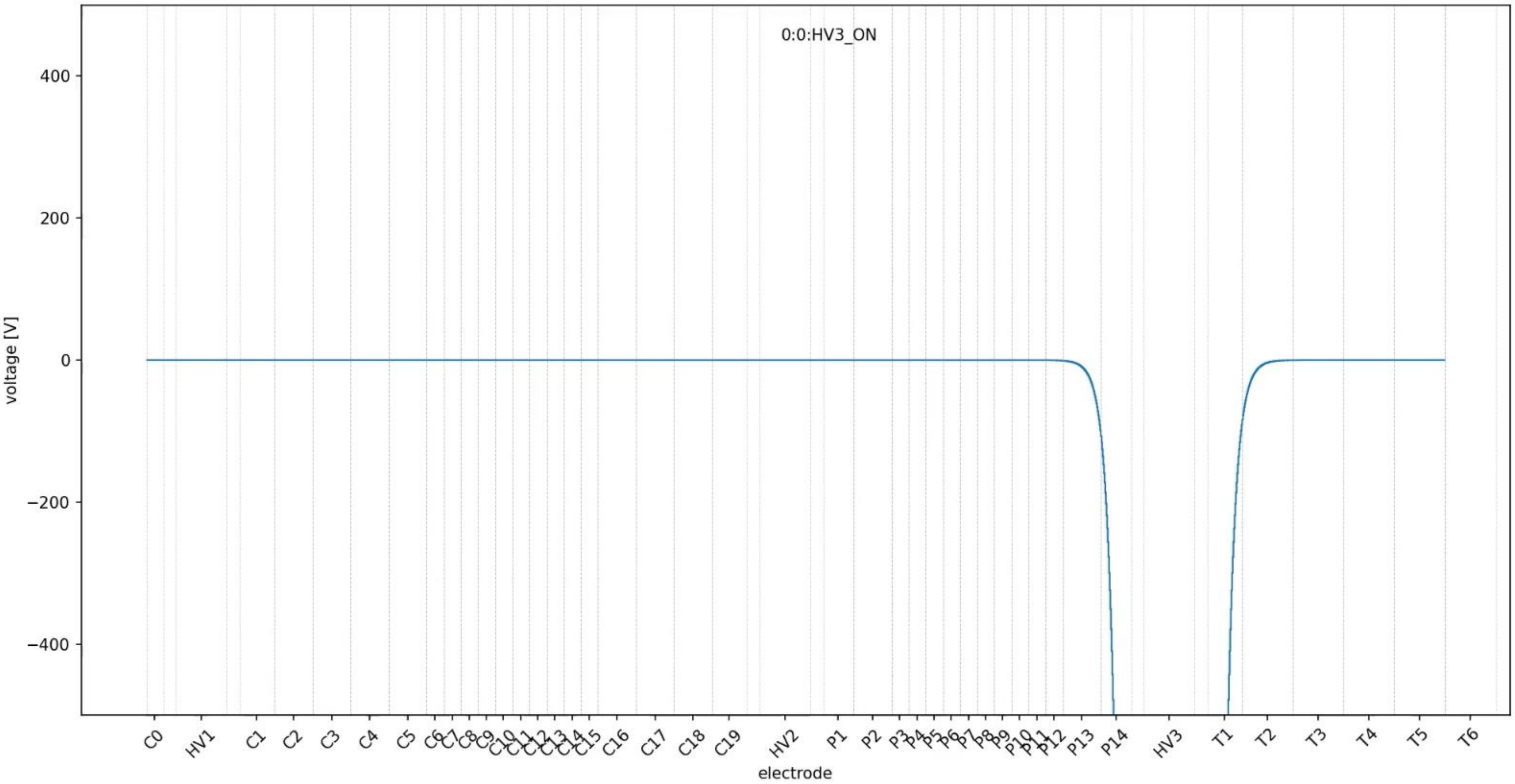


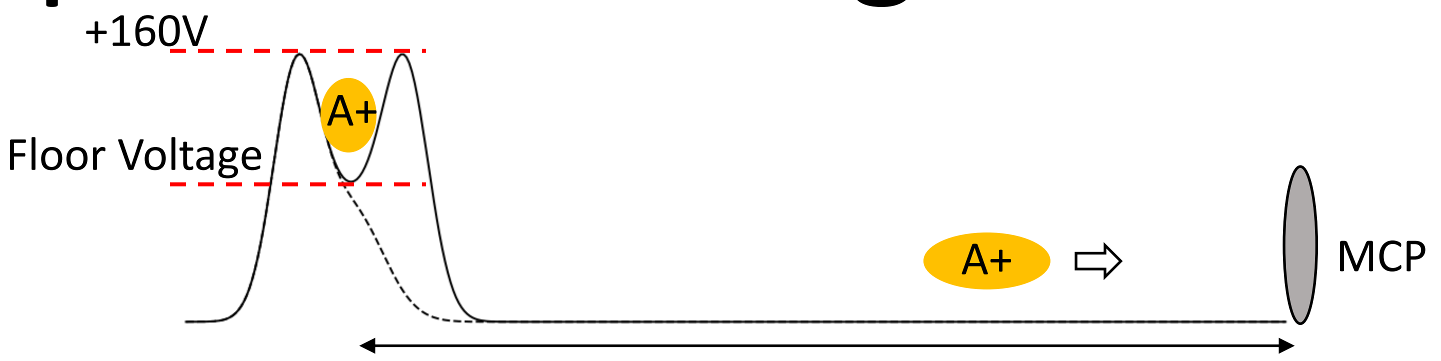
# Capturing positive ions formed from antiproton annihilations

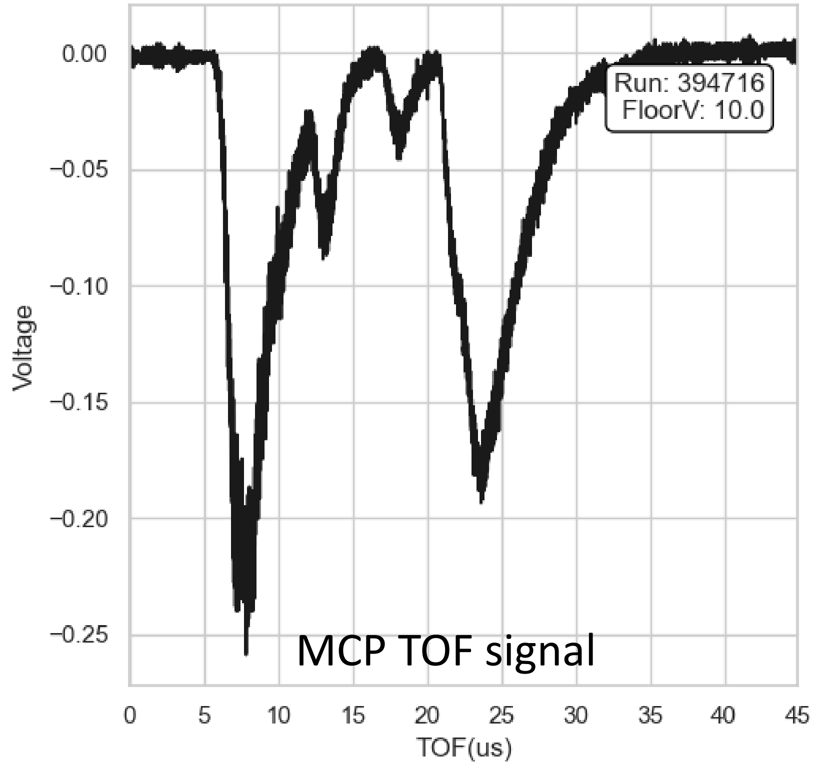


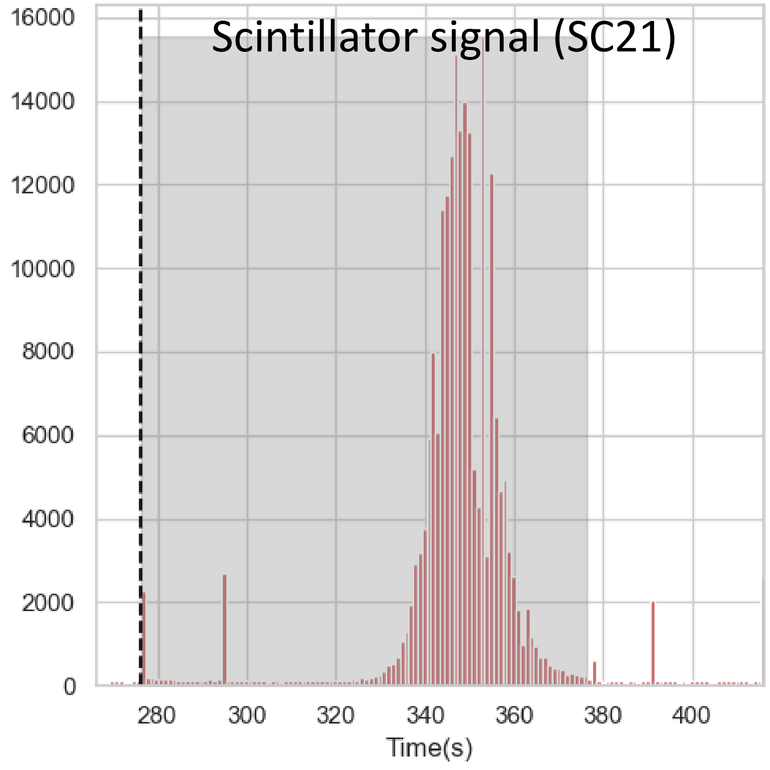
Animation by Jakub

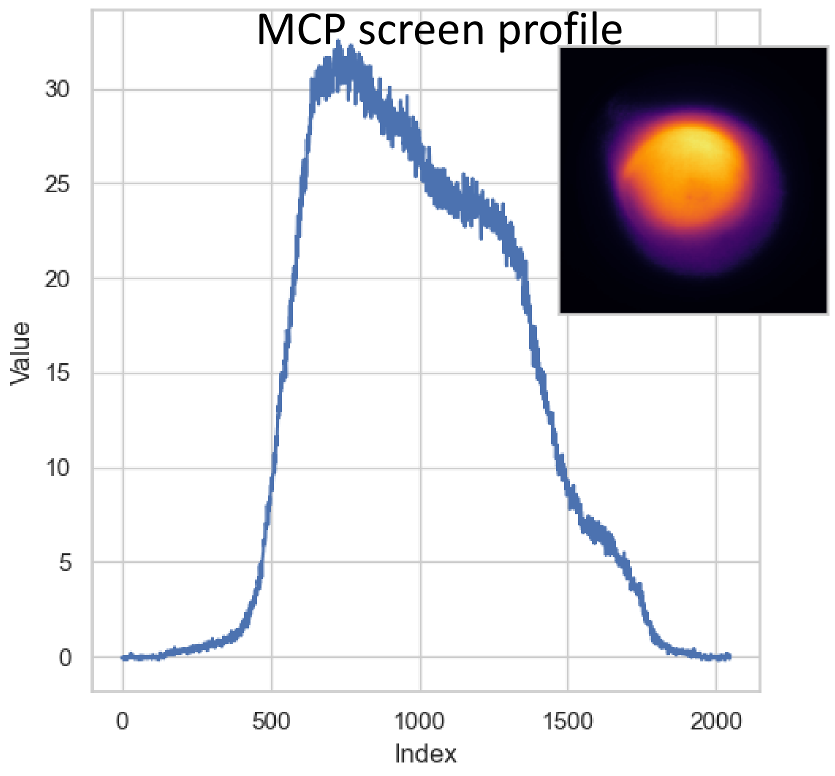


# Sample data during air leak campaign

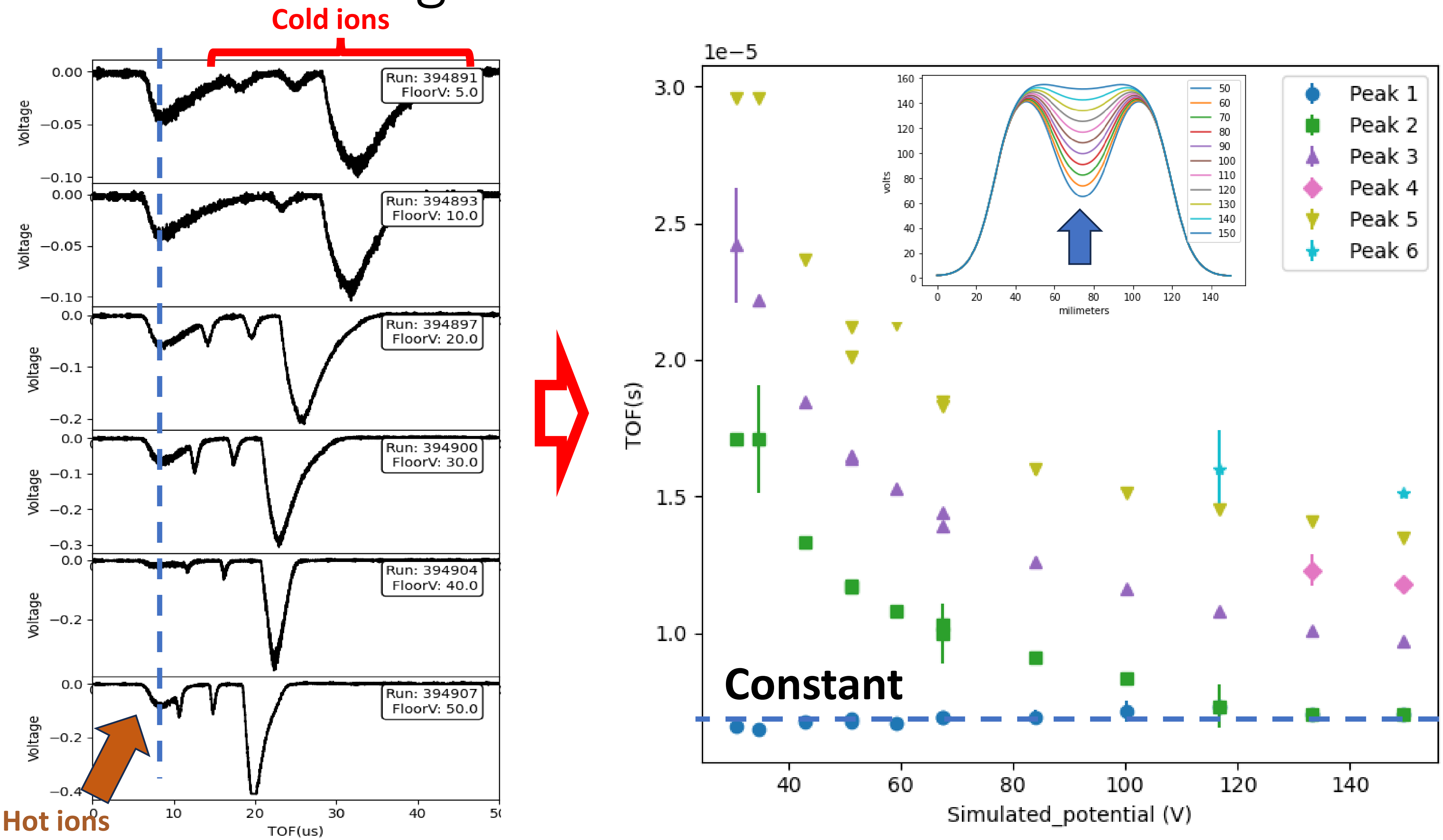


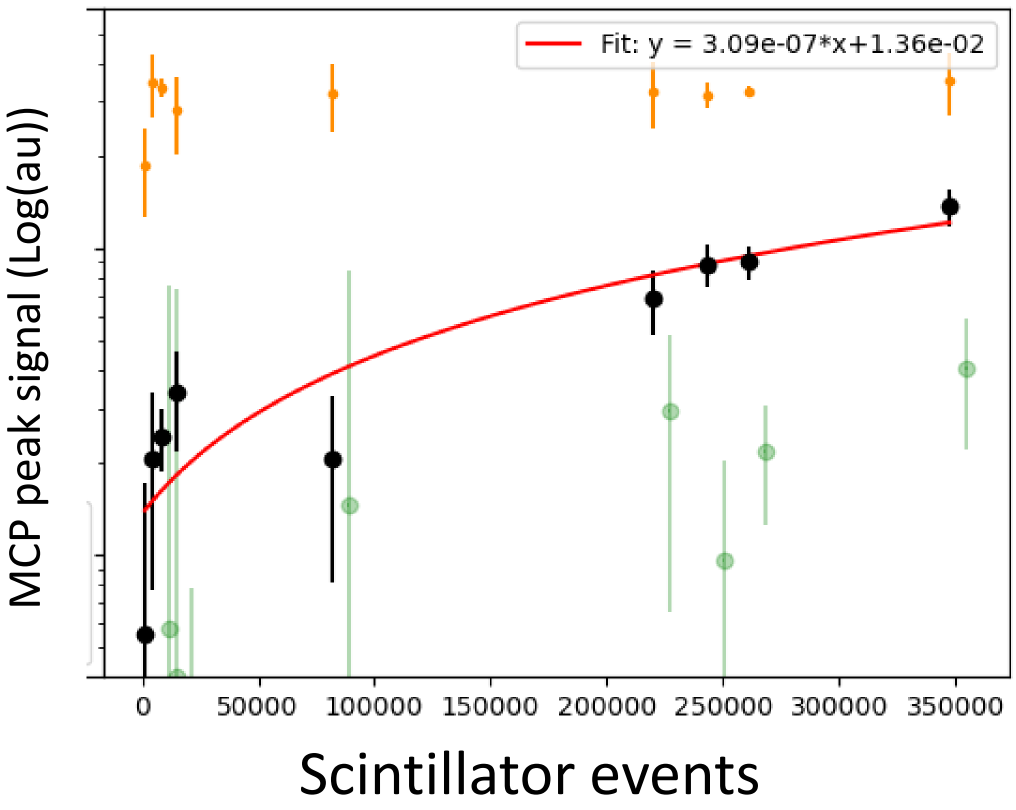



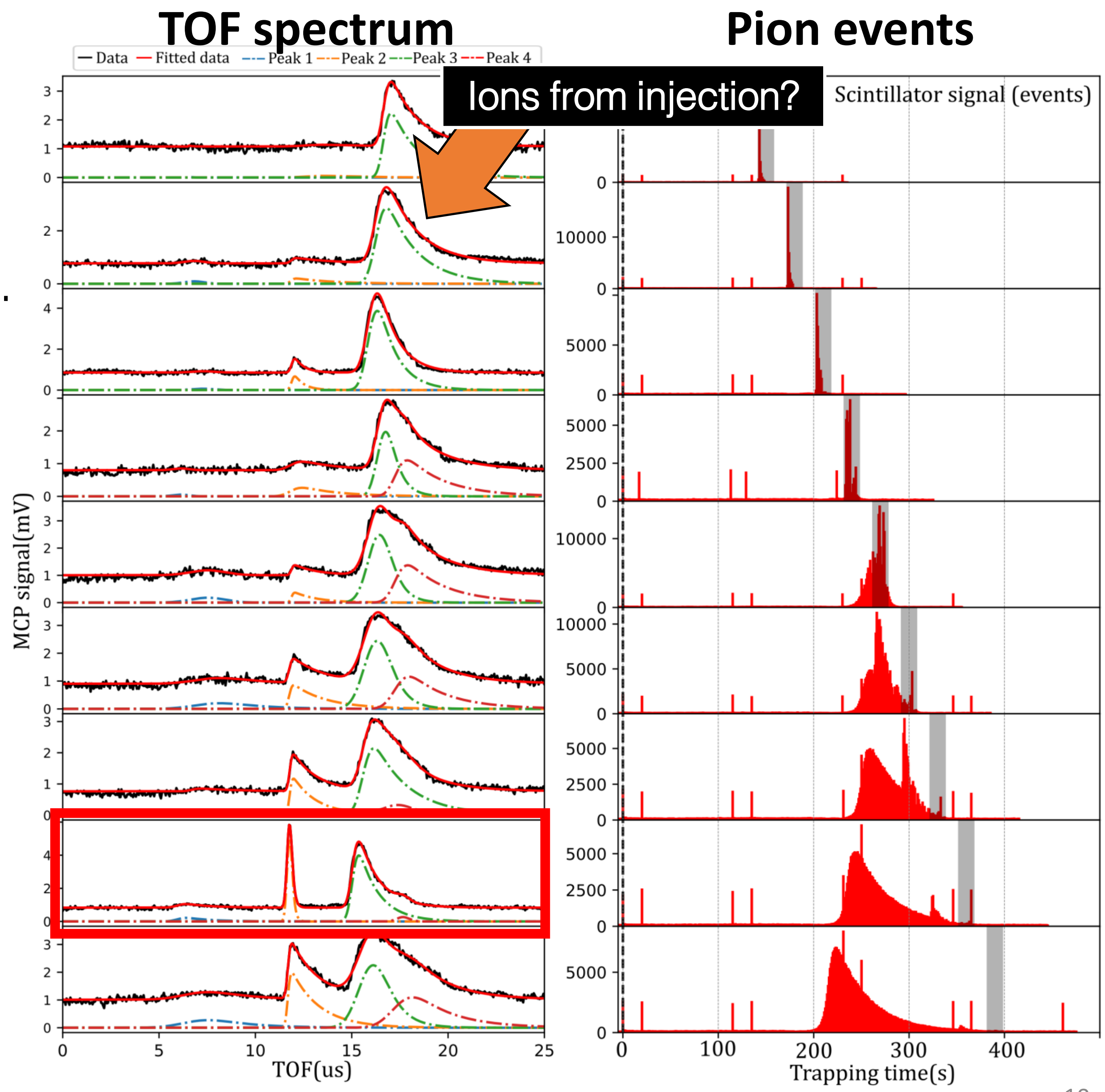
# Floor voltage scan with release from MCP side



# TOF spectrum vs scintillator signal

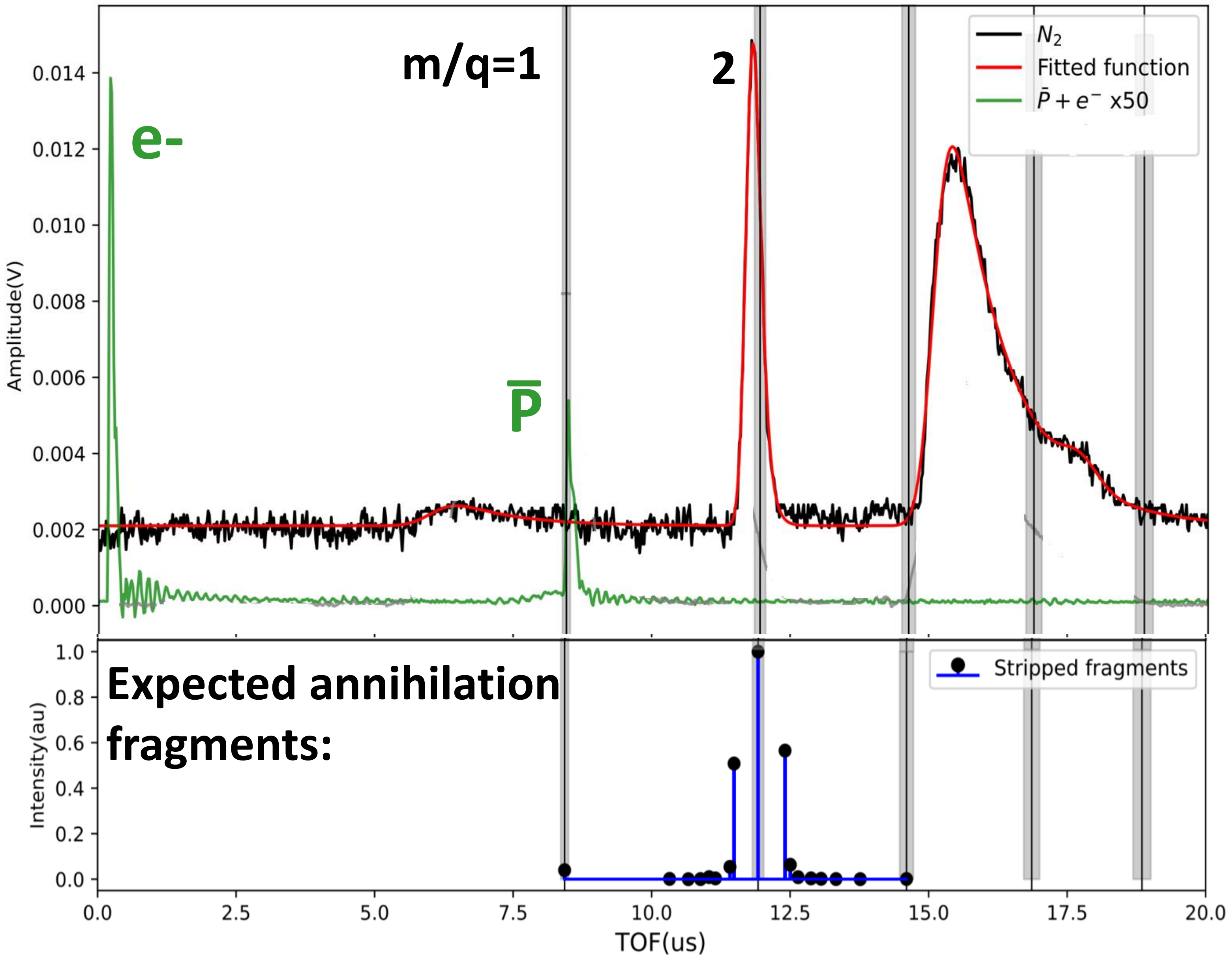
- Observation of a **TOF signal vs antiproton annihilation events** from nitrogen injection.



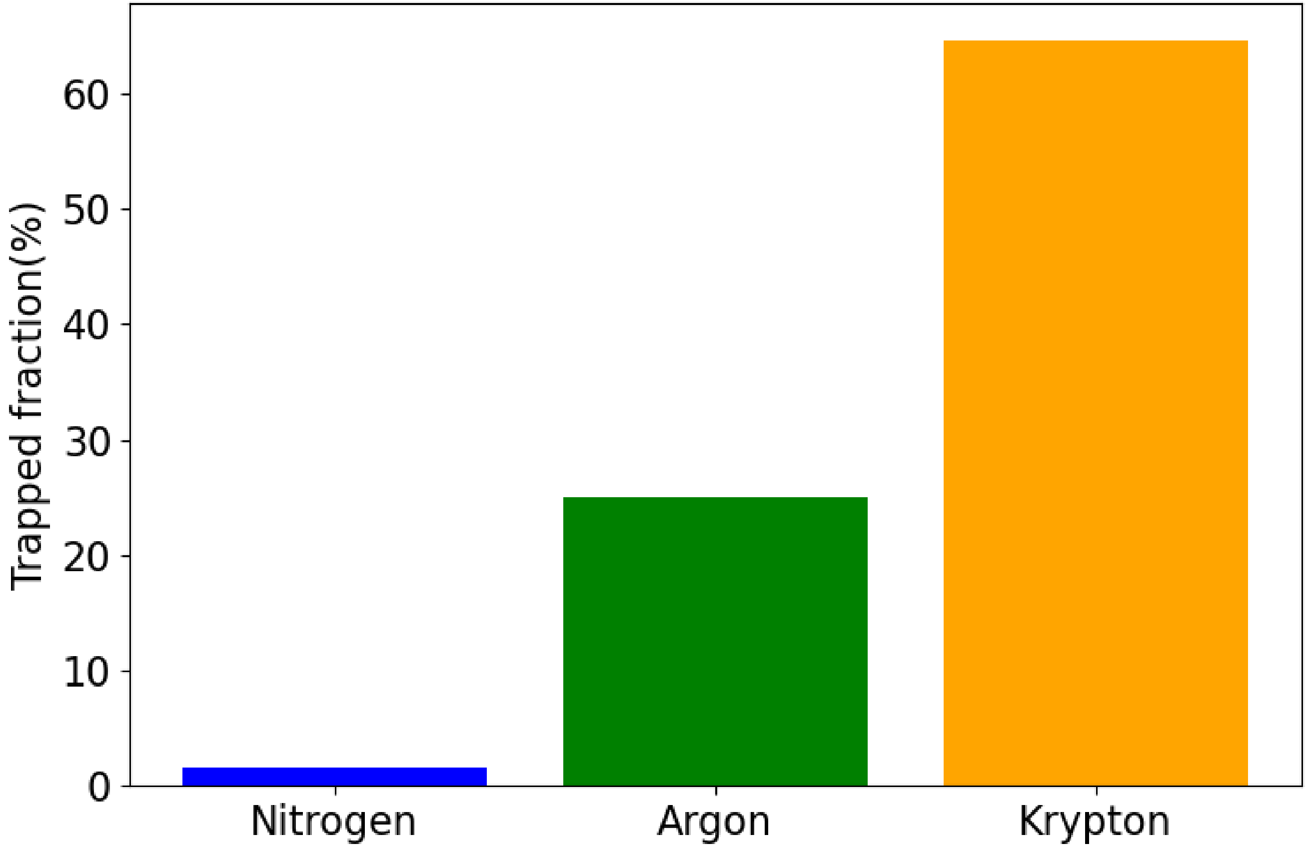



# Identification of trapped ions formed from antiproton annihilation

- TOF spectrum calibrated using e-, $\bar{p}$ and H+.
- Ions trapped with m/q=2.0(1)
- Signal observed for low energy antiprotons <1 keV -> Antiproton energy too low for collissional ionisation.
- Expected annihilation fragments from GEANT4 simulations: $^{12}C^{6+}$, $^{10}B^{5+}$, $^{6}Li^{3+}$, $^{4}He^{2+}$ ,..?

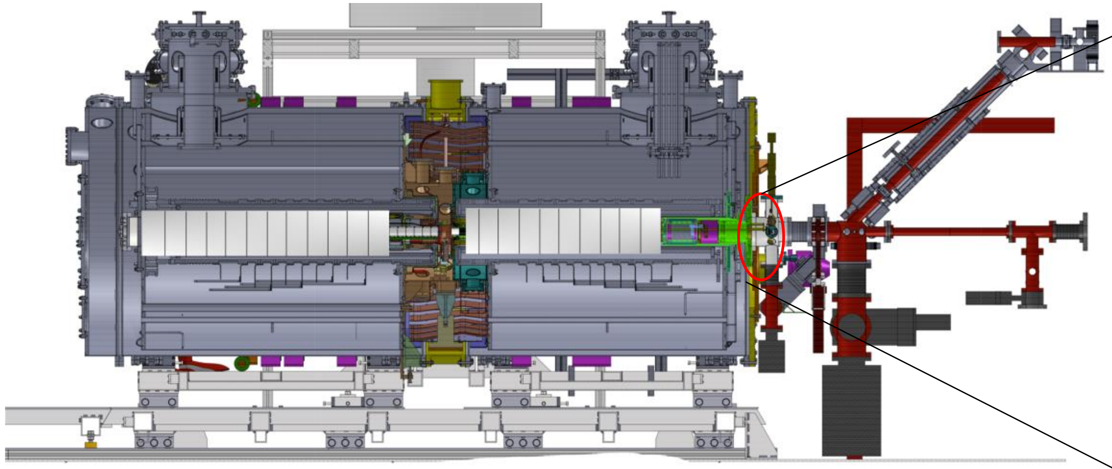


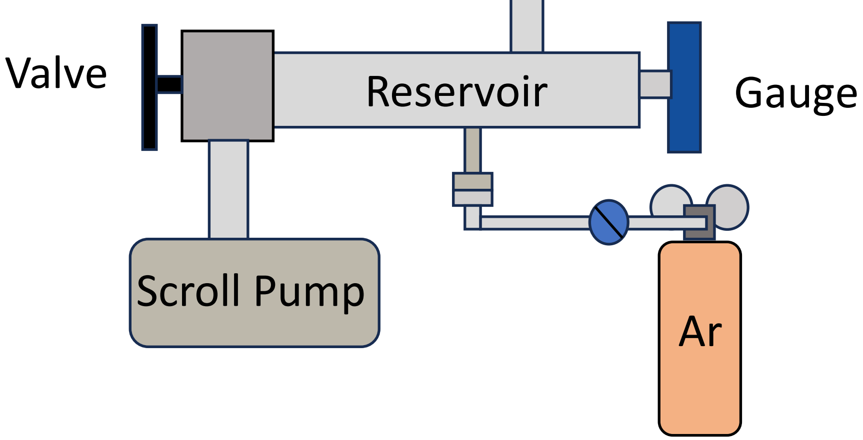
# Argon campaigns 2024:



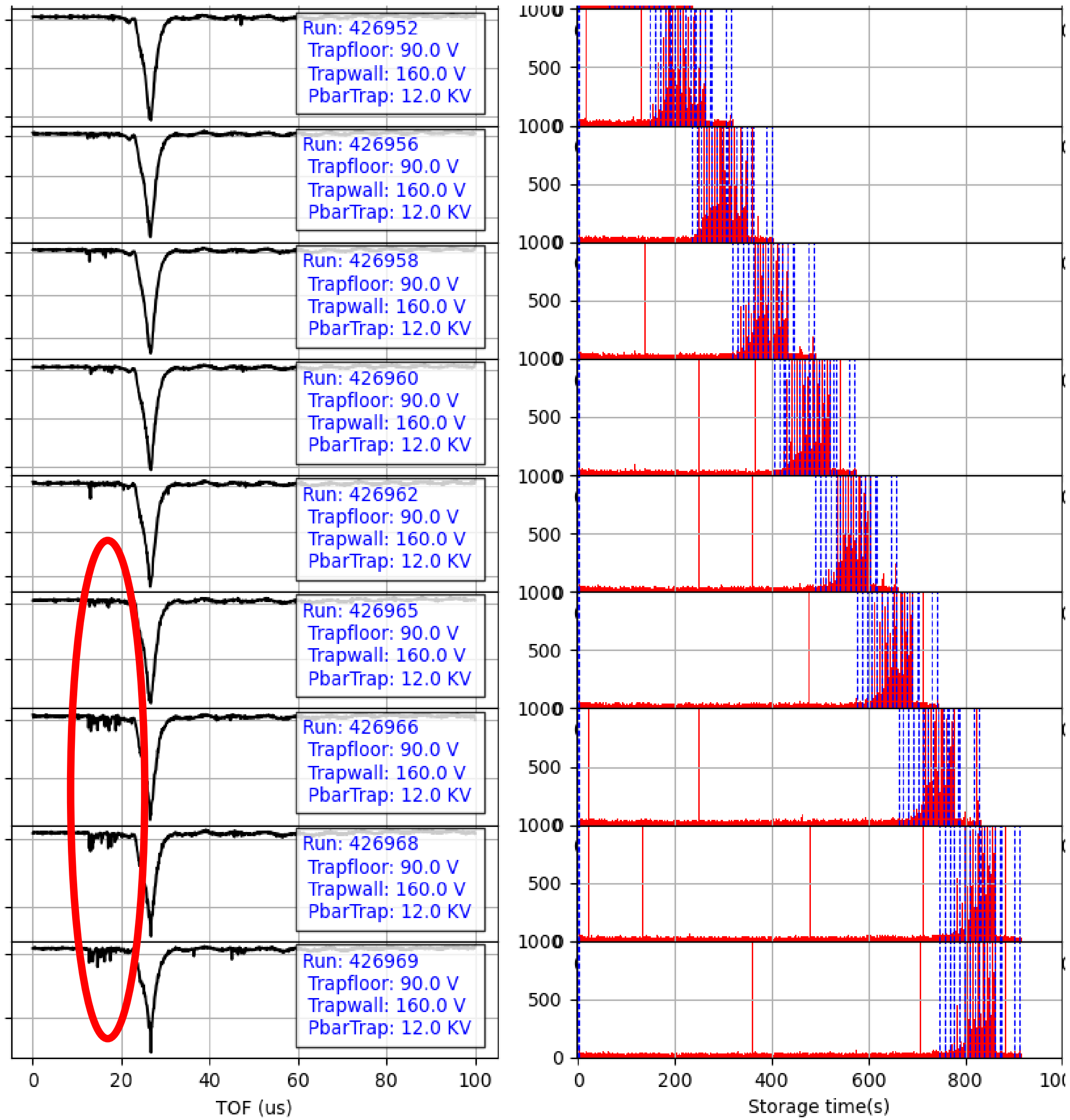

- **18 electrons** -> **15000 eV required for full stripping.**
- **Mass = 40 amu**
- Well studied in literature, confirmed full stripping from antiprotonic atom cascade.
- Nobel gas, no positively charged molecules.
- **Greater trapping fragments**

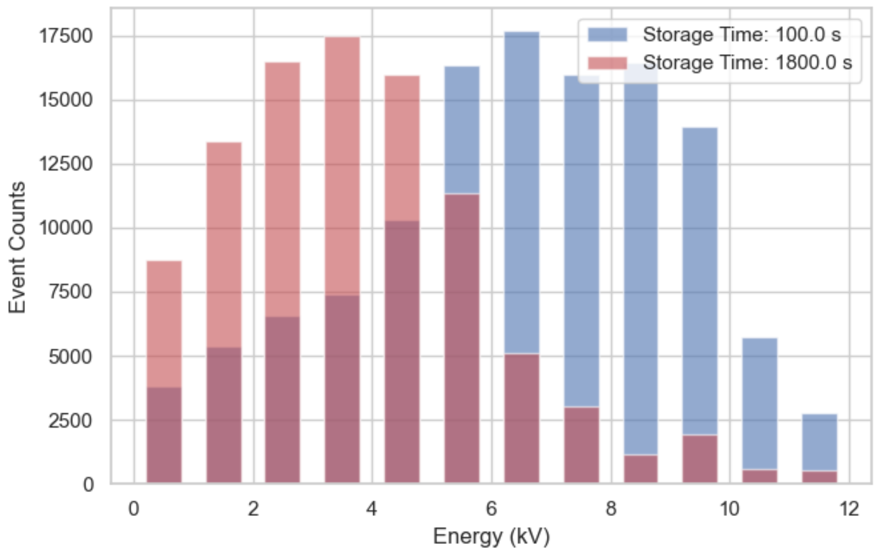
# Gas injection procedure

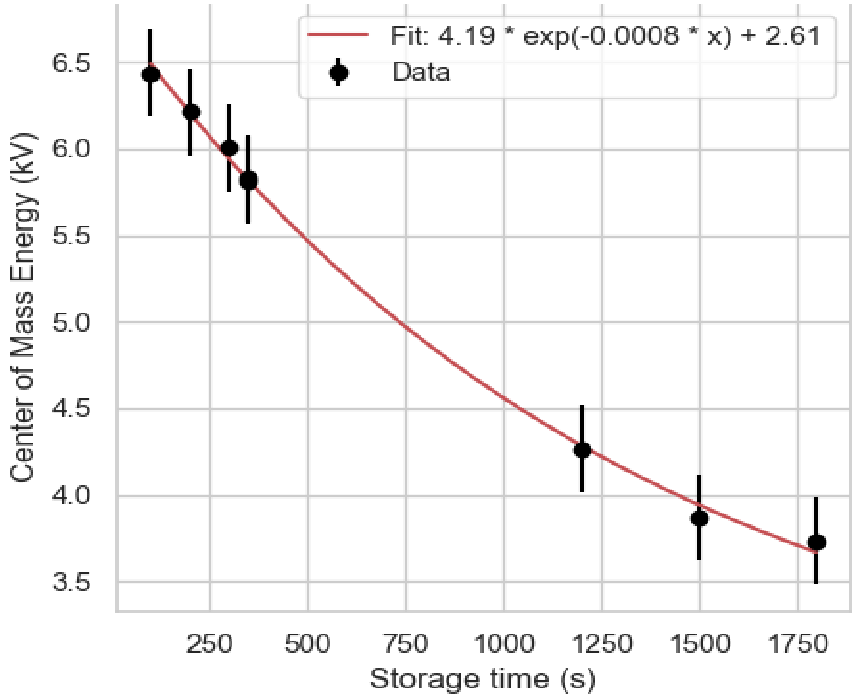




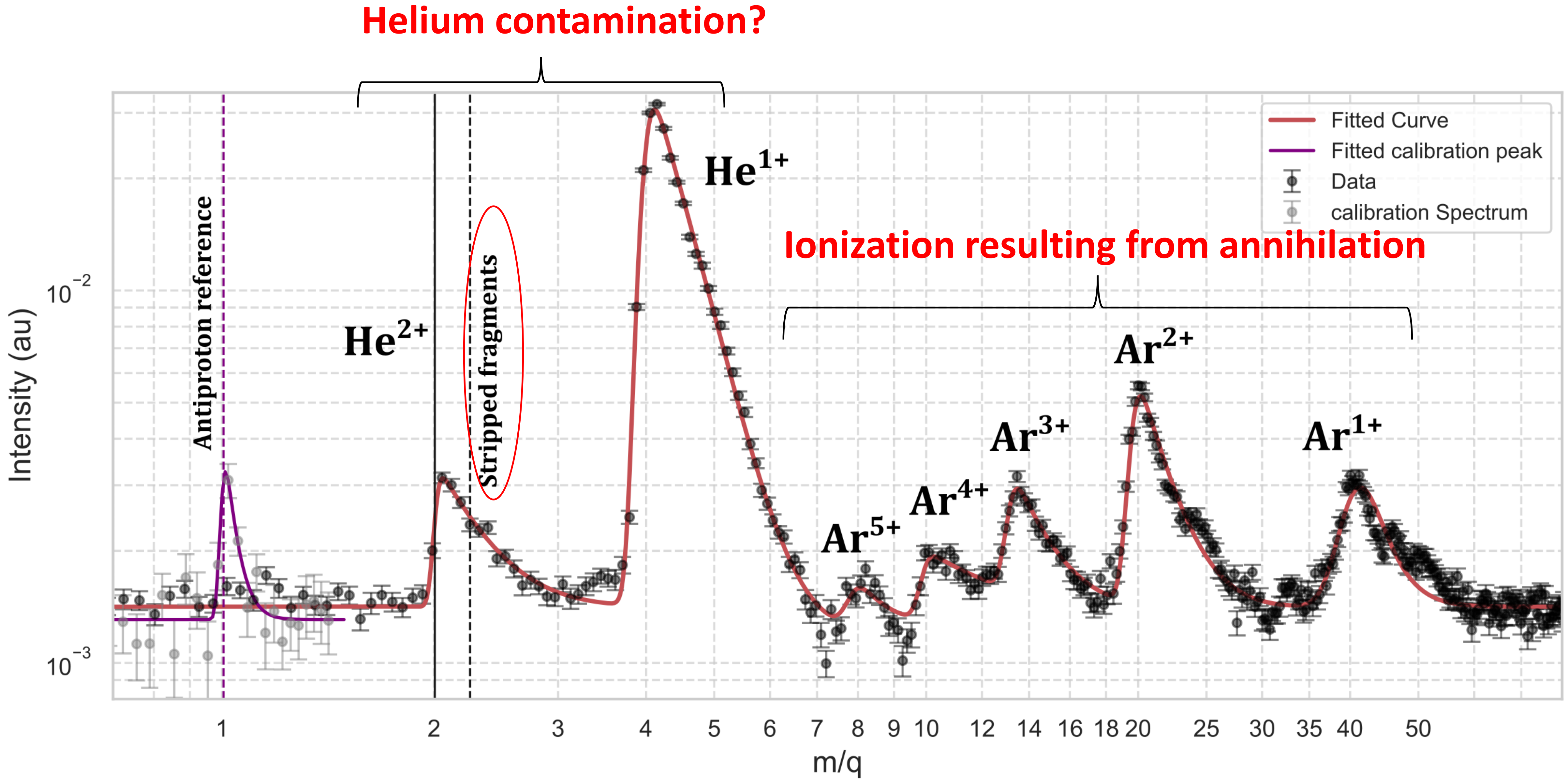

# Scan over antiproton storage time



# Argon TOF spectrum:



PRL 101, 043201 (2008) PHYSICAL REVIEW LETTERS week ending 25 JULY 2008

# Ionization of Helium and Argon by Very Slow Antiproton Impact

H. Knudsen,[1] H.-P. E. Kristiansen,[1] H. D. Thomsen,[1] U. I. Uggerhøj,[1] T. Ichioka,[1,*] S. P. Møller,[2] C. A. Hunniford,[3] R. W. McCullough,[3] M. Charlton,[4] N. Kuroda,[5] Y. Nagata,[5] H. A. Torii,[5] Y. Yamazaki,[5,6] H. Imao,[6] H. H. Andersen,[7] and K. Tökesi[8]

[1]*Department of Physics and Astronomy, University of Aarhus, Denmark*
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[5]*Institute of Physics, Komaba, University of Tokyo, Japan*
[6]*Atomic Physics Laboratory, RIKEN, (Saitama) Japan*
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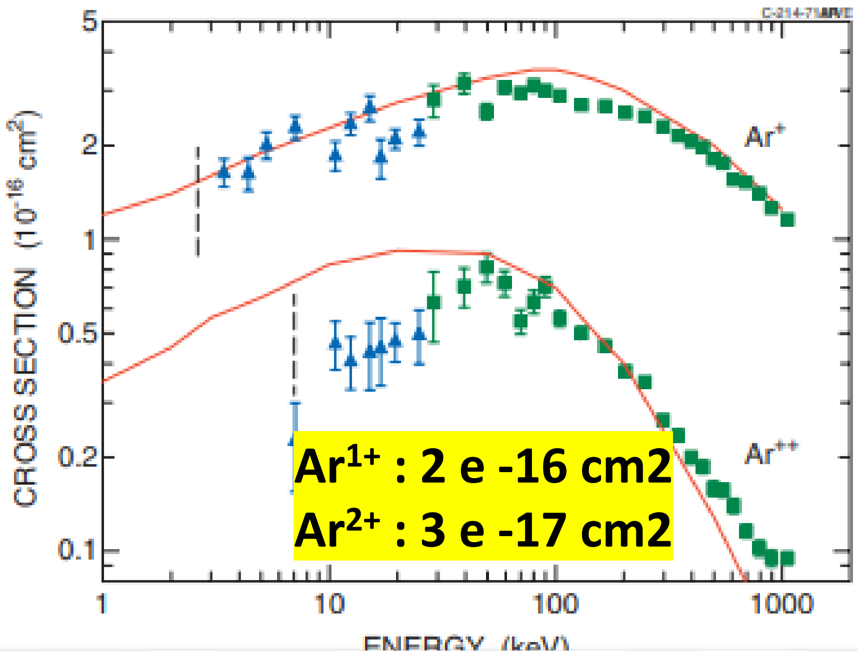
[8]*ATOMKI, Debrecen, Hungary*

(Received 17 March 2008; published 25 July 2008)

The total cross sections for single ionization of helium and single and double ionization of argon by antiproton impact have been measured in the kinetic energy range from 3 to 25 keV using a new technique for the creation of intense slow antiproton beams. The new data provide benchmark results for the development of advanced descriptions of atomic collisions and we show that they can be used to judge, for the first time, the validity of the many recent theories.

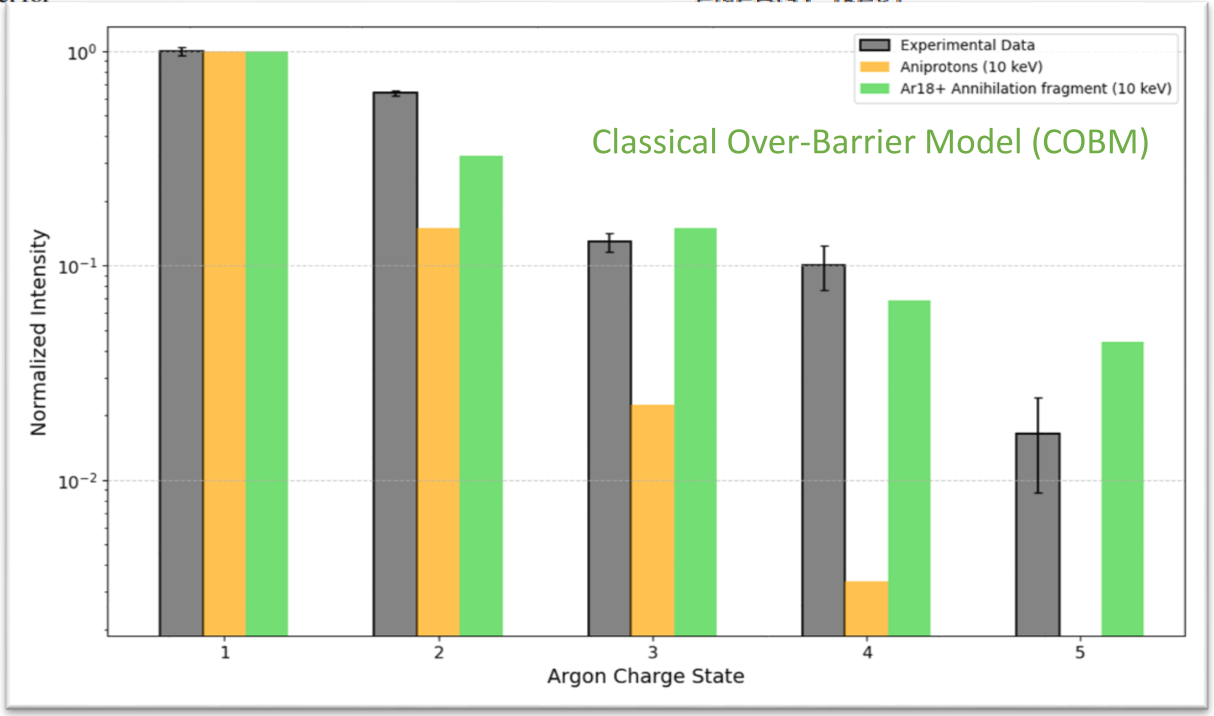



spectrum (TOF). The spectra show clear peaks at the expected positions for $He^+$, $Ar^{++}$, and $Ar^+$, and show no other features except for a low and almost flat background of accidental coincidences.

**Observed ionization is a result of highly charged nuclear fragments in the trap.**

## Paper draft in circulation

**Technique for the capture and spectroscopy of antiproton-nucleus annihilation fragments**



# November 2024 Argon campaign

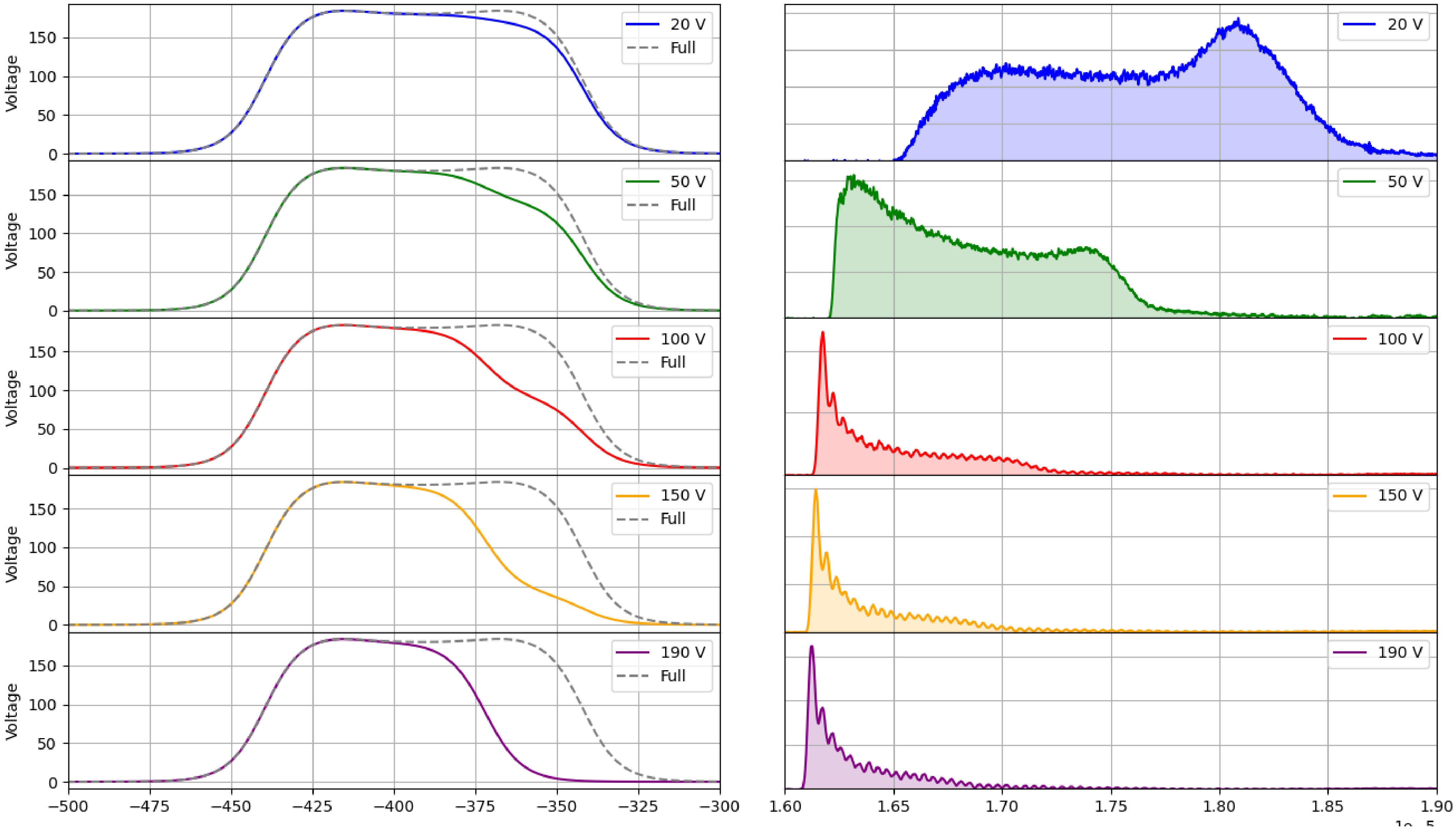
- **1T MCP replaced -> Characterising new MCP signal, TOF calibration, reduced ringing?**
- **Refining technique, symmetric trap for removing microwells.**

**Vacuum**

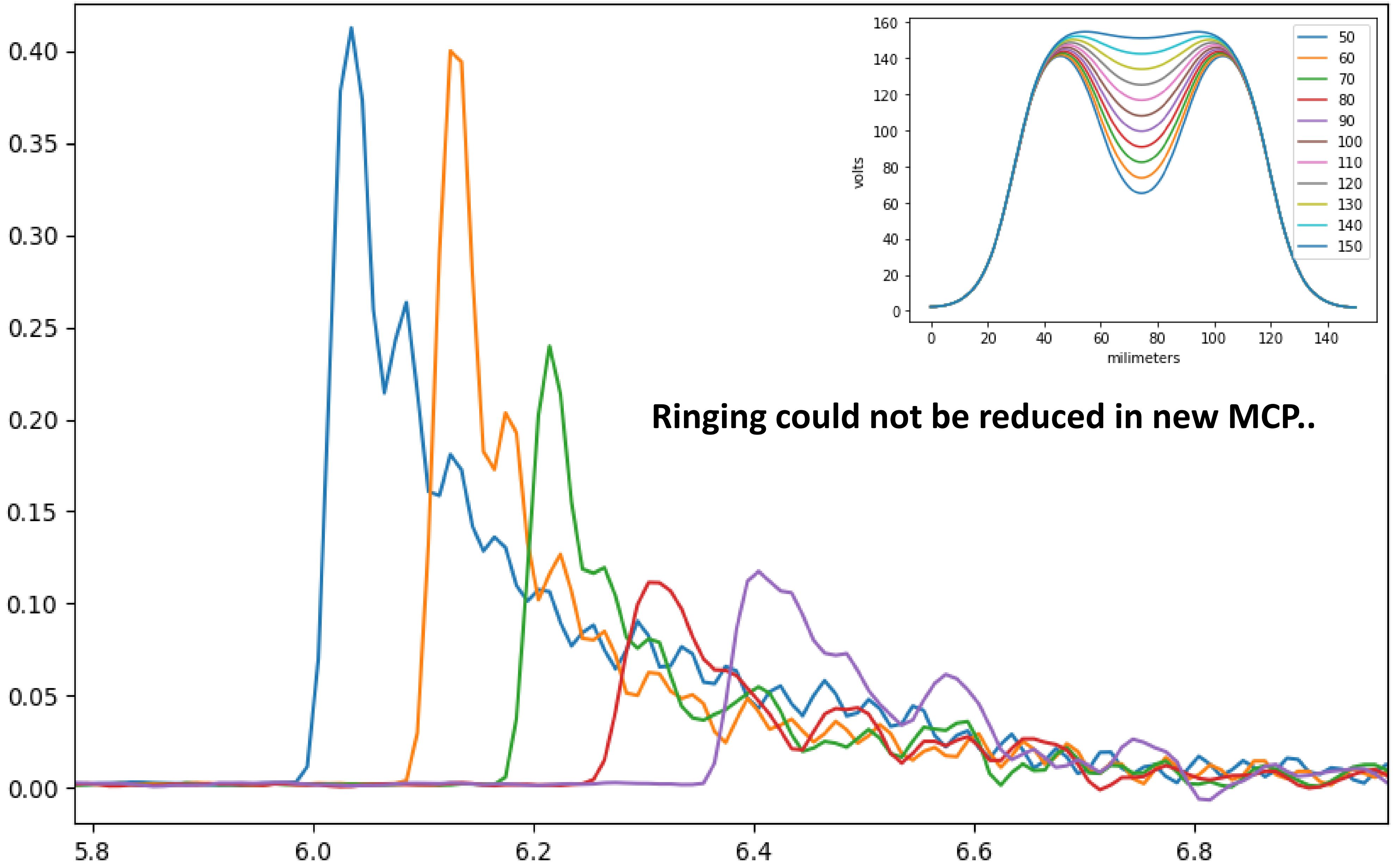
- **Gathering statistics with Argon injection, refining spectrum for paper.**
- **Study pressure influence on signal.**
- **Vacuum recovery test and helium injection.**

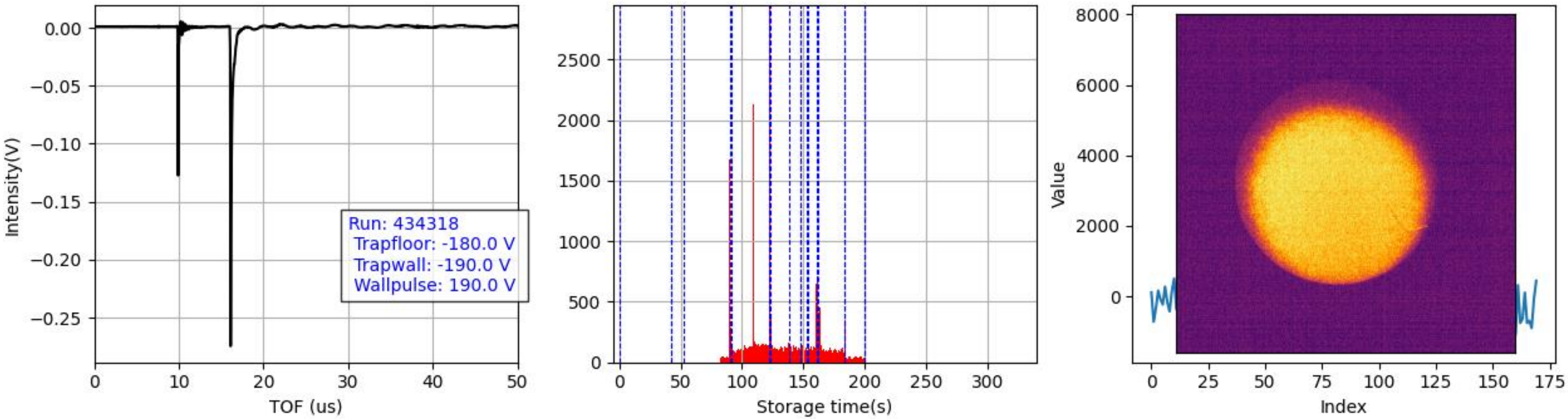
**Gas injection**

# Trap potential study using antiprotons

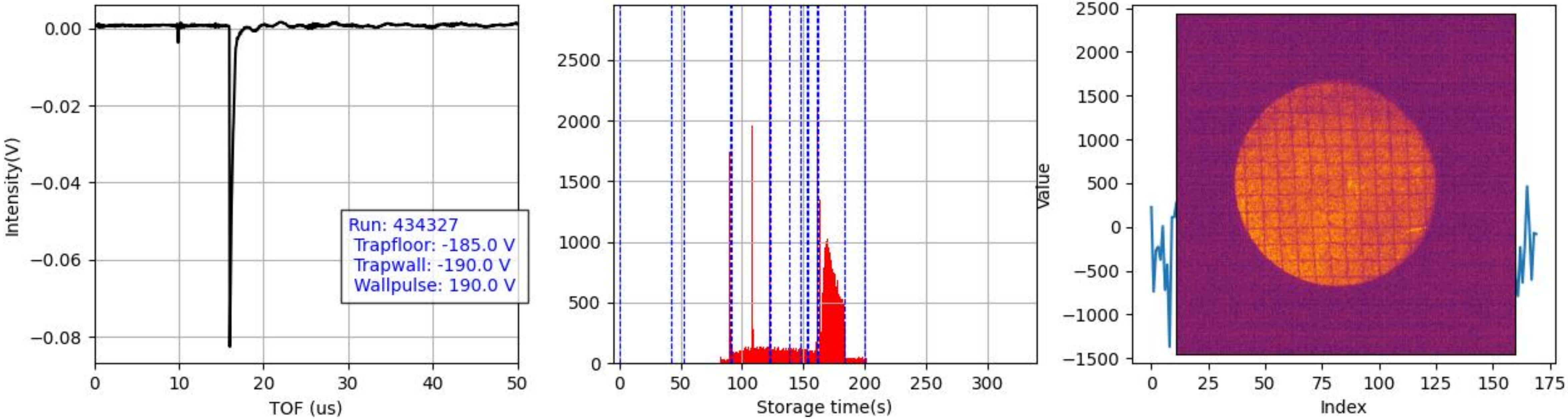


# Antiproton TOF calibration

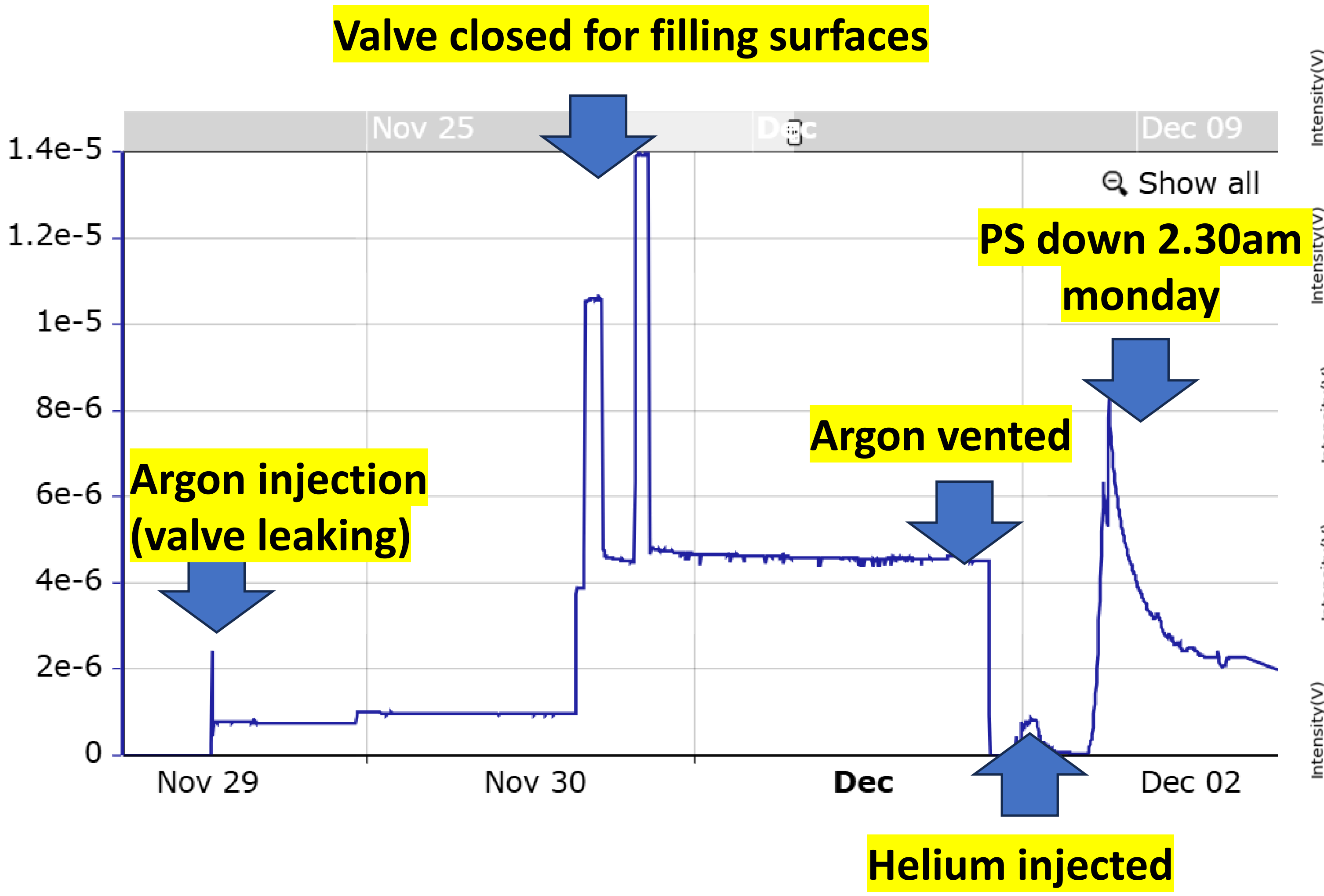


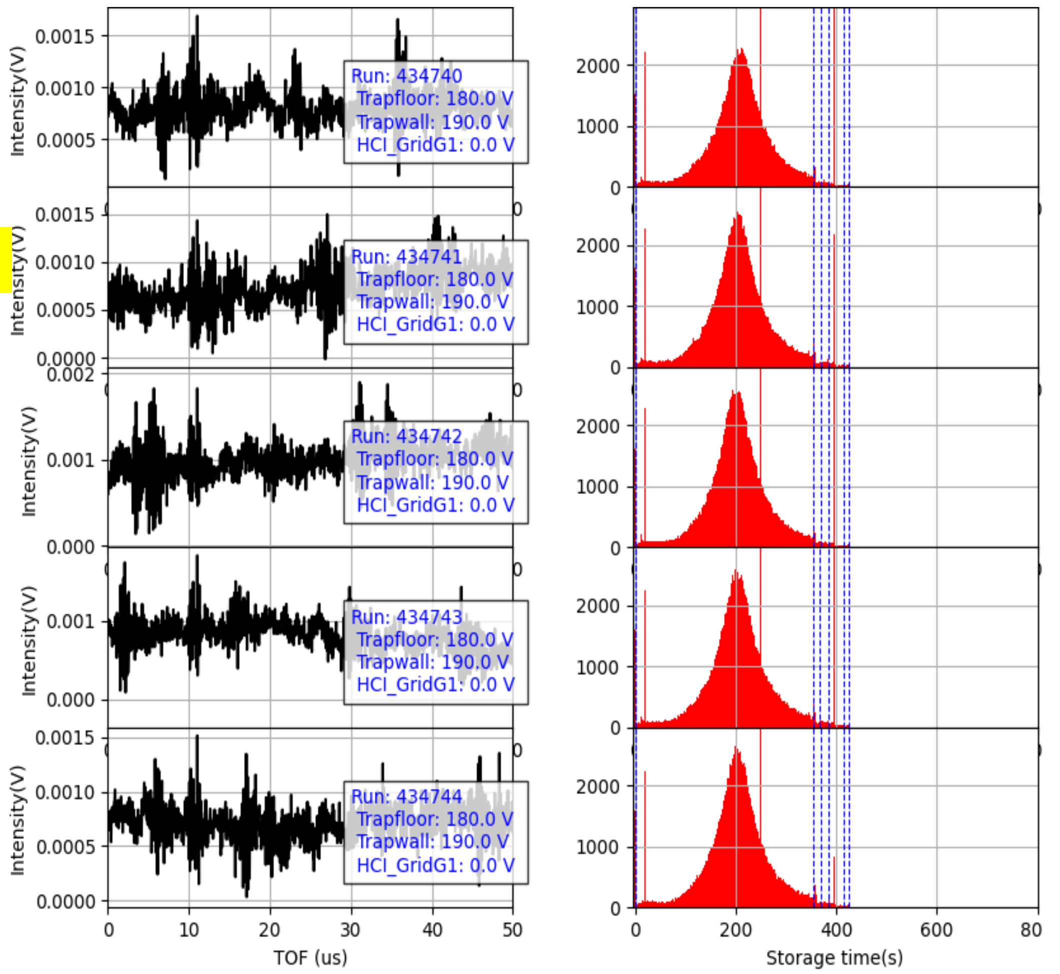



# Could the antiproton calibration script have damaged the MCP?



# Gas injection timeline

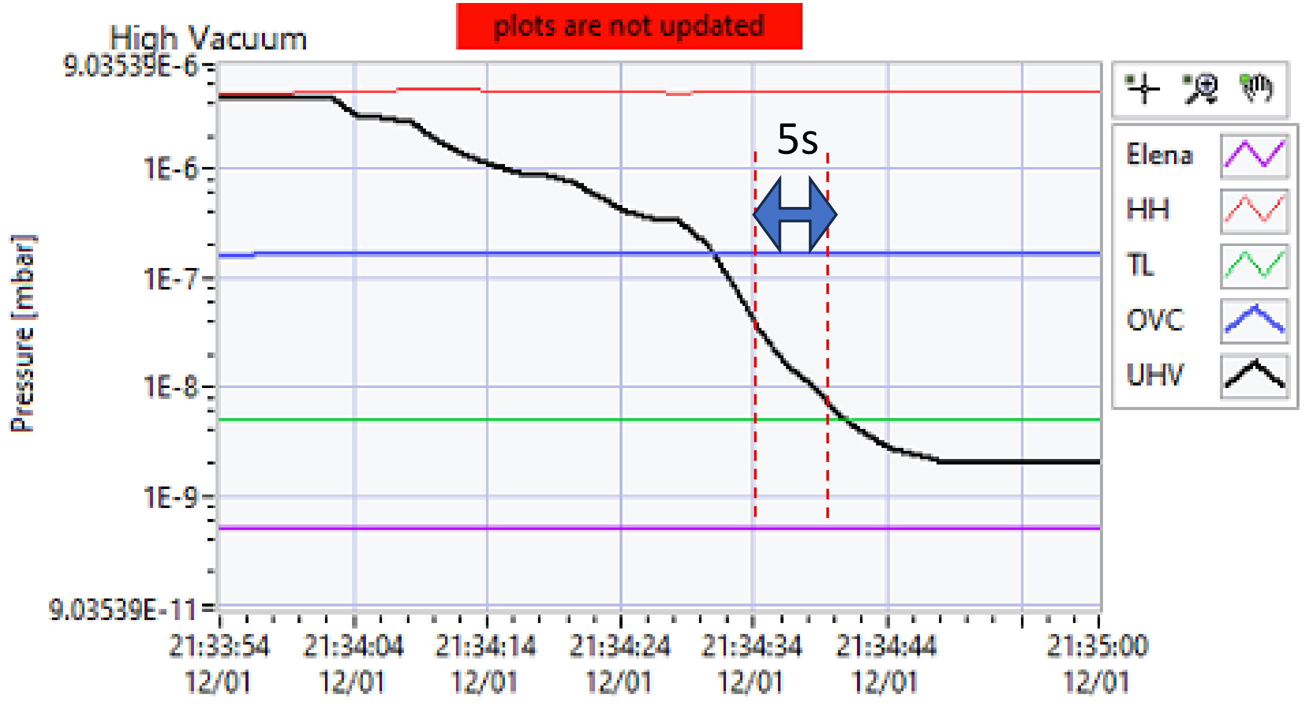


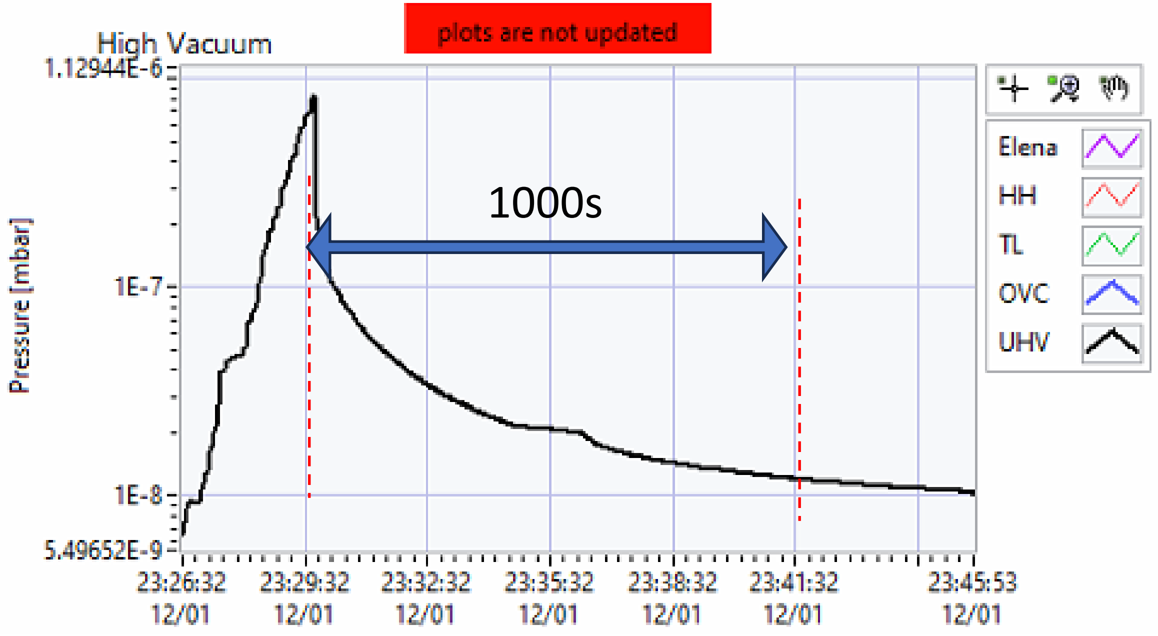
# Vacuum recovery time

## Argon

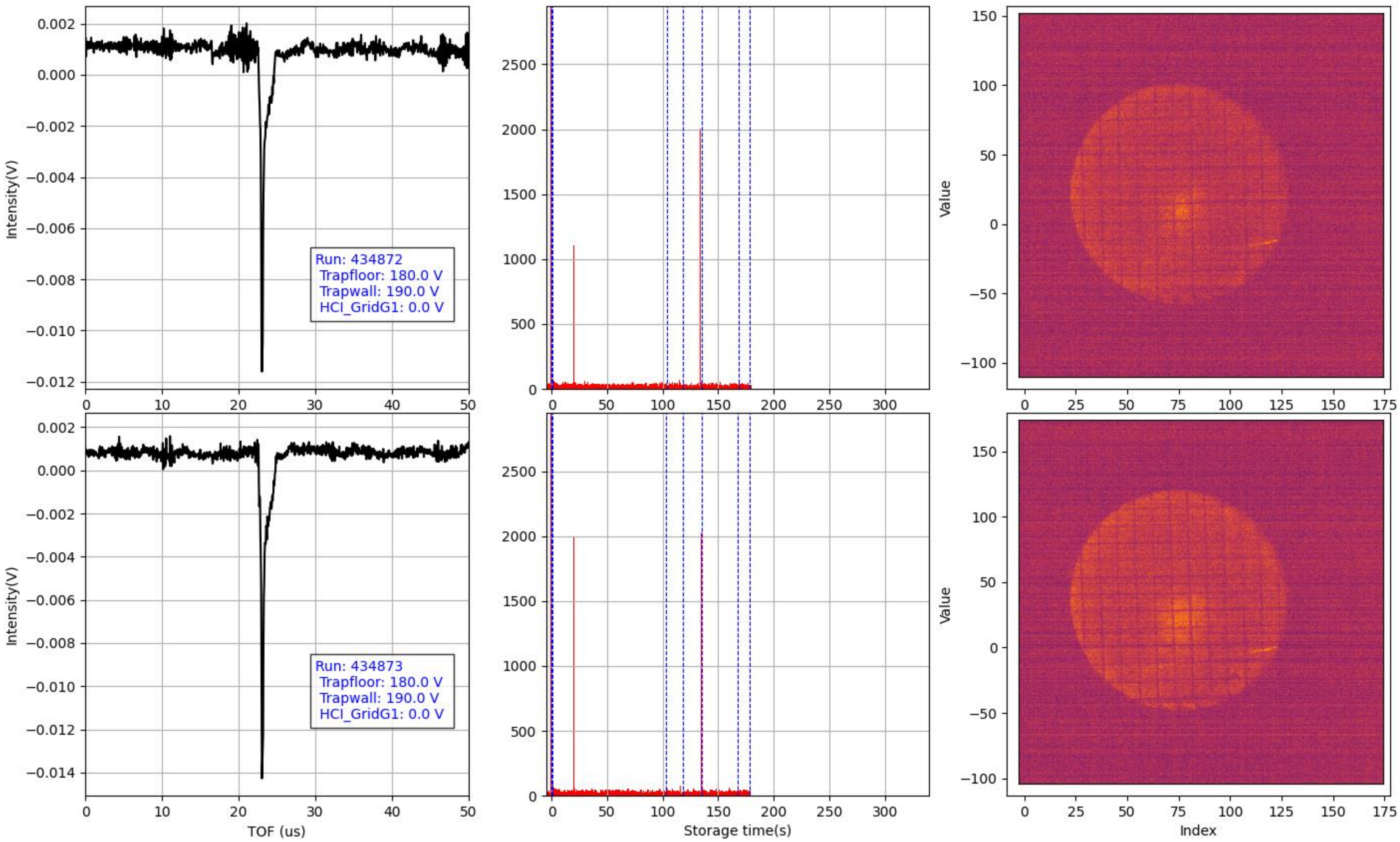
immediate recovery



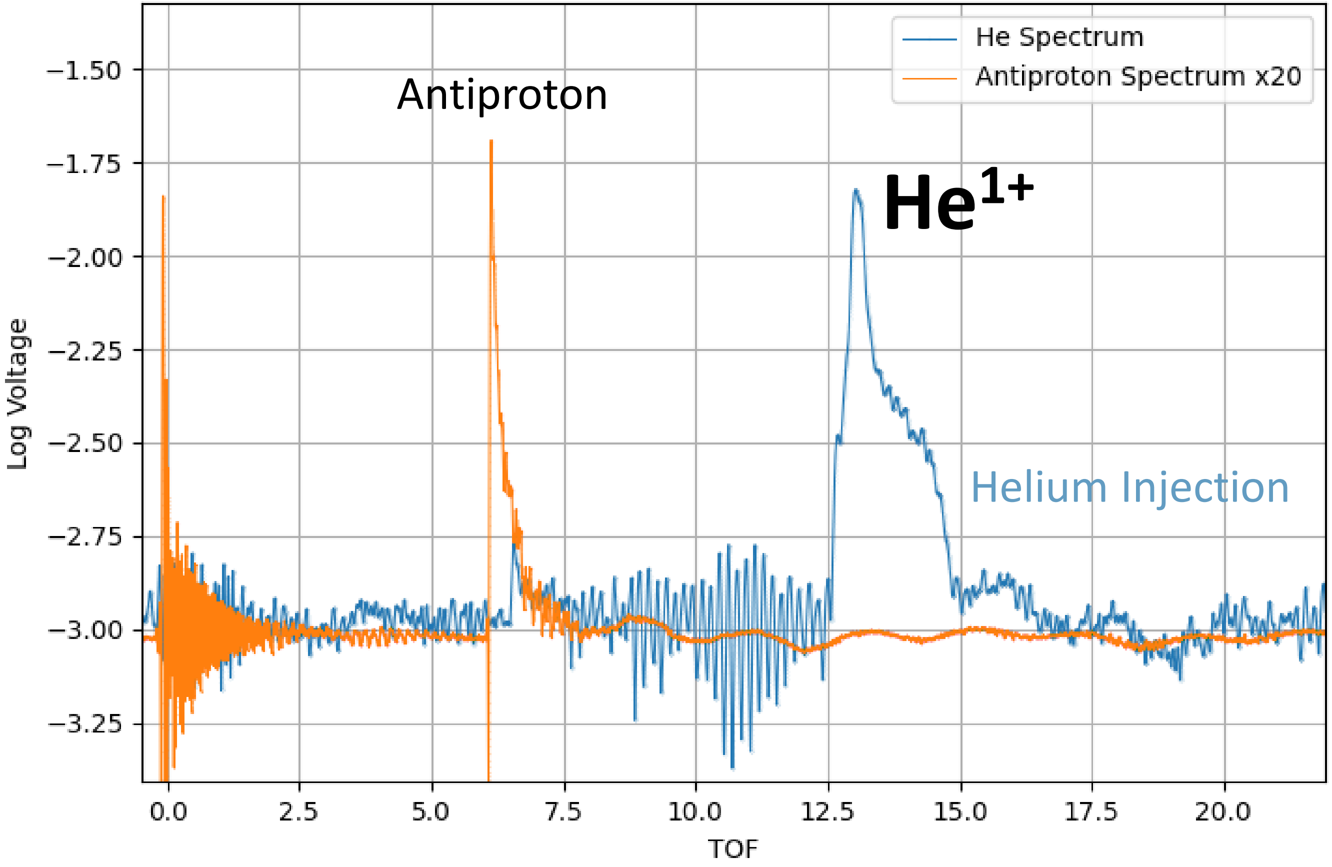

## Helium

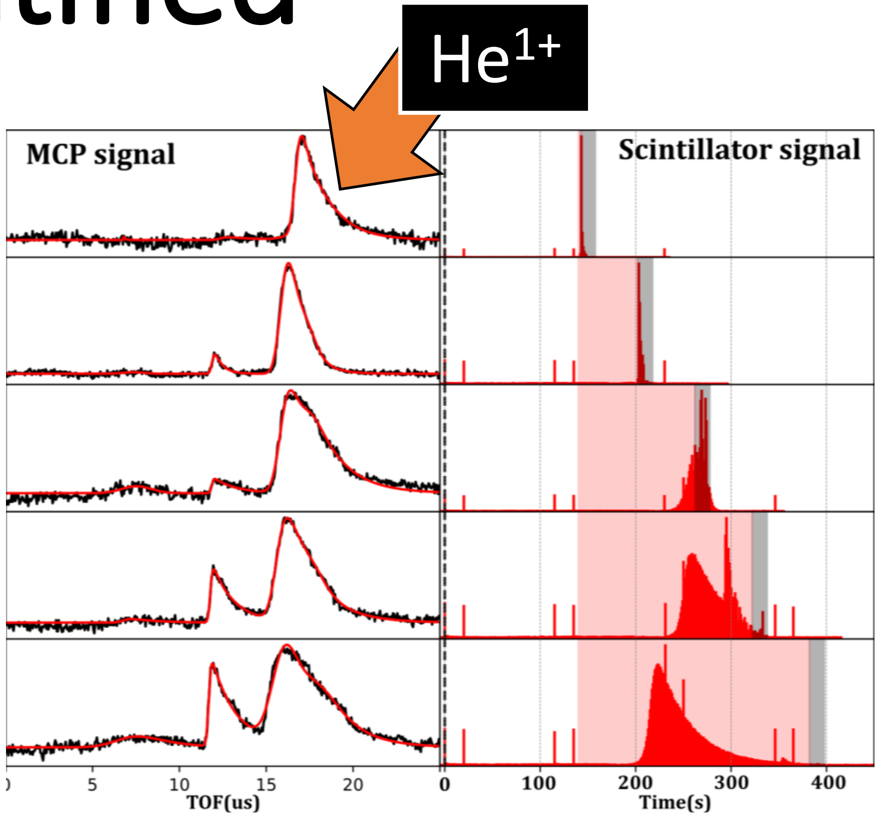


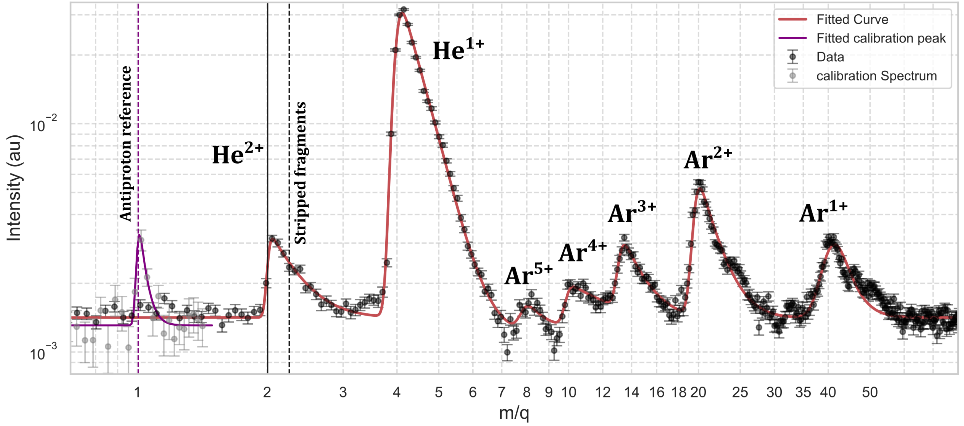
# Helium collissional ionization signal



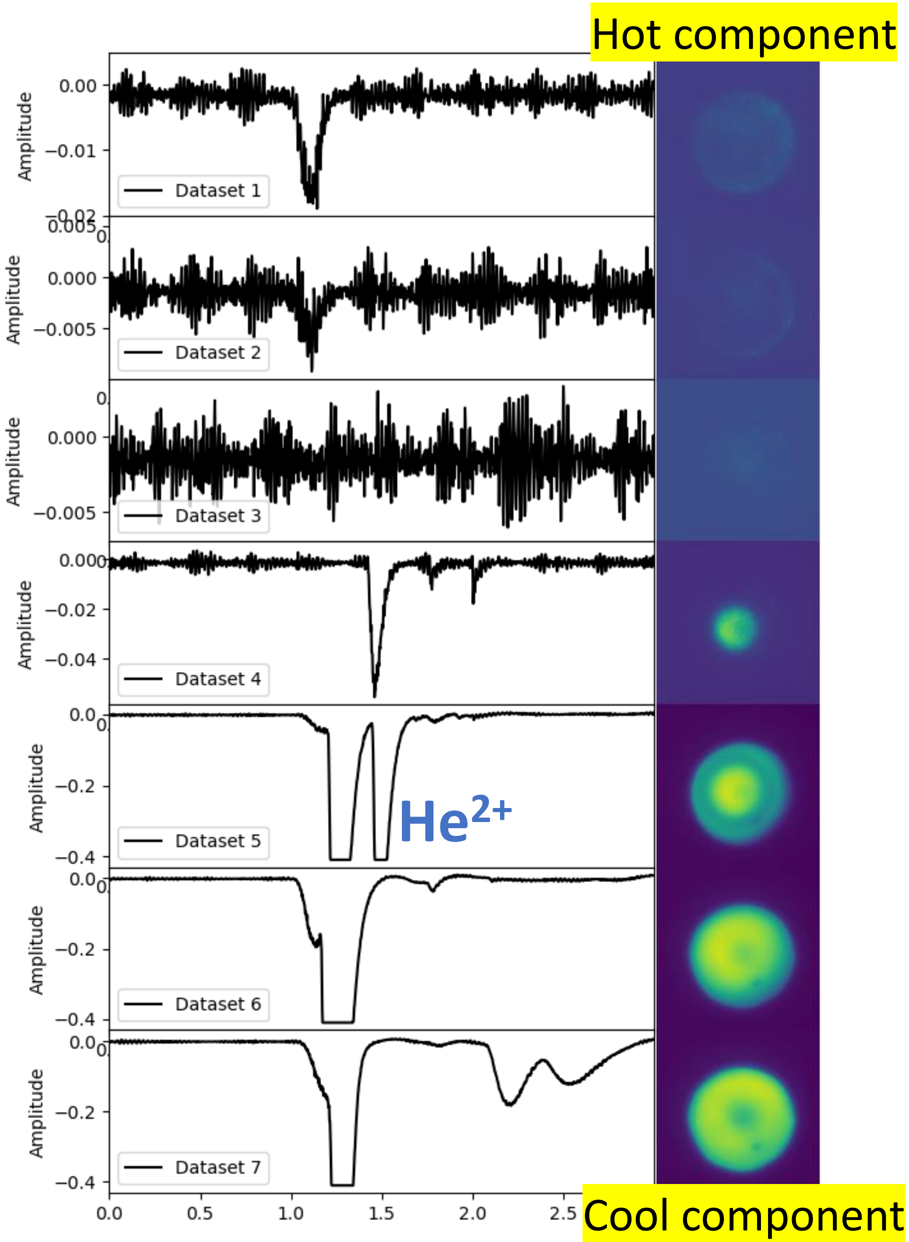
# Helium signal identified

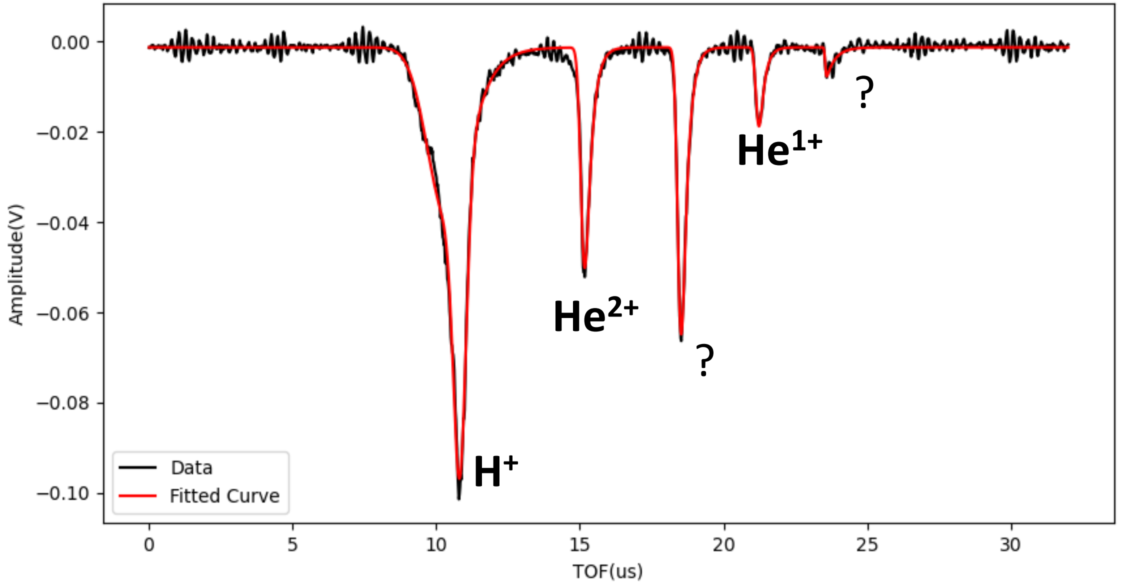


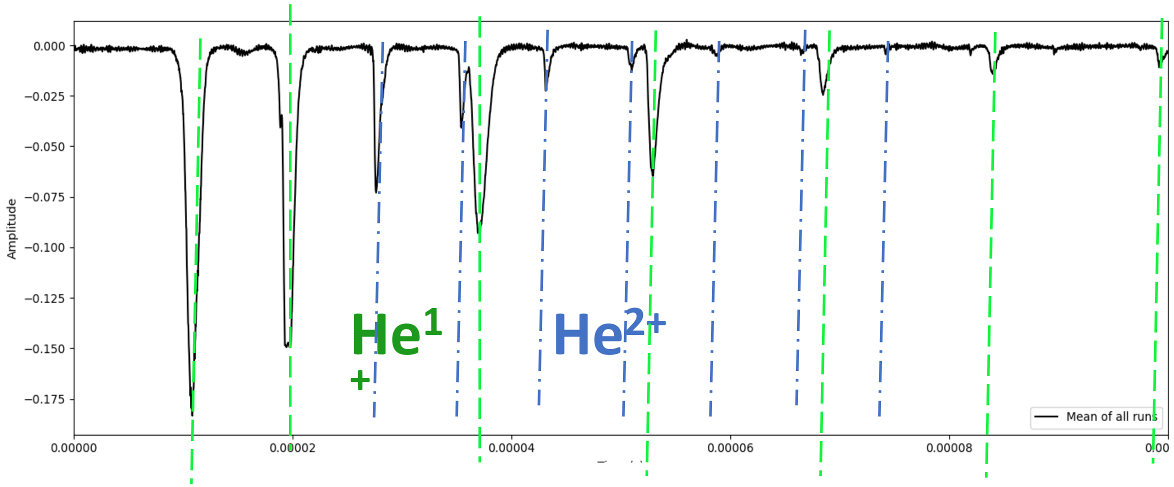



# Helium signal seen in data from 2023




**Old data can now be better understood**



# Overview of HCI campaigns

## 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.

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

- Nitrogen injection.

- Confirming HCI formation from nitrogen.

## 2024

- **Argon campaign**: (2w):

  - Needle valve installed for controlled injection
  - Argon injected, antiproton energy loss measurements
  - Electron cooling of antiprotons with gas.
  - HCI Argon ions identified

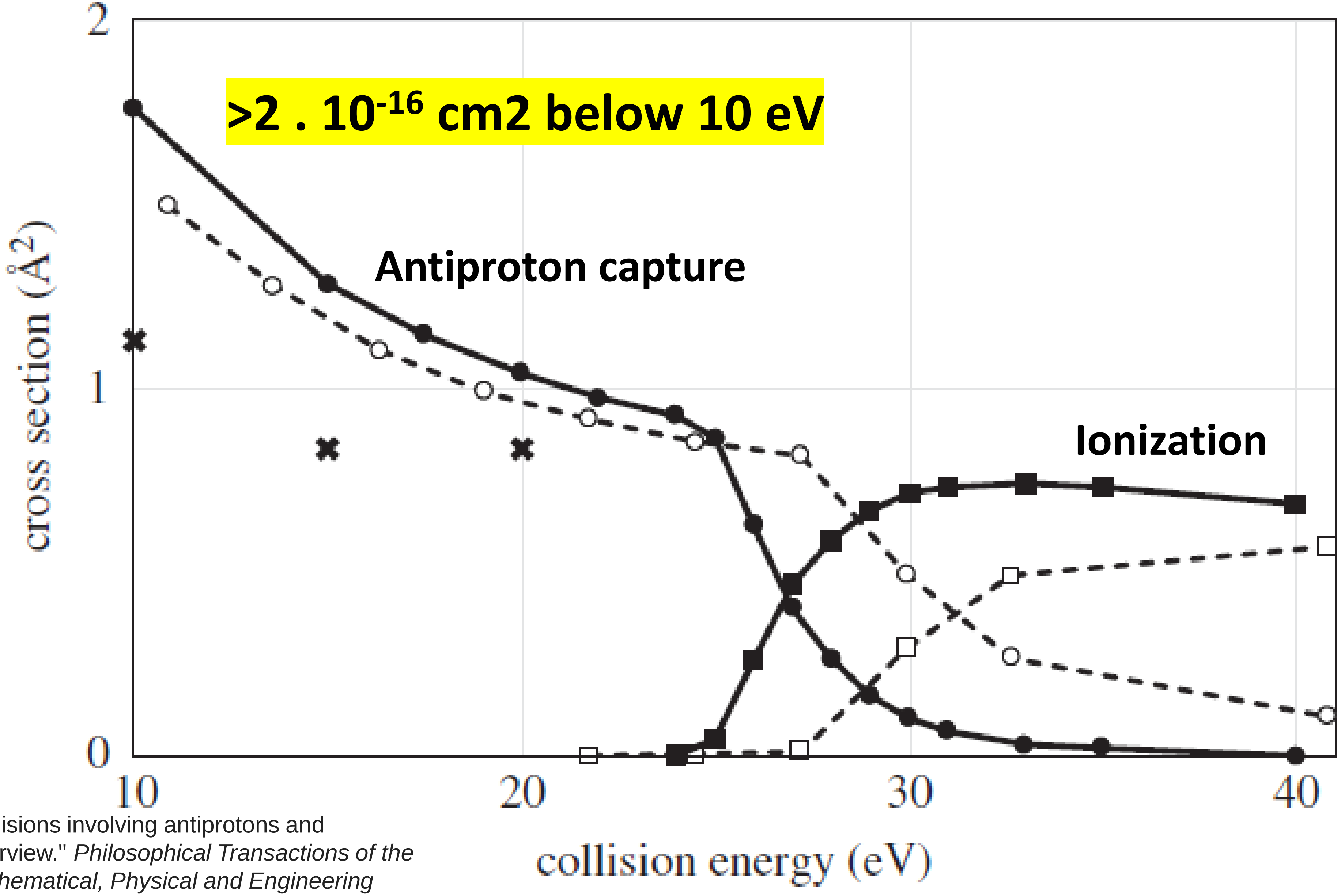
- **Argon/Helium campaign**: (3d):

  - Trap configuration better understood.
  - Collissional ionization origin of helium signal confirmed.

# End of the dirty injection...

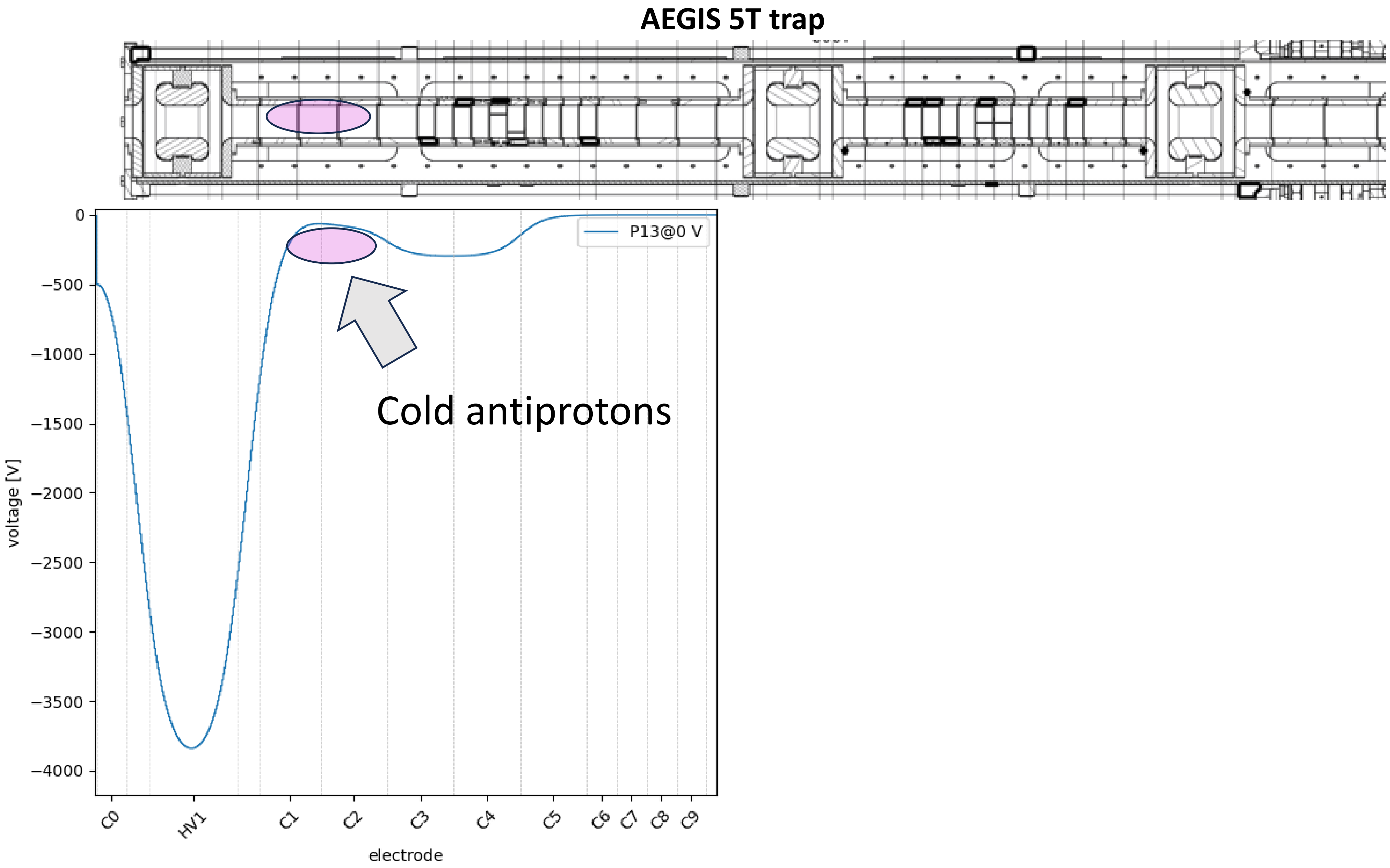
# So what is next?

# Antiproton-Helium capture cross-section

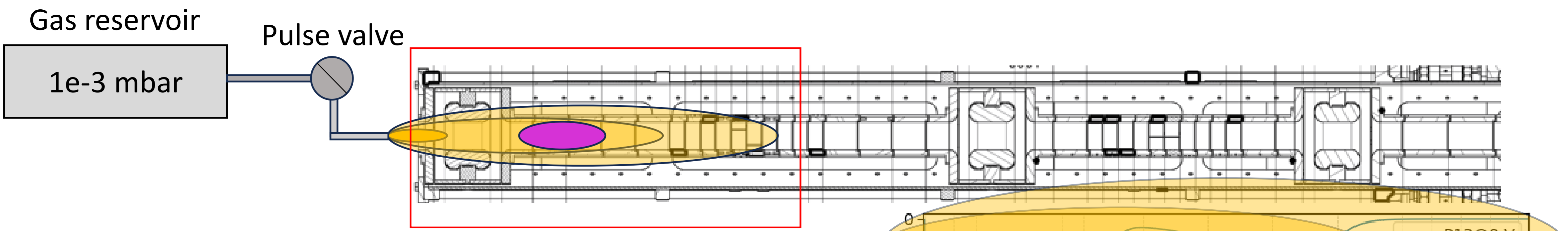



Jonsell, Svante. "Collisions involving antiprotons and antihydrogen: an overview." *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences* 376.2116 (2018): 20170271.

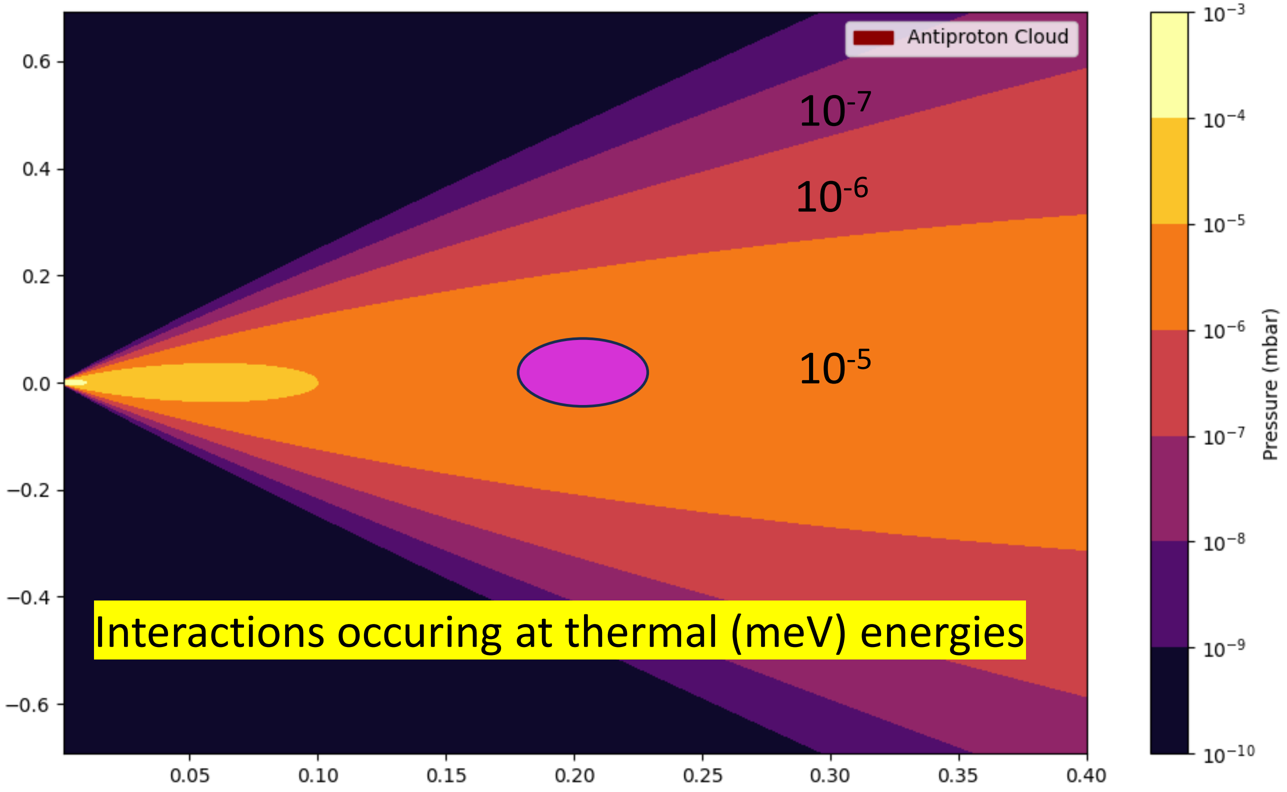
# Step 1: Capture and cool antiprotons near HV1

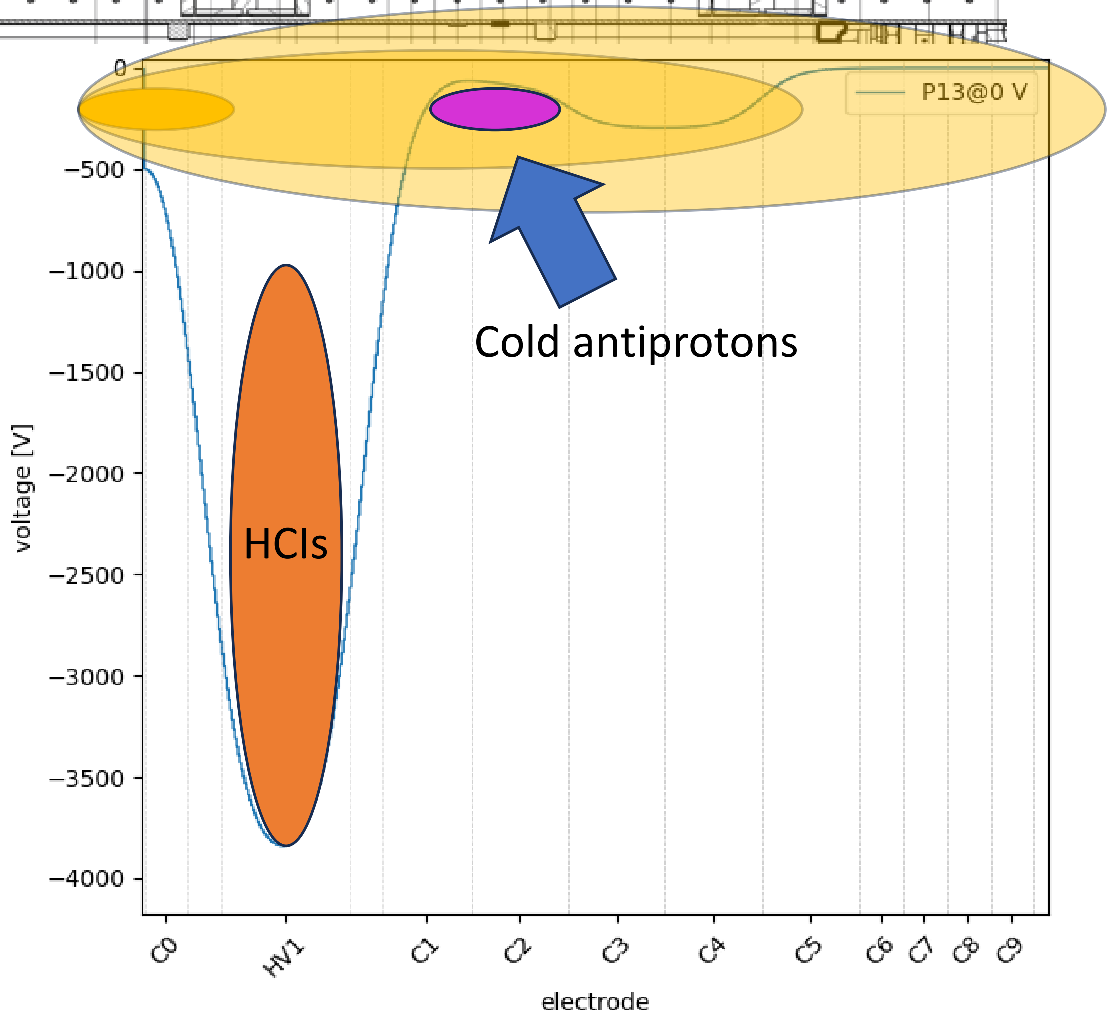


# Step 2: Exposing antiprotons to gas jet



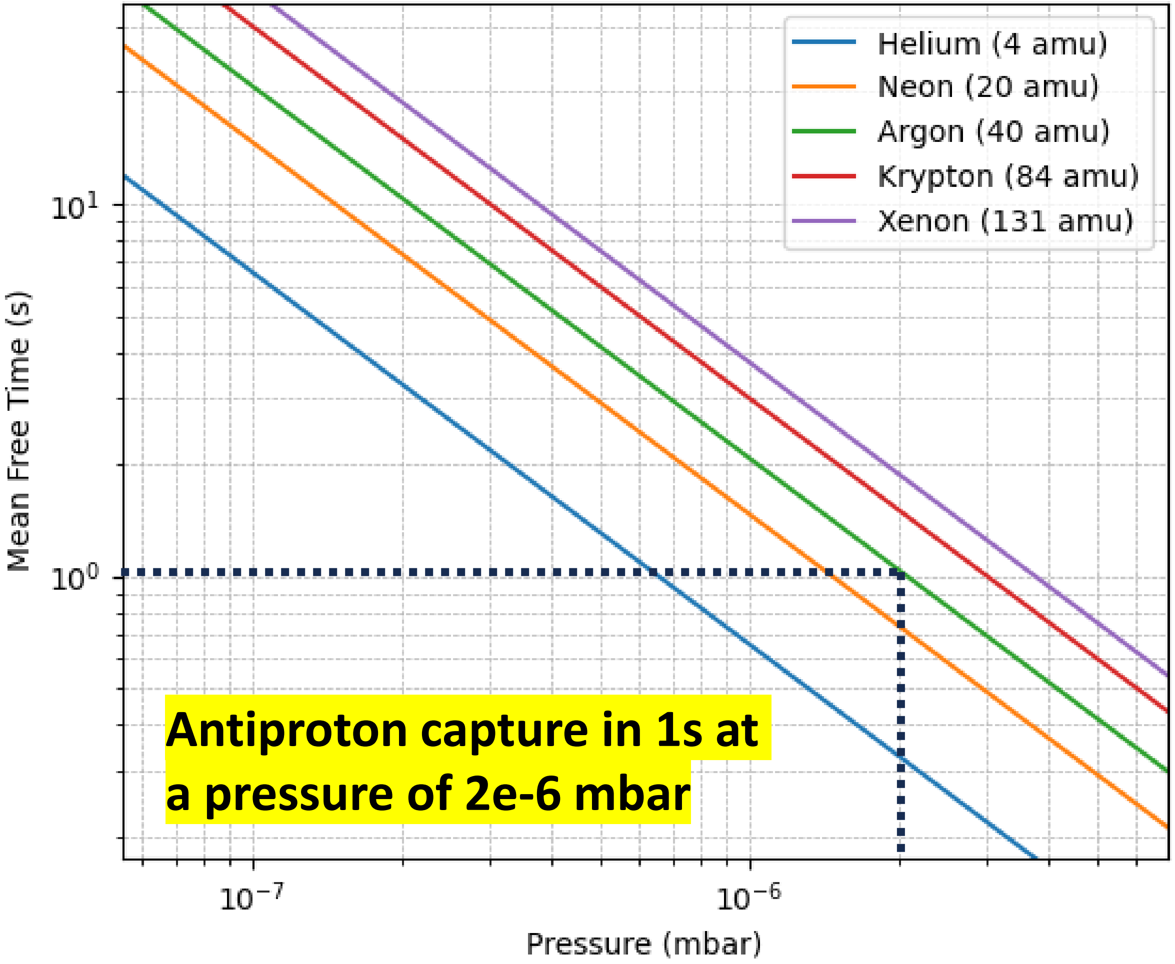

1 mm gas jet nossle

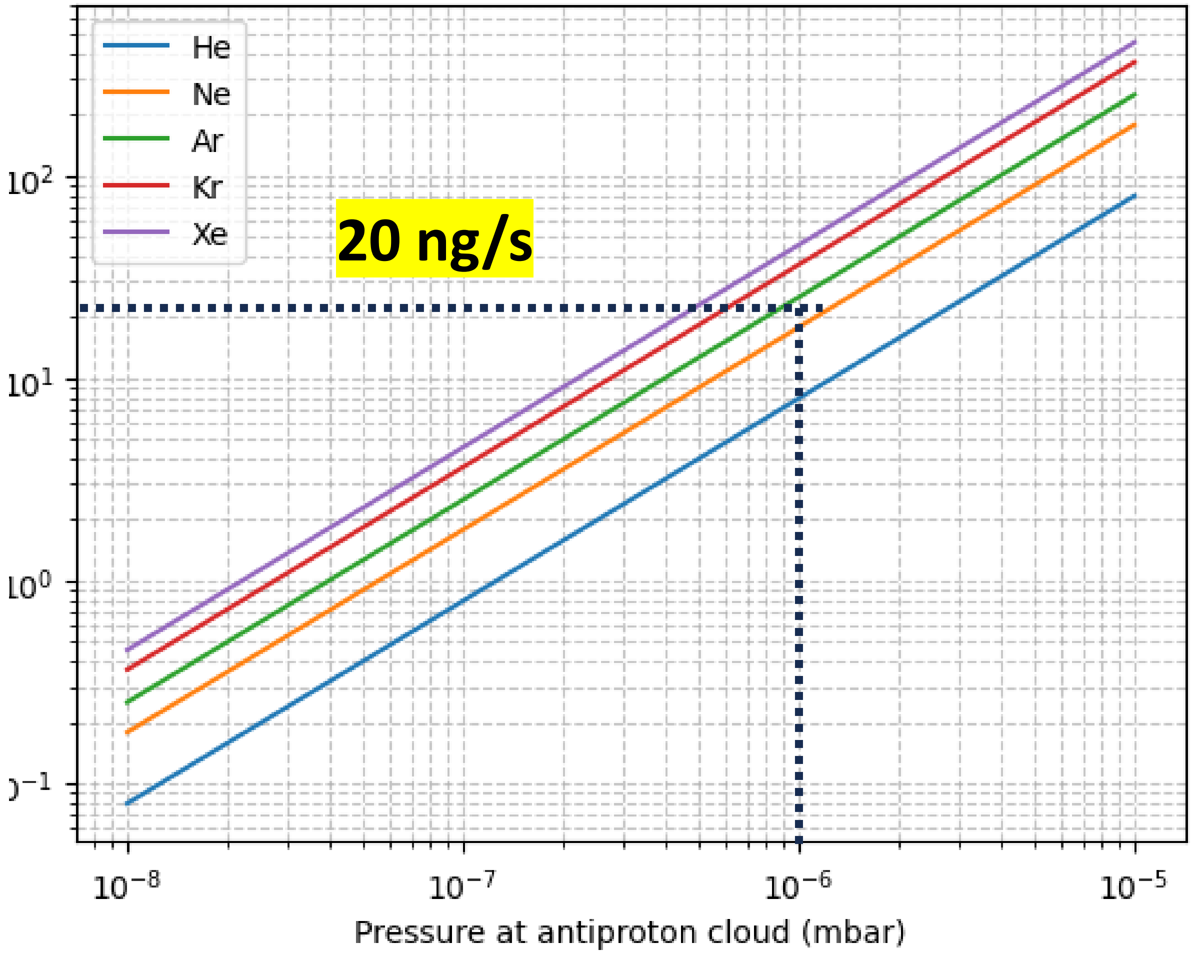


# How much gas is needed?

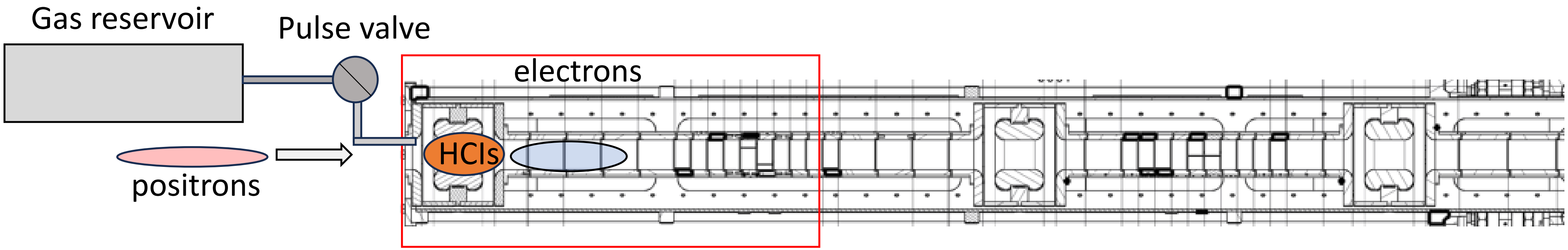
Assuming capture CS of 5e-16 $cm^2$ at T=300K

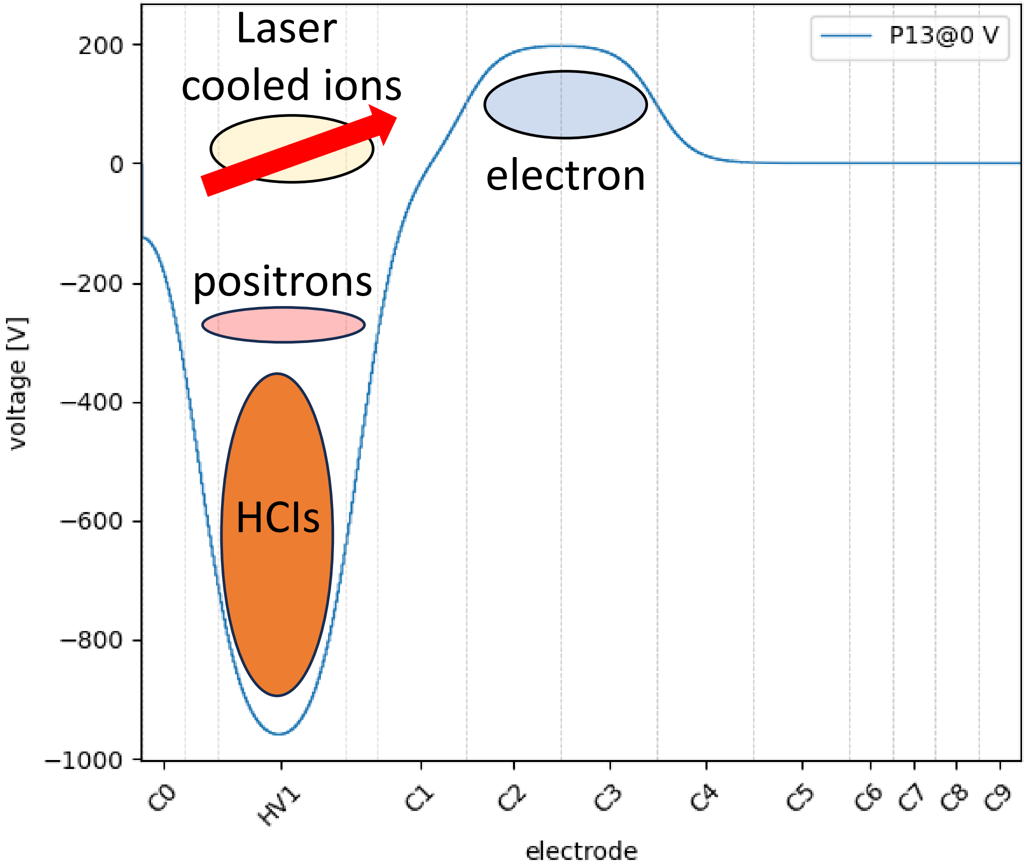


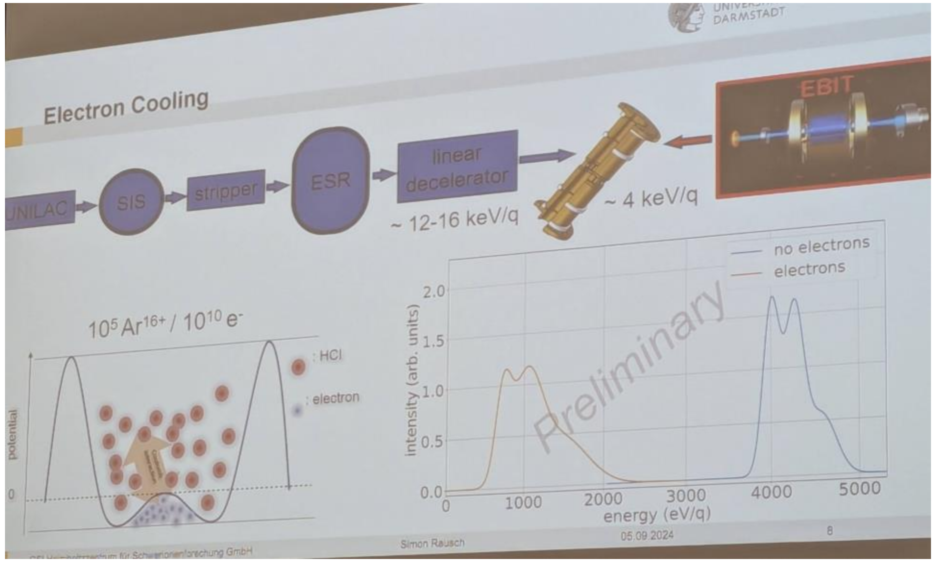

>10000 times less gas injected compared to 'dirty' injection

# Step 3: Cooling of HCIs in trap

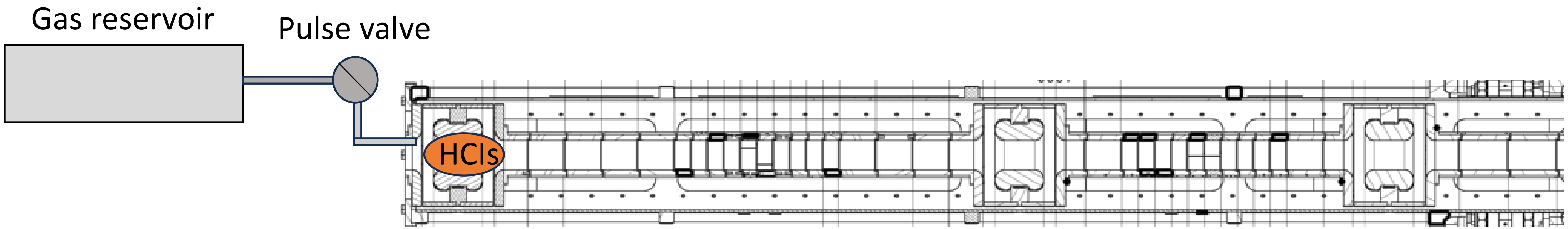


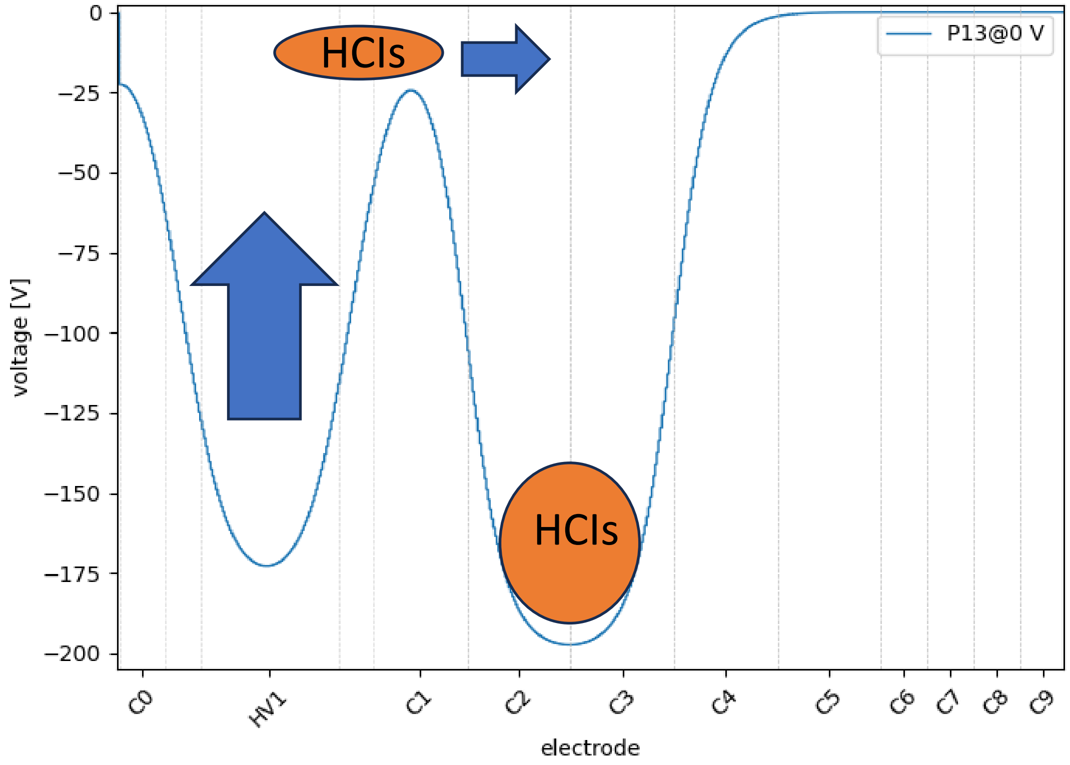




## Recently from GSI:

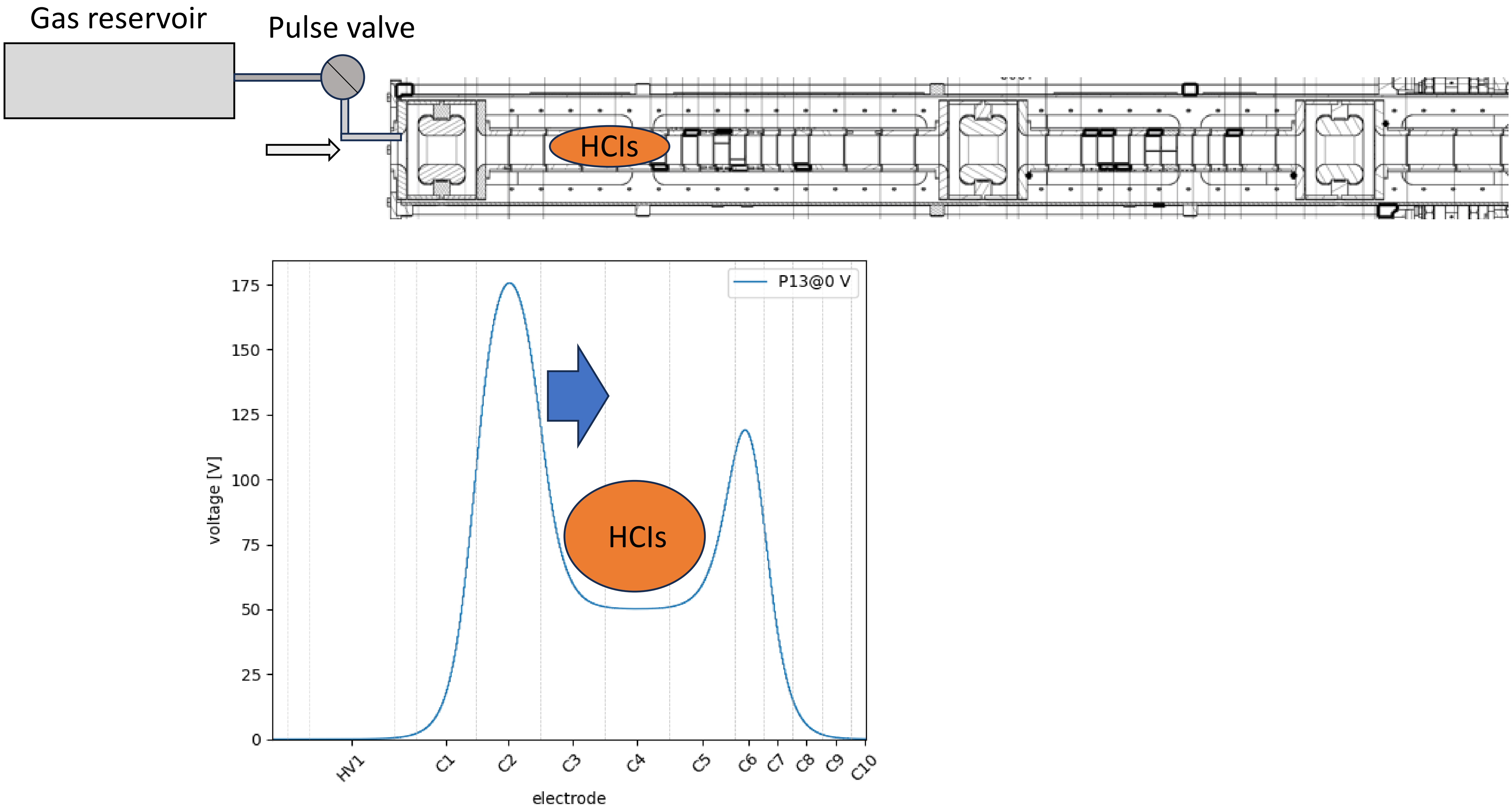


# Step 4: Moving cold HCIs from HV1 to C-electrodes



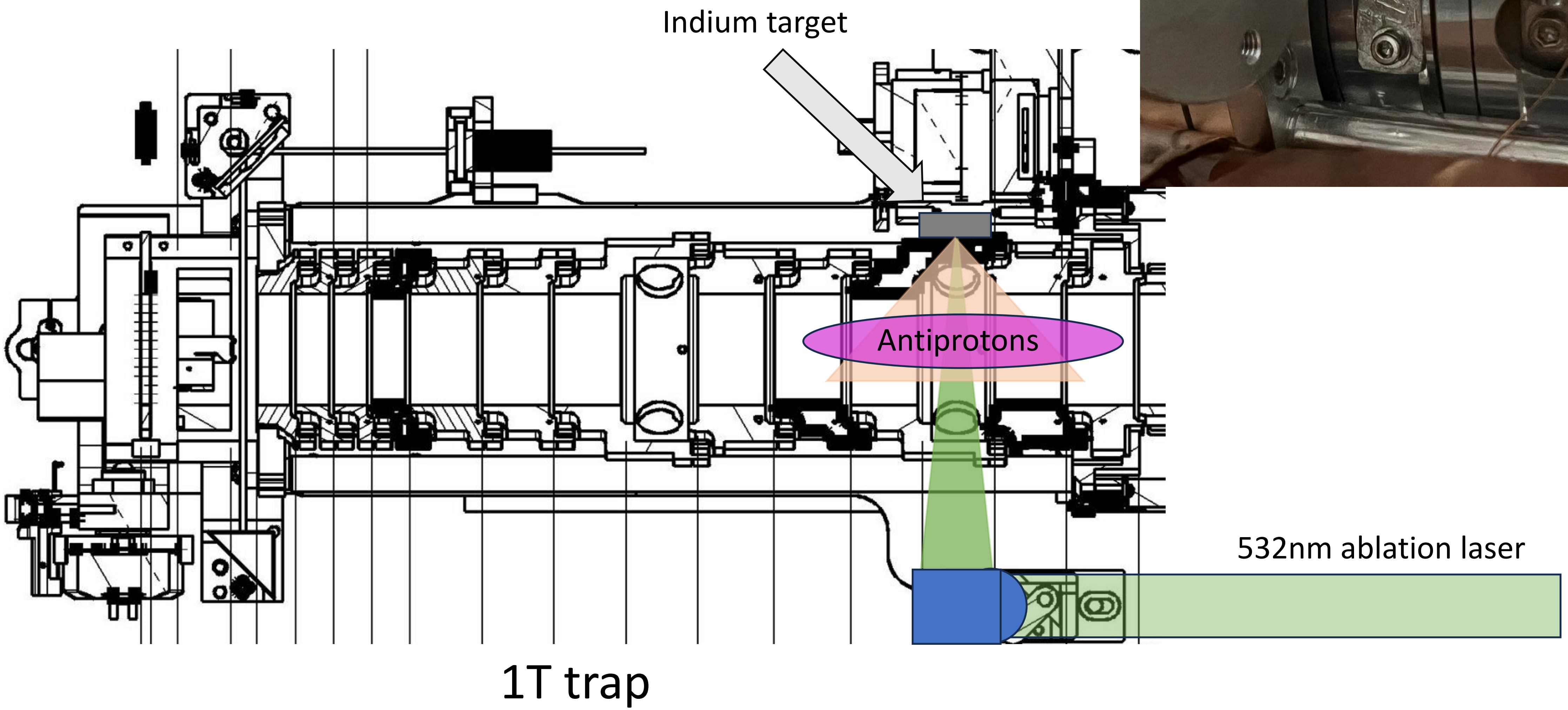



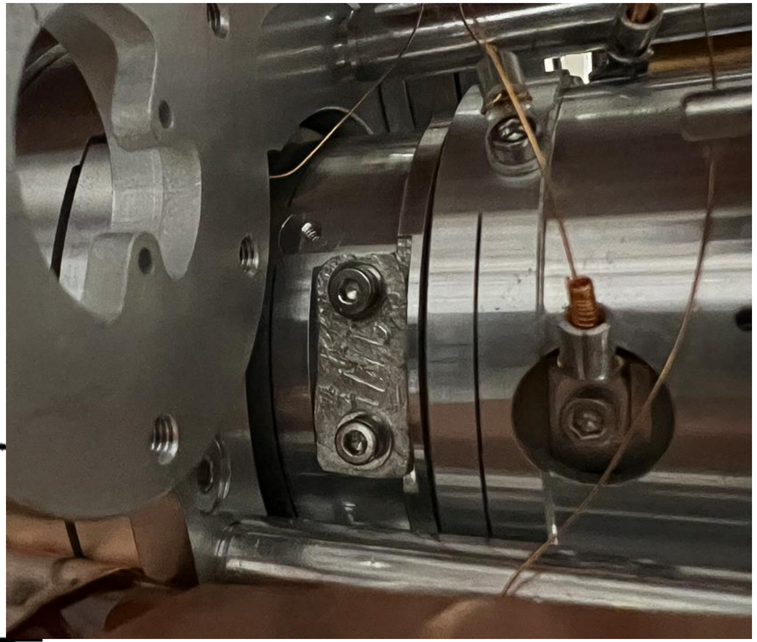
# Step 3: Transport and ejection for TOF spectroscopy

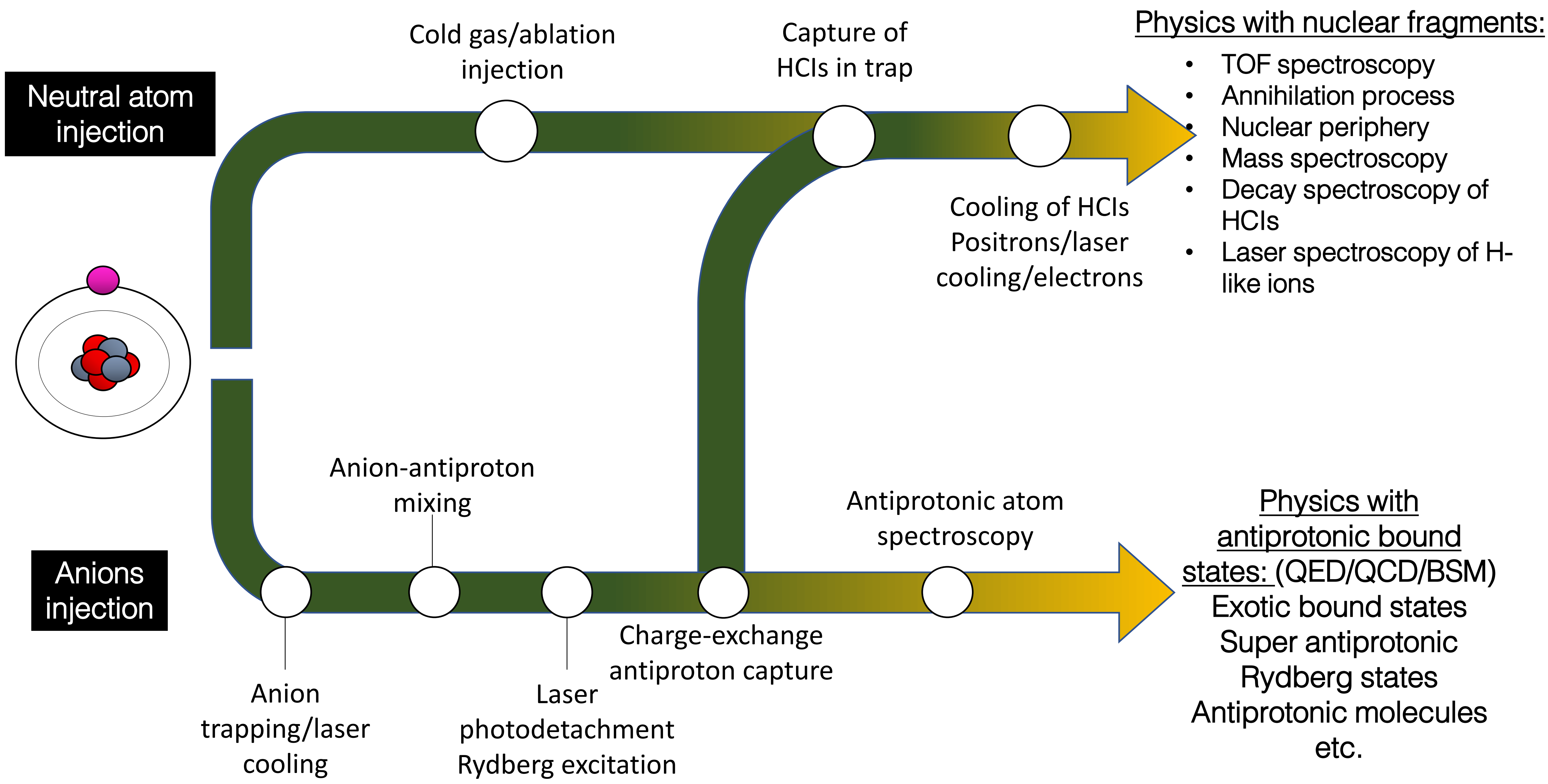


# Laser ablation

*'Laser triggered formation of antiprotonic atoms.'*



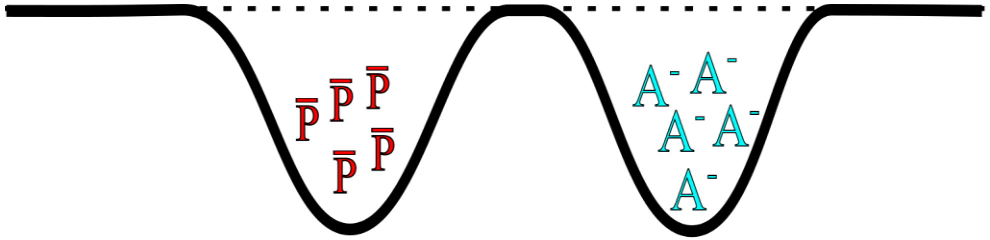





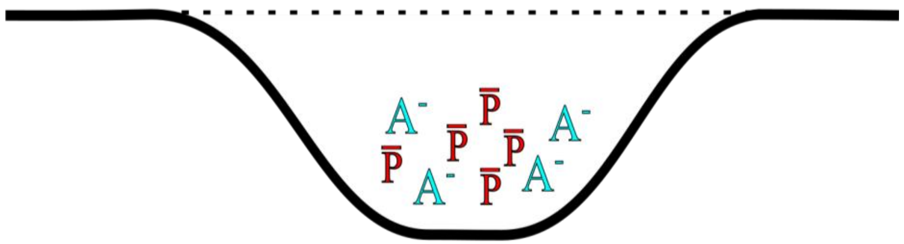
Neutral atom injection
Cold gas/ablation injection
Capture of HCIs in trap
Physics with nuclear fragments:
• TOF spectroscopy
• Annihilation process
• Nuclear periphery
• Mass spectroscopy
• Decay spectroscopy of HCIs
• Laser spectroscopy of H-like ions
Cooling of HCIs
Positrons/laser cooling/electrons
Anion-antiproton mixing
Antiprotonic atom spectroscopy
Physics with antiprotonic bound states: (QED/QCD/BSM)
Exotic bound states
Super antiprotonic Rydberg states
Antiprotonic molecules
etc.
Anions injection
Anion trapping/laser cooling
Laser photodetachment
Rydberg excitation
Charge-exchange antiproton capture

# Outlook: Towards the laser triggered synthesis

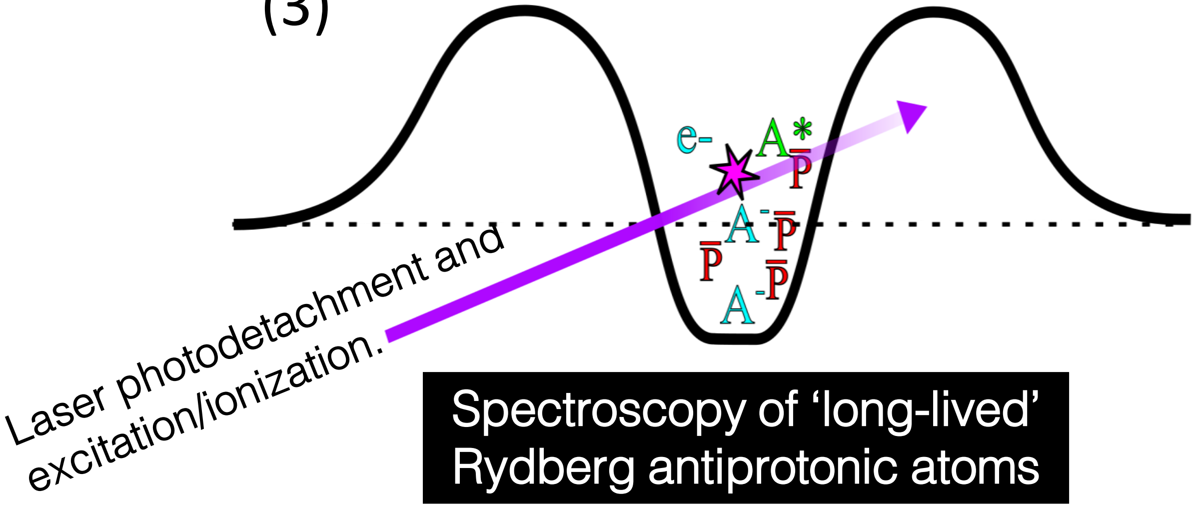
(1) Cotrapping of anions and antiprotons cooled using electrons.




(2) Mixing anions with antiprotons.

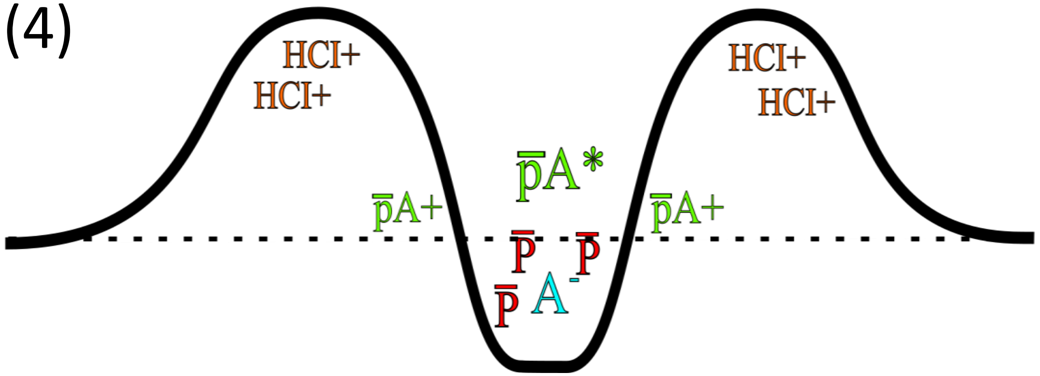



(3) Nested trap is created.




**Spectroscopy of 'long-lived' Rydberg antiprotonic atoms**

(4) Capture of HCI fragments from annihilation.




**HCIs can be further cooled and studied in trap**

- Benefits: No laser needed
- Neutral gas – no need to worry about overlapping plasmas

- Orders of magnitude cleaner, 0.1ng/ antiproton shot.

- CS can be enhanced by exciting atoms to rydberg states,

- Limitation, only works with gases

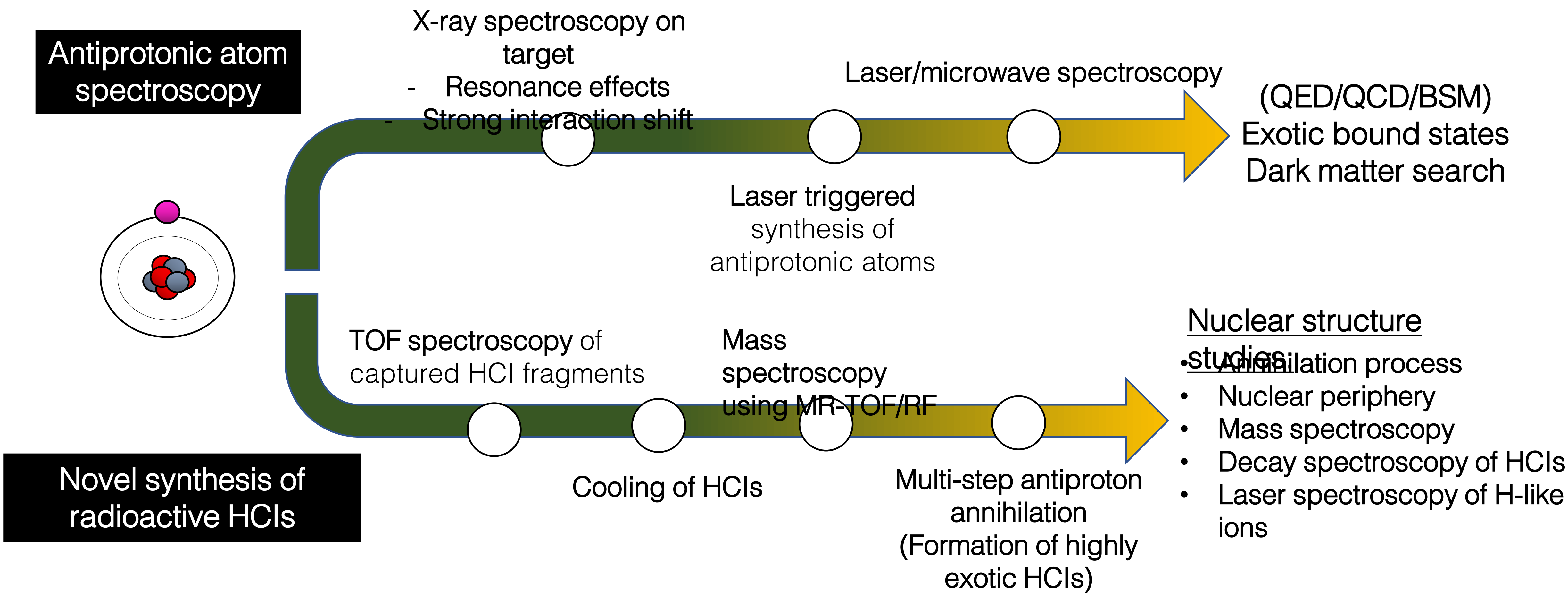
- Laser Ablation? Local pressure after ablation?

# Clean injection approaches

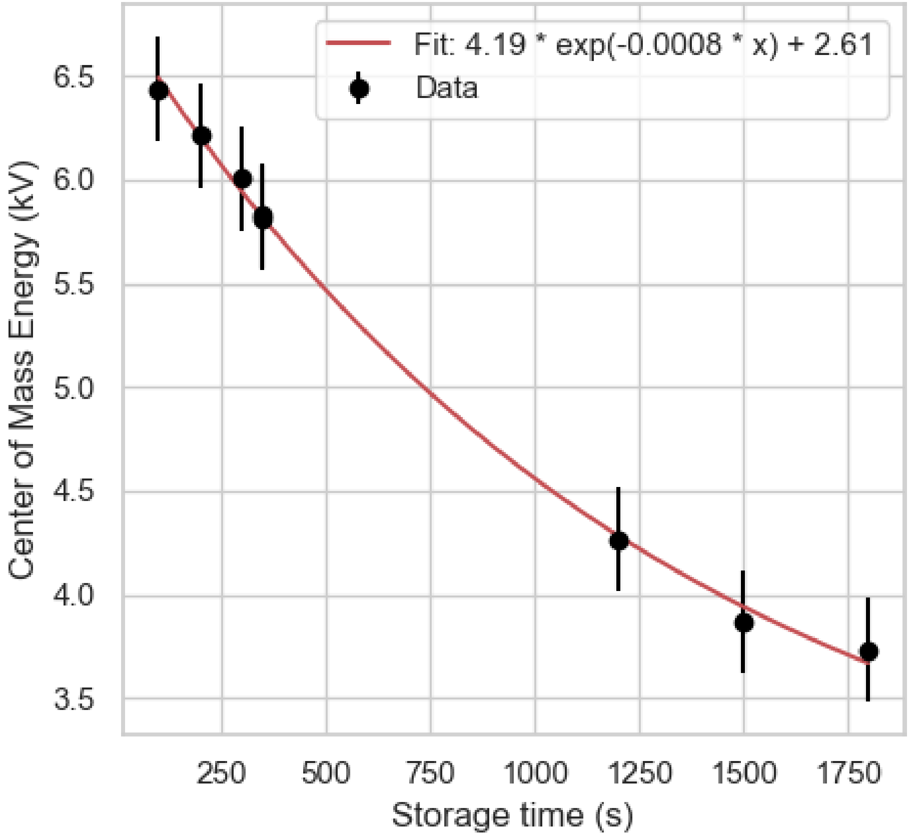
- **Anion source**

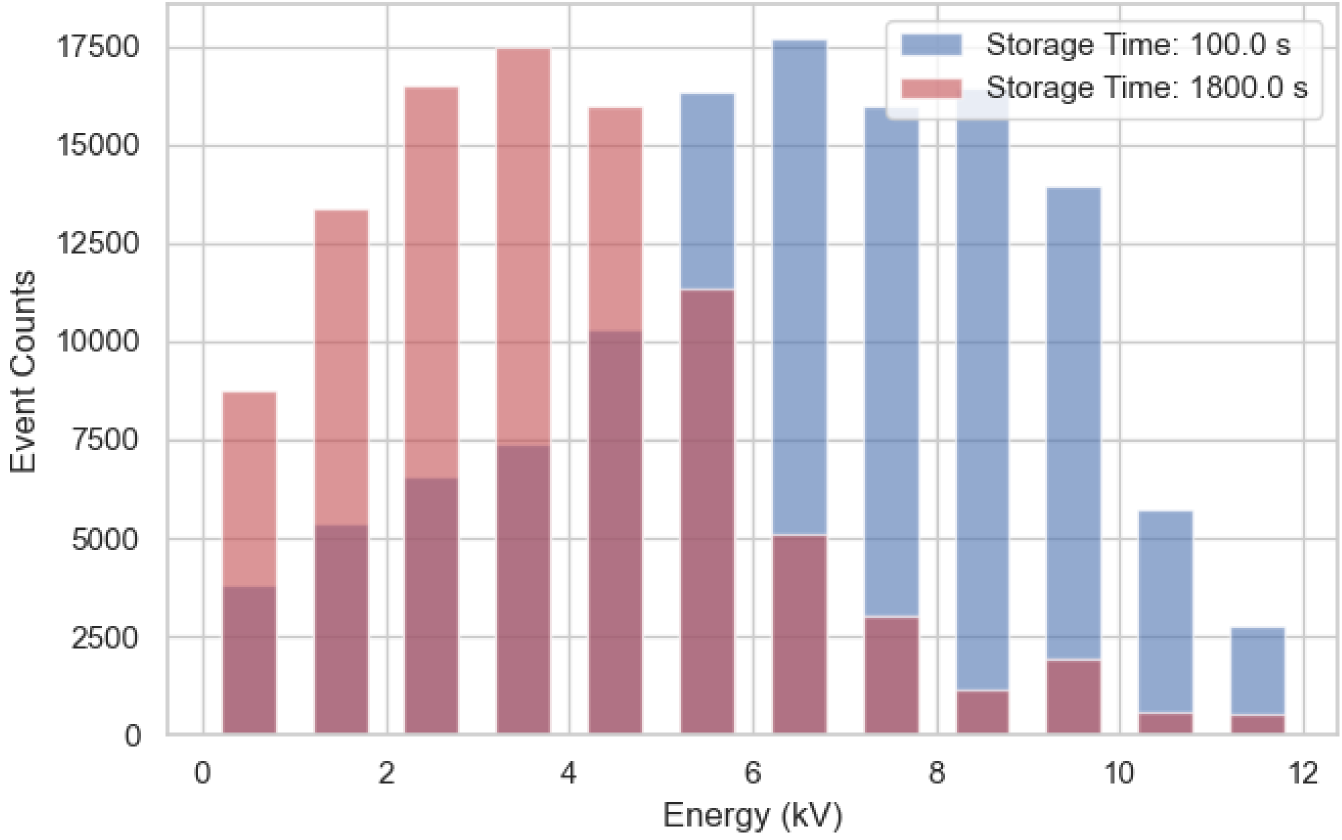
- **Alternative?**
- Pulsed gas injection
- Laser ablation

# Summary and outlook:

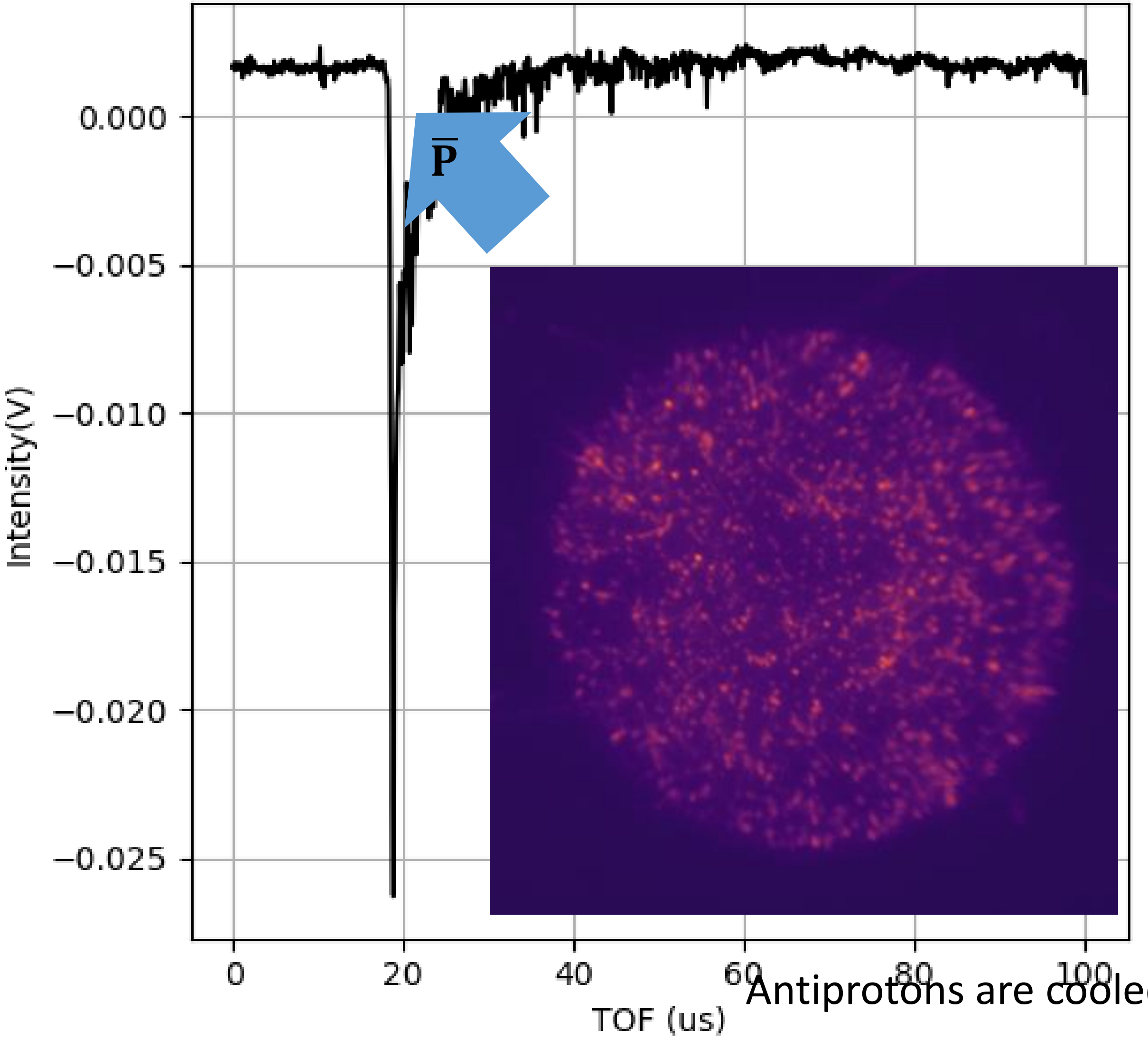


# Collissonal cooling on buffer gas 2e-12 mbar in sun region:



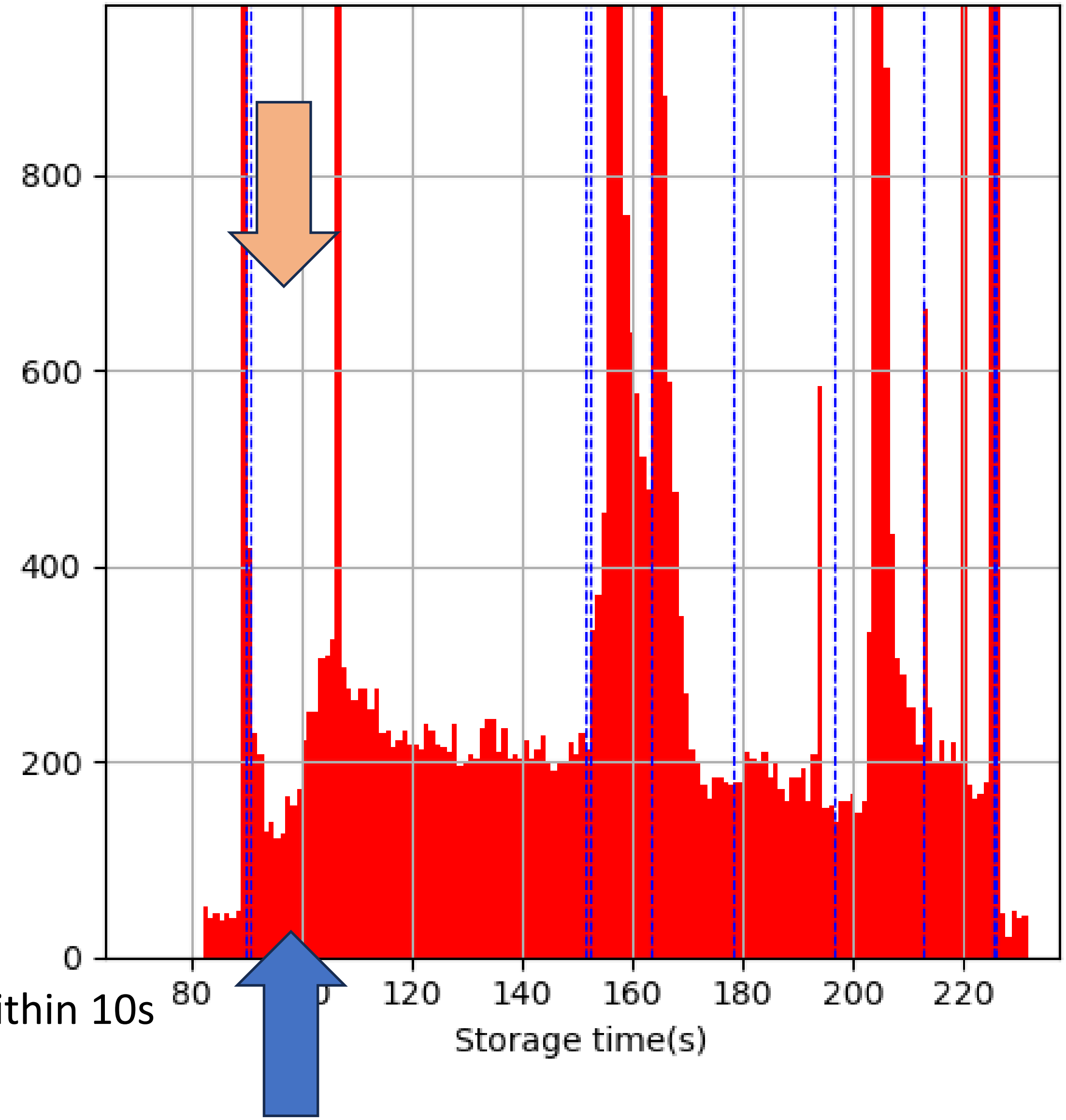



# Electron cooling script working

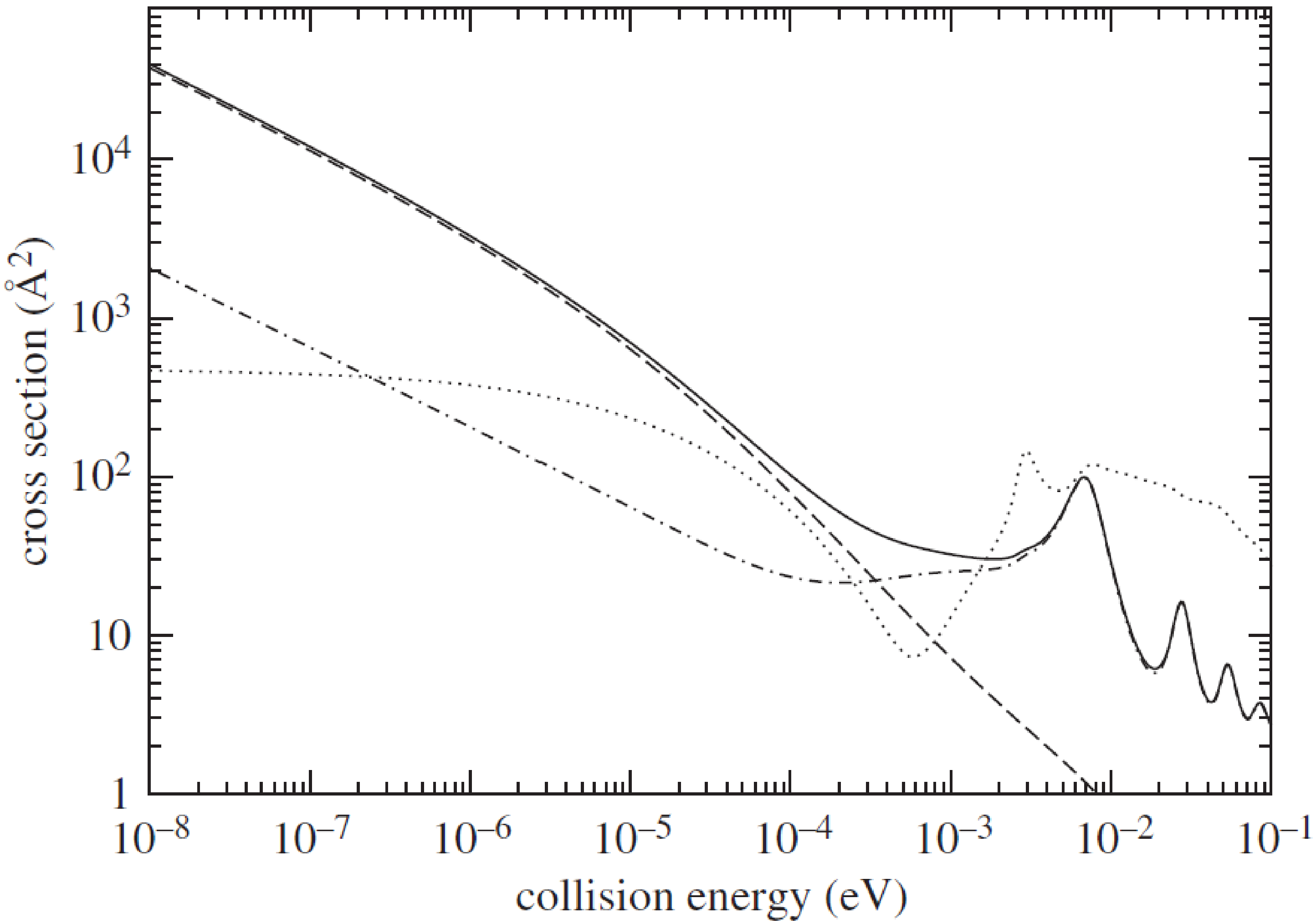


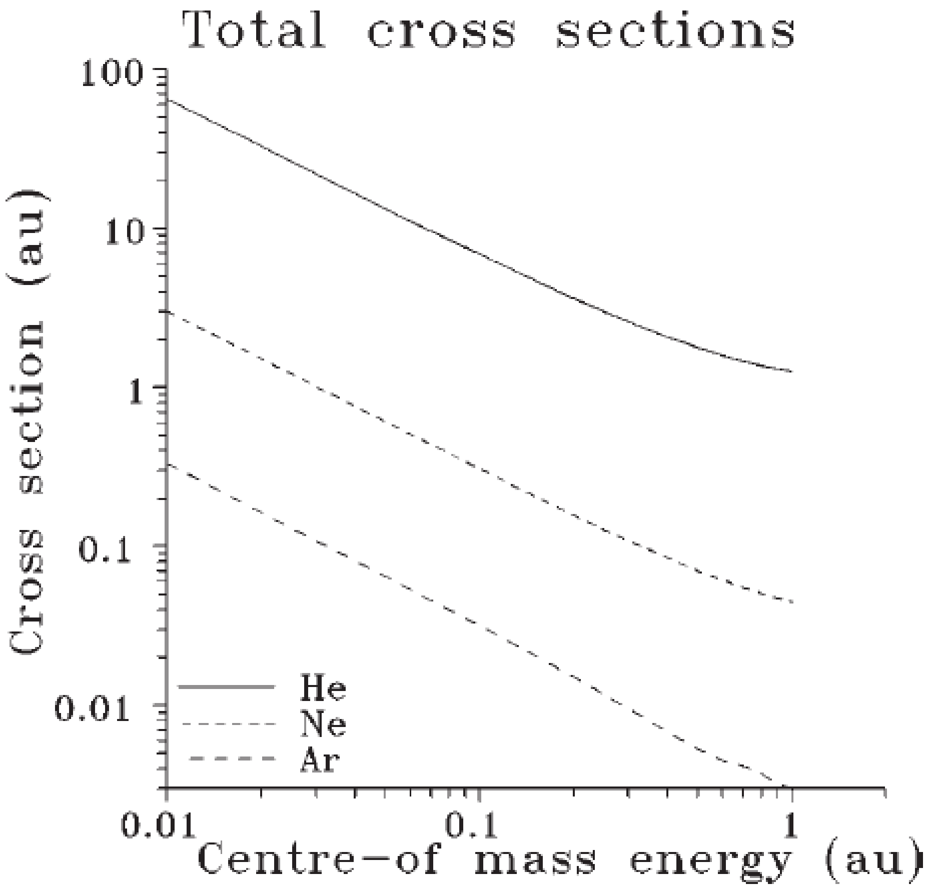

Antiprotons are cooled within 10s

Many antiprotons trapped in microwells

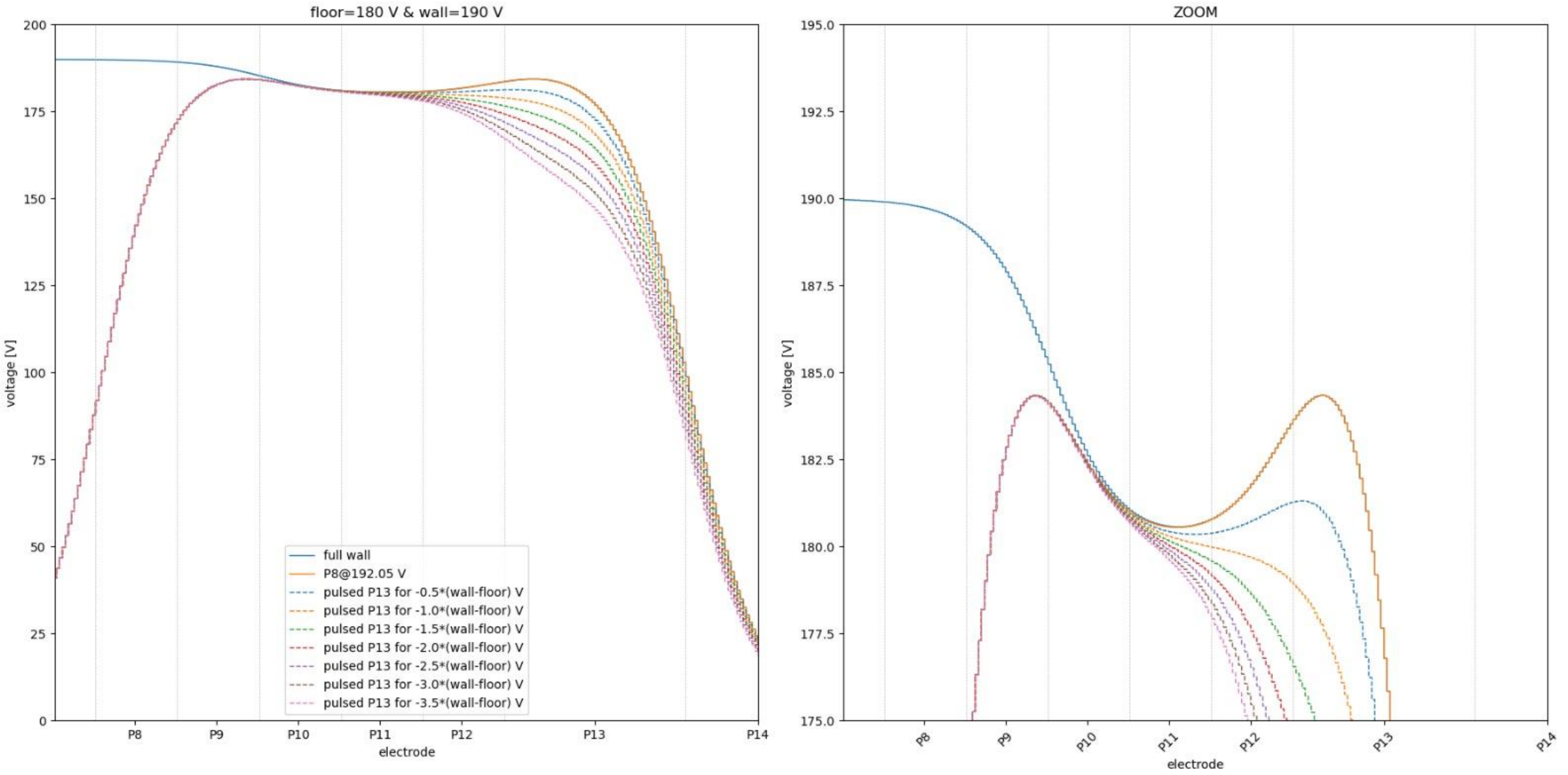


# Capture cross-section



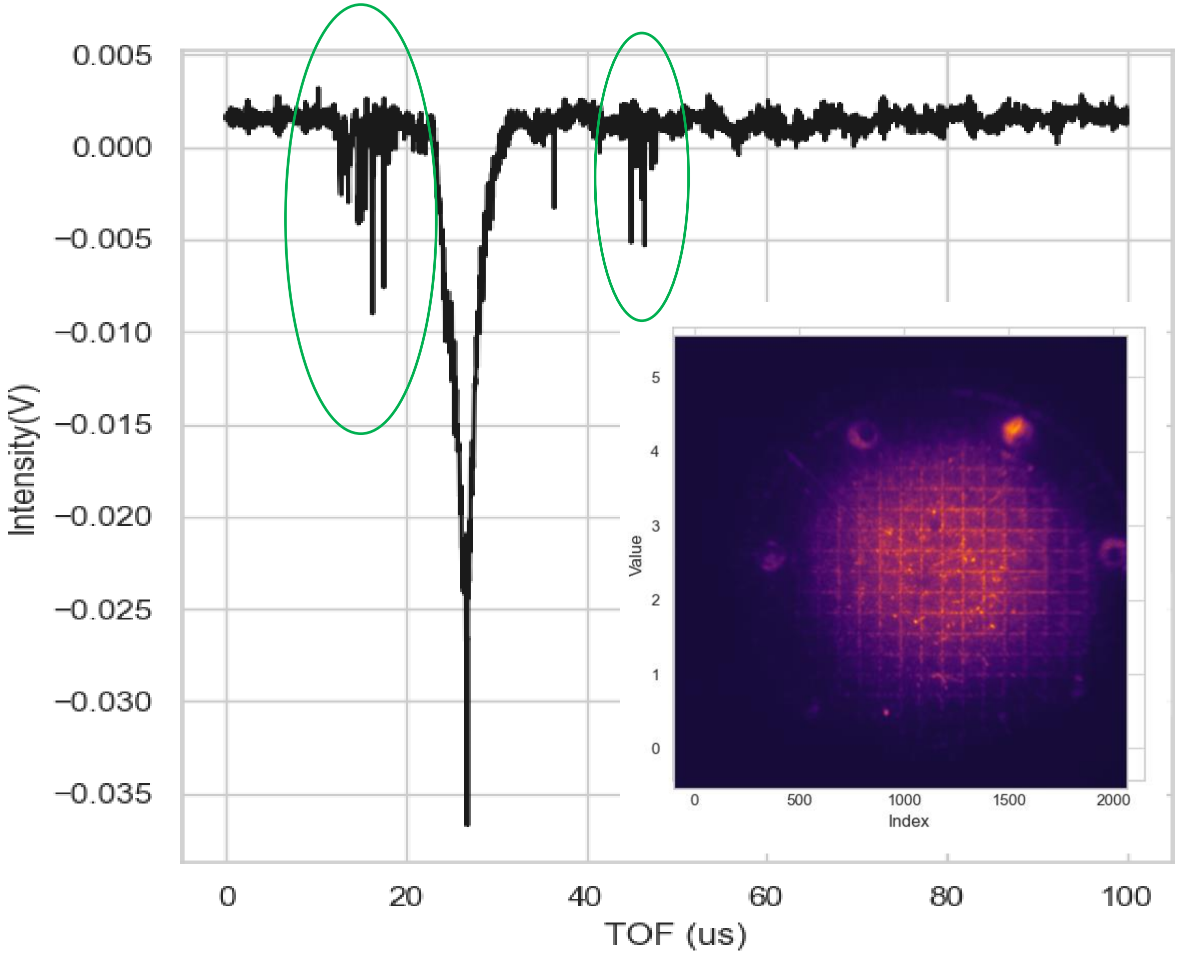



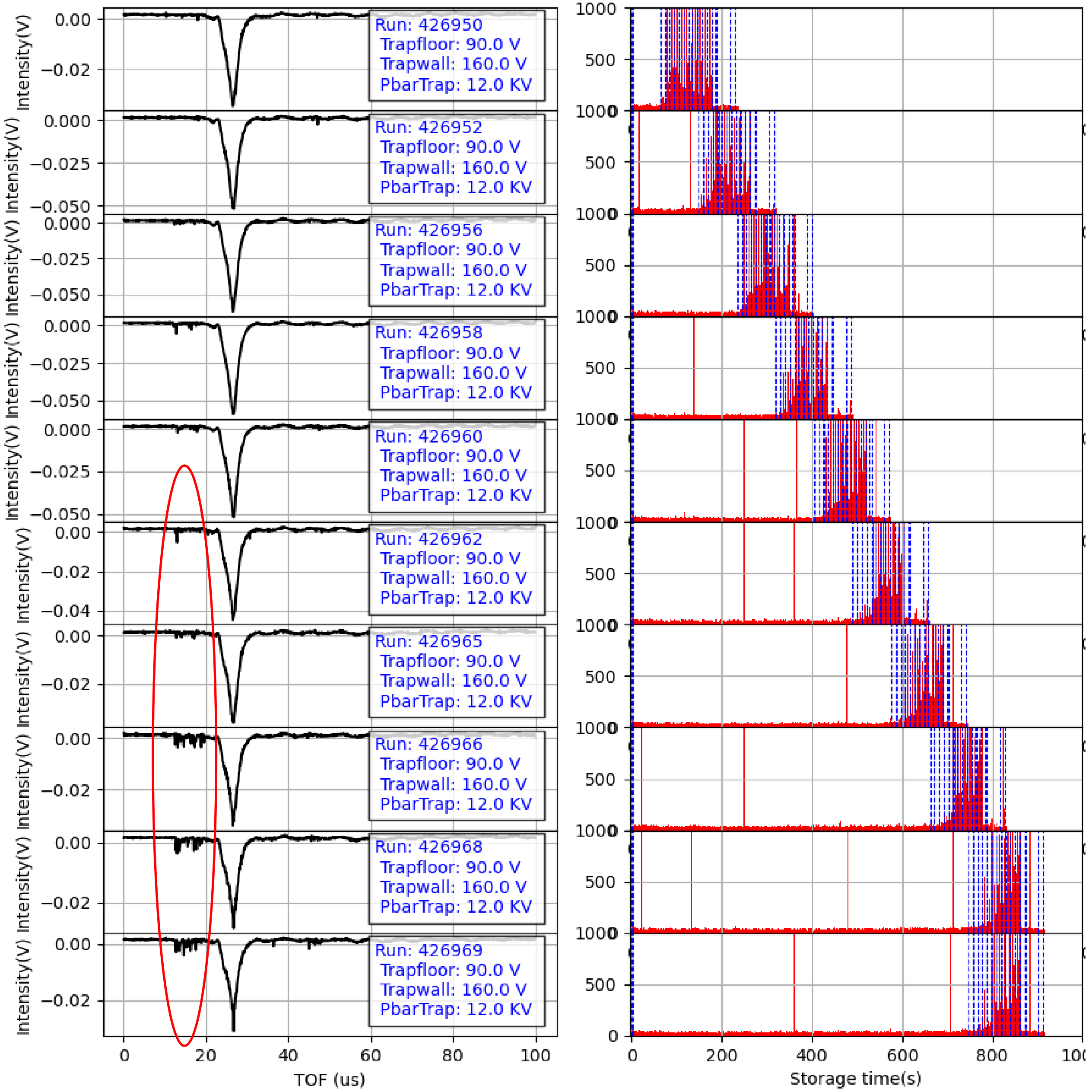
# Study of new trap

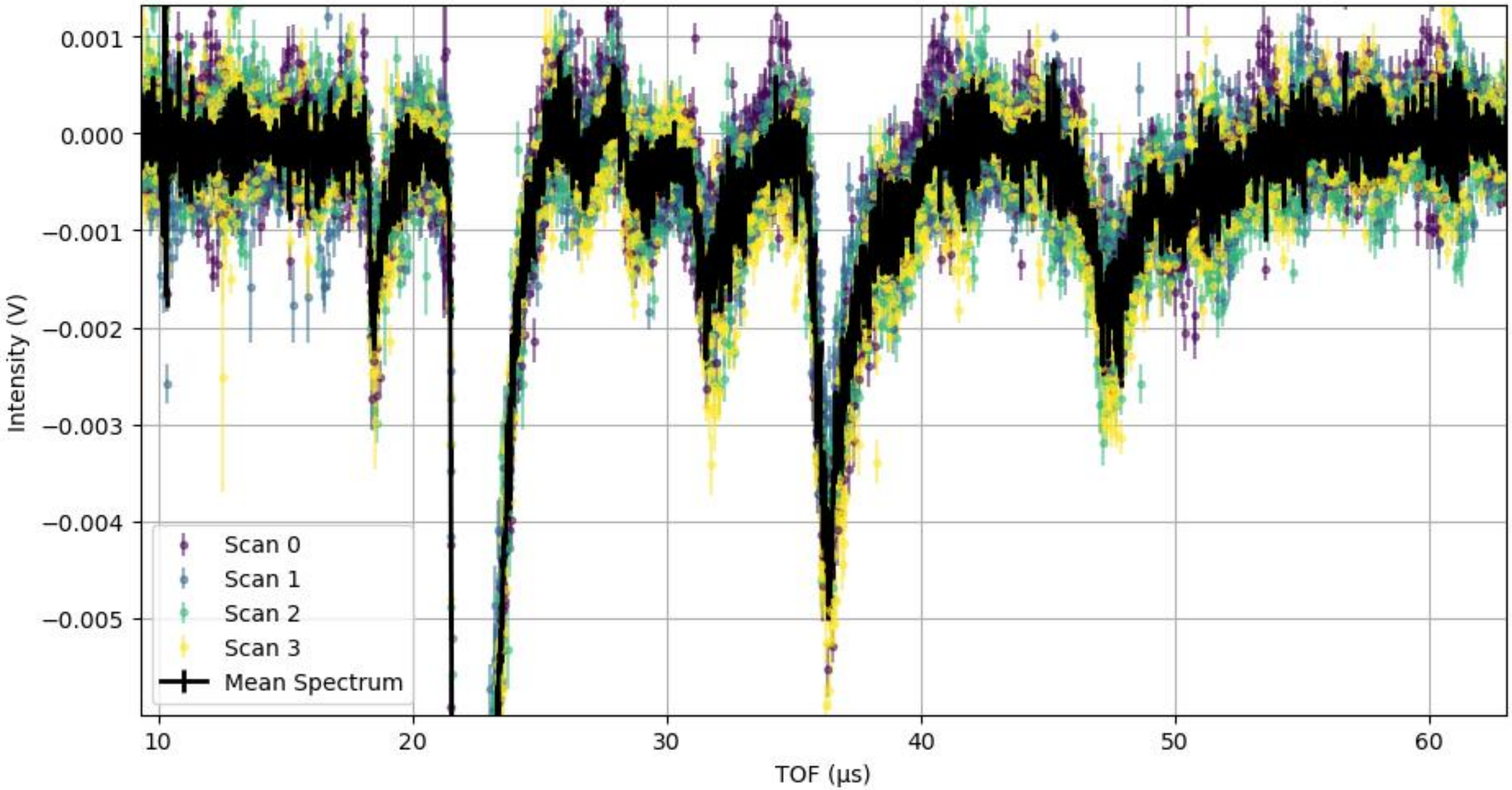


# Cold antiprotons observed

Direct capture of annihilation fragment?



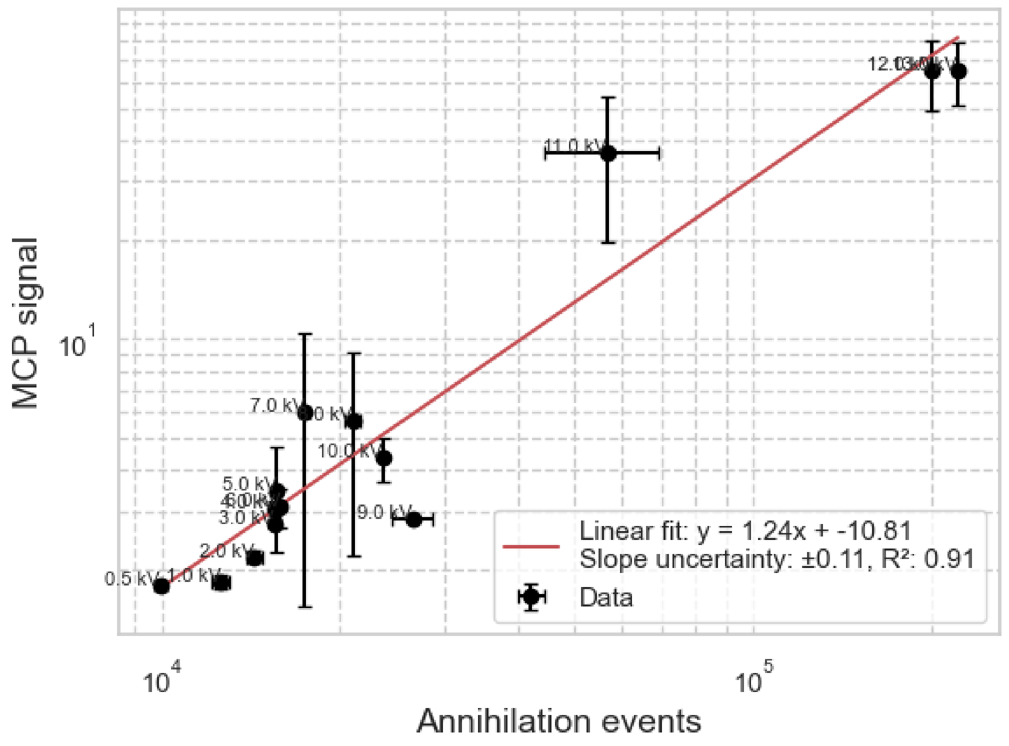



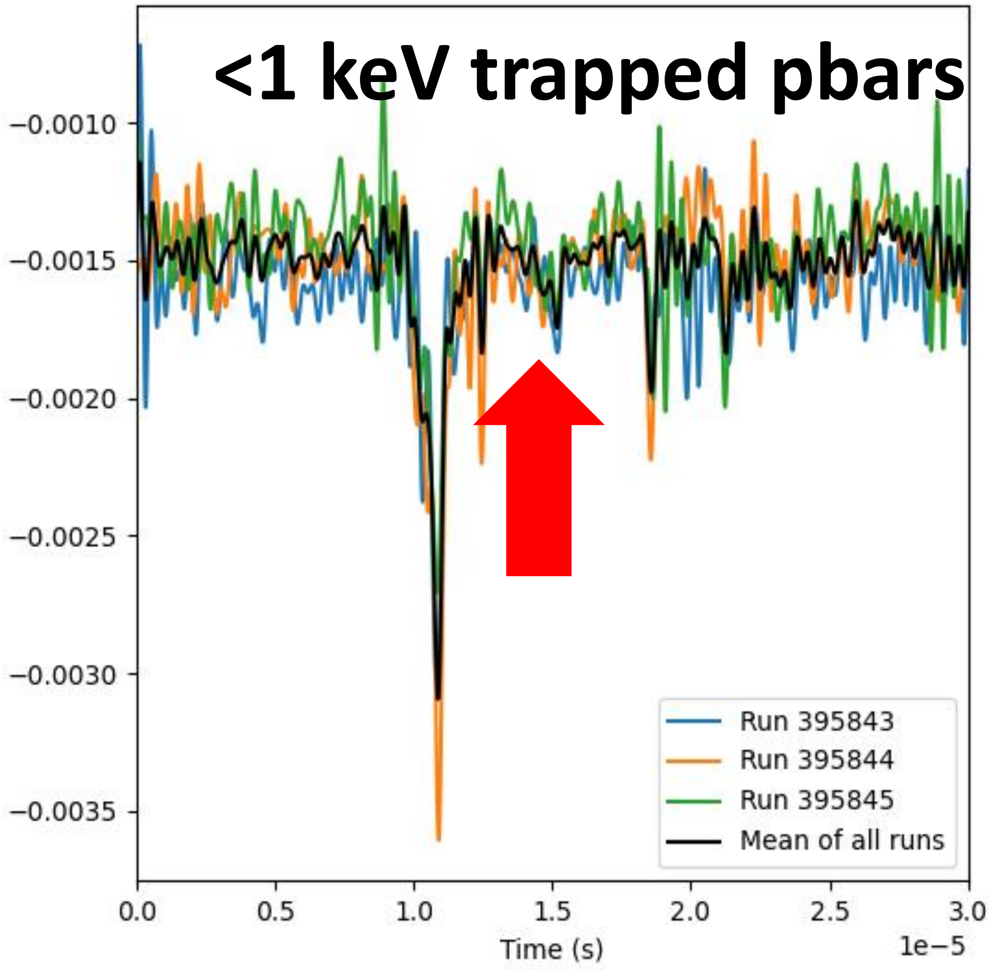


0.001
0.000
−0.001
−0.002
−0.003
−0.004
−0.005
Intensity (V)
10
20
30
40
50
60
TOF (μs)
Scan 0
Scan 1
Scan 2
Scan 3
Mean Spectrum

# Low energy antiproton interactions

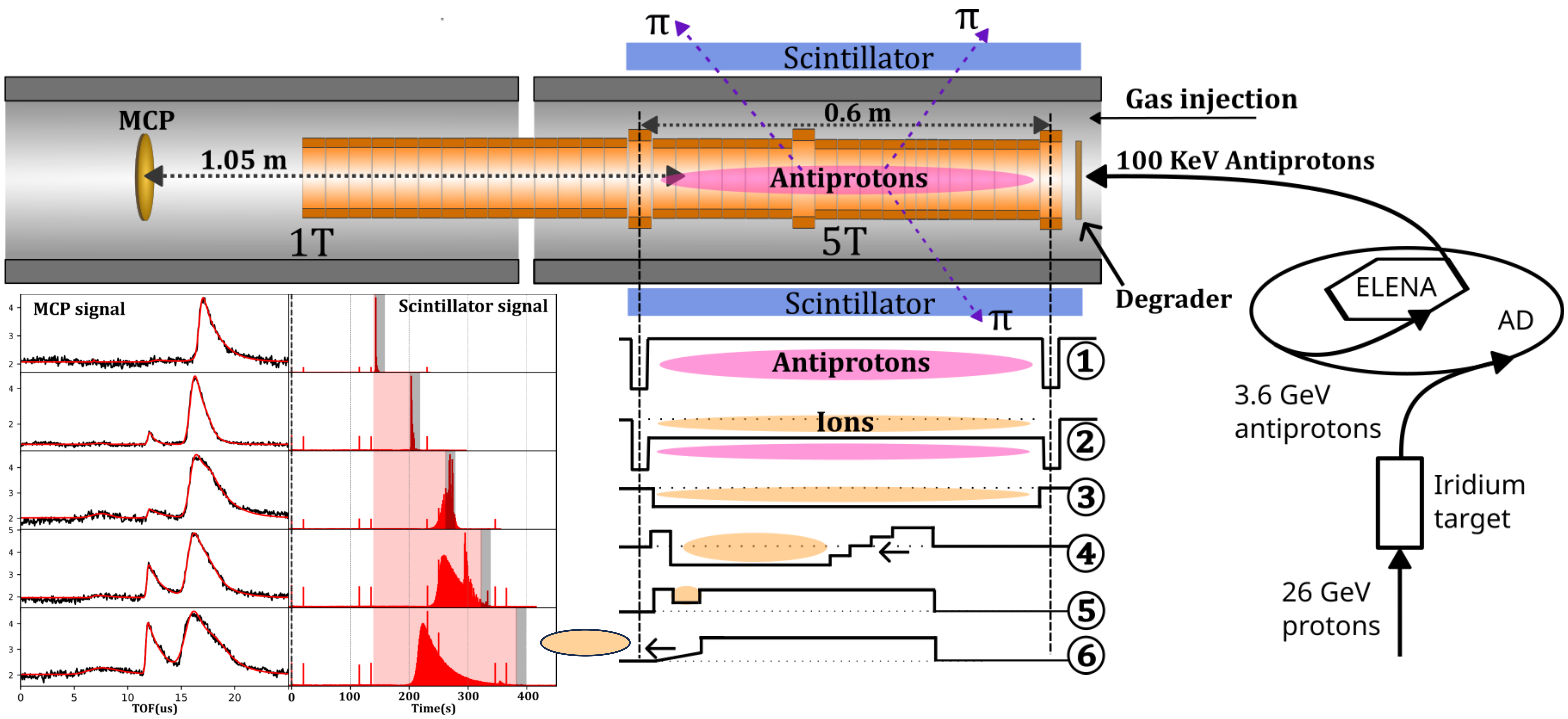
**Signal of m/q=2 peak vs annihilation event:**



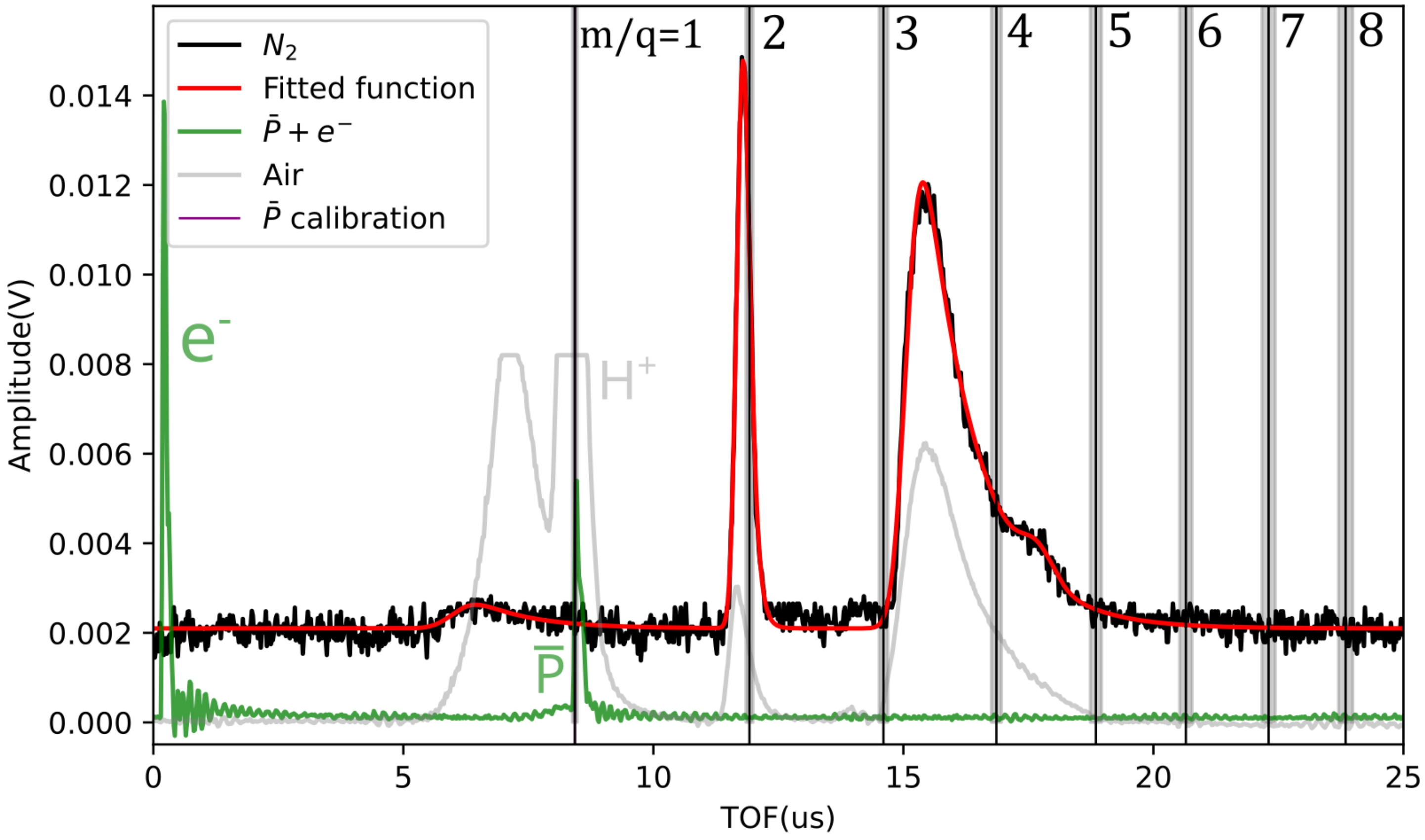



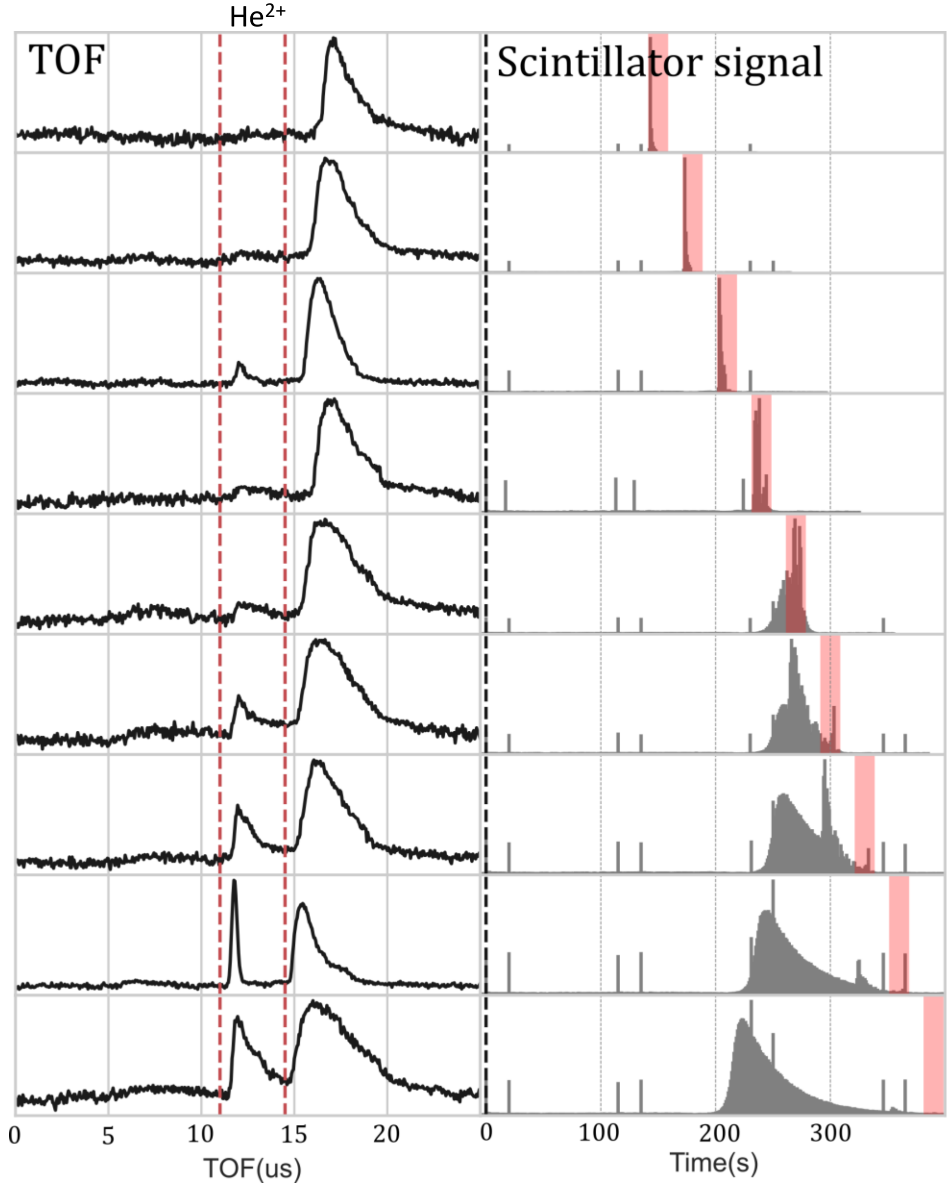

What could result in the formation of m/q=2 from nitrogen?

# Overview of the fragment capture procedure

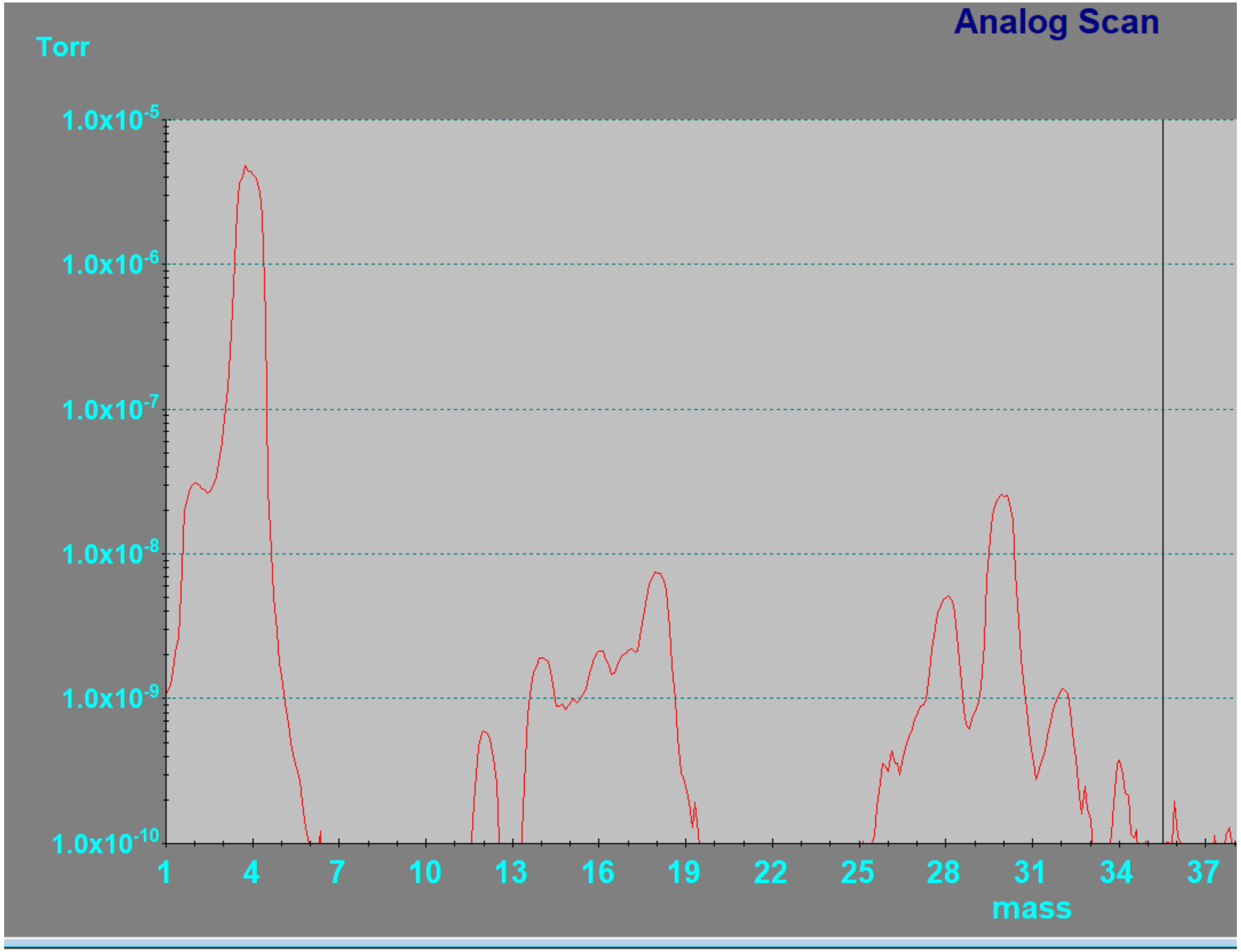


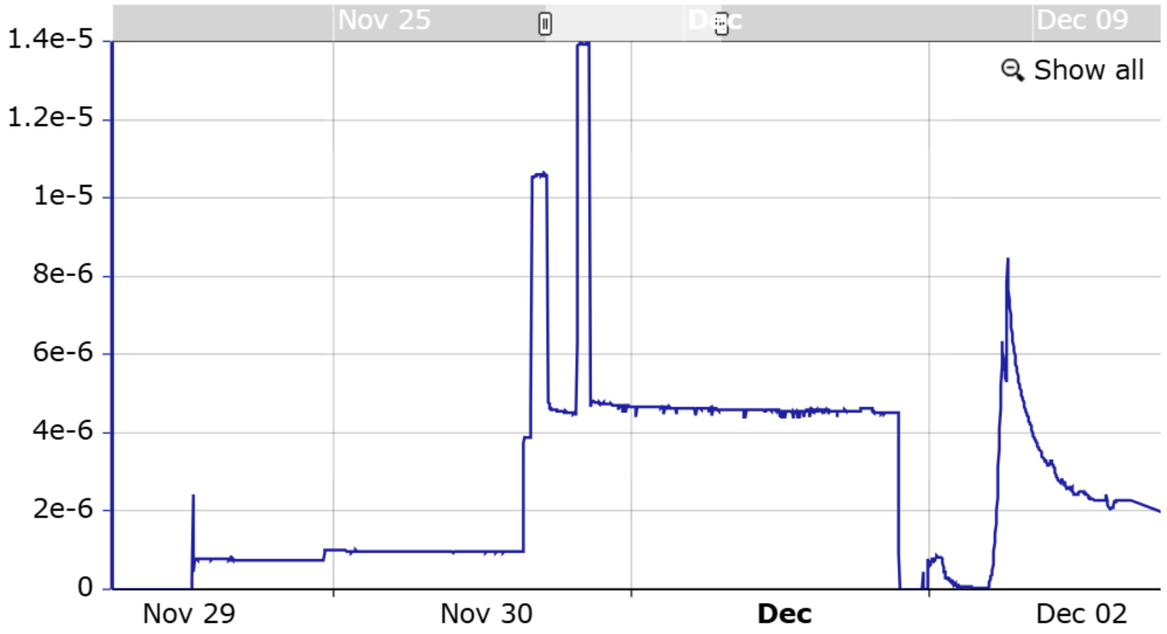
# Helium interaction with antiprotons

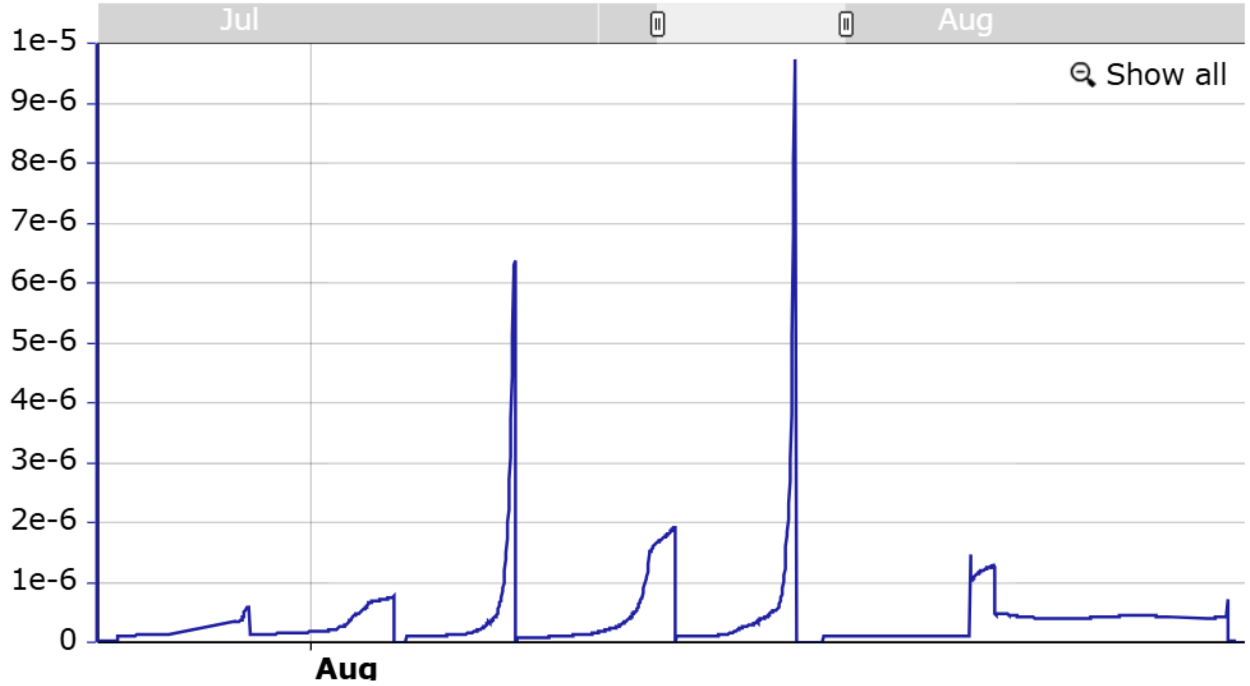


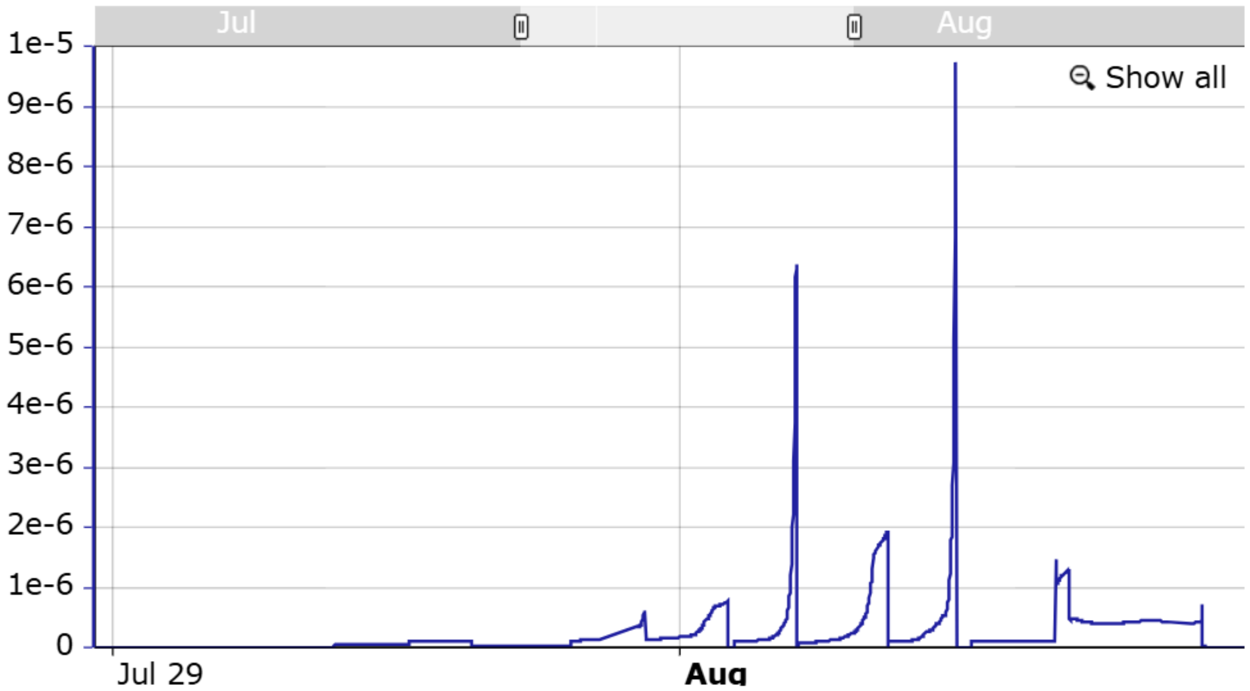



# RGA measurment




Nov 25
Dec
Dec 09
Show all
1.4e-5
1.2e-5
1e-5
8e-6
6e-6
4e-6
2e-6
0
Nov 29
Nov 30
Dec
Dec 02


Jul
Aug
Show all
1e-5
9e-6
8e-6
7e-6
6e-6
5e-6
4e-6
3e-6
2e-6
1e-6
0
Aug


Jul
Aug
Show all
1e-5
9e-6
8e-6
7e-6
6e-6
5e-6
4e-6
3e-6
2e-6
1e-6
0
Jul 29
Aug

PRL **101,** 043201 (2008) PHYSICAL REVIEW LETTERS week ending 25 JULY 2008

# Ionization of Helium and Argon by Very Slow Antiproton Impact

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R. W. McCullough,[3] M. Charlton,[4] N. Kuroda,[5] Y. Nagata,[5] H. A. Torii,[5] Y. Yamazaki,[5,6] H. Imao,[6]
H. H. Andersen,[7] and K. Tökesi[8]

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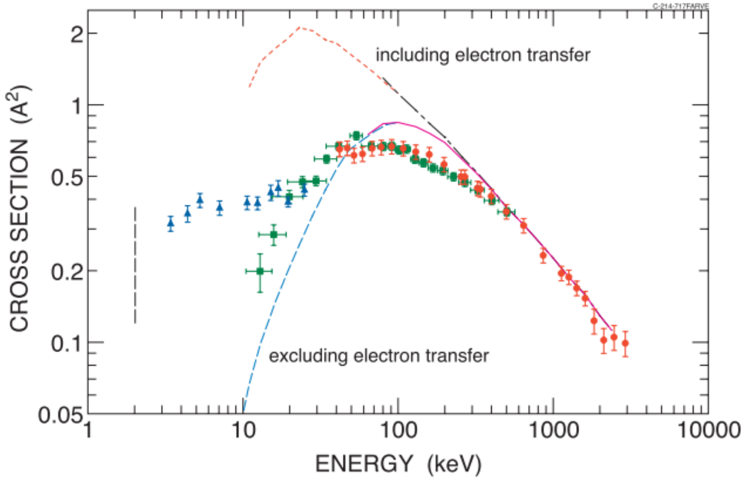
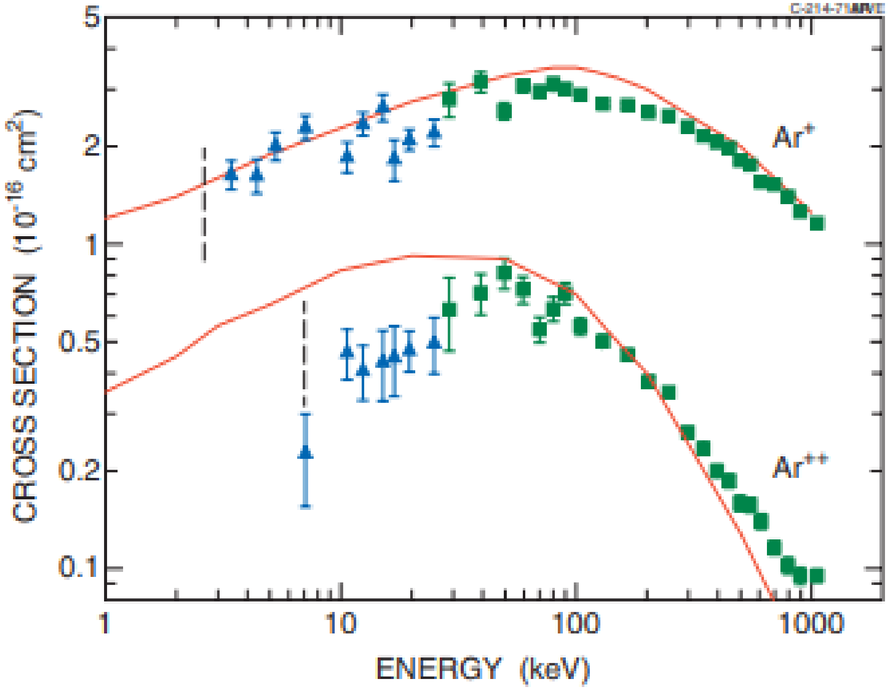
(Received 17 March 2008; published 25 July 2008)

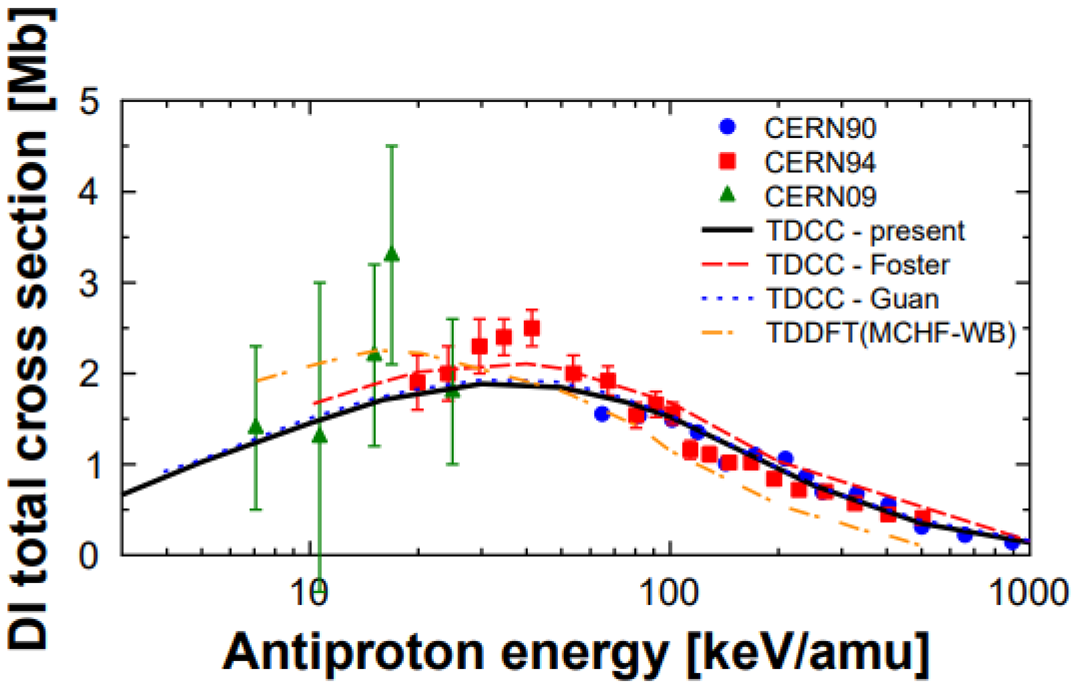
The total cross sections for single ionization of helium and single and double ionization of argon by antiproton impact have been measured in the kinetic energy range from 3 to 25 keV using a new technique for the creation of intense slow antiproton beams. The new data provide benchmark results for the development of advanced descriptions of atomic collisions and we show that they can be used to judge, for the first time, the validity of the many recent theories.

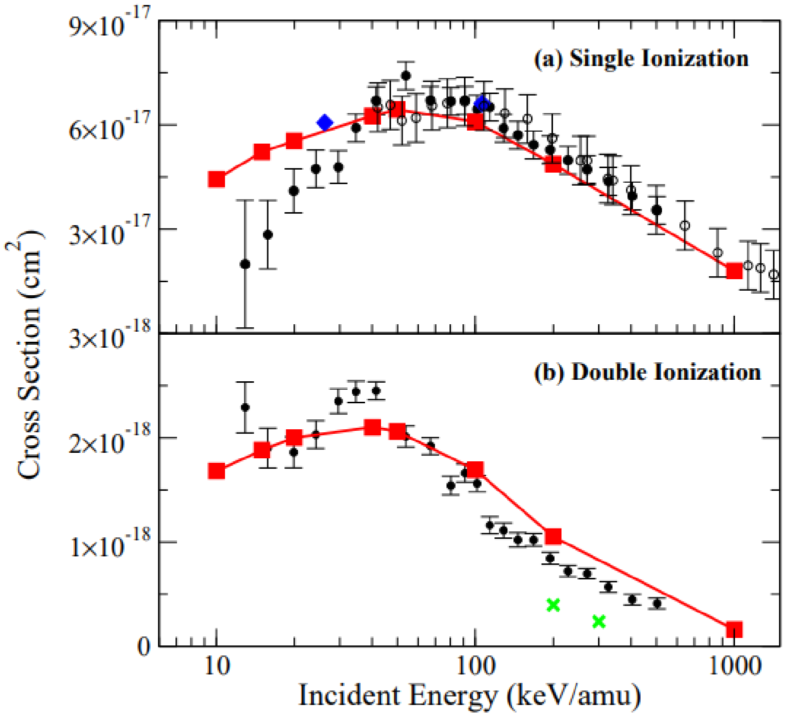
spectrum (TOF). The spectra show clear peaks at the expected positions for $He^+$, $Ar^{++}$, and $Ar^+$, and show no other features except for a low and almost flat background of accidental coincidences.

**Ar1+ : 2 e -16 cm2**
**Ar2+ : 3 e -17 cm2**






**He1+ : 4.0 e -17 cm2**

**He2+ : 1.8 e -18 cm2**

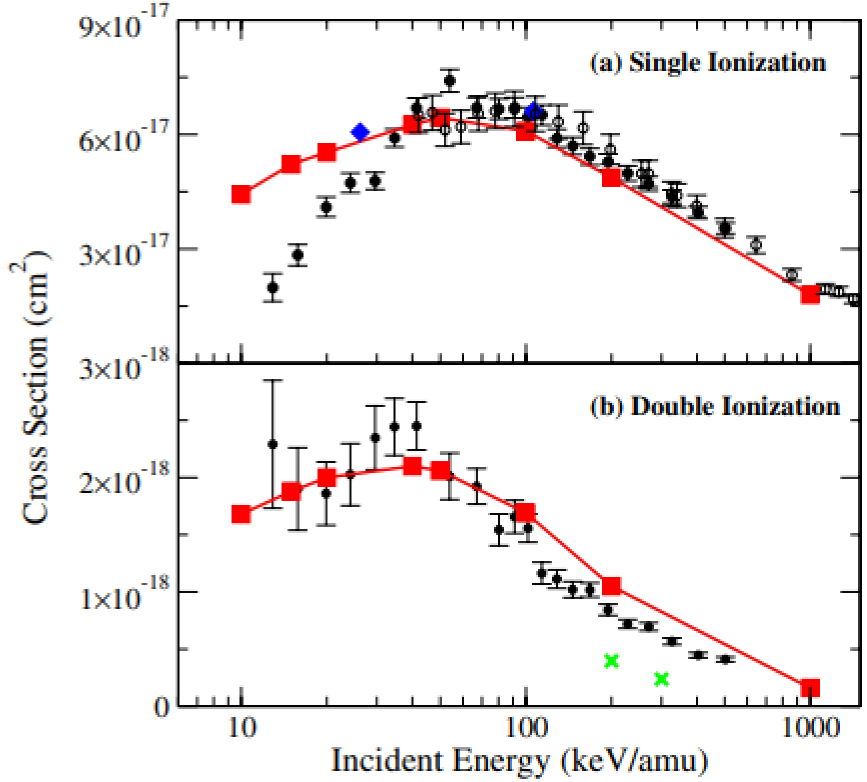



FIG. 1 (color online). (a) Cross sections for single ionization of helium by antiproton impact. Filled squares: TDCC calculations; filled diamonds: calculations of Schultz and Krstić [5]; filled and open circles: experimental measurements of [4,15]. (b) Cross sections for double ionization of helium by antiproton impact. Filled squares: TDCC calculations; crosses: calculations of Diaz *et al.* [10]; filled circles: experimental measurements of [4].

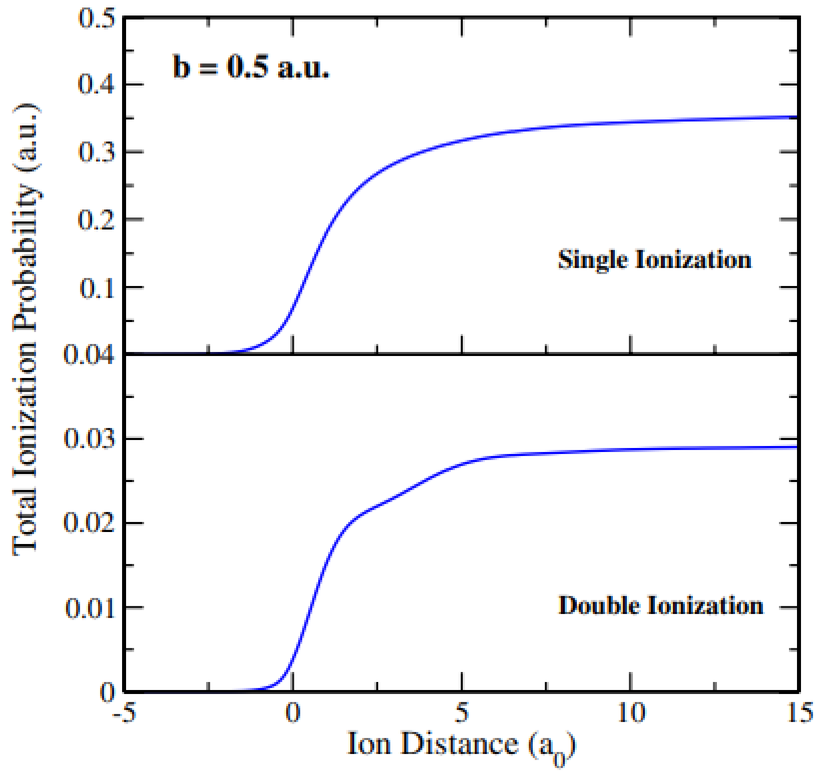
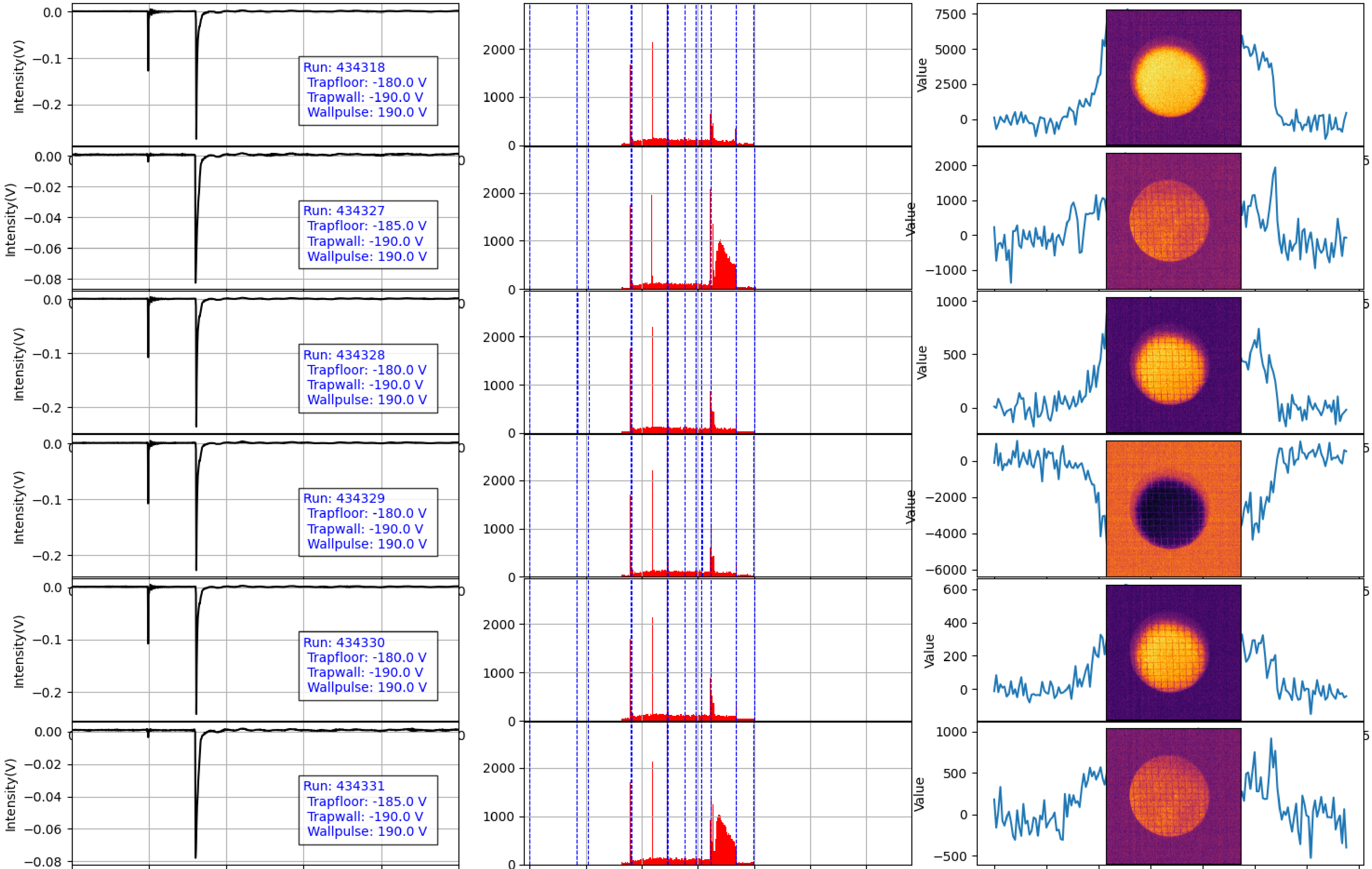



FIG. 2 (color online). Evolution of the ionization probability, $\mathcal{P}(E, b = 0.5a_0)$, for a 50 keV antiproton collision with a helium atom as a function of the impacting ion distance. Upper panel: single ionization probability summed over all partial waves. Lower panel: double ionization probability. The helium atom is located at the origin of the collision system ($d_0 = 0$).

tioned at $d_0 = 0a_0$), and then tend to a constant value

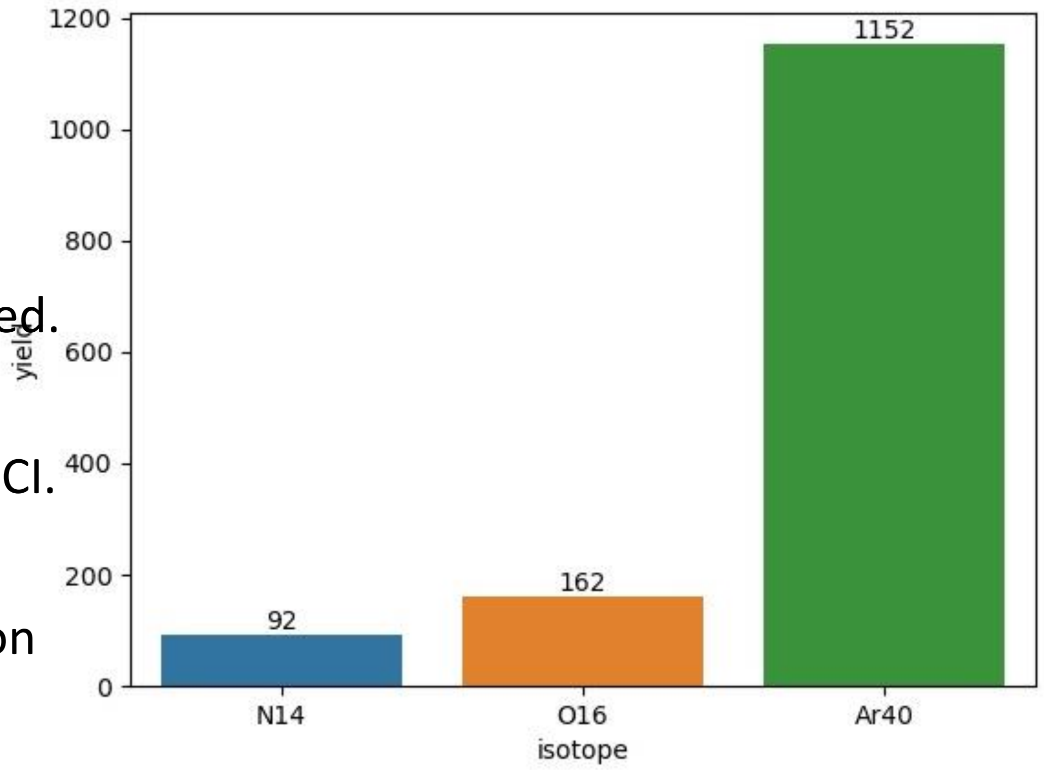


Run: 434318
Trapfloor: -180.0 V
Trapwall: -190.0 V
Wallpulse: 190.0 V
Run: 434327
Trapfloor: -185.0 V
Trapwall: -190.0 V
Wallpulse: 190.0 V
Run: 434328
Trapfloor: -180.0 V
Trapwall: -190.0 V
Wallpulse: 190.0 V
Run: 434329
Trapfloor: -180.0 V
Trapwall: -190.0 V
Wallpulse: 190.0 V
Run: 434330
Trapfloor: -180.0 V
Trapwall: -190.0 V
Wallpulse: 190.0 V
Run: 434331
Trapfloor: -185.0 V
Trapwall: -190.0 V
Wallpulse: 190.0 V
Intensity(V)
Value

# Outlook

# 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

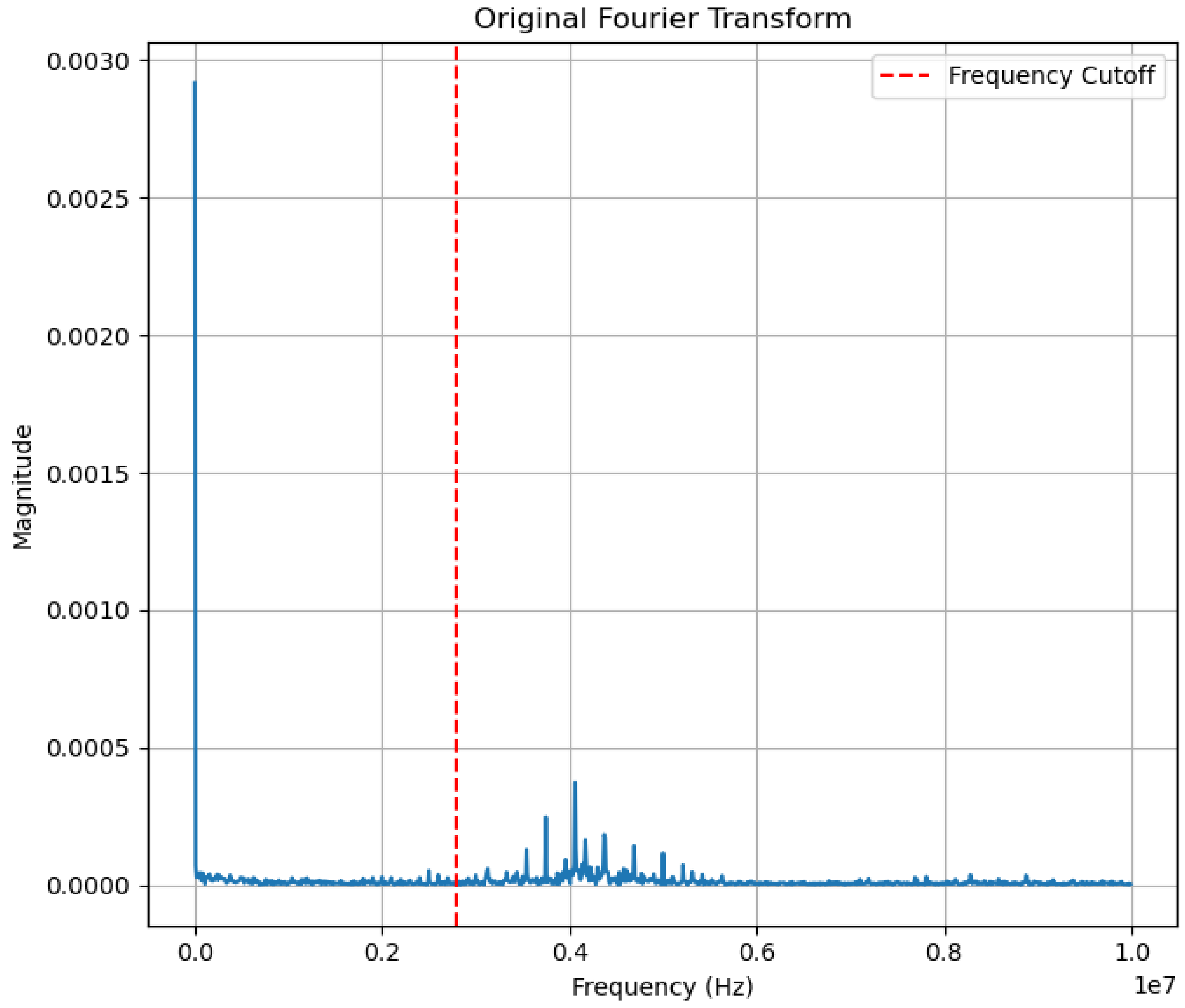
- Continuing LEAR era measurments: Plenty of physics cases!
- Teaching us the procedure for antiprotonic atom x-ray spectroscopy.

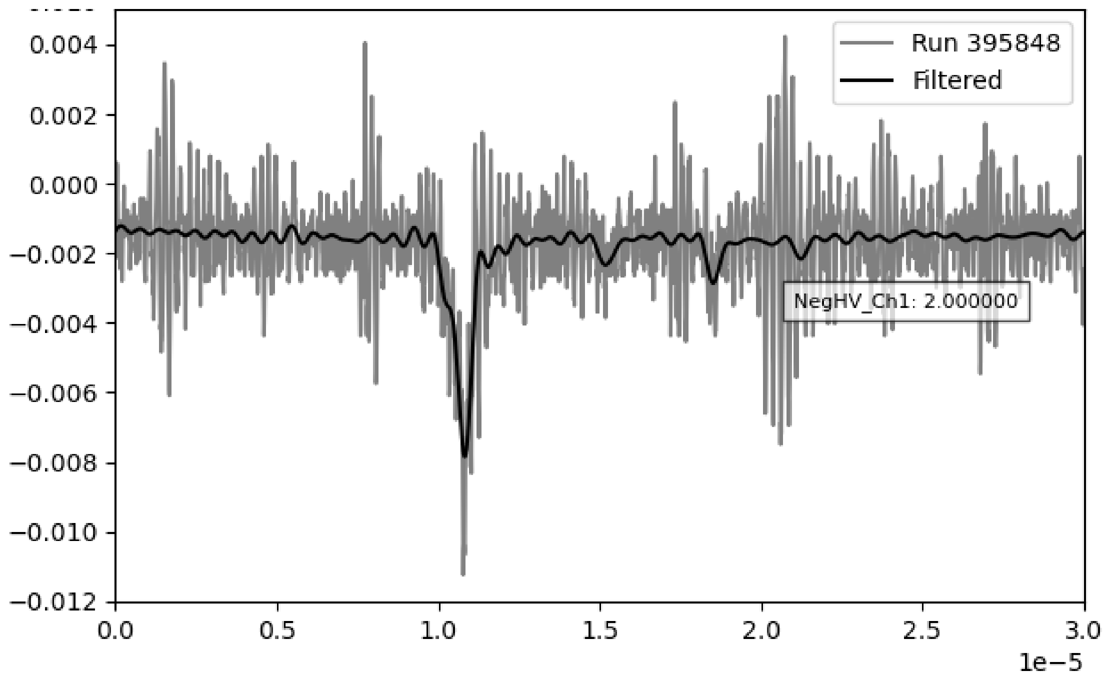
# Summary of outlook:

- 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.

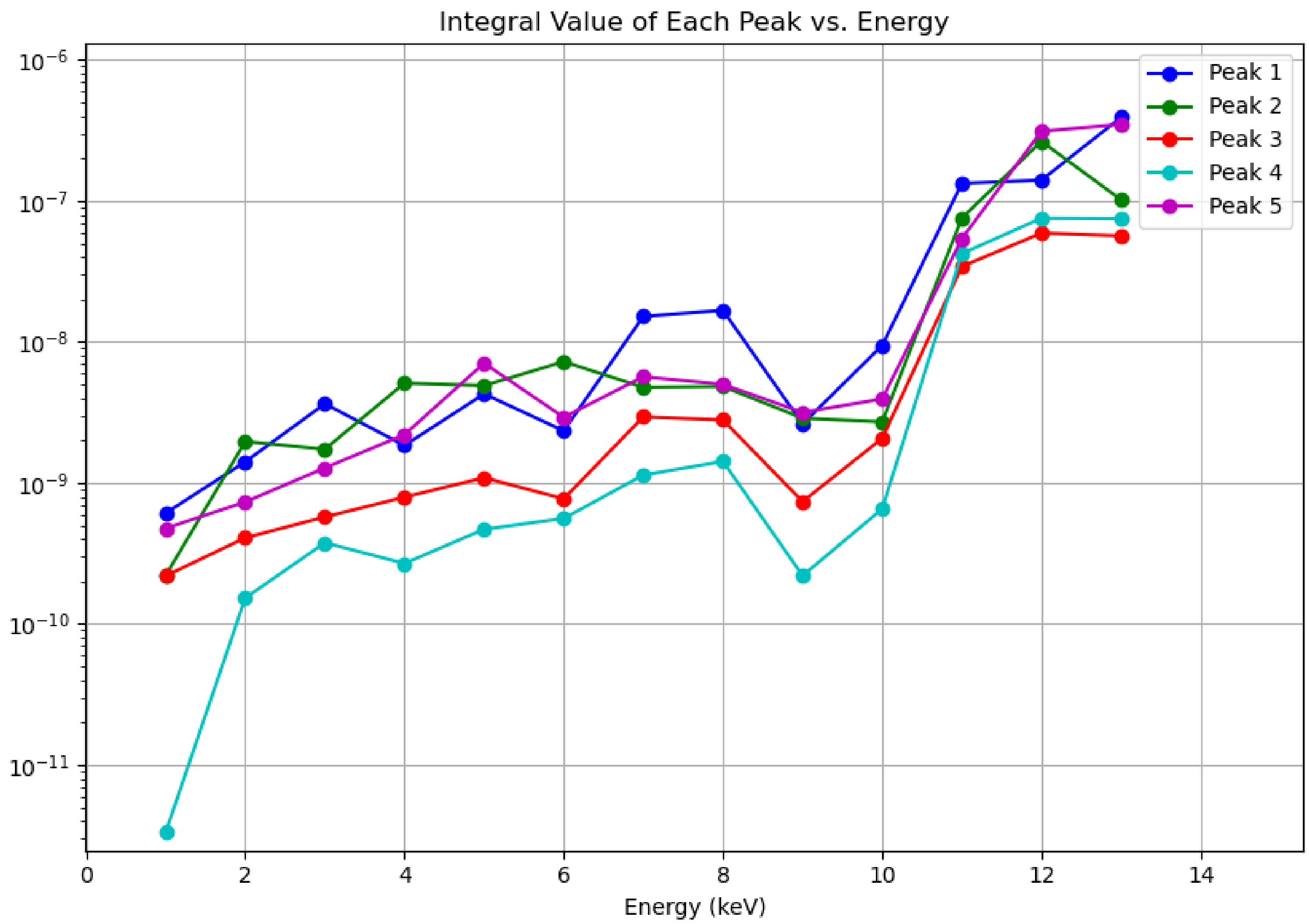
**Goal: Laser triggered formation of antiprotonic atoms (laser/x-ray/auger spectroscopy) and trapping and cooling of resulting HCI fragments.**

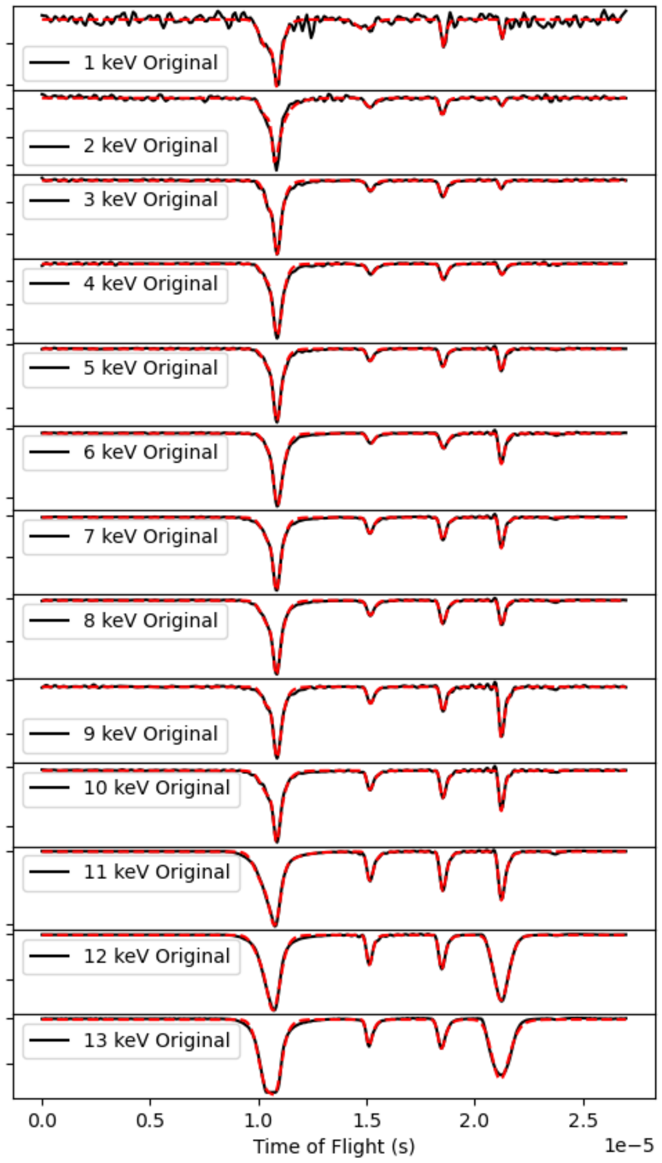
# Noise filtering



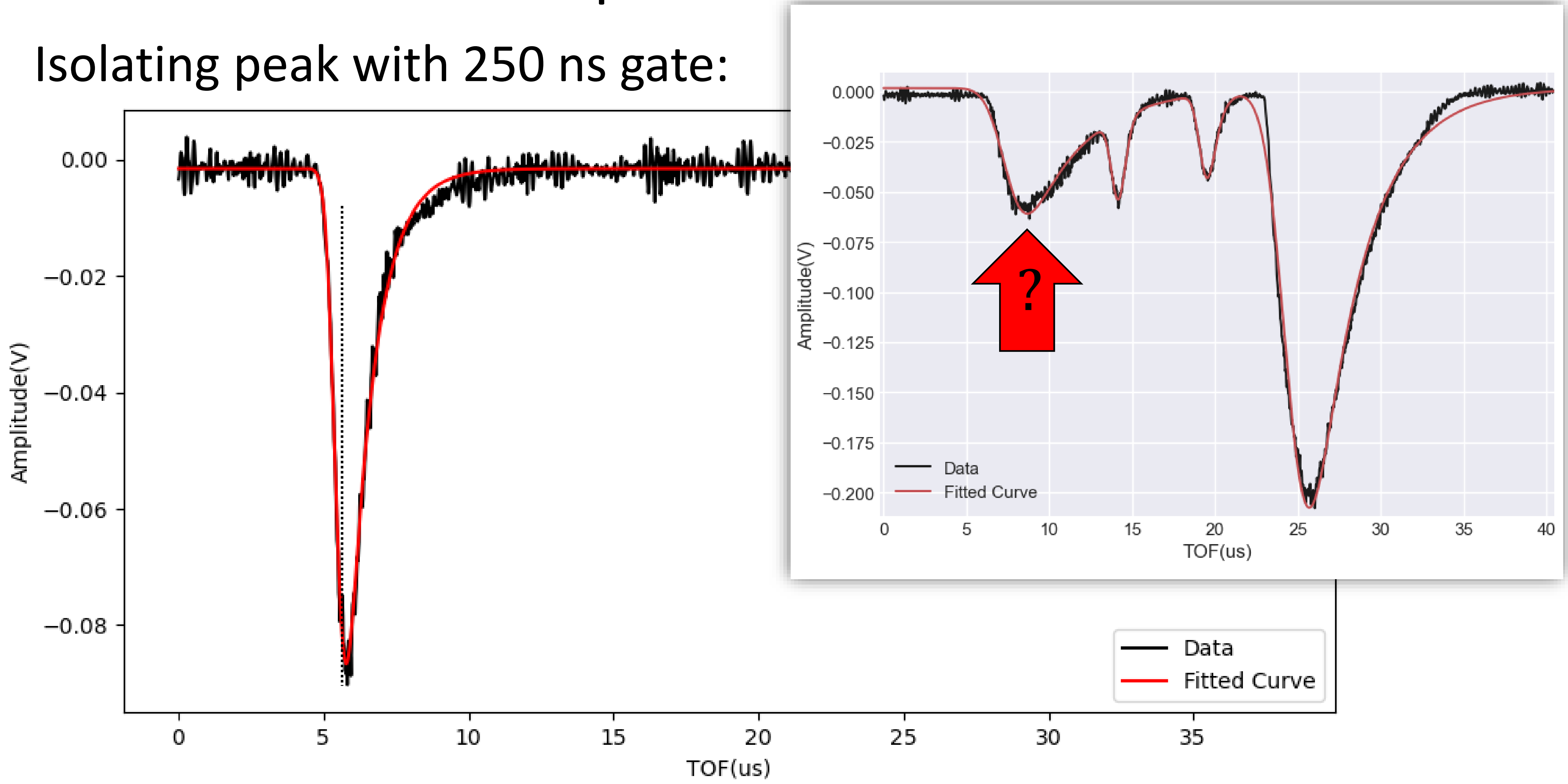
# Pbar trapping voltage vs MCP signal



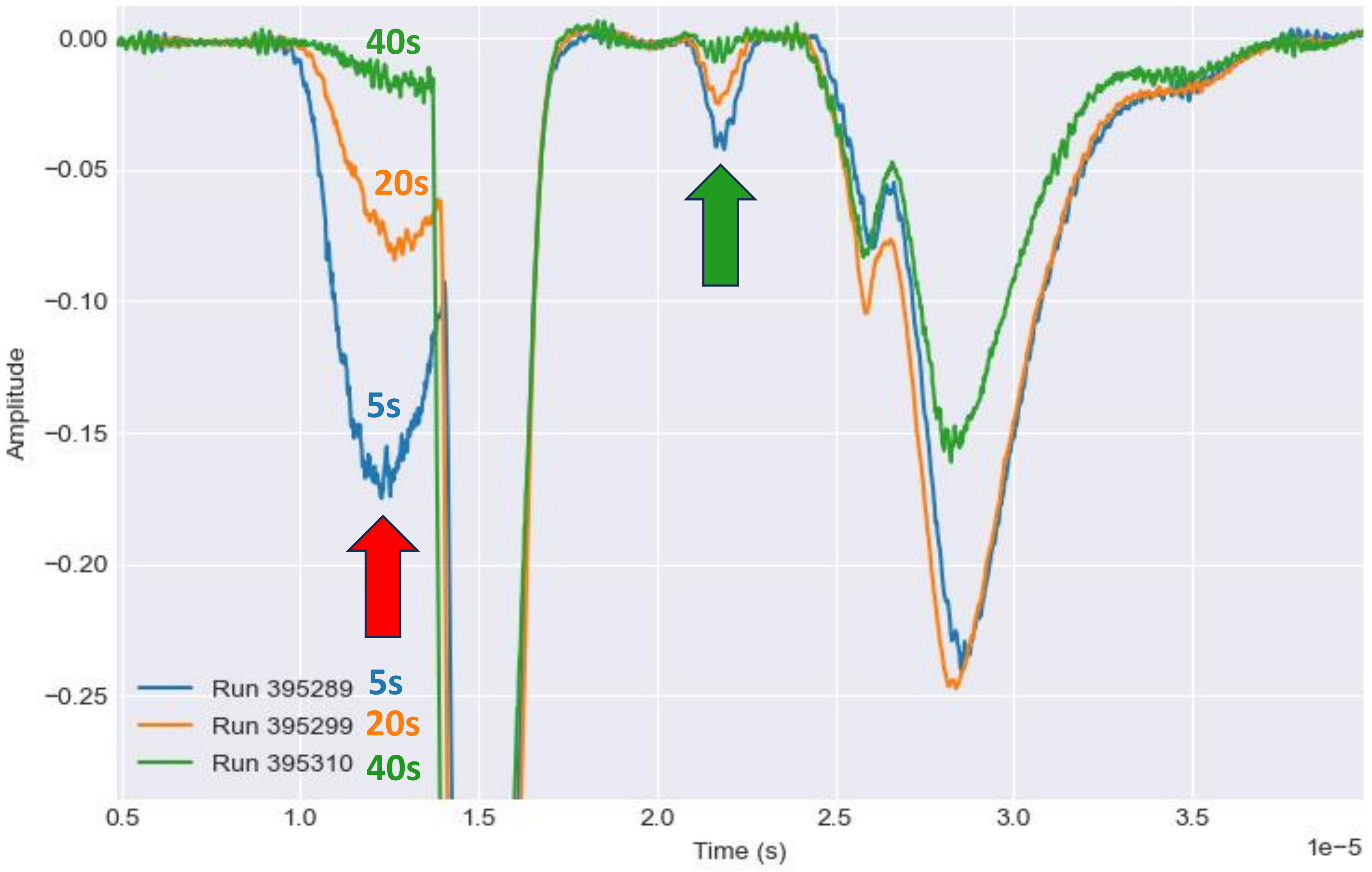



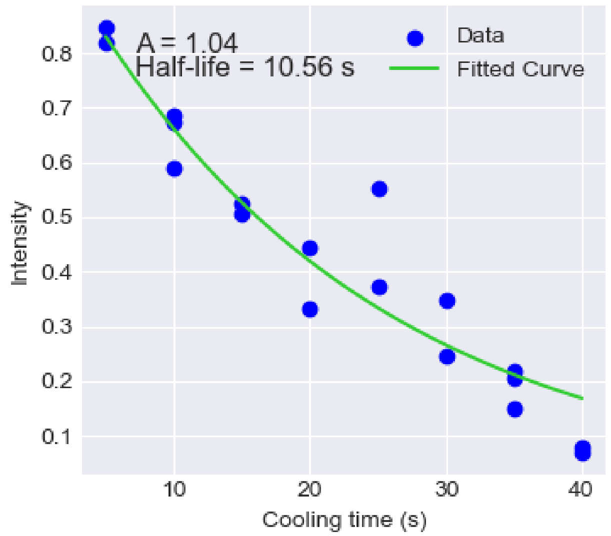
# Fast TOF component?

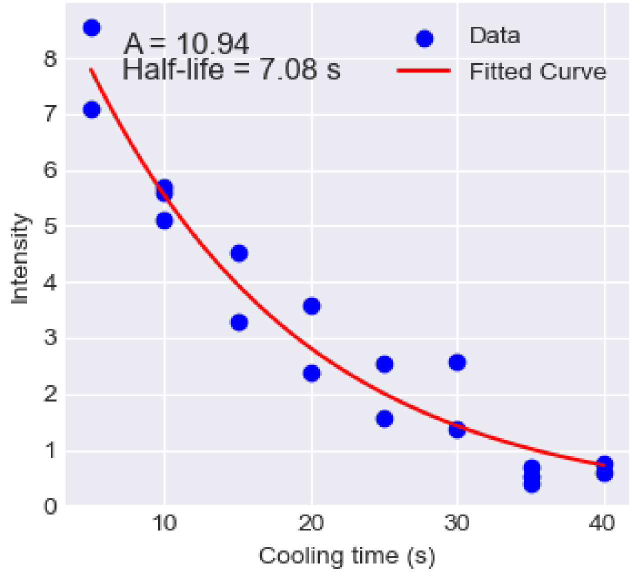
Isolating peak with 250 ns gate:



# Ion time changes the 7+ population



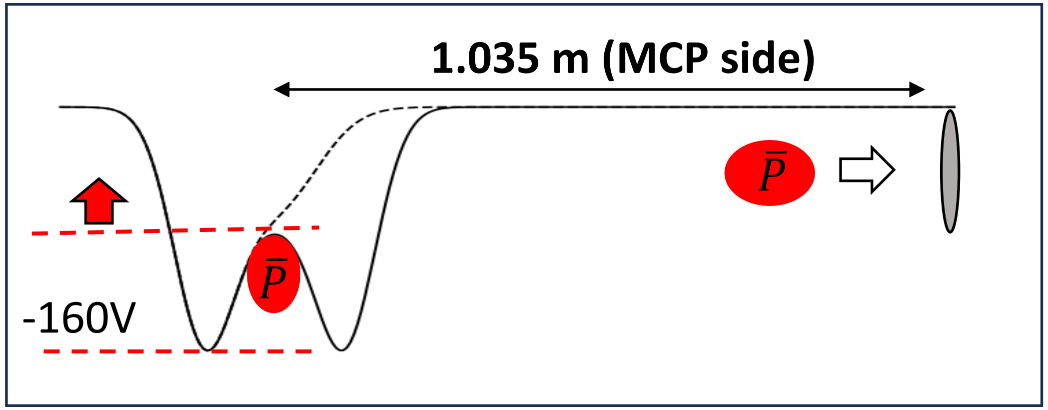



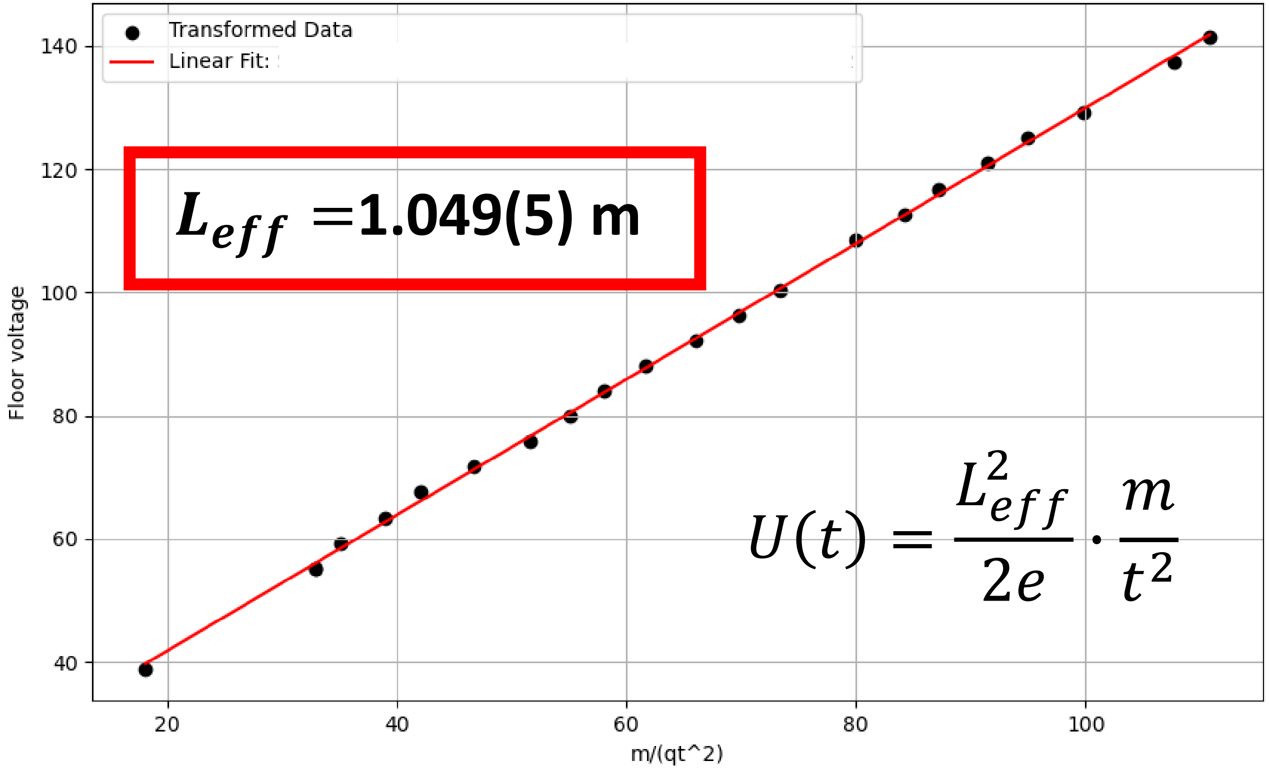

The other peaks do not change significantly with time

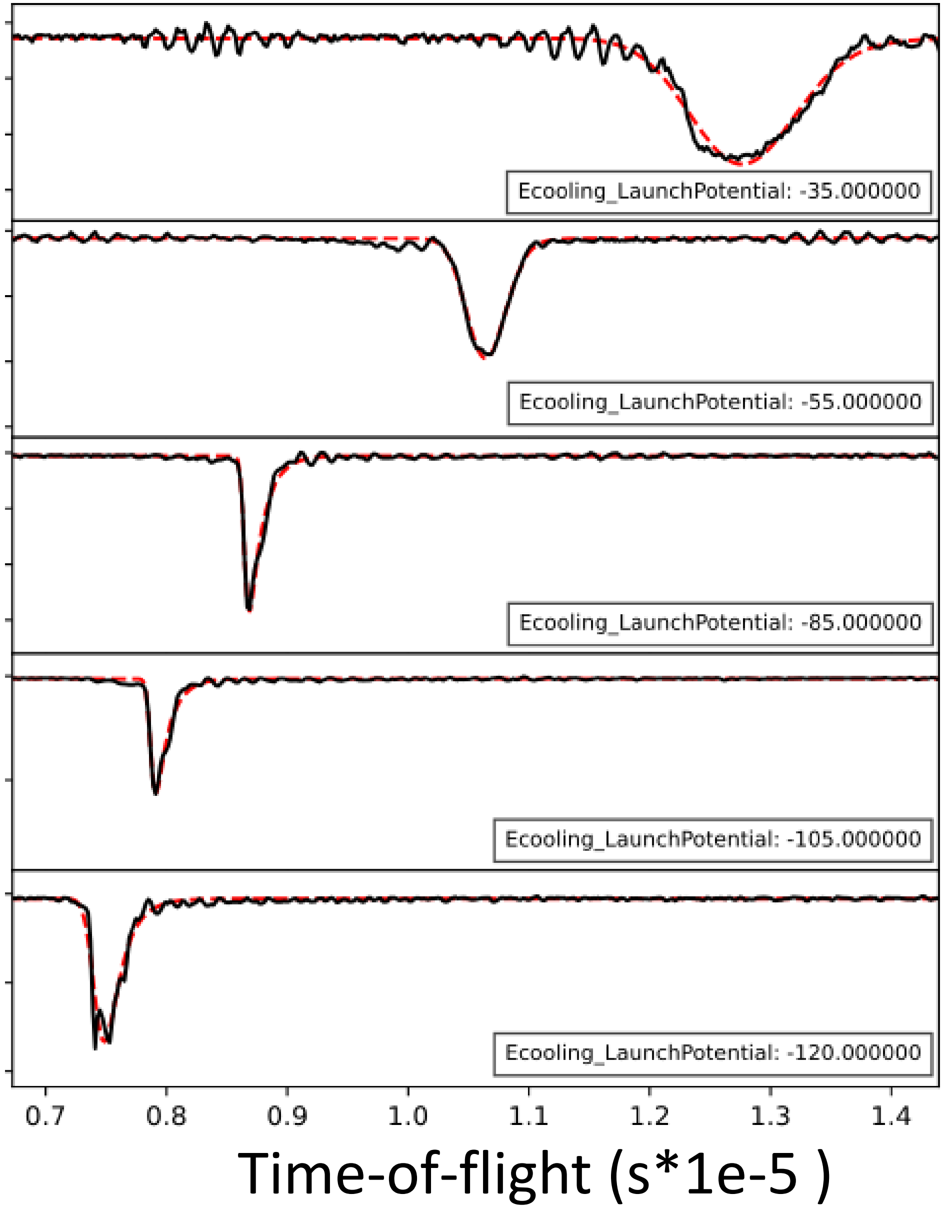
**Table 2:** Ideal production conditions for ions of different isoelectronic sequences. Given are the ionization factor $j_e\tau$ ($e^-$ $cm^{-2}$), the optimal electron beam energy (keV) and the required ionization time (ms or s) for an assumed ionization factor of $j_e\tau = 3 \times 10^{22}$ $e^-$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

| 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 | $2 \times 10^{21}$ | $2 \times 10^{21}$ | $3 \times 10^{22}$ | $2 \times 10^{23}$ | $6 \times 10^{23}$ | $2 \times 10^{24+}$ |
| ionized | 3 | 9 | 40 | 80 | 180 | 300 |
| | 7 ms | 67 ms | 1 s | 7 s | 20 s | 67 s |

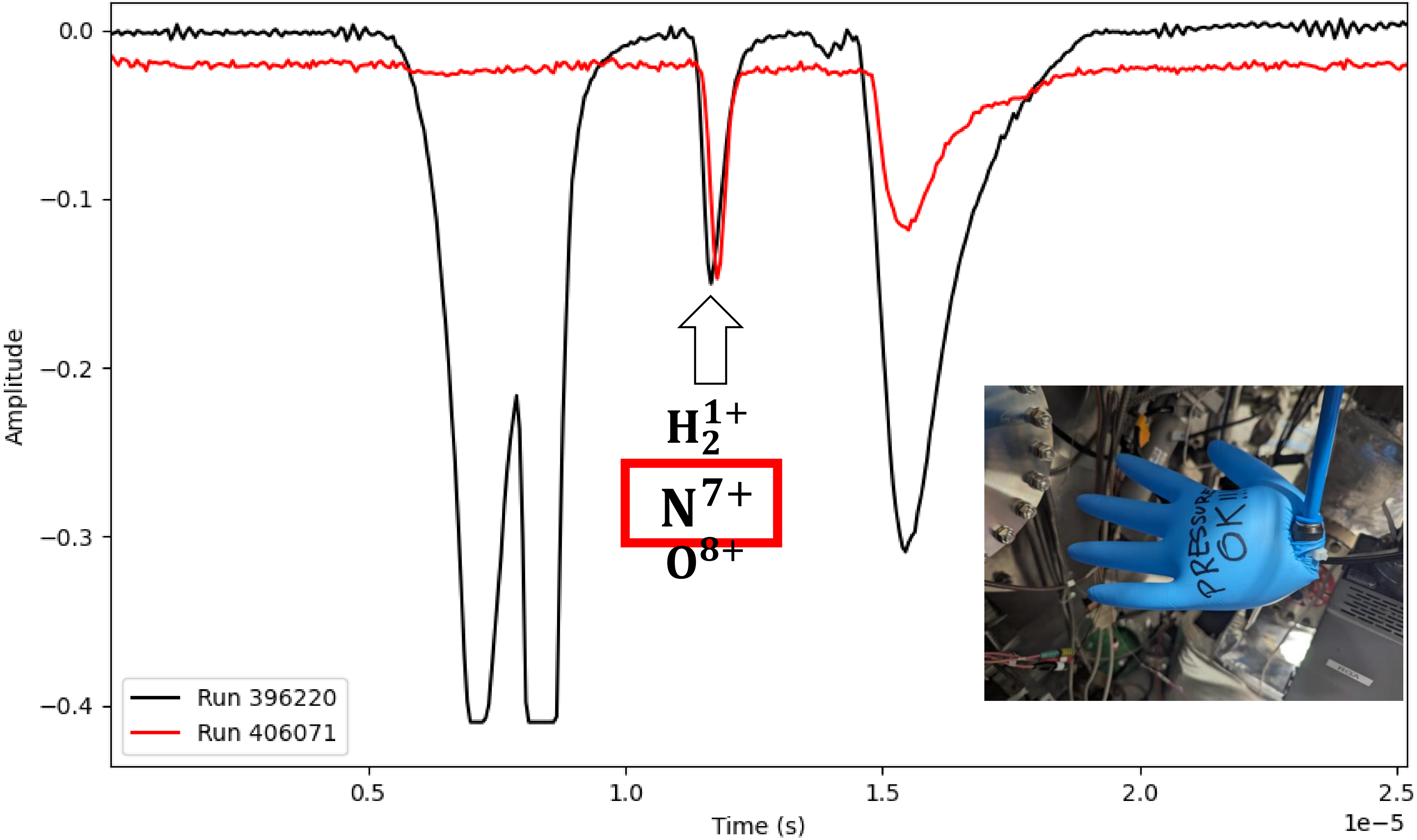
# Time-of-flight calibration using Pbars



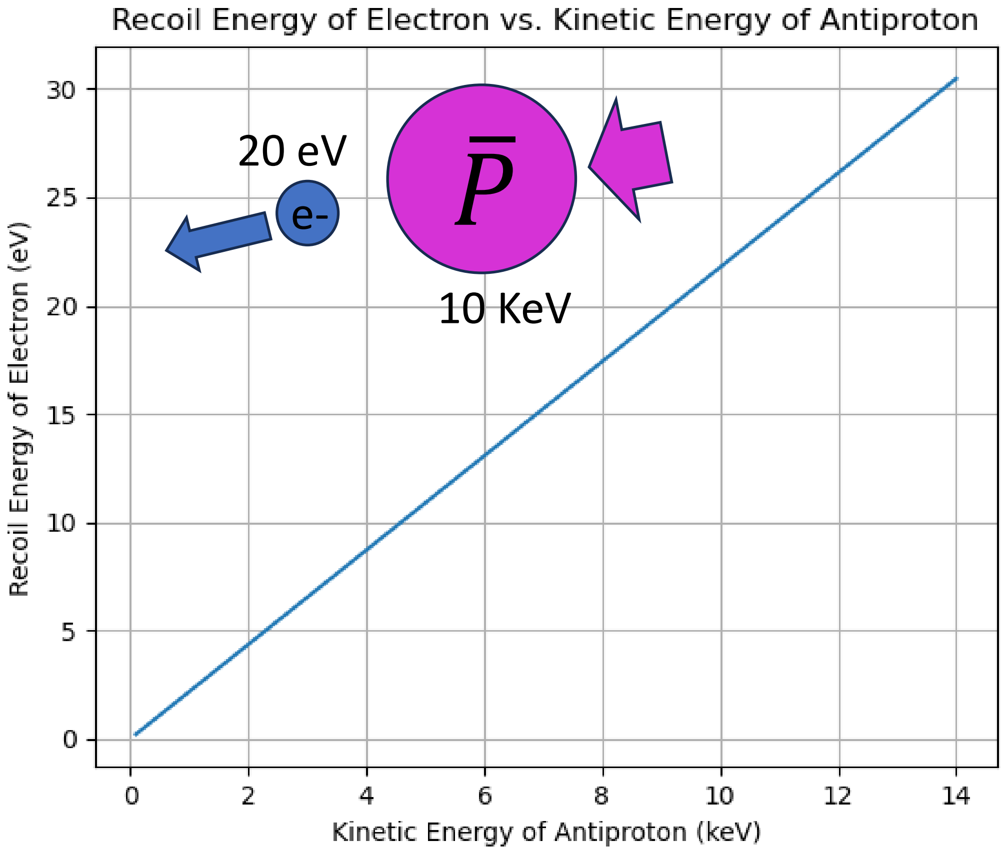



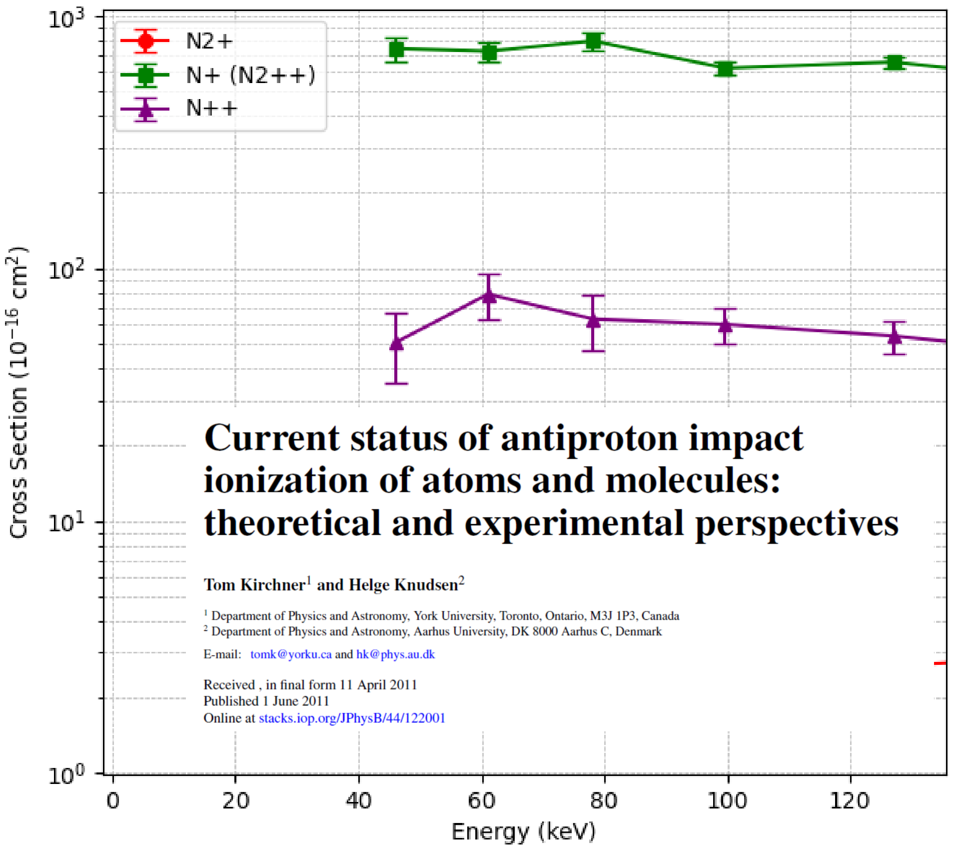
# Peak at m/q=2
# Fully stripped nitrogen identified?



# 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...