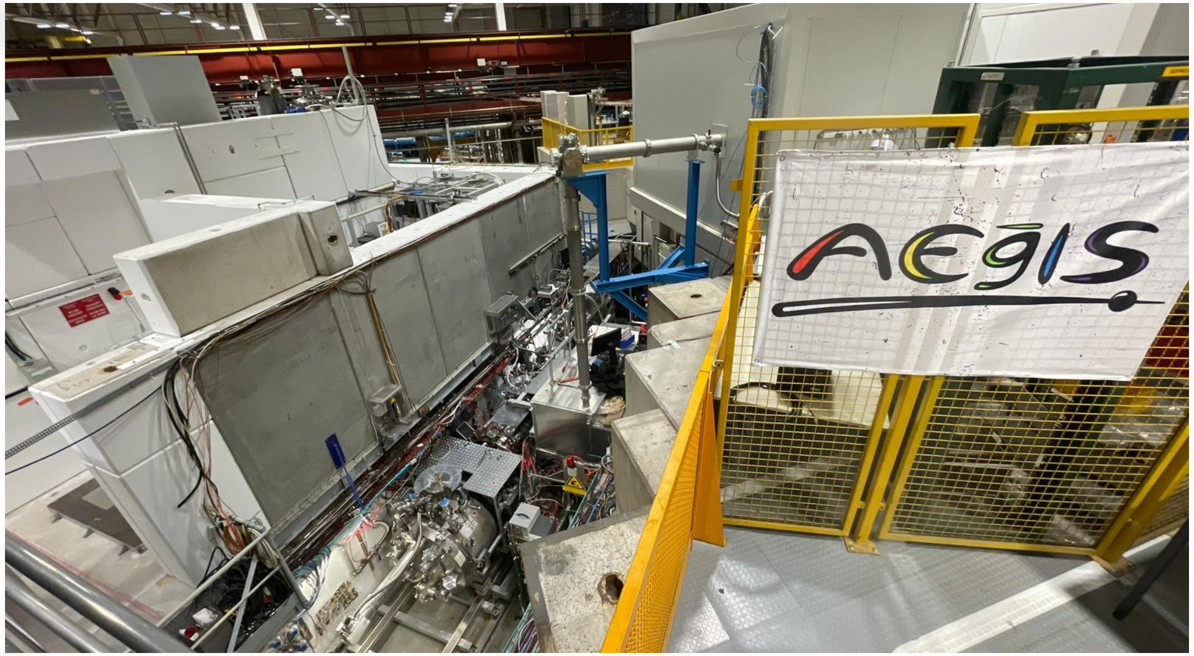
Status report of the AEgIS experiment

156th meeting of the SPSC
February 11th, 2025

R. Caravita*
*INFN – TIFPA, Trento (IT)

on behalf of the **AEgIS Collaboration**

The AEgIS collaboration



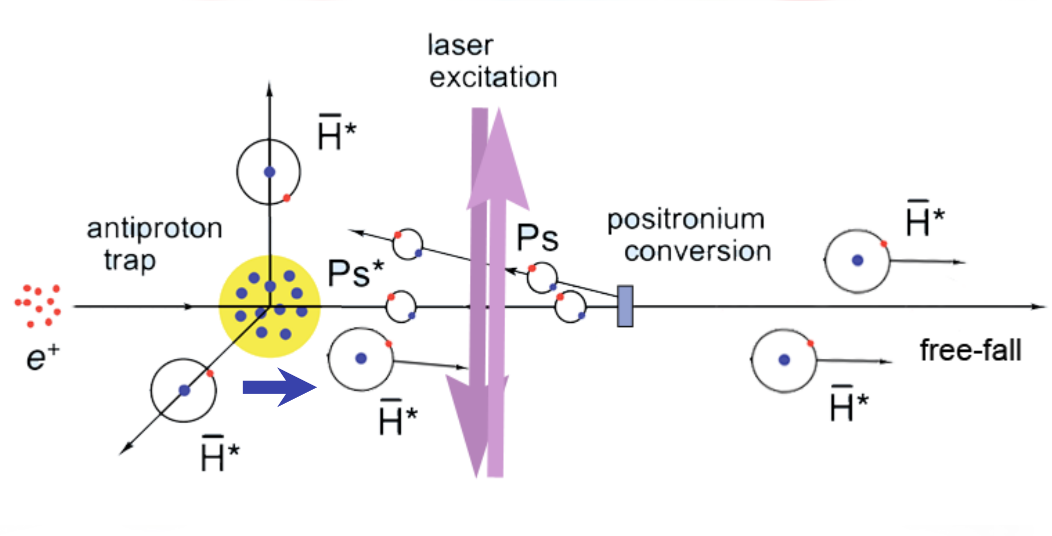
Antimatter **E**xperiment:
gravity, **I**nterferometry, **S**pectroscopy

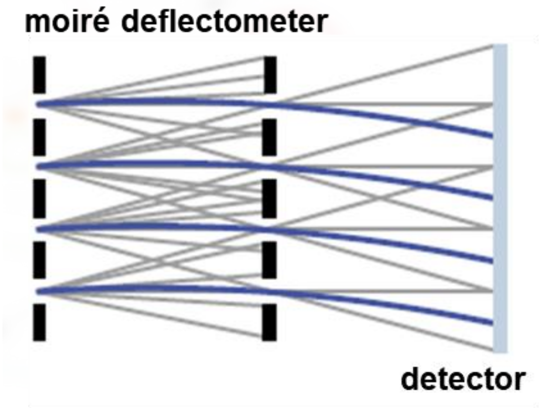
Main physics drives
- Tests of the Weak Equivalence Principle
- Spectroscopy and CPT tests
- … and many more!

Available systems at AEgIS
- antihydrogen, positronium, antiprotonic atoms

Specialties at AEgIS
- Pulsed antihydrogen and positronium sources
- Laser-controlled charge-exchange processes
- Moiré deflectometry
- Pulsed laser spectroscopy

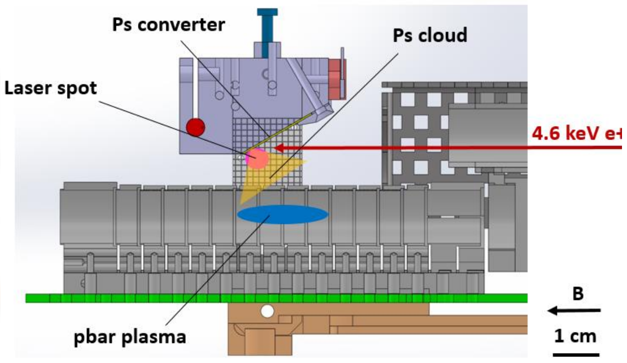
AEgIS flagship program: antihydrogen free-fall

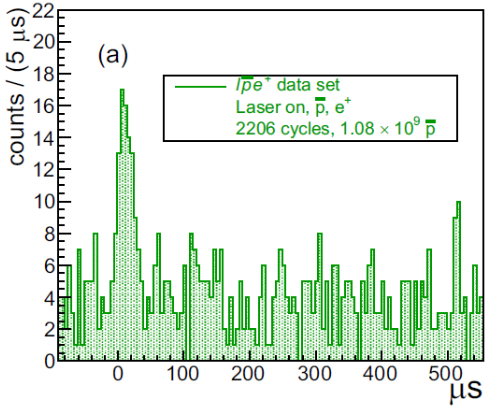




https://doi.org/10.1038/s42005-020-00494-z OPEN

Pulsed production of antihydrogen

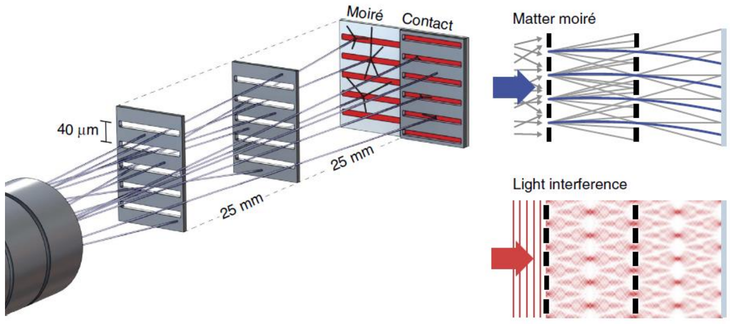




ARTICLE

Received 5 Nov 2013 | Accepted 27 Jun 2014 | Published 28 Jul 2014 DOI: 10.1038/ncomms5538 OPEN

A moiré deflectometer for antimatter



Research lines and main achievements

Research lines

$\bar{H}$ + Ps + $\bar{p}$ atoms + Shared dev. R&Ds

PROPOSAL

2008

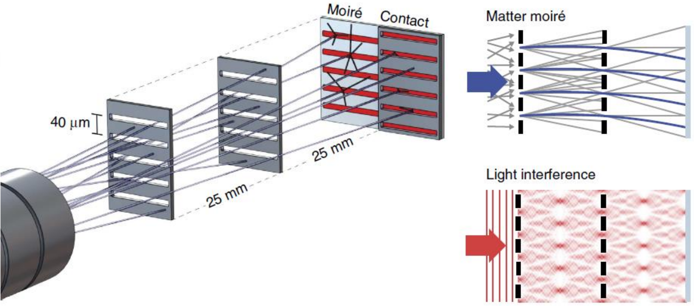
2012

Construction began

2014

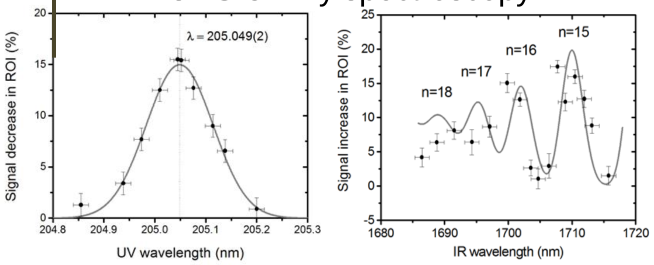
Received 5 Nov 2013 | Accepted 27 Jun 2014 | Published 28 Jul 2014 DOI: 10.1038/ncomms5538 OPEN

A moiré deflectometer for antimatter



2016

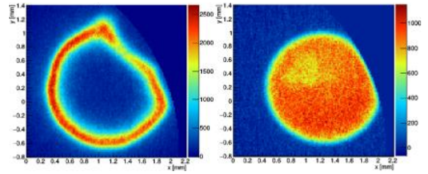
Ps 1S-3P-Ry spectroscopy



S. Aghion et al., PRA **94,** 012507 (2016)

2017

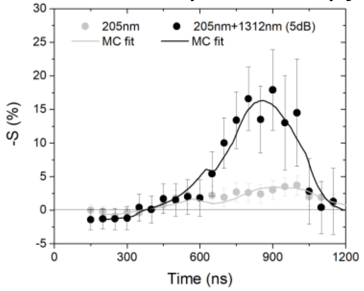
Pbar compression to mm radius



S. Aghion et al., Eur. Phys. J. D (2018) 72: 76

2018

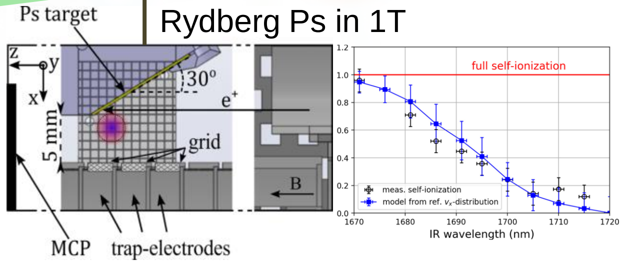
Ps 2S-3P spectroscopy



M. Antonello et al., PRA **100,** 063414 (2019)

2019

Rydberg Ps in 1T



M. Antonello et al., PRA **102,** 013101 (2020)

2020

https://doi.org/10.1038/s42005-020-00494-z OPEN

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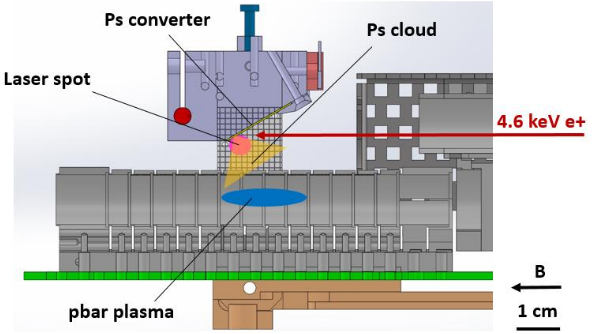
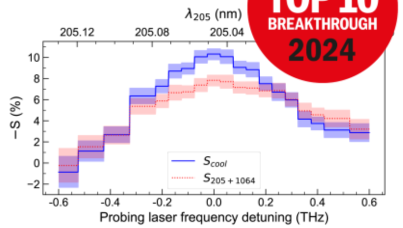


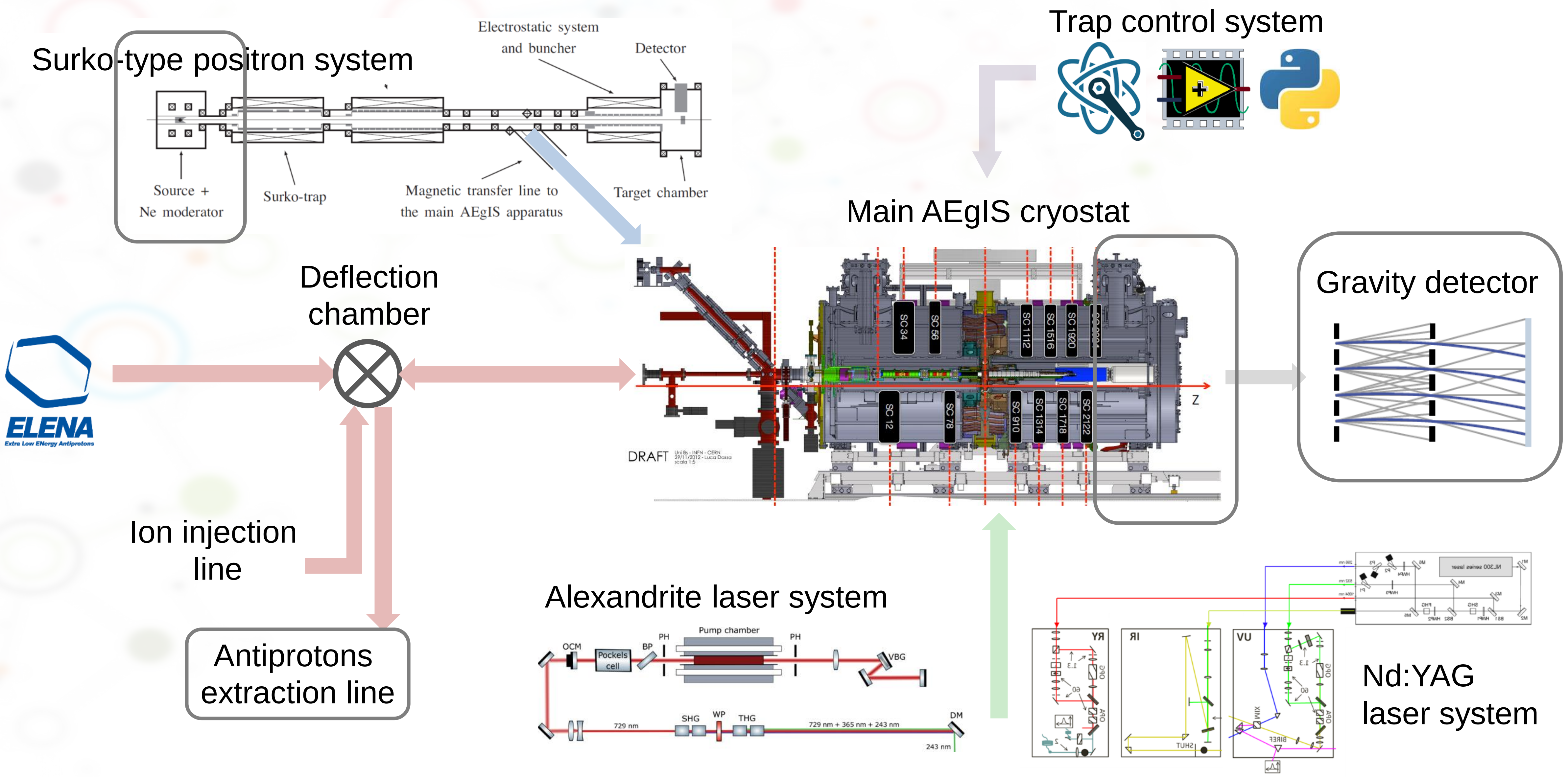
2024

physicsworld TOP 10 BREAKTHROUGH 2024

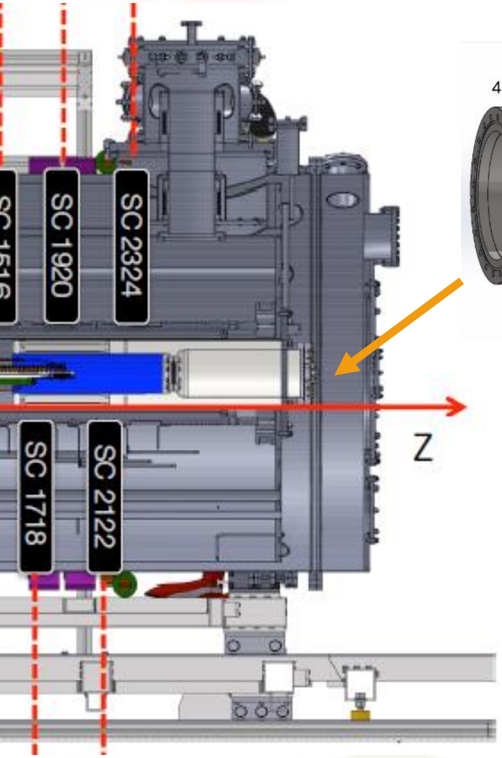


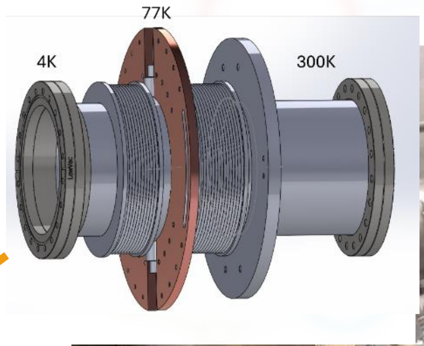
Ps laser cooling

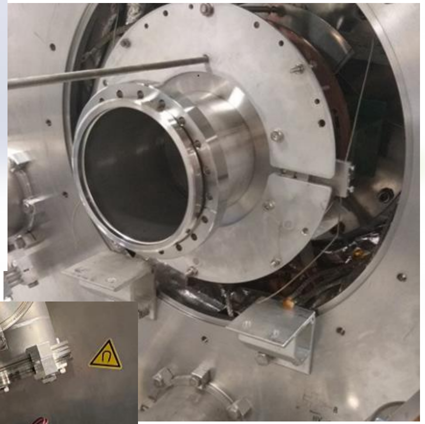
The AEgIS apparatus in 2024

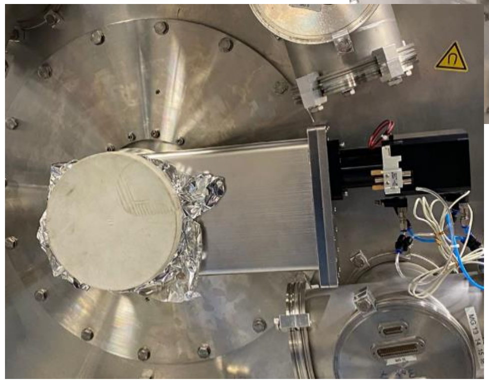


Main Developments in 2024: the beam extraction line







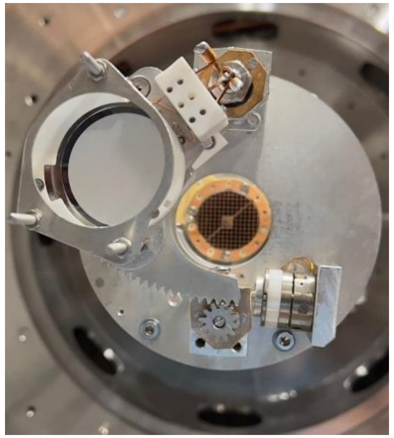


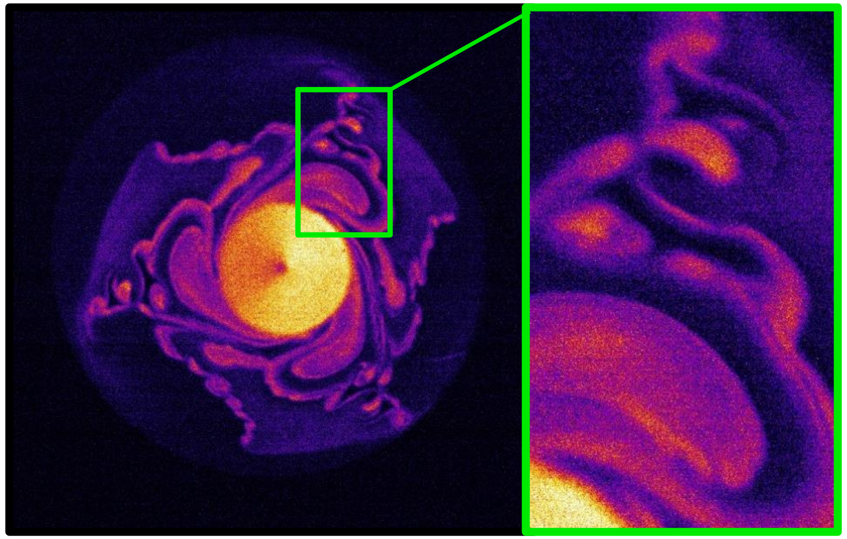
Downstream beam extraction port

- Opened a new CF150 downstream port
- New bellows assembly with complex vacuum and thermal design
- Terminated with gate valve for modularity

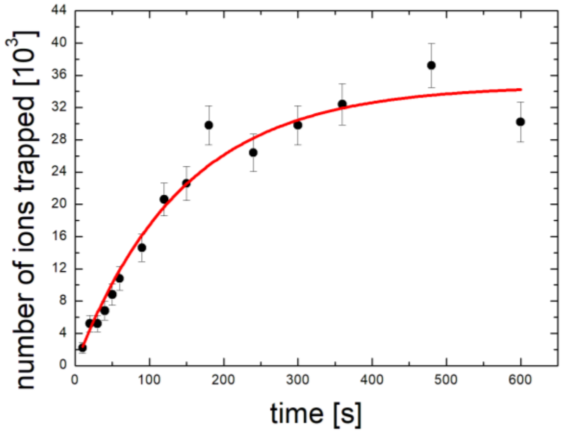
Removable micro-channel plate assembly

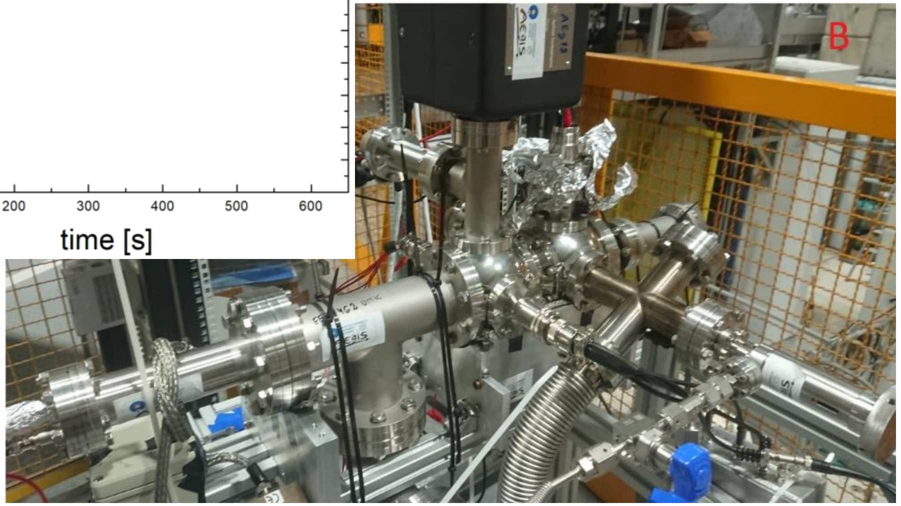
- Can be moved in/out beam axis
- New imaging system with < 50 um resolution





Main Developments in 2024: new sources for Physics





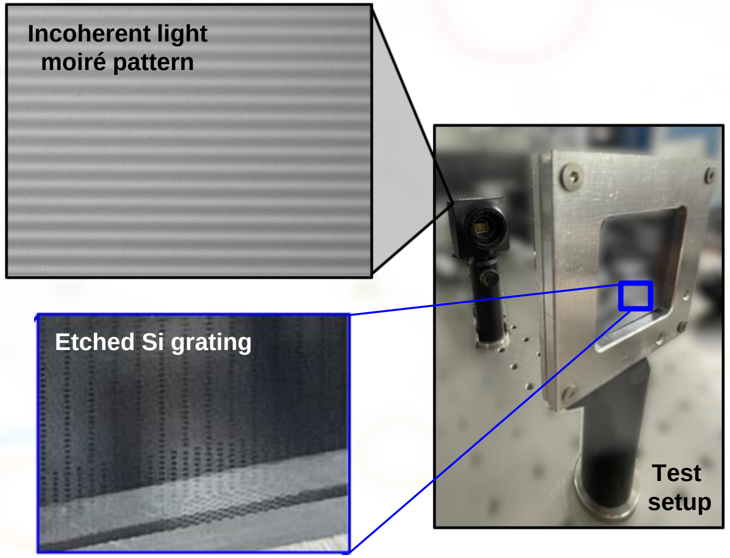
Source of negative iodine for antiprotonic atoms

- Commissioned, provides 10^4 anions per minute
- **Transported to AD hall**, linking to AEgIS
- Outlook: co-trapping I^- with pbars in 2025

Finally installed our new ^{22}Na source

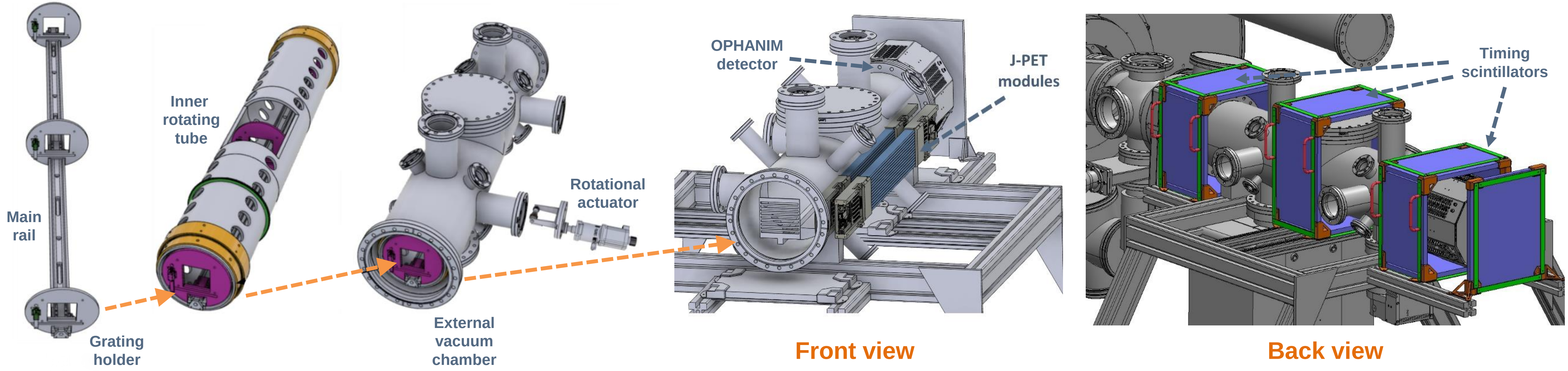
- Delivery in wrong capsule: extra 9 months delay
- Thanks to CERN robotics team, now fixed
- Installed in Sep24, **fully functional**

Main Developments in 2024: the moiré deflectometer



Design of external moiré deflectometer

- Two etched-Si 100 um gratings, tested on optical bench
- 3 detectors: imaging + timing + beam monitoring
- Rotating inner tube for B/G decoupling
- All mechanics designed and in production
- Goal: commissioning in the 2025 pbar run



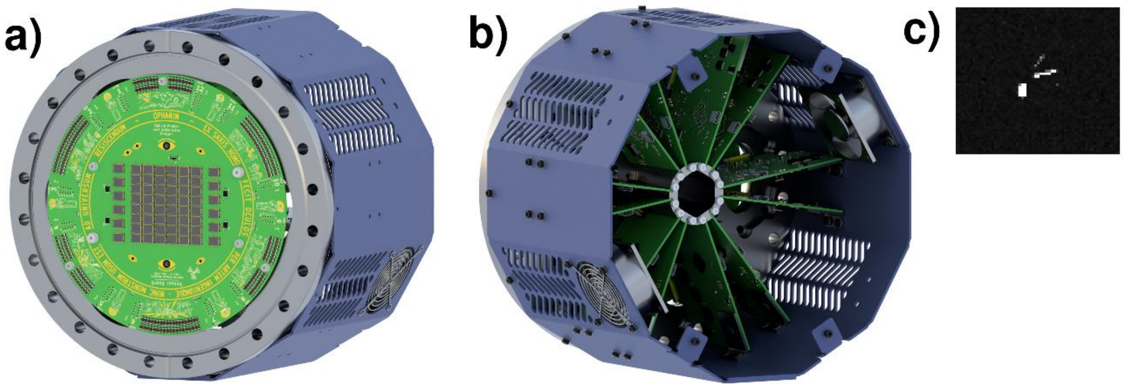
Front view

Back view

Main Developments in 2024: the OPHANIM detector

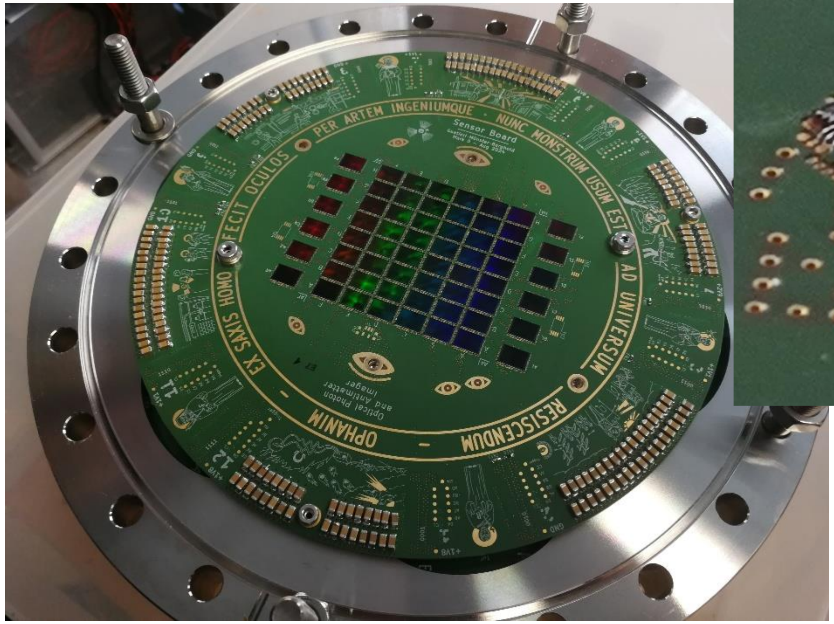
The Optical PHoton and ANtimatter IMager (OPHANIM)

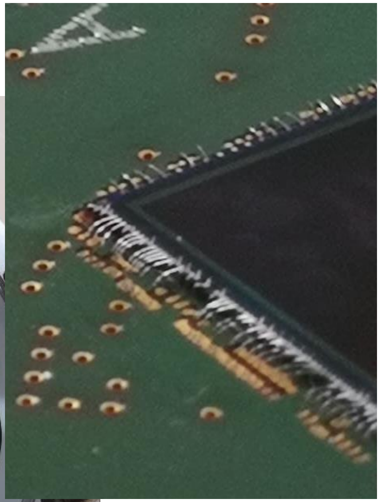
- 60 CMOS sensors, 30.8 cm^2 coverage, 0.8 um pixels
- 64% fill factor, ~70% detection efficiency → 45% total
- World-record-breaking pixel count: 3.84 Gpx [1]
- Vacuum-compatible electronic design at tech. edge



Readiness

- Sony IMX686 validated with antiprotons in April 2024
- 2 x full design → procurement → construction → testing
- All CMOS sensors successfully readout (no PCB flaws)
- Preliminary pbar-annihilation imaging successful in late 2024 run





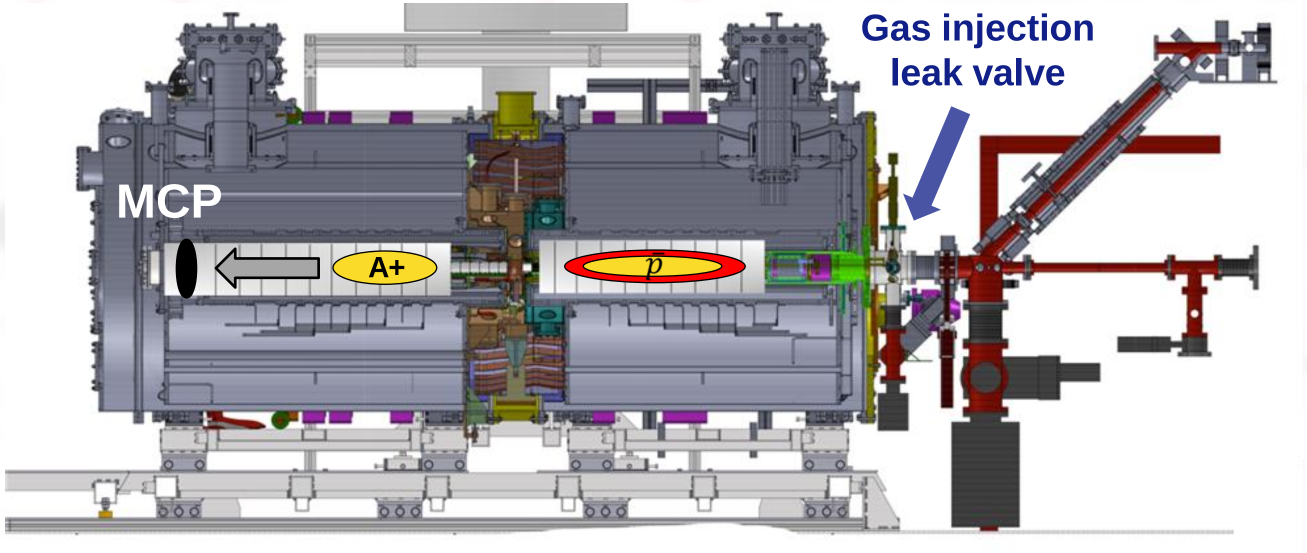
Will be deployed in early 2025 for first beam extraction.

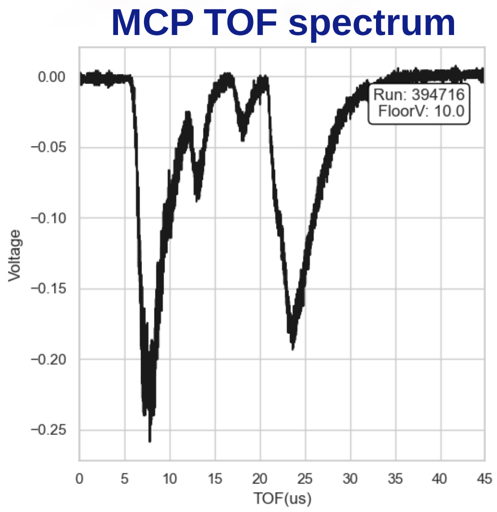
[1] more than the Rubin Observatory LSST camera

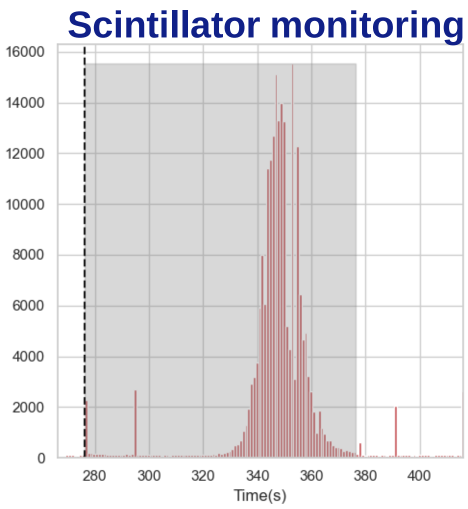
Achievements of the 2024 Physics Run

ANTIPROTONIC ATOMS

Technique to form and detect antiprotonic atoms





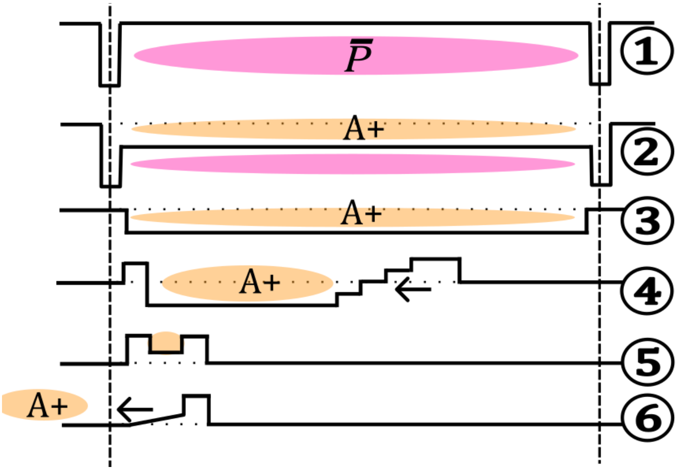


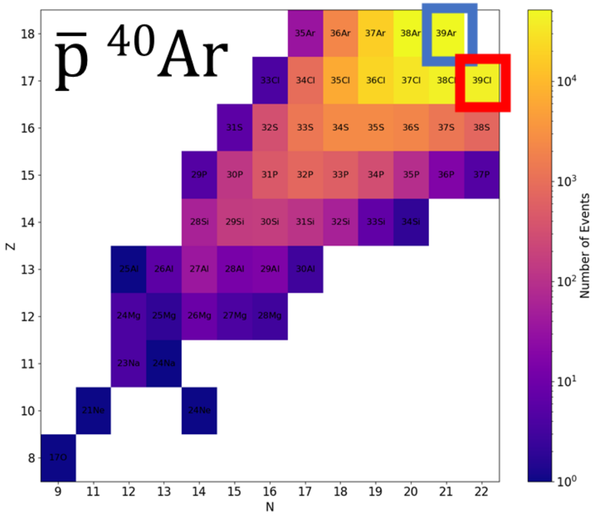
Formation of antiprotonic atoms on buffer gas

observed by the highly charged ions resulting from antiproton annihilation on gas atoms

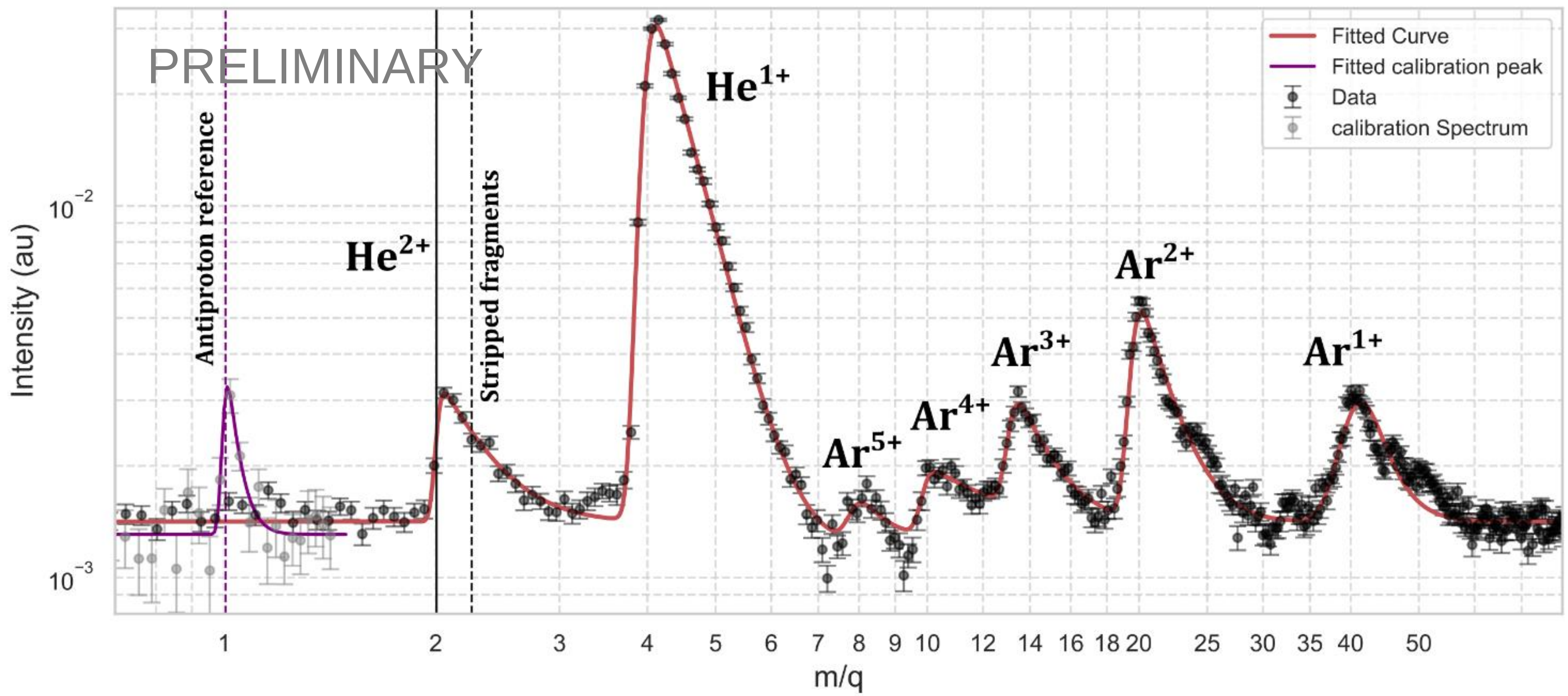
Upgrade to the 2023 methodology

- Controlled gas injection by needle valve
- Total of 4 data taking campaigns (Ar, He)
- Improved data acquisition chain, q/m calibration with electrons and antiprotons





Observation of trapped HCIs from antiproton annihilations



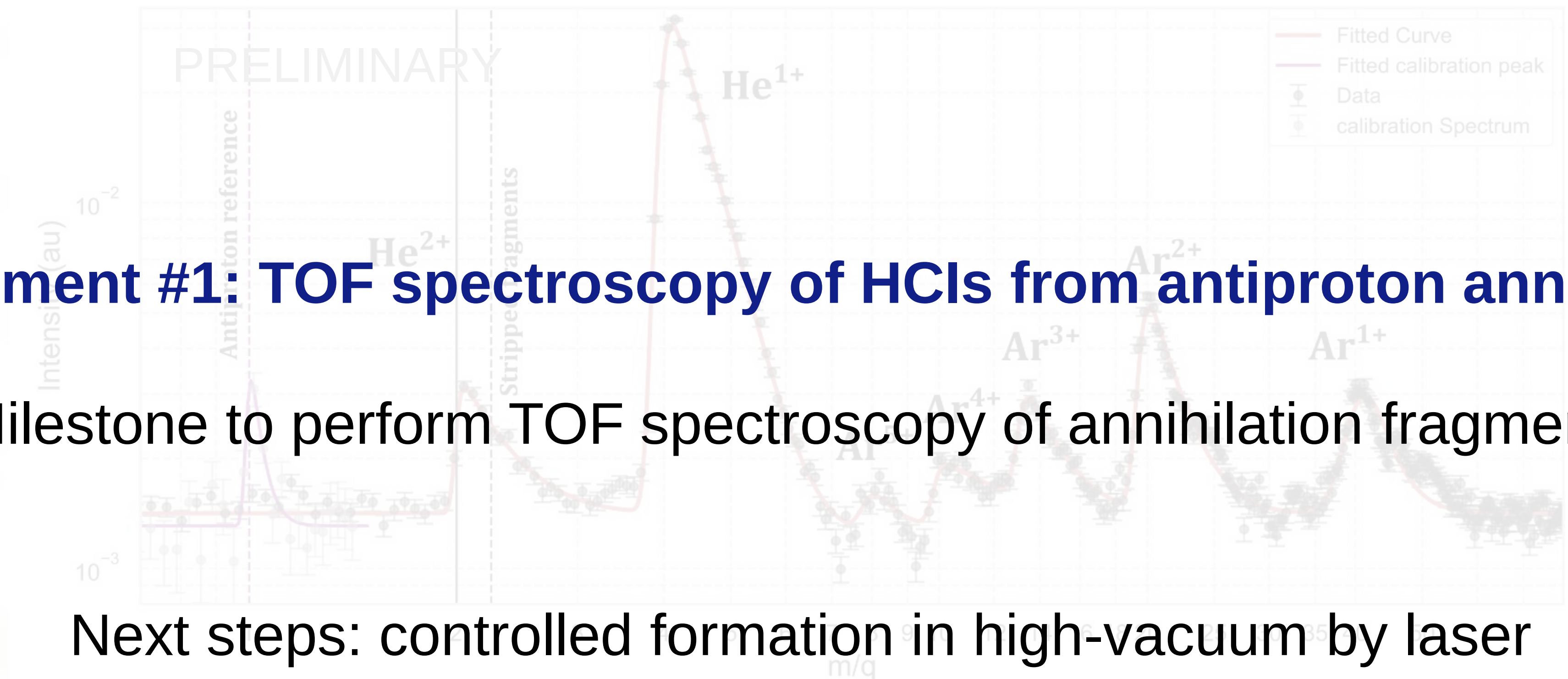
Time-of-flight spectroscopy of trapped Highly Charged Ions resulting from antiproton annihilation

- Observed charged ions higher than Ar^{2+} incompatible with collisional ionization by slow antiprotons.
- We only observe strong ionization of atoms in the trap in coincidence with annihilation events
- Helium peak linked to the presence of a He in the rest gas, masks the fully stripped Ar^{7+}

Achievement #1: TOF spectroscopy of HCIs from antiproton annihilations

Milestone to perform TOF spectroscopy of annihilation fragments

Next steps: controlled formation in high-vacuum by laser photo-detachment of anions, cooling of annihilation fragments



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Achievements of the 2024 Physics Run

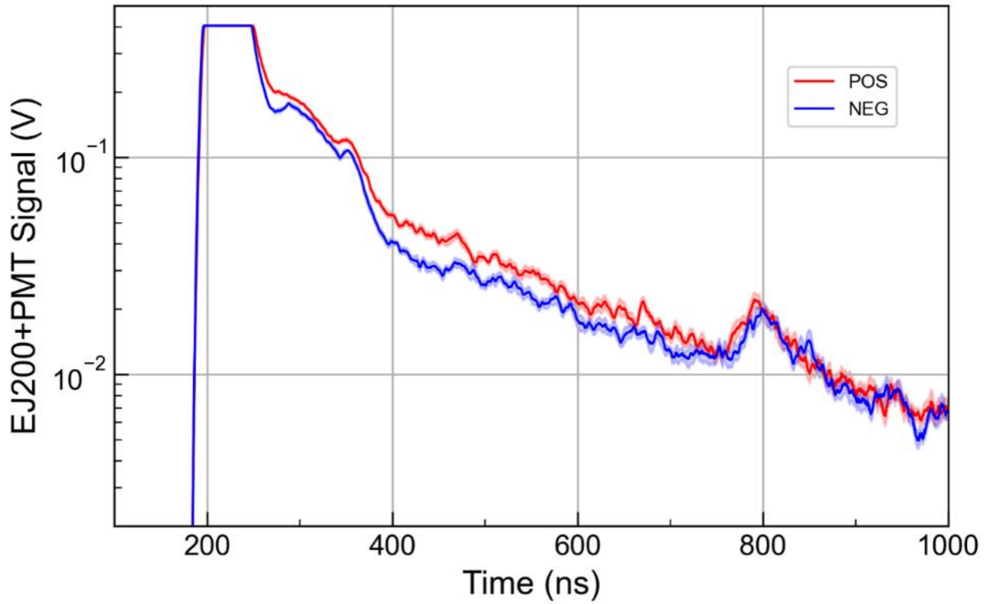
POSITRONIUM

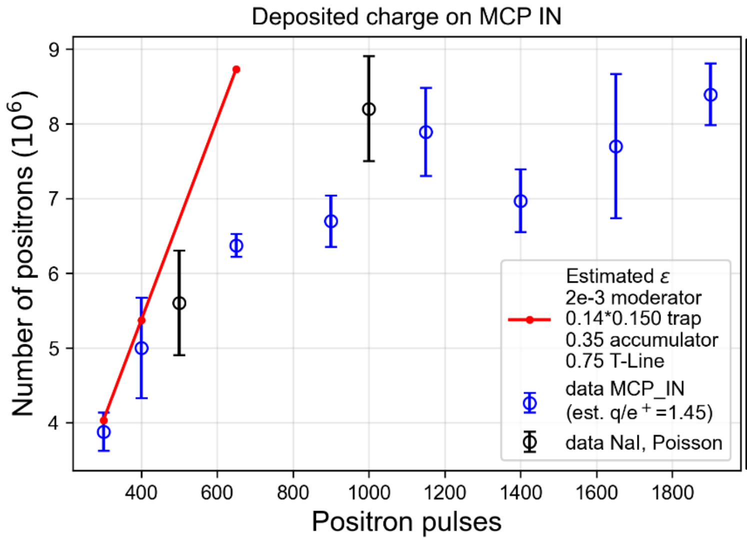
Improvements in Ps target manufacturing

- Minimized exposure to air moisture
- New cut method to shape in final form

>> from 2.5% to 10% yield (x 4)*
consistent with 2018

*a further x 2.5 may be obtained by reducing to 0.2 T



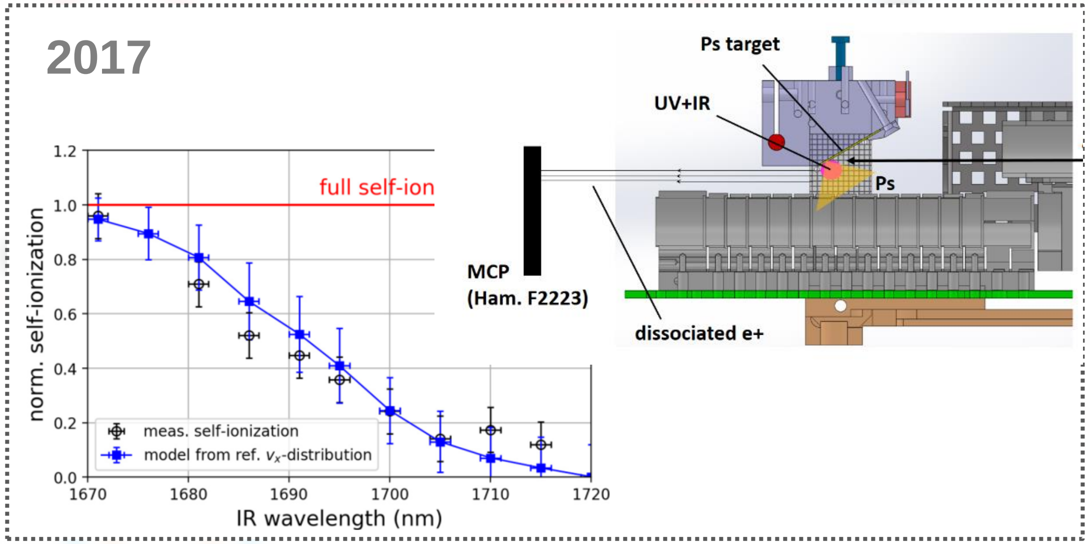


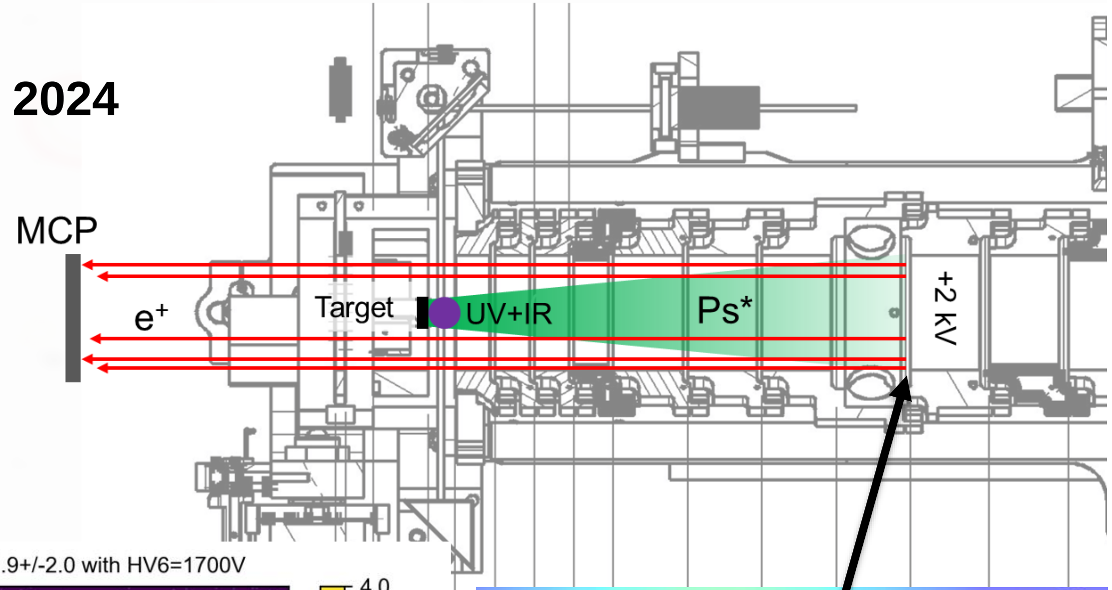
Impact of the new positron source

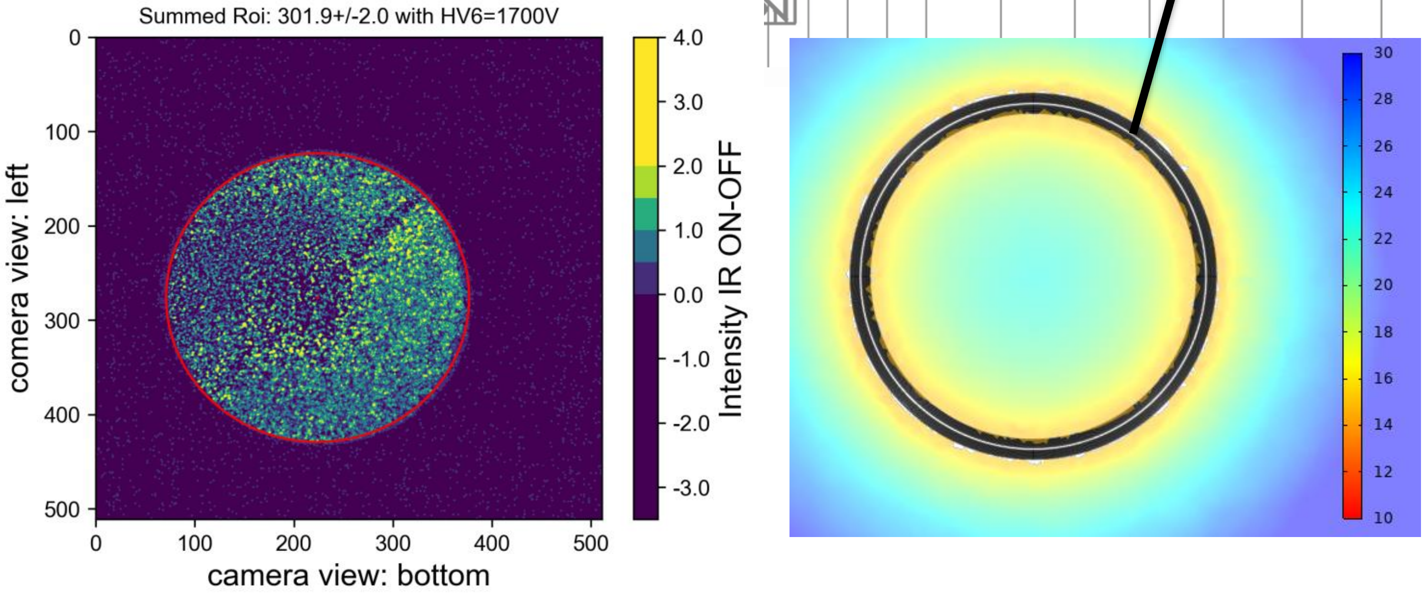
- Increase of factor x 8 in number of e^+
- Reproducible e^+ plasmas with r = 0.6 mm
- 30% higher acceleration efficiency

>> increase of factor x 10

Direct Rydberg Positronium diagnostics







Method for a direct Rydberg Ps diagnostics

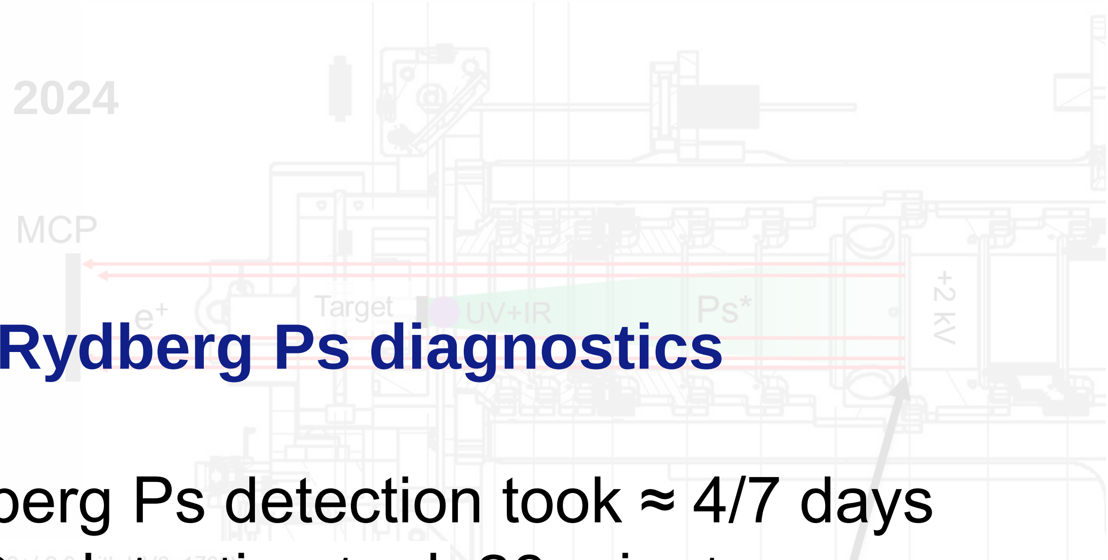
- Field-ionize Rydberg Ps and detect liberated e^+ with MCP
- Clear signature (20:1 SNR) in laser ON/OFF measurements
- Signal scaling vs ionization HV
- Validates Rydberg excitation in-situ
- Sensitivity to Ps *n* quantum number

Achievement #2: Single-shot Rydberg Ps diagnostics

From 2017 to 2023: unambiguous Rydberg Ps detection took ≈ 4/7 days

In 2024: unambiguous Rydberg Ps detection took 30 minutes

Enables Rydberg Ps spectroscopy in 1T field



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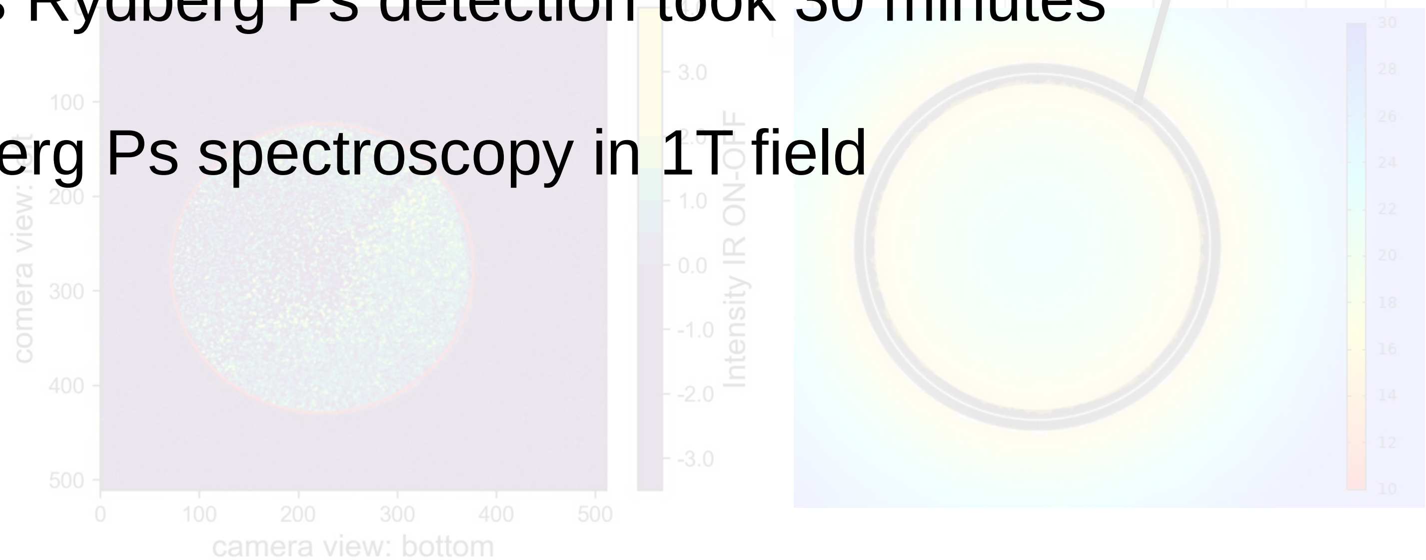
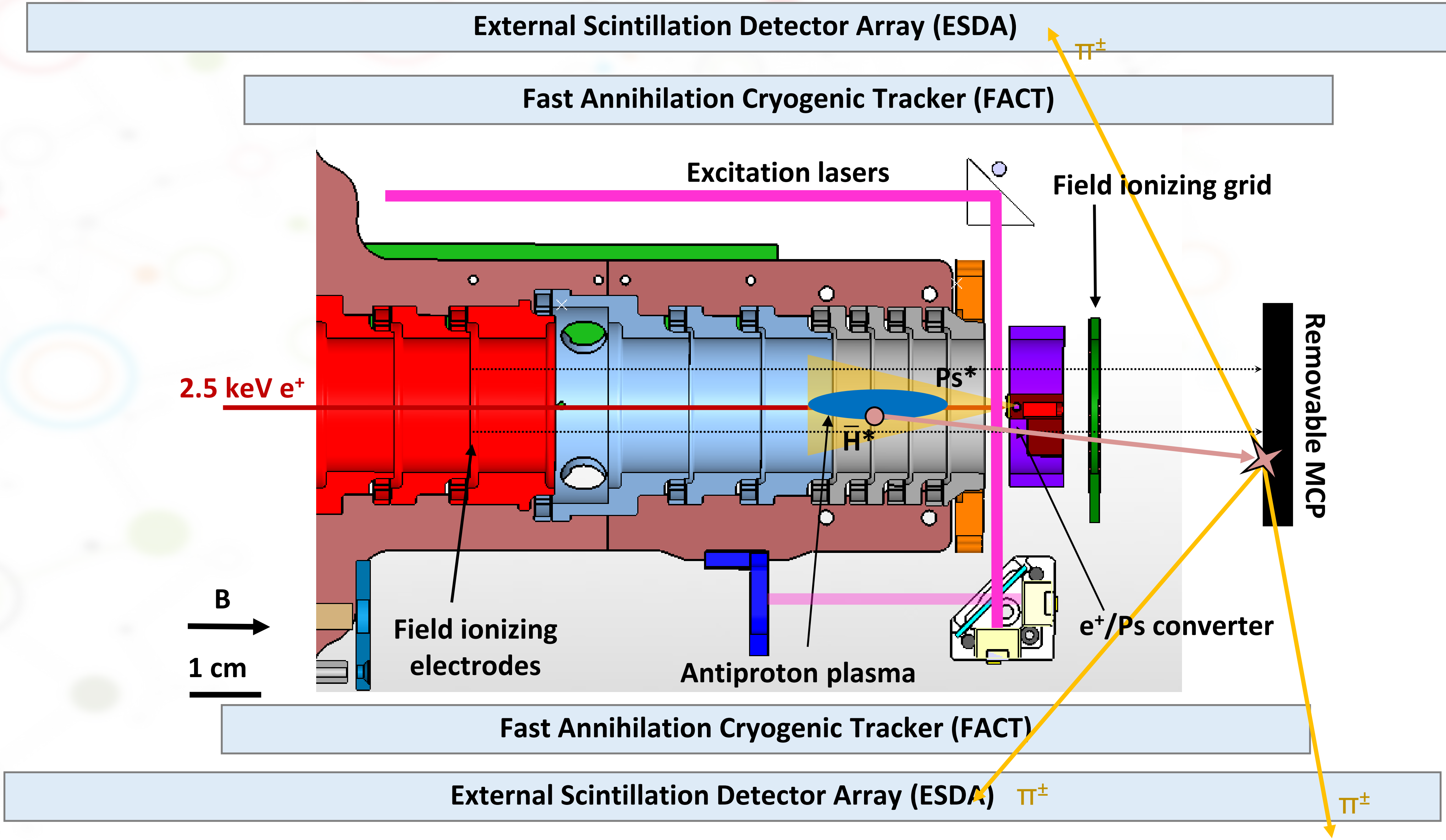


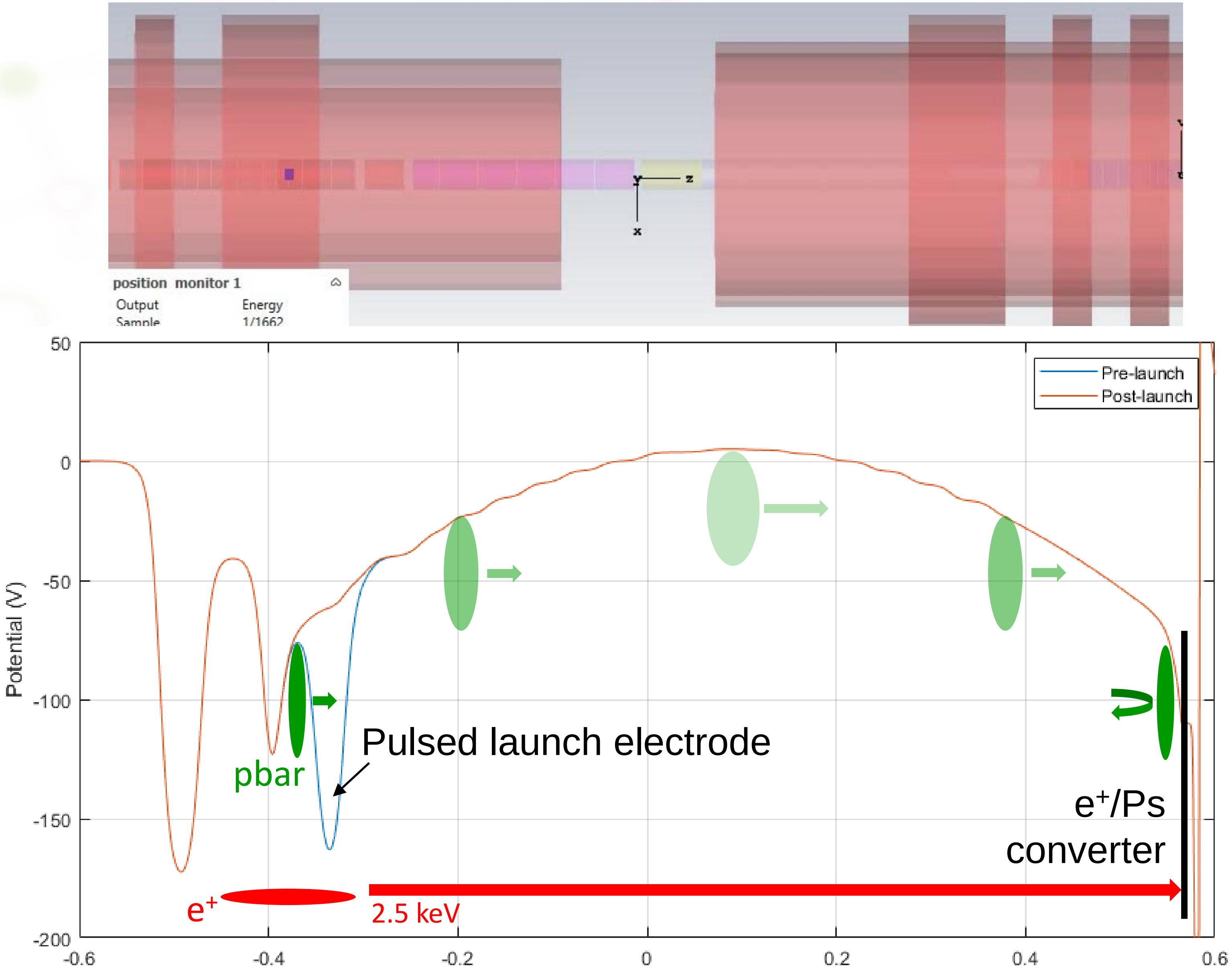
Achievements of the 2024 Physics Run

ANTIHYDROGEN

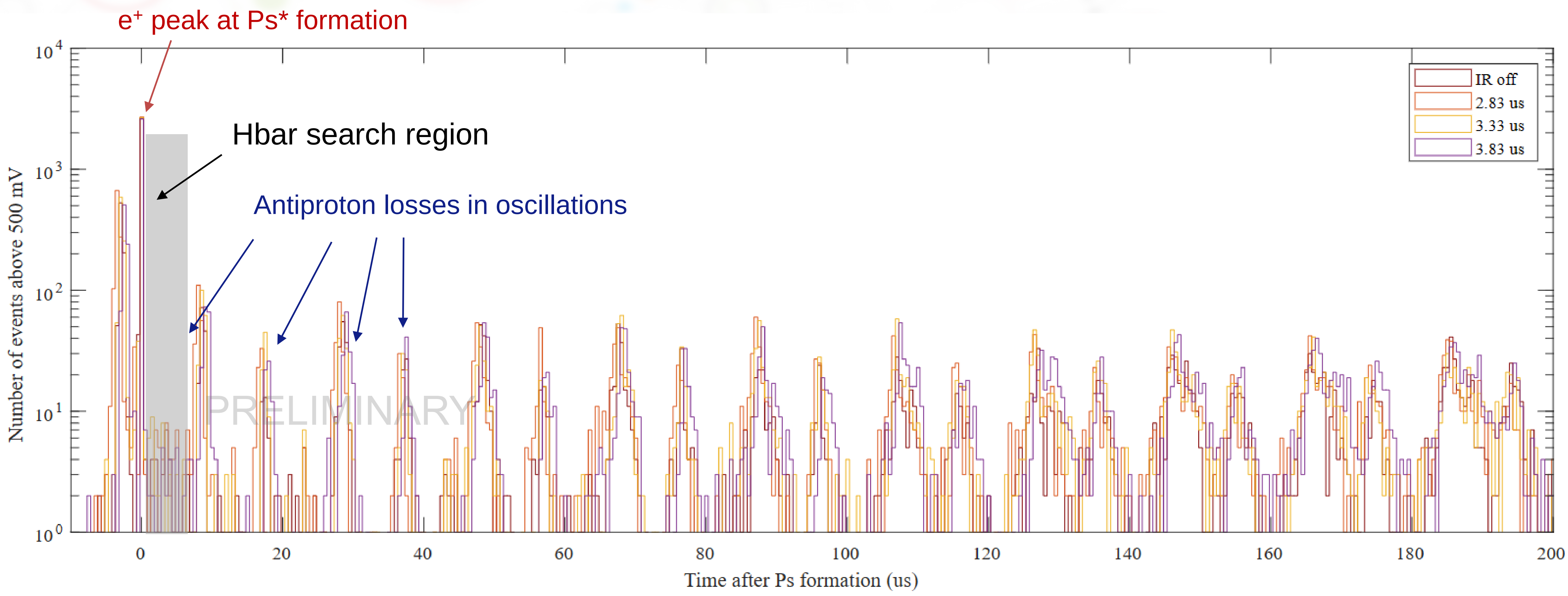
Antihydrogen production scheme



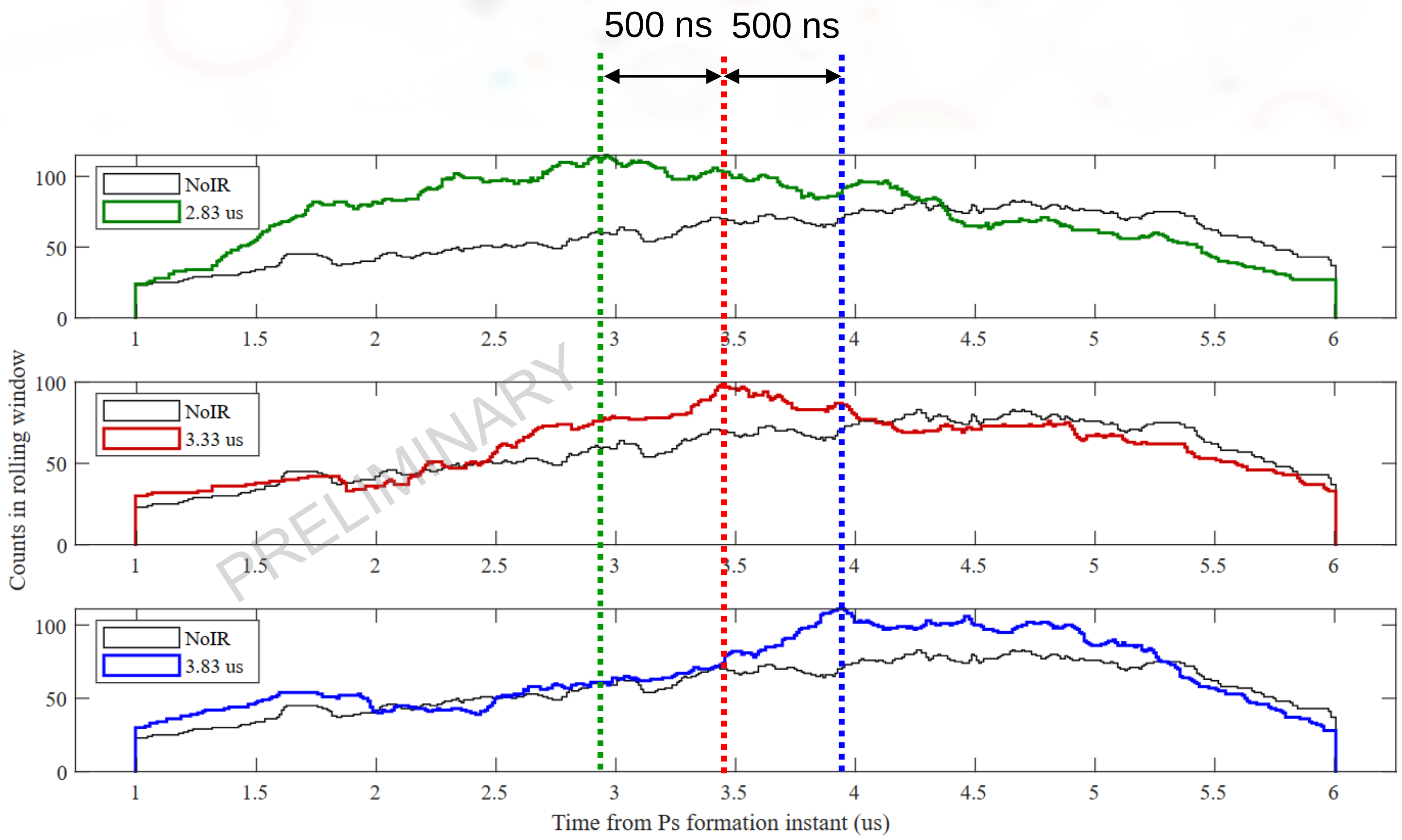
Antiprotons swinging in a parabolic potential



Example signal of antiprotons swinging

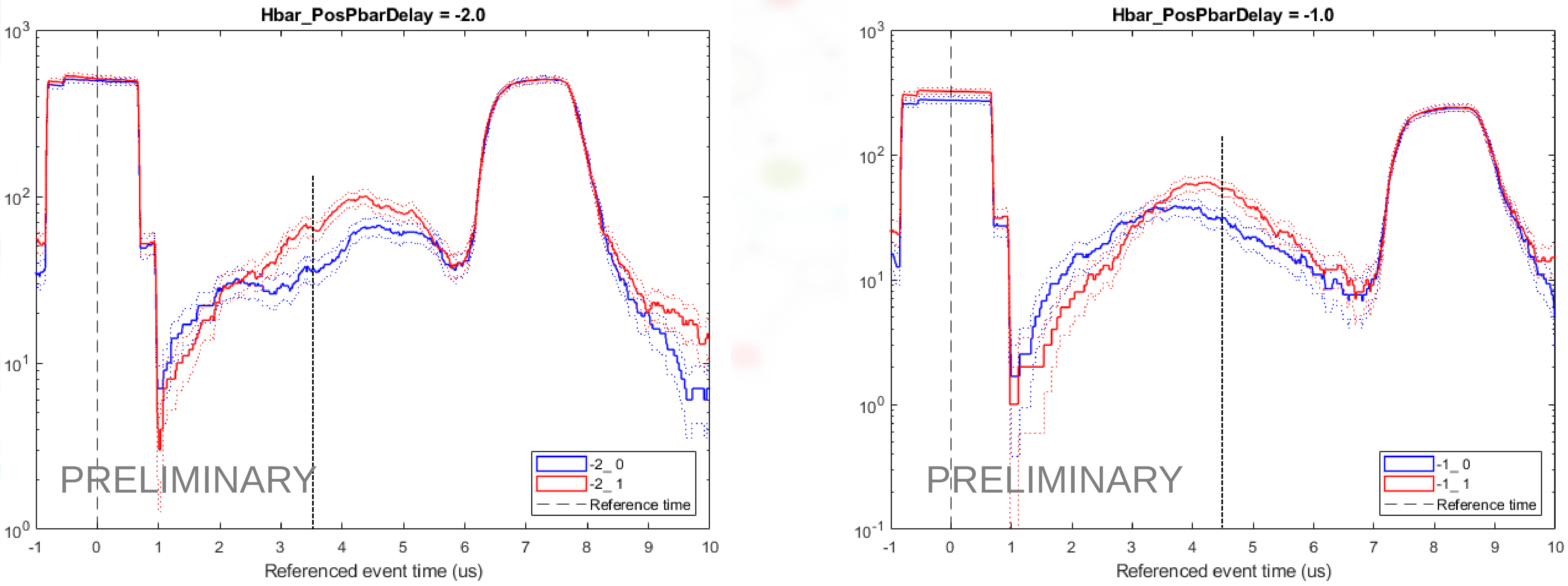


Pulsed antihydrogen boosting: an example signal from 2023



Evidence of antihydrogen production in the collinear scheme and controlled time shift
from the 2023 Physics run with 1.5 months of data taking

Enhanced pulsed production of antihydrogen



Production results with upgraded Rydberg Ps source

- Excess in laser ON/OFF data, significant in one night of data taking
- Confirmed timing shift proportional to e^+-pbar delay as in 2023
- 0.8 events per run in 1.5 us window
- 40% detection efficiency: 2.0 Hbar per run

Achievement #3: enhanced antihydrogen production rate

2018: 0.05 antihydrogens run^{-1}
2024: 2.0 antihydrogens run^{-1}

factor x40 gain

thanks to:

Efficient catching of ELENA antiprotons
All Ps improvements since 2020
(collinear scheme and new trap geometry, higher Rydberg Ps, new e^+ source …)

Next step: a velocity-controlled pulsed antihydrogen beam

Summary and short term plans

Main developments
1) The downstream **beam extraction port**
2) The **moiré** deflectometer and its antihydrogen **imaging detector** (OPHANIM)
3) The **anion source** for controlled antiprotonic atoms formation

Achievements
1) Time-of-flight **spectroscopy for antiprotonic atoms** fragments
2) Single-shot **Rydberg Ps diagnostics**
3) A **40-fold increase** in **antihydrogen** production rate

Main plans for 2025
1) Install and **commission** the **moiré** deflectometer
2) Develop a **forward-boosted** antihydrogen **beam**
3) Controlled antiprotonic atoms formation

Bonuses
1) New **concept** of **room-temperature portable Paul trap** for antiprotons
2) **Rydberg Ps spectroscopy** in 1T
3) Further **progresses** on **Ps laser cooling**

Medium and long term plans

Before LS3

Antihydrogen beam with 10 Hbar min^{-1} or higher

First WEP test with antihydrogen in null magnetic field

Laser cooling of positronium

Cryogenic Ps transmiss. targets

Form Rydberg antiprotonic ions

Form highly charged ions

Time-of-flight spectroscopy of trapped nuclear isotopes

During LS3

Upgrade for Ps transmission targets and Ps cooling

Ps 1^3S-2^3P and 1^3S-3^3P spectroscopy with laser cooling

Ps n=3 hyperfine RF spectroscopy

2D Ps cooling and in B field

Ps charge-exchange with neutralized anions

After LS3

Precision antihydrogen WEP test in a null magnetic field

OTIMA atom interferometry with antihydrogen

Ps 1^3S-2^3S and 1^3S-3^3S spectroscopy with laser cooling

Spectroscopy of Rydberg antiprotonic atoms

Inertial sensing with Rydberg antiprotonic atoms

Search of hexaquark DM candidate via pbar-^{3}He in traps

LS4 and beyond

Search for an antiproton EDM by antiprotonic molecule spectroscopy

Antideuteronic atoms formation and measurement of X-ray cascade

Anti-^{3}He and Anti-T synthesis by antideuteron fusion in Penning traps

Rich antiproton and e^+ physics program well beyond LS3

We would like to renew our interest in the ELENA team's ongoing efforts to investigate the possibility of an antideuteron beam.


The AEgIS collaboration, CERN, 2024

Thank you for your attention