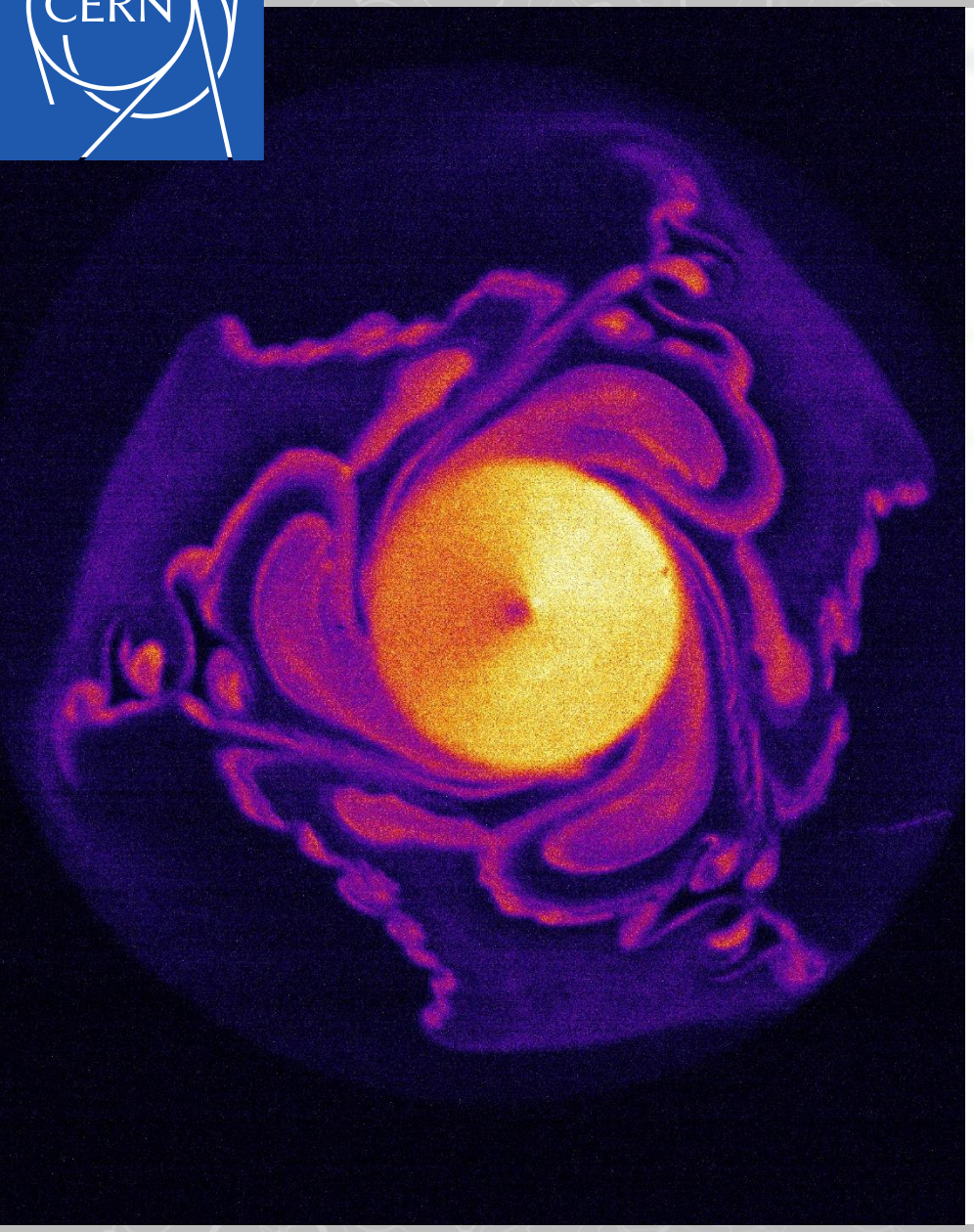


Preventivi LEA-AEgIS 2025

R. Caravita
(AEgIS Spokesperson)

*INFN – TIFPA, Trento (IT)

Istituto Nazionale di Fisica Nucleare
TIFPA
Trento Institute for Fundamental Physics and Applications

AEgIS

Fellini
Fellowship for Innovation at INFN

Test del Principio di Equivalenza Debole: stato dell'arte

ALPHA-g $\overline{\eta_F} = 0.14$

BASE $\overline{\eta_C} = 0.03$

Come si svolge un test del Principio di Equivalenza Debole?

- Misurando il red-shift di una transizione interna ad uno stato legato (WEP_c)
  - Red-shift di una riga atomico dello ^{87}Sr
  - Frequenza di ciclotrone modificata dell'antiprotone in trappola di Penning
- Confrontando la caduta libera di corpi con composizioni interne differenti (WEP_{ff})
  - Bilancia di torsione/masse test in orbita con diverse composizioni isotopiche
  - Caduta differenziale di atomi e antiatomi

Che tipo di modelli teorici sono vincolati da un test di WEP?

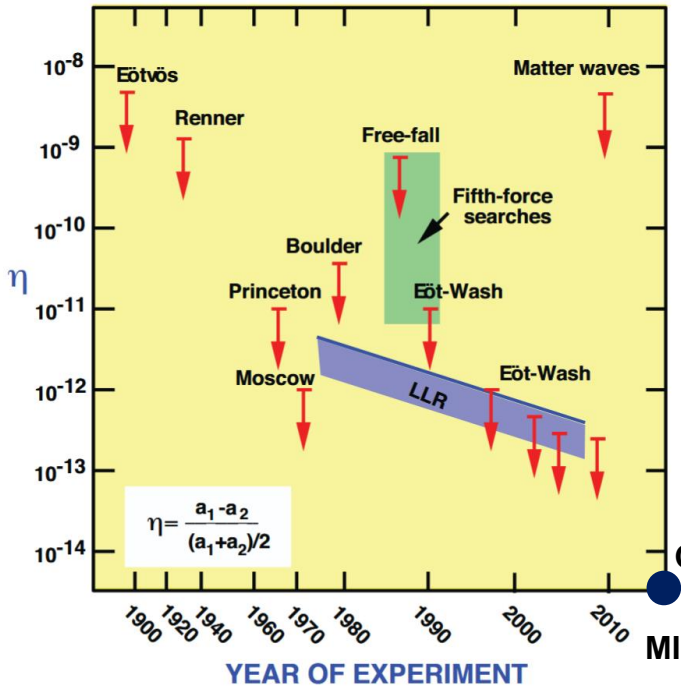
Ipotetiche quinte forze che violano il potenziale newtoniano

gravi-vettore attrattivo/repulsivo

gravi-scalare attrattivo

$$V = -\frac{G_\infty}{r} m_1 m_2 (1 \mp a e^{-r/v} + b e^{-r/s})$$

con cancellazioni in esperimenti di materia se a ~ b e v ~ s

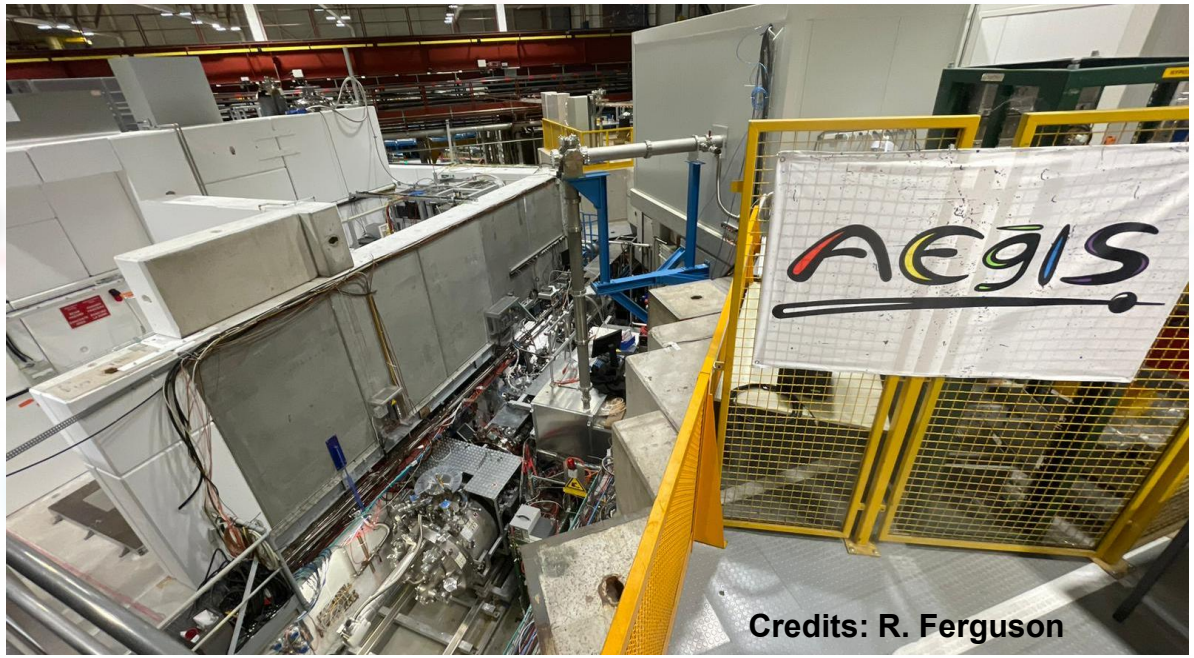


GW170817

MICROSCOPE

C. Will, *The Confrontation Between GR and experiment*, Living Reviews in Relativity (2014)

La collaborazione AEgIS



Antimatter Experiment: gravity, Interferometry, Spectroscopy

- Test del Principio di Equivalenza Debole con un fascio di antidrogeno freddo (goal 1%)
- Sviluppo delle tecniche di raffreddamento, spettroscopia ed interferometria di sistemi neutri (antidrogeno e positronio - antideuterio?)

In numeri: 57 membri, 15 istituti, 10 paesi

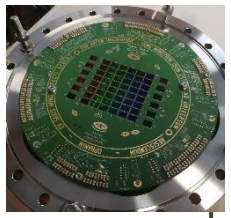
Switzerland	France
Poland	Latvia
Italy	India
Germany	Czech Republic
Norway	UK

Research lines and main achievements

Research lines

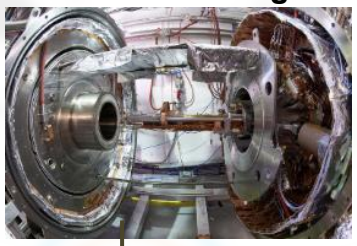
$\bar{H}$ + Ps + $\bar{p}$ atoms + Shared dev. R&Ds

Antihydrogen detector



2008 PROPOSAL

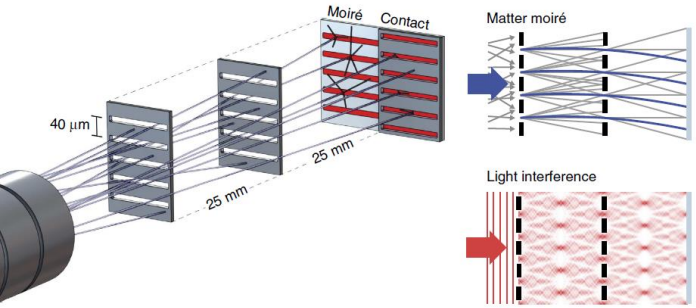
2012 Construction began



2014

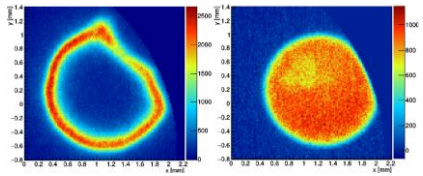
Received 5 Nov 2013 | Accepted 27 Jun 2014 | Published 28 Jul 2014 DOI: 10.1038/ncomms5538 OPEN

A moiré deflectometer for antimatter



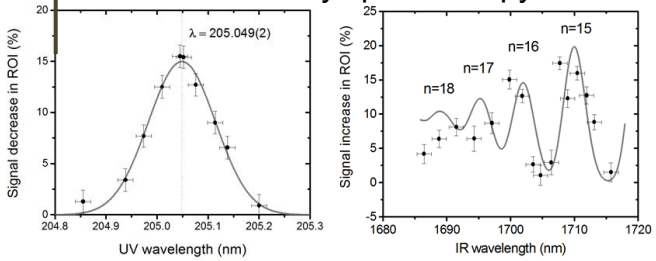
2016

2017 Pbar compression to mm radius



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

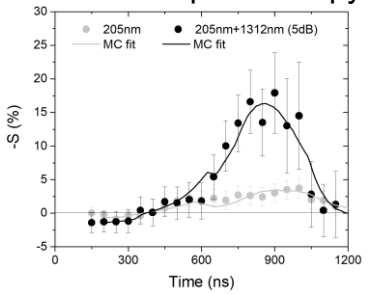
Ps 1S-3P-Ry spectroscopy



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

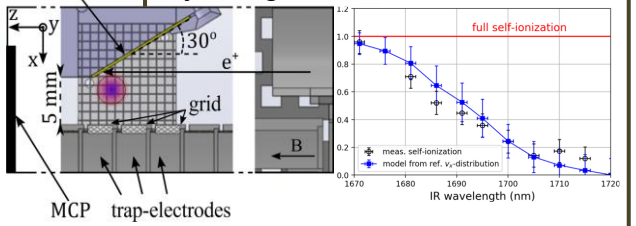
2018

Ps 2S-3P spectroscopy



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

2019 Rydberg Ps in 1T

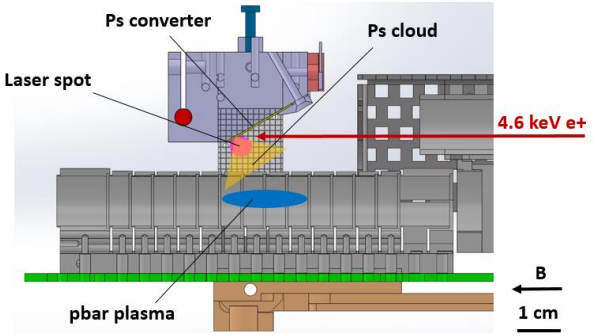


M. Antonello et al., PRA **102,** 013101 (2020)

2020

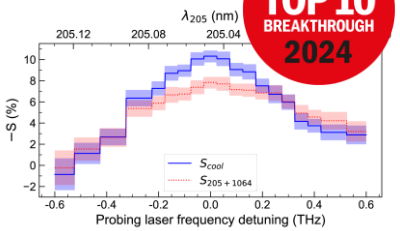
https://doi.org/10.1038/s42005-020-00494-z OPEN

Pulsed production of antihydrogen



2024 2025

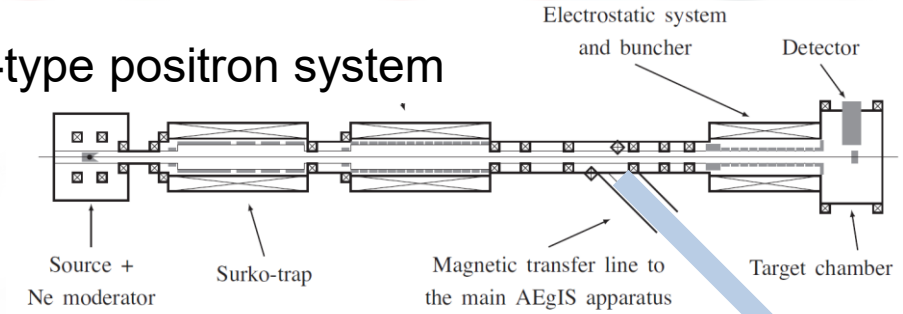
physicsworld TOP 10 BREAKTHROUGH 2024



Ps laser cooling

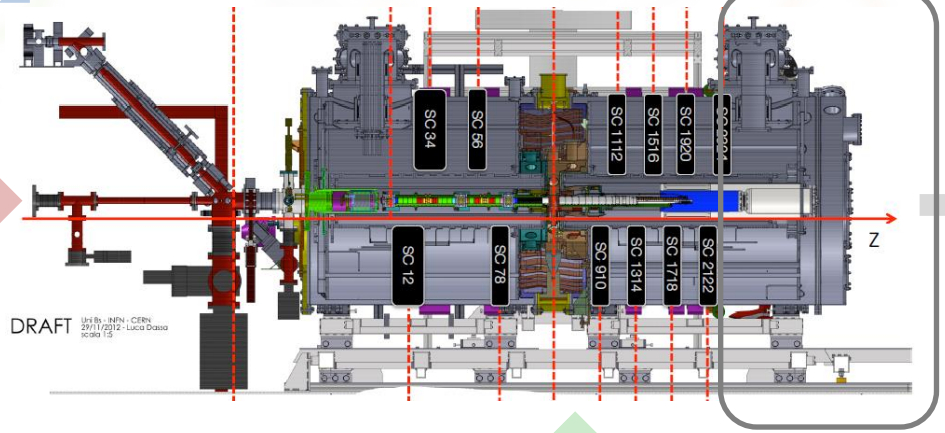
The AEgIS apparatus in 2025

Surko-type positron system

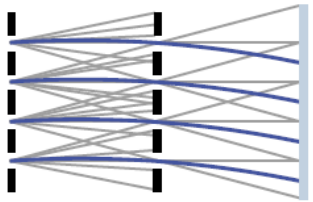


Trap control system

Main AEgIS cryostat



Gravity detector



Deflection chamber

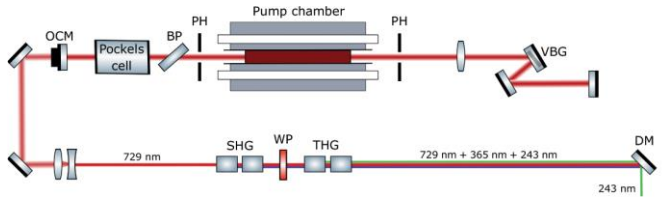
ELENA

Extra Low ENergy Antiprotons

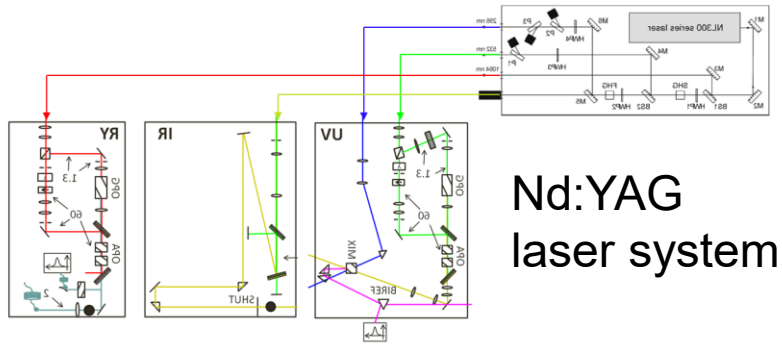
Ion injection line

Antiprotons extraction line

Alexandrite laser system



Nd:YAG laser system



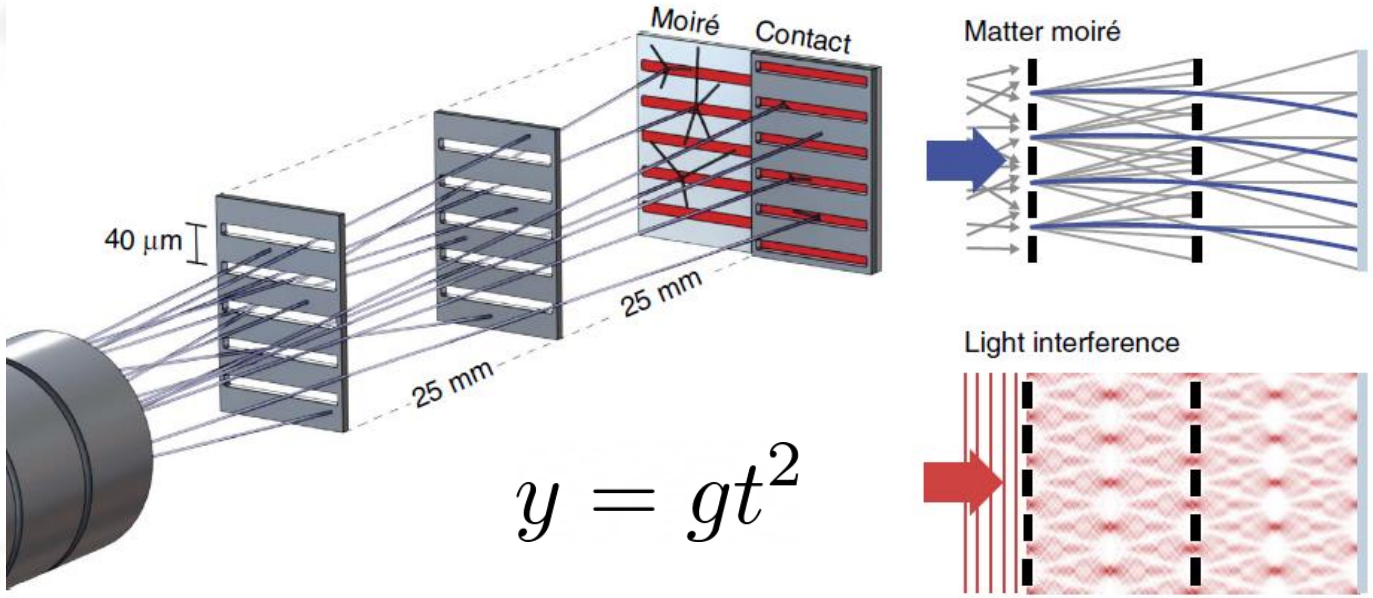
Lo schema di AEgIS: deflettometria/interferometria in campo nullo

ARTICLE

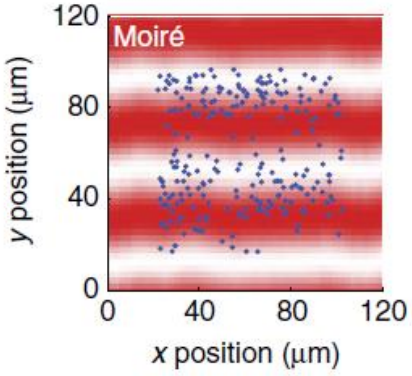
Received 5 Nov 2013 | Accepted 27 Jun 2014 | Published 28 Jul 2014

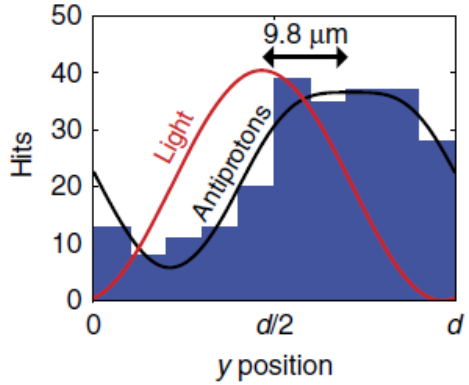
DOI: 10.1038/ncomms5538 OPEN

A moiré deflectometer for antimatter



$$y = gt^2$$





$$\left(\frac{\delta a}{a}\right)^2 = \left(\frac{\delta y}{y}\right)^2 + \left(2\frac{\delta \tau}{\tau}\right)^2$$

$$\begin{cases} t = 1\ \mathrm{ms} \\ \delta g/g = 10\,\% \end{cases} \rightarrow \begin{cases} \delta y \ll 1\,\mu\mathrm{m} \\ \delta t \ll 50\,\mu\mathrm{s} \end{cases}$$

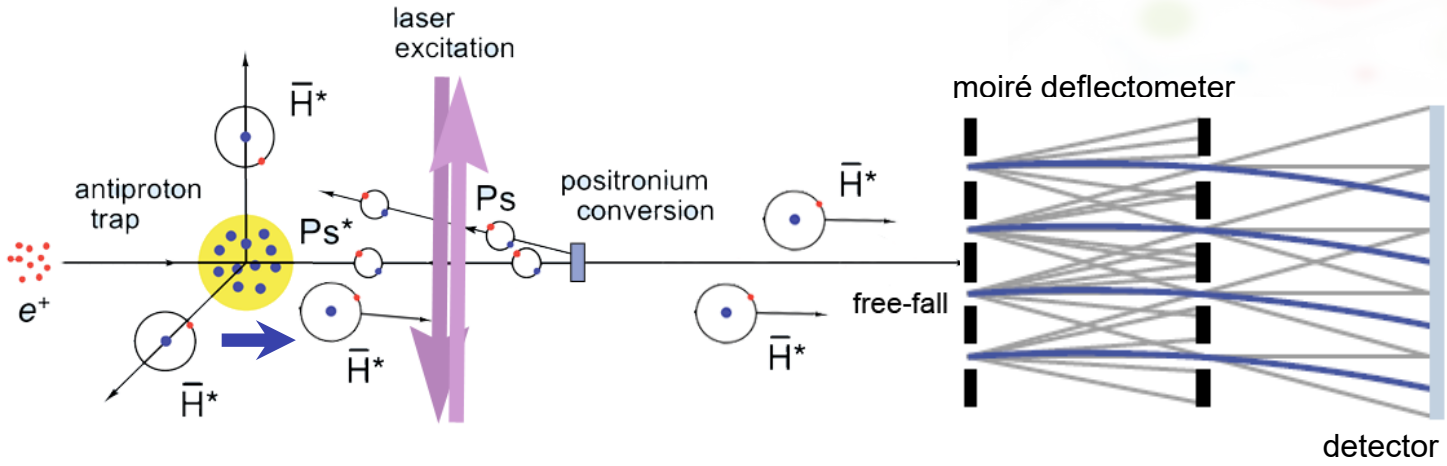
- Deflettometro di moiré: sistema di due reticoli + rivelatore
- Misura della deflessione e del tempo di volo
- Riferimento non deflesso di luce, cross-calibrato con particelle

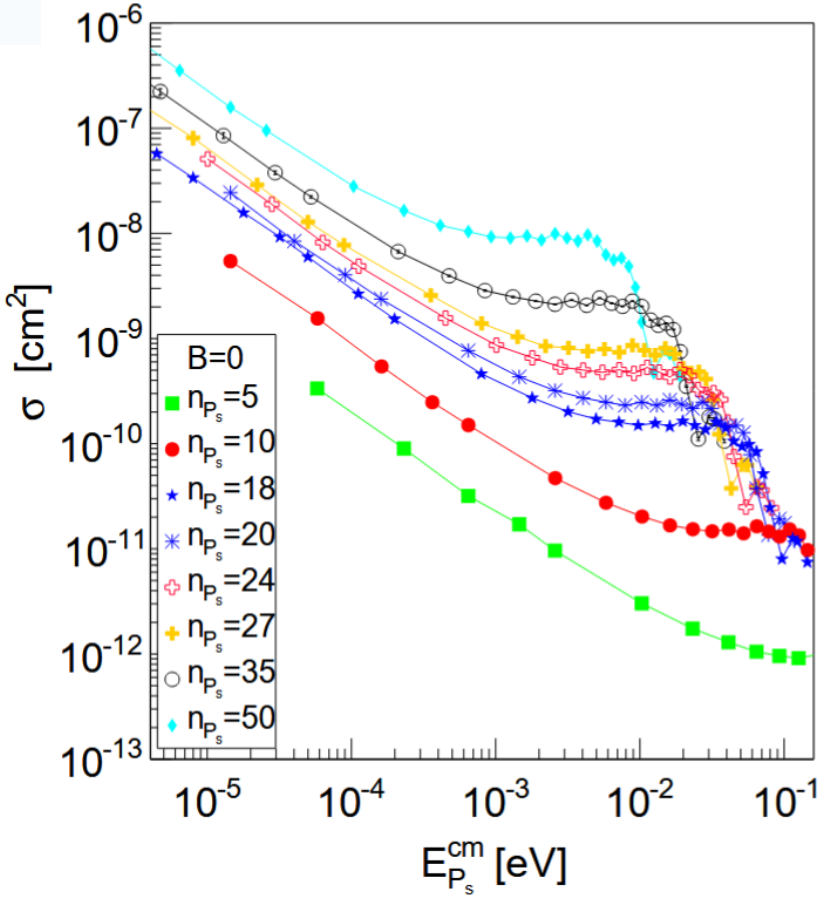
Richiede una sorgente pulsata e ...

➡ **Rivelatore di vertice ad alta risoluzione spaziale**

La sorgente pulsata di antidrogeno

$$Ps^* + \bar{p} \rightarrow \bar{H}^* + e^-$$





Sezione d'urto di scambio carica

- Cresce come n_{Ps}^4 (ma n > 30 è difficile)
- Cresce come E_{Ps}^{-1} : richiede sorgenti di positronio fredde

➡ **Laser cooling del positronio**

C. Amsler et al. (The AEgIS collaboration), Communications Physics **4** (2021) 19
D. Krasnicky, R. Caravita, C. Canali, G. Testera, Phys. Rev. A **94** (2016) arXiv:1608.02785v1

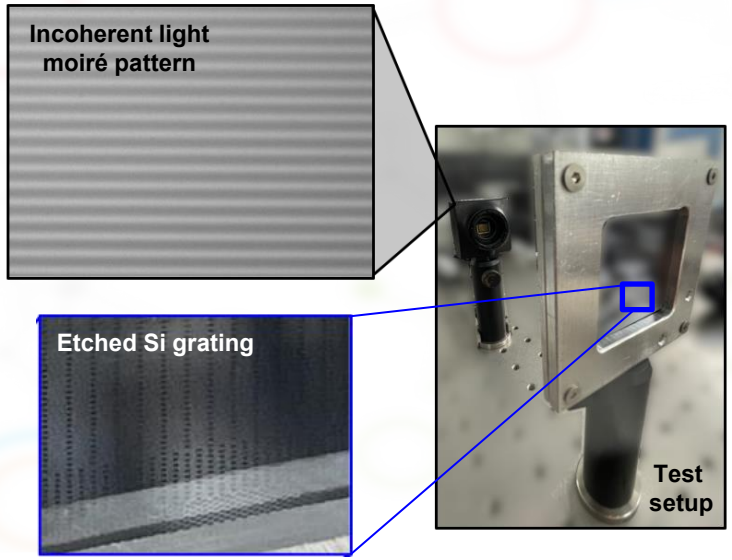
Roadmap AEgIS

AEgIS roadmap	2023		2024		2025		2026	
Nominal catching pbar from ELENA	X							
Pbar electron cooling and transfer to 1T		X						
Formation Hbar		X	X					
Beam formation of Hbar in Rydberg state			X	X				
Increasing number of Hbar				X				
Extraction of the antihydrogen beam					X	X		
Study of inertial sensing scheme for Rydberg Hbar	X	X						
Moirè deflectometer construction			X	X	X			
Moirè deflectometer installation						X		
Hbar interaction with grids (proof-of-concept gravity?)							X	
Implementation of position sensitive detector for Hbar			X	X				
Proof-of-concept positronium cooling	X							
Positronium cooling to cryogenic temperatures								X

Milestone proposte per il 2026

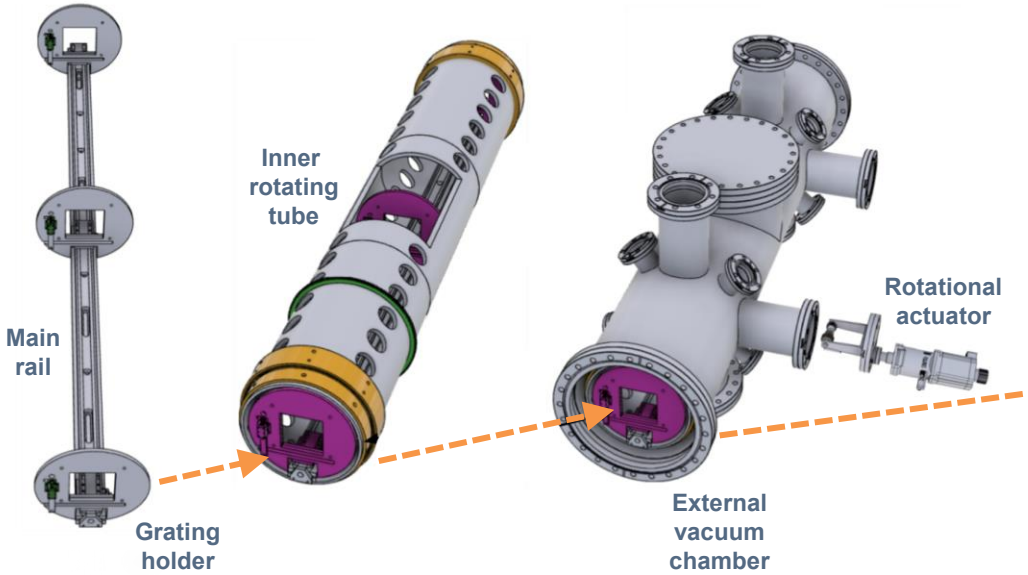
- Rivelazione di annichilazioni nel deflettometro di moiré, definizione della procedura di riferimento e caratterizzazione delle sistematiche per la misura di gravità
- Raffreddamento laser del positronio a temperature criogeniche

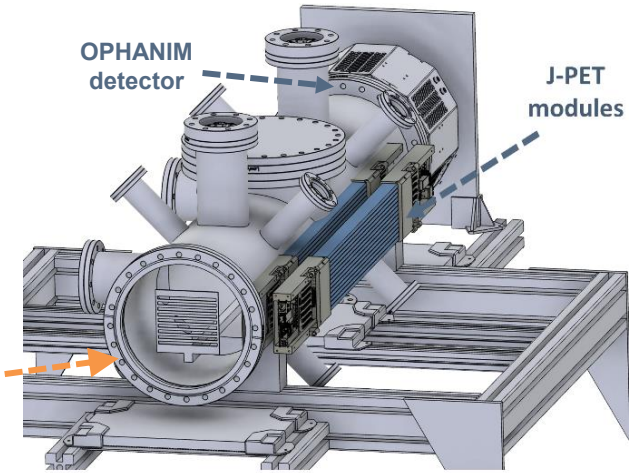
Main Developments in 2024: the moiré deflectometer



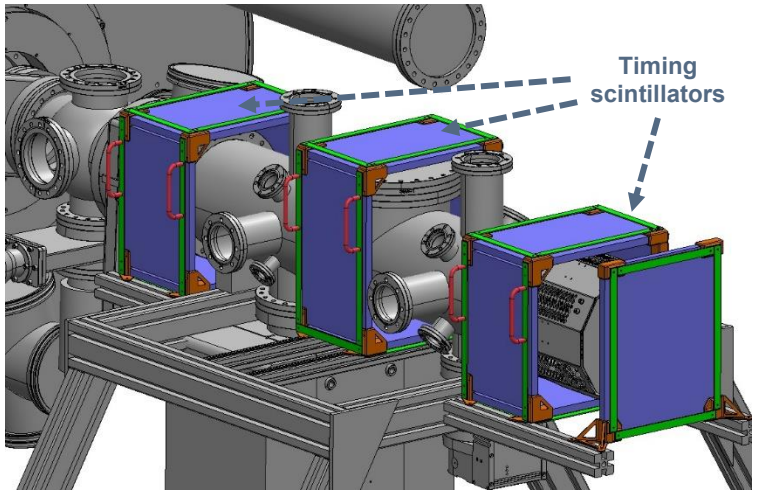
Design of external moiré deflectometer

- 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



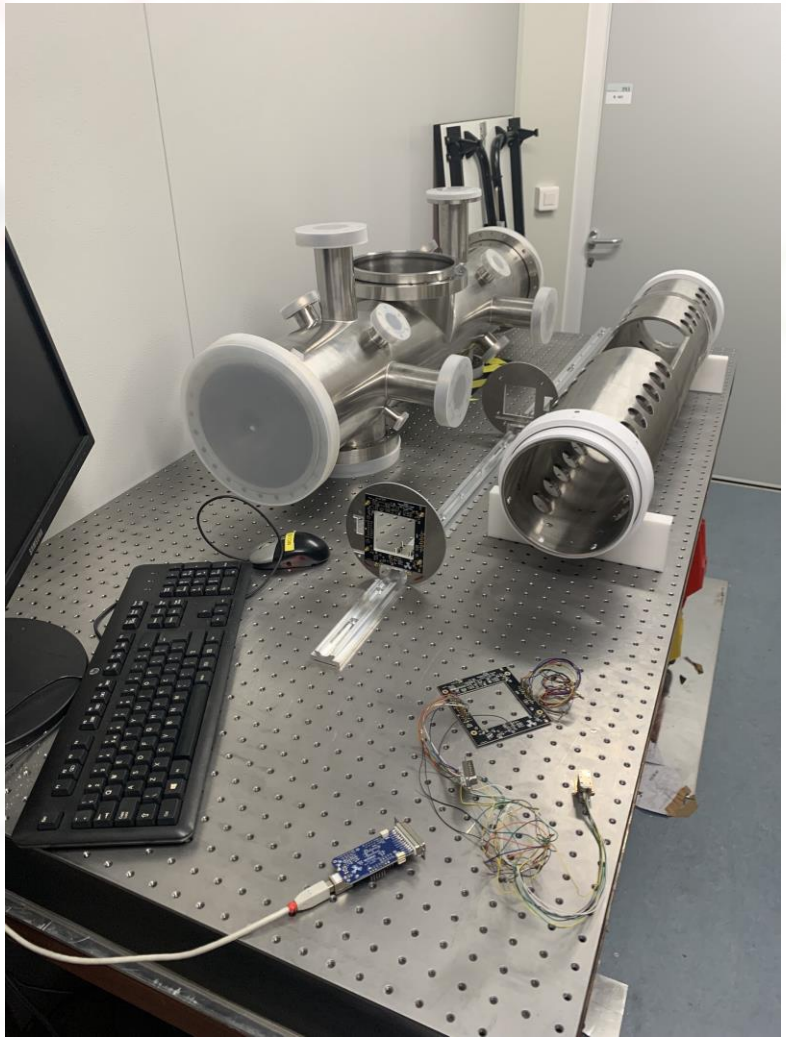


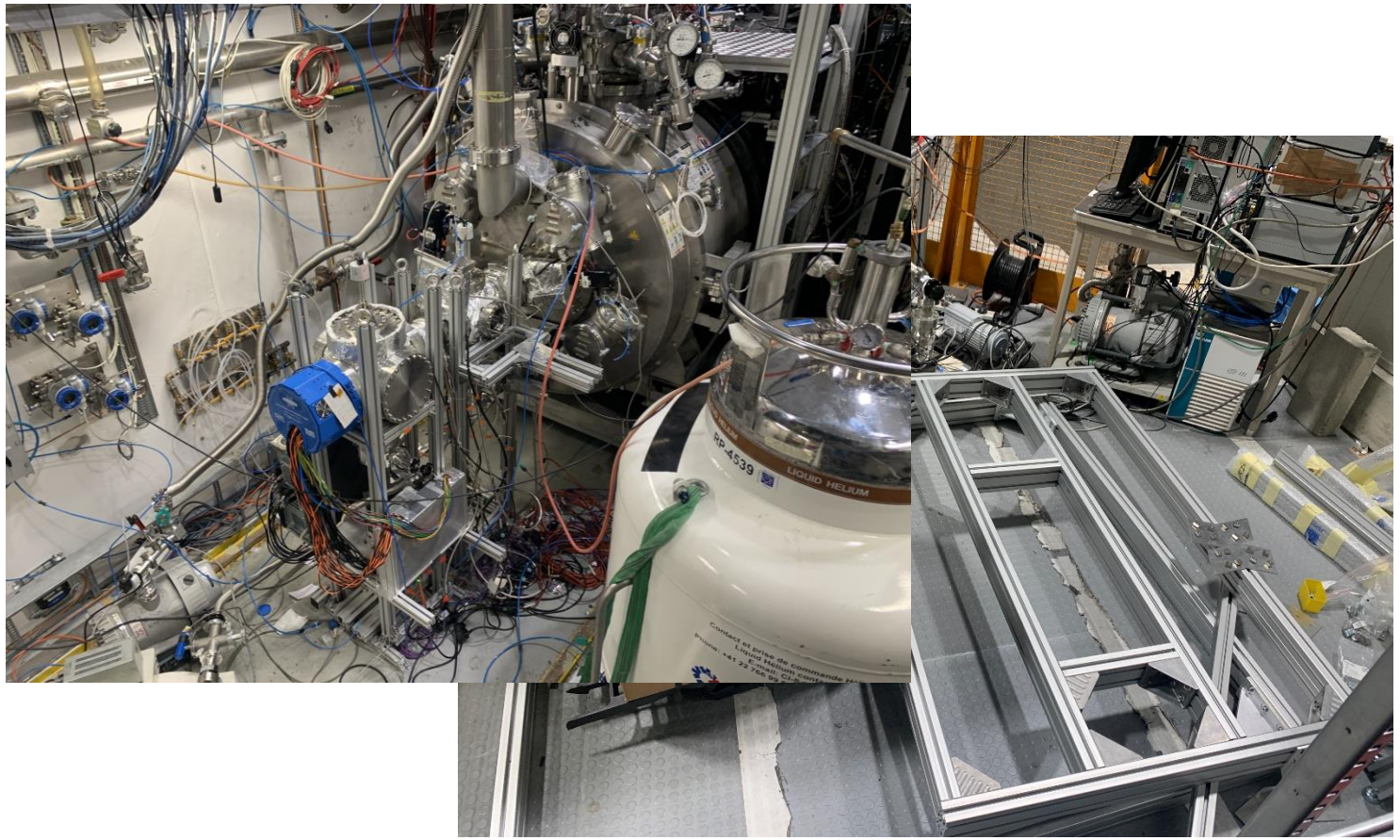
Front view



Back view

Work in progress





Tutte le parti al CERN, supportato da INFN SimilFellow

Richieste per il 2025

Anagrafica	AEgIS (4.5 + “1.2” FTE)
Caravita	0.8
Brusa	0.5
Mariazzi	0.2
Chehaimi	0.2
Ferguson	1.0
Penasa	0.6 (tec)
Zurlo	0.2
Castelli	0.4
Consolati	0.4
Prelz	0.2
*PhD1	0.2
*PhD2	1.0

Richieste per il 2026

Richieste AEgIS 2026			
Capitolo	Sede richiedente	Richiesta	costo
Common Funds	TIFPA-Mi-Polimi-Pavia (Brescia)	3 CHF x 8	24 CHF – 26 k€
Apparati	Polimi	Crate NIM (sostituzione, guasto)	~~5~~ 3.5 k€
Apparati	TIFPA	MCP (sostituzione, rotto)	5 k€
		Camera (sostituzione, guasto)	15 k€
		Turbo CF100 (sostituzione, guasto)	10 k€
		Scroll (sostituzione, end-of-life)	5 k€
		Manutenzione 2 Cryopompe	10 k€
Totale			**~~76~~ 71.9 k€**
Missioni	TIFPA	3 Ricercatori (con Spoke) + Tecnico + 3 PhD (no SimilFellow – end Mar25) Missioni collaboration meeting (5 k) Laser-Positroni-trappole (50/50)-moirè Presa dati antidrogeno (20 w) e positronio (5 w): 50 w/uomo (50 k)	55 k€
	Mi-Polimi	2 stud - 3 Ricercatori (con Chairman Board) Missioni CERN + 2 Collaboration Board + missioni Italia (3k) Detectors-moirè-presa dati-supporto gestione apparato (5k)	8 k€
	Pavia (Brescia)	1 ricercatore x 2 settimane per manutenzione fototubi e turni di calibrazioni durante la presa dati con antiprotoni (2k)	2 k€
Totale			**65 k€**

Sul cryocooler

Stefan Ulmer

To: Jeffrey Scott Hangst; Ruggero Caravita

Cc: Francois Butin

You forwarded this message on Fri 4/11/2025 19:10

Dear Jeff, dear Ruggero,

I share here a few statements forwarded by the new PS/SPS coordinator Martin Jaeckel, after a discussion with our research director Joachim Mnich

Statement 1: From the physics side (after discussing it with Joachim), the existing agreement should stay (largely) unchanged.

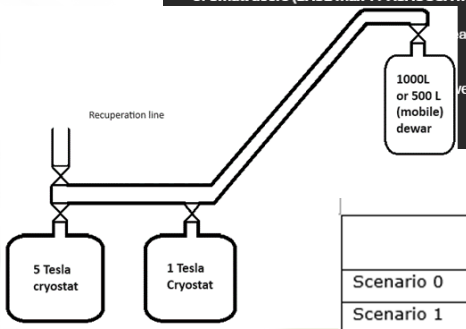
- **20 dewar limit for AD**
- **First pick of helium is for the smaller consumer, so they do not get punished**
- **9 dewars are reserved for Alpha, the rest can go to Aegis and Alpha according to the internal coordination by Stefan.**
- **in case the internal coordination will not work, Joachim and myself will invite the spokespersons to a meeting.**

It is also defined what the existing agreement means:

1. **AEGIS 6 per week**
2. **ALPHA 9 per week**
3. **Small users (BASE max 1 / ASACUSA max 2 / GBAR and STEP small amounts) will be supplied.**

adquarters:

eek and GBAR/ASACUSA from time to time 1/week)



	Total helium evaporation	% of a 500-l dewar		Increase w.r.t. scenario 0
Scenario 0	137.4 L / week	27.5 %		-
Scenario 1	187.6 L / week	37.5 %		+50.2 Liters / week (+1.9%)
Scenario 2a	255.2 L / week	51.0 %		+117.8 Liters / week (+4.4%)
Scenario 2b	298.9 L / week	59.8 %		+161.5 Liters / week (+6.1%)
Scenario 3	387.9 L / week	77.6 %		+250.5 Liters / week (+9.4%)

Novità

- Apparato AEgIS completato in 2024 con foro frontale per estrazione. Consumo passato da 6 a 9.5 dewar/settimana.
- Statement del CERN che definisce limite a 6 dewar/week, oltre è sotto arbitraggio
- Vincolo al posizionamento dei dewar per sicurezza -> transfer lines lunghe -> incremento consumi di elio

Necessità di un margine per garantire l'operation

- Riduzione angolo solido disponibile all'estrazione antidrogeno di un fattore 10 (heat shield)
- Upgrade con pulse tube cryocooler

Delibera CB meeting Mar 2025 per reperimento risorse (circa 150 k€) per Cryomech PT450

Evoluzione negli ultimi dieci giorni: misurato il rate di consumo di elio con heat shield in 6.5 dewar/week, superiore di 0.5 al limite: garantita operation con ridotto angolo solido (al pelo ...)

Possiamo sopravvivere: spostata la richiesta al 2027 e installazione durante LS3, ma richiesta fondi per cryocooler rimane (sopravvivenza ...)

Sul cryocooler

Warsaw University of Technology

Faculty of Physics

Warsaw, 10.07.2025

Dr hab. Georgy Kornakov, prof. PW
Nuclear Physics department

To whom in may concern

In 2025, the CERN Director of Research has indicated a normal-operation level liquid helium consumption of 6 dewars/week to the AEgIS experiment. Currently, the experiment had to limit the consumption of helium to fit this limitation by reducing the solid angle opening to extract the antihydrogen beam, resulting in a limitation in the maximum cold antihydrogen that could be sent to its moiré deflectometer. In order to overcome this limitation, and still fulfill the constraint, a pulse tube cryocooler installation with a cooling capacity of 5W at 4.2K has been envisaged by the AEgIS Collaboration Board in its April 2025 meeting.

The participartion of the WUT Team is supported thtough different schemes, among them, the construction, maintentance and operation of infrastructure is granted by the Science and Education ministry of Poland. The current grant period lasts until end of 2026 and the request for its continuation for the next 5 years will be submitted in the first half of 2026 with starting funding period in 2027. This resource have been instrumental in the last 4 years to keep a permanent presence at the experiment and contribute with a total refurbushment of the control system.

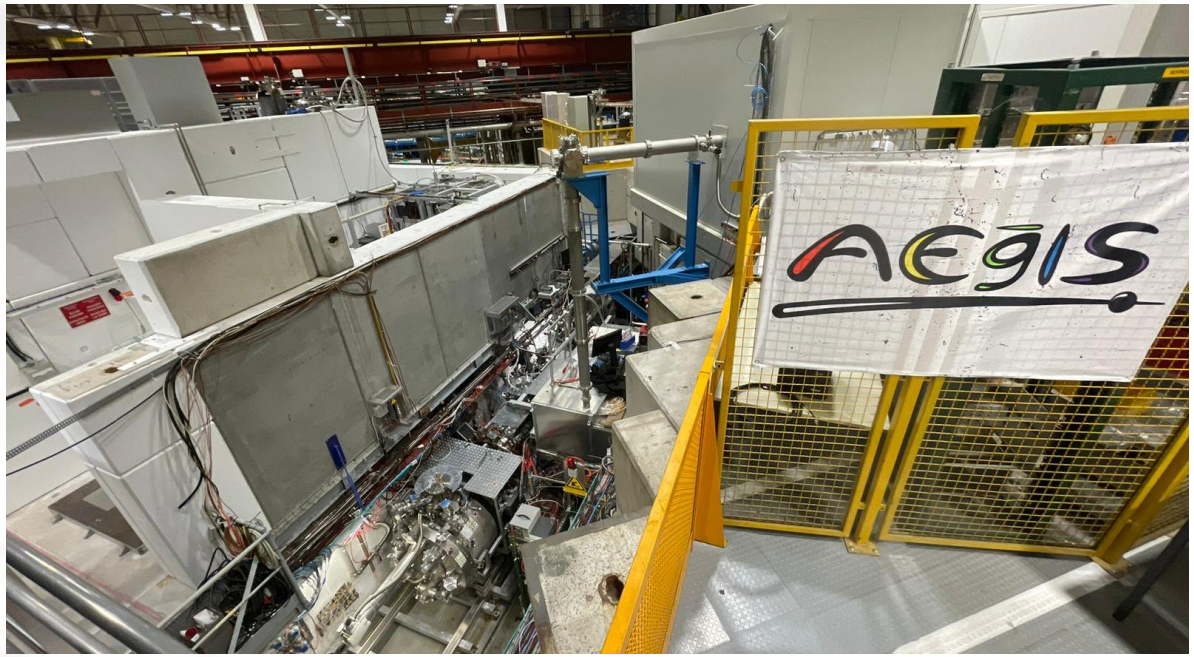
We commit to request funding to solidarly support the procurement of one pulse tube cryocooler with 5W cooling power at 4.2K (namely, a CryoMech PT450) with a total cost estimated at 150 000 €, with a WUT share of 50 %,

Kind regards
Georgy Kornakov

The AEgIS collaboration, CERN, 2024

Thank you for your attention

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!

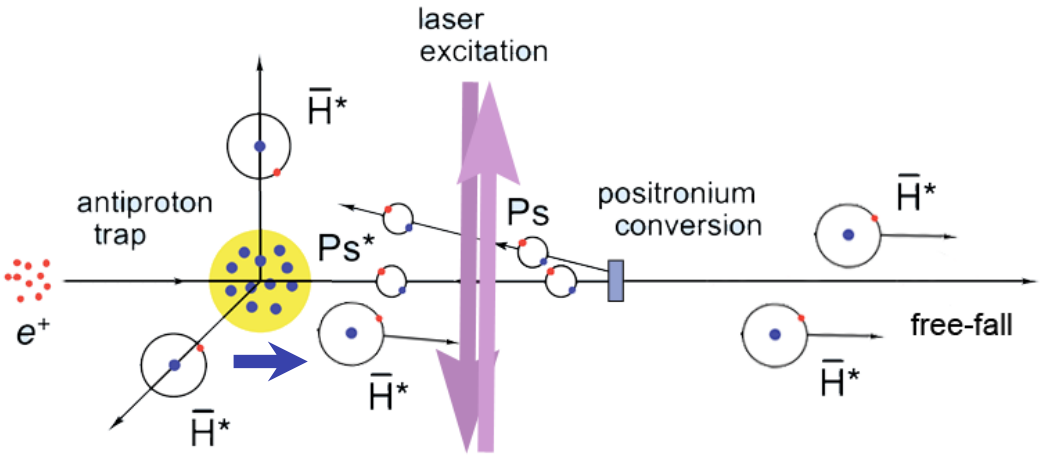
Available systems at AEgIS

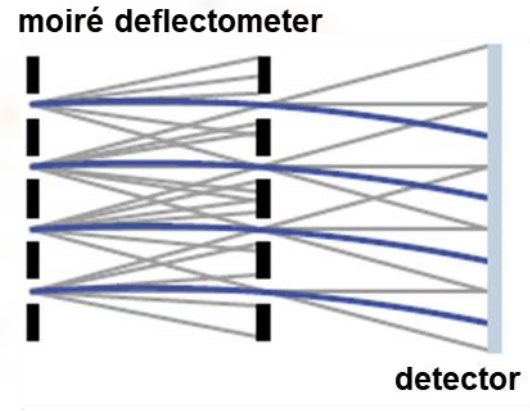
antihydrogen, positronium, antiprotonic atoms

Specialties at AEgIS

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

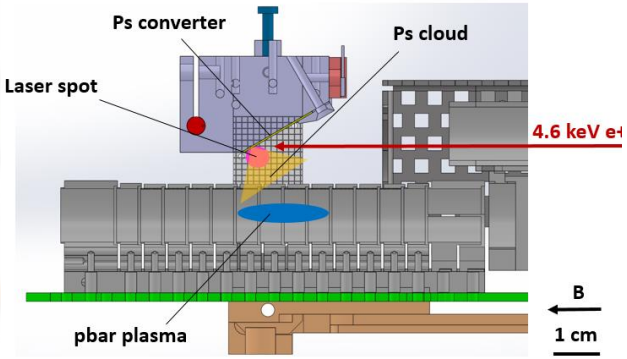
AEgIS flagship program: antihydrogen free-fall

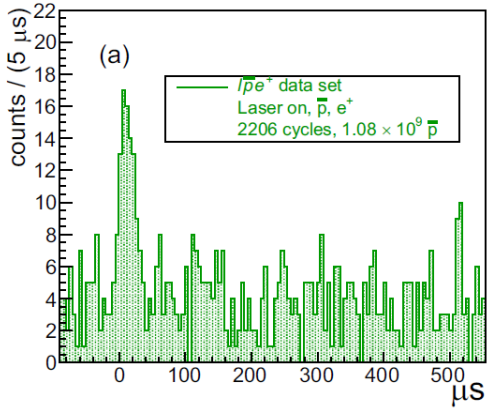




https://doi.org/10.1038/s42005-020-00494-z OPEN

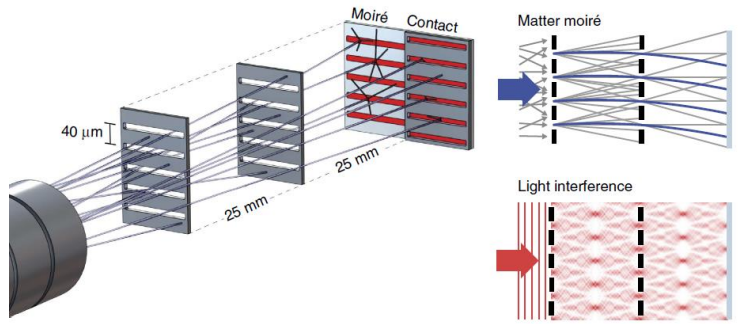
Pulsed production of antihydrogen





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

A moiré deflectometer for antimatter



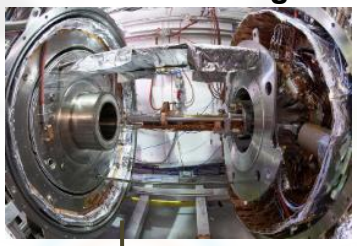
Research lines and main achievements

Research lines

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

2008 PROPOSAL

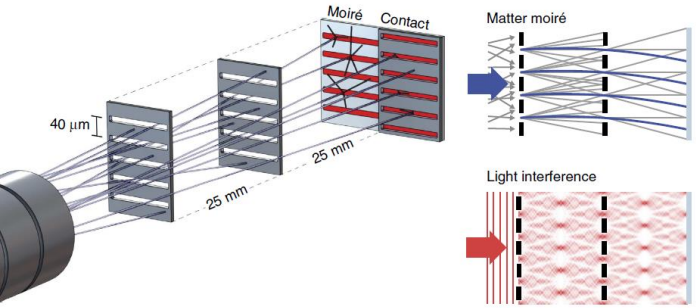
2012 **Construction began**



2014

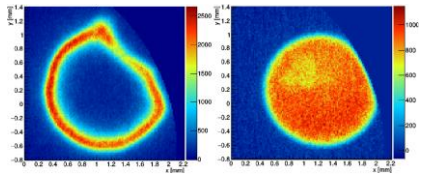
Received 5 Nov 2013 | Accepted 27 Jun 2014 | Published 28 Jul 2014 DOI: 10.1038/ncomms5538 OPEN

A moiré deflectometer for antimatter



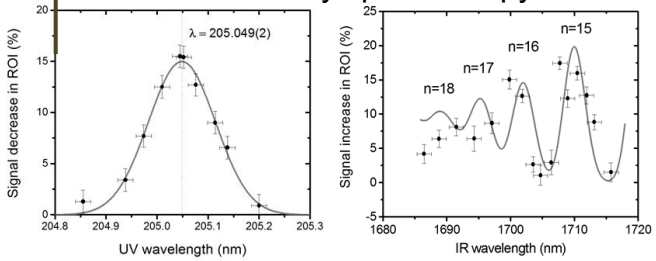
2016

2017 Pbar compression to mm radius



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

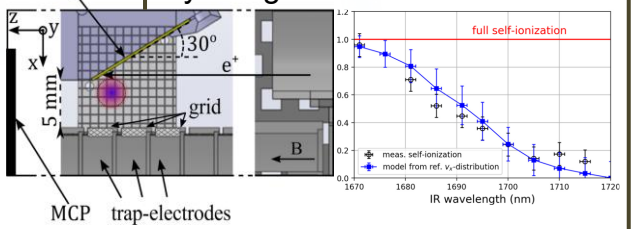
Ps 1S-3P-Ry spectroscopy



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

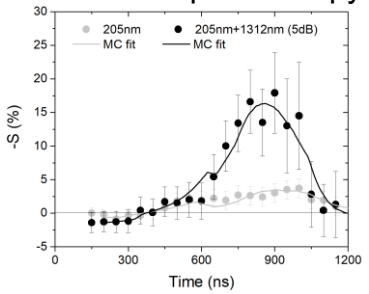
2018

2019 Rydberg Ps in 1T



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

Ps 2S-3P spectroscopy

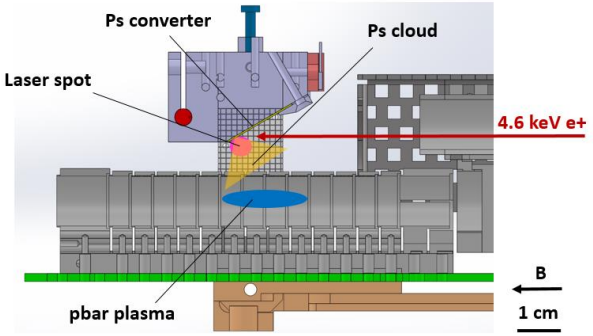


M. Antonello et al., PRA **100,** 063414 (2019)

2020

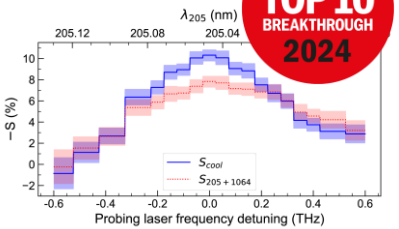
https://doi.org/10.1038/s42005-020-00494-z OPEN

Pulsed production of antihydrogen



2024

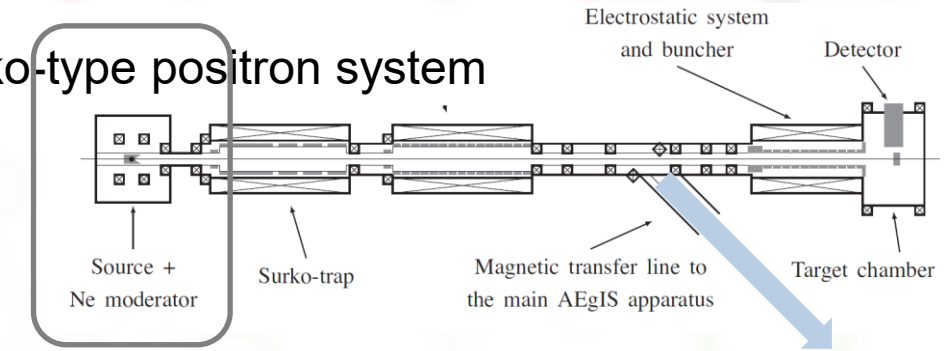
physicsworld TOP 10 BREAKTHROUGH 2024



Ps laser cooling

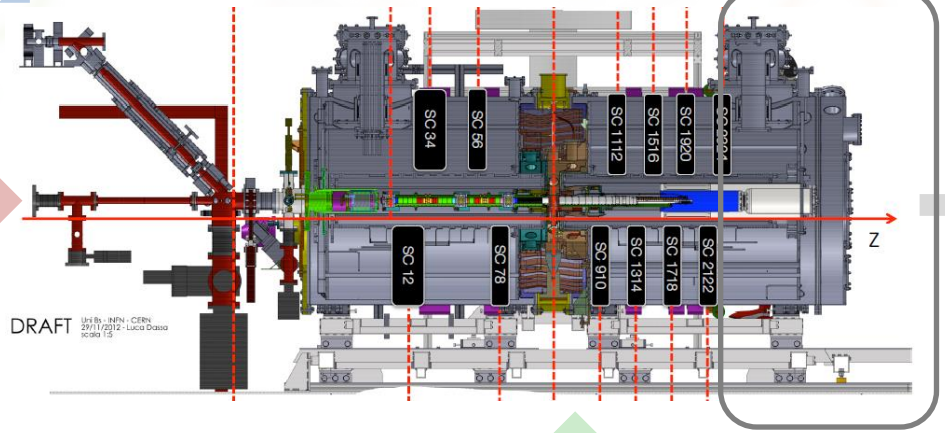
The AEgIS apparatus in 2024

Surko-type positron system

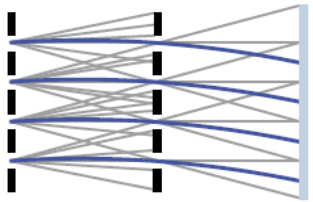


Trap control system

Main AEgIS cryostat



Gravity detector



Deflection chamber

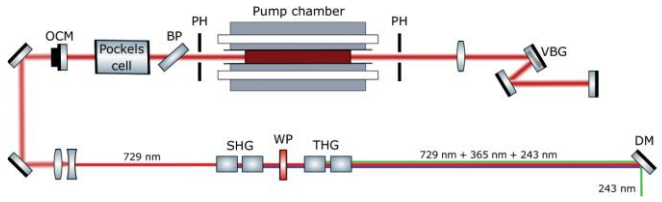
ELENA

Extra Low ENergy Antiprotons

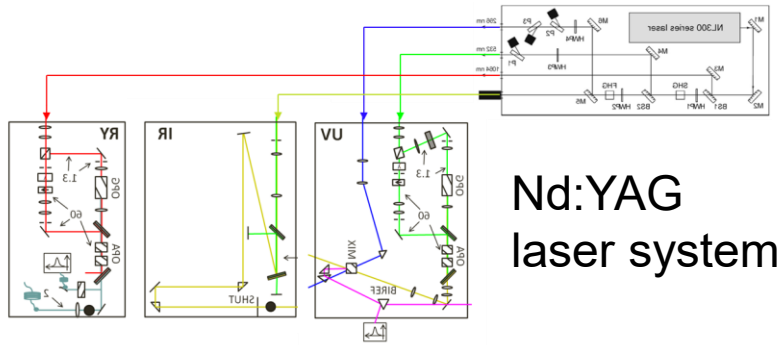
Ion injection line

Antiprotons extraction line

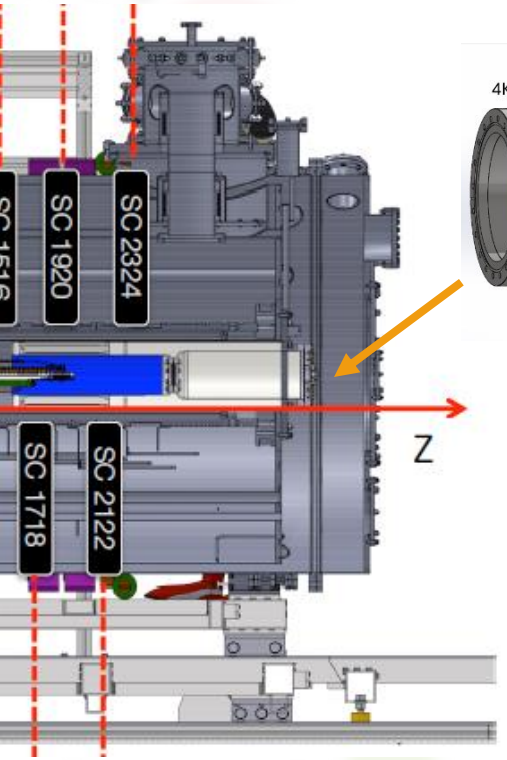
Alexandrite laser system

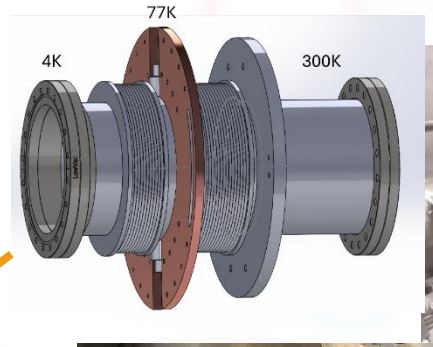


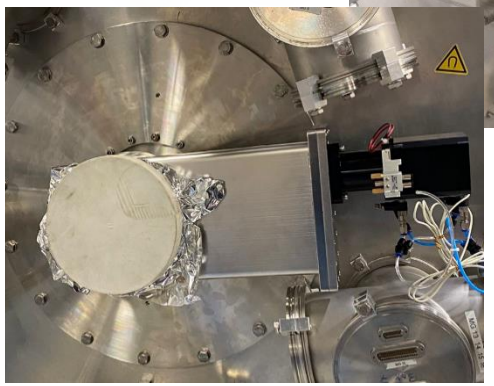
Nd:YAG laser system



Main Developments in 2024: the beam extraction line

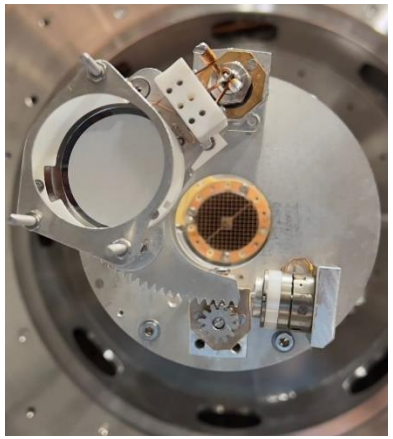


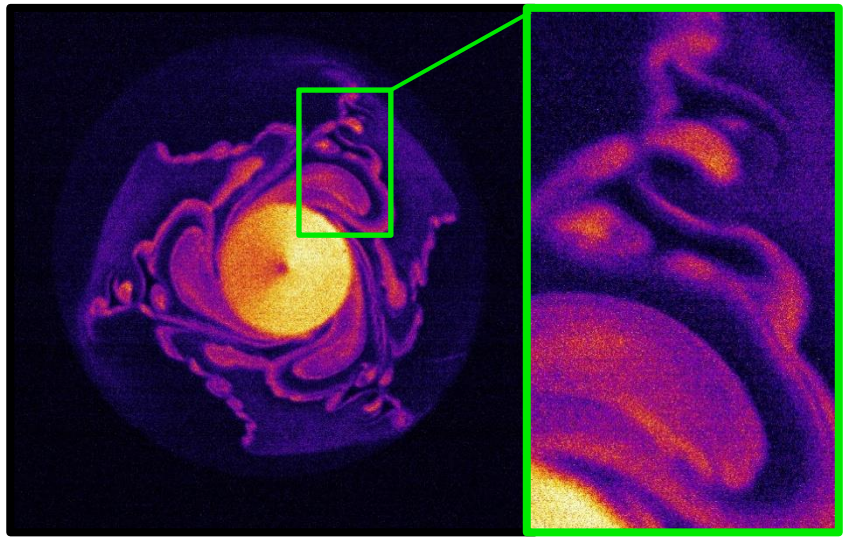




Downstream beam extraction port

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





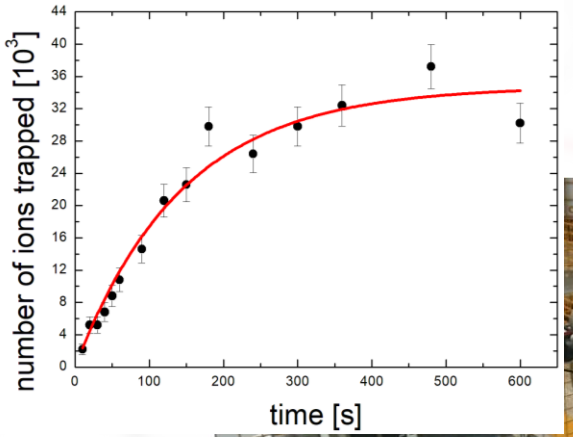
Removable micro-channel plate assembly

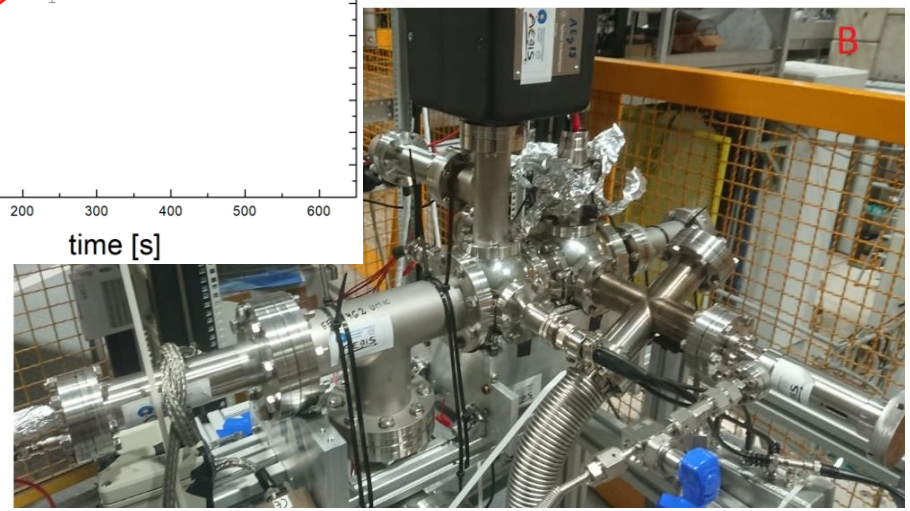
- Can be moved in/out beam axis
- New imaging system with < 50 um resolution

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

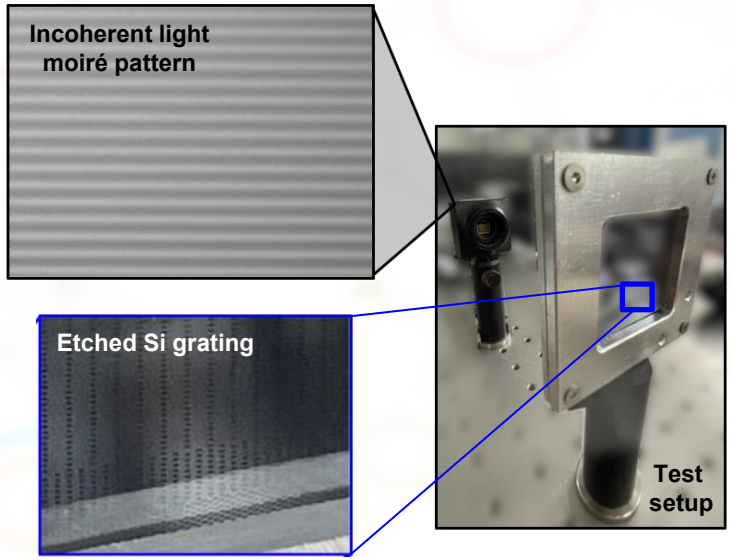




Finally installed our new ^{22}Na source

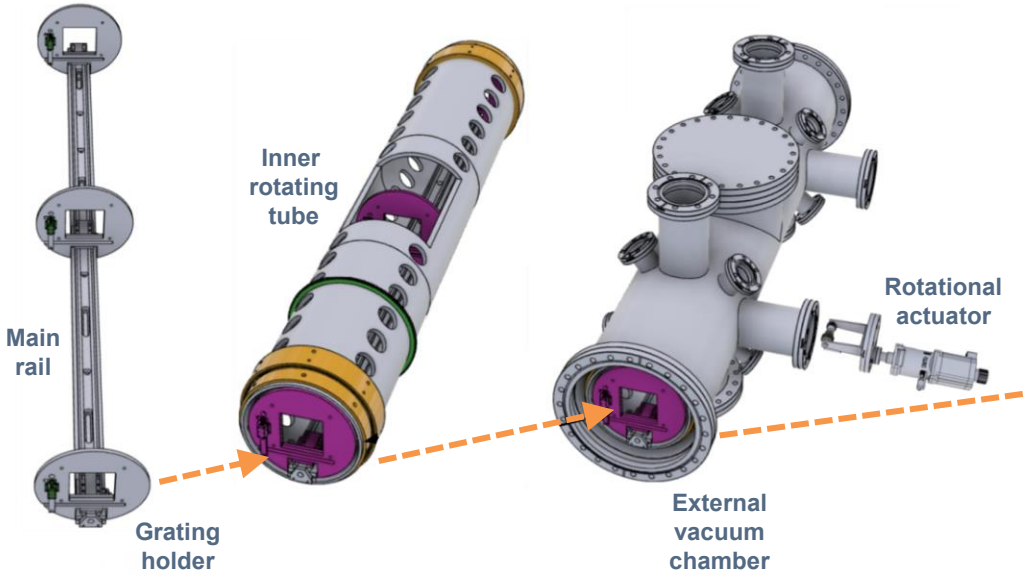
- Delivery in wrong capsule: extra 9 months delay
- Thanks to CERN robotics team, now fixed
- Installed in Sep24, **fully functional**

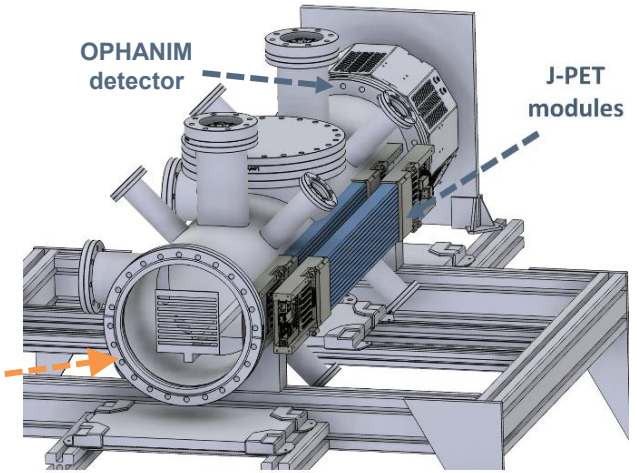
Main Developments in 2024: the moiré deflectometer



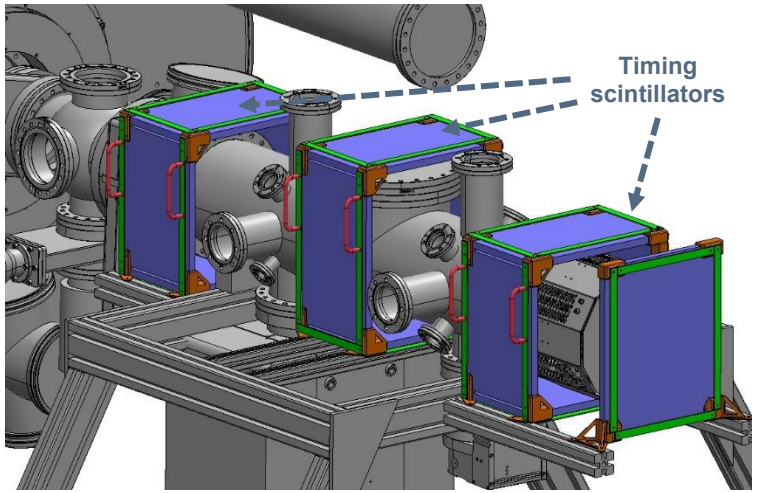
Design of external moiré deflectometer

- 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

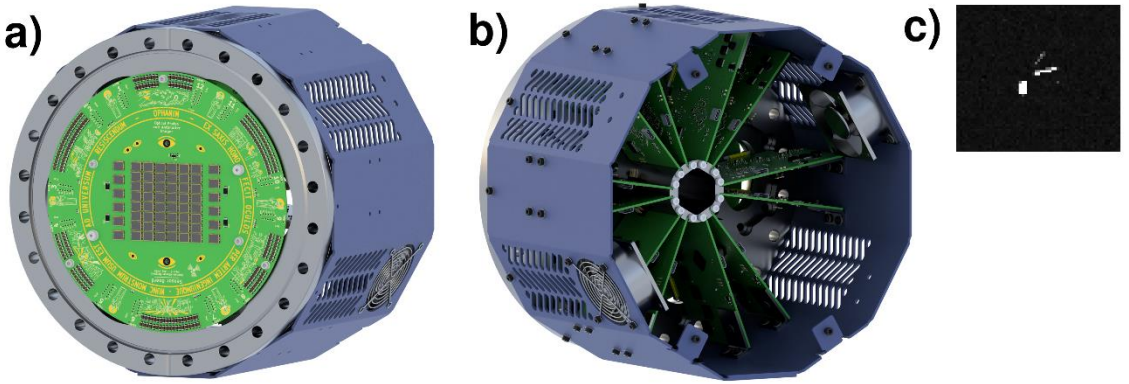


Back view

Main Developments in 2024: the OPHANIM detector

The Optical PHoton and ANtimatter IMager (OPHANIM)

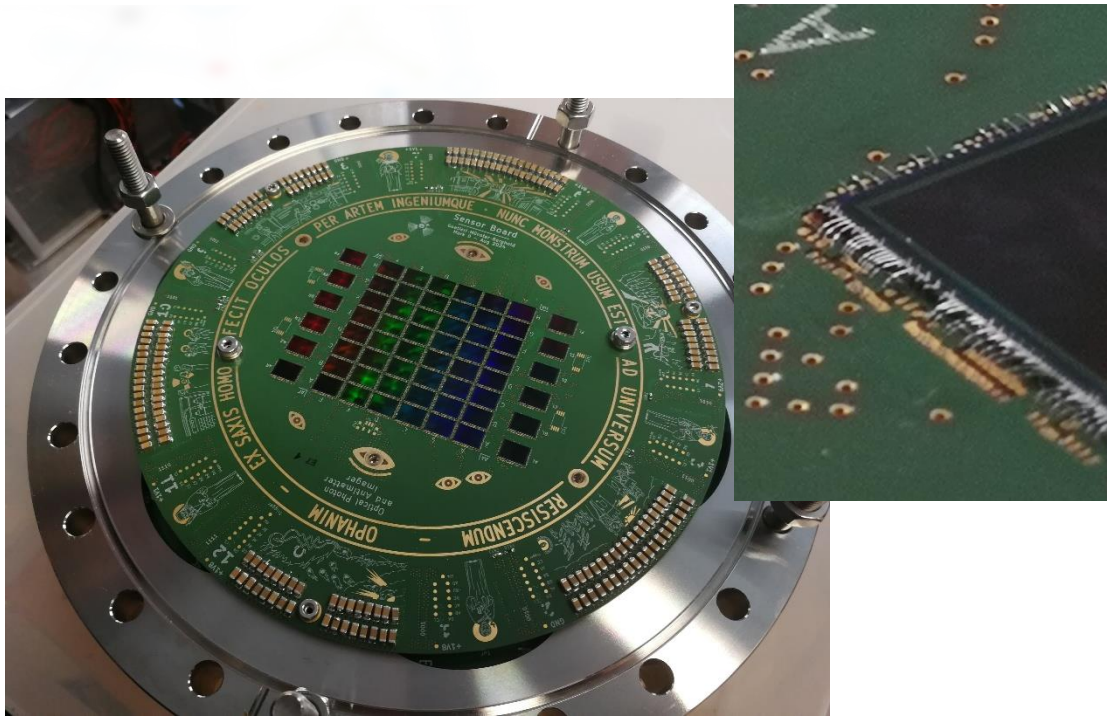
- 60 CMOS sensors, 30.8 cm^2 coverage, 0.8 um pixels
- 64% fill factor, ~70% detection efficiency → 45% total
- World-record-breaking pixel count: 3.84 Gpx [1]
- Vacuum-compatible electronic design at tech. edge



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.

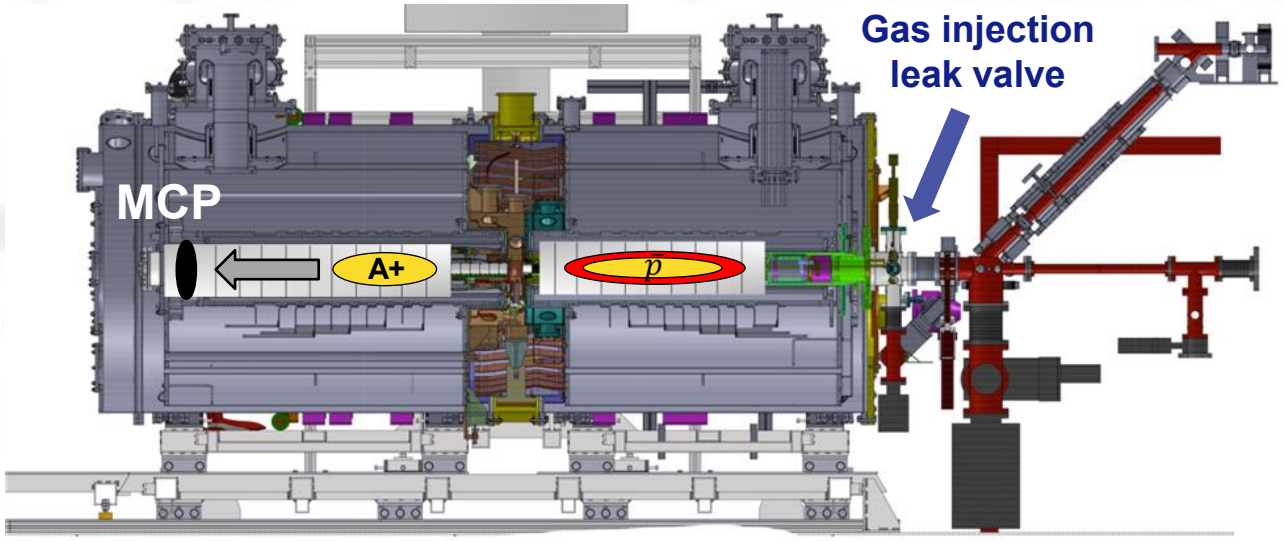


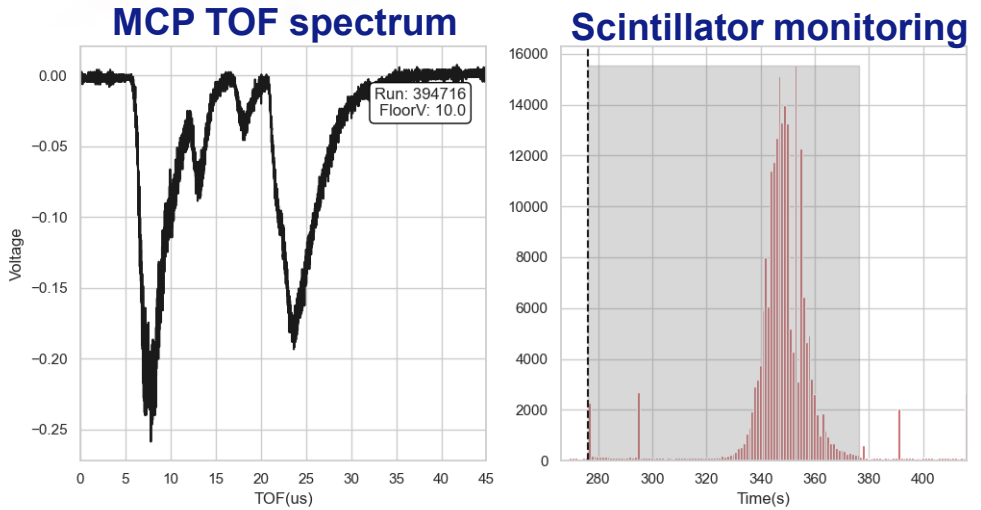
[1] more than the Rubin Observatory LSST camera

Achievements of the 2024 Physics Run

ANTIPROTONIC ATOMS

Technique to form and detect antiprotonic atoms



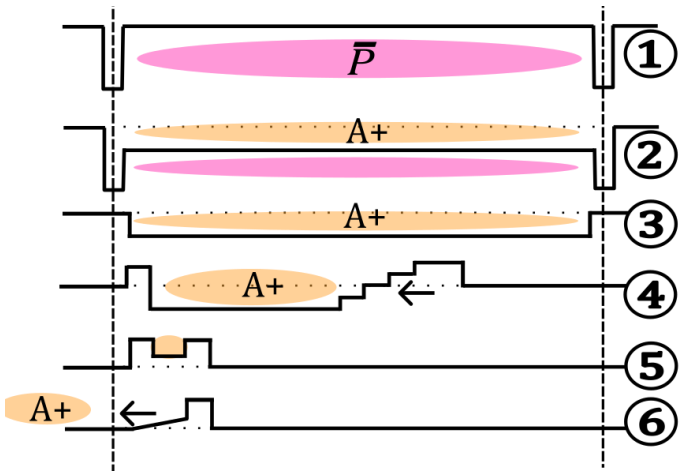


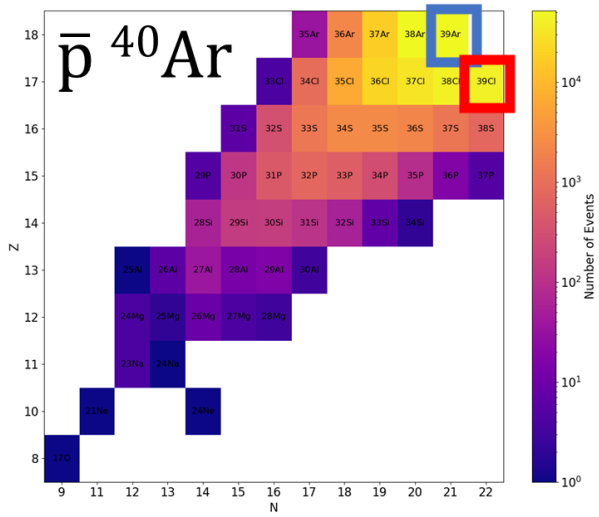
Formation of antiprotonic atoms on buffer gas

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

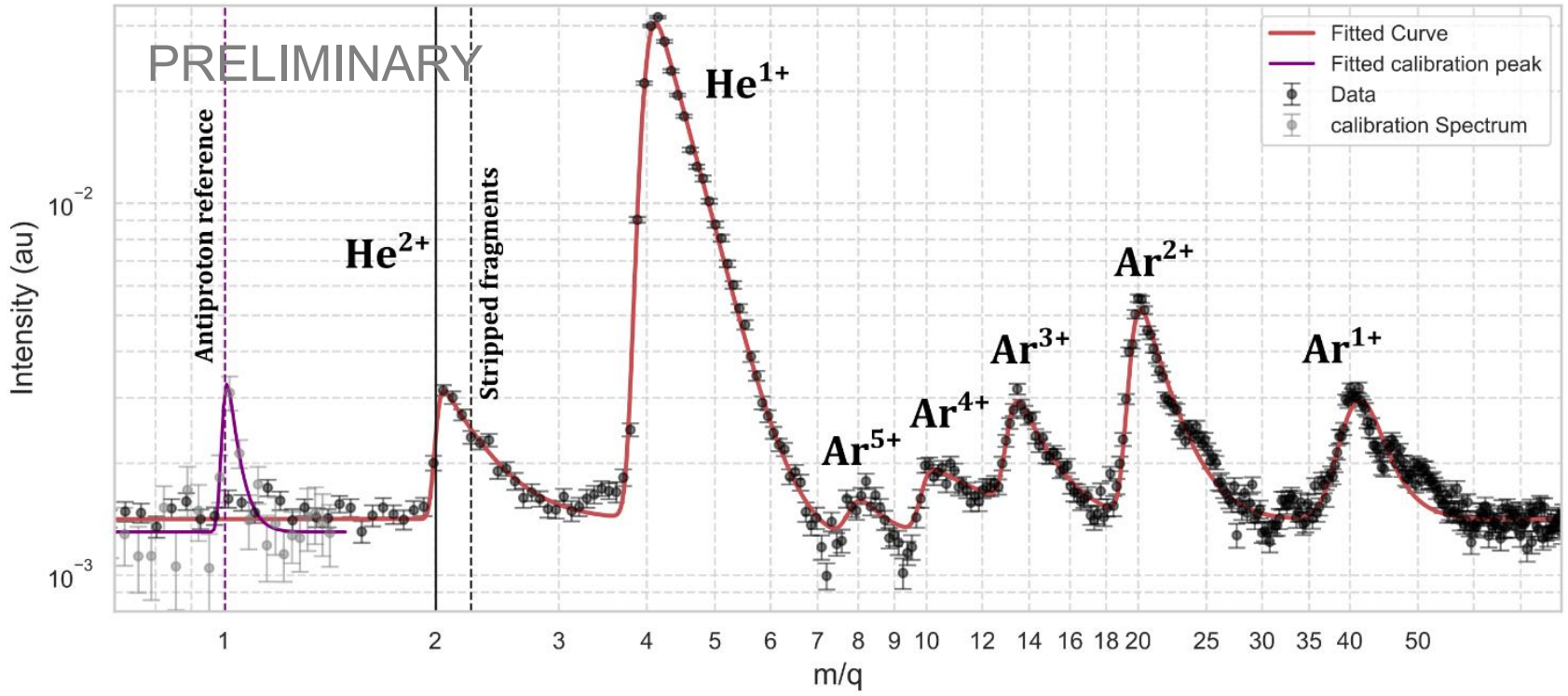
Upgrade to the 2023 methodology

- 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



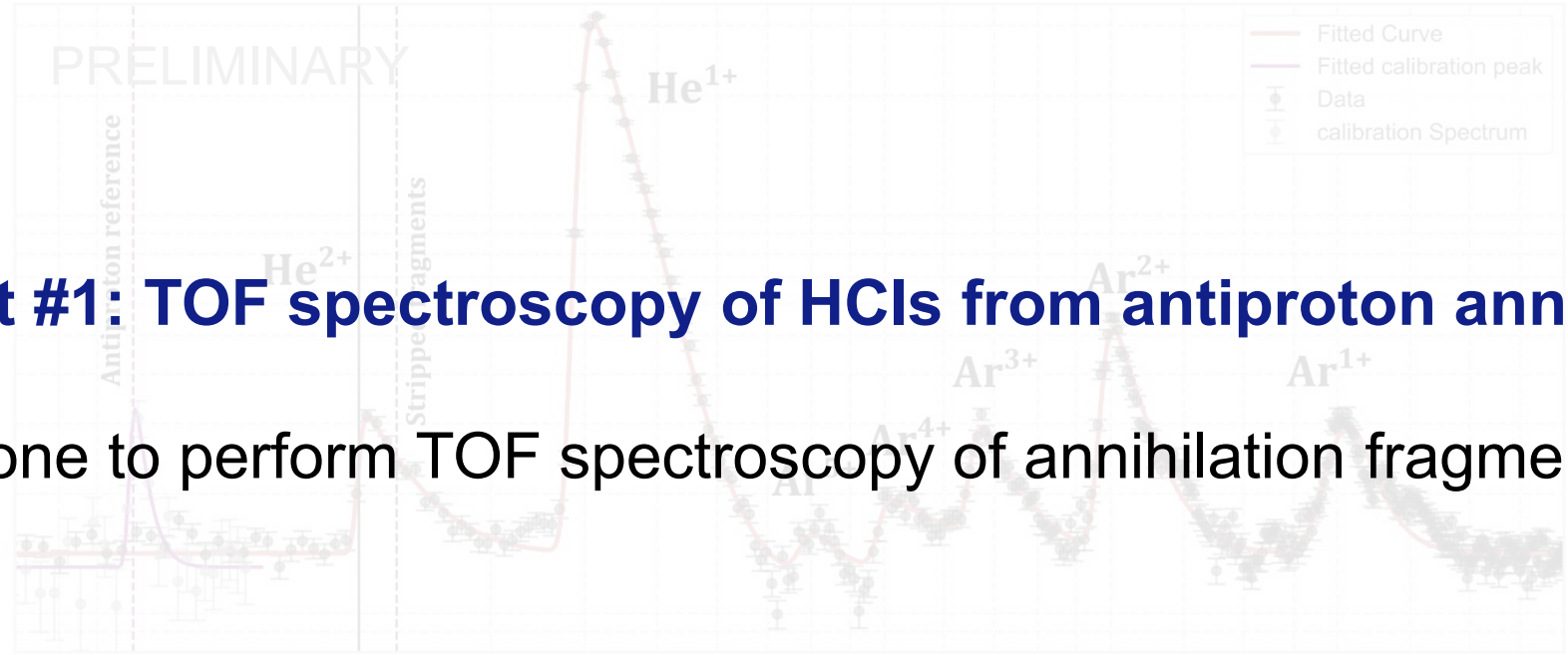


Observation of trapped HCIs from antiproton annihilations



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

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
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Achievements of the 2024 Physics Run

POSITRONIUM

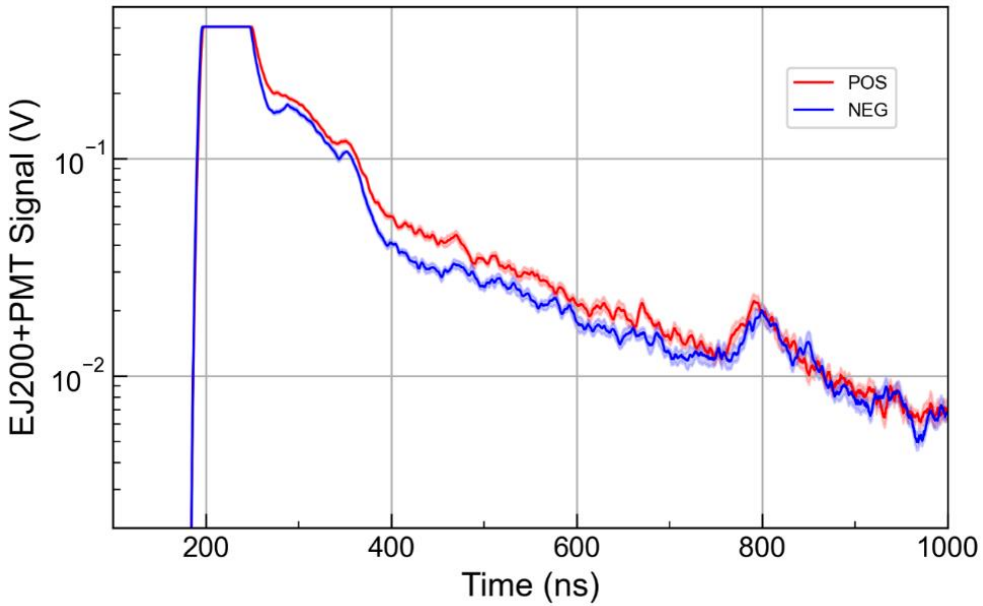
Solving 2022/2023 low Ps formation issues

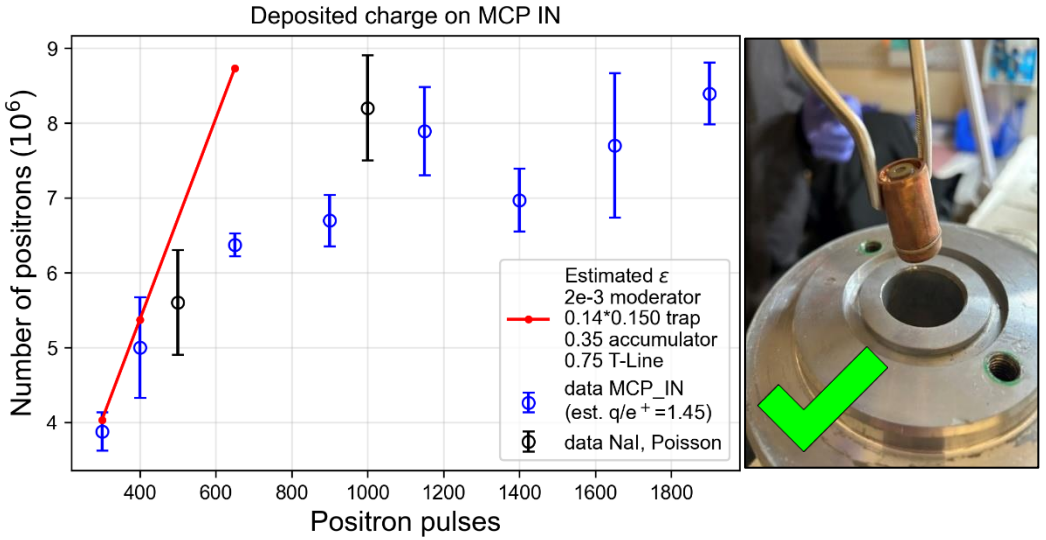
Improvements in Ps target manufacturing

- 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



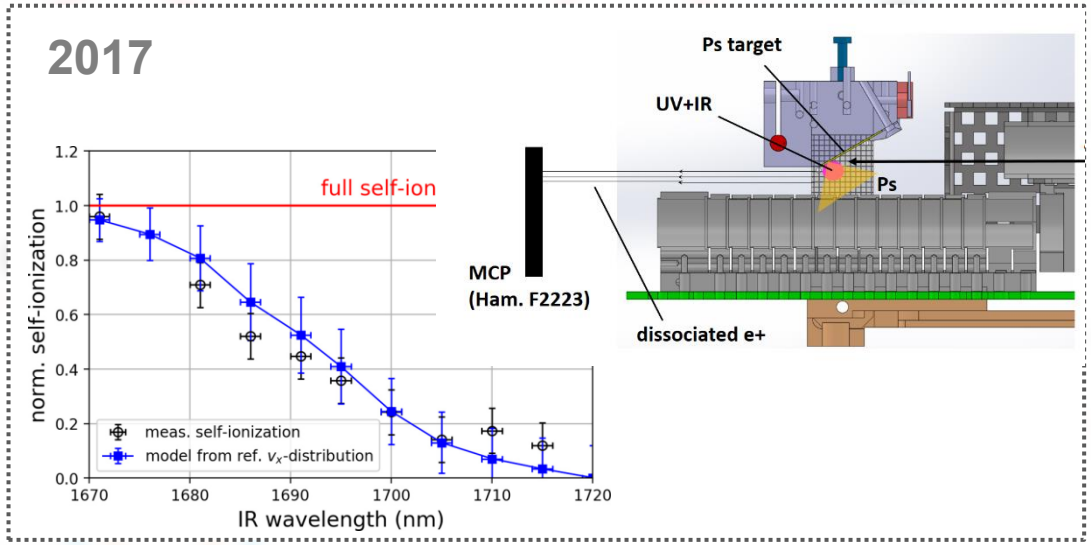


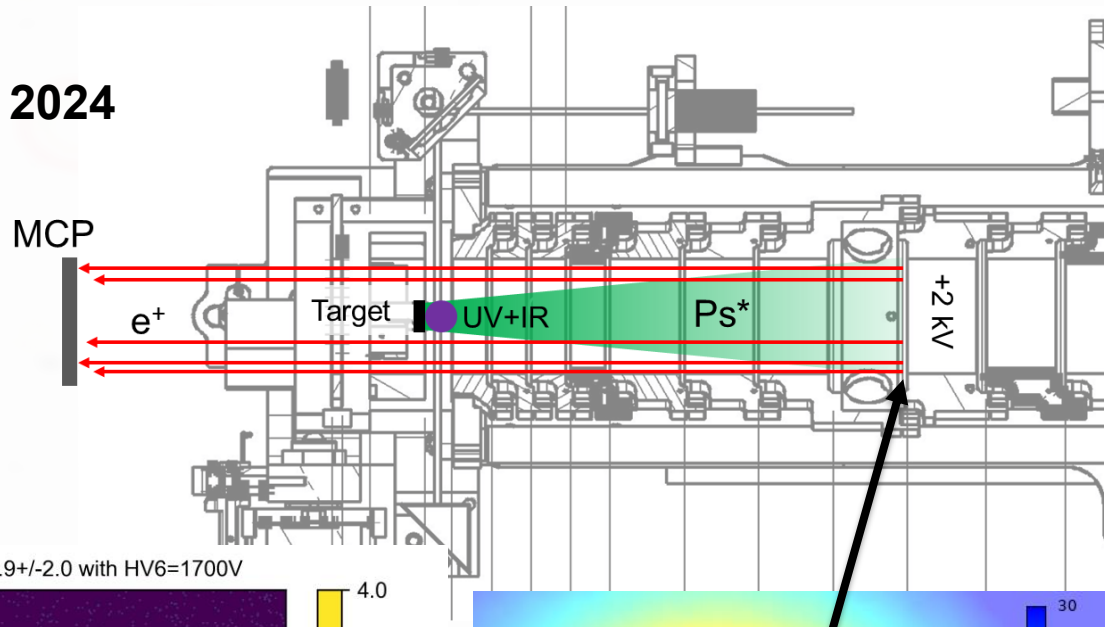
Impact of the new positron source

- 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

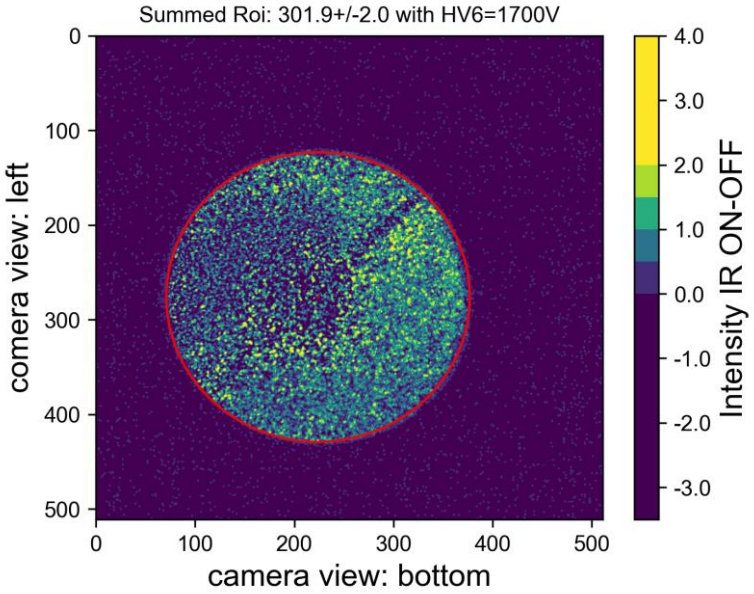
Direct Rydberg Positronium diagnostics

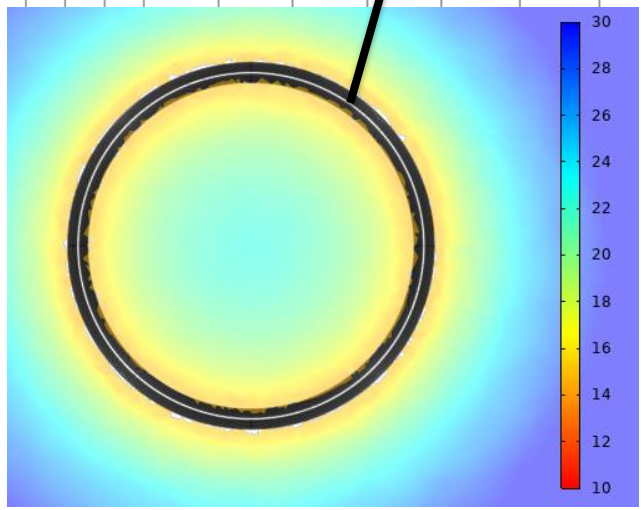




Method for a direct Rydberg Ps diagnostics

- 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

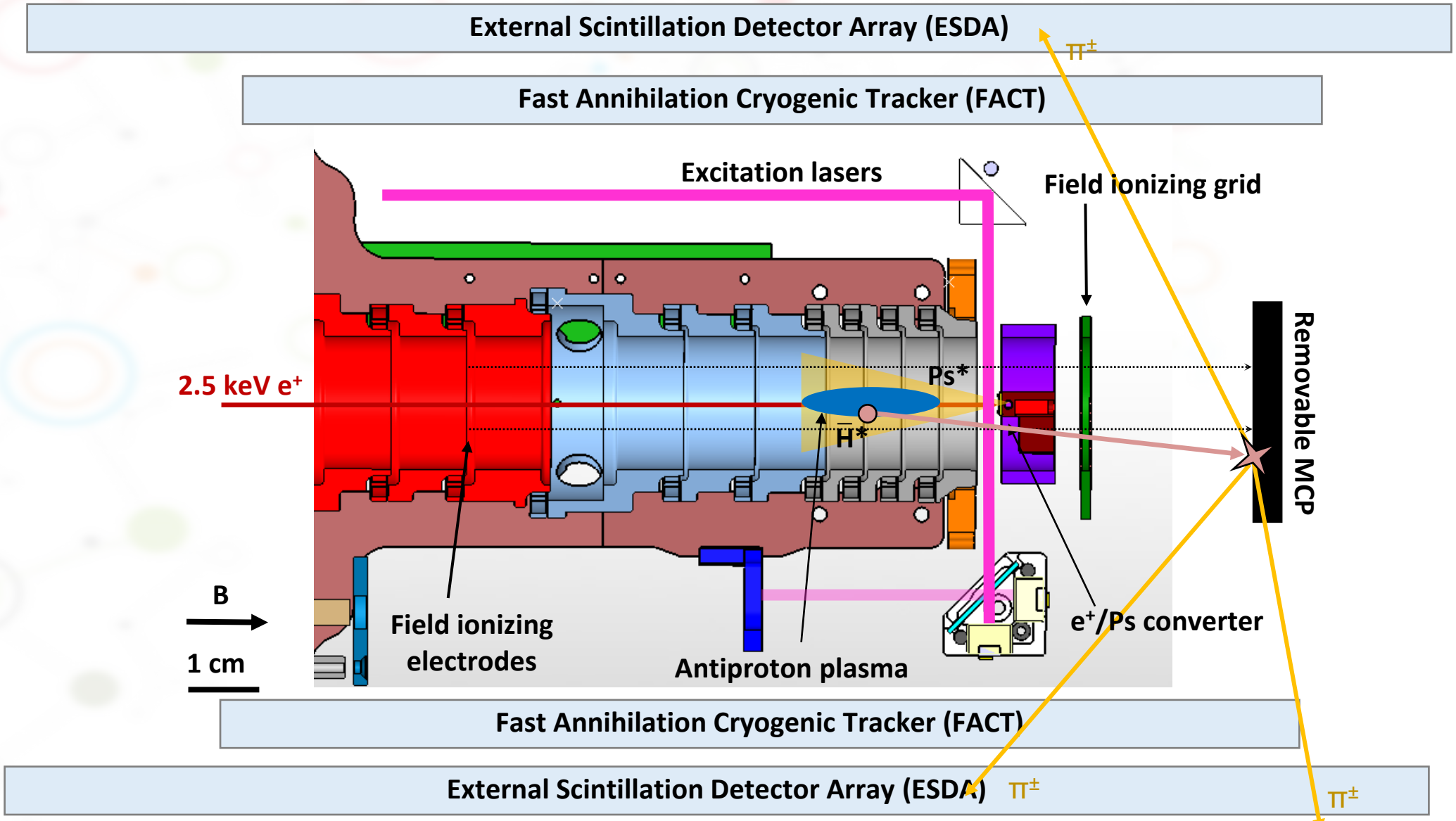
In 2024: unambiguous Rydberg Ps detection took 30 minutes

Enables Rydberg Ps spectroscopy in 1T field

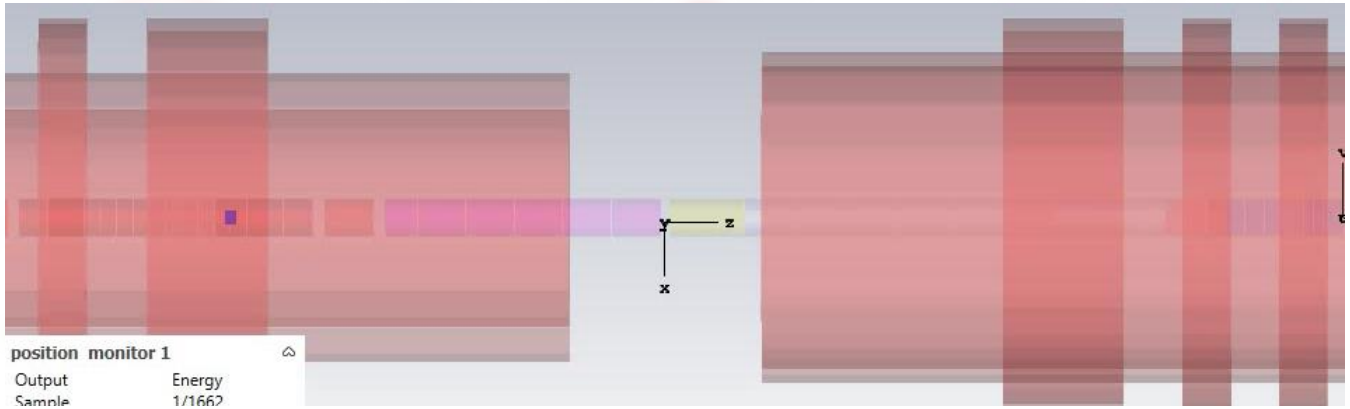
Achievements of the 2024 Physics Run

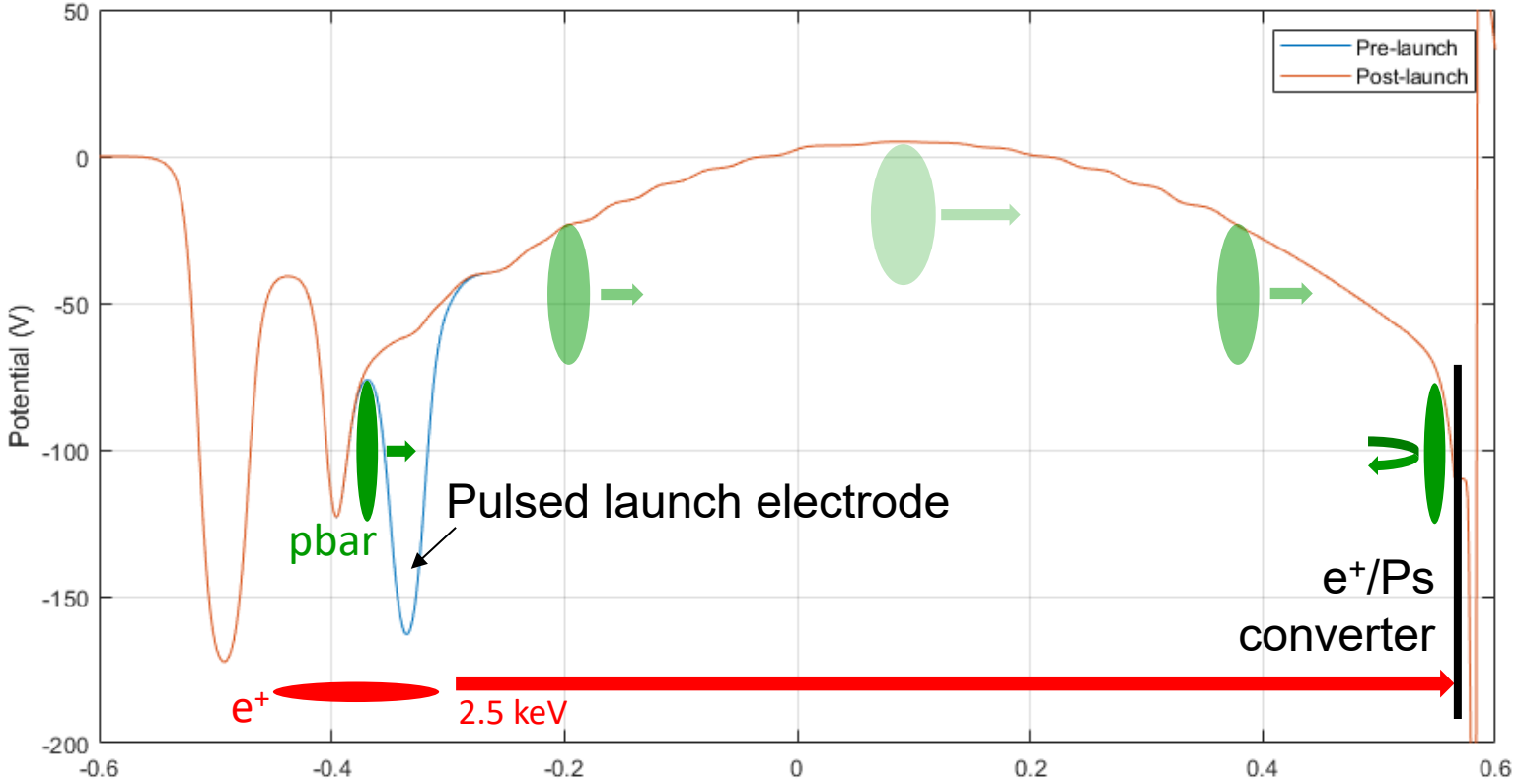
ANTIHYDROGEN

Antihydrogen production scheme

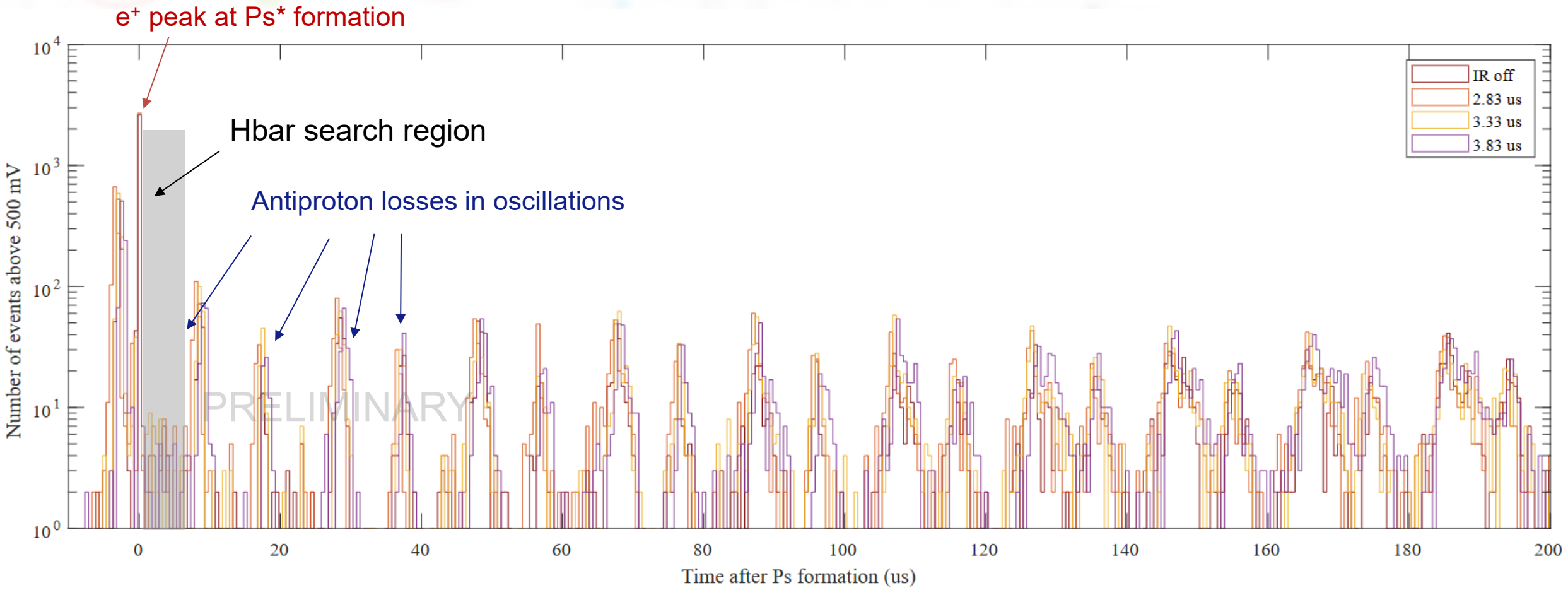


Antiprotons swinging in a parabolic potential

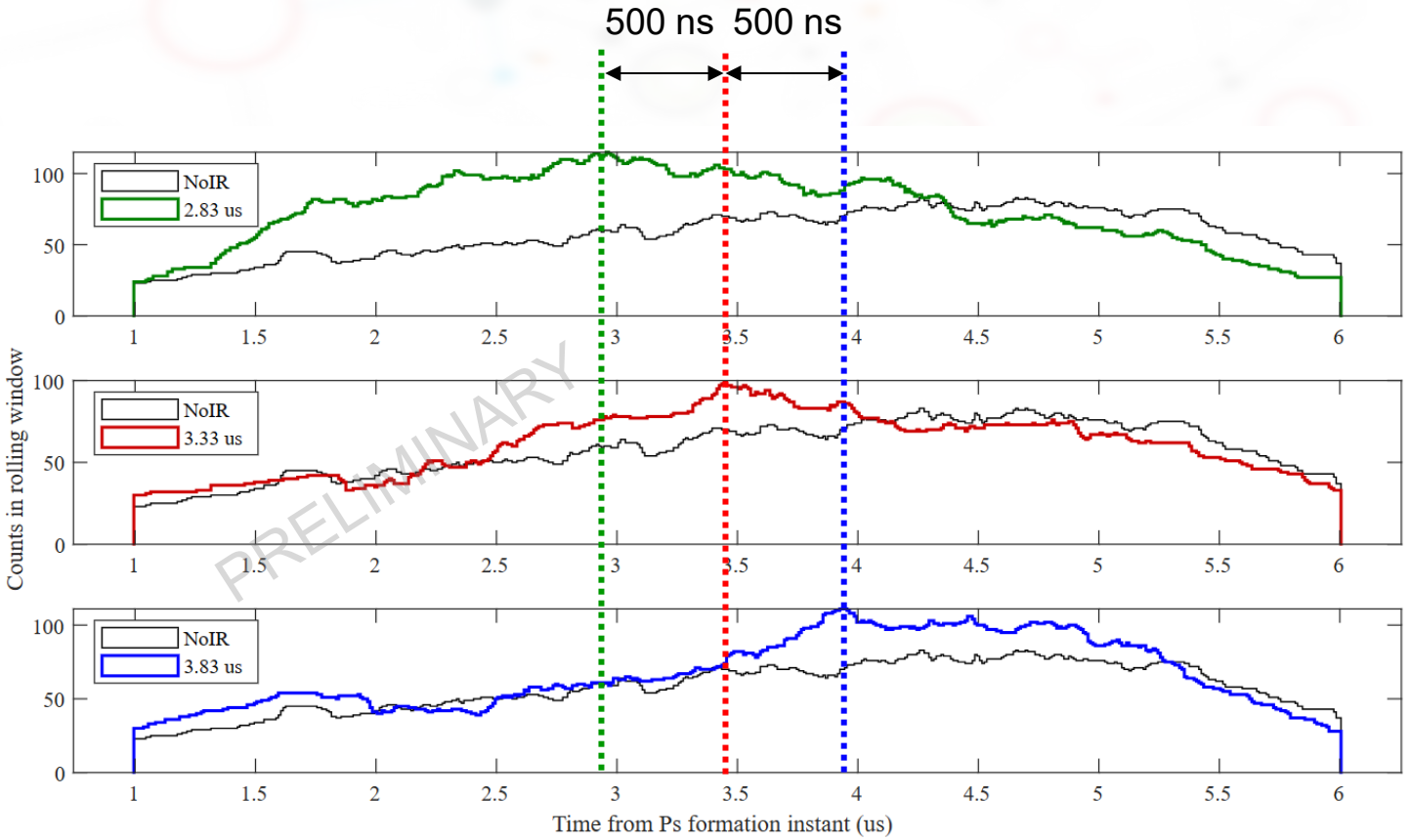




Example signal of antiprotons swinging



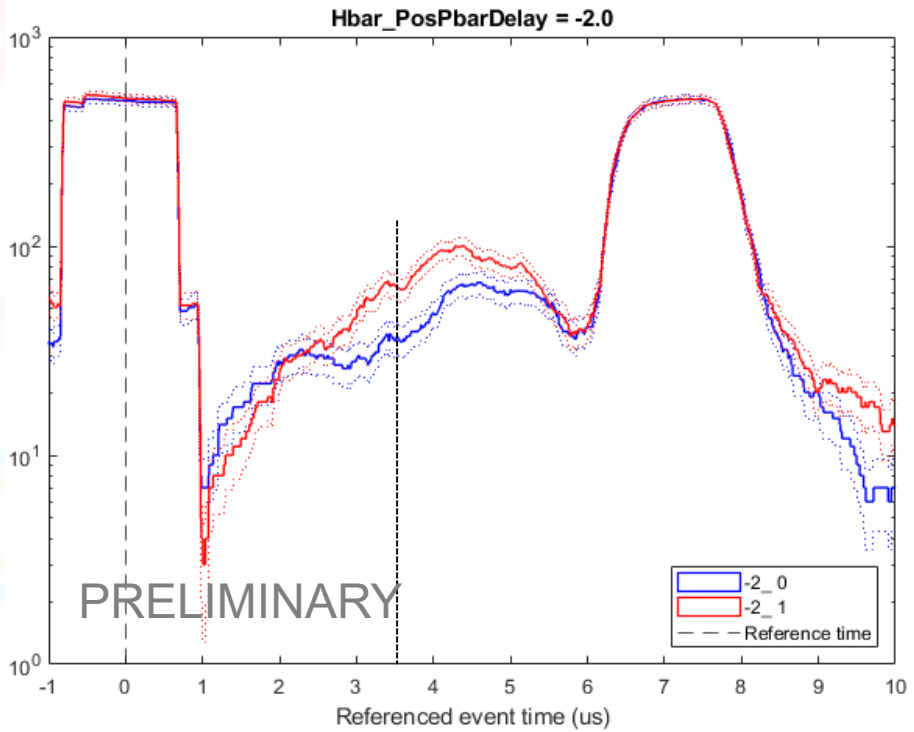
Pulsed antihydrogen boosting: an example signal from 2023

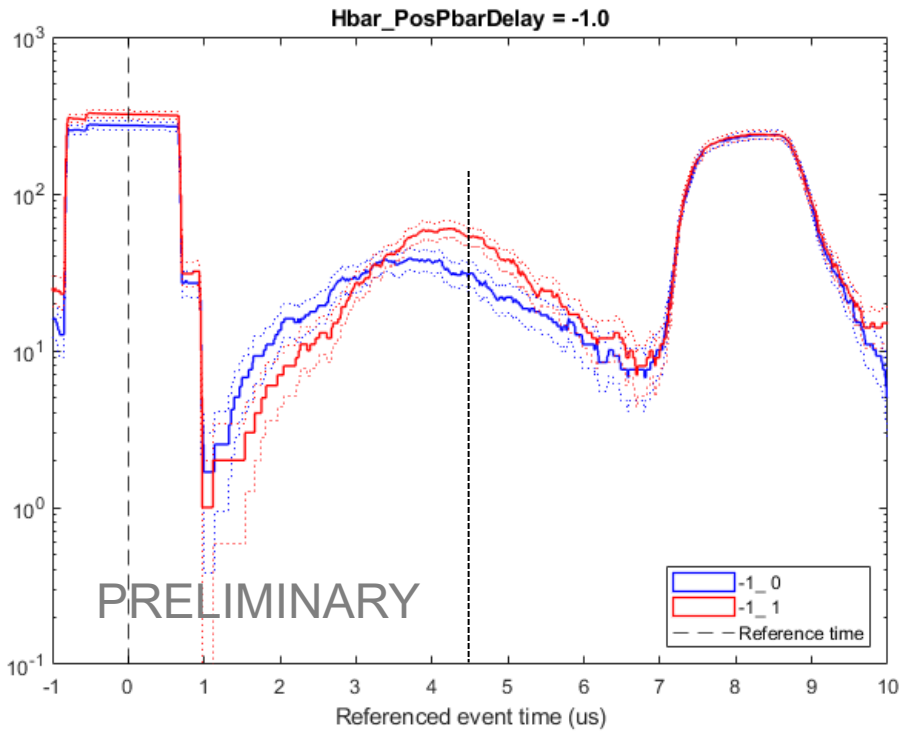


Evidence of antihydrogen production in the collinear scheme and controlled time shift

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.