LEA - Low Energy Antimatter

STATUS REPORT 2025

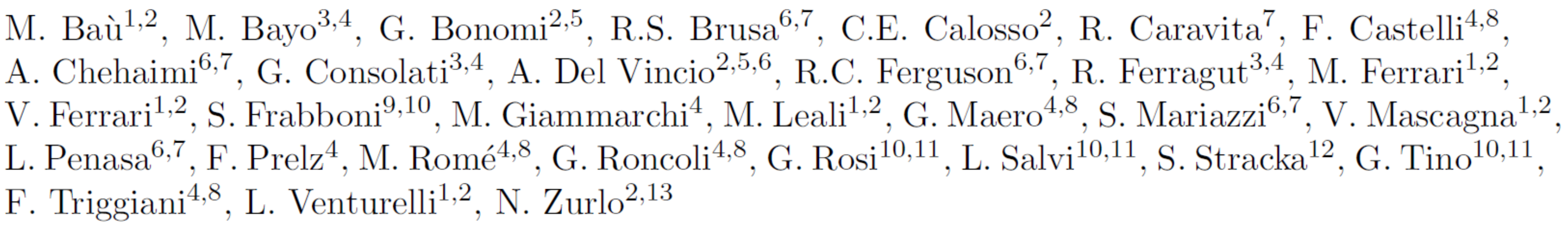
CSN3

Luca Venturelli - Università di Brescia & INFN Pavia
on behalf of the LEA collaboration

CSN3 Meeting Firenze
24 aprile 2026

LEA members

2025 members



M. Baù[1,2], M. Bayo[3,4], G. Bonomi[2,5], R.S. Brusa[6,7], C.E. Calosso[2], R. Caravita[7], F. Castelli[4,8], A. Chehaimi[6,7], G. Consolati[3,4], A. Del Vincio[2,5,6], R.C. Ferguson[6,7], R. Ferragut[3,4], M. Ferrari[1,2], V. Ferrari[1,2], S. Frabboni[9,10], M. Giammarchi[4], M. Leali[1,2], G. Maero[4,8], S. Mariazzi[6,7], V. Mascagna[1,2], L. Penasa[6,7], F. Prelz[4], M. Romé[4,8], G. Roncoli[4,8], G. Rosi[10,11], L. Salvi[10,11], S. Stracka[12], G. Tino[10,11], F. Triggiani[4,8], L. Venturelli[1,2], N. Zurlo[2,13]

+ 19 INFN collaborators which are external to LEA

2025:
31 people
19.5 FTE

[1] Dipartimento di Ingegneria dell'Informazione, Università degli Studi di Brescia, Brescia, Italy.
[2] Istituto Nazionale di Fisica Nucleare, sez. di Pavia, Pavia, Italy.
[3] Department of Physics, Politecnico di Milano, Milano, Italy.
[4] Istituto Nazionale di Fisica Nucleare, sez. di Milano, Milano, Italy.
[5] Dipartimento di Ingegneria Meccanica e Industriale, Università degli Studi di Brescia, Brescia, Italy.
[6] Department of Physics, University of Trento, 38123 Povo, Trento, Italy.
[7] TIFPA/INFN Trento, 38123 Povo, Trento, Italy.
[8] Department of Physics "Aldo Pontremoli", Università degli Studi di Milano, Milano, Italy.
[9] Dipartimento FIM, Università di Modena e Reggio-Emilia, Italy.
[10] Istituto Nazionale di Fisica Nucleare, sez. di Firenze, Firenze, Italy.
[11] Dipartimento di Fisica e Astronomia e LENS, Università di Firenze, Firenze, Italy.
[12] Istituto Nazionale di Fisica Nucleare, sez. di Pisa, Pisa, Italy.
[13] Department of Civil, Environmental, Architectural Engineering and Mathematics, University of Brescia, 25123 Brescia, Italy.

New entries

- **Borsisti**: F.Mombelli (ASACUSA/QUPLAS, Brescia)
- **Dottorandi**: A.Galanti (QUPLAS/ASACUSA, Como); A.Pappalardo (QUPLAS, Firenze); T.Mariani (ALPHA, Firenze); P.Conte (AEgIS 20%, Milano); E.Sokal (Psico, Trento)
- **Laureandi**: S.Bolzoni (AEgIS, Trento); F.Pozzi (AEgIS, Trento)

In Memory of Prof. Fabrizio Castelli (1957–2026)

His Work and Legacy
A passionate theoretical physicist, always in close dialogue with experiments
From nonlinear optics and laser physics to atomic and quantum physics
In the last 15 years, a key contributor to positronium and antimatter research

Collaborations
AEGIS and PsICO: antihydrogen and gravity with antimatter
QUPLAS: interferometry, CPT symmetry, Aharonov–Bohm effect

Fabrizio will be remembered for his intellectual honesty, his genuine curiosity, his pragmatic approach to fundamental questions, and above all for his humanity.

LEA project

approved by CSN3 in 2021 and started in 2022

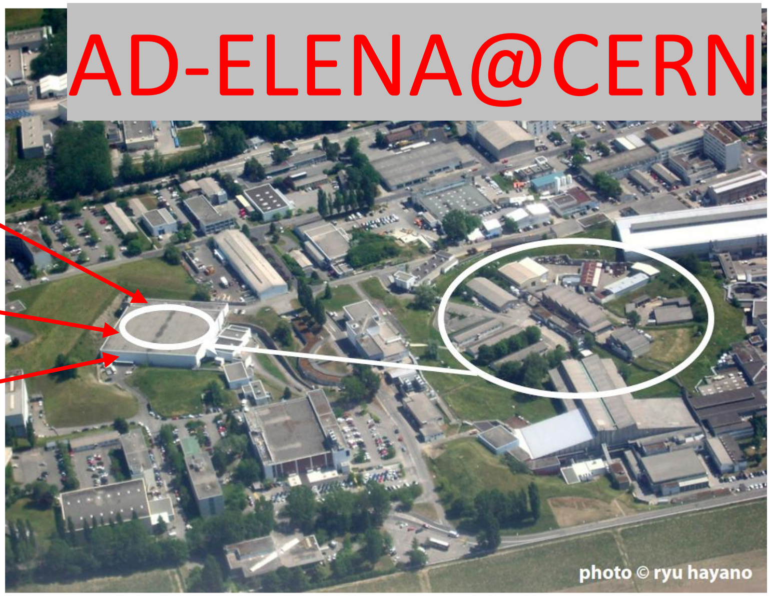
grouping **experiments** focused on low-energy antimatter:

AEgIS	funded by INFN since 2010
ALPHA	funded by INFN since 2022
ASACUSA	funded by INFN since 2005
PsICO	spin-off of AEgIS (+ long-term expertise on e+ from UniTN)
QUPLAS	spin-off of AEgIS-ASACUSA (+ long-term expertise on e+ from PoliMI)

- CDR 2026–2030 approved (Sep 2025)
- AIABE Addendum approved (Feb 2026)
- QUPLAS–Gravitation LoI approved (Feb 2026)

LEA Experiments

- AEgIS $\bar{p}$ e+ Ps $\bar{H}$
- ALPHA $\bar{p}$ e+ $\bar{H}$
- ASACUSA $\bar{p}$ e+ $\bar{H}$



AD-ELENA@CERN

photo © ryu hayano

- PsICO e+ Ps
- QUPLAS e+ Ps

TIFPA-TN

L-NESS-CO

EXPERIMENTS AT CERN

AEgIS ALPHA ASACUSA

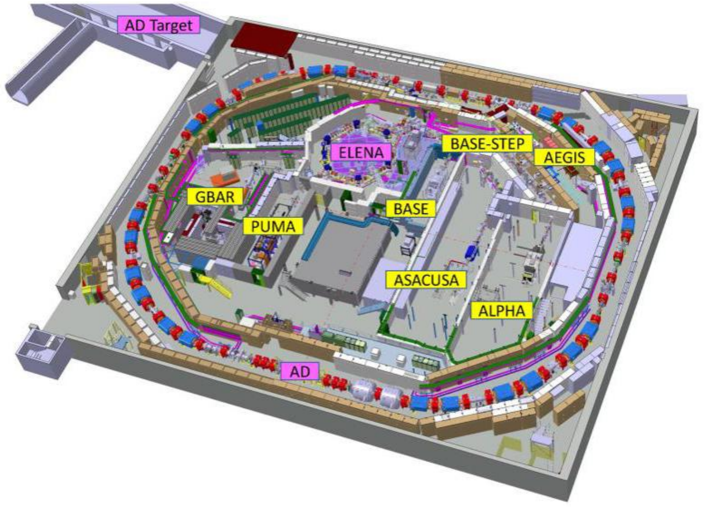
Antimatter Factory: AD-ELENA

The only low-energy $\bar{p}$ source

AD: 5.3 MeV pulsed beam: 3-4x10^7 $\bar{p}$ every ~ 100 s

ELENA: 5.3 MeV → 100 keV
4 experiments run in parallel (24h/day)

- In 2025 very good operation



2025

Physics starts on 5-5

Physics stops on 8-12

Jan Feb Mar Apr May Jun Jul Aug Sept Oct Nov Dec

2026

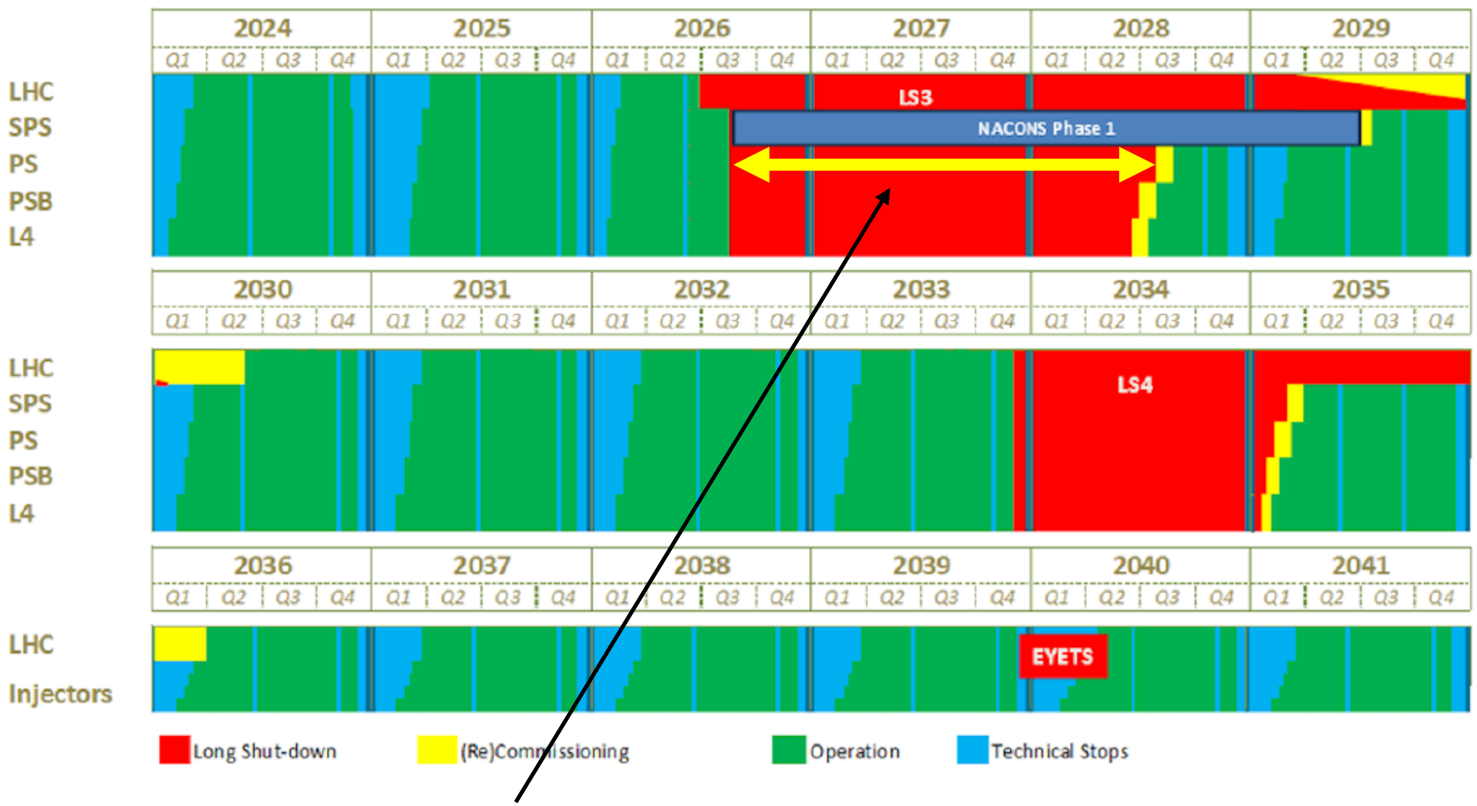
Physics starts on 27-02

Physics stops on 31-08

Jan Feb Mar Apr May Jun Jul Aug Sept Oct Nov Dec

LS3 and Run4

Long Term Schedule for CERN Accelerator complex



- For AD experiments, the LS3 period runs from Sept-2026 to Oct-2028.
- Both 2026 and 2028 will include data-taking periods, although shorter than usual.
- In practice, **2027 is the only full shutdown year**.

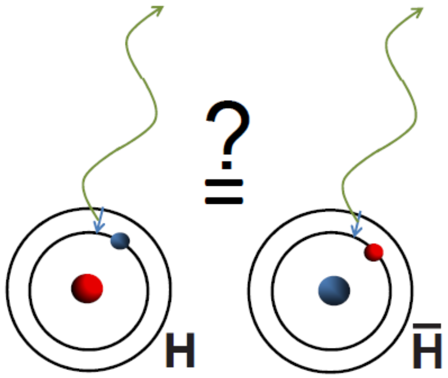
From the AD perspective, it would be more appropriate to refer to LS3 as ***"Short Shutdown 3."***

PHYSICS MOTIVATIONS

Why study antihydrogen?

1) Precise matter/antimatter comparison

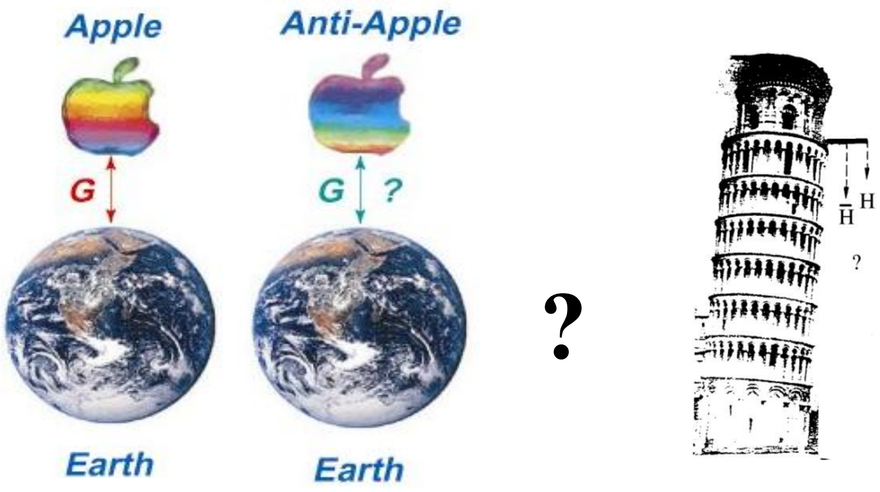
→ test of CPT symmetry



Spectroscopy of $\bar{\text{H}}$

2) Measurement of the gravitational behaviour of antimatter

→ test of WEP



Not possible with charged antiparticle

only with neutral system → $\bar{\text{H}}$ (or Ps)

INFN contact person: Roberto Brusa (Tn)

AEgIS

INFN

TIFPA Trento Institute for Fundamental Physics and Applications

UNIVERSITÀ DI TRENTO

UNIVERSITY OF LIVERPOOL

CERN

NICOLAUS COPERNICUS UNIVERSITY IN TORUŃ

RRI

The collaboration includes about **60 researchers** from **17 Institutes/Universities**. In 2026, 1 group is expected to retire by the end of the year, and 1 more group showed interest in joining (MoU pending)

Italian institutes

- TIFPA/INFN Trento, Via Sommarive 14, 38123 Povo (TN)
- INFN, sez. di Milano, Via Celoria 16, 20133 Milano
- INFN, sez. di Pavia, Via Bassi 6, 27100 Pavia
- Department of Physics, University of Trento, Via Sommarive 14, 38123 Povo (TN)
- Department of Physics "Aldo Pontremoli", Università degli Studi di Milano, Via Celoria 16, 20133 Milano
- Department of Aerospace Science and Technology, Politecnico di Milano
- Department of Civil, Environmental, Architectural Engineering and Mathematics, University of Brescia,via Branze 43, 25123 Brescia, Italy
- Politecnico di Milano (Department of Aerospace Science and Technology), via La Masa 34, 20156 Milano, Italy

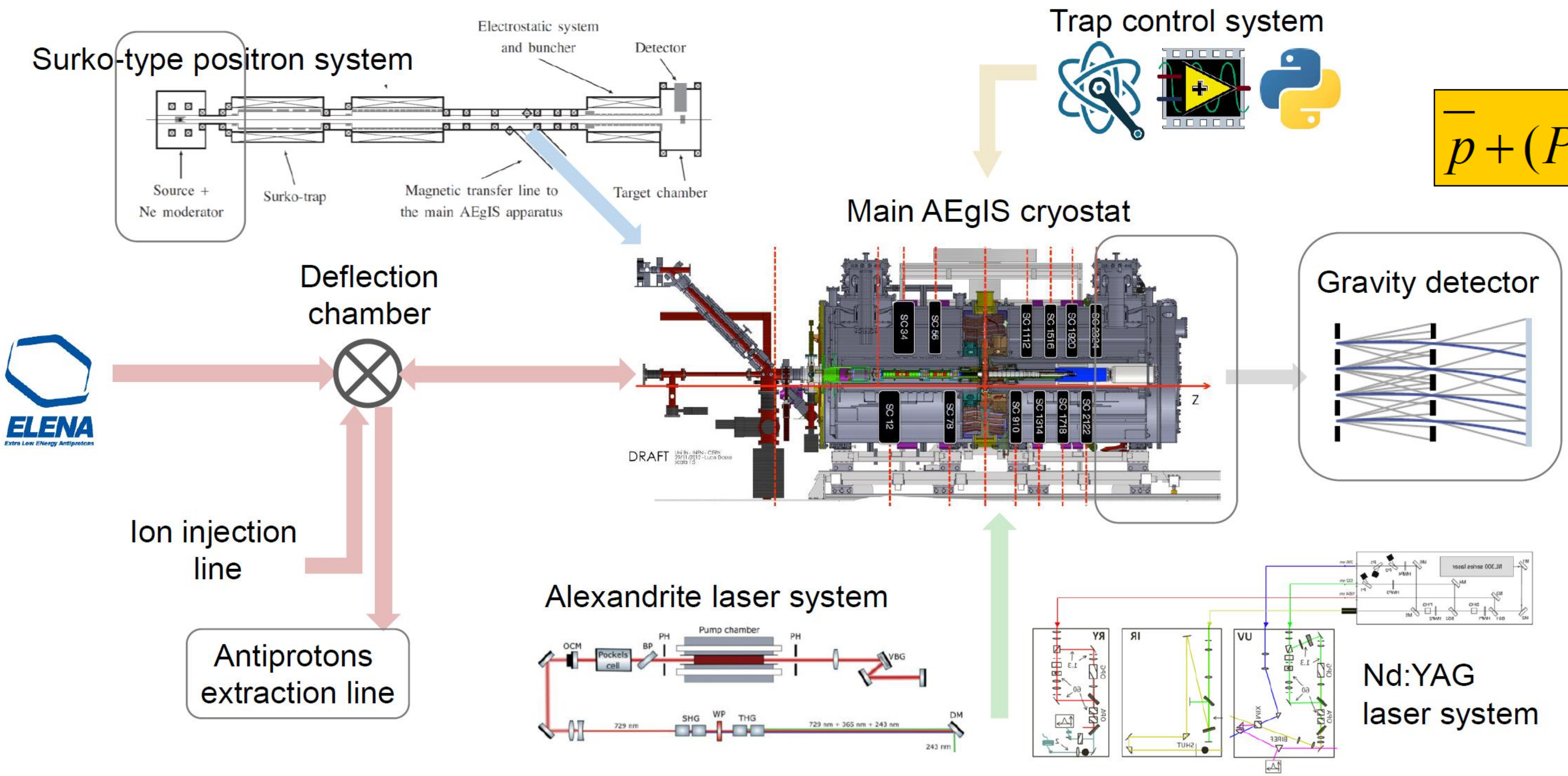
Italian responsabilities in AEgIS

Spokeperson : Ruggero Caravita

Chair of the Board: Giovanni Consolati

11 LEA members
FTE 6.2

The AEgIS apparatus in 2025



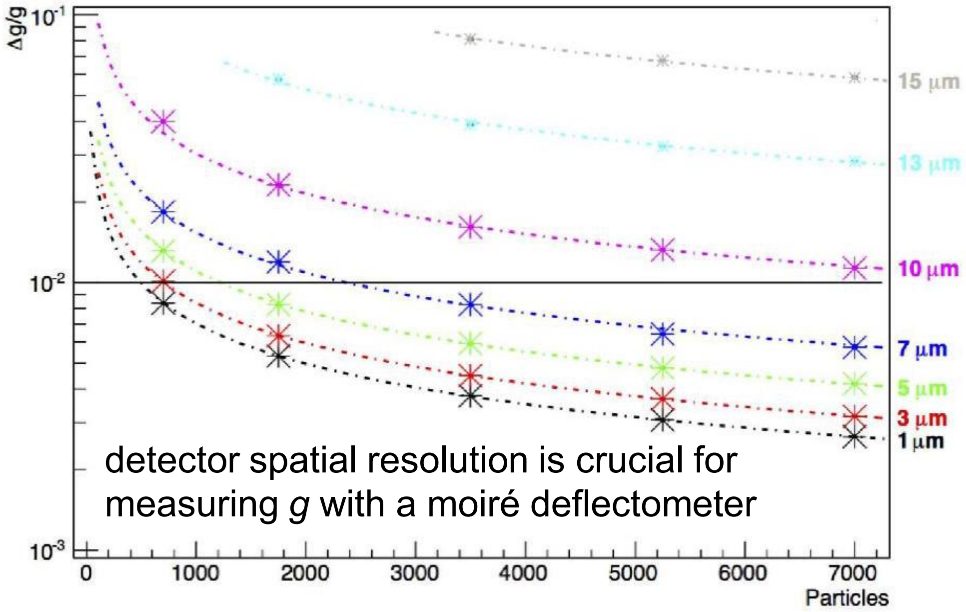
$$\bar{p} + (Ps)^{*} \rightarrow \bar{H}^{*} + e^{-}$$

Main scientific goal

Measurement of the free fall of antihydrogen in the Earth's gravitational field

Using a pulsed antihydrogen beam produced via charge exchange between positronium and antiprotons, and detected with a moiré deflectometer

OPHANIM: Sub-micron Antimatter Imaging



detector spatial resolution is crucial for measuring *g* with a moiré deflectometer

- Old idea: active detectors (e.g. Timepix, ~15 μm resolution) or nuclear emulsions (2–3 μm) were considered, with trade-offs in complexity and operation.

- Today: **OPHANIM (Optical PHoton and ANtimatter IMager)** developed with TUM and used by AEgIS.
  - Achieved **~0.6 μm spatial resolution** on antiproton annihilation vertices .
  - Currently no time resolution, but not limiting for present measurements.

Based on **modified smartphone CMOS sensors** with **0.8 μm pixel size**.

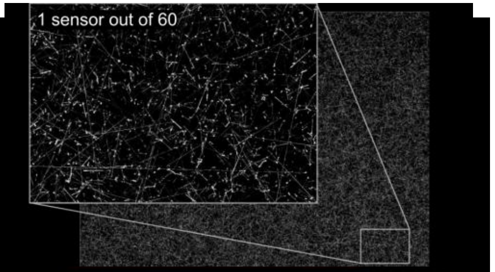
Composed of **60 sensors**, forming a **~5.8 × 5.8 cm² detector (~3.8 Gpixels total)**

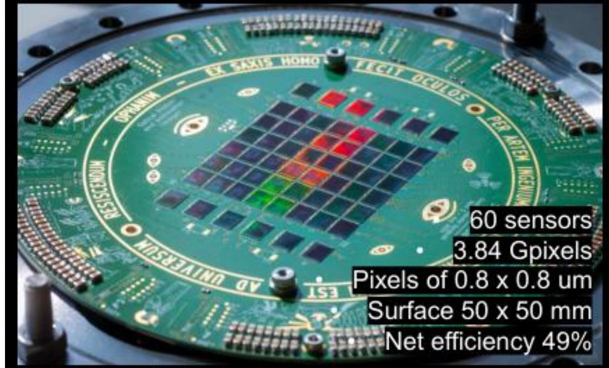
Main challenge: **simultaneous readout of ~4 billion pixels**.

RESEARCH ARTICLE | PHYSICS

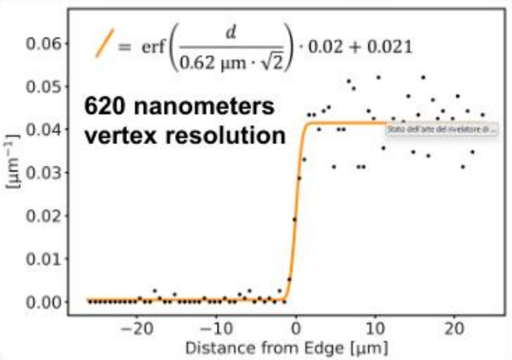
Real-time antiproton annihilation vertexing with submicrometer resolution

MICHAEL BERGHOLD, DAVIDE ORSUCCI, FRANCESCO GUATIERI, SARA ALFARO, MARCIS AUZINS, BENEDIKT BERGMANN, PETR BURIAN, ROBERTO SENNEN BRUSA, ANTOINE CAMPER, ... AND AEGIS COLLABORATION +57 authors Authors Info & Affiliations





60 sensors
3.84 Gpixels
Pixels of 0.8 x 0.8 um
Surface 50 x 50 mm
Net efficiency 49%



$= \mathrm{erf}\left(\frac{d}{0.62\ \mu\mathrm{m} \cdot \sqrt{2}}\right) \cdot 0.02 + 0.021$

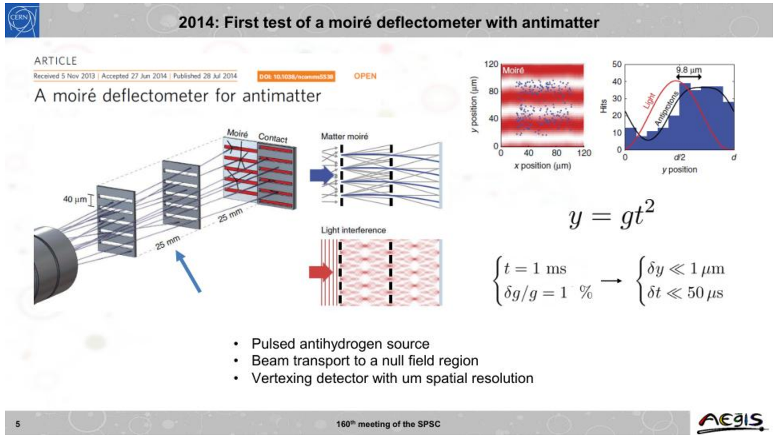
620 nanometers vertex resolution

Credits: A. Heddergott / TUM

Moiré Deflectometer

for Antimatter Gravity and Inertial Sensing

- **Installed** in AEgIS apparatus (with OPHANIM detector)
- Scale-up from **5 cm (2014 prototype)** to **~1 m baseline** today
- Alignment system uses **piezoelectric actuators operating in vacuum**.
- Continuous (pulsed) **optical feedback system** maintains grating alignment.
- First **Moiré patterns with 100 keV antiprotons** recorded in November 2025.
- Demonstrated **inertial sensing capability**:
  - Magnetic field variation (~0.2 G) produces measurable shifts.
  - Sensitivity at the ~100 aN level, ~5× better than 2014.
- AEgIS can operate as an **attoNewton-scale inertial sensor**, capable of separating vertical forces from cylindrically symmetric ones via rotation.



2014: First test of a moiré deflectometer with antimatter

ARTICLE

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

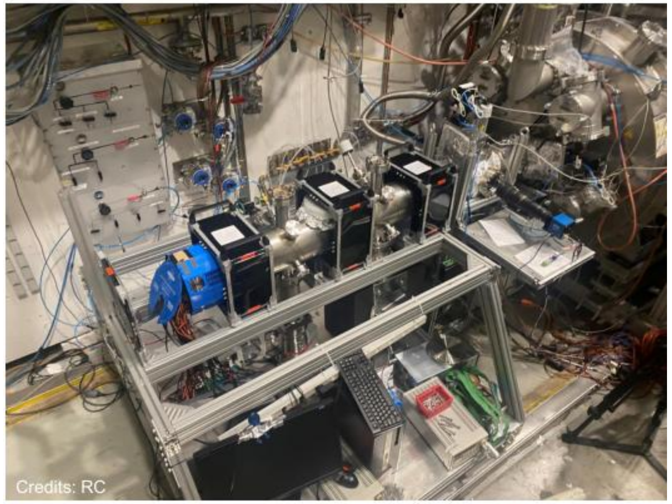
A moiré deflectometer for antimatter

$$y = gt^2$$

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

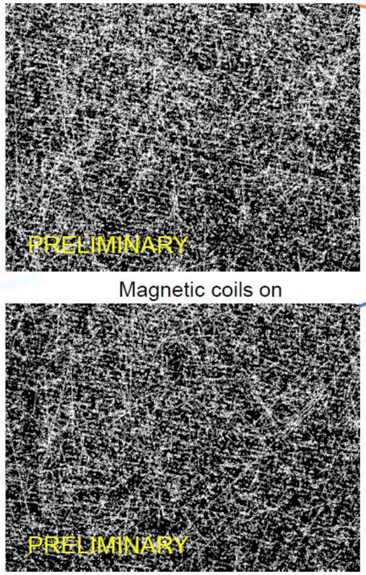
- Pulsed antihydrogen source
- Beam transport to a null field region
- Vertexing detector with um spatial resolution

5 160th meeting of the SPSC

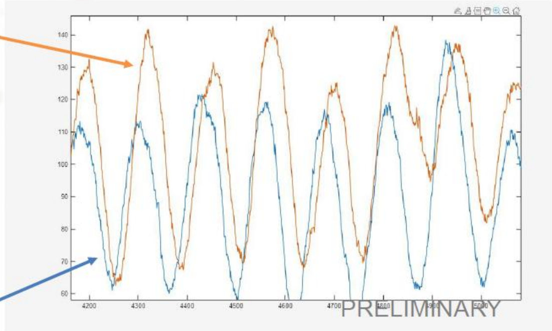


Credits: RC

Magnetic coils off



Magnetic coils on



Coils produced < 0.2 G implying << 100 aN
(our 2014 measurement was 530 aN)

AEgIS operates an attonewton inertial sensor with antimatter in a < 10 G magnetic field

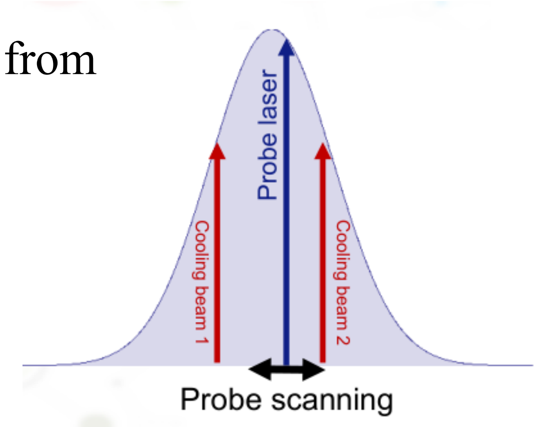
First moiré pattern on 9/11/2025

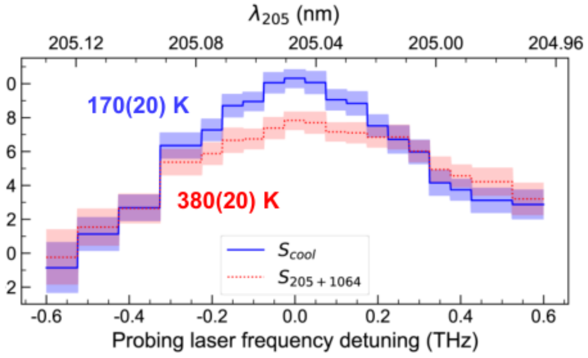
100 keV collimated pbars, 1 meter baseline

MEDUSA up and running for the 2026 beam time

Laser Cooling of Positronium

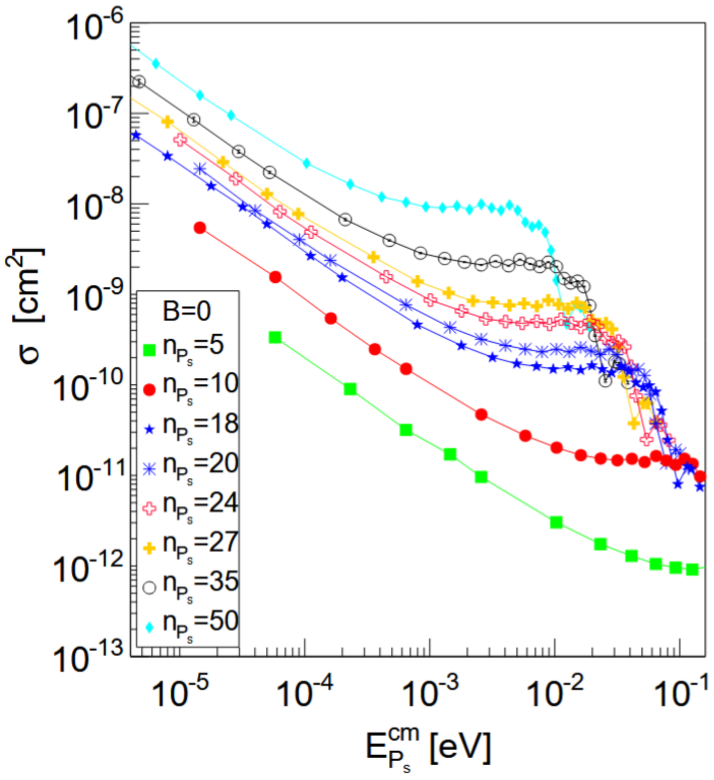
- First demonstration published in **2024** using a broadband alexandrite laser system
- Temperature reduction from ~380 K to ~170 K via Doppler narrowing



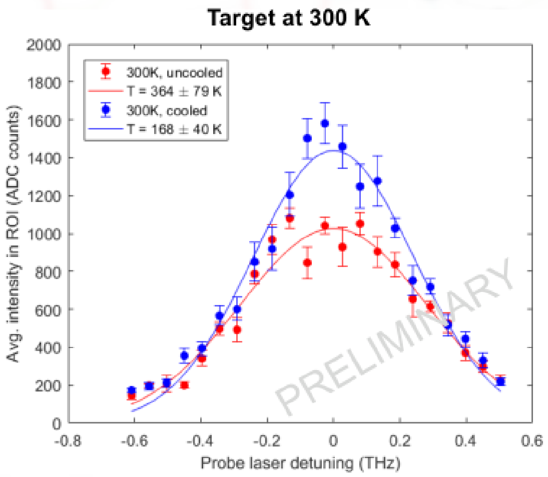


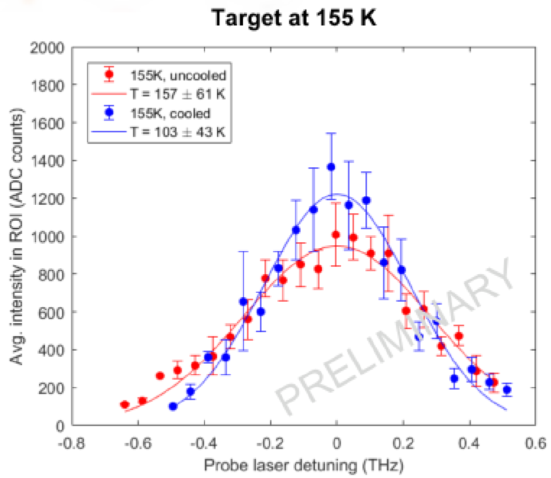
Observed narrowing consistent with 210(30) K cooling

Consistent with the entire Ps cloud being addressed



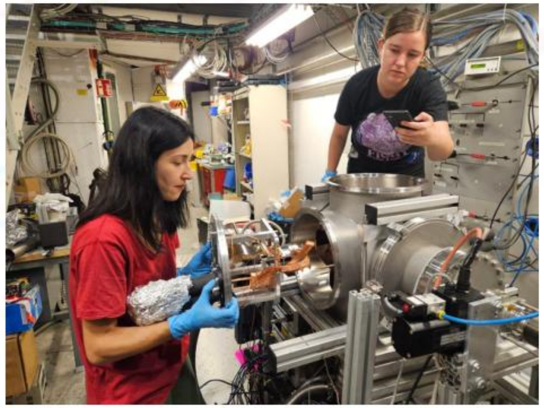
- **Upgrade**: installation of a **cryostat cooling the target to ~150 K**
- Results from Doppler broadening of the 1s–3p transition:
  - At 300 K target: 365 K → 170 K
  - At 155 K target: **160 K → 100 K**
- Demonstrates **first fully cryogenic positronium source**
- Ongoing improvements aim at better spectroscopy resolution and laser stability

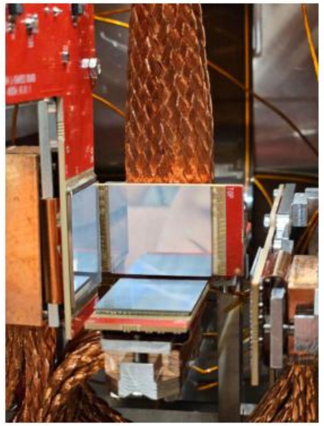


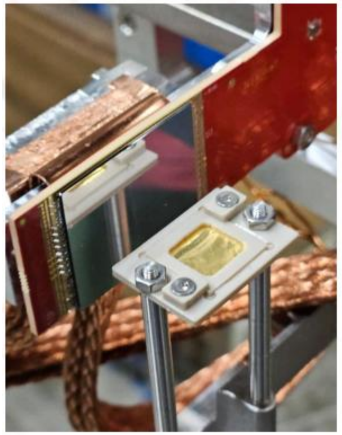


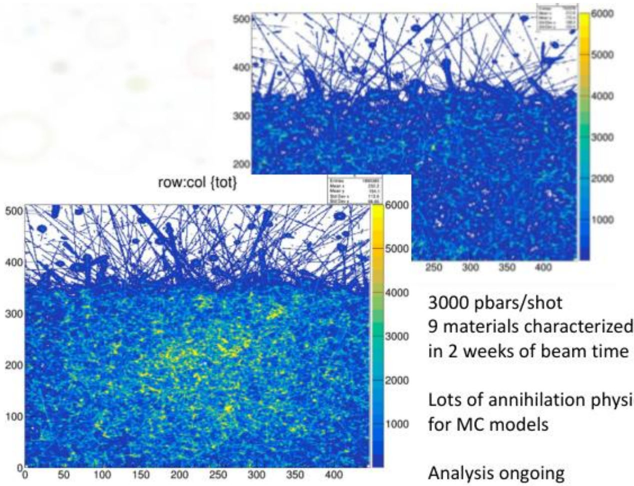
Antiproton Annihilation at Rest

- AEgIS + ASACUSA **synergy**
- By-product of antiproton extraction development for AEgIS
- Detector: **six Timepix4 silicon sensors**, nearly **4π coverage**
- Goals:
  - -Study **low-energy antiproton annihilation on materials**
  - -Measure **nuclear fragments, multiplicity, and angular correlations**
  - -Benchmark **Monte Carlo models**
  - -Investigate **backscattering and large-angle scattering probabilities**
- Measurements performed on **9 different materials**
- Energy scan from **~13 keV down to ~100 eV, in 250 eV steps**
- High-statistics dataset enabling detailed annihilation physics studies









3000 pbars/shot
9 materials characterized
in 2 weeks of beam time

Lots of annihilation physics
for MC models

Analysis ongoing

Publications in 2025

Published

- **Real-time antiproton annihilation vertexing with sub-um resolution**
  Science Advances (2025) 10.1126/sciadv.ads1176 – coordinated press release! CERN & INFN
- **An alexandrite laser system for positronium laser cooling**
  Optics and Laser Technology (2025) 10.1016/j.optlastec.2024.112097
- **Positronium Laser cooling**
  Nuovo Cimento C 48 (2025) – best contribution at SIF2024
- **+8 peer-reviewed confeerence proceedings**

Accepted

- **Spectrometry of captured highly charged ions produced following antiproton annihilations,** accepted in PRR, arXiv 2510.08440

Milestones

MILESTONE 2025- AEgIS- raggiungimento al 31-12-2025

AEgIS: Ottimizzazione fascio positroni, produzione positronio, sincronizzazione lasers, parametri di lancio balistico degli antiprotoni	100%
AEgIS: Test del deflettometro di moiré per misure di gravità	100%

MILESTONE 2026- AEgIS- previsione completamento al 31-12-2026

AEgIS: Rivelazione di annichilazioni nel deflettometro di moiré, definizione della procedura di riferimento e caratterizzazione delle sistematiche per la misura di gravità	100%
AEgIS: Raffreddamento laser del positronio a temperature criogeniche	100%

LEA_ALPHA – ALPHA COLLABORATION

INFN contact person: Germano Bonomi (Bs-Pv)

55 researchers

Aarhus University, Denmark

University of Brescia, Italy

University of British Columbia, Canada

University of California Berkeley, USA

University of Calgary, Canada

CERN

University of Liverpool, UK

University of Manchester, UK

NRCN - Nuclear Res. Center Negev, Israel

Purdue University, USA

Federal University of Rio de Janeiro, Brazil

INFN (Pavia, Pisa) Italy

Stockholm University, Sweden

Simon Fraser University, Canada `

TRIUMF, Canada

University of Wales Swansea, UK

Cockcroft Institute, UK

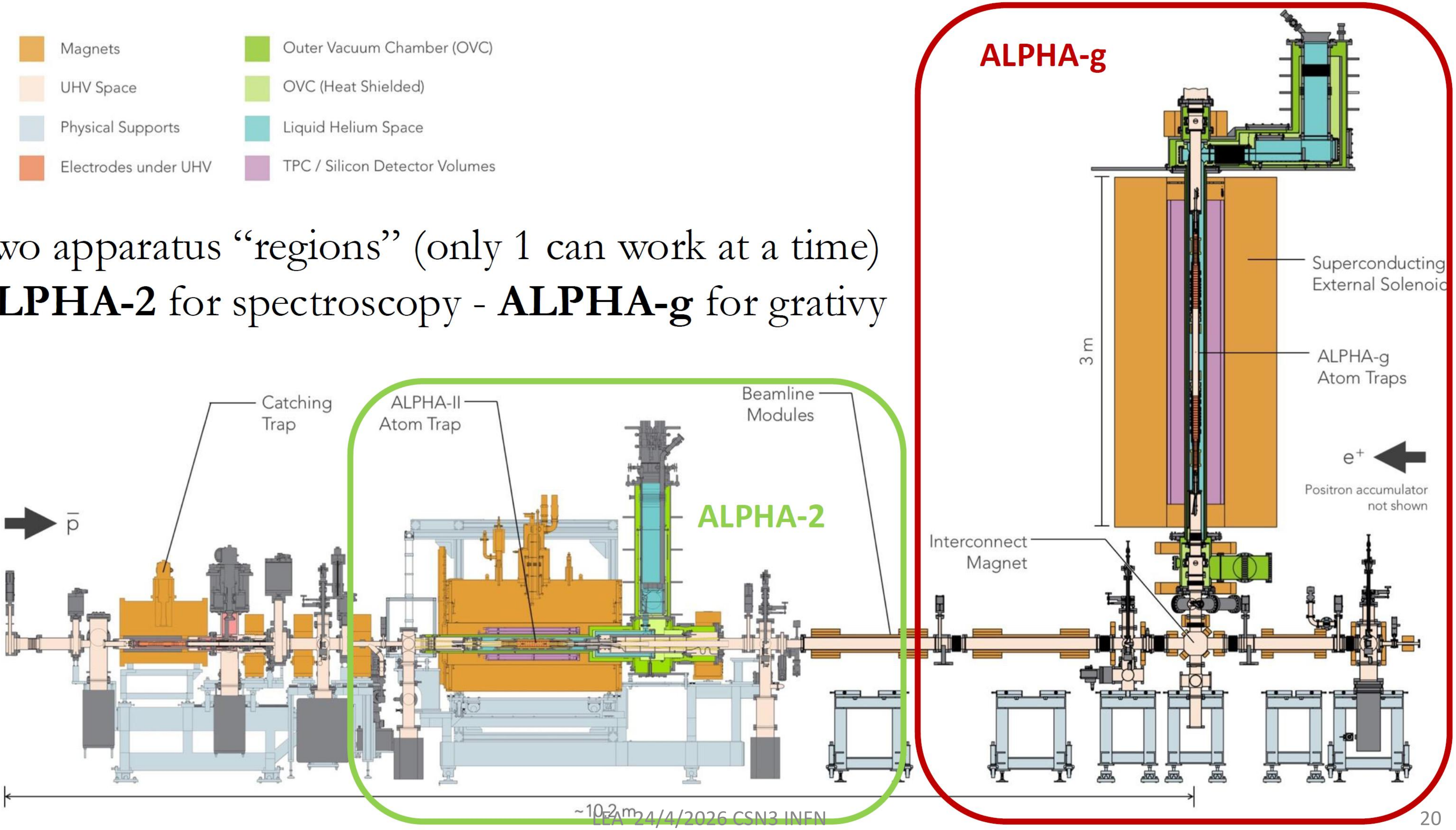
York University, Canada

INFN in ALPHA since 2022

INFN 2025: 3 people for 1.8 FTE → 2026: +1 staff member (G.Tino)

for gravity interferometry

In 2025 the focus has been on ALPHA-g (gravity) + some activity on ALPHA-2
In 2026 the focus will be both on ALPHA-3 (for spectroscopy) and (maybe) on ALPHA-g (gravity)



Two apparatus “regions” (only 1 can work at a time)

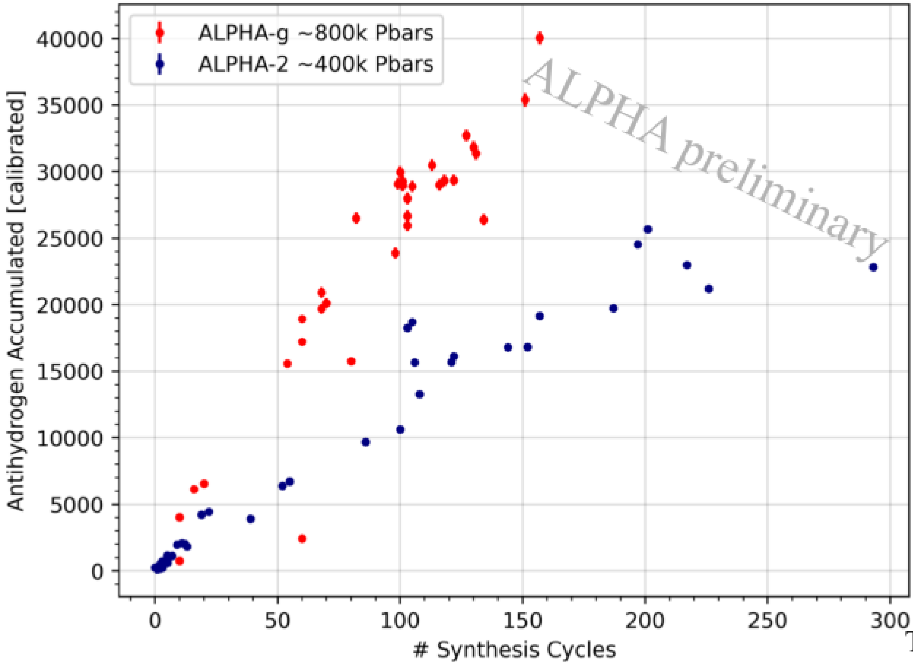
ALPHA-2 for spectroscopy - **ALPHA-g** for grativy

Enhanced Production via New Cooling Technique (Be^+)

- **Be^+ sympathetic cooling** of positrons (7 K from 20 K)
  → more efficient antihydrogen formation
- Published in *Nature Communications (2025):* Up to ~15,000 antihydrogen atoms overnight *(based on earlier runs)*

- **Improved ELENA usage** in 2025
  → capture of every cycle
- New stacking sequences
- **ALPHA-g outperforms ALPHA-2**
- Results:
  - rapid growth of accumulated antihydrogen
  - **10^4 trapped atoms overnight** (2025 state of the art)
  - much larger, colder samples
  - enables high-precision measurements

Anthydrogen accumulation rates for ALPHA-g and ALPHA-2 in 2025

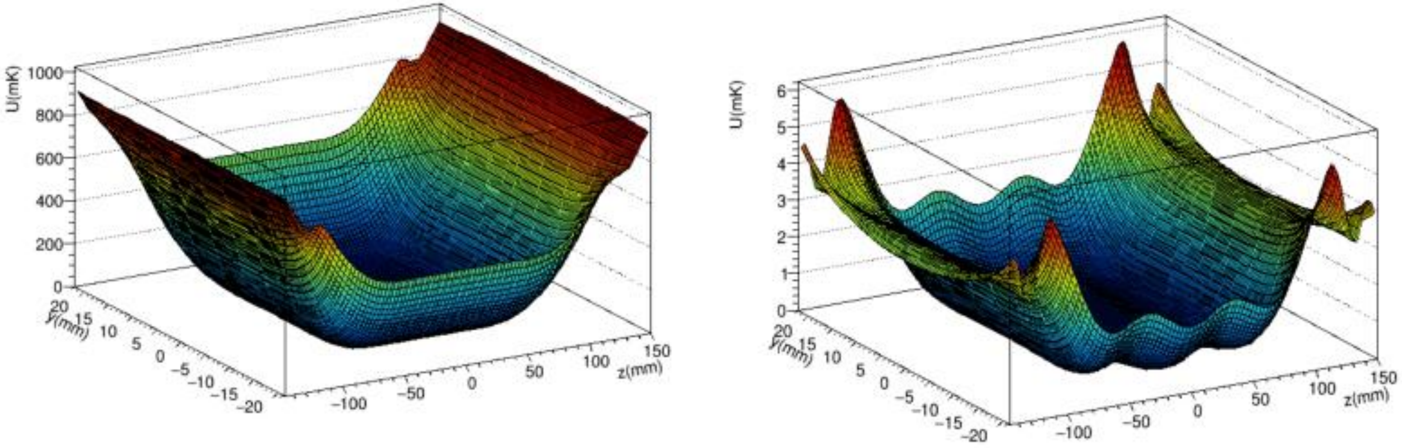


- 15 cycles/hr
- ALPHA-g was using pbars from 2 ELENA cycles

Ultra-Cold Antihydrogen via Adiabatic Cooling

- **Laser cooling**:
    - mean kinetic energy ~ **10 mK**
- **Adiabatic cooling**:
    - expansion of the magnetic trap
    - energies down to **~1 mK**
- Capability:
    - thousands of ultra-cold trapped atoms

Adiabatic cooling in ALPHA-2 in 2025



Experimental Procedure

1. Stack overnight
2. Laser cool to ~10mK

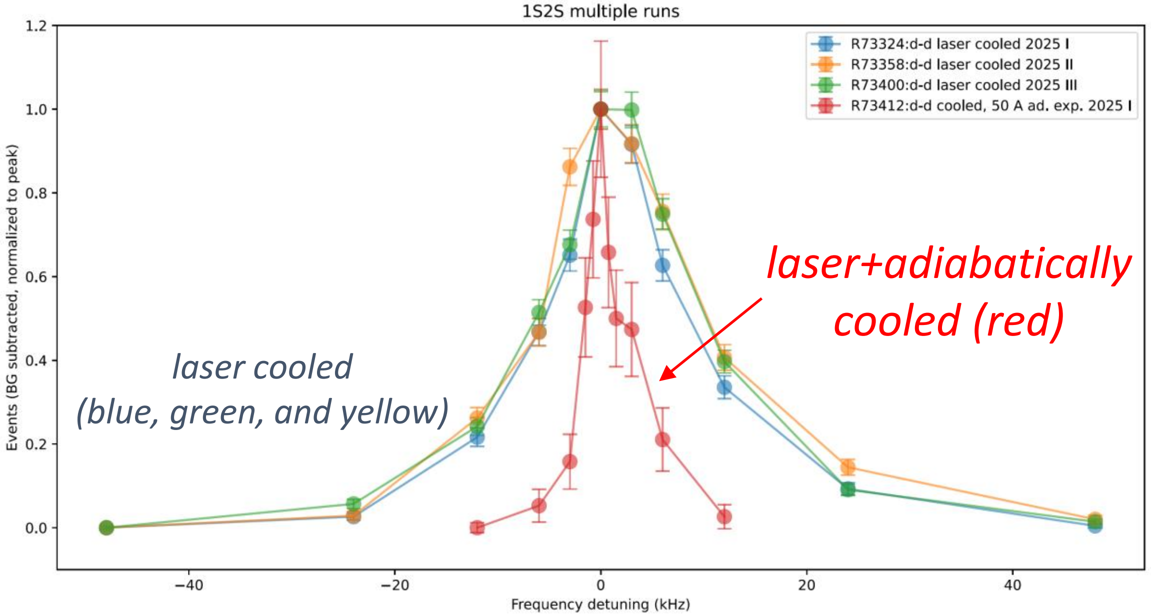
Adiabatic expansion:
Simultaneous axial and radial expansion
≈200x reduction in trap depth

The magnetic potential well in ALPHA-2 before (left) and after (right) adiabatic cooling. We use temperature units
Note the change in vertical scale

Spectroscopy and Gravity

Spectroscopy (ALPHA-2):

- Cooling → **narrower 1S–2S spectral lines**
- systematic uncertainties not yet under control
- adiabatic cooling has huge potential
- Improves precision on fundamental frequencies



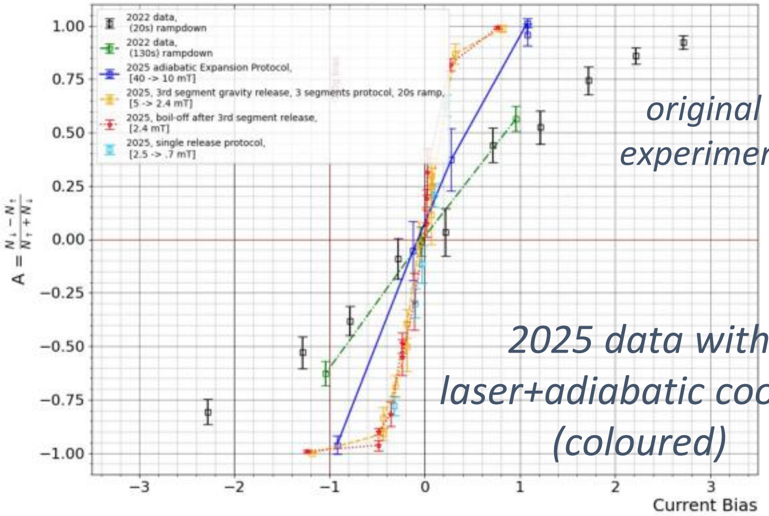
laser cooled (blue, green, and yellow)

laser+adiabatically cooled (red)

Gravity (ALPHA-g):

- First **laser cooling achieved in ALPHA-g**
- Study with **laser and adiabatic cooling**
- Observed: **asymmetry consistent with gravitational effects**
- Outlook: increasingly precise measurement of gravity on antimatter

Note: curves shifted on abscissa so that the 'balance points' coincide



original gravity experiment (black)

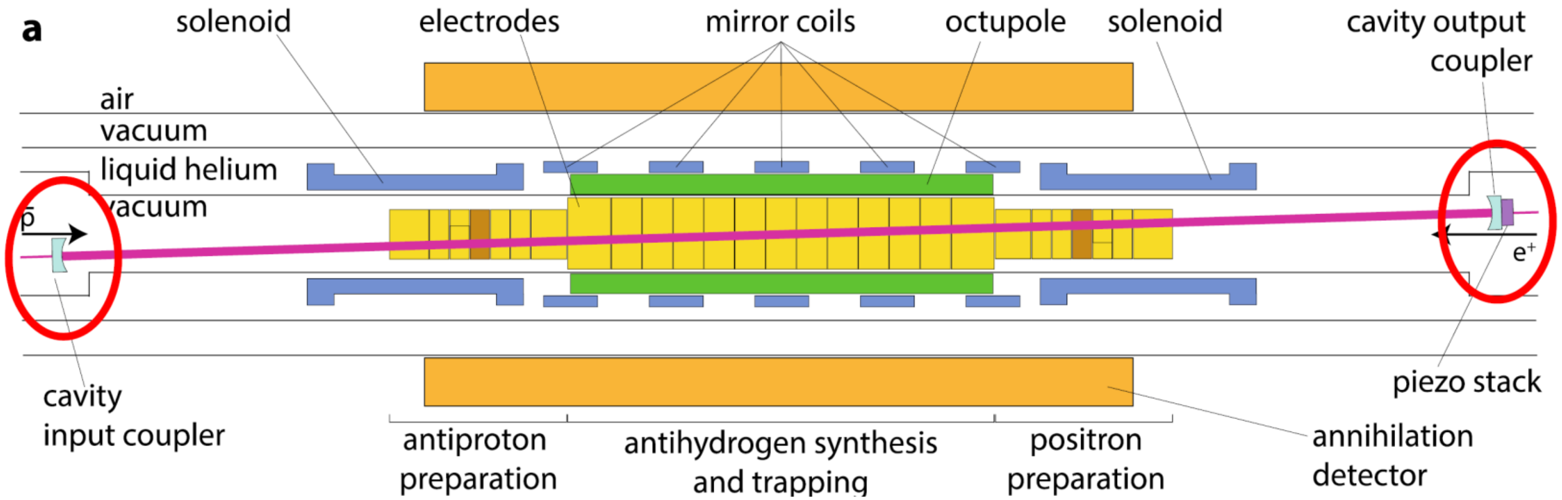
2025 data with laser+adiabatic cooling (coloured)

ALPHA-3 Upgrade

New Penning trap

Many problems: not yet ready for Hbar

New enhancement cavity



Publications

o) Be+ assisted, simultaneous confinement of more than 15000 antihydrogen atoms;
***Nature Communications* 16, 10106 (2025)**.
o) Antihydrogen spectroscopy without annihilation detection for a direct, in-situ comparison with hydrogen (**submitted to Nature Communications**)
o) Precision measurement of the 1S-2S transition in laser cooled antihydrogen
(**analysis complete; to be submitted to Nature**)

o) Four ppm measurement of the antihydrogen ground state hyperfine splitting: a hundred-fold improvement (**accepted at Nature – in publication phase – under embargo**) **Fundamental contribution by INFN**

Milestones

MILESTONE 2025 - ALPHA raggiungimento al 31-12-2025

ALPHA: Improved antihydrogen GS-HFS measurement	100%
ALPHA: Improved antihydrogen 1S-2S measurement	100%

MILESTONE 2026 - ALPHA- previsione completamento al 31-12-2026

ALPHA: Ottimizzazione produzione anti-idrogeno in ALPHA-g, mediante le tecniche sviluppate per ALPHA-2	100%

ASACUSA

Atomic Spectroscopy And Collisions Using Slow Antiprotons

INFN contact person: Luca Venturelli (Bs-Pv)

19 Institutions (14 in 2024)

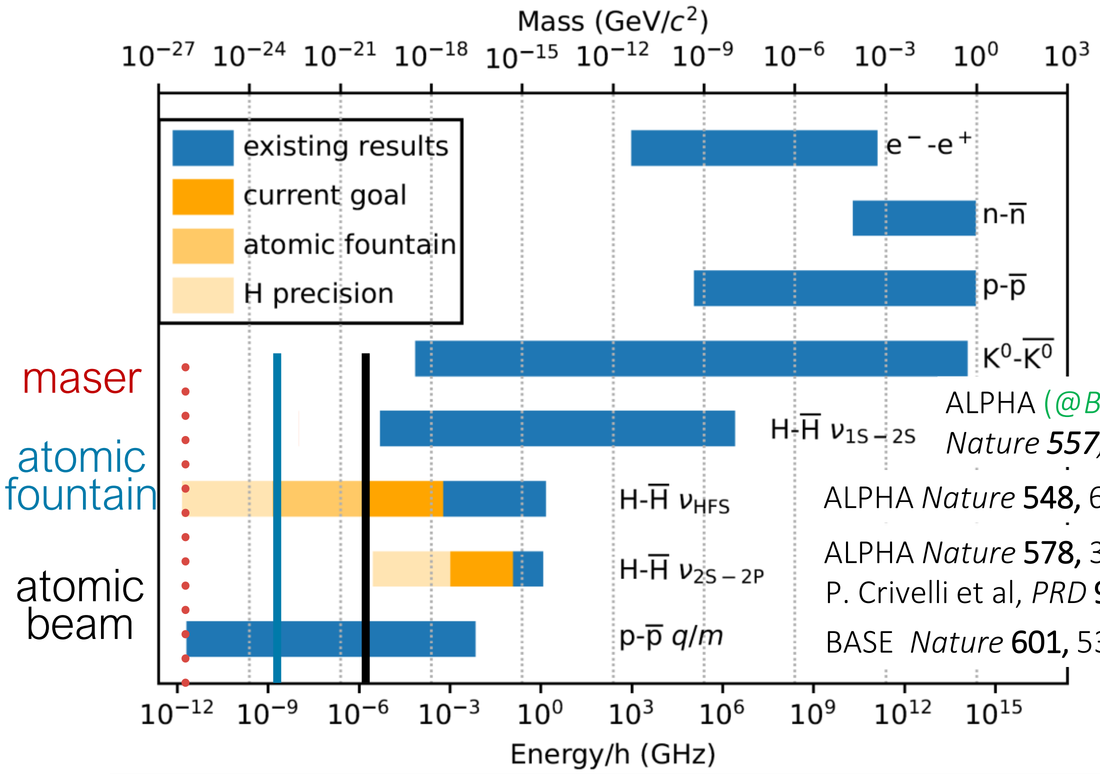
48 Researchers (43 in 2024)

- antiprotonic helium atoms with laser spectroscopy to test CPT
- X-ray spectroscopy of antiprotonic atoms NEW!
- **antihydrogen ground-state hyperfine structure to test CPT.**
- **atomic and nuclear collision cross sections of antiprotons at low energies.**

Spokespersons: M.Hori, E.Widmann

$\bar{\text{H}}$ ground-state hyperfine structure measurement

- Absolute precision of CPT tests



ALPHA (@*B*~1 T)
Nature **557**, 71–75 (2018).

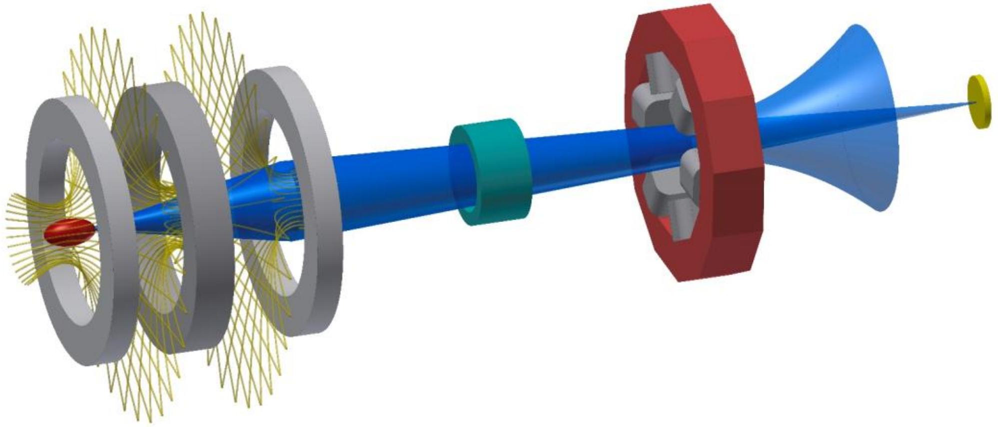
ALPHA *Nature* **548,** 66–69 (2017).

ALPHA *Nature* **578,** 375–380 (2020).
P. Crivelli et al, *PRD* **94,** 52008 (2016).

BASE *Nature* **601,** 53–57 (2022).

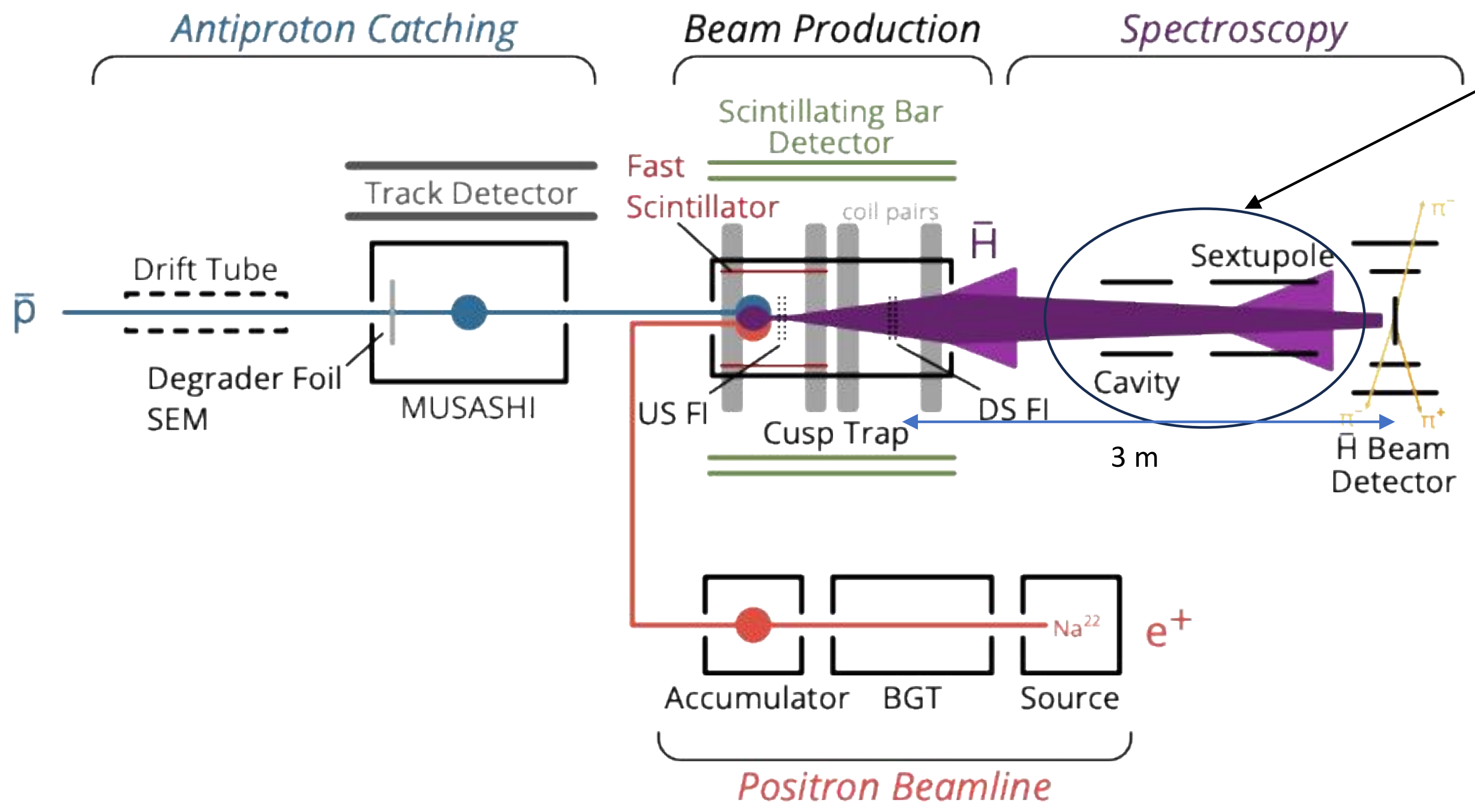
EW, Phys. Part. Nuclei **53**, 790–794 (2022). arXiv:2111.04056 [hep-ex]

- In-beam hyperfine spectropscopy
  - Field-free region: no Zeeman shifts
  - Needs polarised beam: Cusp field
  - Formation in nested Penning trap
    - Three-body recombination: Rydberg states
  - Spin selection by sextupole
    - Max. velocity ~1500 m/s (≡ T~ 100 K)



ASACUSA Cusp experiment

In 2025 the **cavity and sextupole** were **installed:** the production–detector distance is now approximately twice that of the 2024 configuration.



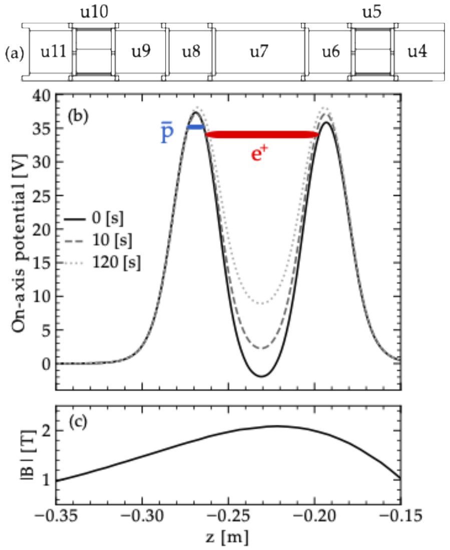
2025 results

- AD/ELENA delivered 13 × 10^6 pbars per cycle (10 × 10^6 in 2024)
  every 2 minutes

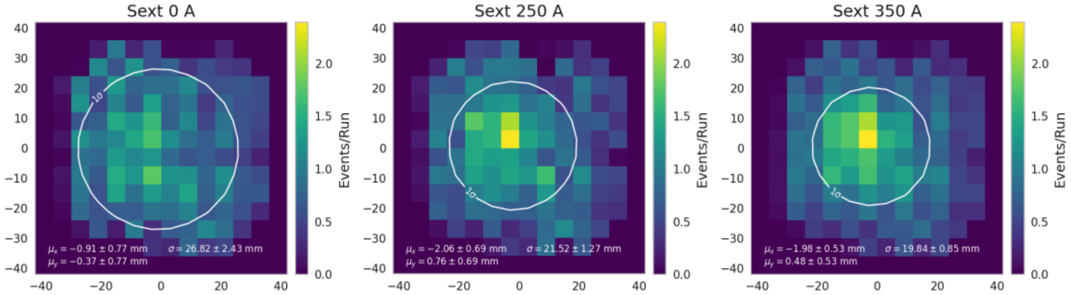
- **Mixing parameters 2025**
  - $7x10^6$ $\bar{\mathrm{p}}$ (4 stacks), *2.5x increase vs 2024*
  - $130x10^6$ e^+, $T \sim$ 45 K
  - $4x10^6$ $\bar{\mathrm{H}}$, *2x increase*
  - Mixing cycle 120 s
  - Repeated every 17 minutes

- **$\bar{\mathrm{H}}$ beam rate: 150 counts per cycle** on the detector at 3 m

- Mixing scheme: slow merge



- **Focussing action of sextupole comfirmed**



- 2D picture $\bar{\mathrm{H}}$ beam detector

  focusing effect is clearly visible but small, indicating a high velocity of the Hbars

Microwave ON/OFF Spectroscopy Test

Measurement method

- Microwave cavity tuned near the ground-state hyperfine transition
- Microwaves periodically switched **ON/OFF**
- Sextupole magnet selects spin states downstream

Signal searched for: $N_{ON} < N_{OFF}$
due to spin-flip transitions that defocus atoms in the sextupole.

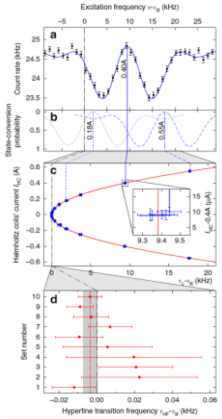
Asymmetry parameter $A = \frac{N_{OFF}-N_{ON}}{N_{OFF}+N_{ON}}$
Cumulative asymmetry monitored as statistics increase.

- Spectrometer line was tested with H beam
  - velocity ~1000 m/s
  - method leads to signal drop on resonance
  - Achieved precision:
    - 2.7 ppb using same spectrometer line

Received 4 Oct 2016 | Accepted 24 Apr 2017 | Published 12 Jun 2017 DOI: 10.1038/ncomms15749 OPEN

In-beam measurement of the hydrogen hyperfine splitting and prospects for antihydrogen spectroscopy

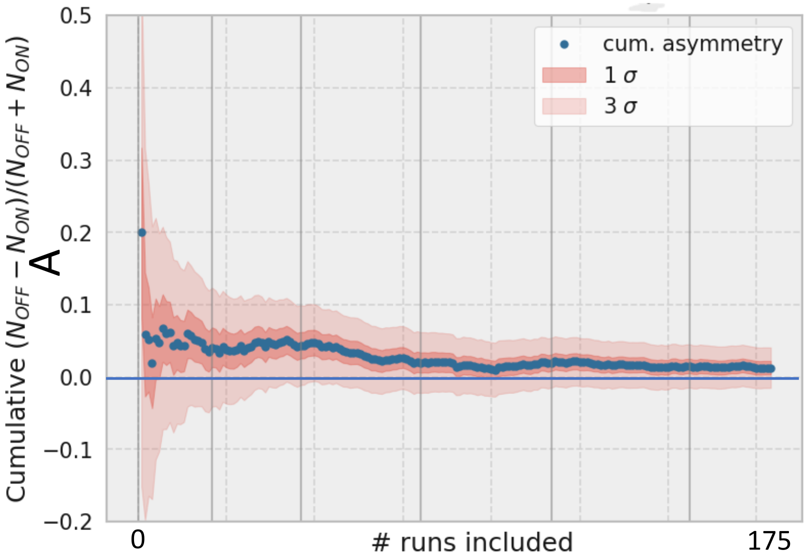
M. Diermaier[1], C.B. Jepsen[2,1], B. Kolbinger[1], C. Malbrunot[1,2], O. Massiczek[1], C. Sauerzopf[1], M.C. Simon[1], J. Zmeskal[1] & E. Widmann[1]



Result of scan

- 4000 $\overline{\mathrm{H}}$ for each condition
- Sensitivity: 7% drop at 3 σ (A≈0.036)

With 4000 events, the statistical uncertainty is $\sigma_A \approx 0.011$ giving a sensitivity of about 3σ

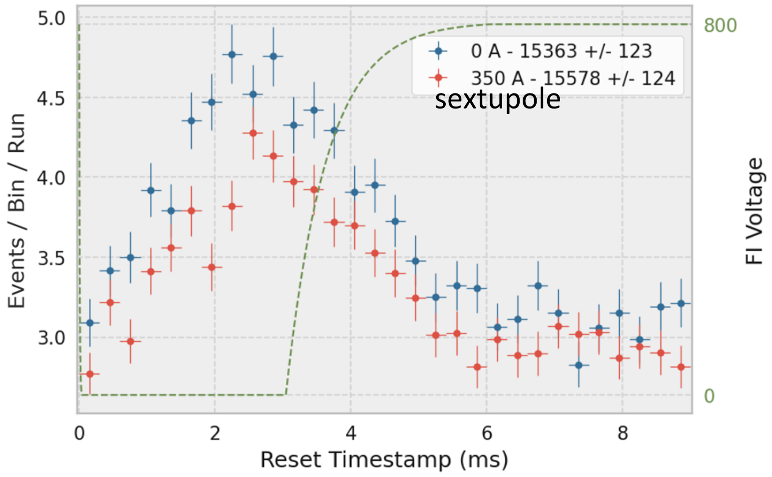


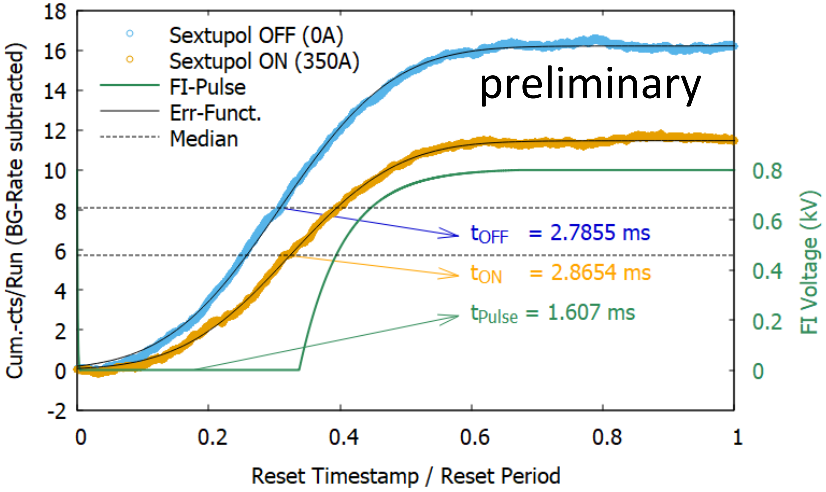
Not a clear signal

Possible reasons

- Antihydrogen beam velocity is too high→ short interaction time
- Ground-state fraction is too low
- Limited statistics

Antihydrogen Beam Velocity Measurement



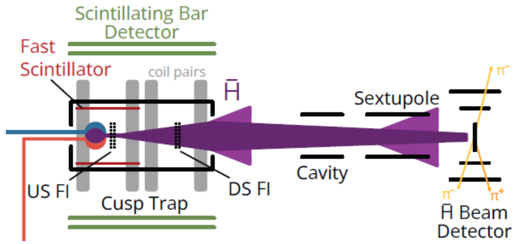


v ≈ 2500 m/s

Ideal: < 1000 m/s

Measurement method

Time-of-flight using pulsed field ionizer (DS FI)



- Voltage pulsed 800 V → 0 V for 3 ms
- Rydberg atoms (n> 27) pass during this window
- Arrival time measured at detector $v = \frac{L}{t}$

Result $\boldsymbol{v \approx 2400 - 2550\, m/s}$

Hbars produced at the end of the cycle are slower

Impact on spectroscopy

Ideal velocity: $v \lesssim 1000\, m/s$

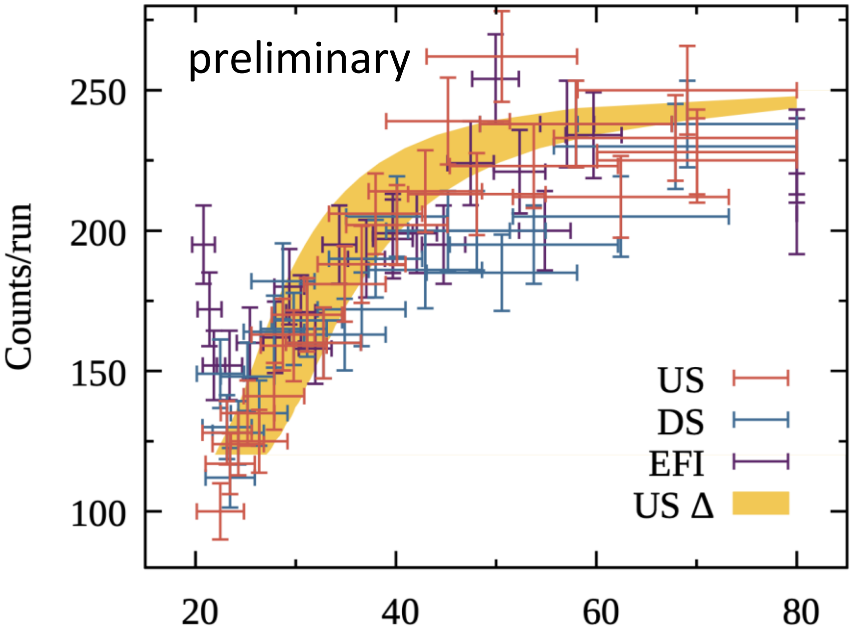
Fast atoms →

- short interaction time in microwave cavity
- lower transition probability
- weaker sextupole spin analysis

The antihydrogen beam is likely too fast for efficient microwave spectroscopy

2025 results

- Principle quantum number distribution



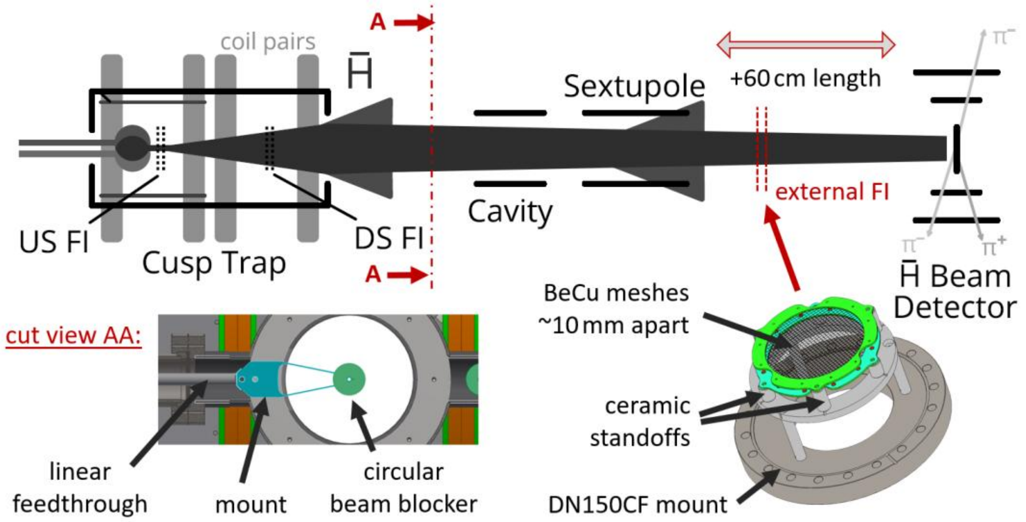
Field ionisers
US: $n \lesssim 27$
DS: $n \lesssim 27$
EFI: $n \lesssim 20$
US Δ: opposite polarity

The experimental data were compared with numerical simulations

It was necessary to include states up to n > 400 in the simulation, since models limited to n = 150 do not converge properly.

Plans for 2026

- **2026**
  - Longer e+ plasma for more collisional de-excitation
    - Increase number (100 → 400 Me+). Then the plasma can be longer and thicker without reducing density. Expected increase of ground state Hbar is 2x
  - Optimize mixing to generate slower $\bar{H}$
  - Reducing background
    - Use beam blockers (to remove Hbars on the axis, unsensible to sextupole)
    - external field ionizer (remove n>15)
  - Perform MW interacions



Central beam blocker

FI to ionise down to $n \sim 15$

Pubblicazioni - ASACUSA

- Hunter E. D. et al. *Antihydrogen Yield, Binding Energy, and Beam Velocity*, in preparation (submission to PRL)
- Hunter E. D. et al. *Optimizing Antihydrogen Production via Slow Plasma Merging,* Physics of Plasma, 2026
- Alexandrov A. et al*. Antiproton Interferometry and Aharonov-Bohm Effect (AIABE)* (submitted to Symmetry)

Proceedings

- Venturelli L. et al., *Pontecorvo Reactions,* PoS EXA-LEAP2024 002
- Mascagna V. et al., The scintillating bar detector of the ASACUSA experiment*,* PoS EXA-LEAP2024 077
- Bianconi A. et al., Optical potential analysis of antiproton-nucleus data at low energy, PoS EXA-LEAP2024 080
- Kraxberger V. et al., Towards a Study of Low Energy Antiproton Annihilations on Nuclei, PoS EXA-LEAP2024 104
- Hunter E. D. et al., Best Practices for the Manufacture of Antimatter Atoms, PoS EXA-LEAP2024 021

Proposals, Letter of Intents

- Hori M. and Widmann E. et al., *Experiments on a Lower-Energy and Slow Extraction Antiproton Beam,* CERN-SPSC-2025-018 ; SPSC-I-267 (LOI)
- Hori M. and Widmann E. et al., *ASACUSA Proposal for Run4 and Beyond*, CERN-SPSC-2025-020 ; SPSC-P-307-ADD-3 (proposal)
- Losekamm, M. J. et al., *Precision Measurement of the Cross-Sections for Inelastic Interactions of Antiprotons and Antideuterons with Nuclei for Cosmic-Ray Research*, CERN-SPSC-2025-015 ; SPSC-I-265 (LOI)
- Amsler C. et al., Low-Energy Antineutron Beamline at the Antiproton Decelerator for Scattering Experiments, CERN-SPSC-2025-010 (LOI)
- ADUC, *CERN AD/ELENA Antimatter Program*, Input to the European Strategy for Particle Physics 2026 - update

Milestones

MILESTONE 2025 - ASACUSA raggiungimento al 31-12-2025

ASACUSA: Test nuove tecniche di formazione di fascio di anti-idrogeno	100%
ASACUSA: Test di prime misure di fisica con nuova linea di fascio secondaria	100%

Realizzato con l'apparato di AEgIS + strumentazione ASACUSA (sinergia)

MILESTONE 2026 – ASACUSA - previsione completamento al 31-12-2026

ASACUSA: steering del fascio di anti-idrogeno lungo la linea di spettroscopia	100%

QUPLAS and PsICO

Physics motivation for e+ and Ps studies

Fundamental Physics with positrons/electrons and the most fundamental atom: Positronium

Ps

- Historically: tests of higher-order radiative QED correction (mass, lifetime…)

- Studying CPT (LIV) and the WEP physical with fundamental fermions, implying a direct violation of the
- Standard Model at the level of the Dirac terms:

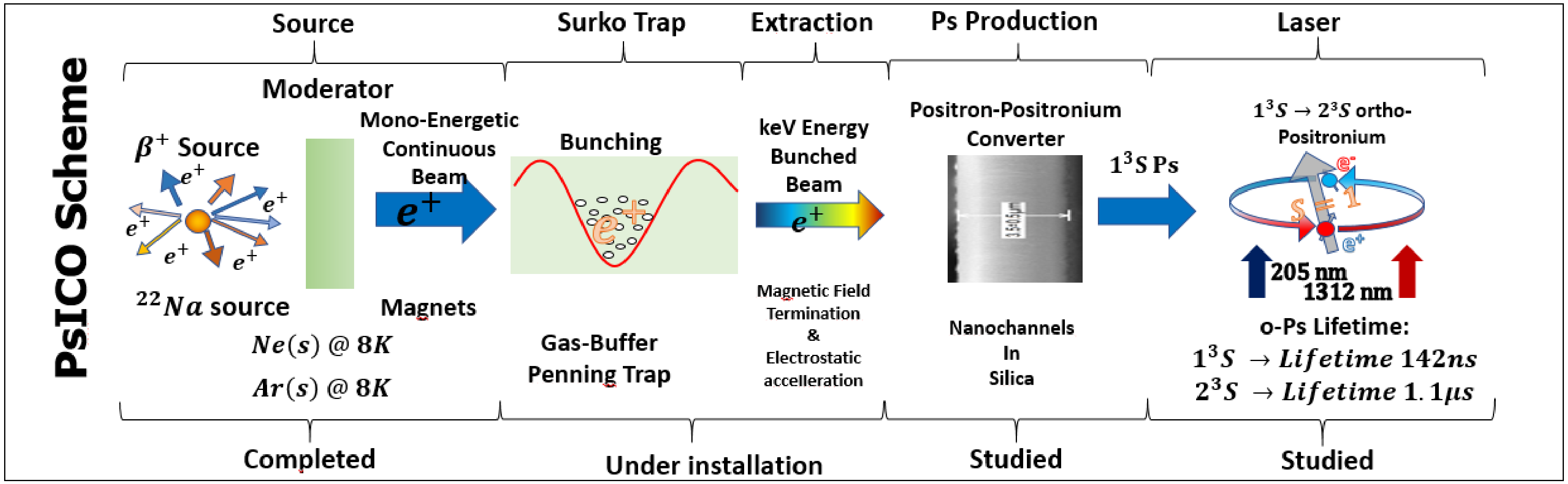
$$(i\gamma^\mu \partial_\mu - eA_\mu \gamma^\mu \boxed{- a_\mu \gamma^\mu - b_\mu \gamma_5 \gamma^\mu} - m)\psi = 0\,,$$

- Sensitive to different operators of the Standard Model Extension than hadronic systems.

PsICO goals
production of a positronium (Ps) beam excited to the long-lived 2^3S state for:

i) entanglement measurements of the 3γ coming from the annihilation of Ps prepared in selected quantum states

ii) inertial sensing measurements with the purely leptonic system



PsICO Scheme

Source — Moderator

β^+ Source

^{22}Na source

$Ne(s)$ @ $8K$

$Ar(s)$ @ $8K$

Mono-Energetic Continuous Beam

Magnets

Surko Trap

Bunching

Gas-Buffer Penning Trap

Extraction

keV Energy Bunched Beam

Magnetic Field Termination & Electrostatic accelleration

Ps Production

Positron-Positronium Converter

Nanochannels In Silica

1^3S Ps

Laser

$1^3S \to 2^3S$ ortho-Positronium

205 nm

1312 nm

o-Ps Lifetime:

$1^3S \to Lifetime\ 142ns$

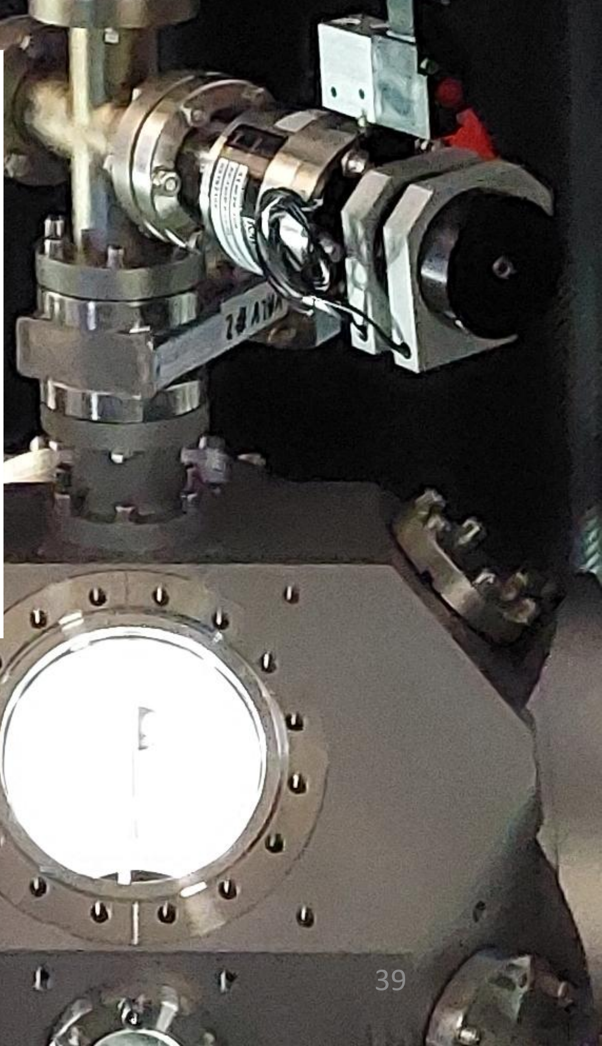
$2^3S \to Lifetime\ 1.1\mu s$

Completed

Under installation

Studied

Studied



Both experiments requires:

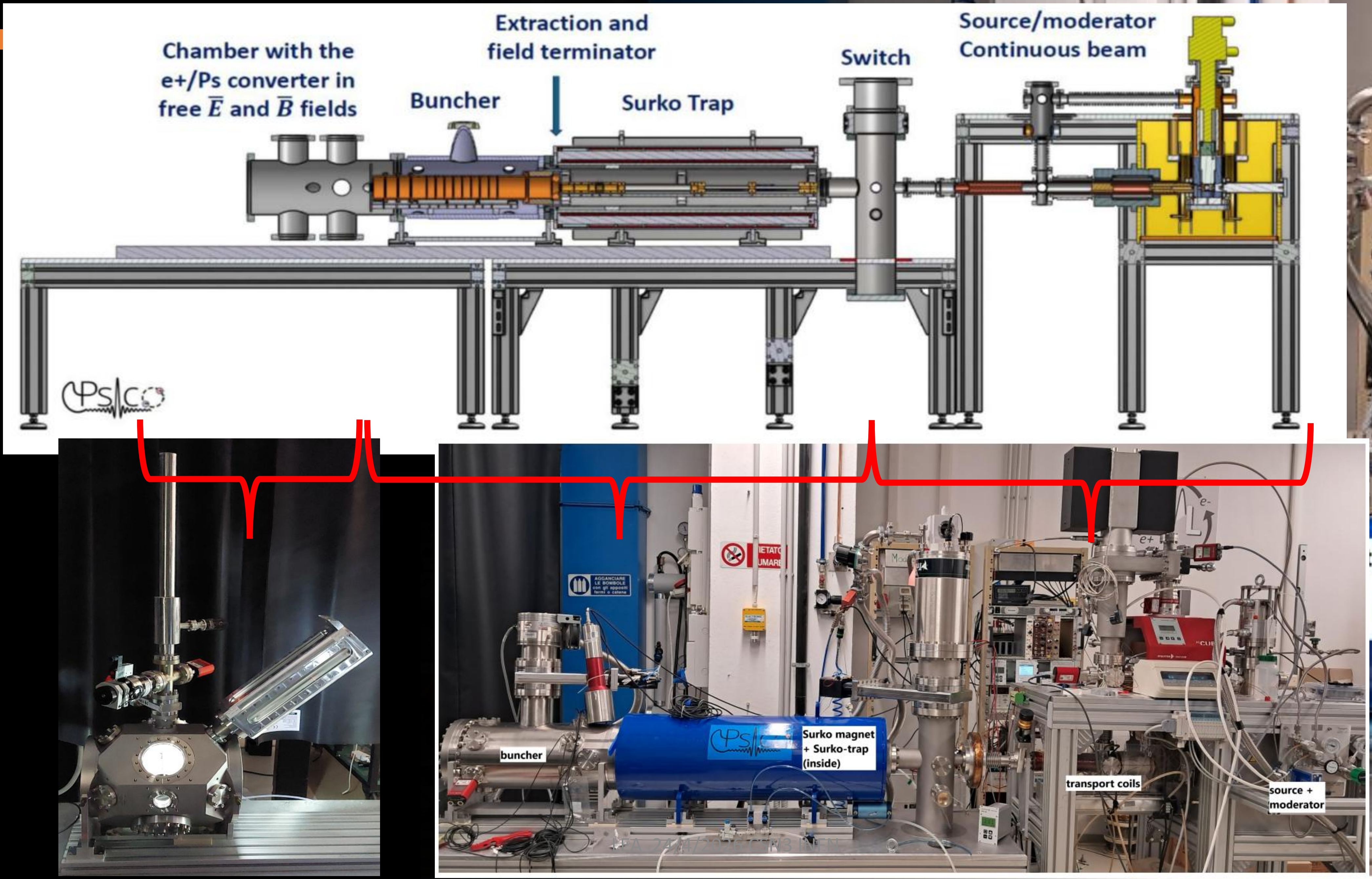
1) continuous positron beam (based on the use of a radioactive source and a moderator);

2) positron Surko trap for e^+ cooling and trapping for the production of e^+ bunches;

3) buncher-elevator and high efficiency e^+/Ps converter placed in the free field region;

4) a laser system to excite the metastable 2^3S level (lifetime 1142 ns)

PsICO apparatus

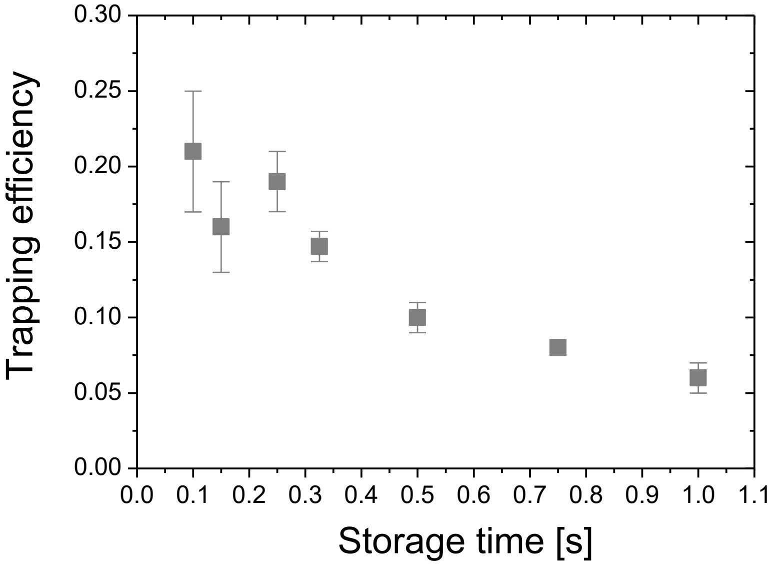


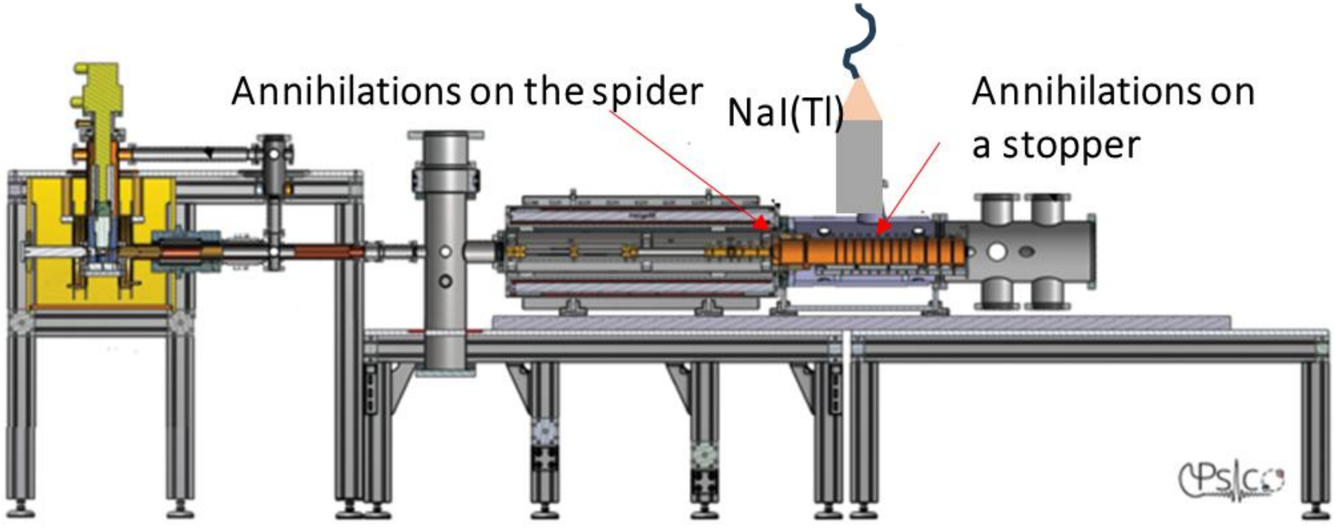
Achievements (2025 - Early 2026)

Trapping Efficiency in the Surko trap:

- Demonstrated efficiency of **~20%** for short storage times (<200 ms), exceeding the expected 15%

Positrons are injected into a 700-Gauss magnetic field and cooled via collisions with buffer gases (N_2, SF_6), becoming trapped in an electrostatic potential well.
Efficiency decreases for longer accumulation times due to positron annihilation with the residual gas



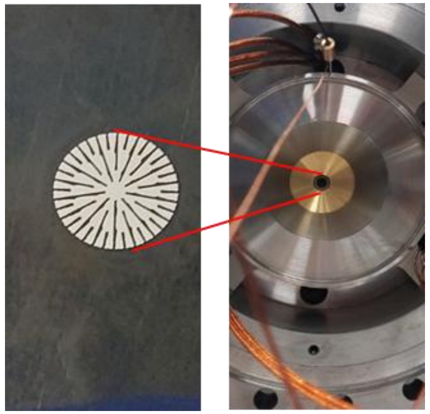


Magnetic Field Extraction:

- Extraction efficiency of **~50%** through the field terminator, in agreement with simulations

A spider (field terminator) deflects the magnetic field lines, cutting off the field at the trap exit

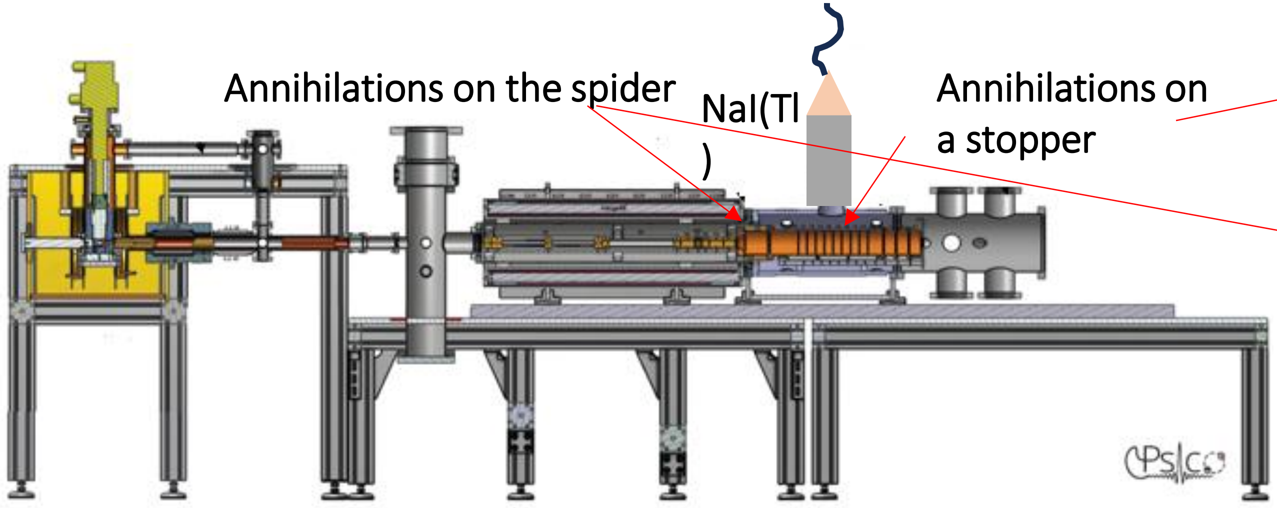
spider



Achievements (2025 - Early 2026)

Bunch Quality:.

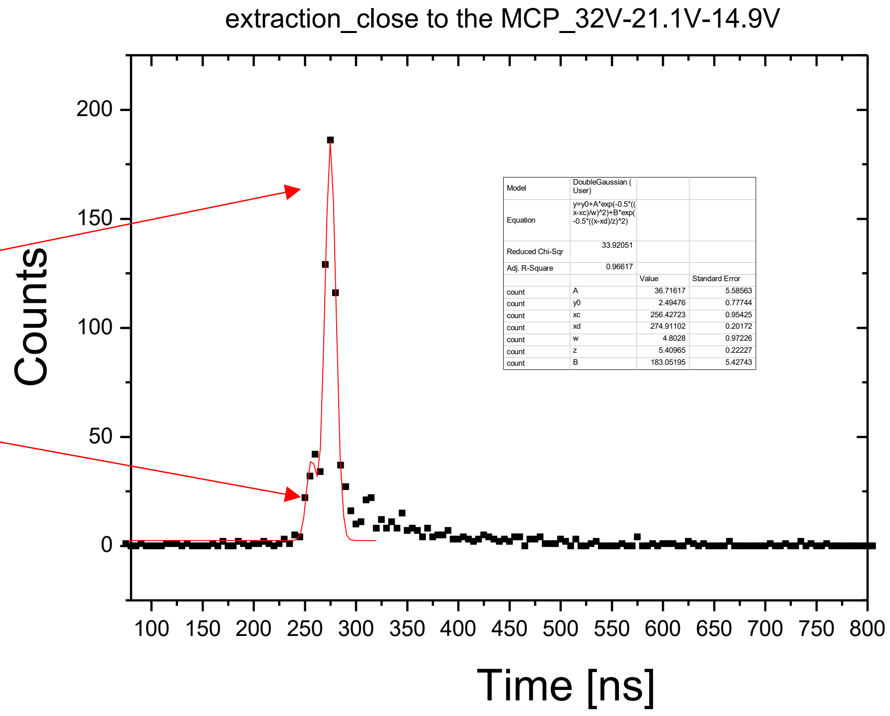
- Using a "pre-bunched" release technique, the time distribution of the positron cloud was measured to be **less than 5 ns (σ)**



Annihilations on the spider

NaI(Tl)

Annihilations on a stopper



extraction_close to the MCP_32V-21.1V-14.9V

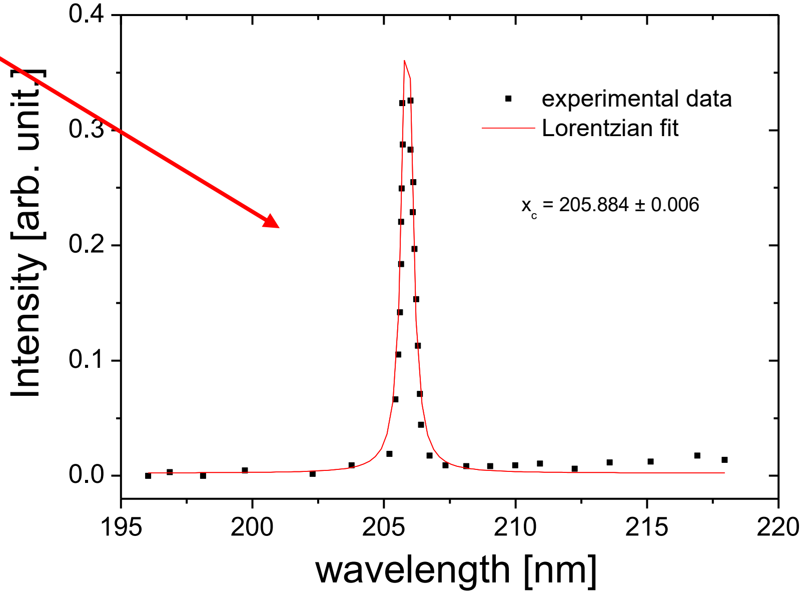
Model	DoubleGaussian (User)		
Equation	y=y0+A*exp(-0.5*((x-xc)/w)^2)+B*exp(-0.5*((x-xd)/z)^2)		
Reduced Chi-Sqr	33.92051		
Adj. R-Square	0.96617		
		Value	Standard Error
count	A	36.71617	5.58563
count	y0	2.49476	0.77744
count	xc	256.42723	0.95425
count	xd	274.91102	0.20172
count	w	4.8028	0.97226
count	z	5.40965	0.22227
count	B	183.05195	5.42743

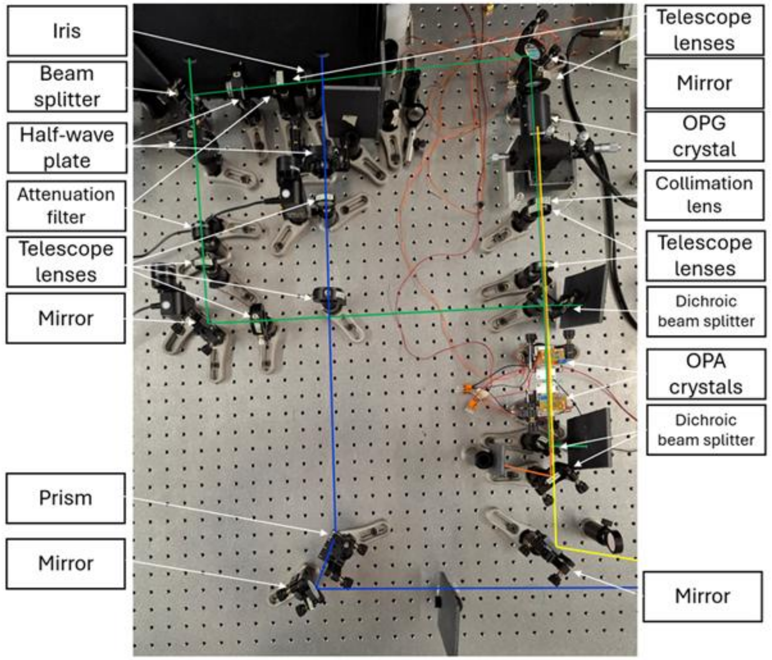
Instead of a standard release, the trap electrode potentials are shaped to generate a parabolic extraction ramp toward the trap exit.
Such a narrow positron bunch is required to ensure efficient injection into the buncher–elevator, which increases the positron energy and further compresses the bunch prior to implantation into the converter.

Achievements (2025 - Early 2026)

Laser Status:

- Characterized and optimized the 1312 nm beam; the 205 nm beam (14 mJ) has been observed, with a strategy identified for further enhancement.

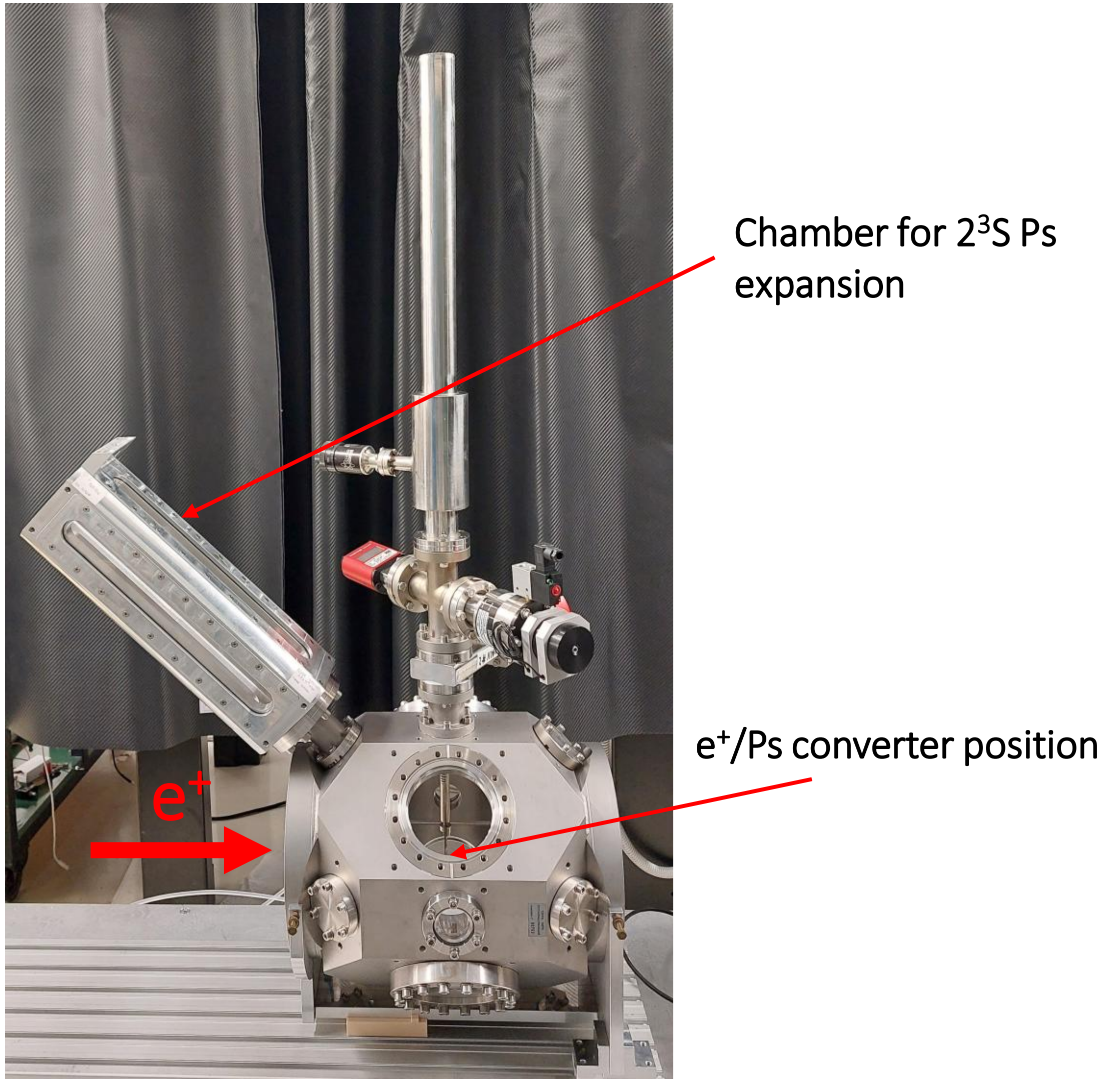




Excitation of metastable Ps requires a dual-frequency laser system operating simultaneously.
1312 nm: fully characterized and optimized beam, 2.6 mJ (≫ 0.4 mJ required).
205 nm: required for the transition, observed energy 14 mJ.
Power upgrade: saturation (~40 mJ) to be achieved using longer nonlinear crystals to increase output power.

Current Progress and Future Plans

- **Hardware Installation:** Final buncher and experimental chamber installation is currently in progress (expected within a few weeks).
- **Laser Optimization:** Completion of Ps laser excitation tests (milestone currently 60% achieved).
- **Detector Integration:** Integration of detectors from the University of Krakow for entanglement measurements.
- **2026 Objective:** Completion of Ps excitation tests and start of the full scientific measurement campaign.



Positron Source Situation

Messaggio del 23-4-2026 di Roberto Brusa:

a) la **procedura tramite il RUP** di TIFPA è partita in **ottobre 2025** quando i soldi di cofinanziamento da UNITN finalmente sono stati trasferiti da UNITN a INFN centrale e da INFN centrale a TIFPA
b) dopo una prima fase con Debbie (la persona che tratta a IThemba le sorgenti Na22) la cosa si è **arenata** in quanto **iThemba avrebbe dovuto compilare online un modulo ANAC**, di non facile interpretazione neanche per addetti ai lavori.
c) a **febbraio** ho fatto un incontro con l'amministrazione di Pavia con presente il Direttore di TIFPA Rivetti . Ci hanno insegnato che la **procedura ANAC** nel nostro caso **poteva essere superata** dato un decreto uscito nel Luglio 2025
d) la pratica è ritornata di nuovo in mano al nostro RUP che sembra abbia avuto nuovamente difficoltà di comunicazione-collaborazione con Debbie.
f) due giorni fa (21 aprile) ho scritto a Debbie di iThemba che mi ha risposto scusandosi del silenzio prolungato. Ho rimesso Debbie in contatto il RUP TIFPA .

Viste le difficoltà e l'importanza di riuscire a concludere l'ordine Il **Direttore di TIFPA Rivetti attiverà tutta l'amministrazione** per seguire con priorità l'ordine.
Settimana prossima **sentirà anche Faïçal Azaiez** che era stato direttore iThemba, per chiedere, nel caso che le procedure dovessero fermarsi, un suo consiglio-intervento.

Publications 2025-2026

Fundamental Experiments with Positronium Confined in Micro-Cavities And Emitted into Vacuum with the New Bunched Positron Beam at the Antimatter Lab of Trento
Mariazzi, S., Chehaimi, A., L. Penasa, R. Caravita, Brusa, R.S.
Solid Stat. Phen. 374, 513 (2025)

Developing Si samples with nanochannels connected to buried cavities for positronium collection
S. Mariazzi, A. Chehaimi, E. Socal, A. Wagner, M.O. Liedke, E. Hirschmann, C. Grivas, I. Sorokina, E. Sorokin and R.S. Brusa
J. Phys.: Conf. Ser. 3149, 012025 (2025)

Considerations about positronium sticking and quantum reflection in silica pores and cavities
A. Chehaimi, L. Penasa, R. Caravita, M.D. Naia, R.S. Brusa and S. Mariazzi
Phys. Scripta, submitted (2026)

Conferences 2025-2026

Developing Si samples with nanochannels connected to buried cavities for positronium collection
International Conference on Positron Annhilation 2025, Takamatsu, Japan 30/6-6/7/2025
S. Mariazzi invited talk

Positronium sticking: towards spectroscopy of positronium in silicon microcavities
International Conference on Positron Annhilation 2025, Takamatsu, Japan 30/6-6/7/2025
A. Chehaimi poster

Preliminary tests of positronium gathering in microcavities connected to nanochannels
2nd Symposium on New Trends in Nuclear and Medical Physics, Cracow, Poland 24-26/9/2025
S. Mariazzi invited talk

Positronium cooling in AEgIS and PsICO
111° Congresso Nazionale della Società Italiana di Fisica, Palermo, Italia 22-26/9/2025
A. Chehaimi talk

People

-Department of Physics, University of Trento- TIFPA/INFN Trento

Design of the experiments, development of the experimental bunched positron system and the laser system for Ps excitation to long-lived states

--Department of Aerospace Science and Technology, Politecnico di Milano

7 researchers 2.6 FTE

Other Institutes:

CERN
University of Oslo (Norway),
Norwegian University of Science and Technology (Norway),
University of Liverpool (United Kingdom),
Jagiellonian University of Krakow (Poland),
Fondazione Bruno Kesler (FBK) (Italy)

Responsible for the detector of gamma polarization

Milestones

MILESTONE 2025- PsICO raggiungimento al 31-12-2025

PsICO: Production of Ps clouds	100%
PsICO: Tests of Ps laser excitation to 2^3S state	60% Per ritardo nella realizzazione dell’elettronica della trappola Surko (ora completata) e nell’attivazione del sistema laser (completato anch’esso)

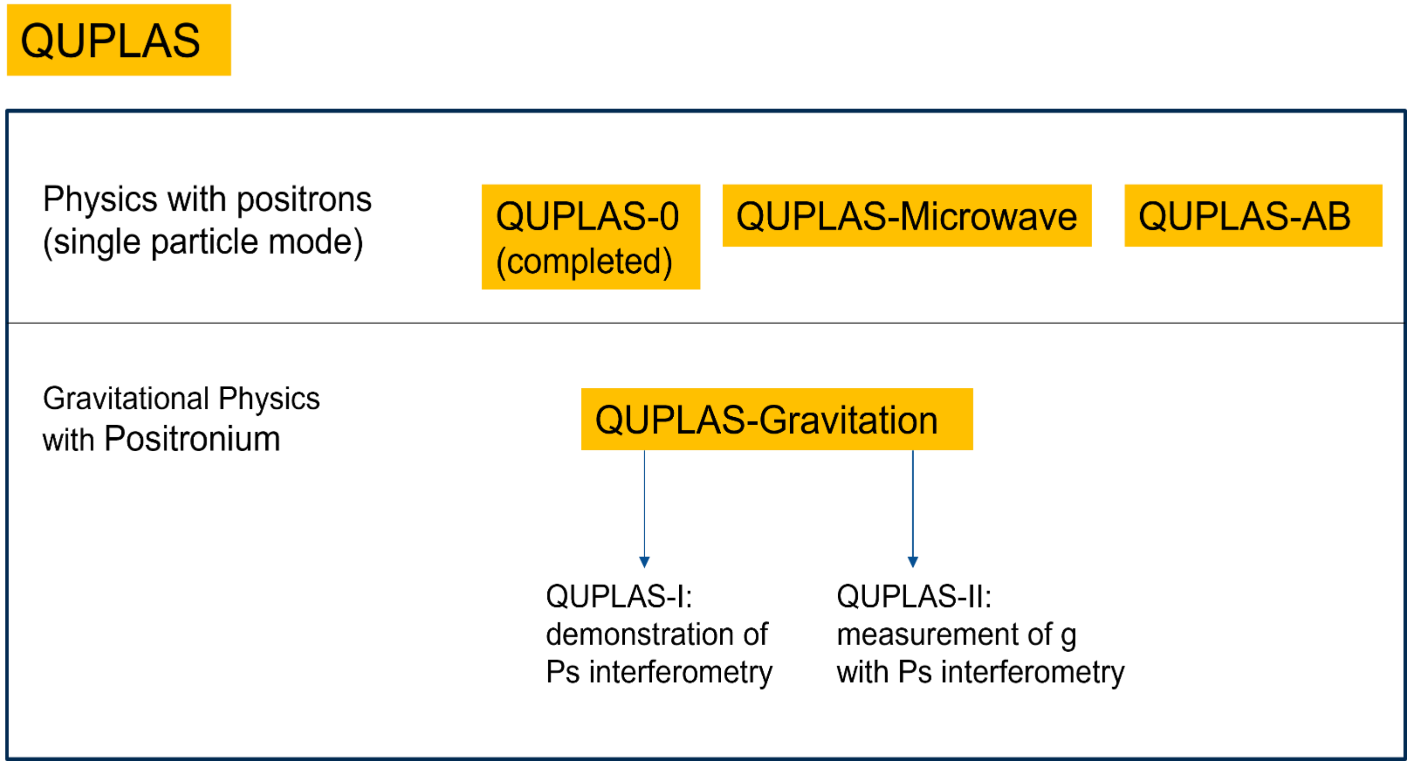
MILESTONE 2026- PsICO previsione completamento al 31-12-2026

PsICO: Commissioning of the Ps entanglement apparatus	100%

Q U P L A S

QUantum interferometry and gravitation with Positrons and LASers

Low
Energy
Antimatter



QUPLAS

Physics with positrons (single particle mode)

QUPLAS-0 (completed)

QUPLAS-Microwave

QUPLAS-AB

Gravitational Physics with Positronium

QUPLAS-Gravitation

QUPLAS-I: demonstration of Ps interferometry

QUPLAS-II: measurement of g with Ps interferometry

circa 6 INFN FTE

Circa 2 non-INFN FTE

Inside LEA Borsisti e Dottorandi

Milano: Giammarchi, Romè, Maero, Triggiani
Como: Bayo, Galanti, Ferragut
Firenze: Tino, Rosi, Salvi, Beleggia, Frabboni, Pappalardo, Mariani
Brescia-Pavia: Venturelli, Mombelli

LASA: Bacci, Rossetti-Conti, Drebot, Foggetta
New collaboration: C. Conci (ERC Starting su Fisica Medica con positroni)
Existing collaborations: Napoli, LNGS, Toho University (Japan), CNR Nanoscience

Progressi 2025-26

- Completamento del lavoro sulla cavità di photodetachment a Firenze (imminente il trasferimento a Como)
- Realizzazione del sistema per la produzione di Ps- a Como (test estensivi con effetto fotoelettrico)

Pubblicazione tecnica in preparazione

- Arrivo della sorgente di Na-22 a Como
- Progettazione fascio e^+ al LASA iniziata Como (QUPLAS, progetto di C. Conci, interesse da parte di PSYCO)

Source Status Update

- Source **delivered** a few weeks ago in Como
- Total lead time: ~1.5 years (procurement + delivery)
- Currently **in installation phase**
- Mechanical adjustments in progress for compatibility and safety
- Expected to be **operational in ~1 week**

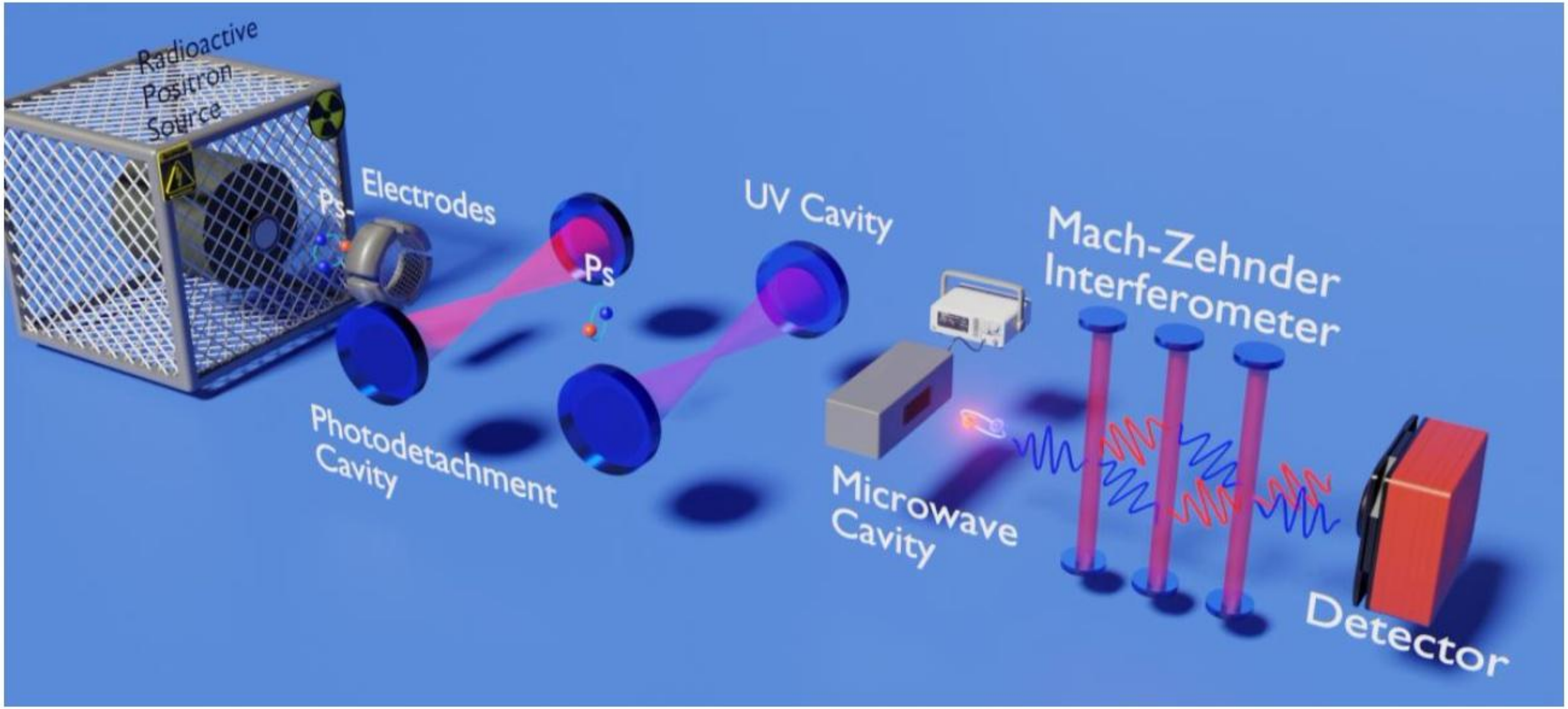
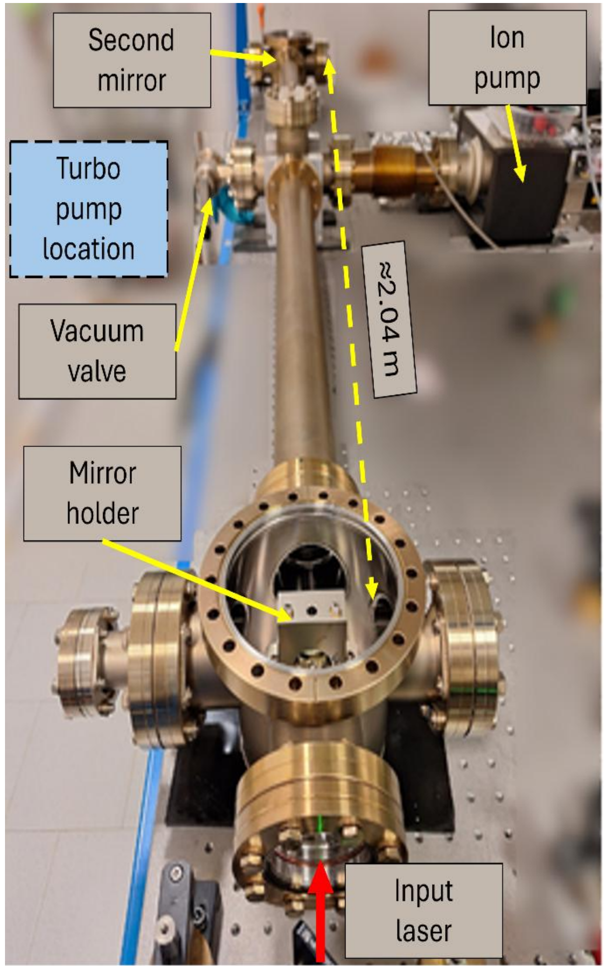
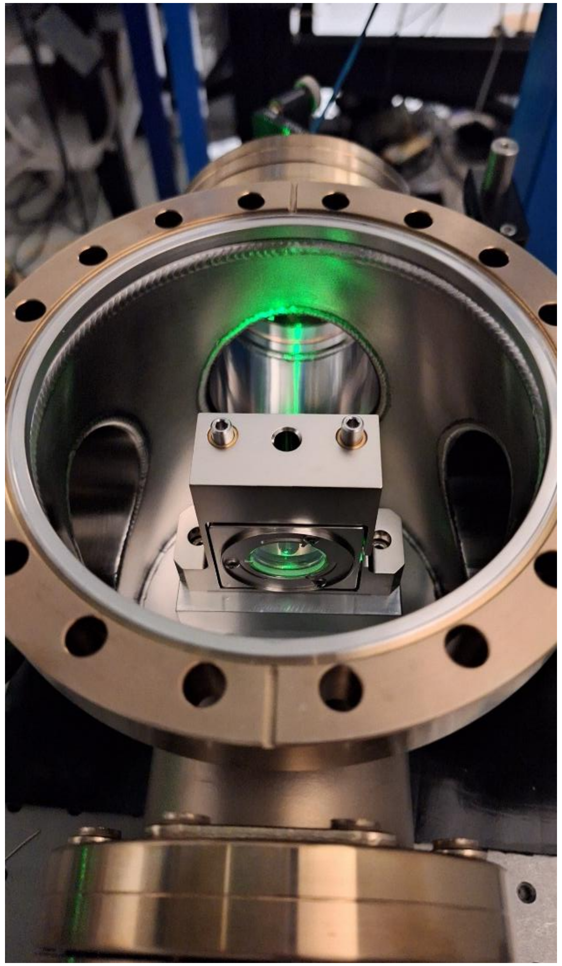
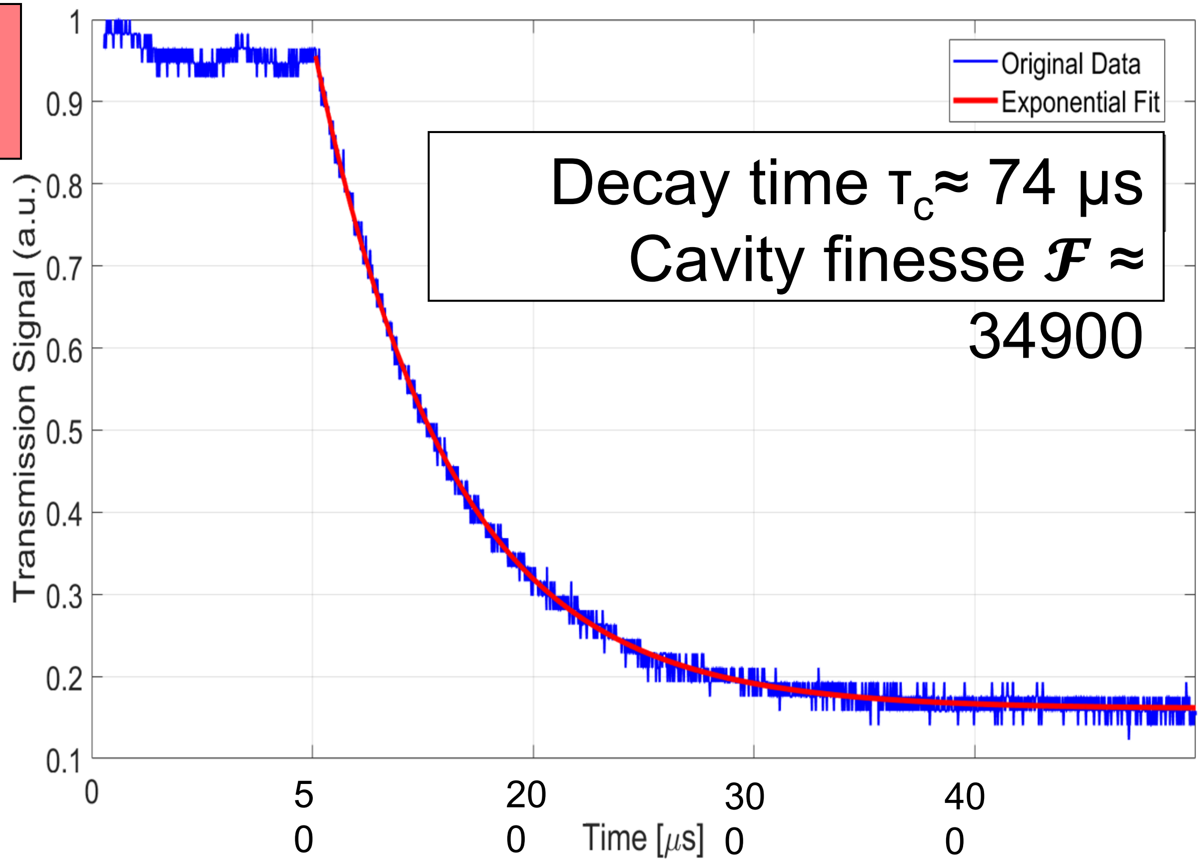


Figure 1: Schematic diagram of the experimental setup showing the above metioned high-power (200 kW) enhancement cavity for photodetachment of the positronium negative ion and the large momentum transfer Mach-Zehnder interferometer.

Photodetachment cavity fully operational in Firenze





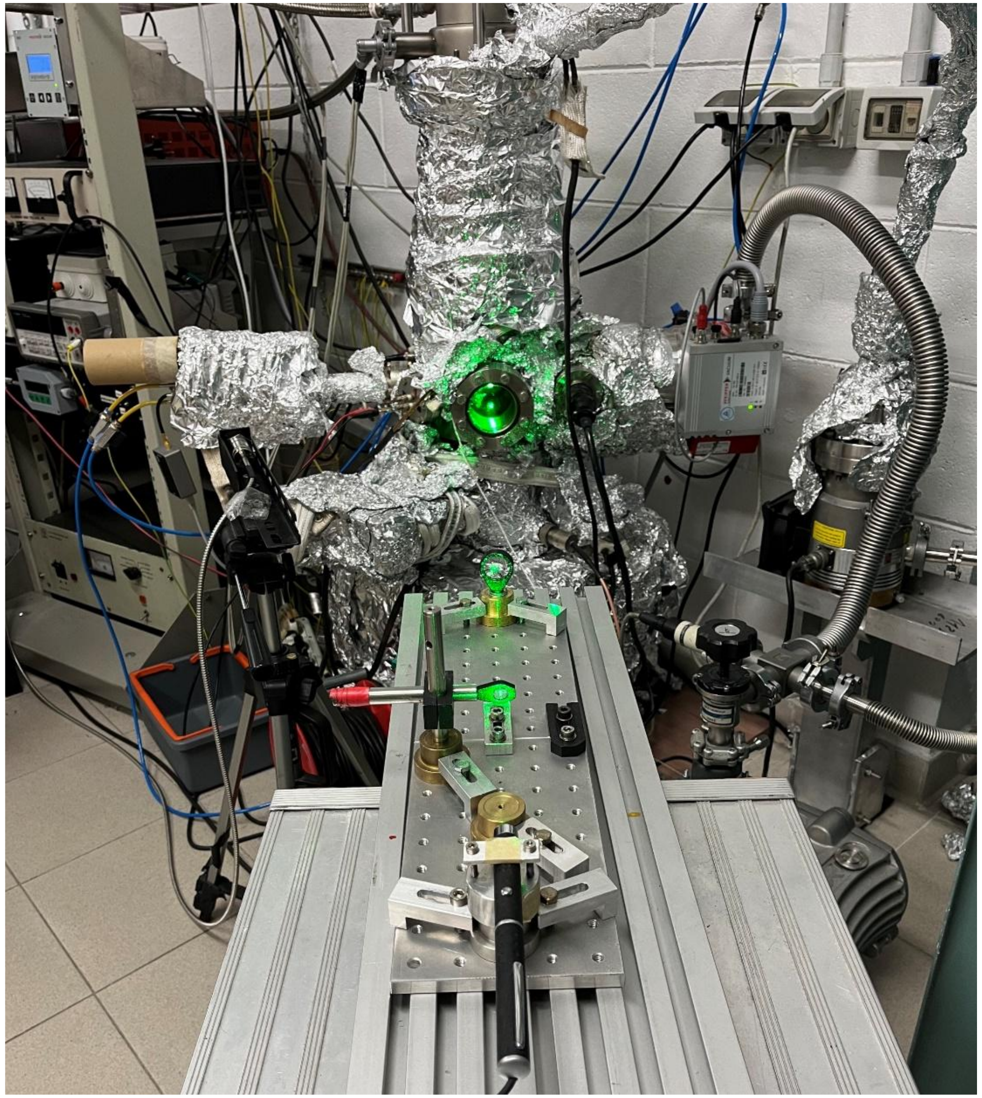


Decay time $\tau_c \approx$ 74 μs
Cavity finesse $\mathcal{F} \approx$ 34900

Potenza ottenuta: 200 kW (goal ottenuto)

- **Preparation of transfer to Como**
- **Old fashion Laser table installed in Como**

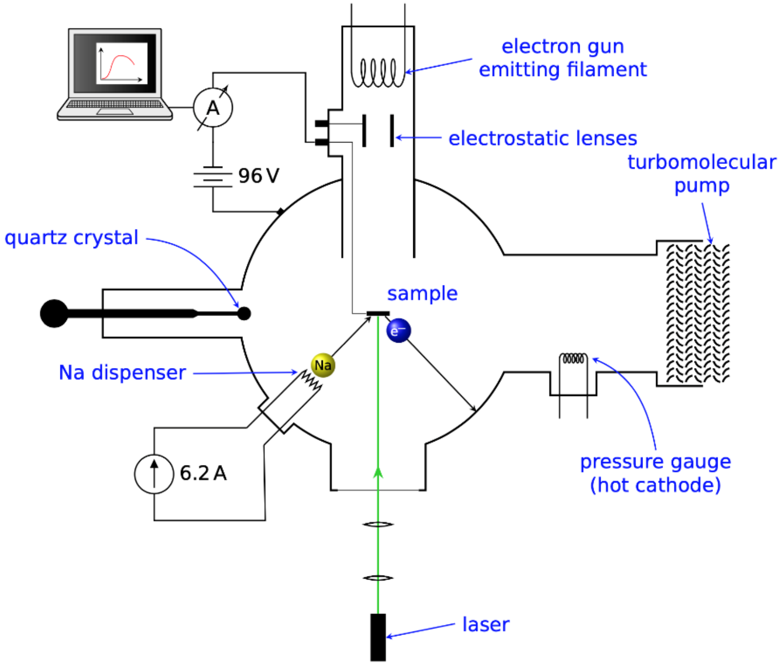
Ps- formation and acceleration tests (photoelectric effect)



Camera Calloni equipped with the Na deposition system

532 nm laser (provided by the Firenze group)

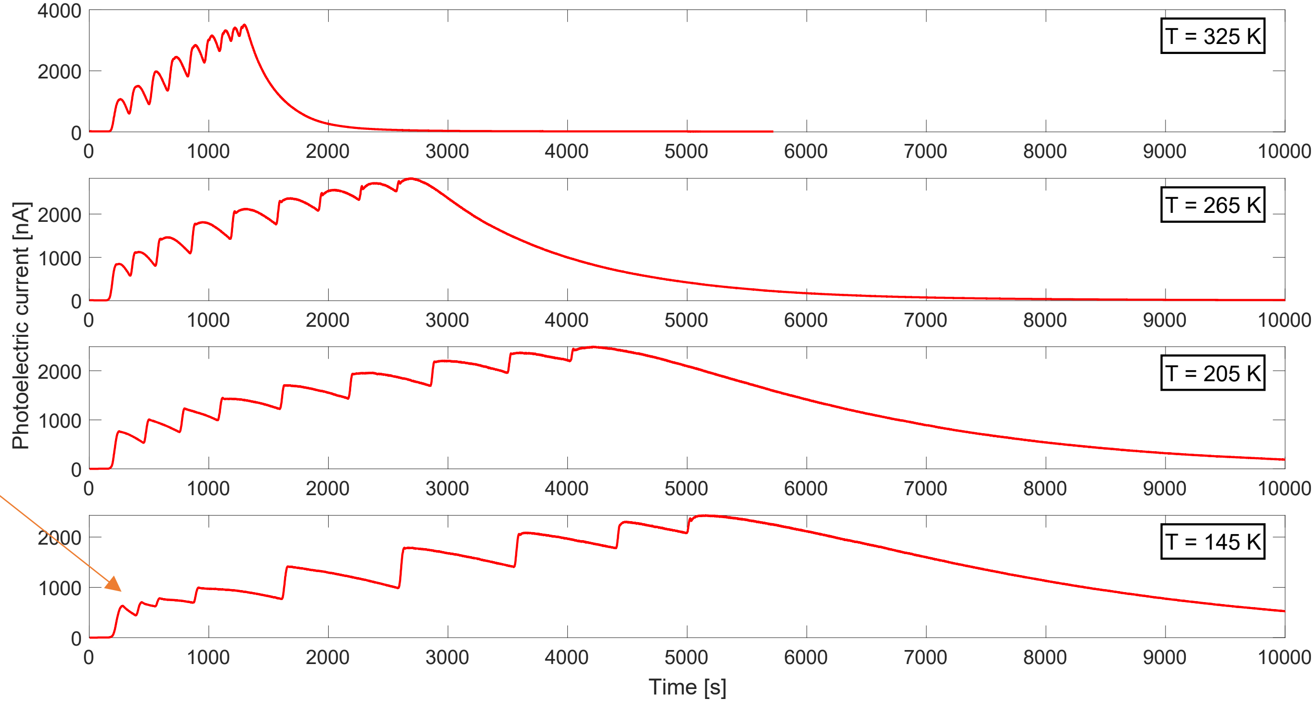
Enhancement of photoelectric effect with Na-deposition on Tungsten



Photoelectric effect was used as an analog process of Ps- formation from a surface, where the availability of «free» electrons is critical

Photoelectric Current as a function of various Na-deposition steps

- Measurements performed at different temperatures
- Short annealing at 2100 K for 6 minutes before each measurement



Na-deposition steps

- **Demonstrated optimization of photoelectric effect by Na-deposition (to be published)**

- **Arrival of the new Na-22 source (work underway to the automatization of the moderator preparation)**
- **Will be followed by Na-22 installation**
- **Installation of new coils to keep positron beam in place to prepare for Ps- production**
- **Vacuum 10^-10 to be reached (currently 10^-9) in the system**
- **Preparation of MCP and CCD system will need to be done**

Pubblicazioni

Experimental setup for the formation of an intense positronium beam via Ps- production (in preparation)

M. Vicini, P. Folegati, R. Ferragut, C. Conci, Advances in Medical Imaging: Will Positron Annihilation Spectroscopy Be the Promise of Preventive Diagnostics, *Solid State Phenomena* **374**, 125 (2025), doi: 10.4028/p-WJwI48

Conferenze

M. Giammarchi – CPT Invariance and the QUPLAS Experiment
X CPT and Lorentz Symmetry Meeting – U. of Indiana (USA) 2025

M. Giammarchi - Antimatter Gravitation
XXII Lomonosov Conference on Elementary Particle Physics – 2025

Good practices for the preparation of a sodium-coated tungsten surface through photoelectric effect studies Towards the formation of a Ps- beam. M. Bayo, A. Galanti, R. Ferragut, A. Calloni, M. Giammarchi, G. Vinelli and G. Rosi in “20th International Conference on Positron Annihilation (ICPA-20)” Takamatsu, Japan (June 2025).

Toward the First Gravitational Test of Elementary Particles. R. Ferragut, on behalf of the QUPLAS collaboration in “20th International Conference on Positron Annihilation (ICPA-20)” Takamatsu, Japan (June 1st-6th, 2025).

Experimental setup for the formation of an intense positronium beam for gravitation experiments. A. Galanti, M. Bayo, M. Giammarchi, G. Vinelli, G. Rosi and R. Ferragut on behalf of the QUPLAS Collaboration in 7th International Forum on Advances in Radiation Physics (IFARP-7), Buenos Aires, Argentina (March 12-13, 2026).

Milestones

Milestones 2025
- Studio della Produzione di Ps- (100%)
- Completamento cavità photodetachment (100%)

Previsione milestones 2026
Produzione di Ps- al laboratorio di Como (100%)

LEA Summary of Results (2025–early 2026)

- **AEgIS:** first moiré patterns with antiprotons; sub-μm detector resolution; laser cooling of Ps reaching temperatures as low as 100 K; high-statistics antiproton annihilation studies
- **ALPHA:** major increase in antihydrogen production (~10^4 atoms/night); ultra-cold samples (mK); improved spectroscopy and further gravity indications
- **ASACUSA:** higher antihydrogen yields; beam diagnostics (confirmed the focusing action of the sextupole) and spectroscopy tests; limitations identified (high velocity, low signal)
- **PsICO:** efficient positron trapping/extraction; sub-5 ns bunches; laser system validated; setup close to full operation
- **QUPLAS:** key hardware completed; positron source ready to be installed; first tests toward Ps-based interferometry