STATUS REPORT OF ASACUSA AD-3 COLLABORATION FOR 2024

Progress in 2024 and plans for 2025

SPSC Meeting

11 February 2025

ASACUSA collaboration

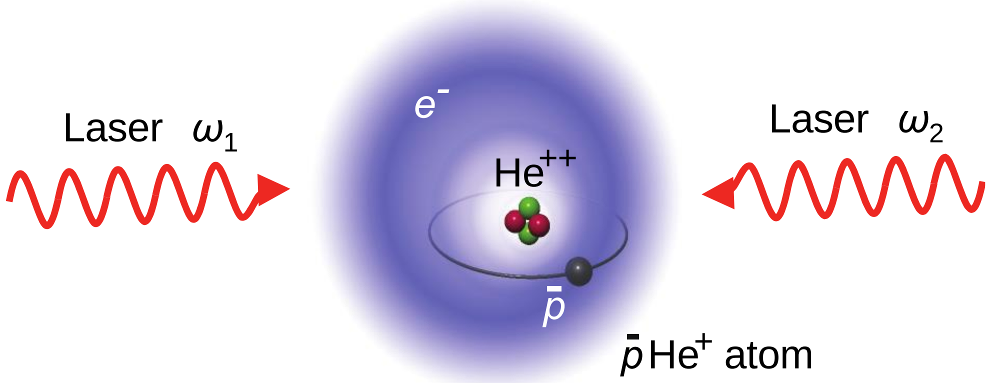
C. Amsler[a], D. Barna[b], M.N. Bayo[c,d], H. Breuker[e], M. Bumbar[f,i], M. Cerwenka[a], G. Costantini[g], A. Dax[h], R. Ferragut[c,d], A. Forsyth Daneri[i], M. Giammarchi[d], A. Gligorova[a], G. Gosta[g], M. Harley[f,j], T. Higuchi[k], M. Hori[i,l*], E. D. Hunter[f,i], K. Imai[i], C. Killian[a], V. Kraxberger[a], N. Kuroda[m], A. Lanz[a,1], M. Leali[g], G. Maero[n], C. Malbrunot[f,2], V. Mascagna[g], Y. Matsuda[m], S. Migliorati[g], D. J. Murtagh[a], A. Nanda[a], L. Nowak[a,f], M. Romé[n], G. Roncoli[n], R. E. Sheldon[a], M. C. Simon[a], M. Tajima[i,o], V. Toso[g], U. Uggerhøj[p], S. Ulmer[e], L. Venturelli[g], A. Weiser[a], E. Widmann[a*], Y. Yamazaki[e],

[a]Stefan Meyer Institute, [b]Wigner Research Centre for Physics, [c]Politechnico di Milano, [d]INFN Milano, [e]Ulmer Fundamental Symmetries Laboratory, RIKEN, [f]Experimental Physics Department, CERN, [g]Dipartimento di Ingegneria dell'Informazione, Università degli Studi di Brescia and INFN Pavia, [h]Paul Scherrer Institute, [i]Department of Physics, Imperial College London, [j]Physics and Astronomy Department, University College London, [k]Institute for Integrated Radiation and Nuclear Science, Kyoto University, [l]Max-Planck-Institut für Quantenoptik, [m]Institute of Physics, the University of Tokyo, [n]Dipartimento di Fisica, Università degli Studi di Milano and INFN Milano, [o]Japan Synchrotron Radiation Research Institute, [p]Department of Physics and Astronomy, Aarhus University

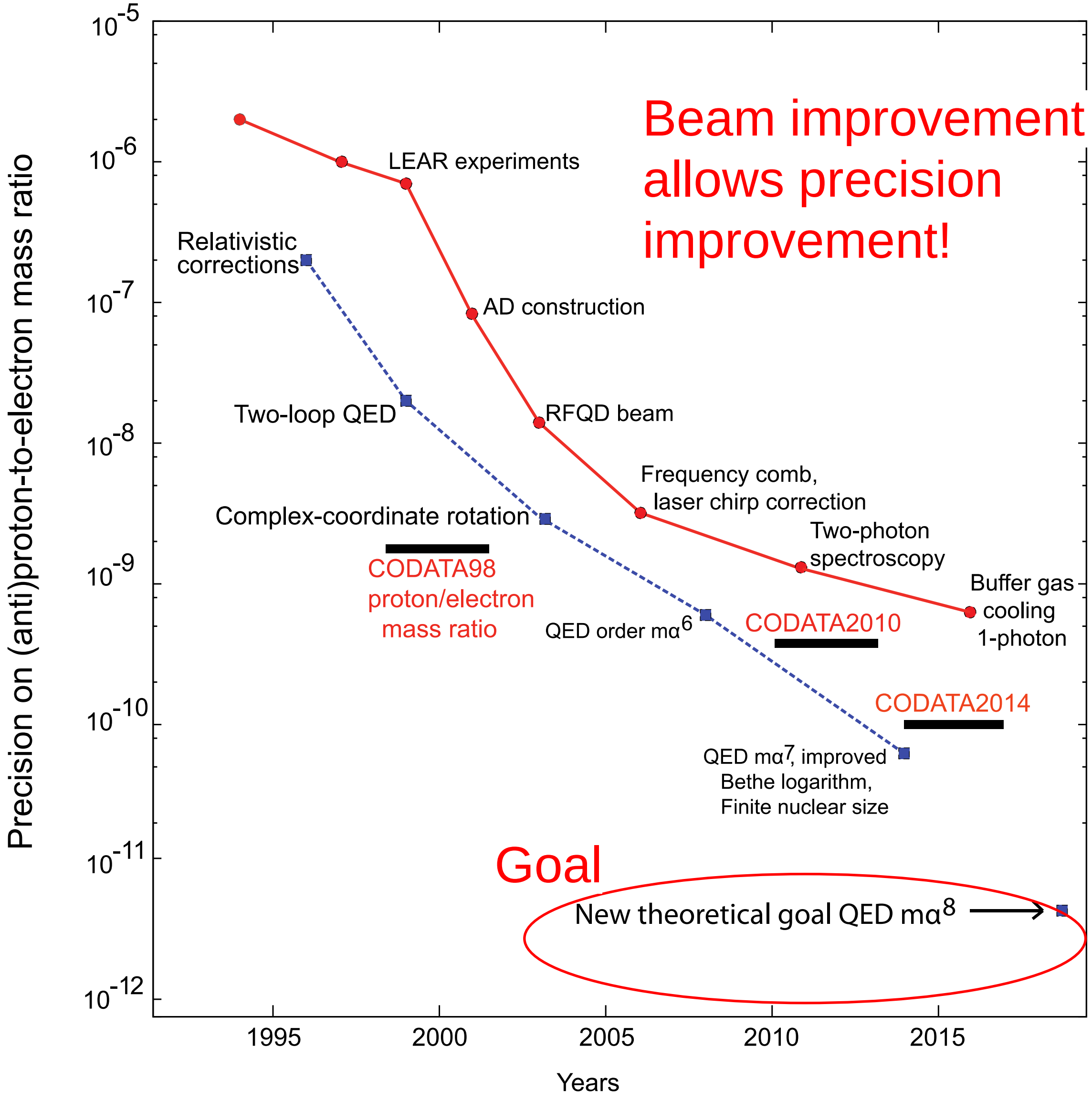
* Co-spokespersons

[1]present address: University College London, Gower St, London WC1E 6BT, United Kingdom
[2]present address: TRIUMF, Vancouver, Canada

Antiprotonic helium



- Hadron-antihadron system with the longest known lifetime (4-10 μs), remains important atom complementary to antihydrogen.
- Utilize the high-quality ELENA beam to carry out sub-Doppler two-photon laser spectroscopy of narrow resonances at 100 times higher precision (10^{-11}) and test QED in matter-antimatter system and determine antiproton-to-electron mass ratio and search for new physics beyond Standard Model.

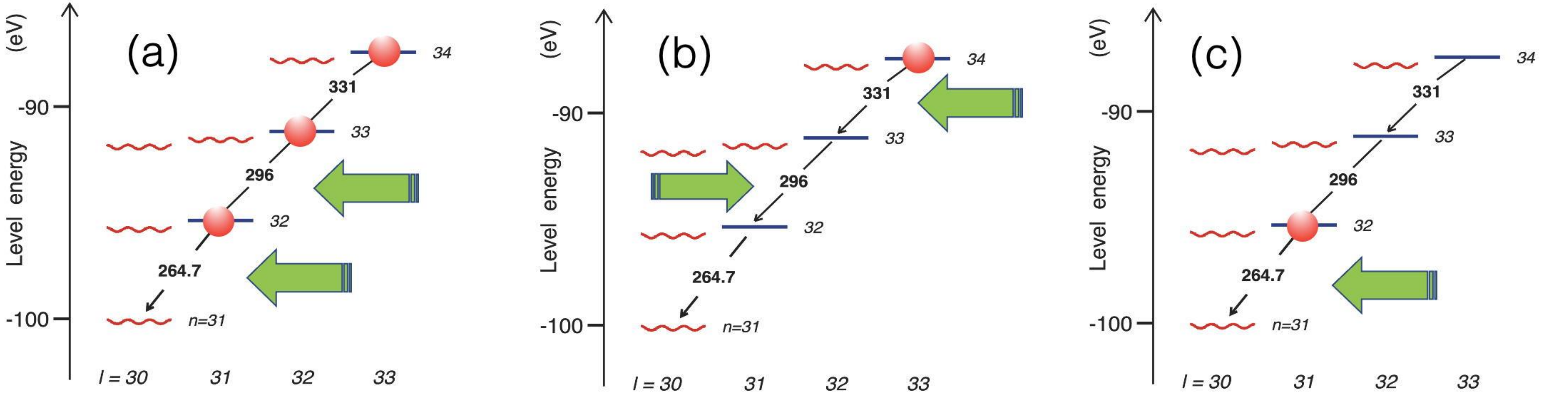


Primary goal: laser spectroscopy of narrow resonances

Experiment needs: 5 narrowband laser beams — ongoing

Very high density, reproducible sample of antiprotonic atoms — achieved

Atoms synthesized in low-density gas target (low collisions) — achieved

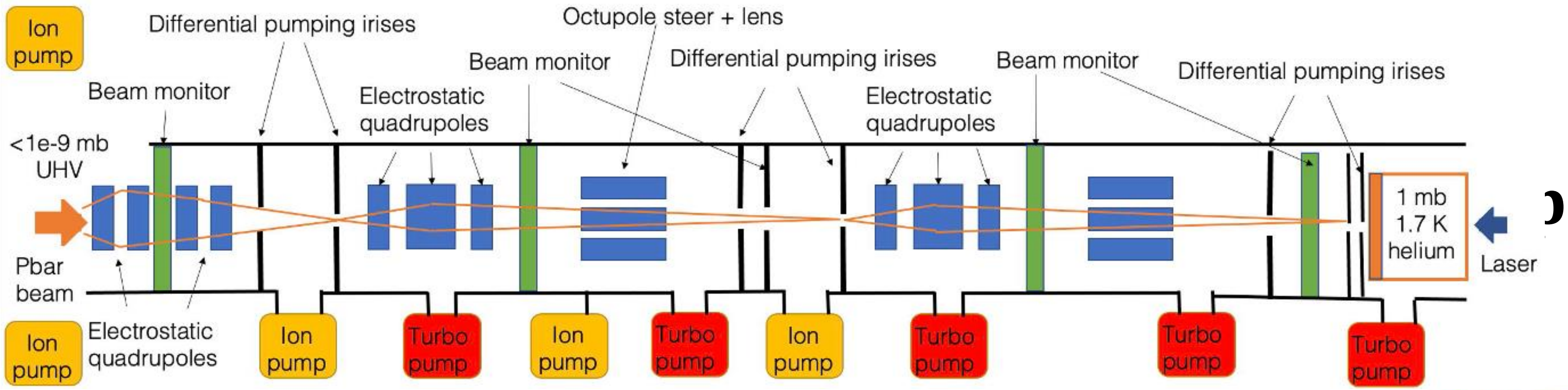


Empty antiprotons in (n,l)=(33,32) and (32,31) and create population asymmetry using UV lasers 1 and 2.

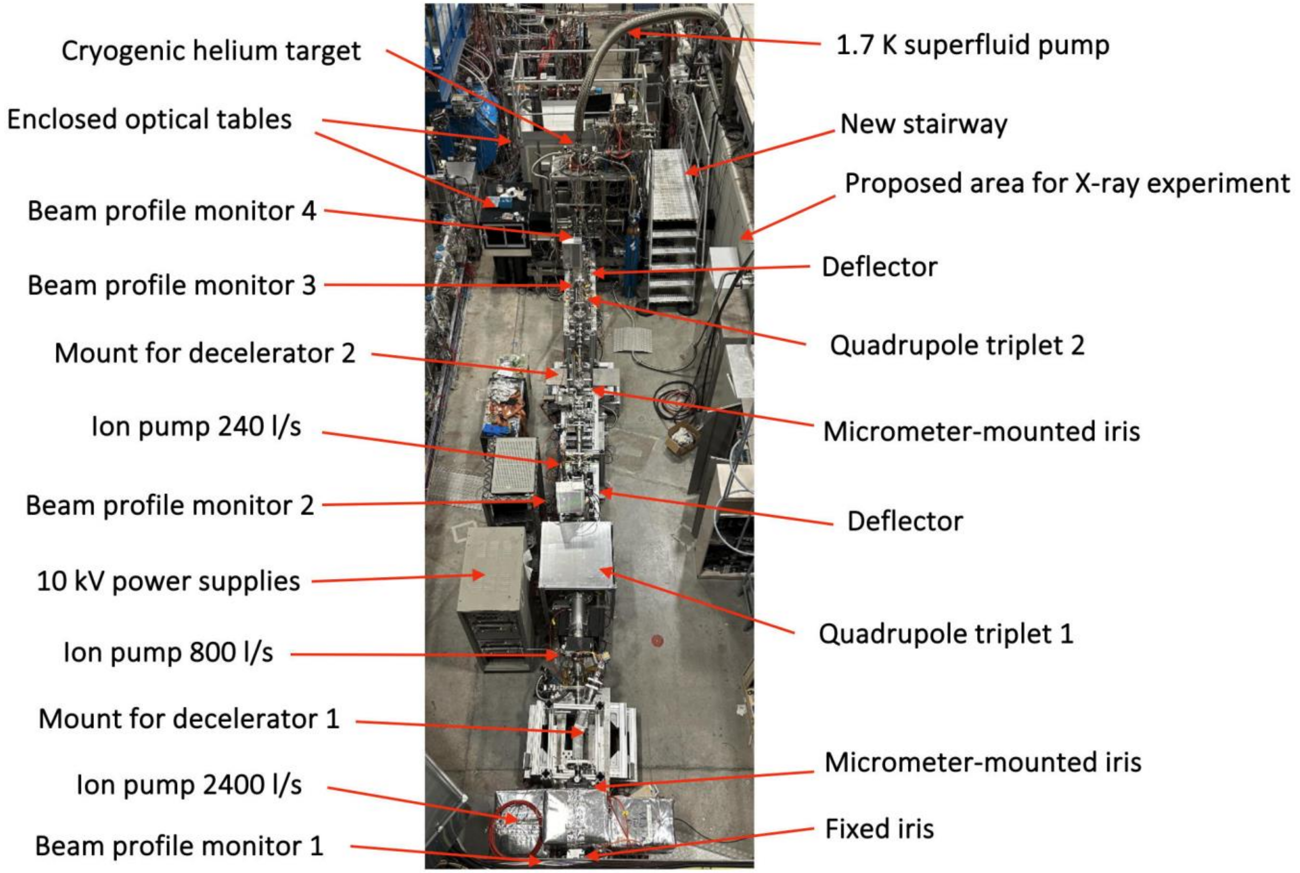
Excite narrow (natural width 0.1-0.2 MHz) two photon transition with lasers 3 and 4.

Detect population asymmetry with laser 5.

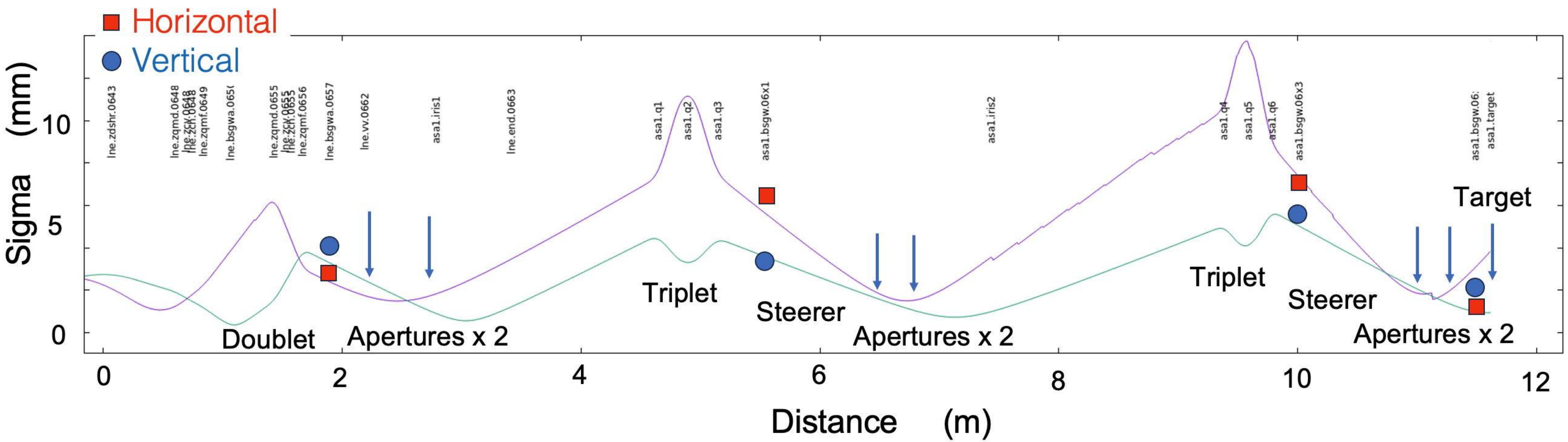
Differentially-pumped antiproton beamline



- 12 m beamline with 8 differentially-pumped diaphragms to achieve 10^{-10} mb vacuum in ELENA beamline regardless of 1 mb / 1.7 K helium gas target.
- In 2024 consolidated beamline, improved mechanical stability and precision.
- Higher-stability power supplies to reduce mm-scale fluctuations in beam position.
- 10^{7} antiprotonic helium atoms per hour stable production in low-density gas target.

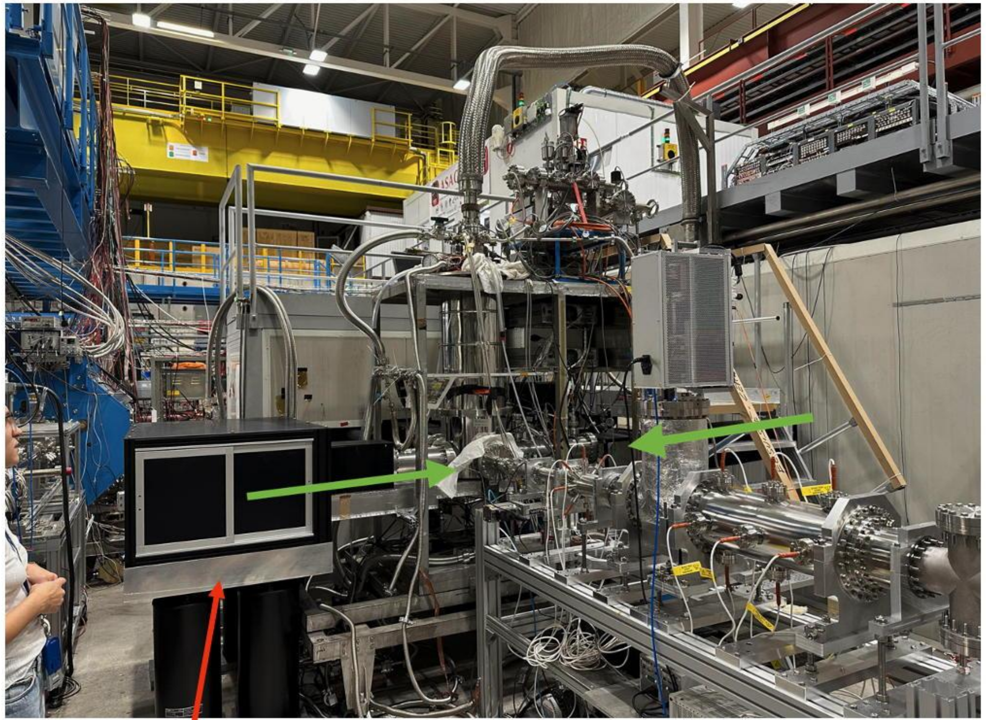


Simulated and measured beam trajectories 2024



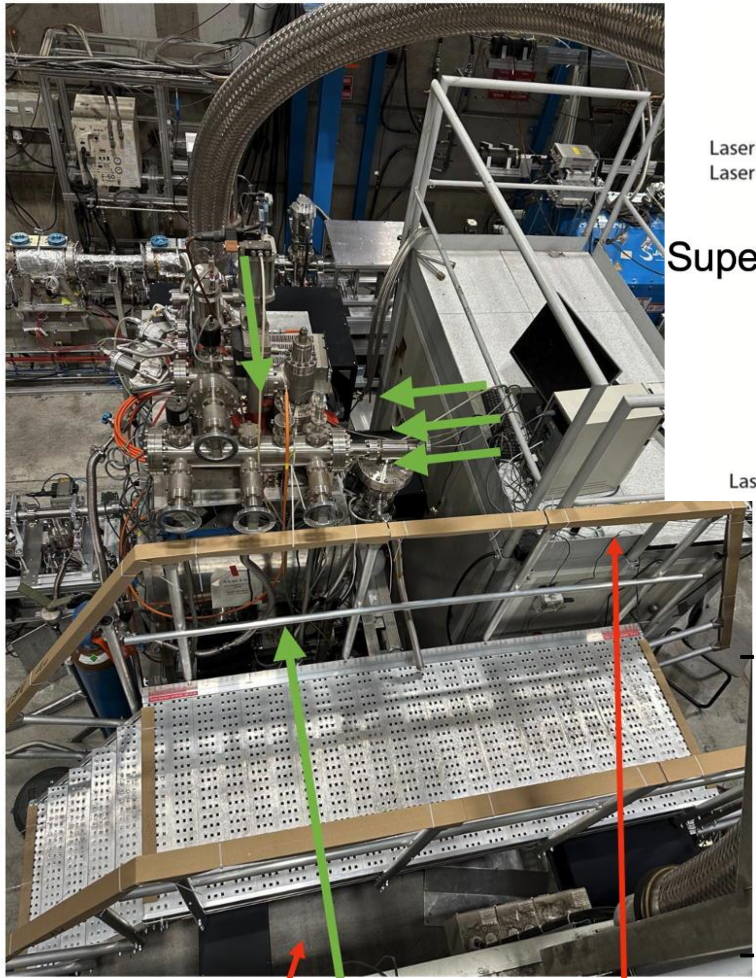
- New beam-matching optics developed in 2024 by AD-ELENA operations team.
- Increased throughput and antiproton density at focus (sigma=1.4-2.0 mm) by 2-2.5x compared to 2023. Beam intensity and position now highly stable.
- Beam diameters measured at 4 locations well-agree with theoretical envelope.

Consolidation of cryogenic target and laser transport



Interlocked non-magnetic optical table

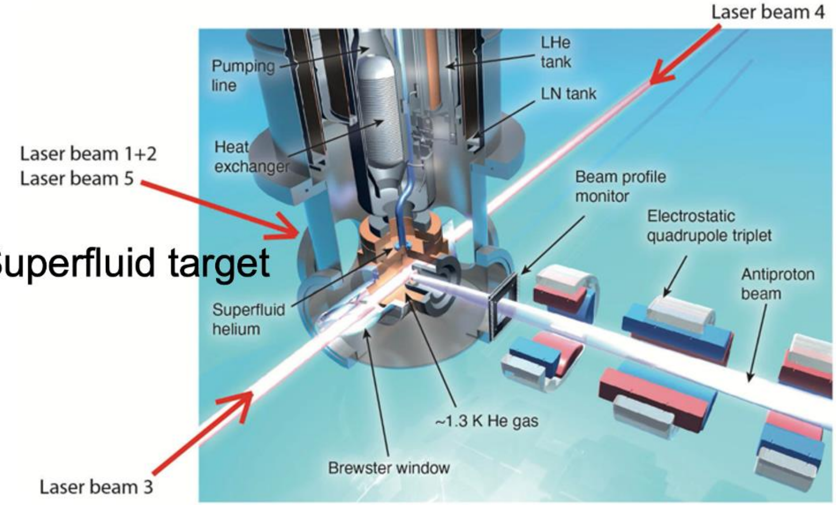
Interlocked optical table



Laser delivery tubes

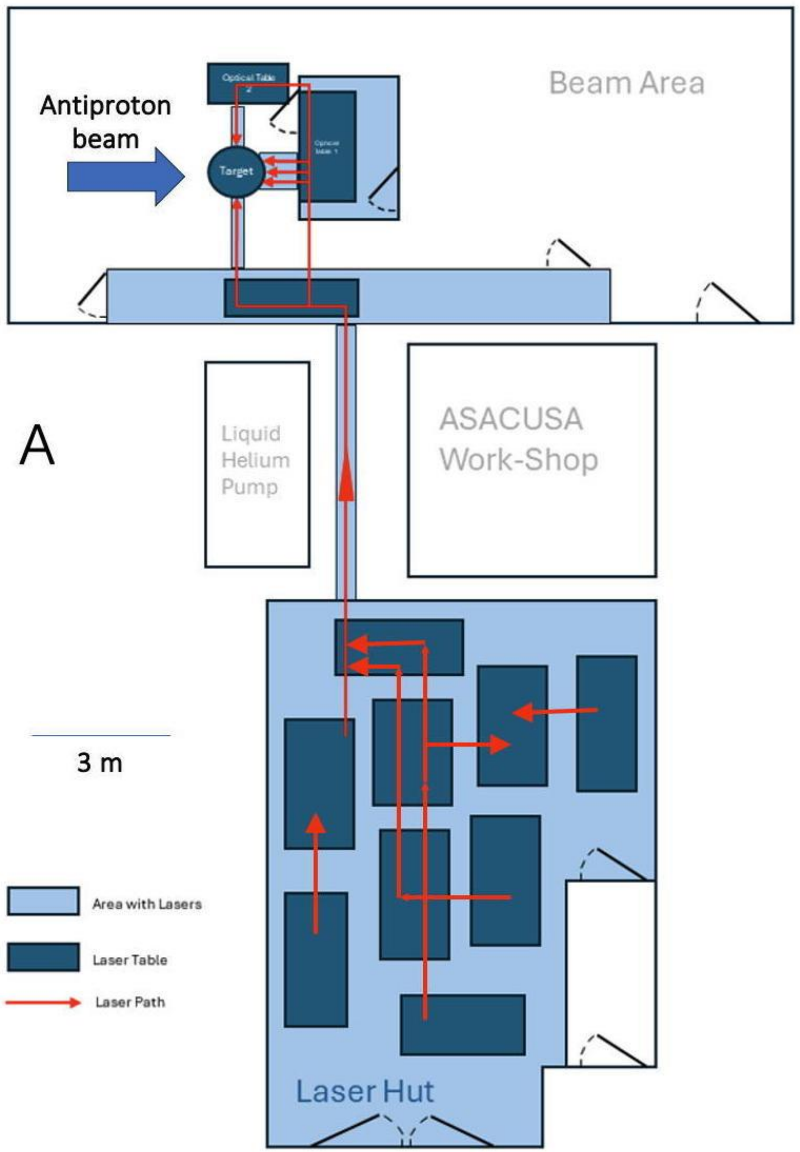
Laser hut

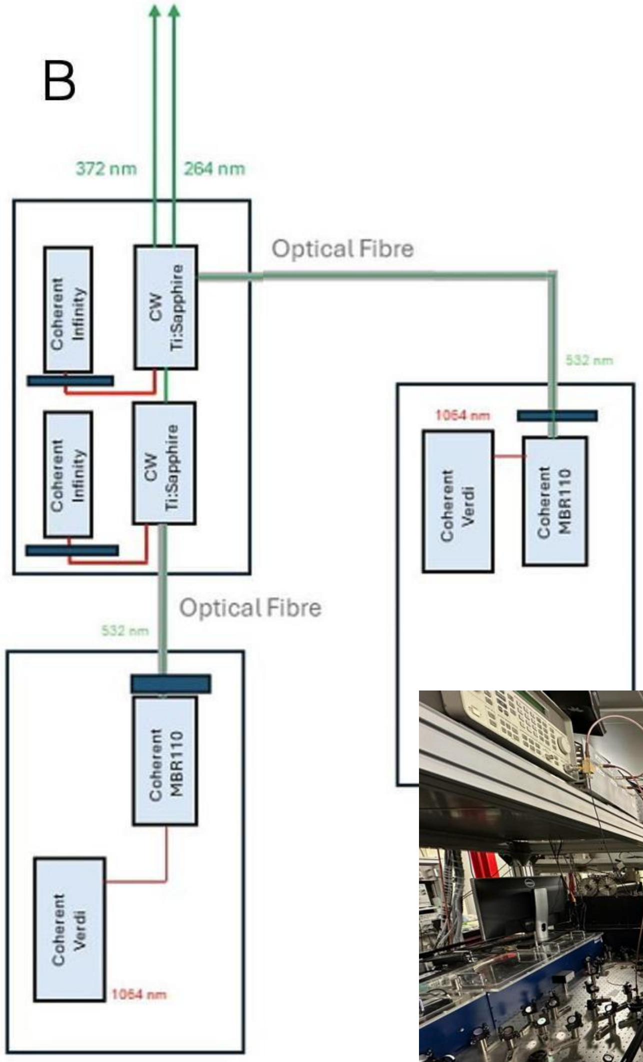
Superfluid target

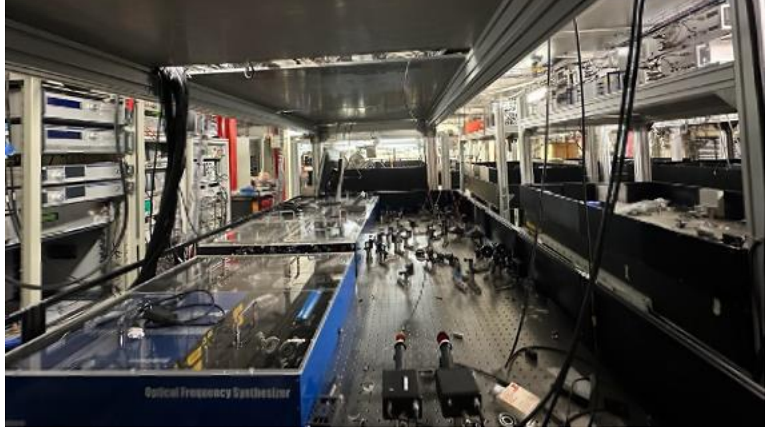


- Installation of 5 optical tables for transporting 5 laser beams over 20-30 m to experimental target.
- Interlocked optical beam paths.
- Stable beam pointing.

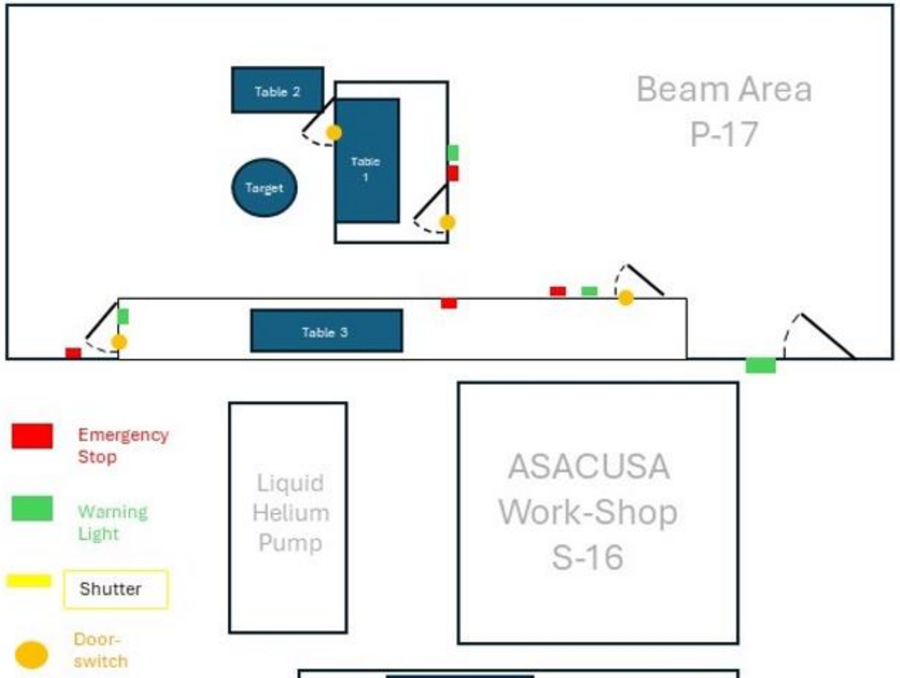
Laser system (re)installed 2024

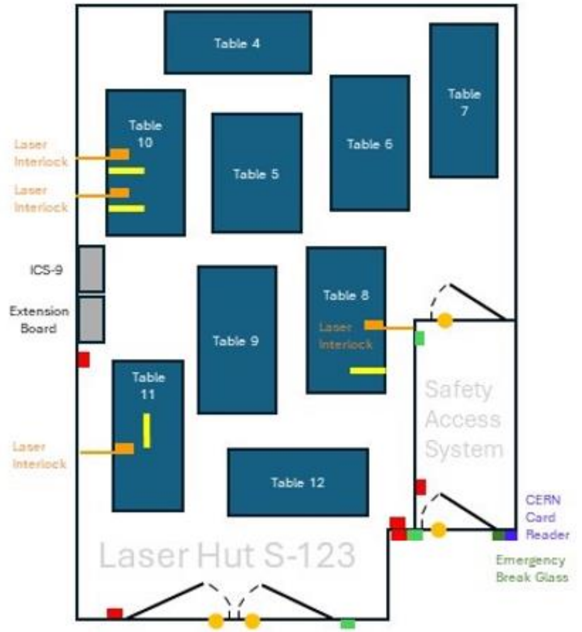






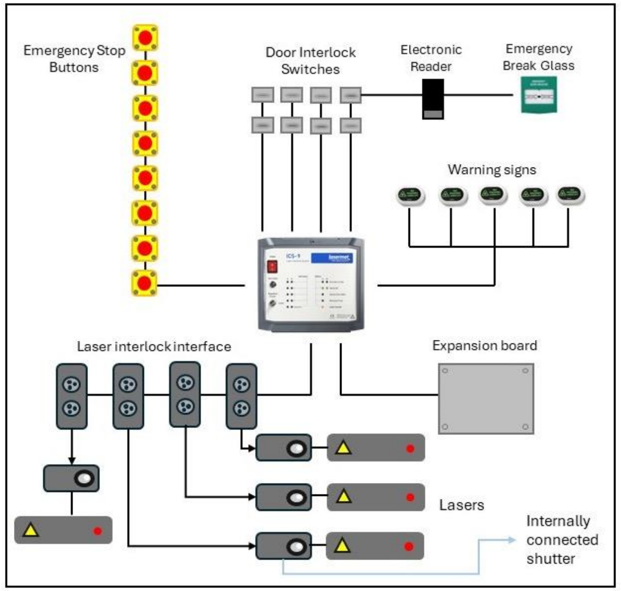
- Reinstalled 8 high-precision lasers in 2024
- Final system will span 13 optical tables with 17 lasers for frequency metrology and excitation of antiprotonic atom and laser transport, efforts ongoing.



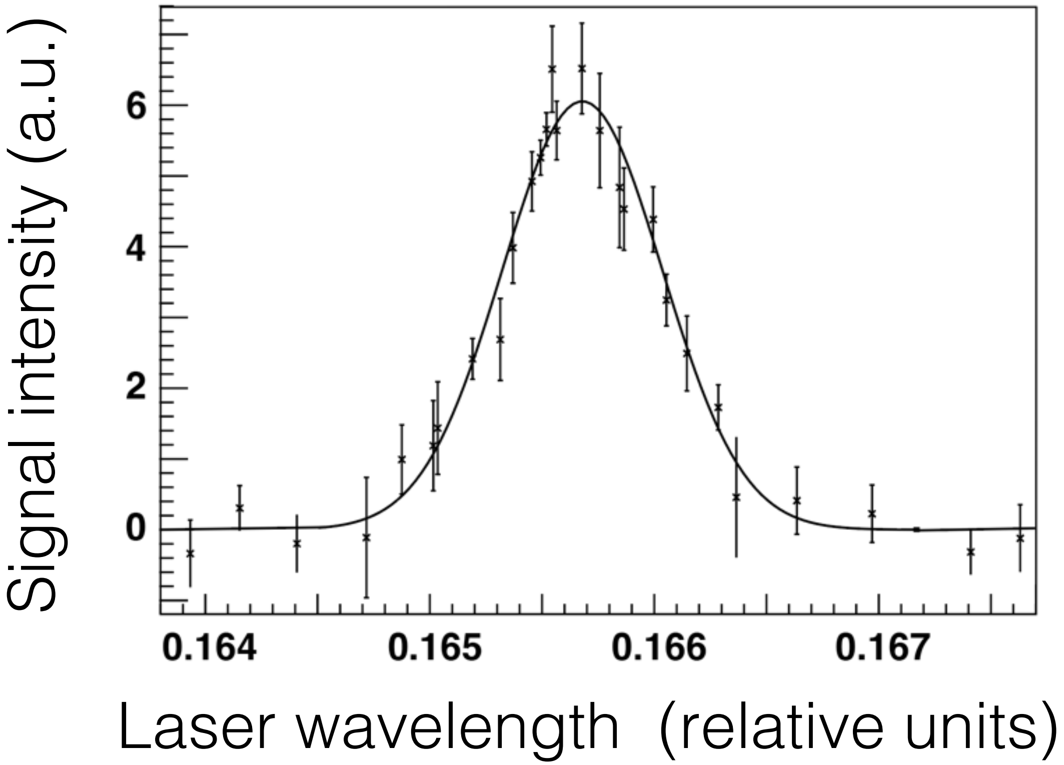


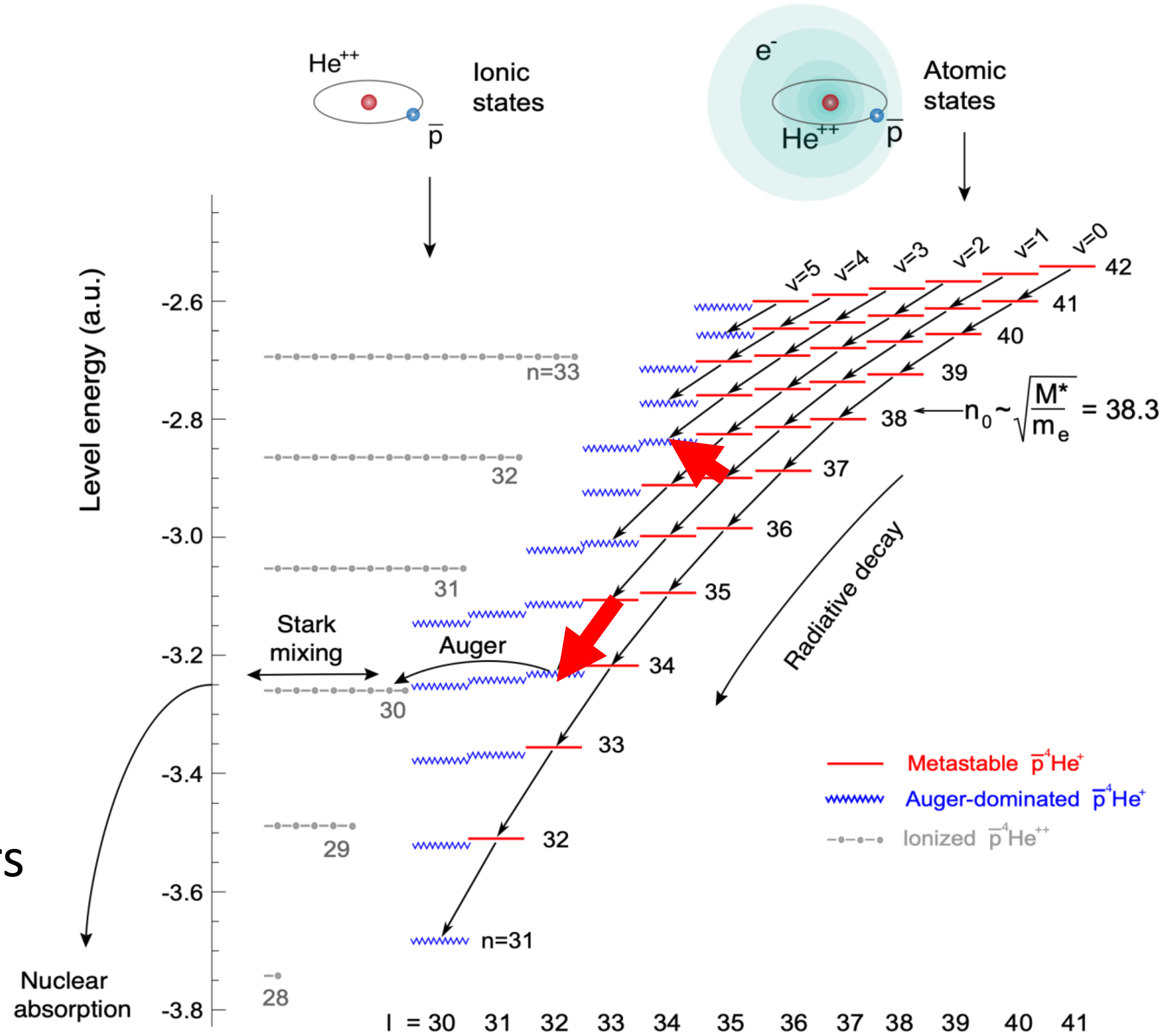
New laser safety system

- Essential due to complexity of laser system and parallel operation with antihydrogen experiment.
- Final system needs 17 lasers. Installed fast-acting shutters, 12 doors interlocked, emergency shutdown buttons, ID card access interface, escape doors
- Installed >250 m of cabling in 2024.
- Laser beam paths covered with **>150 m** of plating.



Spectra of (n,l)=(35,33)->(34,32) measured in 2024





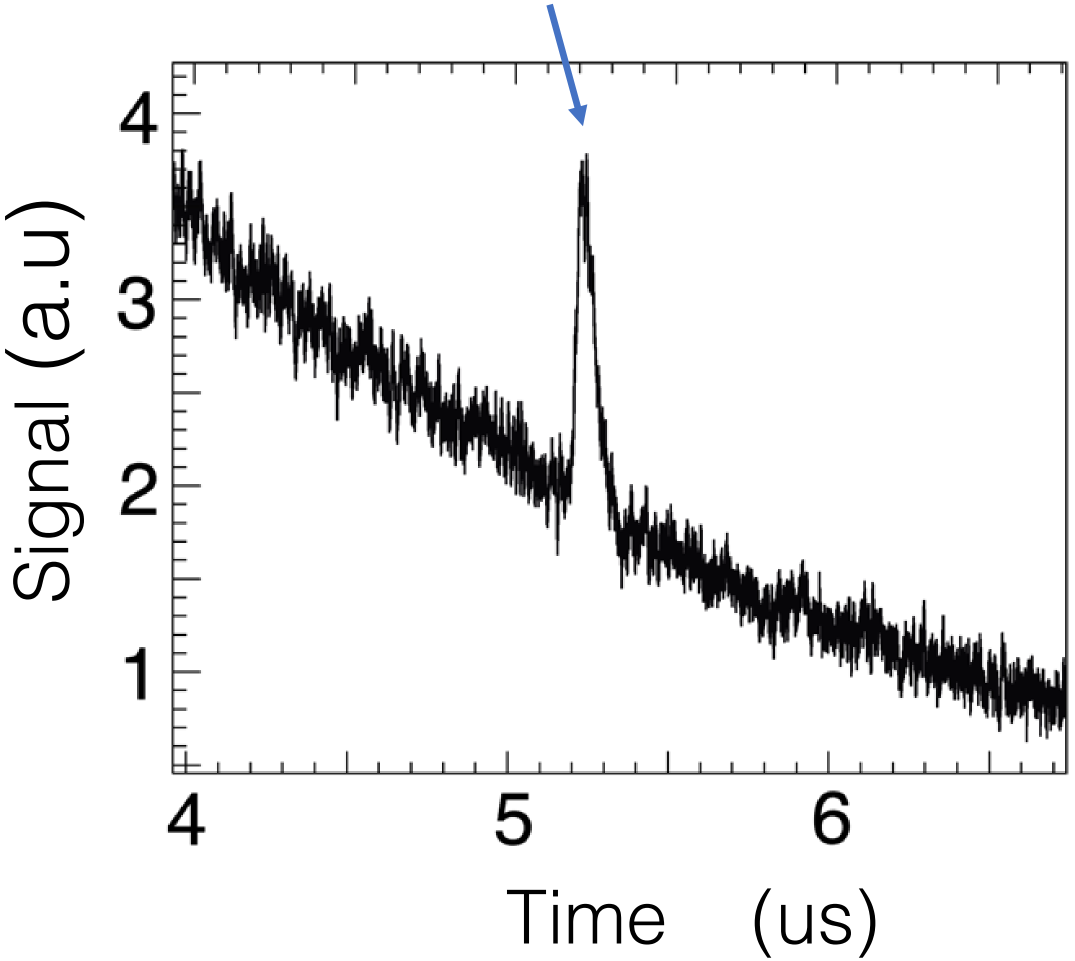
Two resonance transitions of antiprotonic helium-4 measured using (re)installed lasers

(n,l)=(35,33)->(34,32) at 372 nm (UV)

(n,l)=(37,35)->(38,34) at 726 nm (IR)

Spectra of (n,l)=(35,33)->(34,32) measured in 2024

Laser resonance signal of antiprotonic helium atom



- Efficient stopping of antiprotons in P=250 ub, T=4.5K gas target (1/10x lower density than RFQD precision experiments)
- Dense sample of antiprotonic helium atoms in low-density target, production rate 10^7 atoms/h fully ready for experiments.
- 10x greater data acquisition rate compared to RFQD measurements at comparable target densities.
- High SN ratio of laser spectroscopic signal.
- Induction decelerator still being assembled, should increase the density by additional factor 2-3x (theoretical maximum).

Antiprotonic helium achievements 2024

- **Antiproton intensity** at the helium gas target increased by 2-2.5x compared to 2023.
- **Stable and routine formation** of high-density samples (10^7 atoms per hour) of antiprotonic helium in low-density helium target. Atom production part is ready.

- **Installed part of the laser system, safety interlocks, beam delivery systems**

❖ Final 5 laser spectroscopy experiment will need 17 lasers, efforts ongoing....

- **Carried out laser spectroscopy** of two transitions UV (n,l)=(35,33)->(34,32) and IR (n,l)=(37,35)->(38,34) of antiprotonic helium-4.

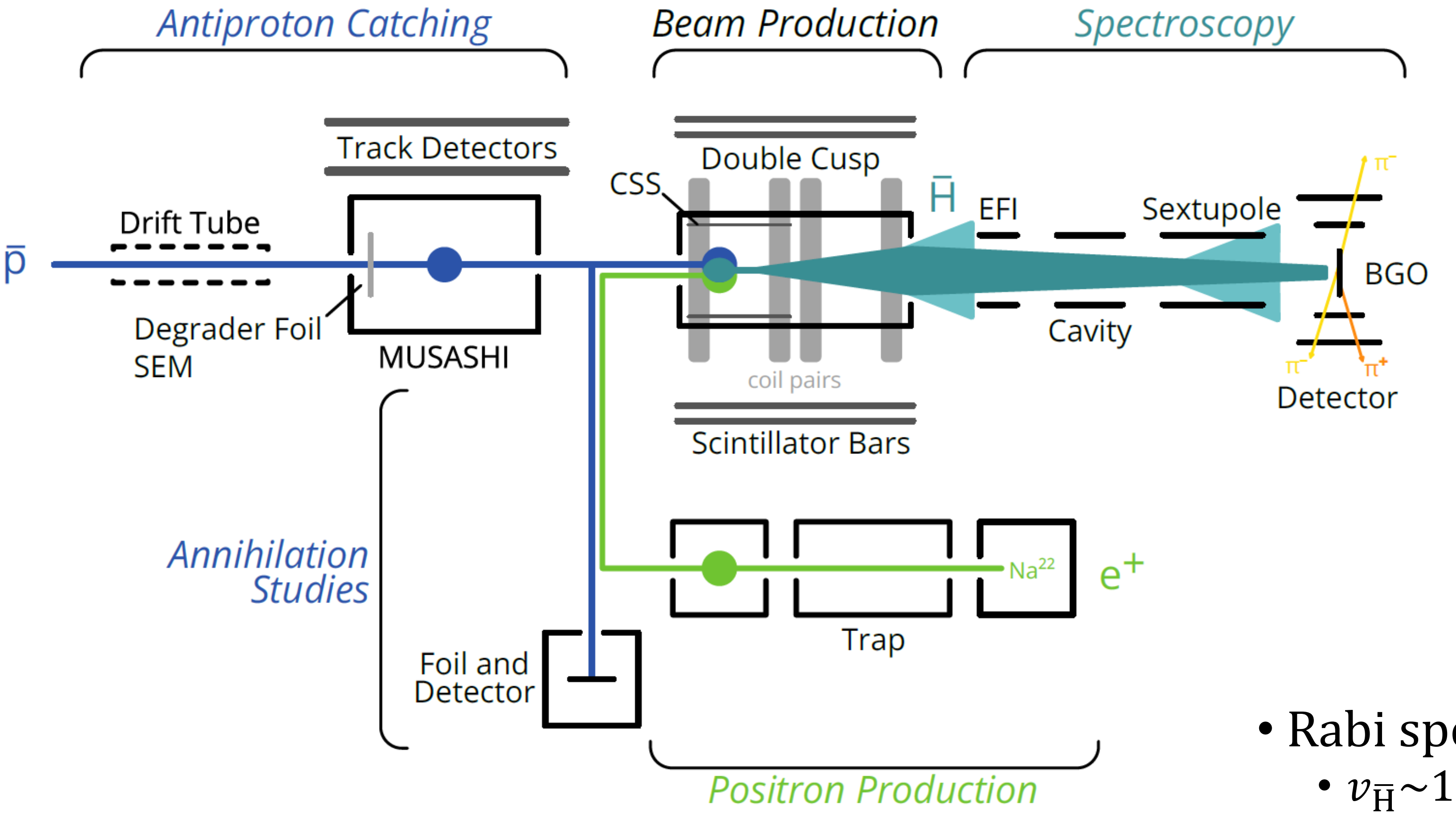
❖ Unprecedentedly high signal-to-noise ratio even at 1/10x lower density targets compared to previous high-precision experiments carried out pre-ELENA.

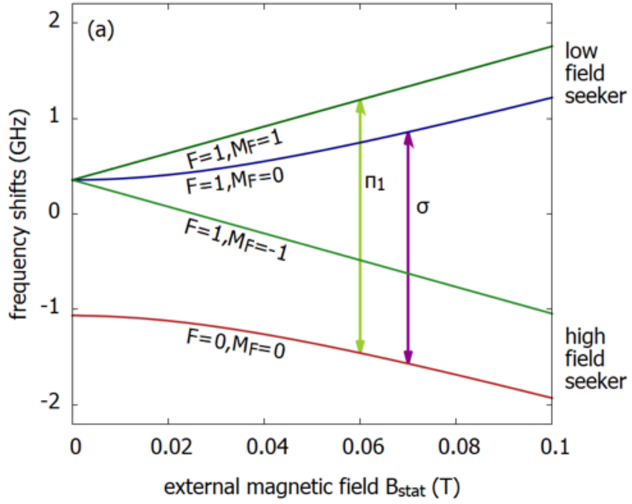
❖ This new capability allows us to expect **significant new physics results in 2025-2026**

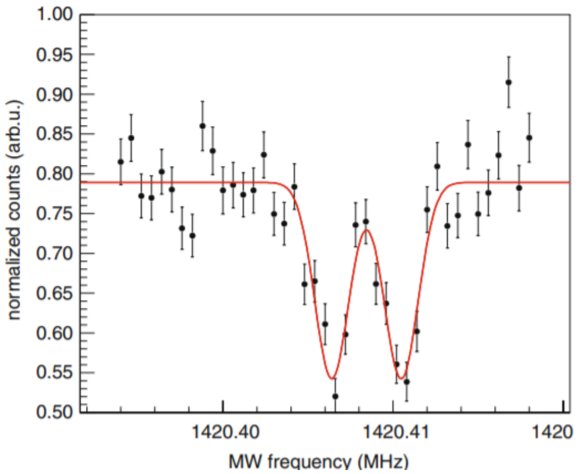
We will continue development work to complete the 5 lasers and new frequency comb system and attempt to detect narrow two-photon transitions in 2025-2026.

- New London group being set up, funding requested…

Antihydrogen experiment

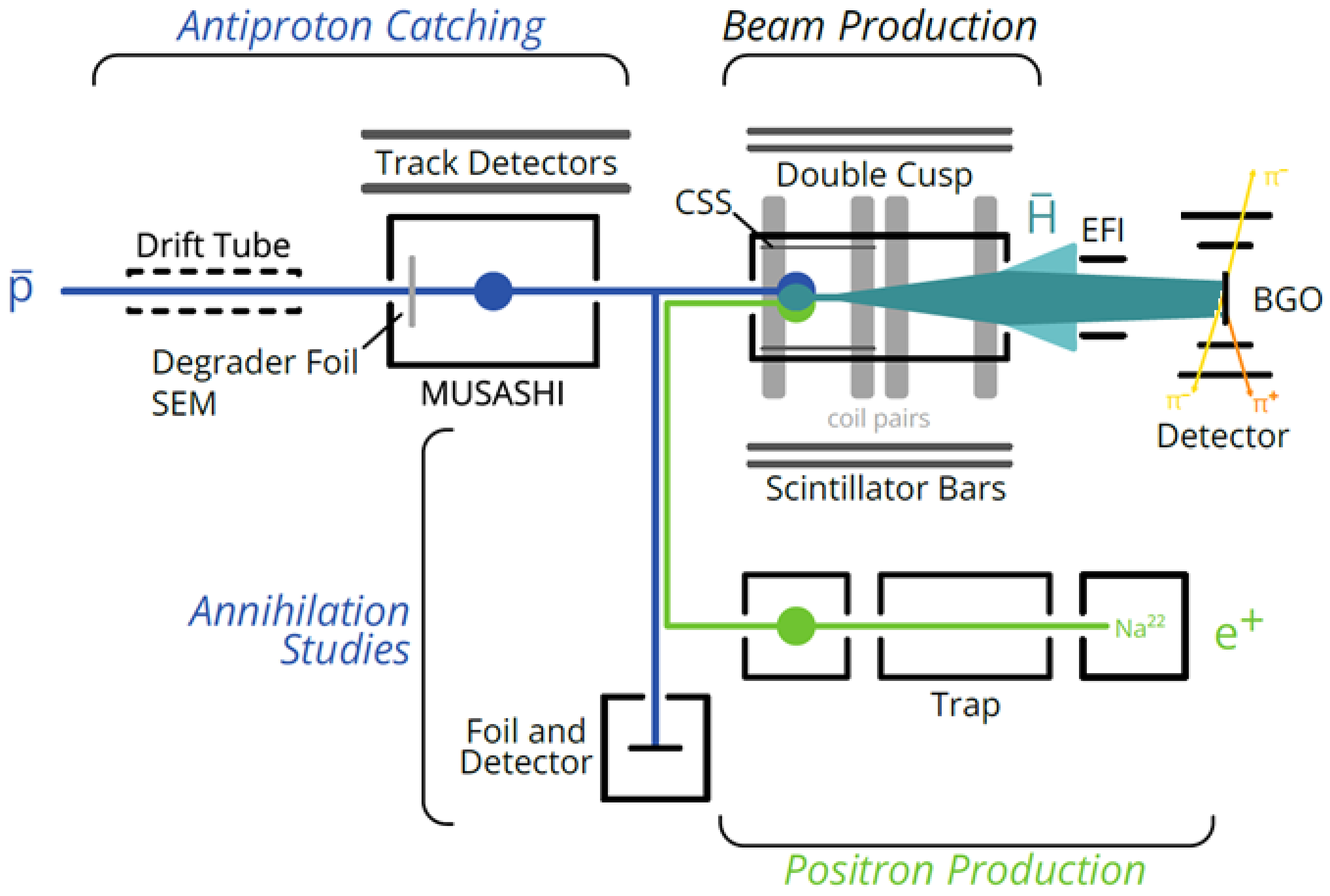






- Rabi spectroscopy @$T_{\bar{\mathrm{H}}}$∼50 K
  - $v_{\bar{\mathrm{H}}}$∼1 km/s, cavity length 10 cm
- Line width ∼10 kHz: precision ∼ppm

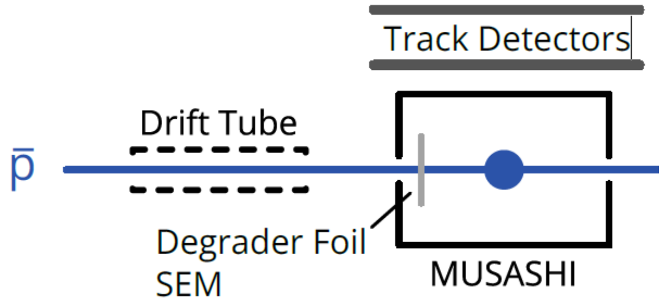
Overview



- Shorter setup used in 2024
  - No cavity + sextupole
  - Provides larger solid angle for detecting $\overline{\mathrm{H}}$
- Alternate beam line for slow extracted $\bar{\mathrm{p}}$ from MUSASHI
  - $E \sim 250$ eV, 10^4 $\bar{\mathrm{p}}$/cycle
  - $\bar{\mathrm{p}}$ annihilation studies

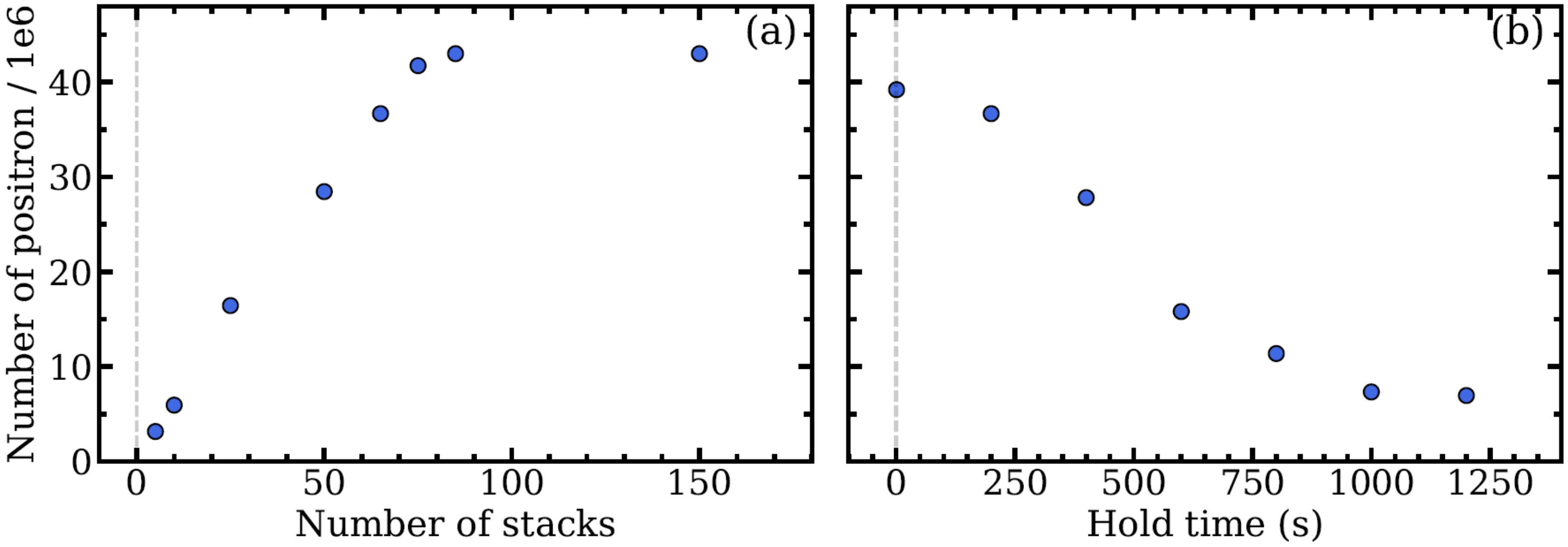
Antiprotons

- For a **single** ELENA shot of $1x10^7$ antiprotons **$2.7x10^6$** $\bar{p}$ were caught and cooled in MUSASHI
- Transfer efficiency to the Cusp trap for a single shot ~ 80% (**$2.1x10^6$**)
- **Five** ELENA shots yielded **$1x10^7$ cooled pbar**
- Transfer efficiency drops when stacking
  - poor vacuum expands the cloud
- For mixing cycles **3 ELENA shots** were used which gave us approximately **3 million $\bar{p}$** in the Cusp trap.



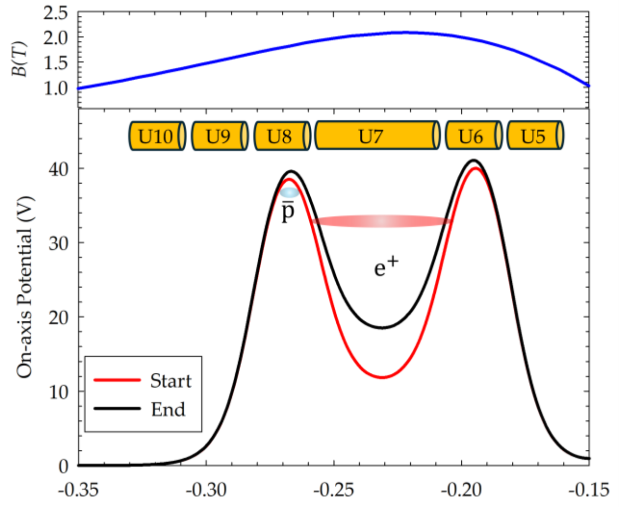
Positrons – new 50 mCi ^{22}Na source

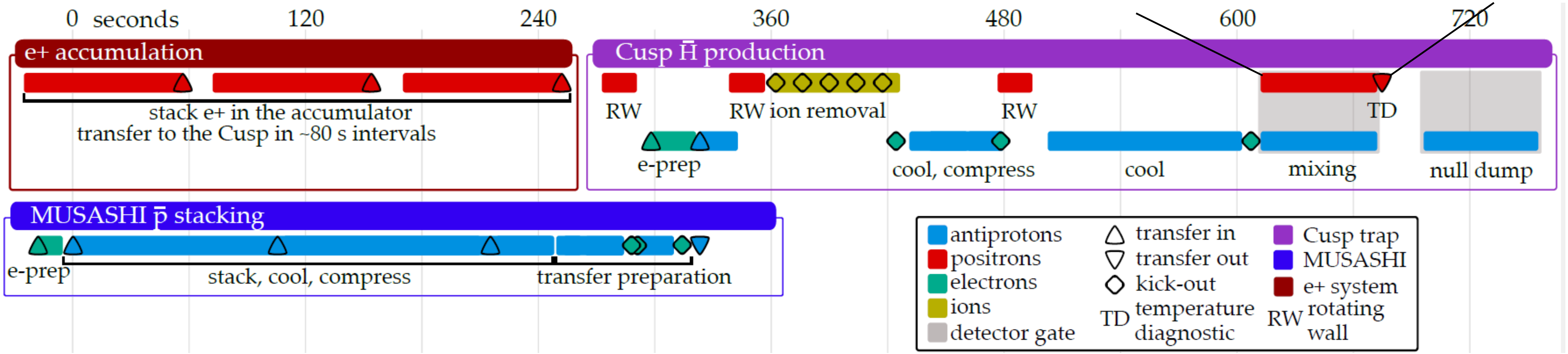
- DC beam increased from 0.14×10^6 to 2.2×10^6 (factor of 16)
- Trap efficiency good (24%)
- Moderator efficiency still can be improved (0.13%)



Mixing

- Slow merge method
- 3 million $\bar{p}$
- 130 million e^+

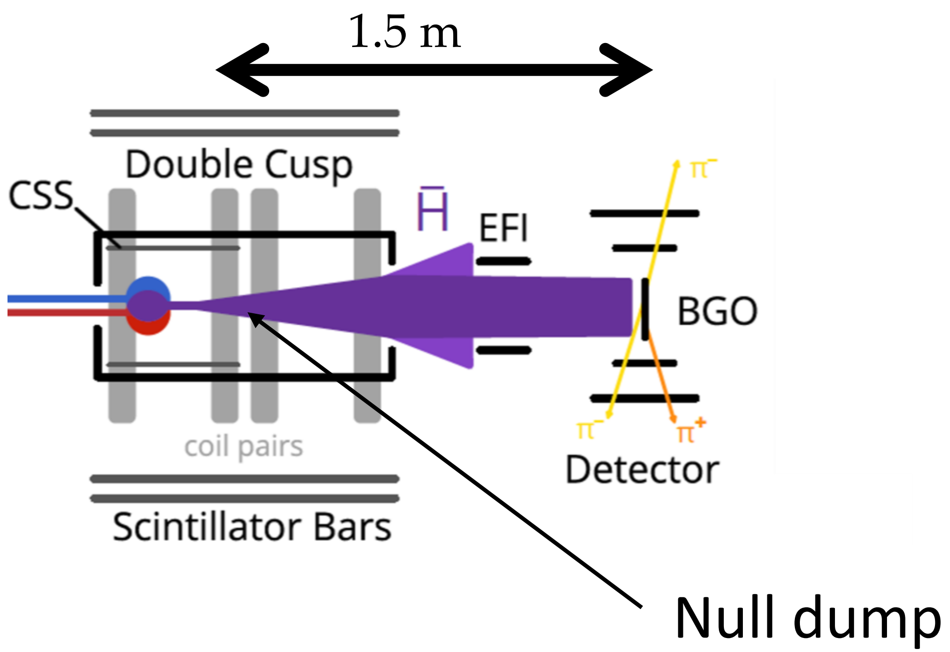




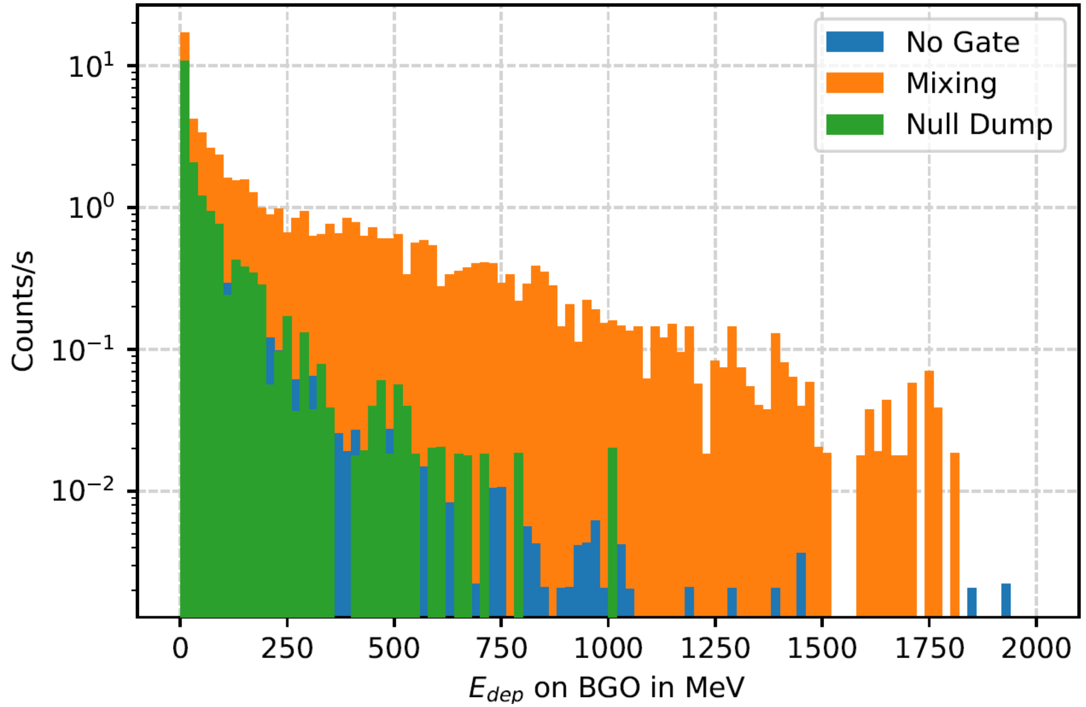
- Before beginning mixing experiments 10-15 stacks of positrons were loaded, between cycles positrons could be recycled so only 3-5 stacks were required.

Mixing results: observation of beam component

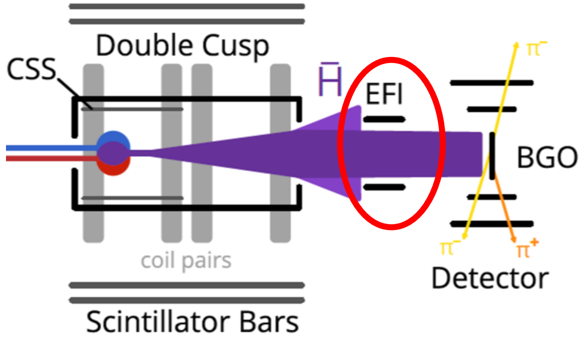
- Energy deposit on BGO
  - Triple coincidence
  - BGO + both layers of hodoscope
    - Set threshold $E_{\mathrm{dep}} > 45$ MeV



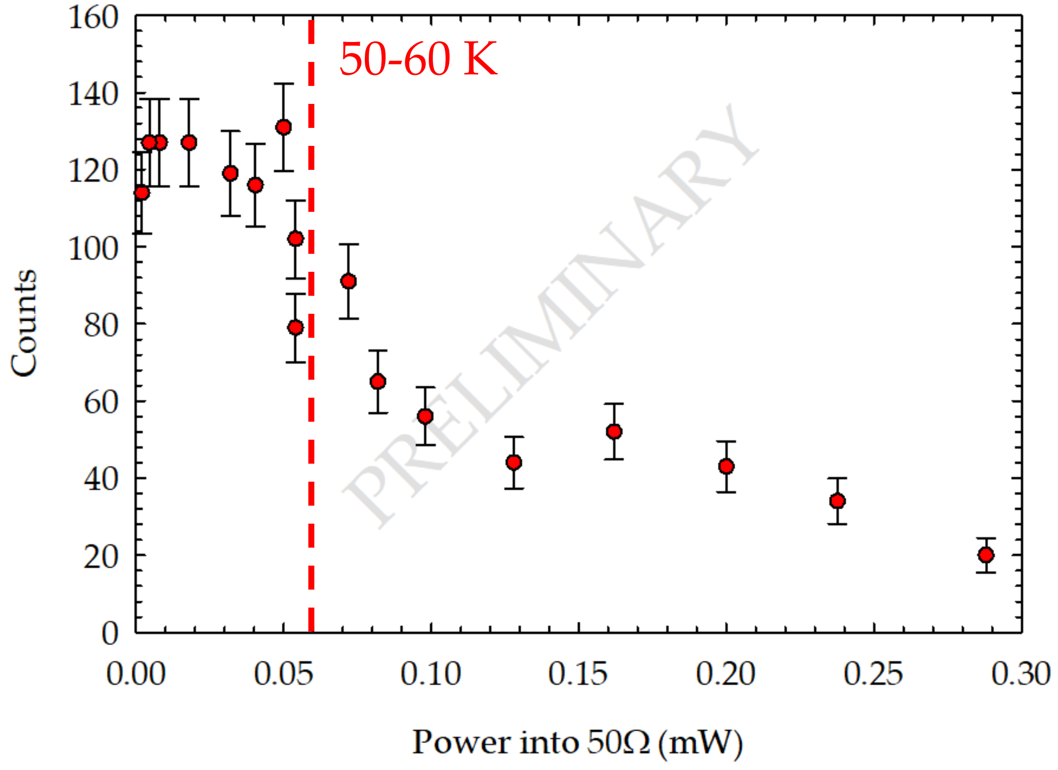
- Annihilation signal: energy deposit in BGO
  - No gate: full cycle of 12 min
  - Mixing: during 60 s mixing cycle



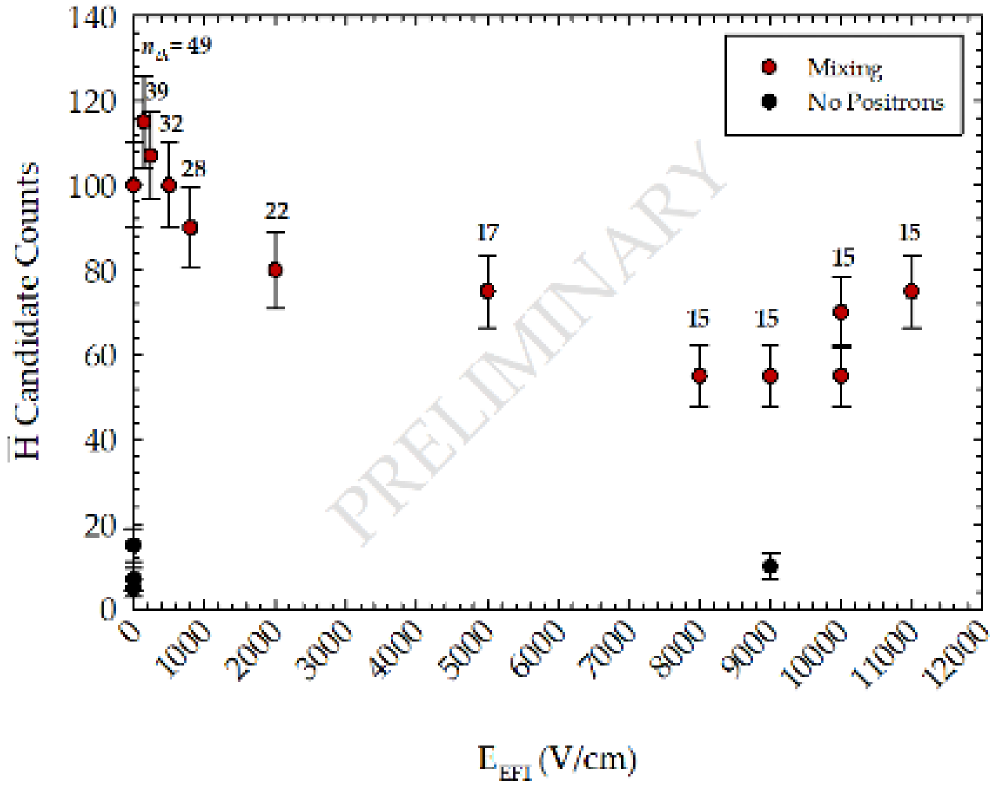
Beam characterisation I



- $\bar{H}$ candidates per mixing cycle
  - Plasma heating leads to reduction of signal

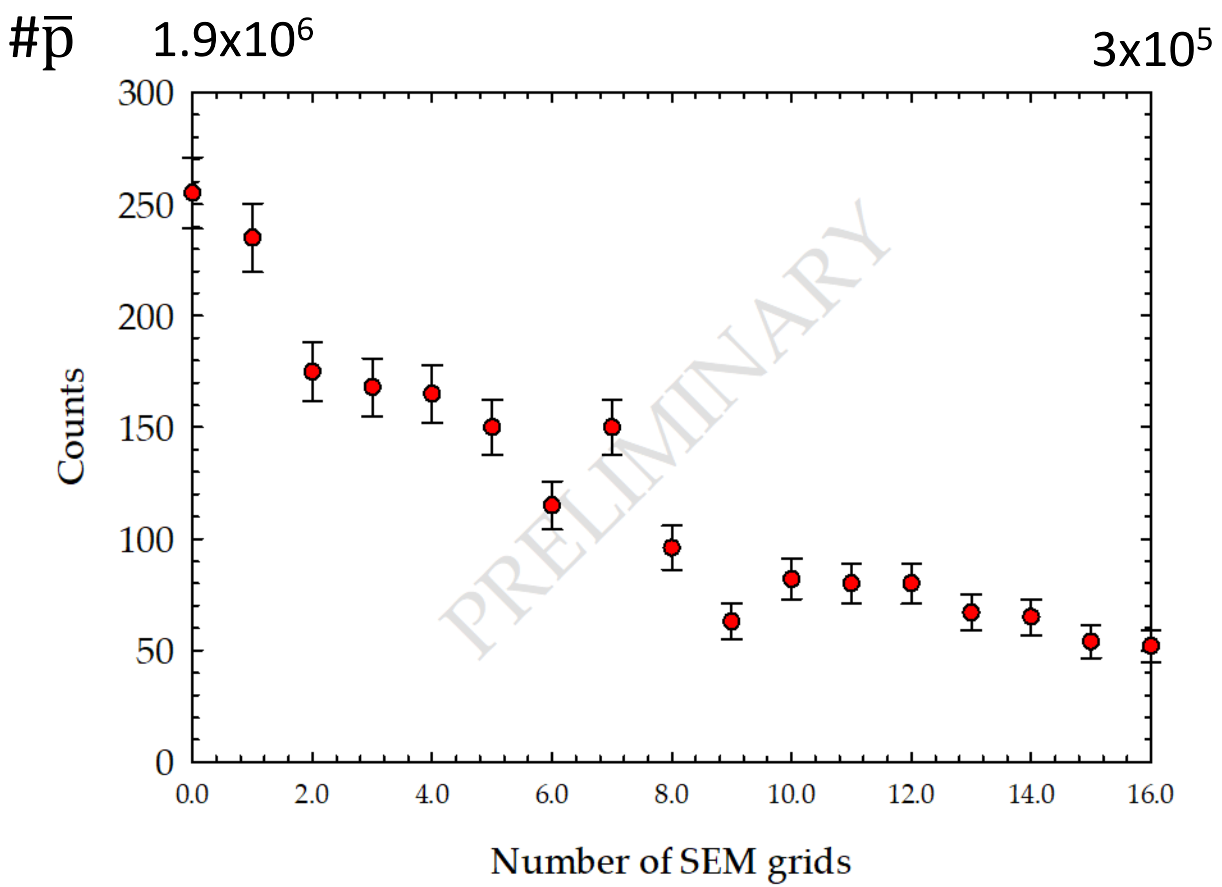


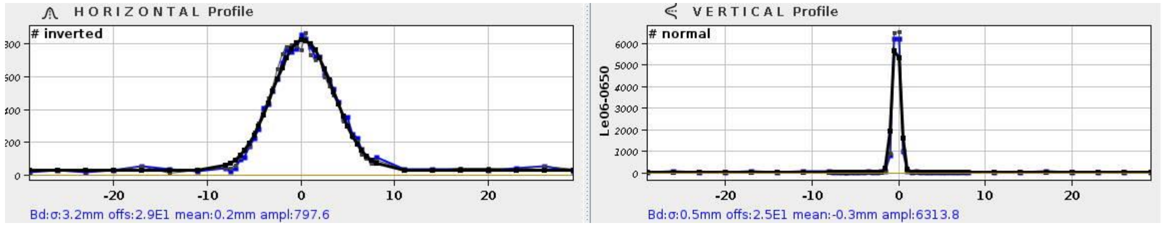
- Field ionisation
  - n_{th} : lowest n state which is being ionised

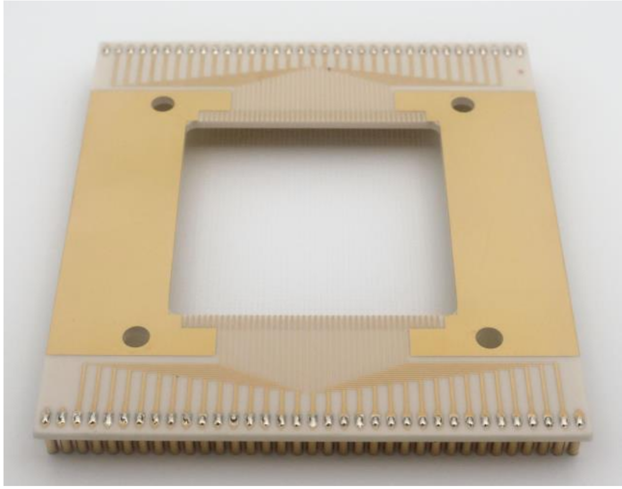


Beam characterisation II: does the signal scale with $\bar{p}$ number?

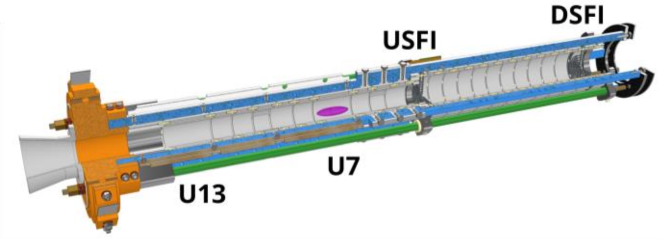
- Beam intensity reduction by insertion of SEM grids

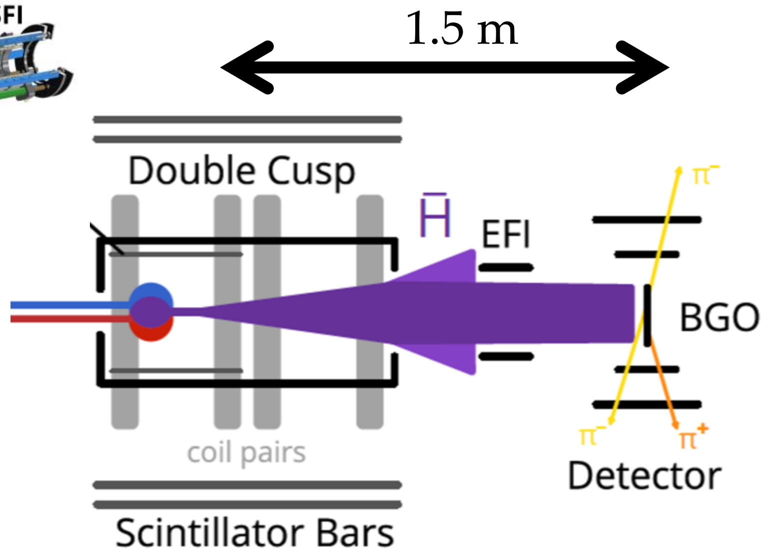


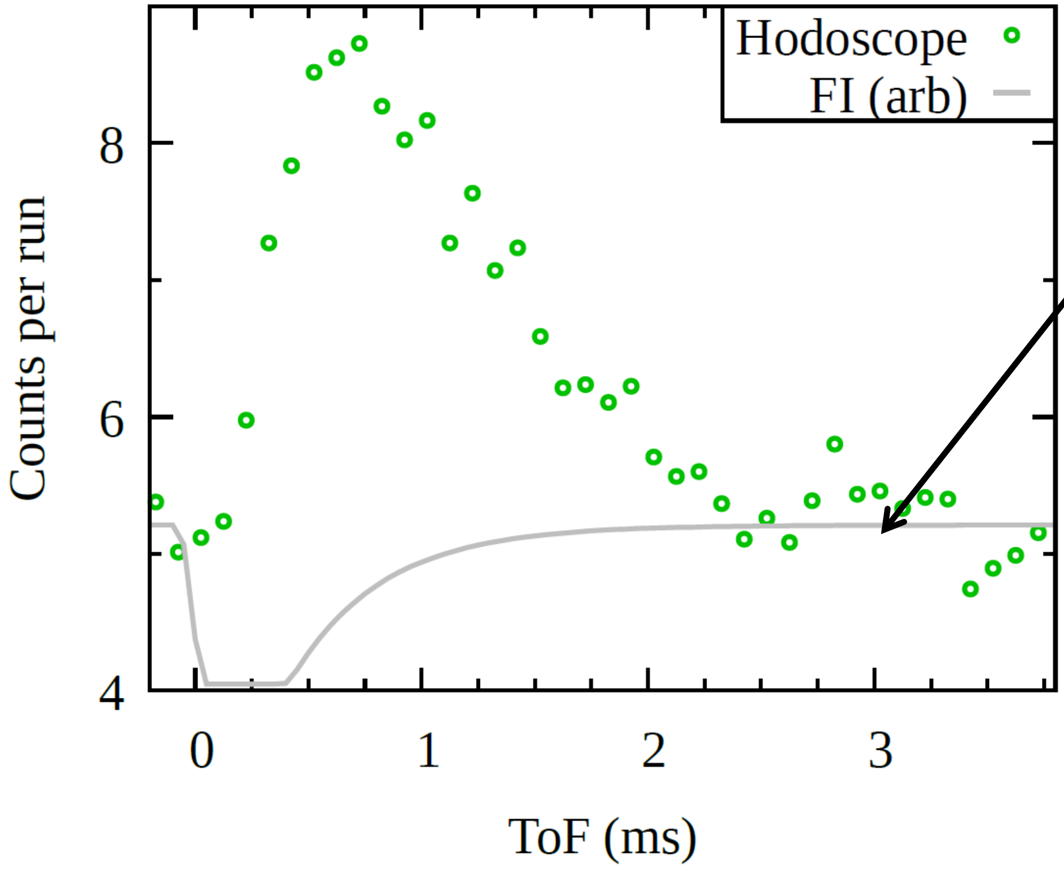




Measuring the velocity





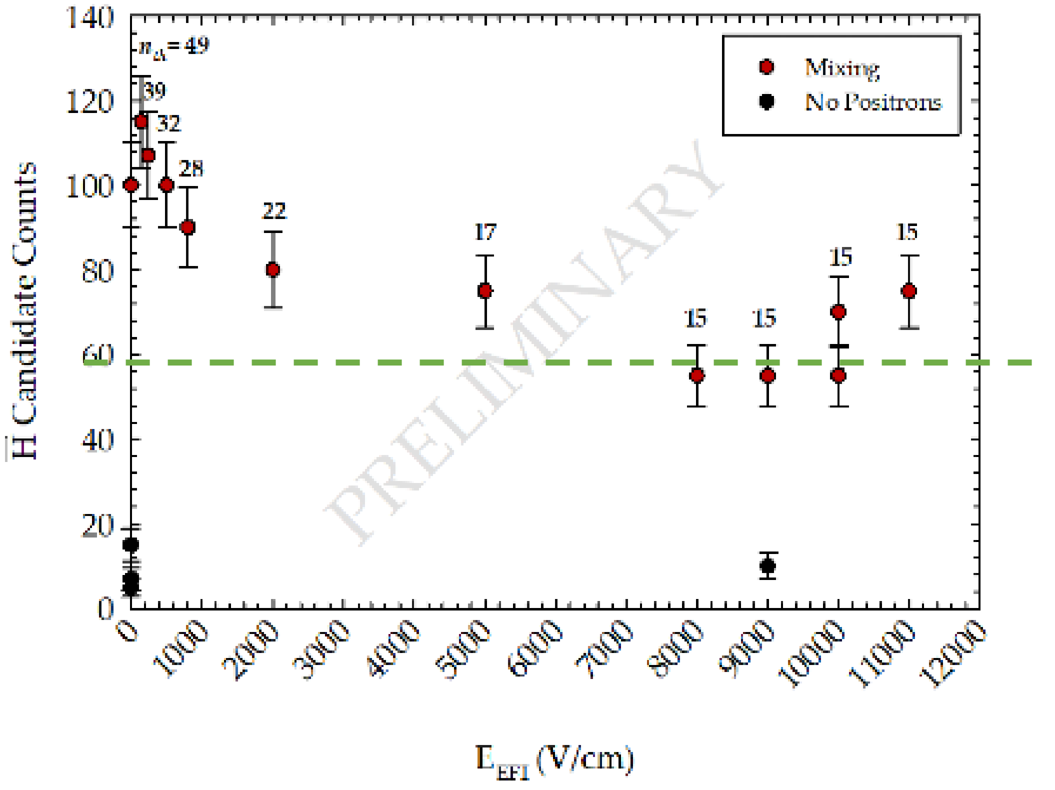


800 V → n_{th} = 22

- First time this has been attempted
- Using the USFI a pulse is applied to chop the high *n* beam during a 60 s mixing cycle
  - Pulse from 800 V to 0
  - Width 500 μs
  - Rate ~ 200 Hz
- Delay ≤ 1 ms at d = 1.5 m: $v_{\bar{H}} \leq 1.5$ km/s
  - Detailed analysis in progress

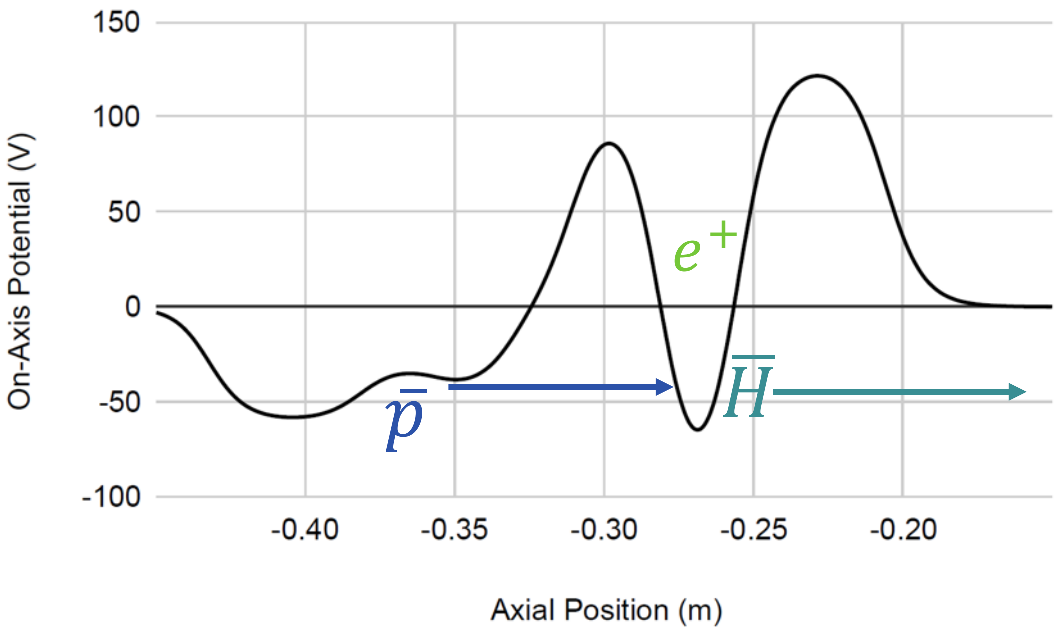
Results

- Analysis for the 2024 beamtime results is complex and still ongoing
- Preliminary findings
  - 100 antihydrogen candidates per mixing cycle (all n)
  - 10,000 antihydrogen candidate events per 24 h
  - First measurement of TOF using chopped beam method
- Next steps
  - Tracking $\overline{\text{H}}$ annihilation in the hodoscope
  - Full analysis of beam velocity distribution
  - Estimate of the ground state contribution
  - Open: beam polarisation



Plans for 2025

- YETS
  - Install full spectroscopy beamline
  - Measurements of stray field from Cusp in Cavity
- Plasma studies
  - Goal : maximise the number of $\overline{\mathrm{H}}$ transmitted through the cavity & sextupole
  - Attempt 'beam scheme' with antiproton reservoir to make short timed (100 μs) pulses
- First attempt of $\overline{\mathrm{H}}$ microwave interaction



S. Jonsell and M. Charlton, *Formation of Antihydrogen Beams from Positron–Antiproton Interactions*, New J. Phys. **21**, 073020 (2019).