ASACUSA Activities in 2023 and Plans for 2024

SPSC Meeting

6 February 2024

ASACUSA collaboration

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

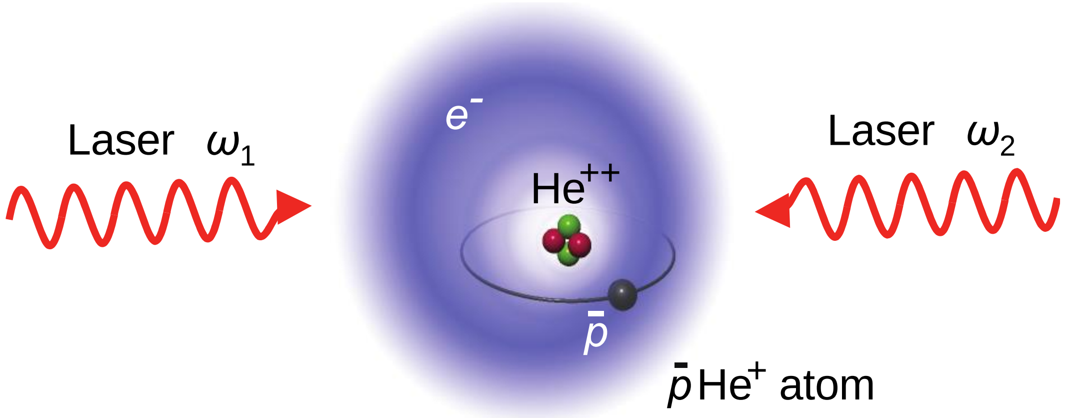
[a]Stefan Meyer Institute, [b]Wigner Research Centre for Physics, [c]Politechnico di Milano, [d]INFN Milano, [e]Ulmer Fundamental Symmetries Laboratory, RIKEN, [f]Experimental Physics Department, CERN, [g]Dipartimento di Ingegneria dell'Informazione, Università degli Studi di Brescia and INFN Pavia, [h]Graduate School of Advanced Science and Engineering, Hiroshima University, [i]Faculty of Natural Sciences, Imperial College London, [j]QUANTUM Institut für Physik, Johannes Gutenberg-Universität Mainz, [k]Max-Planck-Institut für Quantenoptik, [l]Institute of Physics, the University of Tokyo, [m]Dipartimento di Fisica, Università degli Studi di Milano and INFN Milano, [n]Nishina Center for Accelerator-Based Science, RIKEN, [o]Department of Physics and Astronomy, Aarhus University

* Co-spokespersons

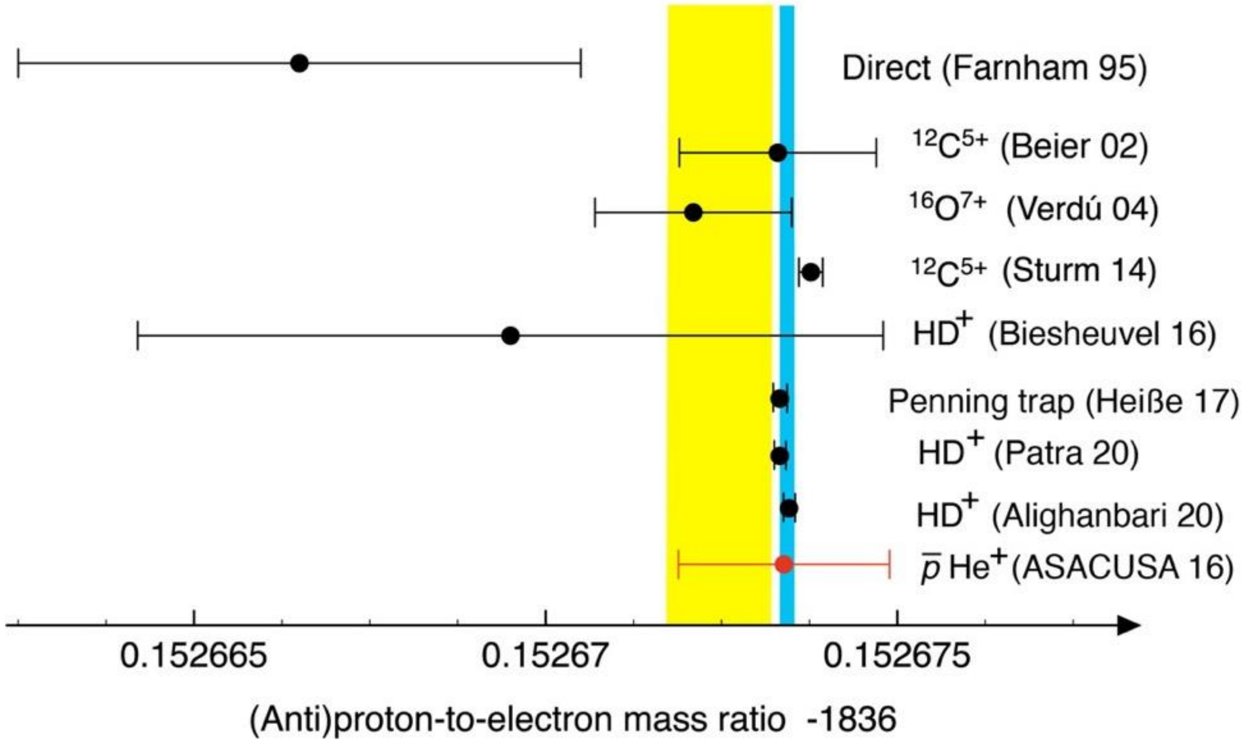
[1]present address: University College London, Gower St, London WC1E 6BT, United Kingdom
[2]present address: TRIUMF, Vancouver, Canada

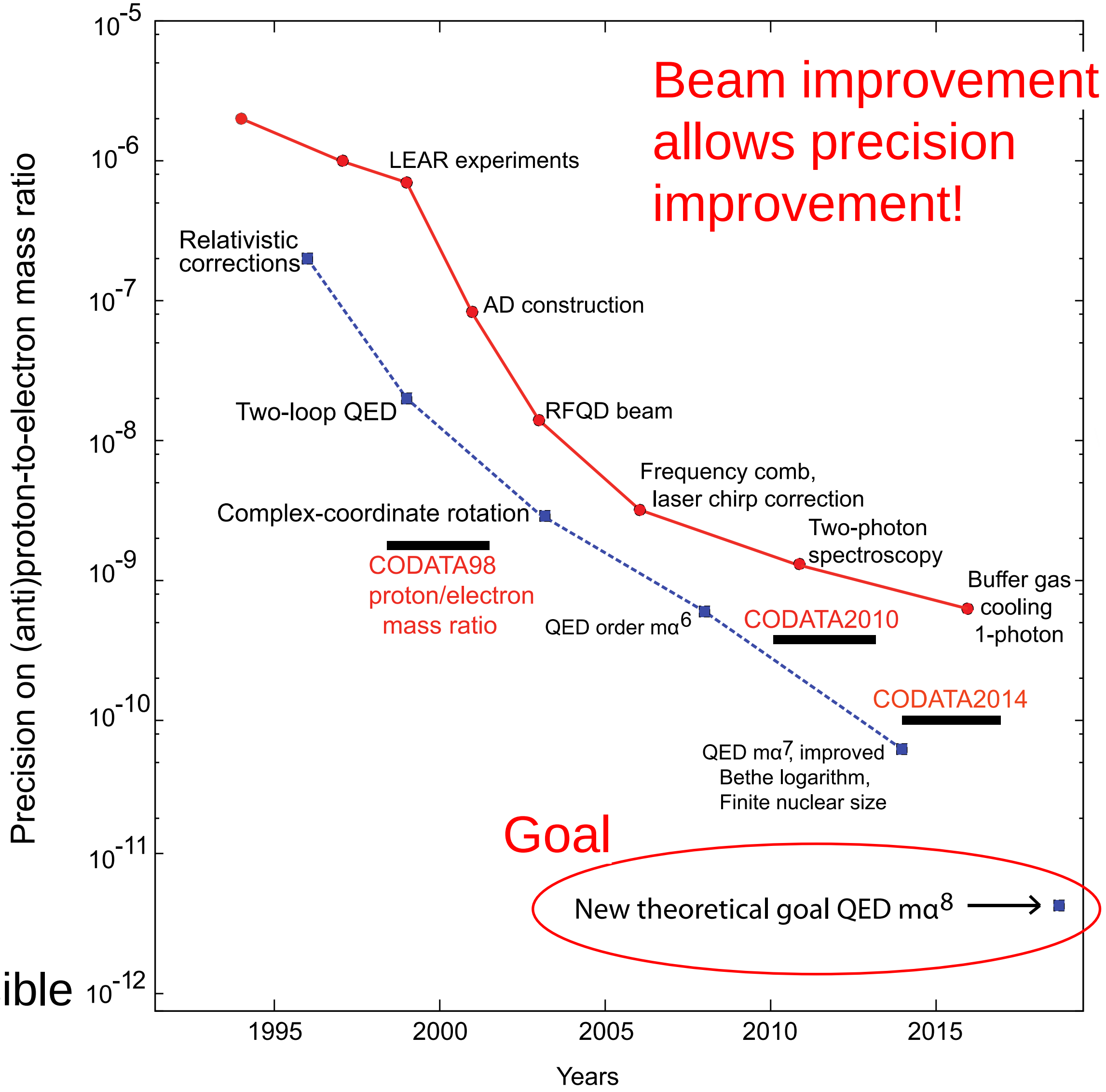
Antiprotonic helium atom

- Whereas spectroscopy of antihydrogen probes the interaction between an antilepton and antihadron,
- Antiprotonic helium is a hadron-antihadron quantum bound system with the longest known lifetime (4 μs), and thus remains an important complementary atom for spectroscopic study in the ELENA era.
- QED remains the most accurately understood quantum field theory.
- Propose to utilize the high-quality beam provided by ELENA to carry out sub-Doppler two-photon laser spectroscopy of new narrow resonances at 100 times higher precision (10^{-11}) than before and test QED in matter-antimatter system and determine antiproton-to-electron mass ratio and search for new physics beyond Standard Model.



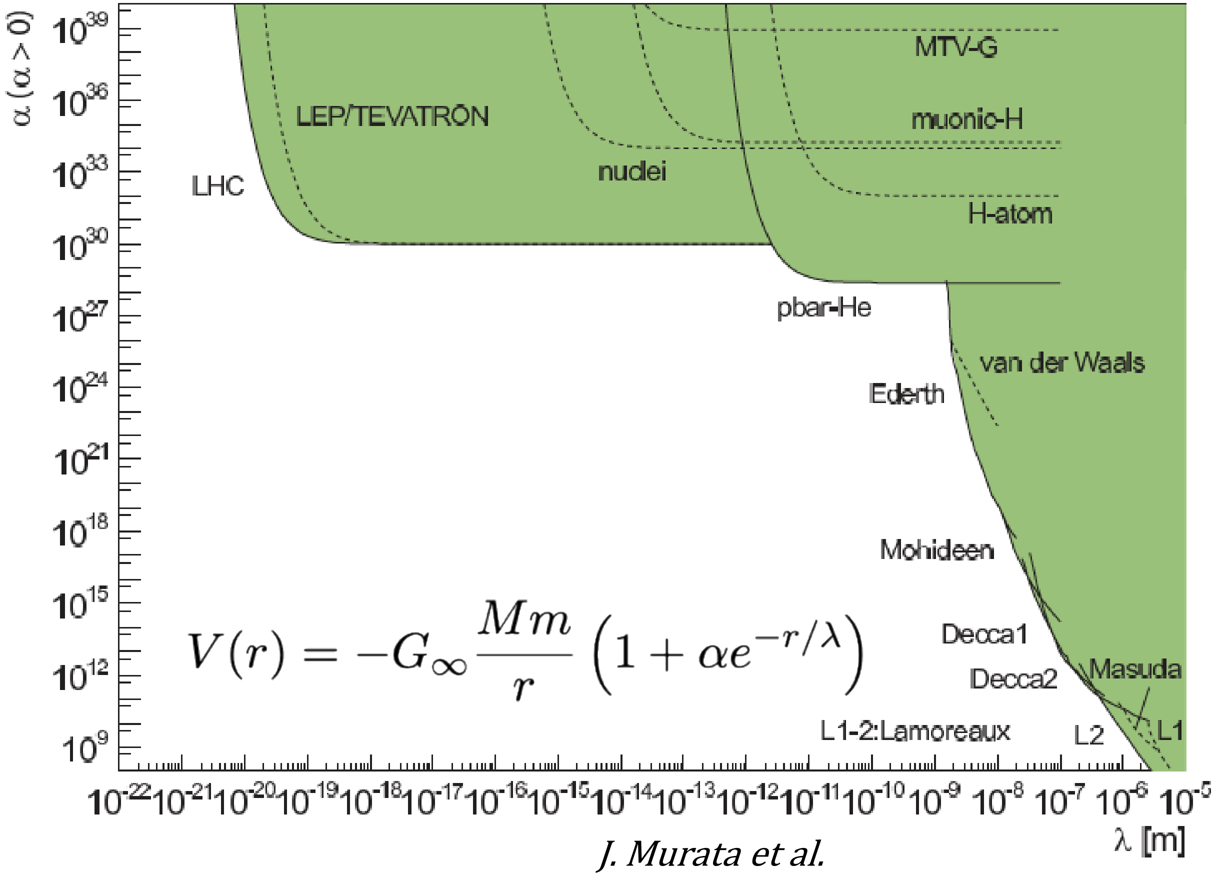
Towards antiproton-to-electron mass ratio at 10^{-11}



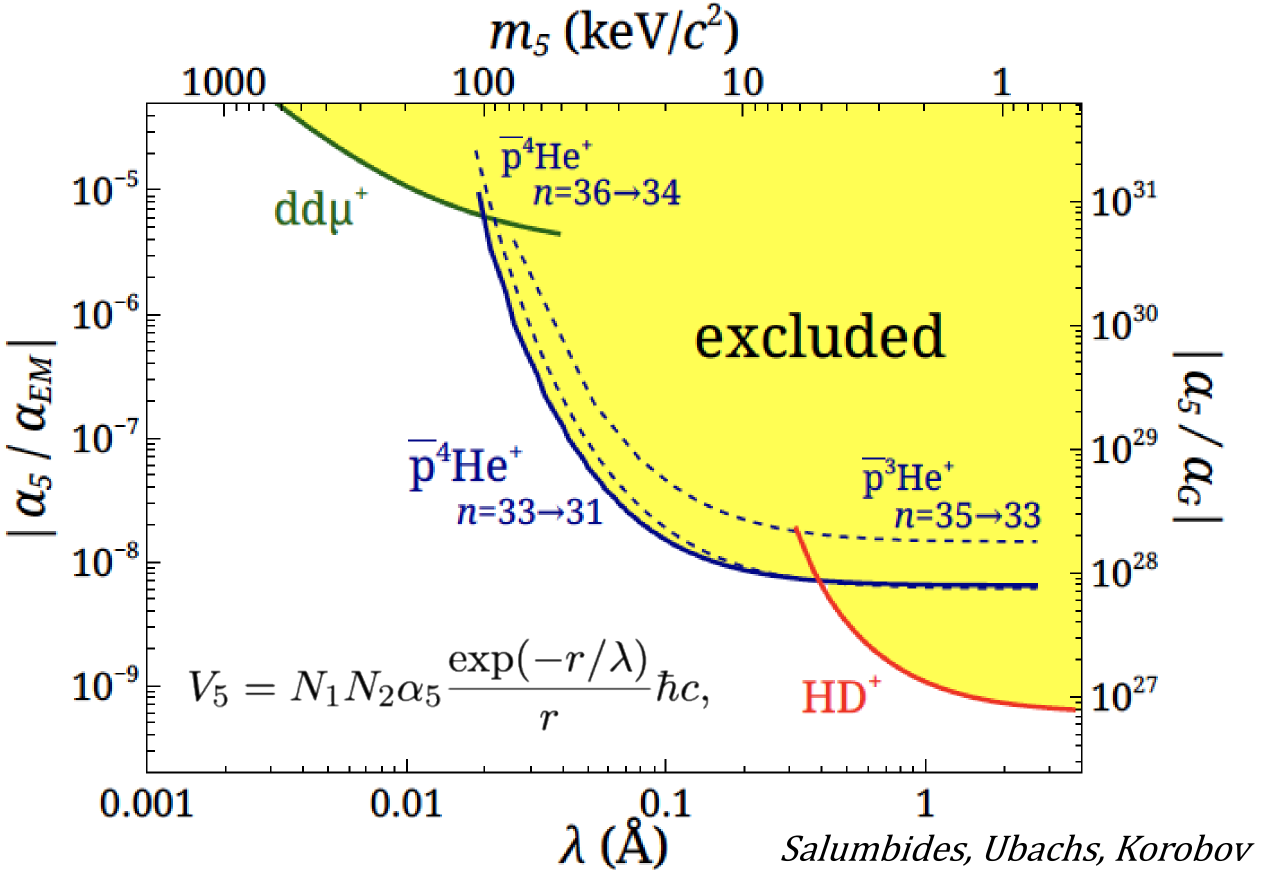


- Stable (anti)hadron/charged lepton mass ratio that can be precisely measured; CPT consistency test.
- Forms the basis of the international scientific units.
- Should be measured in as many independent ways as possible to avoid – lesson of proton size puzzle!

Bounds on the 5th force at 10^{-11} to 10^{-9} m length scales



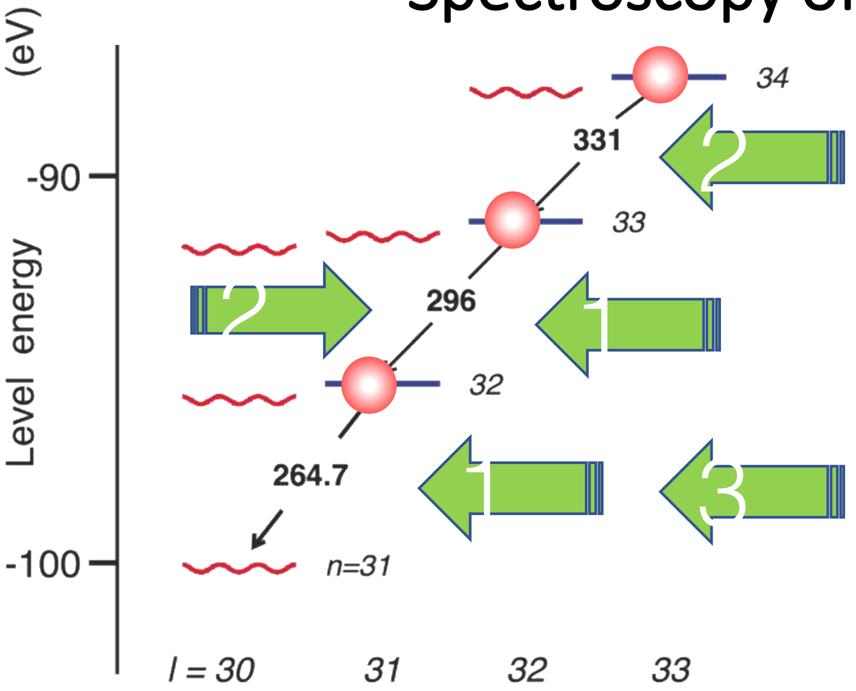
J. Murata et al.
Class Quantum Grav. 32, 033001 (2015)

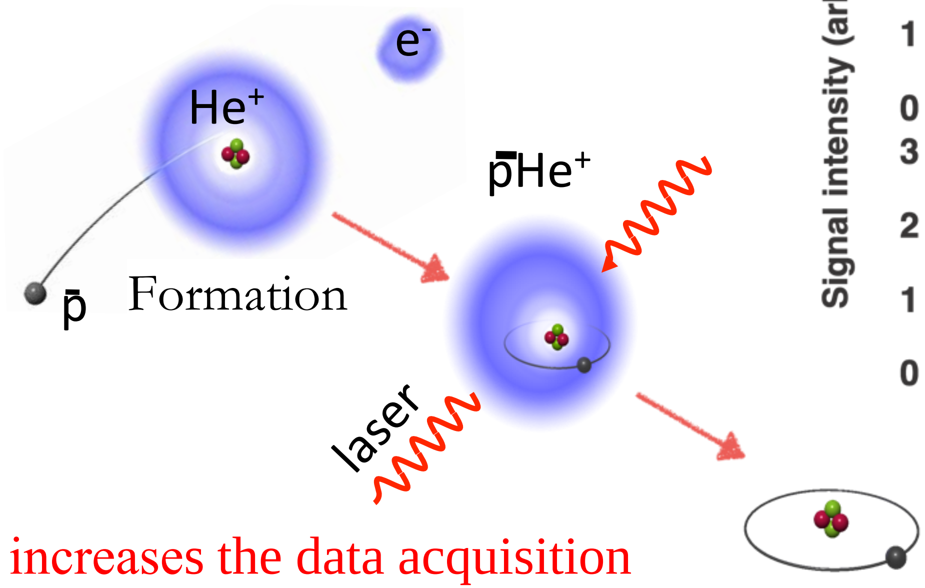


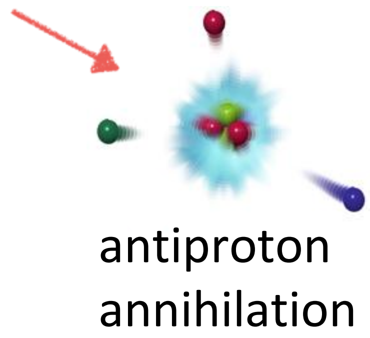
Salumbides, Ubachs, Korobov
J. Mol. Spect. 300, 65 (2014)

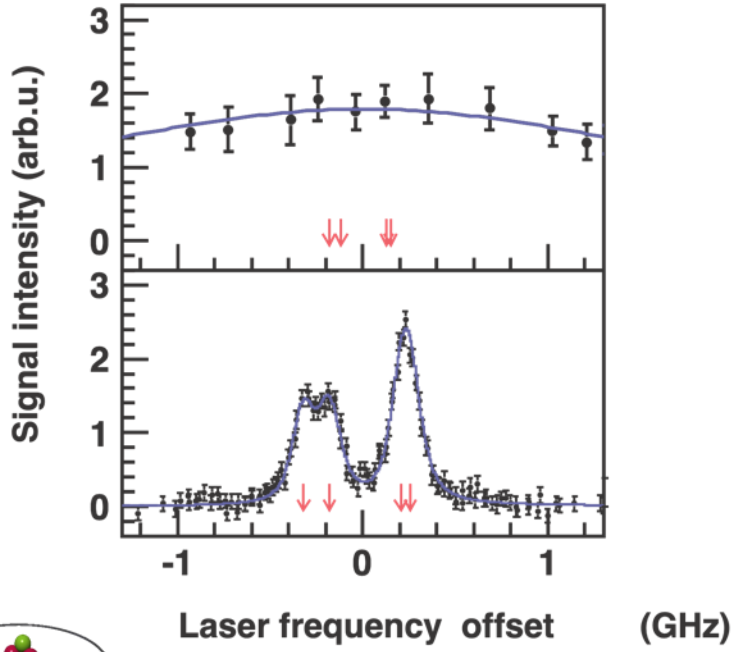
- Inverse square law of gravity has not been tested at length scales <100 μm. Only upper limits that are many orders of magnitude larger than the Newtonian force exist.
- $\bar{p}He^+$ constrains Yukawa-like part of potential to $\alpha<10^{28}$ times the Newtonian one.

Spectroscopy of narrow resonances by using 5 lasers at ELENA







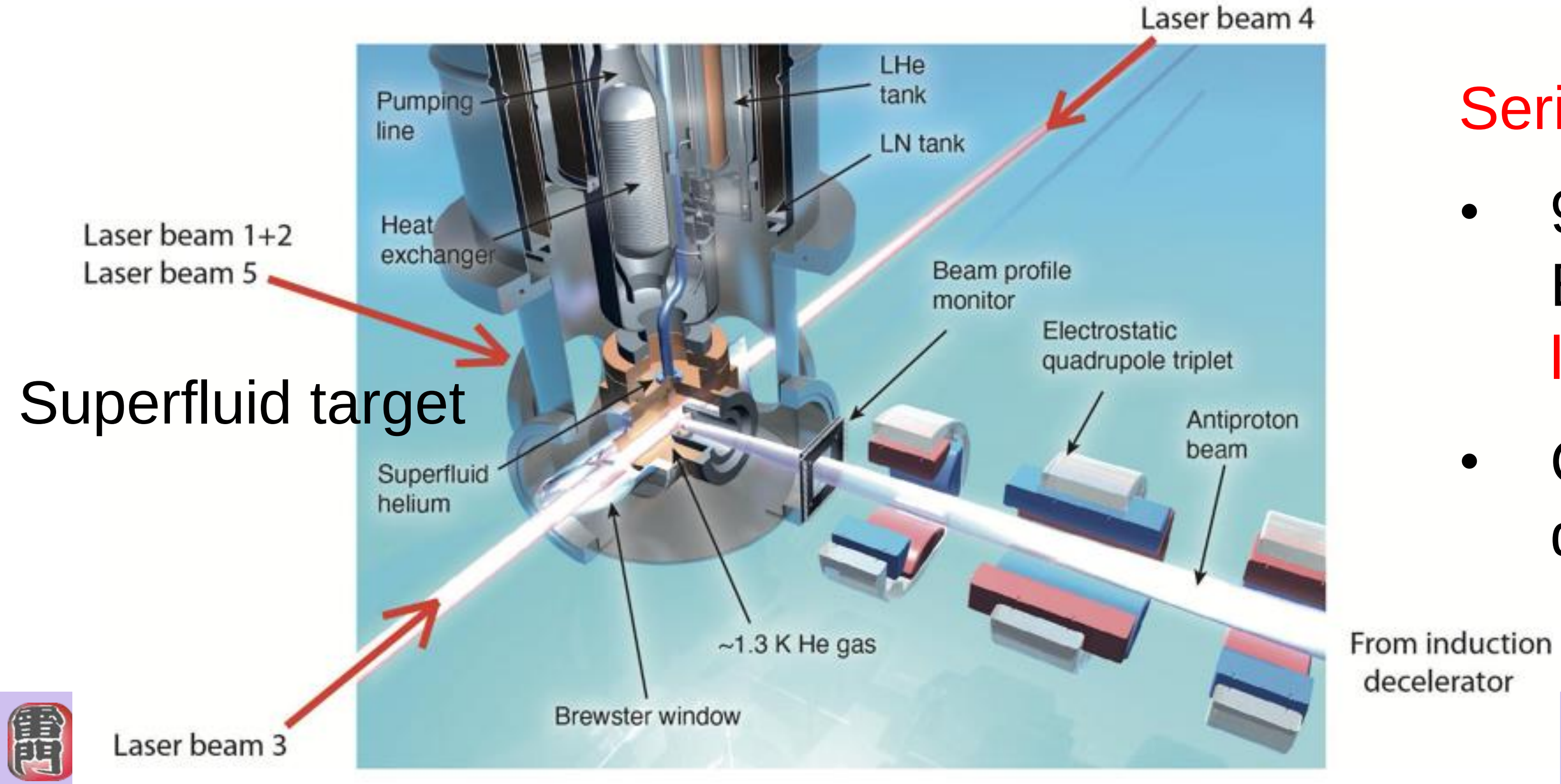


- ELENA's cooled antiproton beams vastly increases the data acquisition rate and signal-to-noise ratio.
- Detect new resonances with 100 times smaller natural widths compared to known ones.
- Improve experimental precision by >2 orders of magnitude.

1. Empty antiprotons in two states and create asymmetry.
2. Excite narrow (0.2-0.3 MHz) sub-Doppler two-photon transition.
3. Detect population asymmetry.

Goal 2021-2023: Produce antiprotonic helium with very high density

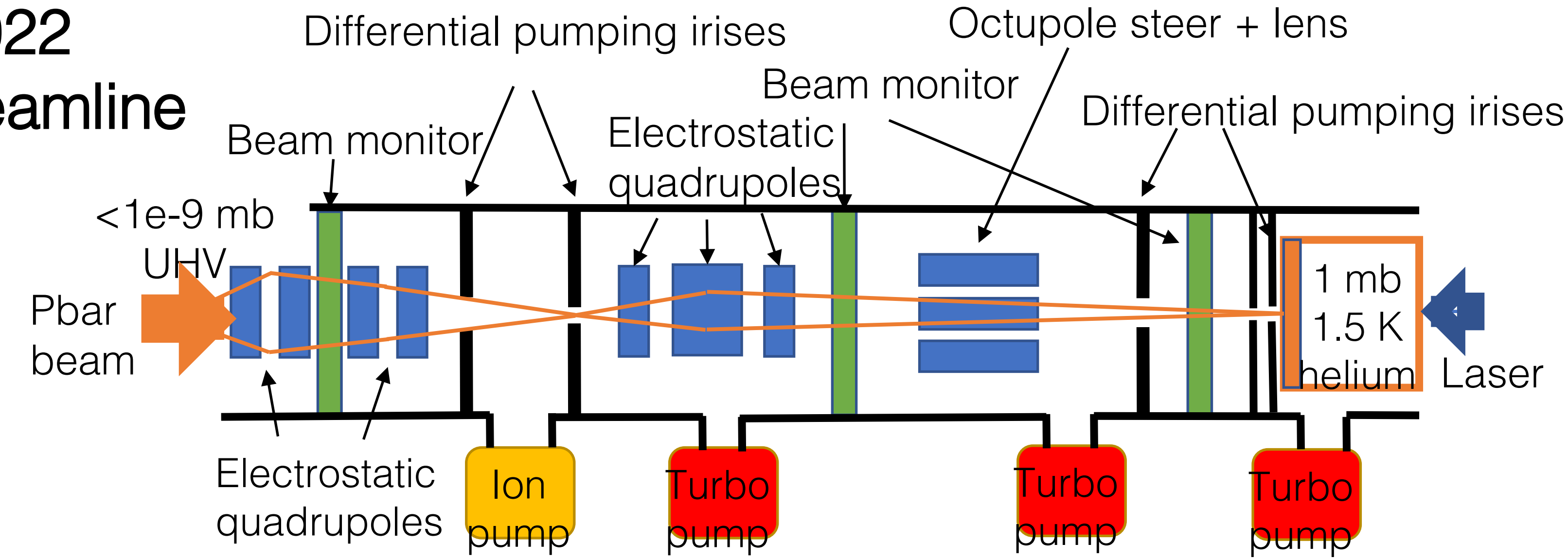
- ELENA should allow 100x higher density of antiprotonic helium atoms compared to all earlier experiments using radiofrequency quadrupole decelerator prior to 2018.
- Extremely vital goal for achieving high precision laser spectroscopy.
- Disappointment: only >8x improvement in 2021-2022 (beam diameter too large)



Serious issue discovered in 2022

- 900 nm thick, 10 mm diam BoPET beam window slowly leaks superfluid helium.
- Contaminates ELENA and destroys 20% of antiprotons

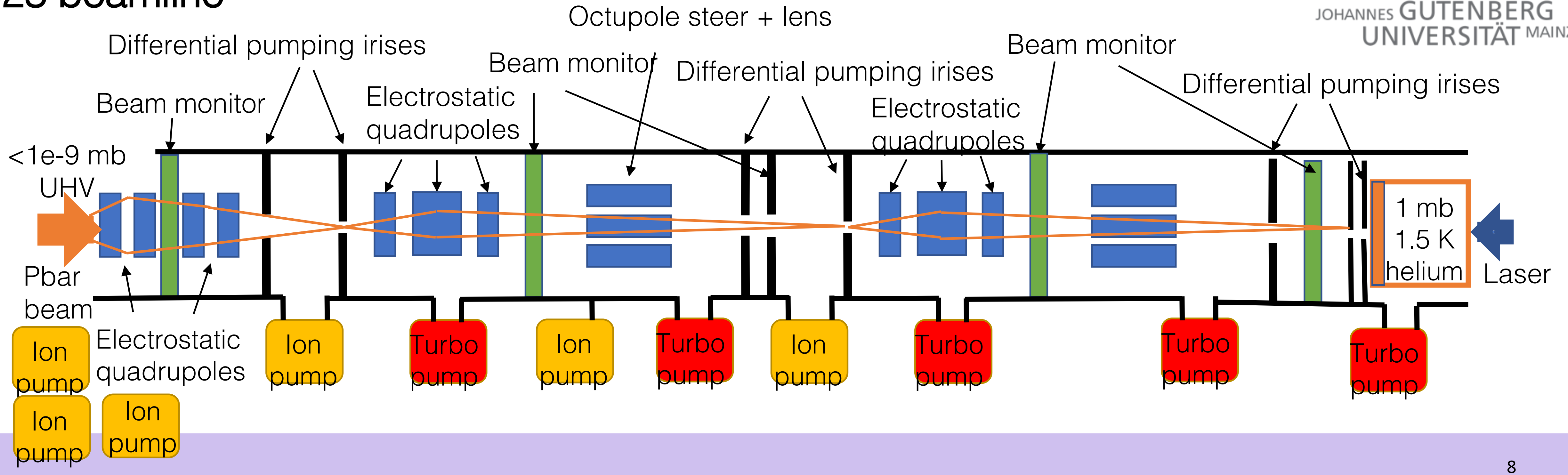
2022 beamline



- 2023 goal (DFG fund) Construction of 12 m beamline to achieve differential pumping of 12 orders of magnitude
- Achieve smaller beam diameter

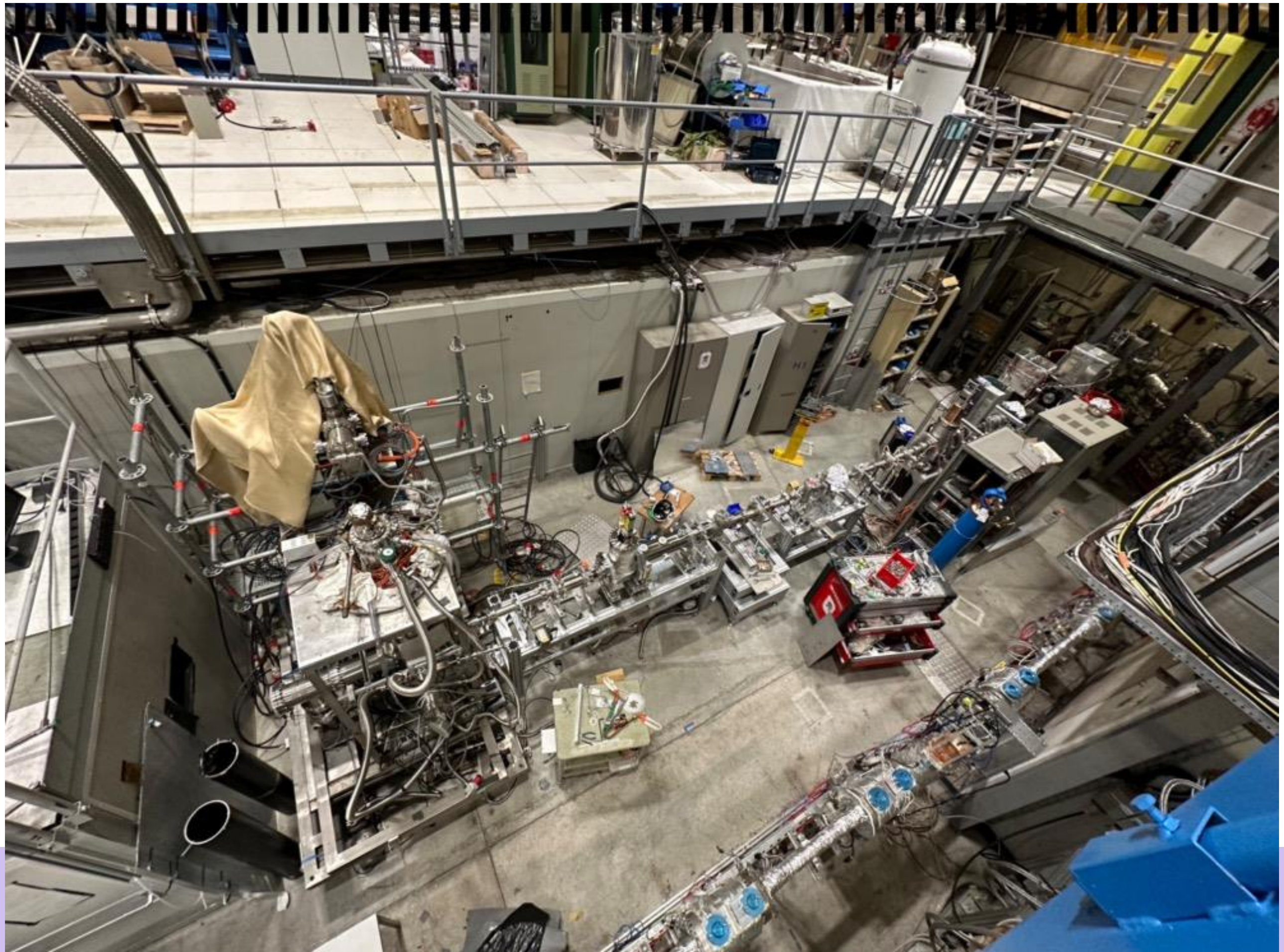
JOHANNES GUTENBERG UNIVERSITÄT MAINZ

2023 beamline

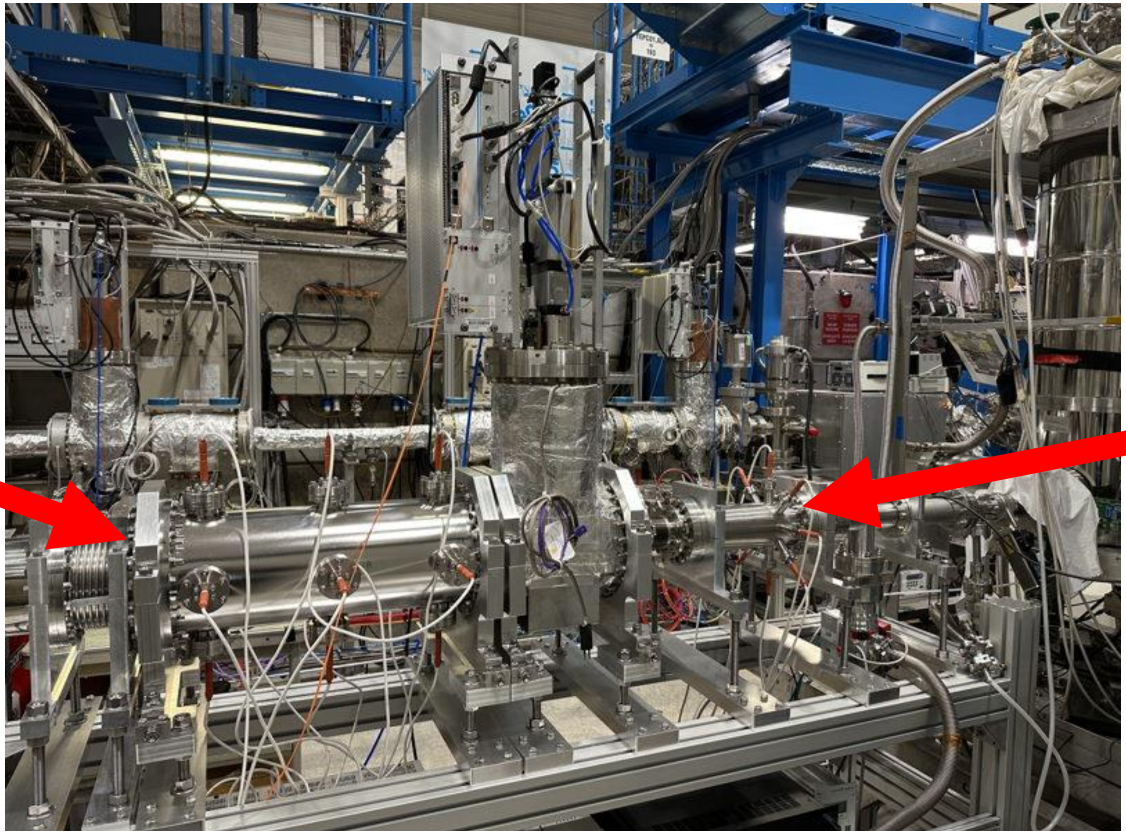


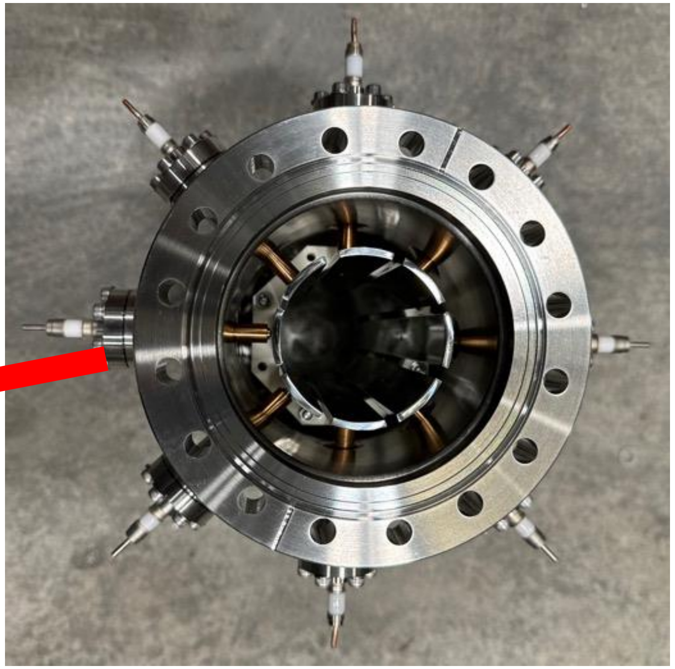
New 12 m beamline (2x longer) constructed in 2023
Fills up available ASACUSA area floor space

Achieved highest density of antiprotonic helium ever produced in a 1 mb cryogenic helium target!
Strong improvement in laser spectroscopy now possible.



Optimized beam optics design compared to 2022

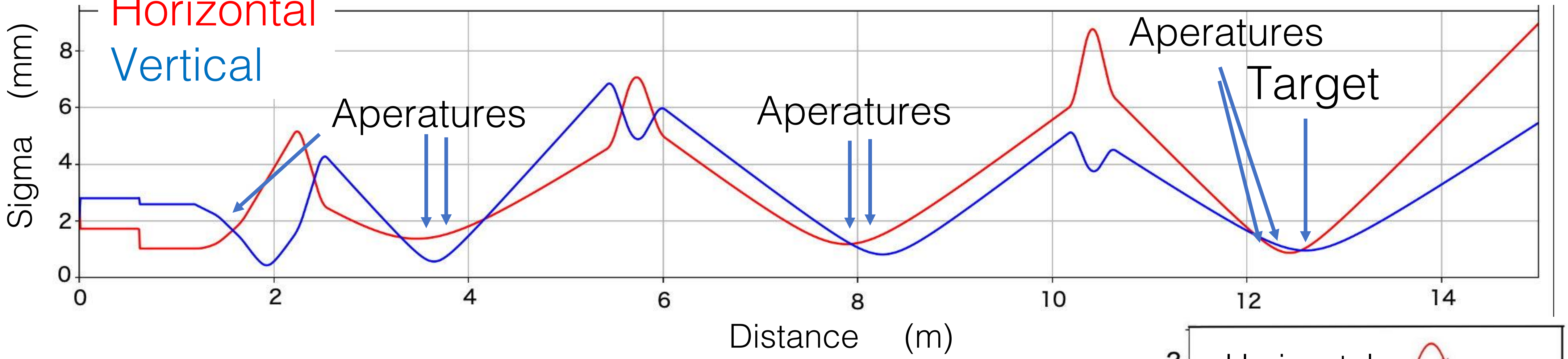




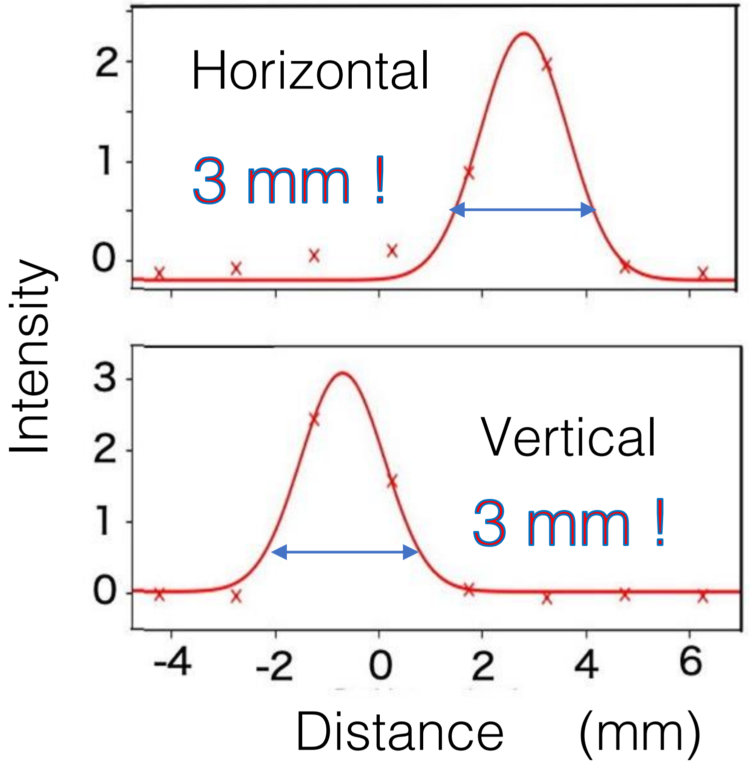
- Quadrupole doublet + two quadrupole triplets minimize aberrations
- System now includes 8 quadrupoles. Achieves smaller beam diameter
- Octupole steers to precisely deflect the beam through apertures

10

Simulated and measured beam trajectories

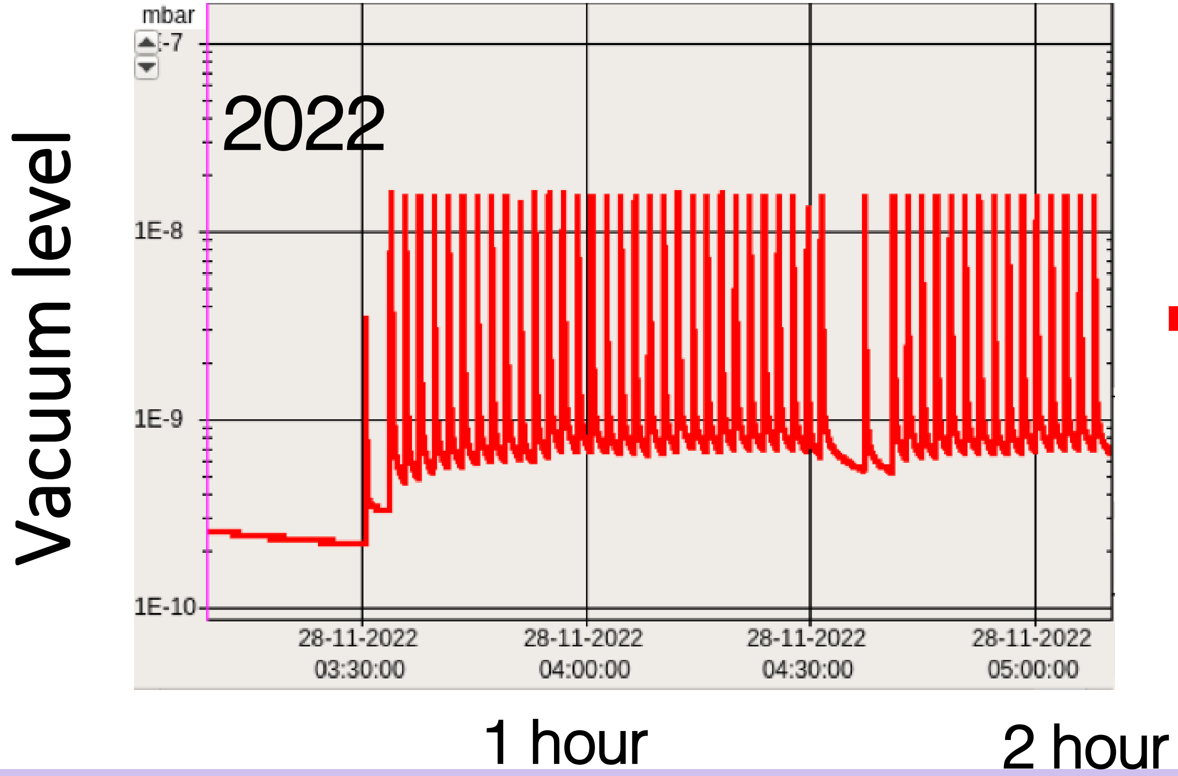


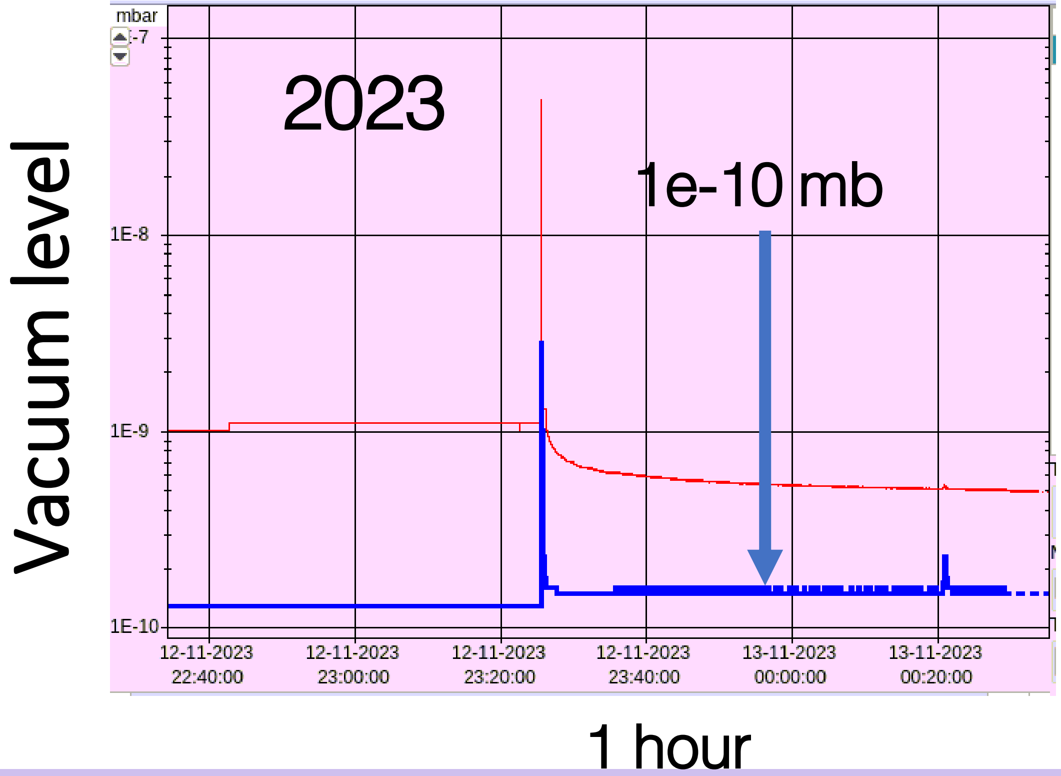
- 3 intermediate foci and 1 final focus in cryogenic helium target
- Beam transport using 100 keV antiproton and H- beams.
- Beam focus of 3 mm achieved (roughly agrees with simulation)
- 6x higher beam flux density compared to 2022.
- 2 orders of magnitude higher beam density compared to radiofrequency quadrupole decelerator in 2018 !
- Highest density of antiprotonic helium atoms ever produced in 1 mb gas target, high precision laser spectroscopy now possible.



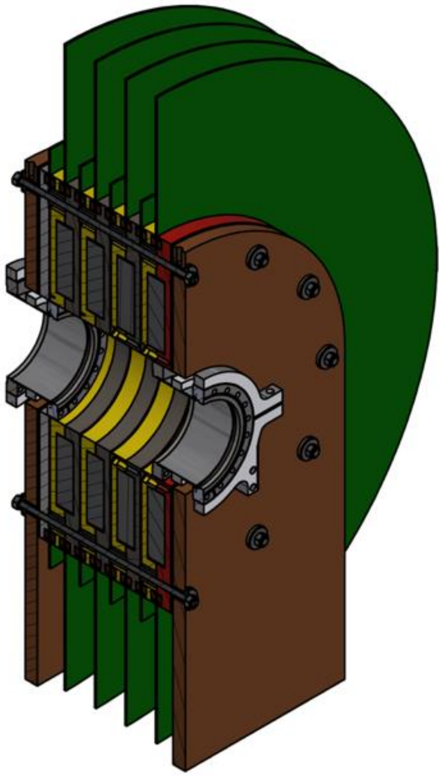
Vacuum now fully compatible with ELENA operation

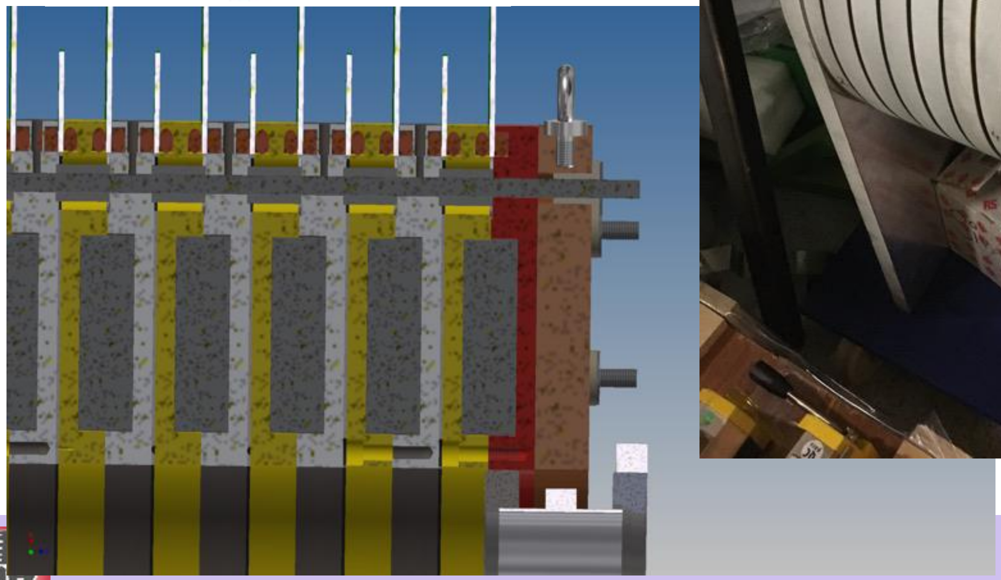
- Antiprotonic helium atoms produced stably without disturbing ELENA.
- ELENA transfer line vacuum maintained at 1×10^{-10} mb.
- Differential pressure of 12 orders of magnitude achieved.
- No “opening and shutting of gate valve to minimize gas contamination” necessary





Induction decelerator





- Needed to achieve ultimate density of antiprotonic helium atoms
- Compact device decelerates ELENA antiprotons to eventually 50 keV using nanocrystalline amorphous materials with extremely low energy spread and background.
- 10-stage device constructed in MPQ and Mainz
- Installation in ASACUSA 2024-25.
- Collaboration with KEK accelerator group
- Possible collaboration within John Adams Accelerator Research Institute of UK

13

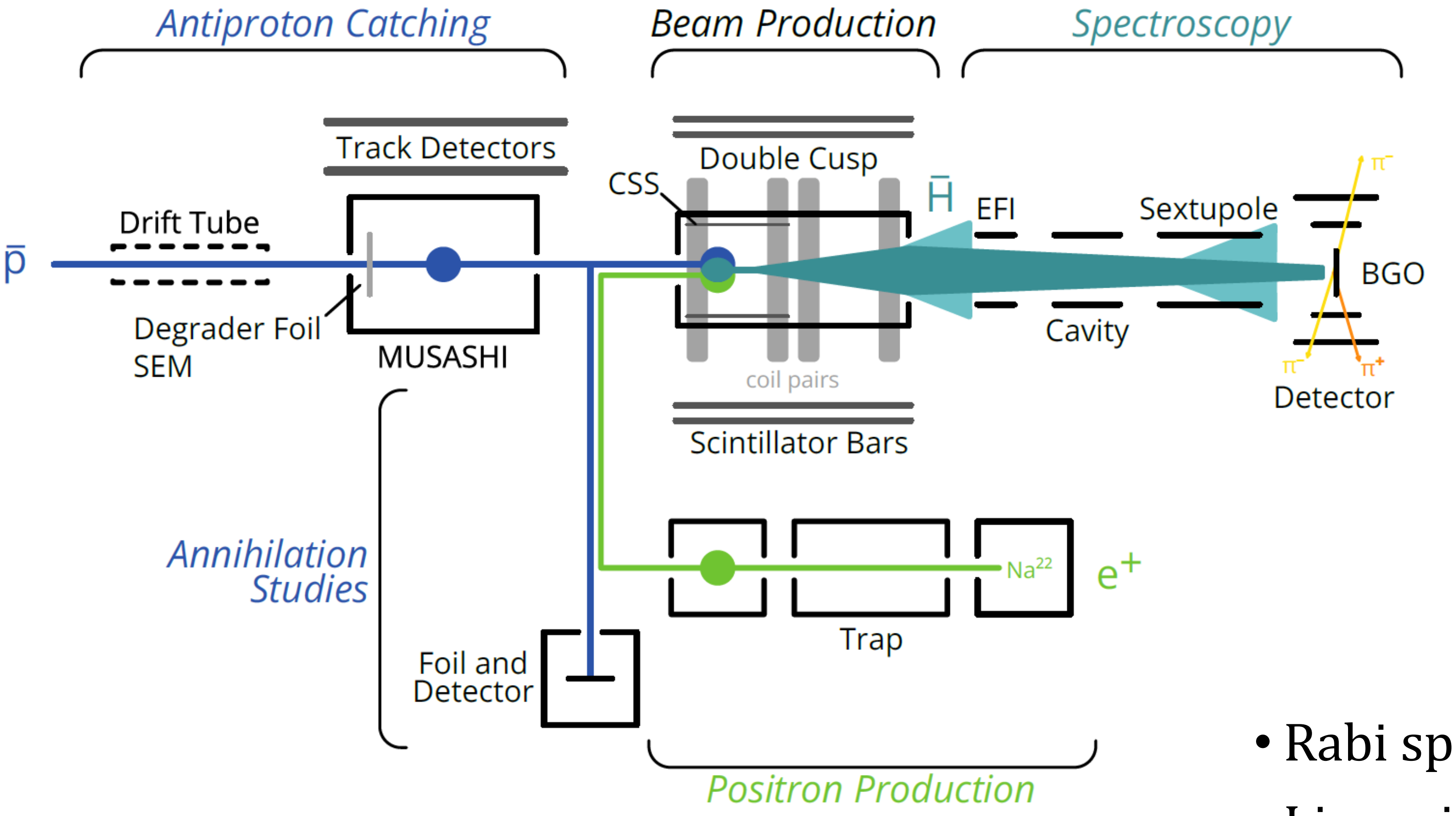
- Design of optical chain to achieve $<10^{-11}$ precision on antiproton-to-electron mass ratio (INRIM + Munich collaborators)
- Continued construction of new laser systems for spectroscopy
- Several scientific publications on antiprotonic helium and atomic collision results and instrumentation in pipeline.

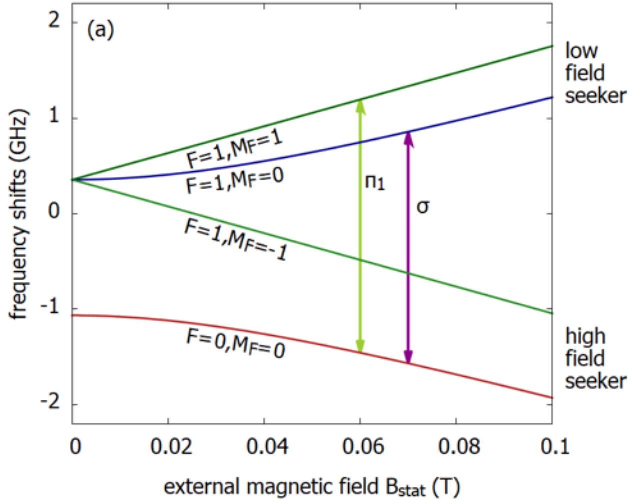
Group move + restructuring in 2023

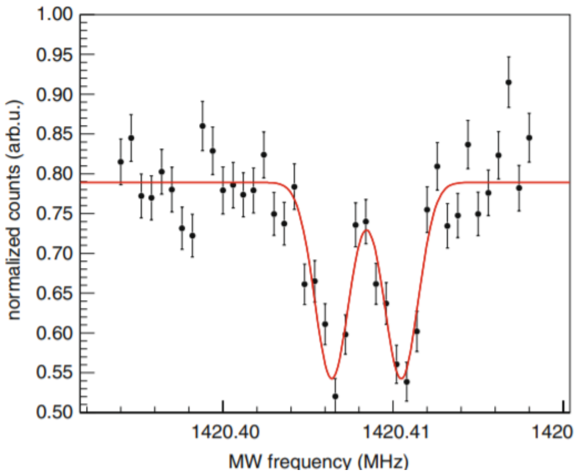
- Dec 2022: Group moved from Munich to JGU Mainz (DFG Heisenberg position)
- Feb 2023: Started construction of 12 m beamline by Mainz
- July 2023: Moved to London (group is now permanent for first time in 20 y)
- Dec 2023: Royal Society funding for induction decelerator (18 months)
- Further funding sought in UK
- Now recruiting new students, rebuilding group (highest priority effort!)
- **Ready to commit to AD-ELENA physics for 17+ years.**

14

Antihydrogen experiment

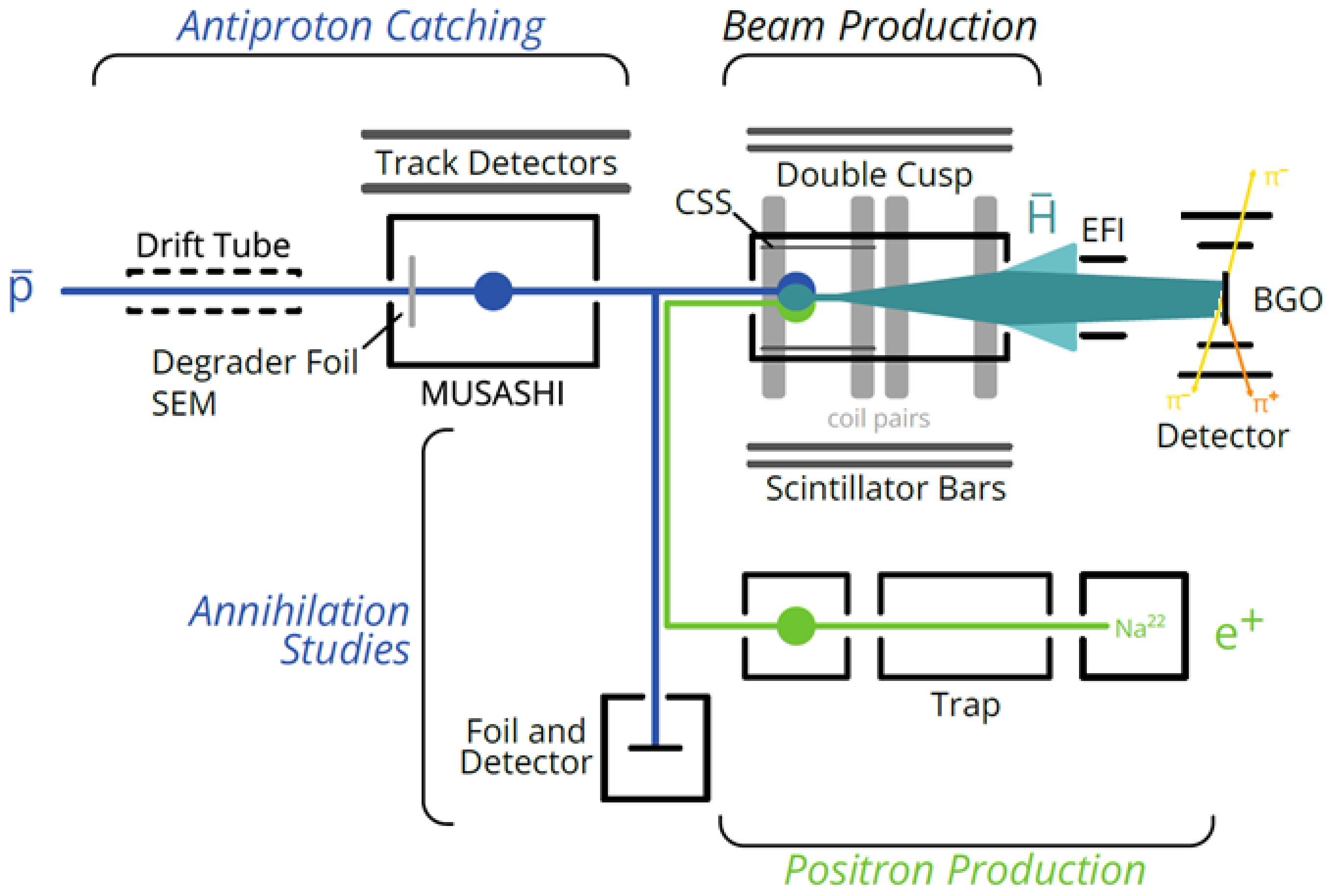






- Rabi spectroscopy @50 K
- Line width ~10 kHz: precision ~ppm

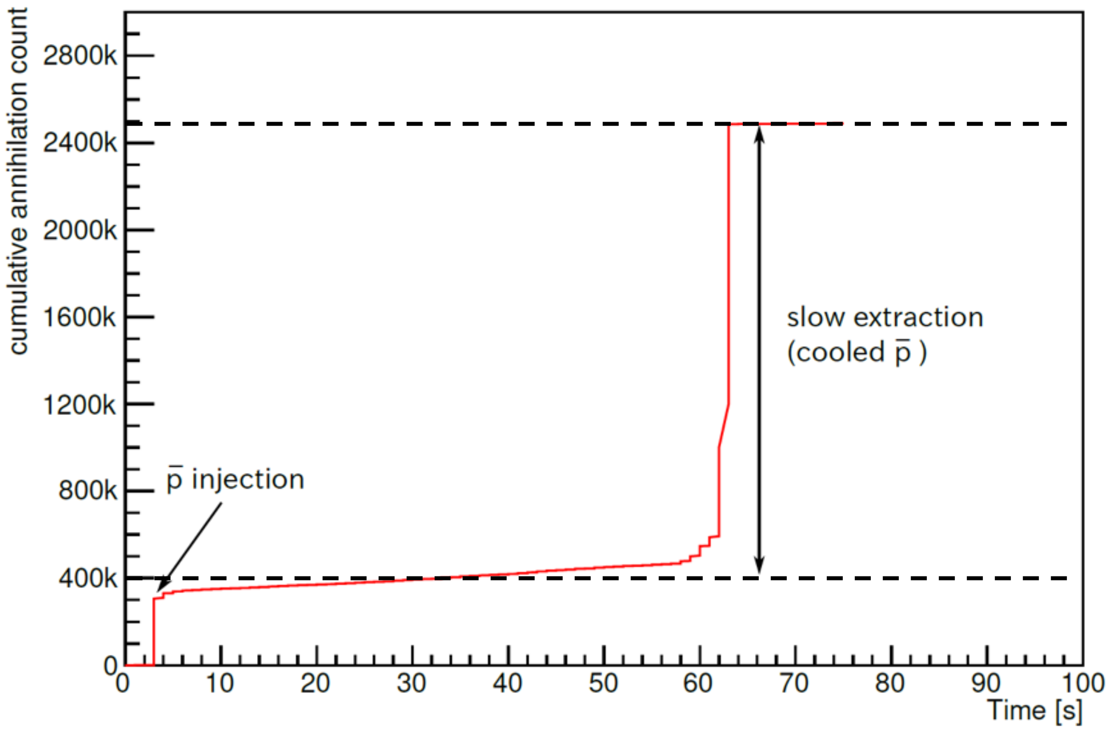
Overview

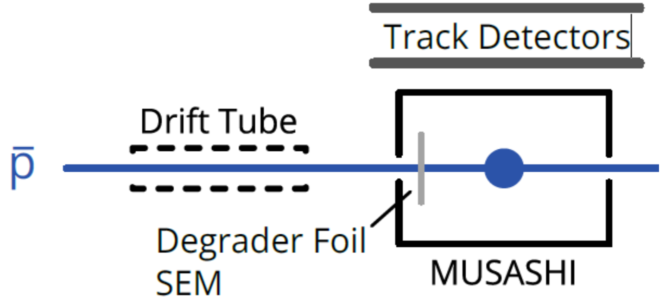


- Shorter setup used in 2023
  - No cavity + sextupole
  - Provides larger solid angle for detecting $\overline{H}$

Antiprotons

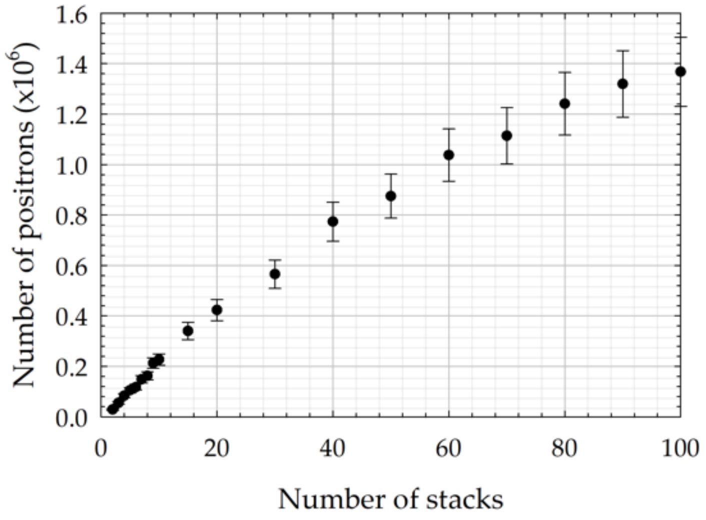
- Beam intensity consistently >8 million per bunch for LNE05 – thanks to AD ELENA team
- 100 s cycle time implemented for efficient use of beam
- Issue with a leak current on the drift tube electrode fixed
- Approximately **2 million $\bar{p}$** per bunch could be trapped & cooled
- Transport to the Cusp trap improved to ~50% → **1 million $\bar{p}$** per experiment

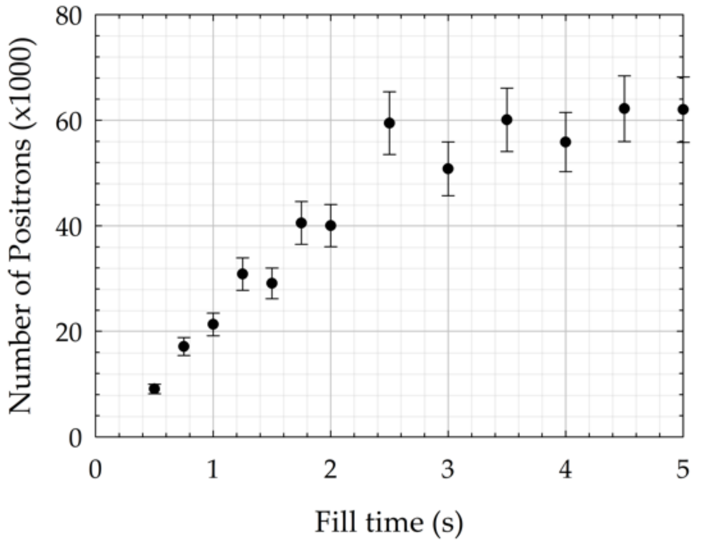




Positrons

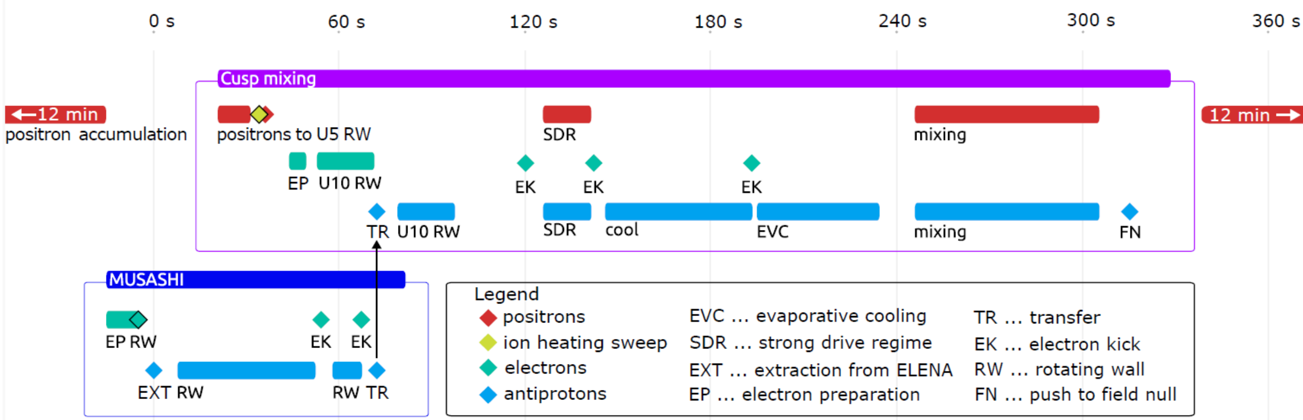
- After problems in 2022 operating optimally
  - Moderator efficiency ~ 0.25 %
  - Trapping efficiency ~15%
  - Accumulator lifetime ~ 100s
- Still waiting for new ^{22}Na source from iThemba laboratories
  - Experiments in 2023 used 90 MBq source
  - This required multiple 60s accumulation time bunches to be transferred to have **~ 4 million** e^+ in the Cusp
  - New source will be 20 times stronger

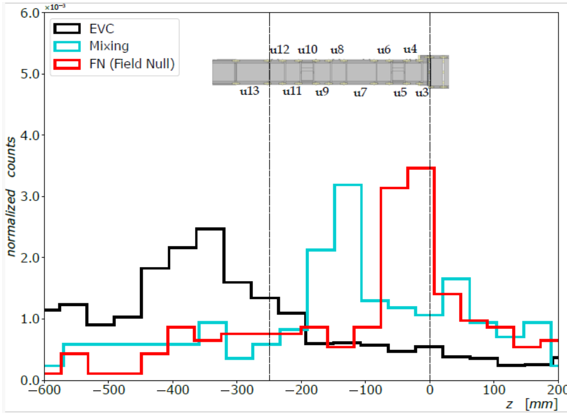


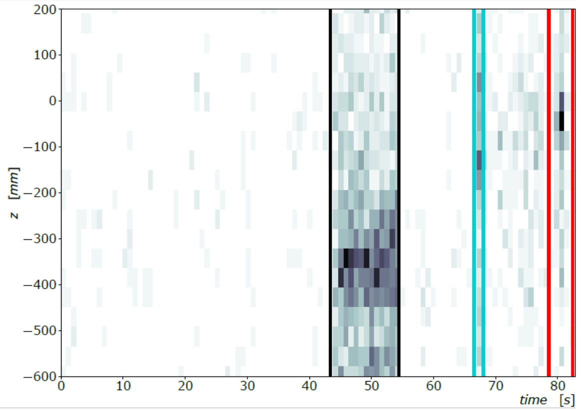


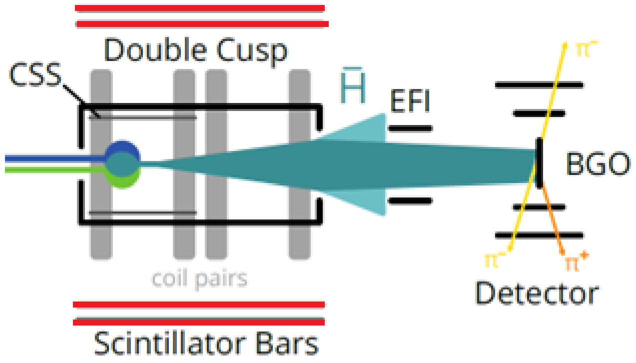
Mixing Experiments

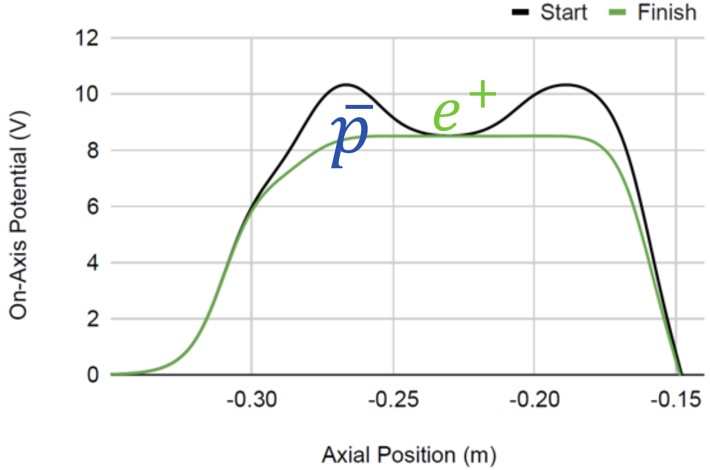
- In 2023 mixing experiments used the so-called *slow merge* method
- After evaporative cooling **500 k** $\bar{p}$ remained for mixing
- Approximately 4 million e^+ were transferred to the Cusp and allowed to passively cool to ∼25 K
  - Taking roughly 12 minutes due to the weak source
- Due to the passive cooling, we were able to mix over a period up to 60s without change in positron temperature
- We could investigate the effect of mixing on the plasma in detail





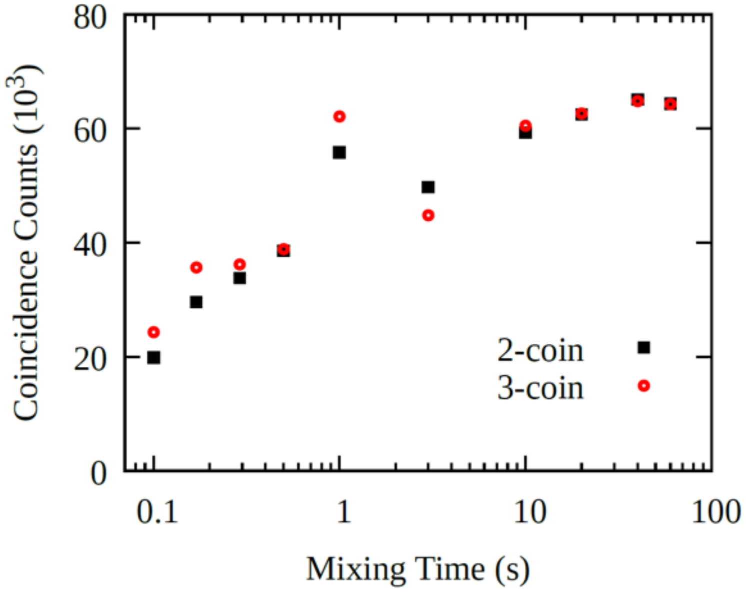


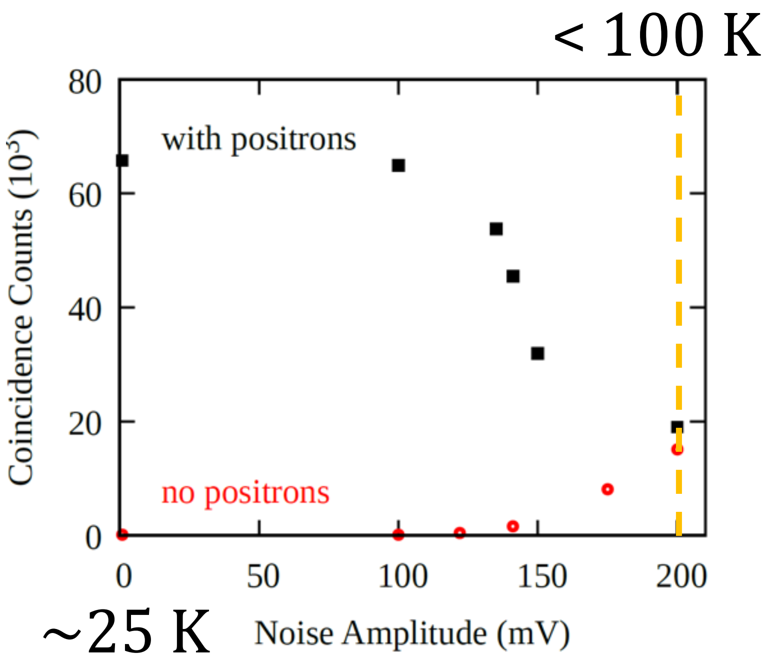


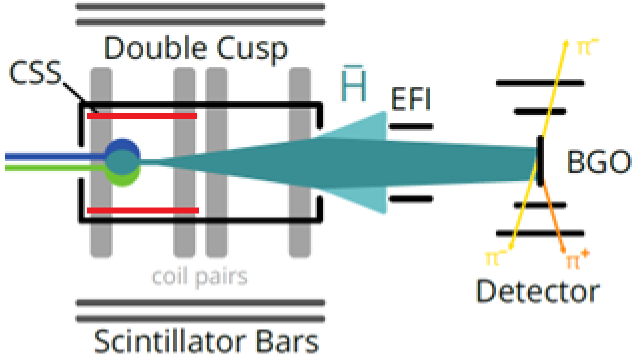


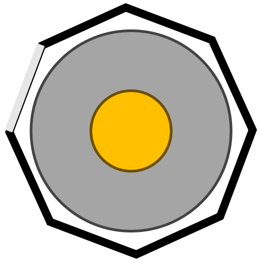
Mixing Experiments

- A detailed analysis is in progress preliminary observations below
- Antihydrogen yield between 50 and 80%
  - **250 – 400 k** Antihydrogen atoms
- Increasing the temperature of the positrons causes dramatic drop in yield



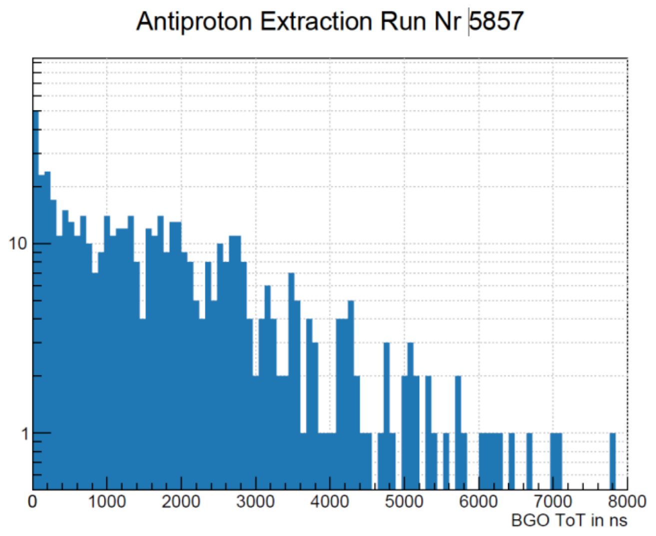


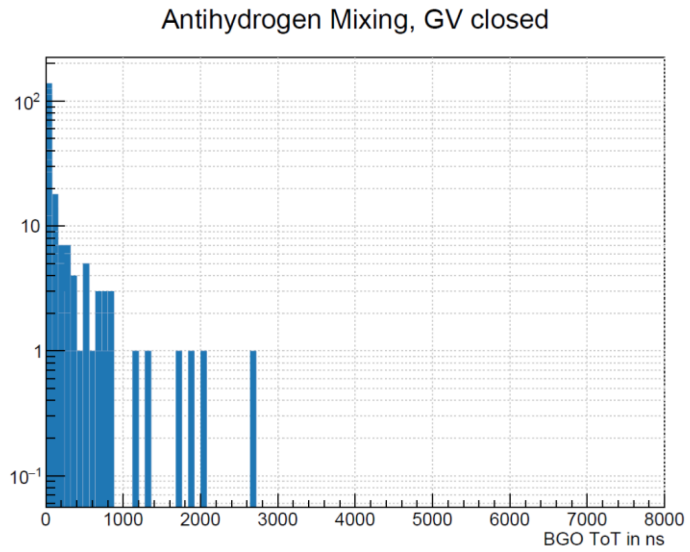


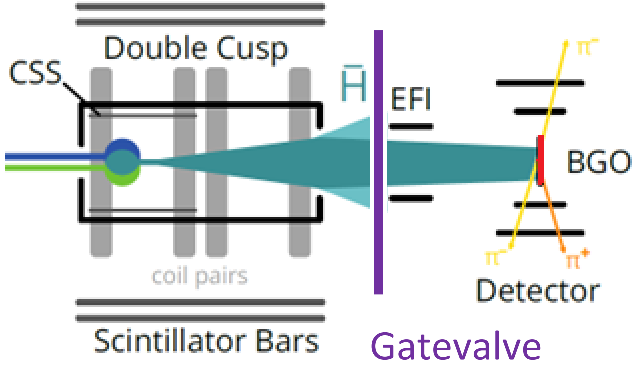


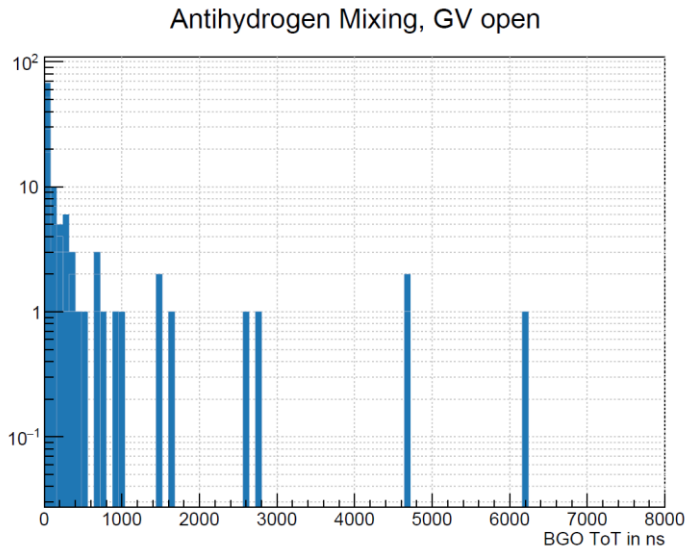
Mixing Experiments

- A detailed analysis is in progress preliminary observations below
- Antihydrogen yield between 50 and 80%
  - **250 – 400 k** Antihydrogen atoms
- Using the BGO downstream of the mixing region showed **no beam like behaviour** using this mixing method



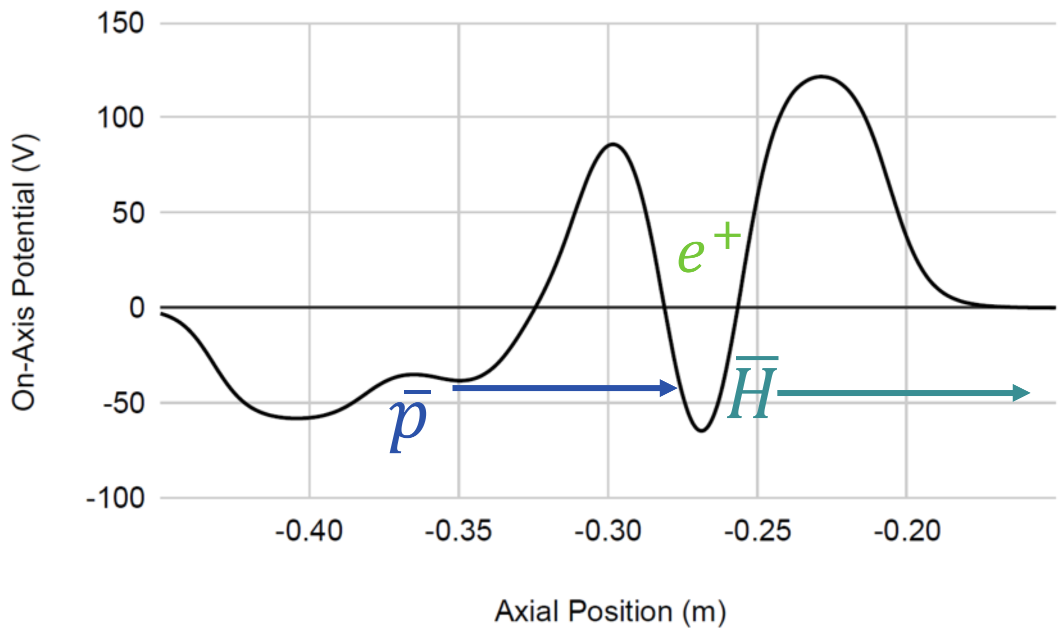






Plans for 2024

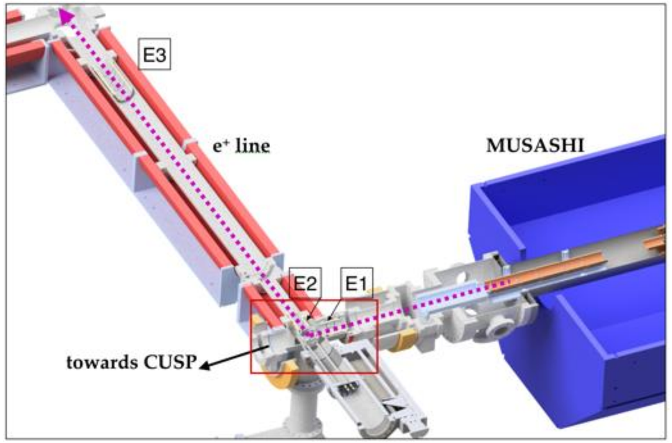
- Switch to new mixing method so called ***beam scheme***
  - SDREVC developed for both $\bar{p}$ and e^+
  - Need control over $\bar{p}$ energy 0.01 eV
  - Maintain cold dense positron plasma over long mixing cycle
- Predicts 100s of $\bar{H}$ downstream for 1 million antiprotons and 30 K positrons

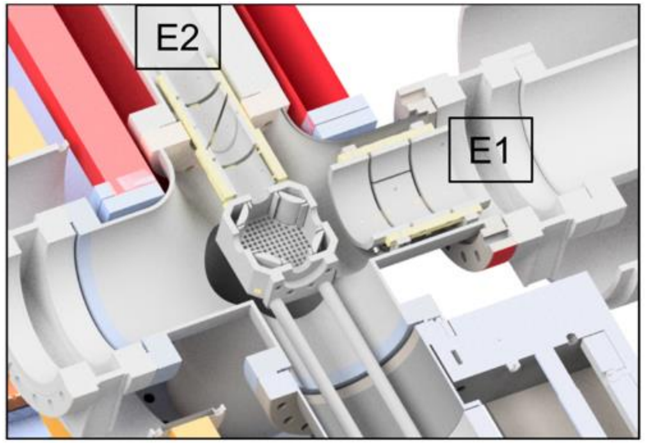


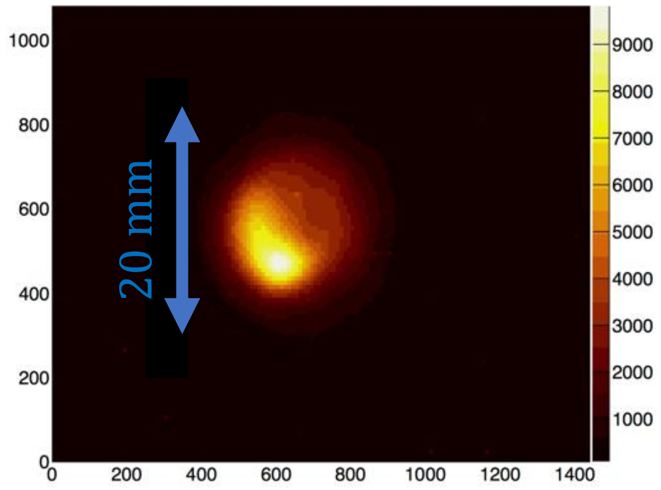
S. Jonsell and M. Charlton, *Formation of Antihydrogen Beams from Positron–Antiproton Interactions*, New J. Phys. **21**, 073020 (2019).

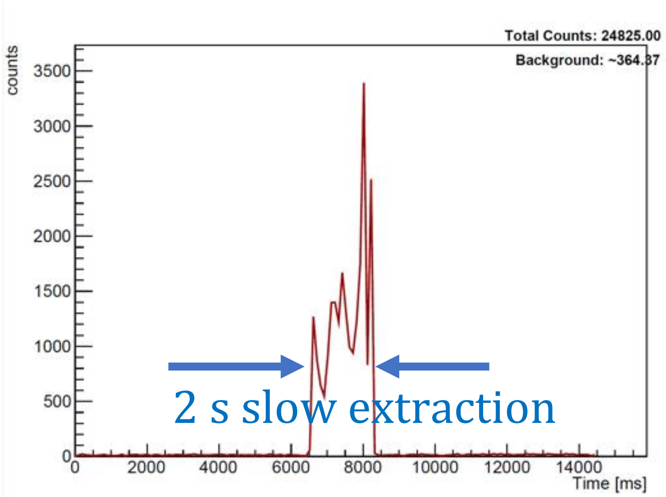
Slow extraction beam line

- Experiments to transport a slow extracted beam of $\bar{p}$ out of MUSASHI along the existing e^+ transfer line using electrostatic beam elements
- Approximately 25,000 $\bar{p}$ detected and imaged on an MCP detector
  - Transport efficiency ~ 10%
  - Beamspot < 1cm



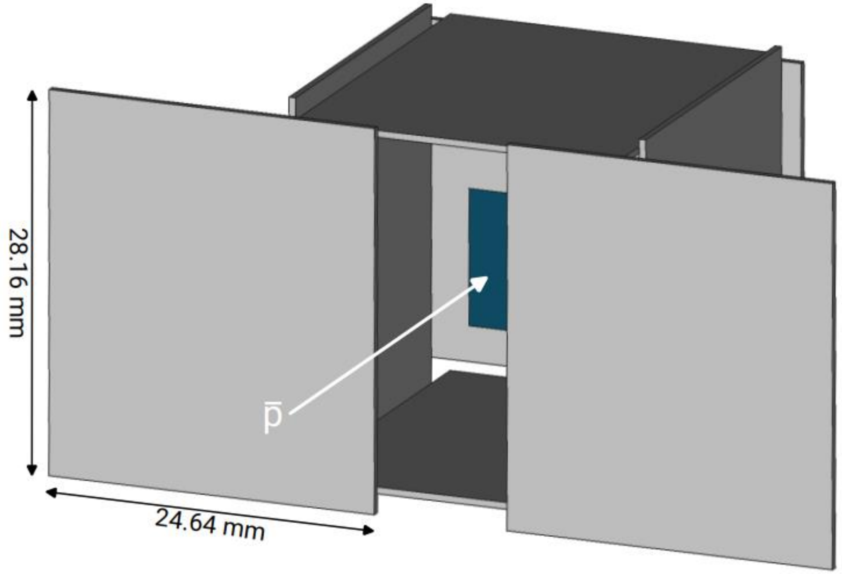


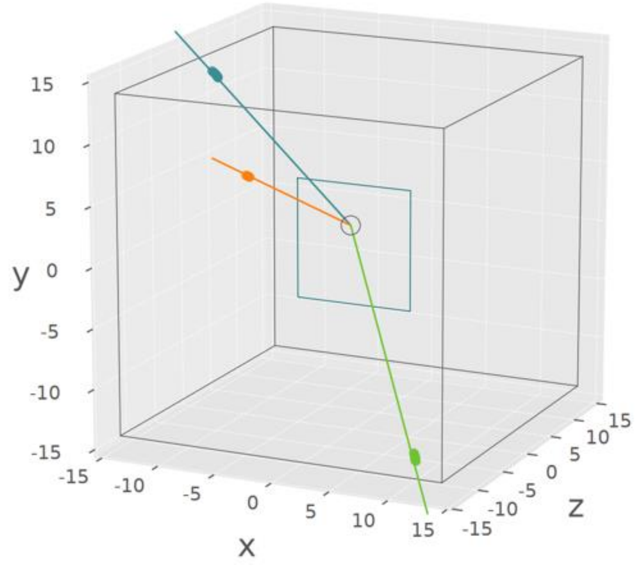


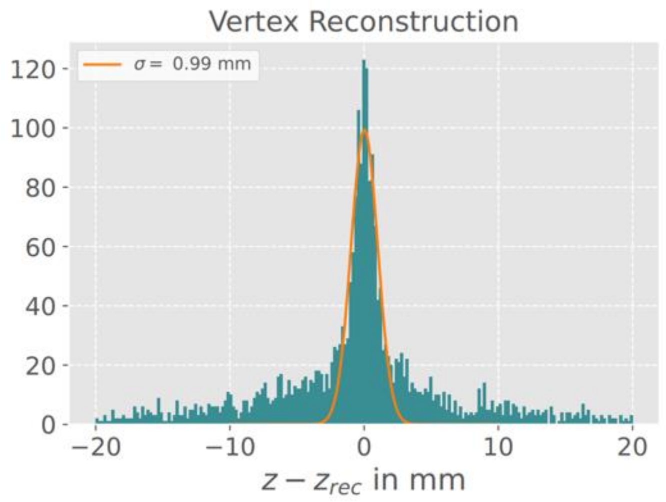


Annihilation measurements

- Systematic studies of antiproton – nucleus annihilation
  - Using thin targets (~ 15)
  - Detection of prongs with ~ 4π solid angle
    - Detector based on Timepix 4
    - 3D vertex reconstruction with single plane pixel detectors
  - Multiplicity, Kinetic Energy, and Angular Distributions

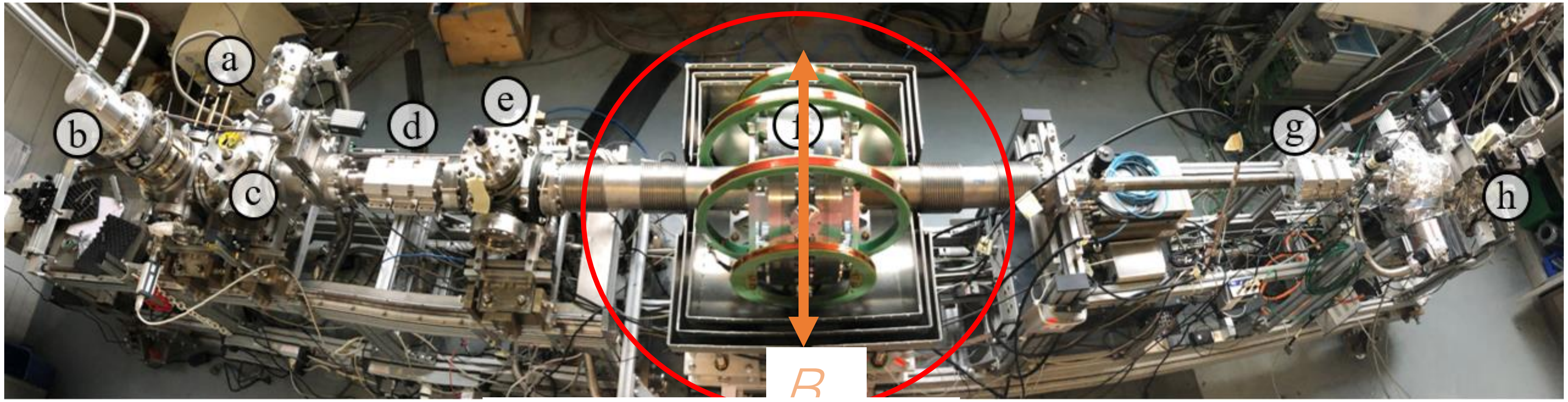


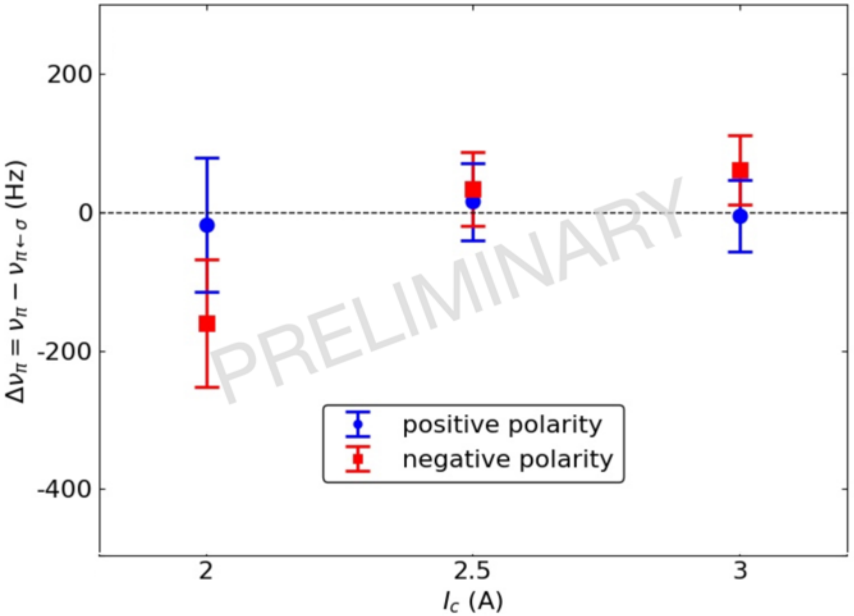




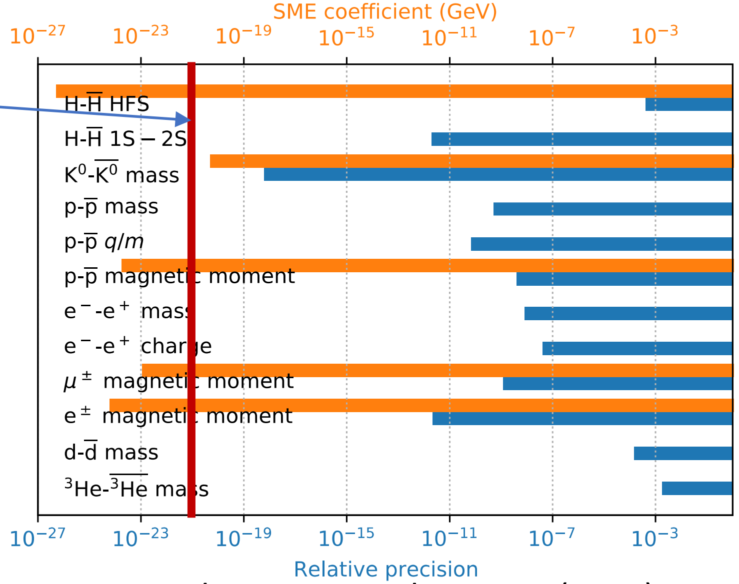
Hydrogen beam result

To be used for $\overline{\mathrm{H}}$ spectroscopy





Coefficient $\mathcal{K}$	Constraint on $\lvert\mathcal{K}\rvert$
proton	
$H^{\mathrm{NR(0B),Sun}}_{p010}$, $g^{\mathrm{NR(0B),Sun}}_{p010}$	$< 1.2 \times 10^{-21}$ GeV
$H^{\mathrm{NR(1B),Sun}}_{p010}$, $g^{\mathrm{NR(1B),Sun}}_{p010}$	$< 5.8 \times 10^{-22}$ GeV
$H^{\mathrm{NR(0B),Sun}}_{p210}$, $g^{\mathrm{NR(0B),Sun}}_{p210}$	$< 8.4 \times 10^{-11}$ GeV^{-1}
$H^{\mathrm{NR(1B),Sun}}_{p210}$, $g^{\mathrm{NR(1B),Sun}}_{p210}$	$< 4.2 \times 10^{-11}$ GeV^{-1}
$H^{\mathrm{NR(0B),Sun}}_{p410}$, $g^{\mathrm{NR(0B),Sun}}_{p410}$	< 1.2 GeV^{-3}
$H^{\mathrm{NR(1B),Sun}}_{p410}$, $g^{\mathrm{NR(1B),Sun}}_{p410}$	< 0.6 GeV^{-3}
electron	
$H^{\mathrm{NR(0B),Sun}}_{e010}$, $g^{\mathrm{NR(0B),Sun}}_{e010}$	$< 7.7 \times 10^{-19}$ GeV
$H^{\mathrm{NR(1B),Sun}}_{e010}$, $g^{\mathrm{NR(1B),Sun}}_{e010}$	$< 3.8 \times 10^{-19}$ GeV
$H^{\mathrm{NR(0B),Sun}}_{e210}$, $g^{\mathrm{NR(0B),Sun}}_{e210}$	$< 5.5 \times 10^{-8}$ GeV^{-1}
$H^{\mathrm{NR(1B),Sun}}_{e210}$, $g^{\mathrm{NR(1B),Sun}}_{e210}$	$< 2.8 \times 10^{-8}$ GeV^{-1}
$H^{\mathrm{NR(0B),Sun}}_{e410}$, $g^{\mathrm{NR(0B),Sun}}_{e410}$	$< 8.0 \times 10^{2}$ GeV^{-3}
$H^{\mathrm{NR(1B),Sun}}_{e410}$, $g^{\mathrm{NR(1B),Sun}}_{e410}$	$< 4.0 \times 10^{2}$ GeV^{-3}



EW, Phys. Part. Nucl. 53, 790 (2022)

ASACUSA long-range planning

Antiprotonic helium

- **Until LS3**
  - Commission induction decelerator
  - Synthesize high densities of antiprotonic helium
  - Measure strong two-photon transitions
    Nature 475, 28 (2011) + Science 354, 610 (2016)
  - Improve the antiproton to electron mass ratio
  - Detect narrow two-photon transitions
- **Plans During LS3**
  - Install new ultra-precision frequency chain
  - Improve lasers and detectors and target
  - Pionic helium at PSI **Nature 581, 37 (2020)**
- **Plan after LS3**
  - Ultra-high precision spectroscopy
  - Tests of QED to 12 digits
  - Upper limit searches for fifth force
  - Antiproton-to-electron mass ratio to 11-12 digits
  - Superfluid measurements **Nature 603, 411 (2022)**

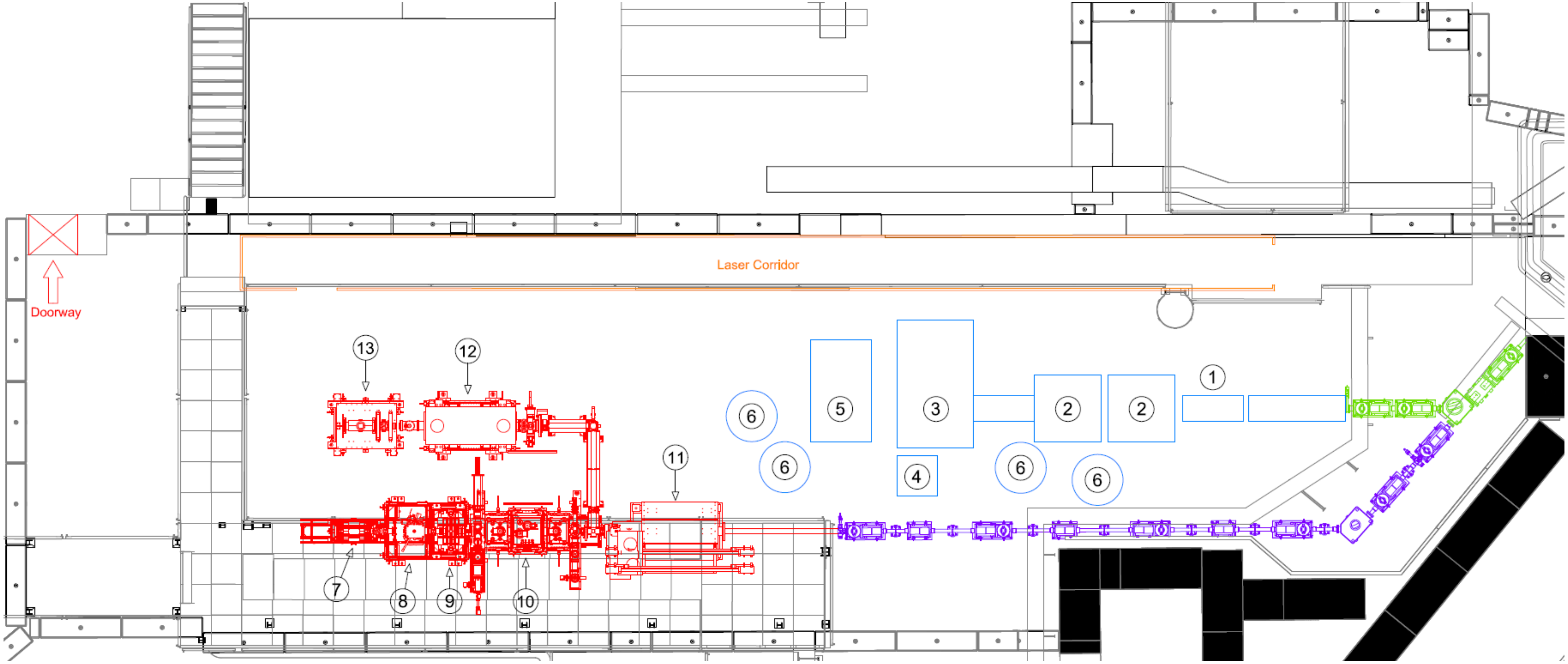
Cusp

- **Until LS3**
  - Continue with antihydrogen beam production
  - Rabi spectroscopy
  - Annihilation experiments with slow extracted $\bar{p}$
  - $\bar{p}$ interferometry
- **Plans During LS3**
  - Improved plasma cooling schemes in the Cusp trap
  - Studies with matter (matter mixing)
  - Develop Ramsey method with H
  - Prepare de-excitation of Rydberg $\bar{\mathrm{H}}$ (if needed)
- **Plan after LS3**
  - Continue with colder $\bar{\mathrm{H}}$ beam
  - Upgraded to Ramsey spectroscopy method
  - Experiments with slow extracted $\bar{p}$
    - Pontecorvo reaction

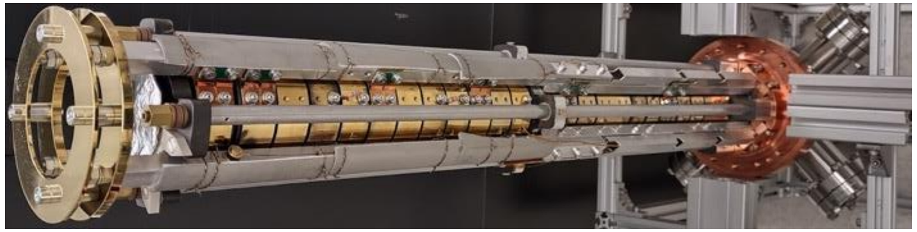
Backup

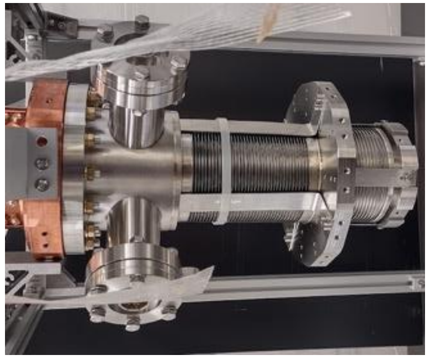
ASACUSA experimental area with ELENA

Permanent installation of experiments allows continuous offline test

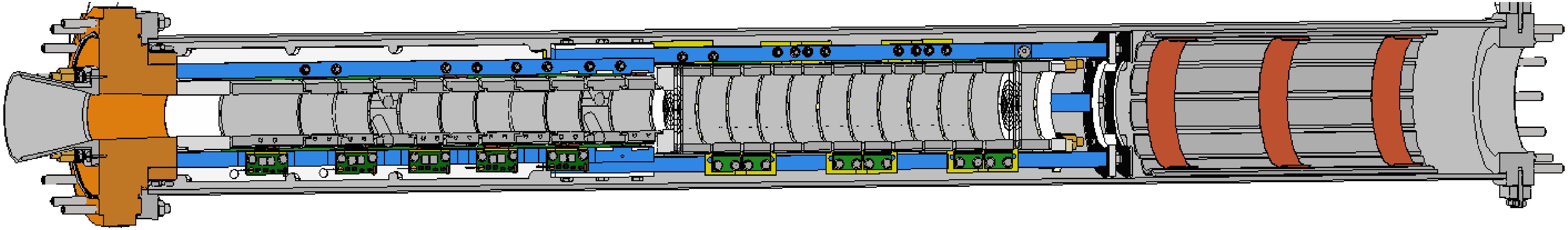


Double Cusp Trap

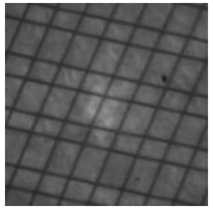




Ceramic "bracelet" to absorb cyclotron radiation from the plasma

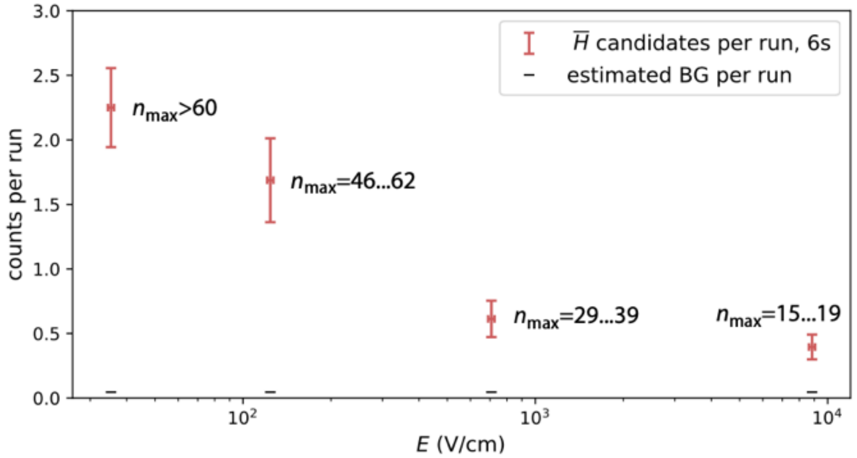


High transparency copper mesh to reflect incoming microwaves
0.25 mm pitch
0.03 mm wire diameter
>20 dB attenuation at 60 GHz



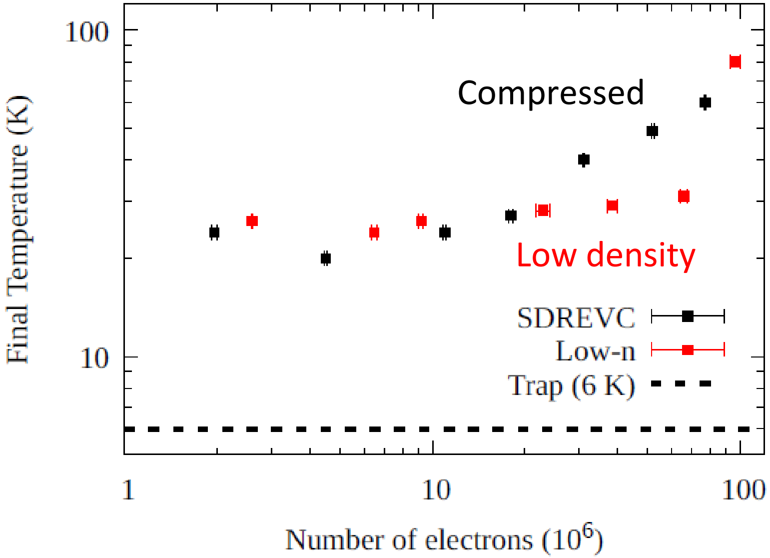
Recent milestones

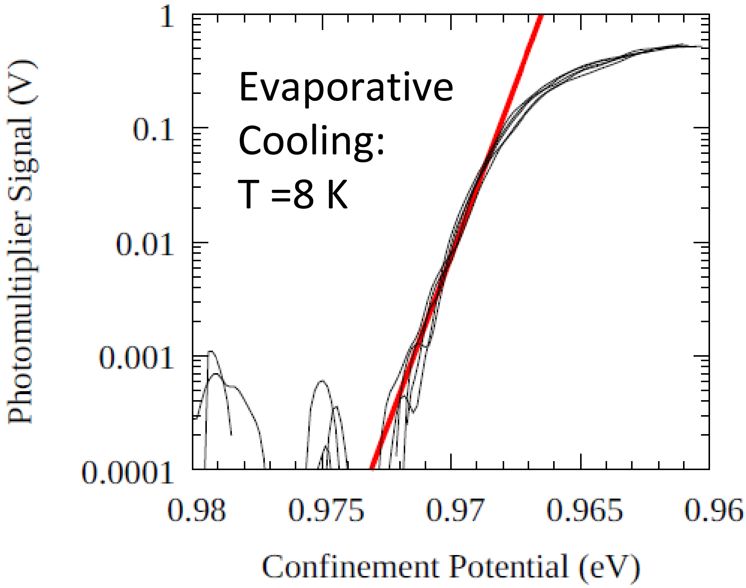
- Quantum number distribution of $\overline{\mathrm{H}}$ beam in field-free region



B. Kolbinger et al. "*Measurement of the principal quantum number distribution in a beam of antihydrogen atoms*" Eur. Phys. J. D **75**, 91 (2021)

- 100 K colder electron plasmas compared to before
  - Meshes to block RF interference, better cooling

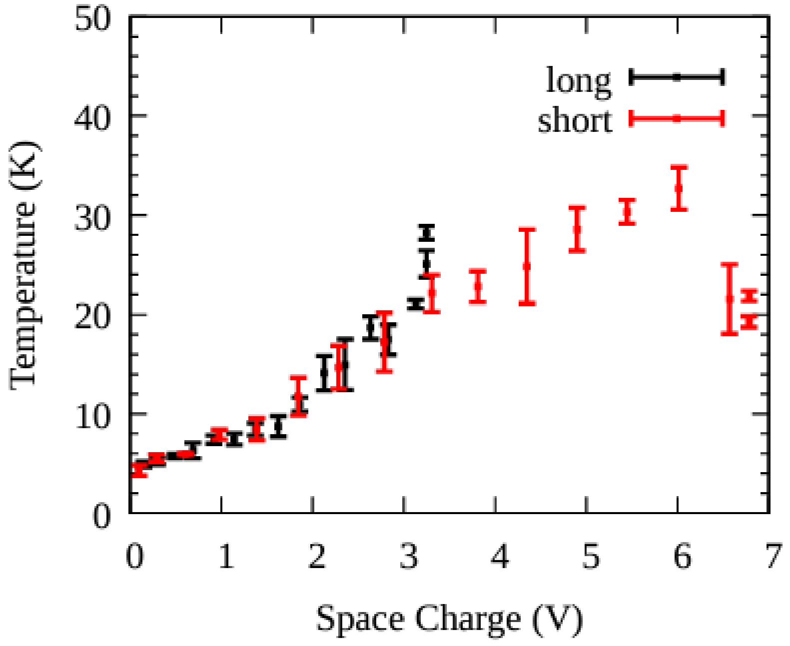


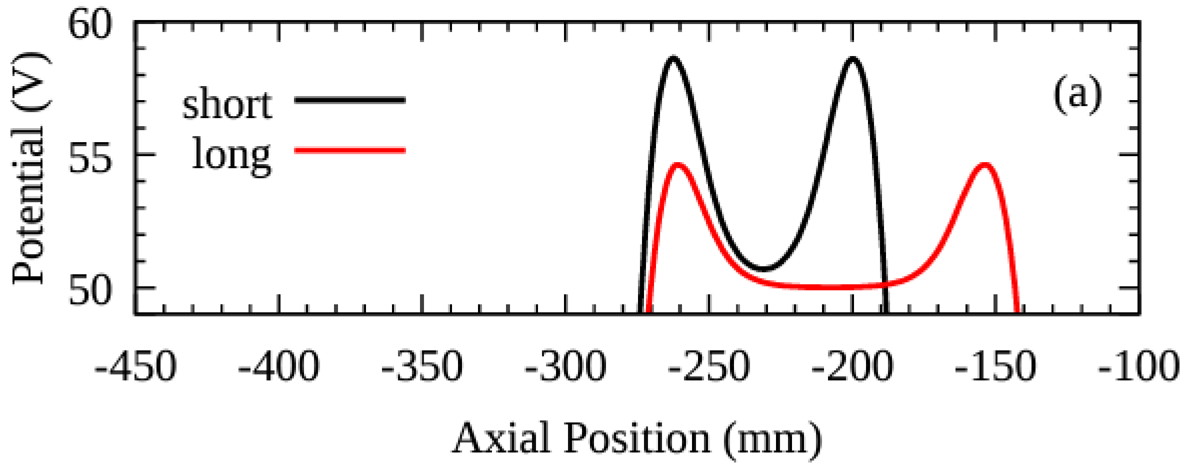


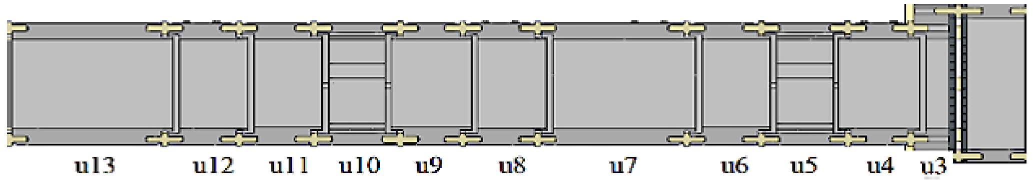
E. Hunter et al. EPJ Web Conf. 262 01007 (2022)
C. Amsler et al. arXiv:2203.14890 [physics.plasm-ph]

1st $\overline{\mathrm{H}}$ interaction with microwaves expected 2022/23

Study of EVC in the Cusp trap with e^- 2023

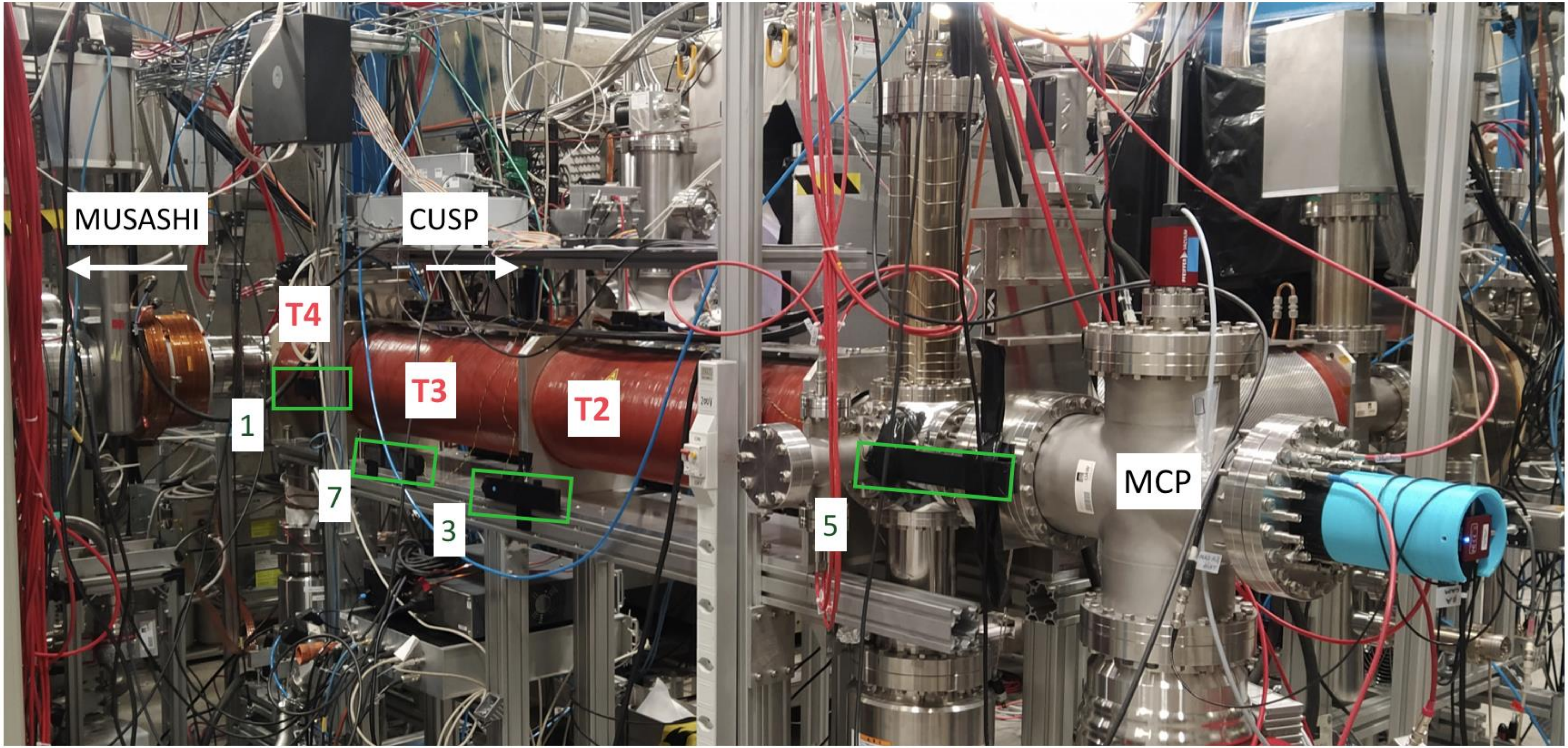




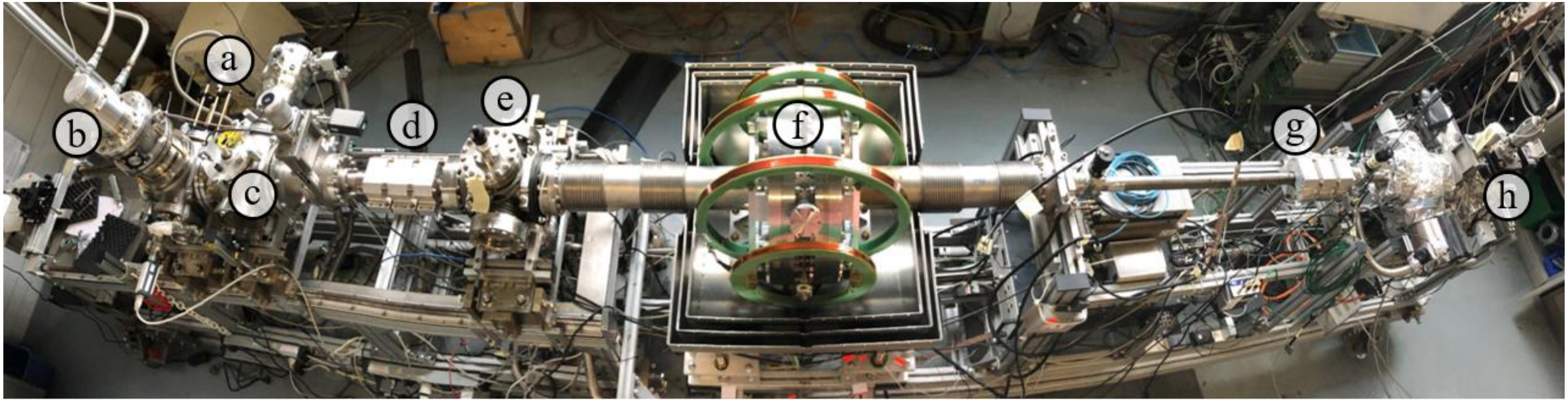


- Above ~2-3V space charge EVC is ineffective

Slow Extraction Beamline

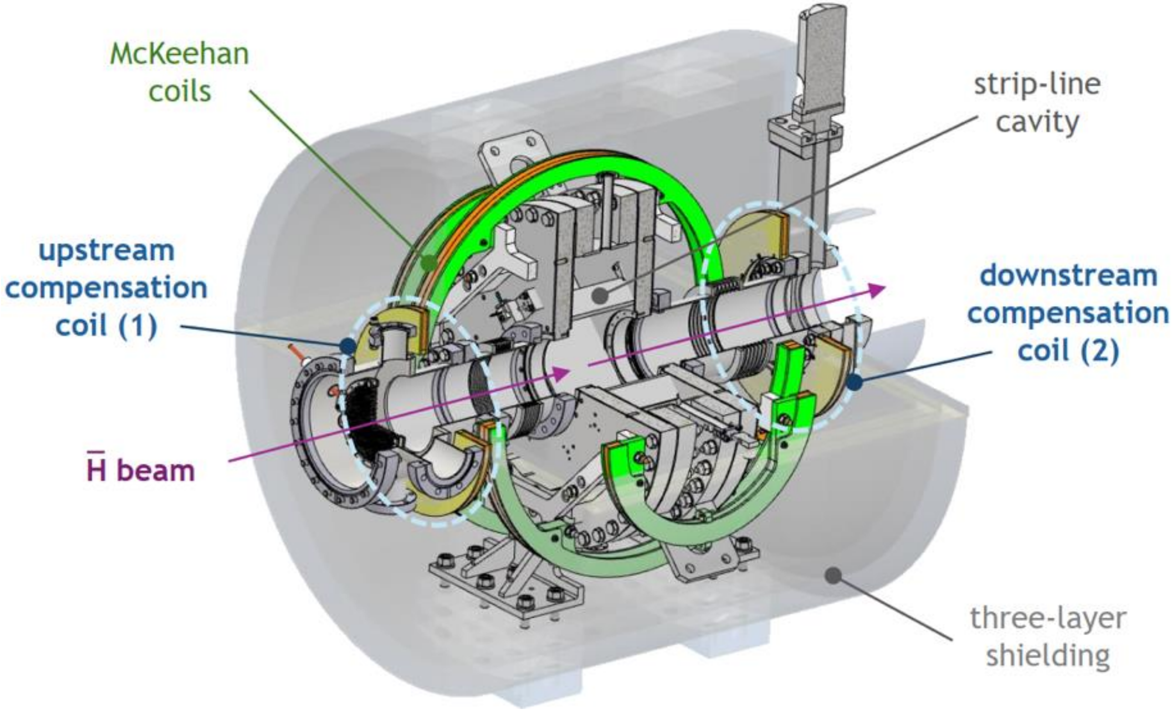


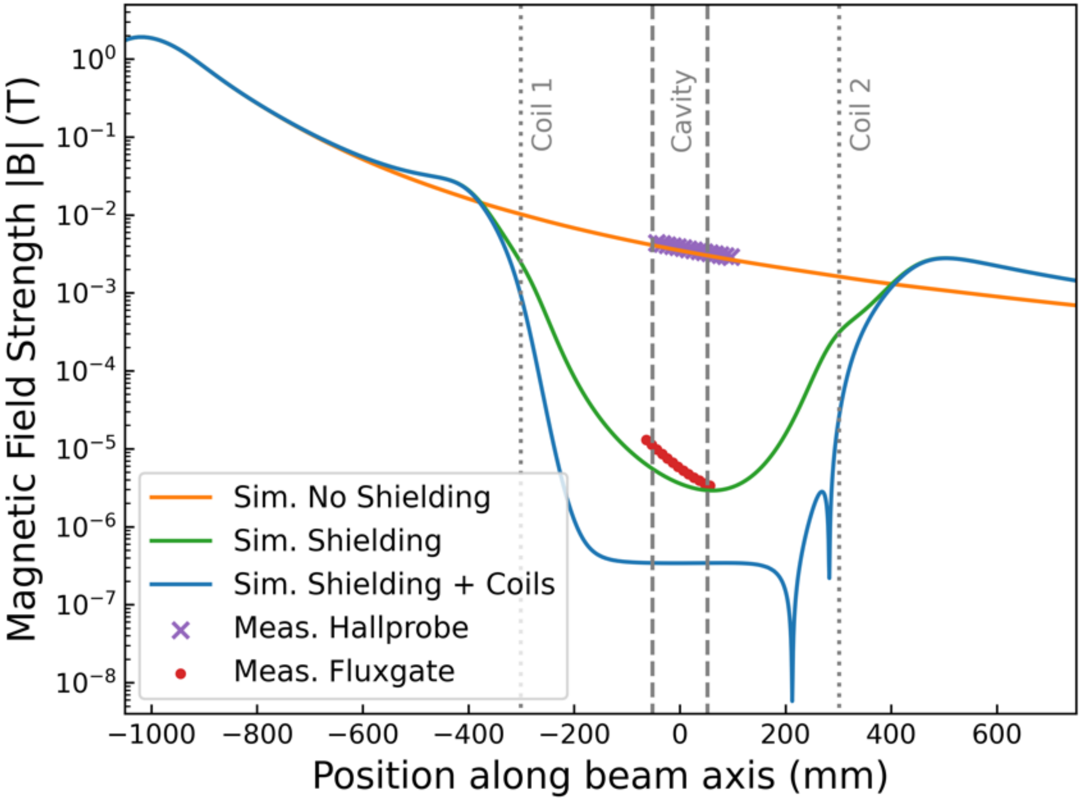
Hydrogen Beam @ CERN 2022



(a) H_2-supply and dissociation plasma tube
(b) Cold head for cooling of H
(c) chopper wheel to modulate the beam for ToF measurements and background suppression
(d) sextupole magnets for beam polarisation
(e) helical beam blocker for two-dimensional beam profile measurements
(f) cavity-assembly consisting of a strip-line cavity, surrounded by McKeehan-like coils and three layers of magnetic shielding
(g) sextupole magnets for spin state analysis
(h) quadrupole mass spectrometer for H-ionisation and mass-selective counting of protons.

Measurement and correction of Cusp stray field





Possible topic: Pontecorvo reaction

- $\bar{p}^3He \rightarrow pn$
- High branching ratio 10^{-6}

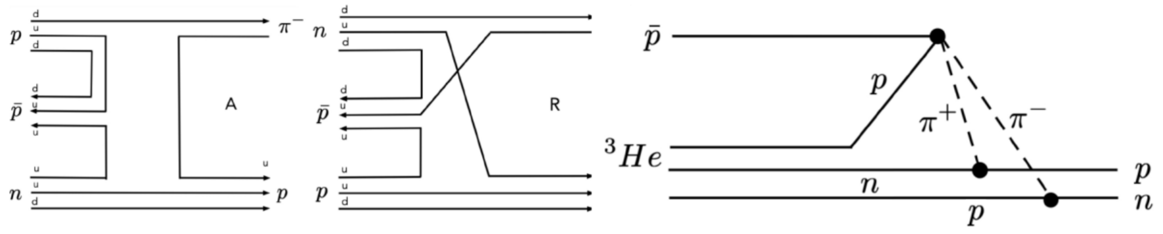
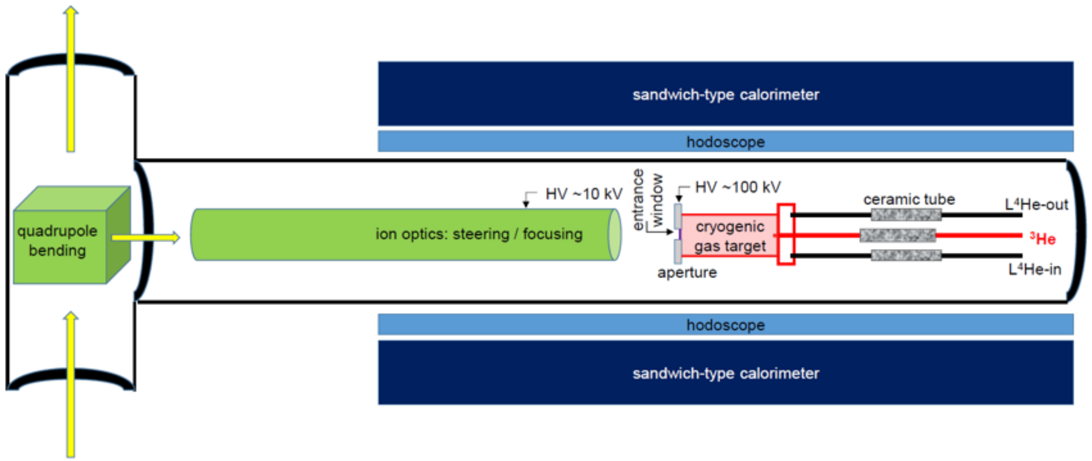


Figure 68 – Left: annihilation and rearrangement graphs in the fireball model. Right: rescattering diagram for $\bar{p}^3He \rightarrow np$.

C. Amsler, "Nucleon-antinucleon annihilation at LEAR," 2019. [Online]. Available: https://arxiv.org/abs/1908.08455



- Other topics
  - Continuation of fragmentation studies
  - Antiprotonic atom spectroscopy for QED tests

Antiprotons accelerated to 100 keV	$1.0 \cdot 10^3$ s^{-1}
Antiprotons stopped in the target cell: 90%	$0.9 \cdot 10^3$ s^{-1}
Neutron detection efficiency: solid angle 50%; intrinsic efficiency 60%	
Proton detection efficiency: solid angle 50%; intrinsic efficiency 100%	
Coincidence rate neutron-proton: 15%	$1.4 \cdot 10^2$ s^{-1}
Pontecorvo reaction branching ratio 10^{-6}	$1.4 \cdot 10^{-4}$ s^{-1}
Detected proton-neutron pairs per day	**$\sim$ 10**