Positron manipulation and control at the ASACUSA Cusp experiment

D. J. Murtagh
On behalf of the ASACUSA collaboration

ÖPG

5th September 2023

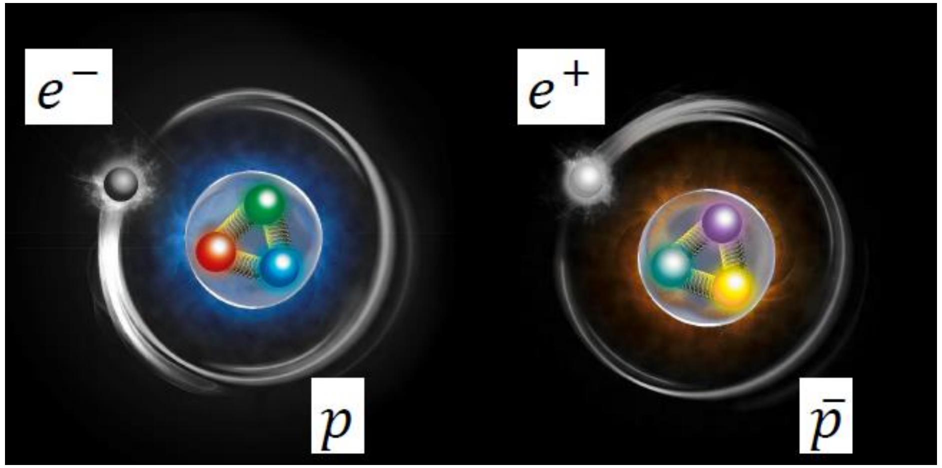
ASACUSA

Atomic
Spectroscopy
And
Collisions
Using
Slow
Antiprotons

Asakusa in Tokyo

What do we study

- The ASACUSA Cusp experiment focuses on producing a beam of antihydrogen for the measurement of the transition frequency ground state hyperfine splitting in a **field free region**.



Why antimatter ?

- The standard model of particle physics predicts matter-antimatter symmetry
  - Matter and antimatter created in equal quantities
  - **C**harge conjugation – **P**arity – **T**ime reversal (**CPT**) unviolated
- Observed matter-antimatter asymmetry in nature

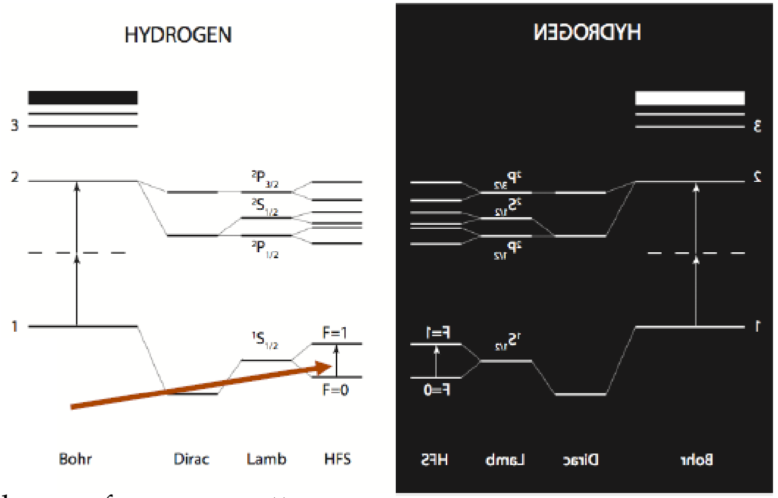
$$\eta = \frac{n_b - n_{\bar{b}}}{n_\gamma} \sim 6.1 \times 10^{-10}$$

  - Where n_b and $n_{\bar{b}}$ are number densities of baryons and antibaryons and n_γ the number density of cosmic background radiation photons
- This violation points to physics beyond the standard model

Komatsu, E., J. Dunkley, M. R. Nolta, C. L. Bennett, B. Gold, G. Hinshaw, N. Jarosik, et al. 'FIVE-YEAR WILKINSON MICROWAVE ANISOTROPY PROBE OBSERVATIONS: COSMOLOGICAL INTERPRETATION'. *The Astrophysical Journal Supplement Series* 180, no. 2 (February 2009): 330–76. https://doi.org/10.1088/0067-0049/180/2/330.

Why the HFS of antihydrogen

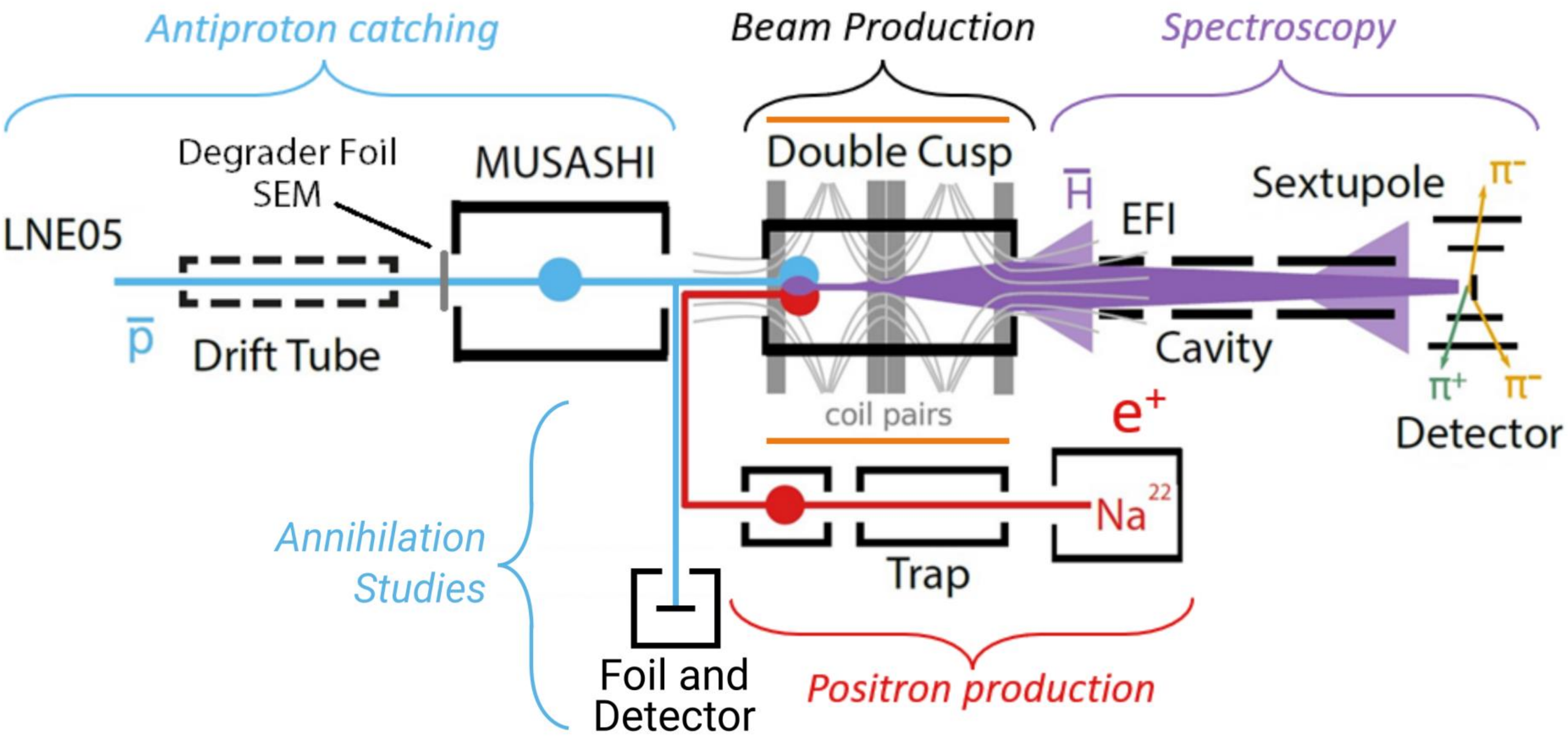
- Antihydrogen is the simplest stable* purely antimatter system
  - Amenable to high precision spectroscopic investigation
- Hydrogen is the most well studied systems in the physical sciences
  - ν_{HFS} = 1,420,405.7513768(1) kHz

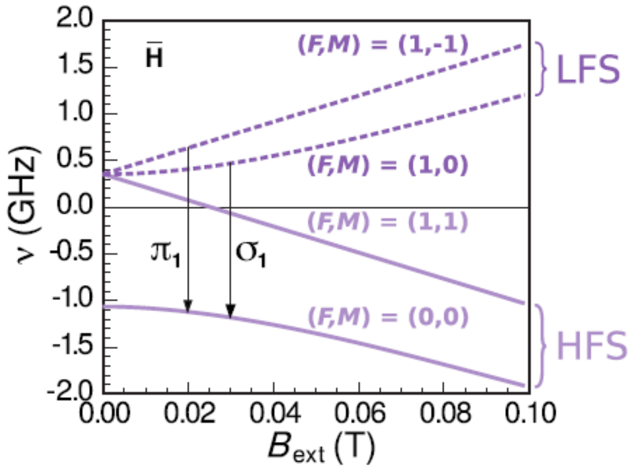


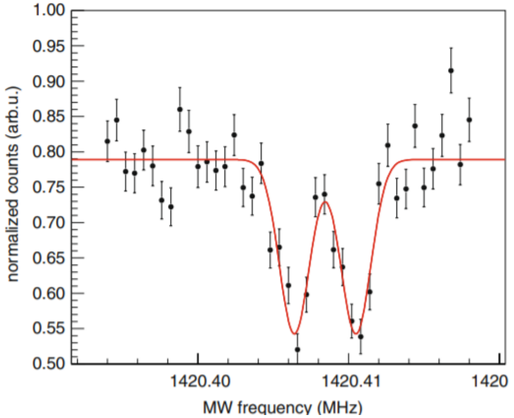
* If kept far enough away from any matter

Karshenboim, Savely G. 'Precision Physics of Simple Atoms: QED Tests, Nuclear Structure and Fundamental Constants'. Physics Reports 422, no. 1 (1 December 2005): 1–63. https://doi.org/10.1016/j.physrep.2005.08.008.

$$\bar{p} + e^{+} + e^{+} \rightarrow \bar{H} + e^{+}$$

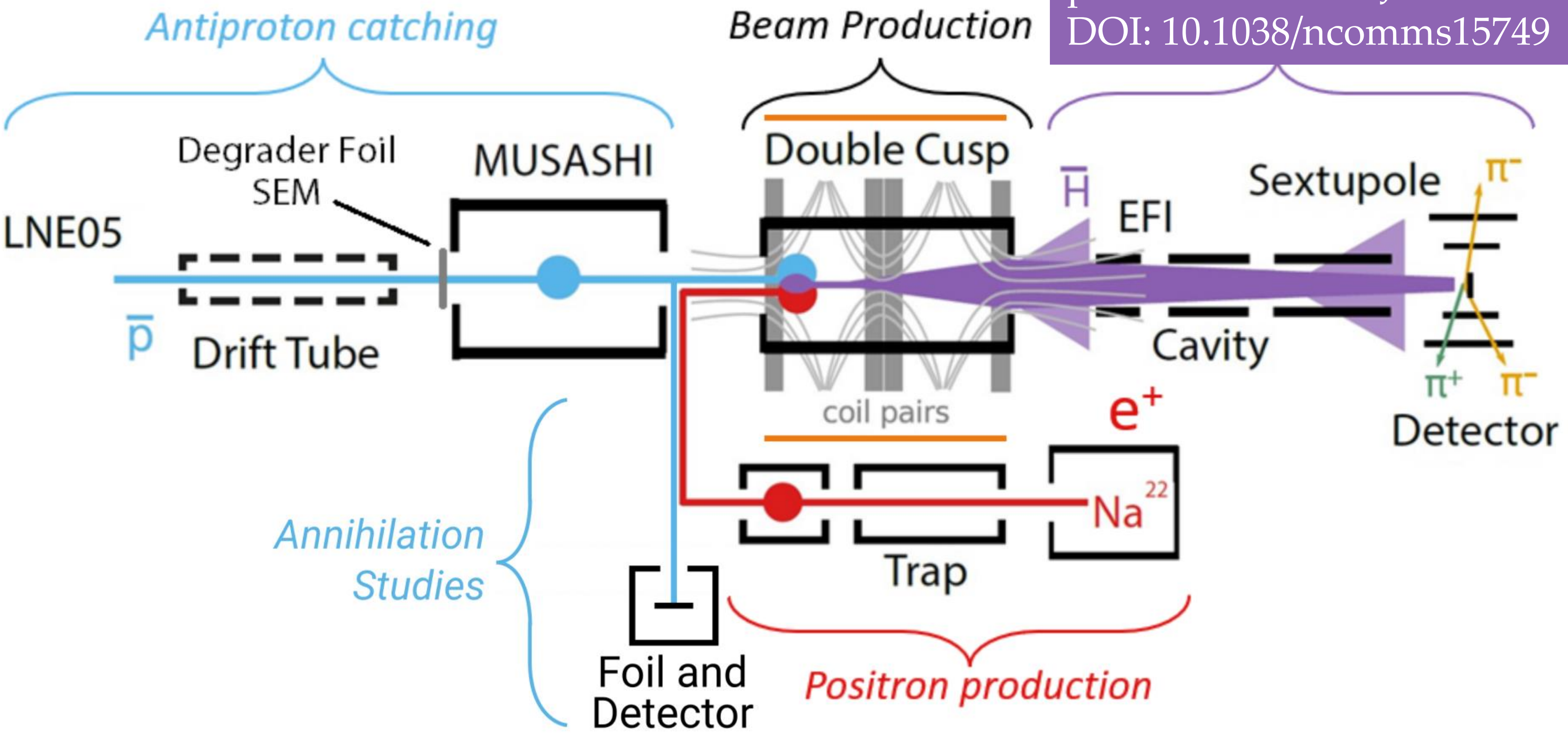


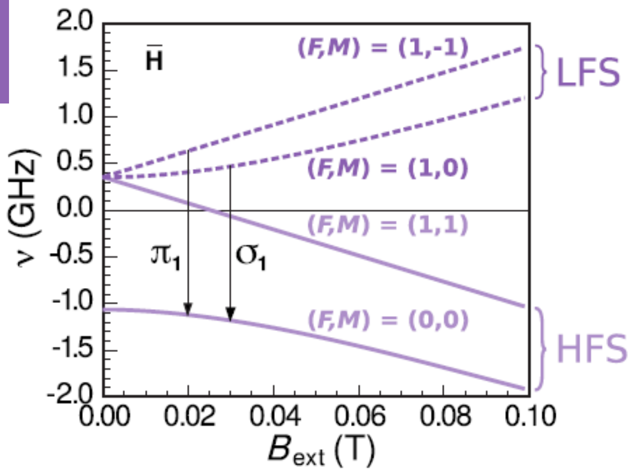


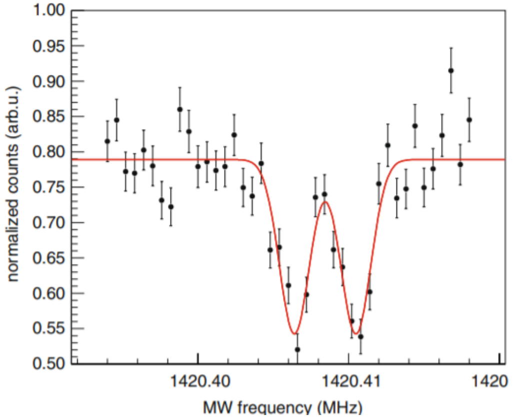


$$\bar{p} + e^{+} + e^{+} \rightarrow \bar{H} + e^{+}$$

Nature Communications, published on 12th June ’17
DOI: 10.1038/ncomms15749

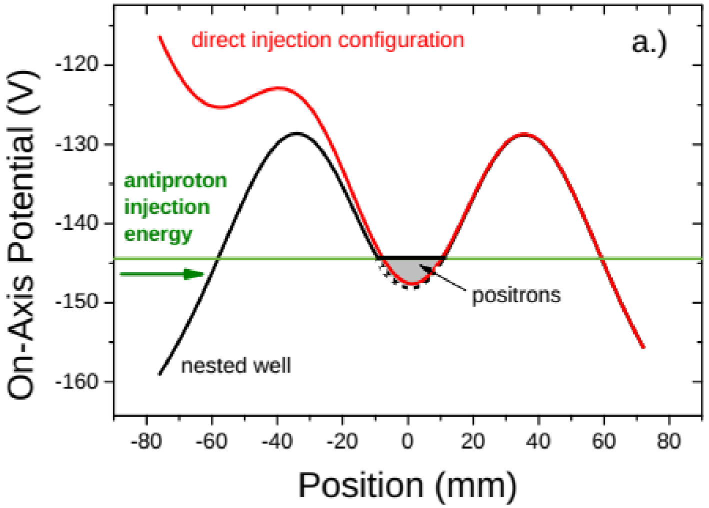


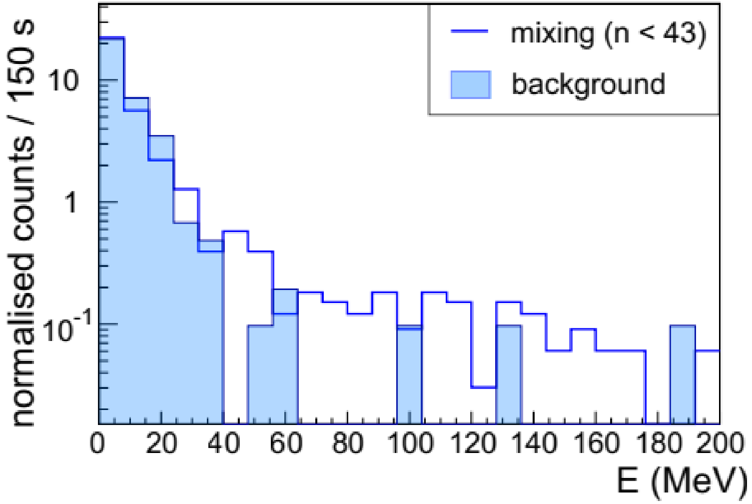


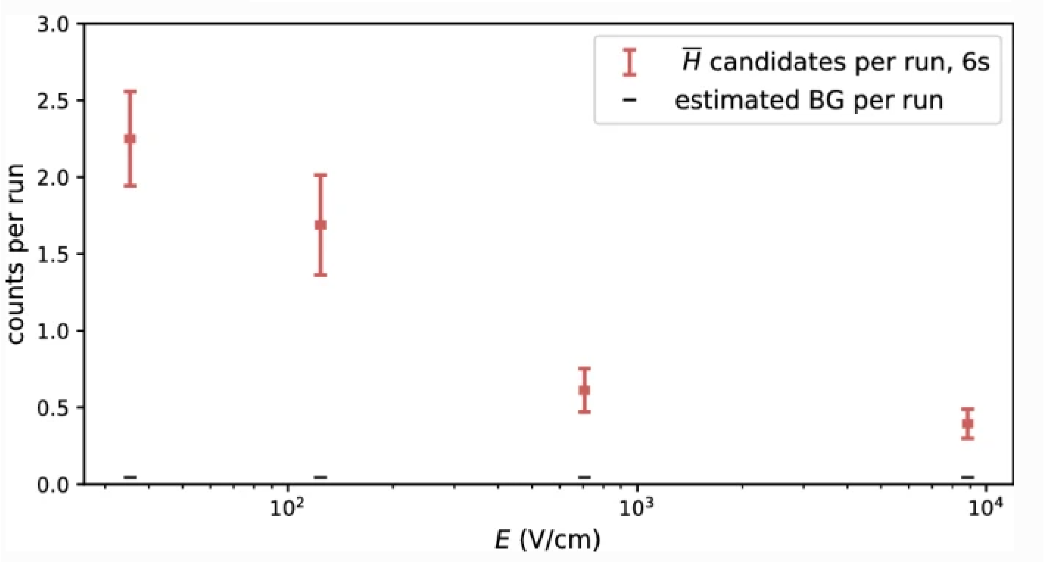


Status

- Beam observed
  - 0.006 s^{-1} (n<60)
- Internal quantum number distribution measured
  - 0.001 s^{-1} (n=1) (4 h^{-1}) if v=1000ms^{-1}
- **How do we improve the beam intensity and the number of ground state atoms?**







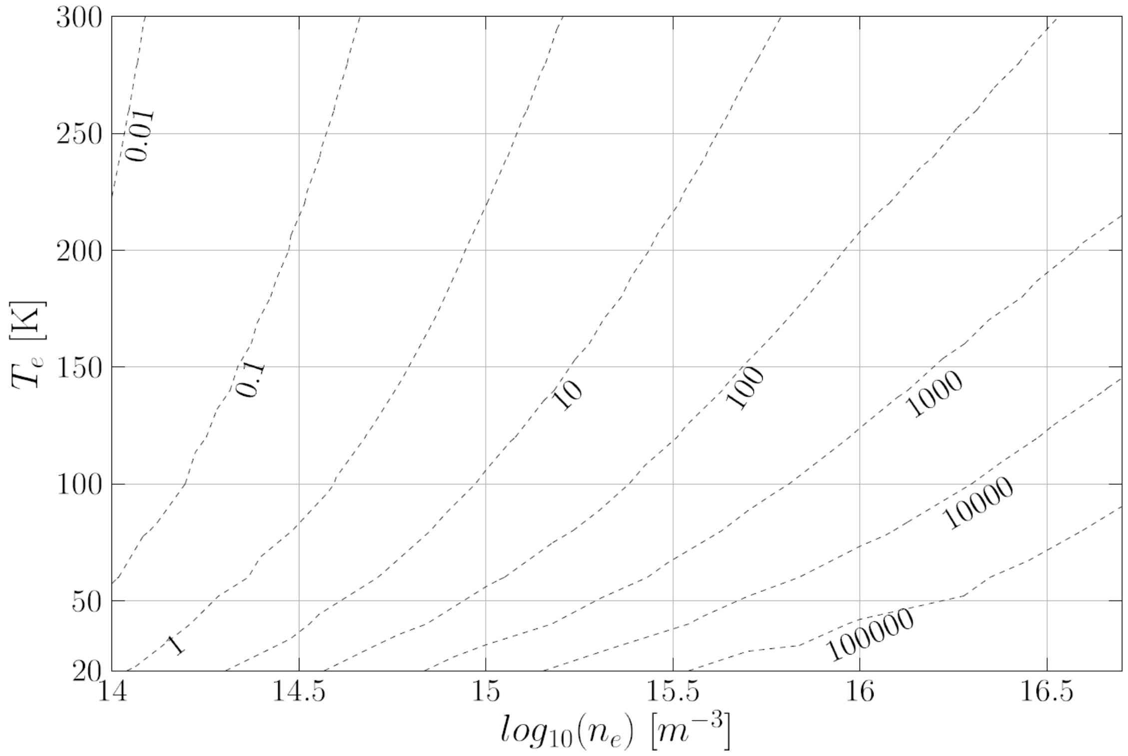
Kuroda, N., S. Ulmer, D. J. Murtagh, S. Van Gorp, Y. Nagata, M. Diermaier, S. Federmann, et al. "A Source of Antihydrogen for In-Flight Hyperfine Spectroscopy." *Nature Communications* 5 (January 21, **2014**).

B. Kolbinger et al. (ASACUSA Collaboration) Eur. Phys. J. D75 (2021) 91

Diermaier, M., C. B. Jepsen, B. Kolbinger, C. Malbrunot, O. Massiczek, C. Sauerzopf, M. C. Simon, J. Zmeskal, and E. Widmann. "In-Beam Measurement of the Hydrogen Hyperfine Splitting and Prospects for Antihydrogen Spectroscopy." *Nature Communications* 8 (June 12, 2017): 15749.

Plasma Temperature

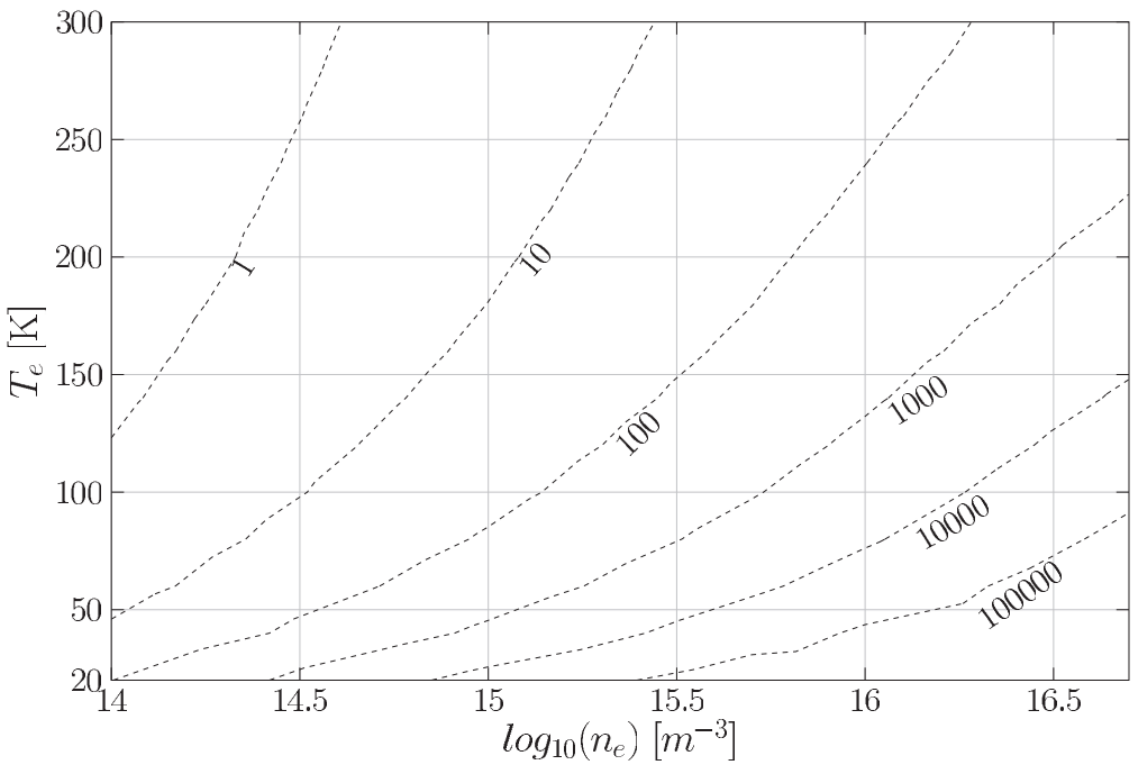
- If the temperature of the positron plasma can be reduced from 200K to 20K we gain **two orders of magnitude** in antihydrogen production



Radics, B., D. J. Murtagh, Y. Yamazaki, and F. Robicheaux. “Scaling Behavior of the Ground-State Antihydrogen Yield as a Function of Positron Density and Temperature from Classical-Trajectory Monte Carlo Simulations.” *Physical Review A* 90, no. 3 (September 3, 2014): 032704.

Plasma Temperature

- If the temperature of the positron plasma can be reduced from 200K to 20K we gain **two orders of magnitude** in antihydrogen production
- If the positron plasma is colder then the antiprotons will be colder producing slower antihydrogen
  - **Longer to cascade →Lower *n* states!**



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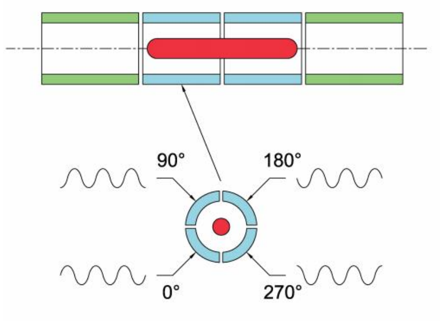
Control of electron/positron plasma properties

- Long Shutdown 2 (LS2) ran from December 2018 to August 2021 during this period no antiprotons were available
- A reproducible cold plasma was needed!

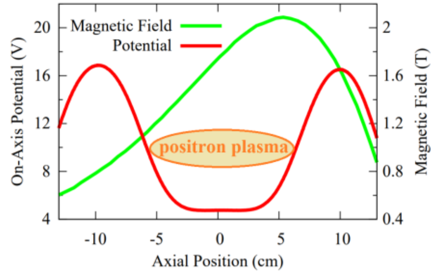
- What are we interested in ?
  - Temperature
  - Density
    - Number
    - Length
    - Radius

Rotating Wall



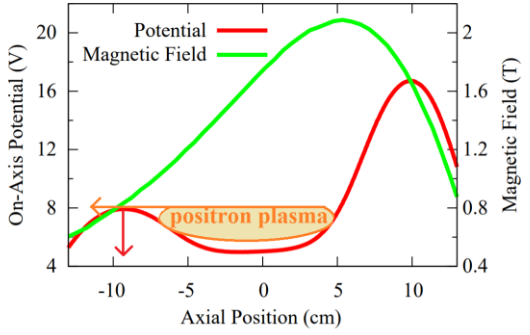
Radius

Electrical Potential



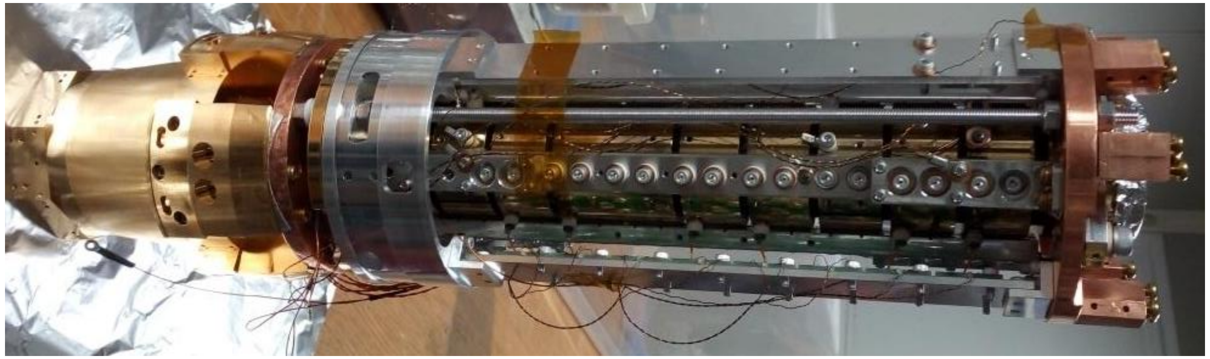
Length

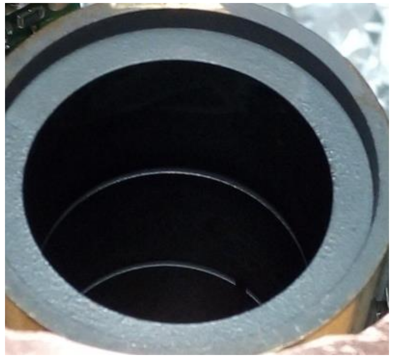
Evaporation

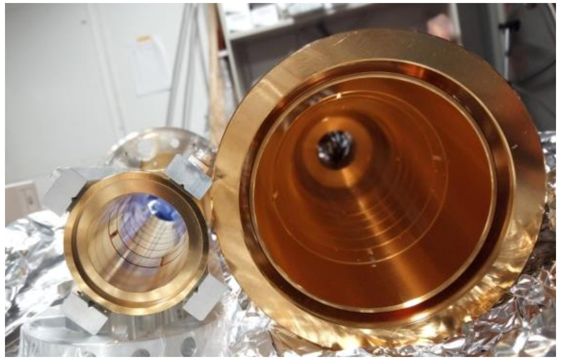


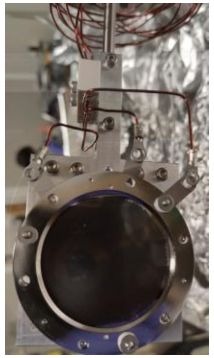
Number & Temperature

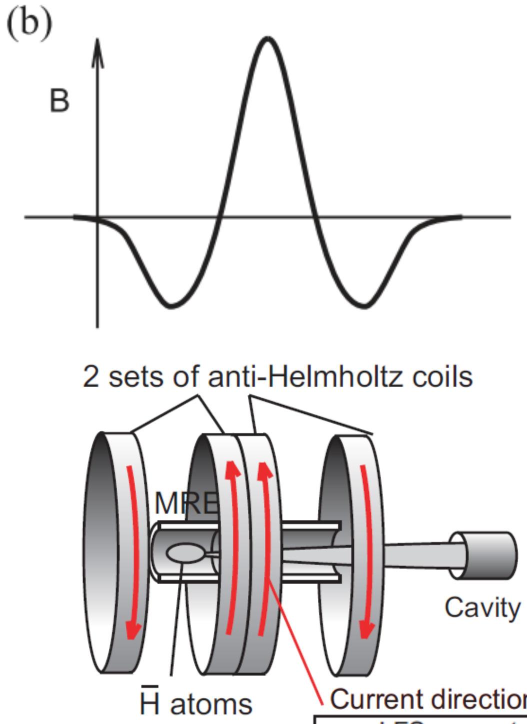
Double Cusp Trap

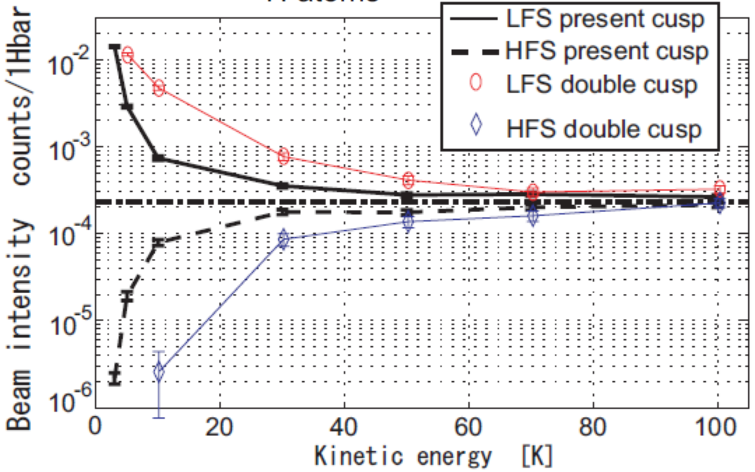








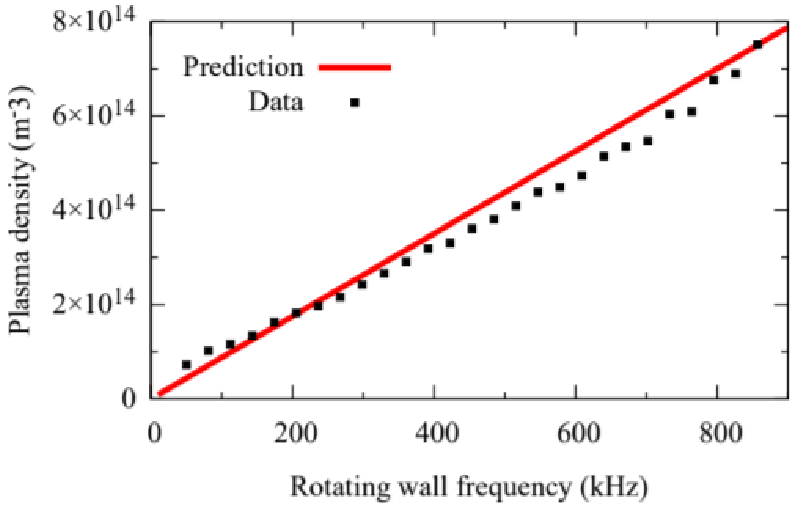




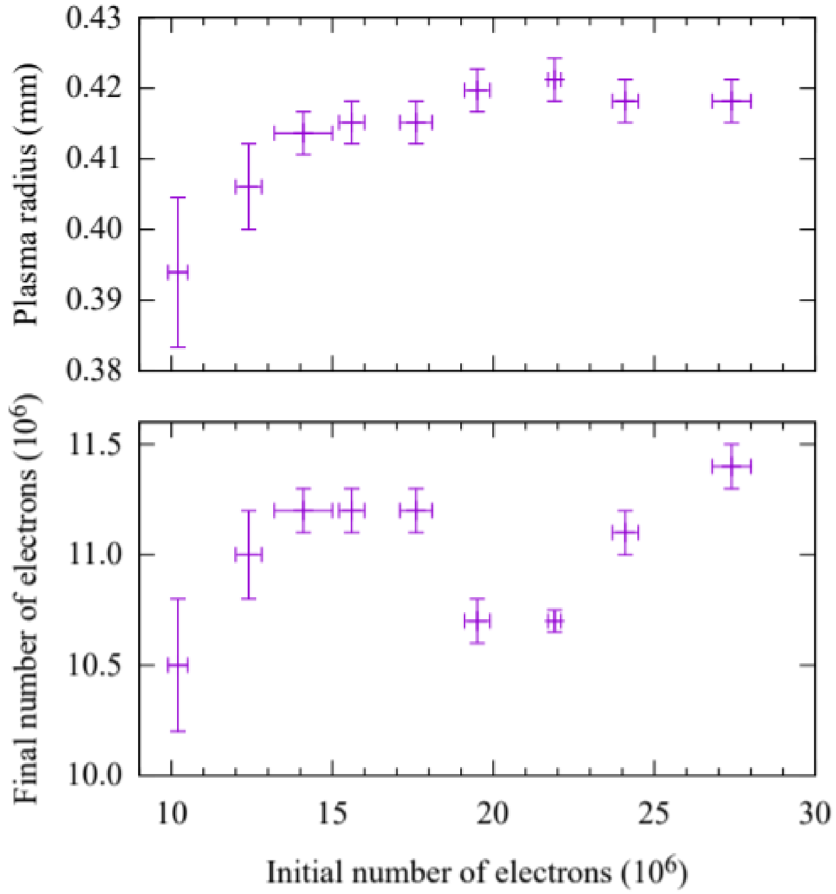
Radics, B., S. Ishikawa, N. Kuroda, D. J. Murtagh, Y. Nagata, M. Tajima, S. Van Gorp, et al. "Antihydrogen Synthesis in a Double-CUSP Trap towards Test of the CPT-Symmetry." *Hyperfine Interactions* 237, no. 1 (December 1, 2016): 156.

Control of electron/positron plasma properties

- To produce the same plasma *each and every* time : we fix a potential, apply strong drive rotating wall and evaporate → **SDR-EVC**

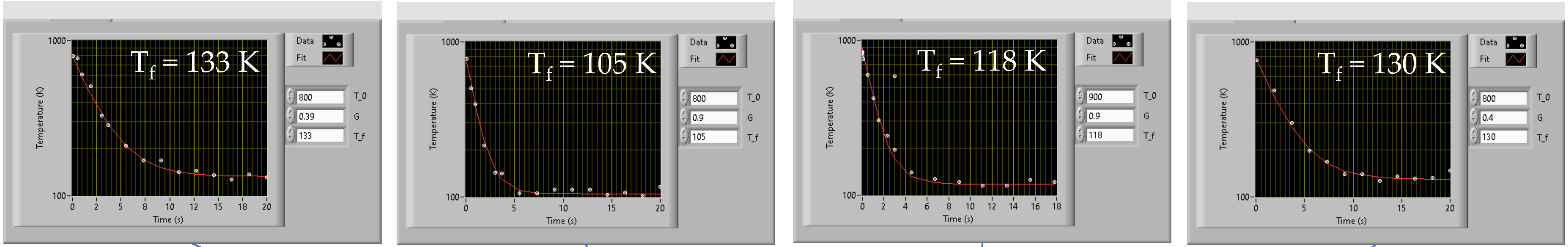


Property	Mean	SD
r_p (mm)	0.417	0.003
T (K)	360	30
N_f (10^6)	11.0	0.3



ALPHA Collaboration, M. Ahmadi, B. X. R. Alves, C. J. Baker, W. Bertsche, A. Capra, C. Carruth, et al. 'Enhanced Control and Reproducibility of Non-Neutral Plasmas'. *Physical Review Letters* 120, no. 2 (8 January 2018): 025001. https://doi.org/10.1103/PhysRevLett.120.025001.

Plasma Cooling Rate

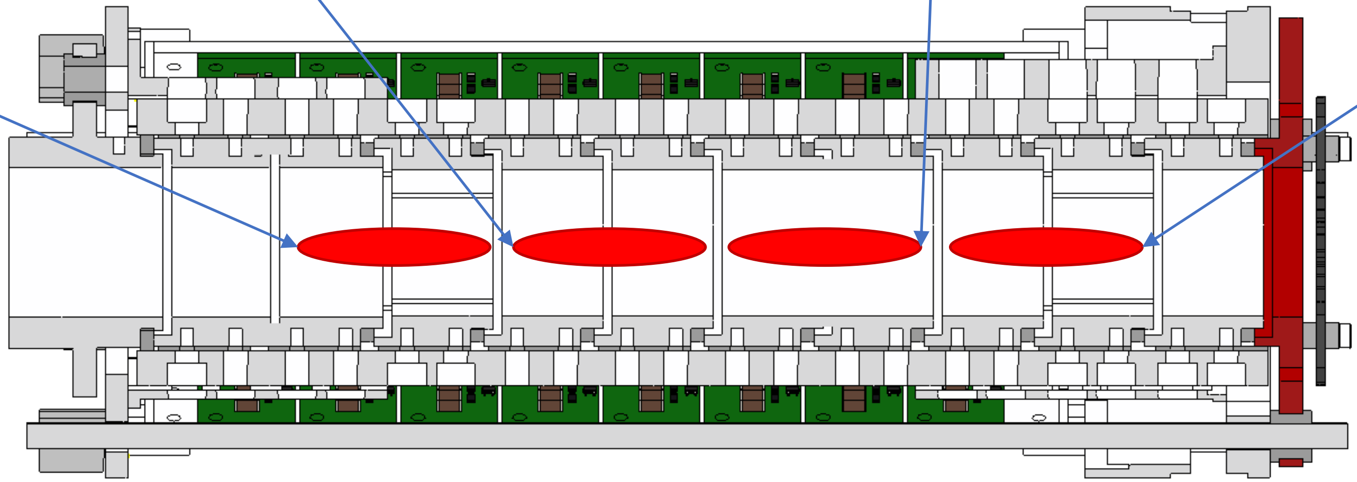


$T_w = 35K$

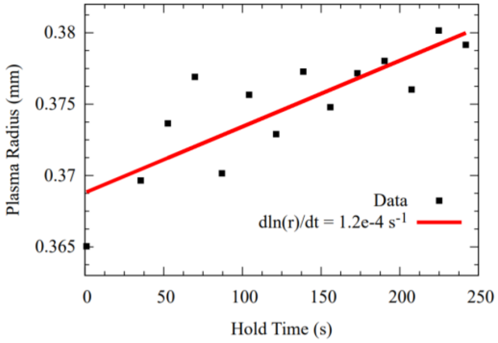
Heating Rate

$$T_f = T_w + H / G$$

Cyclotron Cooling Rate

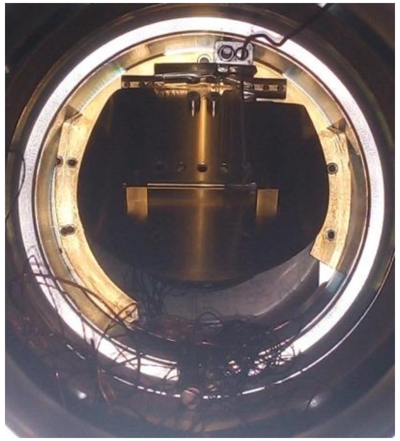


Name:	u13	u12	u11	u10	u9	u8	u7	u6	u5	u4	u3
Filter:	pulsed	slow	slow	none	slow	slow	slow	slow	none	slow	slow

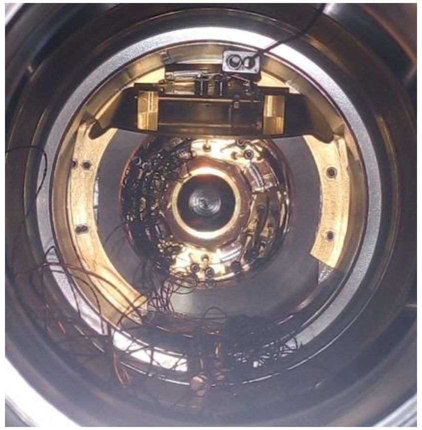


Plasma cooling : radiation environment

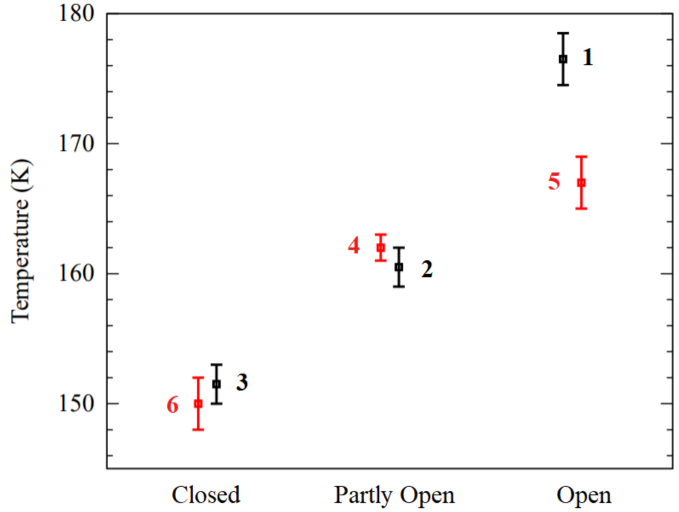
Closed

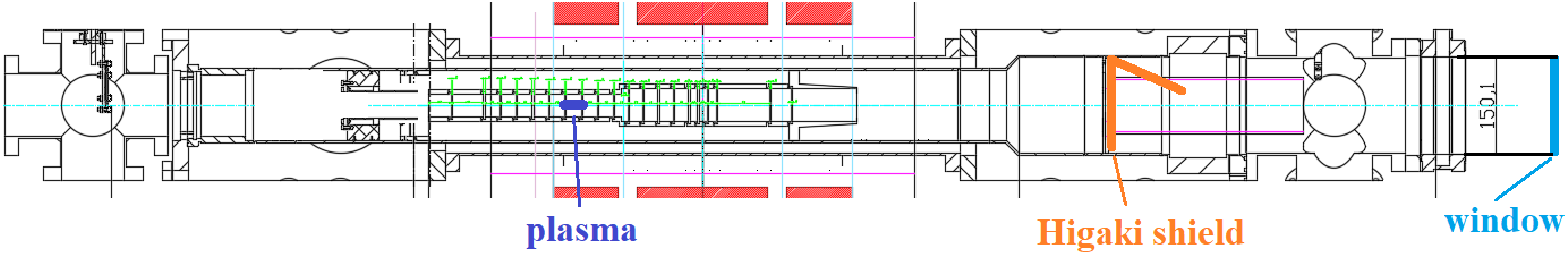


Partly Open

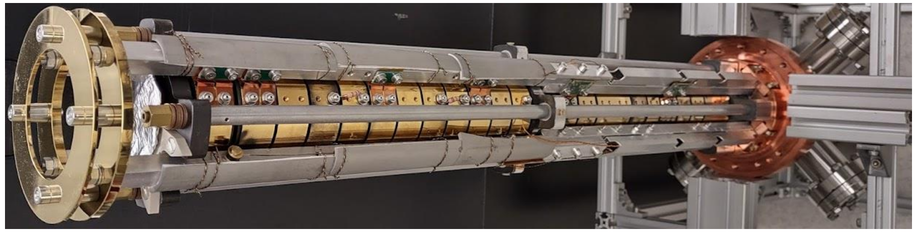


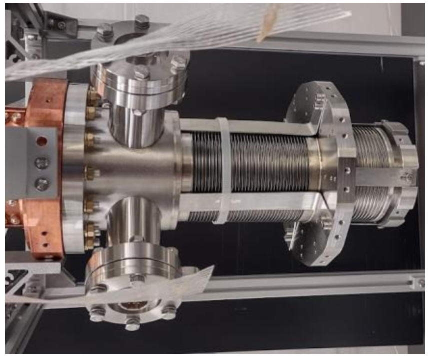
Open



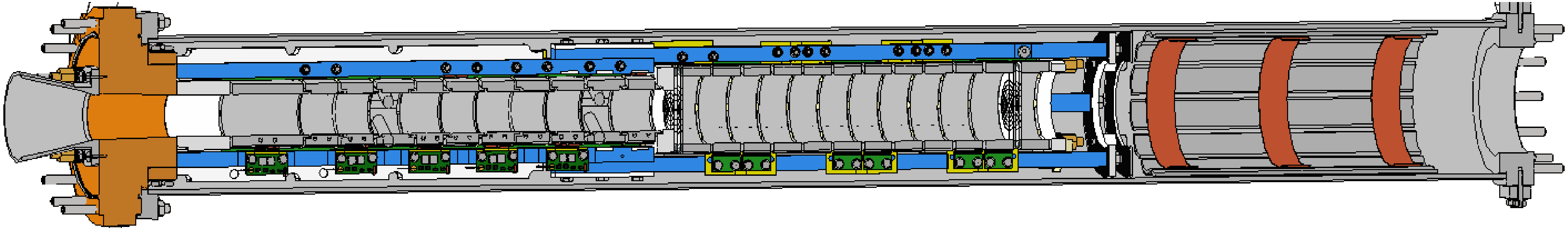


Double Cusp Trap

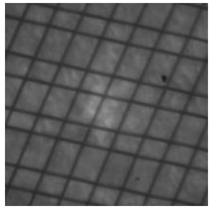




Ceramic “bracelet” to absorb cyclotron radiation from the plasma

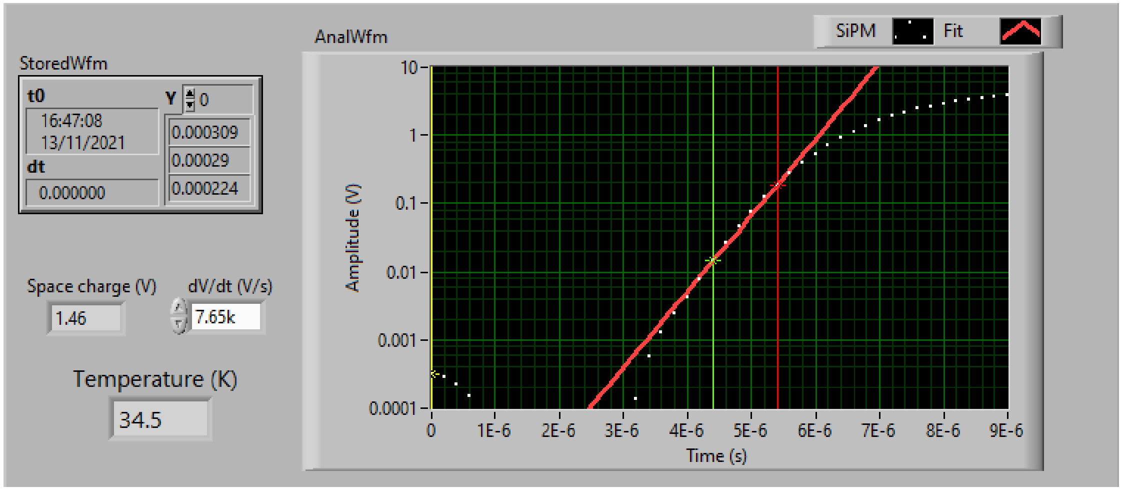


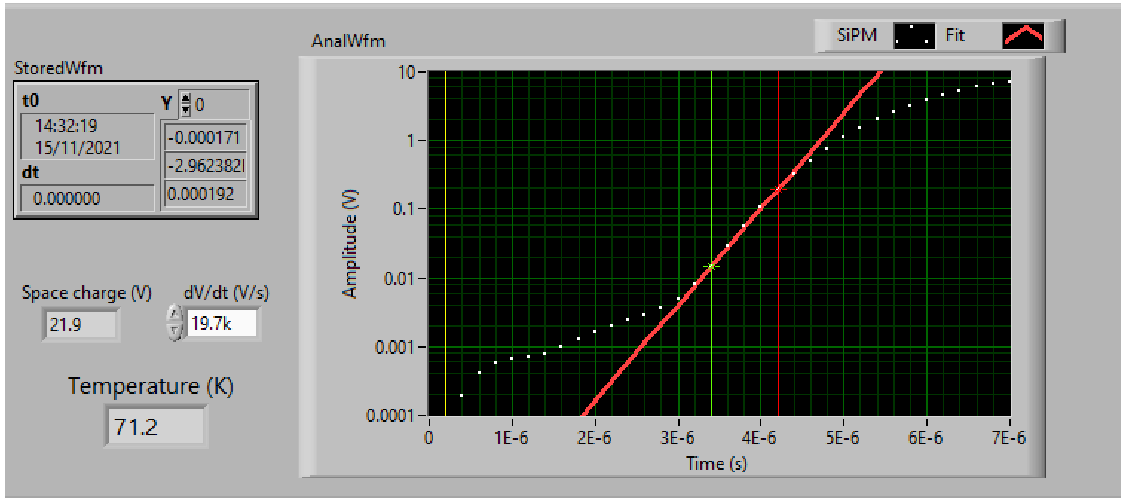
High transparency copper mesh to reflect incoming microwaves
0.25 mm pitch
0.03 mm wire diameter
>20 dB attenuation at 60 GHz



Double Cusp Trap

- First results
  - Electrode temperature 5-6 K
    - Approximately 10 K colder than the previous design
  - Plasma Temperatures
    - 3-4 million electron 35 K (previously 150 K)
    - 60 million electrons 70 K





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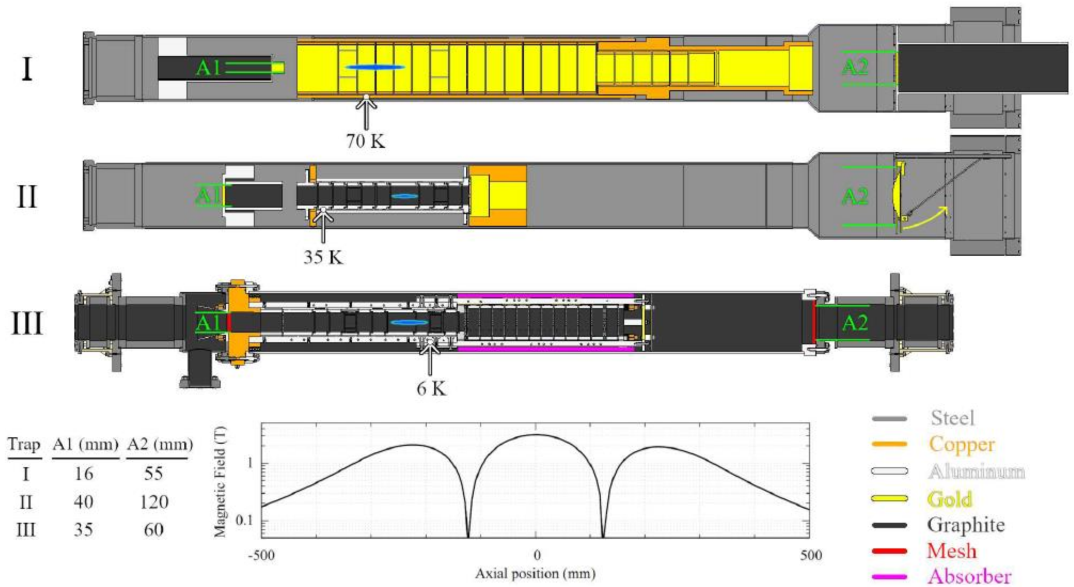
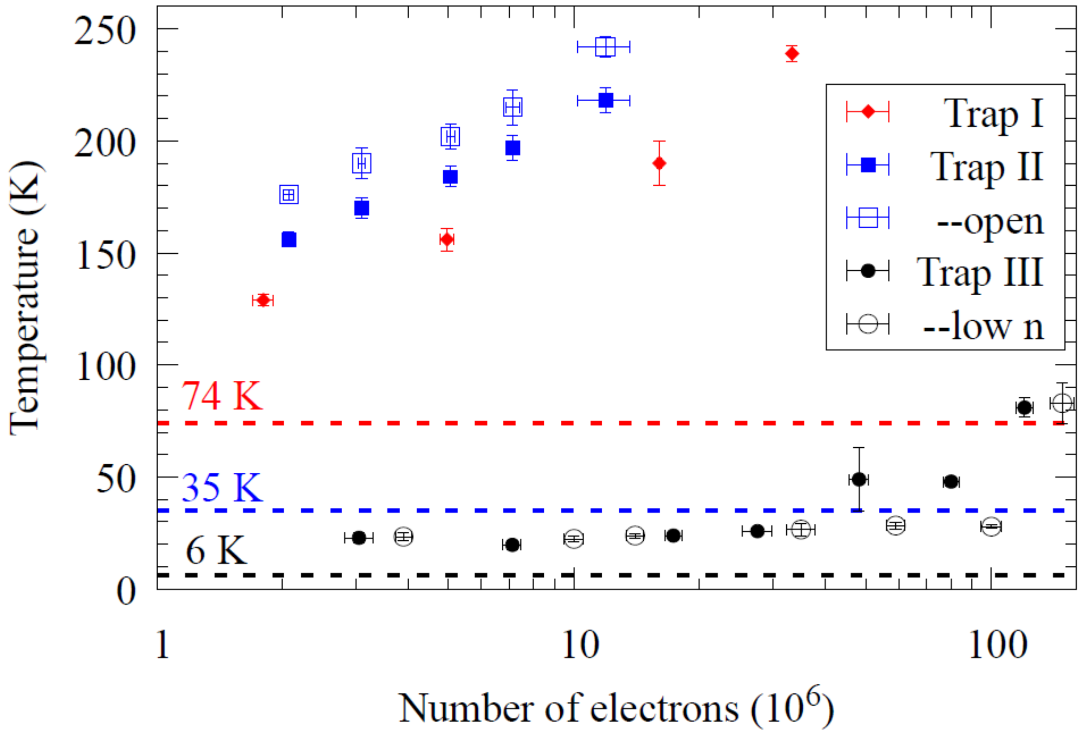




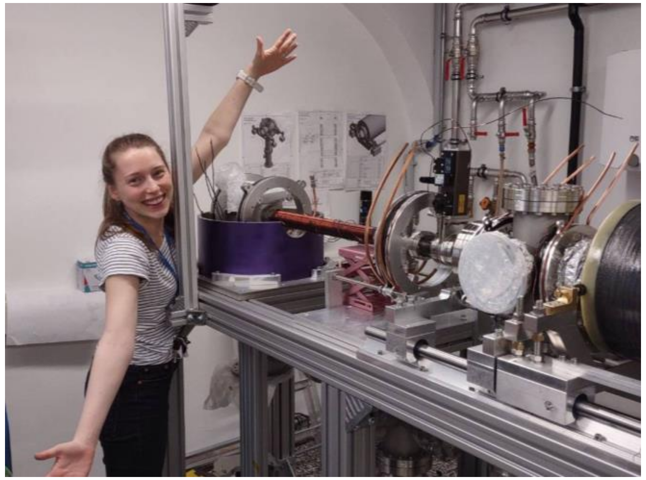
Reducing the background temperature for cyclotron cooling in a cryogenic Penning–Malmberg trap - Physics of Plasmas **29**, 083303 (2022);

Outlook

- The ASACUSA Cusp collaboration successfully detected a very weak and highly excited beam of antihydrogen 2.7 meters from their mixing region
- To increase the brightness and produce a ground state beam, colder mixing plasmas were required
- Thus far we have succeeded in producing cold electron plasmas in the new mixing trap
- This year we are working to repeat this with positrons
- There have been many more developments which I haven't had time to talk about
- We hope the future is cold (plasmas) and bright (beams)

Acknowledgements

- The SMI positron group
  - Dr Eric Hunter
  - Andreas Lanz
  - Alina Weiser



Austrian Science Fund (FWF) - P 32468
FWF Der Wissenschaftsfonds.

Full Collaboration

C. Amsler,[1] H. Breuker,[2] S. Chesnevskaya,[1] G. Costantini,[3,4] R. Ferragut,[5,6] M. Giammarchi,[6] A. Gligorova,[1] G. Gosta,[3,4] H. Higaki,[7] E. D. Hunter,[1] C. Killian,[1] V. Kletzl,[1] V. Kraxberger,[1] N. Kuroda,[8] A. Lanz,[1,9] M. Leali,[3,4] V. Mäckel,[1] G. Maero,[6,10] C. Malbrunot,[11,a)] V. Mascagna,[3,4] Y. Matsuda,[8] S. Migliorati,[3,4] D. J. Murtagh,[1] Y. Nagata,[12] A. Nanda,[1,9] L. Nowak,[11,9] E. Pasino,[6,10] M. Romé,[6,10] M. C. Simon,[1] M. Tajima,[13] V. Toso,[5,6] S. Ulmer,[2] L. Venturelli,[3,4] A. Weiser,[1,9] E. Widmann,[1] T. Wolz,[11] Y. Yamazaki,[2] and J. Zmeskal[1]

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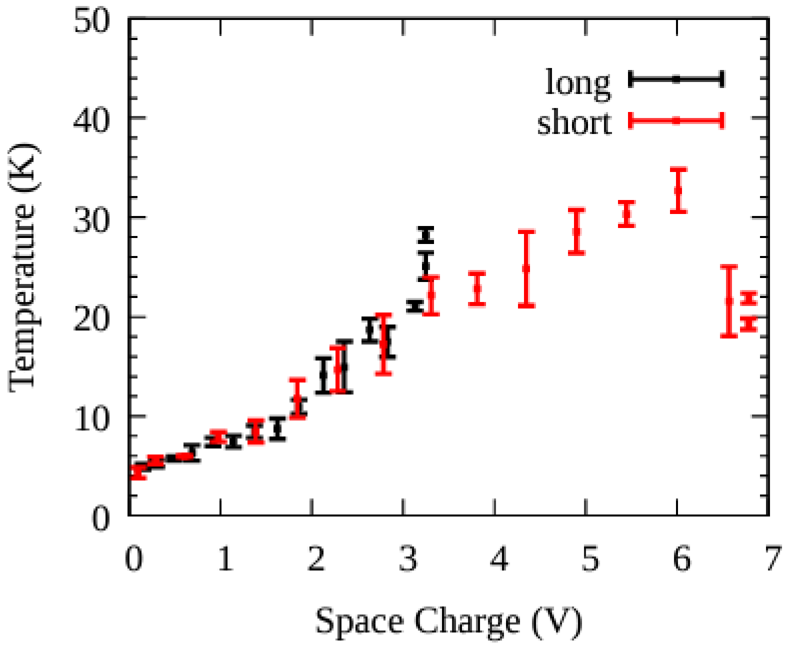
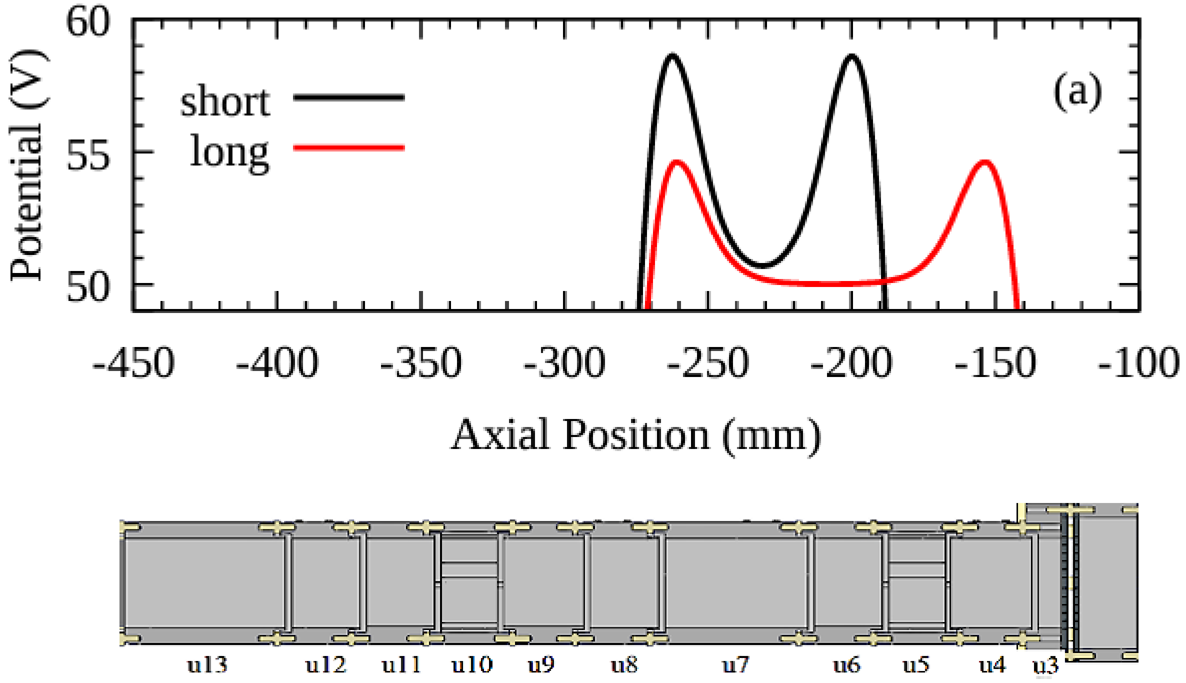
Fin…

Is that enough ?

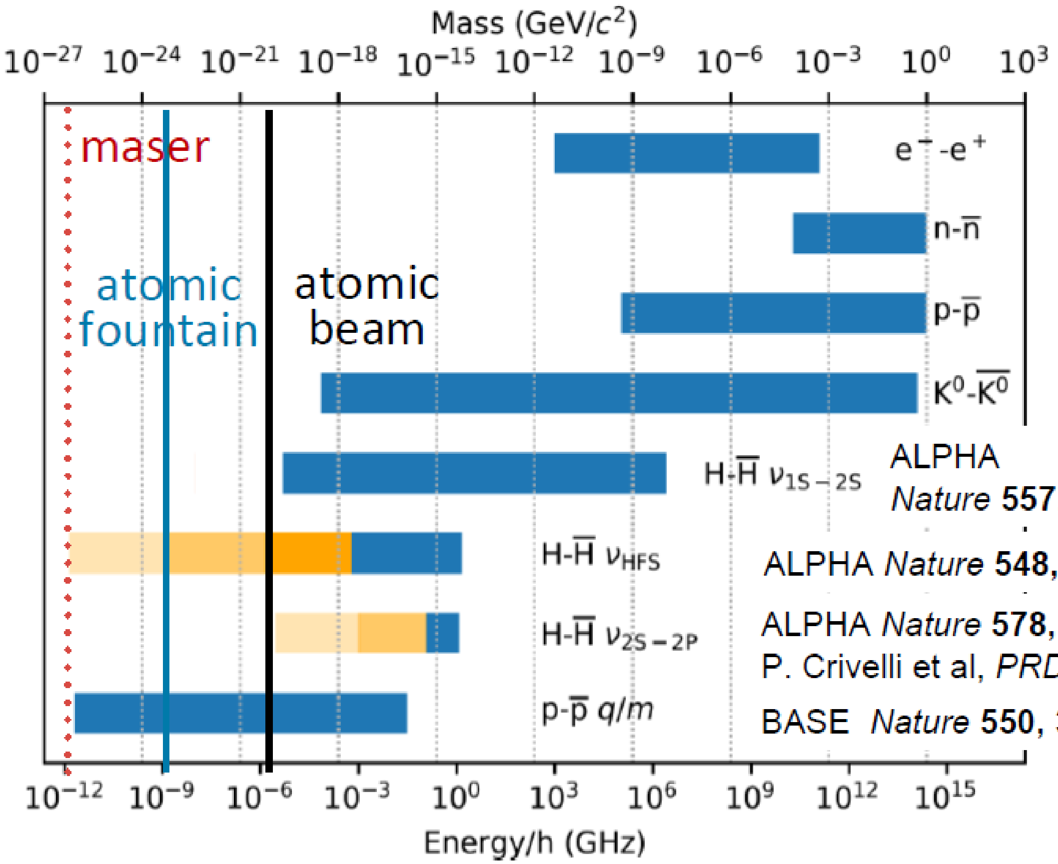
- It should be more than enough…





Why the HFS of antihydrogen

- Key :
  - Right edge: value
  - Bar length: relative precision
  - Left edge: absolute sensitivity
    - Blue: measured
    - Orange: planned
    - Yellow: potentially measurable



ALPHA *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* **550**, 371–374 (2017).

See https://arxiv.org/2111.0456v2 for details

P.A. Zyla et al. (Particle Data Group), Prog. Theor. Exp. Phys. 2020, 083C01 (2020)

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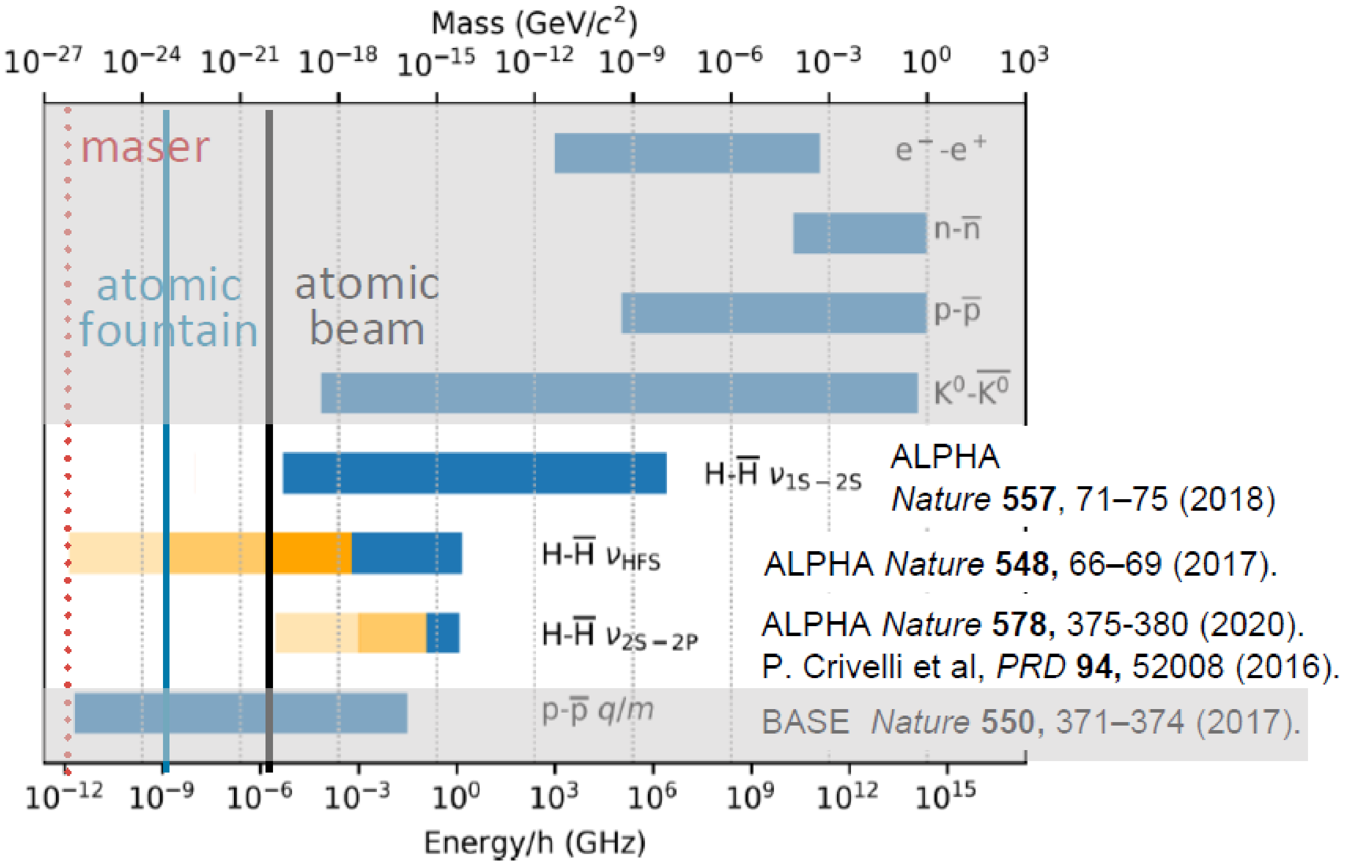
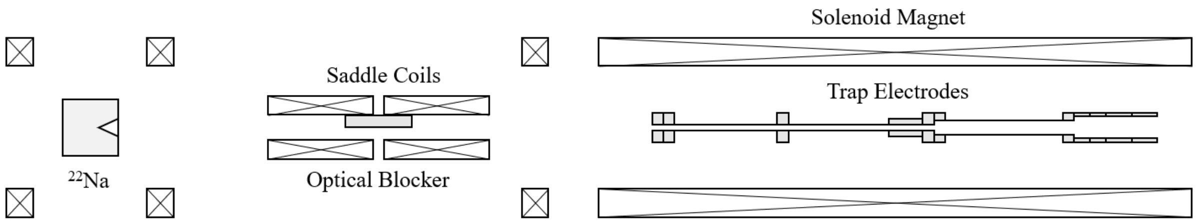


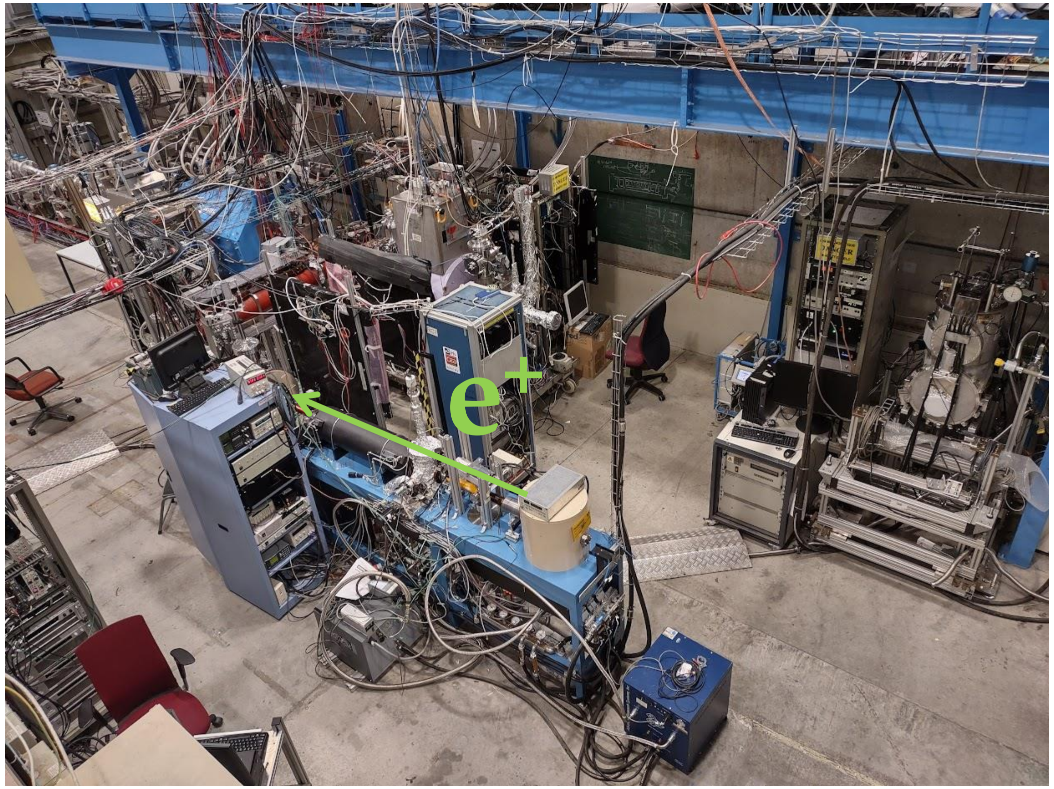
See https://arxiv.org/2111.0456v2 for details

P.A. Zyla et al. (Particle Data Group), Prog. Theor. Exp. Phys. 2020, 083C01 (2020)

Positron Trap Replaced

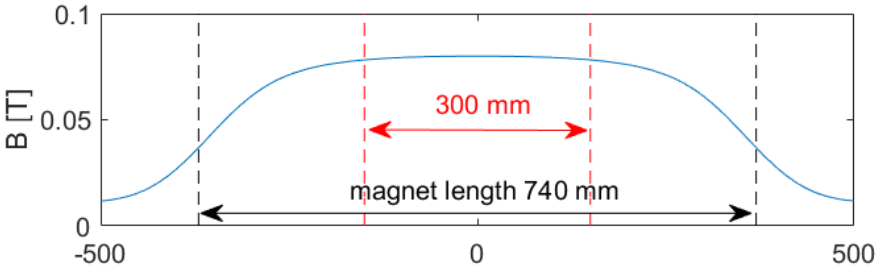
The existing positron trap was due to retire in 2021 but due to a lack of personnel in 2020/1 the new FPS trap was installed in 2022 and is currently being developed.

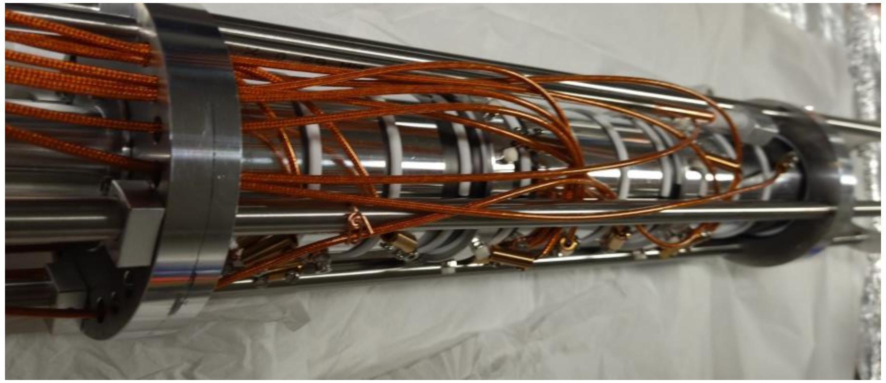


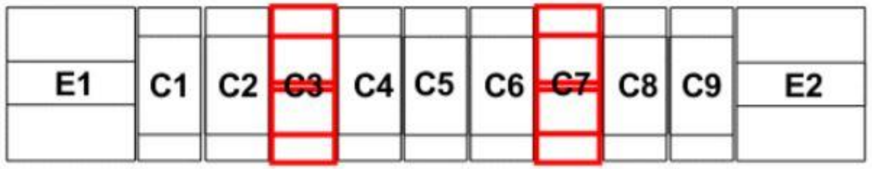


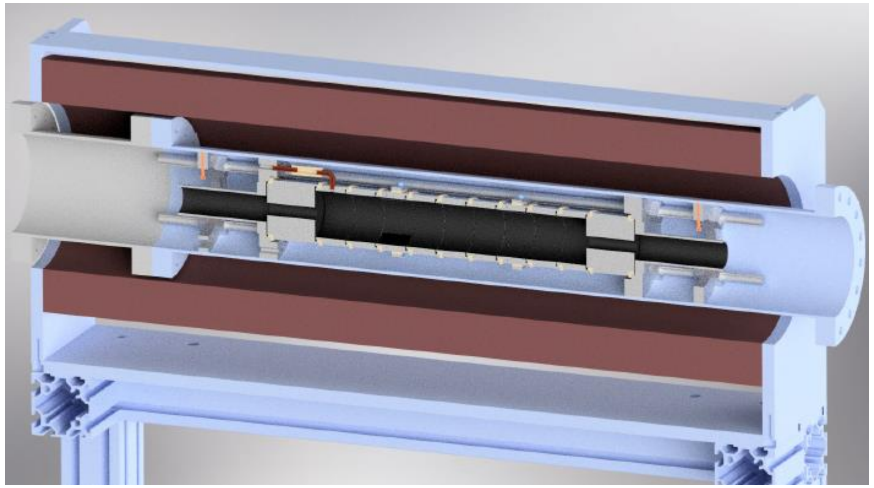
Positron Accumulator

- As the FPS trap has a lifetime of just 2s a new positron accumulator was built in 2021
- At present this device has been installed in the first coil of the positron transfer line and is being commissioned at this moment

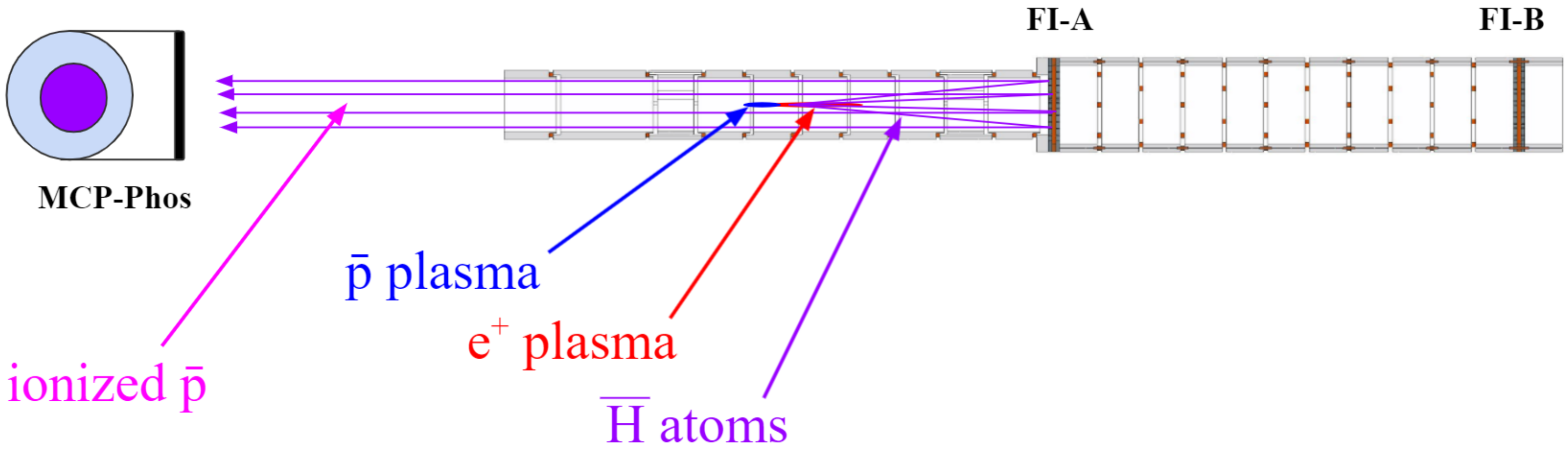




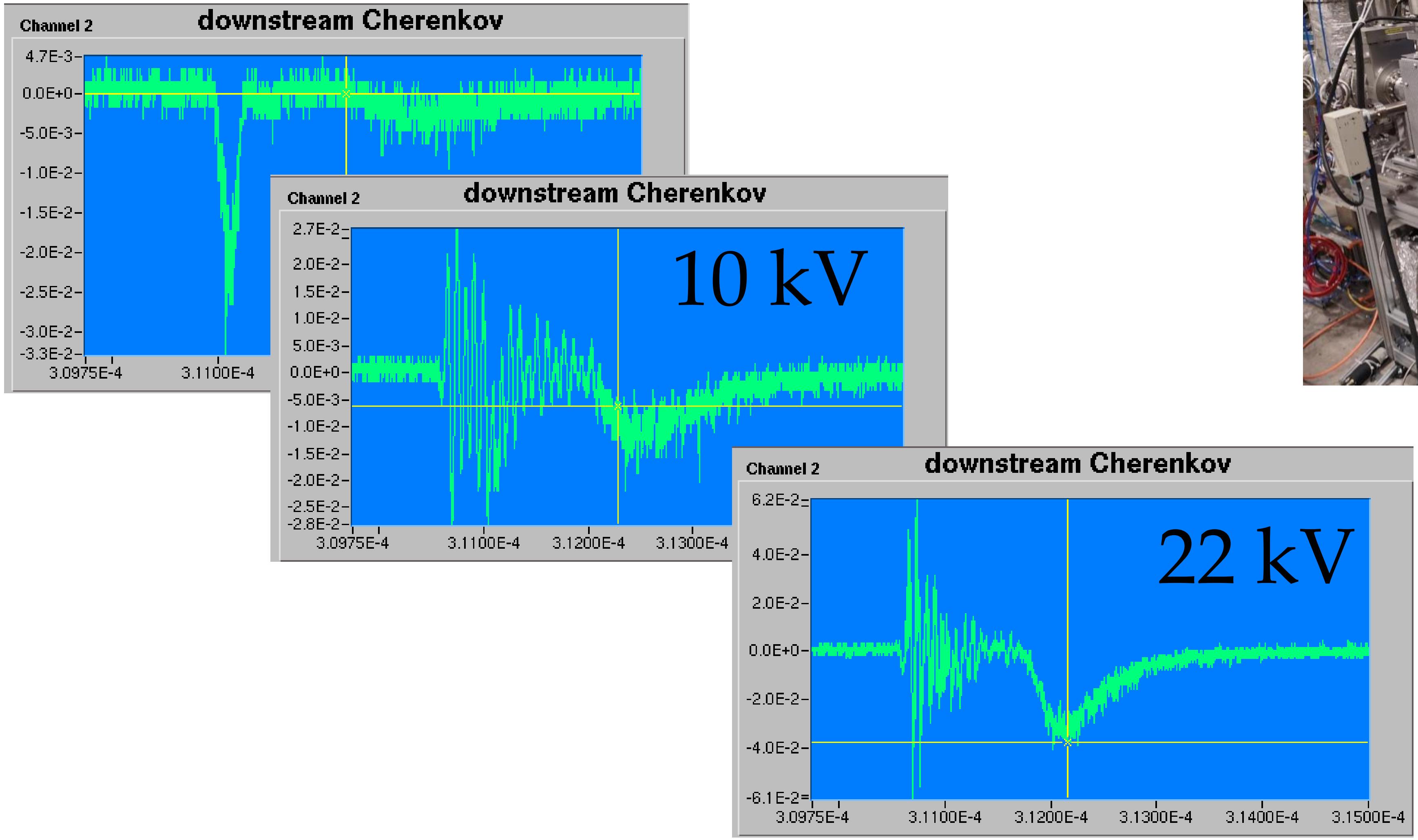


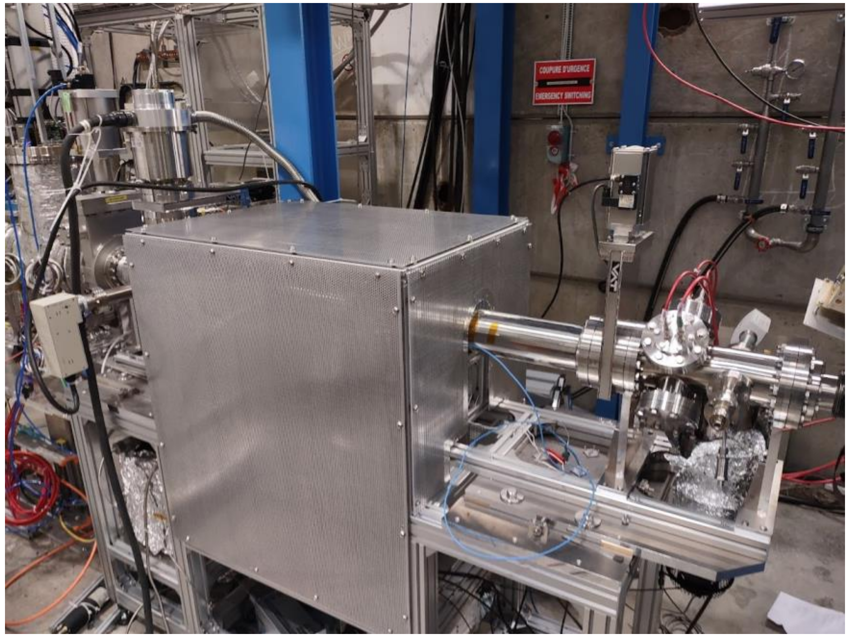


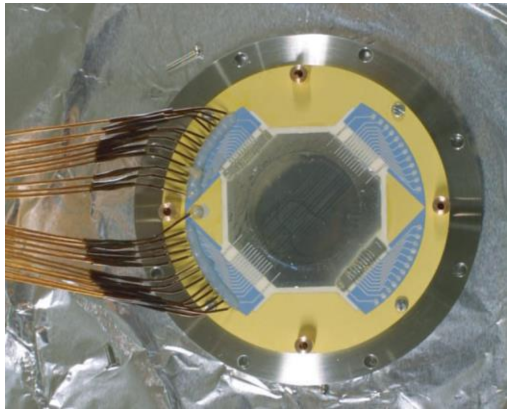
Field Ionizer



Drift Tube

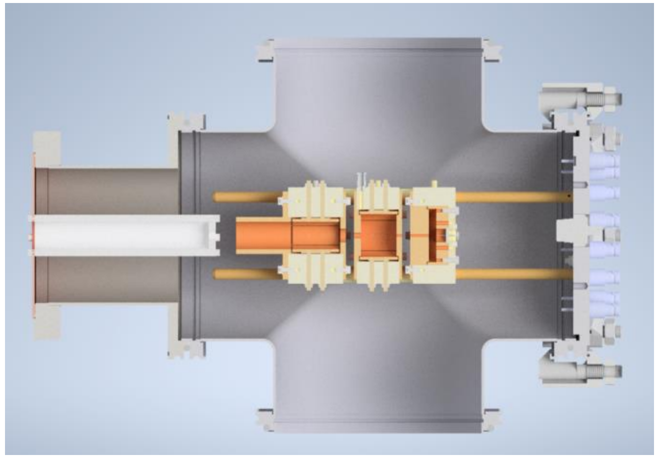

Channel 2
downstream Cherenkov
4.7E-3
0.0E+0
-5.0E-3
-1.0E-2
-1.5E-2
-2.0E-2
-2.5E-2
-3.0E-2
-3.3E-2
3.0975E-4
3.1100E-4
Channel 2
downstream Cherenkov
10 kV
2.7E-2
2.0E-2
1.5E-2
1.0E-2
5.0E-3
0.0E+0
-5.0E-3
-1.0E-2
-1.5E-2
-2.0E-2
-2.5E-2
-2.8E-2
3.0975E-4
3.1100E-4
3.1200E-4
3.1300E-4
Channel 2
downstream Cherenkov
22 kV
6.2E-2
4.0E-2
2.0E-2
0.0E+0
-2.0E-2
-4.0E-2
-6.1E-2
3.0975E-4
3.1100E-4
3.1200E-4
3.1300E-4
3.1400E-4
3.1500E-4

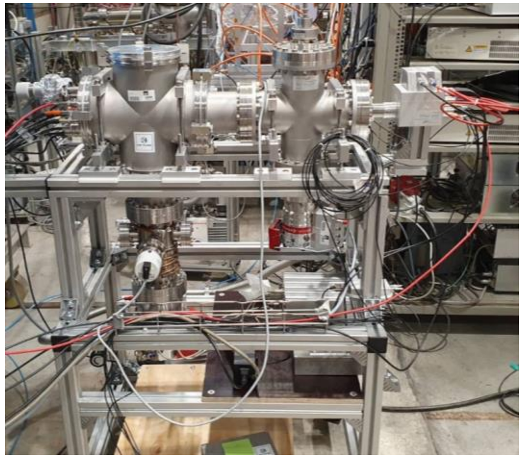


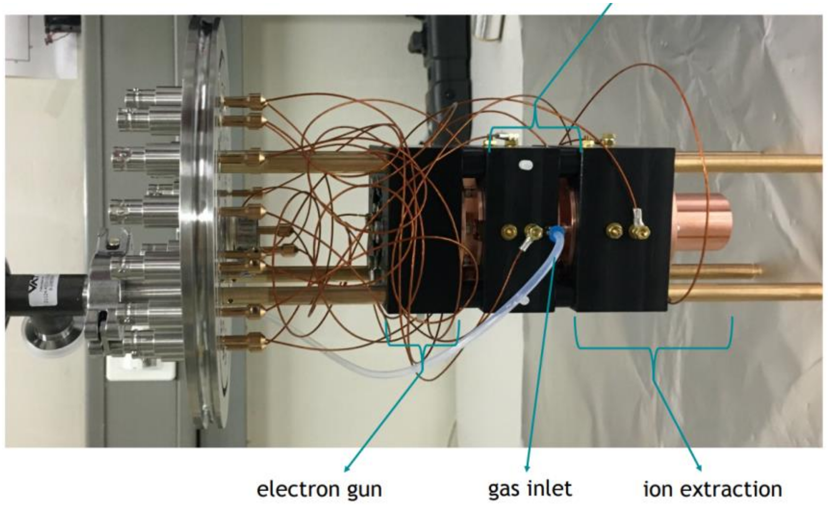


Proton Source

- A novel proton source was developed at SMI
- Protons were produced via electron impact ionization of H_2 gas
- This process typically creates more H_2^+ and H_3^+ ions than protons
- The protons were 'filtered' by trapping the ions in the gas cell while applying a RW drive to 4 split electrodes

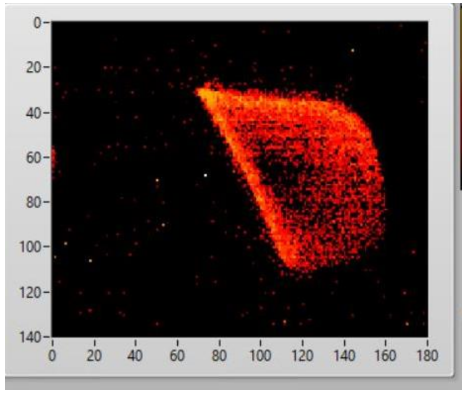


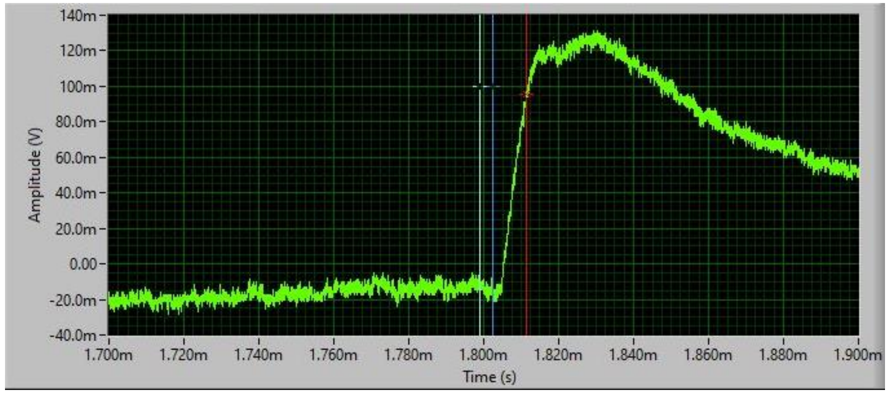


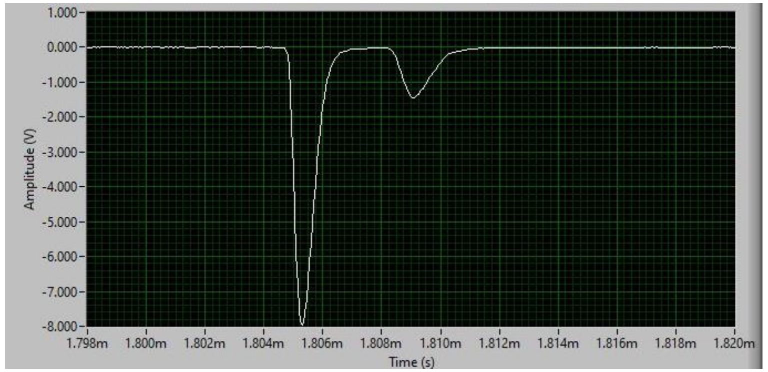


Proton Source

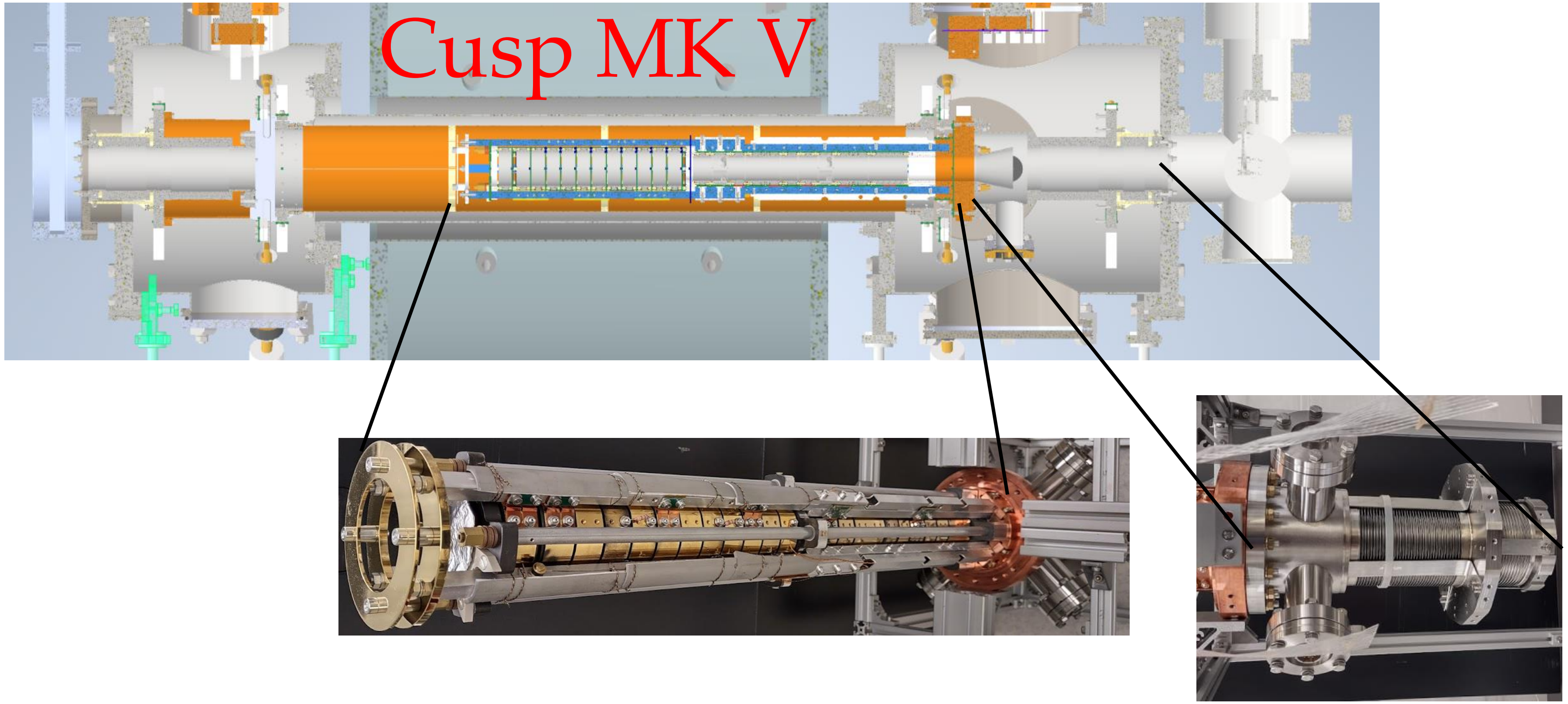
- The proton source was connected to the Cusp Mk IV trap
- We were able to accumulate ~1 million protons in the Cusp within a few seconds
- Unfortunately time ran out for work with protons so it was not possible to try to produce Ry-H



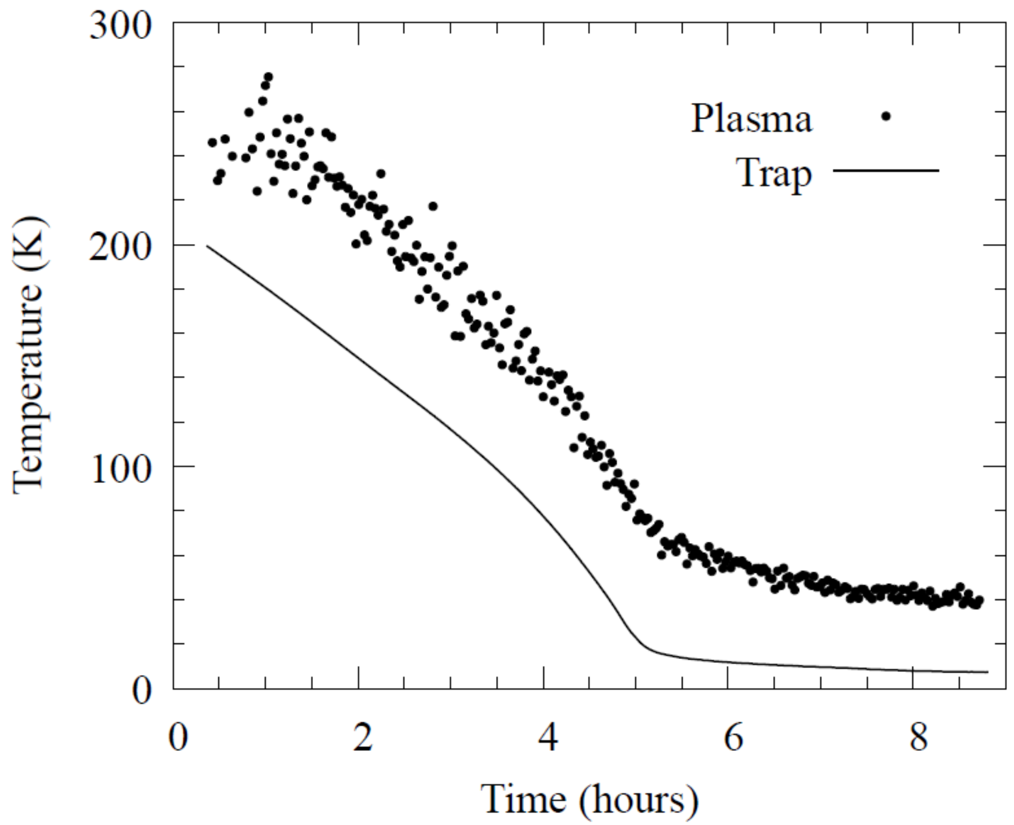


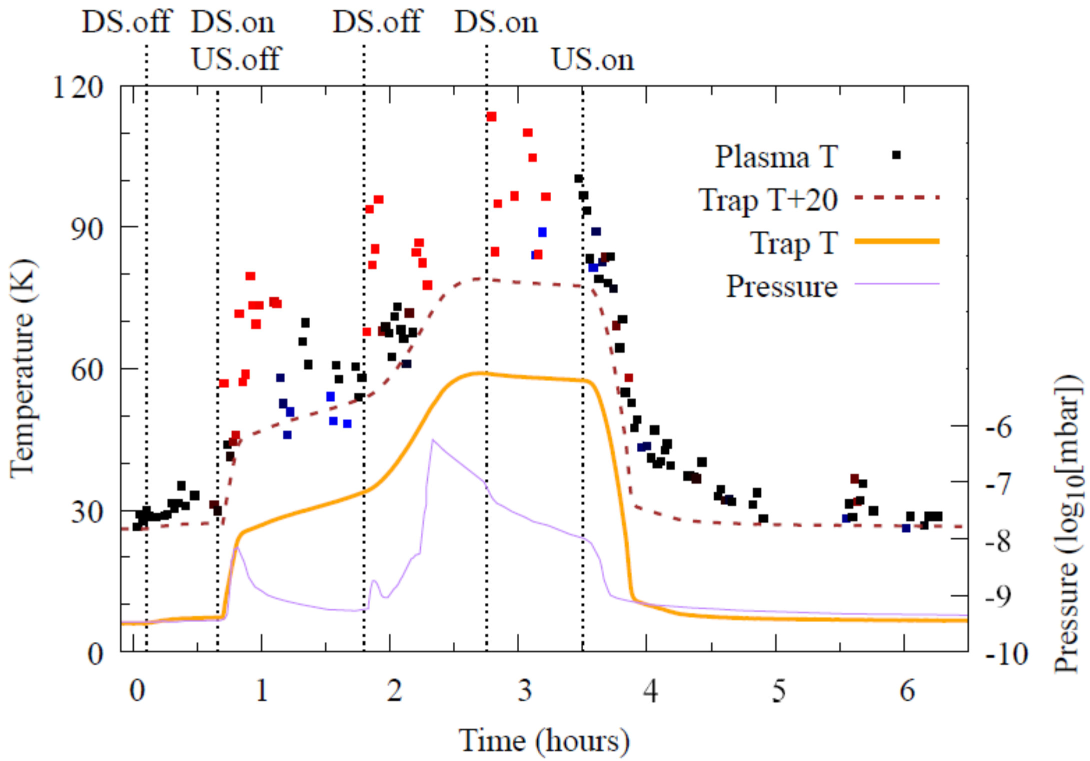


Double Cusp Trap

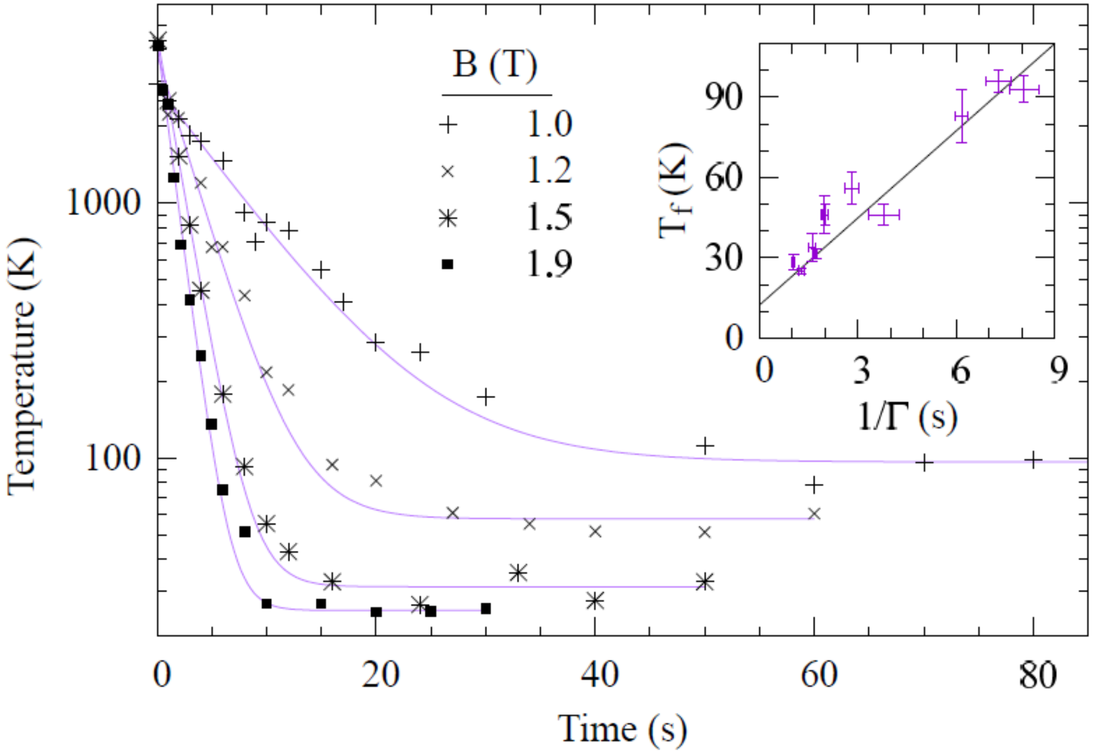


Pressure and Trap Temperature Plasma Temperature Dependence



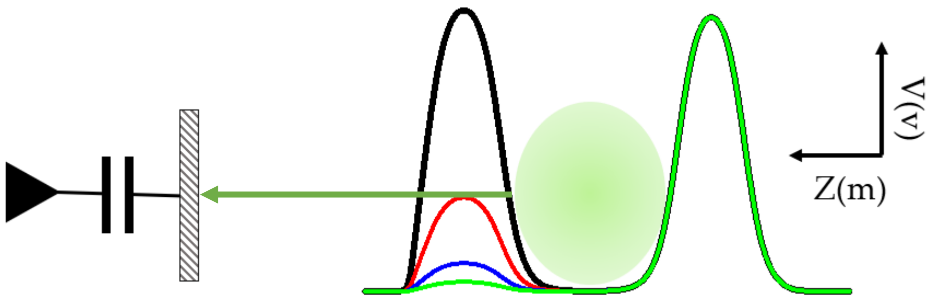


Cooling time Vs B



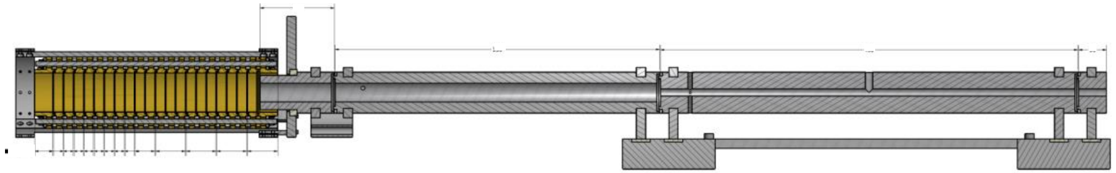
Plasma Temperature

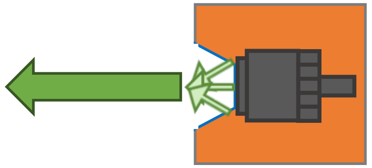
- To measure the plasma temperature the potential barrier is slowly lowered while measuring the current delivered to an MCP (either with a charge amp or using the light from a phosphor screen and SiPM)

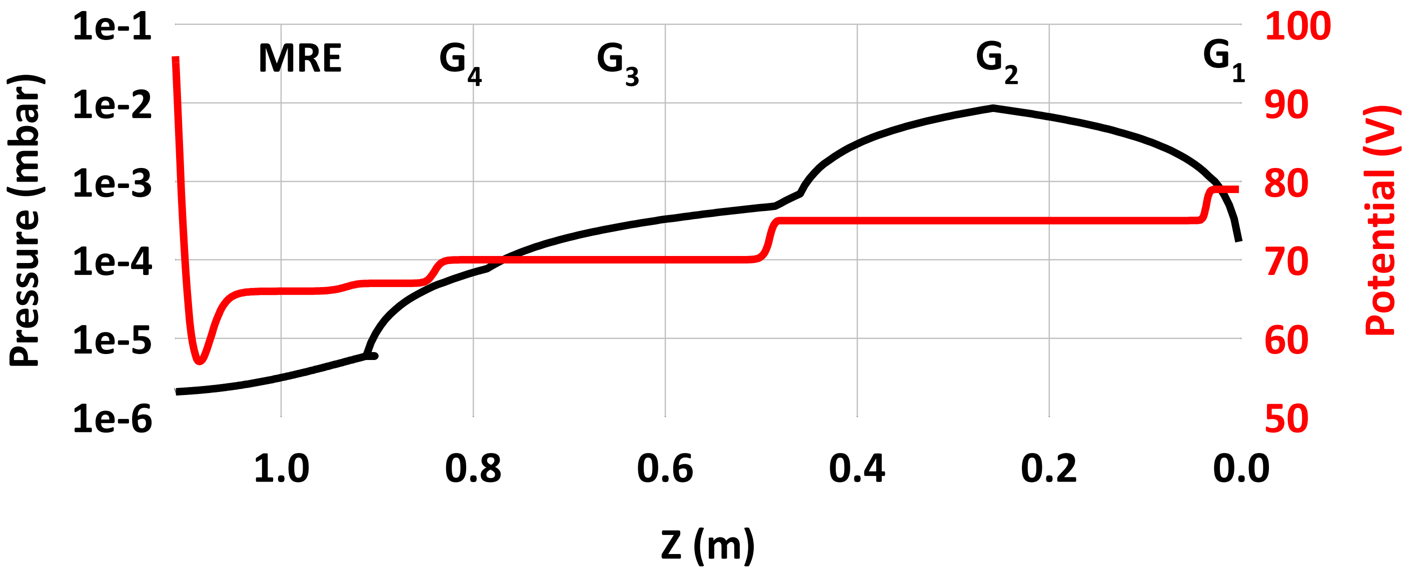


Combination k_bT + space charge determines the dN/dV

Positron Trap

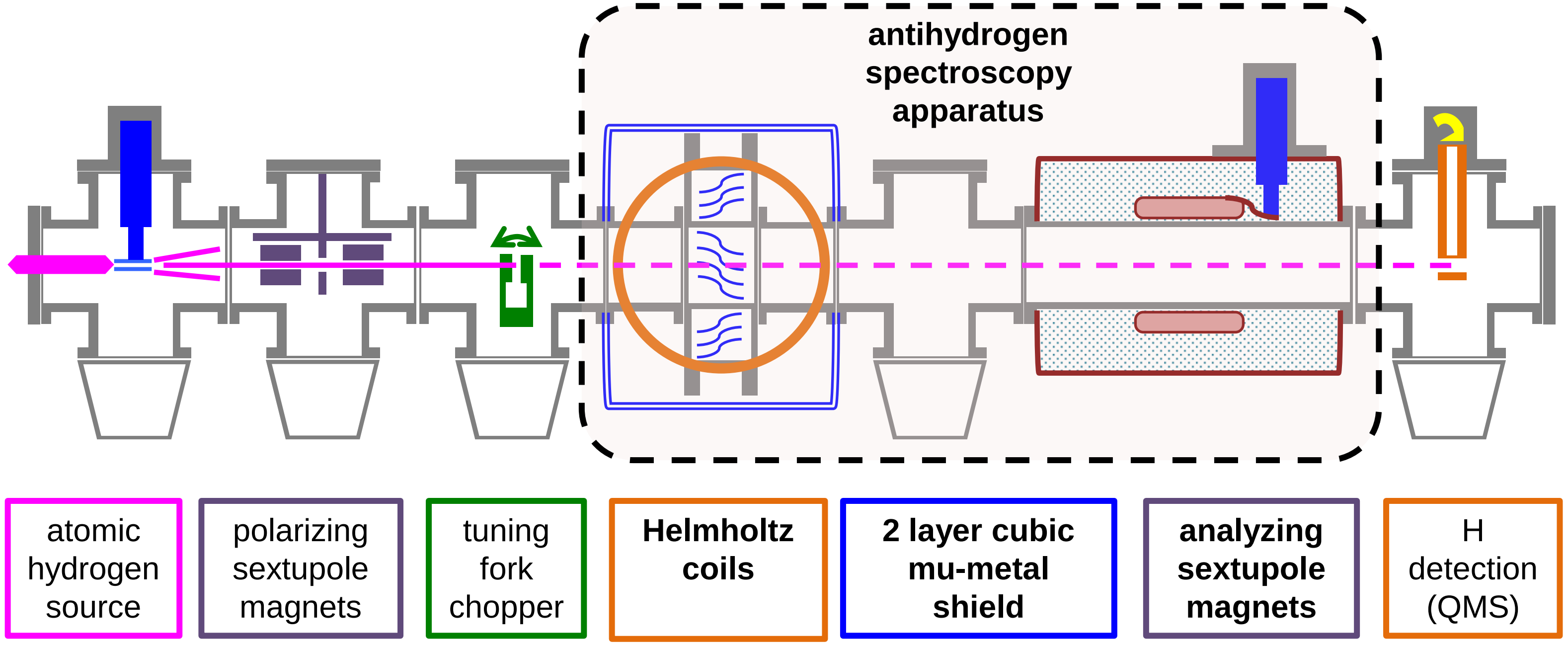


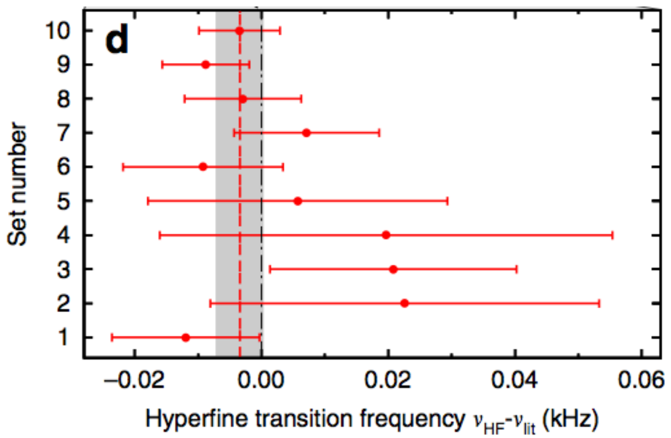




- **Sodium-22**
  - Half-life: 2.6 Years
  - Supplier: iThemba labs
  - Strength: up to 50mCi (1.85GBq)
- **Neon**
  - $5 \times 10^{-3} \leq \varepsilon_m \leq 2.5 \times 10^{-2}$
  - Band Gap Insulator
  - Require cryogenic equipment

Hydrogen Spectroscopy





Main Results

- line-shape understood in detail
- systematic effects? not on few ppb-level
- 8000 Hbar events on detector for ppm result (conservative estimate for σ-transition)

Nature Communications,
published on 12th June '17
DOI: 10.1038/ncomms15749

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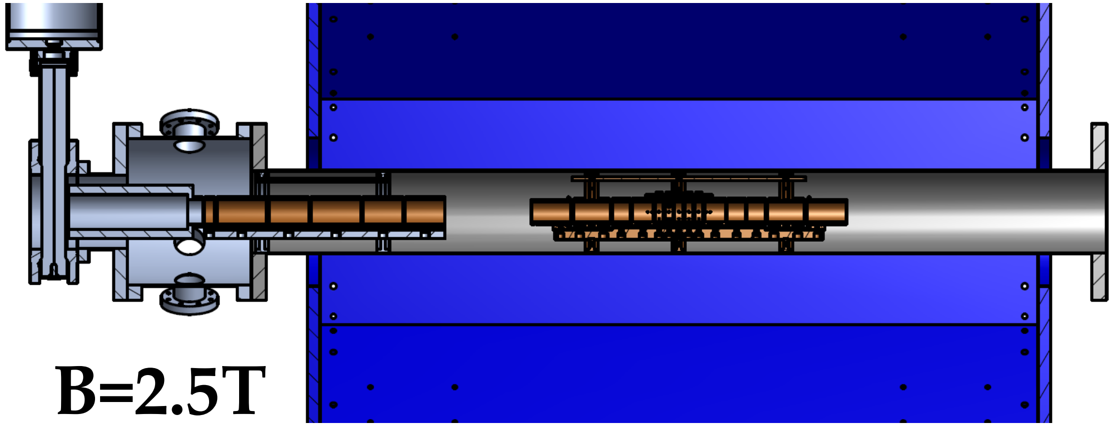
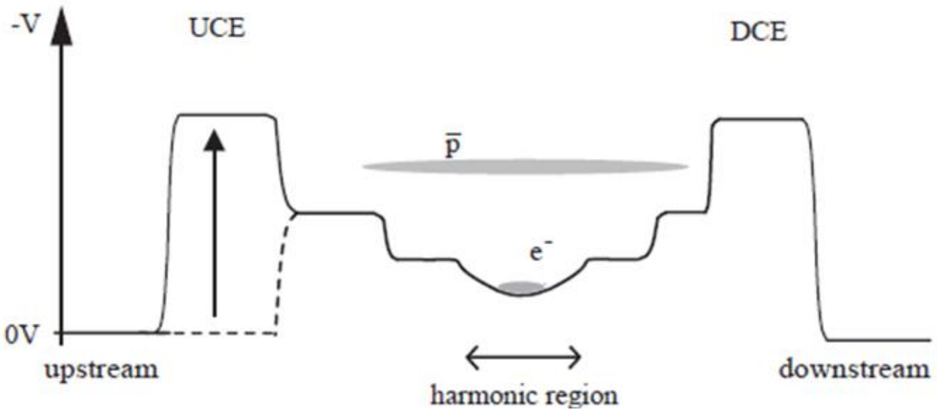
Antiproton Trap - MUSASHI

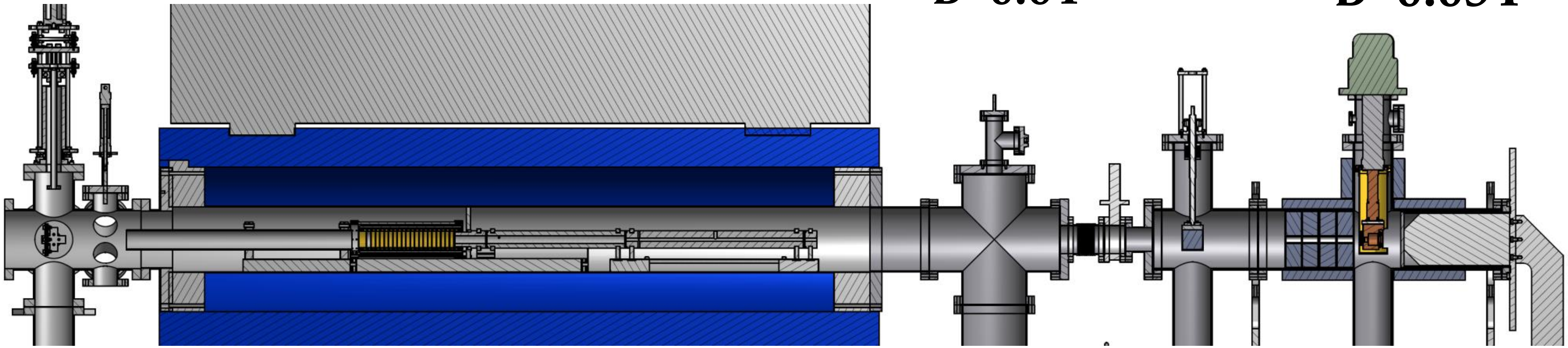


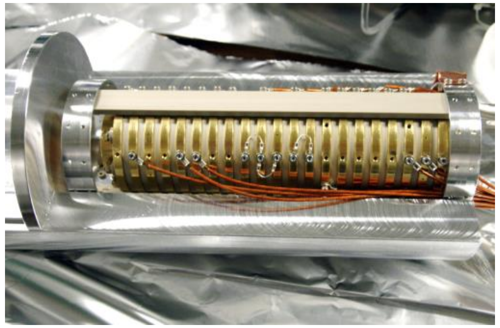


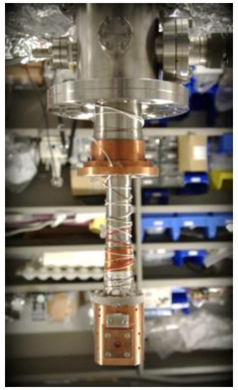
- Degrader foil reduces incoming antiproton energy to ~10keV
- Catching bias -12kV
- Antiprotons are cooled with $\sim 3 \times 10^8$ electrons
- 1-2 million antiprotons are trapped per AD cycle
- Antiprotons can be extracted with eV energies.

Positron Trap

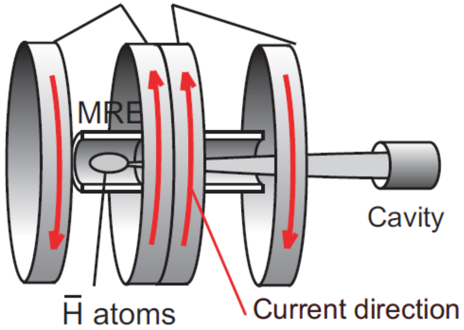
B=0.6T B=0.05T

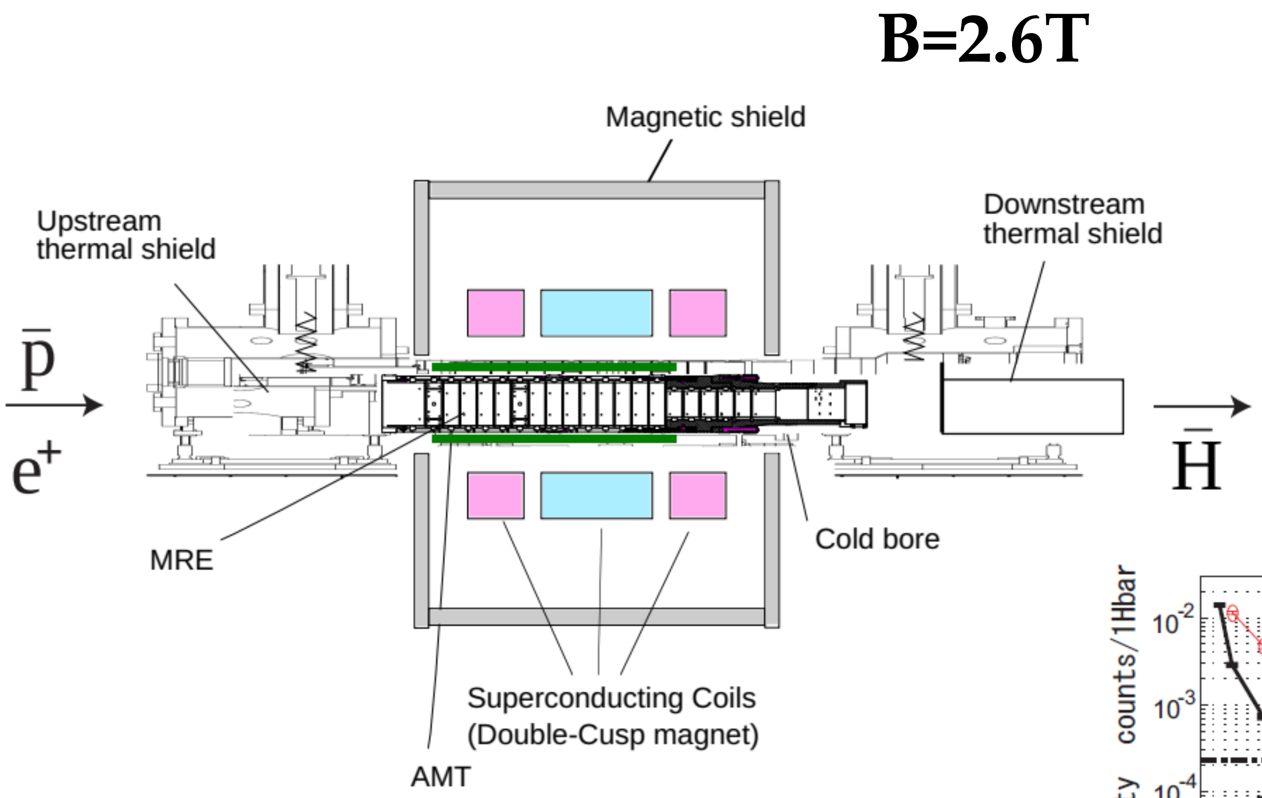


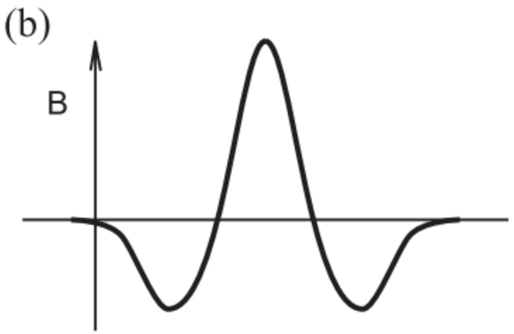


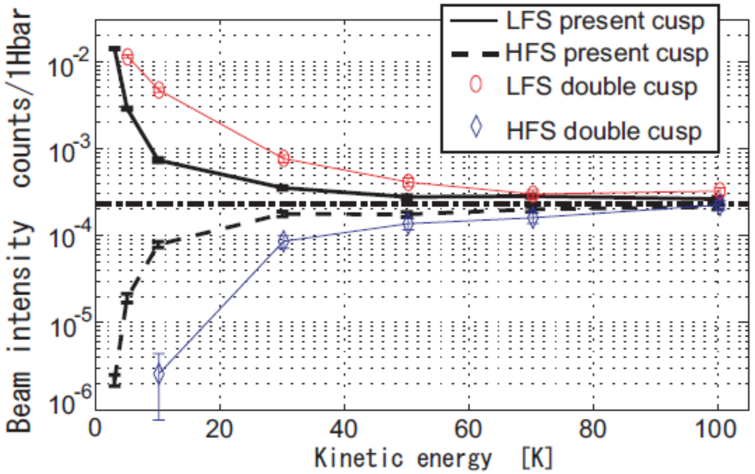


Double Cusp Trap





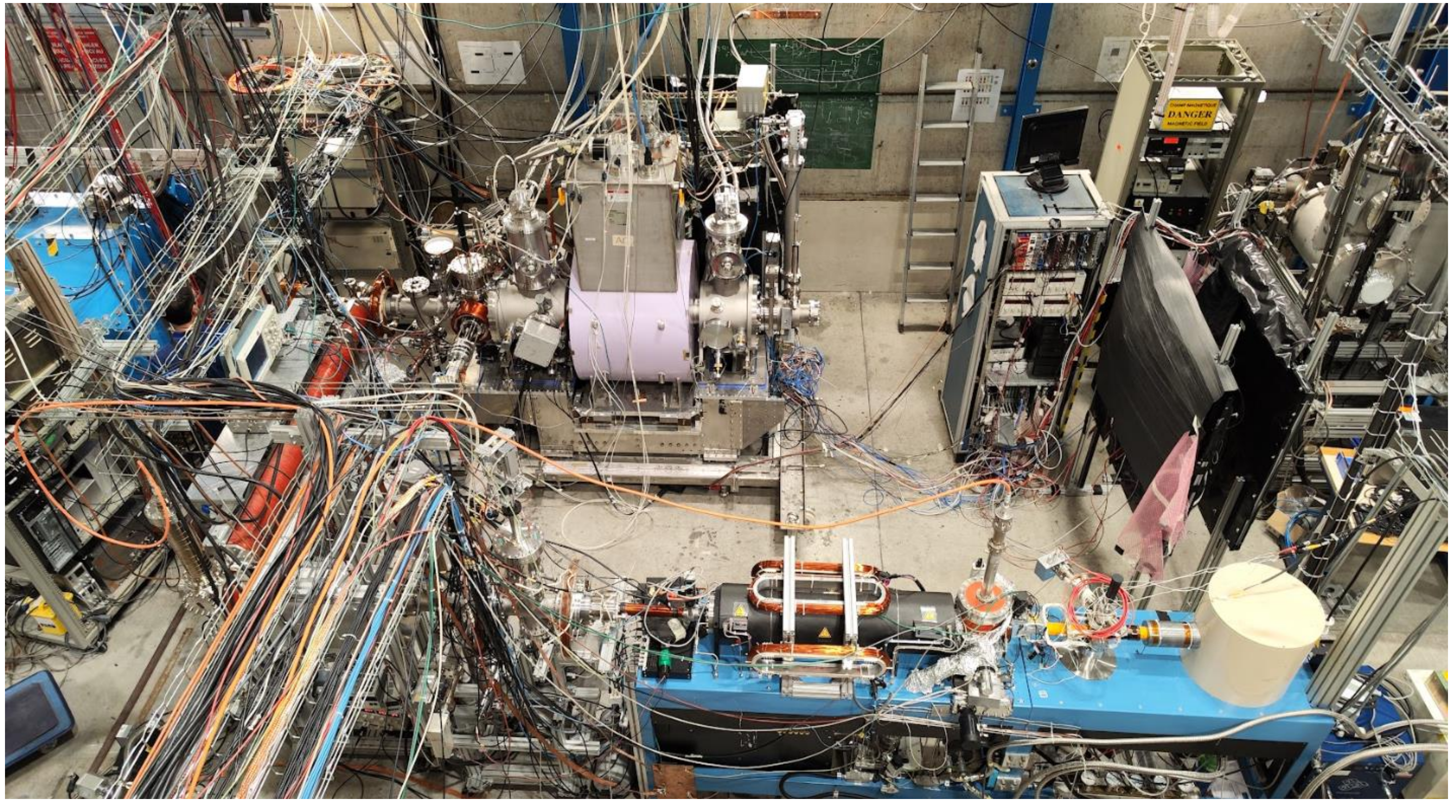




Radics, B., S. Ishikawa, N. Kuroda, D. J. Murtagh, Y. Nagata, M. Tajima, S. Van Gorp, et al. “Antihydrogen Synthesis in a Double-CUSP Trap towards Test of the CPT-Symmetry.” *Hyperfine Interactions* 237, no. 1 (December 1, 2016): 156.

Overview

- The method
- Status of the experiment
- The ELENA Era
  - A new Cusp trap
  - A new positron trap



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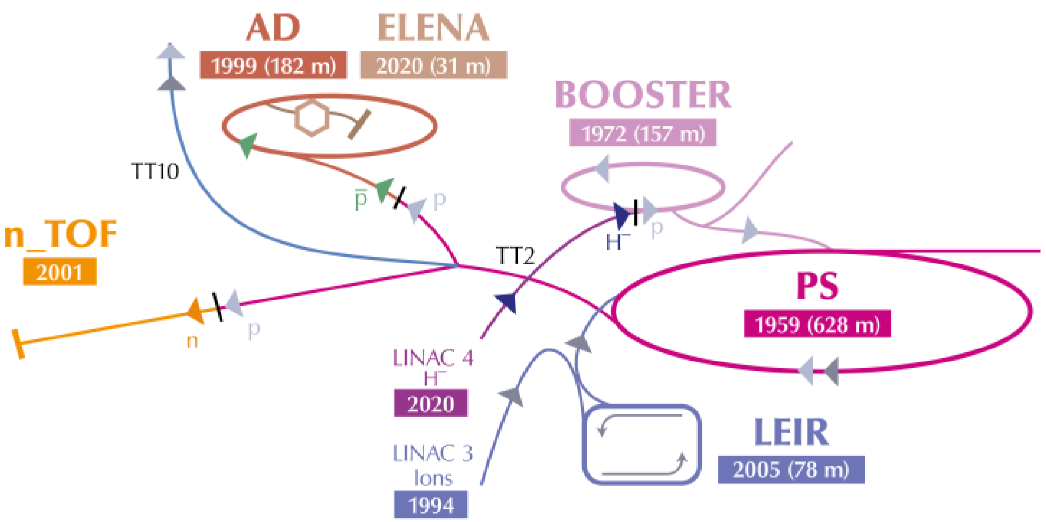
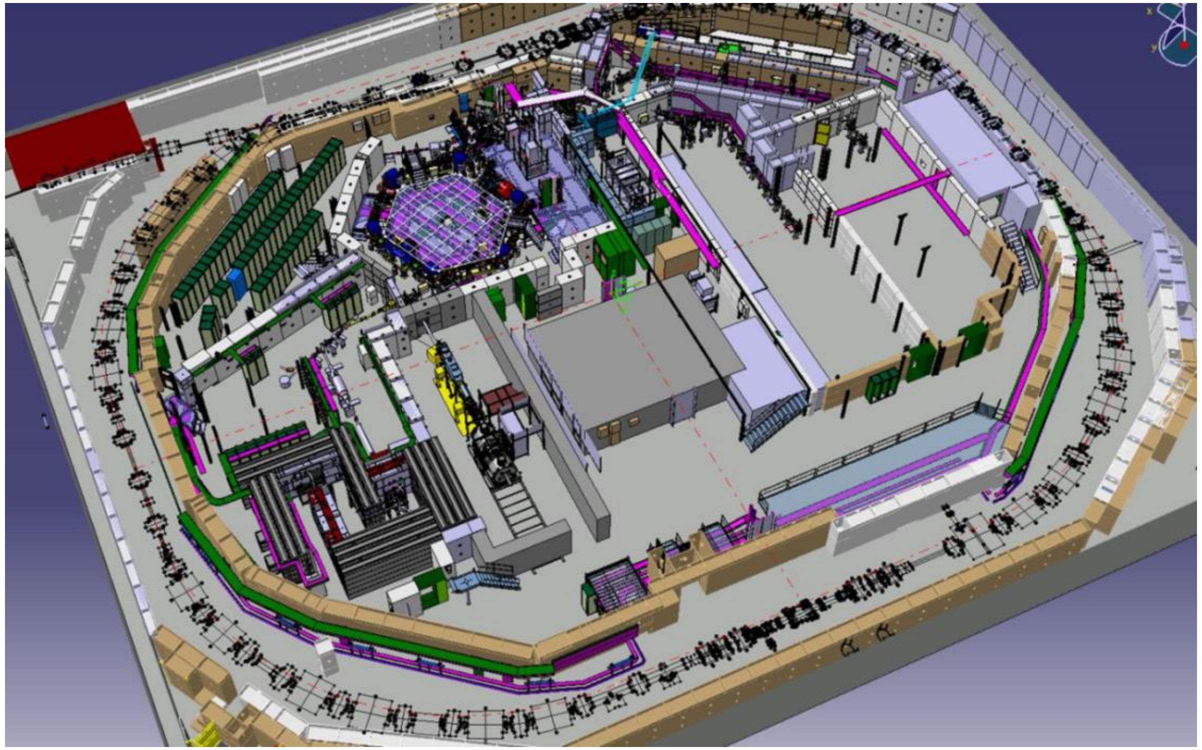
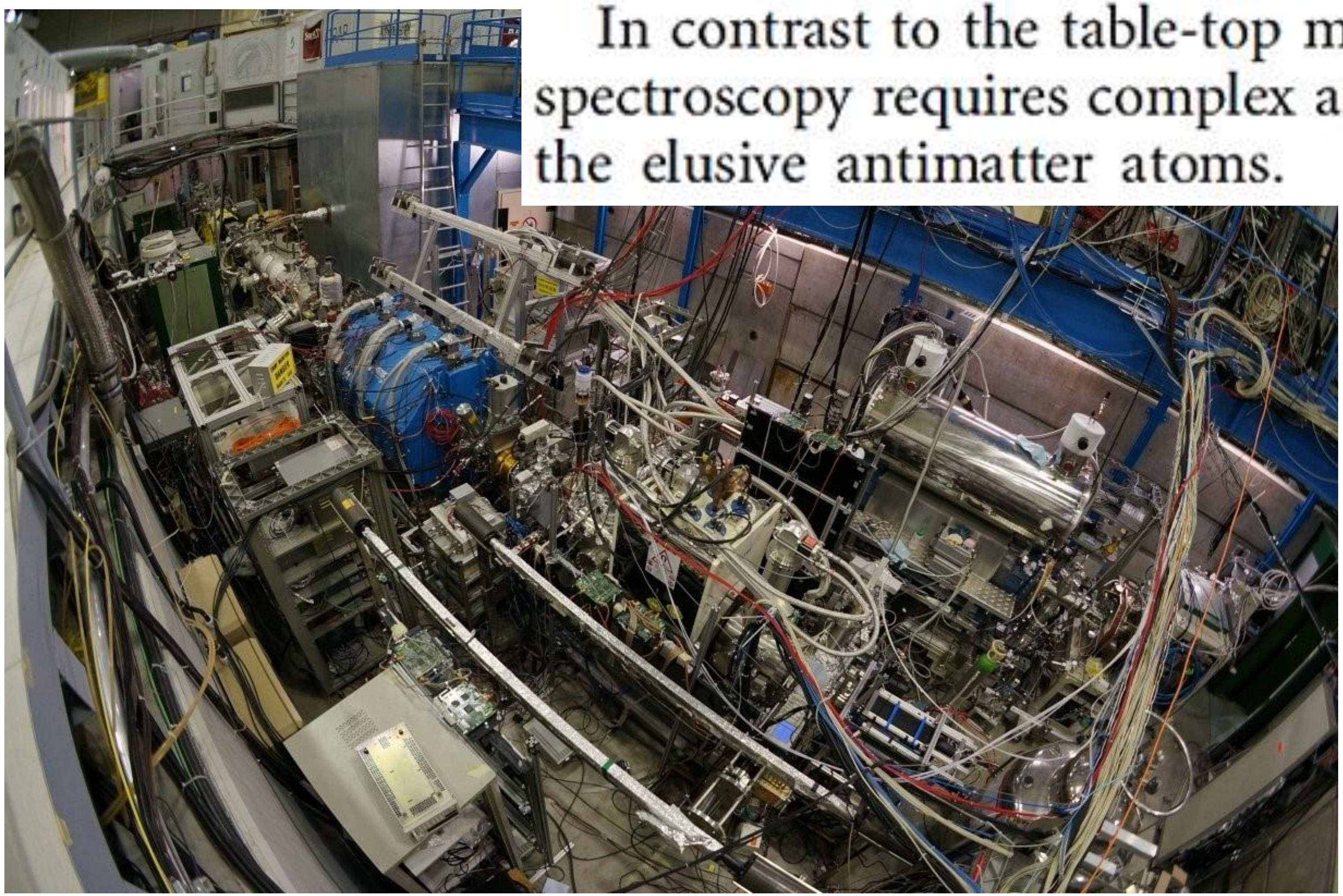
The ASACUSA-Cusp Experiment





In contrast to the table-top matter experiments, antihydrogen spectroscopy requires complex apparatuses for the production of the elusive antimatter atoms.



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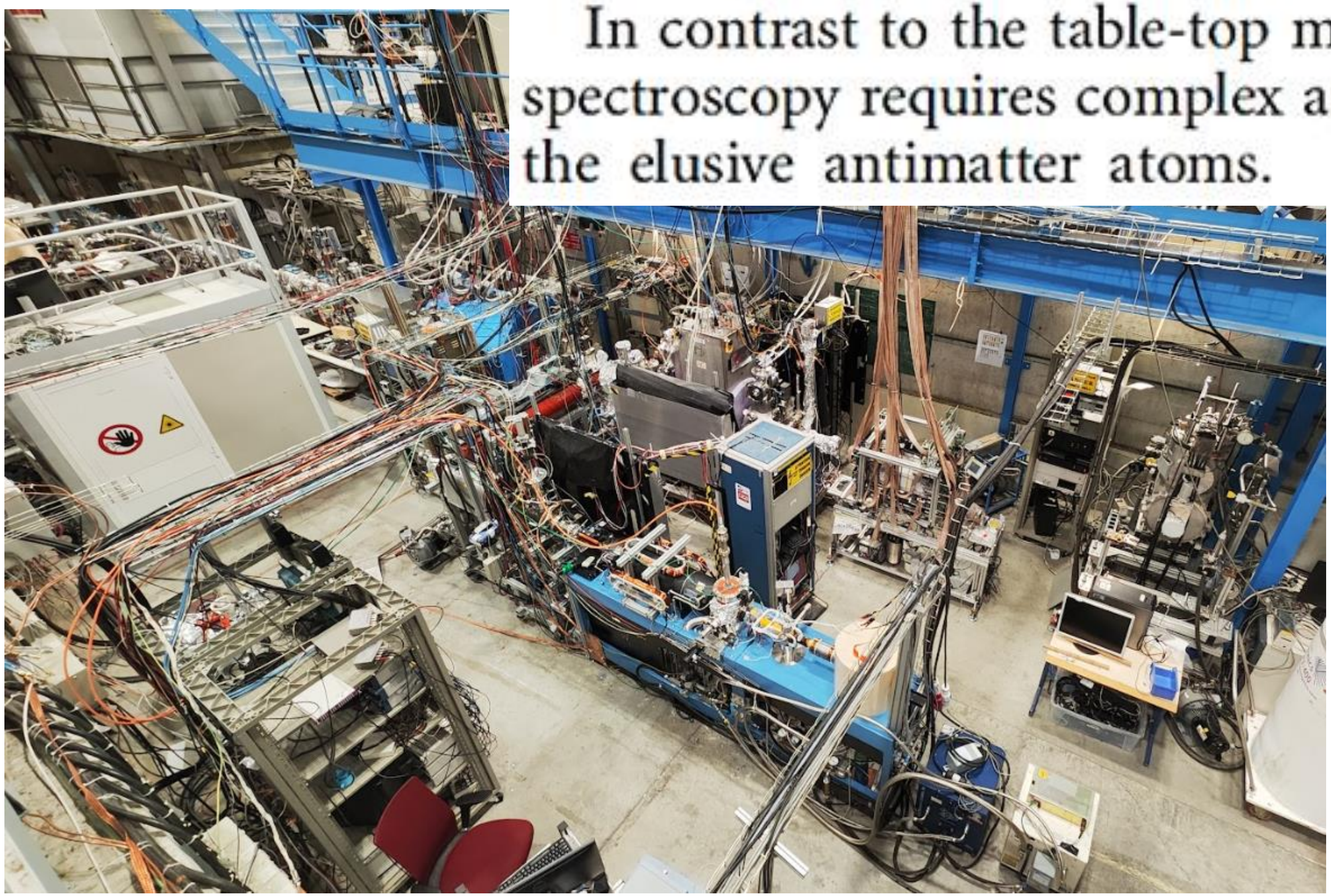
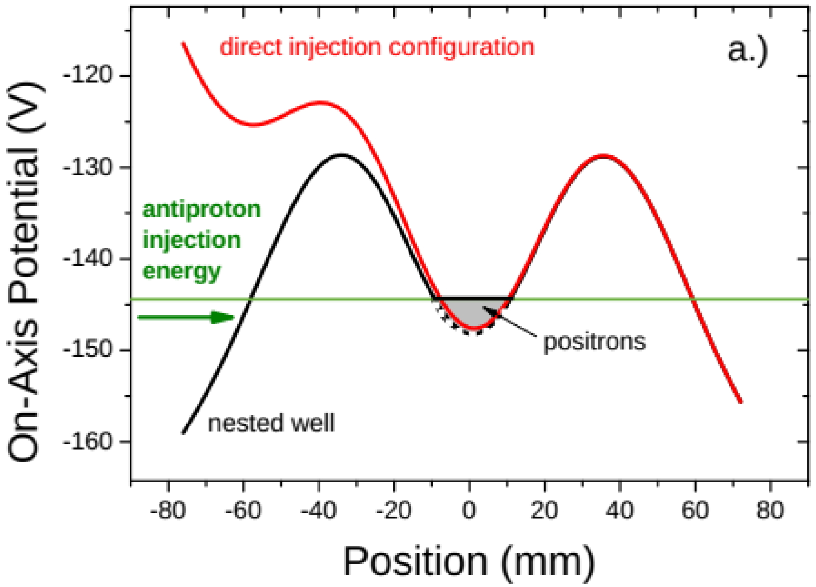
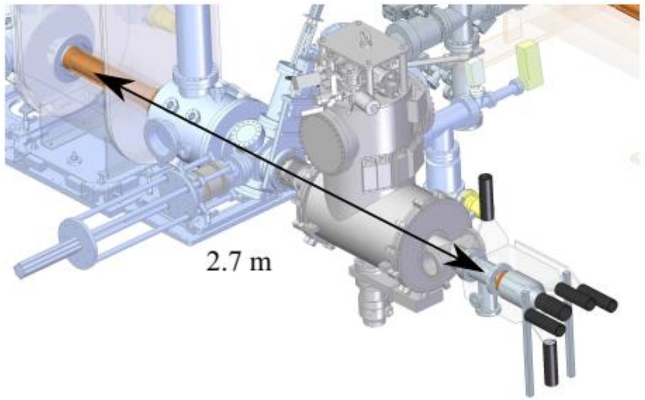
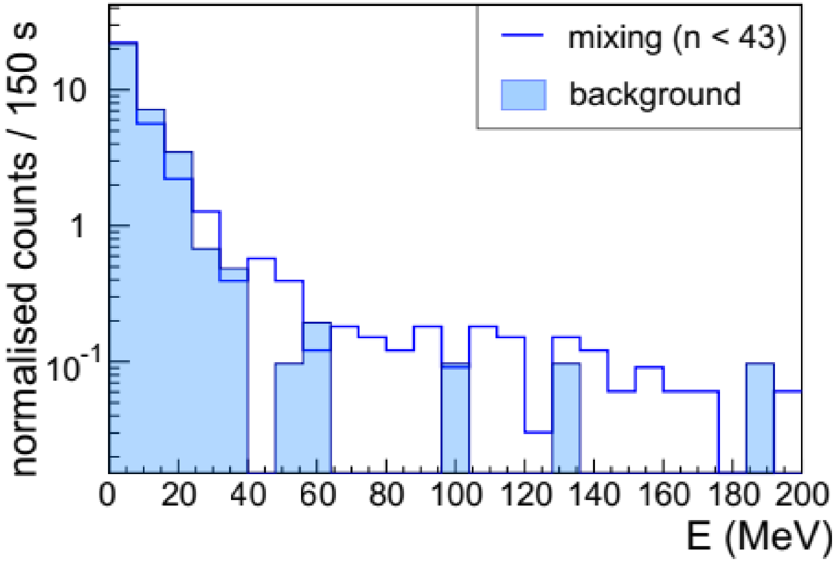


Detection of the first antihydrogen 'beam'



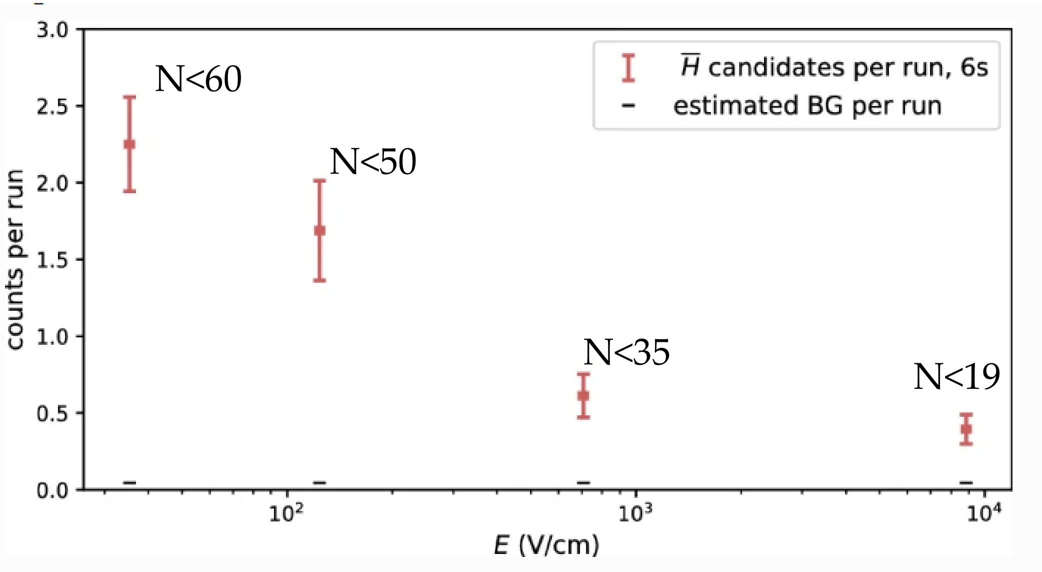


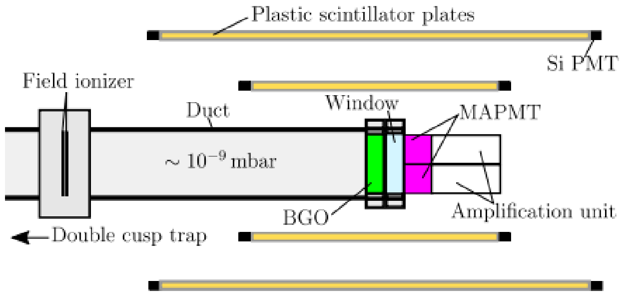


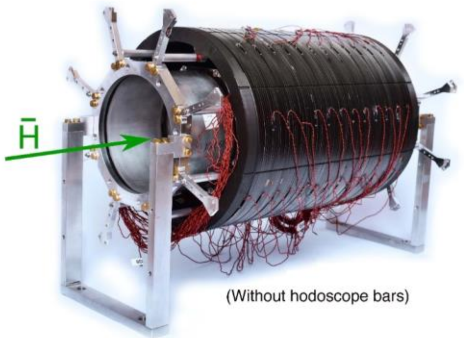
Kuroda, N., S. Ulmer, D. J. Murtagh, S. Van Gorp, Y. Nagata, M. Diermaier, S. Federmann, et al. "A Source of Antihydrogen for In-Flight Hyperfine Spectroscopy." *Nature Communications* 5 (January 21, **2014**).

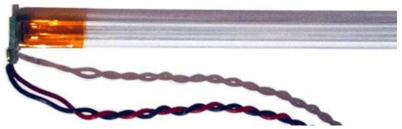
Measurement of Quantum State Distribution

- The data analysis made use of machine learning techniques
  - Trained with p̄ annihilation
  - $\varepsilon_{\bar{p}} \sim 80\%$
  - False cosmic identification 0.25%
  - Cosmic rate 1.6s^{-1} → 0.02 per 5s mixing run









B. Kolbinger et al. (ASACUSA Collaboration) Eur. Phys. J. D75 (2021) 91

How to make more Hbar?

- Modelling of the formation and scattering of antihydrogen formation

$$\frac{dN(i)}{dt} = [C_{rr}(i) + C^{+}_{tbr} n^{+}_{e}]\, n^{+}_{e} N_p - [C^{+}_{ion}(i) n^{+}_{e}]\, N(i) + \sum_{j\neq i} [C^{+}_{col}(j,i) n^{+}_{e} + C_{str}(j,i)]\, N(j) - N(i) \sum_{j\neq i} [C^{+}_{col}(i,j) n^{+}_{e} + C_{str}(i,j)]$$

Antiproton Number

Positron density

Number of Antihydrogen in state

Radiative recombination rate

Three Body recombination rate

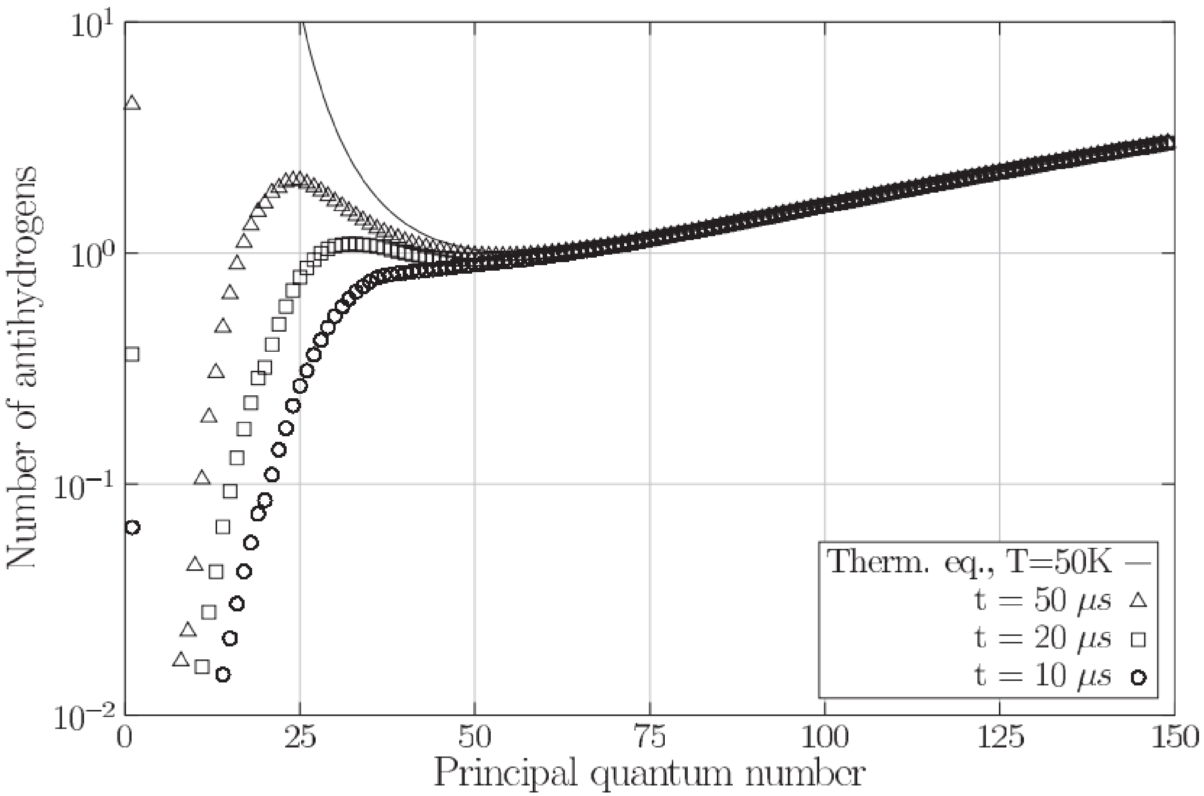
Ionization Rate

Collisional (de)excitation Rate

Simulated/ Spontaneous Transition Rates

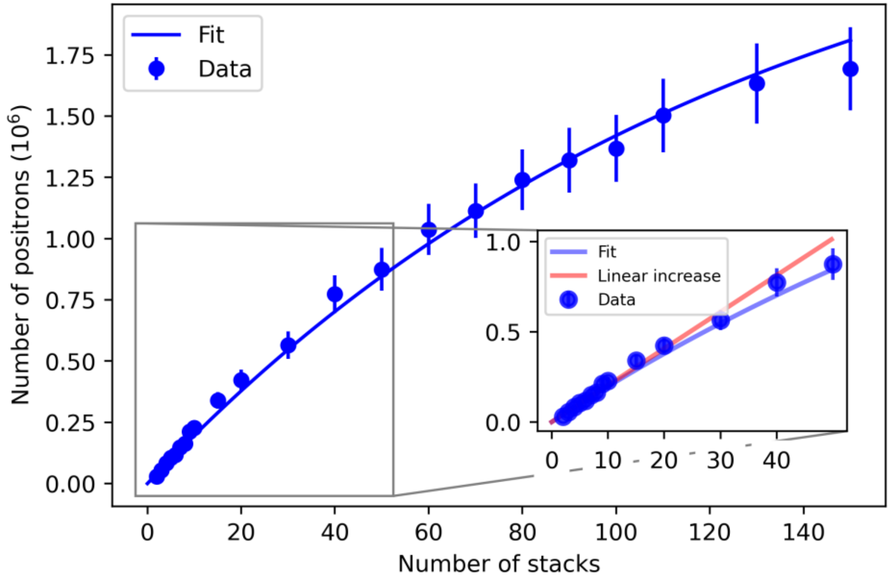
Populating State i

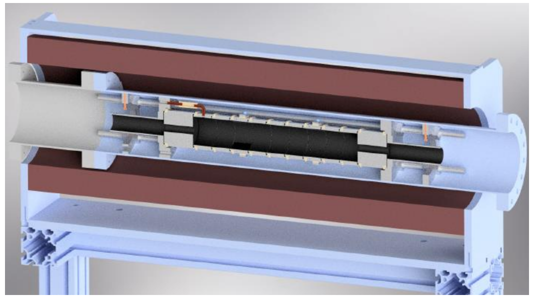
Depopulating State i



Positron System Upgrade

- We replaced the existing positron trap which used a SC magnet with a new room temperature model form First Point Scientific (FPS)
  - Removed weekly requirement for 1000l of Lhe
- Installed a new 3rd stage accumulator to reduce the number of transfer cycles to the Cusp trap.
- With a new source we expect 30 – 90 million e+ per ELENA cycle (110s)



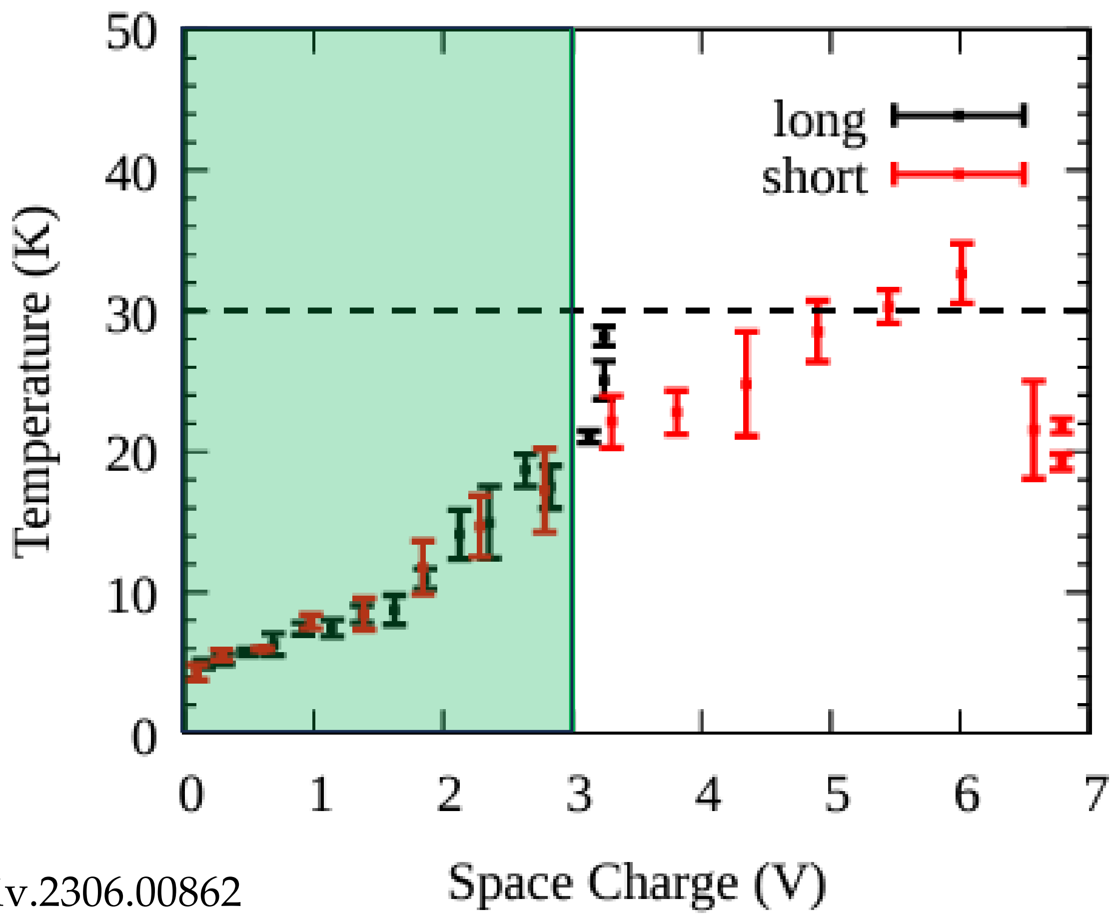


Property	RGM & BGT	Accumulator
Moderator efficiency (%)	0.2 ± 0.1	–
Trapping efficiency (%)	15 ± 4	95 ± 4
Lifetime (s)	3.9 ± 0.8	104 ± 22 / > 600
Energy spread (eV)	1.49 ± 0.01	–
Radius (mm)	2.12 ± 0.03	1.44 ± 0.05-1.85 ± 0.06
Expansion rate (mm/s)	2.24 ± 0.08	0.045 ± 0.003 / 0.013 ± 0.004

Submitted to The Journal of Plasma Physics – https://doi.org/10.48550/arXiv.2307.06133

Is that enough ?

- During a recent study on evaporative cooling after preparation with SDREVC we found that if the space charge exceeded 3 volts the plasma didn't cool !
- During mixing we are developing a regenerative scheme where a positron reservoir will be used to perform multiple mixing cycles in one ELENA cycle (100s)



Accepted by The Journal of Plasma Physics - https://doi.org/10.48550/arXiv.2306.00862