The ASACUSA Experiment

D. J. Murtagh

On behalf on the ASACUSA collaboration

SSP 2022

1/9/2022

ASACUSA

Atomic

Spectroscopy

And

Collisions

Using
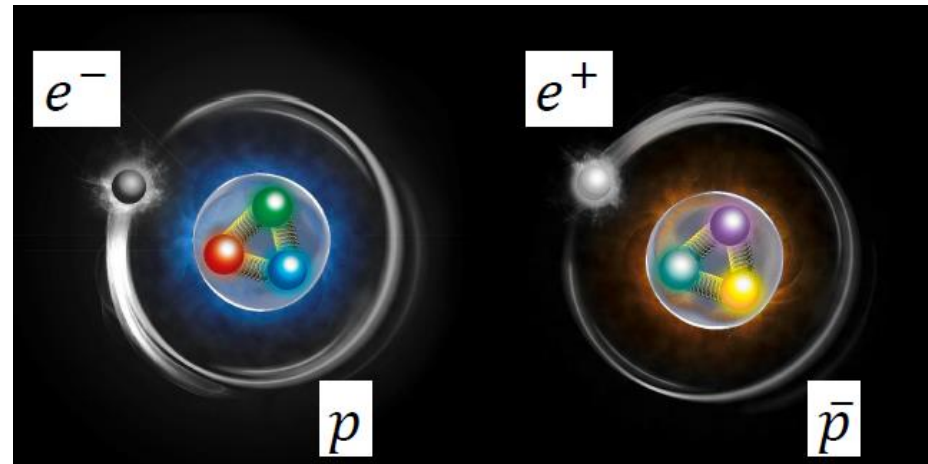
Slow

Antiprotons

Asakusa in Tokyo

The ASACUSA-Cusp Experiment
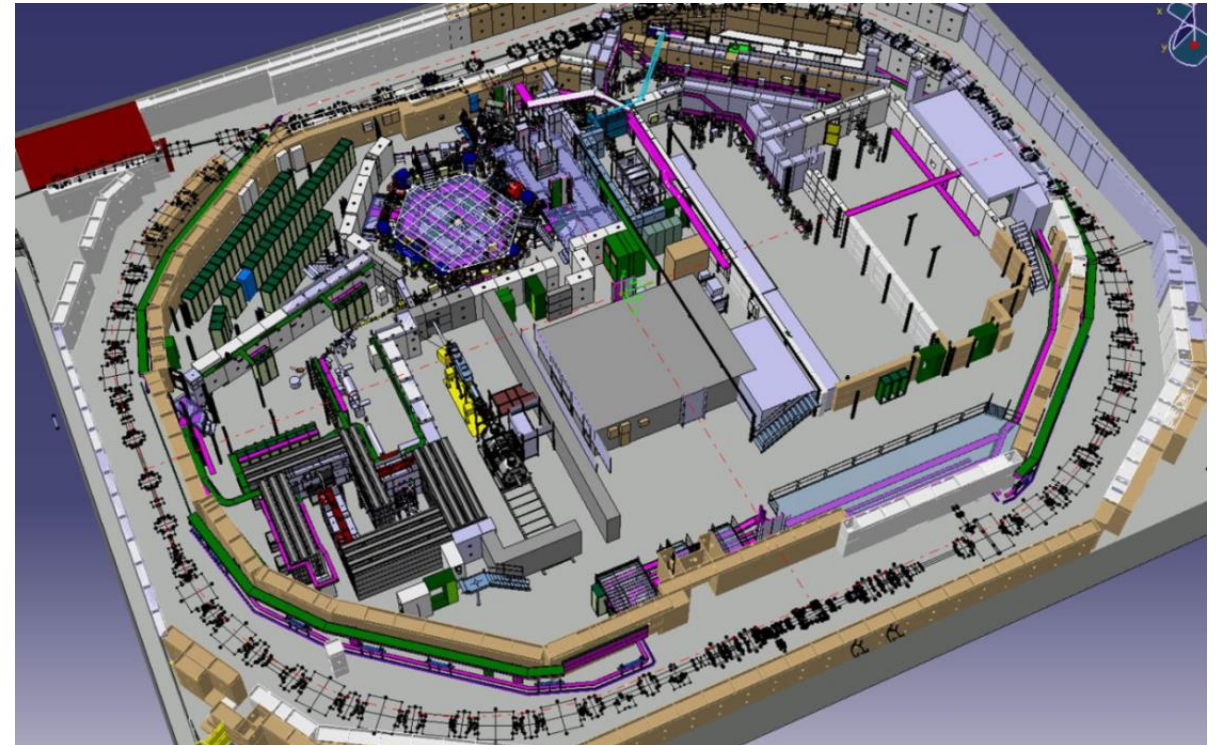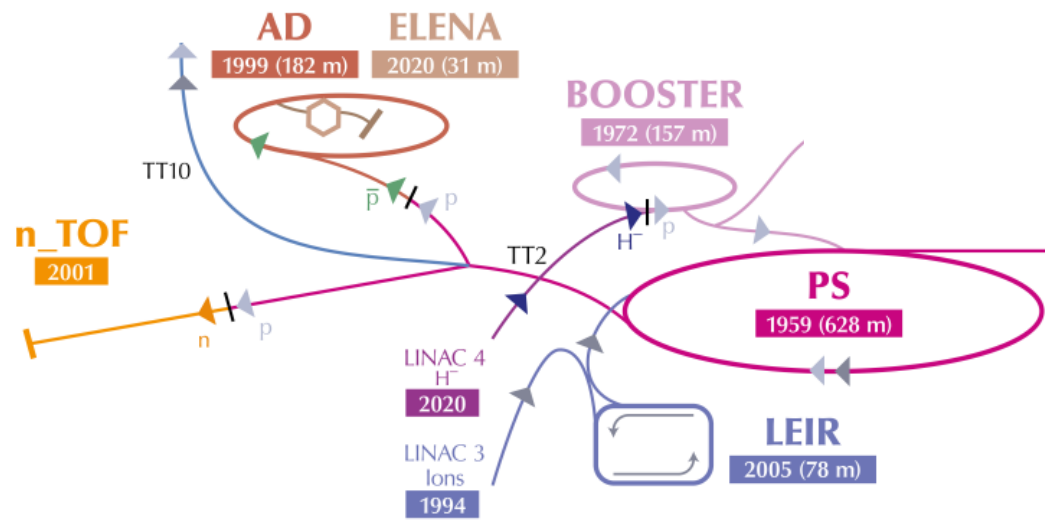
What do we study

- 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.
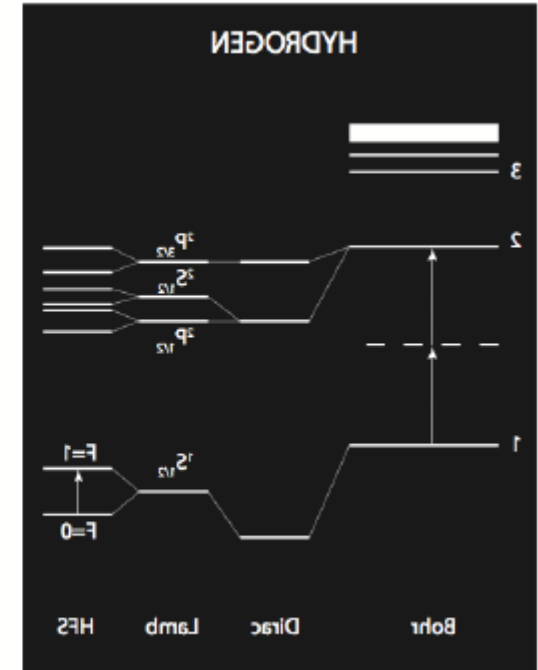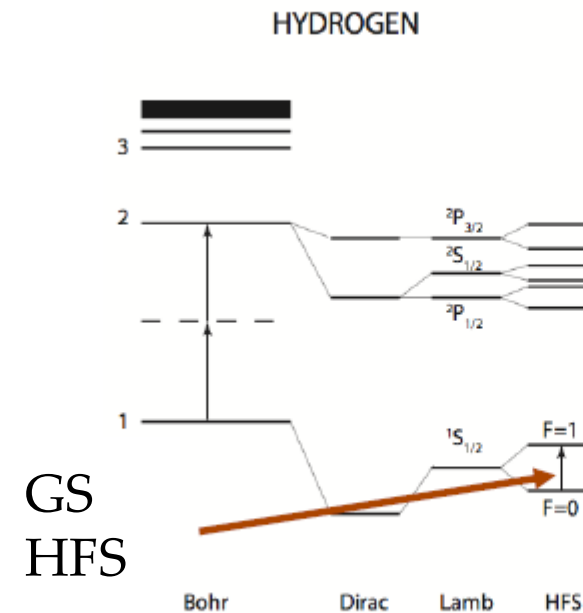
Why antimatter ?

- 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
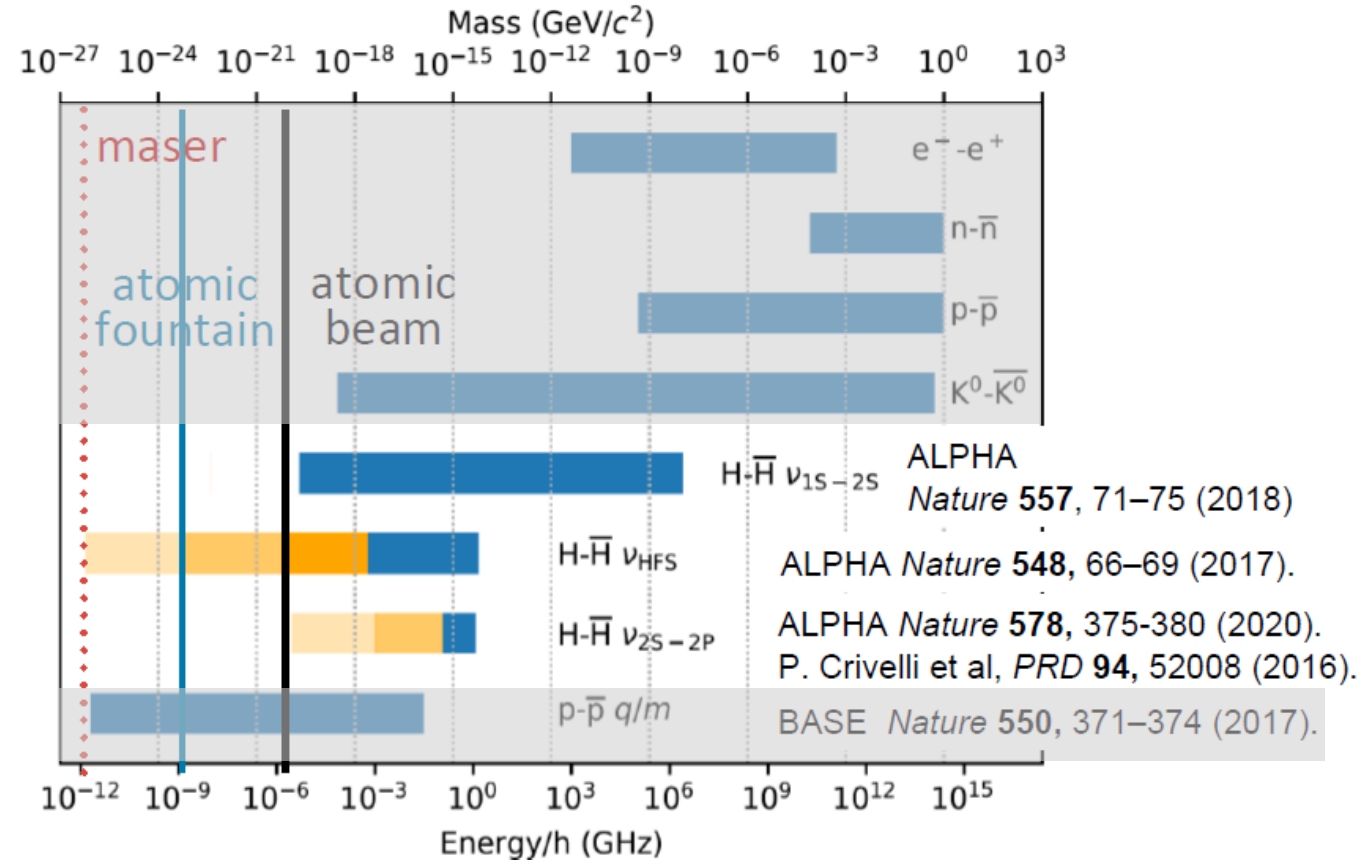

GS HFS

# Why the HFS of antihydrogen

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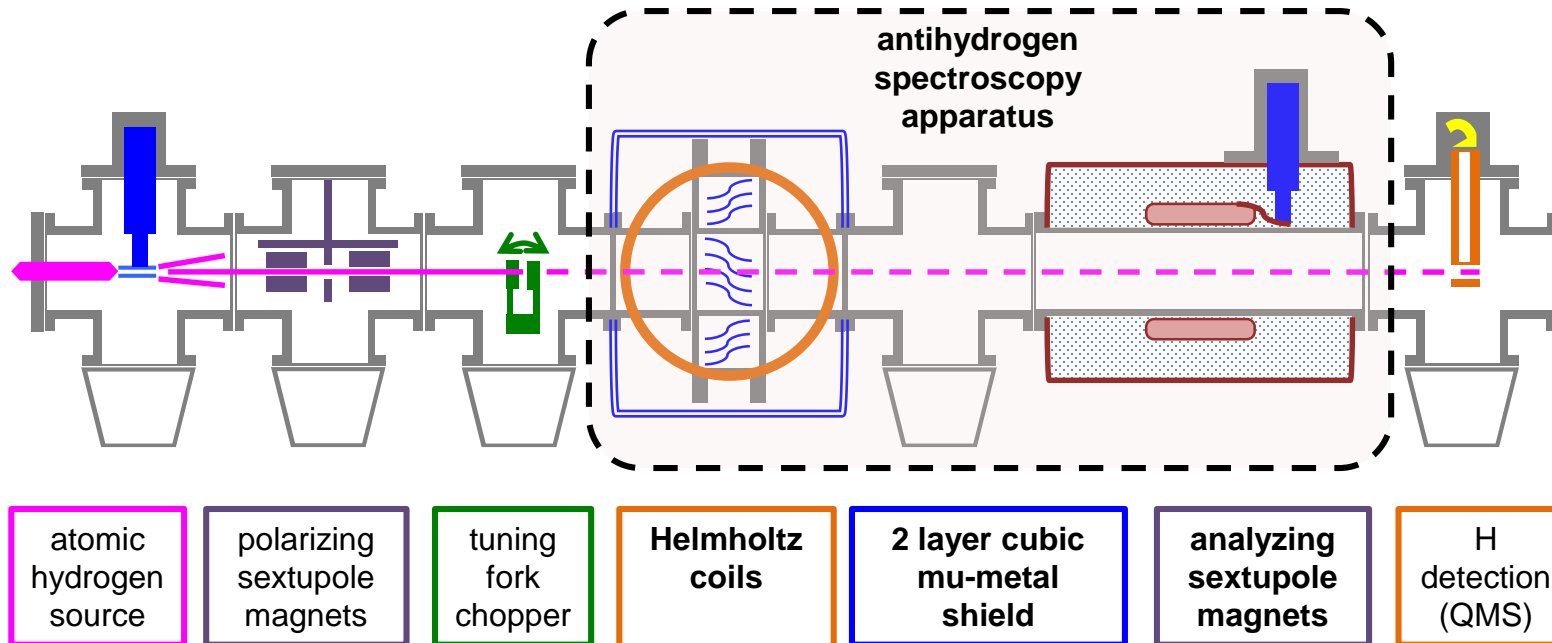   - Orange: planned
    - Yellow: potentially measurable

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

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

Why the HFS of antihydrogen

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

Overview

- The method
- Status of the experiment
- Work during LS2
- The beginning of the ELENA era
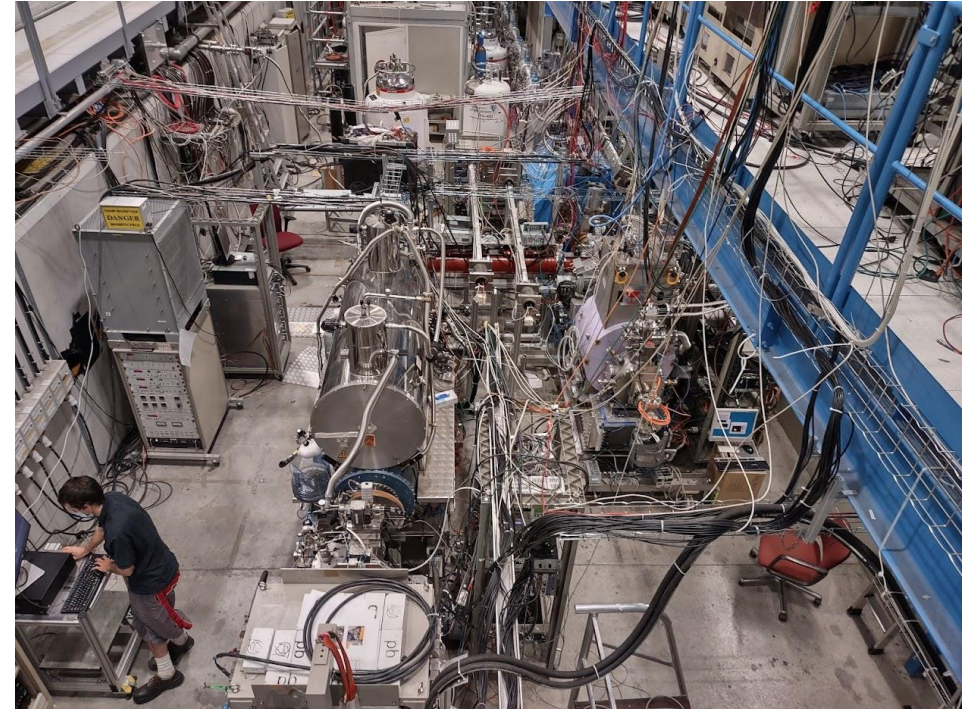
This talk will concentrate on the production and characterisation of an antihydrogen beam for the hyperfine spectroscopy measurement
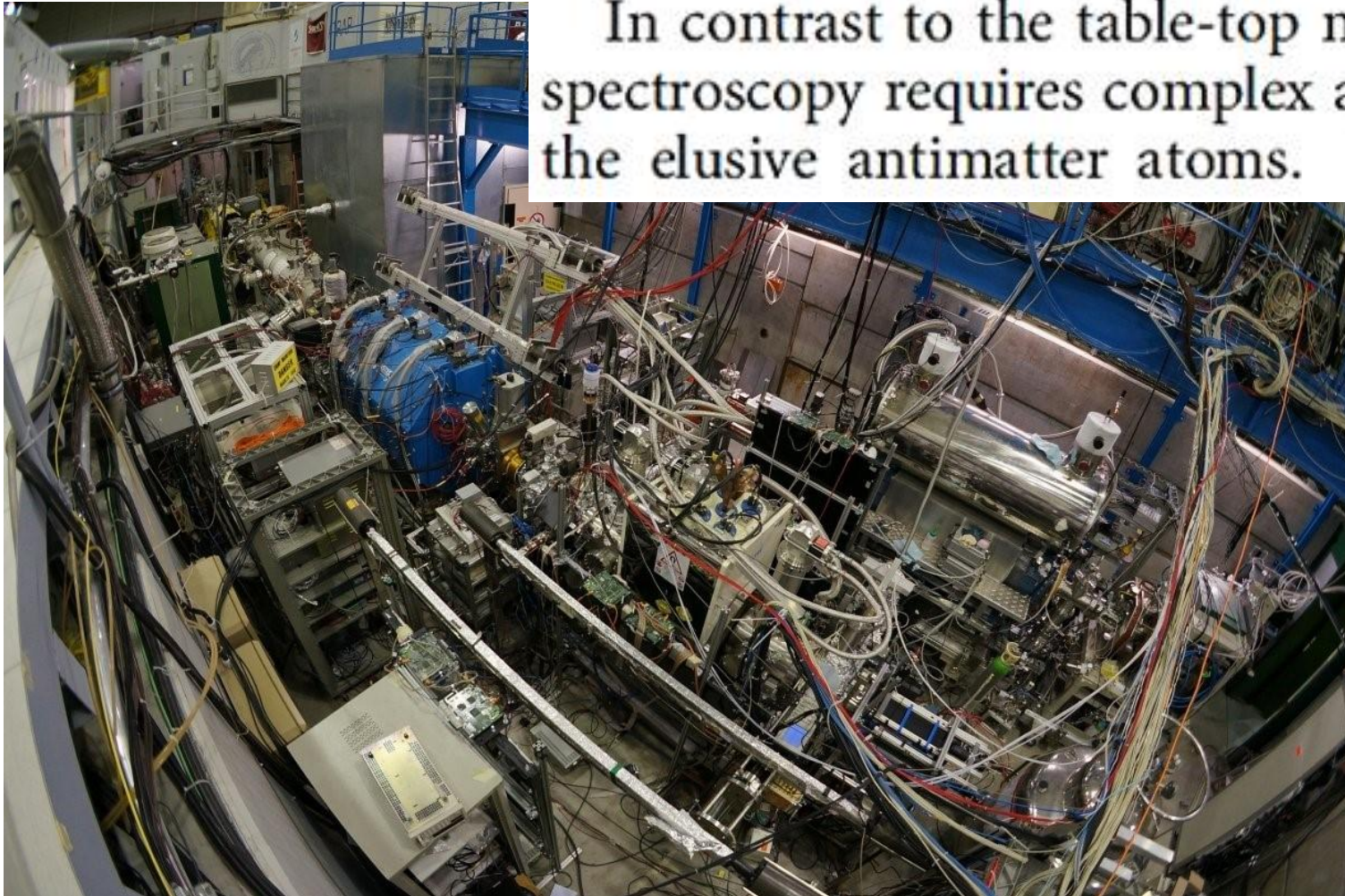
Hydrogen Spectroscopy

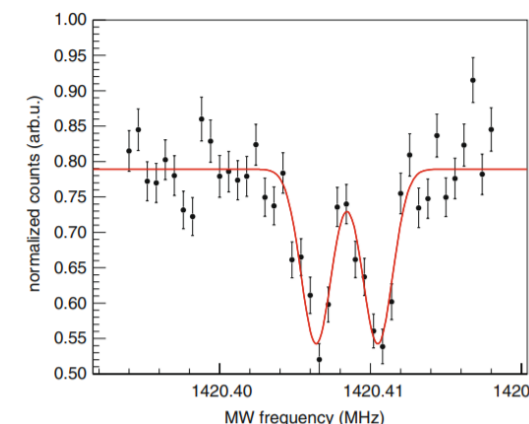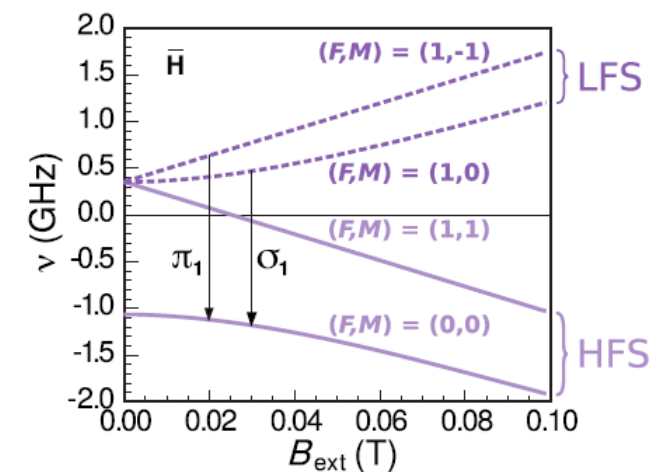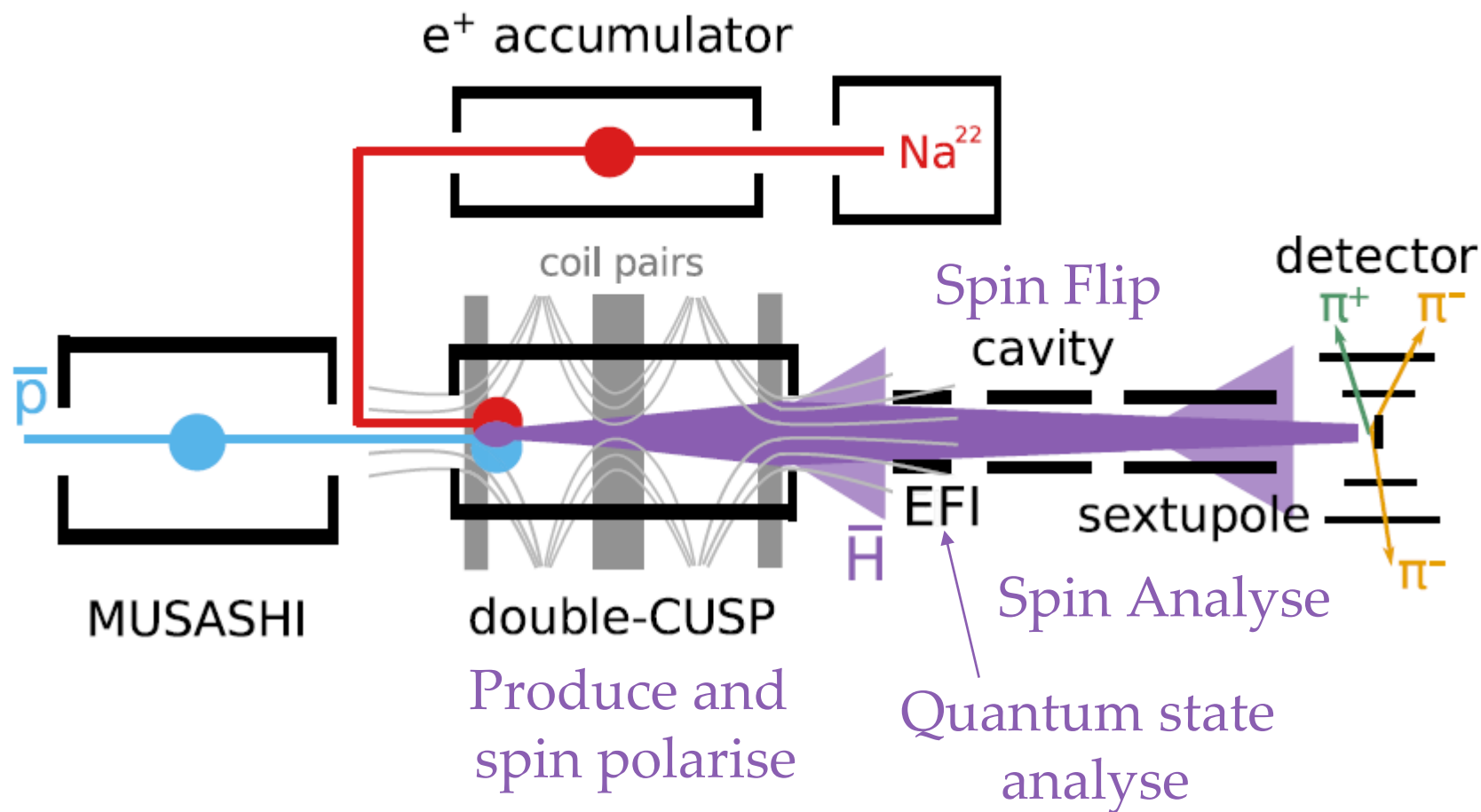| atomic hydrogen source | polarizing sextupole magnets | tuning fork chopper | **Helmholtz coils** | **2 layer cubic mu-metal shield** | **analyzing sextupole magnets** | H detection (QMS) |

Main Results

- line-shape understood in detail

- systematic effects? not on few ppb-level

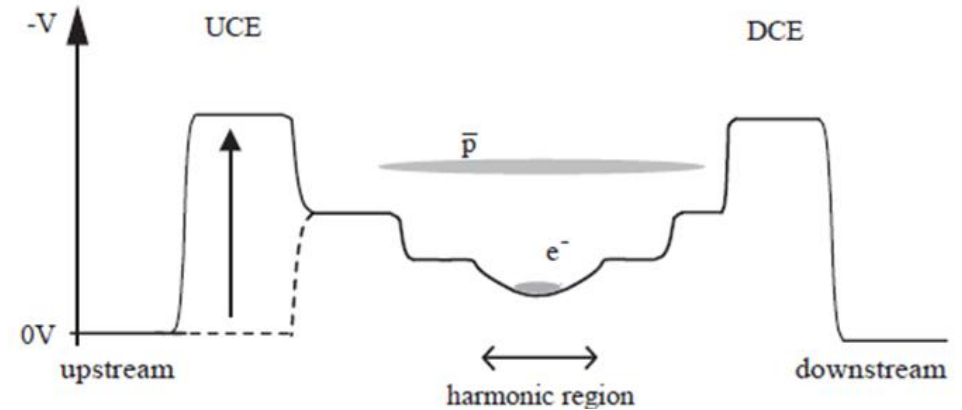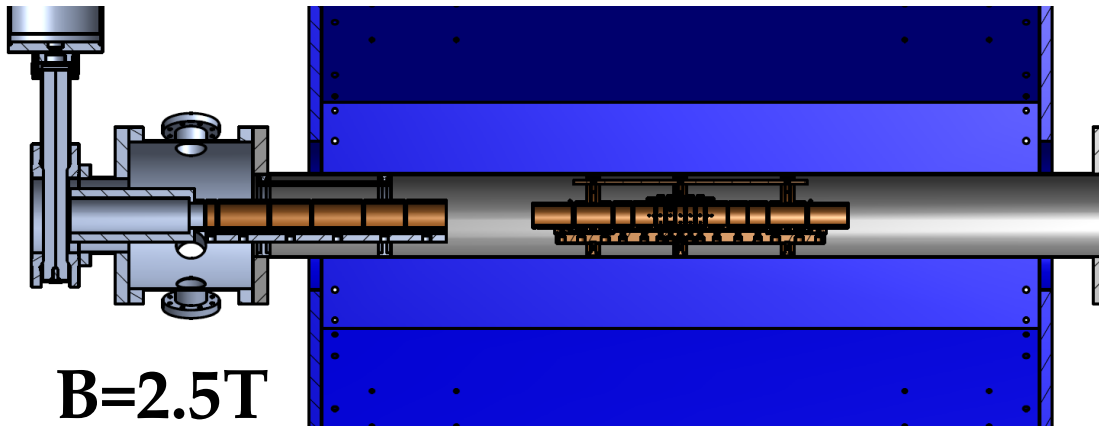- 8000 Hbar events on detector for ppm result (conservative estimate for σ-transition)
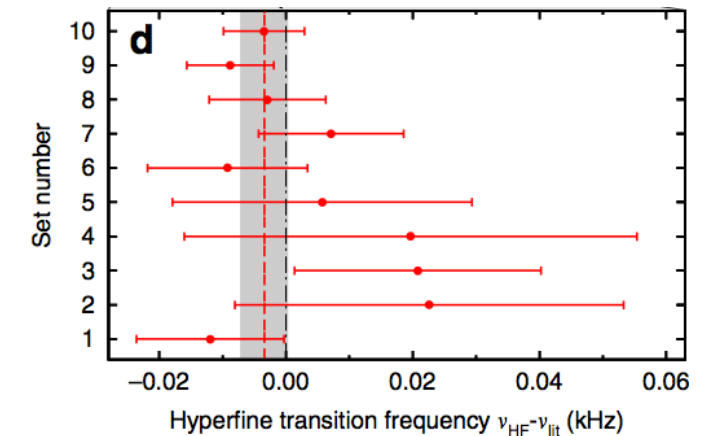
In contrast to the table-top matter experiments, antihydrogen spectroscopy requires complex apparatuses for the production of the elusive antimatter atoms.

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

e$^+$ accumulator

Na^{22}

coil pairs

Spin Flip

detector

cavity

π^+ π^-

$\bar{H}$

EFI

sextupole
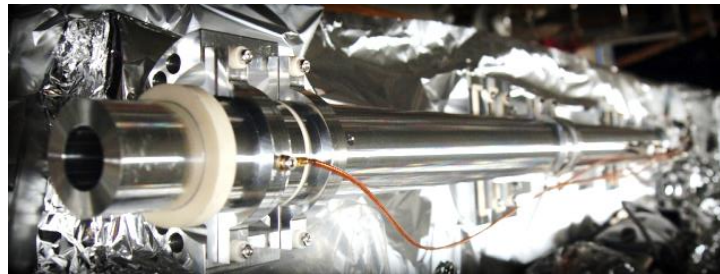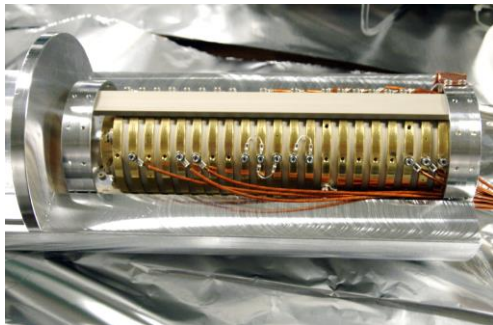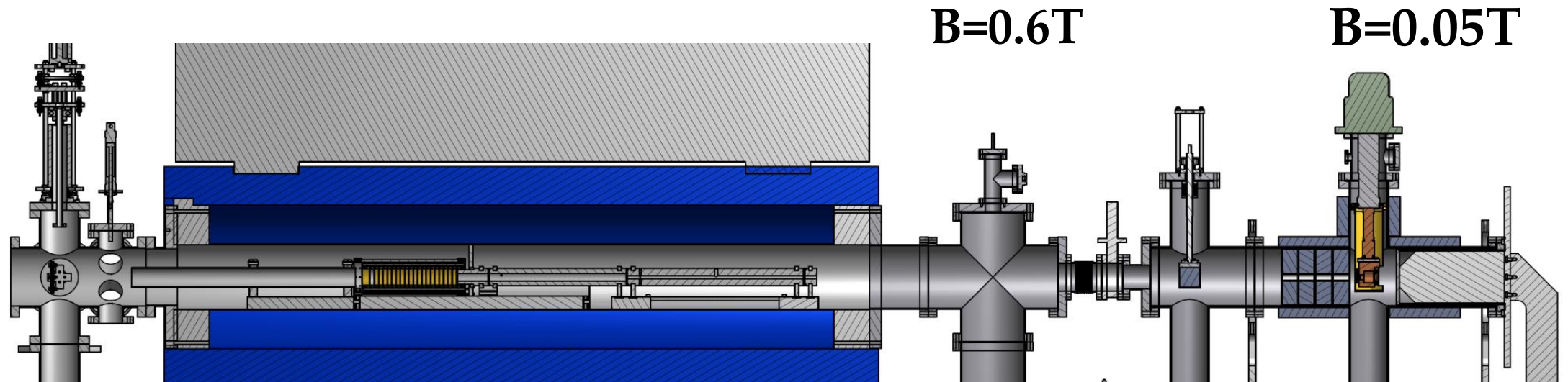
π^-

$\bar{p}$

MUSASHI

double-CUSP

Spin Analyse

Produce and spin polarise

Quantum state analyse

Antiproton Trap - MUSASHI

B=2.5T

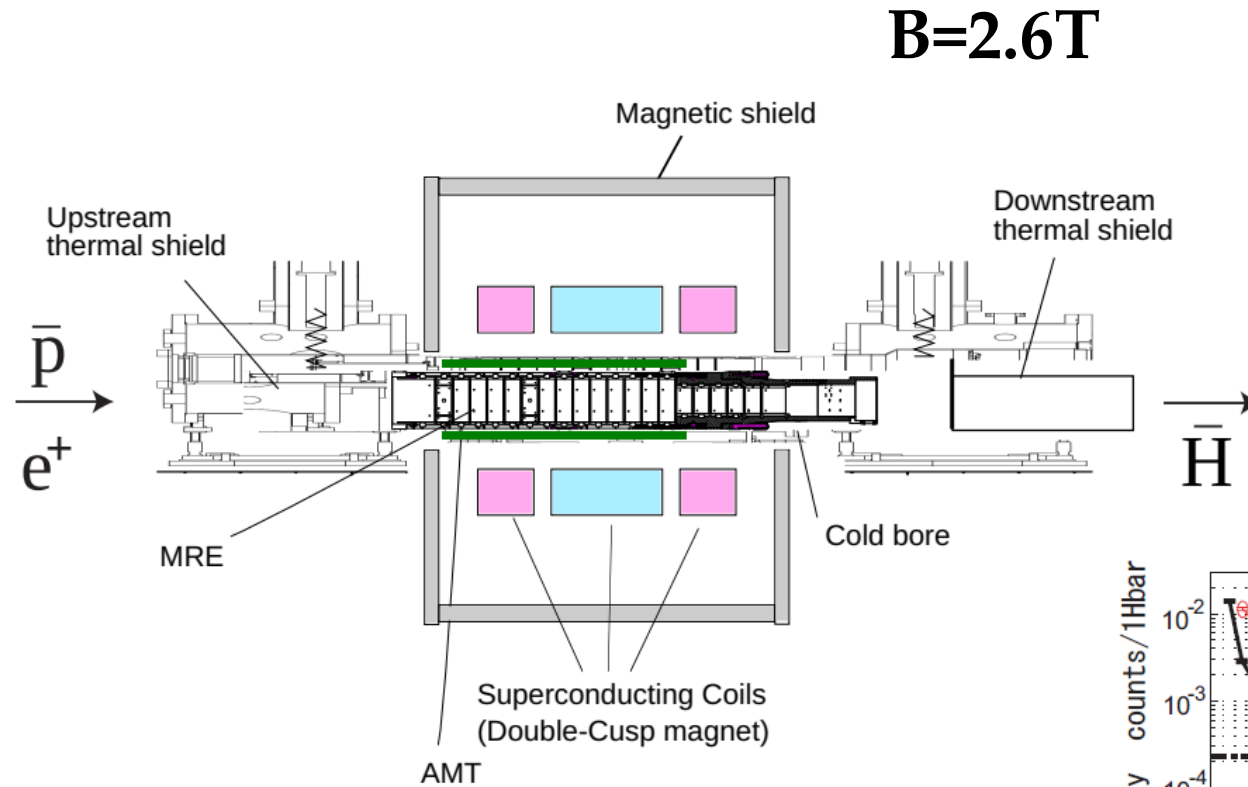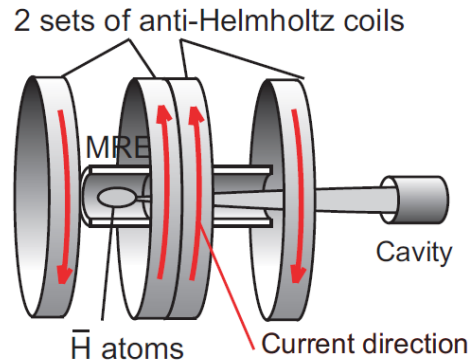

- Degrader foil reduces incoming antiproton energy to ~10keV
- Catching bias -12kV
- Antiprotons are cooled with $\sim 3 \times 10^8$ electrons
- 1-2 million antiprotons are trapped per AD cycle
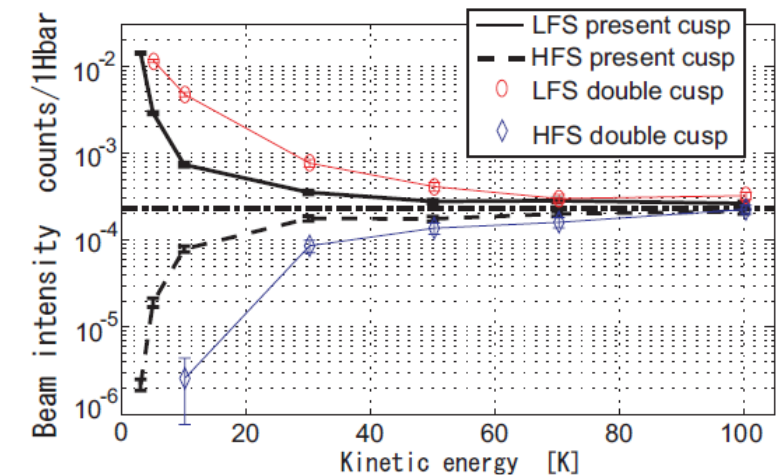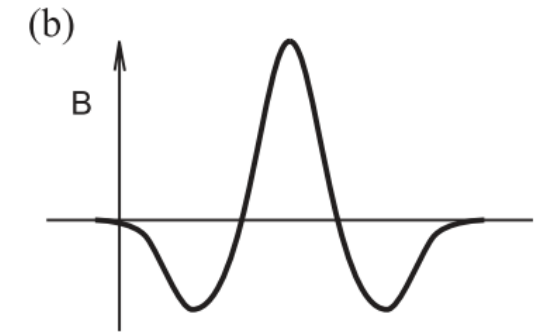- Antiprotons can be extracted with eV energies.

Positron Trap

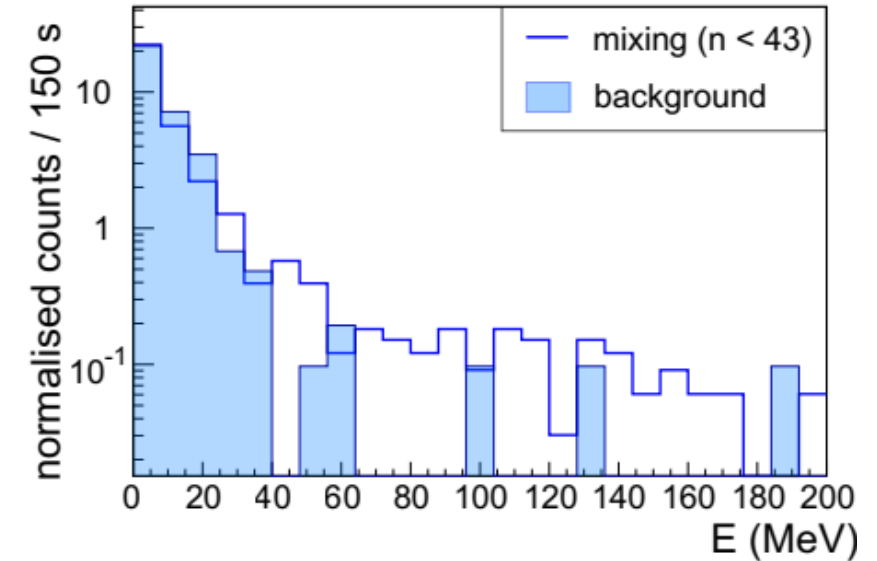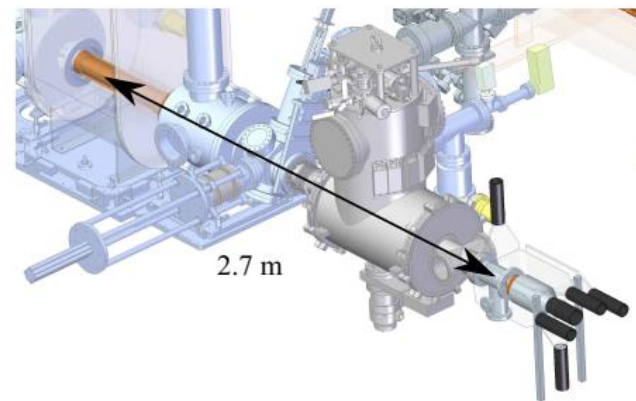B=0.6T   B=0.05T

Double Cusp Trap

B=2.6T

2 sets of anti-Helmholtz coils

MRE

H̄ atoms — Current direction

Cavity

Upstream thermal shield

Magnetic shield

Downstream thermal shield

P̄ →

e⁺

MRE

Superconducting Coils (Double-Cusp magnet)

AMT

Cold bore

H̄ →

(b) B

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.

Beam intensity counts/1Hbar

— LFS present cusp
--- HFS present cusp
○ LFS double cusp
◇ HFS double cusp

Kinetic energy [K]

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**).
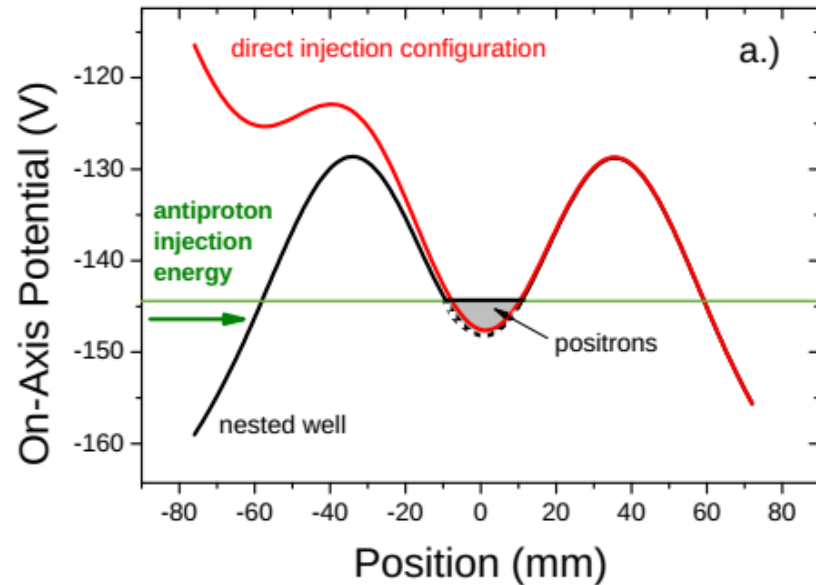
Measurement of Quantum State Distribution

- The data analysis made use of machine learning techniques
  - Trained with $\bar{p}$ 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
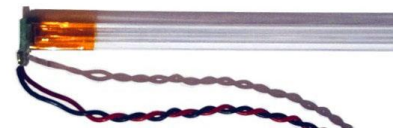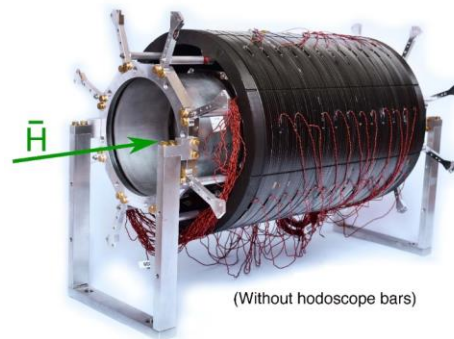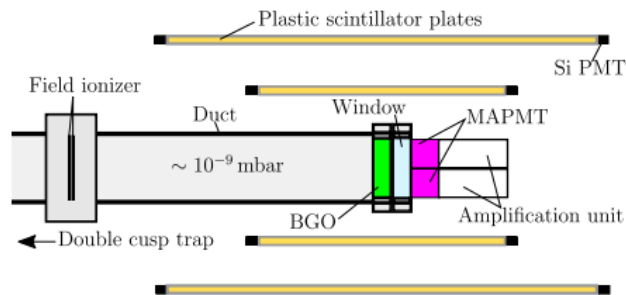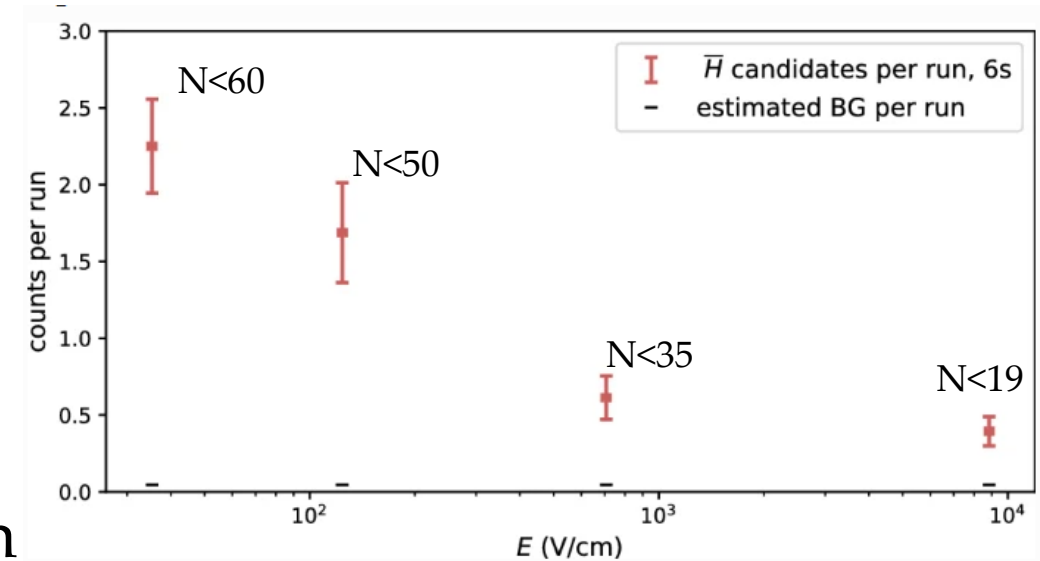
Status

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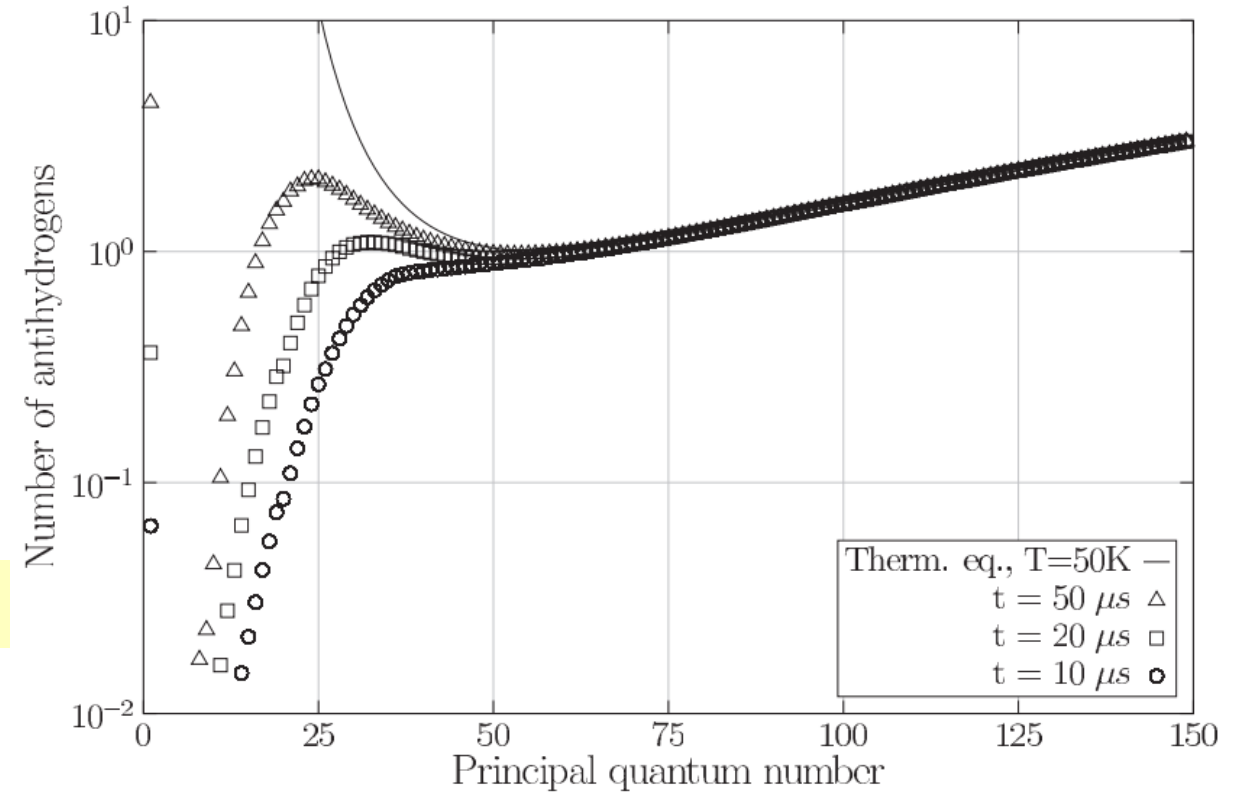- **How do we improve the beam intensity and the number of ground state atoms?**

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.

How to make more Hbar?

- Modelling of the formation and scattering of antihydrogen formation

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

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

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.
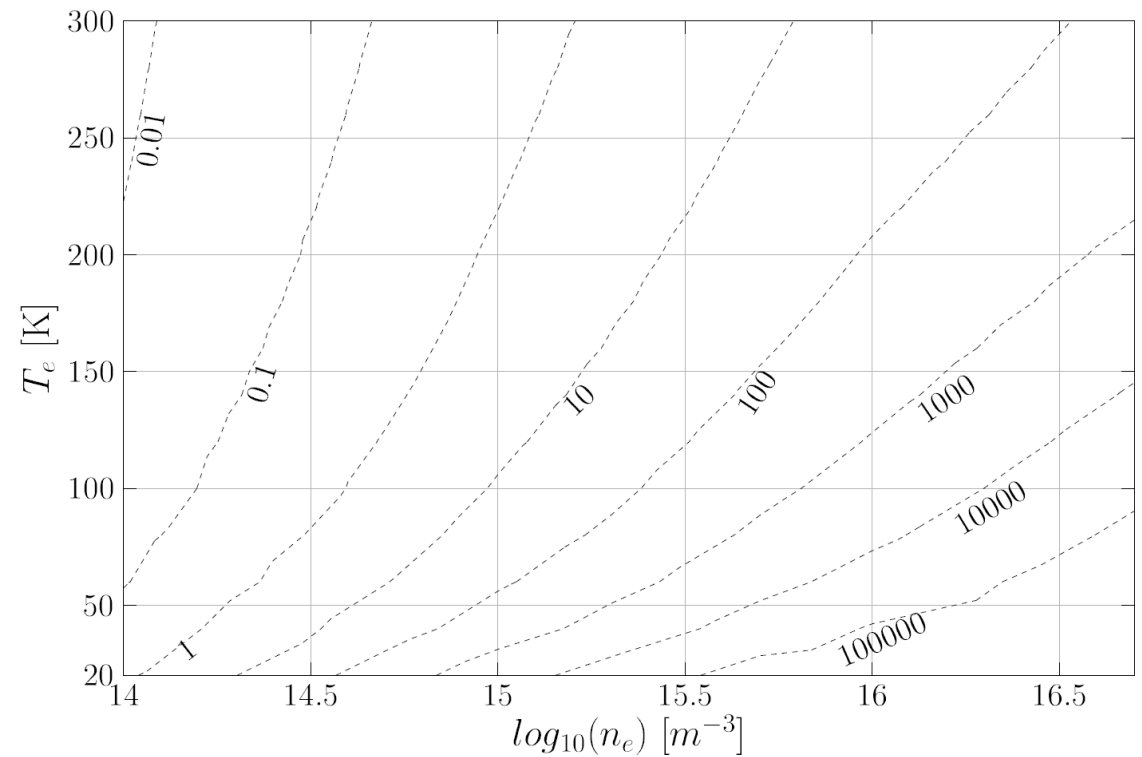
Plasma Temperature

- 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!**

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.
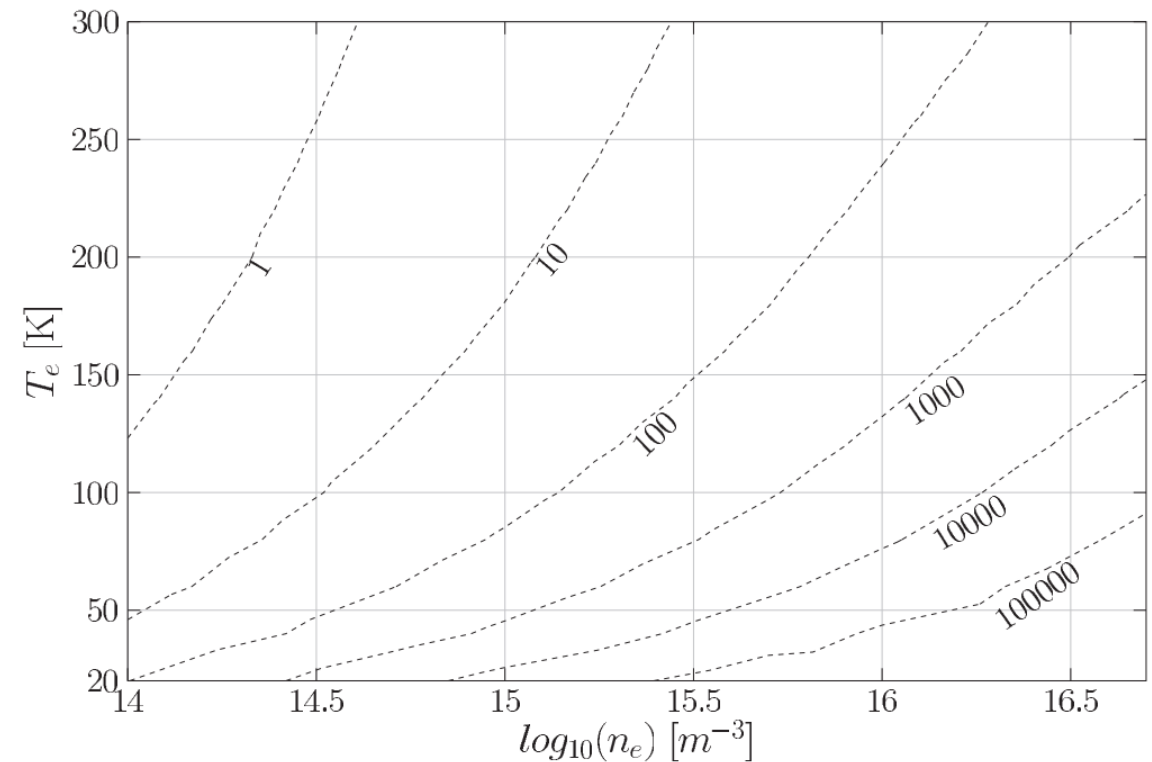
Control of electron/positron plasma properties

- 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
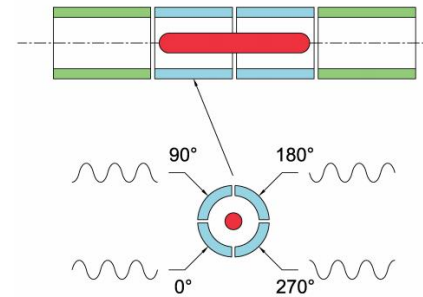
Radius

Electrical Potential
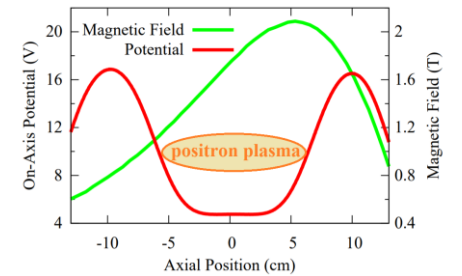
Length

Evaporation
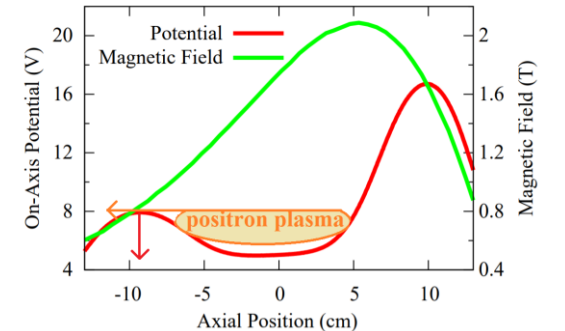
Number & Temperature
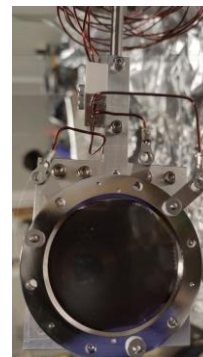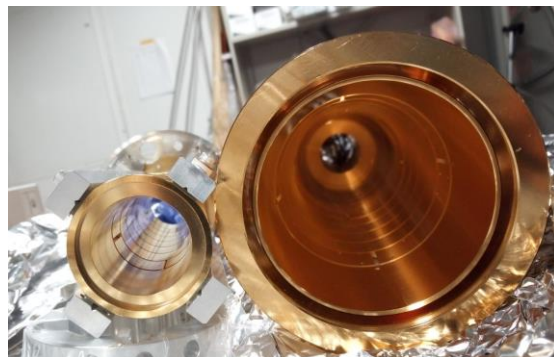
Control of electron/positron plasma properties

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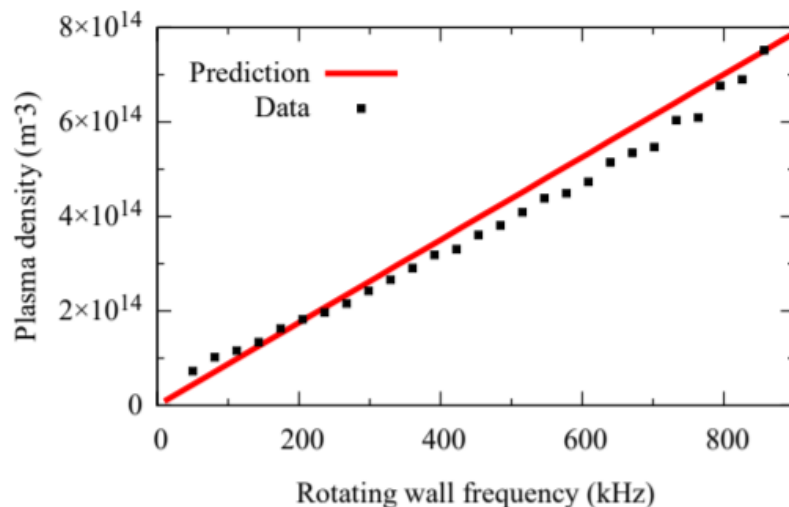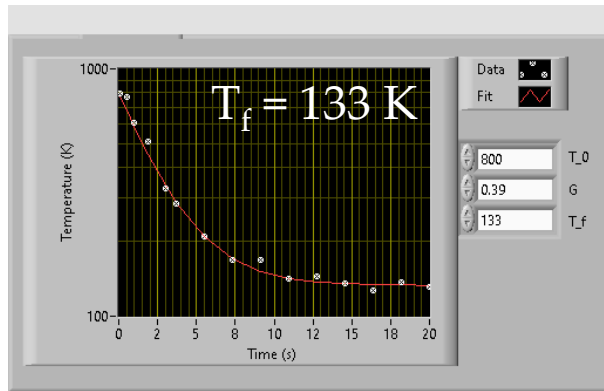

Property	Mean	SD
r_p (mm)	0.417	0.003
T (K)	360	30
N_f (10^6)	11.0	0.3

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.

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.

Plasma Cooling Rate

$T_f = 133 \text{ K}$

$T_f = 105 \text{ K}$

$T_f = 118 \text{ K}$

$T_f = 130 \text{ K}$

$T_w = 35\text{K}$

Heating Rate

$T_f = T_w + H / G$

Cyclotron Cooling Rate

dln(r)/dt = 1.2e-4 s^{-1}
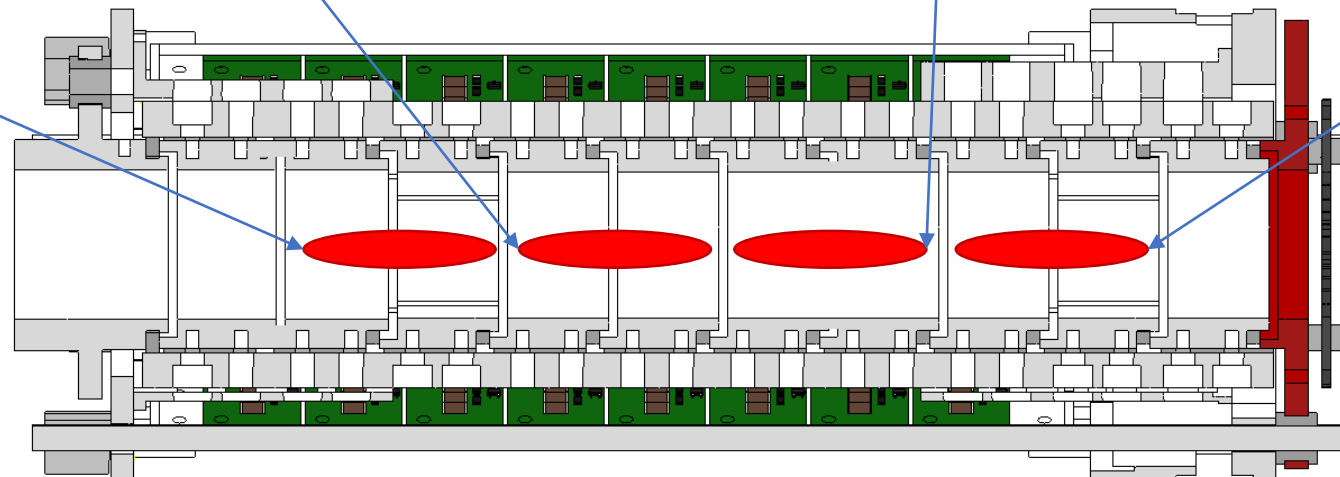
Name:	u13	u12	u11	u10	u9	u8	u7	u6	u5	u4	u3
Filter:	pulsed	slow	slow	none	slow	slow	slow	slow	none	slow	slow
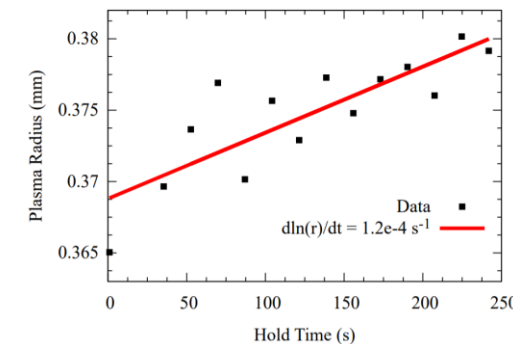
Plasma cooling : radiation environment

Closed

Partly Open

Open

plasma

Higaki shield

window
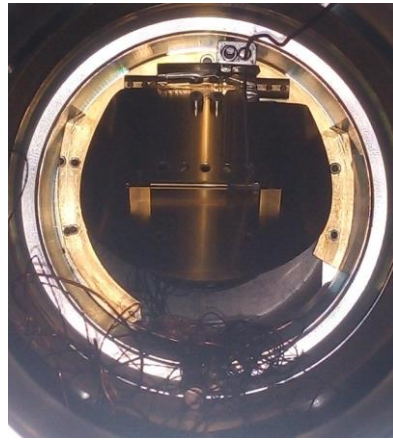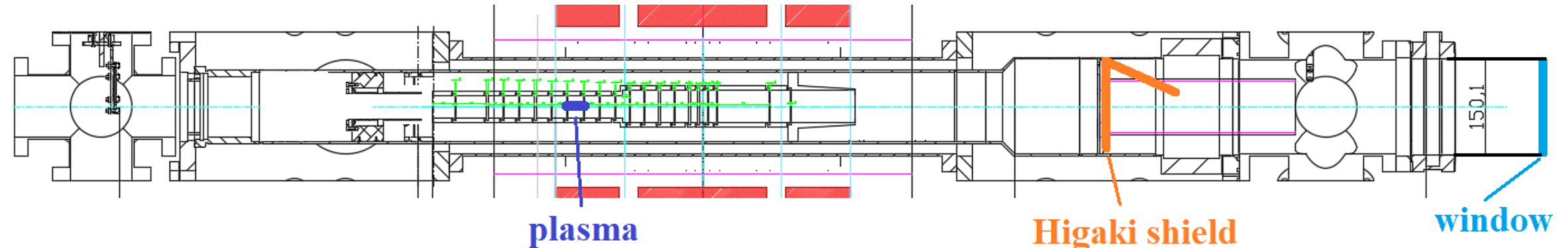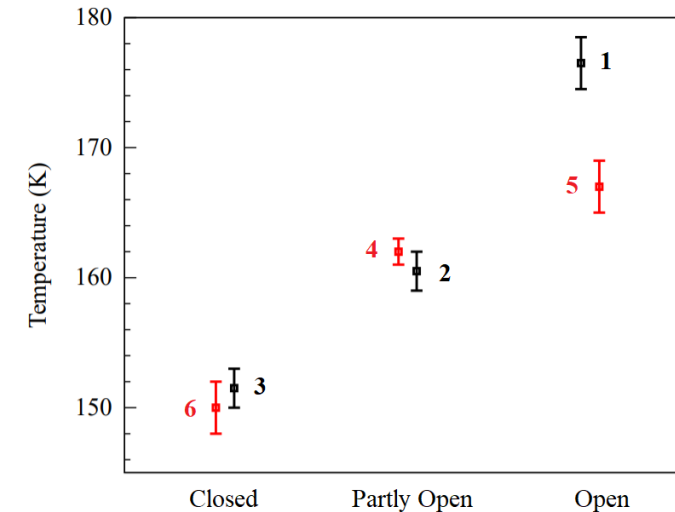
Double Cusp Trap

Ceramic "bracelet" to absorb cyclotron radiation from the plasma
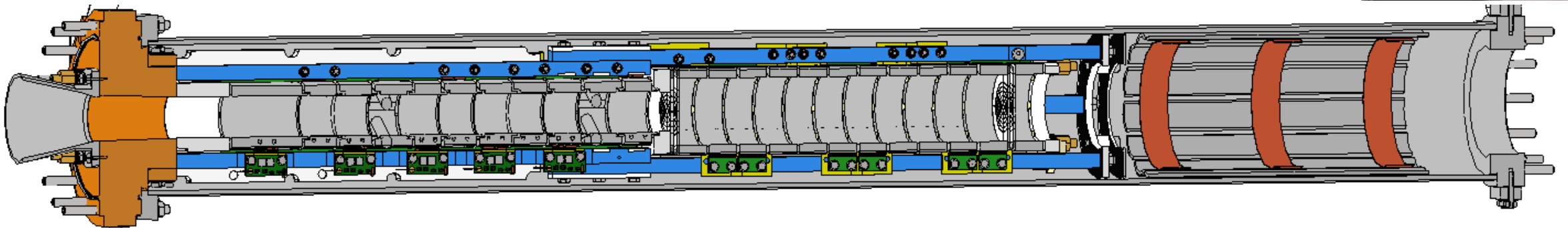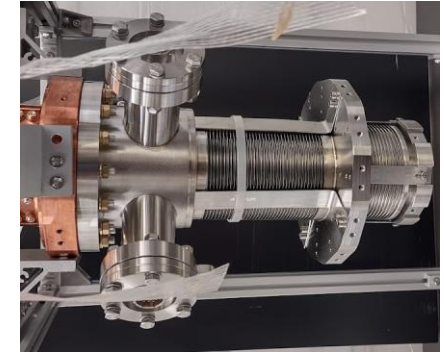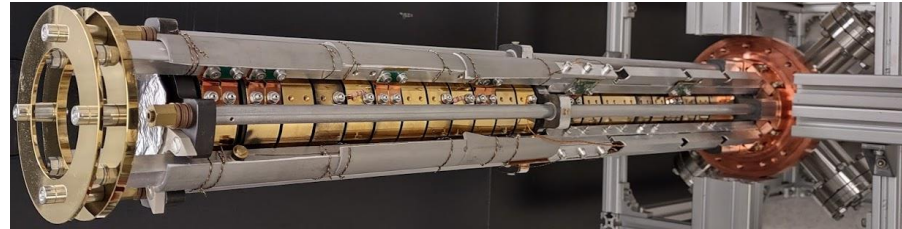
High transparency <u>copper mesh</u> to reflect incoming microwaves
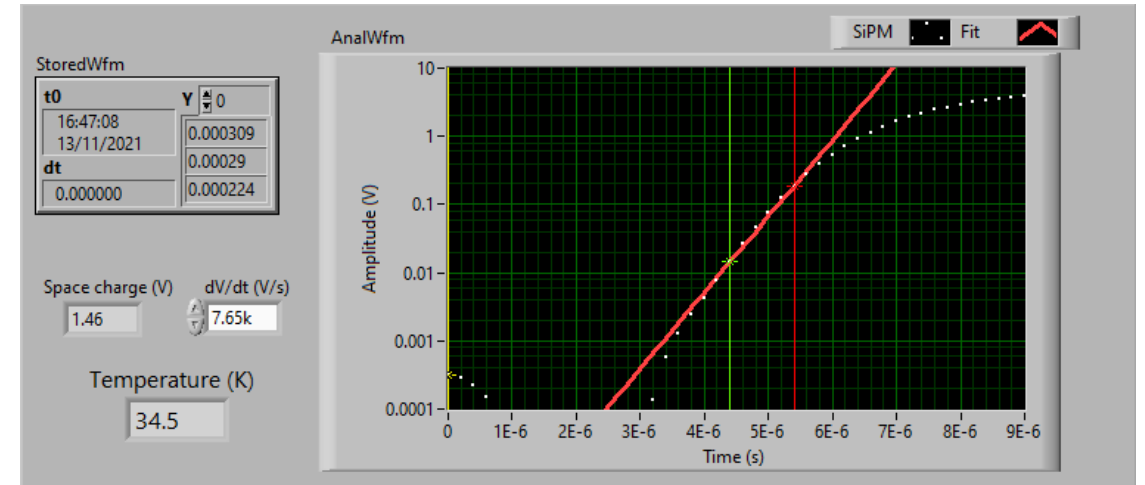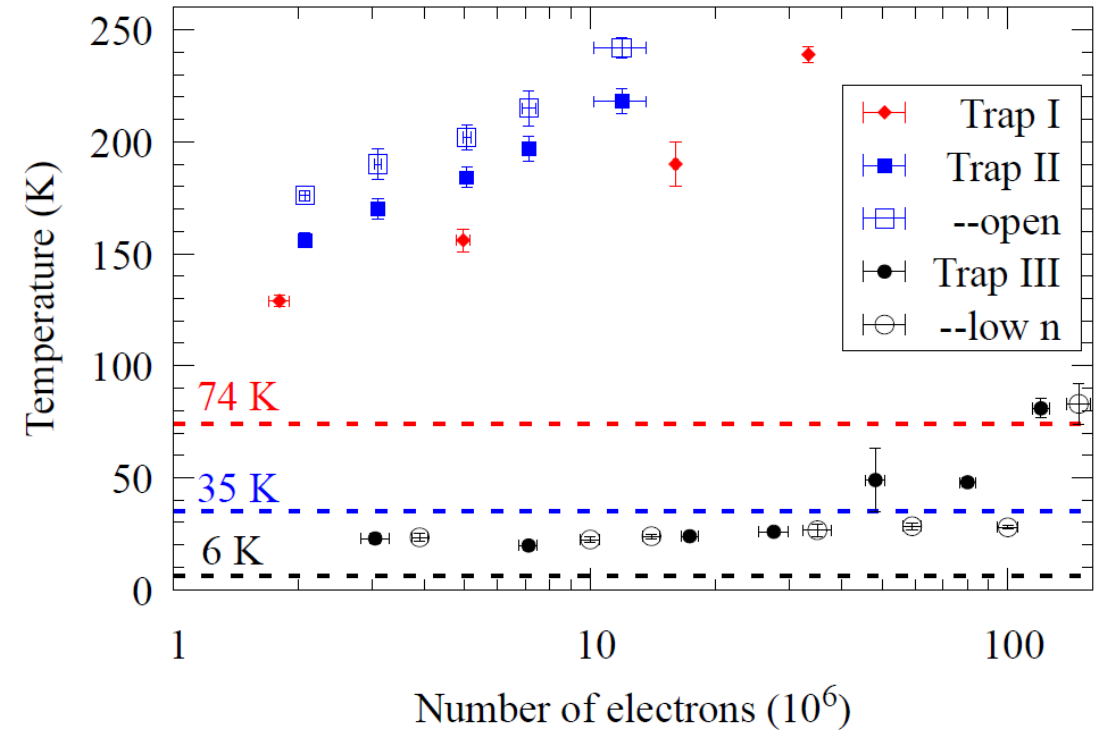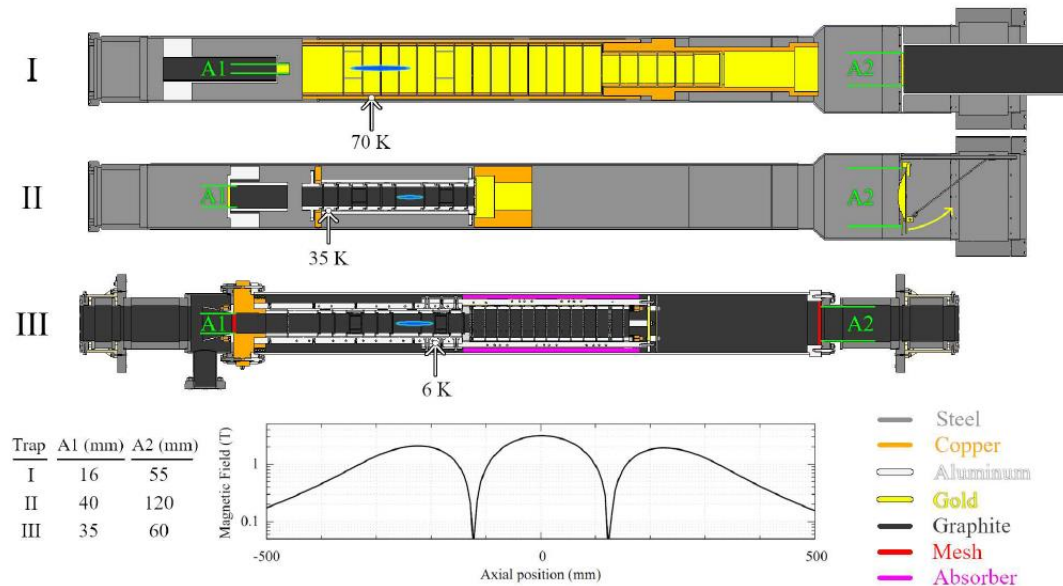0.25 mm pitch
0.03 mm wire diameter
>20 dB attenuation at 60 GHz
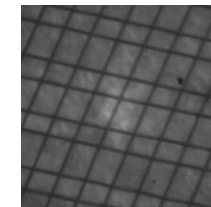
Double Cusp Trap

- 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
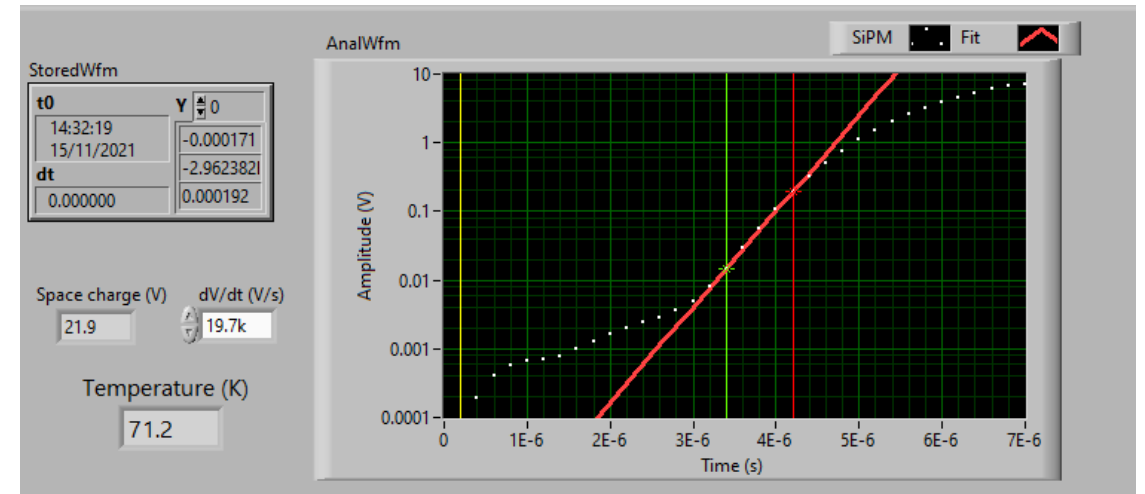
Double Cusp Trap

- Electrode temperature 5-6 K
 - Approximately 10 K colder than the previous design

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 and the cold positrons mixed with antiprotons
- 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
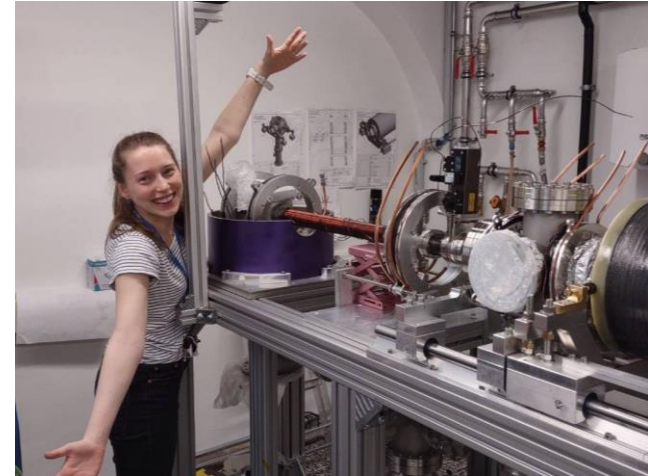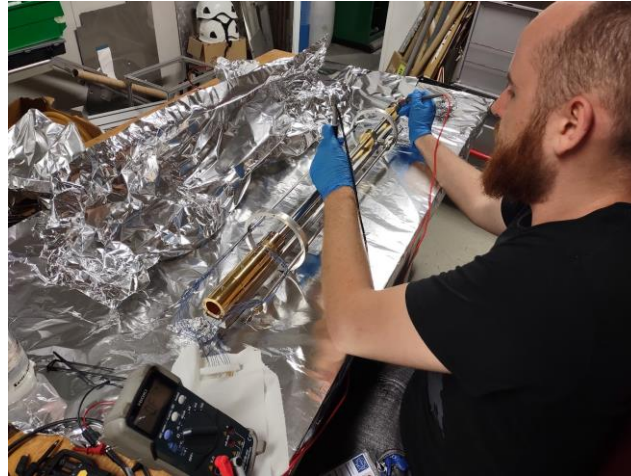
Full Collaboration

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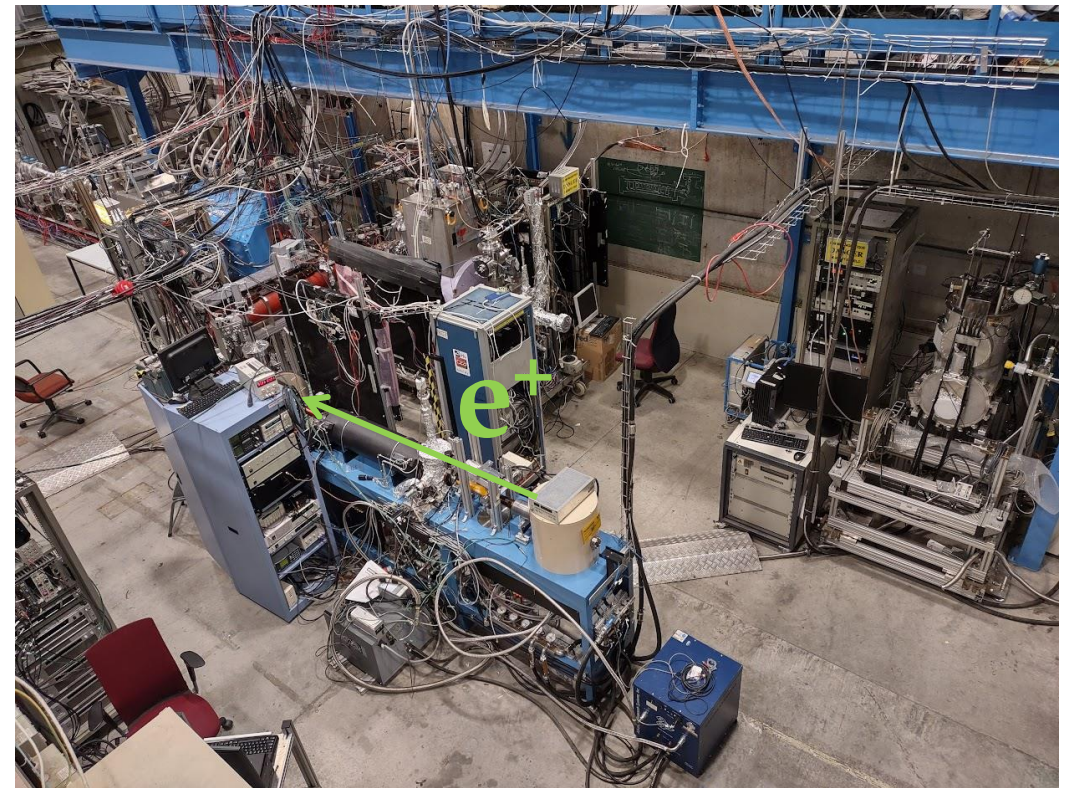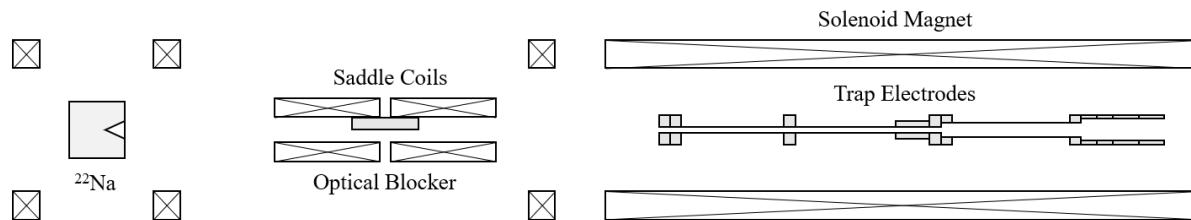[12] Department of Physics, Tokyo University of Science, 162-8601 Tokyo, Japan

[13] RIKEN Nishina Center for Accelerator-Based Science, 351-0198 Saitama,

Backup

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.
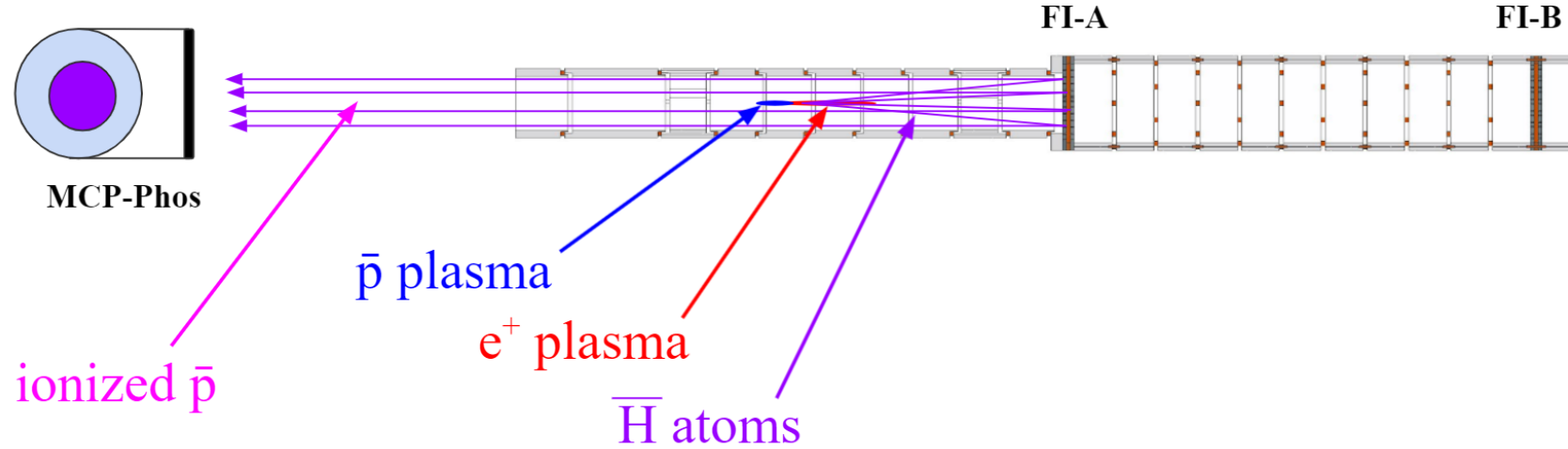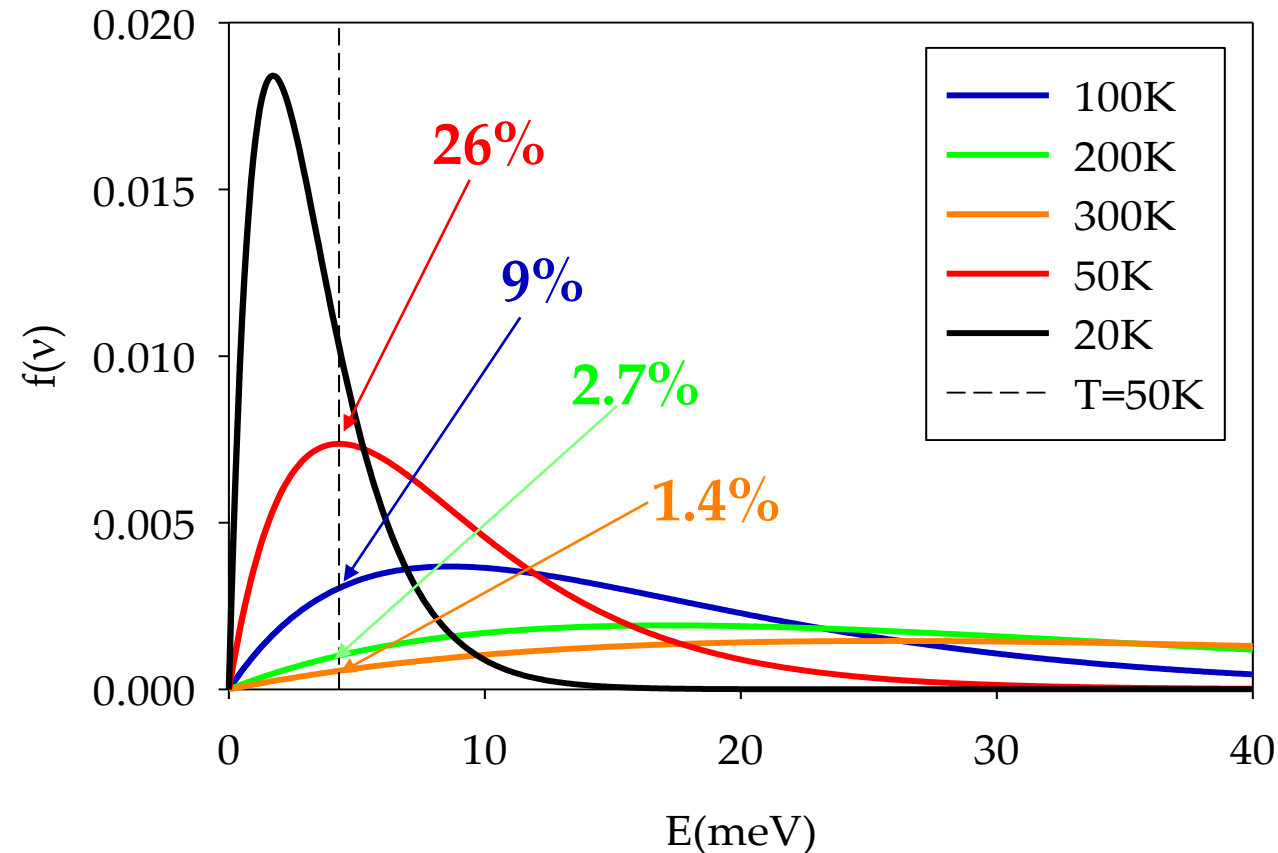
Positron Accumulator

- 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
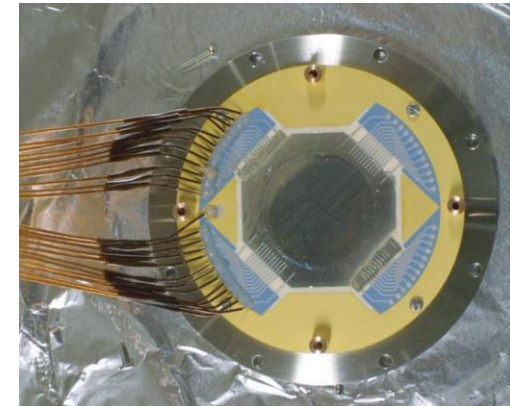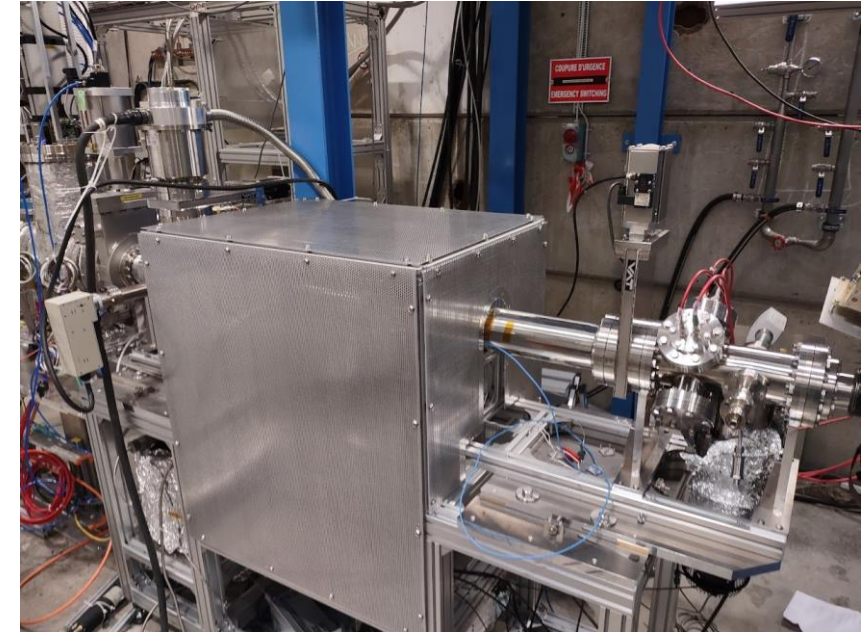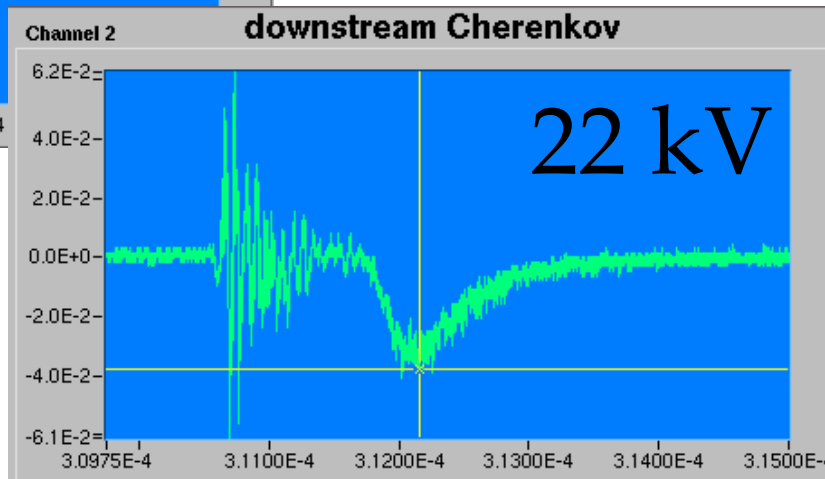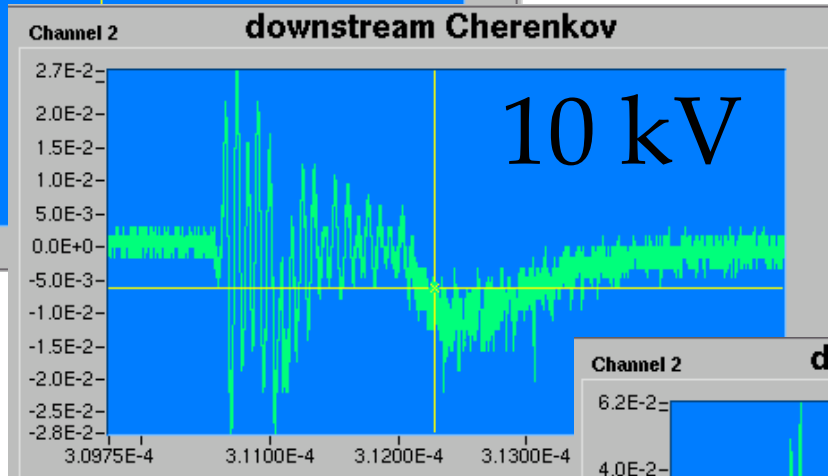
Field Ionizer

FI-A   FI-B

MCP-Phos

$\bar{p}$ plasma

e^+ plasma

ionized $\bar{p}$

$\overline{H}$ atoms
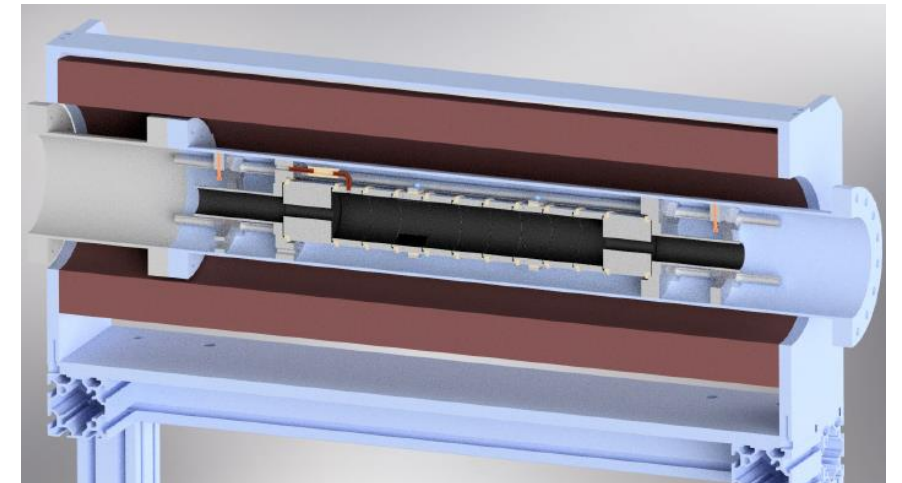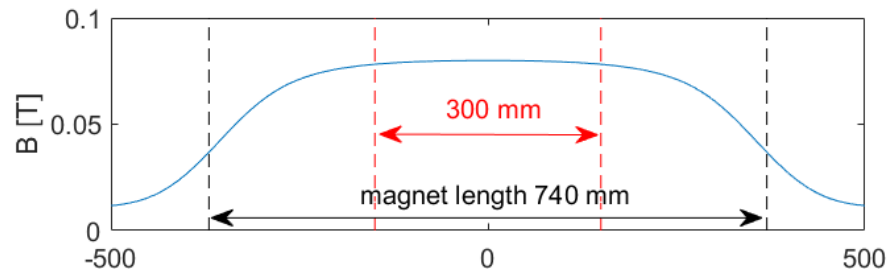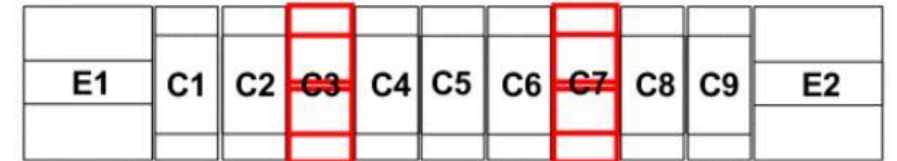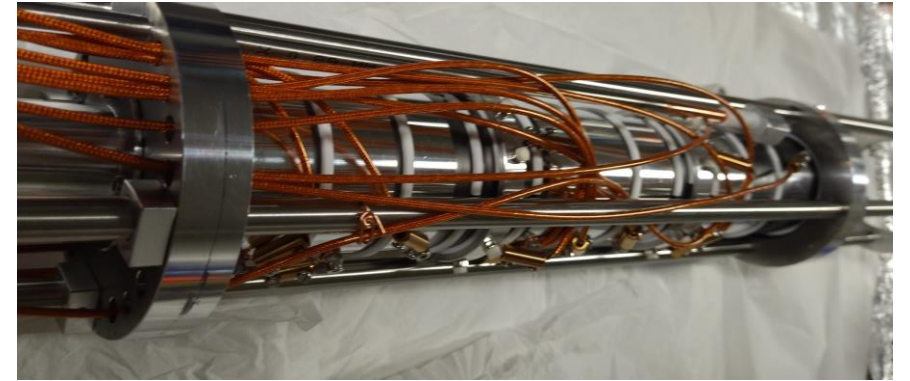
Why start with cold positrons?

Drift Tube
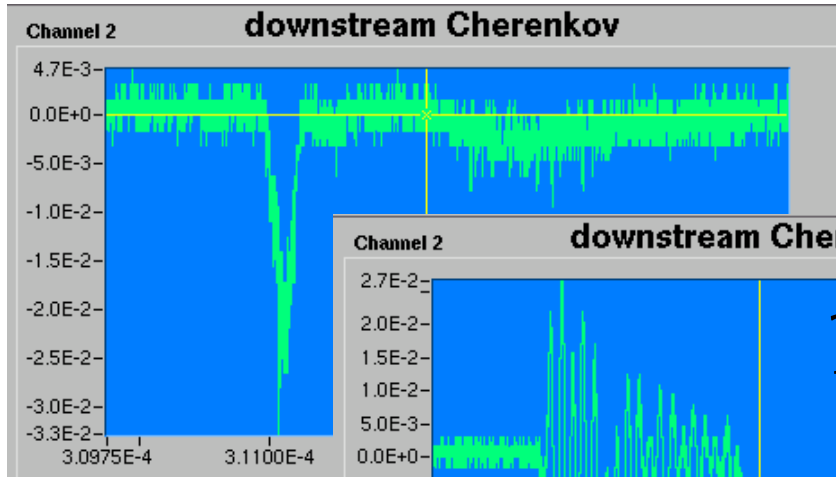
Proton Source

- 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
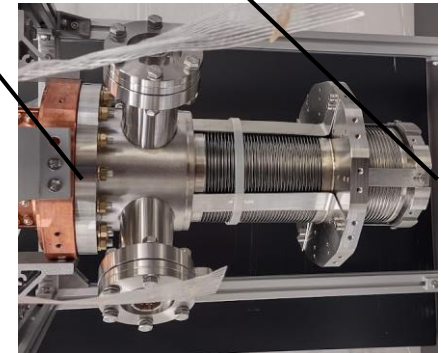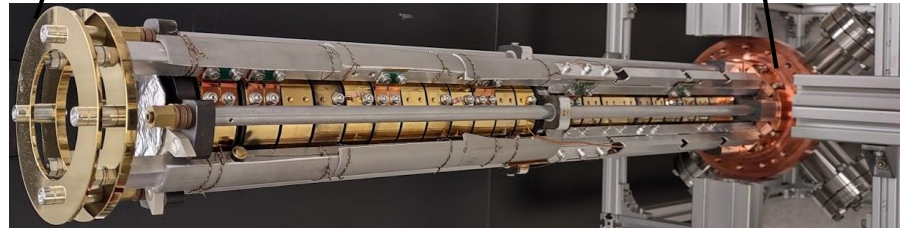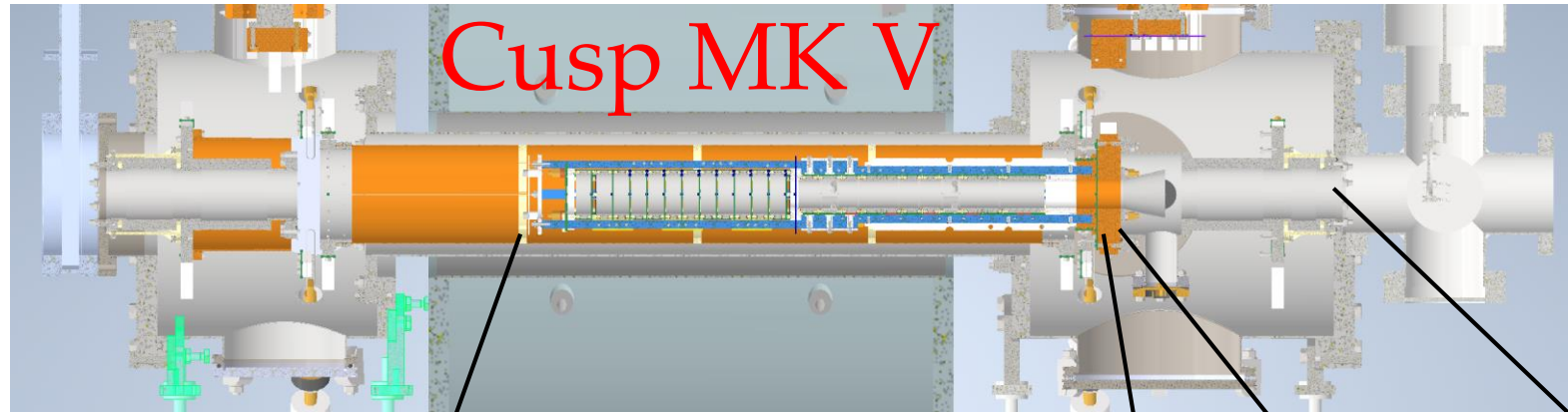

electron gun   gas inlet   ion extraction
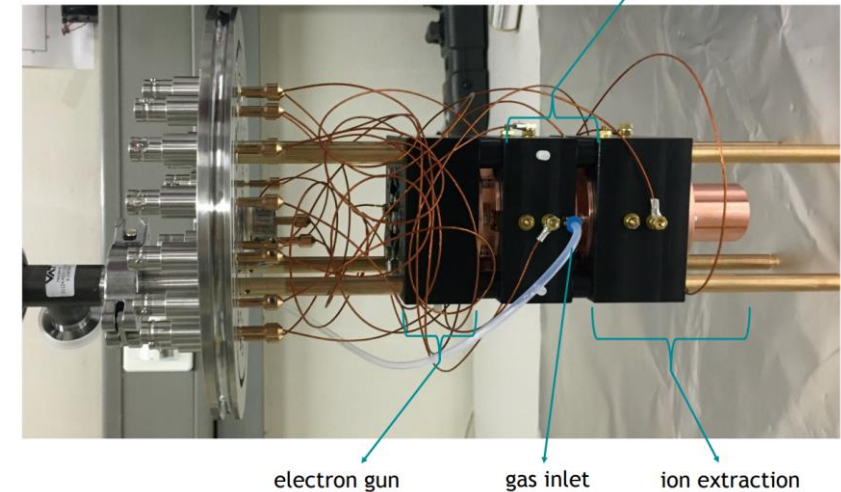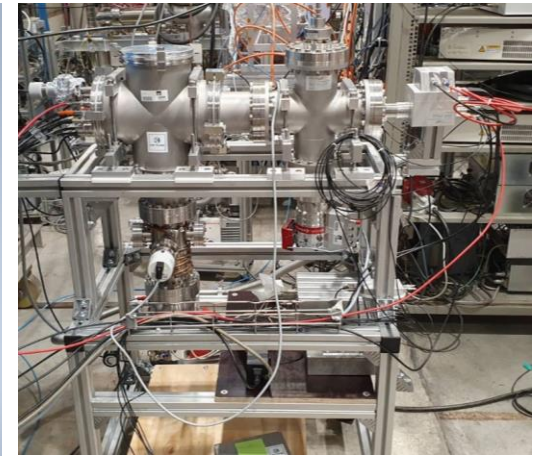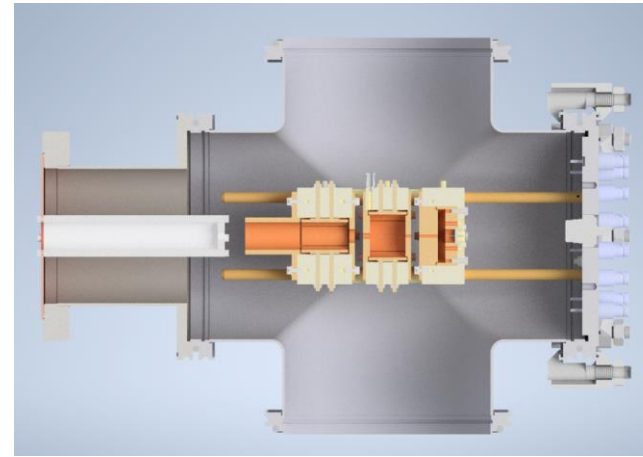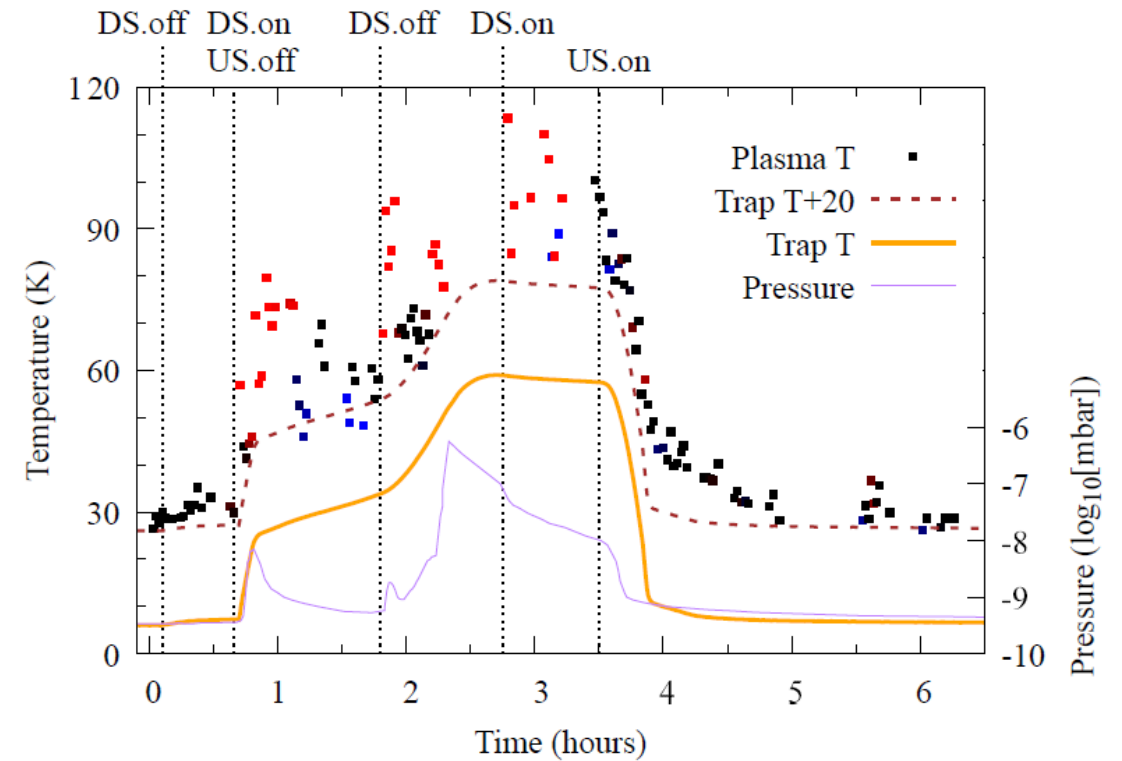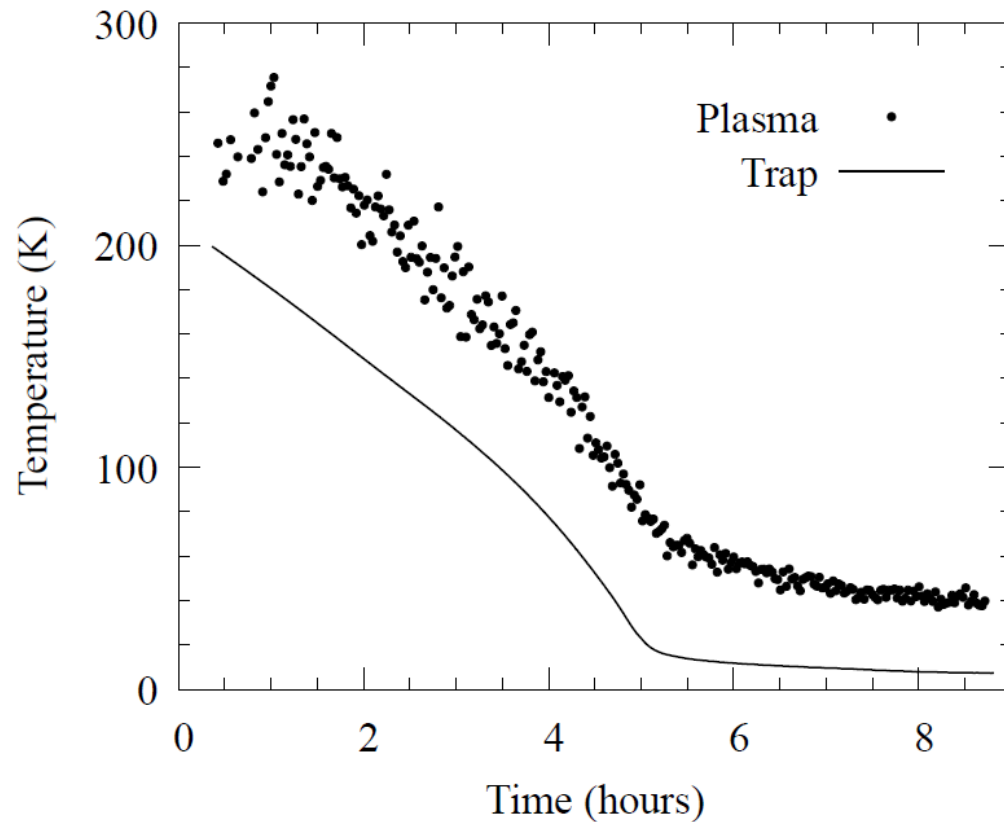
Proton Source

- 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
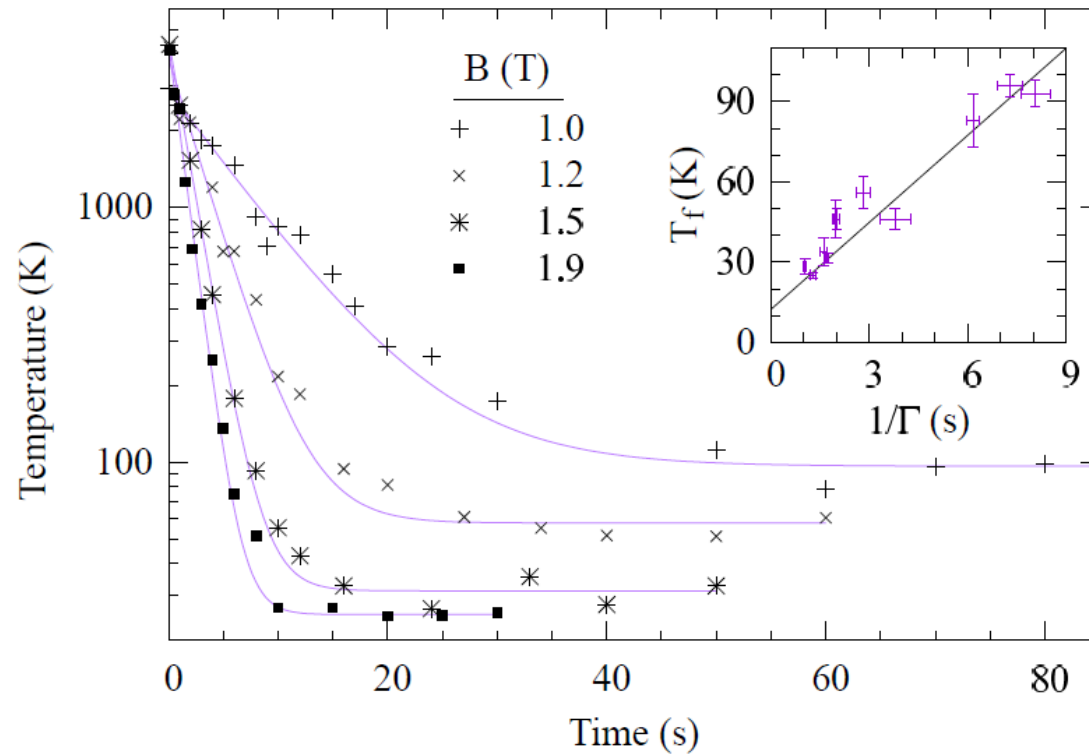- Unfortunately time ran out for work with protons so it was not possible to try to produce Ry-H

Double Cusp Trap

Cusp MK V
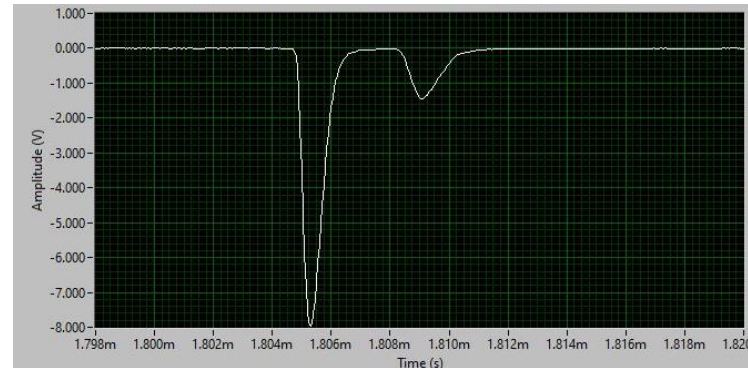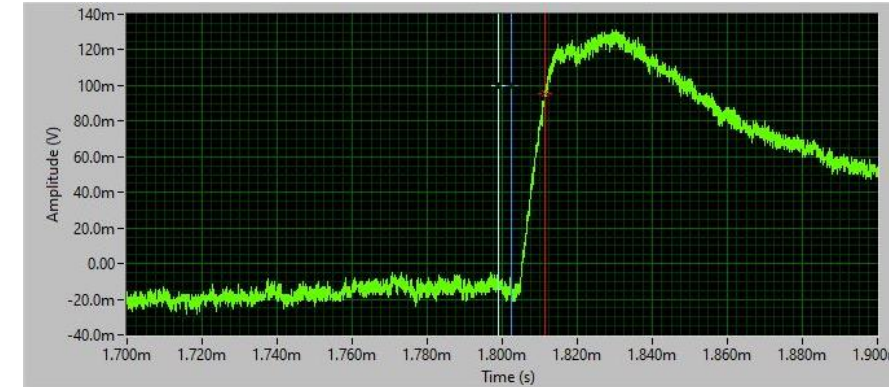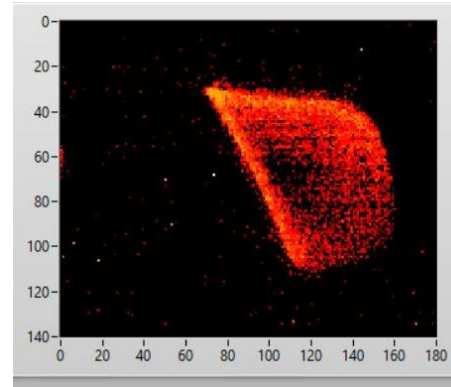
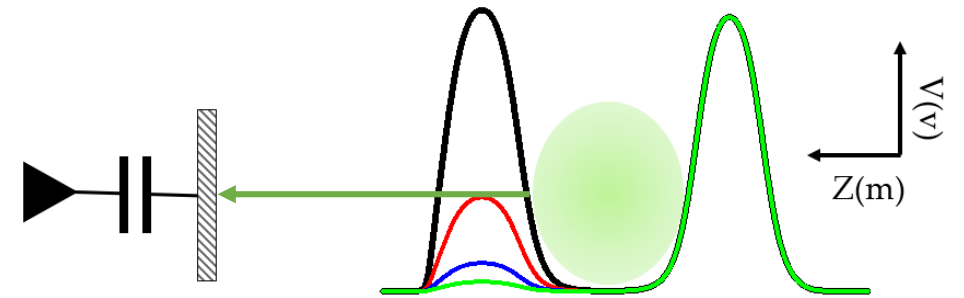# Pressure and Trap Temperature Plasma Temperature Dependence
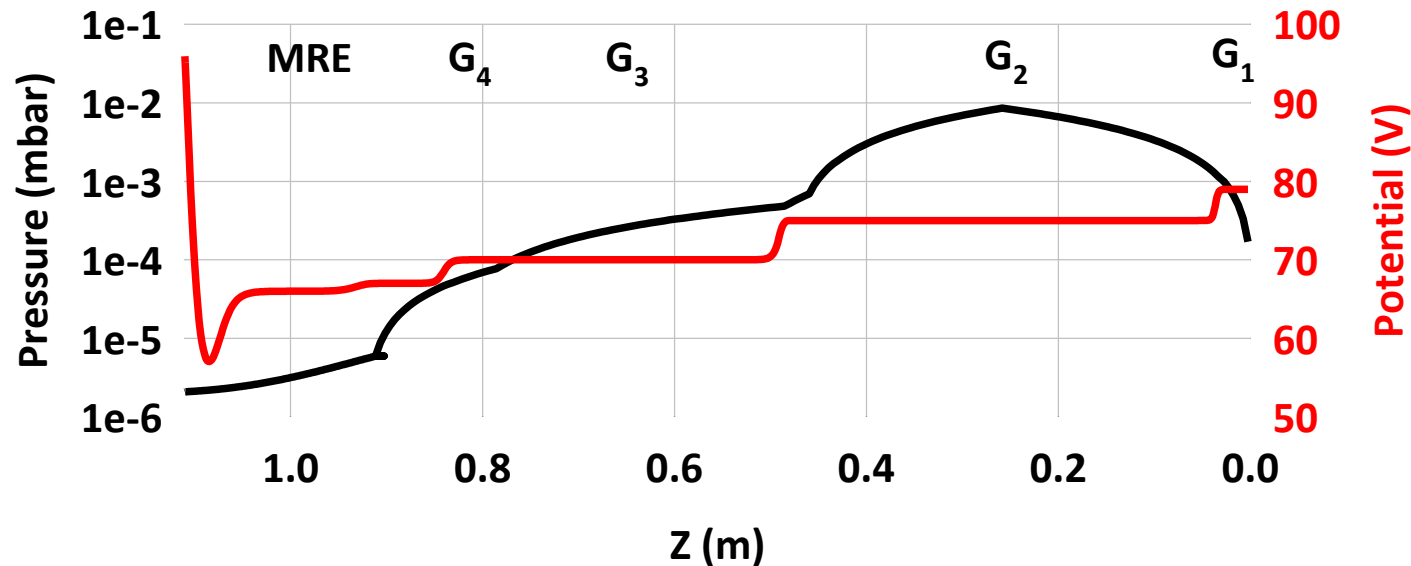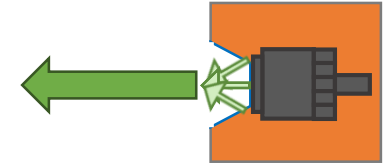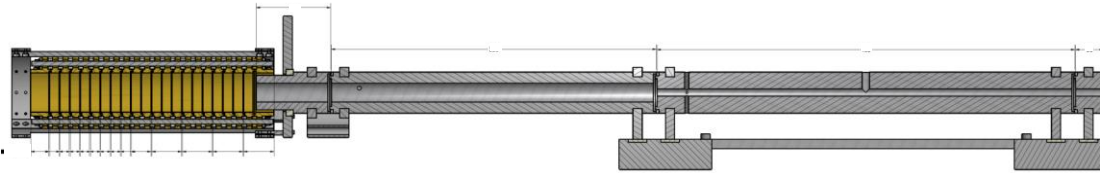
Cooling time Vs B

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 $k_b T$ + 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