ÖAW Austrian Academy of Sciences

MARIETTA BLAU INSTITUTE FOR PARTICLE PHYSICS

An Intense Antihydrogen Beam for Hyperfine Spectroscopy

75th Annual Meeting of the Austrian Physical Society

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on behalf of the ASACUSA collaboration

Where is all the antimatter?

- Standard Model predicts same amount of matter and antimatter
- CPT symmetry is consequence of Lorentz-invariant local quantum field theory
- CPT predicts identical absolute values for matter and antimatter

AI generated

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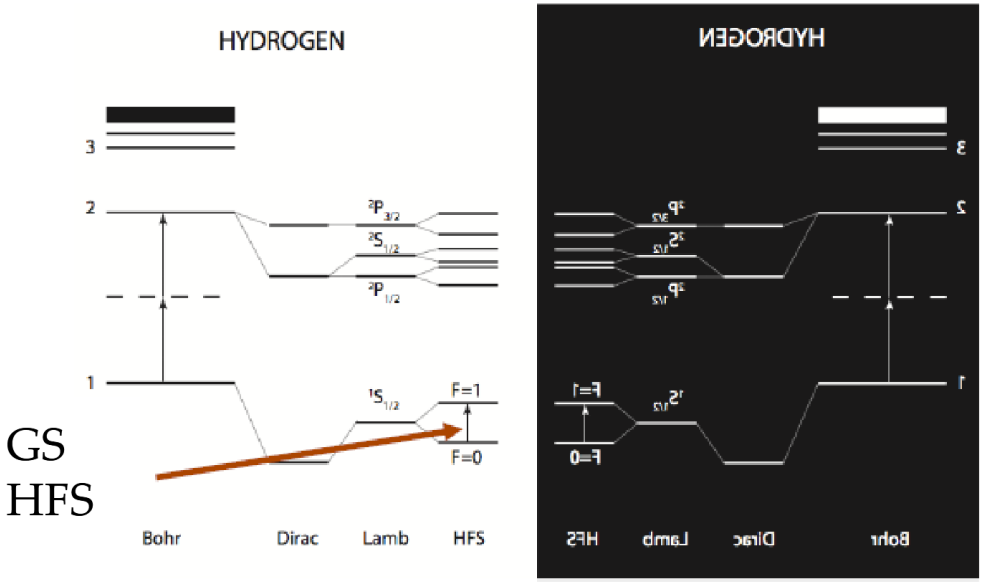
AI generated

The (anti)-Hydrogen Hyperfine Structure

- Hydrogen is the best known atom
- Precision of Ground State Hyperfine Transition in H: 10^{-10}
- $\overline{\mathrm{H}}$ is the most stable anti-atom
- Current precision in $\overline{\mathrm{H}}$: 10^{-6}

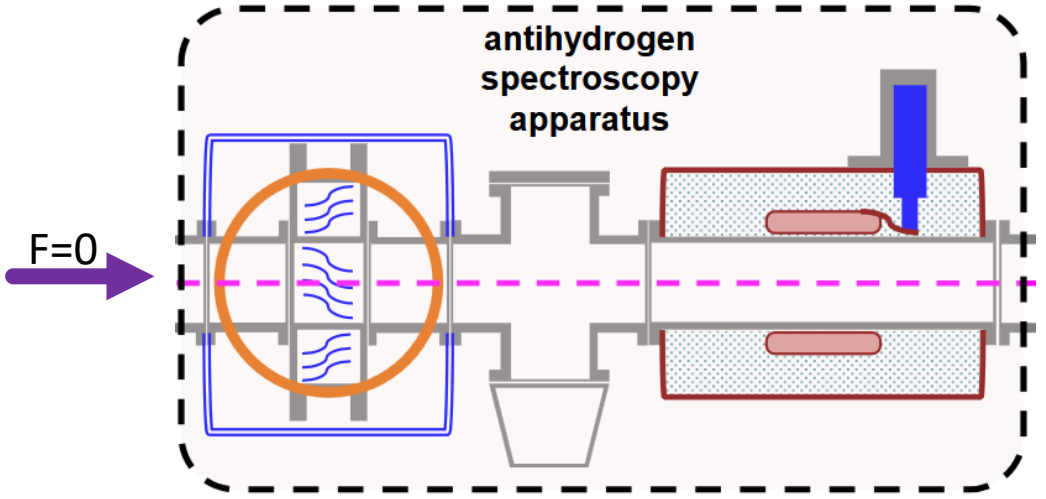


Akbari, R., *et al., Nature* **653**, 1022–1026 (2026).

A beam of antimatter

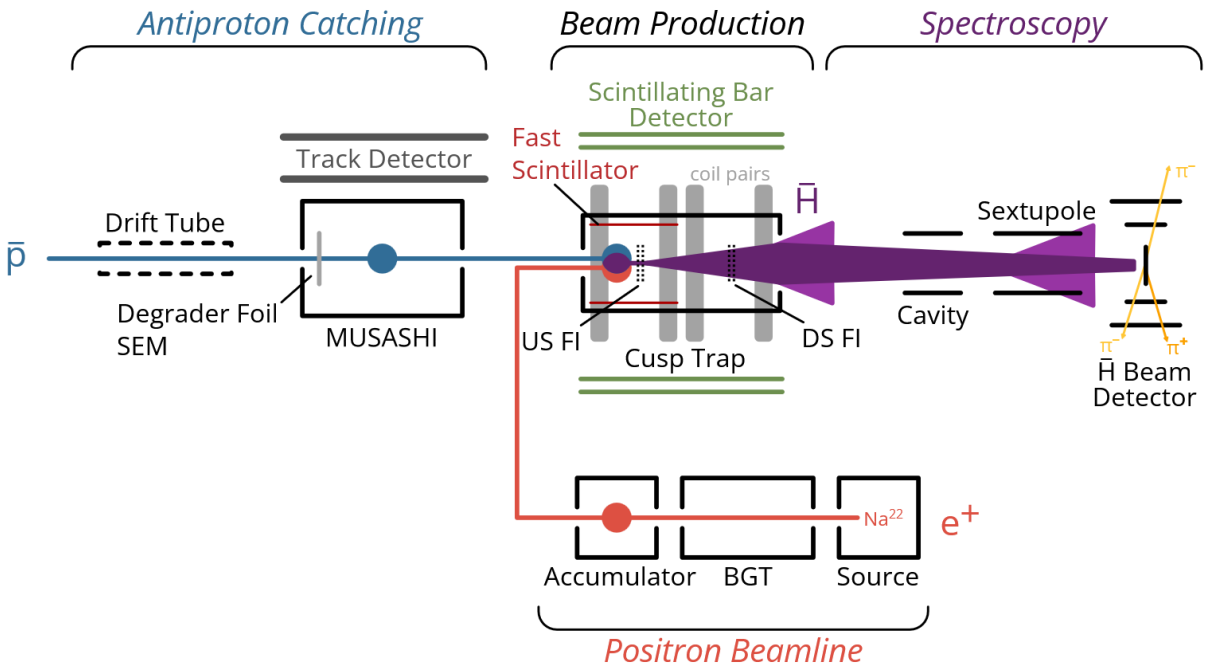
- Produce $\overline{\mathrm{H}}$ in high magnetic field environments
- $\overline{\mathrm{H}}$ moving along the beamline outside the high fields
- Perform Rabi Spectroscopy
- Spectrometer requirements
  - Polarised ground state
  - <1500 m/s
  - Low background

Initial Goal: 10^{-6}

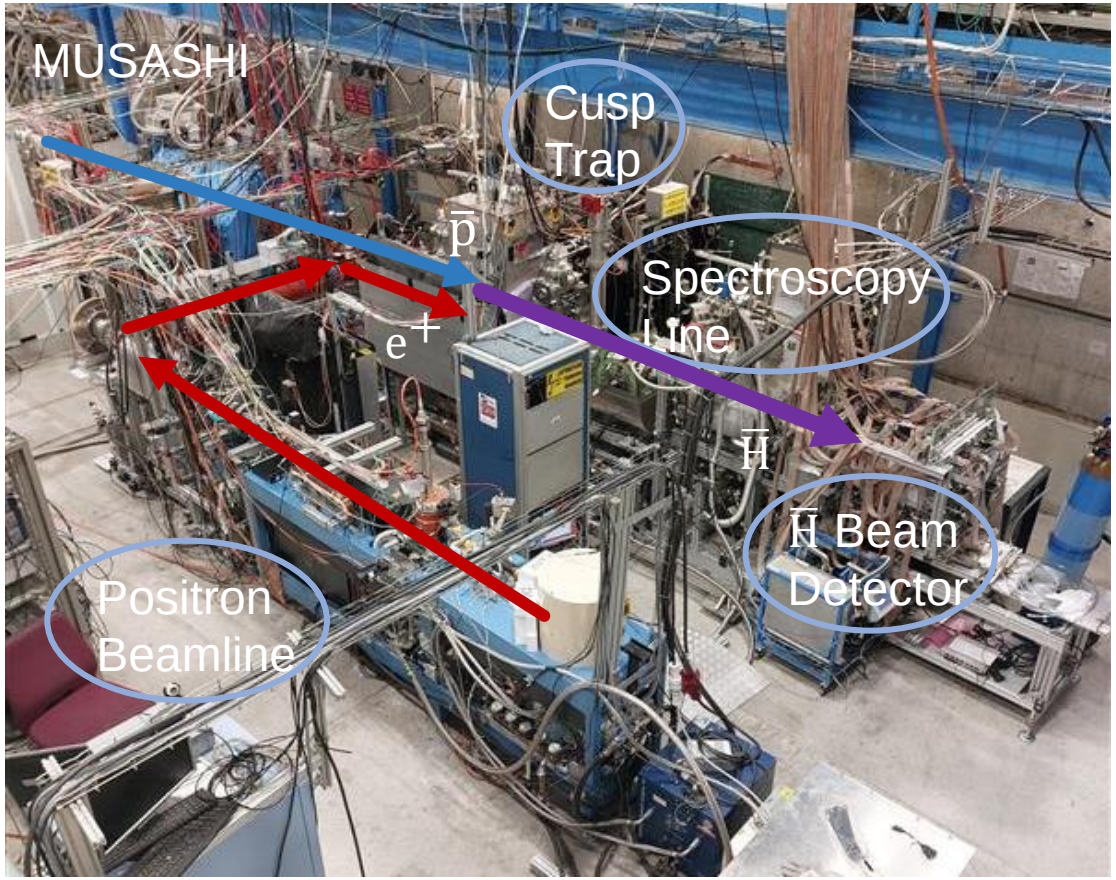


C. Malbrunot et al. *NIM Phys. Res. Sect. A* **935** (2019)

The ASACUSA Experiment Overview



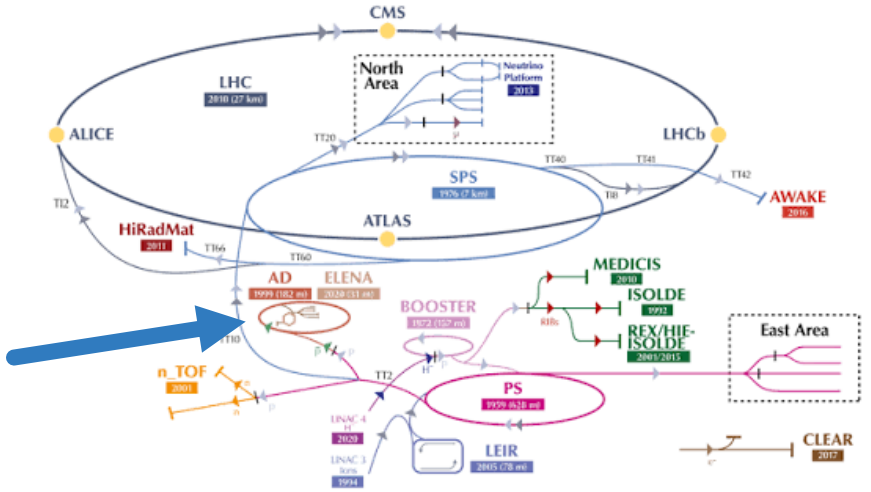
ASACUSA SPSC Report for 2025, SPSC-SR-377.



Positron & Antiprotons

Antiprotons:

- AD/ELENA: 12 million $\bar{p}$ every 2 minutes
- MUSASHI: Capture and cool $\sim 25\%$ of $\bar{p}$



https://en.wikipedia.org/wiki/Antiproton_Decelerator

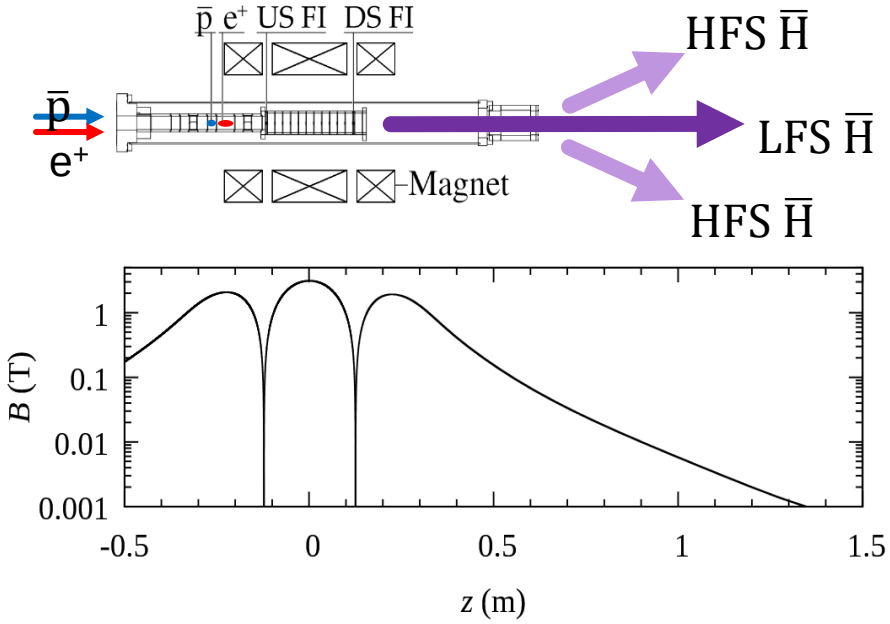
Positrons:

- $^{22}\mathrm{Na}$ positron source
- $2 \times 10^7 e^+$ every 2 minutes

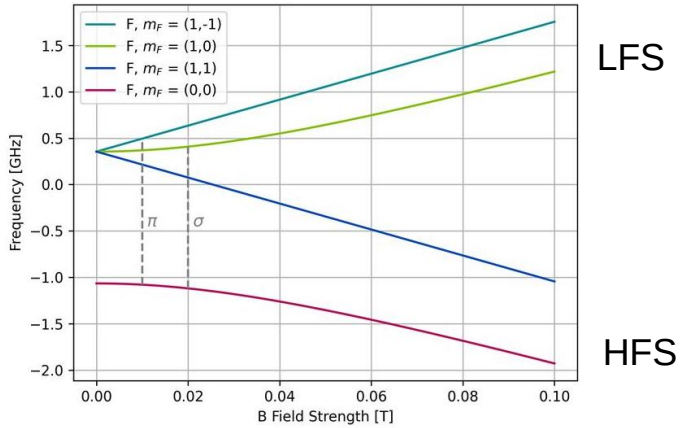
Around 150 beam-like $\bar{\mathrm{H}}$ per cycle!

$\bar{H}$ Production

- Three body recombination
  $\bar{p} + e^+ + e^+ \rightarrow \bar{H} + e^+$
- Large amounts in Rydberg states
- Ground state production most efficient for cold plasmas
  (higher density → more collisions)
- Low field seeking state ($\vec{\mu}$ anti-aligned to B)
  vs
  High field seeking state ($\vec{\mu}$ aligned to B)

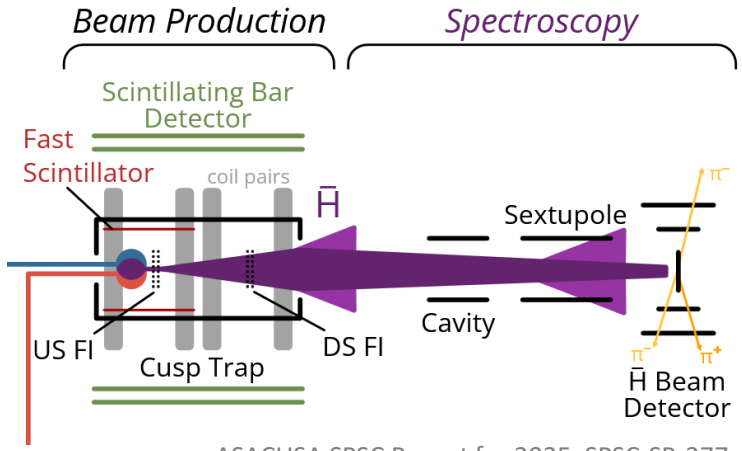


E. D. Hunter et al. *Phys. Plasmas* **33** (2026)



The Spectroscopy Beamline

- Rabi-type experiment
- Magnetically shielded stripline cavity at $\sim 1.4\ \mathrm{GHz}$
- Sextupole: focuses LFS and defocuses HFS
- Induced spin-flip would decrease count rate in detector



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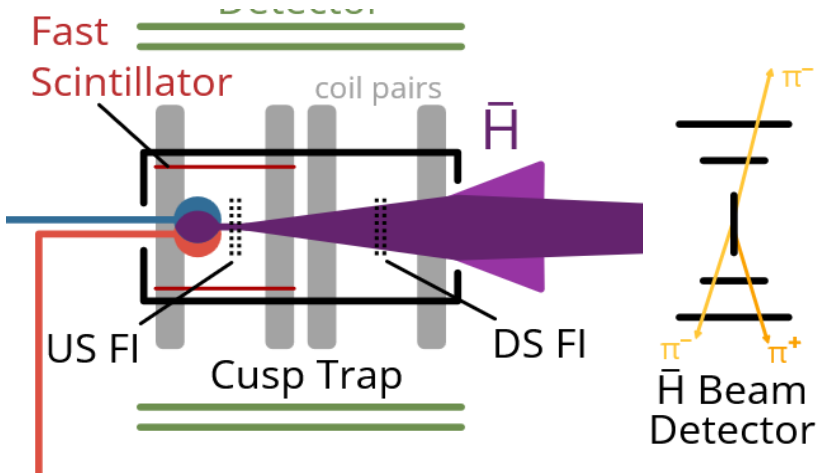
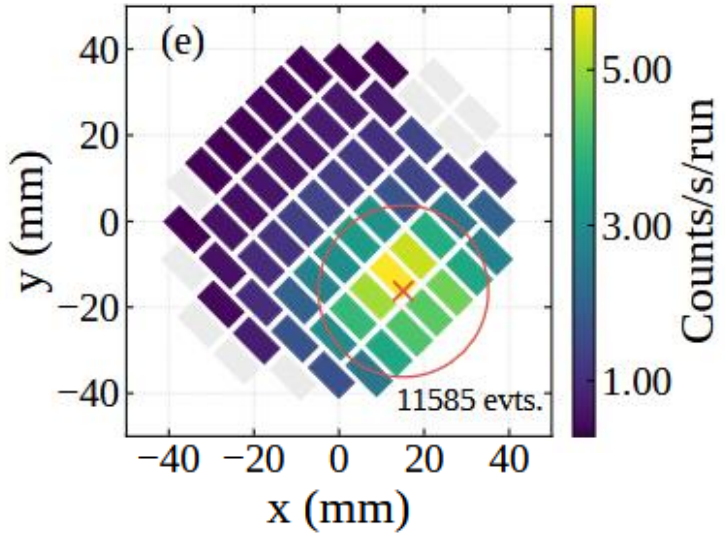
The $\bar{H}$ Beam - Detector

- Detects the $\bar{p}$ annihilation of the $\bar{H}$
- Position sensitive central BGO scintillator calorimeter
- Coincidence with 2-layer hodoscope

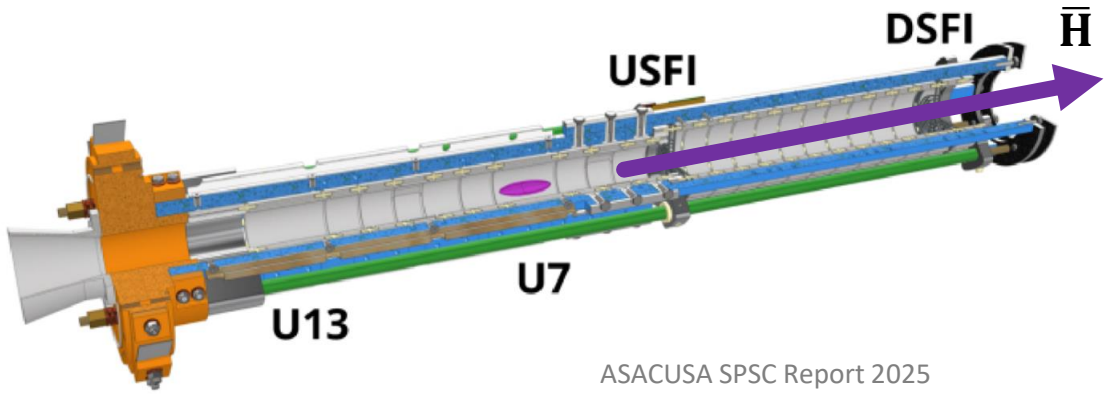


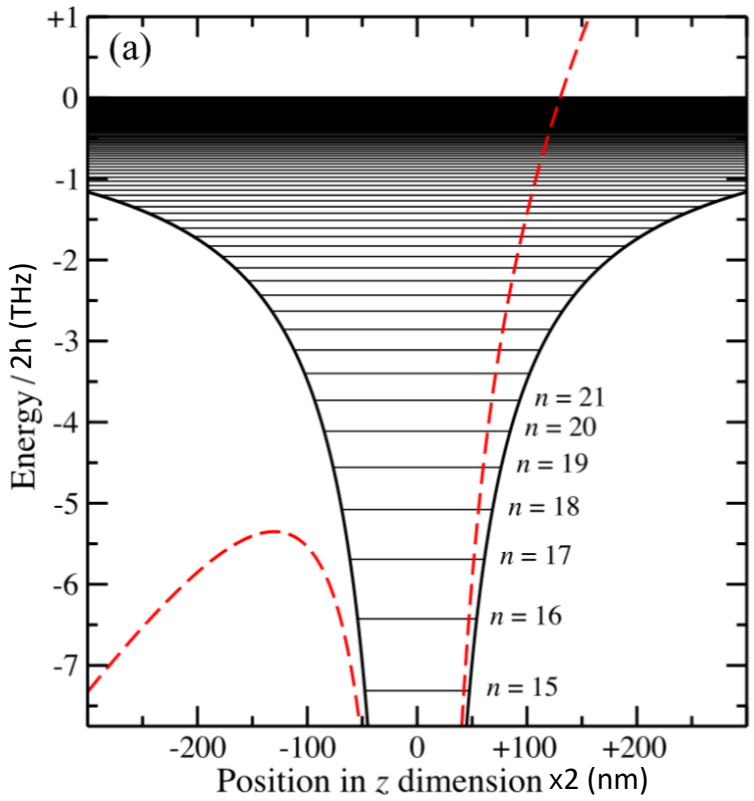


Characterizing the $\bar{H}$ Beam

Reminder for requirements

- Polarised ground state
- <1500 m/s
- Low background





Characterizing the $\bar{H}$ Beam

Reminder for requirements

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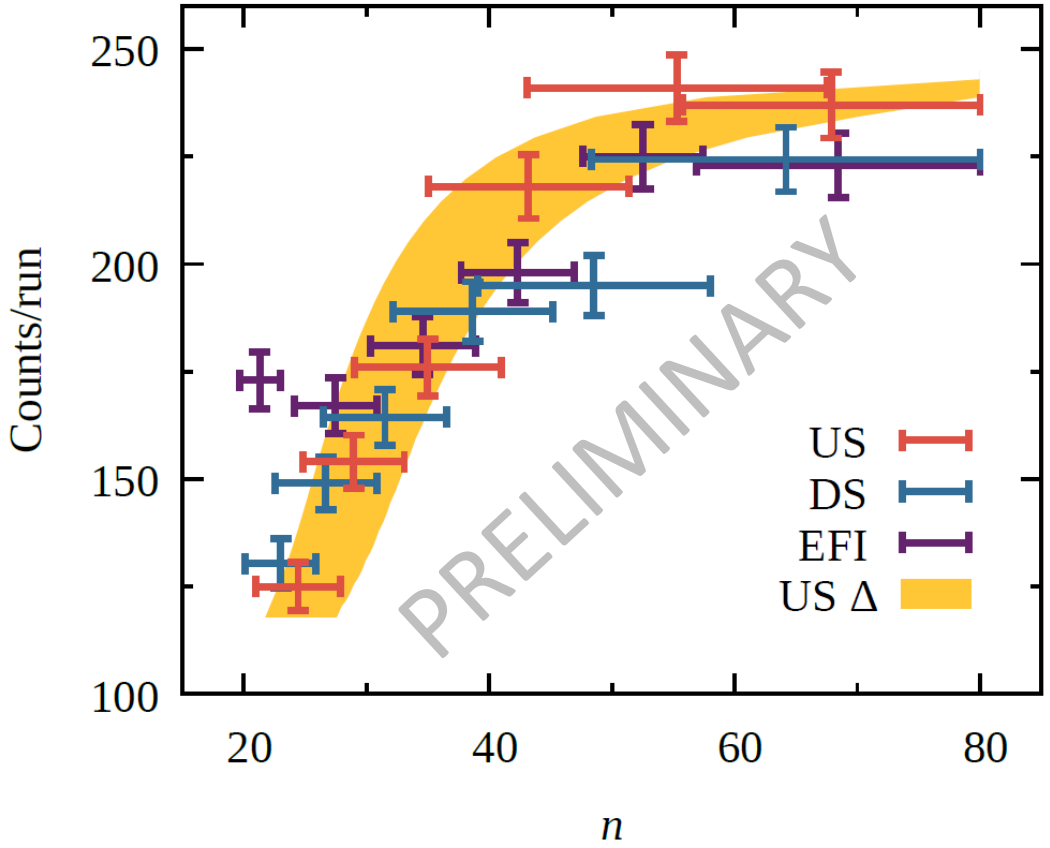
Results

- Approximately 66% in $n > 20$
- $n < 15$ will fluoresce during flight
- Estimate > 10% ground state fraction

E. D. Hunter et al. In Preparation



Characterizing the $\bar{H}$ Beam

Reminder for requirements

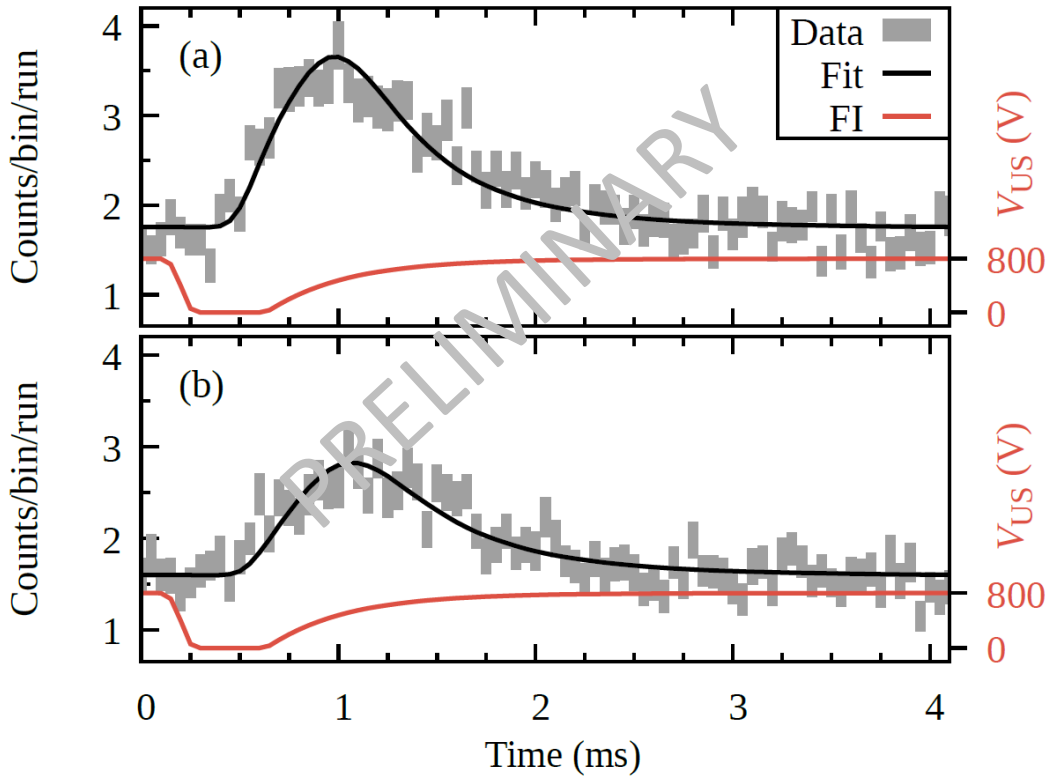
- Polarised ground state
- <1500 m/s
- Low background

Results

- Too high velocity for spectrometer beamline
- Lower $n \longrightarrow$ lower velocity

E. D. Hunter et al. In Preparation

$n > 27$: $\langle v \rangle = 3000 \pm 200$ m/s



$27 < n < 36$: $\langle v \rangle = 2500 \pm 100$ m/s

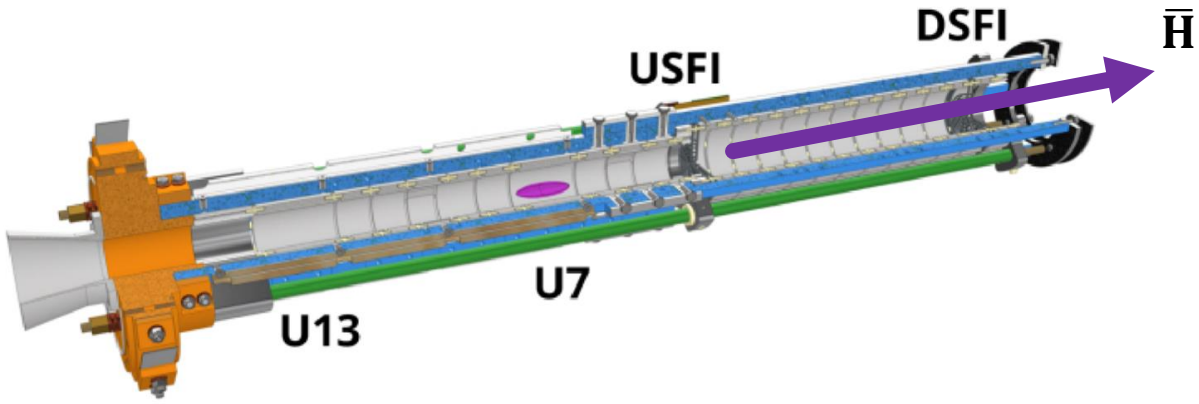
Summary & Outlook

- ASACUSA aims to measure the $\mathrm{H}/\overline{\mathrm{H}}$ ground state HFS
- Experiment produces most intense $\overline{\mathrm{H}}$ beam in the world
- $\overline{\mathrm{H}}$ velocities too high for spectroscopy beamline in 2025/2026
- Upgrades for LS3
  - ➢ Reduce plasma temperatures
  - ➢ Increase Signal-to-Noise ratio

Backup

Antihydrogen production

- Slow merge mixing over 60s
- Production efficiency ~80%



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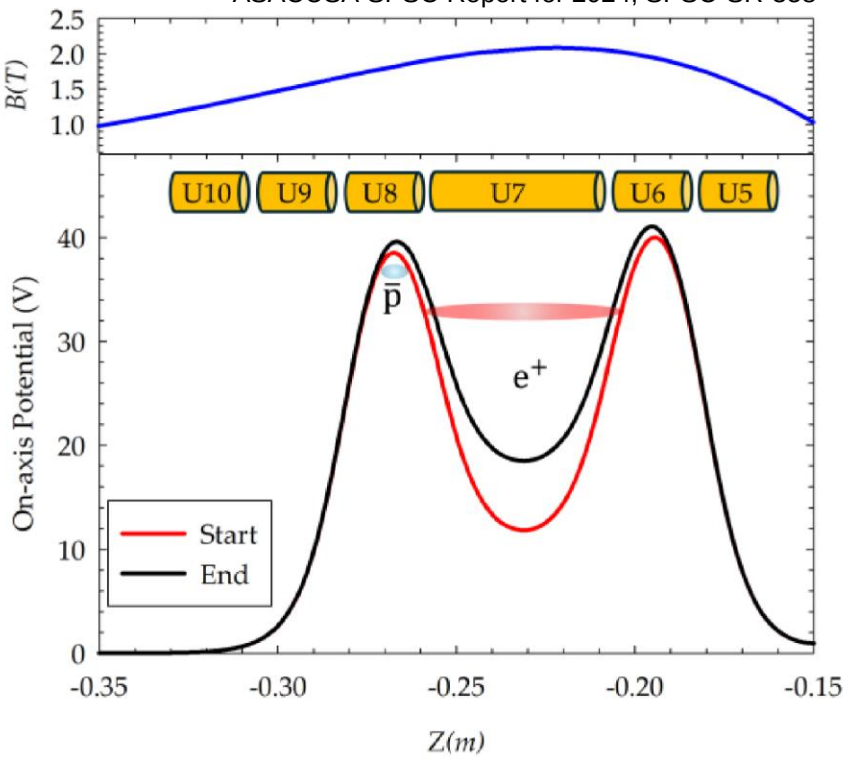
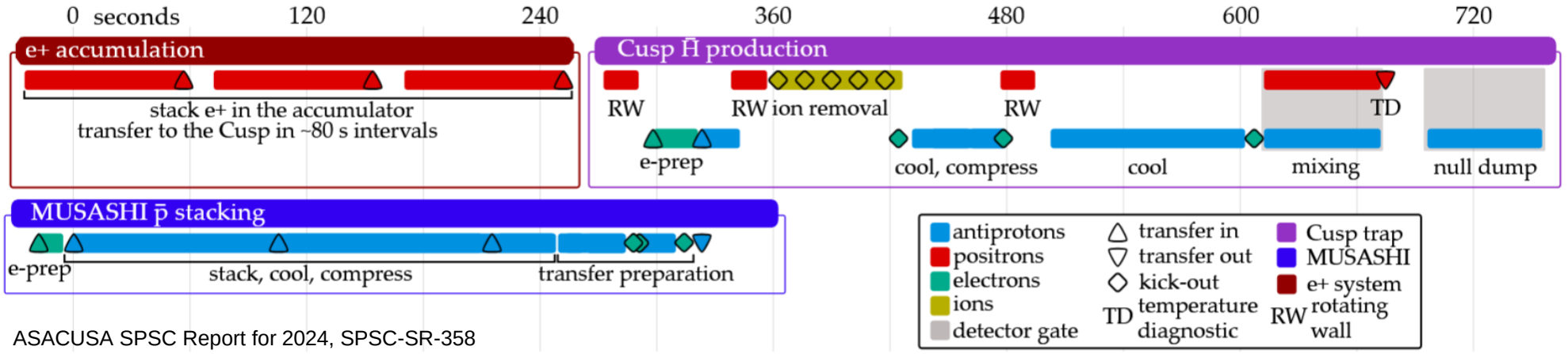


$\bar{H}$ Production cycle

- $\bar{H}$ production cycles takes ~15min
- Key part of this is plasma preparation in the Cusp trap
- Remove electrons from $\bar{p}$ & positive ions from positrons
- Compress & cool using strong-drive regime evaporative cooling



ASACUSA SPSC Report for 2024, SPSC-SR-358

Characterizing the $\bar{H}$ Beam

Reminder for requirements

- Polarised ground state
- <1500 m/s
- Low background

Results

- 26 ± 7% reduction in beam spot size
- No reduction in beam intensity
  - ➢ High Rydberg contribution

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