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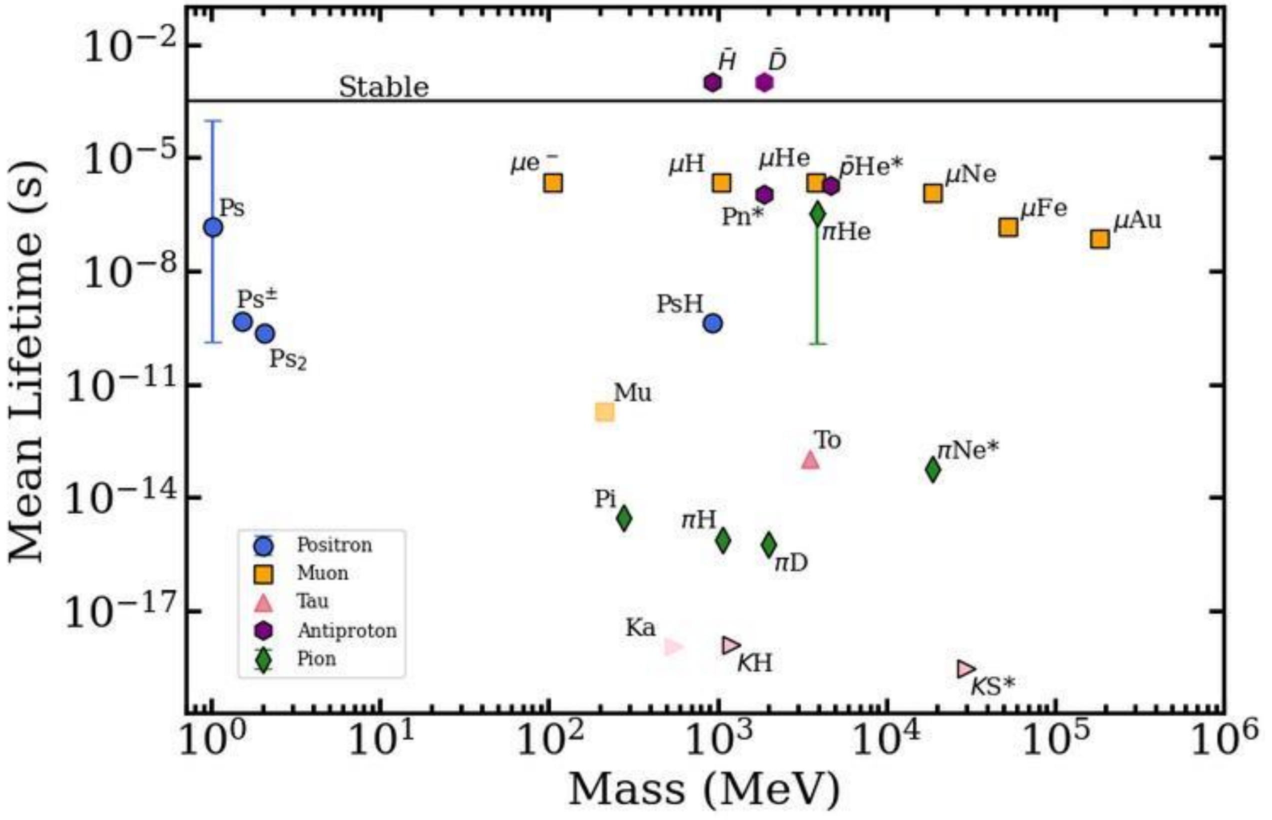
The ASACUSA Antihydrogen beam

Ross Sheldon for the ASACUSA Collaboration
PSAS 2026, Vienna

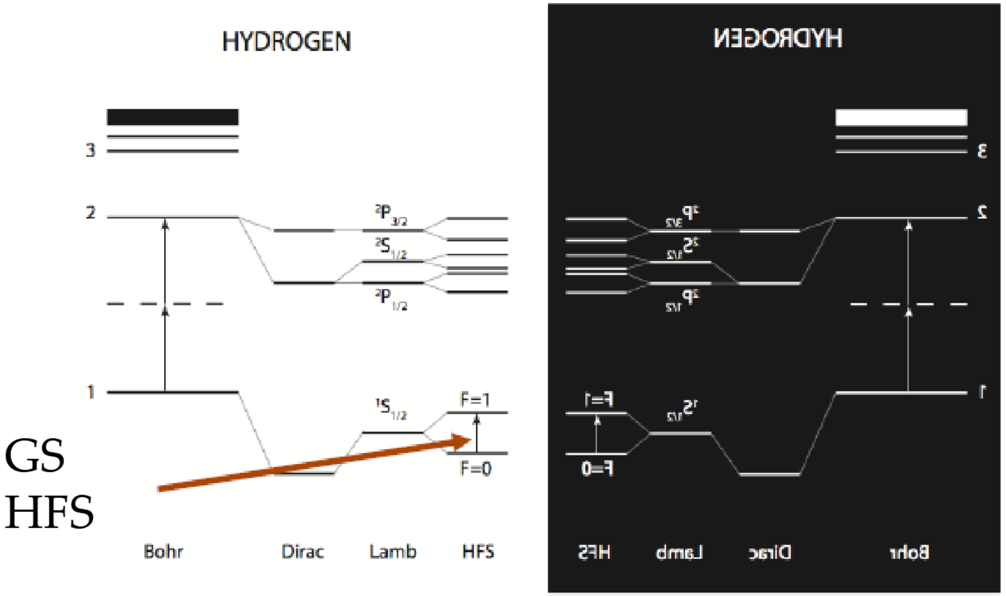
Where is all the antimatter?

- Standard Model predicts matter/antimatter symmetric
- CPT symmetry remains unviolated
- Compare hydrogen (H) & antihydrogen ($\bar{\mathrm{H}}$)
- $\bar{\mathrm{H}}$ the most stable antimatter atom



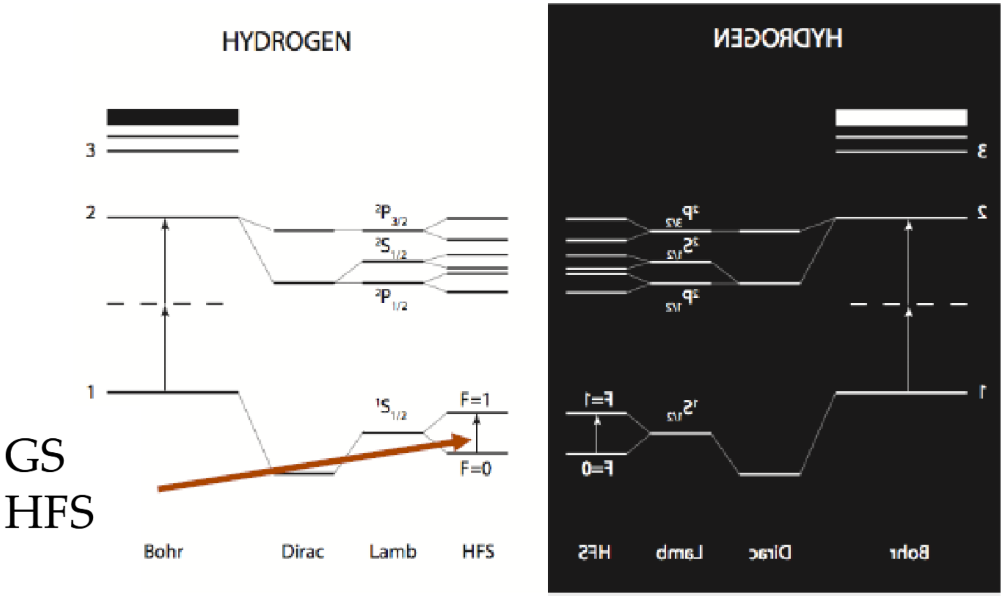
Ground State Hyperfine Structure

- ν_{hfs}: ${}^1S_{1/2}(F=0) \rightarrow {}^1S_{1/2}(F=1)$
- F = total spin quantum number



Ground State Hyperfine Structure

- ν_{hfs}: $^1S_{1/2}(F=0) \rightarrow {}^1S_{1/2}(F=1)$
- F = total spin quantum number
- H precision: 10^{-12}
  High absolute precision: 1 mHz
  S.G. Karshenboim, *Can. J. Phys.* **78** (2000)
- $\bar{\mathrm{H}}$ precision: 10^{-4}
  M. Ahmadi et al. *Nature* **548** (2017)

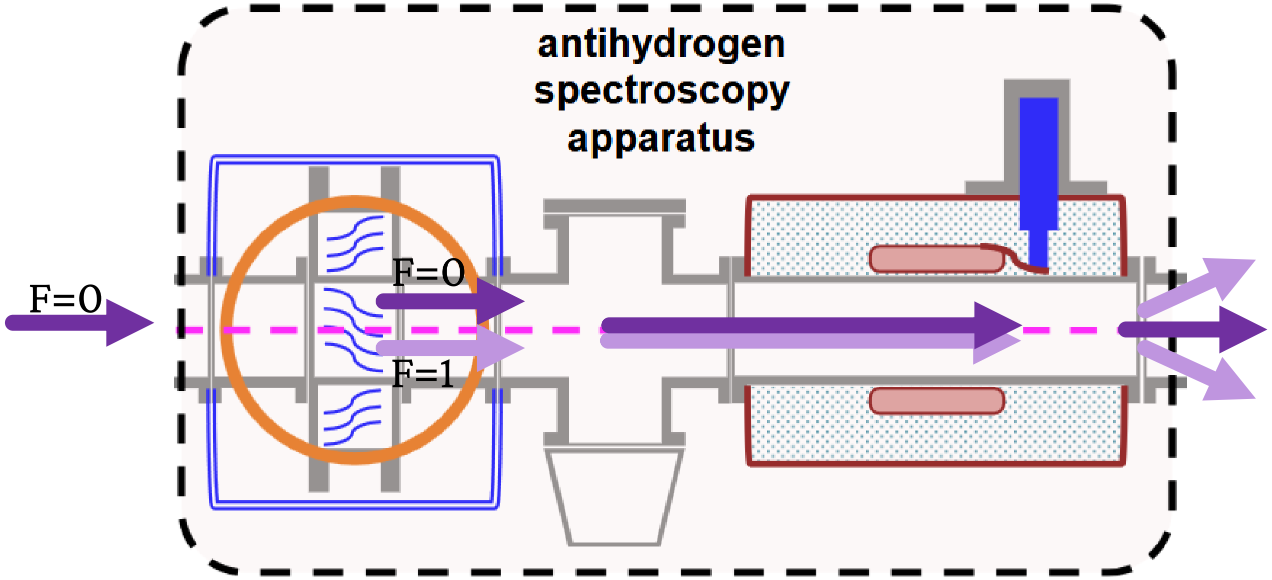


GOAL
10^{-6}

Antihydrogen beam

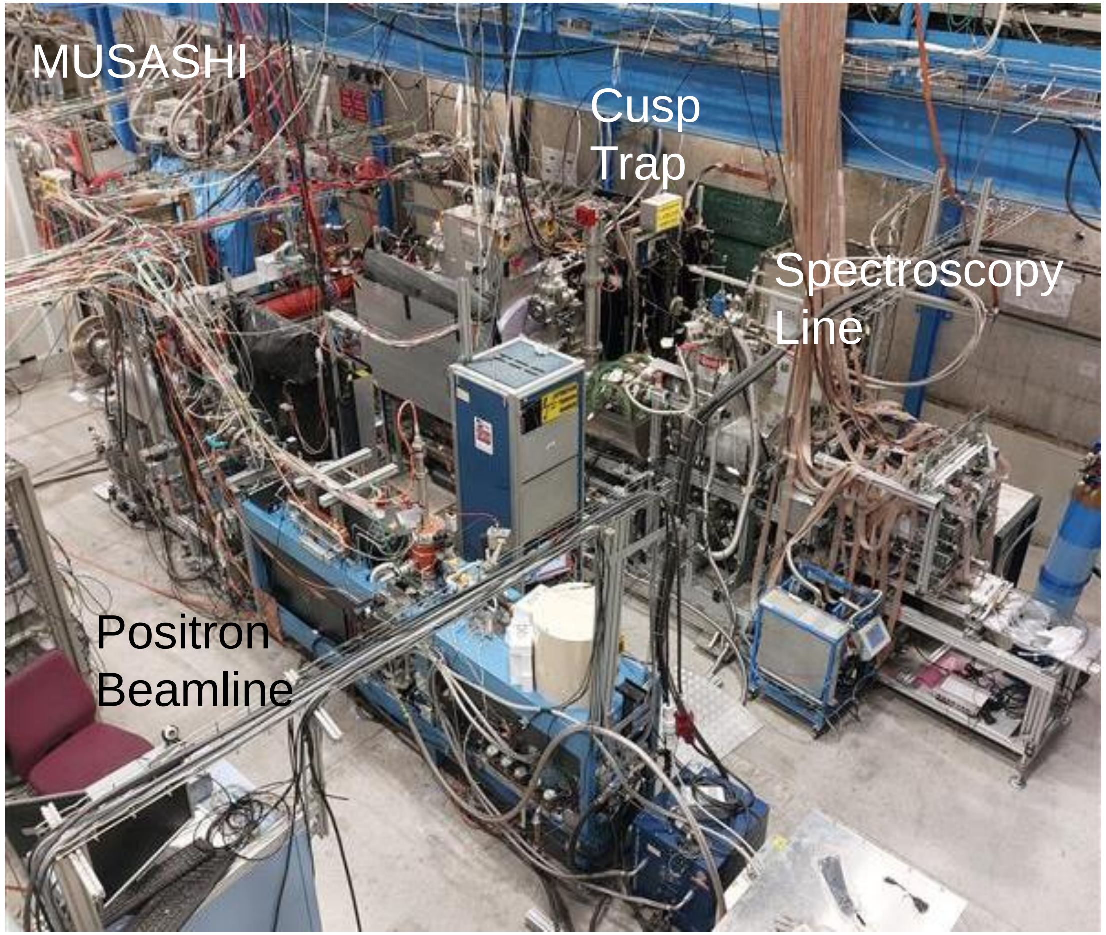
- $\overline{\mathrm{H}}$ production/traps in high field environments
- A beam removes the $\overline{\mathrm{H}}$ from high field environments

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



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

ASACUSA Experiment



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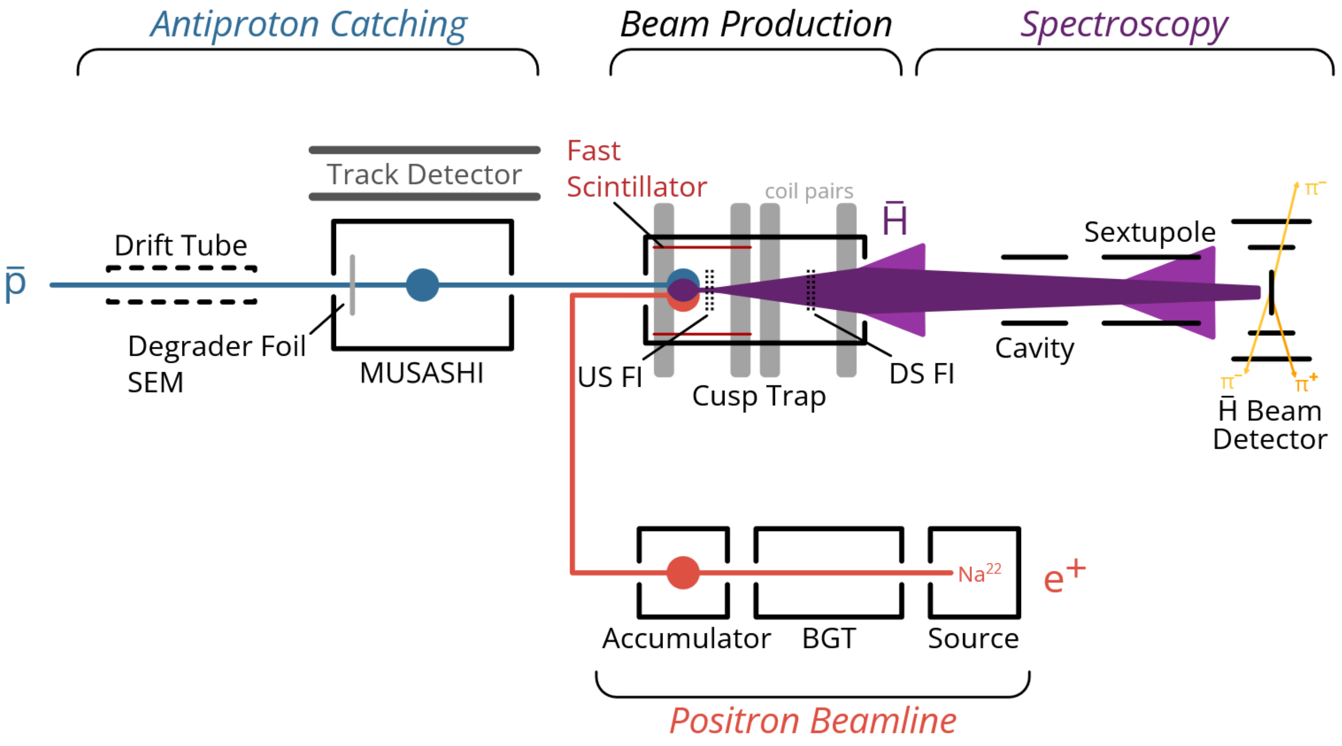

Experiment - Particles

- AD/ELENA
  12 million $\bar{p}$ every 2 min
- MUSASHI
  Catch & cool ~25%
  of the $\bar{p}$

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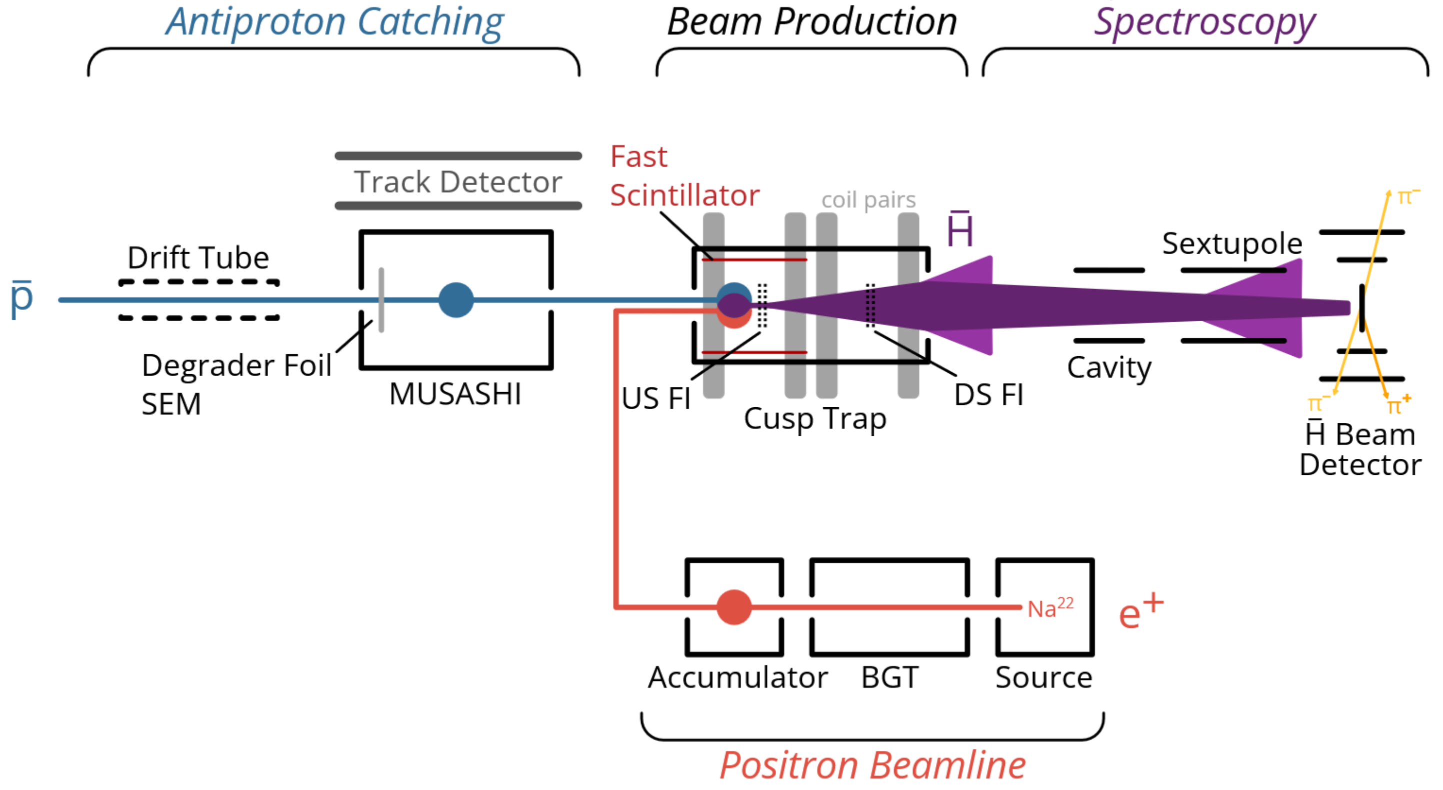
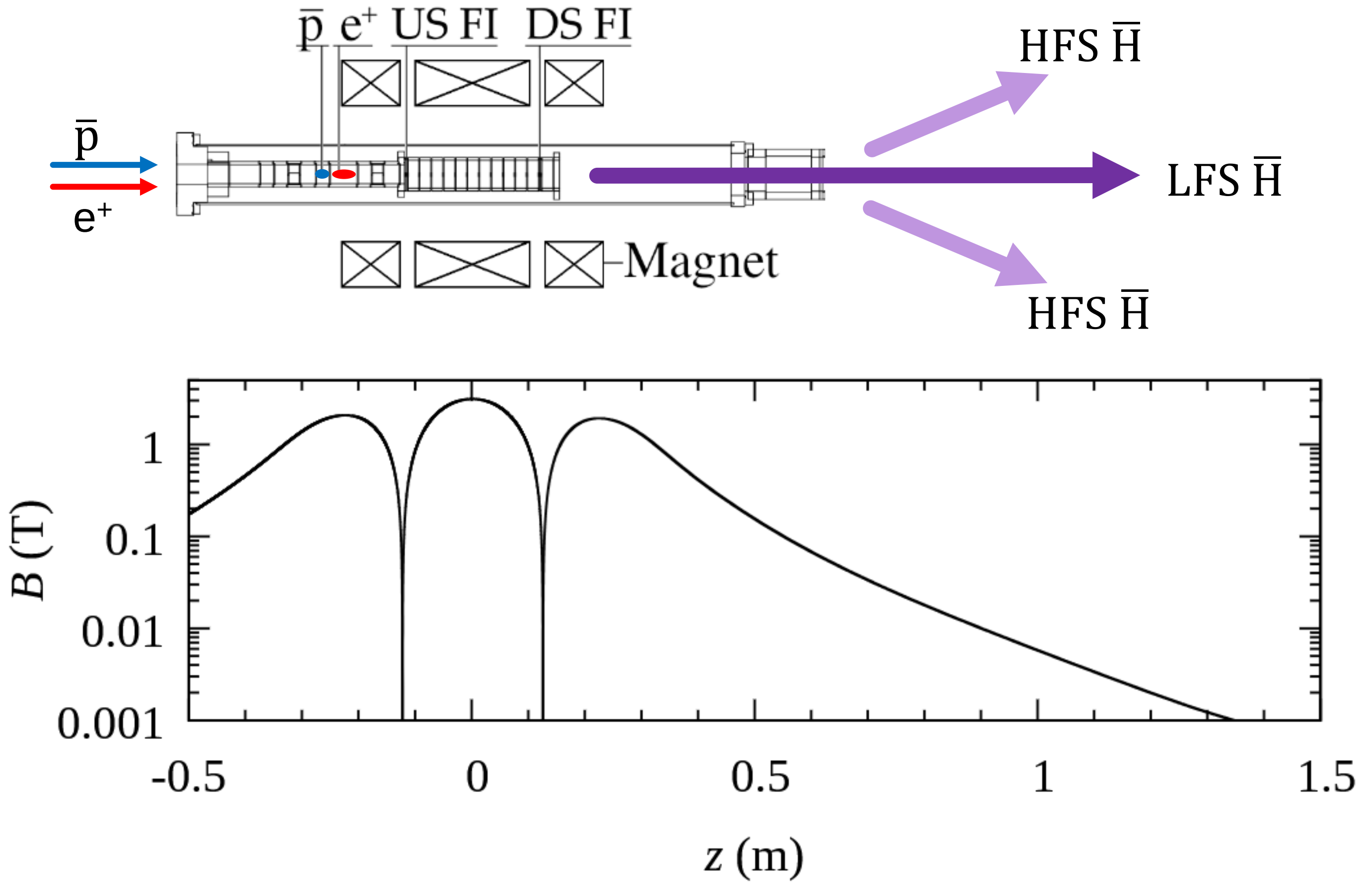


- ^{22}Na positron beam
  21 million positrons every 2 min

Experiment - $\bar{\mathrm{H}}$ production

- $\bar{\mathrm{H}}$ production in the double Cusp trap
- Penning-Malmberg trap
- Polarises beam for <1500 m/s



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

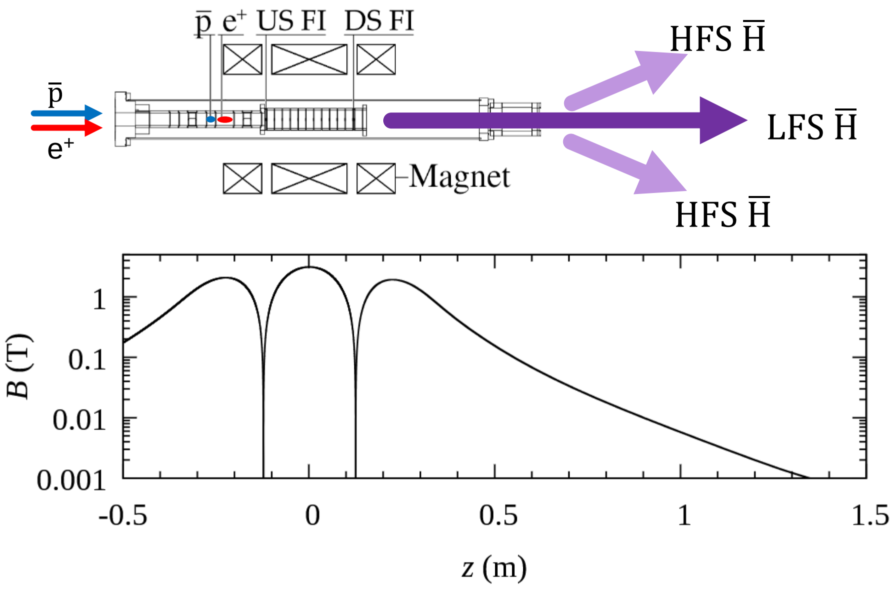
E. D. Hunter et al. *Phys. Plasmas* **33** (2026)

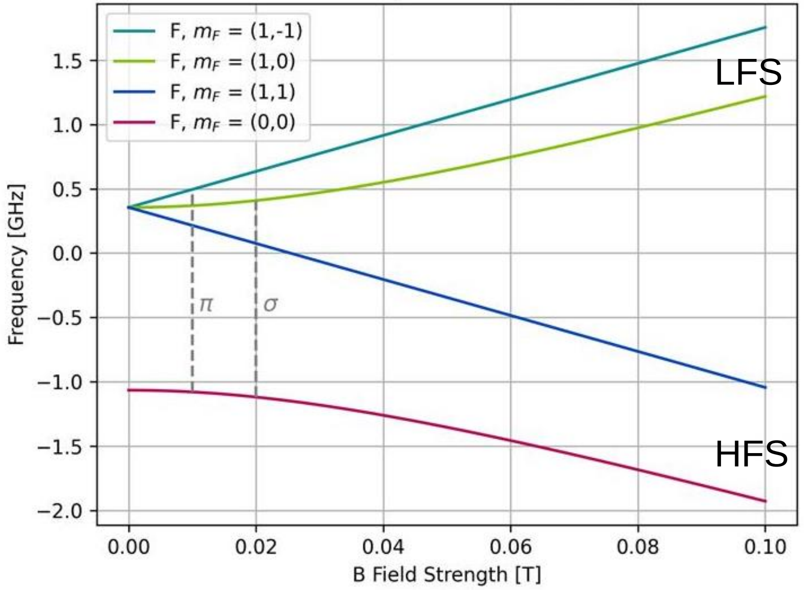
Experiment - $\bar{\mathrm{H}}$ production

- Low field seeker (LFS)
  Magnetic moment anti-align to B

- High field seeker (HFS)
  Magnetic moment align to B

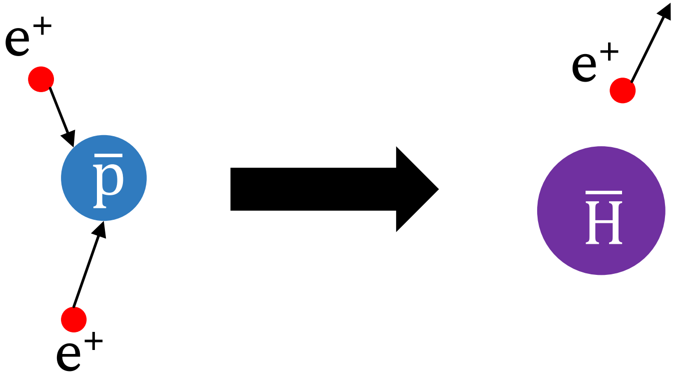
- Polarisation LFS:HFS better for lower velocity
  ~60:40 for 1500 m/s
  ~80:20 for 1000 m/s



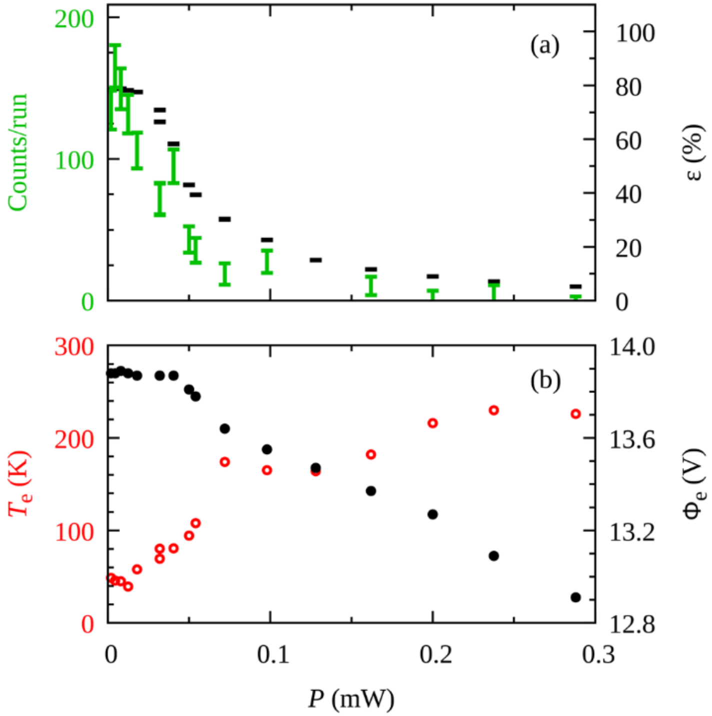


Experiment - $\bar{\mathrm{H}}$ production

- Three body recombination
  $\bar{p} + e^+ + e^+ \rightarrow \bar{H} + e^+$
- Large amounts of Rydberg atoms
- Most efficient for cold plasmas
- Colder/denser plasma → more collisions → more ground state

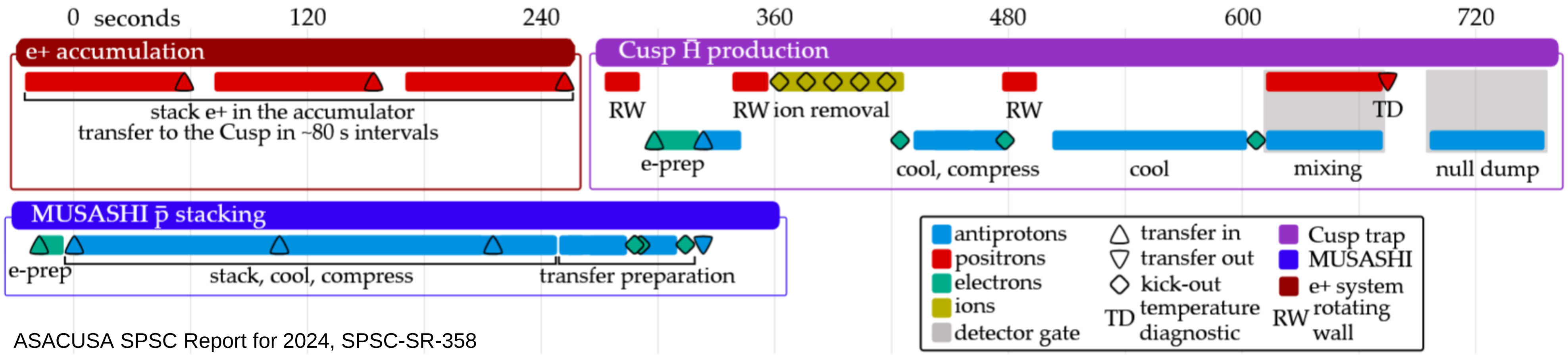


E. D. Hunter et al. Phys. Plasmas **33** (2026)



$\overline{\mathrm{H}}$ Production cycle

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



ASACUSA SPSC Report for 2024, SPSC-SR-358

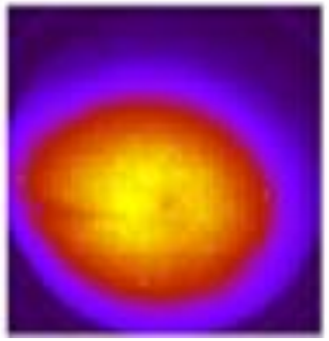
Plasma properties

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

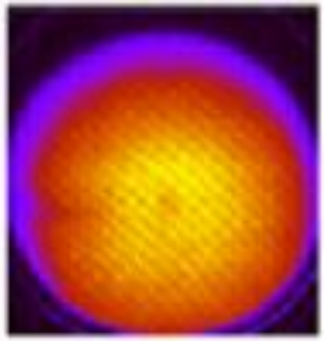
	Number (x10^6)	Temperature (K)	Density* (x10^8 cm^{-1})
Antiprotons	2.89 ± 0.04	1700 ± 200	0.8 ± 0.1
Positrons	100 ± 2	50 ± 20	2.0 ± 0.5

*numerical solver

Antiprotons

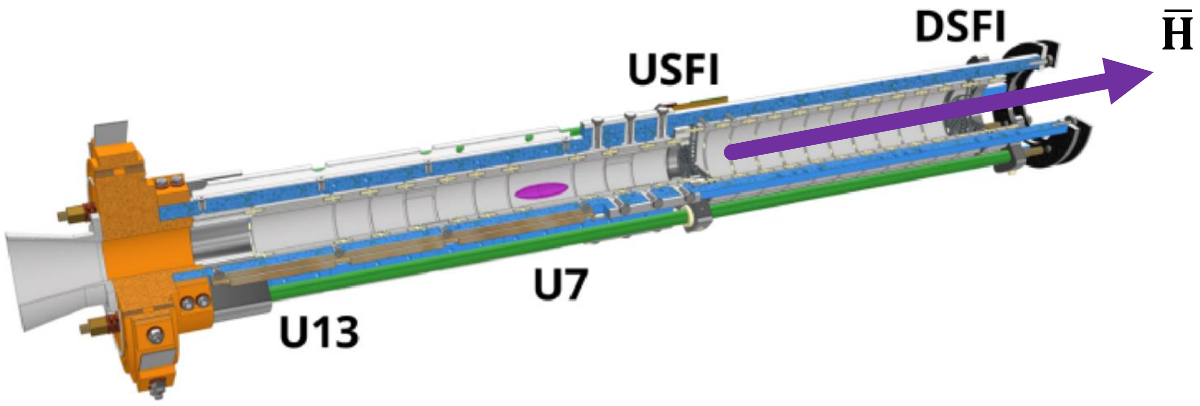


Positrons

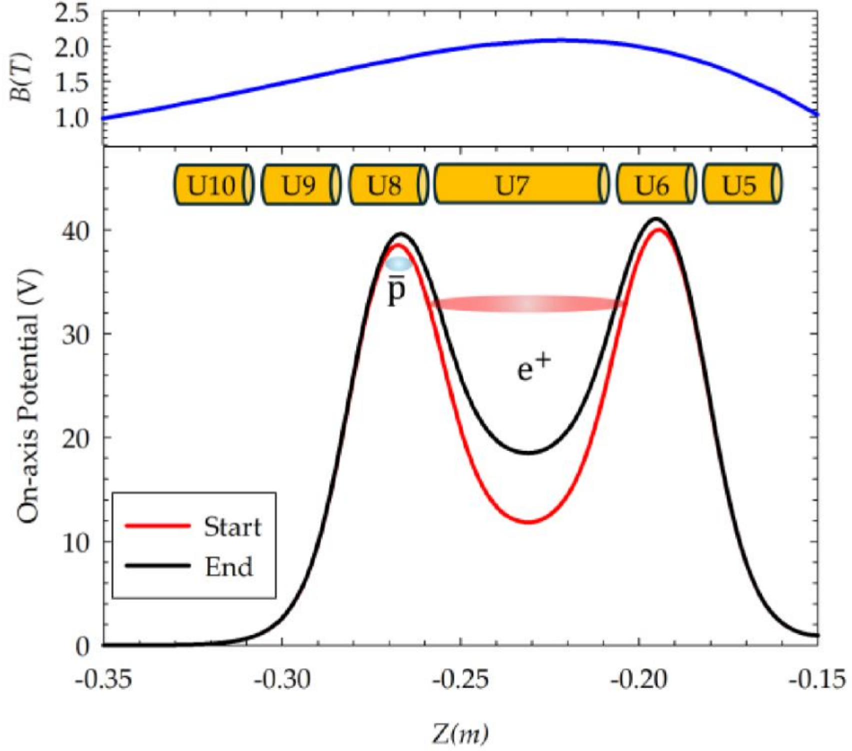


Antihydrogen production

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



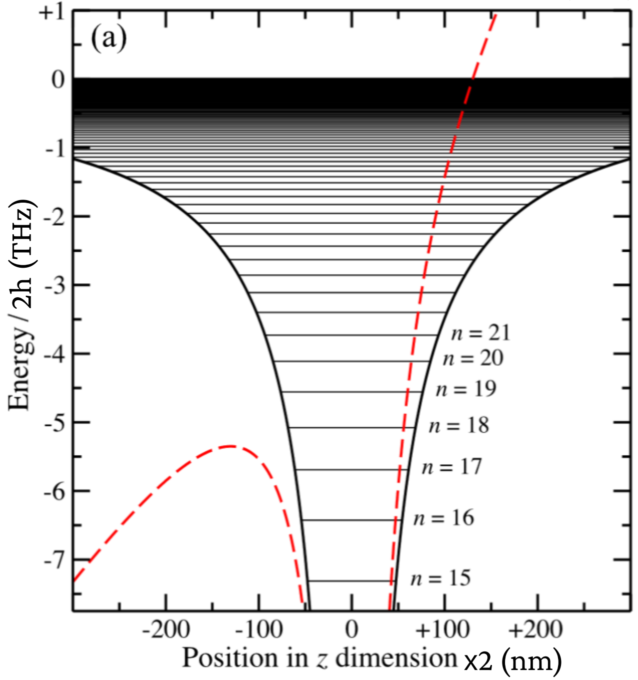
ASACUSA SPSC Report for 2024, SPSC-SR-358

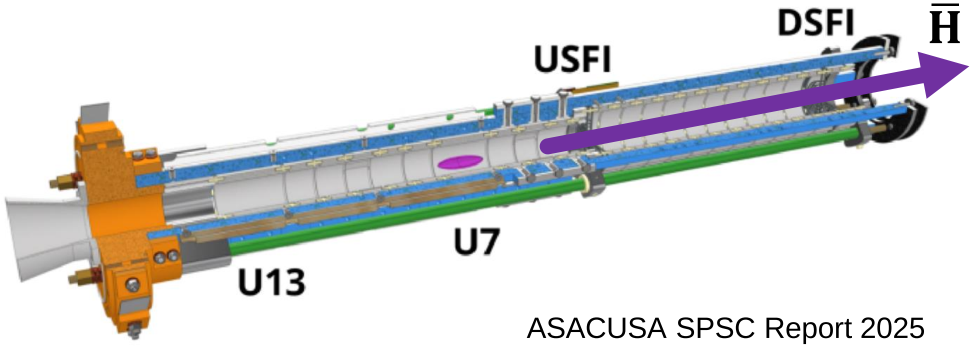


Field ionisers

- Ionise Rydberg $\bar{\mathrm{H}}$ with high electric field
- Lower *n* need more field
- Threshold proportional to n^4

A. M. Alonso et al. PRA 98 (2018)





ASACUSA SPSC Report 2025

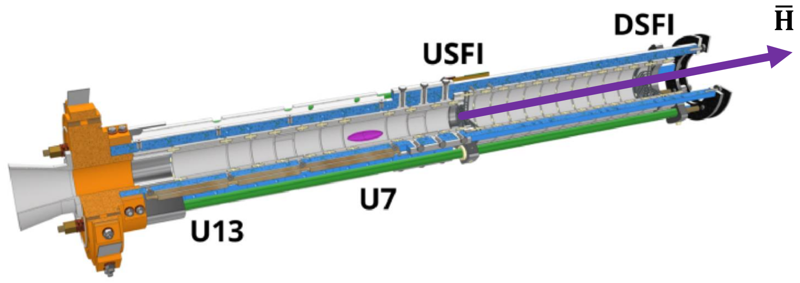
Field ionisers

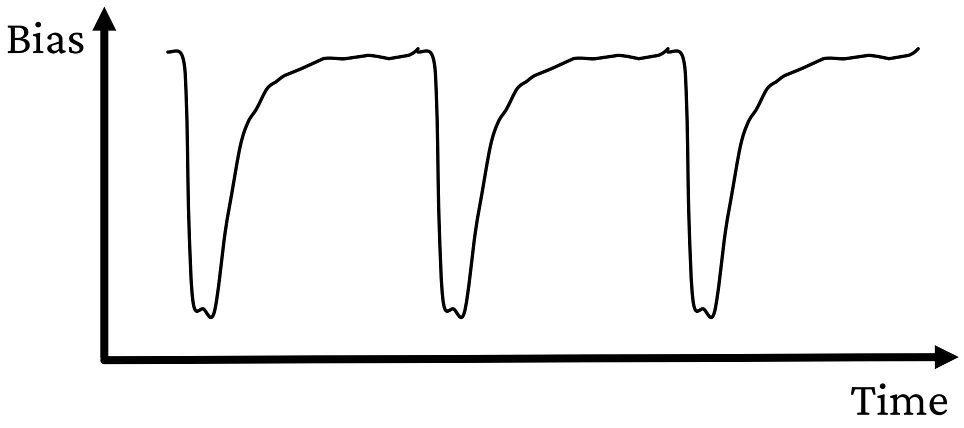
https://arxiv.org/pdf/2509.02583

- Two meshes mm apart
  One grounded, one biased

- Upstream field ioniser - Chopper
  Pulsed from 0-800 V at 240 Hz
  during mixing

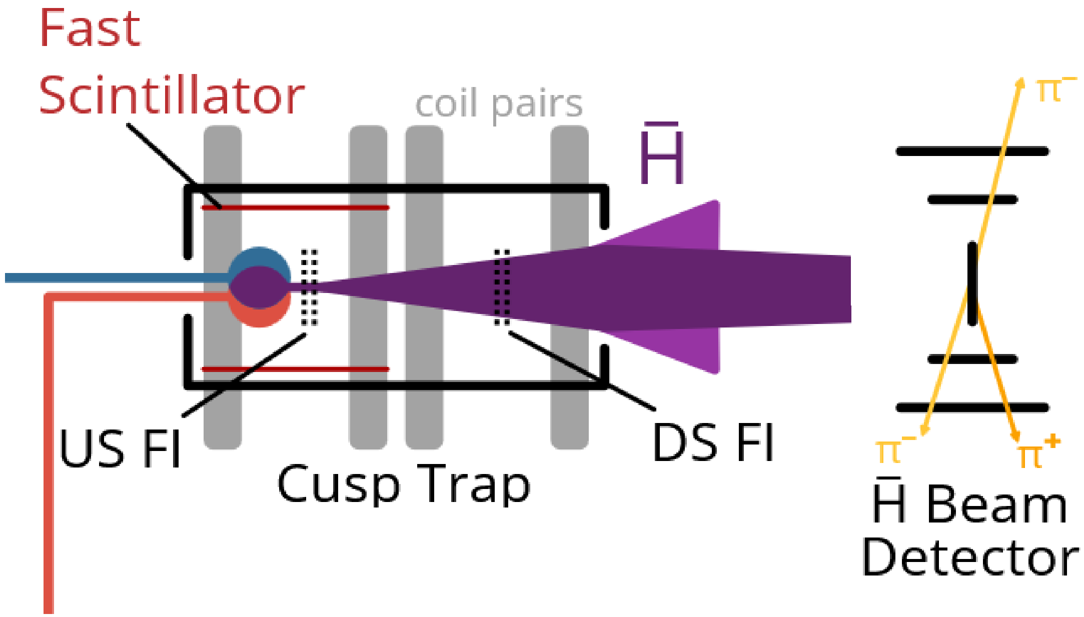
- Downstream field ioniser – Filter
  DC on or off throughout mixing

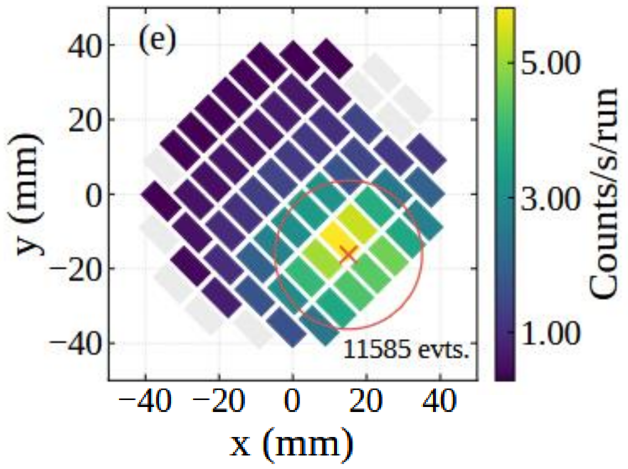




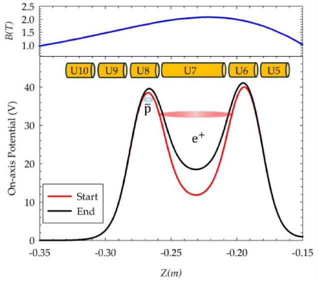
Beam detector

- Detect $\bar{p}$ annihilation of $\bar{H}$
- Pixelated central BGO scintillator calorimeter
- Coincidence with 2-layer hodoscope

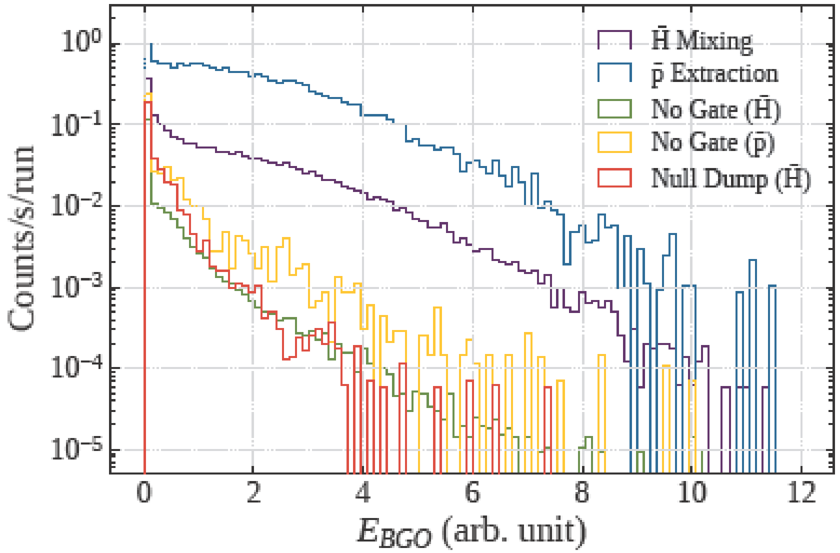




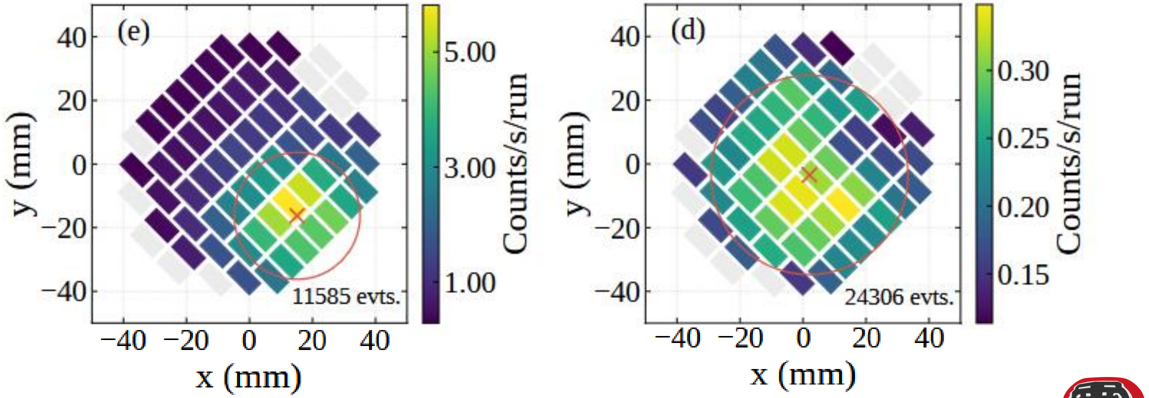
Beam intensity



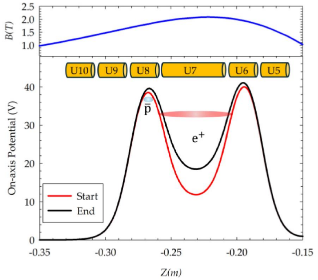
- 2.3 ± 0.2 million $\bar{\mathrm{H}}$ per 60s mixing
- Of which 300 $\bar{\mathrm{H}}$ beam-like
- On the order of solid angle selection
- Observe difference between $\bar{p}$ & $\bar{\mathrm{H}}$ beam spot



E. D. Hunter et al. In Preparation



Beam intensity

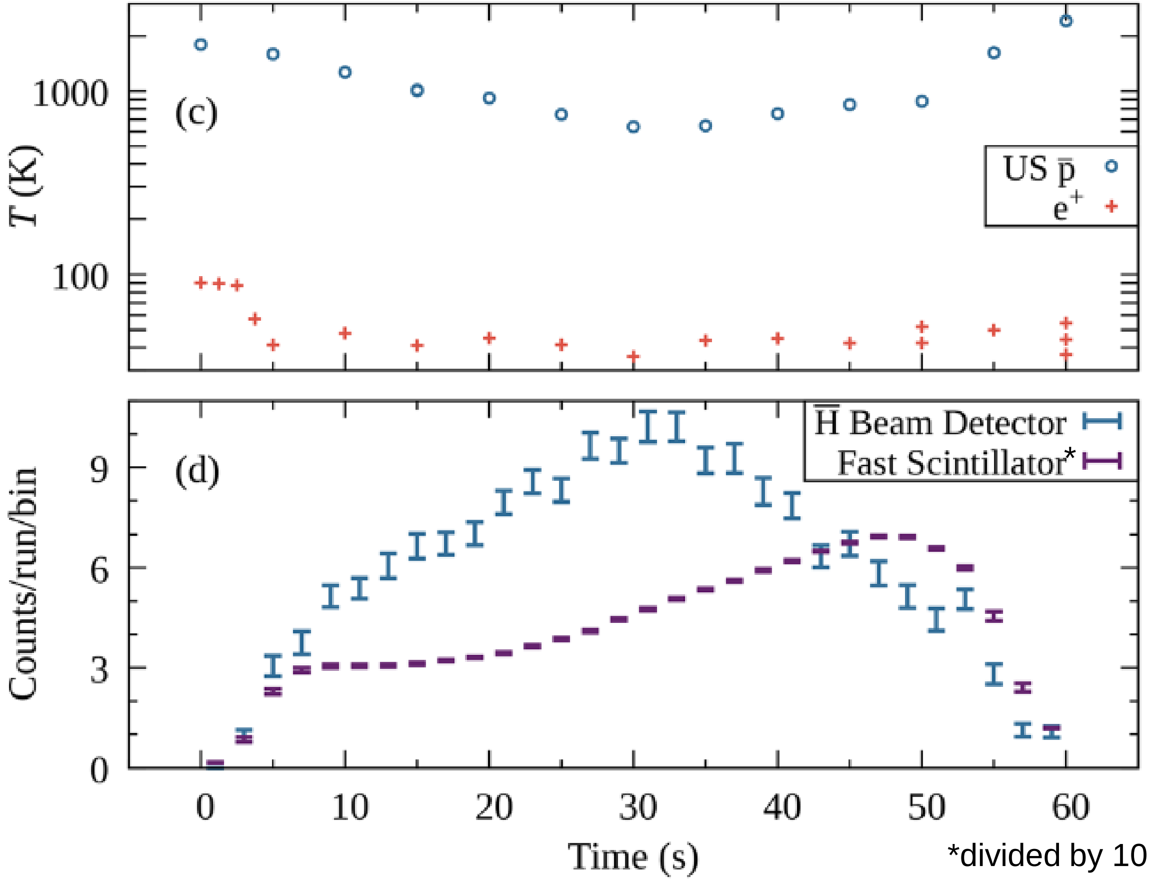


- Monitor beam intensity as a function of plasma properties

- Highest $\overline{\mathrm{H}}$ production rate at end of cycle

- Most beam when plasmas are coldest → highest 3BR rate

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



*divided by 1000

Beam velocity

E. D. Hunter et al. In Preparation

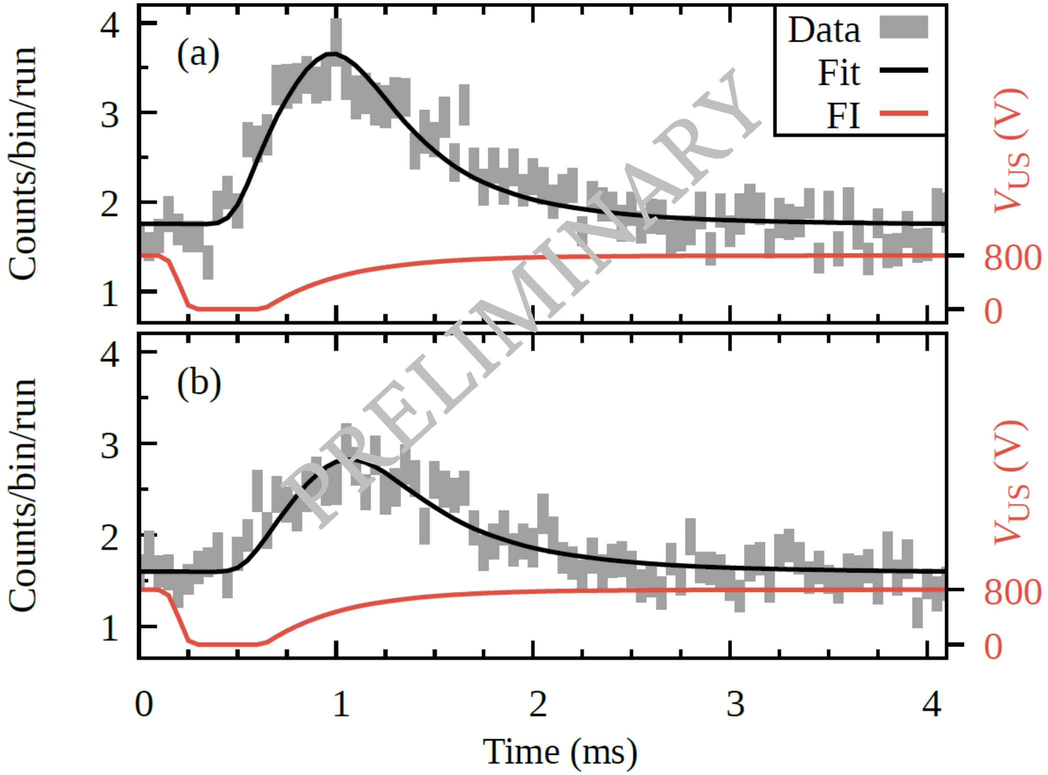
Fit model

- 1D Maxwell-Boltzman - axial p̄
- 2D Maxwell-Boltzman – transverse e^+

- Beam selection
- Time in plasma
- Plasma rotation

- Lower n lower average velocity

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

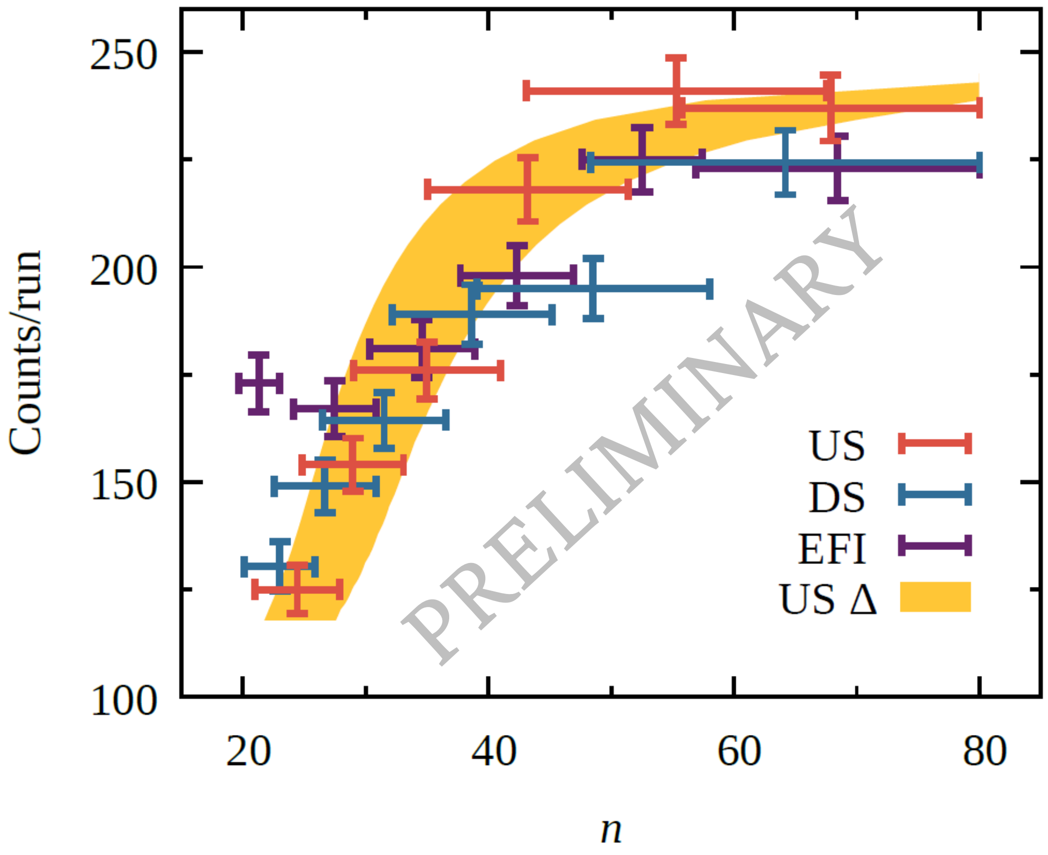


$27 < n < 36$: $\langle v \rangle = 2500 \pm 100$ m/s

Quantum number distribution

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

E. D. Hunter et al. In Preparation



Spectroscopy Line Installation

New 2025

- Stripline cavity at ~1.4 GHz
- Sextupole → focuses LFS and defocuses HFS
- Spin flip would show as decrease in signal at detector

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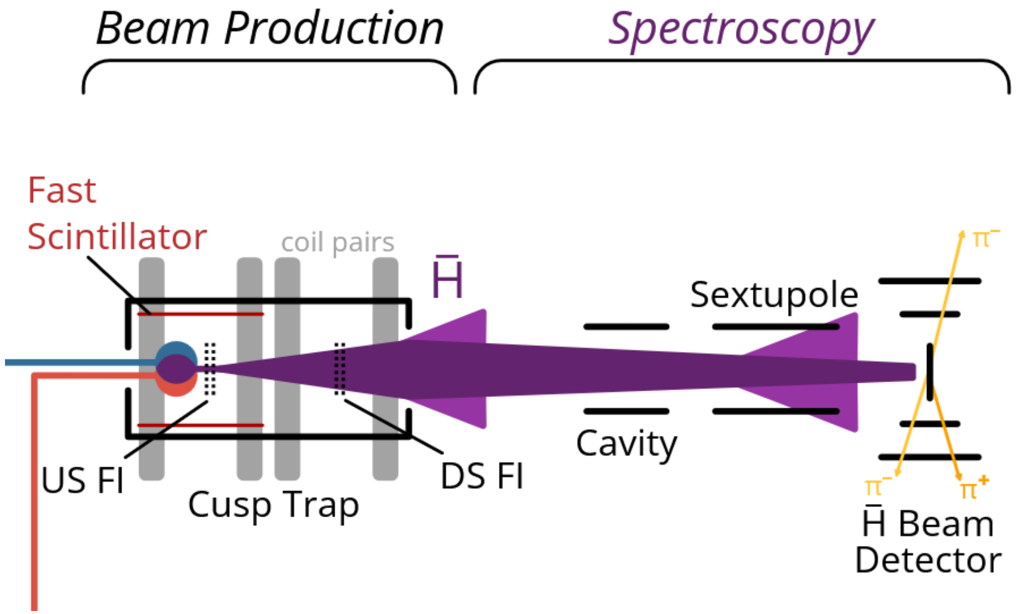

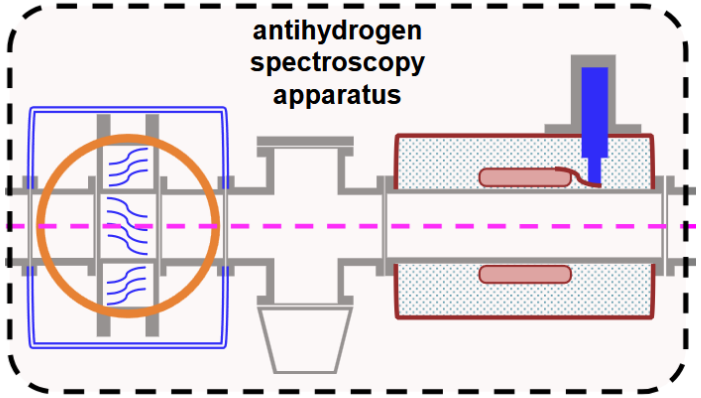

2025 Mixing

New 2025

- >7 million antiprotons
- 130 million positrons
- Similar temperature

- Mixing duration 120 s
- Full cycle ~18 minutes
- 100 beam-like $\overline{\mathrm{H}}$ per cycle

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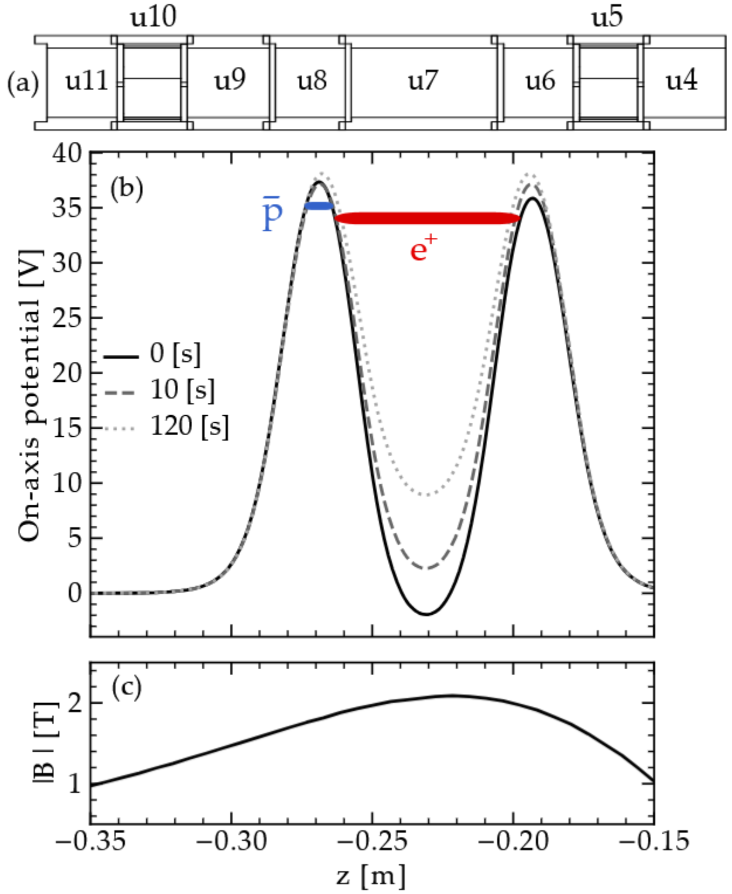
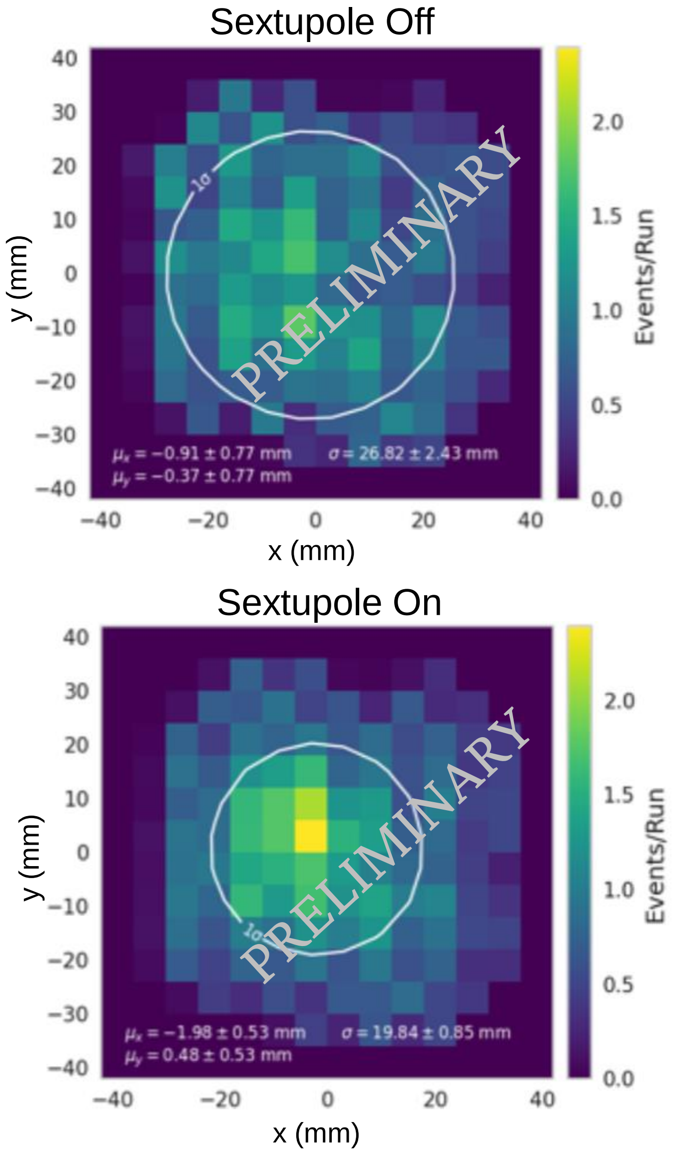


Sextupole Focusing

New
2025

- Focusing with sextupole observed (~2 T)
- 26 ± 7% reduction in beam spot size
- No reduction in beam intensity
- High Rydberg contribution
- On axis atoms not focussed



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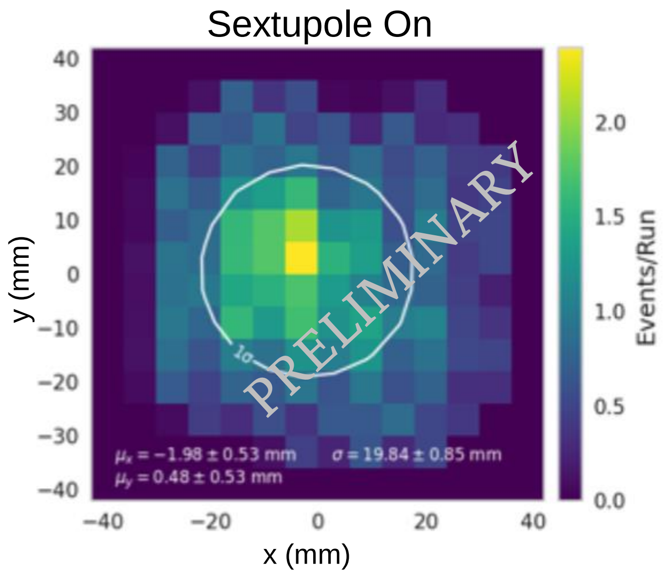
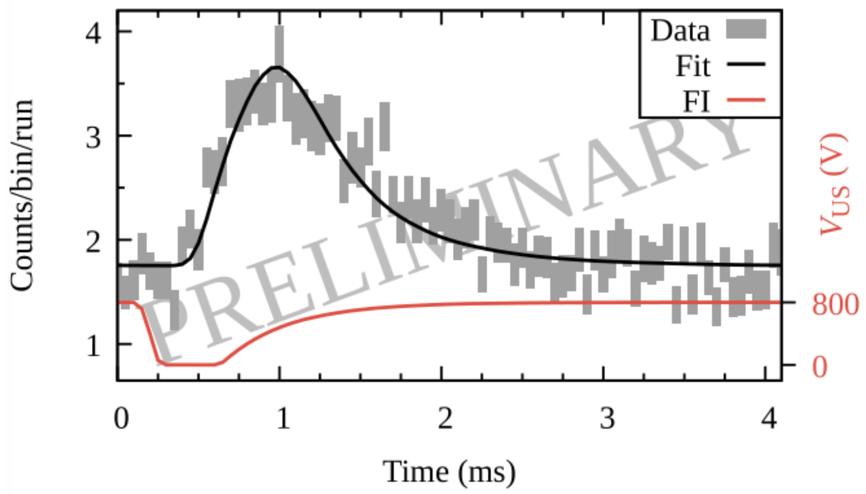
Conclusions

- We have atoms we could use
- Next step: make them useful

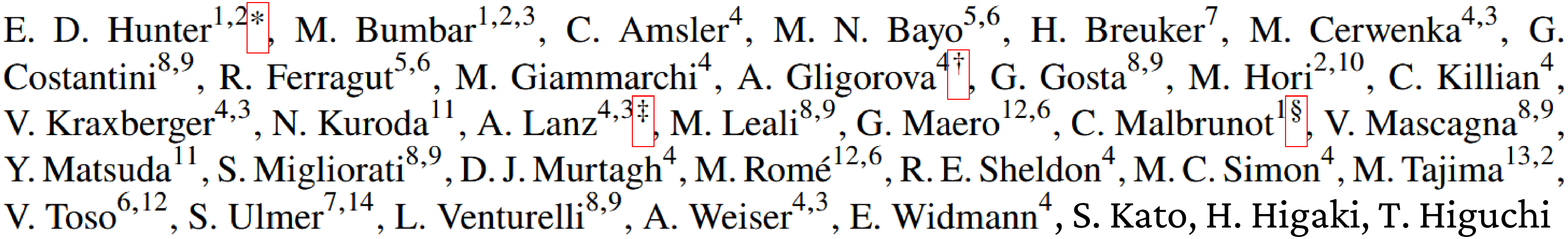
- Beam and plasma optimisation ongoing
  - Colder plasmas → more $\bar{\mathrm{H}}$
  - Denser positrons → slower/lower n $\bar{\mathrm{H}}$

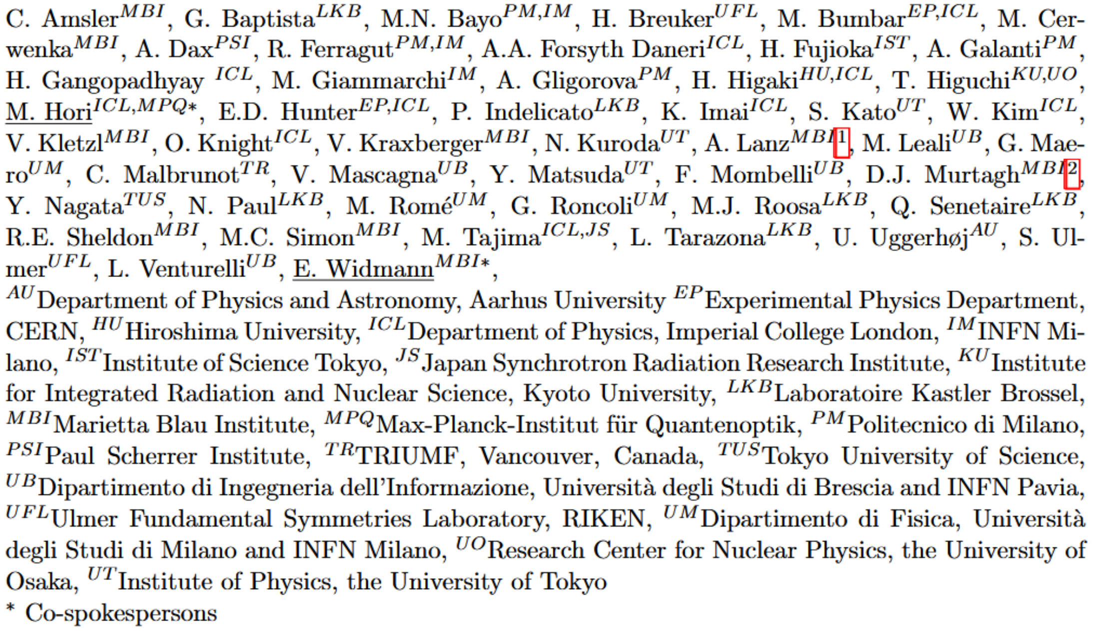
- Improve signal-to-noise ratio
  - Remove central atoms
  - Remove Rydberg atoms





Acknowledgements


E. D. Hunter[1,2][*], M. Bumbar[1,2,3], C. Amsler[4], M. N. Bayo[5,6], H. Breuker[7], M. Cerwenka[4,3], G. Costantini[8,9], R. Ferragut[5,6], M. Giammarchi[4], A. Gligorova[4][†], G. Gosta[8,9], M. Hori[2,10], C. Killian[4], V. Kraxberger[4,3], N. Kuroda[11], A. Lanz[4,3][‡], M. Leali[8,9], G. Maero[12,6], C. Malbrunot[1][§], V. Mascagna[8,9], Y. Matsuda[11], S. Migliorati[8,9], D. J. Murtagh[4], M. Romé[12,6], R. E. Sheldon[4], M. C. Simon[4], M. Tajima[13,2], V. Toso[6,12], S. Ulmer[7,14], L. Venturelli[8,9], A. Weiser[4,3], E. Widmann[4], S. Kato, H. Higaki, T. Higuchi


C. Amsler[MBI], G. Baptista[LKB], M.N. Bayo[PM,IM], H. Breuker[UFL], M. Bumbar[EP,ICL], M. Cerwenka[MBI], A. Dax[PSI], R. Ferragut[PM,IM], A.A. Forsyth Daneri[ICL], H. Fujioka[IST], A. Galanti[PM], H. Gangopadhyay [ICL], M. Giammarchi[IM], A. Gligorova[PM], H. Higaki[HU,ICL], T. Higuchi[KU,UO], M. Hori[ICL,MPQ*], E.D. Hunter[EP,ICL], P. Indelicato[LKB], K. Imai[ICL], S. Kato[UT], W. Kim[ICL], V. Kletzl[MBI], O. Knight[ICL], V. Kraxberger[MBI], N. Kuroda[UT], A. Lanz[MBI][1], M. Leali[UB], G. Maero[UM], C. Malbrunot[TR], V. Mascagna[UB], Y. Matsuda[UT], F. Mombelli[UB], D.J. Murtagh[MBI][2], Y. Nagata[TUS], N. Paul[LKB], M. Romé[UM], G. Roncoli[UM], M.J. Roosa[LKB], Q. Senetaire[LKB], R.E. Sheldon[MBI], M.C. Simon[MBI], M. Tajima[ICL,JS], L. Tarazona[LKB], U. Uggerhøj[AU], S. Ulmer[UFL], L. Venturelli[UB], E. Widmann[MBI*],

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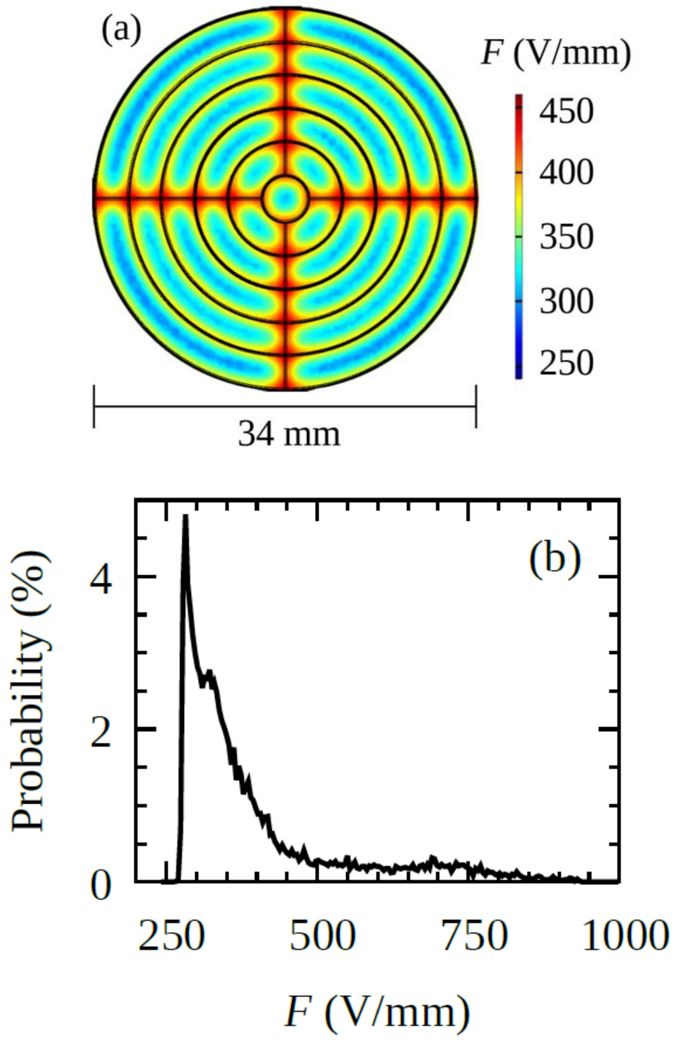
* Co-spokespersons

Bonus – FI bias to *n* conversion

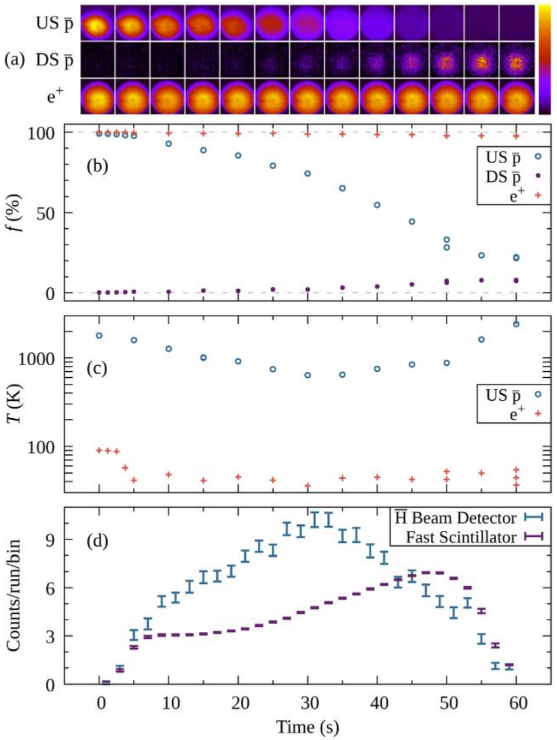
- FI has uneven spatial distribution
- Simulations and modelling converts field distribution to probability of ionising one n
- Simulations classical but agree with approximation
- Quantum state distribution & residual B accounted for

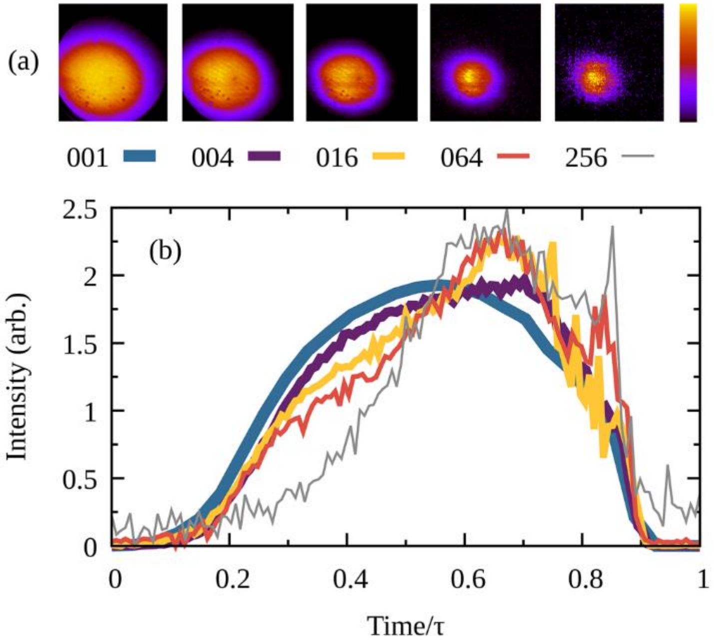


Bonus – Slow Extraction

- Repeat mixing routine but extract antiprotons to MCP instead of into positrons to see how plasma evolves

- Most come out at the end in tight spot





Bonus – Mixing Duration

- The longer we mix the more antihydrogen we make up to a certain limit
- Merging fast allows plasma to hollow out
- Plasma is stable for slower merging