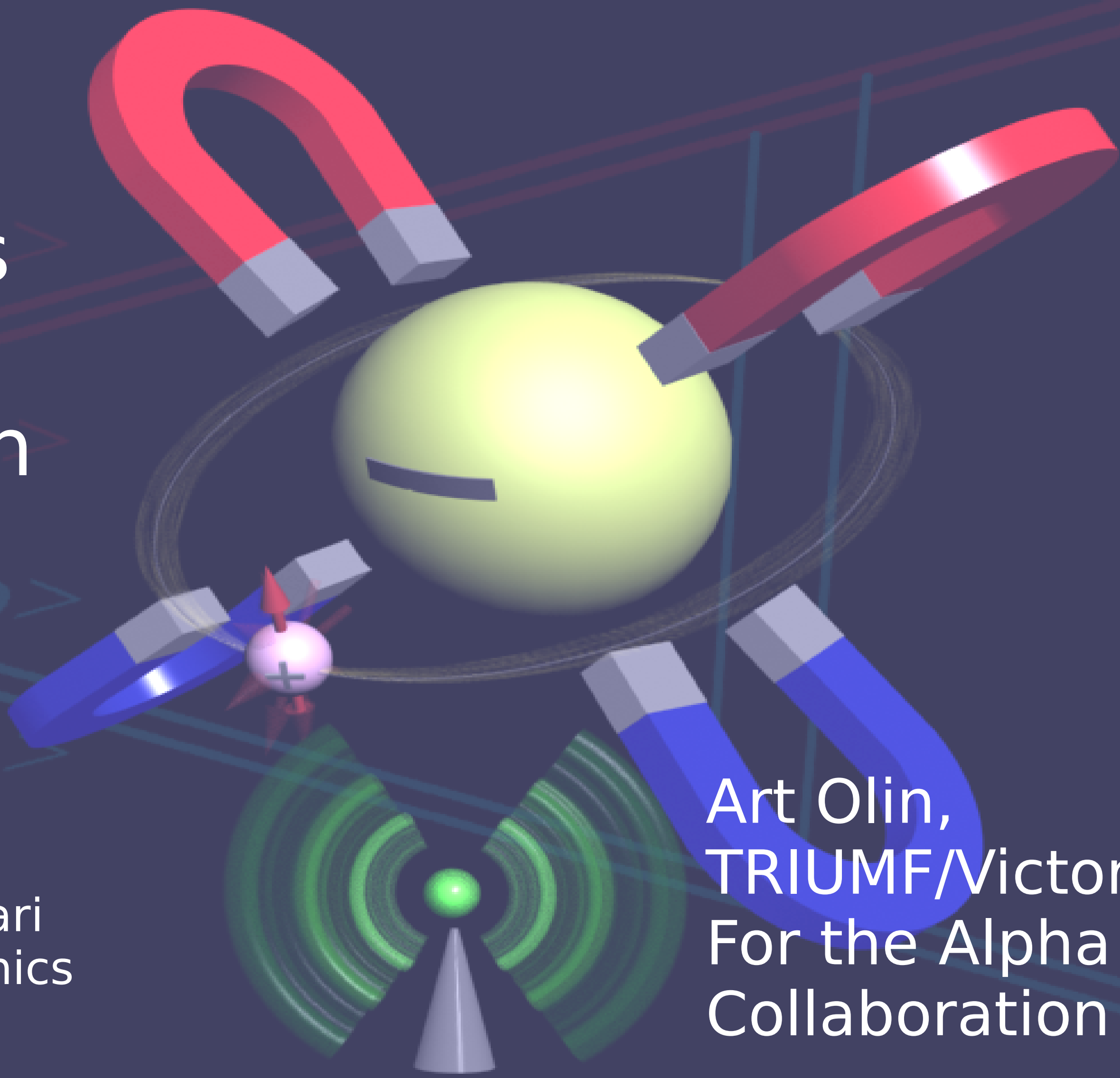
ALPHA

European Organization for Nuclear Research

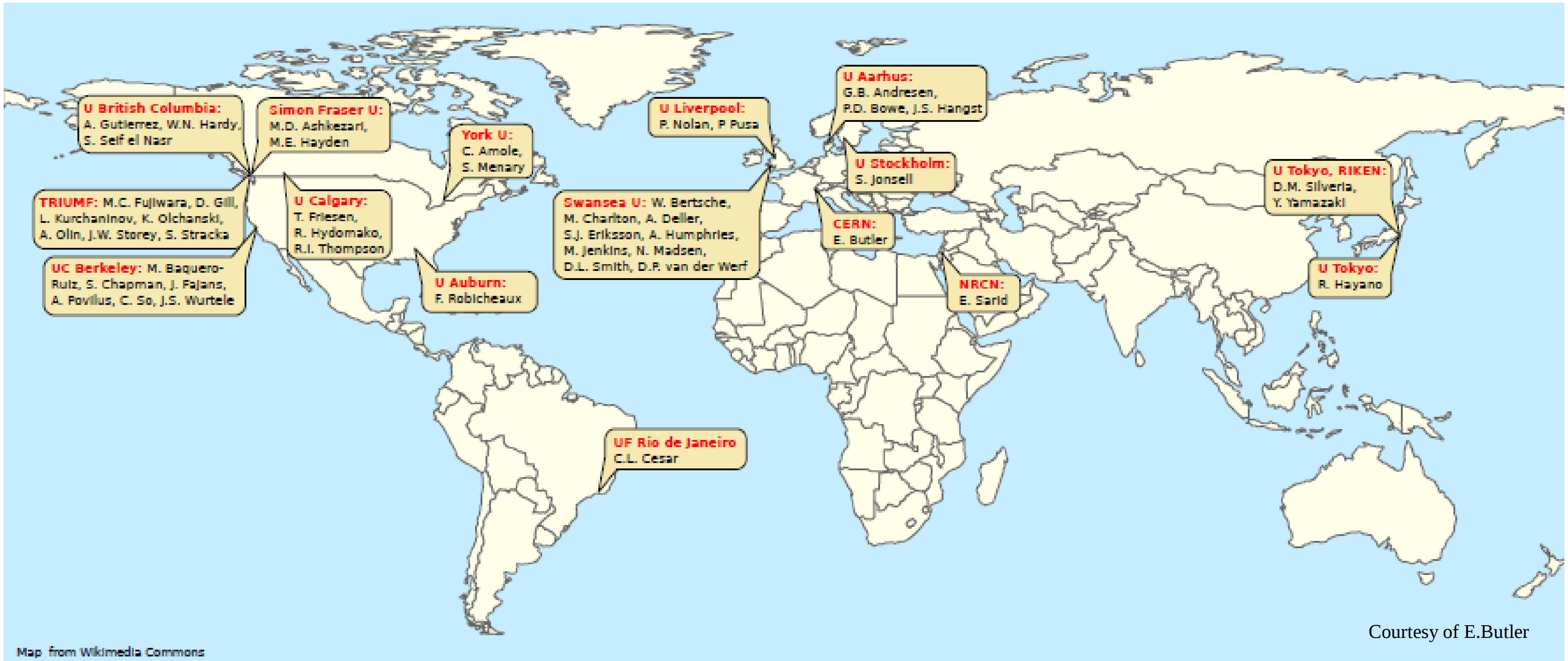
Resonant Microwave Interactions with Antihydrogen



Art Olin, TRIUMF/Victoria
For the Alpha Collaboration

Thanks to M Ashkezari for figures and graphics

ALPHA Collaboration



Physics Areas:
Accelerator, Atomic, Condensed Matter, Particle, and Plasma Physics

Supported by:
CNPq, FINEP/RENAFAE (Brazil)
ISF (Israel); MEXT (Japan)
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EPSRC, the Royal Society and the Leverhulme Trust (UK).

ALPH̄A CPTV in Antihydrogen

1s-2s transition measured by 2 photon laser spectroscopy

- Transition in hydrogen recently measured to 4.2 10^{-15}.
- CPTV precision limit is ~10^{-8} from e^+ e^- mass difference, and ~10^{-9} from $\bar{p}$ mass.
- Measurements initially at ~10^{-10} precision would already represent a significant improvement.

ALPHA2, ATRAP

Ground state hyperfine interval measured by microwave resonance spectroscopy.

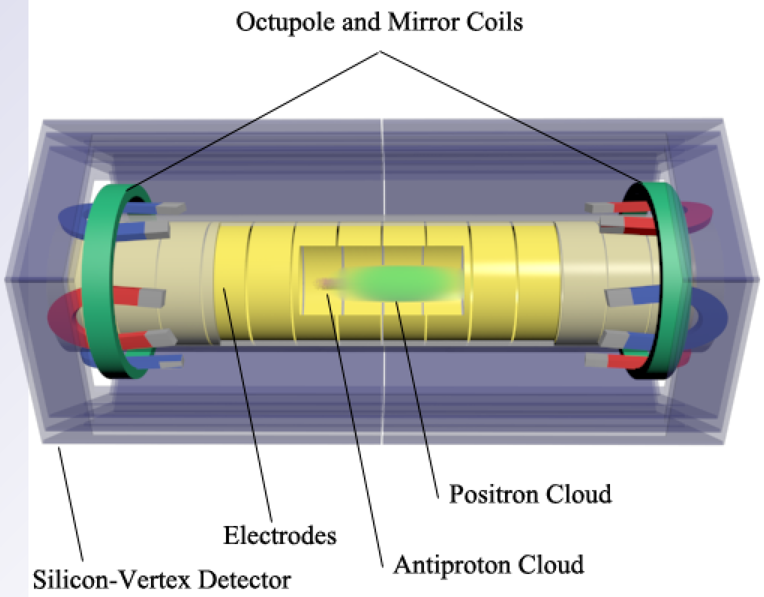
- In hydrogen precision of 10^{-13} or 10^{-23} GeV has been achieved.
- Relative precisions better than 10^{-7} or 10^{-17} GeV in antihydrogen would already challenge the limit from the baryon magnetic moment.
- Favoured in Kostelecky SME.

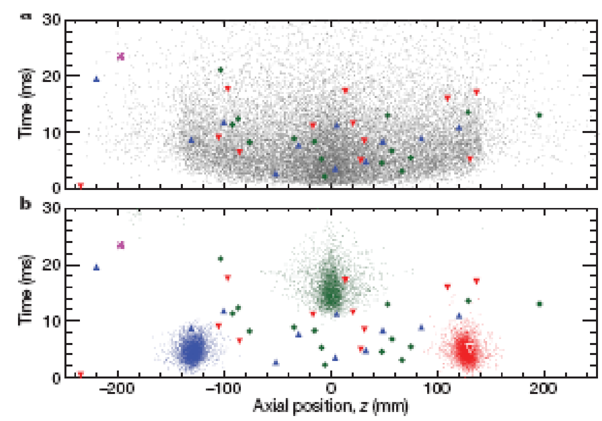
ALPHA, ASACUSA

ALPHA Status 2011

- Succeeded in trapping antihydrogen.
  - Mix $\bar{p}$ and e^+ plasmas in trap for 1s. Most $\bar{H}$ escape ~5000 annihilations.
  - Clear charged particles with E fields.
  - Quench trap magnets.
- Evidence based on the time and spatial distribution of 38 $\bar{H}$ annihilations.
- Position and time of these annihilations reveals the trapping dynamics and eliminates mirror-trapped $\bar{p}$.
- Observation of a microwave resonance in $\bar{H}$ would be an additional validation.

Trapped Antihydrogen
Nature 468, 673(2010)





Trap Lifetime

Procedure: Mix in trap, clear charged particles, wait, quench trap.

Observation of events remaining in the trap after 1000s wait.

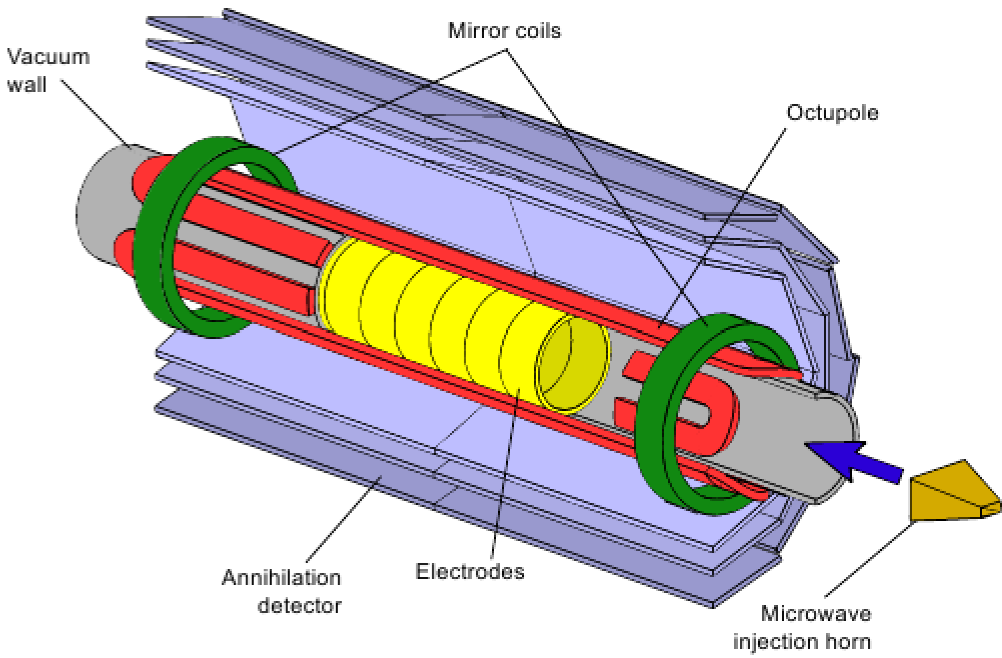
Not based on a measured trap loss rate.
-Number trapped at t=0 not well known.
This suggested that a spectroscopy program was possible even with a low trapping rate!

Nature Physics 7, 558(2011).

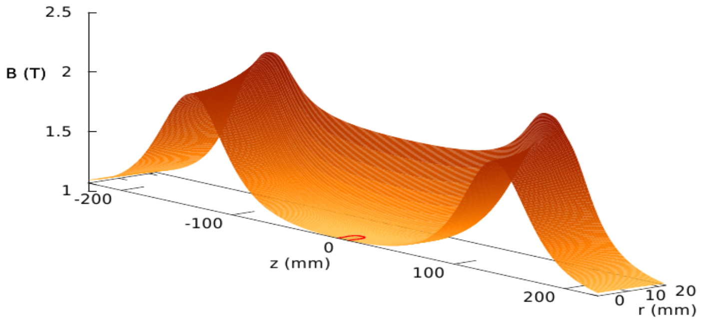
Microwave Interrogation

Microwaving the ALPHA Trap

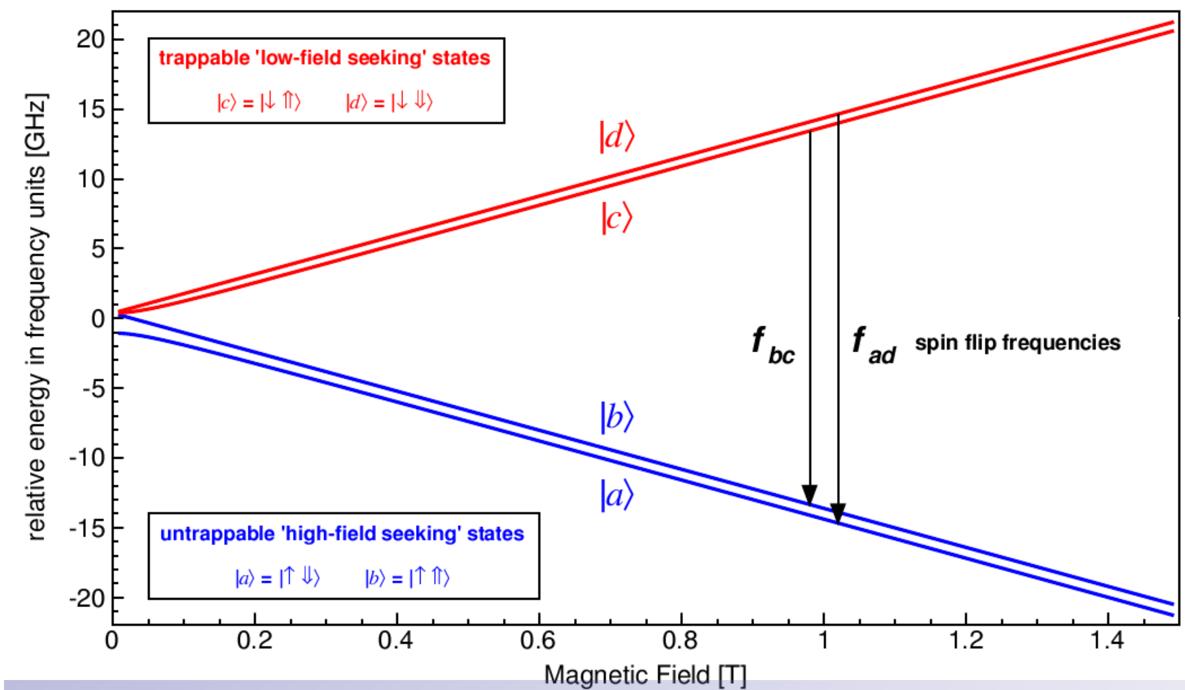
Microwaves are injected along the axis of the trapping volume using a horn antenna, which is located about 130cm from the trap axial midpoint. The electrodes form a waveguide where the standing wave modes vary quickly with frequency. Full power ~700mW at UHV window.



Map of magnetic field strength in the ALPHA antihydrogen trap. The red contour bounds a region up to 0.35mT (or 10MHz in microwave frequency equivalent) above the minimum field, to roughly indicate the size of the resonant volume.



Hydrogen Hyperfine Energy Levels

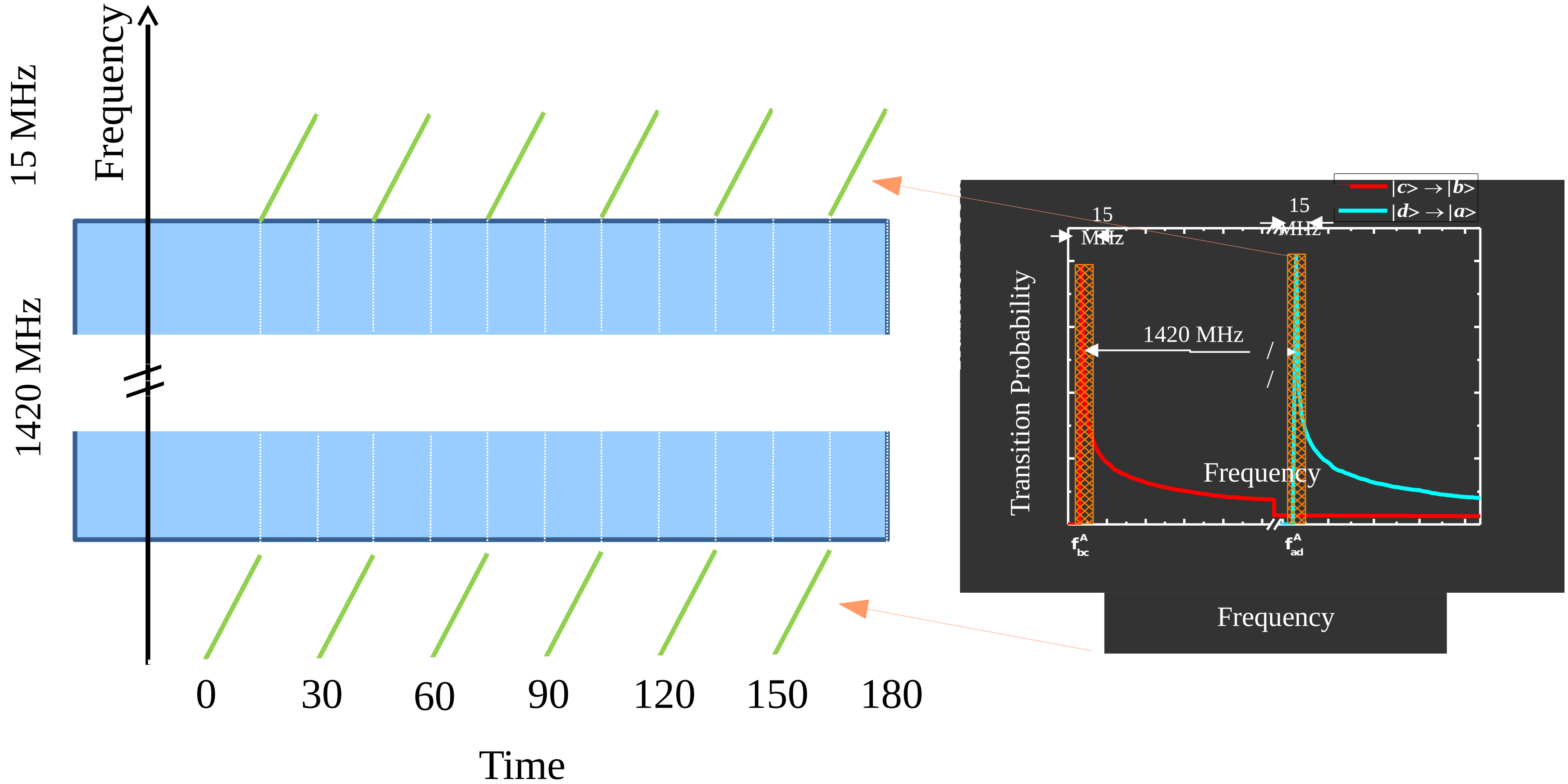


Driving f_{bc} or f_{ad} expels $\bar{H}$ from trap.

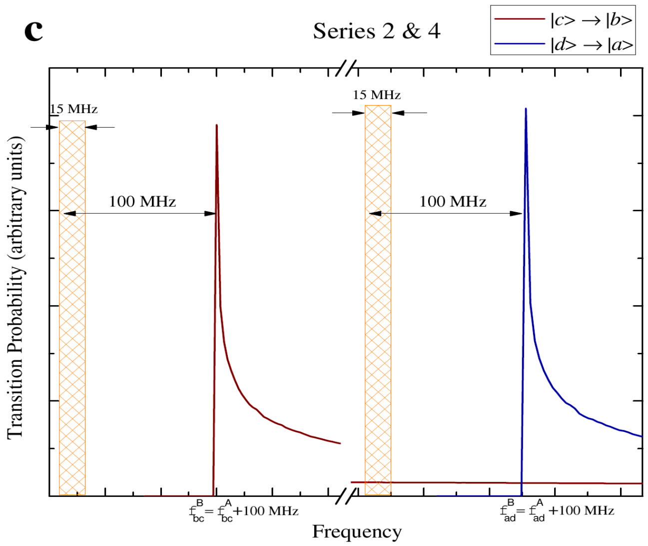
Observe annihilations in vertex detector surrounding trap.

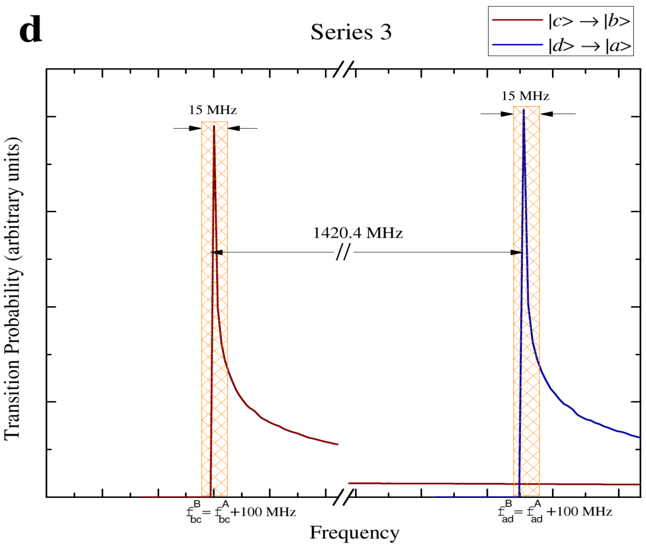
The Breit–Rabi diagram, showing the relative hyperfine energy levels of the ground state of the hydrogen (and antihydrogen, assuming CPT invariance) atom in a magnetic field. In the state vectors shown (for the high-field limit), the single arrow refers to the positron spin and the double arrow refers to the antiproton spin.

Microwave Sweep Sequence



Resonance Conditions

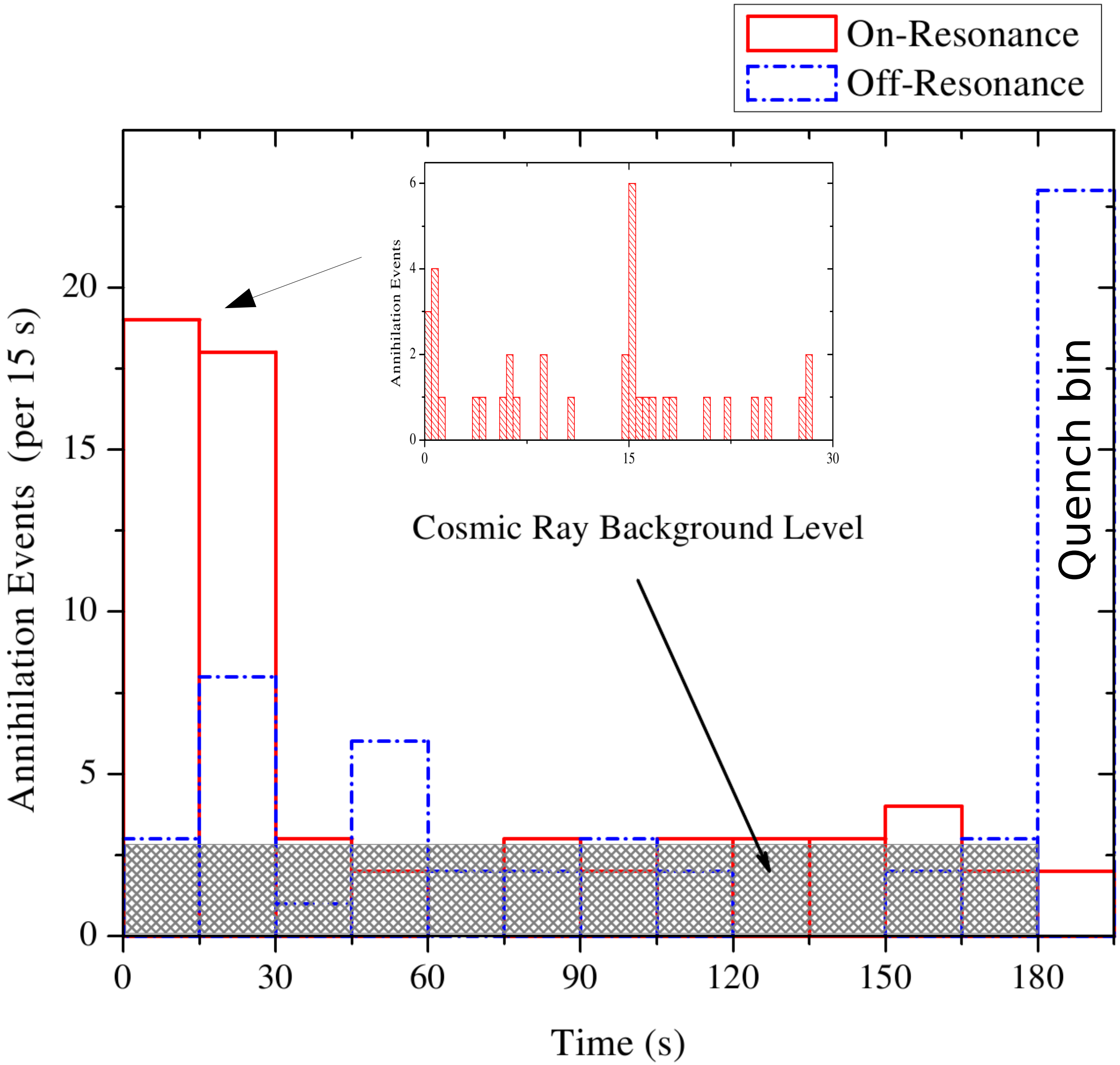




The situation for off-resonance experiments at magnetic field B (series 2 and 4).

The situation for on-resonant experiments at magnetic field B (series 3).

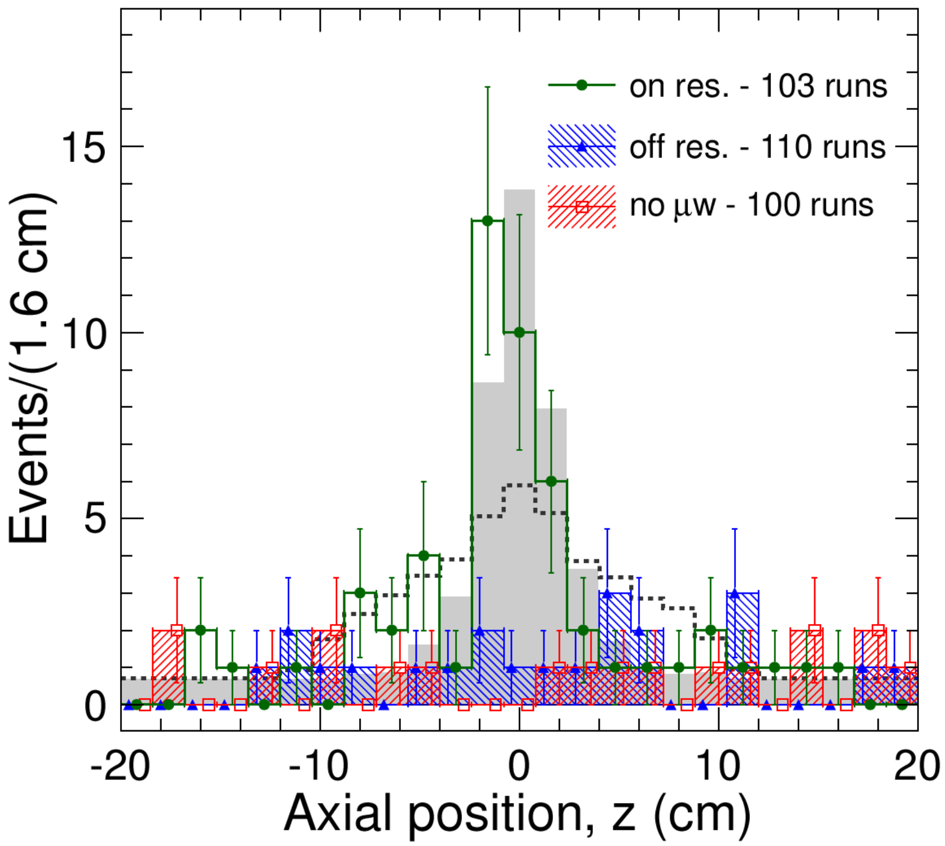
Microwave-Correlated Transitions Observed



Evidence for μWave Resonance

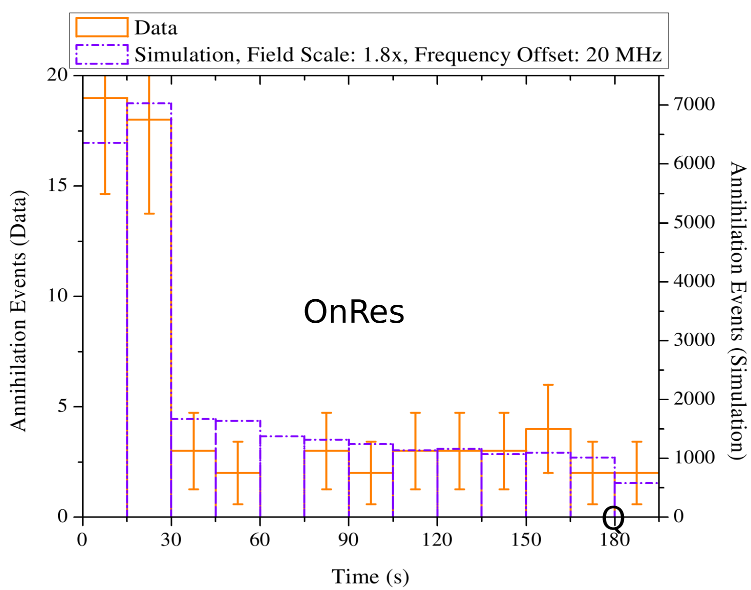
- Resonant and off-resonant histograms differ by >5σ.
- Observed at two different magnetic field values.
- Annihilation vertex locations peaked at trap center.

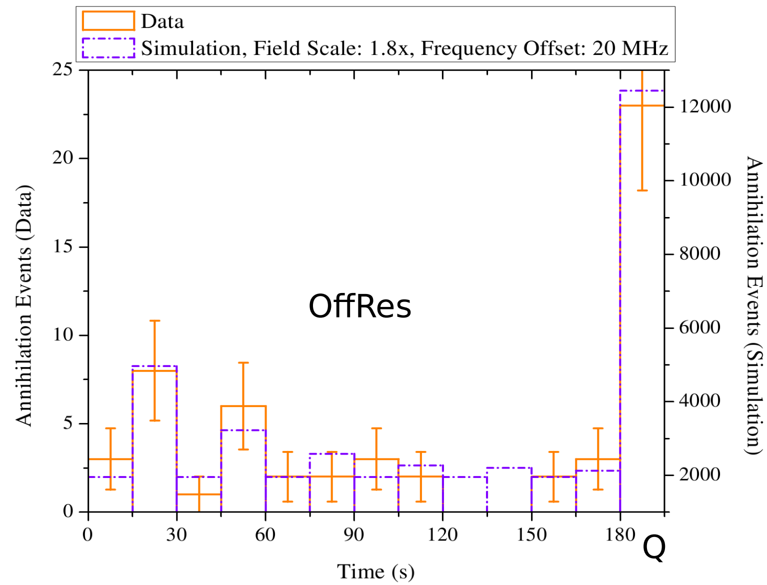
➔Not consistent with annihilations on microwave-induced gas evolution.



Simulation of $\overline{H}$ in Trap

- Inject $\overline{H}$ in trap and allow orbit to randomize.
- Opera-calculated magnetic field shape.
- Plane-wave approximation for µwave field.
- Vary the µwave power and field offset.
  - Best agreement for on and off resonance.
- Landau-Zener approx for spin flip probability at resonance crossing.

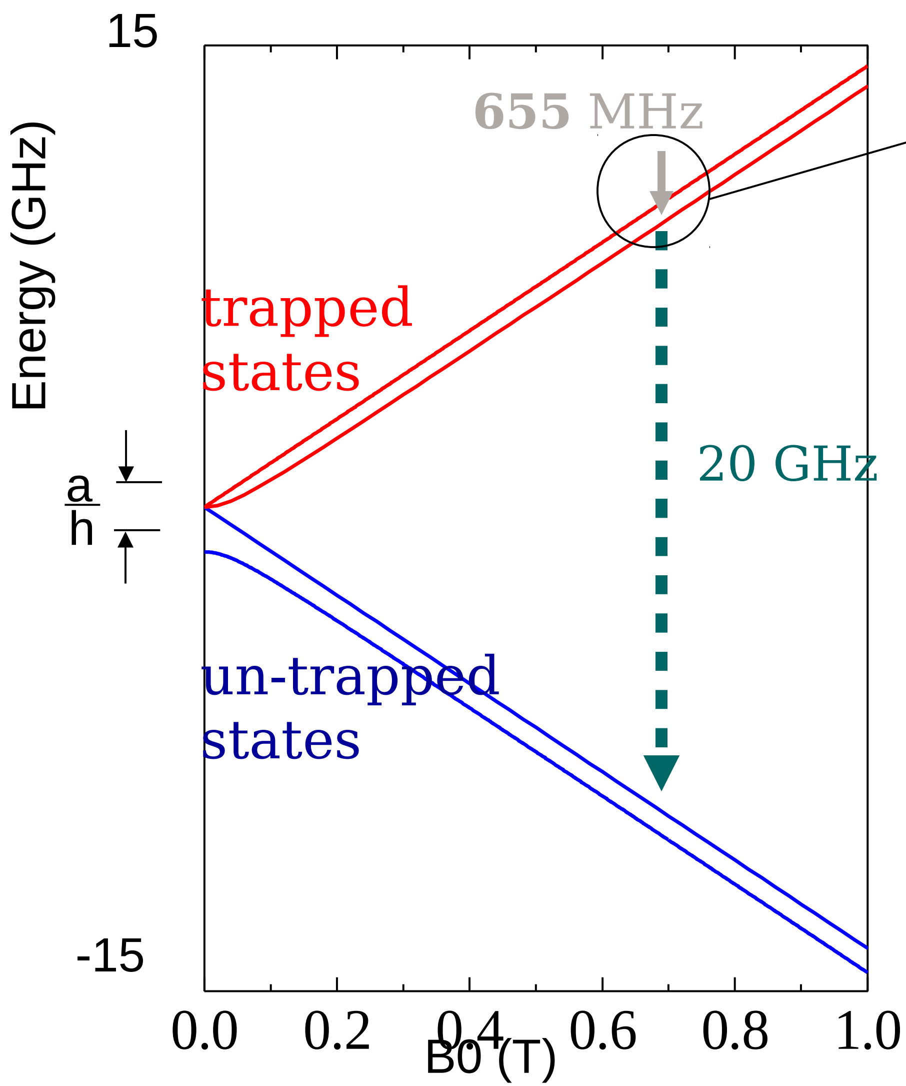


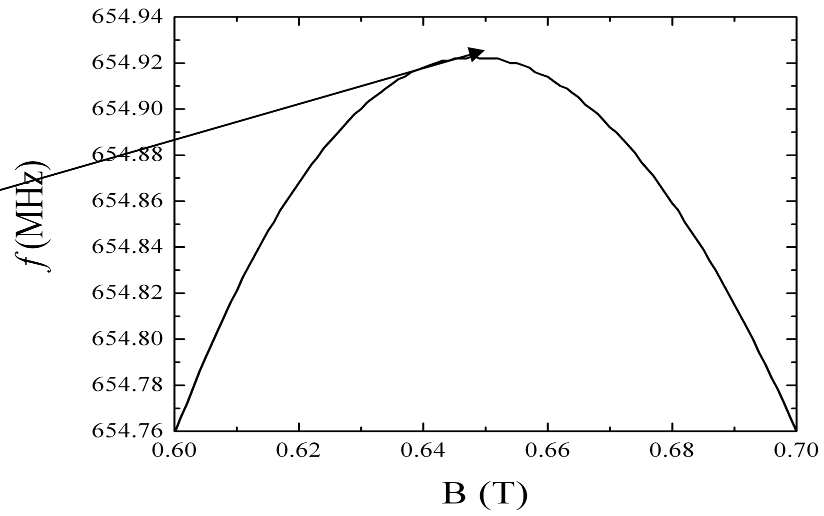


Lessons Learned

- $f_{ad} - f_{bc}$ in $\bar{H}$ is within ±85 MHz of its value in H
  - Test of CPT at 0.3% precision.
- Magnetic field in the trap is hard to measure accurately
  - ECR electron plasma technique developed with precision ~10MHz
  - 40MHz variations seen probably flux pinning in coils
- Microwave magnetic field strength is consistent with our estimates despite the complexity of the transmitted modes.
- We can reliably expel $\bar{H}$ from trap with microwaves
  - Alternative to quenching the coils
  - Improved control of the trap

Road to Precision Spectroscopy





NMR (pbar spin flip)

655 MHz at magic 0.65T turning point: insensitive to 1st order B inhomogeneity

- Double resonance w/ PSR

Precision Goals for NMR Measurement

- Lineshape at the maximum frequency is intense and very sharp.
- A trap-compatible resonator is required to drive the NMR signal.
- Resolution limit is transit-time broadening.
- Resolution improves when $\bar{H}$ are cooled.

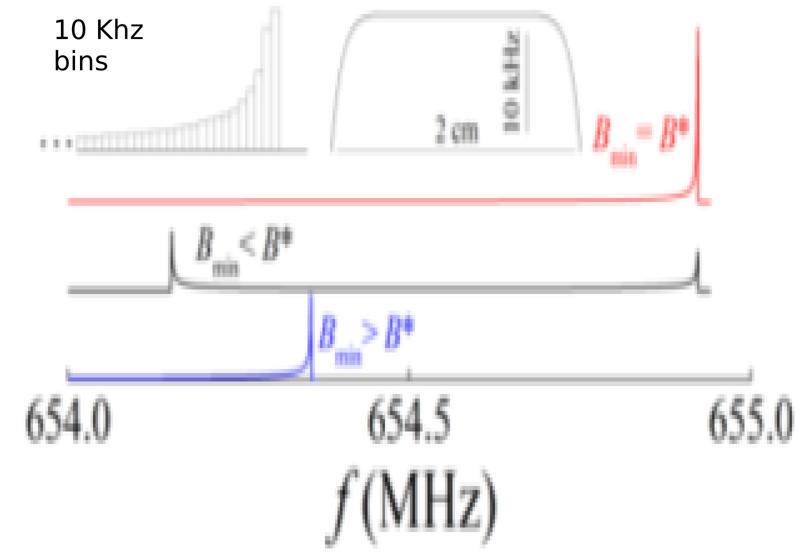
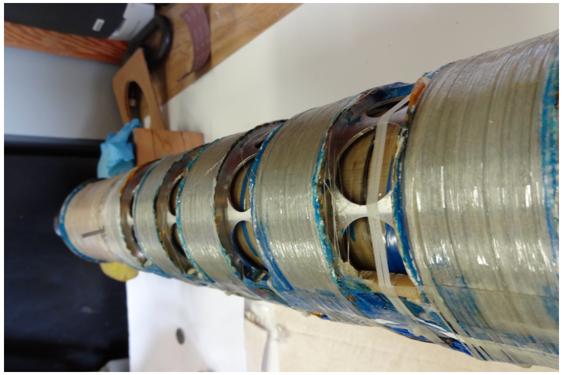


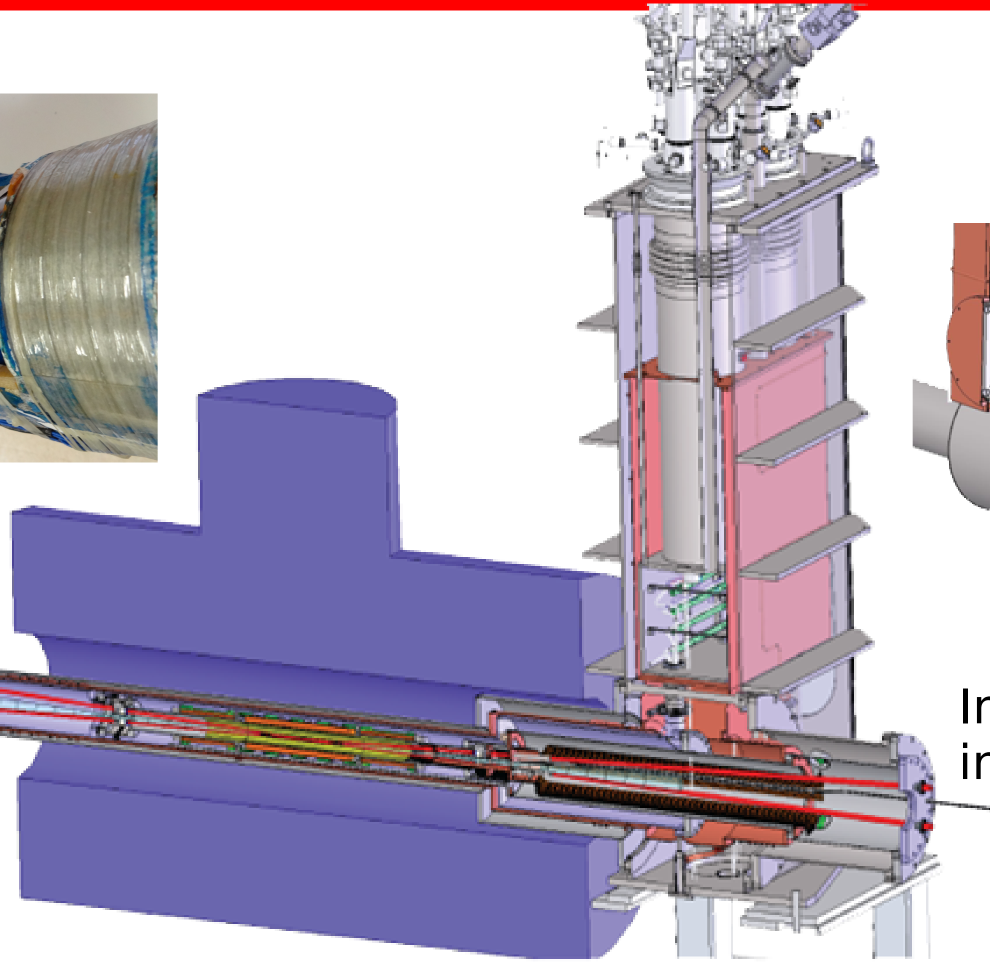
Table 1: Thresholds for onset of systematics (rel. to a/h)

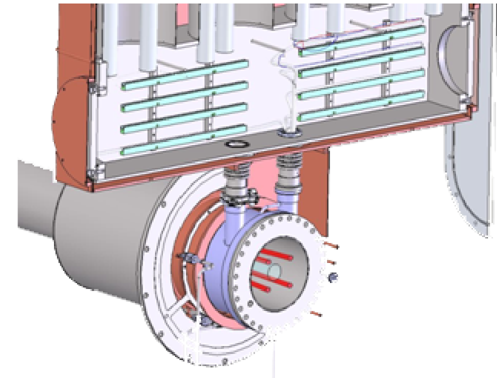
	Conventional Operation	w/ Laser Cooling
Transit time effects		
trap magnet geometry	2×10^{-6}	1×10^{-7}
electrode/resonator length	2×10^{-7}	5×10^{-8}
Doppler effects	1×10^{-7}	1×10^{-8}
Resonator stability	8×10^{-8}	6×10^{-9}
Trap reproducibility		
octupole field	2×10^{-9}	1×10^{-10}
mirror fields	1×10^{-10}	1×10^{-10}
solenoidal field	1×10^{-10}	1×10^{-10}

ALPHA-II

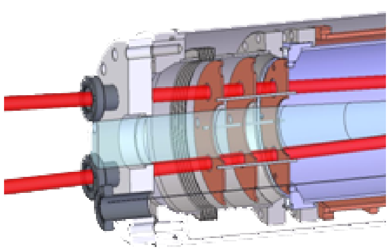


Improved
trap field

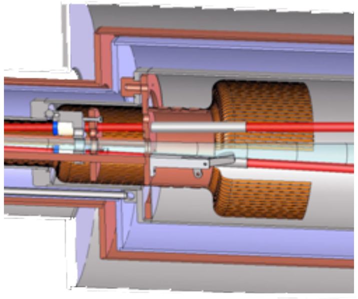




Improved µwave
injection



Laser access enables
magnetometry



Summary and Outlook

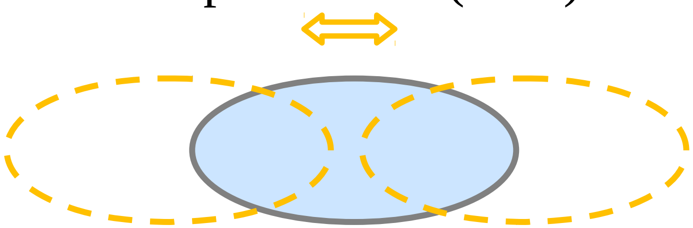
- ALPHA will search for a matter – antimatter asymmetry via precision antihydrogen atomic spectroscopy.
- Sophisticated techniques have been developed to create, cool and mix $\bar{p}$ and e^+ plasmas.
- Antihydrogen atoms have been held in a shallow magnetic trap for up to 16 minutes.
- The first observation of a resonant interaction with the ground state antihydrogen has been accomplished.
- A new apparatus to enable higher precision laser and microwave spectroscopy is being commissioned, and we are developing the difficult lasers required for $\bar{H}$ spectroscopy.
- We are investigating the sensitivity of our trap to gravitational interactions with antimatter.

Back up slides

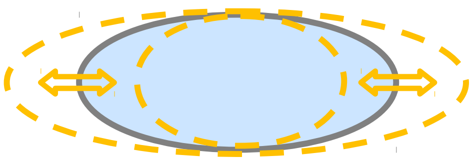
Electron Cyclotron Resonance Diagnostic

Quadrupole mode frequency of plasma can be used as a thermometer.

Dipole Mode (l =1)



Quadrupole Mode (l =2)



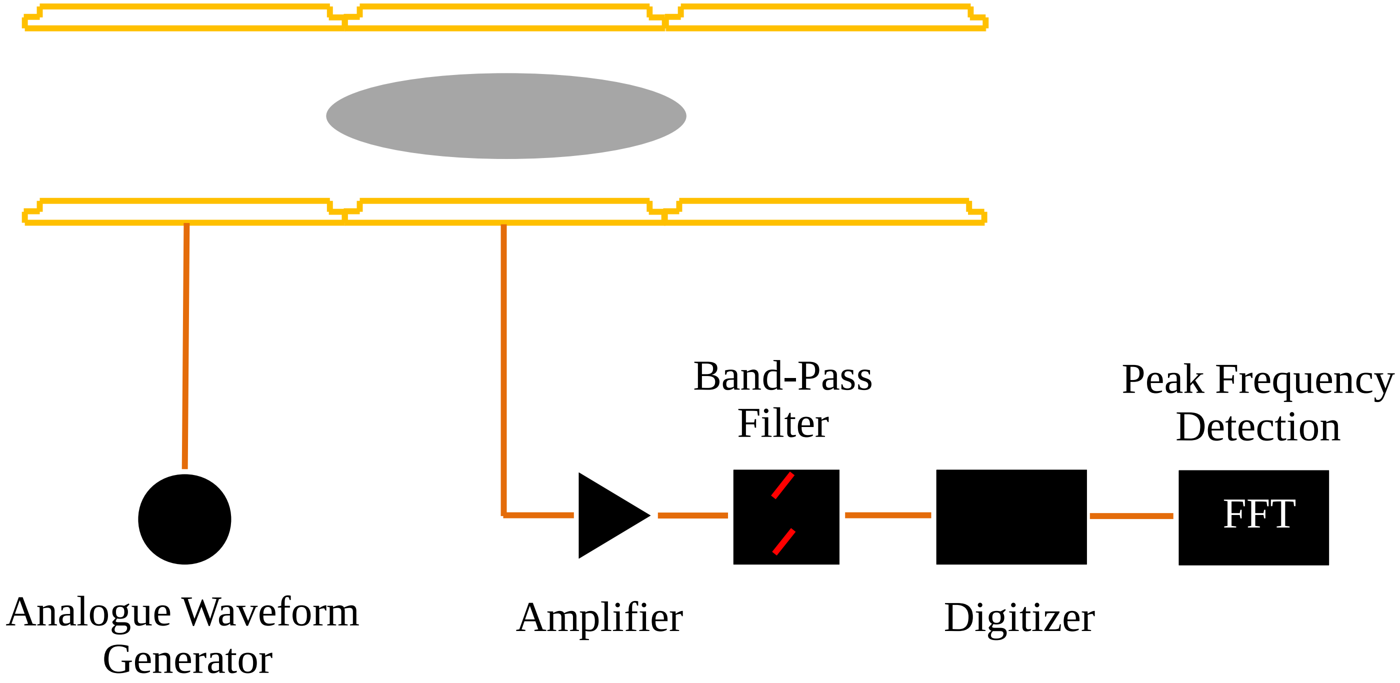
$$(\omega_2^T)^2 = (\omega_2^0)^2 + 20[3 - \frac{\omega_p^2\alpha^2}{2(\omega_2^0)^2}\frac{\partial^2 f(\alpha)}{\partial\alpha^2}]\frac{K_B T}{mL^2}$$

$$\Delta\omega_2^T \propto \Delta T \text{ for small } \Delta \mathrm{T}$$

1. M. D. Tinkle , R. G. Greaves, and C. M. Surko, Phys Plasmas **2**, 2880 (1995).

ECR Diagnostics

- Electron plasma is confined in a harmonic well.
- Quadrupole frequency is continuously monitored.
- Microwave pulses are injected at the cyclotron resonance frequency.



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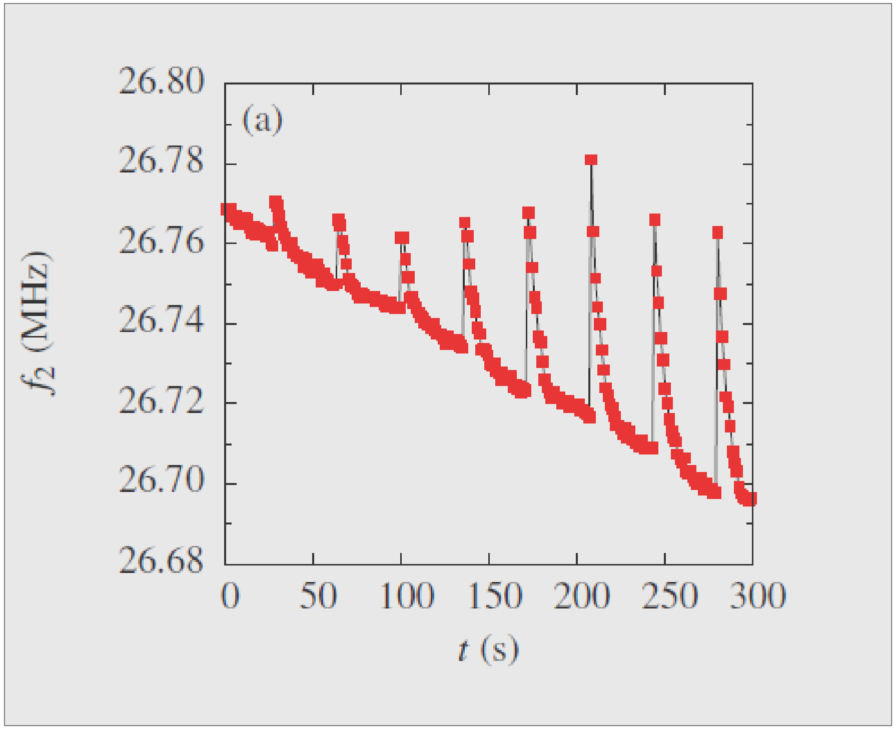
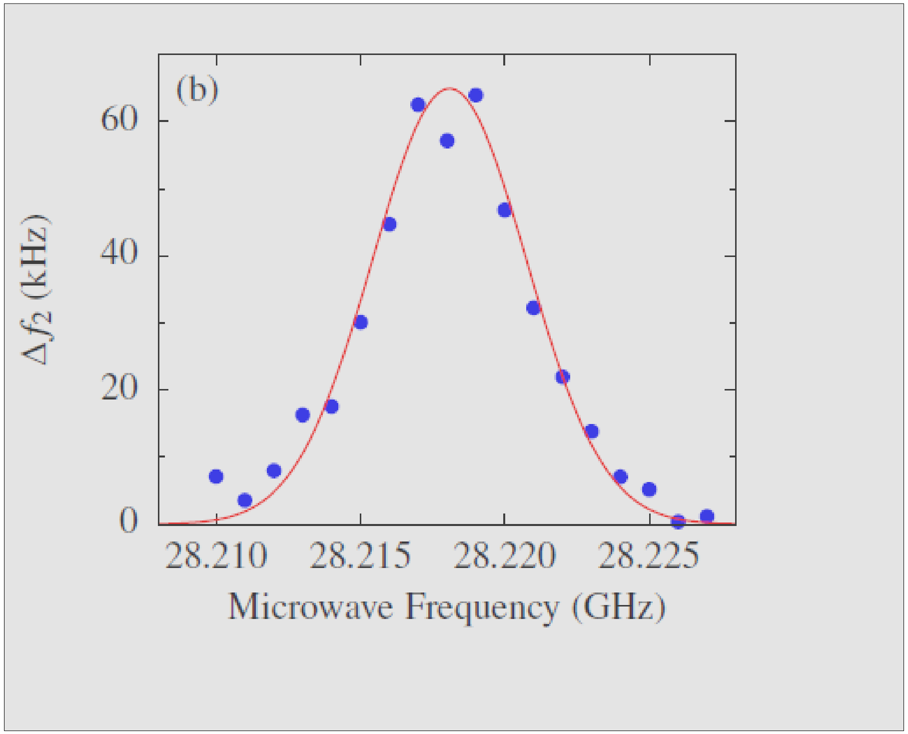
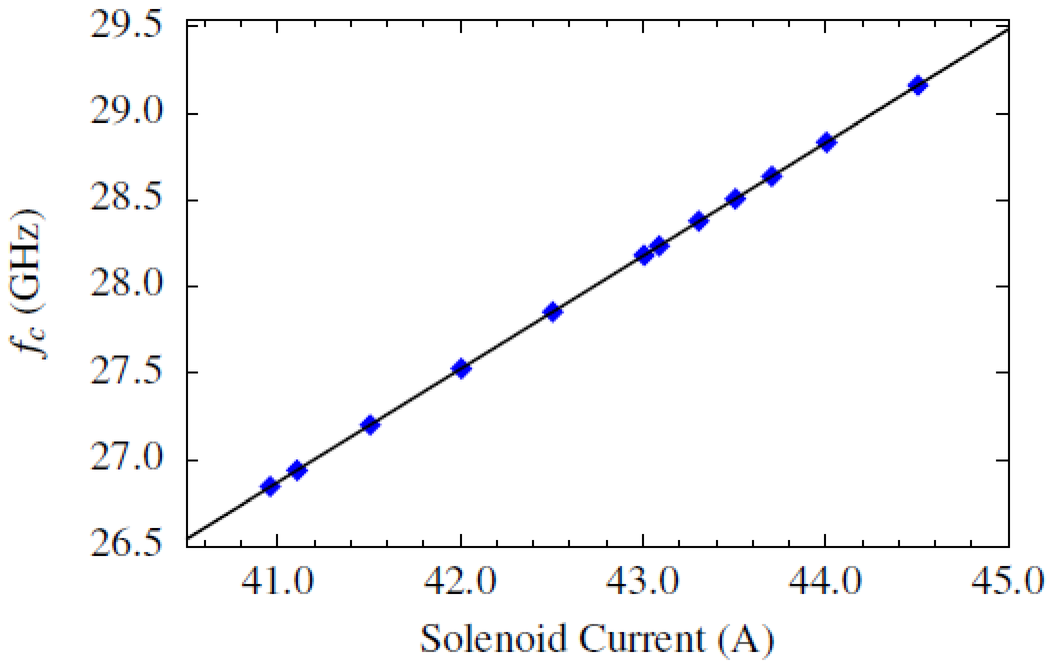
ECR Scans

- A series of 4μs microwave pulses are injected.
- Microwave frequency is scanned across the cyclotron resonance frequency.
- Estimated uncertainty: ~10 MHz.





Magnetic Field Calibration with e⁻ Plasma



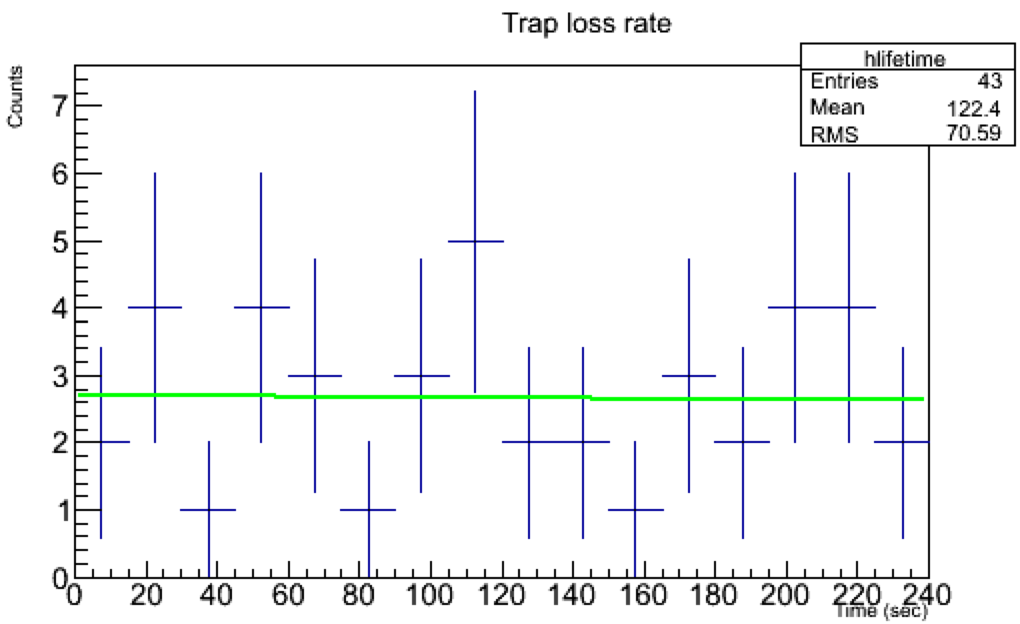
- Onset frequency is linear with magnetic field.
- Used to set and monitor stability of magnetic field.
- Field reproducibility 2MHz.
- Estimated uncertainty of field minimum:
  3.6 G or 10 MHz.

Inhomogenous magnetic field, thermal broadening, and spatially varying microwave distorts lineshape.

Trap Loss Rate

- MVA analysis reduces cosmic background
  - Better estimate of $\bar{H}$ annihilating during the wait time.
- Constrained by 28 $\bar{H}$'s surviving wait.
- Assume exponential model.

$$N = N_{quench}\,\lambda \exp(-\lambda(t-T)) + N_{runs}\, r_{cosmic}$$



Fit to 100 microwave off trapping runs

- Trap remains open for 240s after end of mixing.
- Cosmic ray rate 1.7mHz.
- Exponential loss rate per trapped atom is 0.3 ± 1.3 mHz.
- Consistent with residual gas loss estimate.

ALPHA Physics Reach

Possible CPTV shift (Pospelov)

$$\Delta E \sim \frac{m^{n+1}}{\Lambda^{n}_{CPTV}}$$

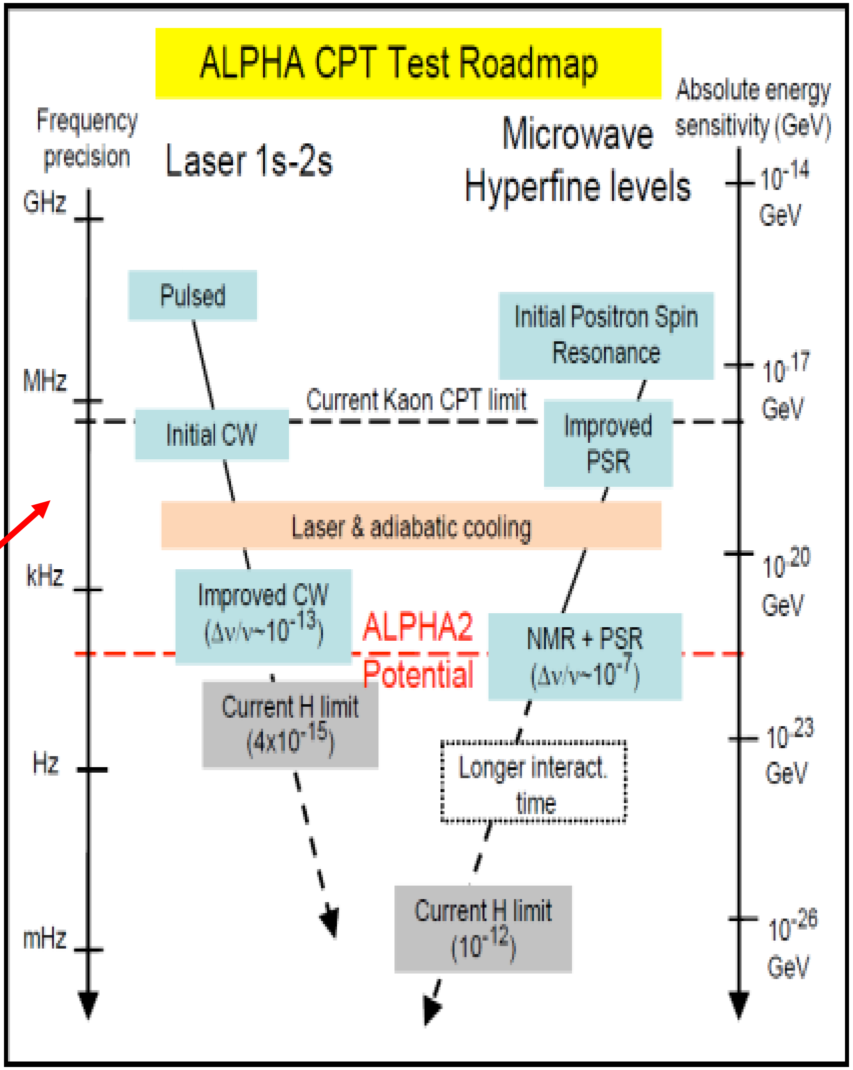
Small absolute energy ΔE probes high energy scale

For n=1, m=1 GeV,

$\Lambda_{CPTV} = M_{Pl} \sim 10^{19}$ GeV

$\Delta E_{CPTV} \sim 10^{-19}$ GeV

(~10 kHz in frequency)



Mirror trapped antihydrogen

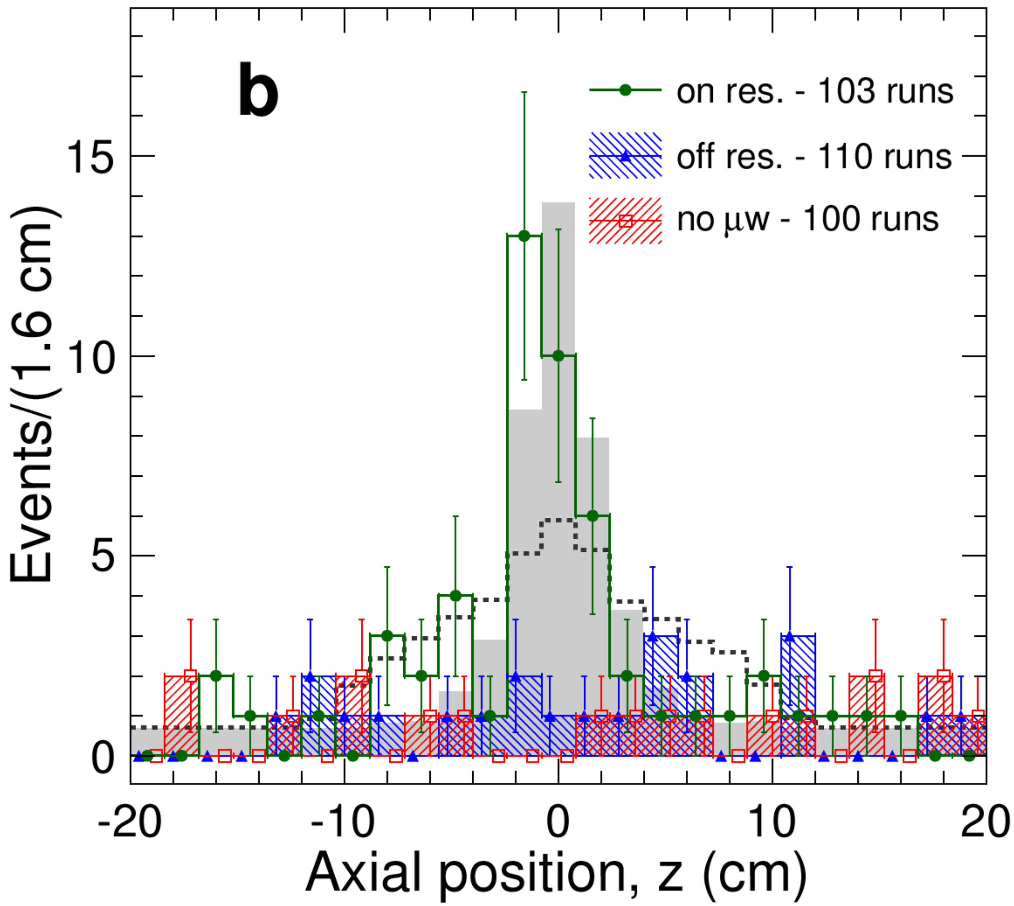
- Ignoring E fields, $\bar{p}$ can be trapped in our anti-H trap via magnetic mirror effect.

$$\frac{E_T}{E_L} > \frac{B_{Max}}{B_{Min}}$$

- Our original identification of trapped $\bar{H}$ was based on the different annihilation distributions for $\bar{H}$ and $\bar{p}$. This was a critical element of our trapping claim.

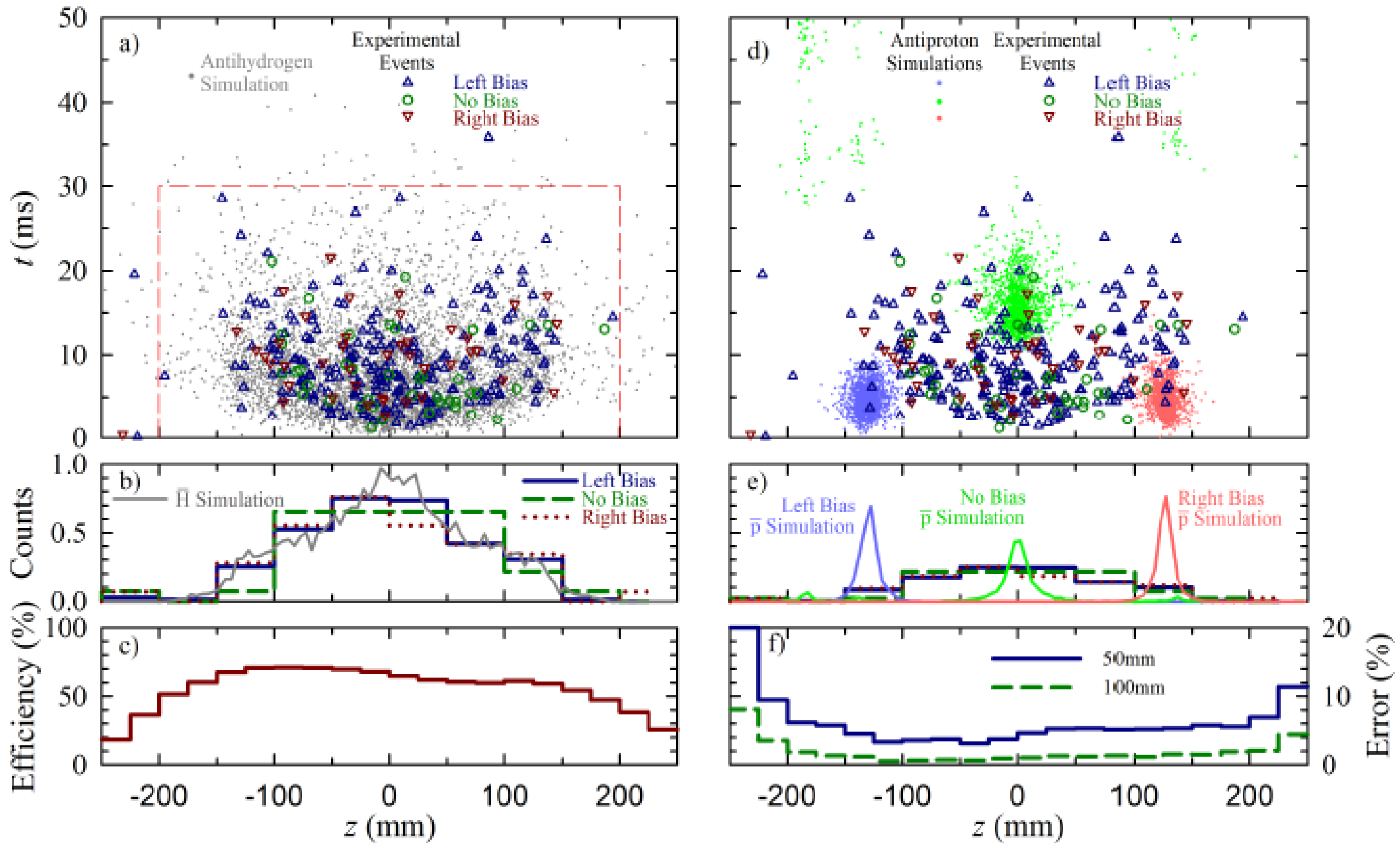
- Observation of resonant transitions in the $\bar{H}$ atom is a confirmation of these results.

Appearance Mode Results



b, The z-distribution of annihilation vertices for 0<t<30 s. The grey histogram is the result of a numerical simulation of the motion of spin-flipped atoms ejected from the trap.
The dashed black curve is the result of a simulation of trapped antihydrogen annihilating on the residual gas .

Trapped $\bar{H}$ Distributions



309 annihilations in 985 trials!

Microwave Circuit

- Low power: *In-Situ* monitor of microwave power and B-field.
- High Power: Interaction with trapped antihydrogen.