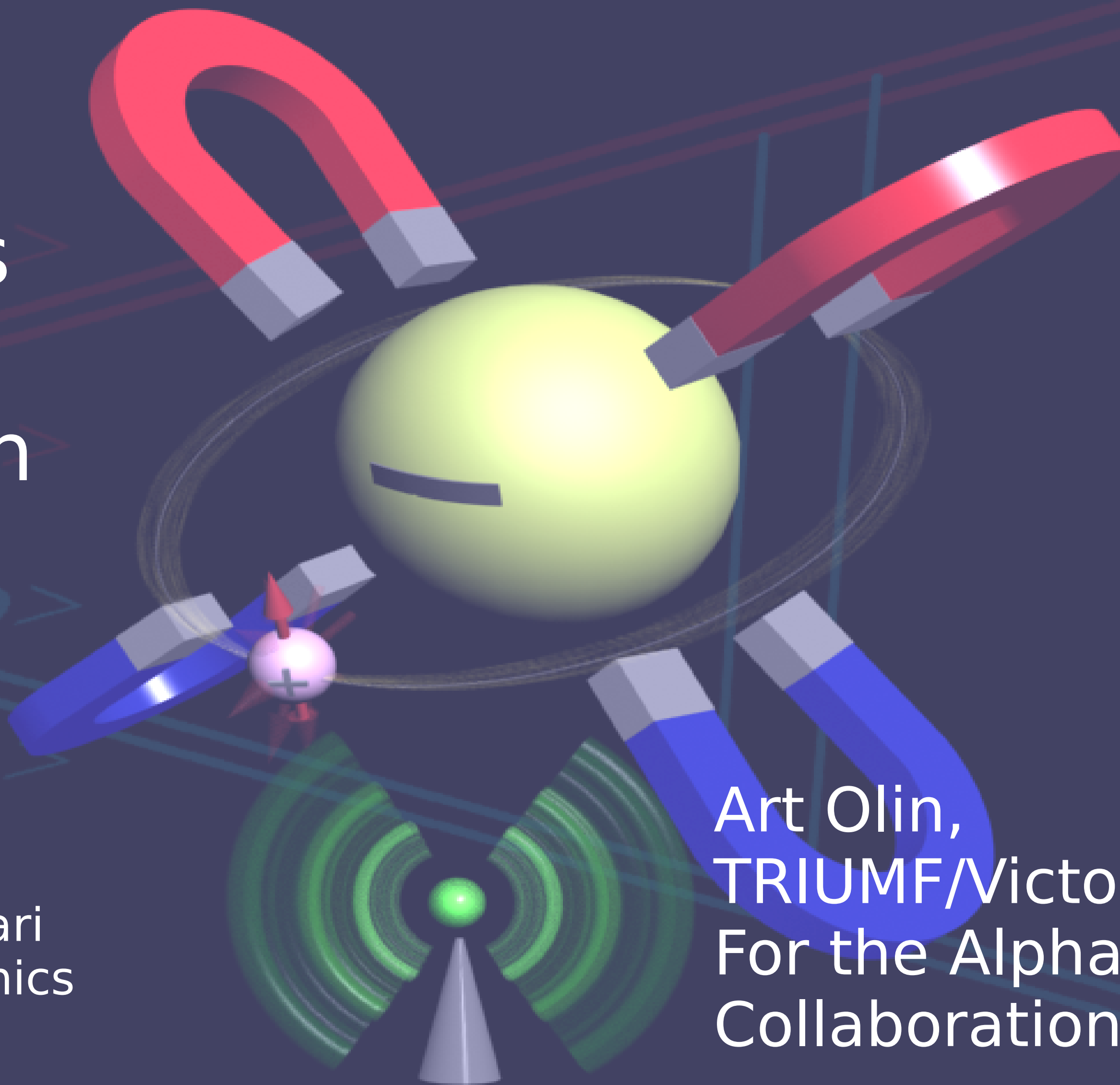
Resonant Microwave Interactions with Antihydrogen



Art Olin, TRIUMF/Victoria
For the Alpha Collaboration

Thanks to M Ashkezari for figures and graphics

CPT Symmetry

CPT Theorem: Luders, Pauli, Schwinger, Bell.
Follows from Lorentz invariance, locality, unitary Hamiltonian.
Quantum field theories must have this symmetry.

- CPT predicts equality of particle and antiparticle masses and decay widths.
- Strings are non-local, and Lorentz invariance may be violated in extra dimension theories or quantum gravity.
- Tests of CPT symmetry determine the experimental limits on these fundamental assumptions.
- There is little theoretical guidance for a CPTV mechanism.
- Experimental limits on CPTV observables in different systems are required.

Where's the Anti?

Sakharov conditions for matter- antimatter asymmetry:

- B violation
- C, CP violation
- out of equilibrium
- Known CP violation is not enough.

- With CPTV, the asymmetry can develop under **equilibrium** conditions.
- CPTV at O(10^{-6}) in t and $\bar{t}$ masses required.
- A.D. Dolgov, Phys. Rep. 222, 309 (1992).

Ground state hyperfine interval:

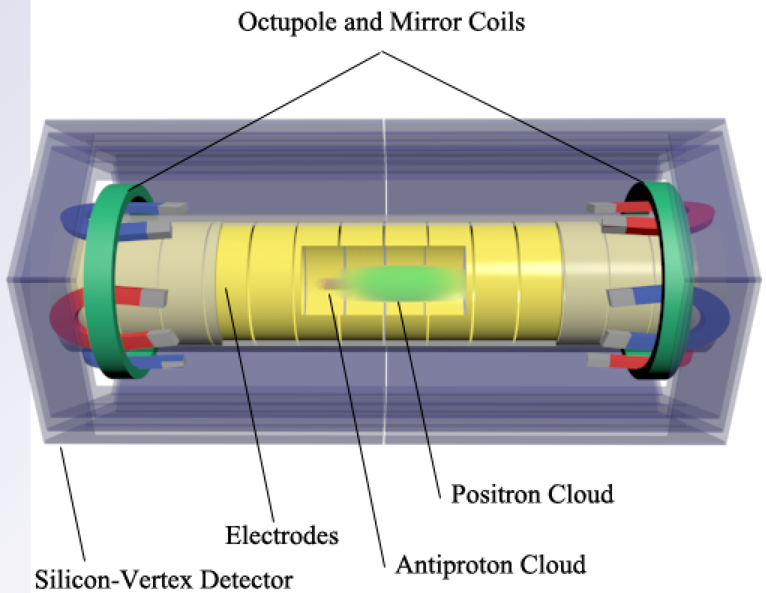
- Measured by microwave resonance spectroscopy.
- In hydrogen precision of 10^{-13} or 10^{-23} GeV has been achieved.
- Favoured in Kostelecky SME.

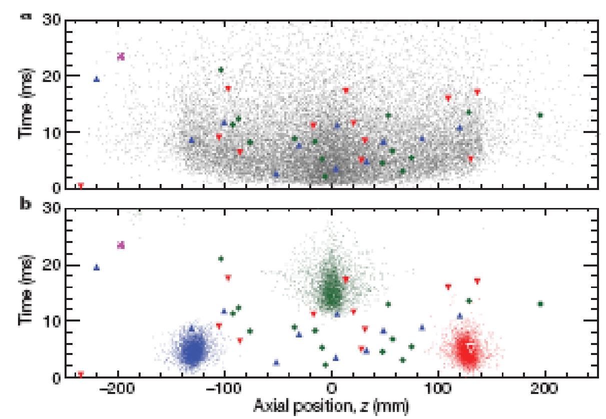
ALPHA, ASACUSA

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 of trapping based on 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 that some $\bar{H}$ remain trapped for 1000 seconds
- Enabled a search for a microwave resonance in $\bar{H}$.

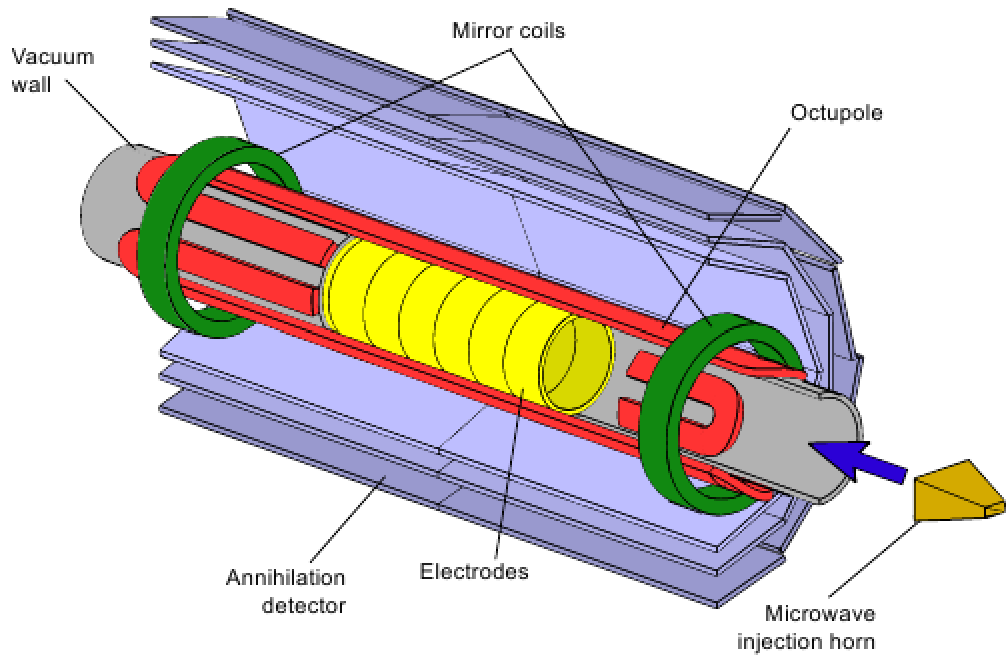
Trapped Antihydrogen
Nature 468, 673(2010)



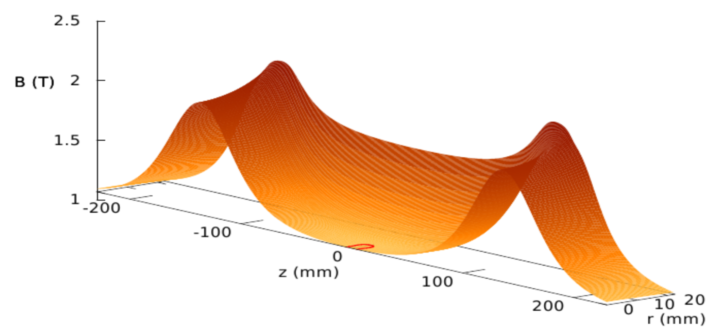


Microwaving the ALPHA Trap

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.



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.

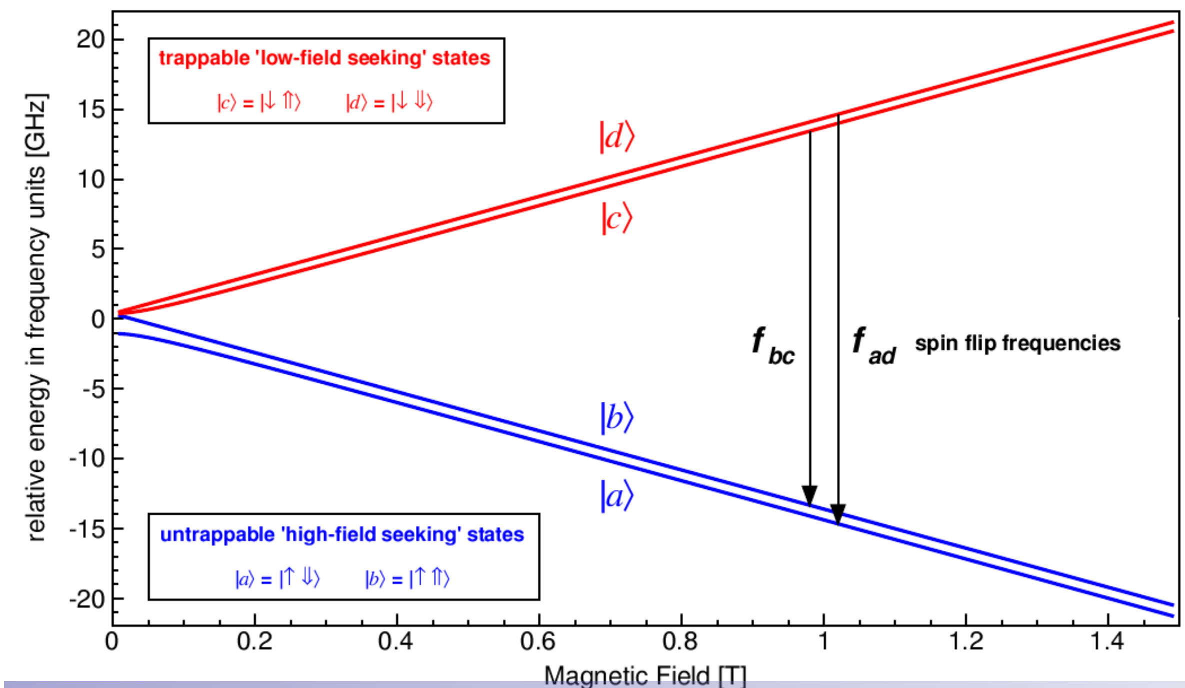


Microwave Experiment Procedure

- $3x10^4$ $\bar{p}$ per attempt (initially 300K).
- $4x10^7$ e^+ per attempt (170K).
- Evaporatively cool both $\bar{p}$ and e^+.
- Gently mix pbars and e^+ in magnetic trap for 1 s (via autoresonant excitation). About 5000 annihilations are observed.
- Clear charged particles by pulsed E fields.
- Set magnetic field and wait 60s to stabilize.
- Microwave irradiation sweeps for 160 s.
- Shut down the neutral trap in ~10 msec applying bias field.
- Record the position and time of the annihilations with the silicon vertex detector.

Resonant Quantum Transitions in Trapped Antihydrogen Atoms
Nature 483,439(2012)

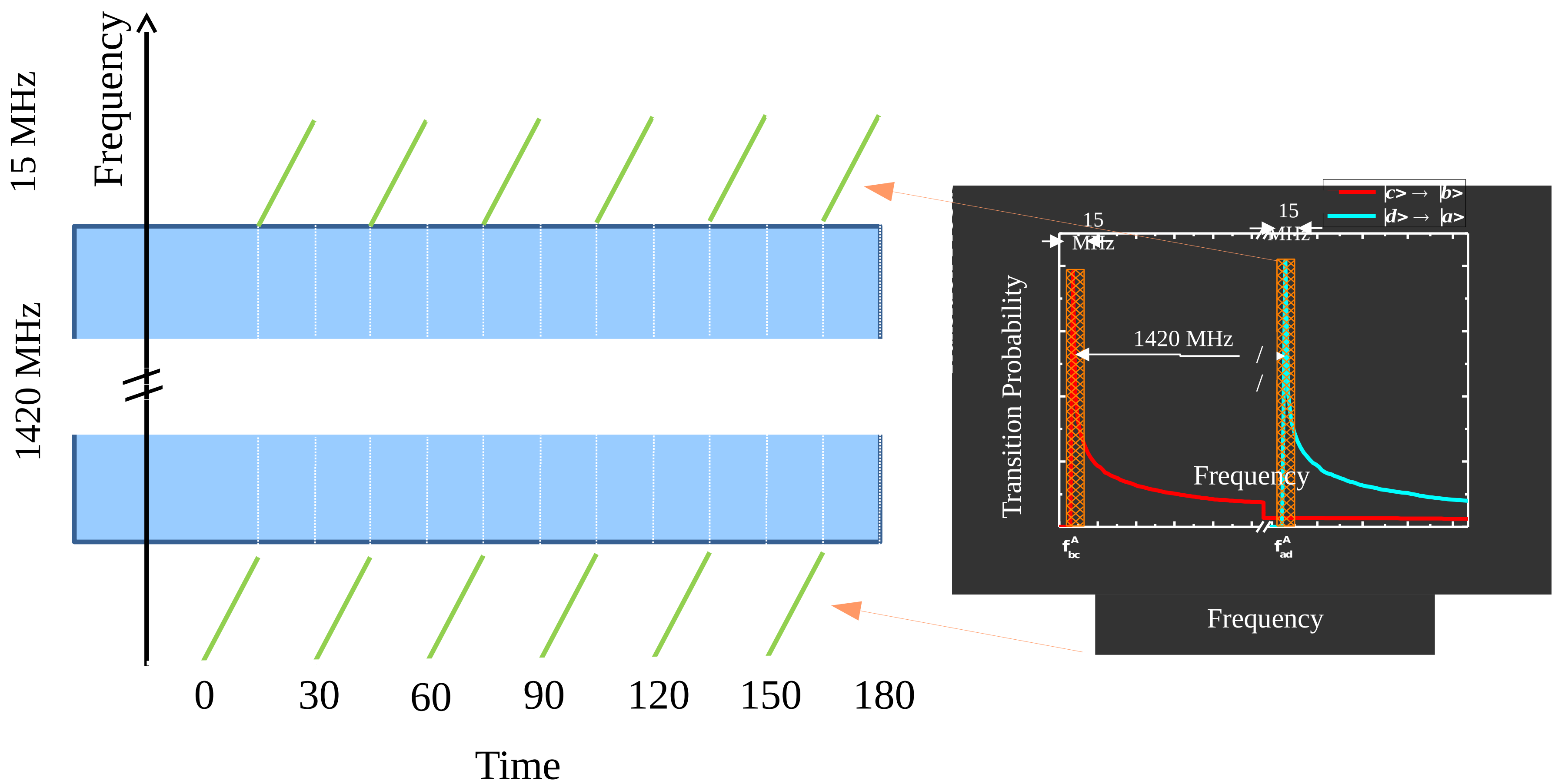
Hydrogen Hyperfine Energy Levels



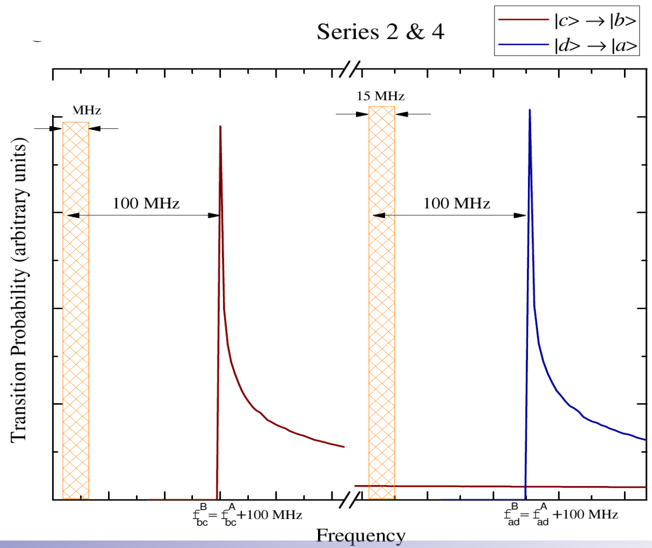
- Hyperfine interval in hydrogen, $\boldsymbol{f}_{\text{ad}}$ - $\boldsymbol{f}_{\text{bc}}$, is measured to $\sim 10^{-12}$.
- A measurement in antihydrogen at this precision is a significant CPT test.
- Driving $\boldsymbol{f}_{\text{bc}}$ or $\boldsymbol{f}_{\text{ad}}$ expels $\overline{\text{H}}$ from 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.

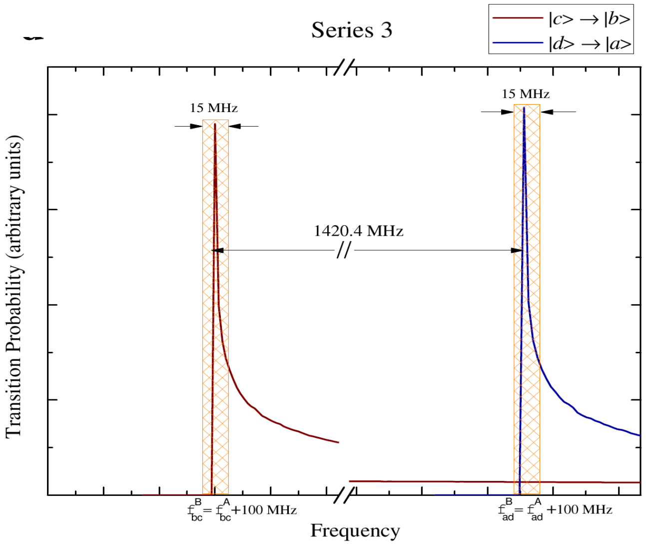
Microwave Sweep Sequence



Resonance Conditions



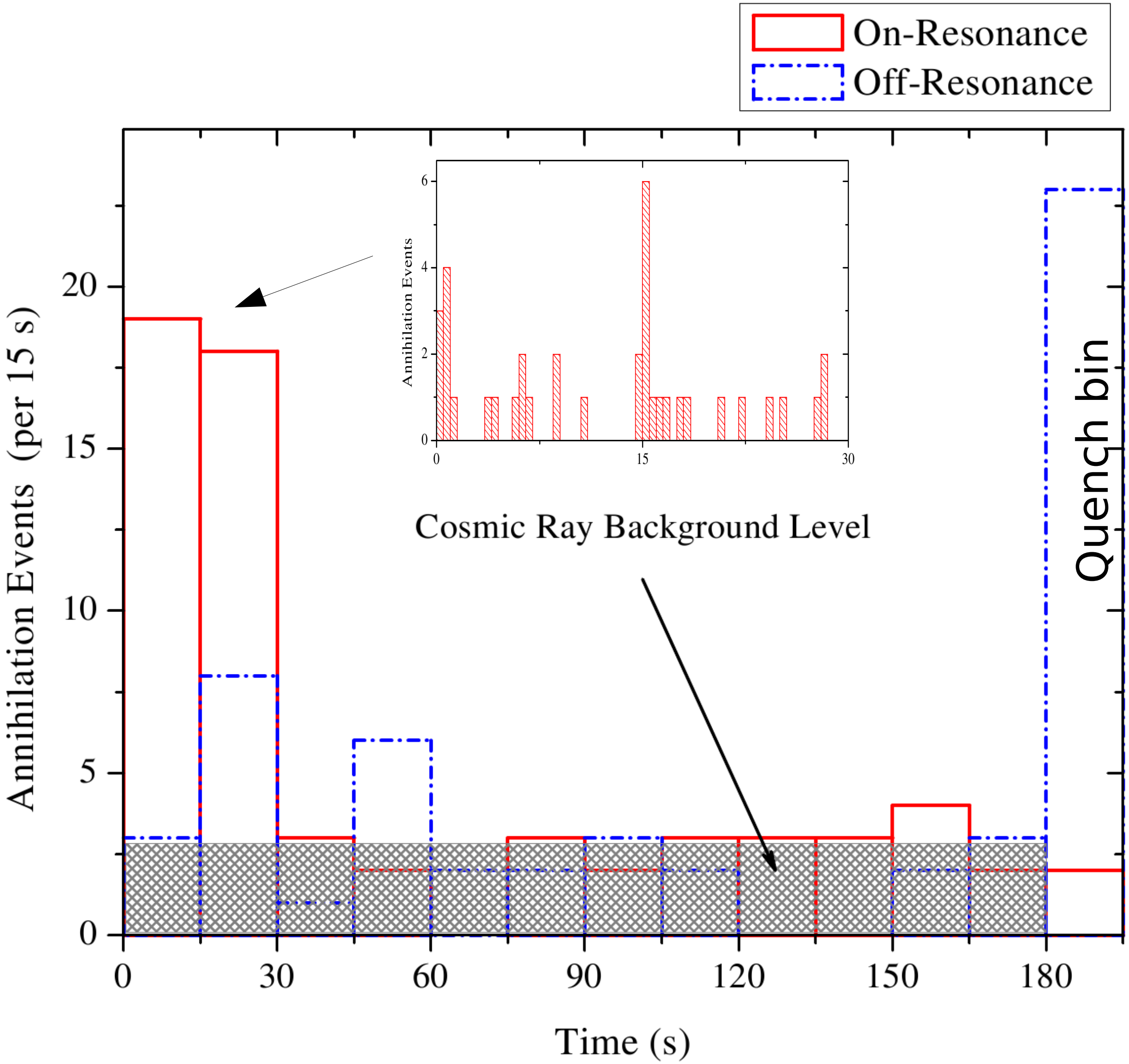
Off-resonance sweeps at magnetic field B (series 2 and 4).



On-resonant sweeps at magnetic field B (series 3).

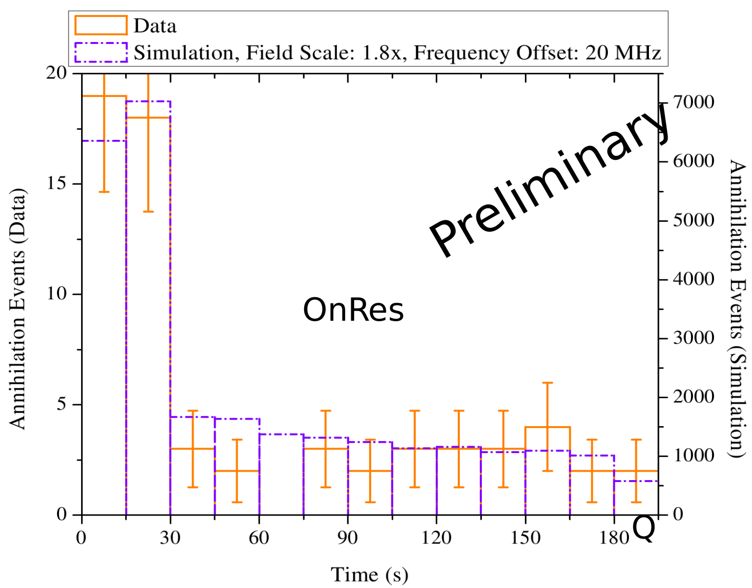
Most sweeps used 700 mW of power sent in to the electrode stack, but a few used 1/4 and 1/16th power. Sweeps for all power levels are included in these results.

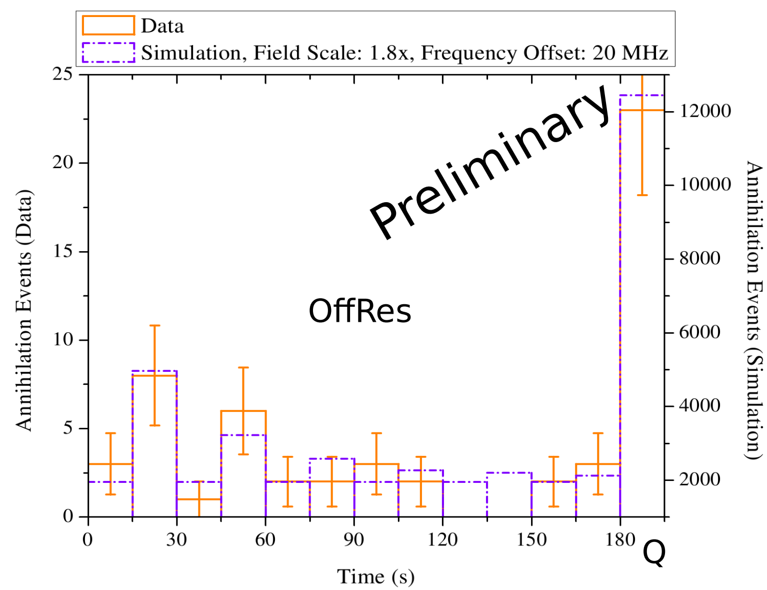
Microwave-Correlated Transitions Observed



Simulation of $\bar{H}$ in Trap

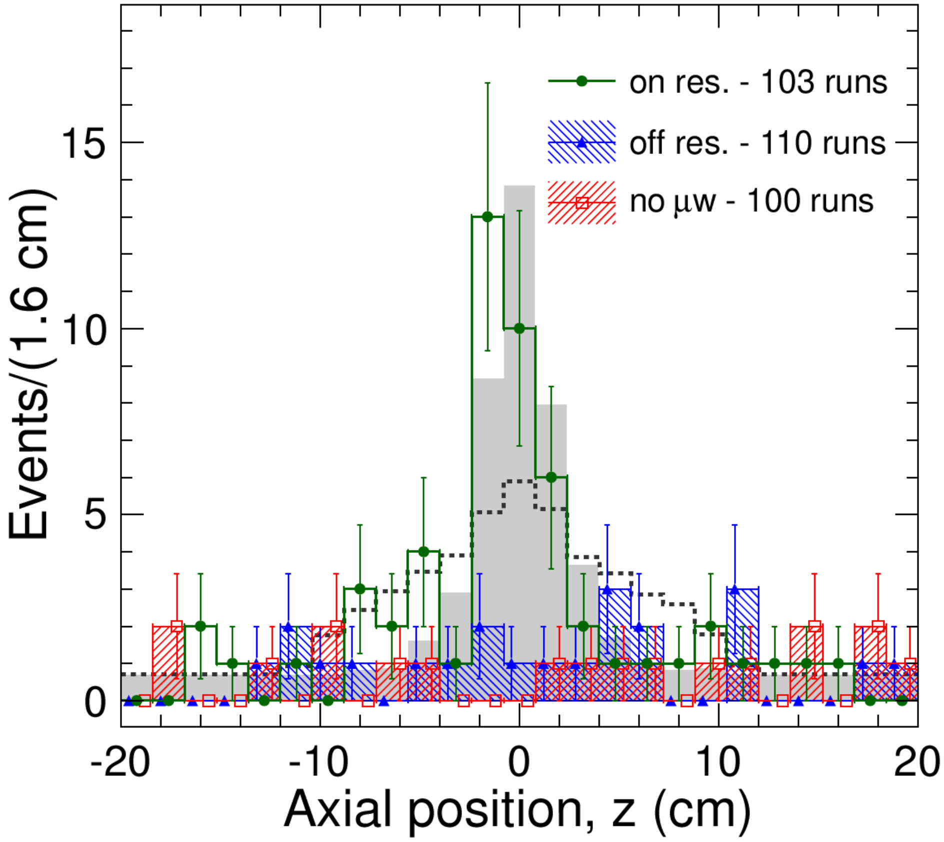
- Inject $\bar{H}$ in trap and allow orbit to randomize.
- Opera-calculated magnetic field shape.
- Plane-wave approximation for microwave field.
- Landau-Zener approx for spin flip probability at resonance crossing.
- Vary the microwave power and field offset.
  - Best agreement for on and off resonance.





Evidence for μWave Resonance

- Resonant and off-resonant histograms differ by >5σ.
- Resonance seen at different magnetic field values.
- Annihilation vertex locations peaked at trap center.
- Not consistent with annihilations on microwave-induced gas evolution.

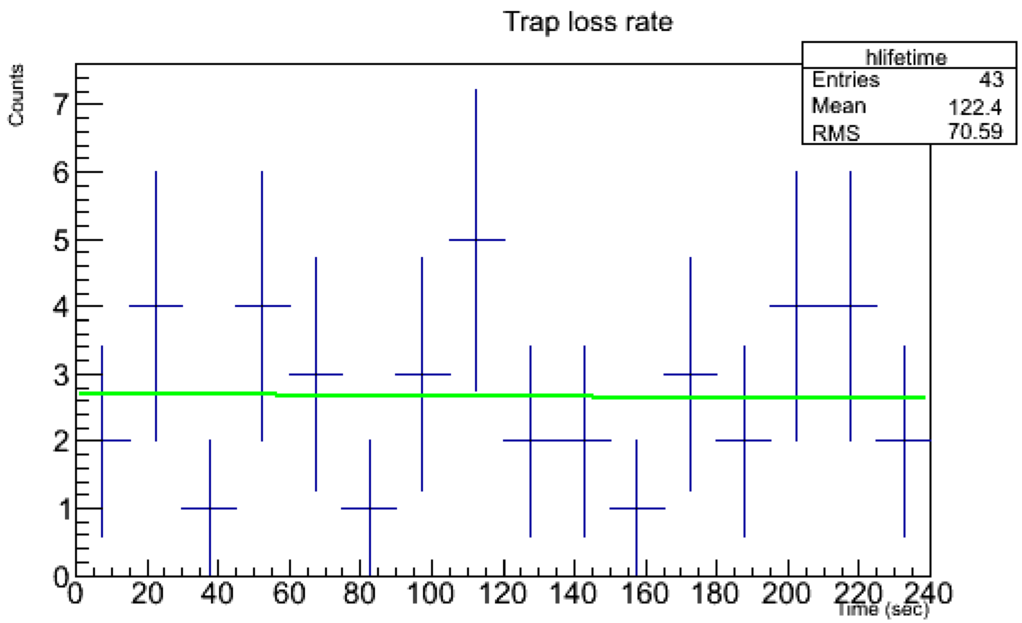


Results

Trials	$\bar{H}$ detected at quench	Rate /trial	Condition
103	2	0.02 ±0.01	On resonance
110	23	0.21 ±0.04	Off resonance
100	40	0.40 ±0.06	No microwaves

- The appearance and disappearance mode rates are consistent.
- The difference between off-resonance and no-microwave rates is consistent with spin-flip driven by the high-frequency tail of the lineshape.
- $f_{bc}^{\bar{H}}$ and $f_{ad}^{\bar{H}}$ have been bounded between the off-resonance scan value and the maximum of the on-resonance sweep. Roughly speaking, the observed resonance in antihydrogen is within 100 MHz of the resonance frequency expected for hydrogen, corresponding to a relative precision of about 4×10^{-3}.
- $f_{cd}^{\bar{H}}$ is bounded to lie within 100 MHz of its value in hydrogen. This bound depends on the repeatability with which we set the field, but not its absolute value.

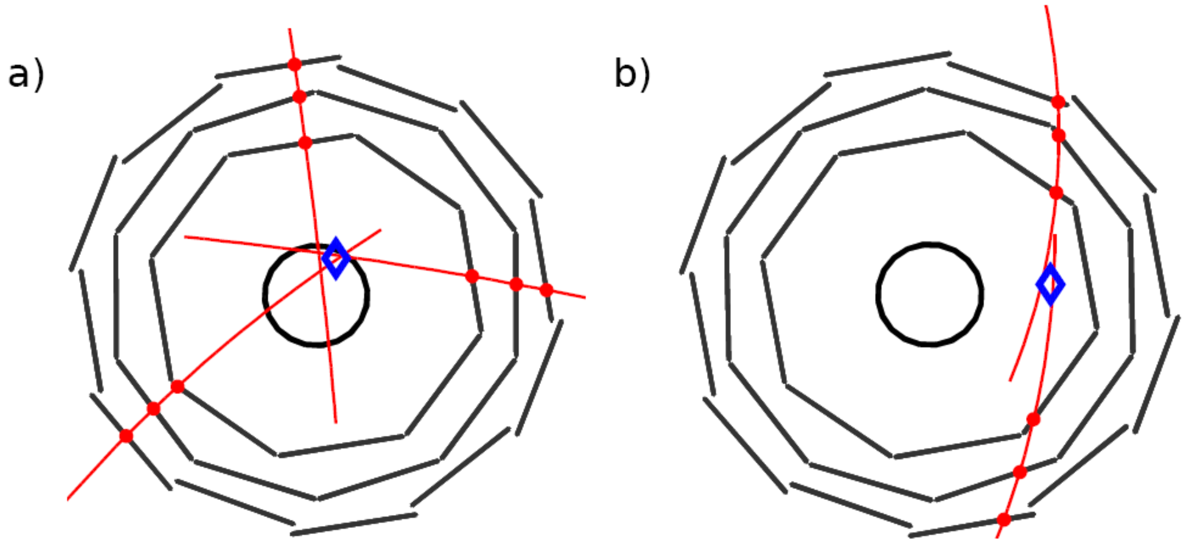
Trap Loss Rate



Preliminary fit to 100 microwave off trapping runs

- Trap remains open for 240s after end of mixing.
- 28 counts observed when the trap magnets are quenched.
- Cosmic ray rate 1.7mHz.
- Exponential loss rate per trapped atom is 0.3 ± 1.3 mHz.
- Consistent with residual gas loss estimate.

Annihilation Event Selection



Antihydrogen Cosmic

- Event topology distinguishes annihilation signal from cosmic background.
- Unbiased, and optimized classification.
- Independent annihilation (mixing) and cosmic (no beam) samples.
- Straight line residuals and vertex near electrode cuts eliminate 99% of cosmics.
- This is not sufficient for 1 atom/attempt yields and long observation times.

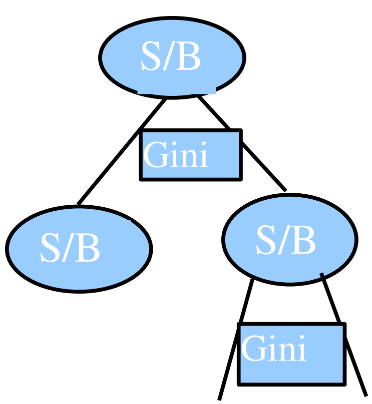
Random Forest Bagged Decision Tree Classifier

Variables used in classification

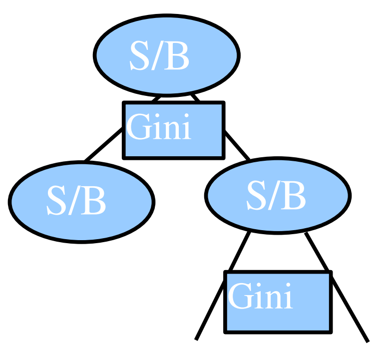
- Sum of residual distance of hits from fitted straight line.
- Number of tracks.
- Total number of hits.
- Event sphericity.
- Orientation to vertical.

Control Data

DecisionTree 1



DecisionTree 2



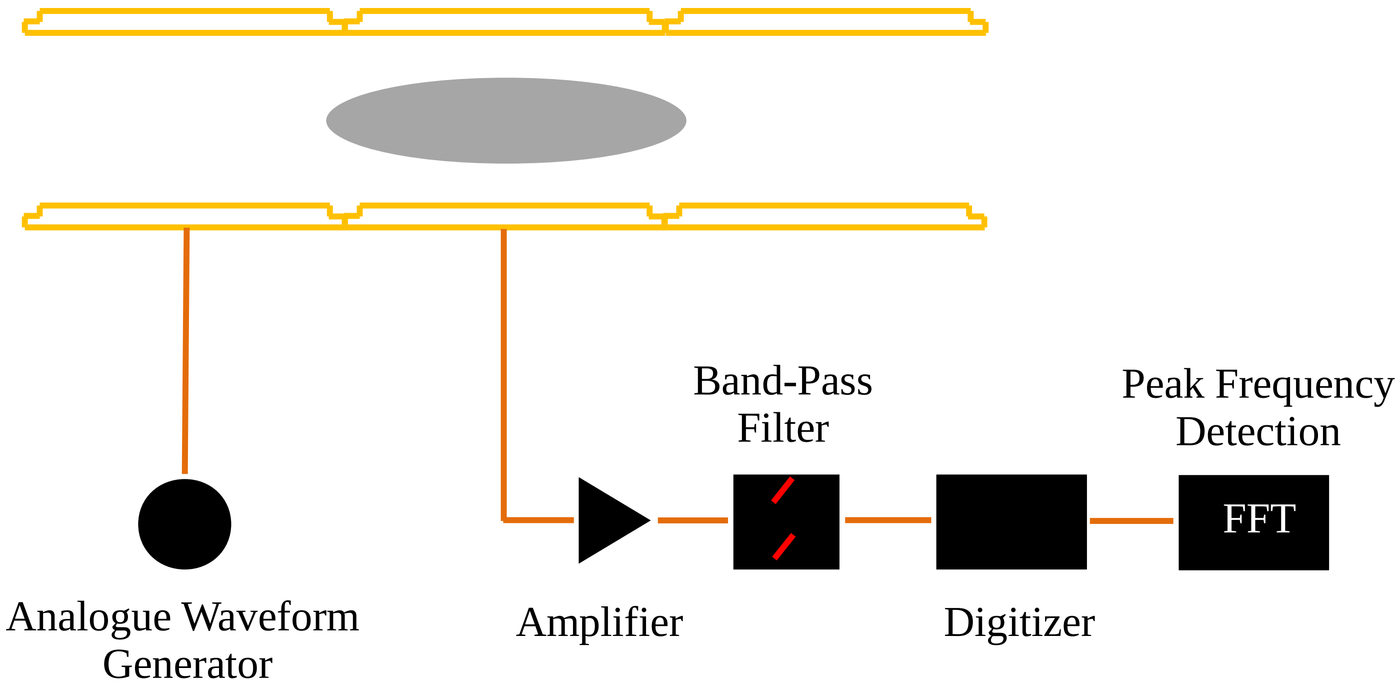
Optimize Punzi significance.

$$\frac{S}{N_{\sigma}/2+\sqrt{N_B}}$$

Background rate reduced to 1.7 mHz

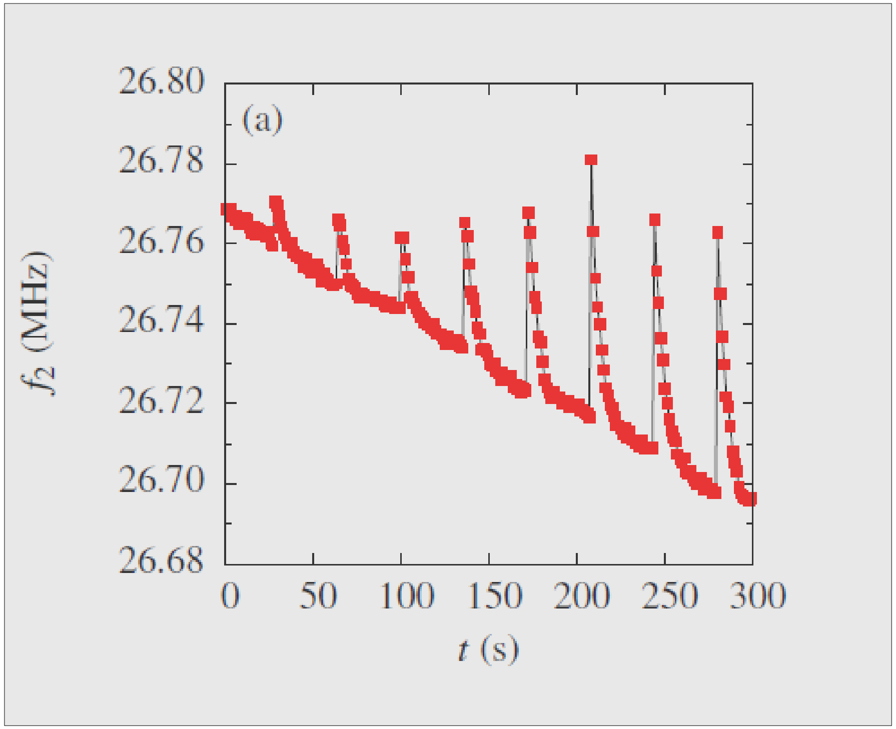
ECR Diagnostics

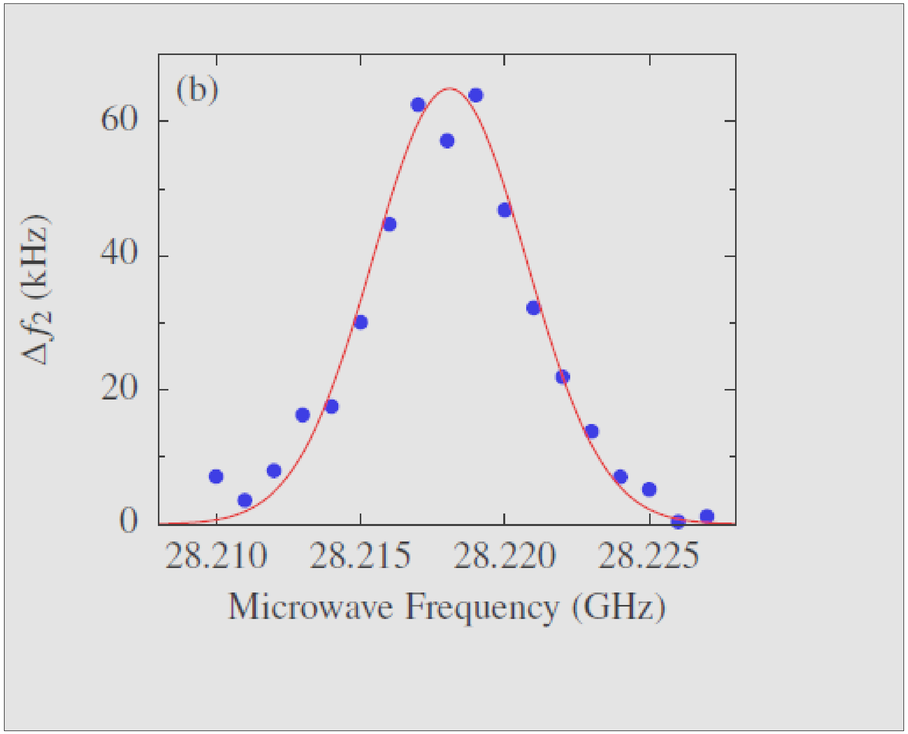
- Electron plasma is confined in a harmonic well.
- Quadrupole frequency is continuously monitored.
- Microwave pulses are injected at the cyclotron resonance frequency.



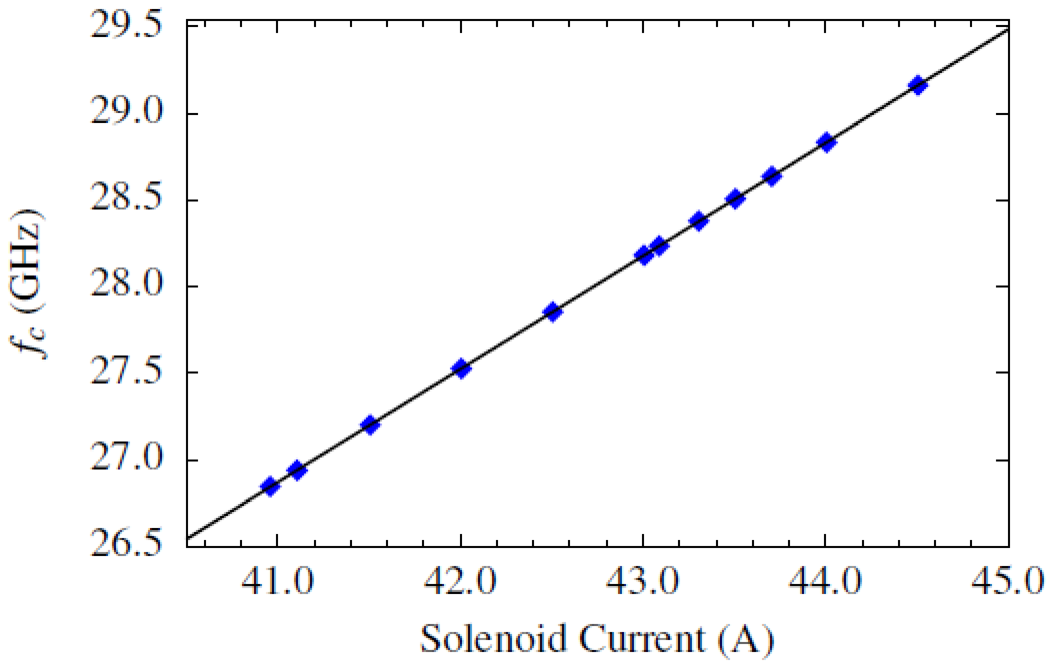
ECR Scans

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



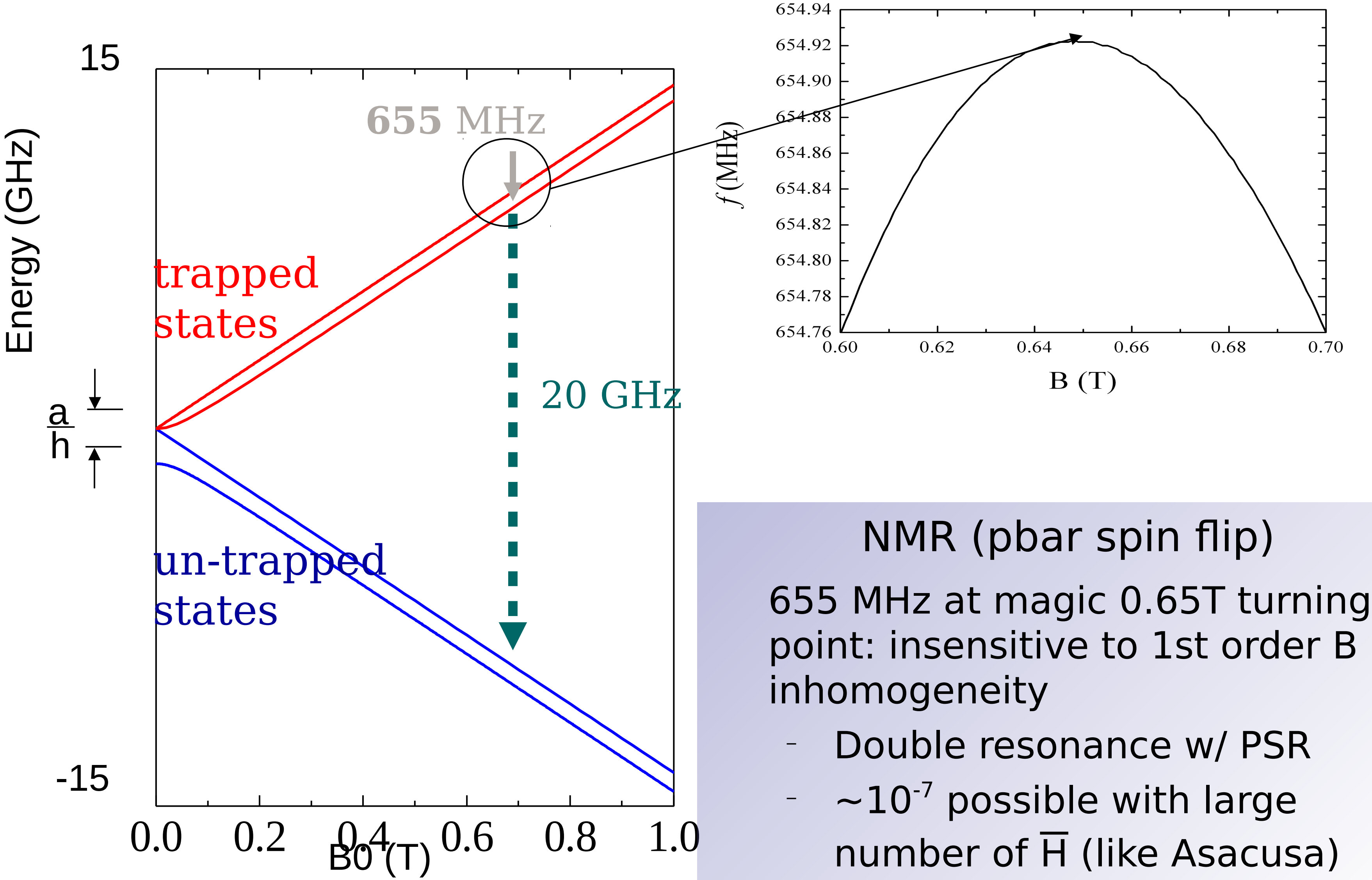


Magnetic Field Calibration with e⁻ Plasma



- 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 distort lineshape.
- Hysteresis effects were observed depending on sequence of powering the magnets – presumably flux pinning.

Road to Precision Spectroscopy

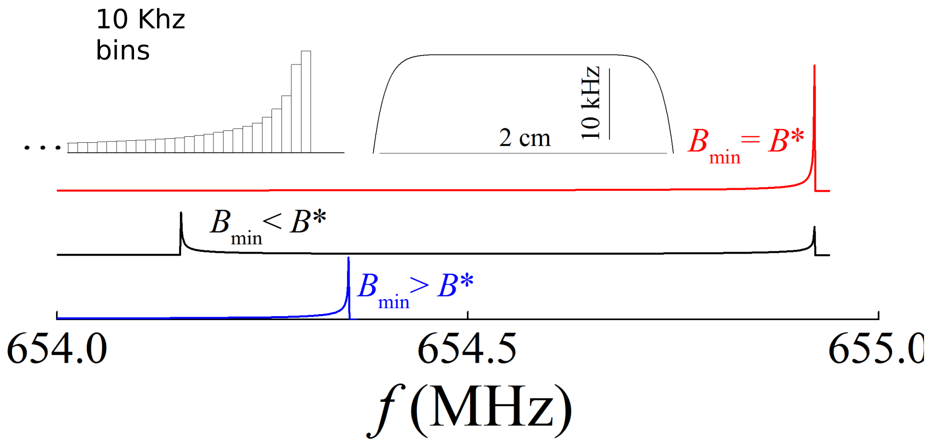


NMR (pbar spin flip)

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

- Double resonance w/ PSR
- ~10^{-7} possible with large number of $\bar{H}$ (like Asacusa)

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.

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}

- Resolution limiting term is transit-time broadening.
- Resolution improves when $\bar{H}$ are cooled.

Summary and Outlook

- $f_{ad} - f_{bc}$ in $\bar{H}$ is within ±100 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
  - 40 MHz variations seen probably from 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
- Measurements at 10^{-7} precision are possible by measuring f_{dc} in a carefully designed cavity.

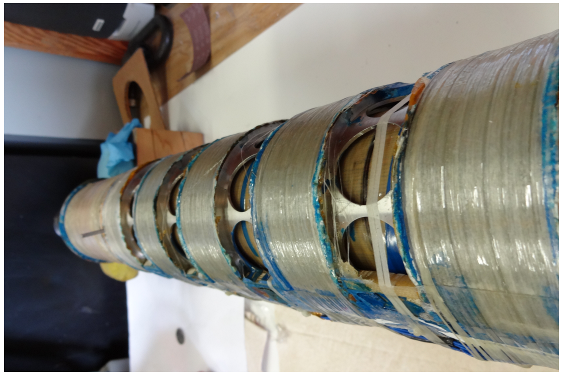
ALPHA Collaboration (2012)

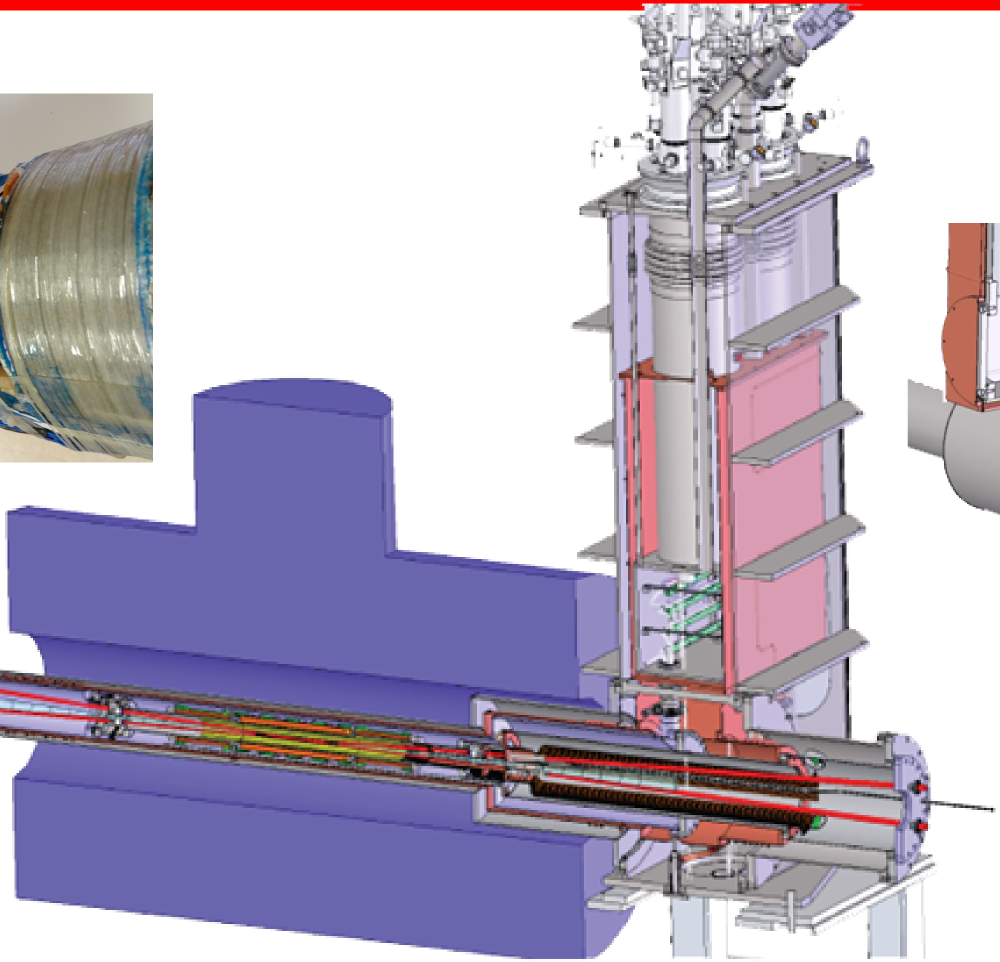
Physics Areas:
Accelerator, Atomic, Condensed Matter, Particle, and Plasma Physics

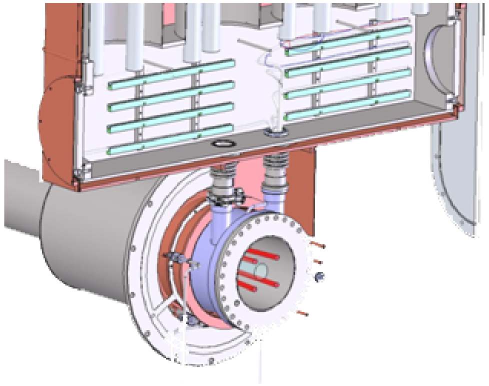
Supported by:
CNPq, FINEP/RENAFAE (Brazil)
ISF (Israel); MEXT (Japan)
FNU, Carlsberg (Denmark); VR (Sweden);
NSERC, NRC/TRIUMF, AIF, FQRNT (Canada); DOE, NSF (USA);
EPSRC, the Royal Society and the Leverhulme Trust (UK).

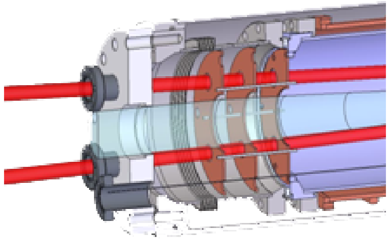
Back up slides

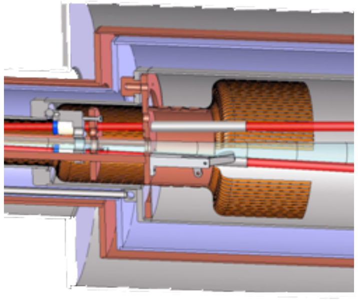
ALPHA-II







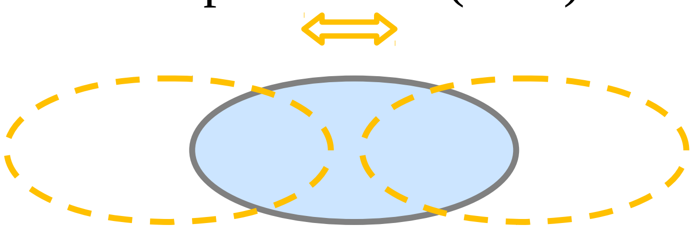




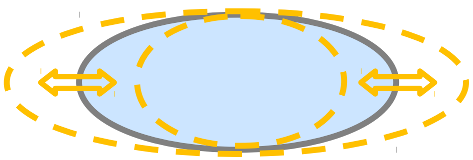
Electron Cyclotron Resonance Diagnostic

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

Dipole Mode (l =1)



Quadrupole Mode (l =2)

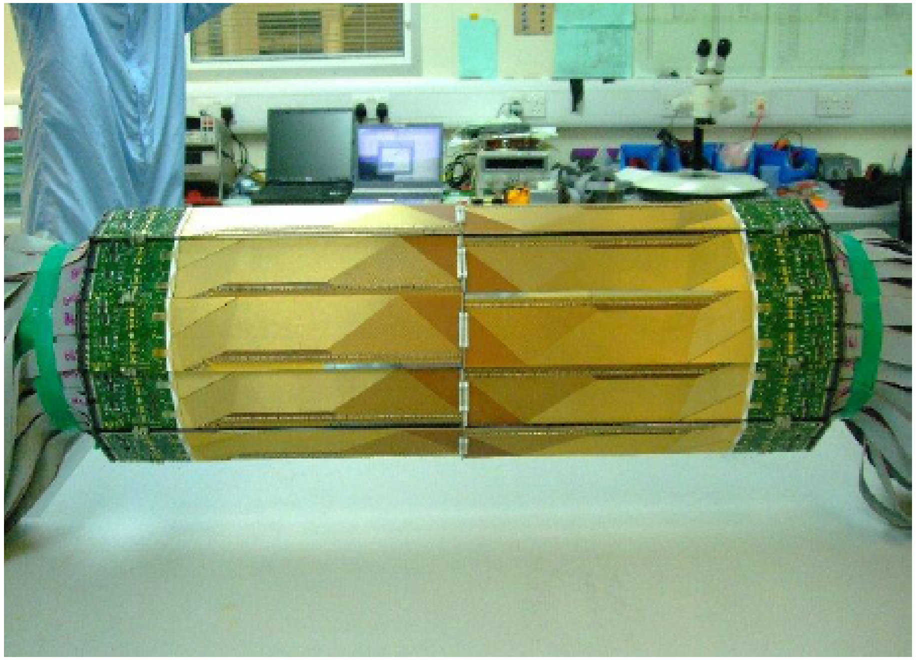


$$(\omega_2^T)^2 = (\omega_2^0)^2 + 20[3 - \frac{\omega_p^2\alpha^2}{2(\omega_2^0)^2}\frac{\partial^2 f(\alpha)}{\partial\alpha^2}]\frac{K_B T}{mL^2}$$

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

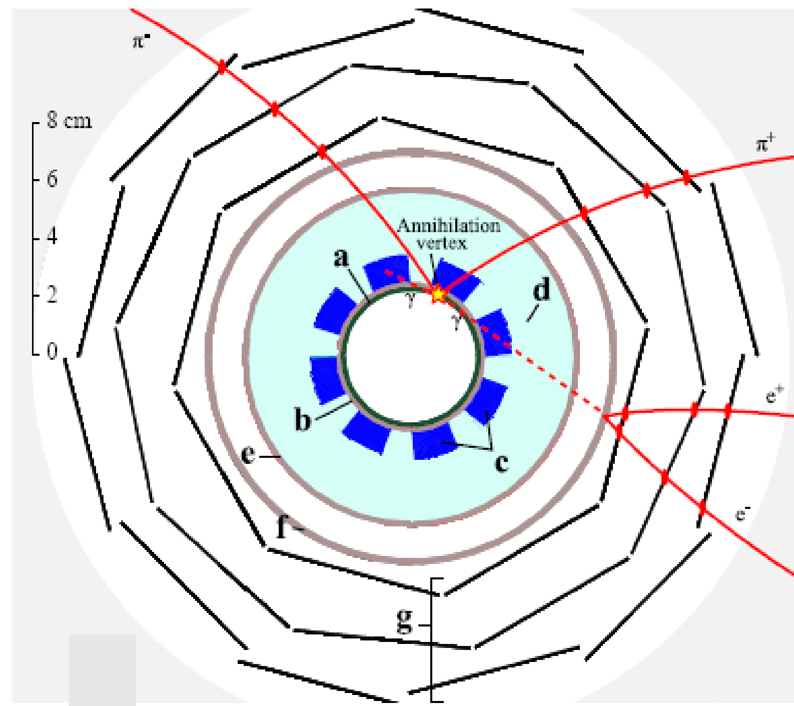
1. M. D. Tinkle , R. G. Greaves, and C. M. Surko, Phys Plasmas **2**, 2880 (1995).

Si Vertex Detector

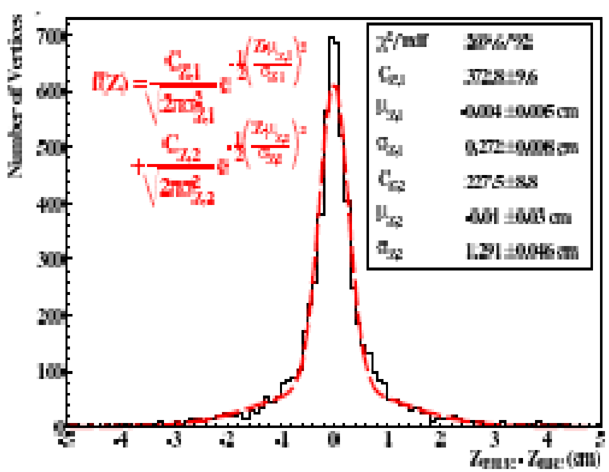


Double sided silicon strips
Vertex Resolution ~7mm
Hit Efficiency > 95%.

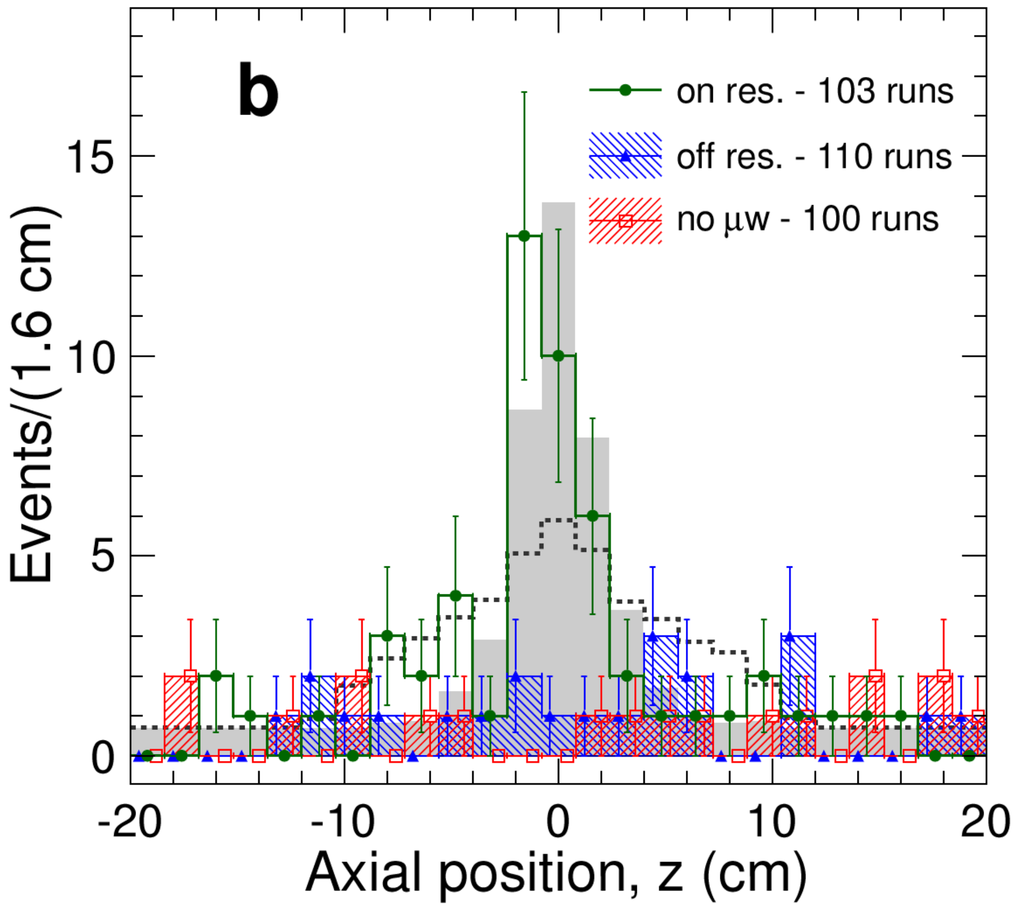
30,000 channel strips
~0.8 m2 active area



Difference between simulated hits and reconstructed track hits.

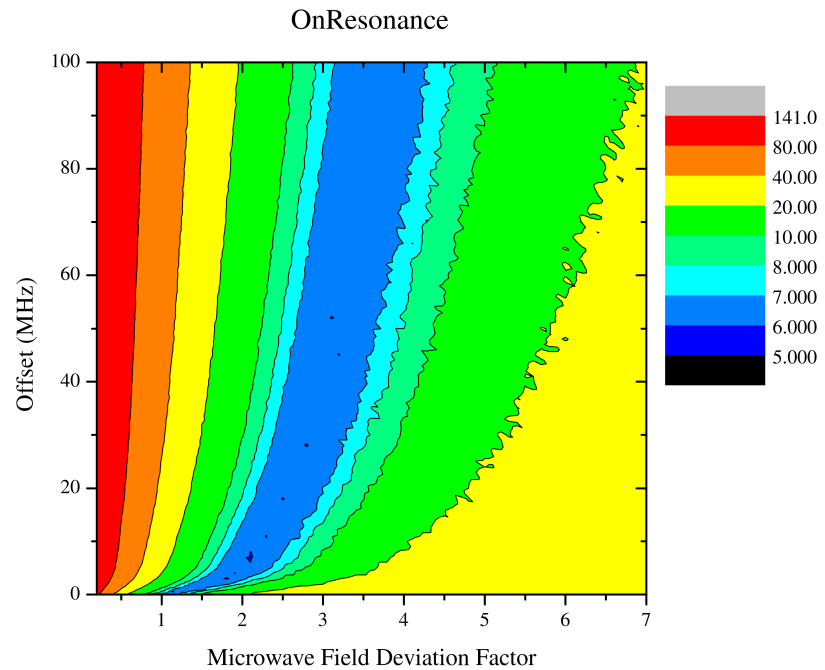


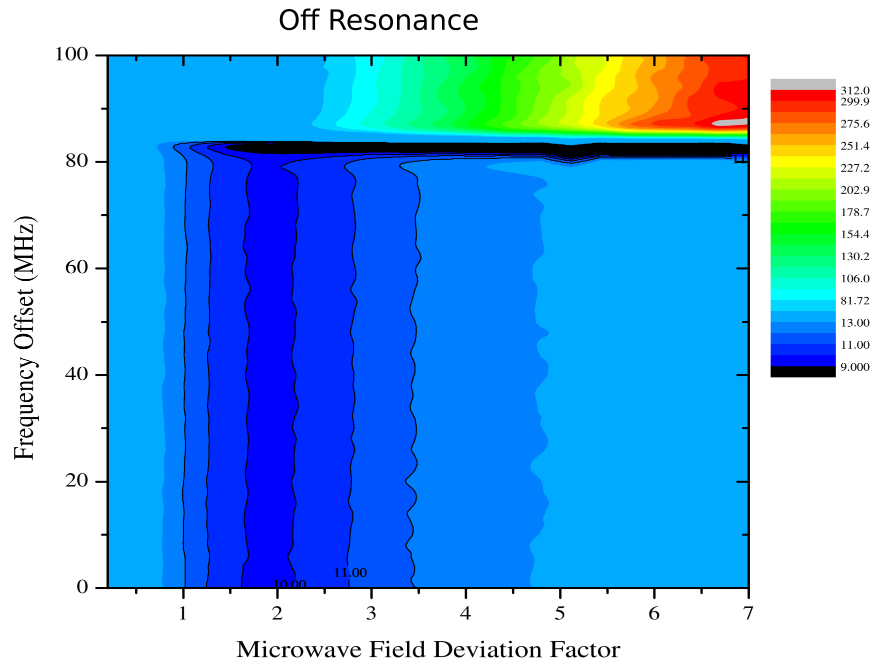
Appearance Mode Results



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 .

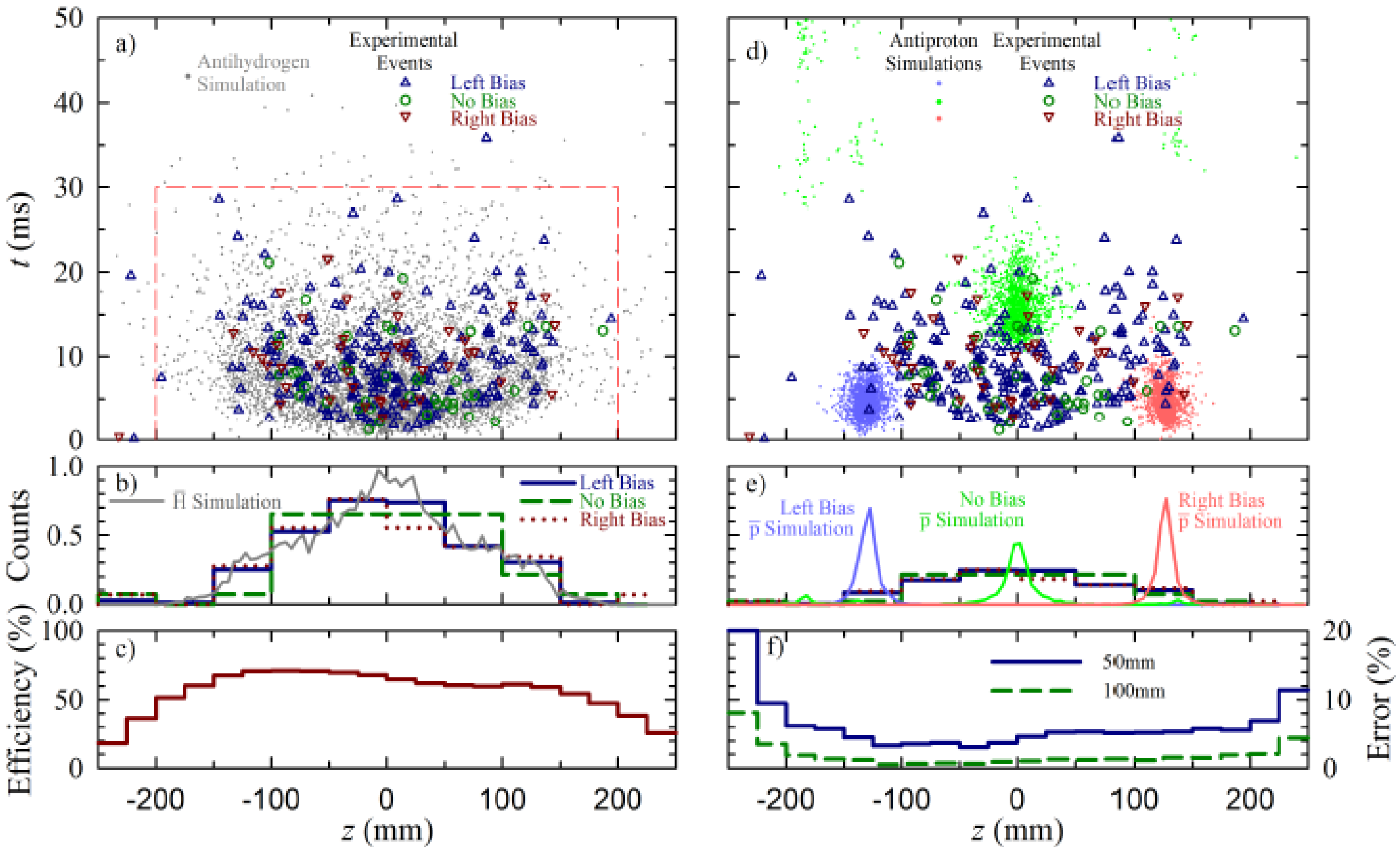
Likelihood Plots





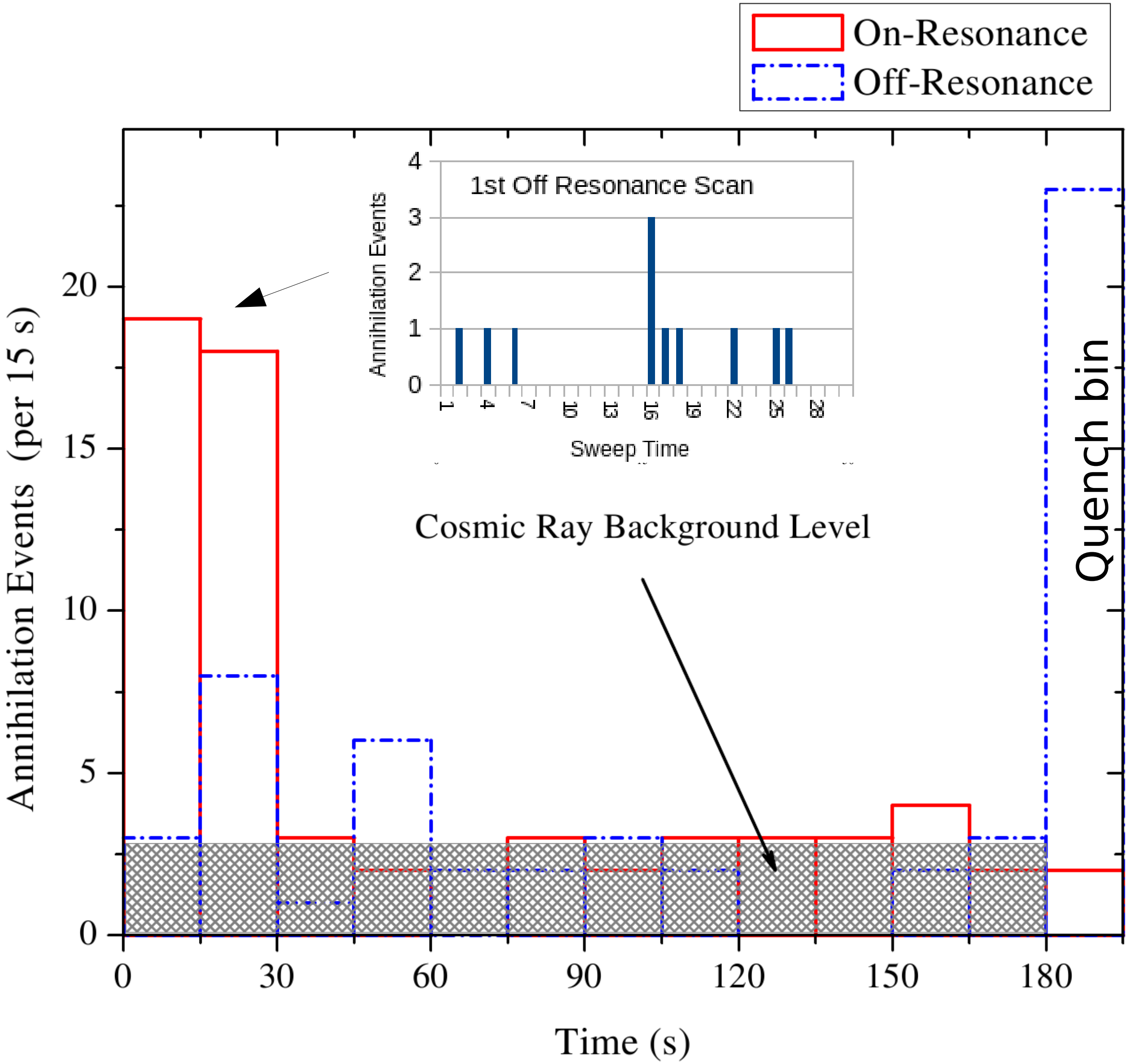
Likelihood plots do not reflect the systematic uncertainties inherent in our simulation.

Trapped $\overline{\mathrm{H}}$ Distributions



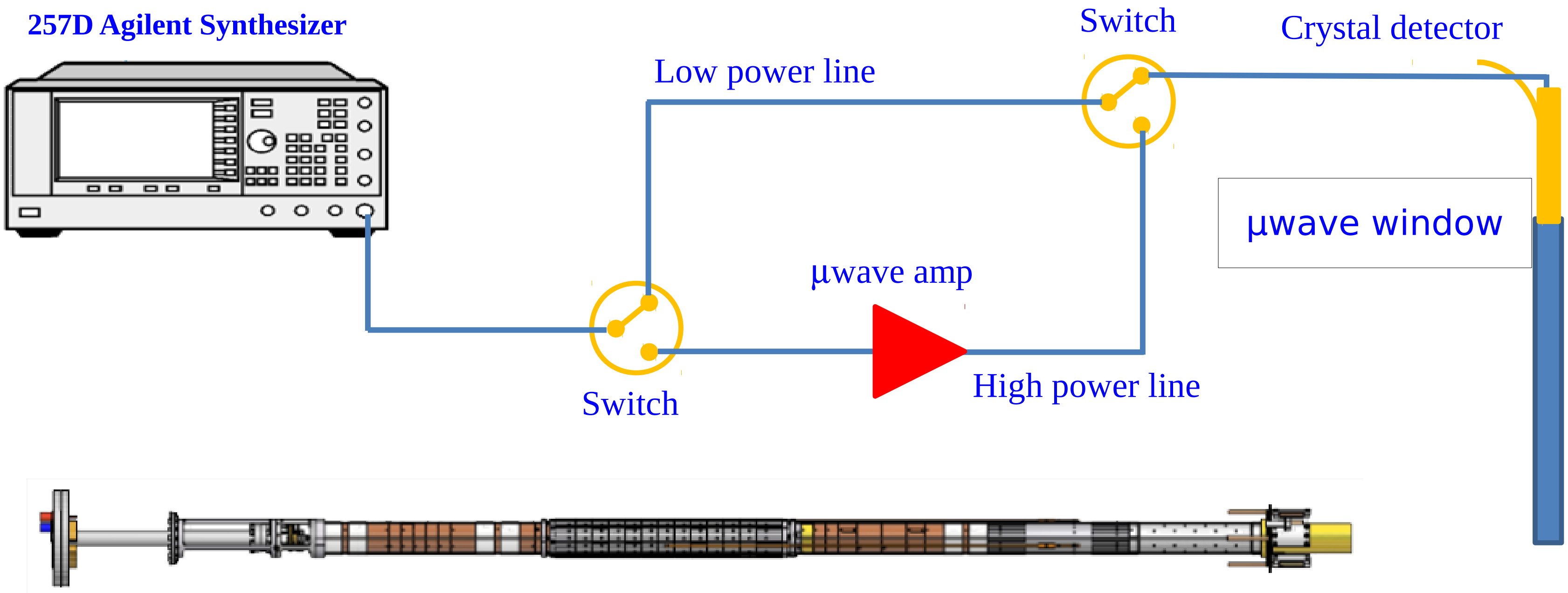
309 annihilations in 985 trials!

Microwave-Correlated Transitions Observed



Microwave Circuit

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



Measuring Microwave Transmission