Microwave spectroscopy of antihydrogen in the ALPHA experiment

CAP2025 – University of Saskatchewan

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on behalf of the ALPHA collaboration
Associate Professor
Department of Physics and Astronomy, University of Calgary

June 12, 2025

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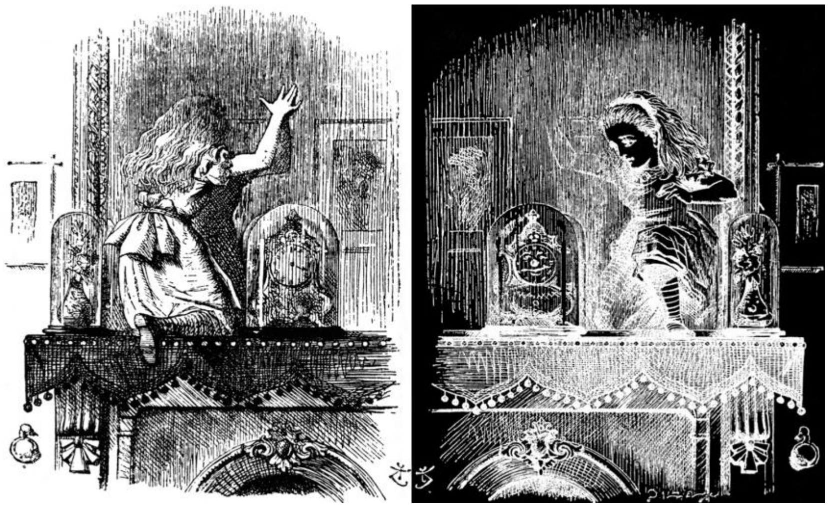
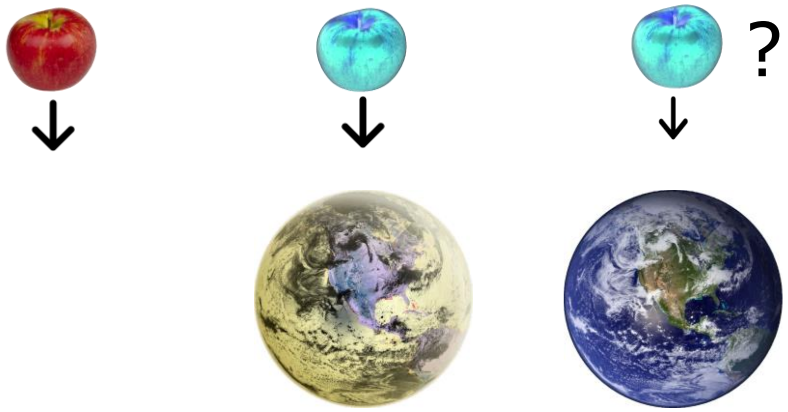
Why study antimatter?

Baryon Asymmetry Problem



Weak equivalence principle



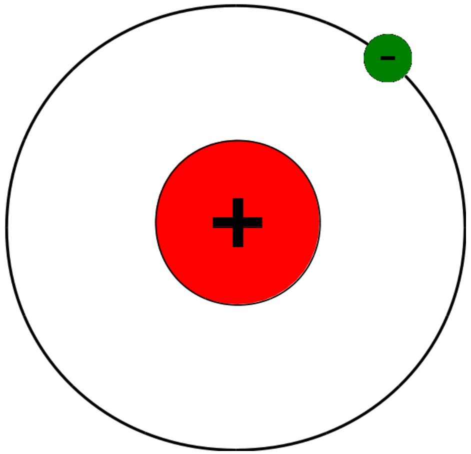
Earth

Anti-Earth (under CPT)

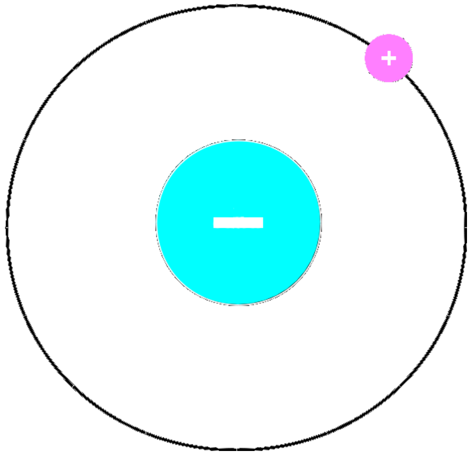
Earth

Antihydrogen

Hydrogen



Antihydrogen



ALPHA experiment

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CERN

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UBC THE UNIVERSITY OF BRITISH COLUMBIA

UNIVERSITY OF CALIFORNIA BERKELEY

BERKELEY LAB

ALPHA

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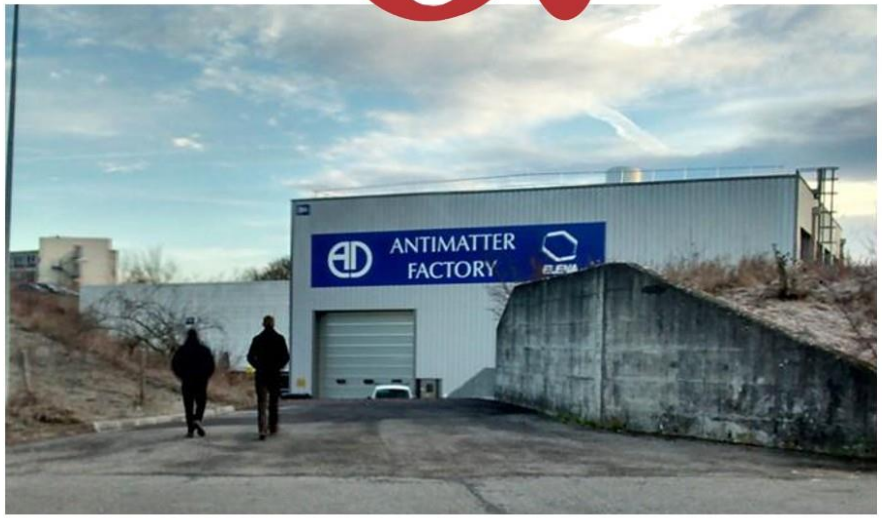
NRCN Nuclear Research Center Negev



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ALPHA

Goal: Precision measurements with antihydrogen atoms to test fundamental physics

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Spectroscopy (CPT tests):

- 1S – 2S (H: 10 Hz/4 x 10^{-15}) [C.G. Parthey et al. Phys. Rev. Let. 107, 203001 (2011).]
- Ground state HFS (H: 2 mHz/1 x 10^{-12}) [H. Hellwig et al. IEEE Trans. on Instr. and Meas. 19, 200 (1970).]
- Lamb shift
- 1S – 2P (laser cooling)
- nS – n'S/P

ALPHA

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Gravity (WEP test):

- Test the Weak Equivalence Principle with free-fall experiments (ALPHA-g)

Approach: Trap antihydrogen in a magnetic minimum neutral atom trap.

ALPHA

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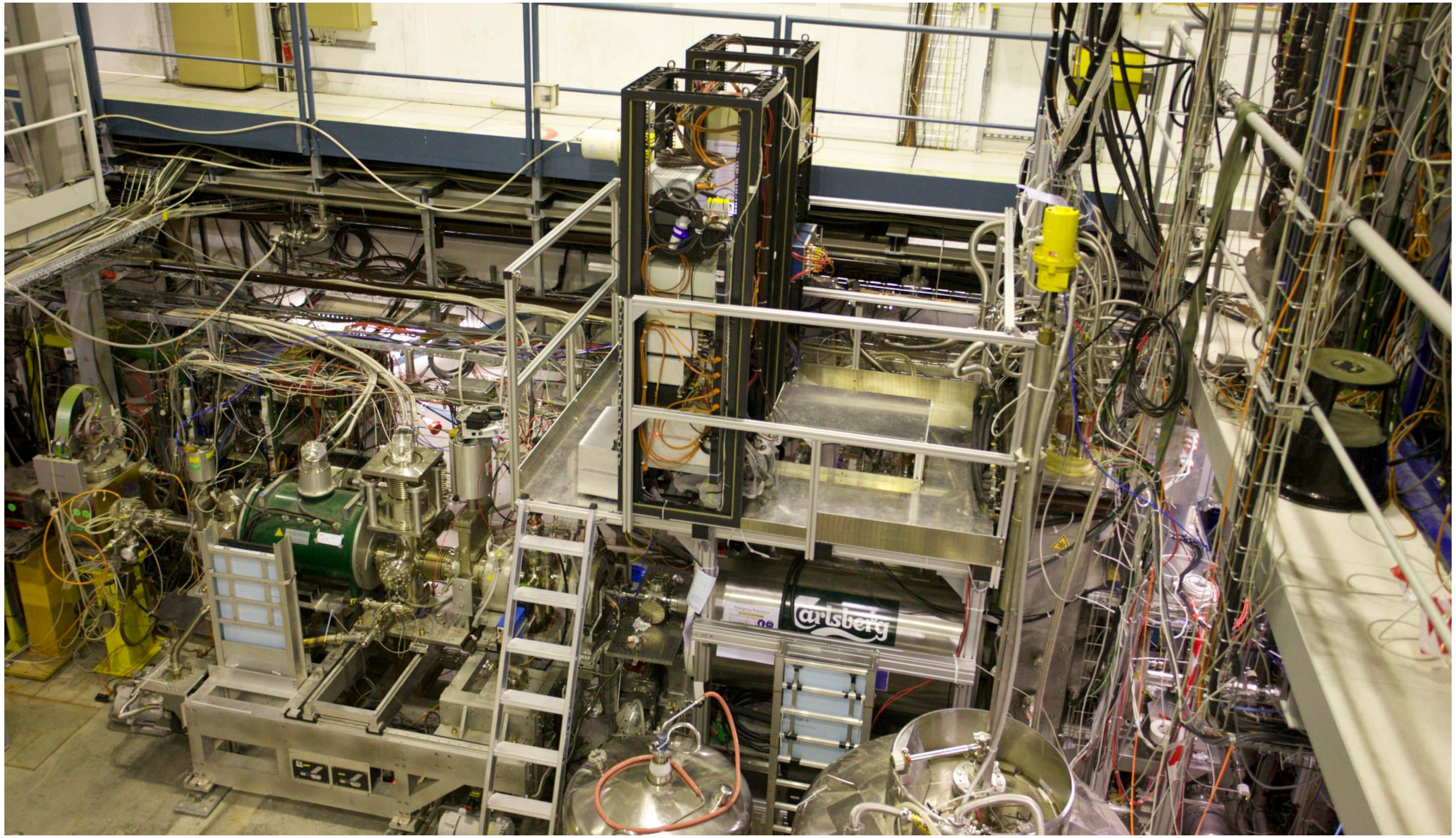
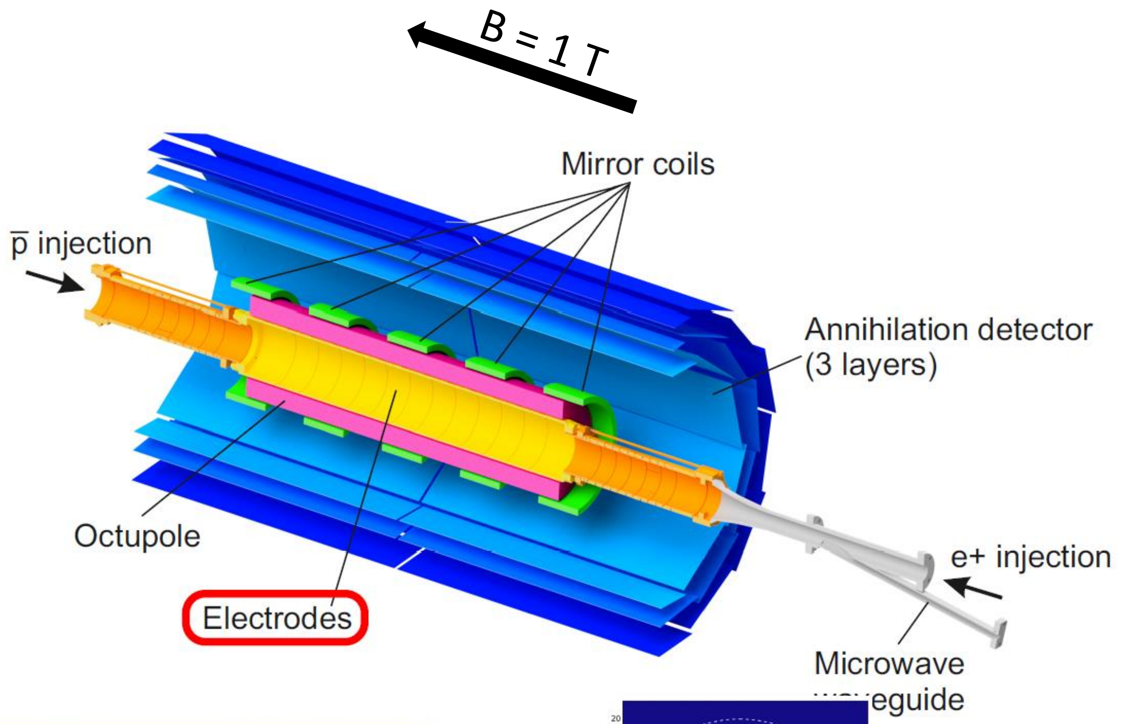
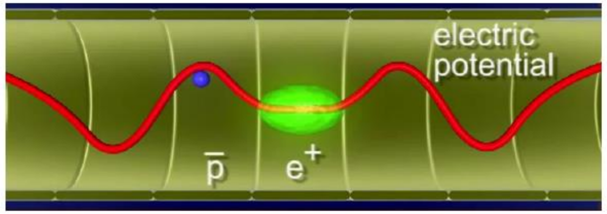
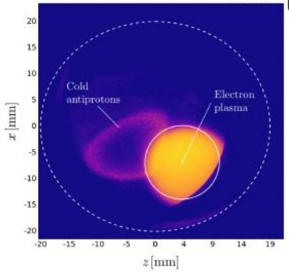
ALPHA-2 Apparatus



Producing and trapping antihydrogen

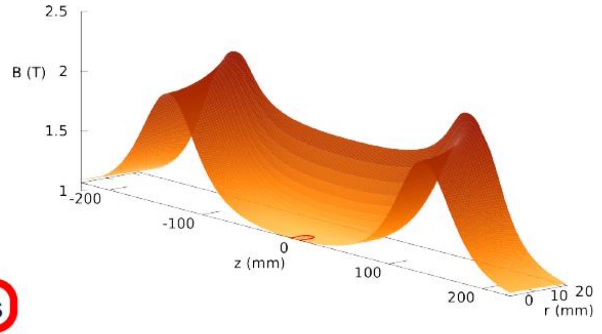






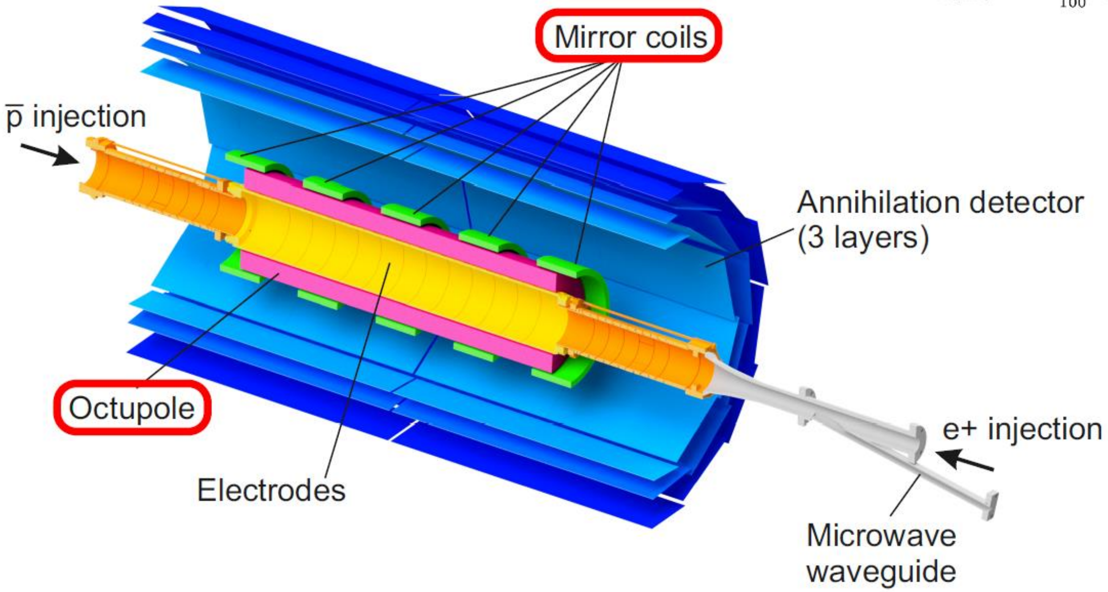
Producing and trapping antihydrogen

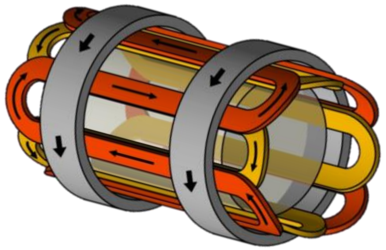
$$U = -\vec{\mu} \cdot \vec{B}$$



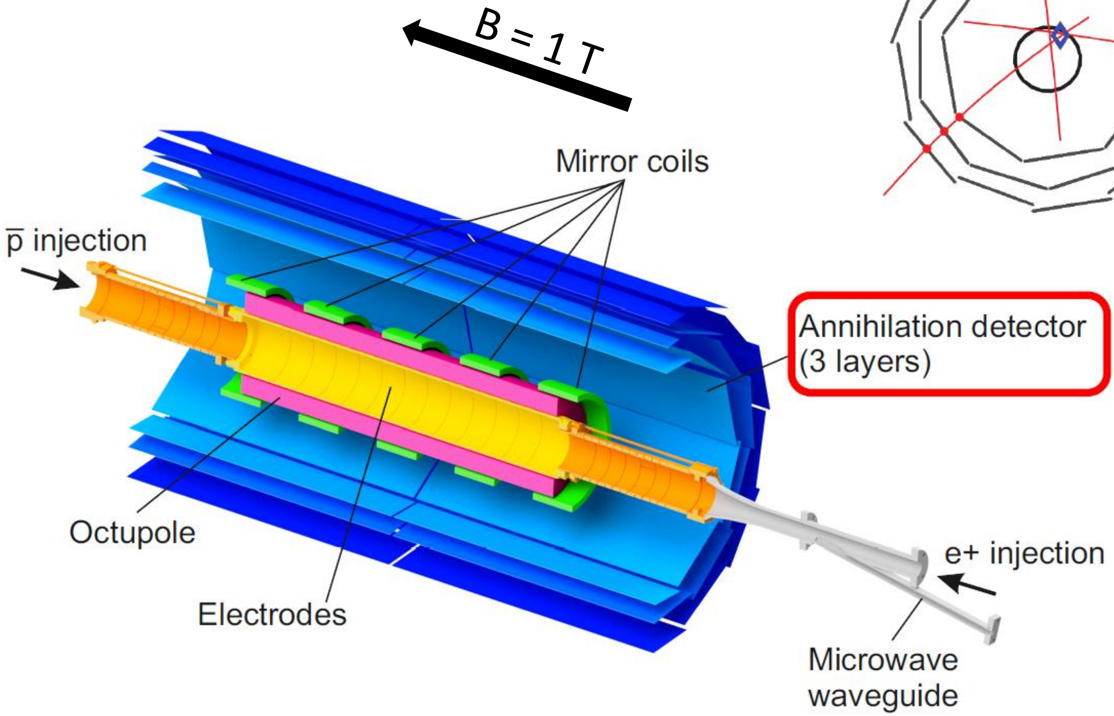
$$\Delta U \approx 0.5 \text{ K}$$

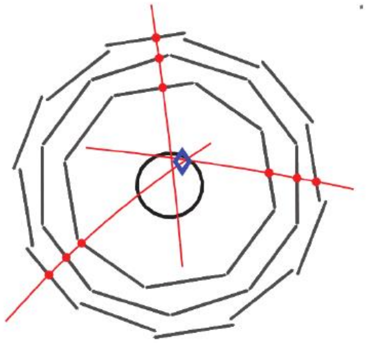
B = 1 T



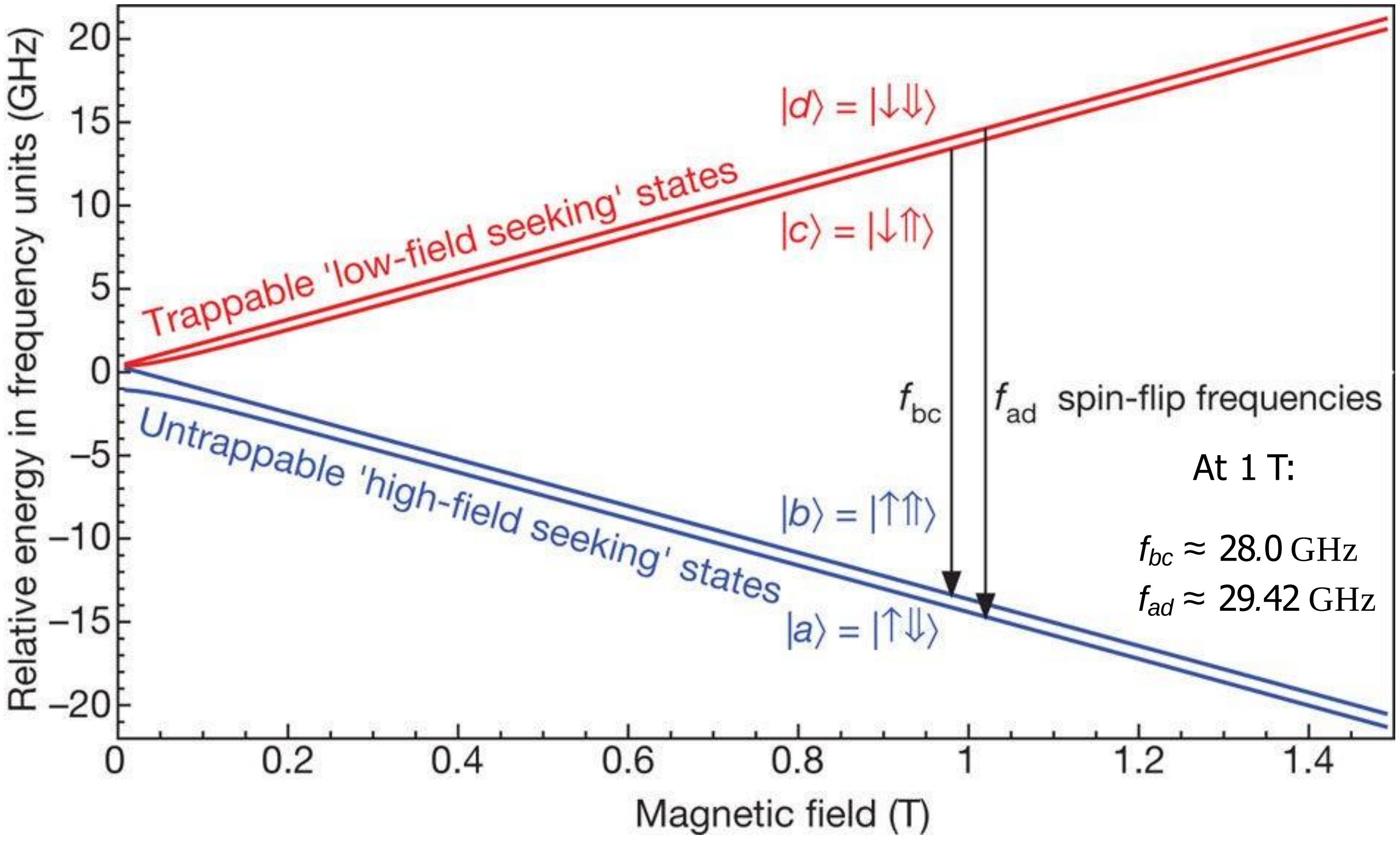


Producing and trapping antihydrogen





Ground state hyperfine splitting



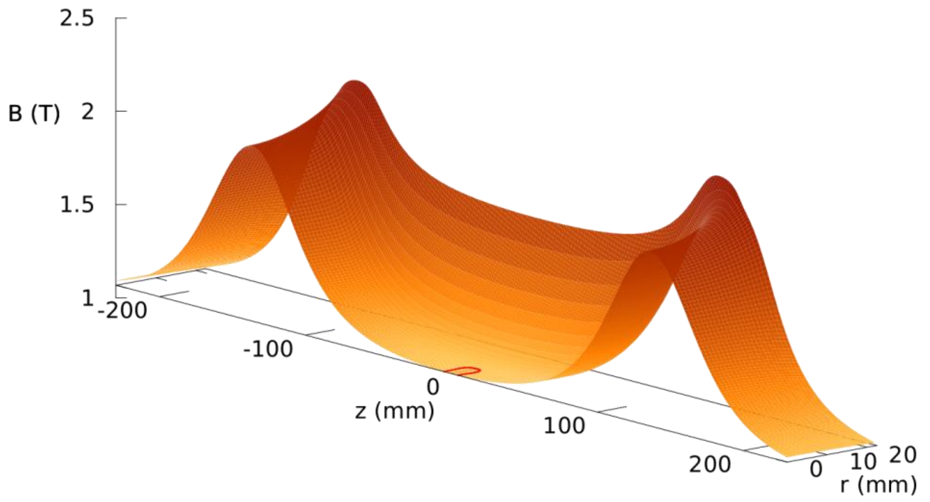
At 1 T:

$f_{bc} \approx 28.0$ GHz

$f_{ad} \approx 29.42$ GHz

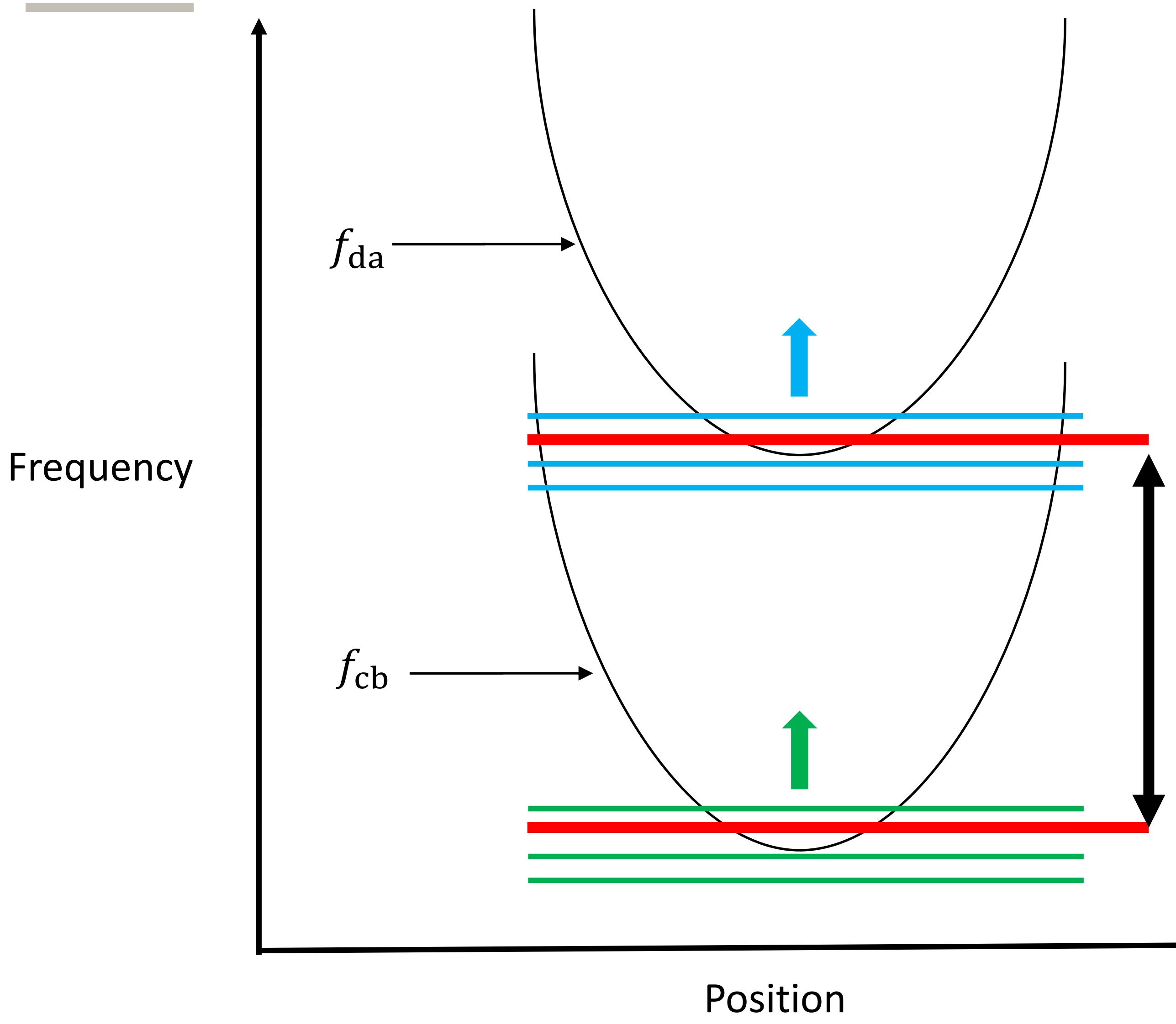
At same magnetic field

$$\Delta f_{\mathrm{HFS}} = f_{\mathrm{da}} - f_{\mathrm{cb}}$$



$0.1 \text{ mT} \Rightarrow 2.8 \text{ MHz}$

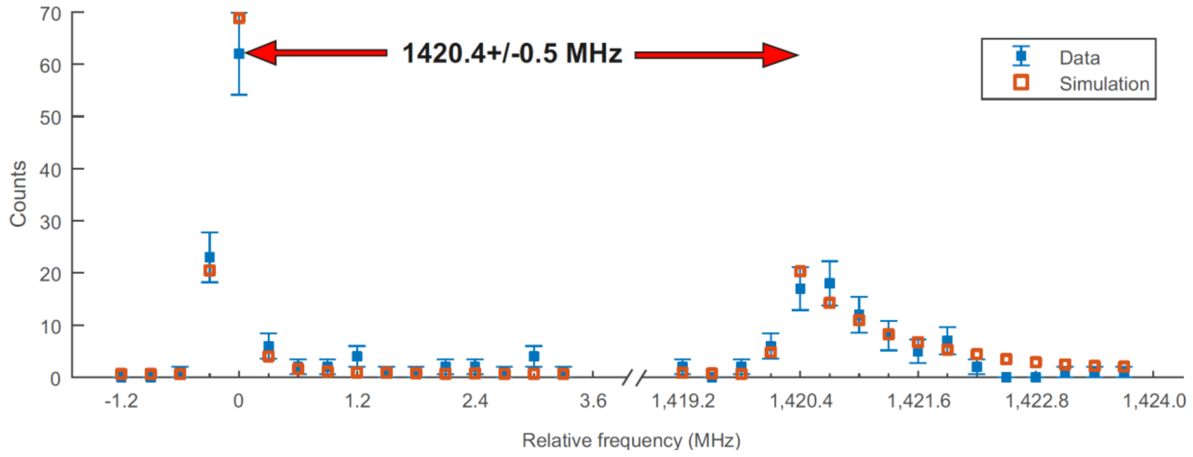
Approach



- Find minimum resonance for both transitions
- Stepped increasing frequency
- Look for appearance of annihilations

$$\Delta f_{hfs} = f_{da,min} - f_{cb,min}$$

Previous result (2017)



[ALPHA, Nature 548, 66 (2017)]

- Dataset – 194 annihilations total
- Sum of 22 separate "runs" with magnetic field ramps between each

2017 – 2024 Improvements:

- Two orders of magnitude improvement in $\overline{\mathrm{H}}$ trapping rate
- Stabilized magnetic fields (DCCTs with PID control)
- No need to cycle superconducting magnets

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2024 HFS Measurement Protocol

- Energize trapping magnets
- Accumulate ~1500 $\overline{\mathrm{H}}$ over roughly 1 hour
- Let magnetic fields settle
- Repeat pairs of resonance scans

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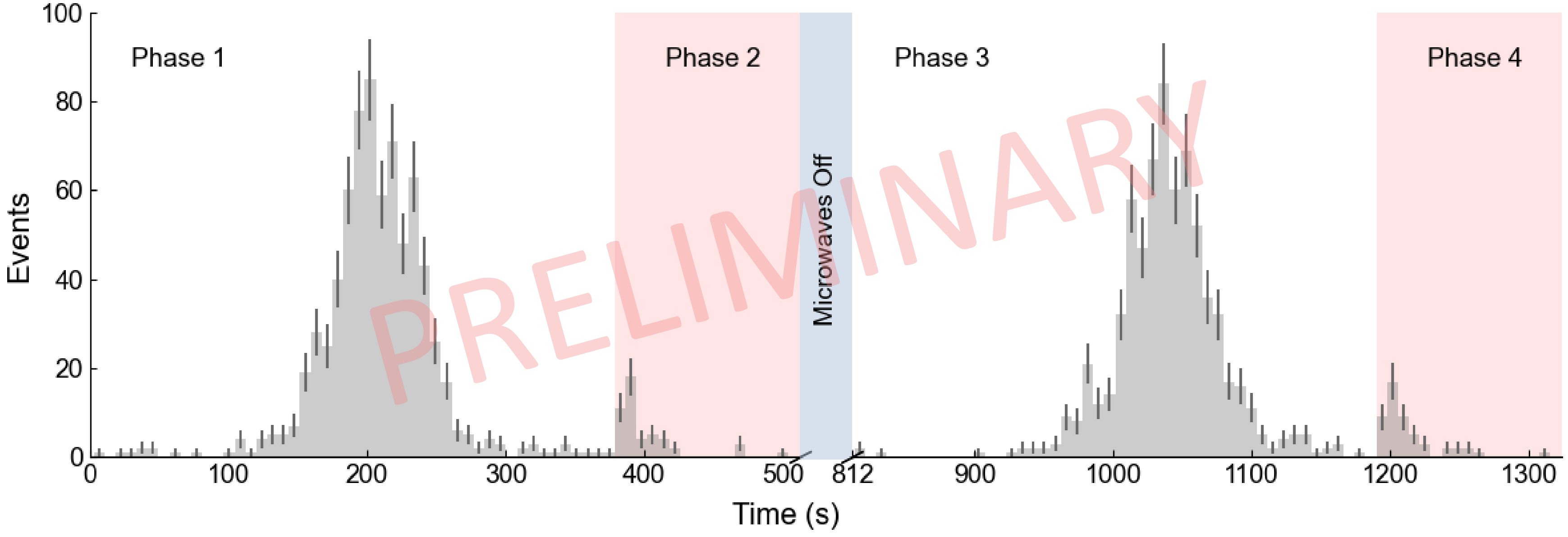
Results



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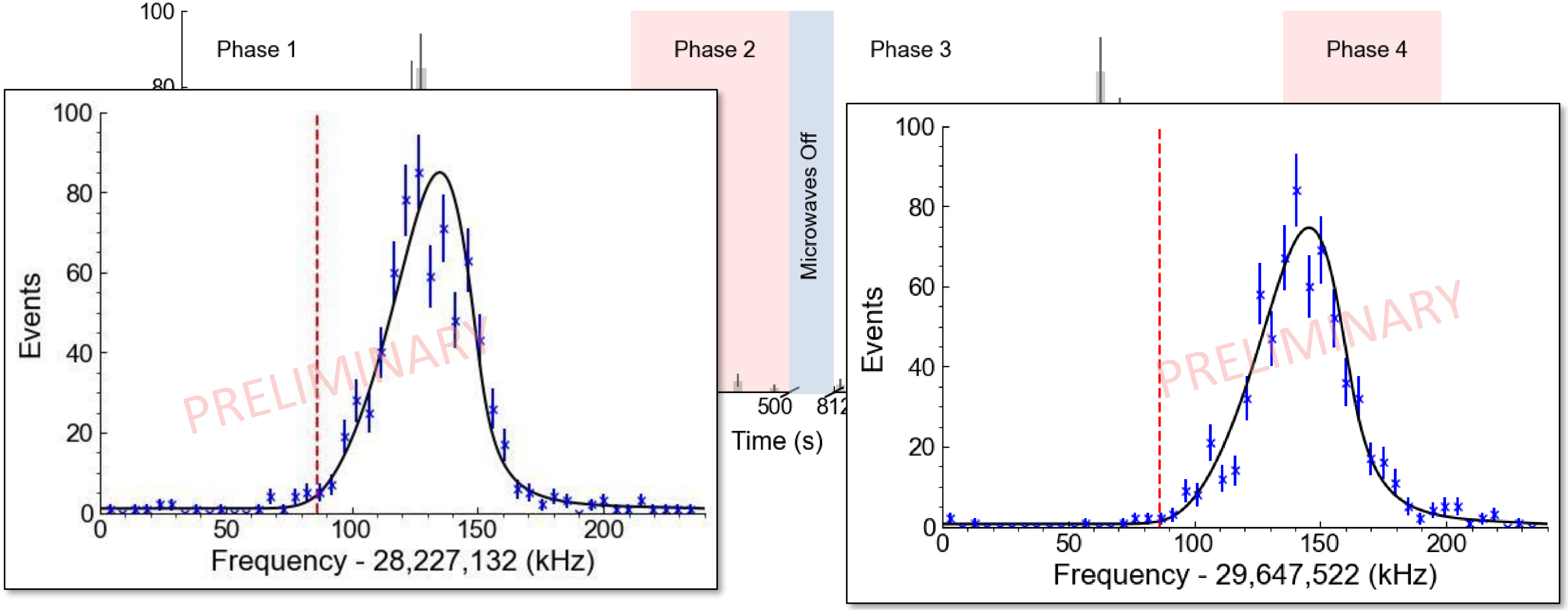

$|c\rangle \rightarrow |b\rangle$

$|d\rangle \rightarrow |a\rangle$

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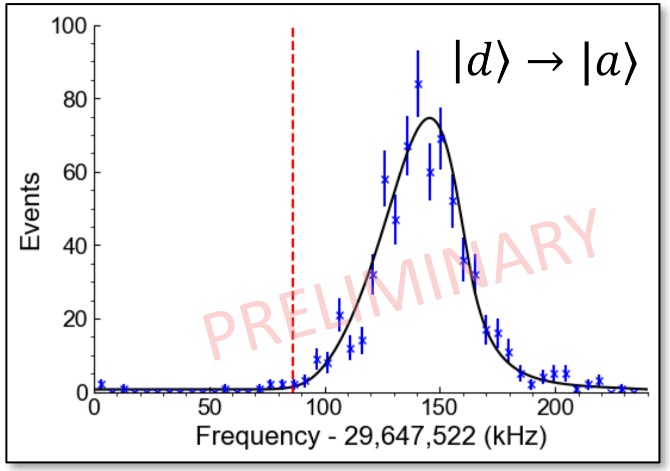
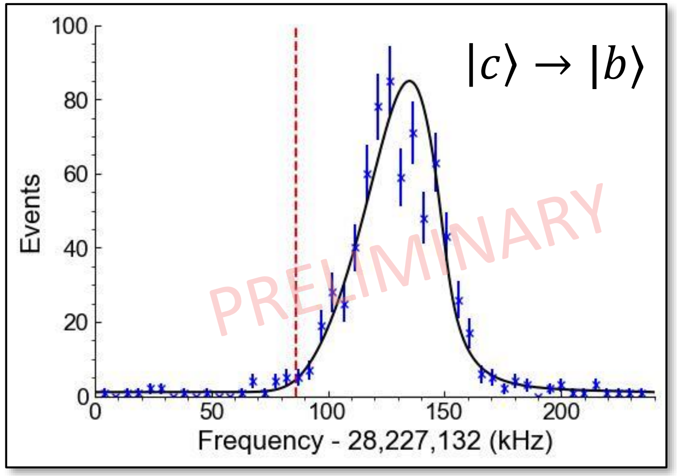
Analysis

Lineshapes

- Magnetic field shape (Zeeman broadening)
- Depletion of trapped population
- Energy distribution of trapped $\overline{\mathrm{H}}$
- $\overline{\mathrm{H}}$ dynamics in non-uniform field
- Local, spatially dependant microwave power
- Motional broadening effects





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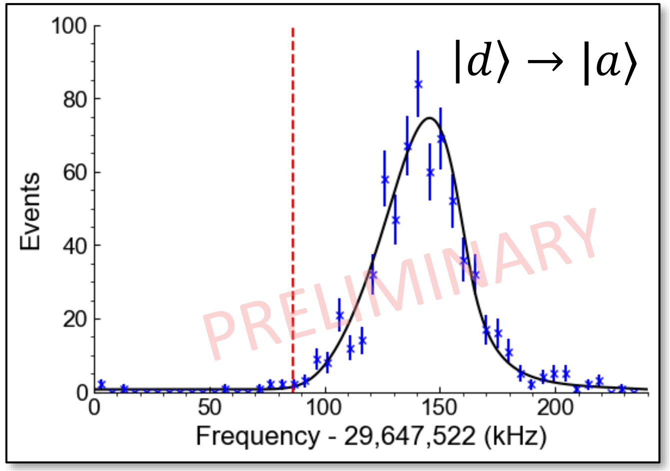
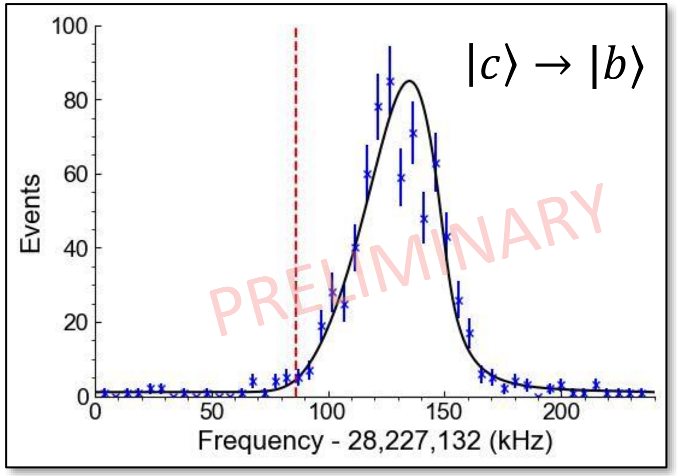
Approach

- Fit with an empirical function with an onset frequency parameter f^{o}
- f^{o} is a proxy for $f_{\min}$
- $\Delta f_{\mathrm{HFS}} = f_{da}^{o} - f_{cb}^{o}$ (if measured at same field)





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Result

Two HFS measurements at two different base fields: 1.03 T and 1.07 T. >30,000 trapped $\overline{\mathrm{H}}$

Paper in preparation…

- Sensitive to antiproton structure effects
- Improved determination of 2S hyperfine splitting
- Absolute frequency precision approaching $\overline{\mathrm{H}}$ 1S – 2S

Systematics:

- Choice of function
- Choice of onset parameter
- Assumption of linear field drift
- Reproducibility of shape between repetitions
- Binning

Thanks!

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https://alpha.web.cern.ch/

UCalgary PSR + NMR:
Jay Suh
Abbygale Swadling
Sean Wilson
Pouya Heidari
Alberto Uribe Jimenez
Reece Stefanyshyn

Modeling:
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Germano Benome (U. Brescia)
Adriano Del Vinicio (U. Brescia)

INNOVATION Canada Foundation for Innovation Fondation canadienne pour l'innovation
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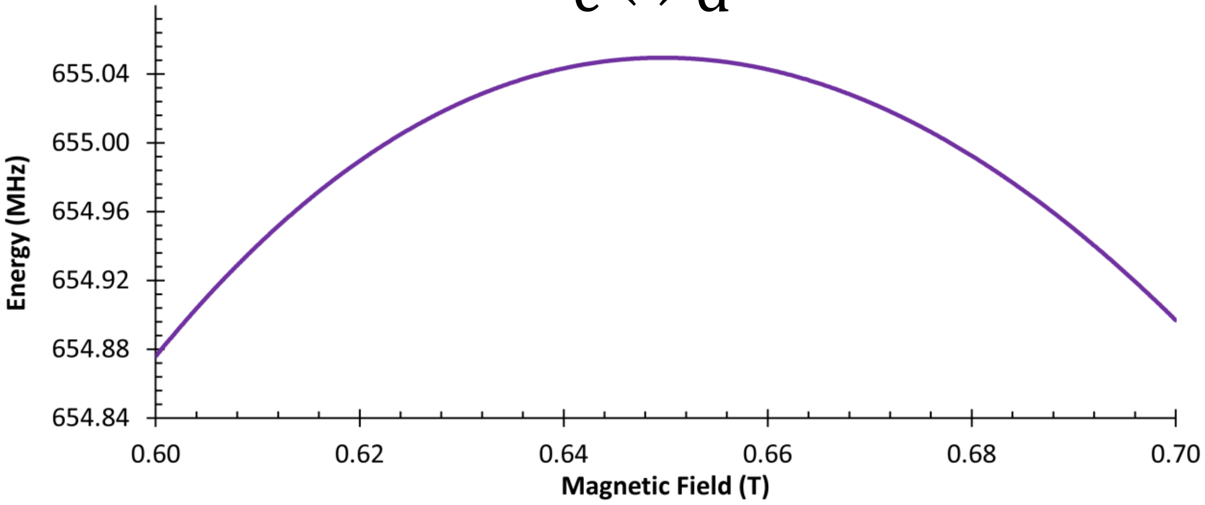
Antiproton NMR

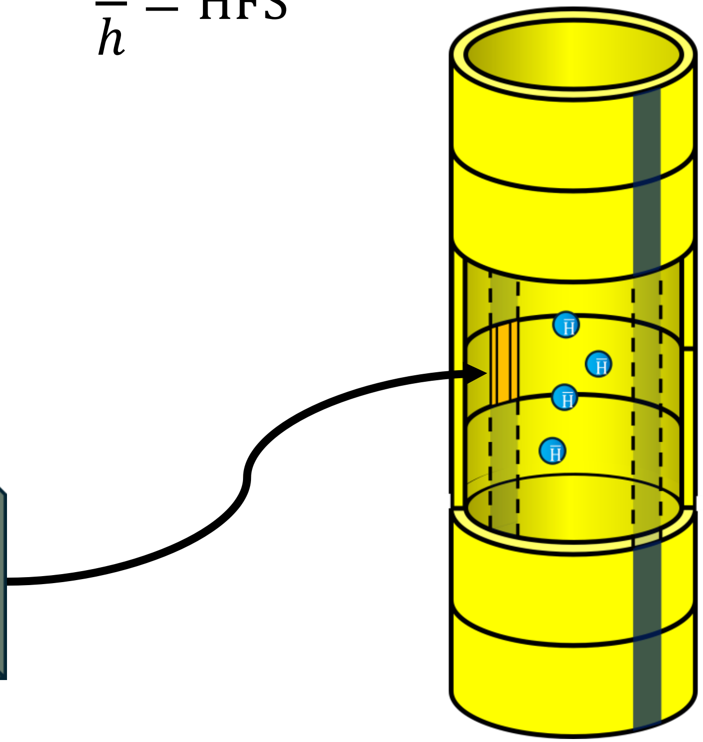
c ↔ d



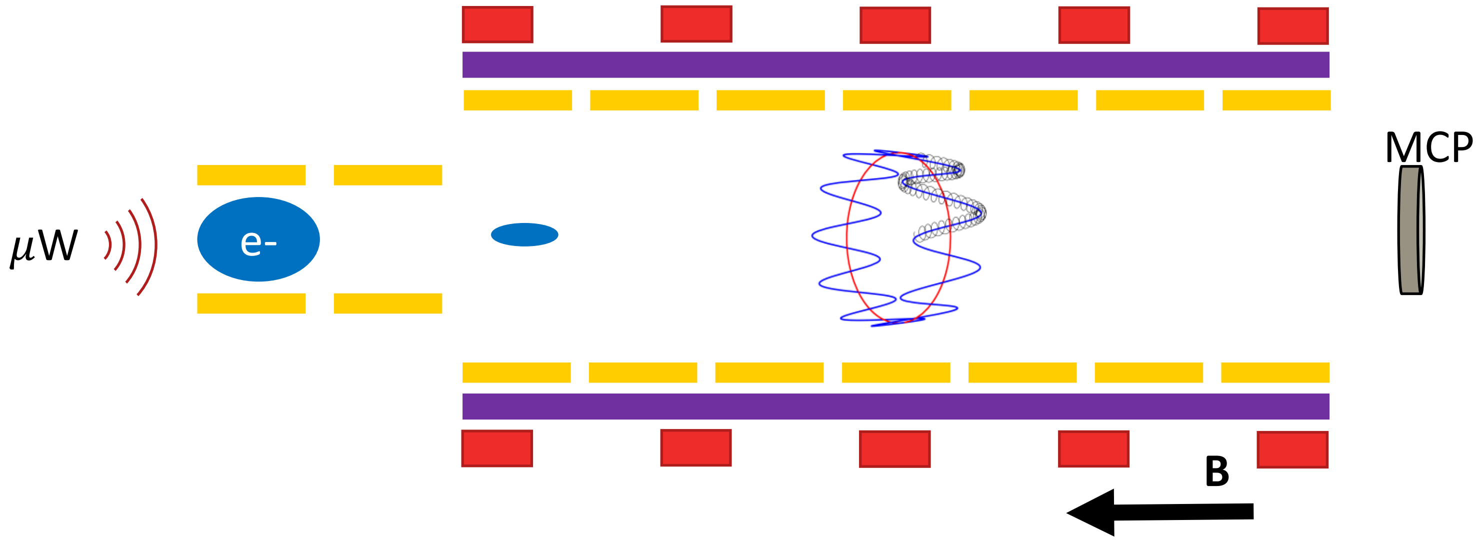
$$f^*_{\mathrm{cd}} = (a/h)([1/2 - \sqrt{\eta}/(1+\eta)],\ \eta = \gamma_{\bar{p}}/\gamma_{e^+}$$

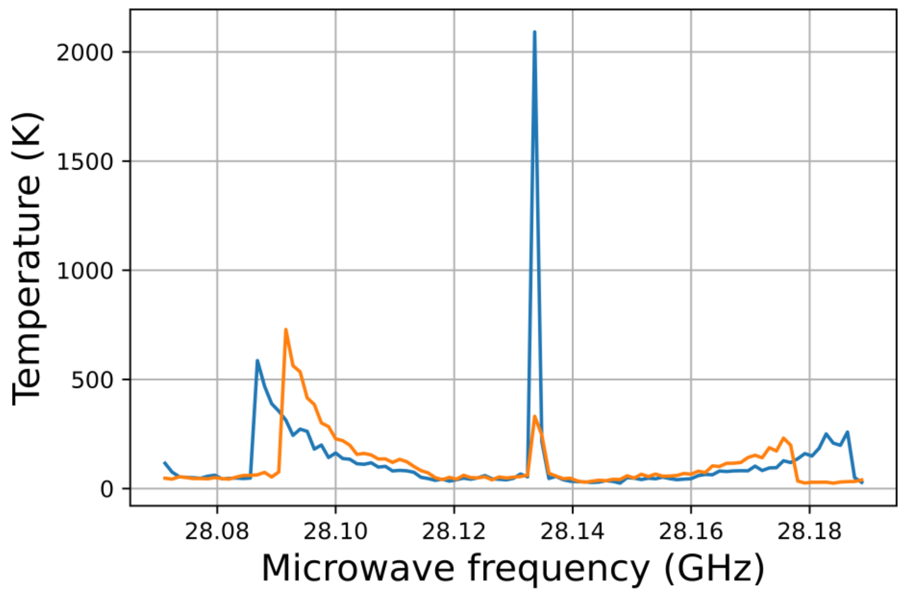
$$\frac{a}{h} = \mathrm{HFS}$$

Stripline $\lambda/2$ resonator antenna



Electron cyclotron resonance magnetometry





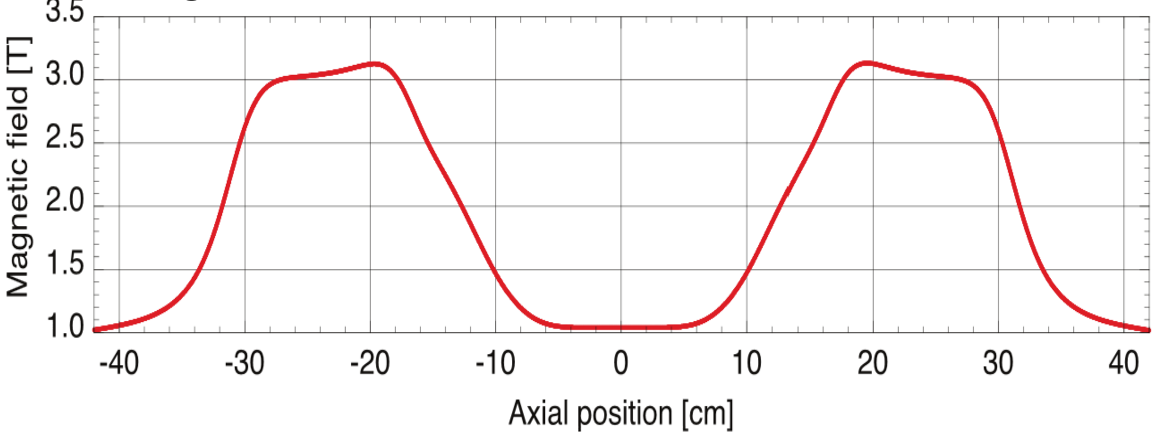
$$f_c = \frac{q\,B}{2\,\pi\,m}$$

1 ppm precision (on-axis)

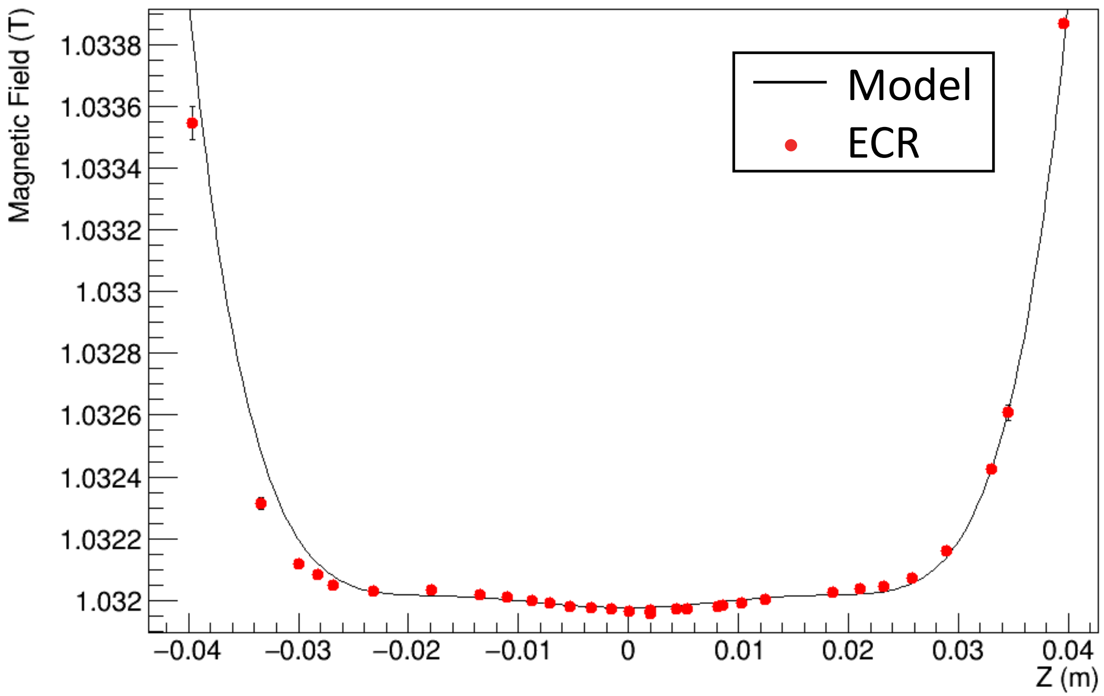
At 1 T $f_c \approx 28$ GHz insert reference

Magnetic field maps

Magnet model



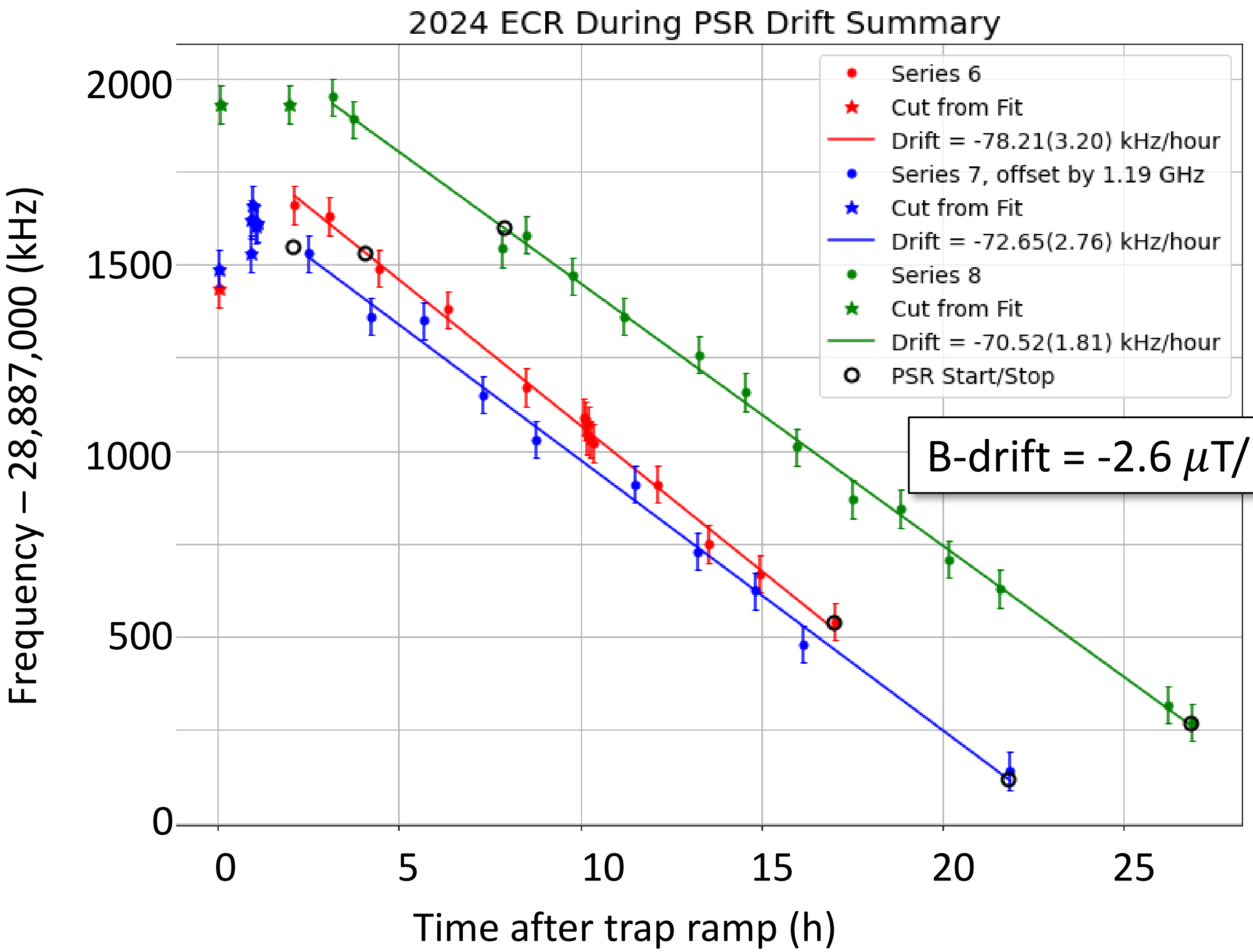
Electron Cyclotron Resonance Measurements



1 ppm on-axis field measurements

[E.D. Hunter et al. Physics of Plasmas, 27, 032106 (2020)]

Magnetic field time evolution



B-drift = -2.6 μT/hr (-73 kHz/hr or -0.02 kHz/s)

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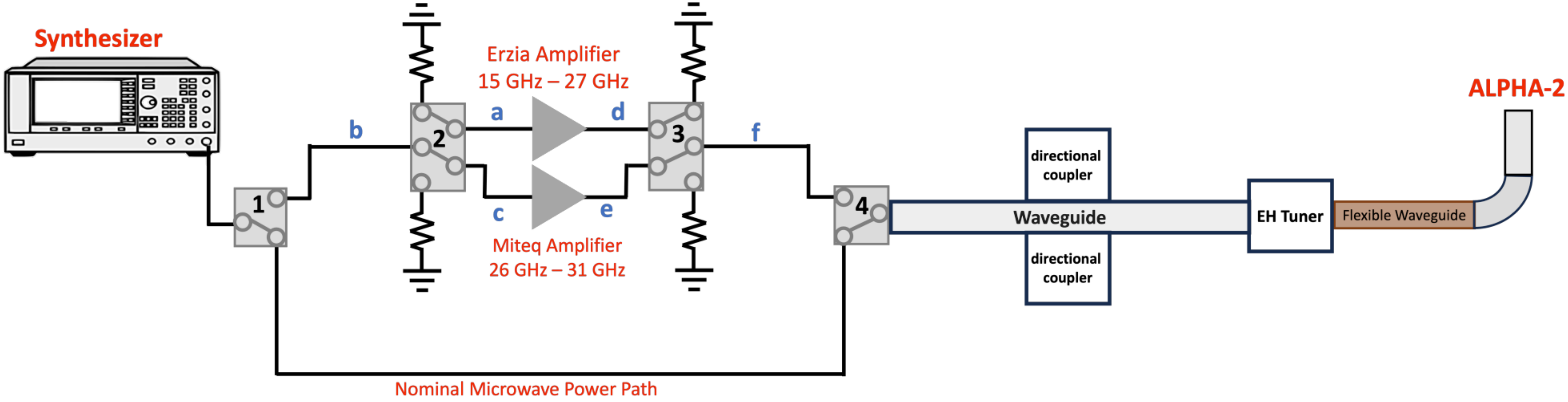

Synthesizer
Erzia Amplifier
15 GHz – 27 GHz
a
b
d
f
1
2
3
4
c
e
Miteq Amplifier
26 GHz – 31 GHz
directional coupler
Waveguide
directional coupler
EH Tuner
Flexible Waveguide
ALPHA-2
Nominal Microwave Power Path

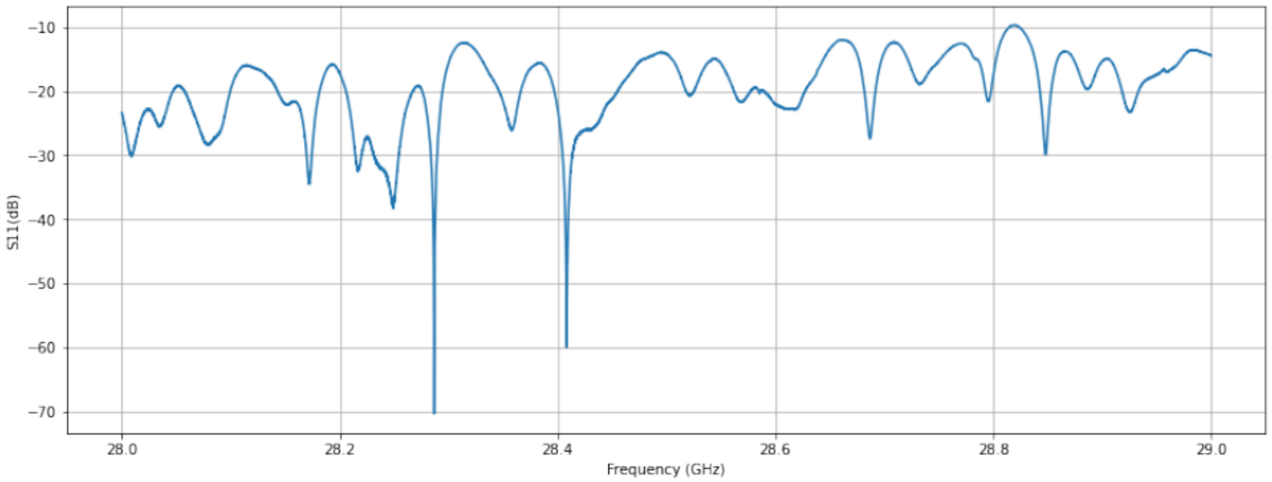


Figure 6: S_{11} coefficient between 28 GHz and 29 GHz

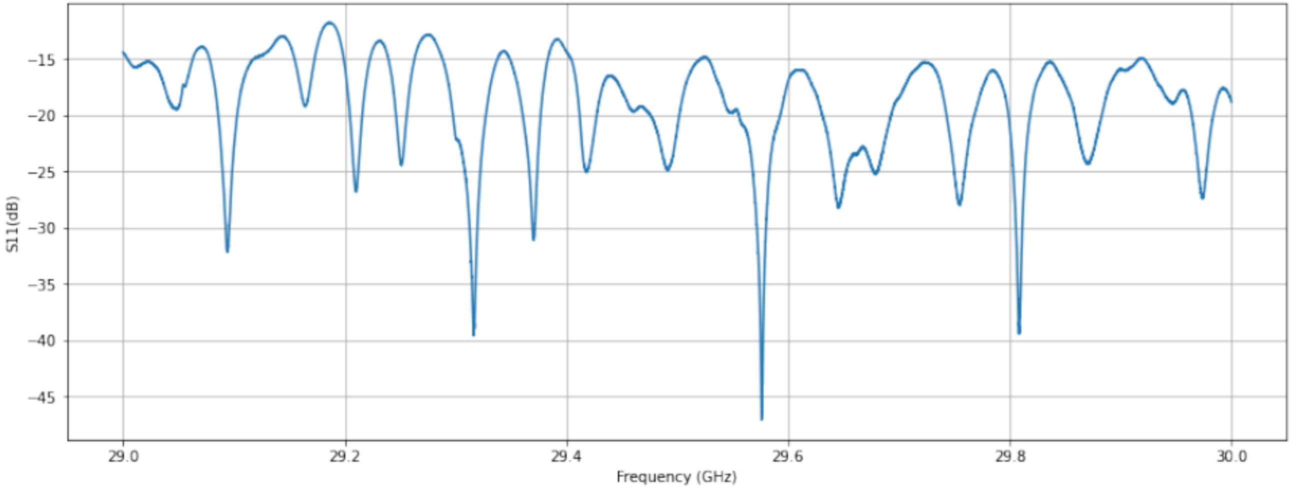


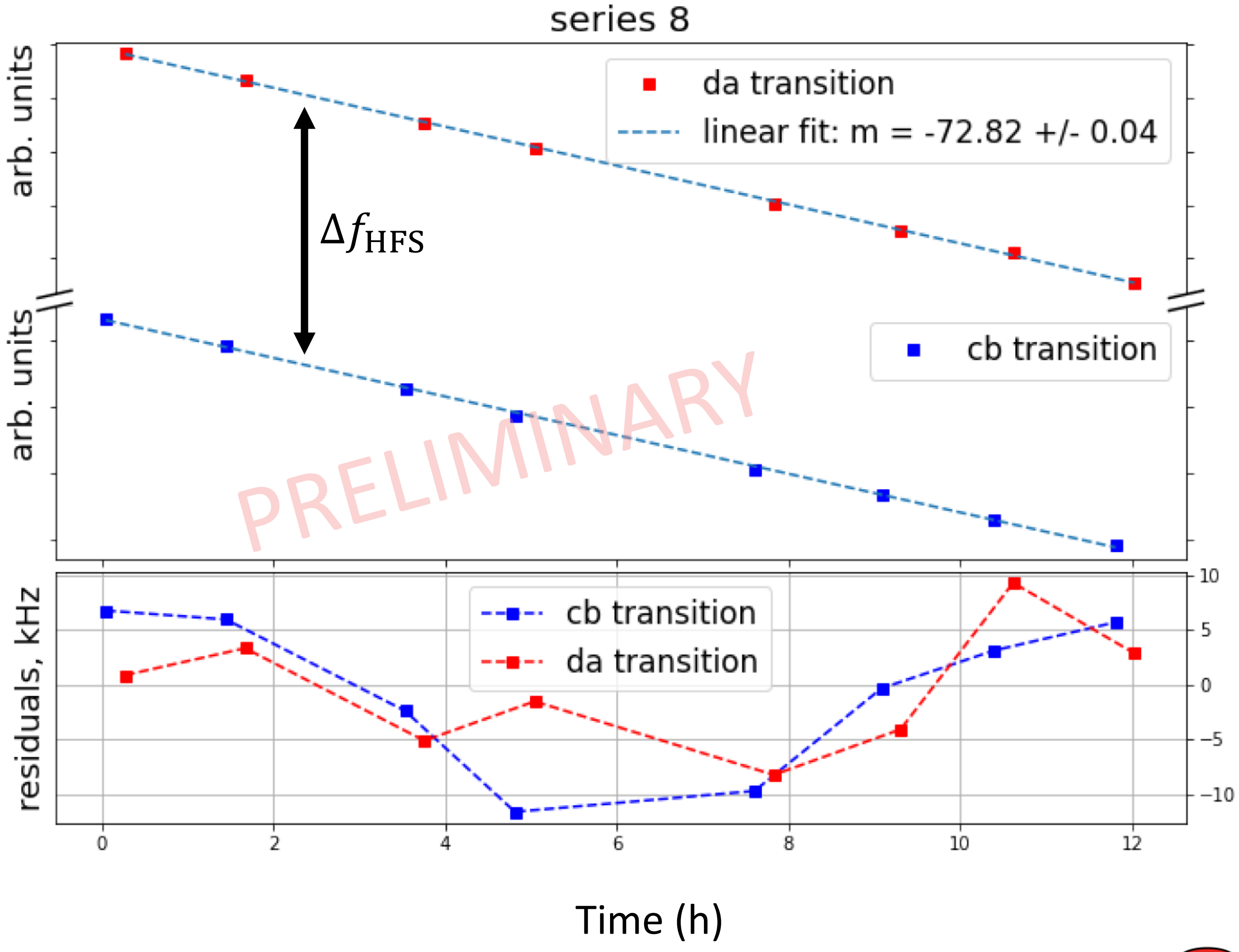
Figure 7: S_{11} coefficient between 29 GHz and 30 GHz

Compensating for B-drift

Repeat cycles of

- Accumulate $\overline{\mathrm{H}}$
- Wait
- Scan $|c\rangle \rightarrow |b\rangle$
- Scan $|d\rangle \rightarrow |a\rangle$

Assume linear drift and fit a common slope



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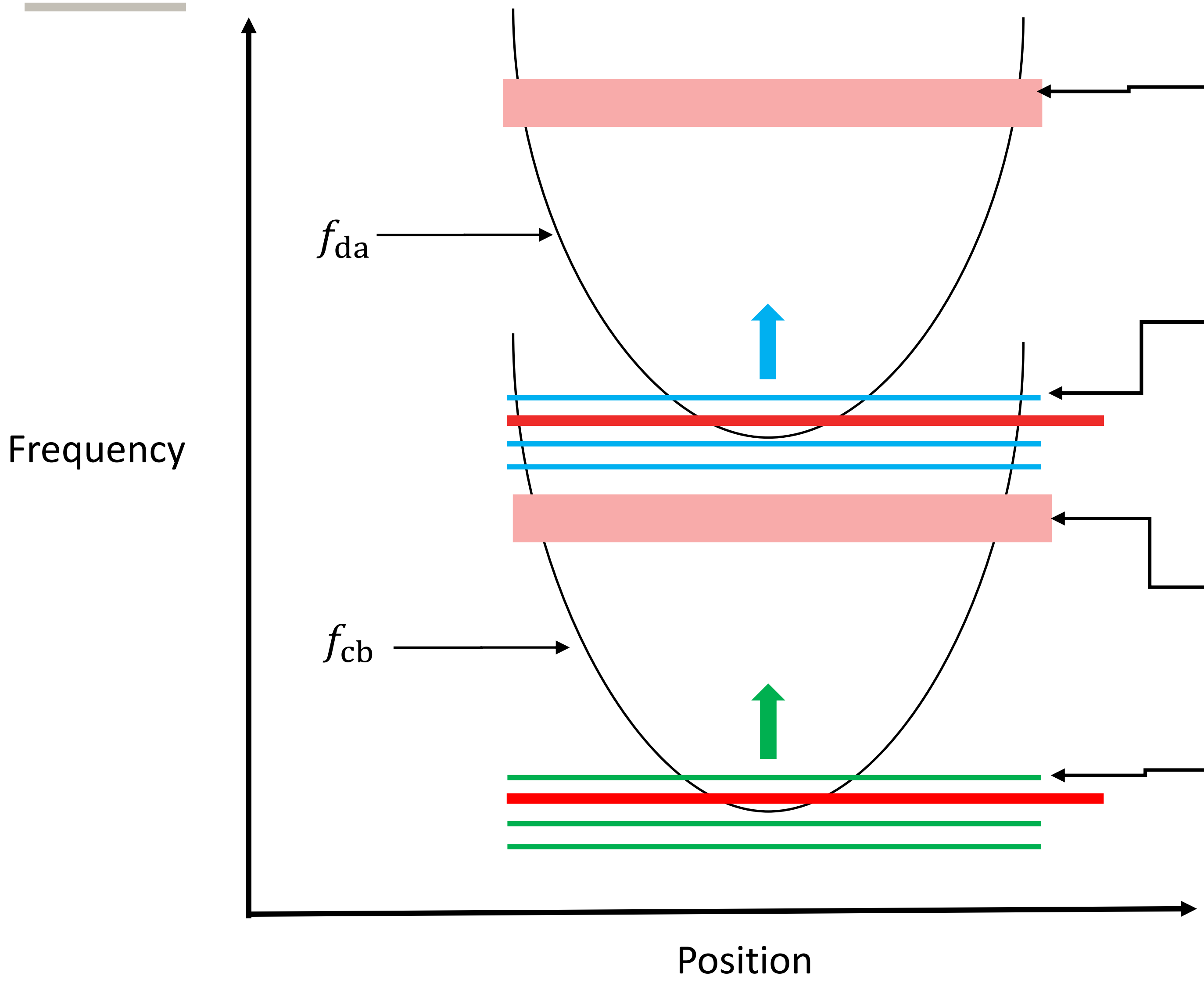
Protocol



Phase 4:
Remove any remaining d-state atoms

Phase 3:
Scan over $f_{\mathrm{da,min}}$
48 steps, Δf_s = 5 kHz/step, $T_s = 8$ s

Phase 2:
Remove any remaining c-state atoms

Phase 1:
Scan over $f_{\mathrm{cb,min}}$
48 steps, Δf_s = 5 kHz/step, $T_s = 8$ s