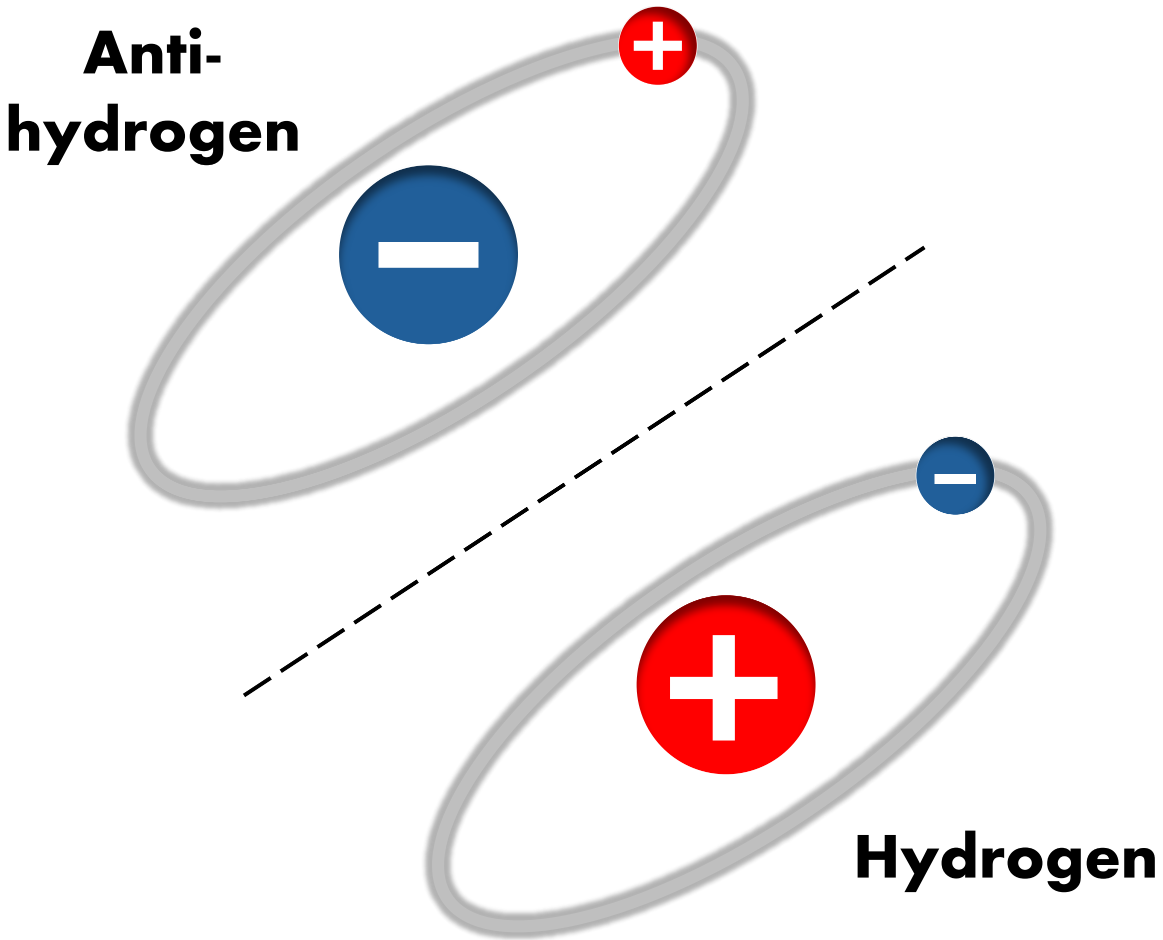
Towards a High Precision Measurement of the Hyperfine Splitting in Antihydrogen using Antiproton Spin Flips

Sean Wilson

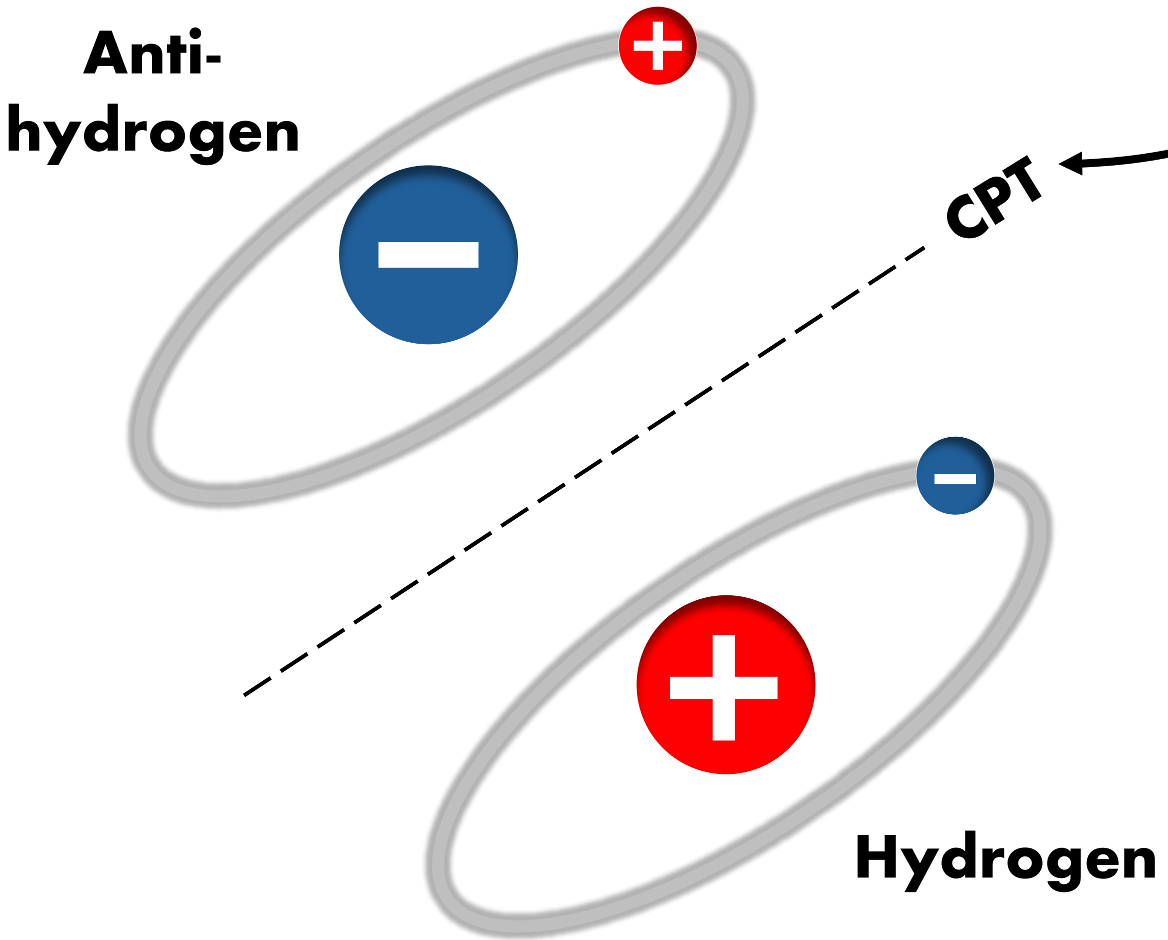
June 23, 2026

Cap Congress 2026

Matter and Antimatter Symmetry

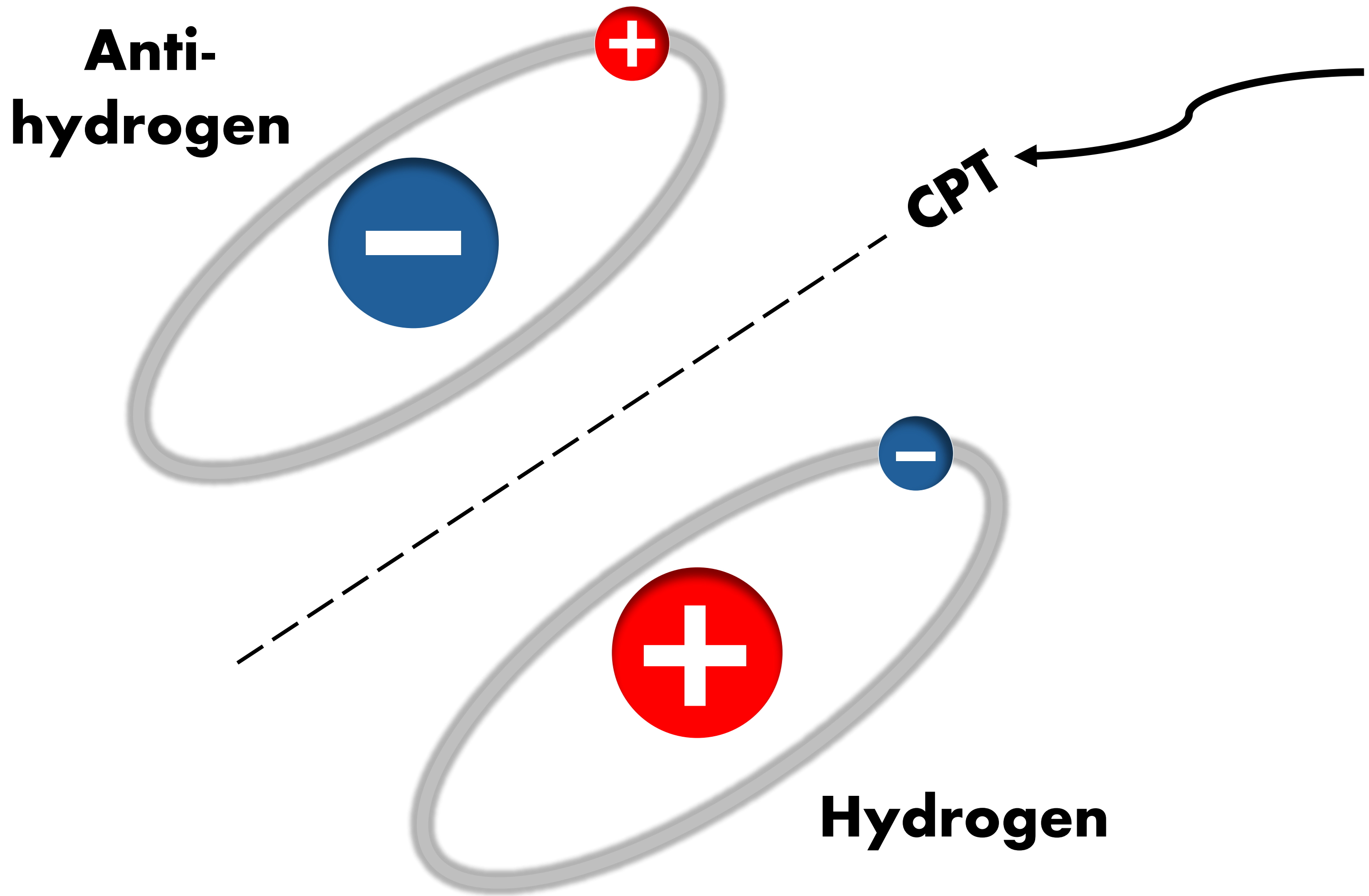


Matter and Antimatter Symmetry



Fundamental Symmetry:
Charge, **Parity**, and **Time**

Matter and Antimatter Symmetry



Fundamental Symmetry:
Charge, **Parity**, and **Time**

⇩

Predicts hydrogen and antihydrogen should have identical spectra

ALPHA Collaboration

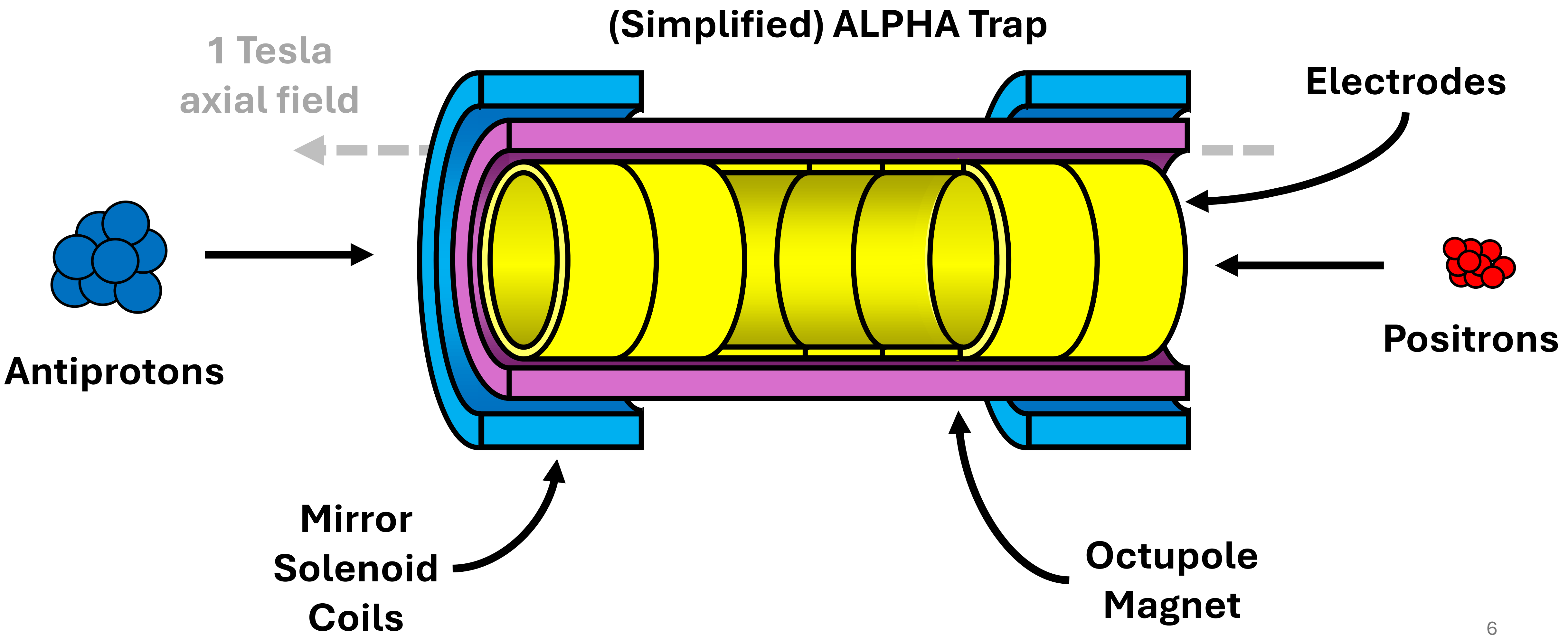
Calgary Contingent of ALPHA

Courtesy of Jay Suh

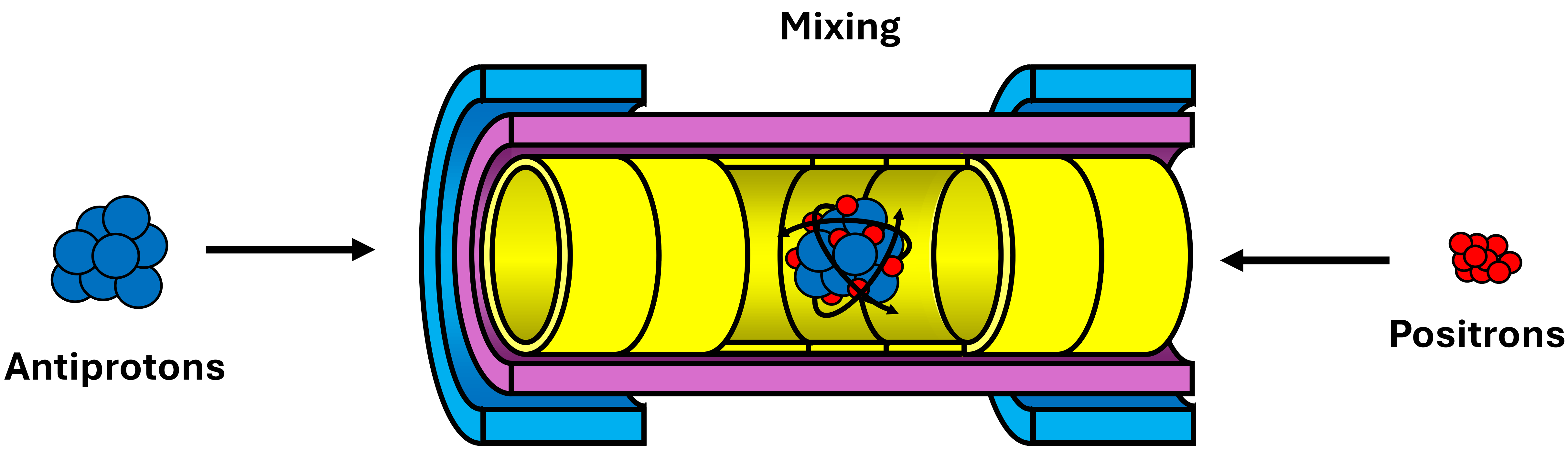
ALPHA:

- Study fundamental symmetries by precise comparison of **hydrogen** and **antihydrogen**
- Spectroscopy of antihydrogen
- Gravitational trajectory experiments

Trapping Antimatter at ALPHA

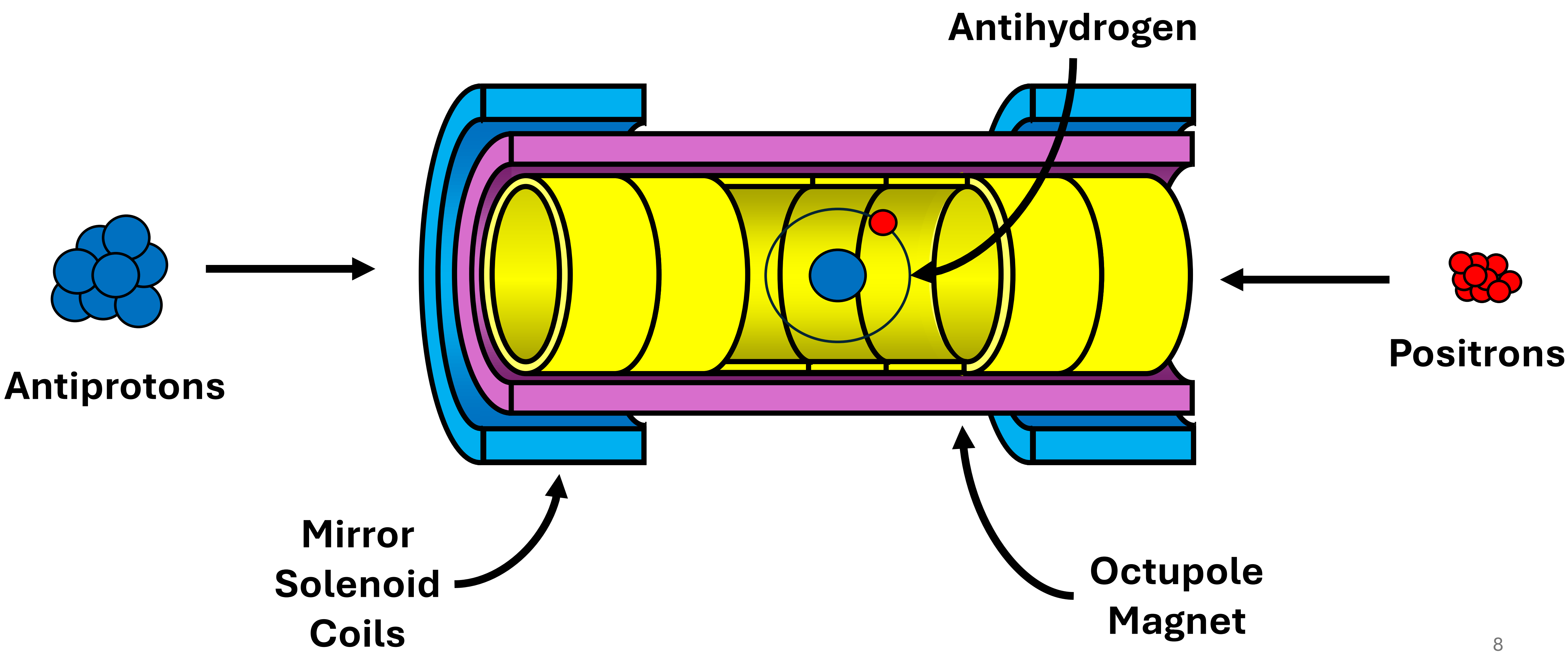


Trapping Antimatter at ALPHA

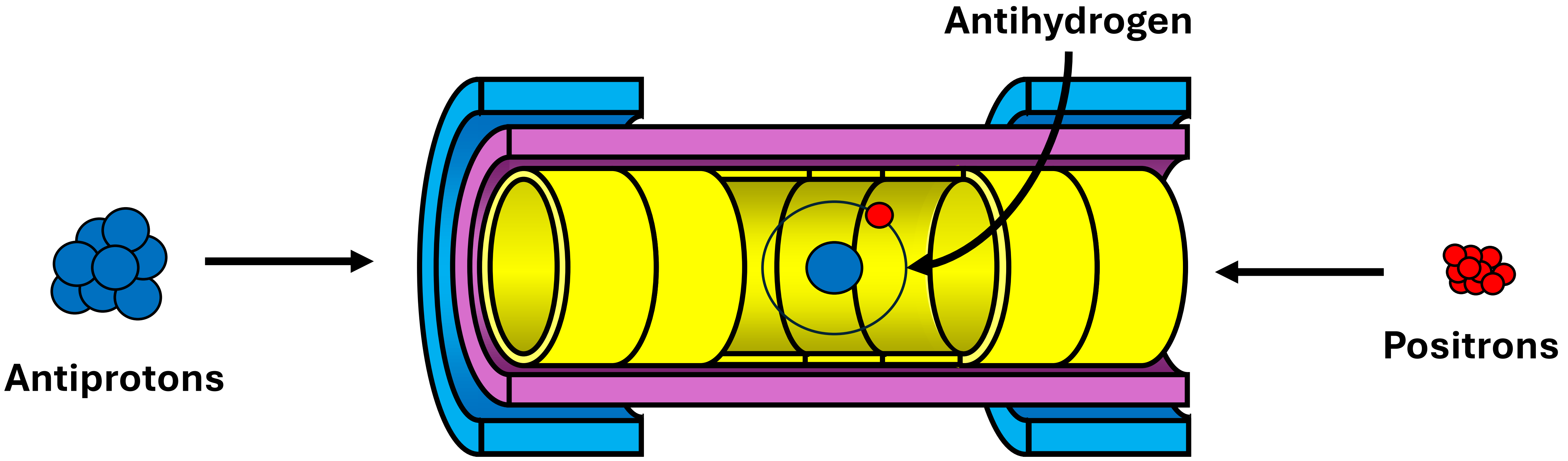


Antiprotons/positrons are cooled and mixed at the centre of the trap

Trapping Antimatter at ALPHA



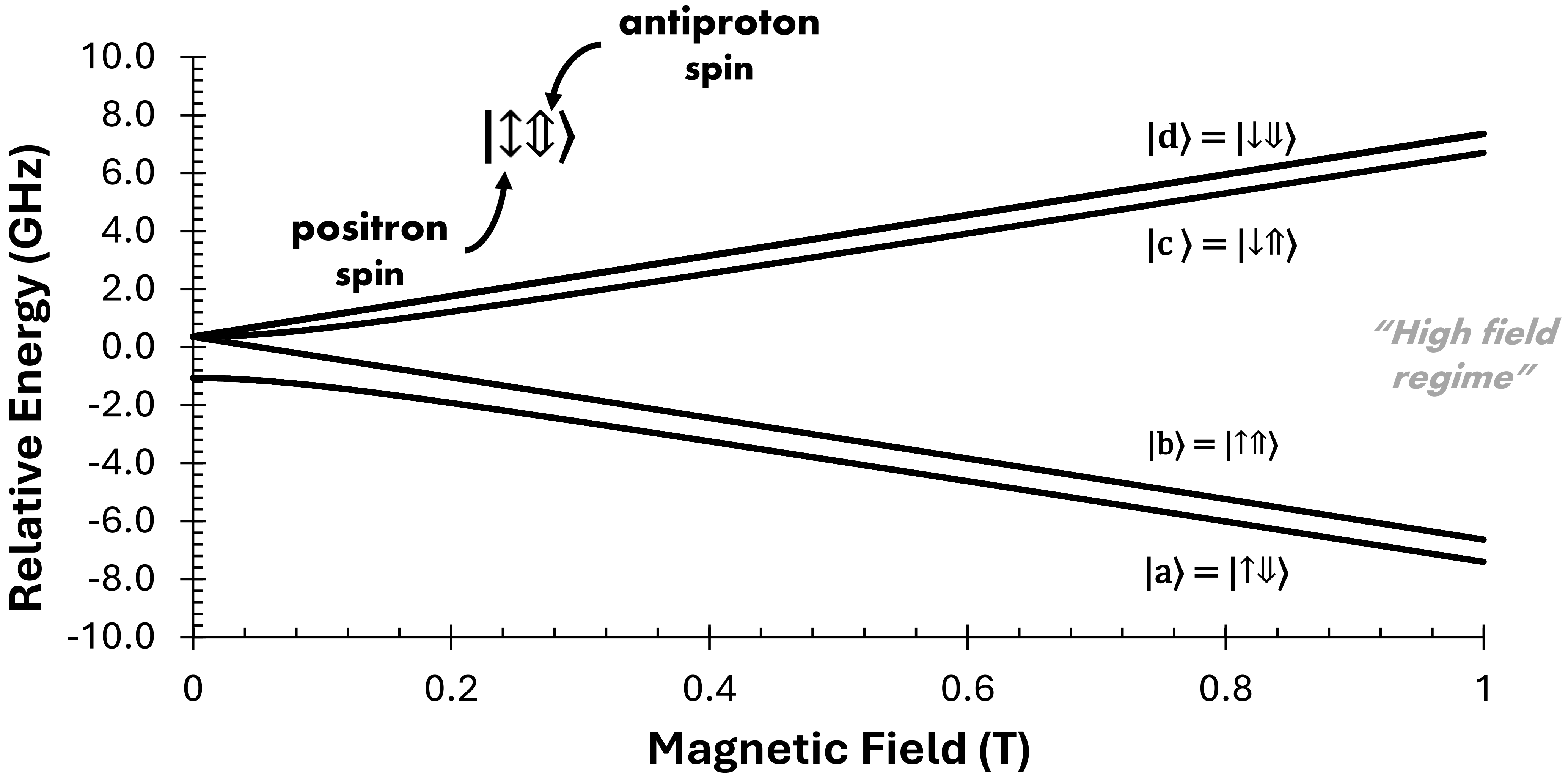
Trapping Antimatter at ALPHA



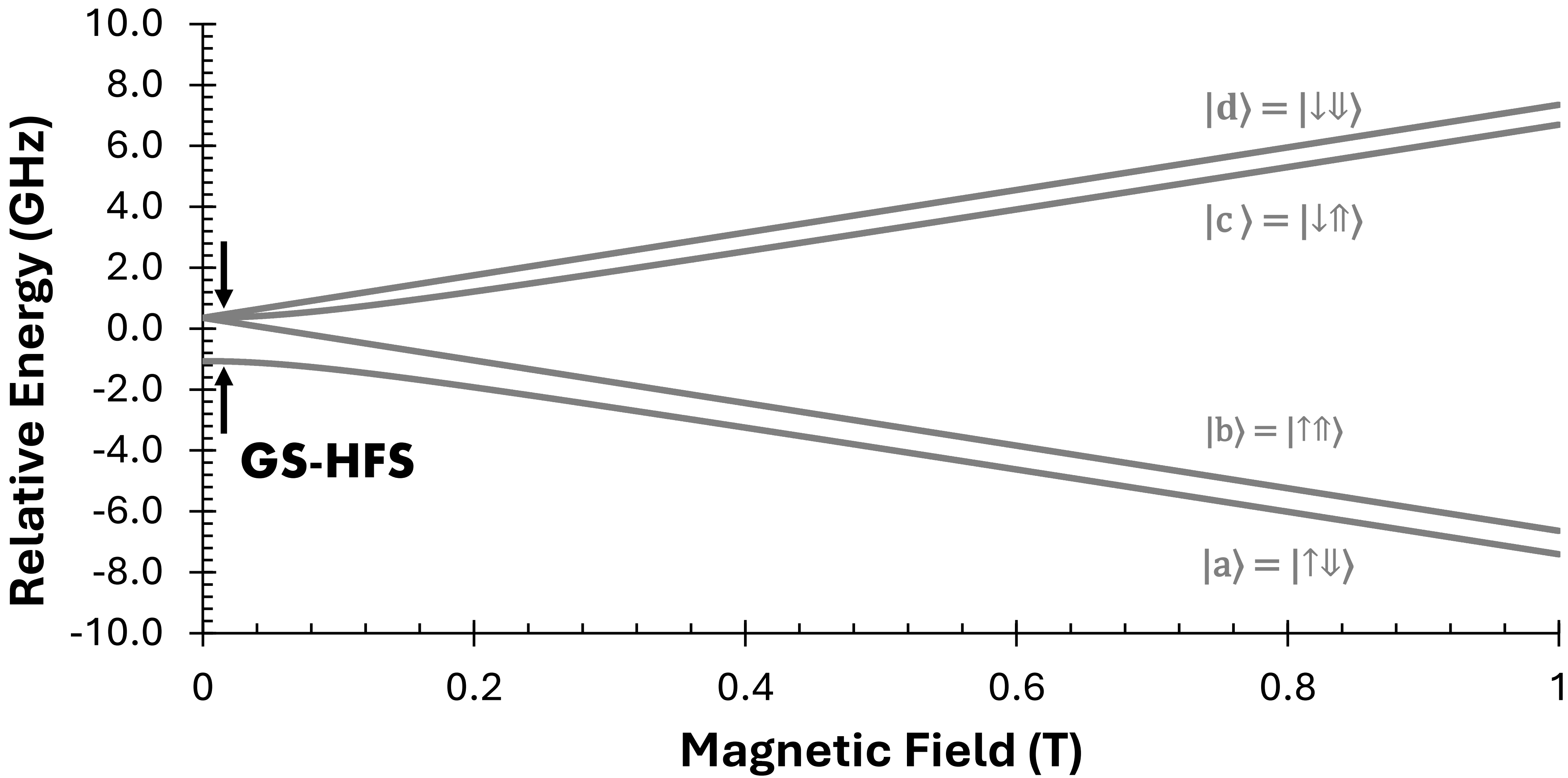
Can produce over **100** antihydrogen atoms in a single mixing step

Thousands of antihydrogen atoms available for each measurement

Ground State Hyperfine Structure



Ground State Hyperfine Structure



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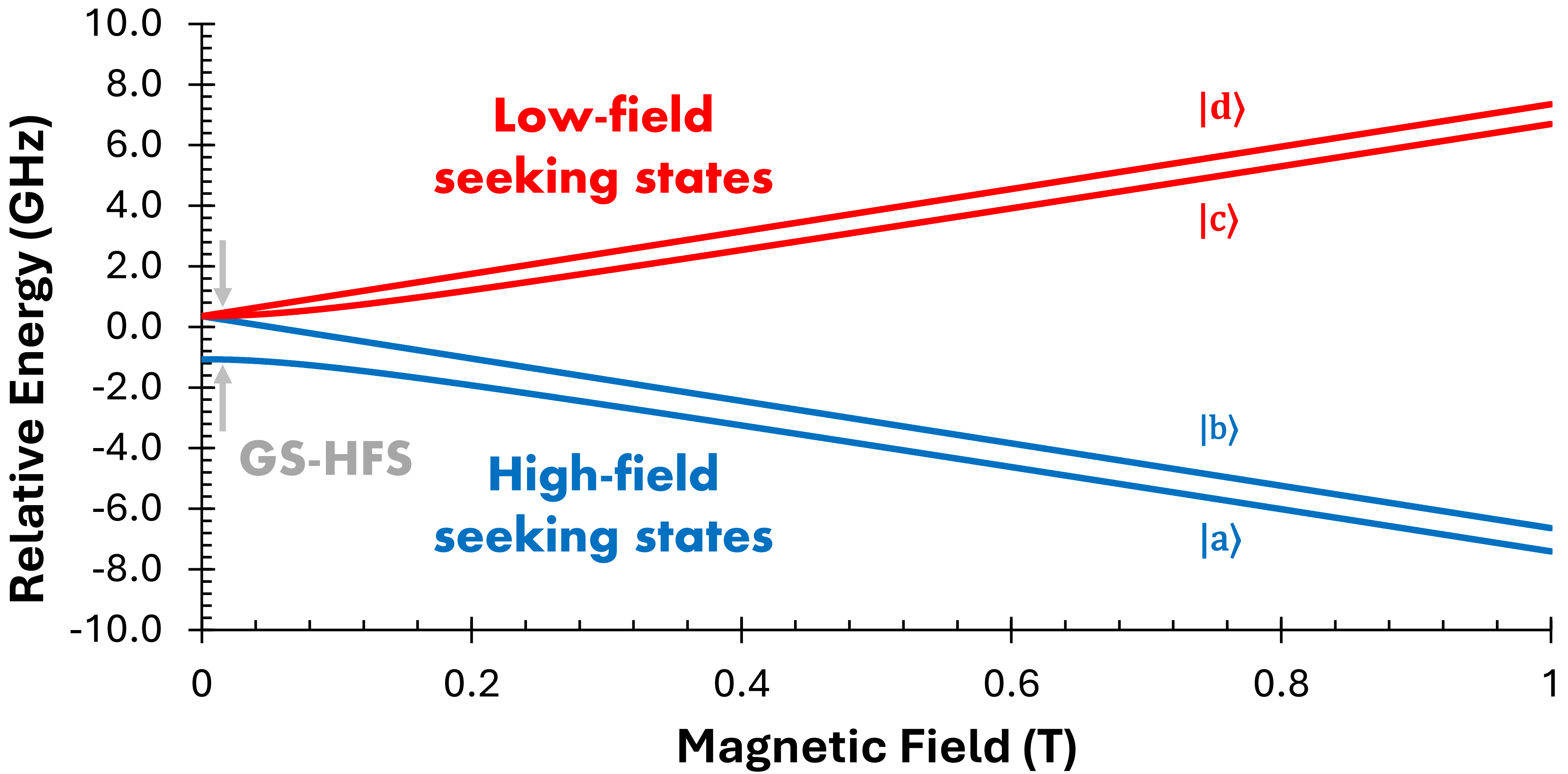

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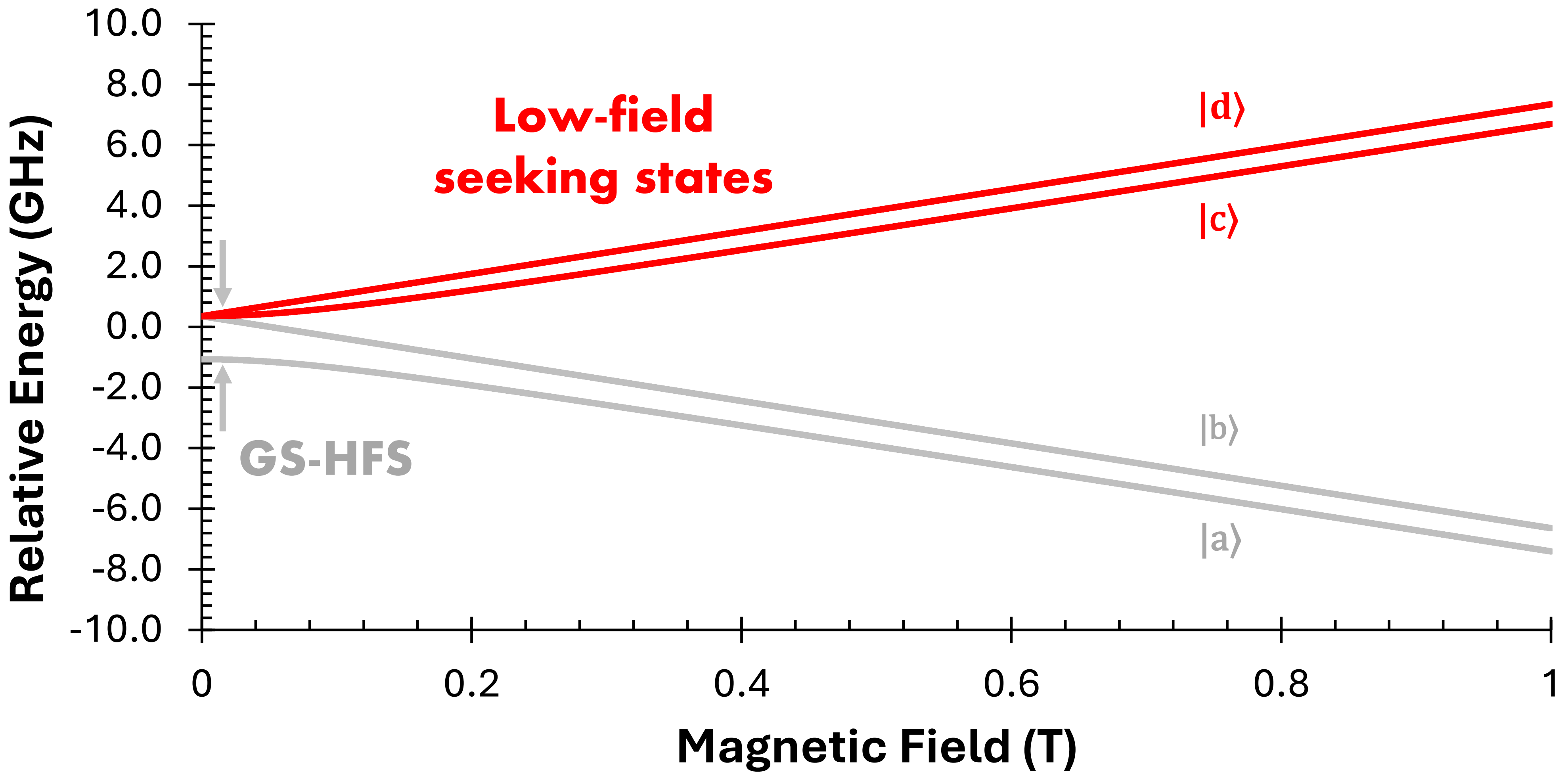

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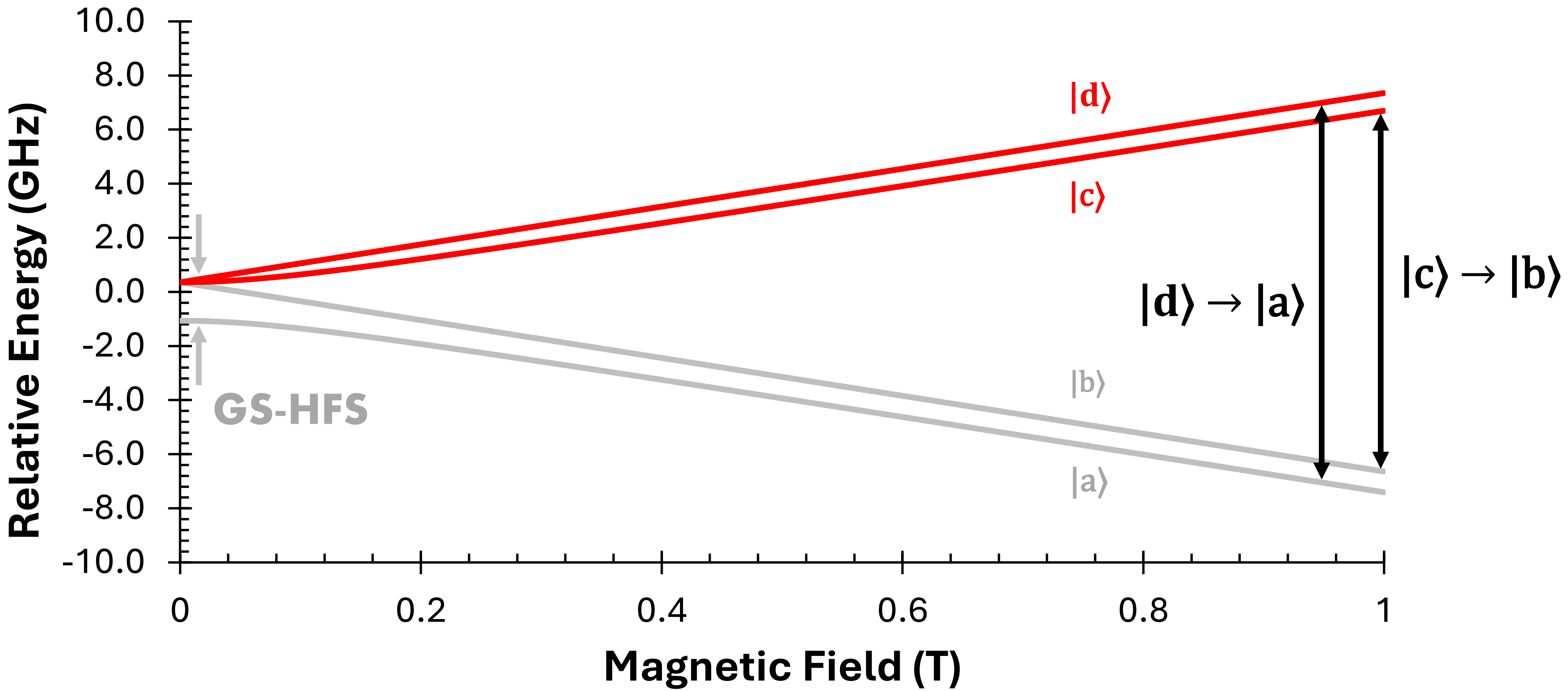

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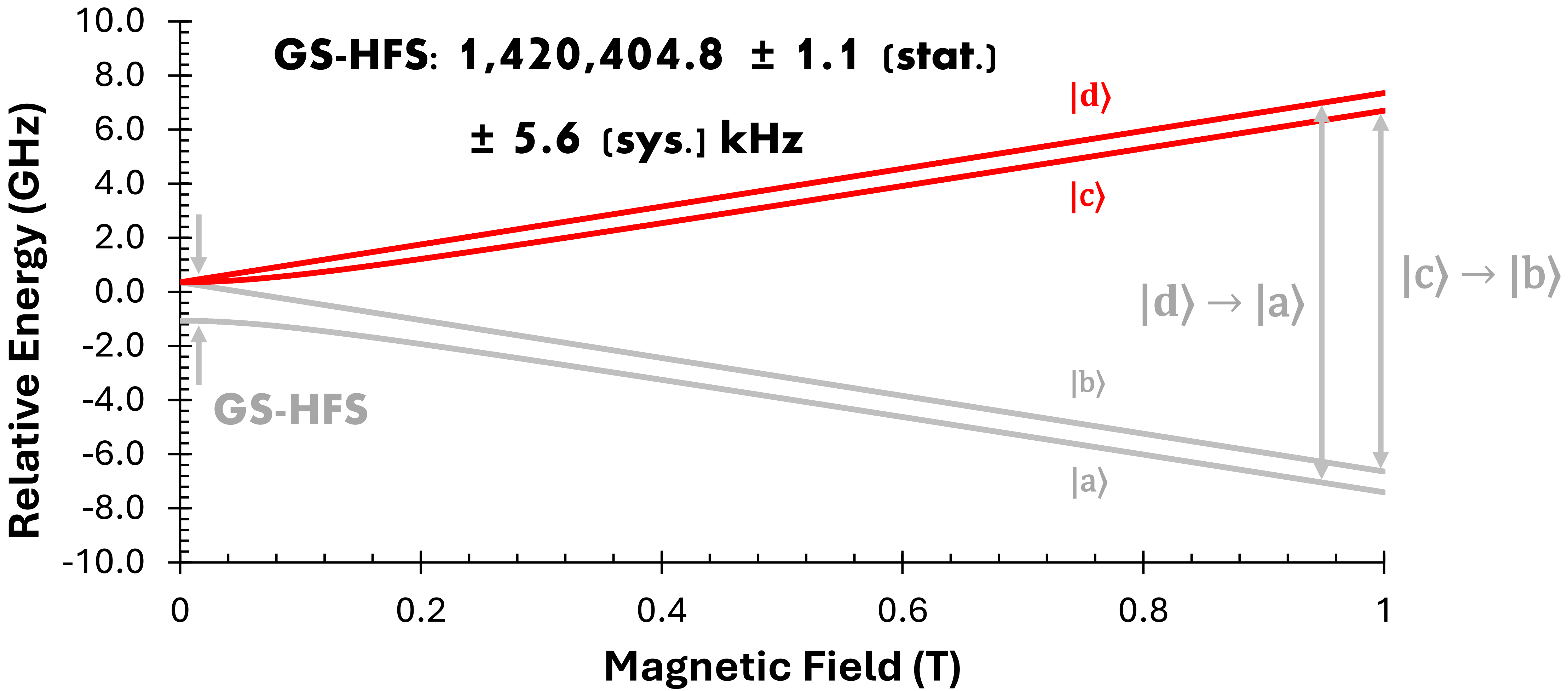
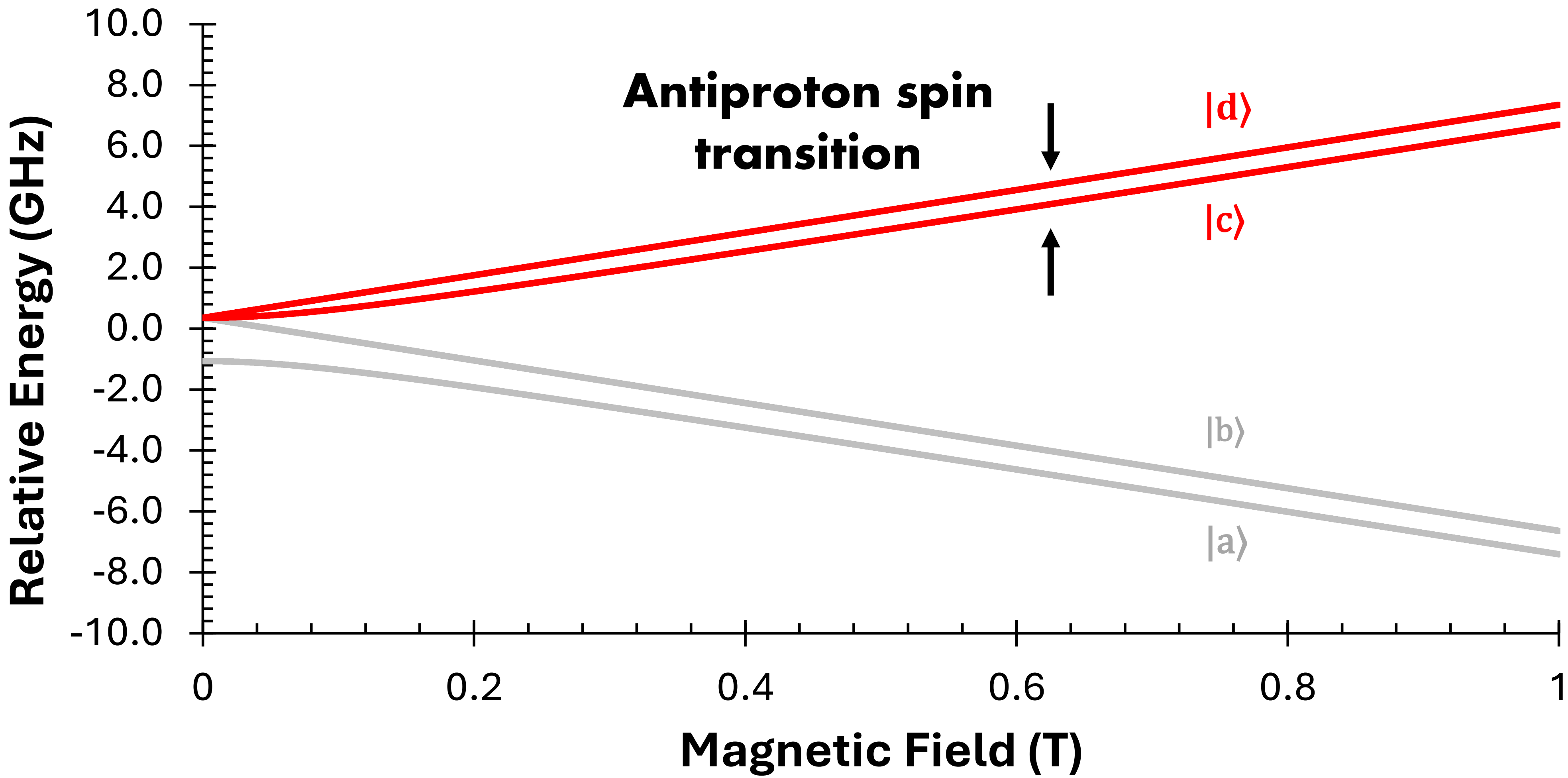
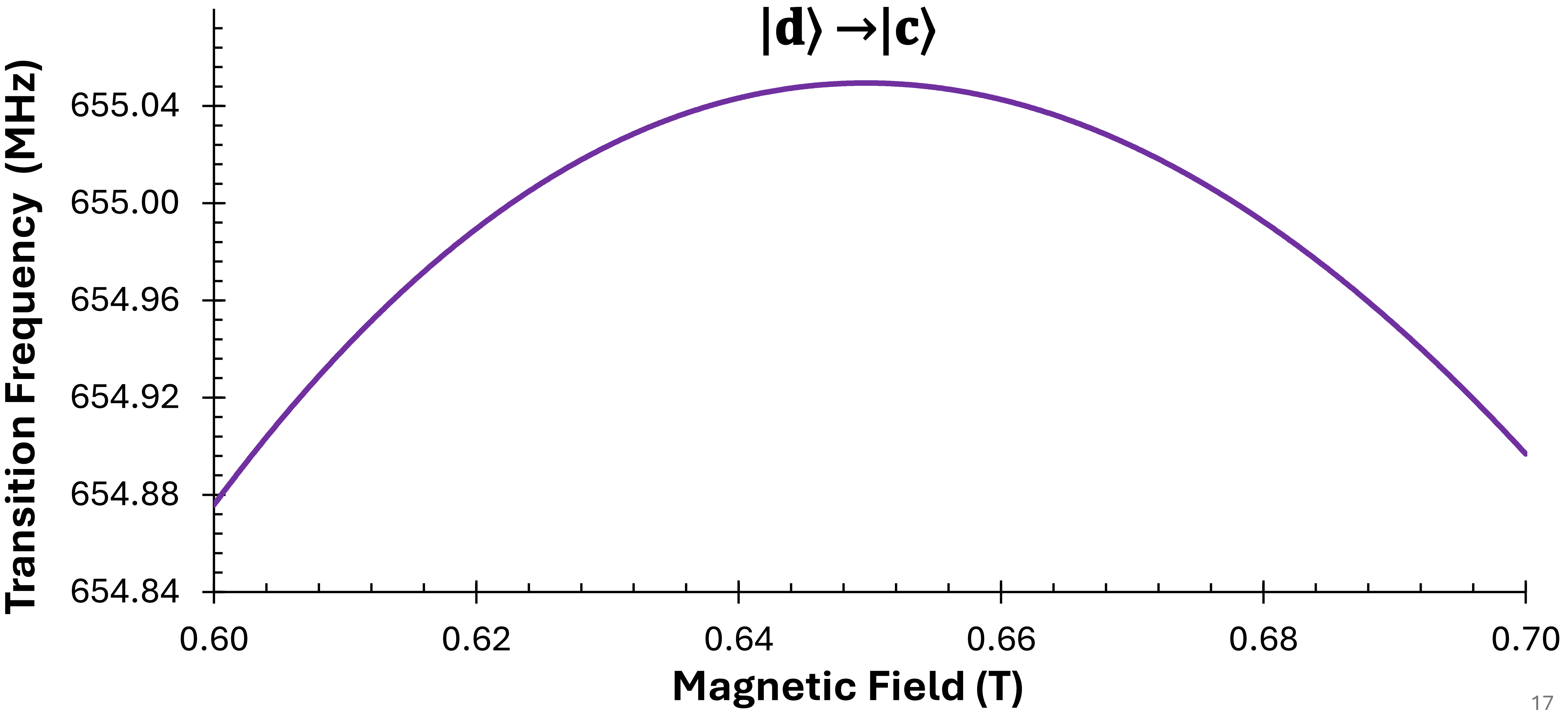


ALPHA Collaboration, **Nature**, 2026

Ground State Hyperfine Structure



NMR-type Transition



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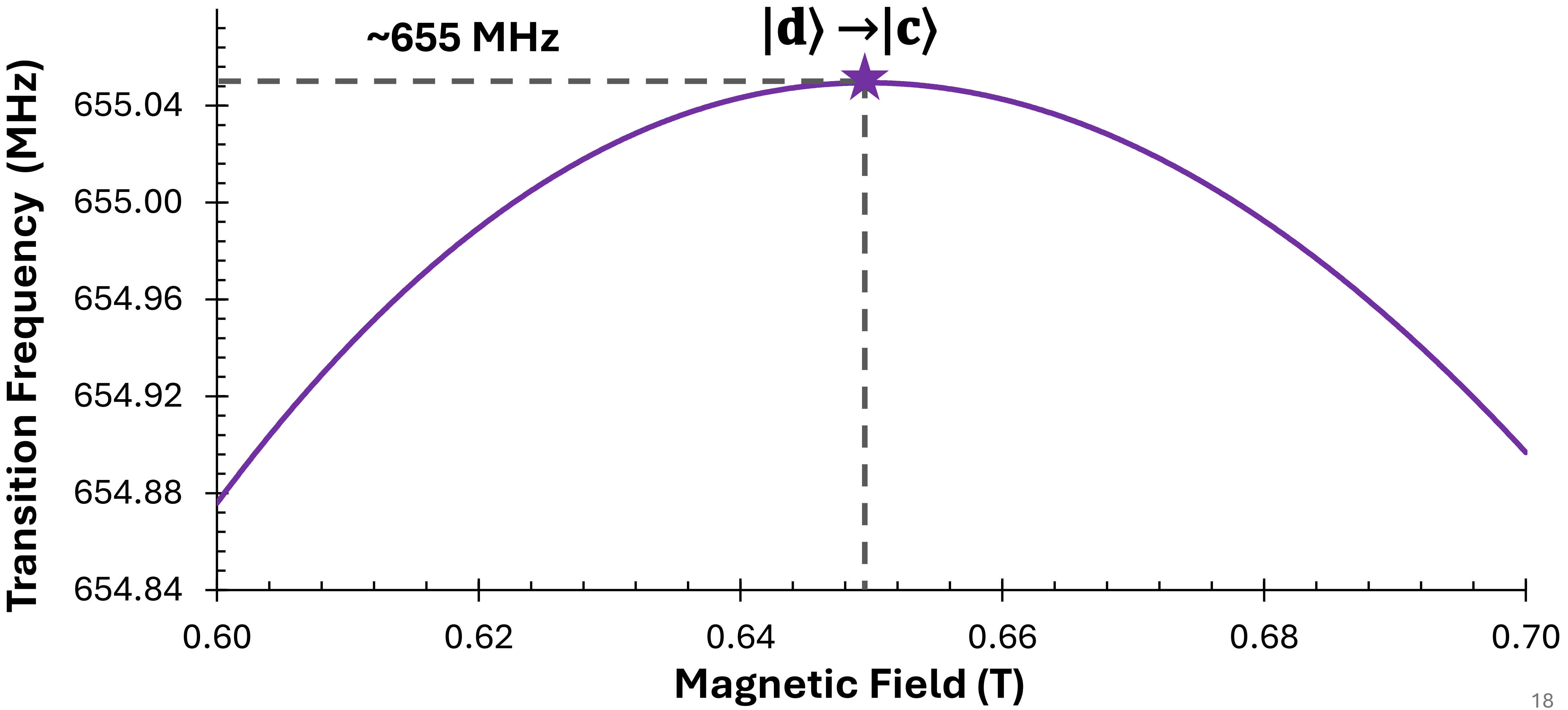
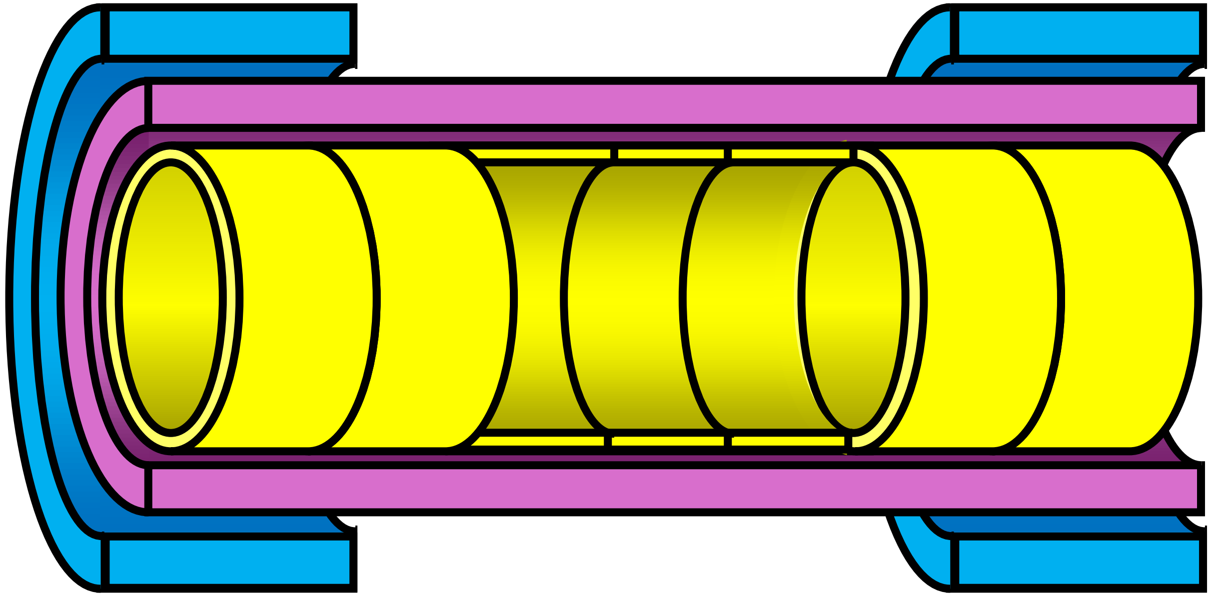


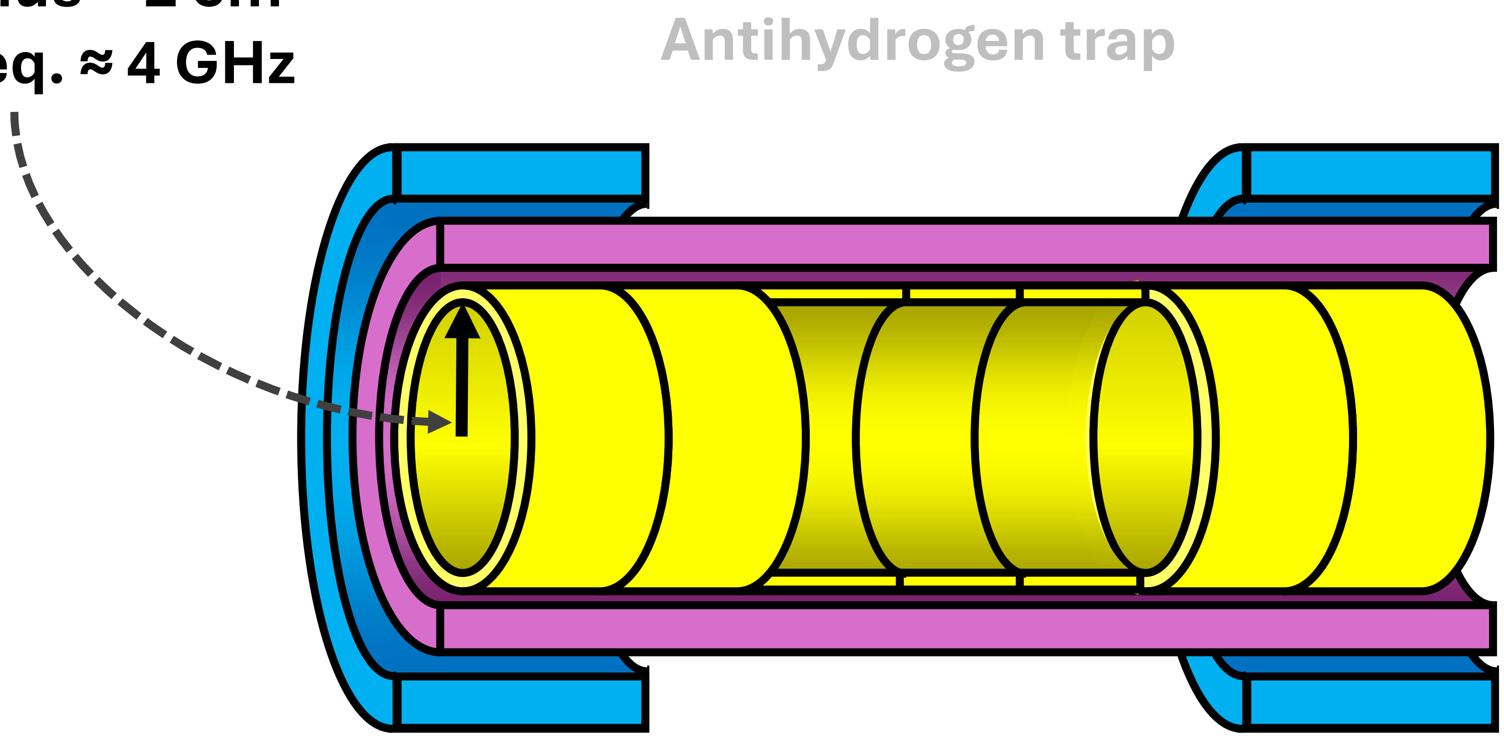
Cutoff Frequency Problem

Antihydrogen trap



Cutoff Frequency Problem

Trap Radius ≈ 2 cm
Cutoff freq. ≈ 4 GHz



Cutoff Frequency Problem

Trap Radius ≈ 2 cm
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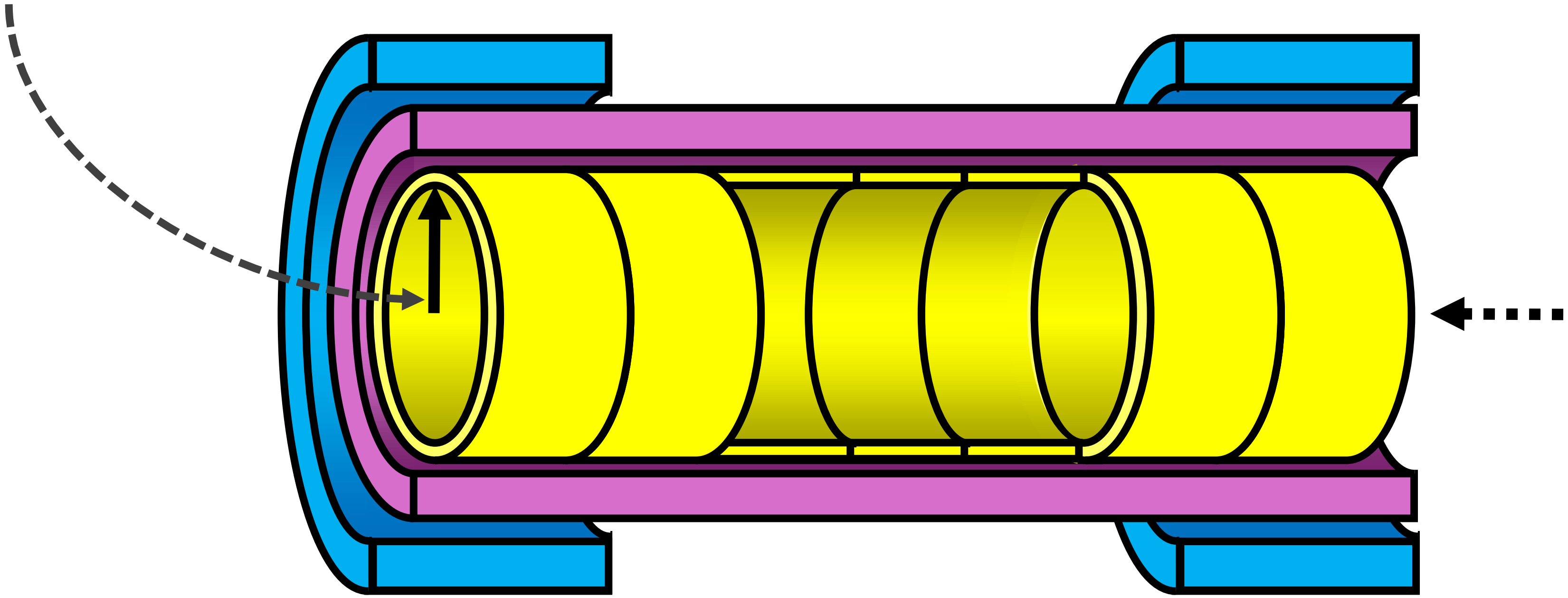
Antihydrogen trap

NMR Transition (655 MHz, λ ≈ 46 cm)



655 MHz

Cutoff Frequency Problem

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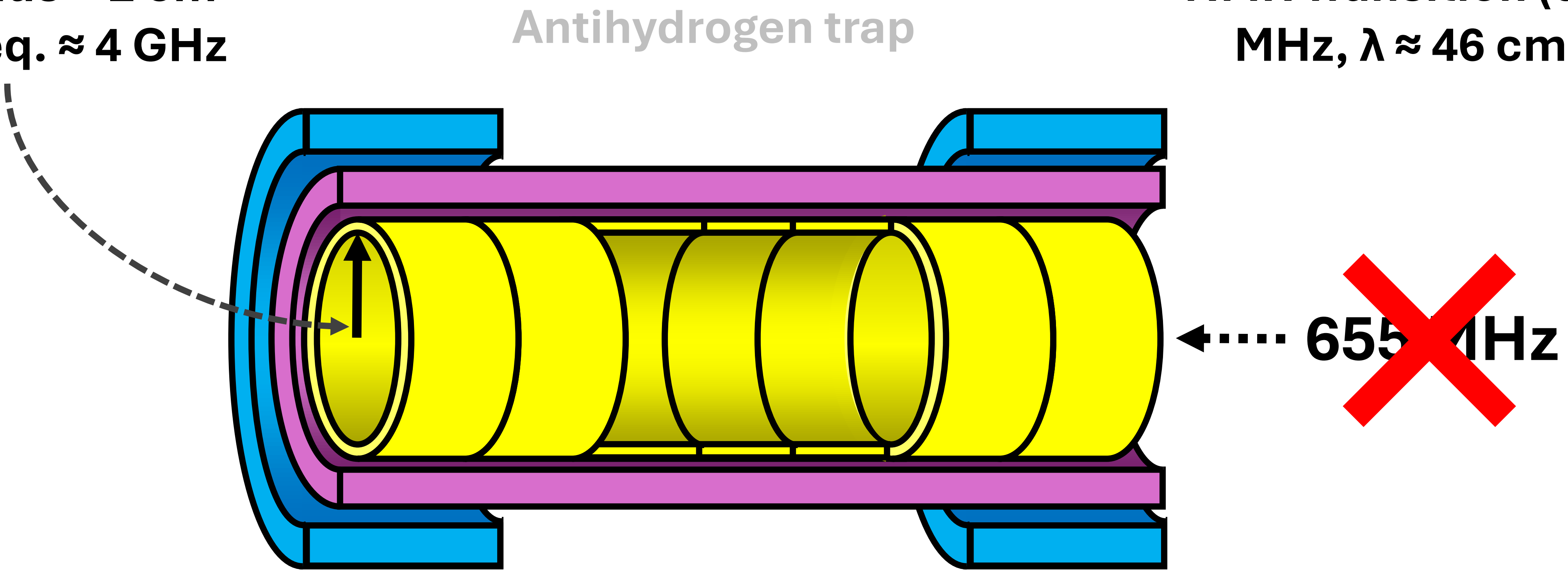
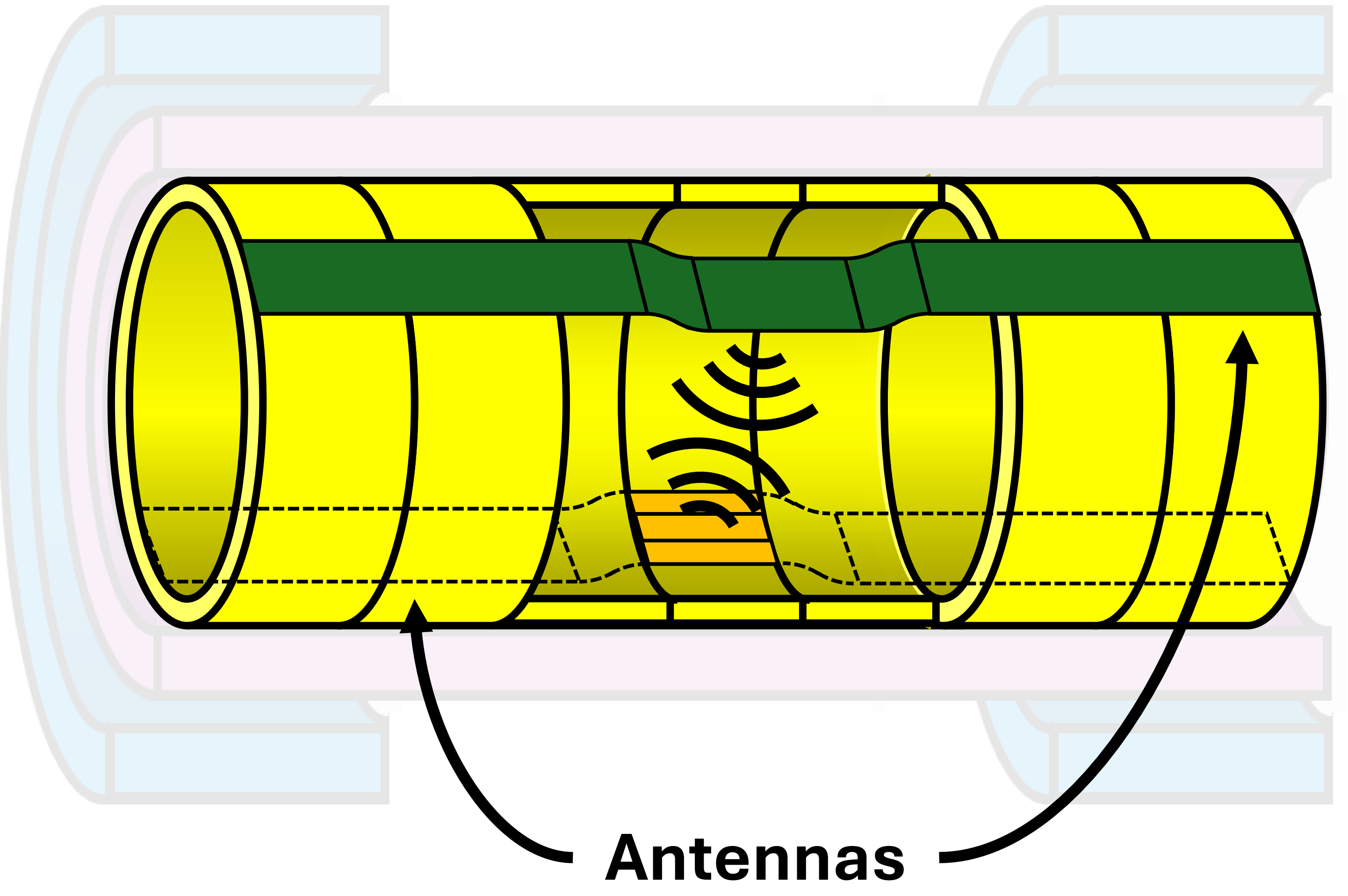


NMR Experiment Design

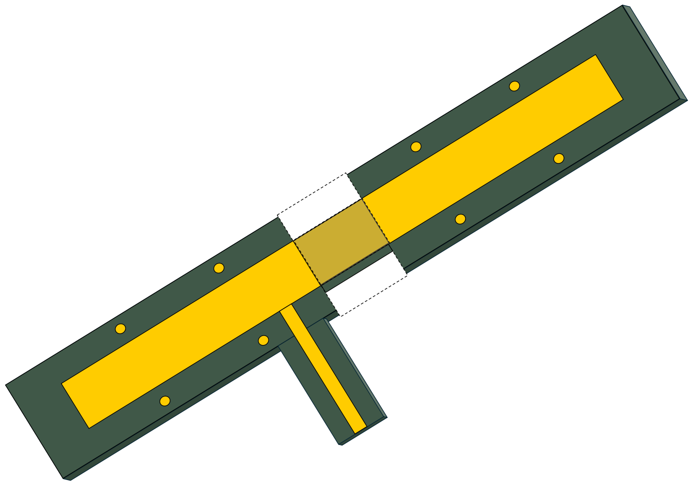
New System:

- Two resonator antennas to inject 655 MHz waves
- Made using ultrathin, cryogenic compatible, flexible PCBs
- Pushing design to manufacturable limits (beyond typical RF solutions)



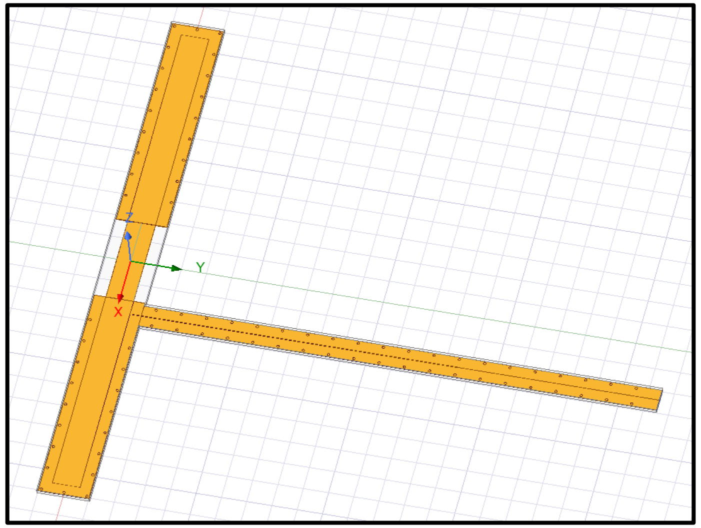
How does the design process work?

Step 1: Propose a design



Design based on theory and objectives

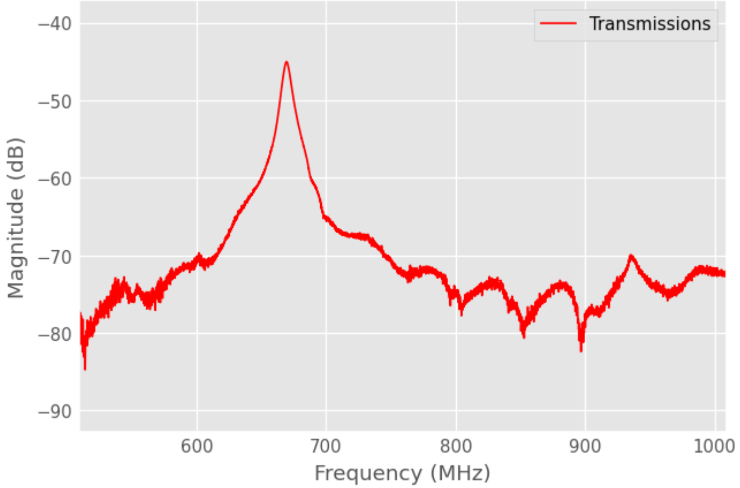
Step 2: Simulate



Ansys / HFSS

Simulate using HF EM modelling software

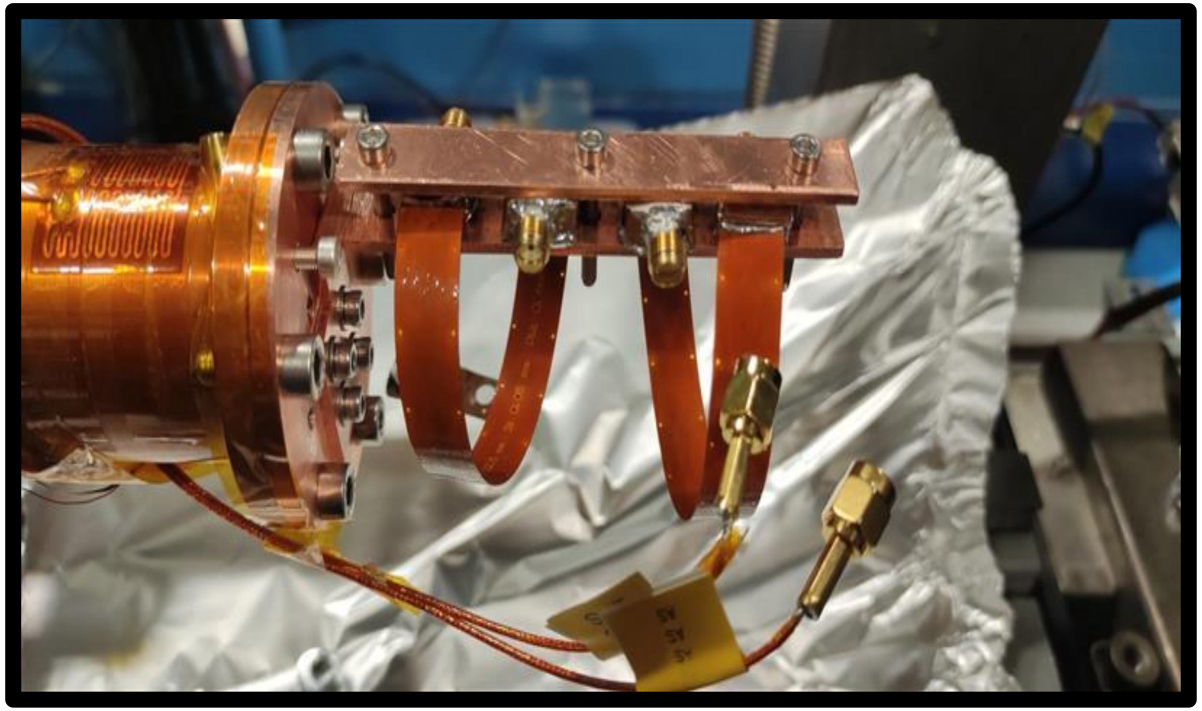
Step 3: Produce and measure

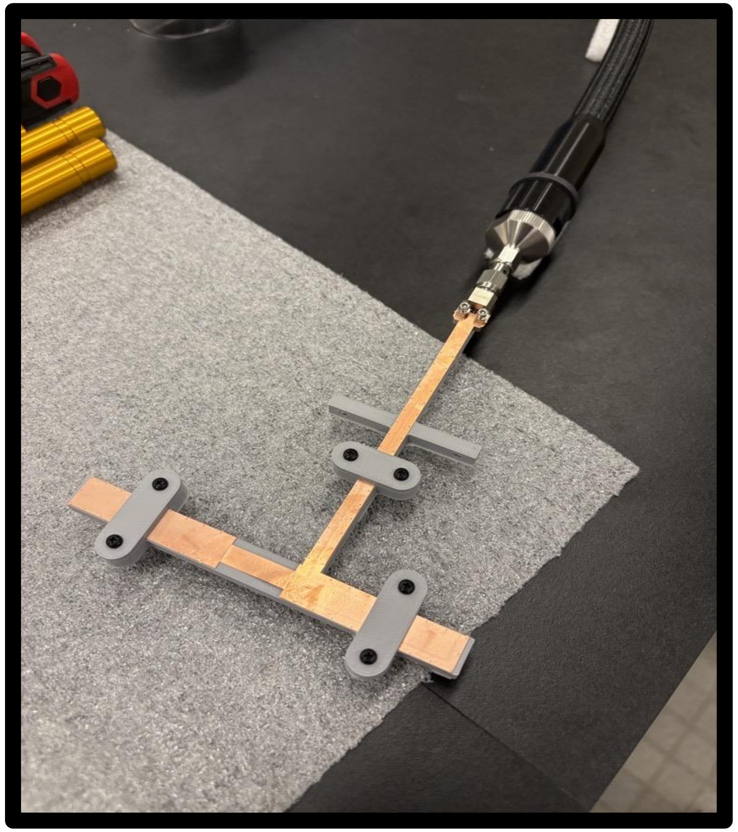


Measure the electronic properties of interest

NMR Test Resonators

Need to prototype circuits to inform the antenna design



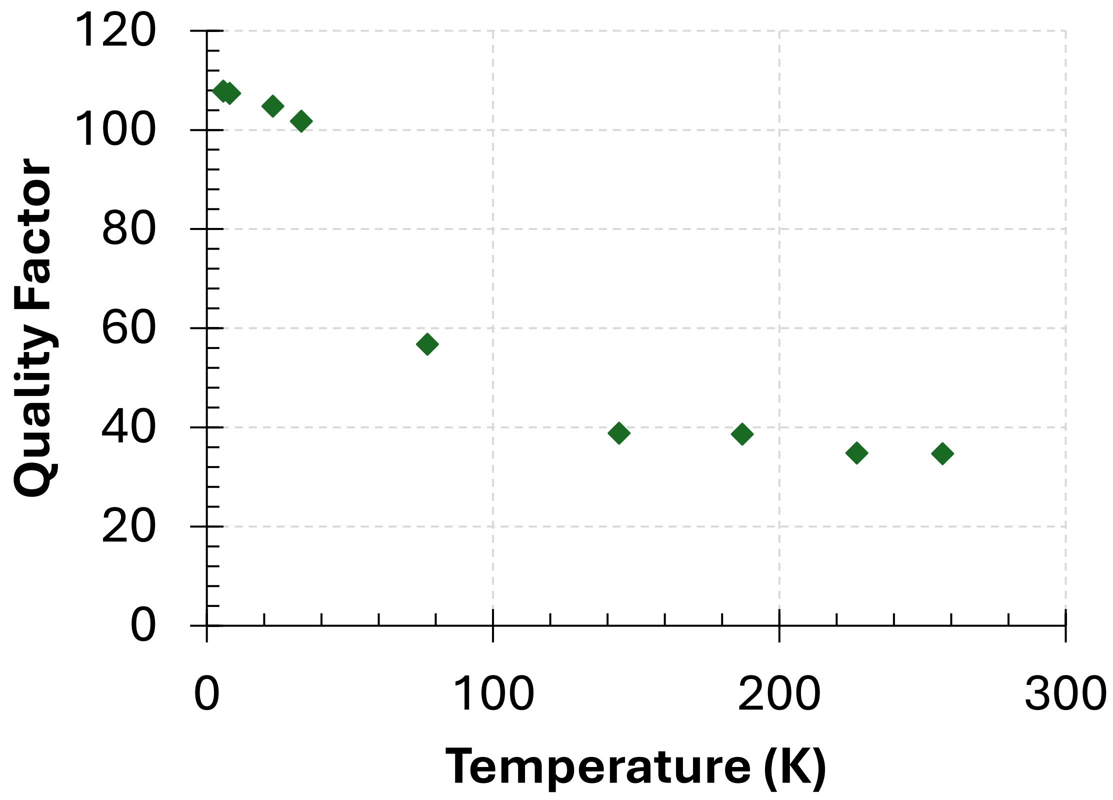


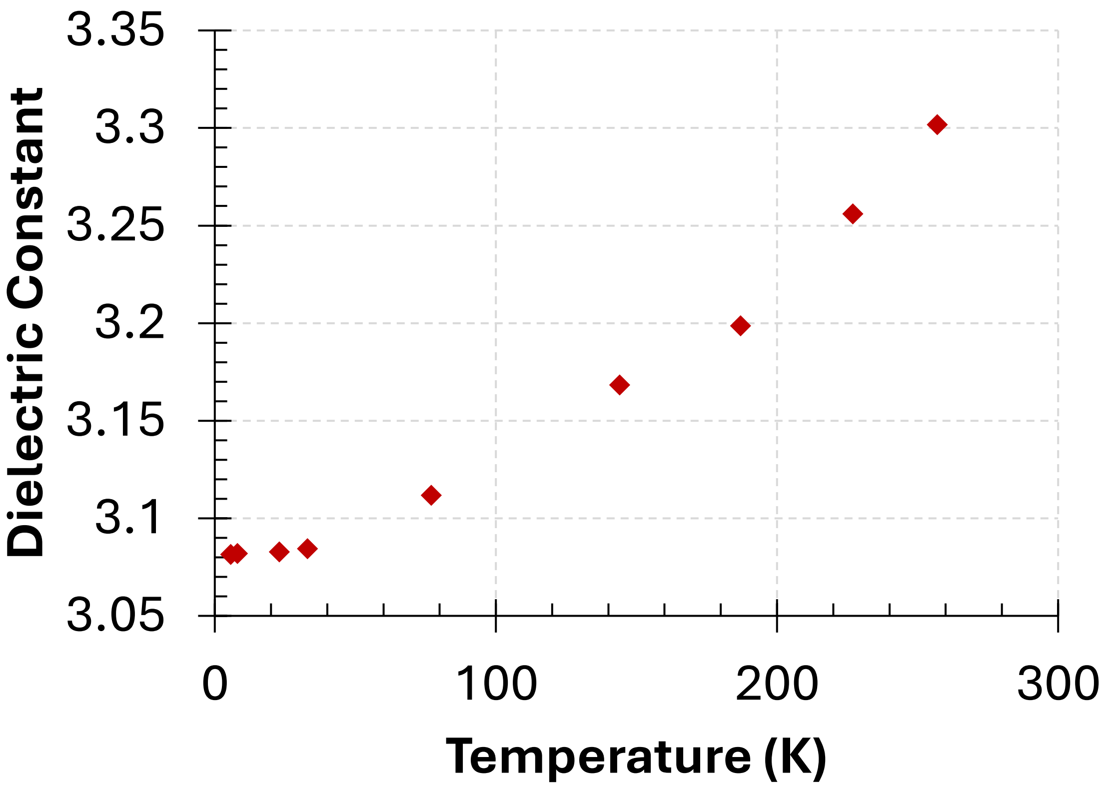
Two Test Resonator Circuits

Courtesy of Alberto Jesus Uribe Jimenez

NMR Test Resonators

First set of test resonators to measure temp. dependence

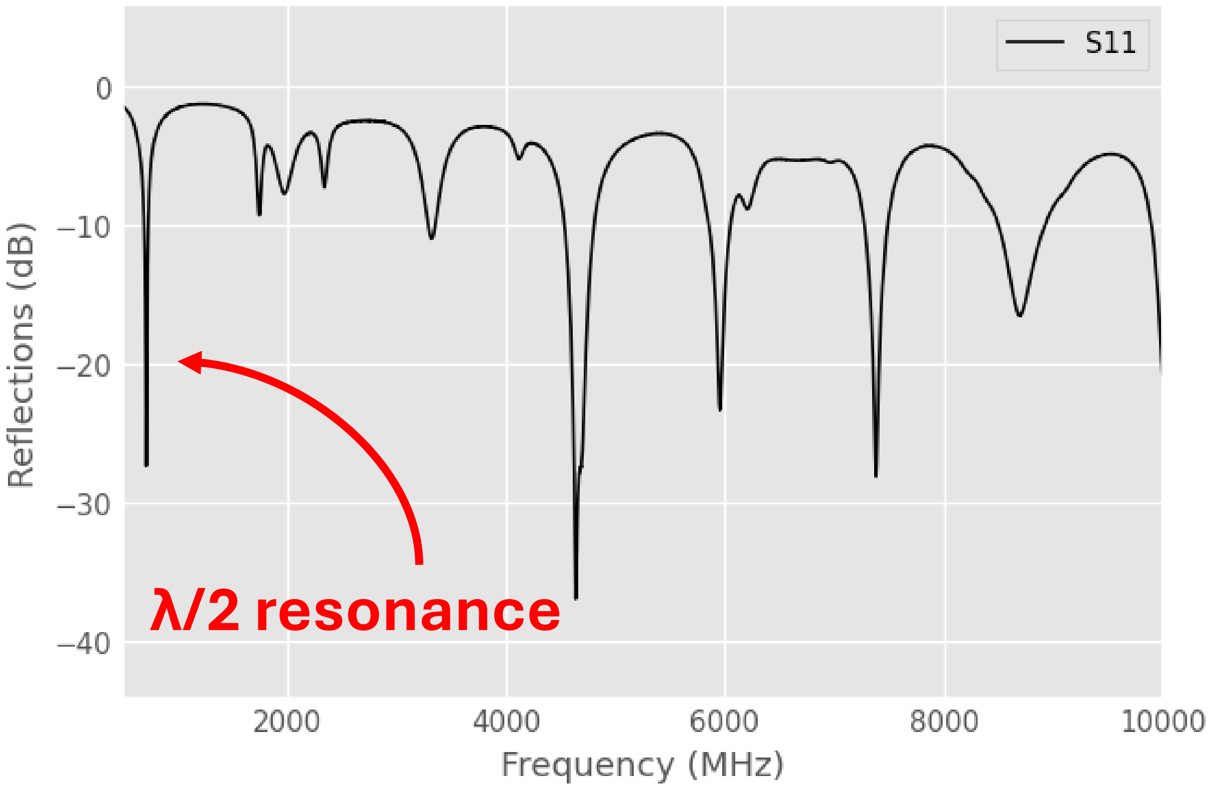




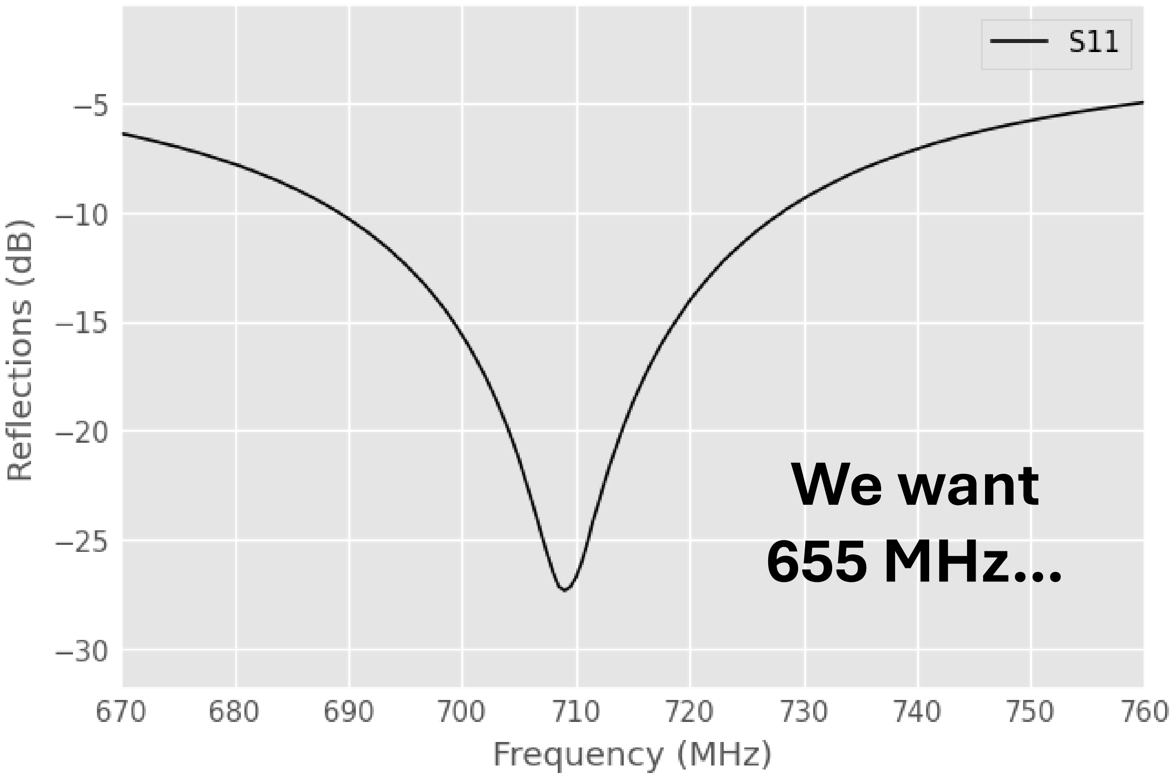
NMR Test Resonators

The most recent set of prototyped circuits:

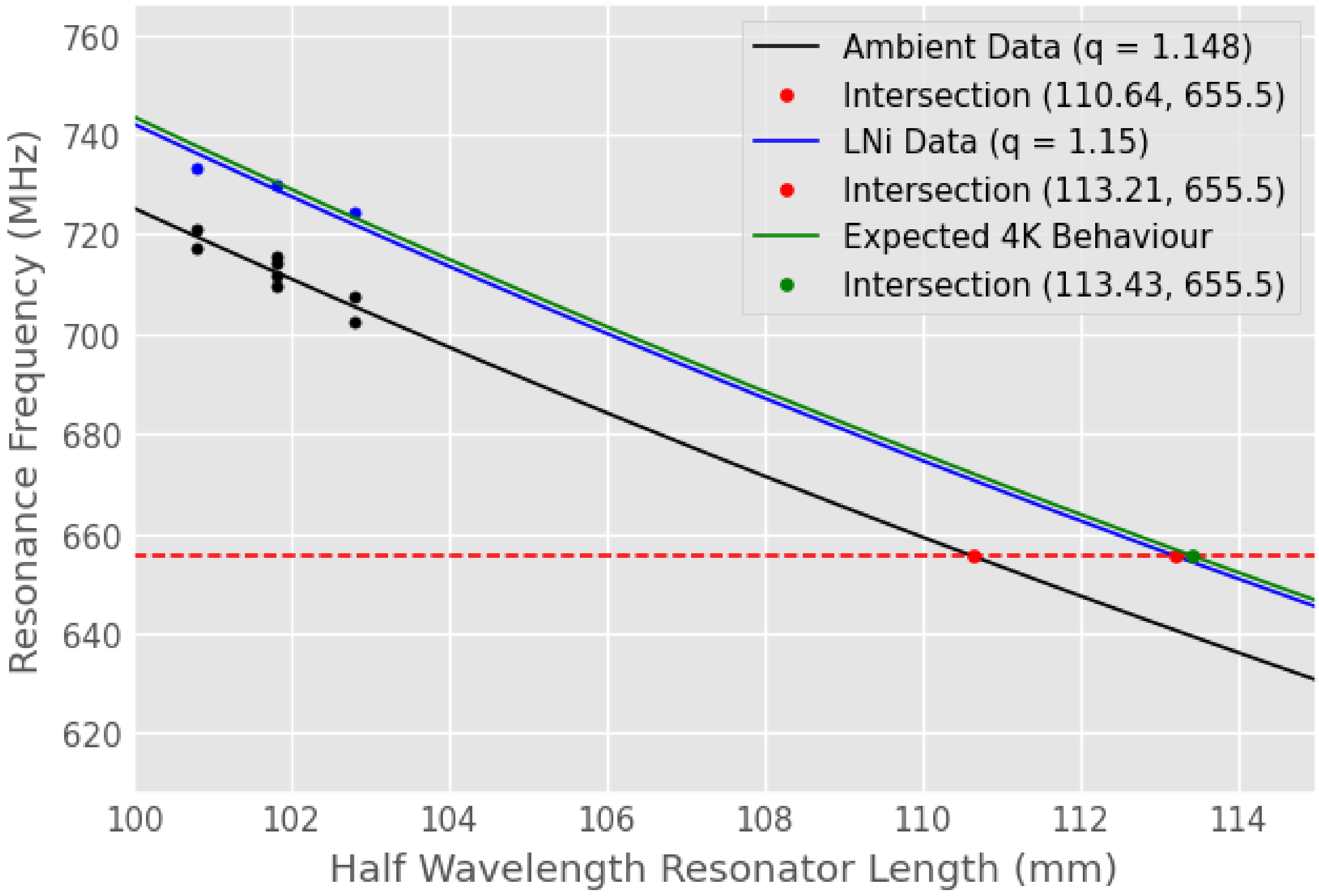
Reflection Spectrum



Around Resonance



NMR Test Resonators

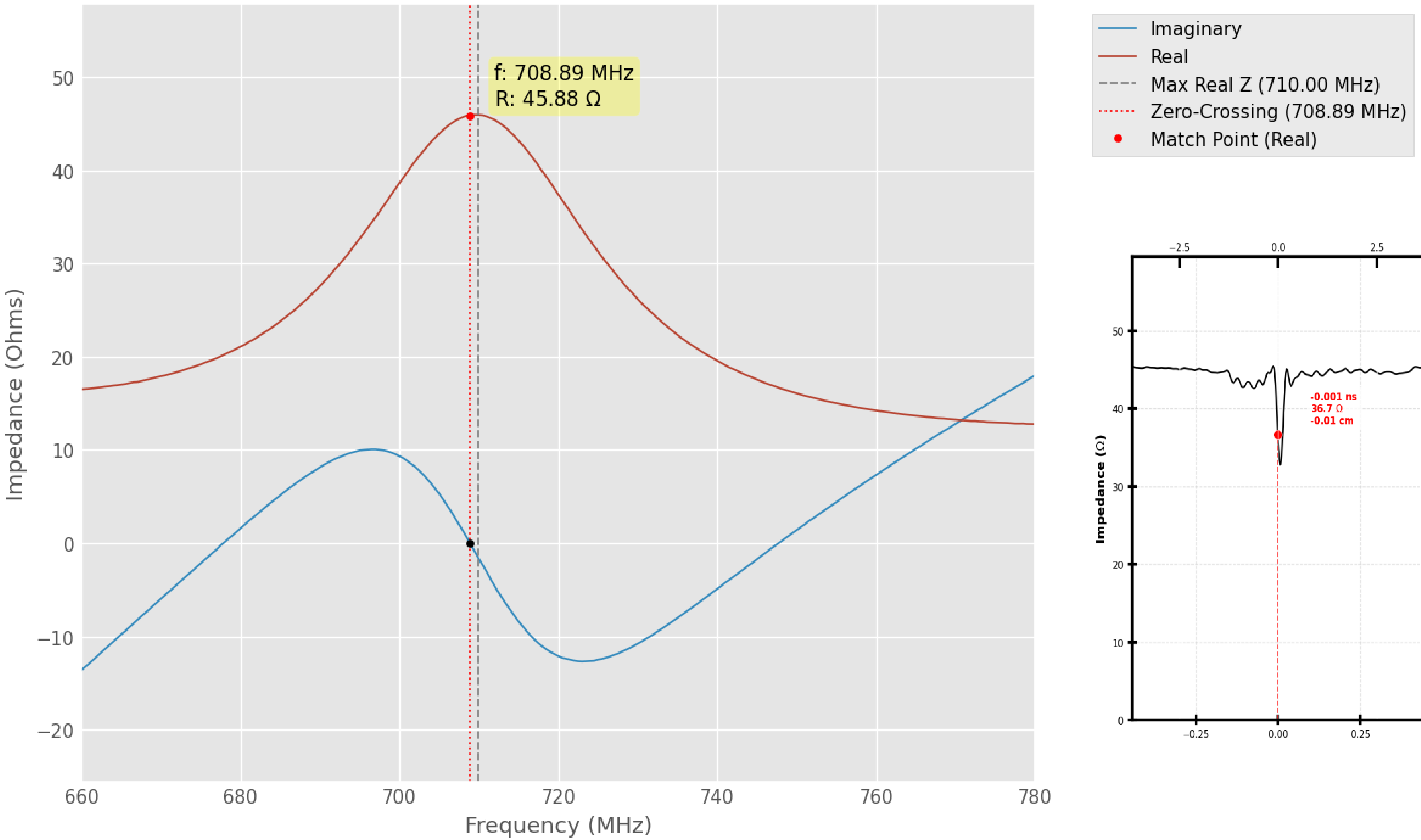


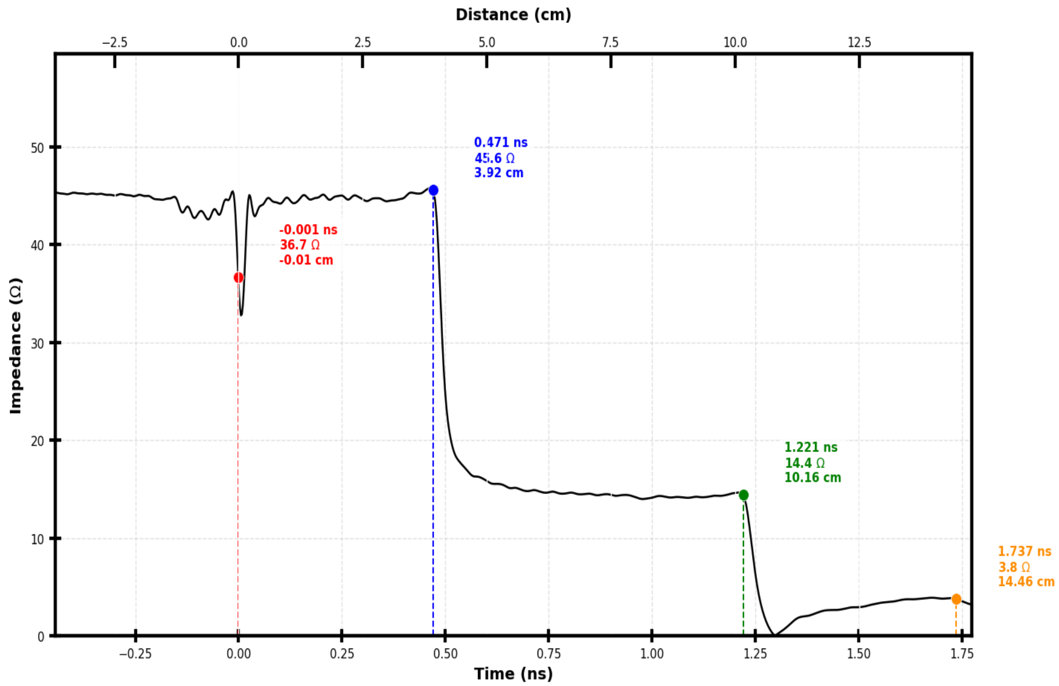
Define an effective length parameter (q) to fit data to theory

↓

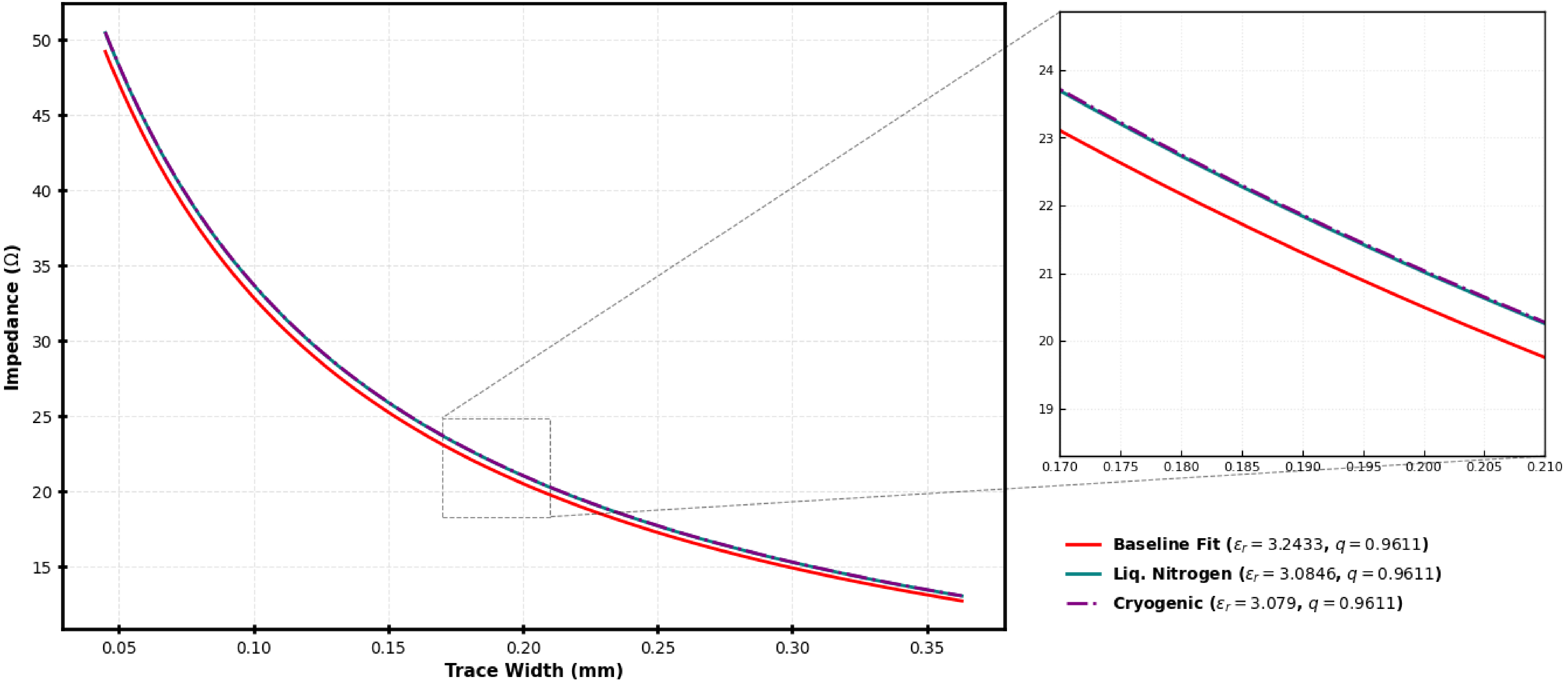
Use this fit to find an experimental half resonance length

NMR Test Resonators



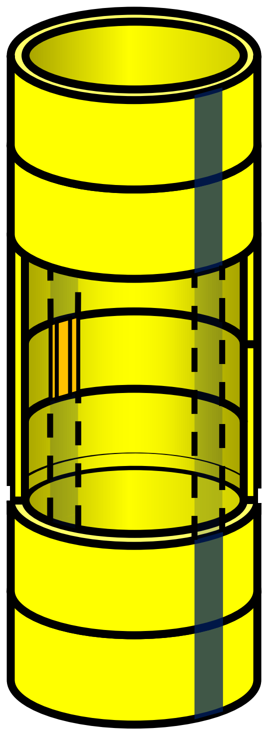


NMR Test Resonators



Summary and Outlook

- **NMR Spectroscopy:** developing a new method to investigate an unprobed feature of antihydrogen, with the potential for high precision.
- **Test Resonators:** producing and analyzing 'test' resonators to inform key components of the design
- **Final Design:** prototype tests have given required information to complete a 'real' design to be implemented at ALPHA

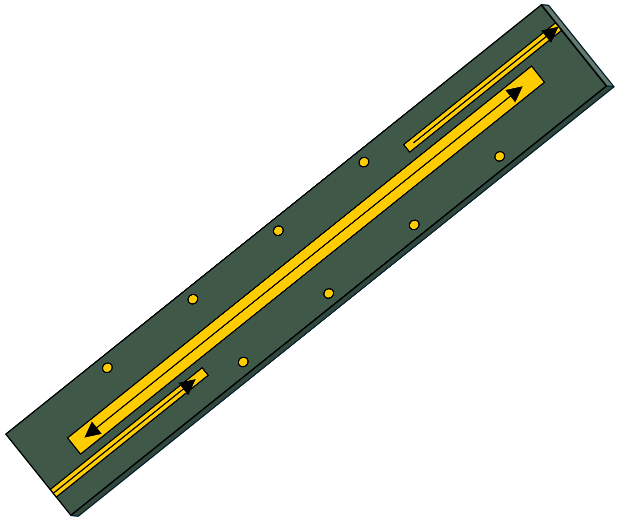


NMR Experiment

Supplemental Slides

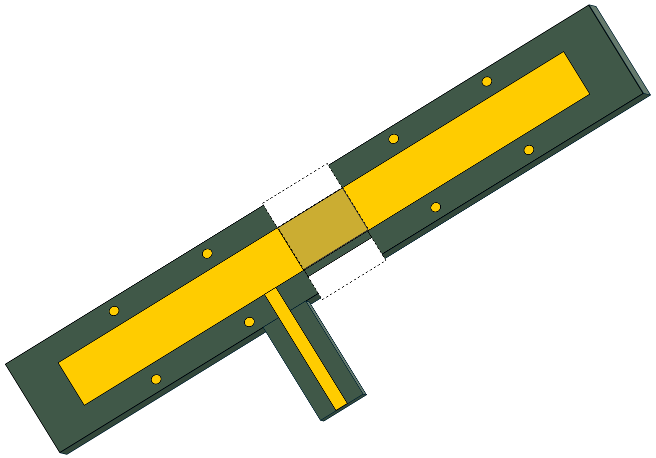
Highlights on some progress

Dielectric
test circuits



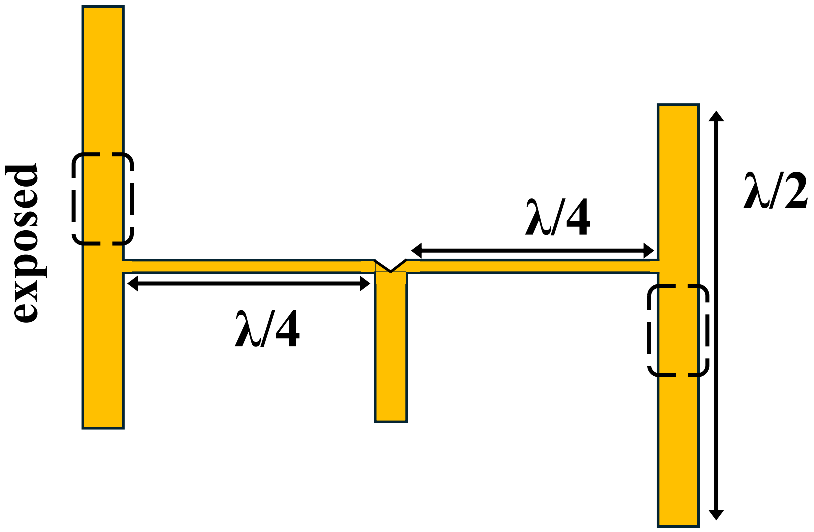
Designed, simulated,
and measured

Impedance matched
test circuits



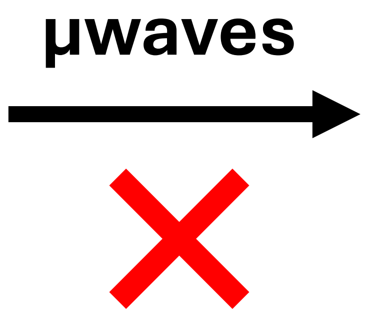
Designed, simulated,
analysis in progress

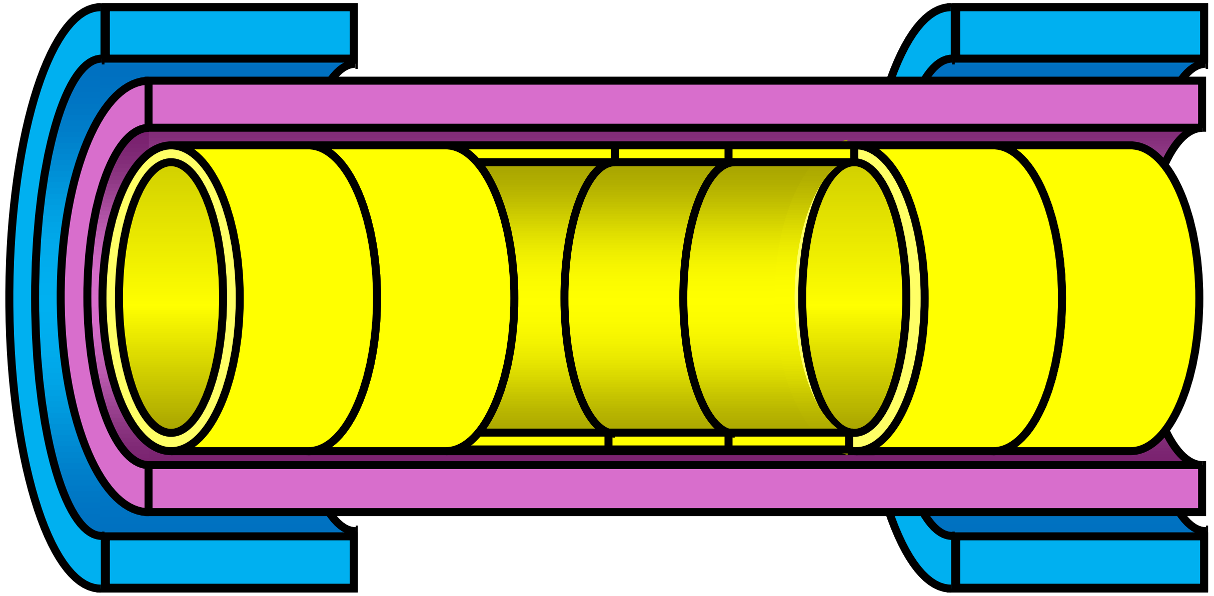
Full circuit designs



In the process of
design + simulation

NMR Experiment Design





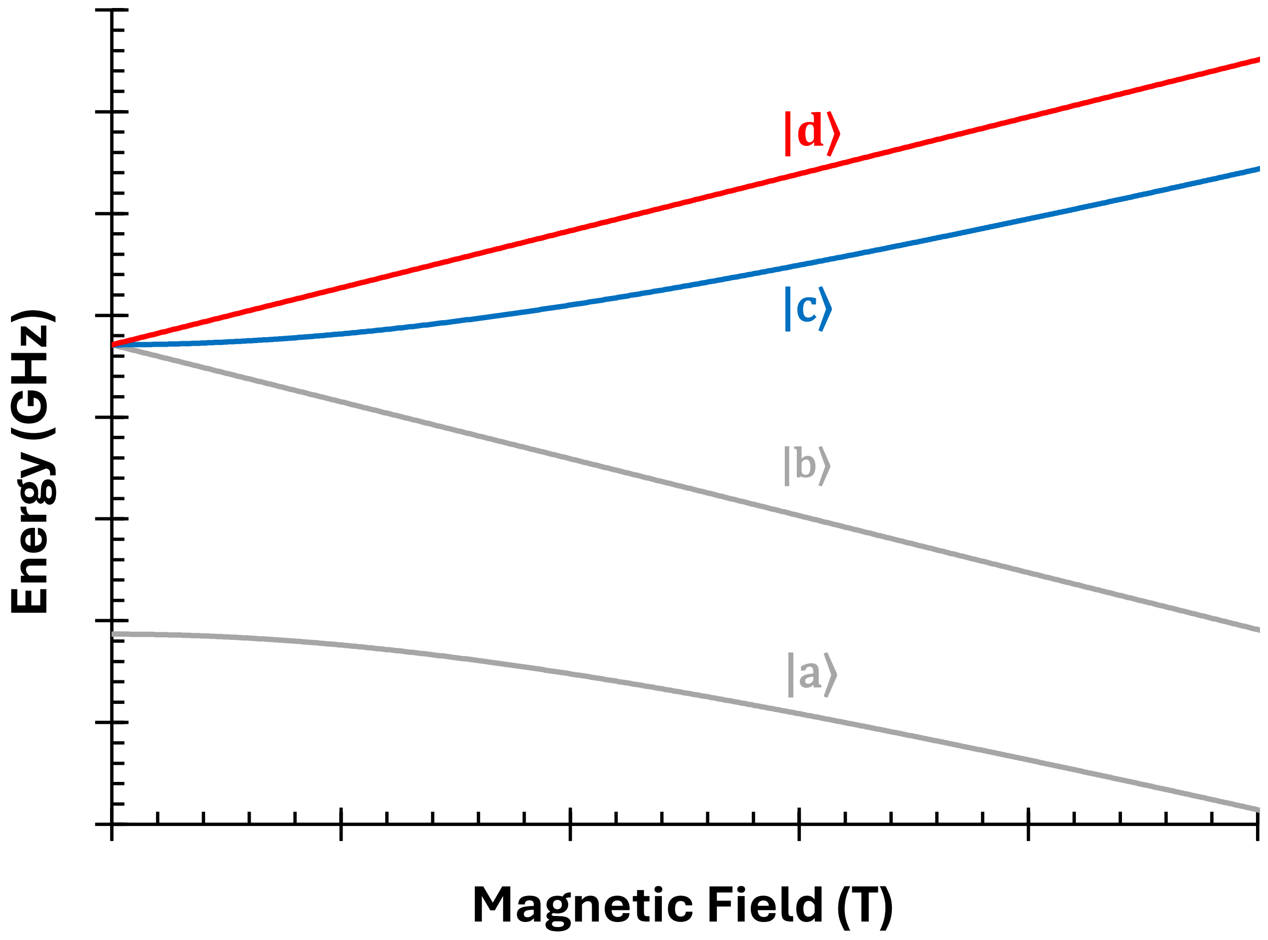
Cannot inject 655 MHz wave axially

ALPHA Trap

Develop a **new microwave injection** system

NMR Experiment Protocol

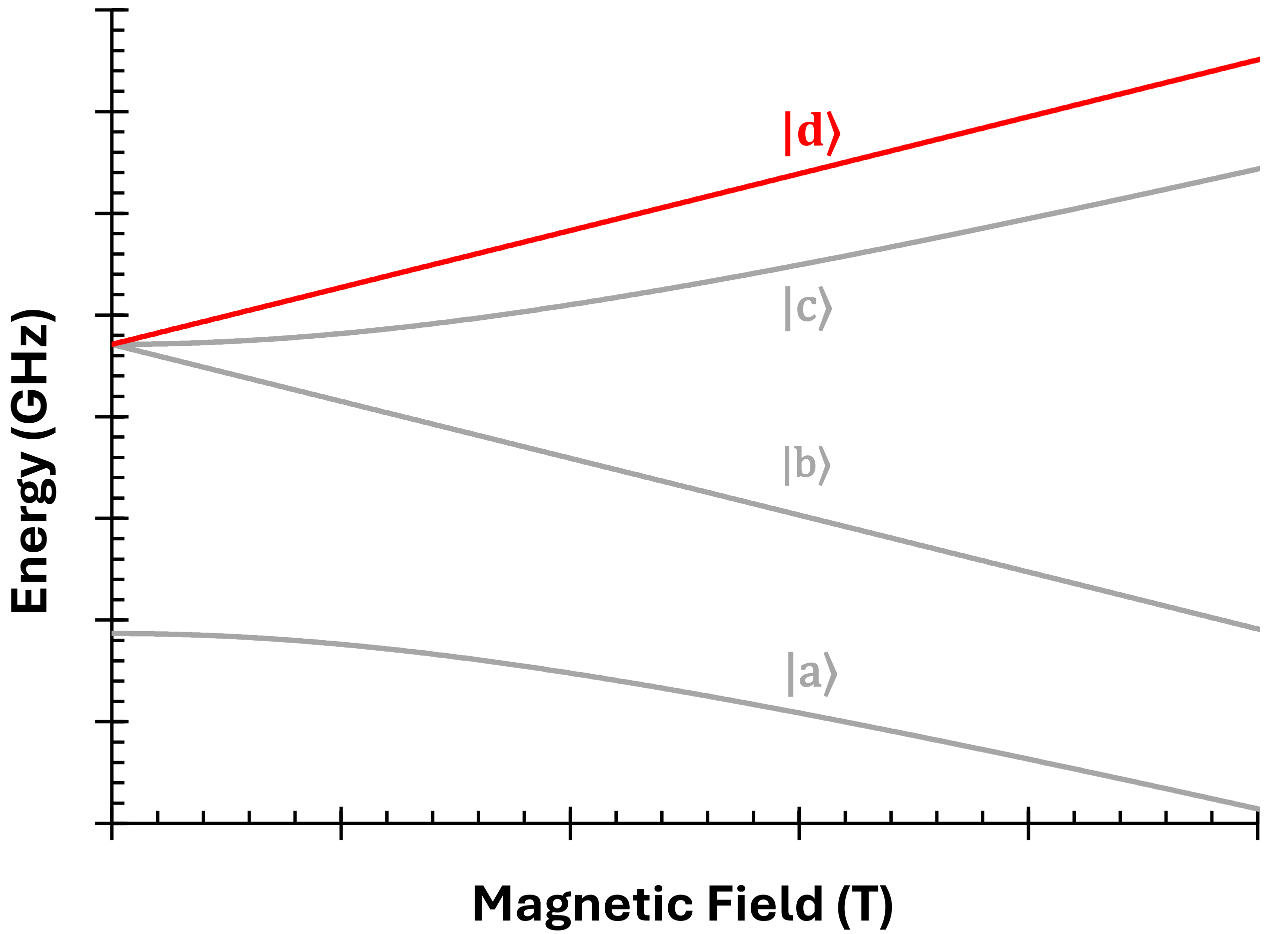
1. Prepare antihydrogen atoms in the $|c\rangle$ and $|d\rangle$ states



NMR Experiment Protocol

1. Prepare antihydrogen atoms in the |c⟩ and |d⟩ states

2. **Empty the |c⟩ state atoms**



NMR Experiment Protocol

1. Prepare antihydrogen atoms in the |c⟩ and |d⟩ states

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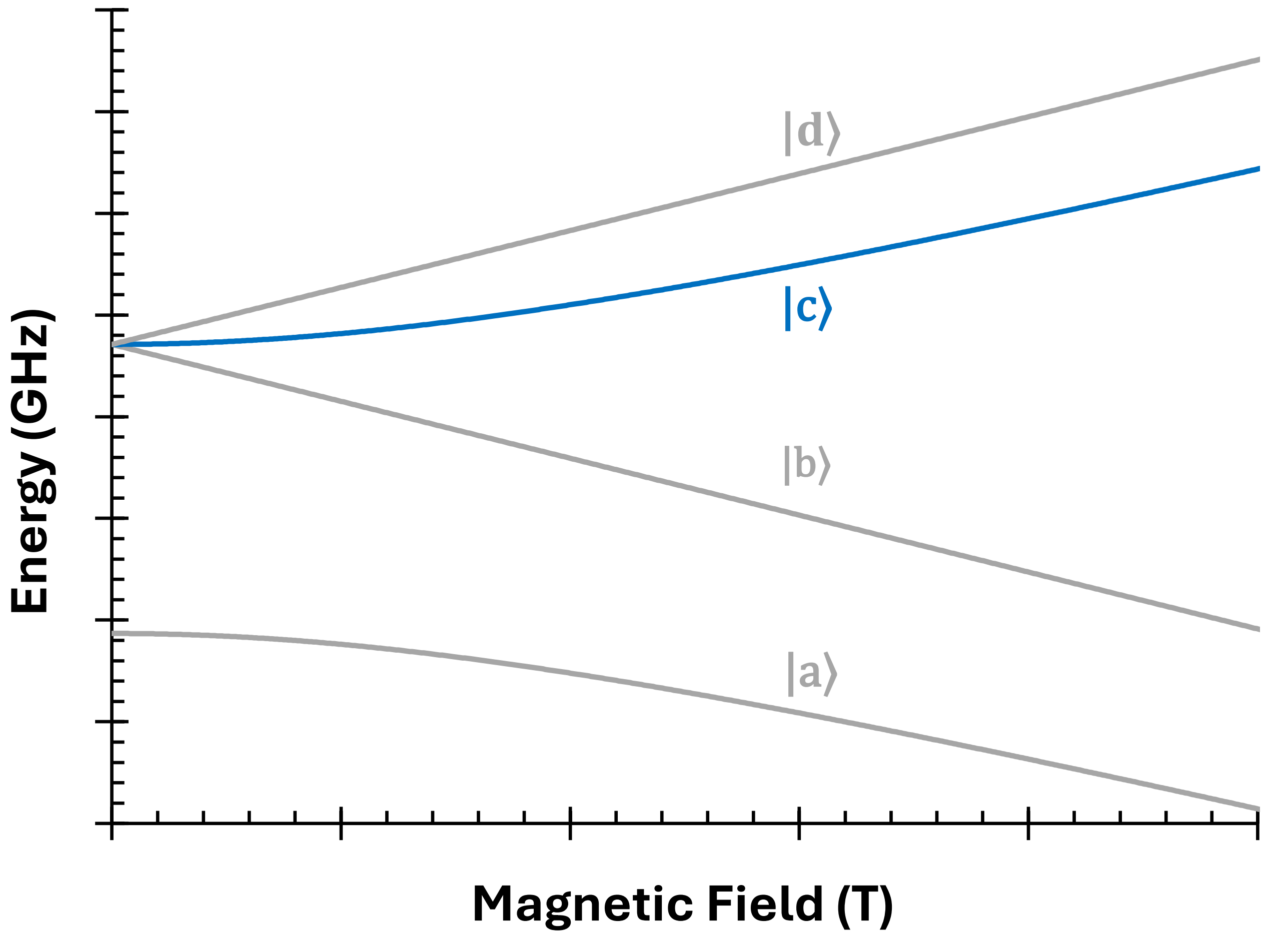
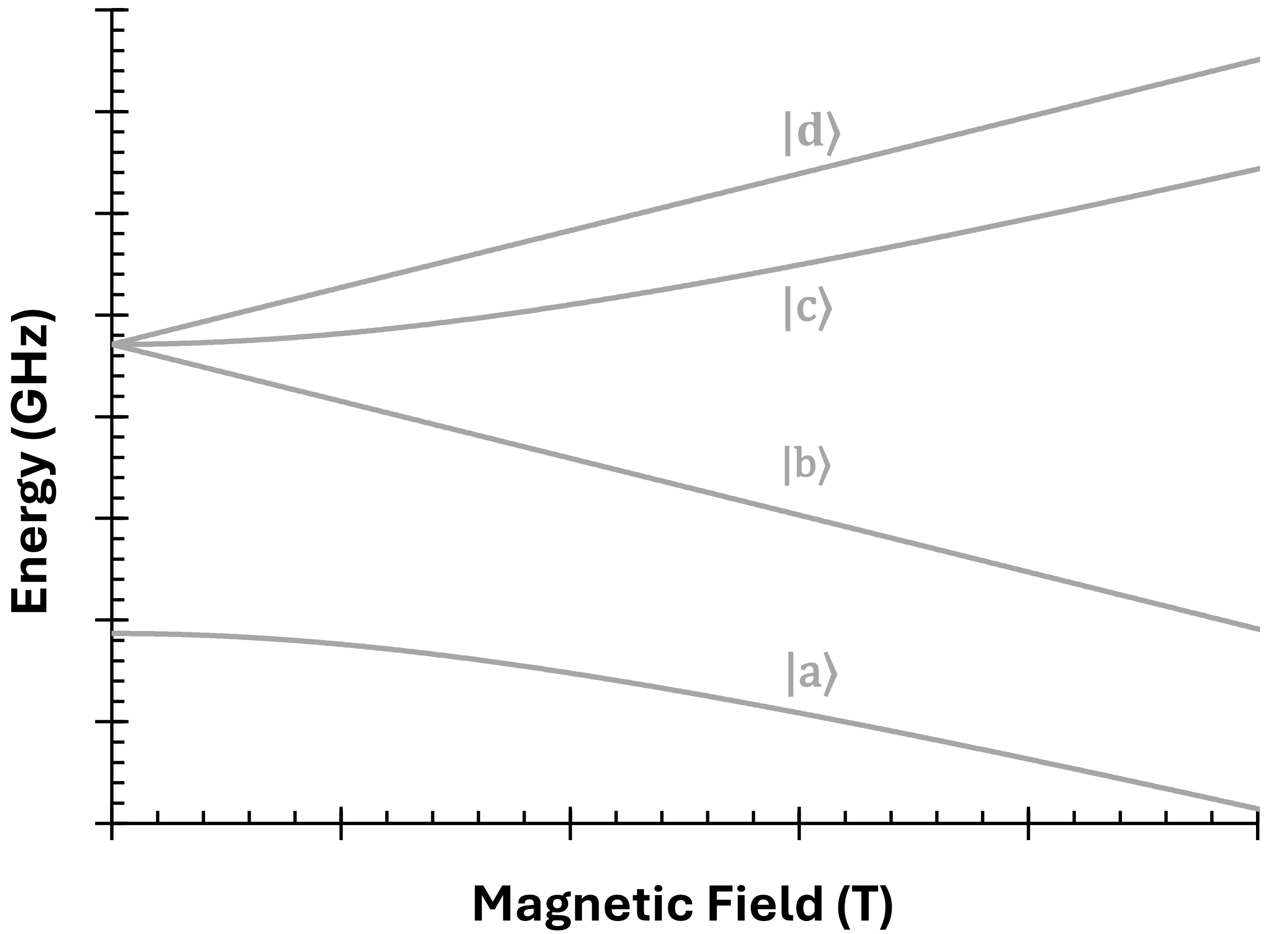
3. **Induce the |d⟩ to |c⟩ (NMR) transition**



NMR Experiment Protocol

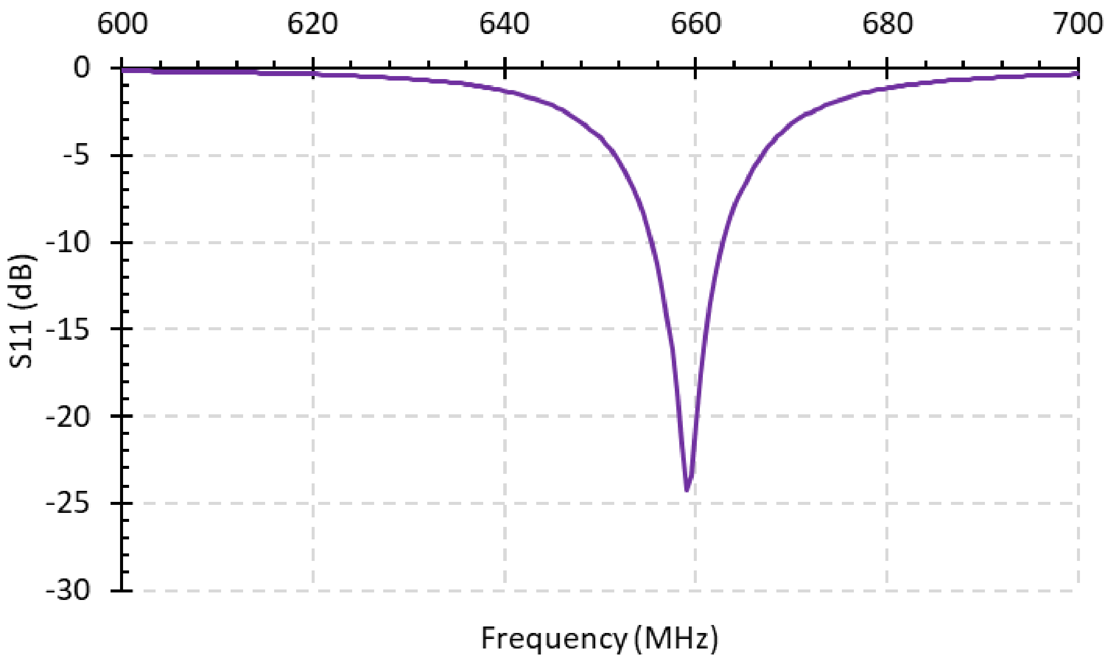
1. Prepare antihydrogen atoms in the |c⟩ and |d⟩ states
2. Empty the |c⟩ state atoms
3. Induce the |c⟩ to |d⟩ (NMR) transition
4. **Empty the |c⟩ state atoms again and observe the counts**



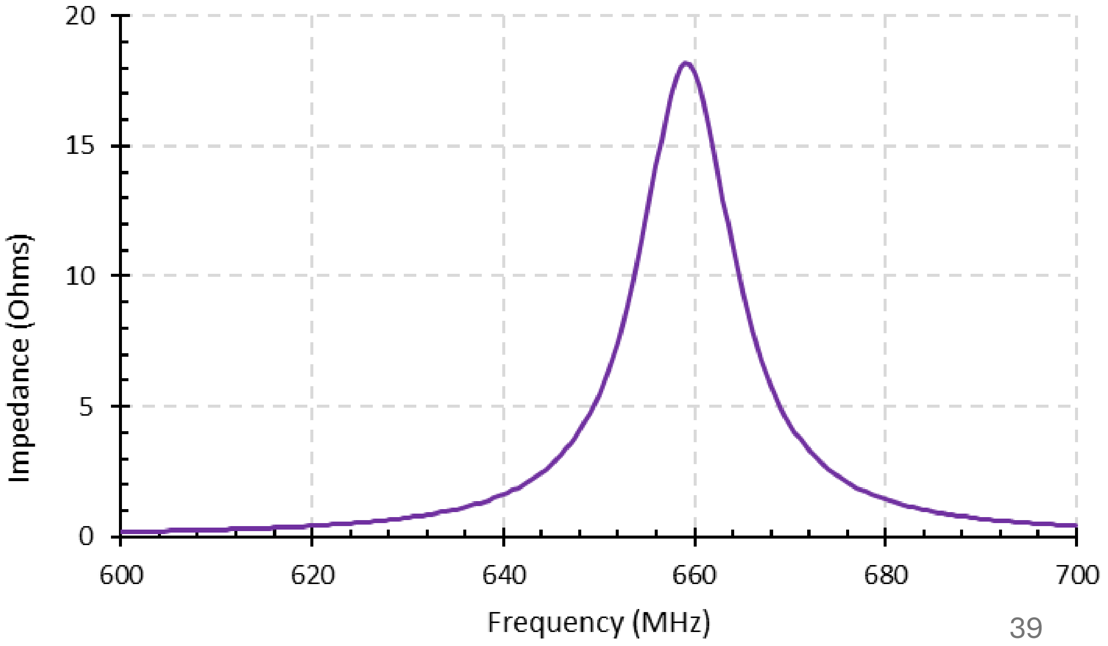
NMR Antenna Simulation Data

Use an electromagnetic modelling software (ANSYS HFSS) to design antennas

Reflections



Real Impedance



Attenuation Factor Calculations

$$\alpha = \alpha_c + \alpha_D$$

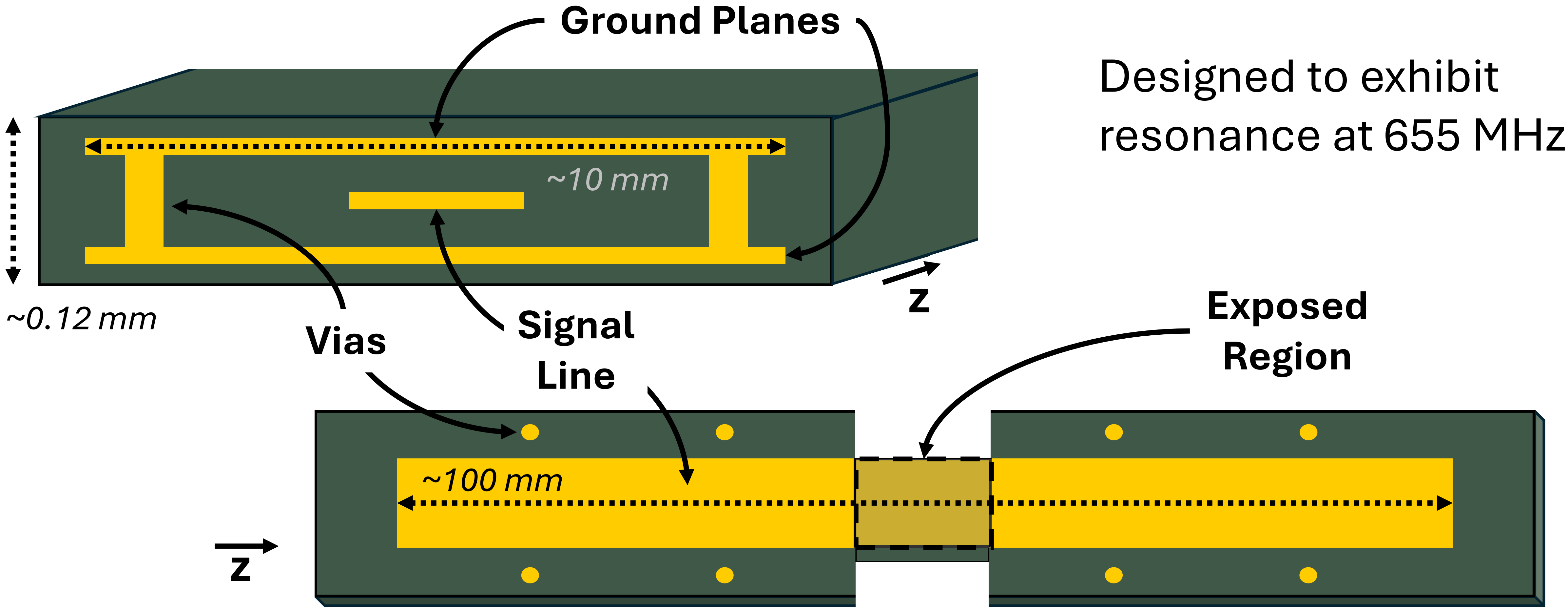
$$\alpha_c = \frac{(2.7 \cdot 10^{-3}) R_S \varepsilon_r Z_0}{30\pi(b - T_R)} A$$

$$R_S = \sqrt{\frac{\mu_0 \pi f}{\sigma}}$$

$$\alpha_D = \frac{\pi\sqrt{\varepsilon_r}\tan\delta f}{c}$$

$$\alpha = \frac{\pi}{2LQ_0}$$

What do these circuits look like?

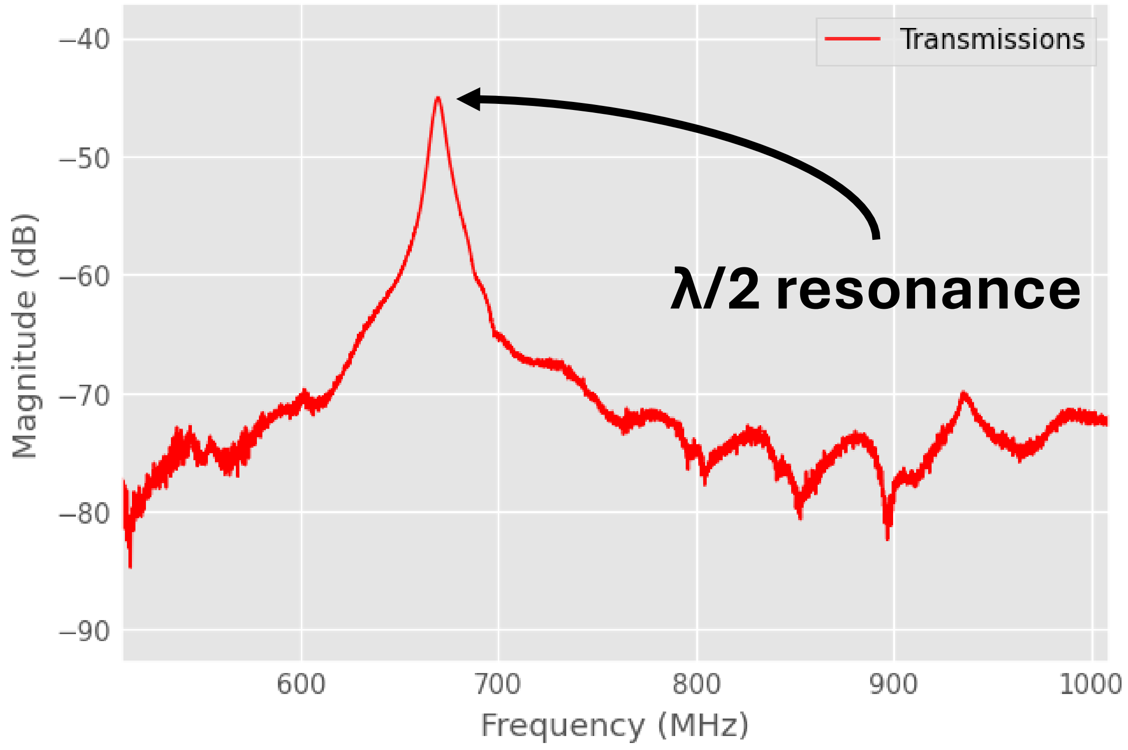


Designed to exhibit resonance at 655 MHz

Dielectric Temperature Measurements

Operate at ~4 K and ultra-high vacuum, need data at these conditions

Transmission Spectrum

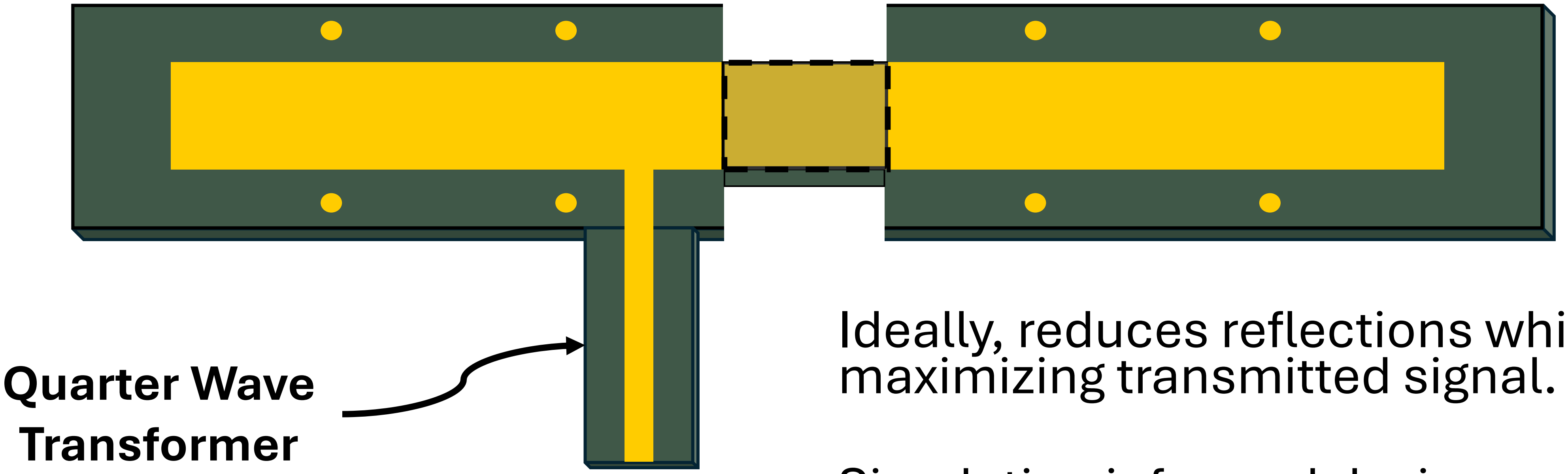


Look at test resonators at low temps for changes:

- **Dielectric** properties
- **Resonance** properties
- **Mechanical** Contraction

Impedance Matched Circuits

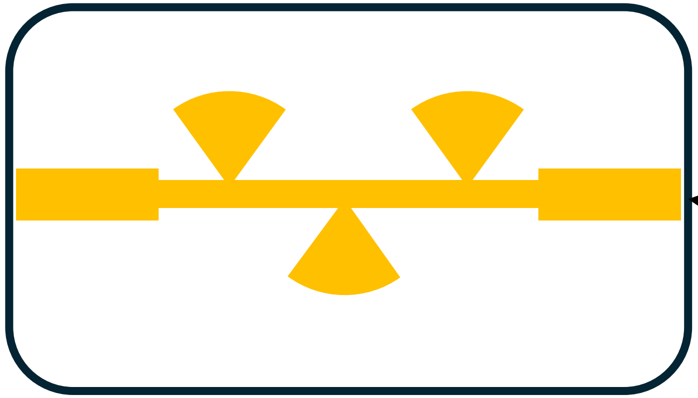
Moving towards circuits with a **‘real’** design, how does enough **power** reach the resonators?



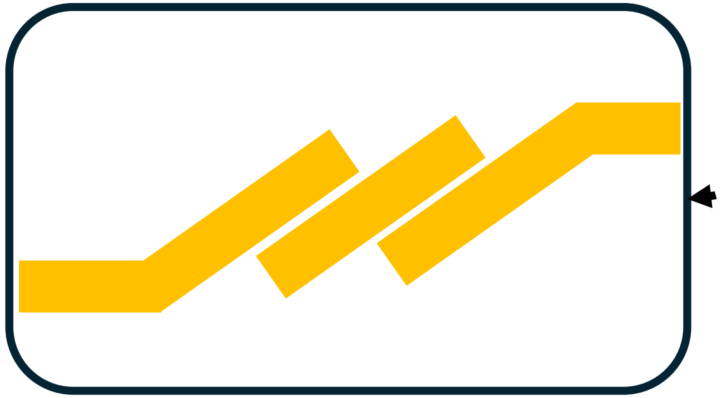
Ideally, reduces reflections while maximizing transmitted signal.

Simulation informed designs were used to produce testable circuits.

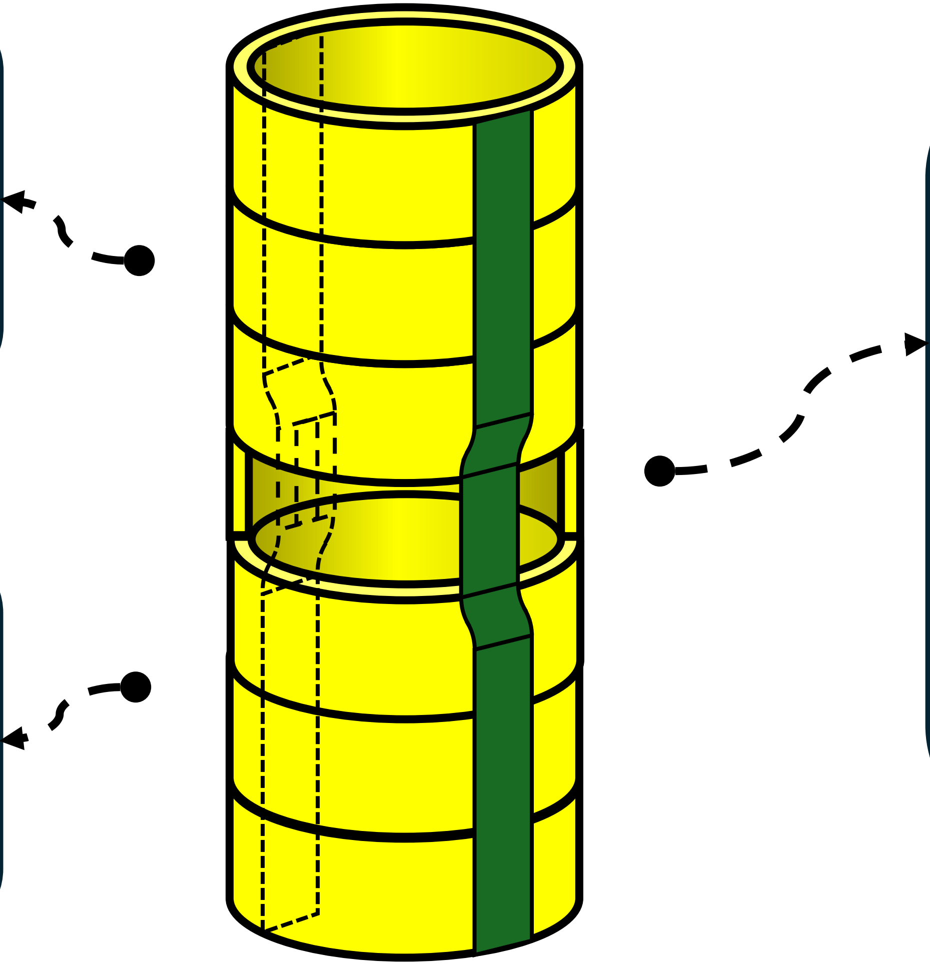
Moving Toward a Full Design



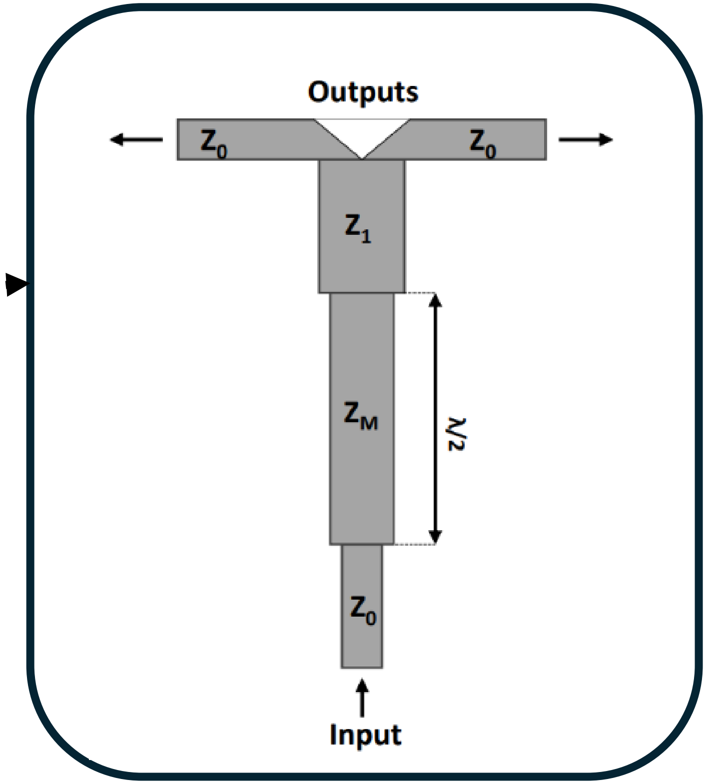
Low pass filter



DC block



Splitting and
phase matching



Test Circuits - Simulations