Magnetometry for Gravitational Measurements of Antihydrogen

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for the ALPHA Collaboration
WNPPC, 2020

Outline

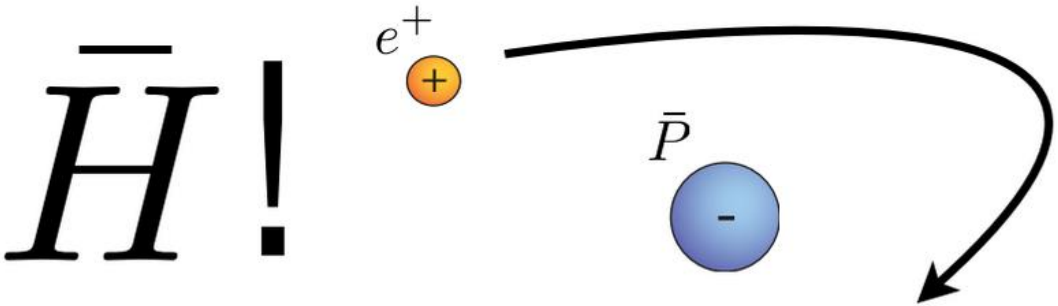
- How to measure the gravitational force on an anti-atom
- Systematic characterization
    - Nuclear Magnetic Resonance (NMR) Magnetometry
- Low temperature NMR challenge

Asymmetry in the Universe

Why study antimatter?

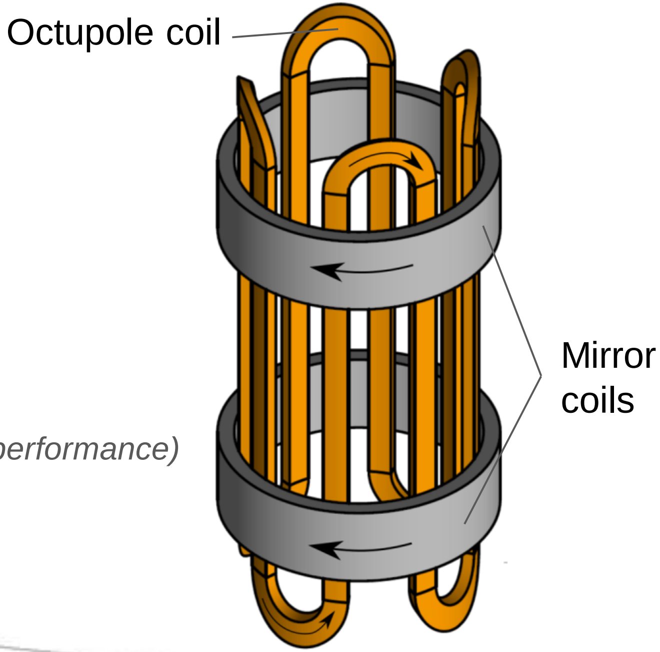
Antihydrogen recipe

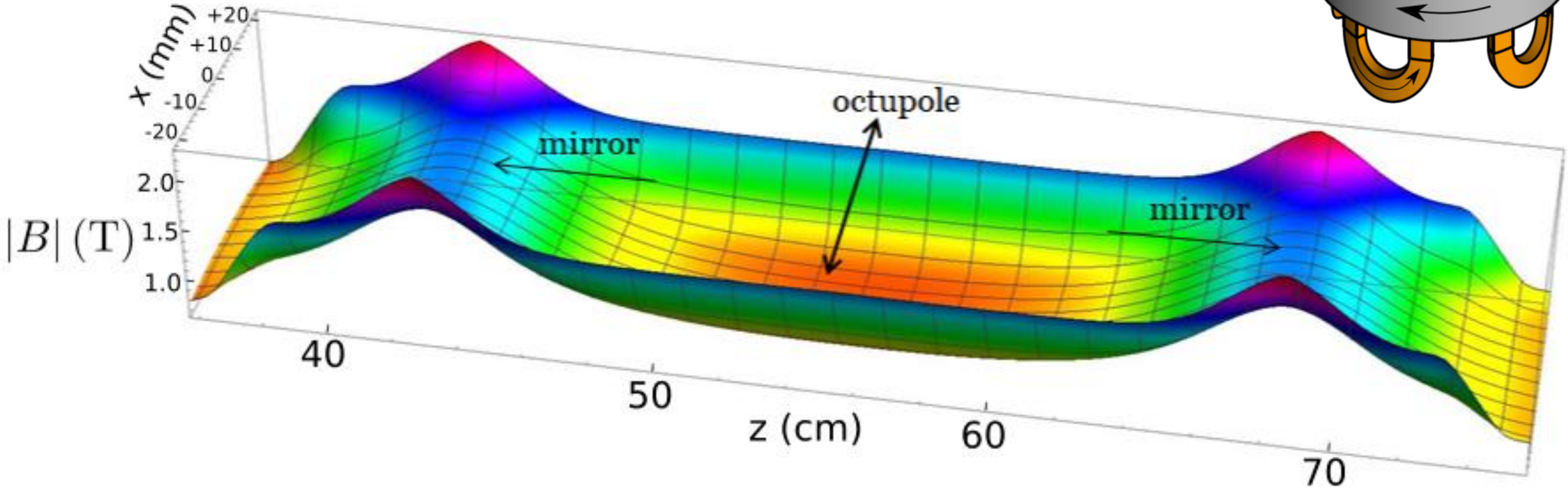
1. ~10^4 antiprotons *(from Antiproton Decelerator, CERN)*
2. ~10^6 positrons *(from beta decay , Na^{22} source)*
3. Cool to ~20 K
4. Mix!



Antihydrogen Magnetic Trap

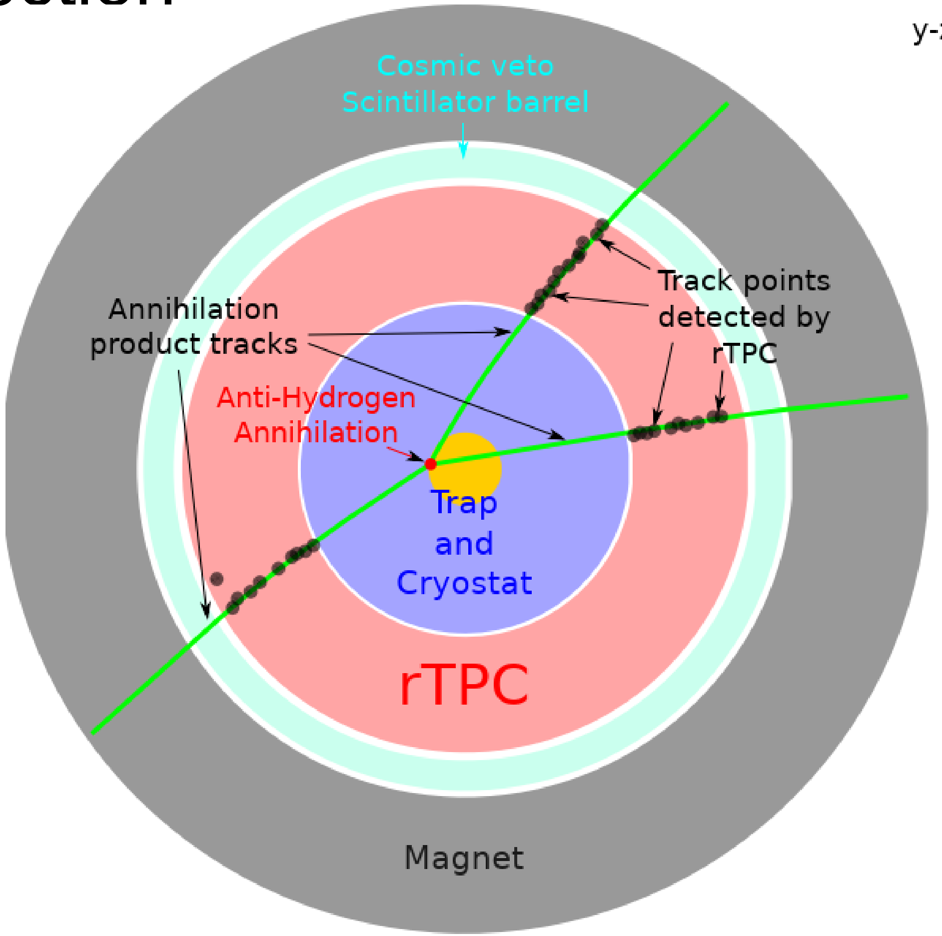
- Vertical Magnetic Trap $E = -\vec{\mu} \cdot \vec{B}$
- Trap depth ~ 0.5 K
- ~1000 anti-atoms trapped per day *(ALPHA2 performance)*

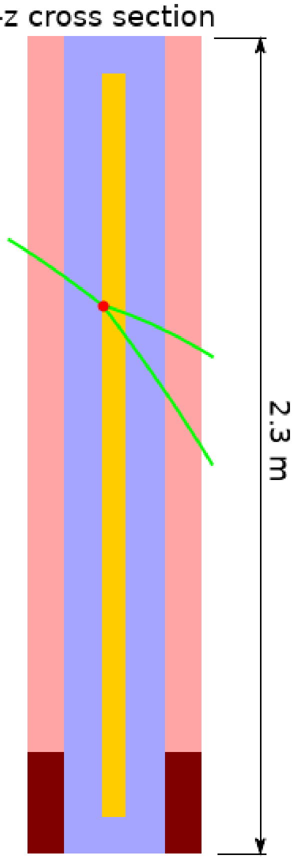




Annihilation detection

- Single atom resolution
- Vertex resolution ~ 6mm

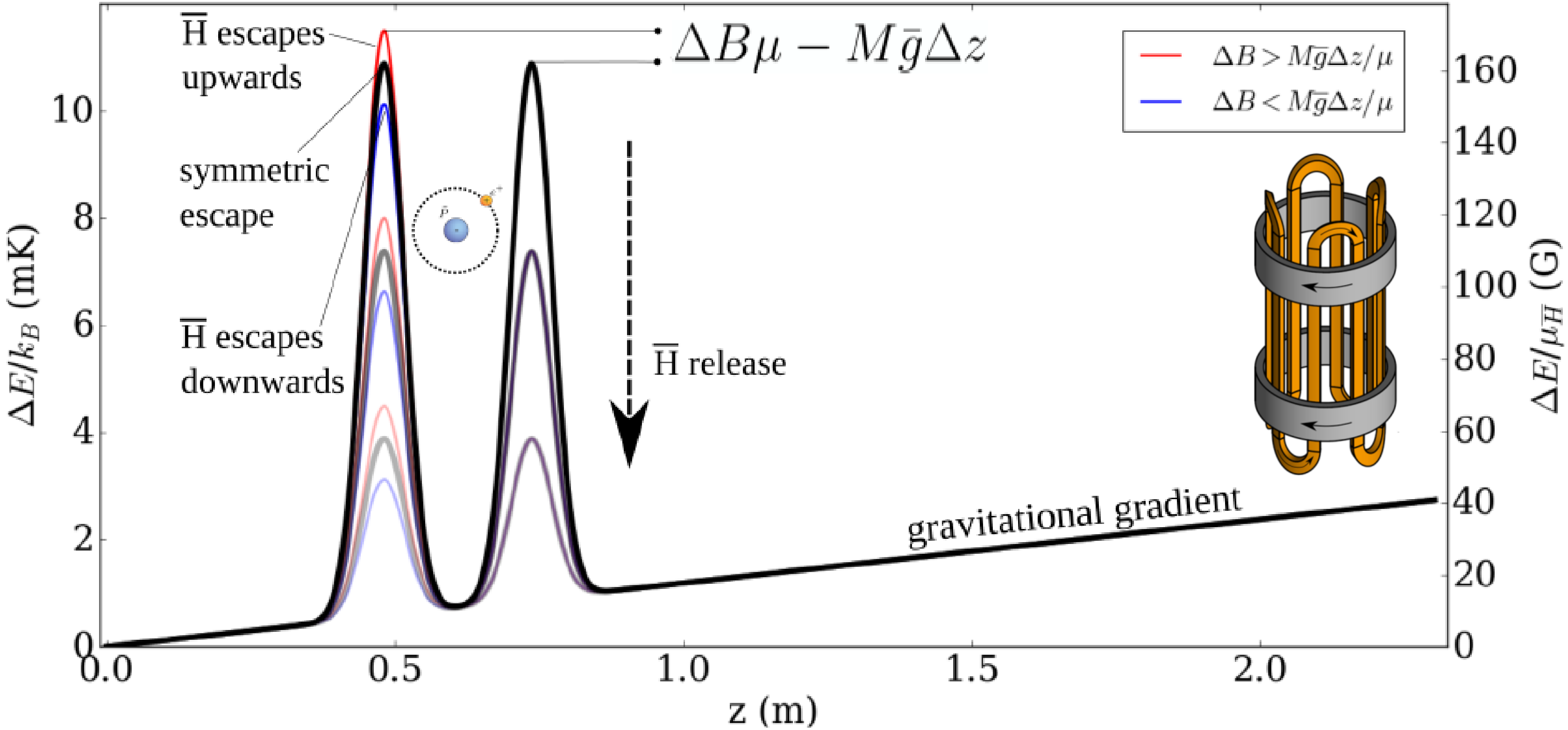




Antihydrogen Gravity Experiment

- Release antiatoms from magnetic trap, infer gravity from annihilation patterns

On-axis potential energy



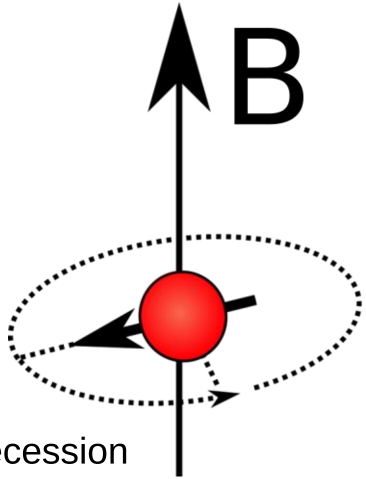
Antihydrogen Gravity Experiment

- “Size” of gravitational signal (magnetic units)

$$M\bar{g}\Delta z/\mu = 400\mu\mathrm{T}$$

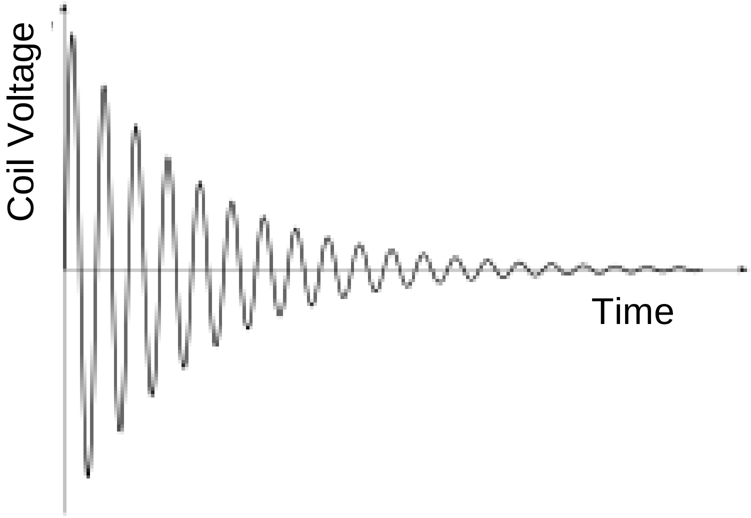
Magnetometry with Nuclear Magnetic Resonance (NMR)

- Spin precession induces voltage in a coil



Spin precession

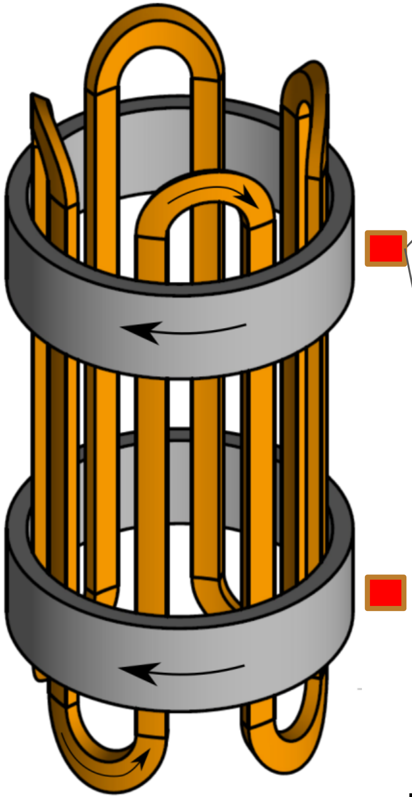
Detection coil



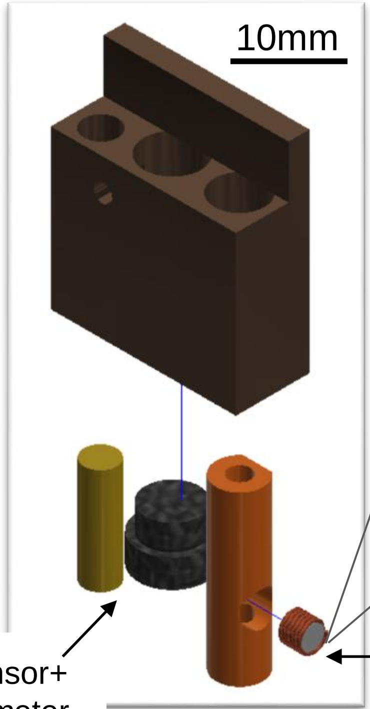
- Precession frequency proportional to magnetic field

$$f = \frac{\gamma}{2\pi} B$$

Cryogenic NMR probes *Mirror coil diagnostic*

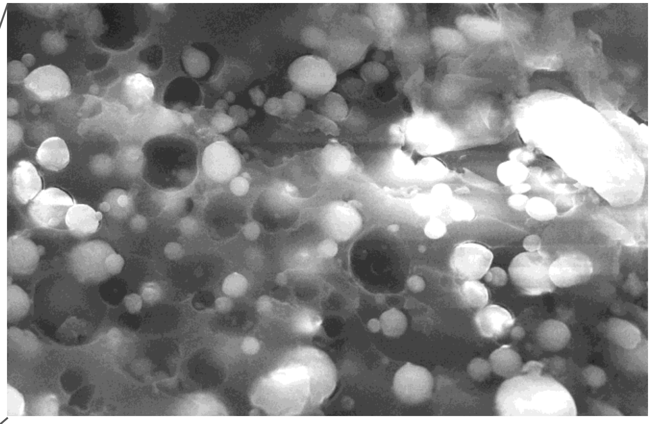


Difficult environment: Cryogenic, poor physical access, non-uniform field, etc…



Hall sensor+
thermometer

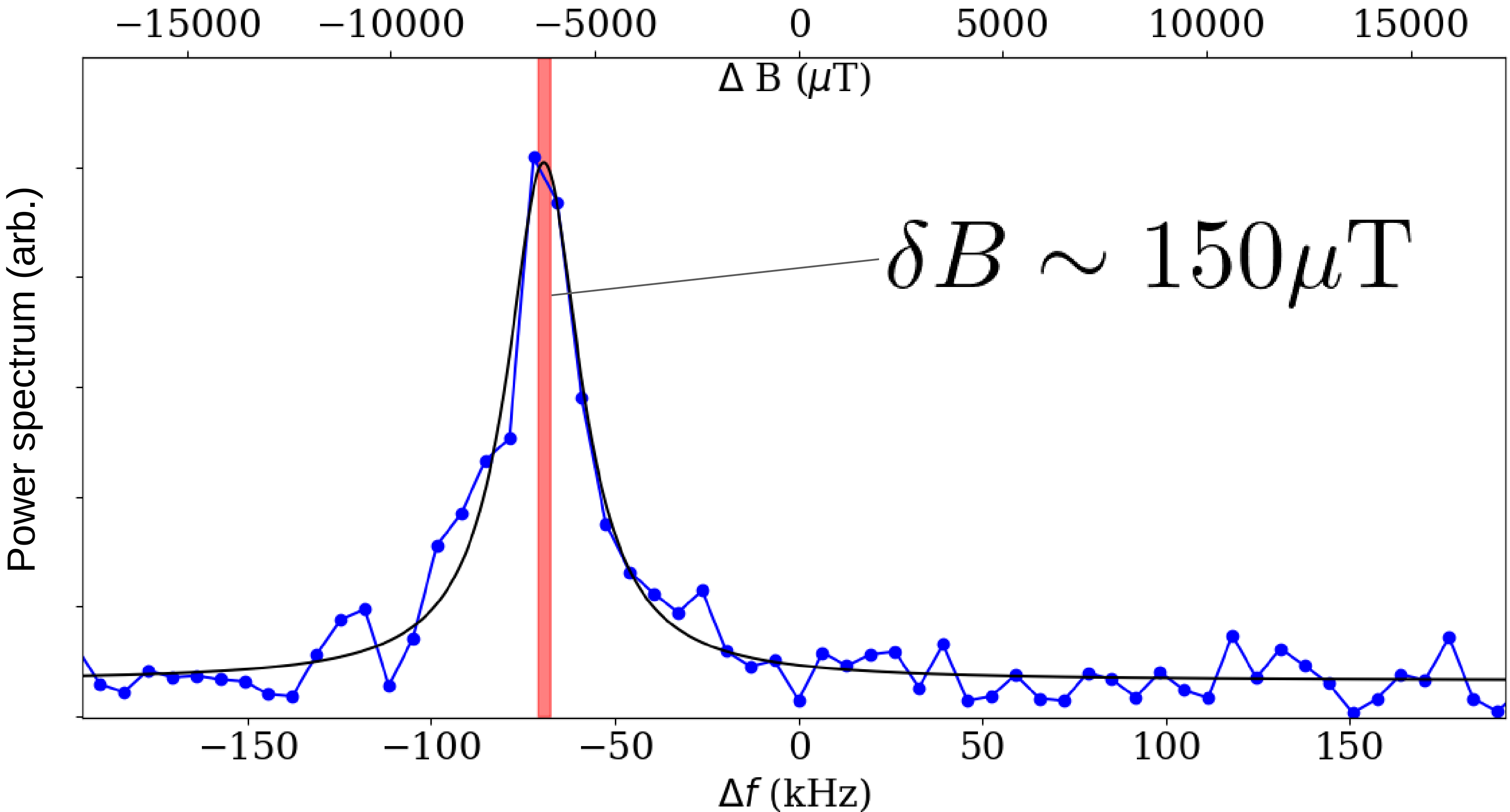
Hand wound
NMR coil



NMR sample:
Aluminum micro-particles

10µm

Aluminium NMR signal (at T~15K)



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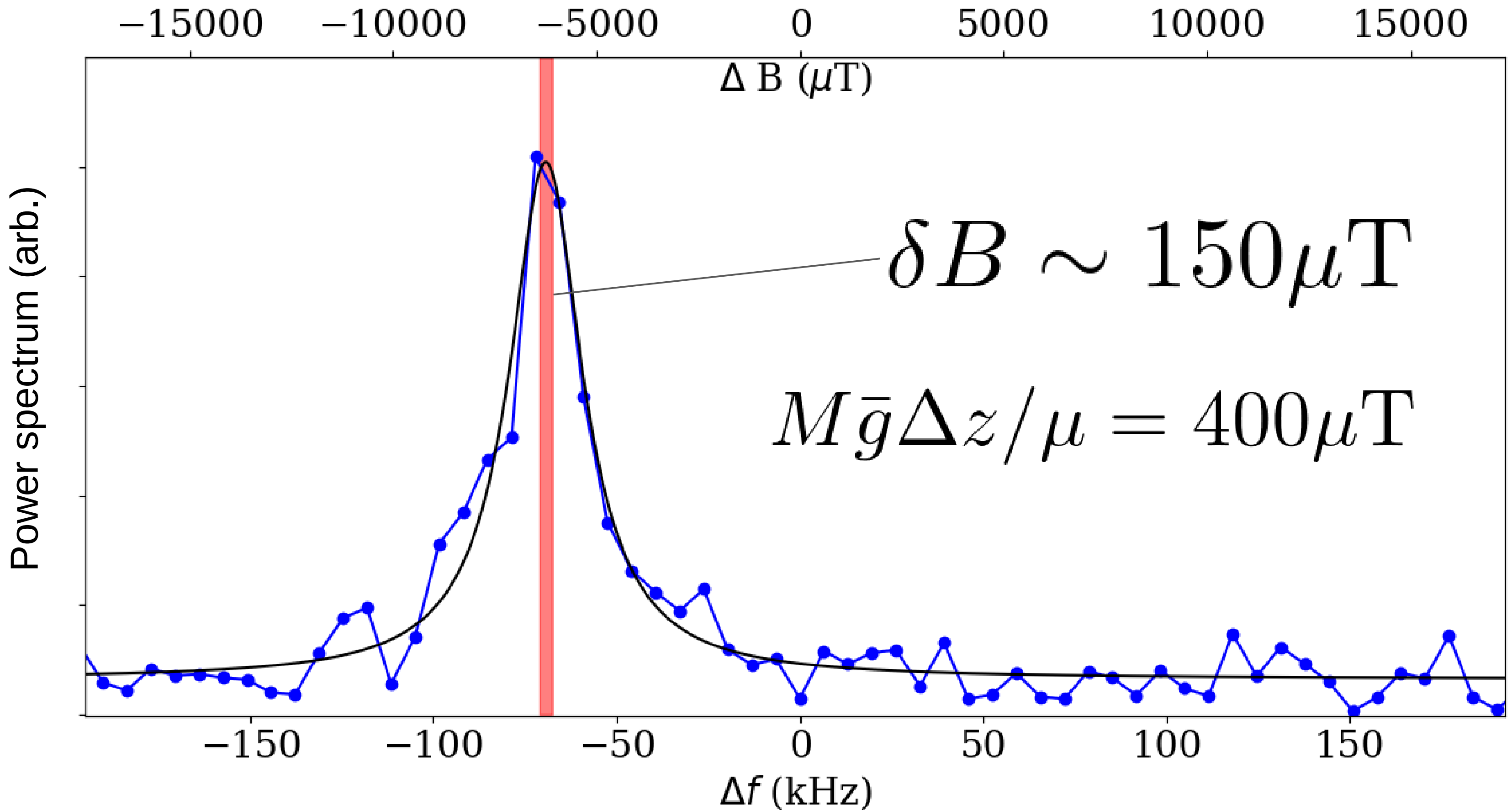
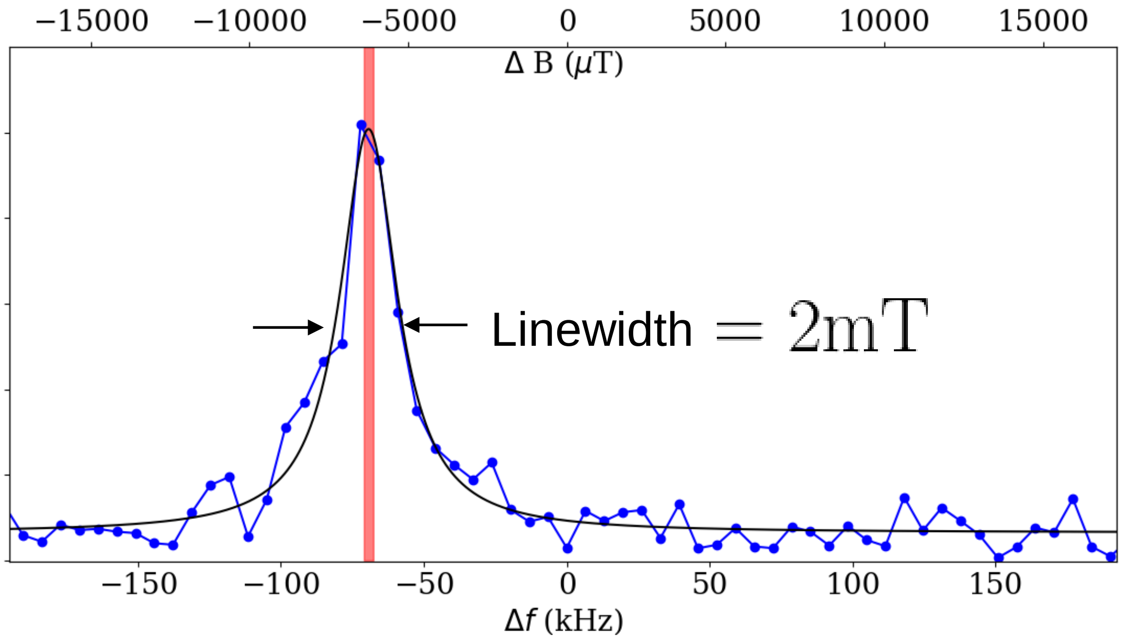


Magnetometer Performance Expectations

Sensor precision [1]: $\delta B \propto \frac{(\text{Linewidth})^{3/2}}{SNR}$
(statistical lower limit)

Other important parameters

Sensor parameter	**"Physics"**	**Estimate**
NMR linewidth [2]	Dipolar broadening ("T2")	$\Delta B \sim \frac{\sqrt{I(I+1)}\gamma\mu_o\hbar}{4\pi d^3}$
Signal-to-noise ratio [2]	Spin magnetization Probe construction …complicated	$SNR \propto \frac{\eta N Q^{1/2} V_c^{1/2} \gamma^{5/2} B^{3/2}}{f_{BW}^{1/2} T^{3/2}}$
Repetition time [3]	Spin lattice relaxation time	$T_1 = \frac{\hbar}{4\pi T \mathscr{K}^2}\left(\frac{\gamma_e}{\gamma_N}\right)^2$



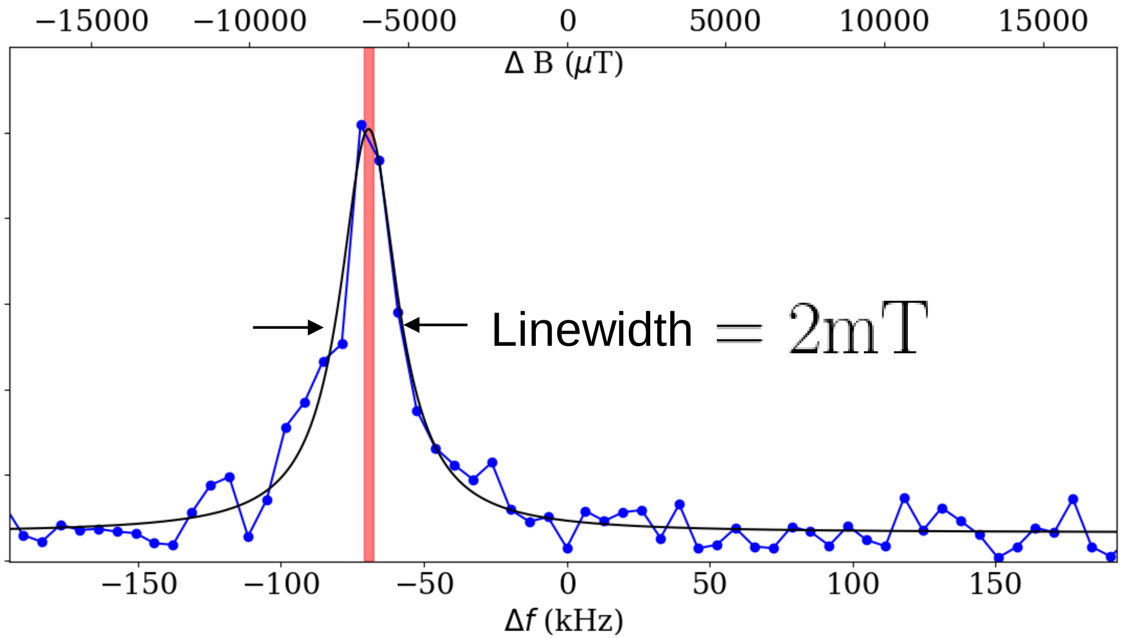
[1] C. Gemmel, et. al. Eur. Phys. J. D (2010)
[2] A. Abragam, Principles of nuclear magnetism (Oxford Univ. Press, 1961)
[3] C. P. Slichter, Principles of magnetic resonance (Harper and Row, 1963)

Magnetometer Performance Expectations

Materials I'd like to characterize

Material	**Linewidth**
Lead	160 µT
Indium Phosphide	230 µT
Titanium - Phosphide	200 µT
Rubber	2000 µT

… and a dozen others...



NMR samples to Enable 1% gravity sensitivity?

Materials I'd like to characterize

Material	**Linewidth**
Lead	160 µT
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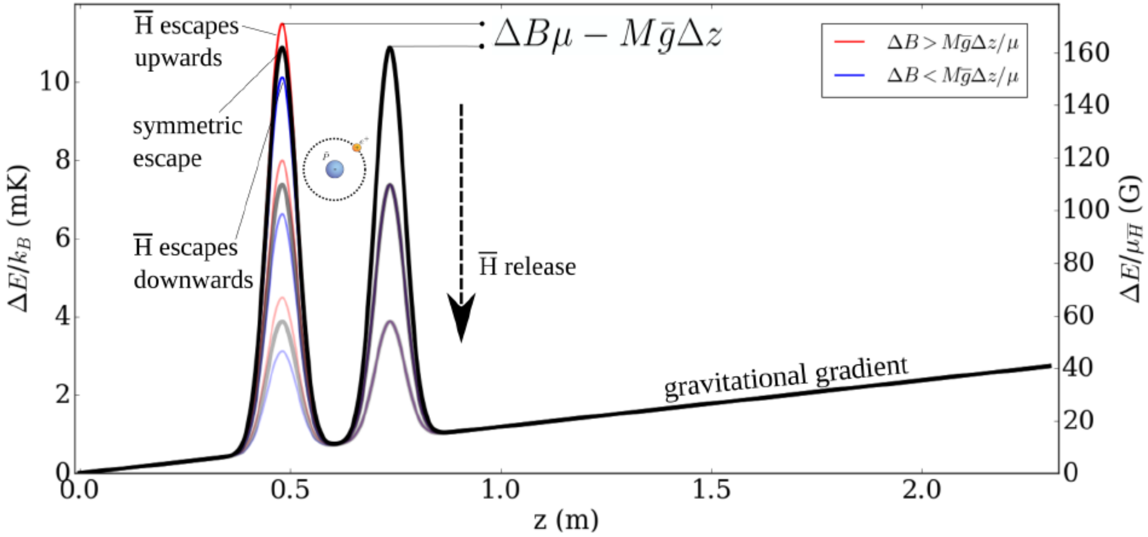
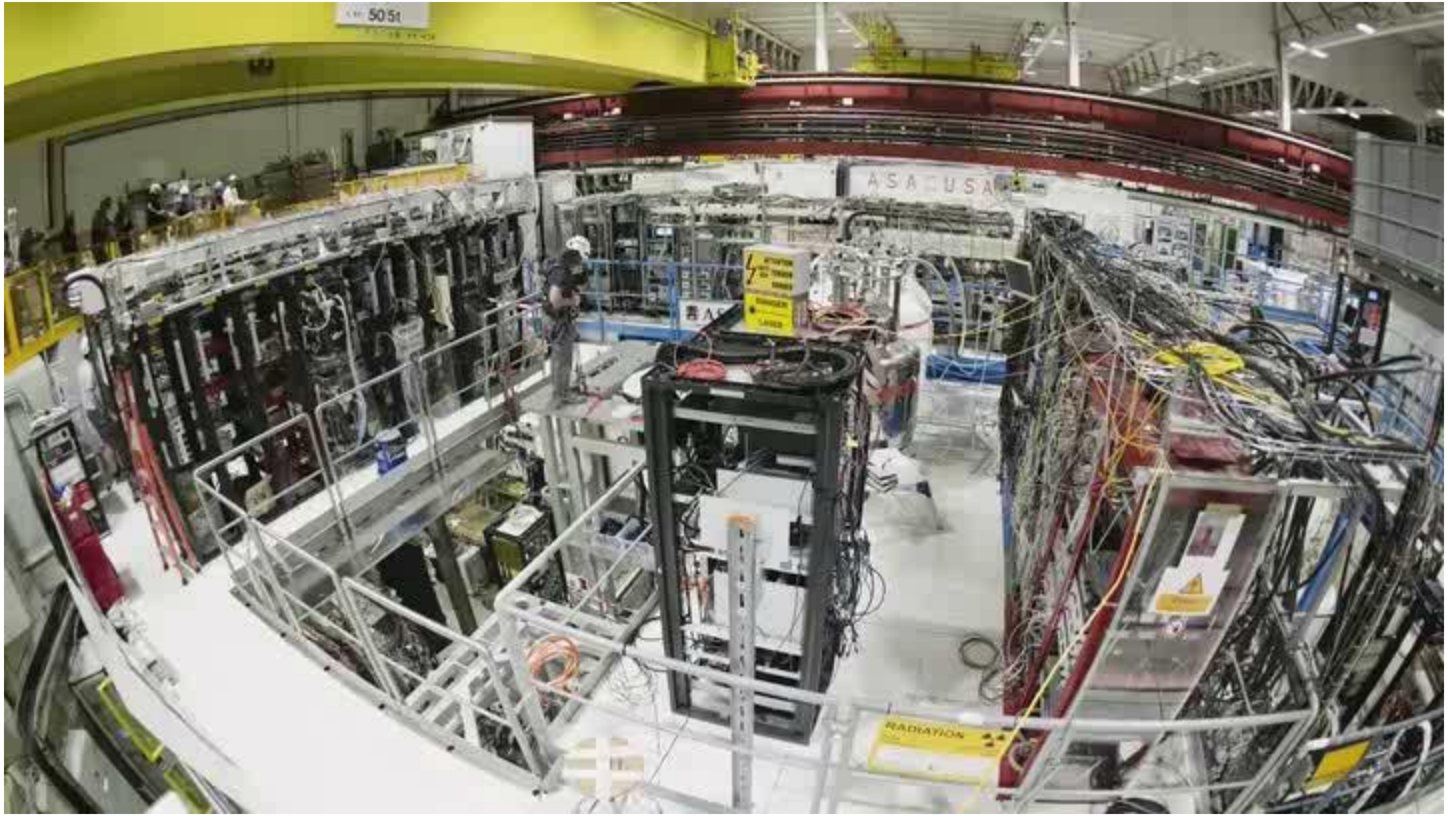
Goal:
obtain precision relevant to a gravity experiment

$$M\bar{g}\Delta z/\mu = 400\mu\mathrm{T}$$

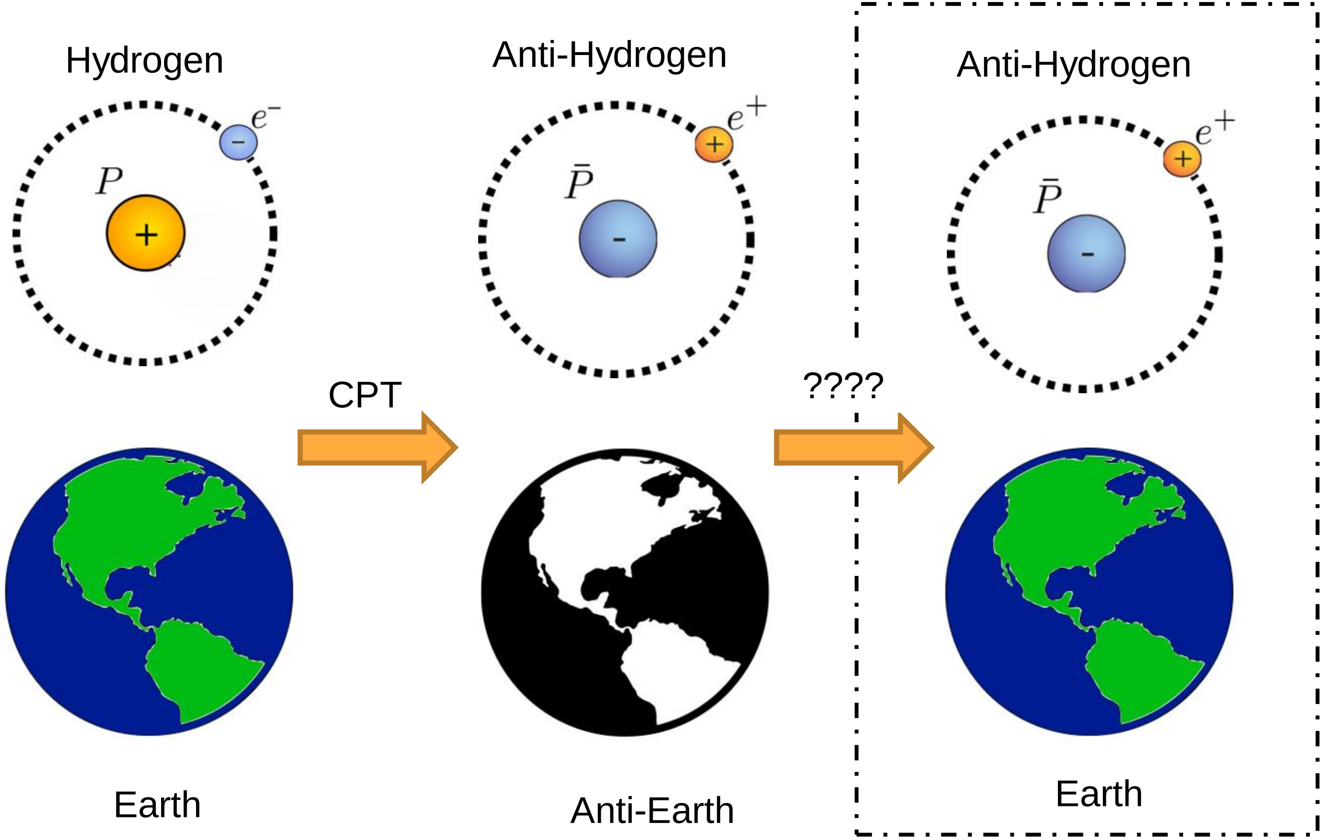


Thank you

Building ALPHA-g



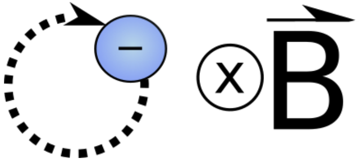
Matter - antimatter gravitational interaction



Tests Equivalence principle (Our experiment)

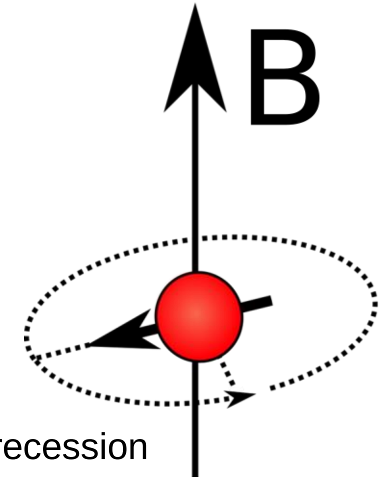
Magnetometry Overview

1. Electron cyclotron resonance
    - Pro: Measures field in-situ
    - Con: not fully understood



$$\omega_c = \frac{eB}{m}$$

1. Nuclear magnetic resonance (NMR)
    - Rubber samples
        - Pro: Sufficient resolution
        - Con: Best at room temperature
    - Aluminium micro-powder samples
        - Pro: Works at Low temperatures
        - Con: Weaker field resolution

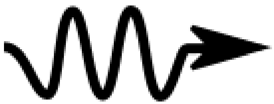


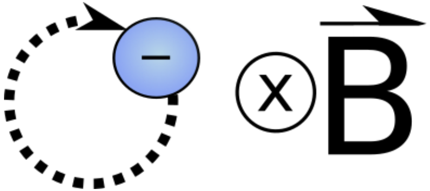
Spin precession

Magnetometry with Plasmas

- Working principle: plasmas heat when irradiated at the cyclotron frequency

incoming microwave pulse

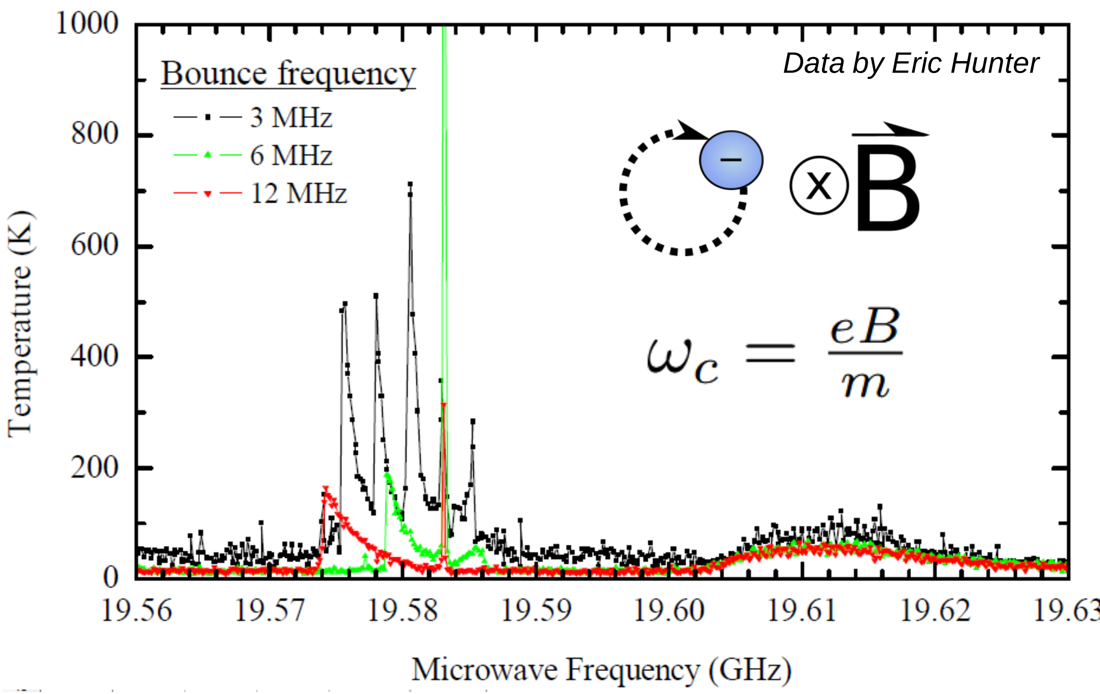


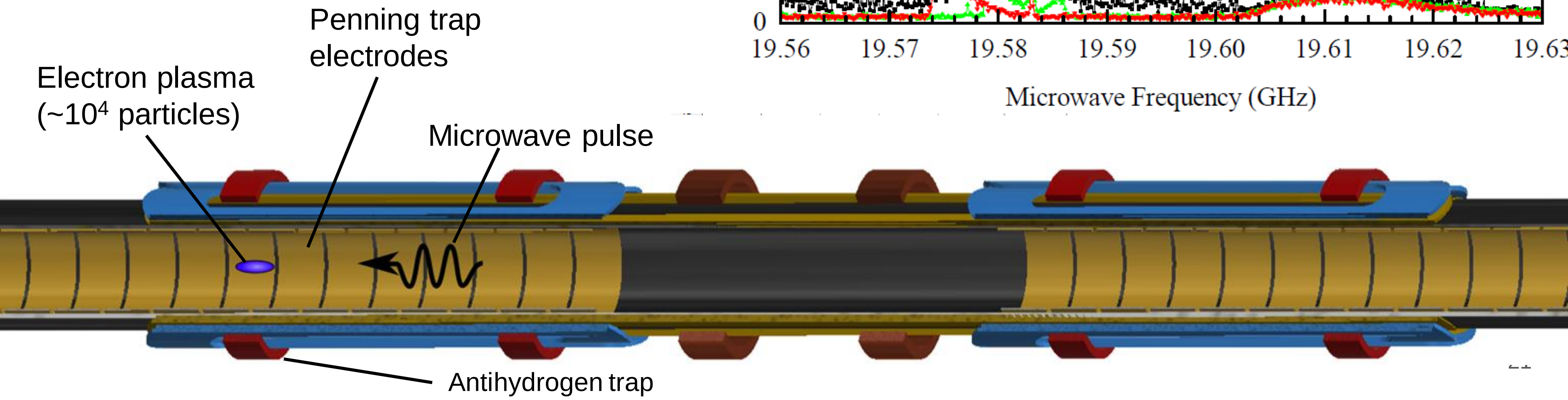


$$\omega_c = \frac{eB}{m}$$

Magnetometry with Plasmas

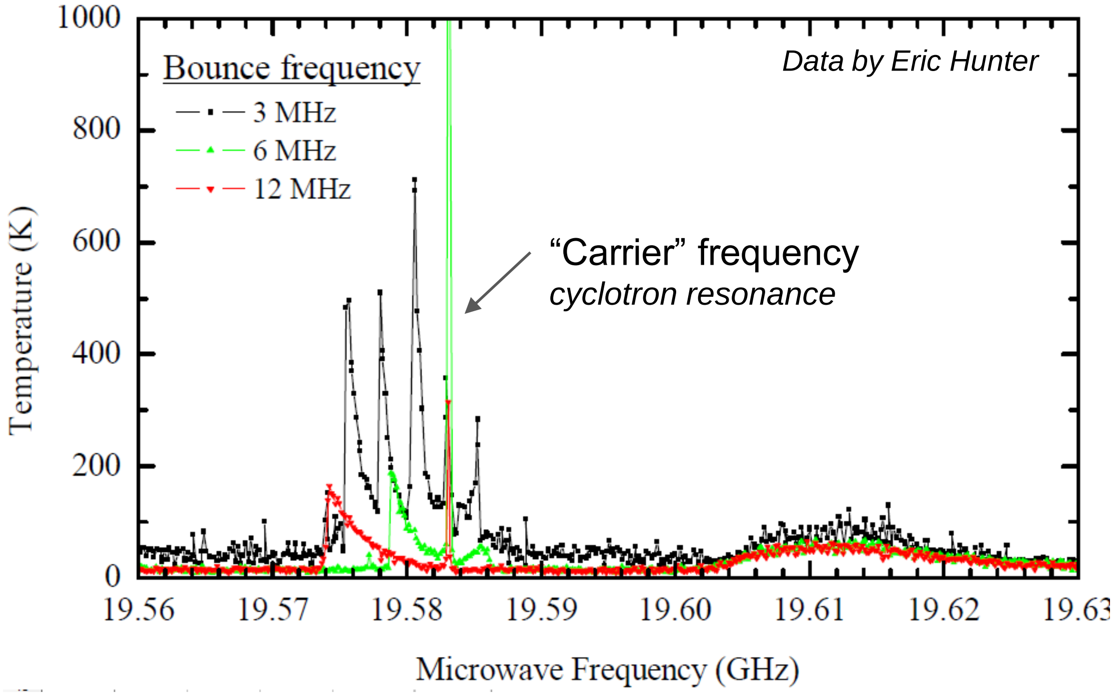
- Plasmas are “hot” when microwave frequency matches cyclotron frequency
- Technique to measure plasma temperature:
  Phys. Fluids B 4 3432–9 1992
  New J. Phys. 16 (2014) 013037.

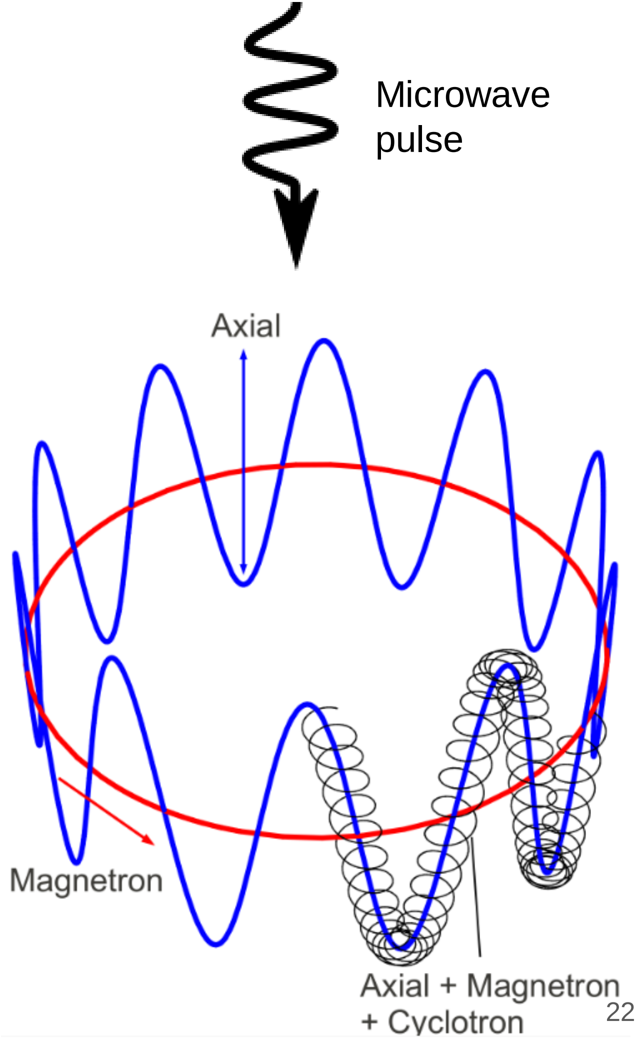




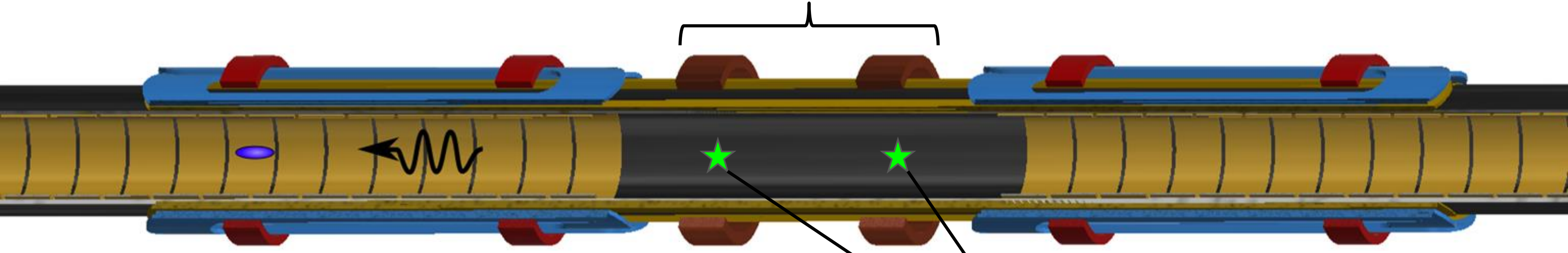
Magnetometry with Plasmas

- Complicated particle motion creates “side-bands”
  - Must identify “carrier” frequency
  - Preliminary resolution < 1ppm





Problem with Cyclotron Resonance Method



$$\Delta B \times 1\% = 4\mu\mathrm{T}$$

- Can’t be used for “precision” gravity region
  - Penning trap electrodes impractical

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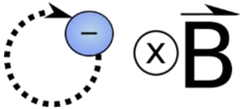

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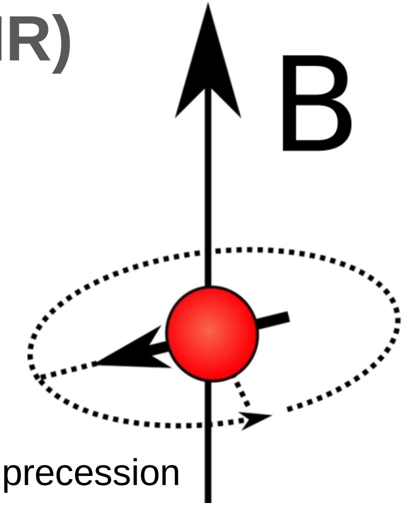
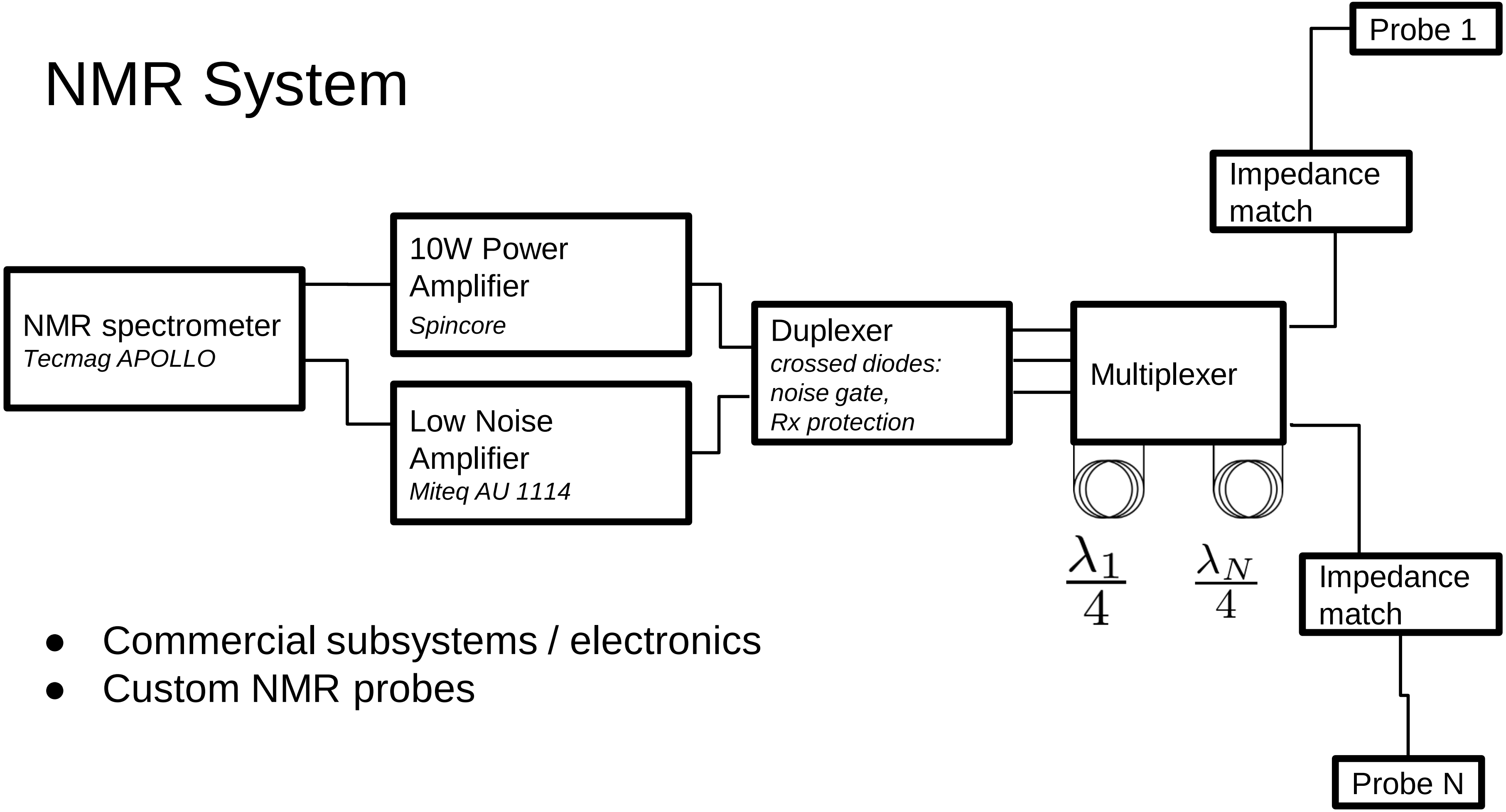


Spin precession

NMR System



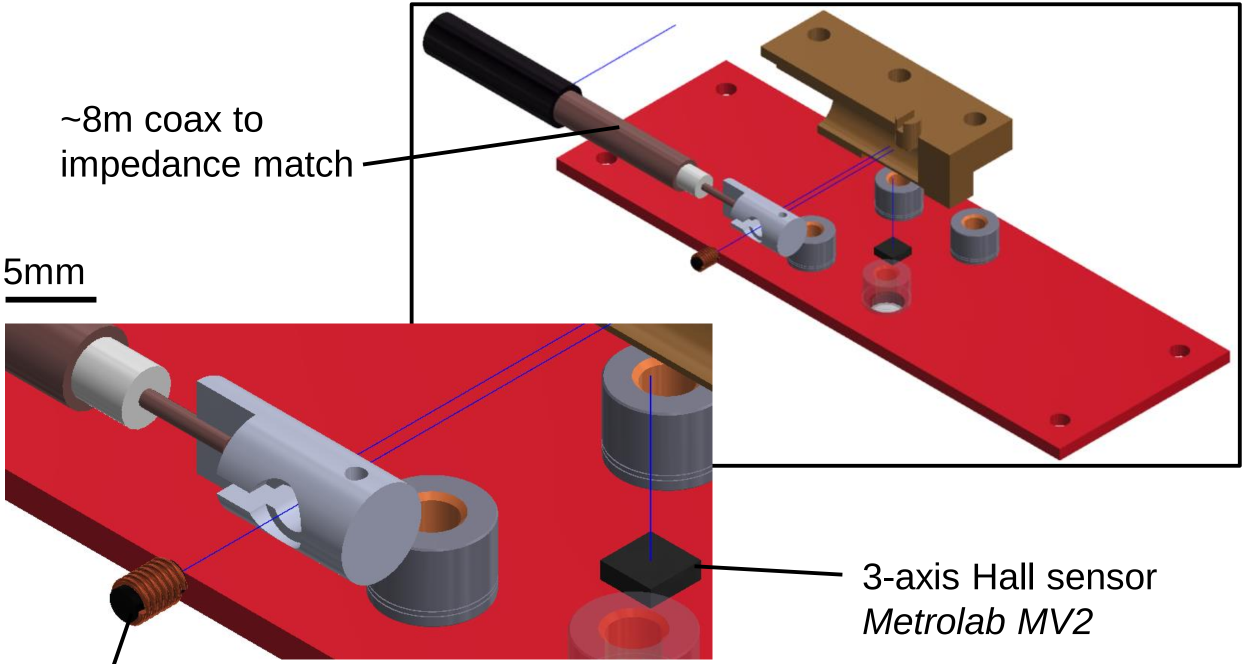
- Commercial subsystems / electronics
- Custom NMR probes

Room temperature NMR / Hall package

Environmental field monitor

~8m coax to
impedance match

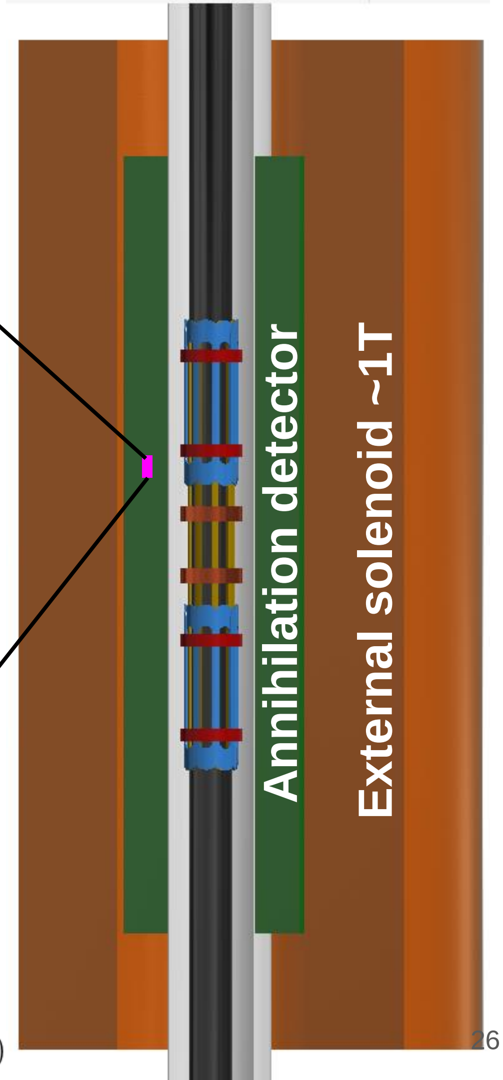
5mm



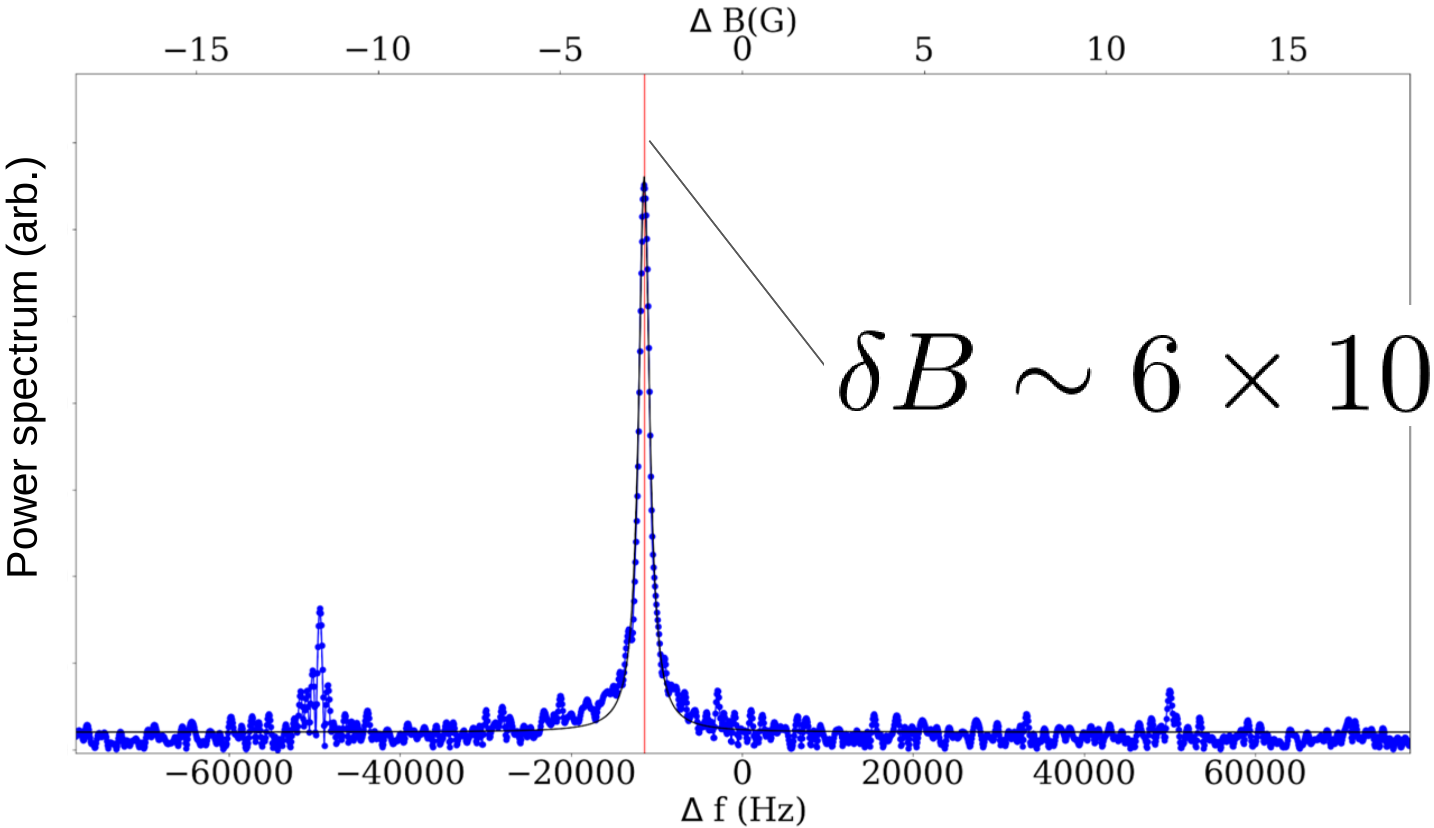
3-axis Hall sensor
Metrolab MV2

Natural Rubber NMR
sample V ~ 4mm^3

Possible improvement:
Remote Tuning of NMR Probe Circuits, J. Mag. Res. (2000)



Rubber NMR Probe Performance



$$\delta B \sim 6 \times 10^{-7}\mathrm{T}$$