Measuring the gravitational free-fall of antihydrogen

CAP2023

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on behalf of the ALPHA collaboration
Assistant Professor
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June 20, 2023

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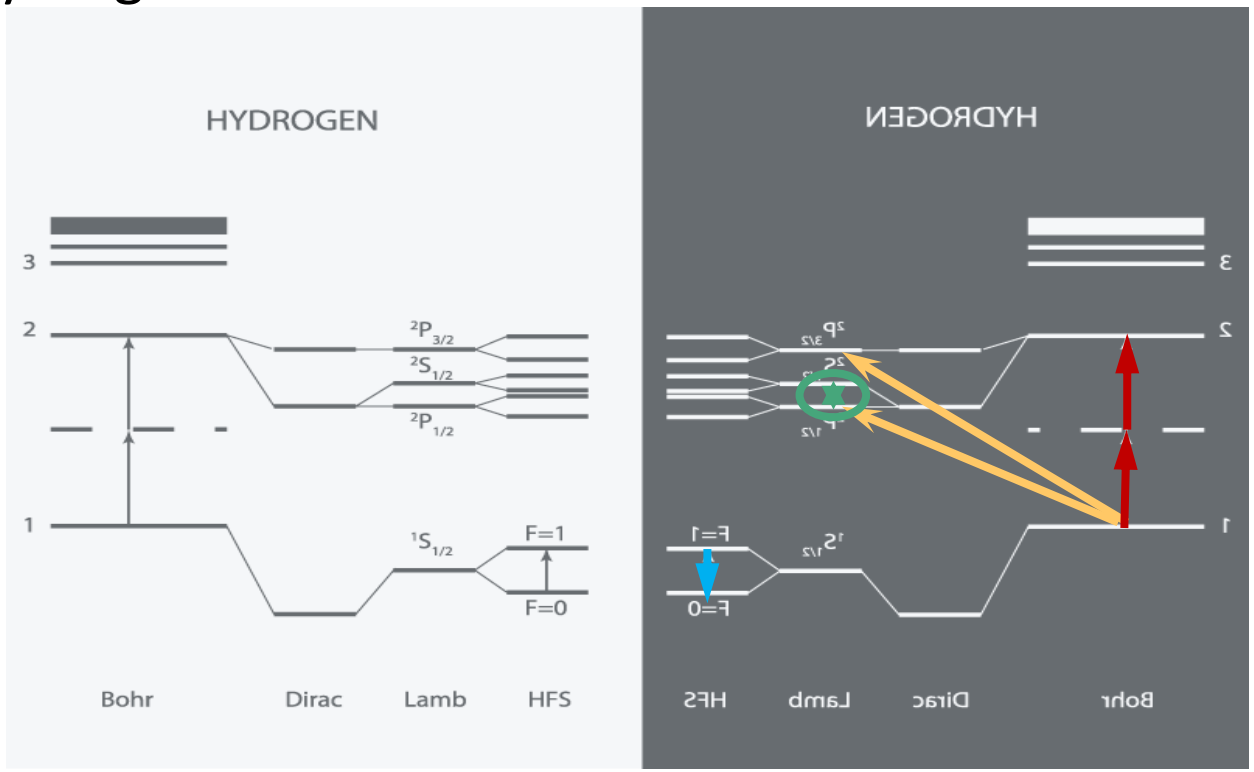
Goal: Precision measurements of antihydrogen atoms

Spectroscopy:

- CPT symmetry?
- 1S – 2S (4.2 x 10^{-15} in H)
- Ground state HFS (1.4 x 10^{-12} in H)
- Lamb shift (3 x 10^{-6} in H)
- nS – n'S/P ?



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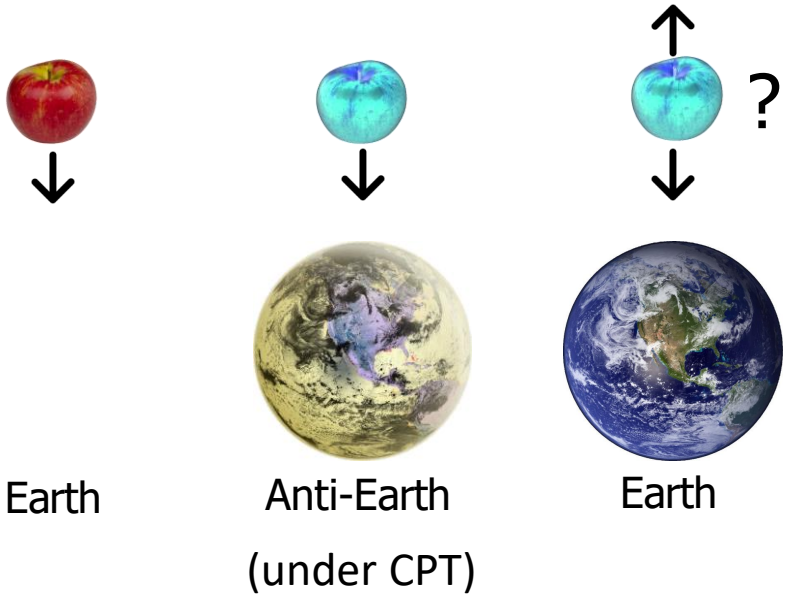

Gravity:

- Test the Weak Equivalence Principle with free-fall experiments

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Goal: Precision measurements of antihydrogen atoms

Spectroscopy:

- 1S – 2S (4.2 x 10^{-15} in H)
- Ground state HFS (1.4 x 10^{-12} in H)
- Lamb shift (3 x 10^{-6} in H)
- 2S – nS

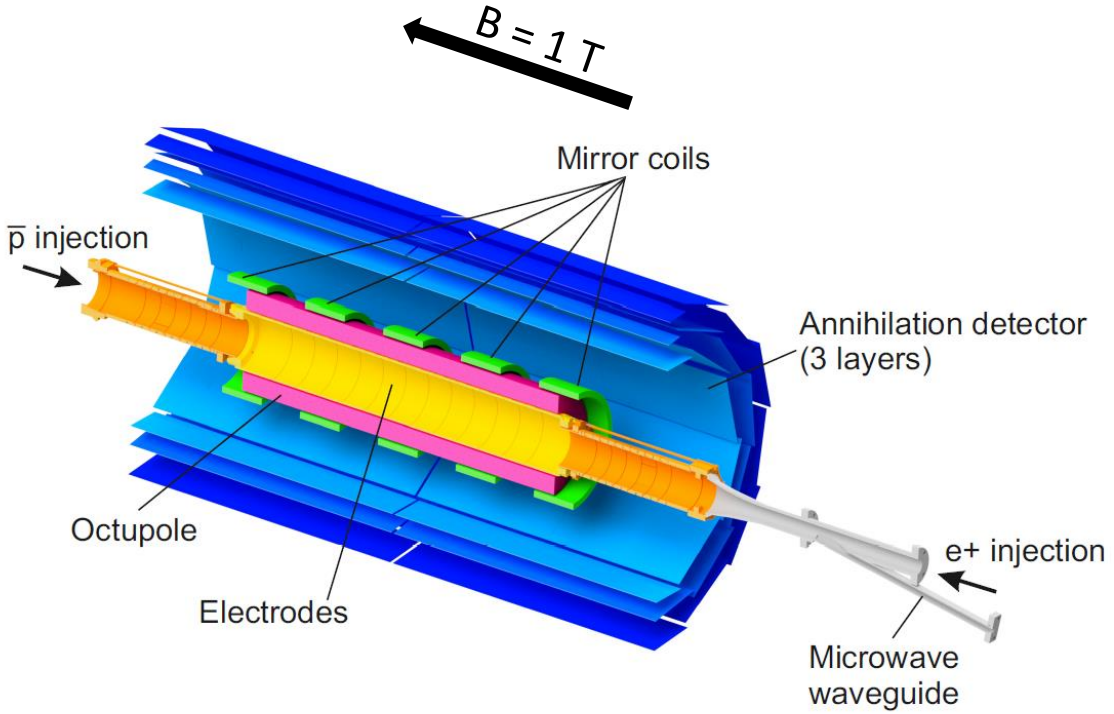
Gravity:

- Test the Weak Equivalence Principle with free-fall experiments

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

ALPHA experiment

Producing and trapping antihydrogen



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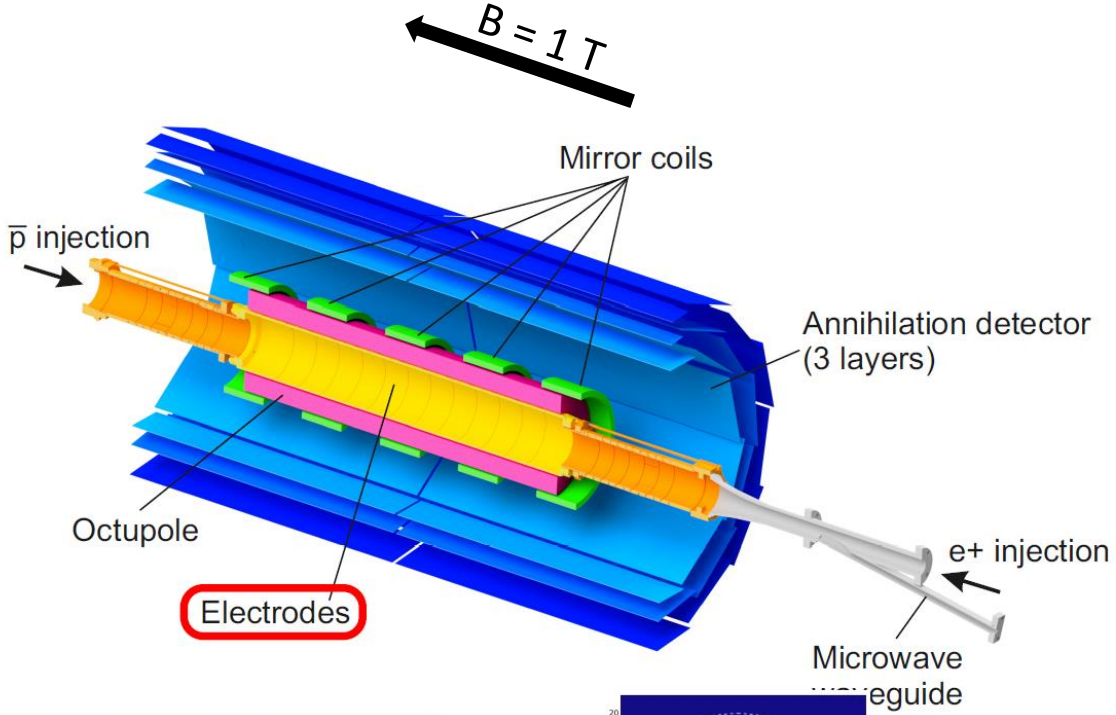
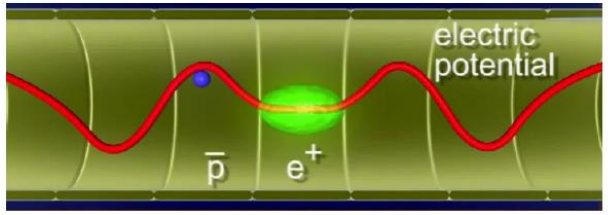
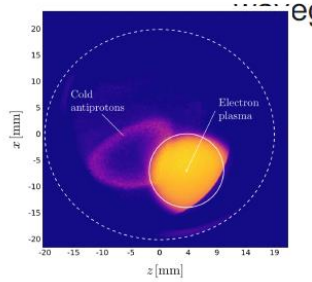
Producing and trapping antihydrogen







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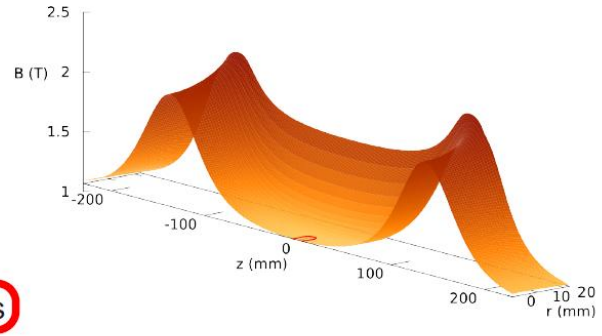
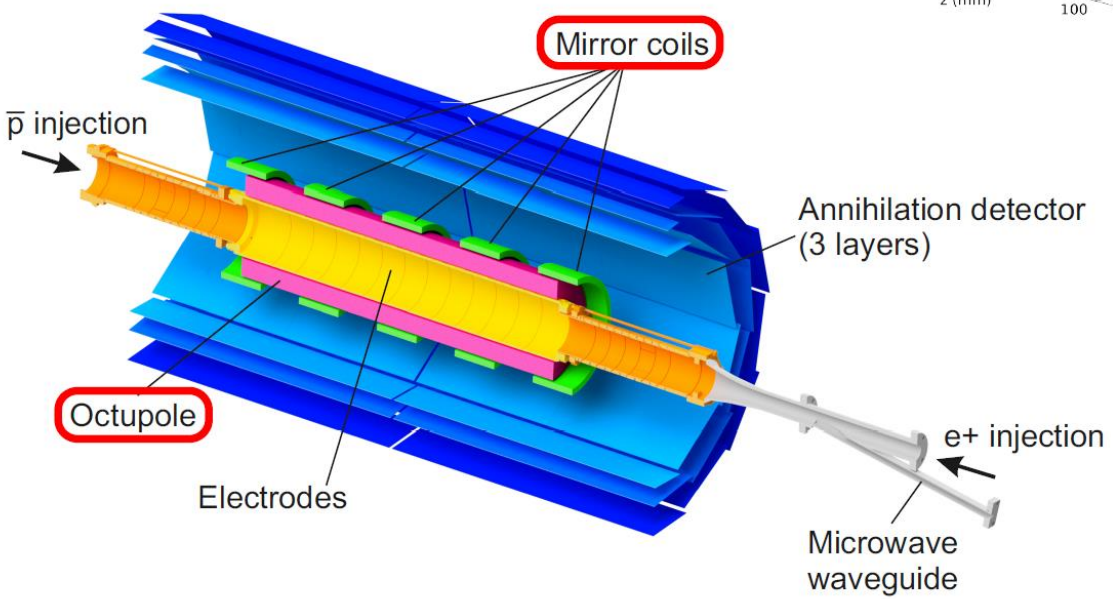
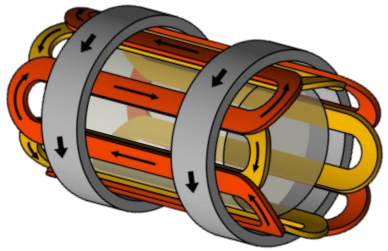
Producing and trapping antihydrogen

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



$\Delta U \approx 0.5$ K





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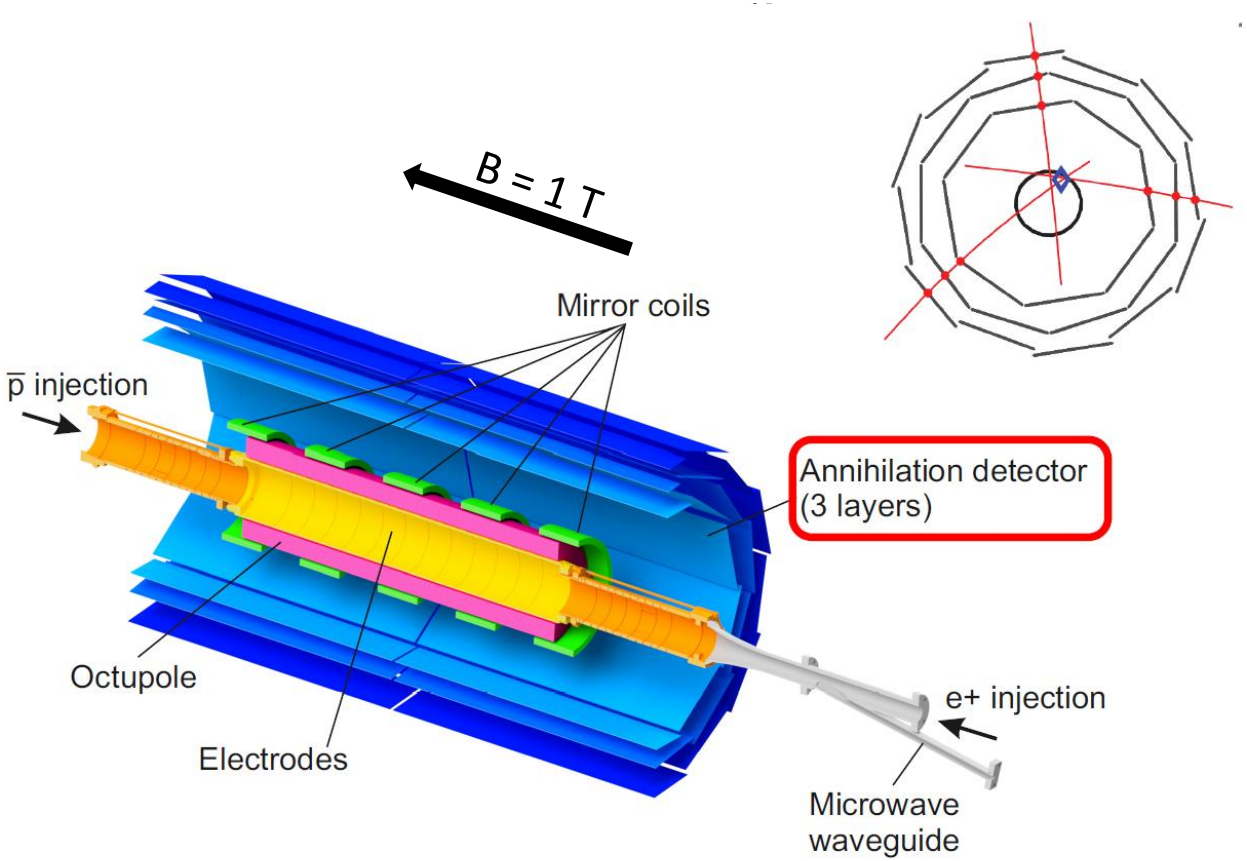
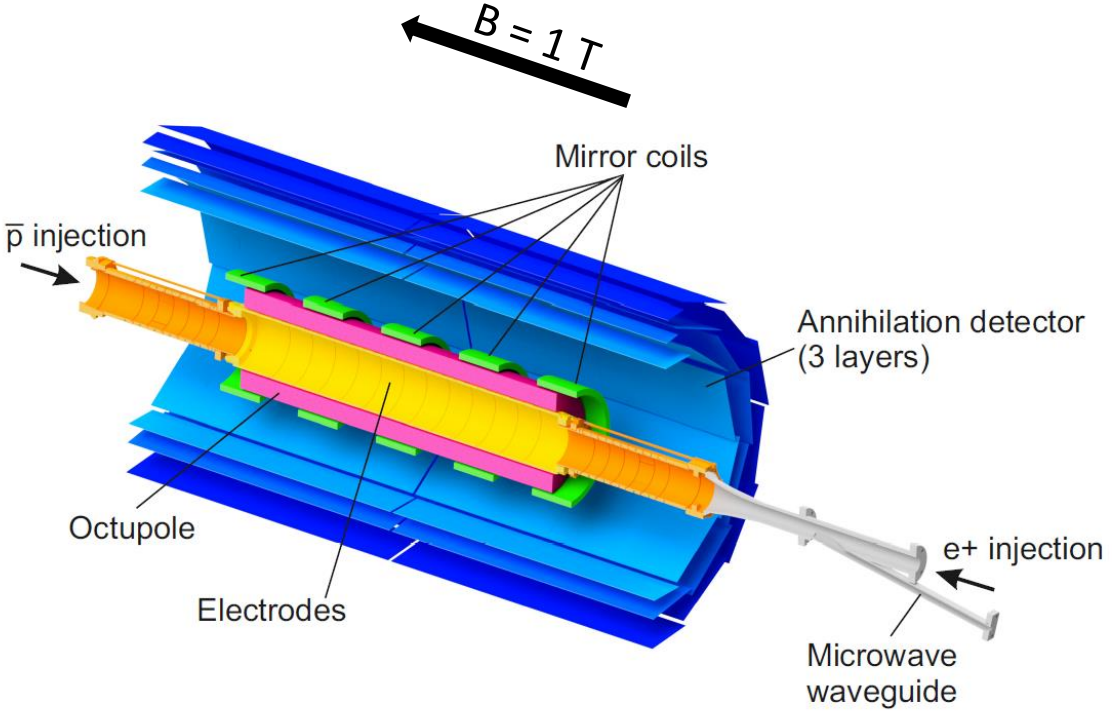
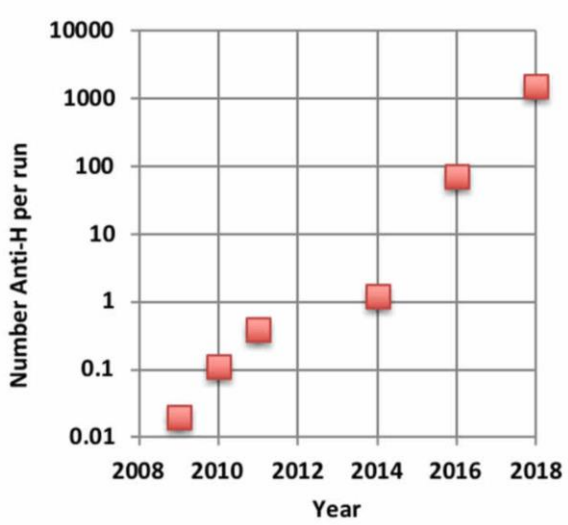
Producing and trapping antihydrogen



Producing and trapping antihydrogen



Improvements to antihydrogen trapping
[Nature Comm. 8, 681 (2017)]



Can accumulate anti-atoms (~2500 over 17 hours)

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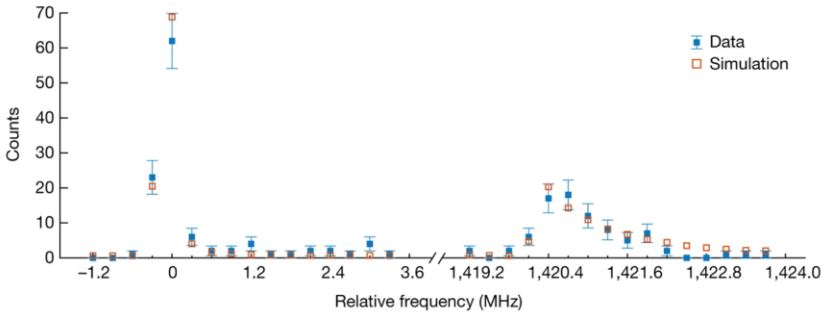
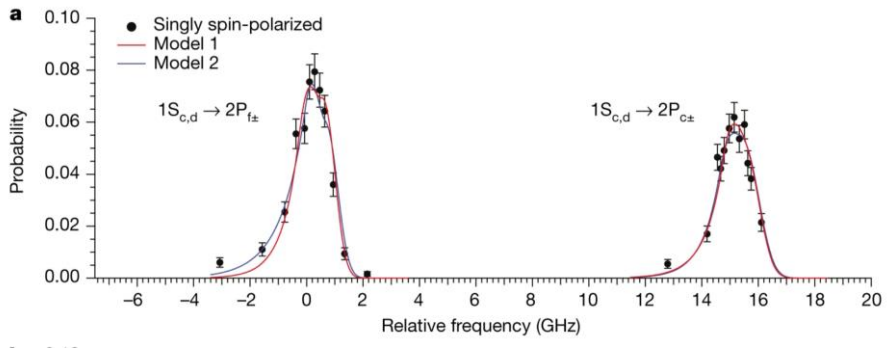
Antihydrogen spectroscopy

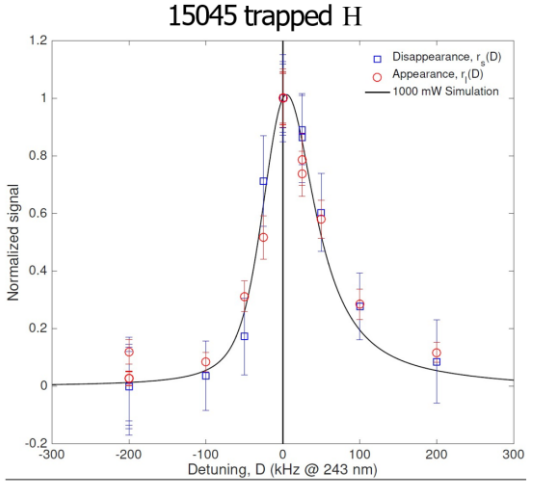
Hyperfine spectrum [*Nature* 548, 66 (2017)]



Fine structure [*Nature* 578, 375 (2020)]

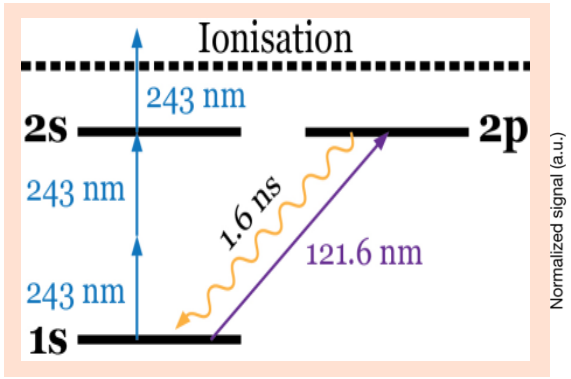


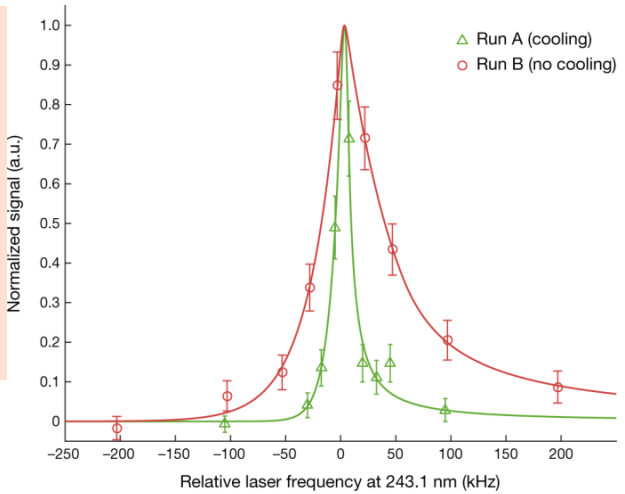
1S – 2S spectroscopy [*Nature* 557, 71 (2018)]



Result: f_{d-d} = 2, 466, 061, 103, 079.4 (5.4) kHz

Laser Cooling [Nature 2021]





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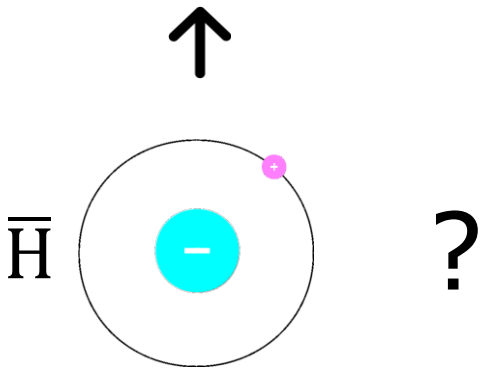
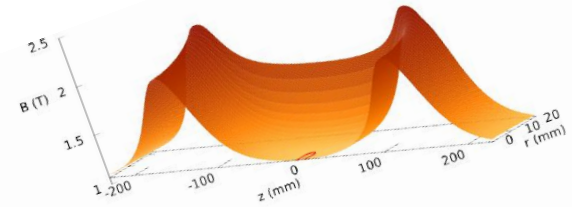
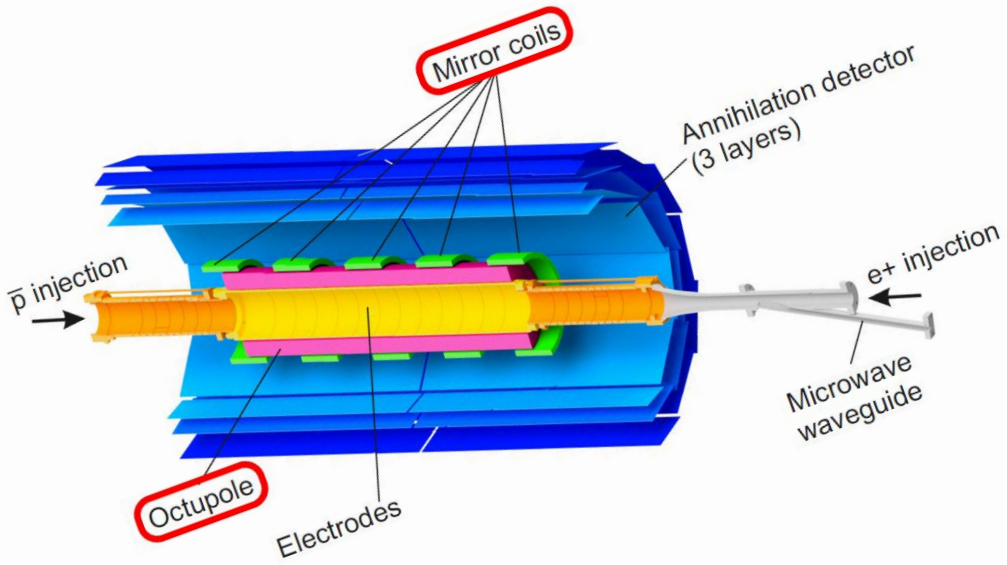

$\overline{\mathrm{H}}$
?

Antihydrogen + gravity: ALPHA-g

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





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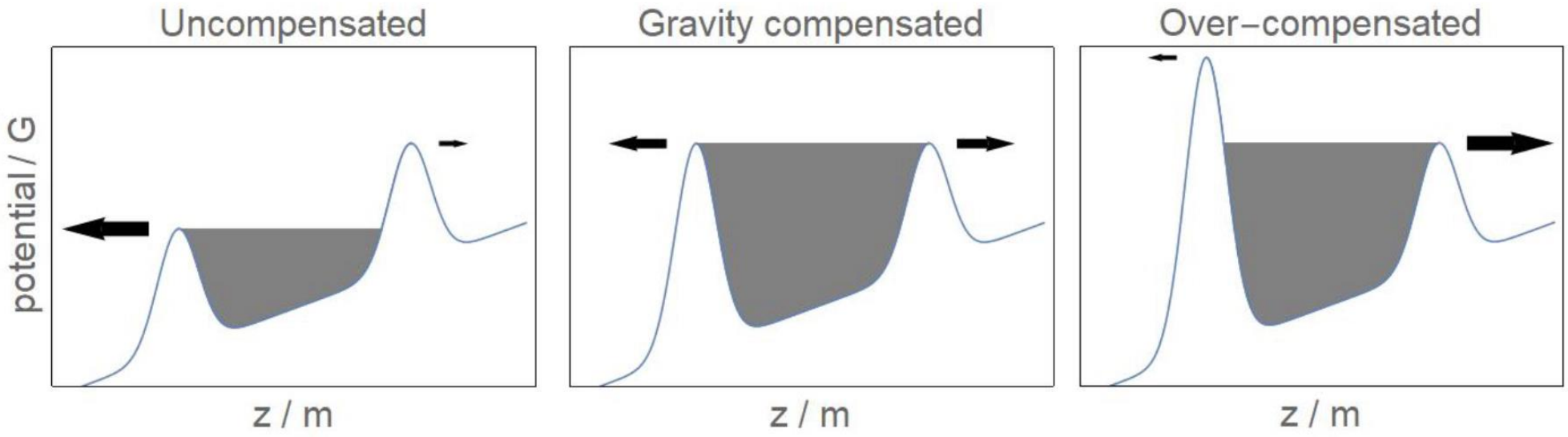
Measuring the effect of gravity



The challenge

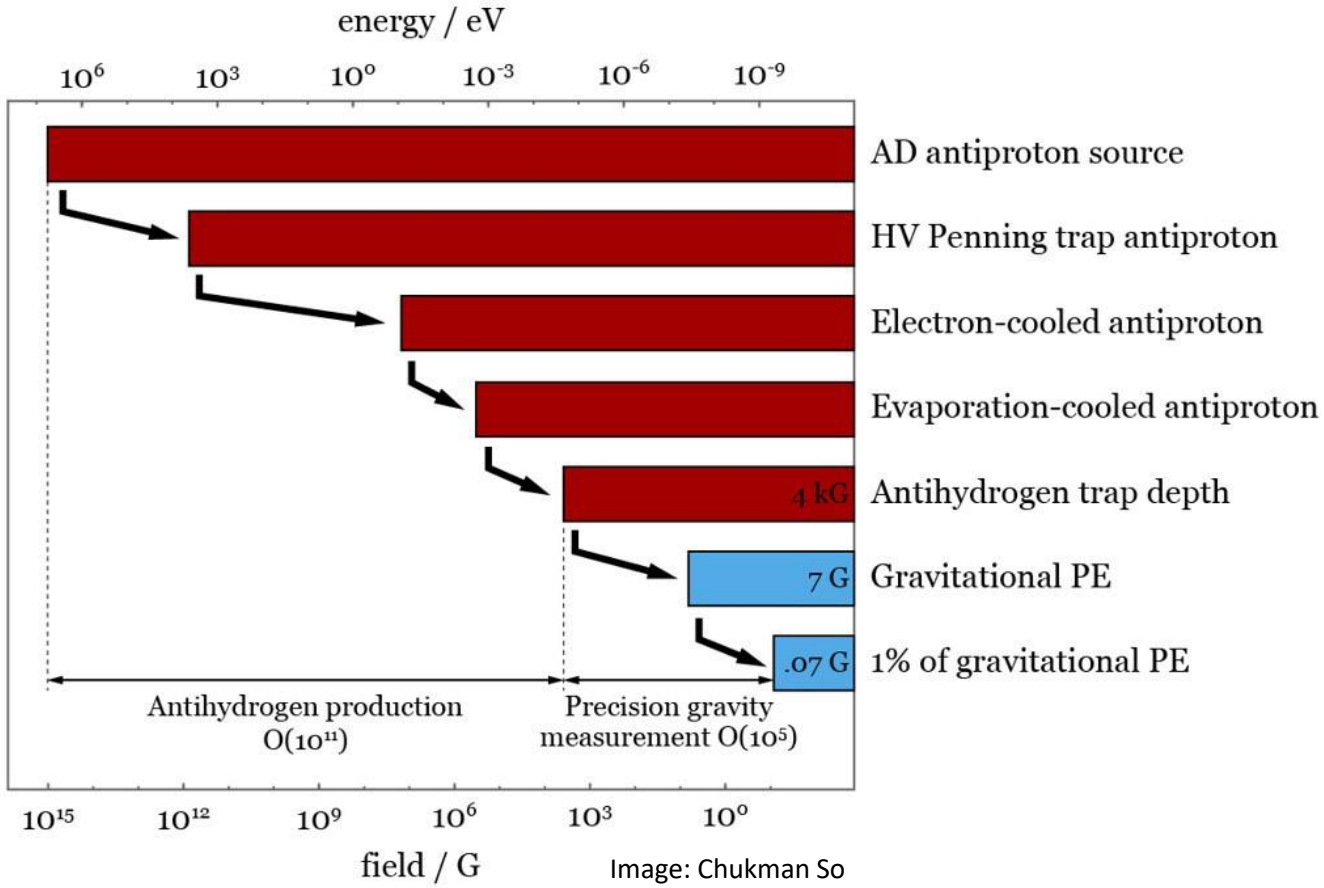
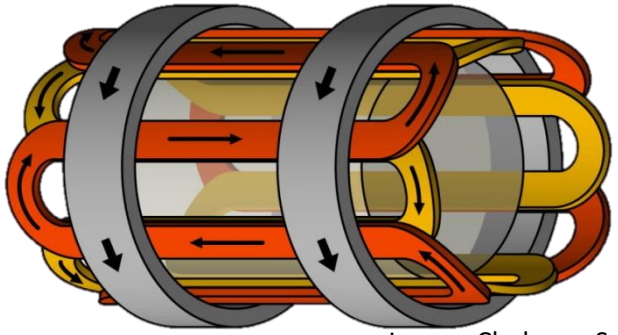


Image: Chukman So

Magnetic traps



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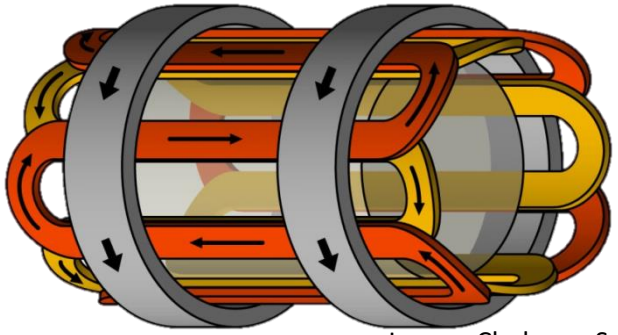
Magnetic traps



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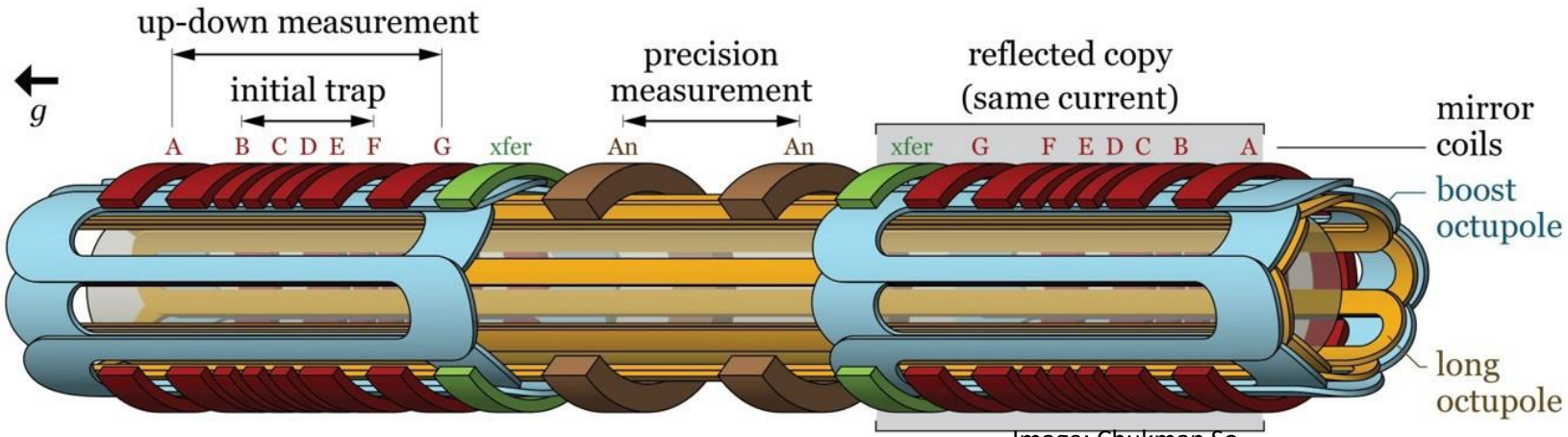

Image: Chukman So

17 superconducting circuits with 34 HTS current leads

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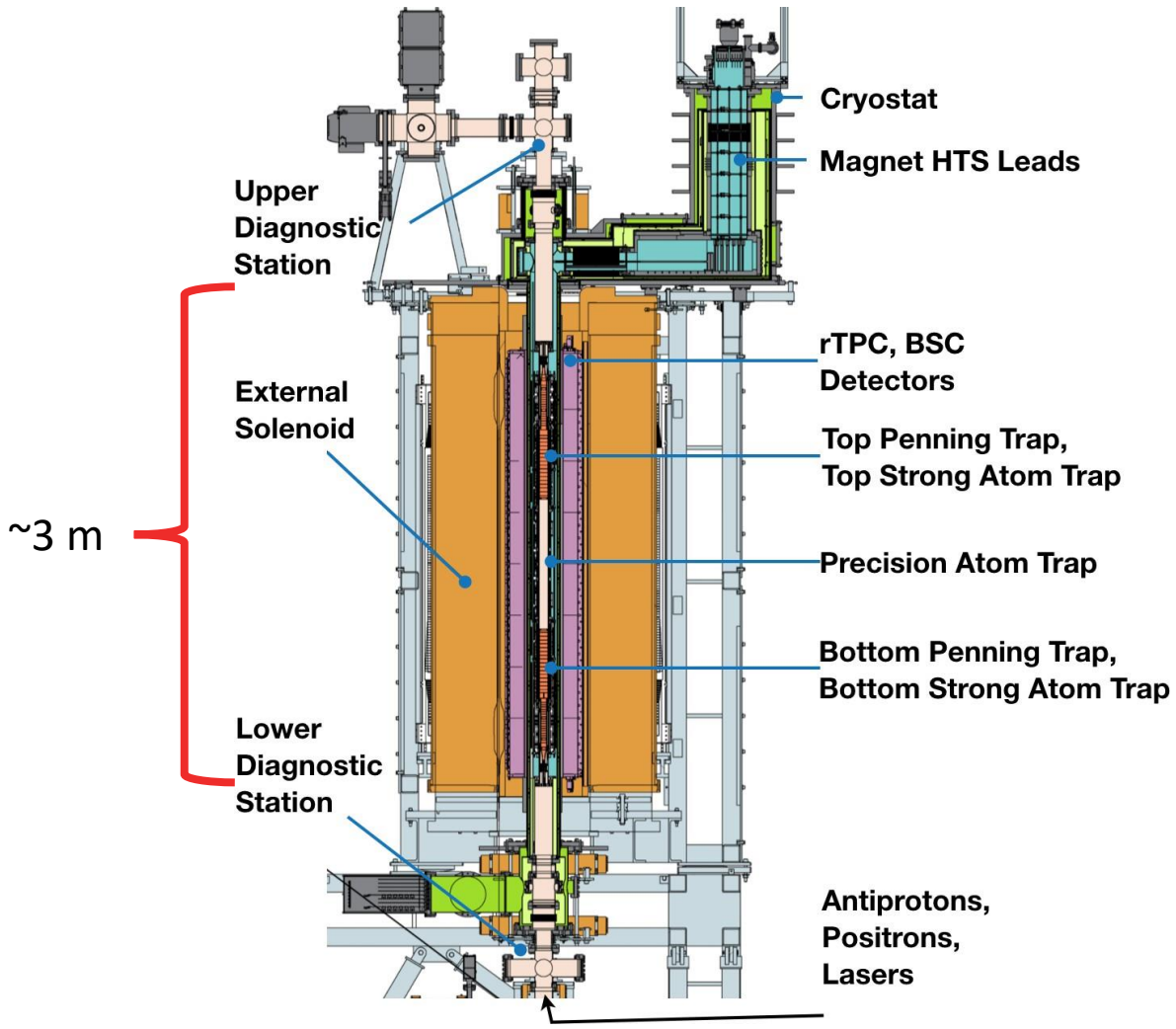
ALPHA-g schematic



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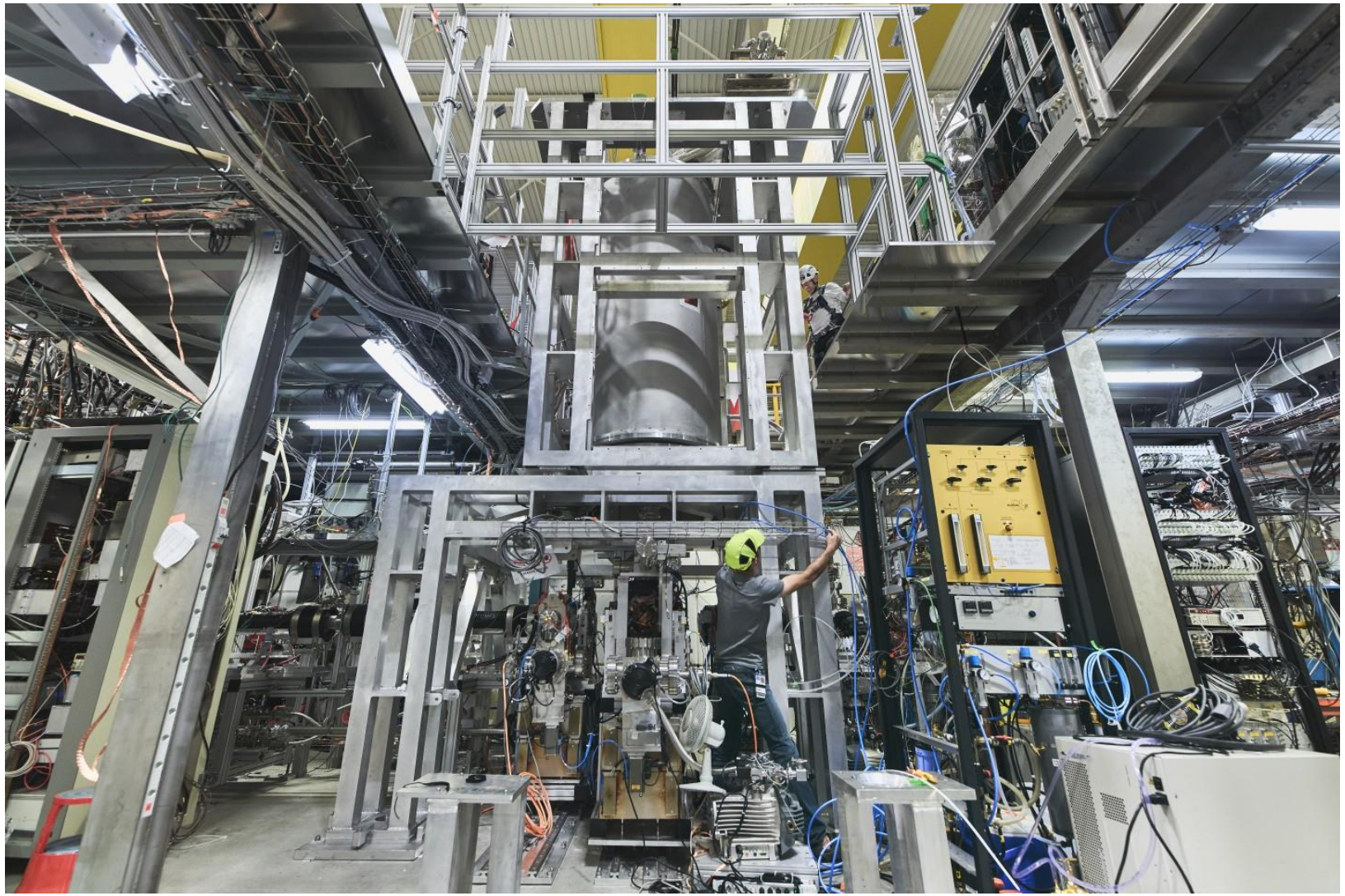
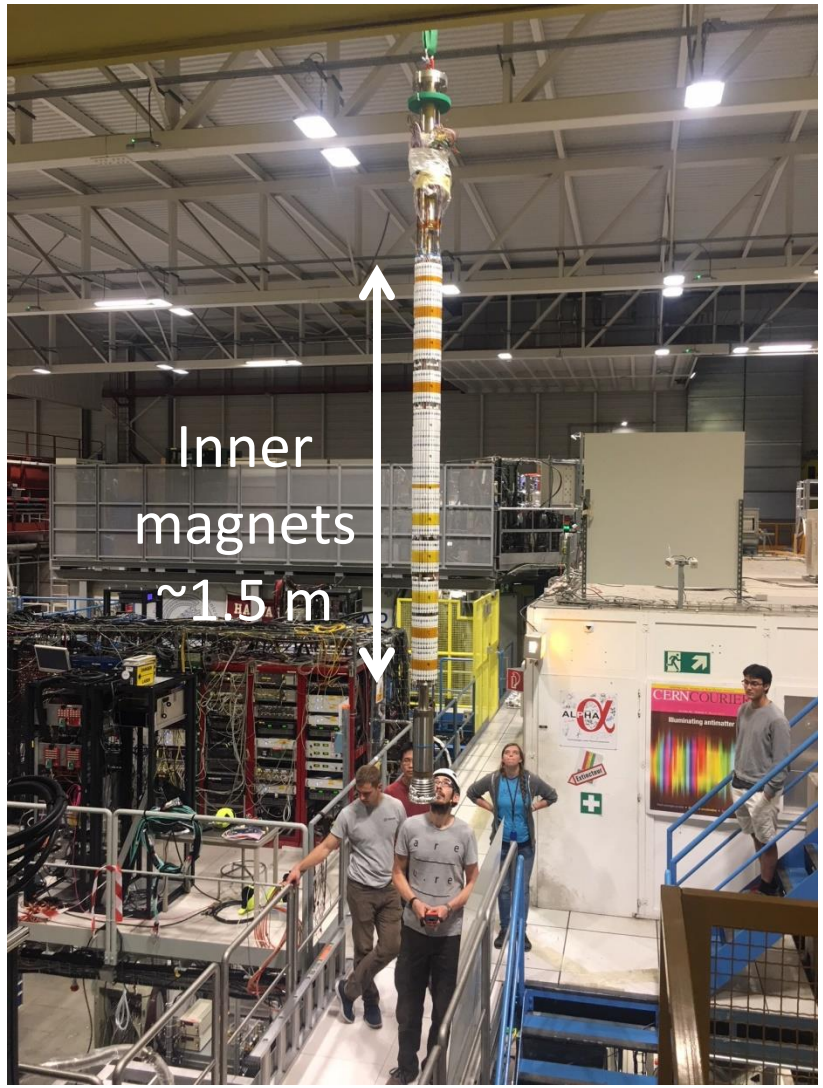
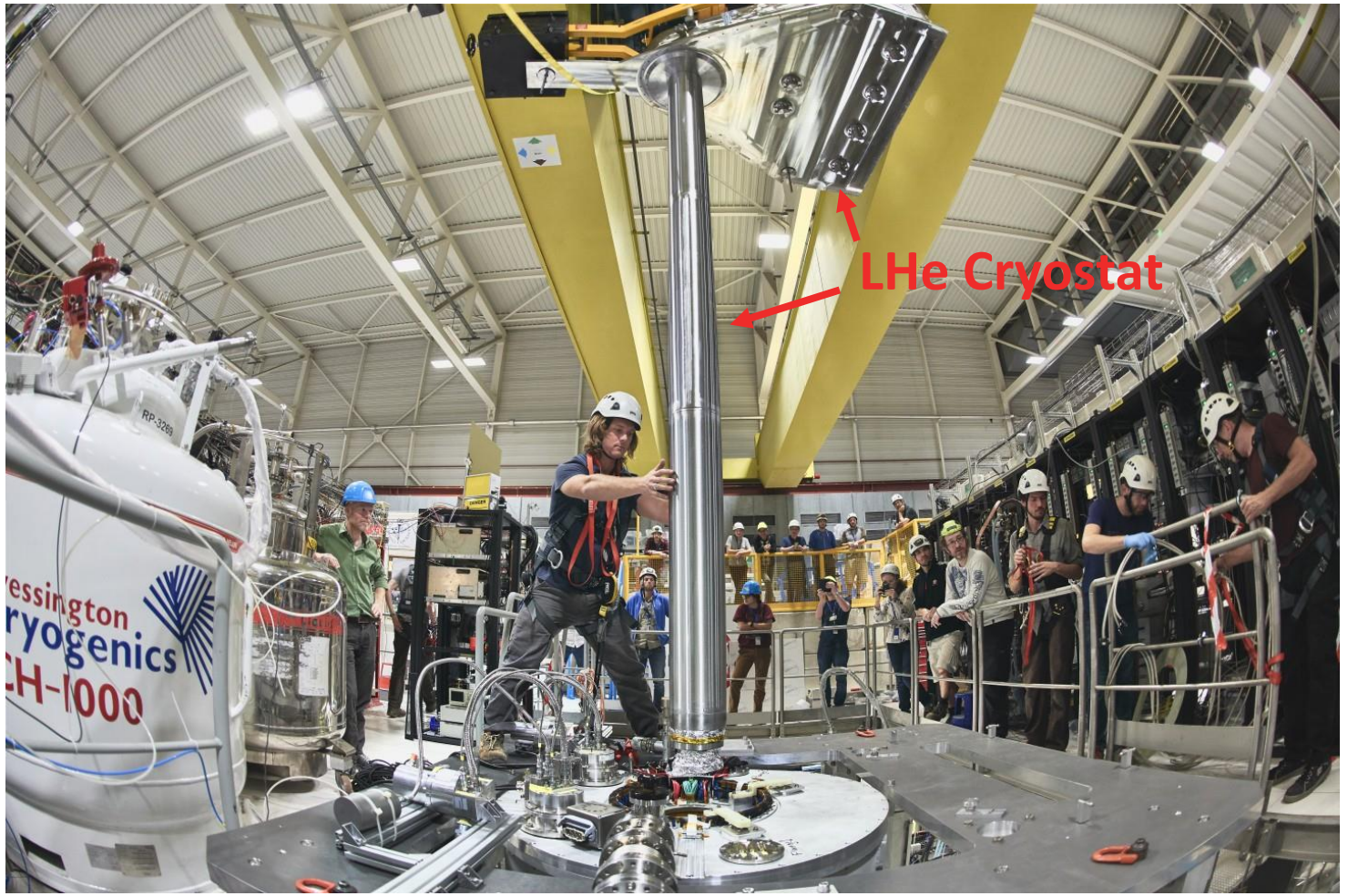
ALPHA-g reality



ALPHA-g reality





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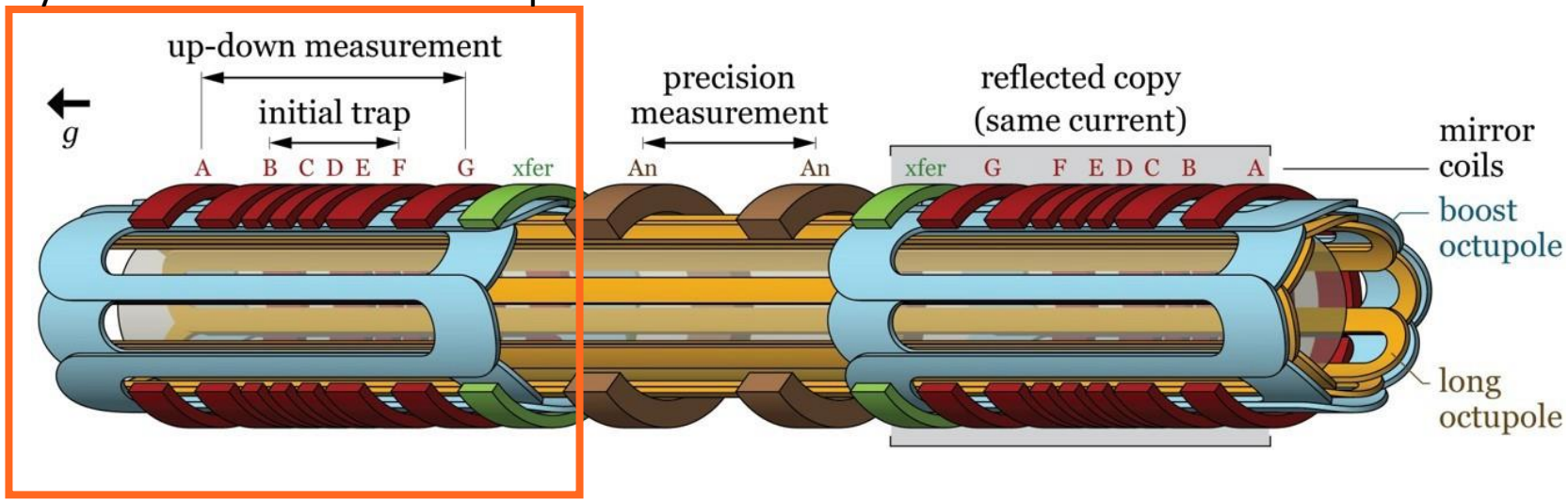
“up-down” measurement

Only coils A + G + bottom octupole



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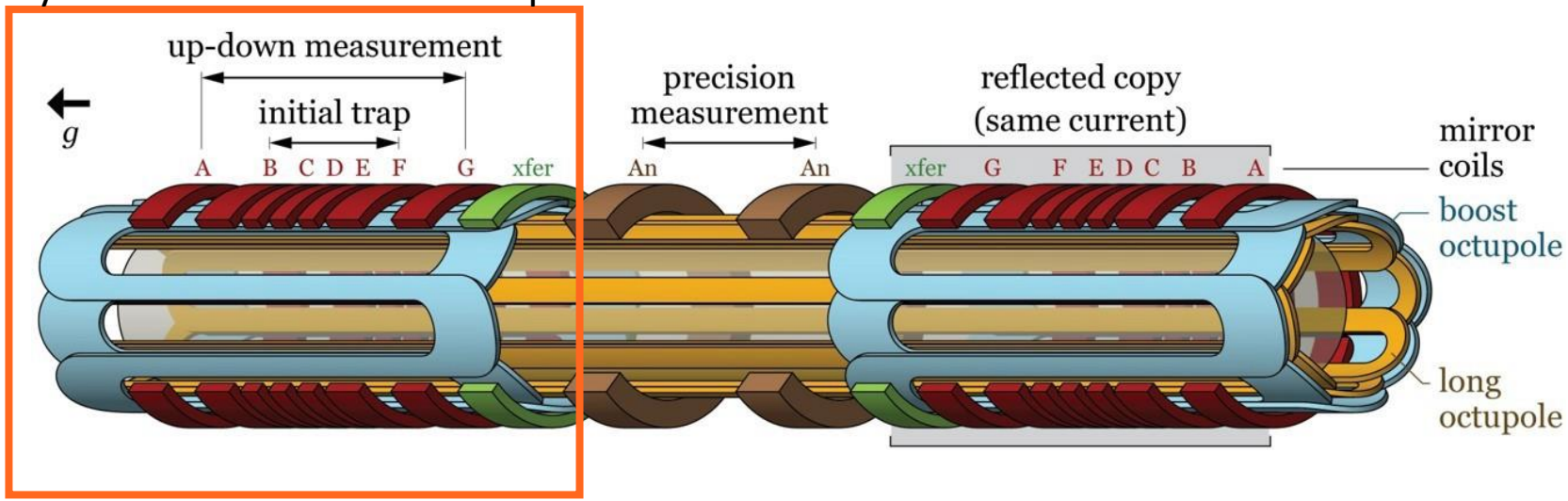
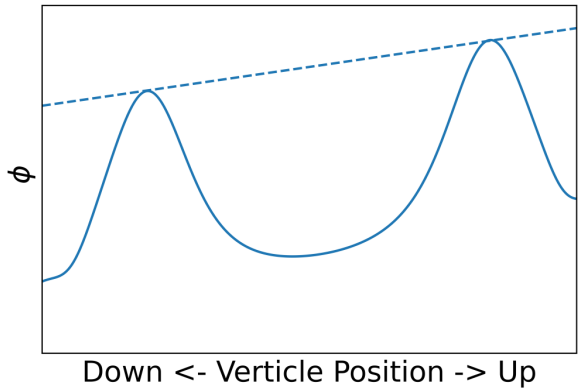


$$\phi = \mu_B B - mgh$$

$$\Delta\phi = -mg\Delta h$$

$$\Delta B \sim 4 \times 10^{-4}\ \mathrm{T}$$



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Magnetic field measurements

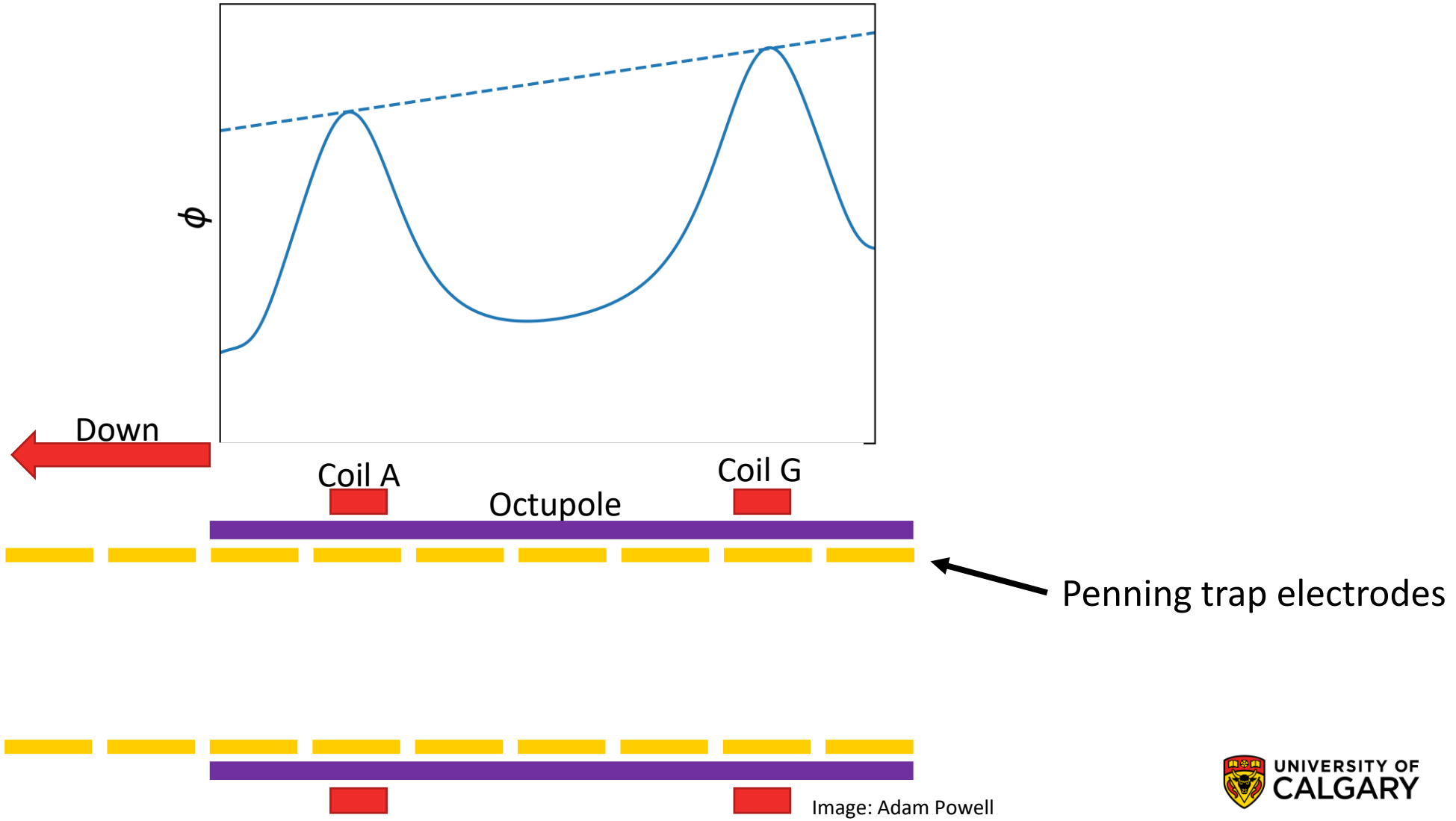

Image: Adam Powell

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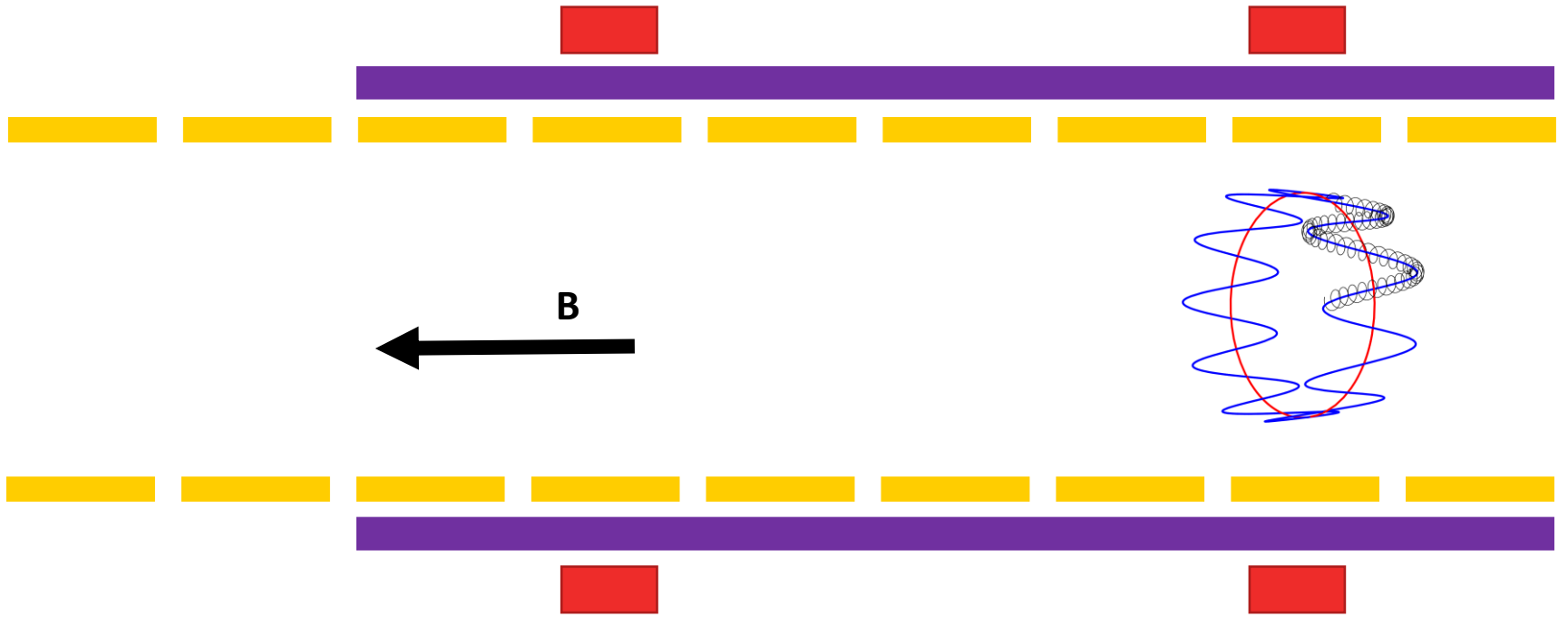
Electron cyclotron resonance magnetometry



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

At 1 T $f_c \approx 28$ GHz

Electron cyclotron resonance

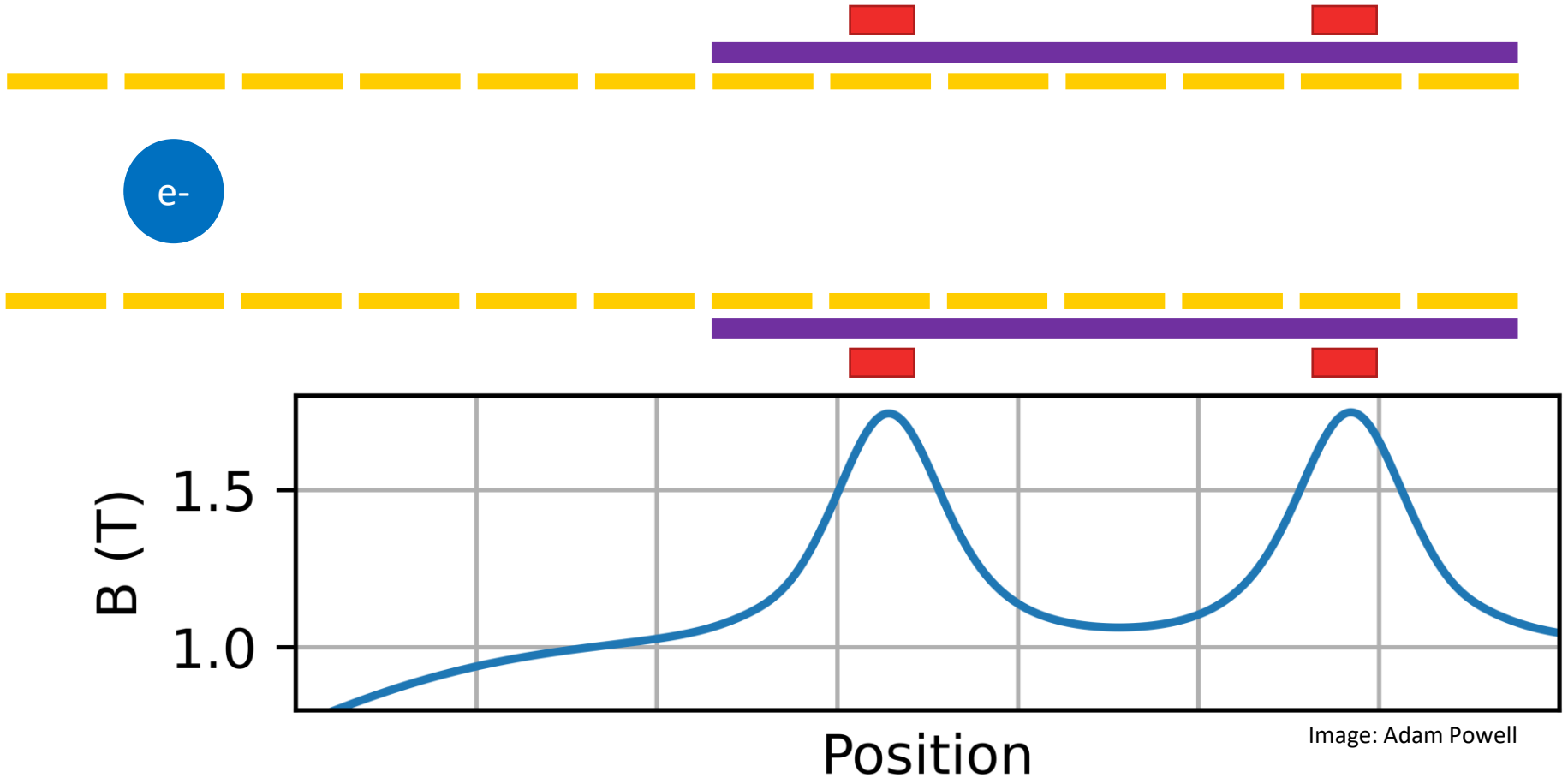


Image: Adam Powell

Electron cyclotron resonance

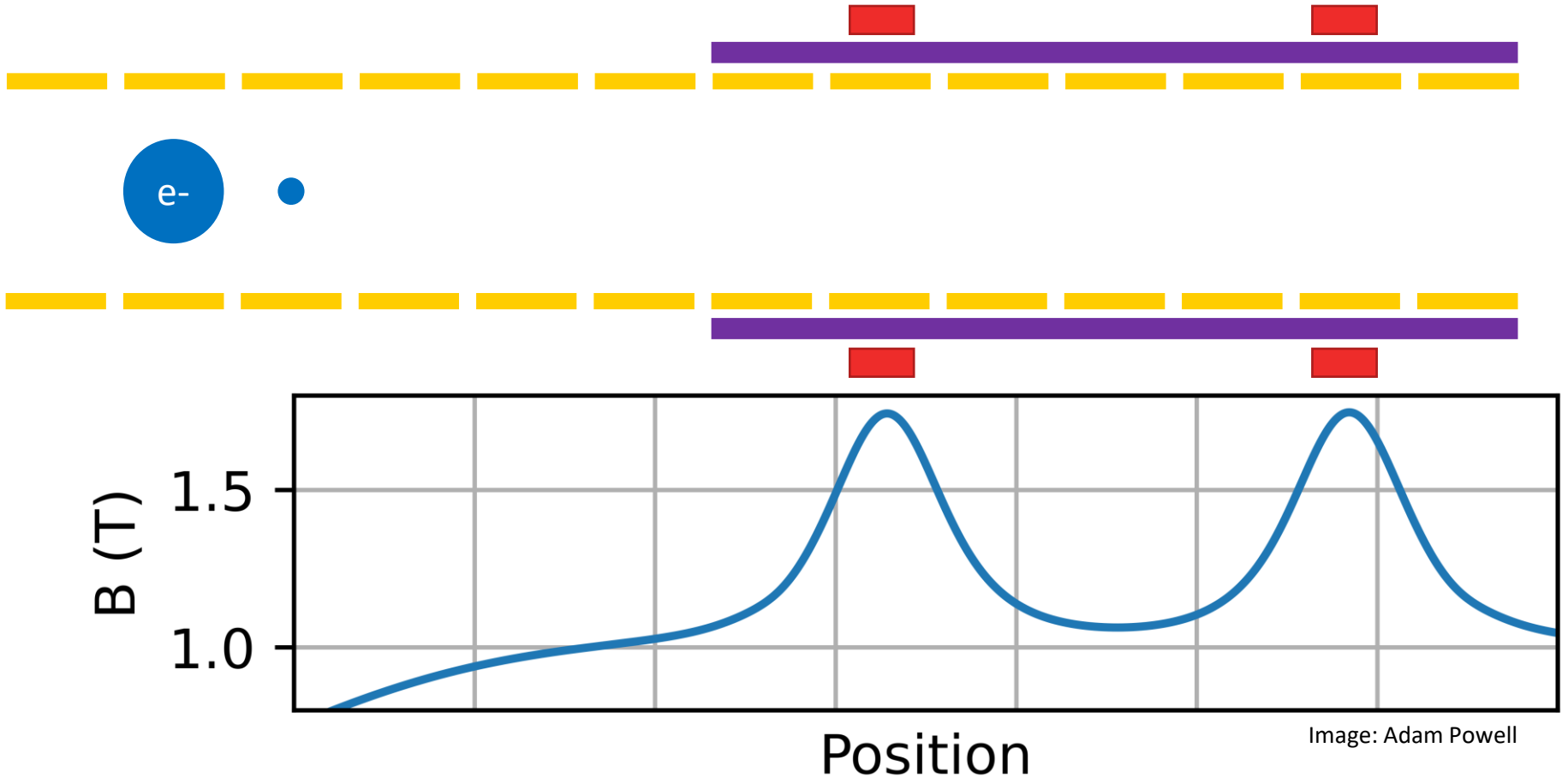


Image: Adam Powell

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Electron cyclotron resonance

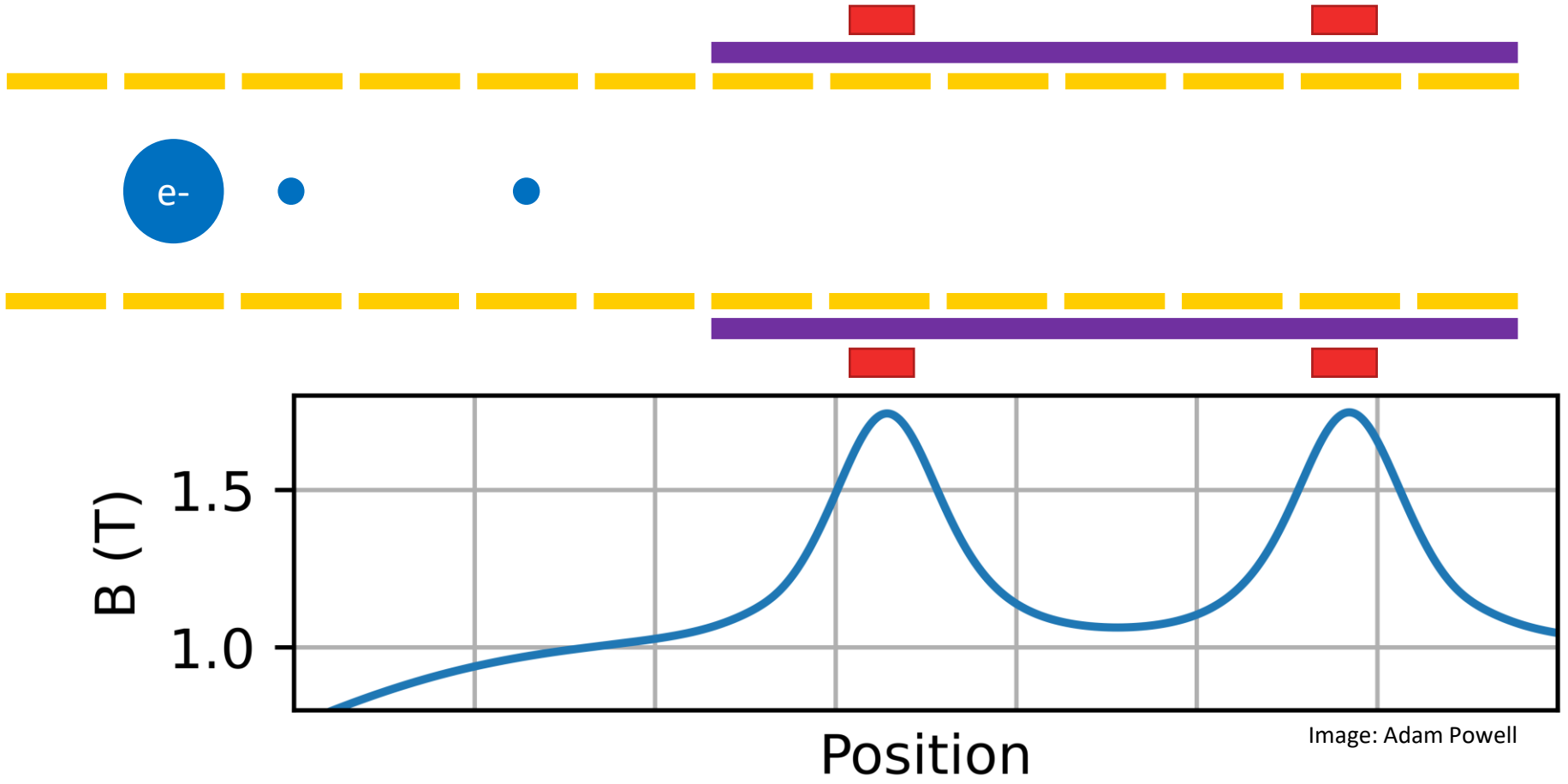


Image: Adam Powell

Electron cyclotron resonance

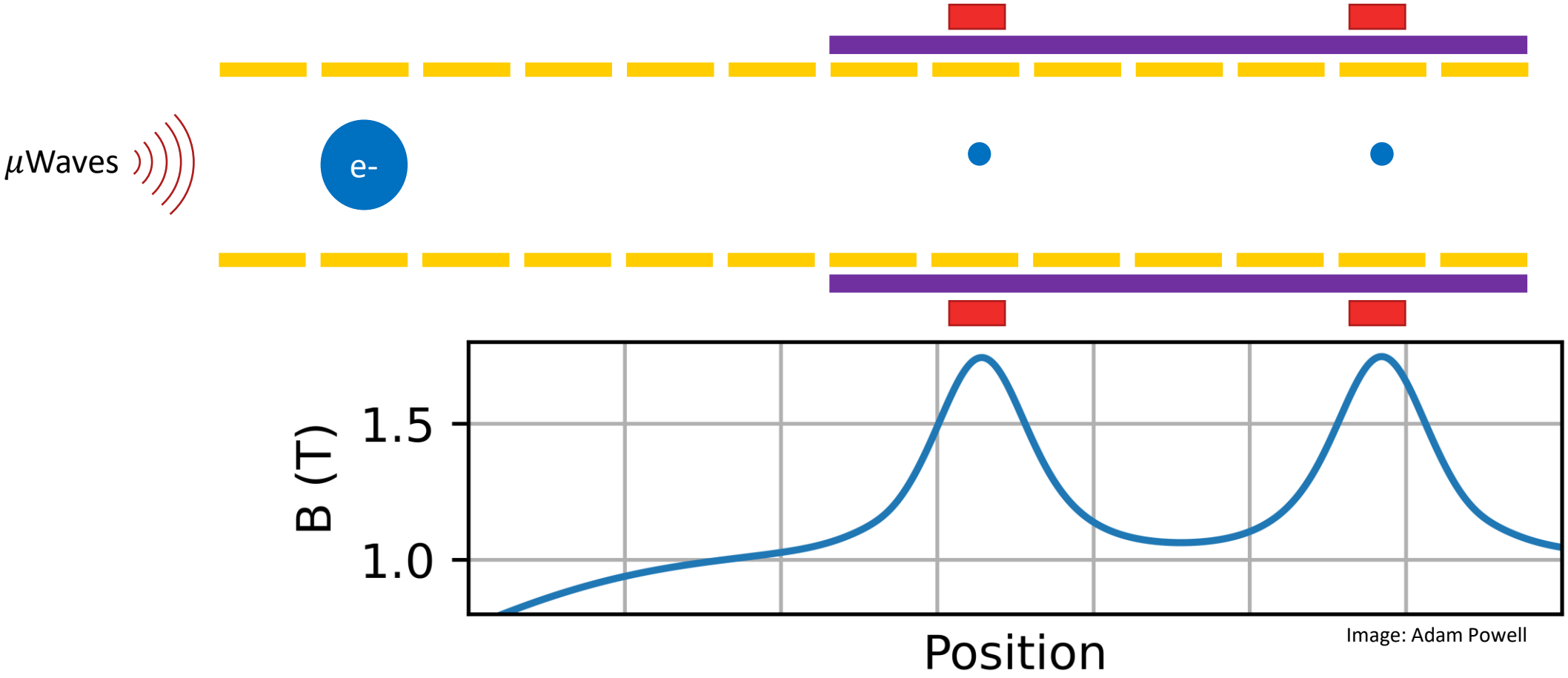


Image: Adam Powell

Electron cyclotron resonance

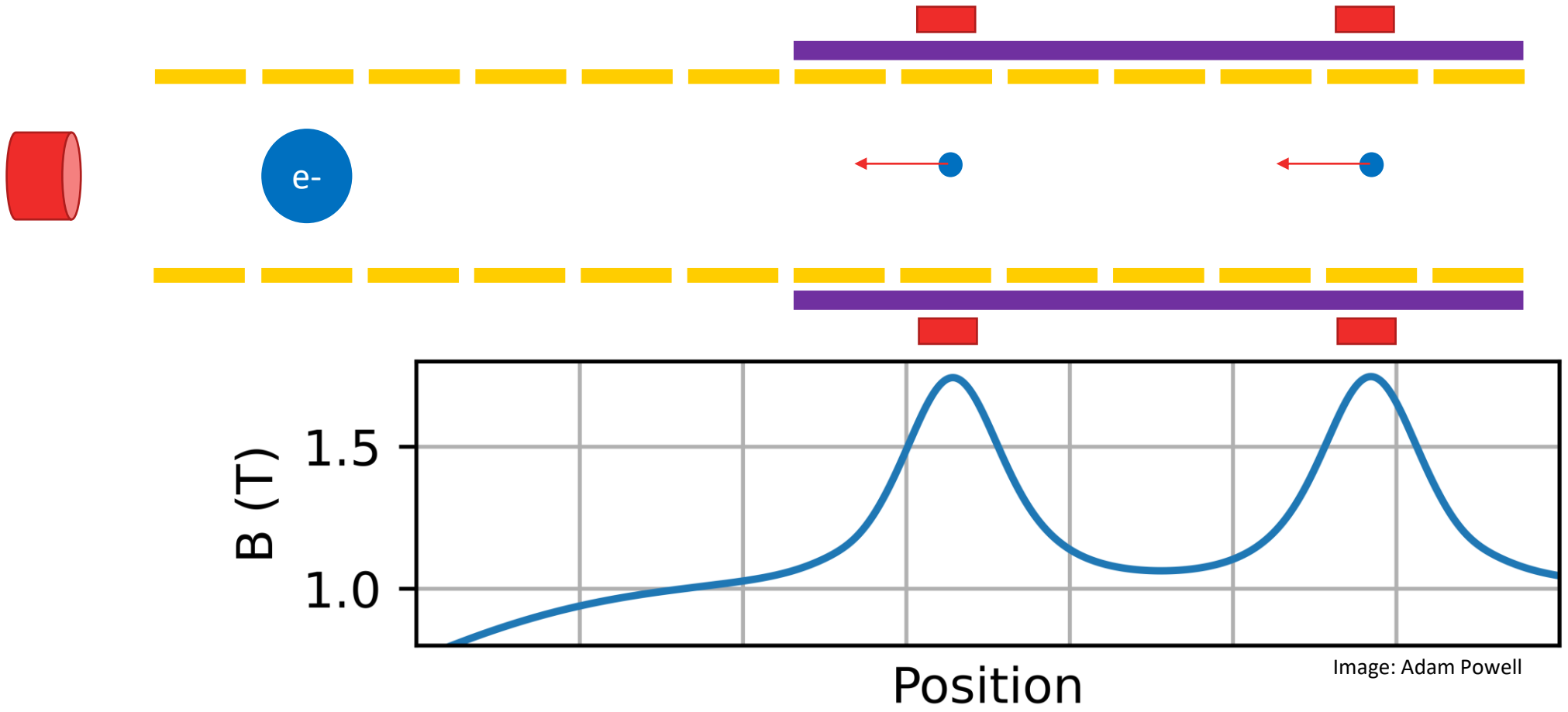
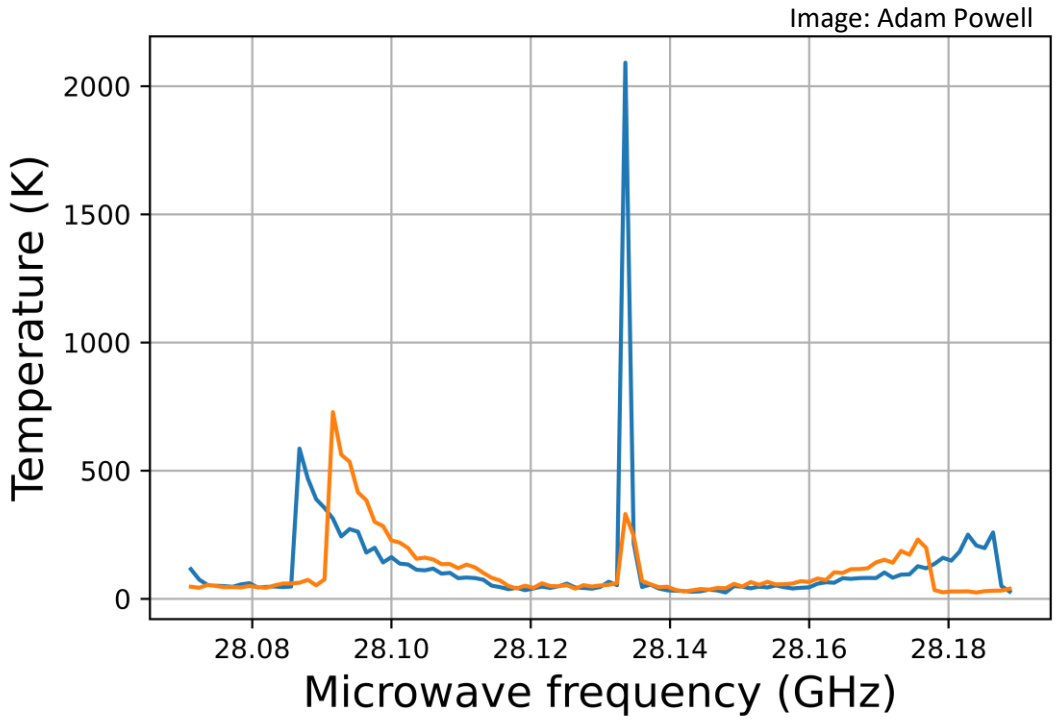


Image: Adam Powell

Electron Cyclotron Resonance (ECR) Magnetometry with a Plasma Reservoir
E. D. Hunter, A. Christensen, J. Fajans , T. Friesen, E. Kur, and J. S. Wurtele (2019)

Electron cyclotron resonance

Image: Adam Powell



- Narrow central peak = $f_c = \frac{q\,B}{2\,\pi\,m}$
- Precision related to peak width
- Broad, asymmetric sidebands from electrons axial motion

Electron cyclotron resonance

Image: Adam Powell

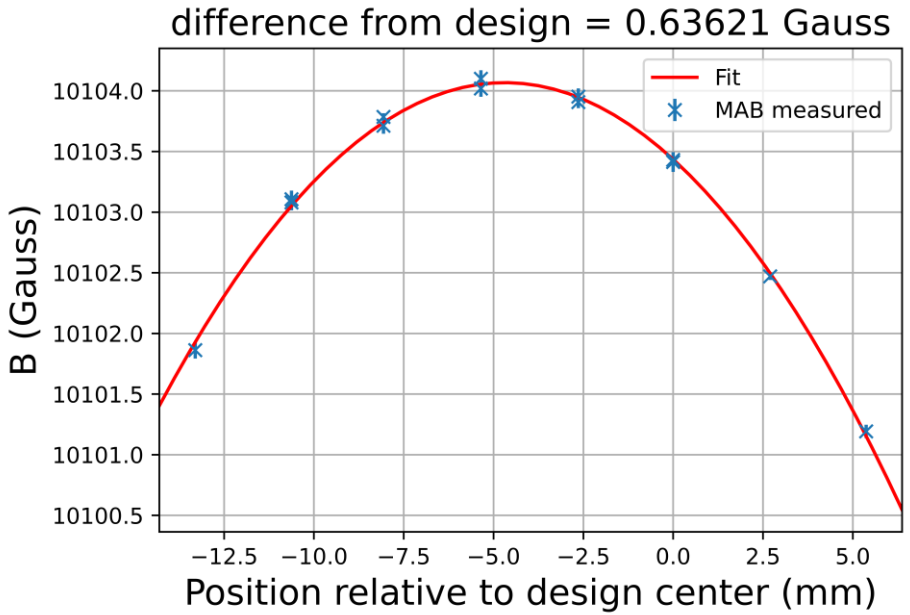
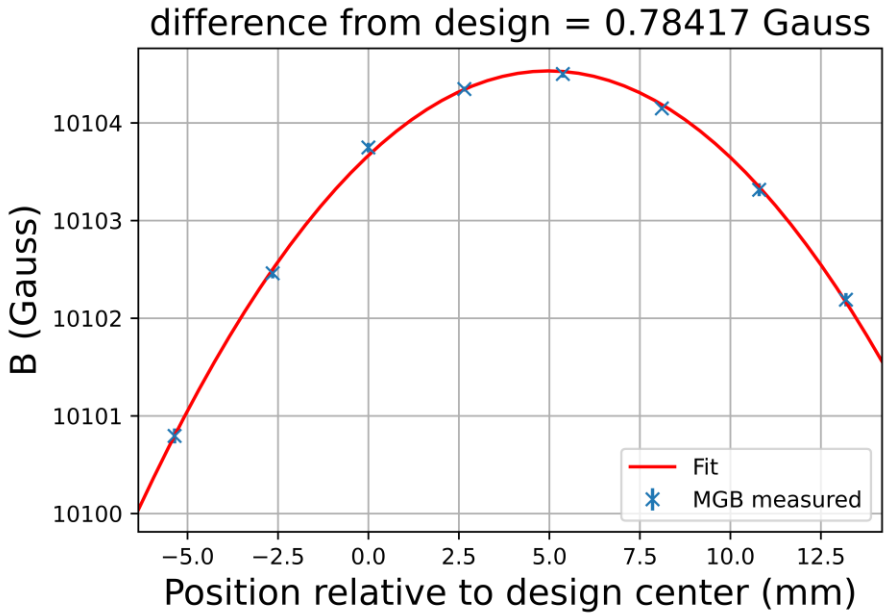
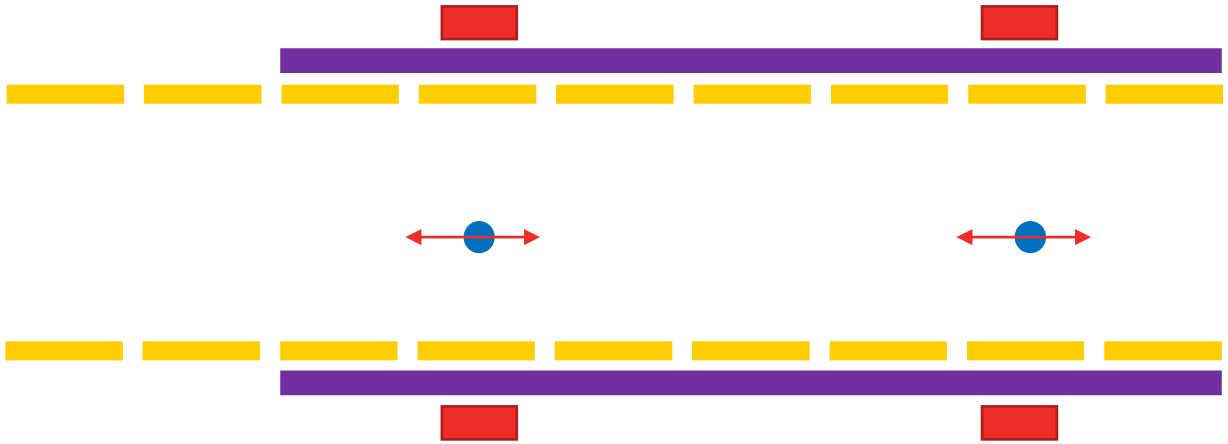


Image: Adam Powell





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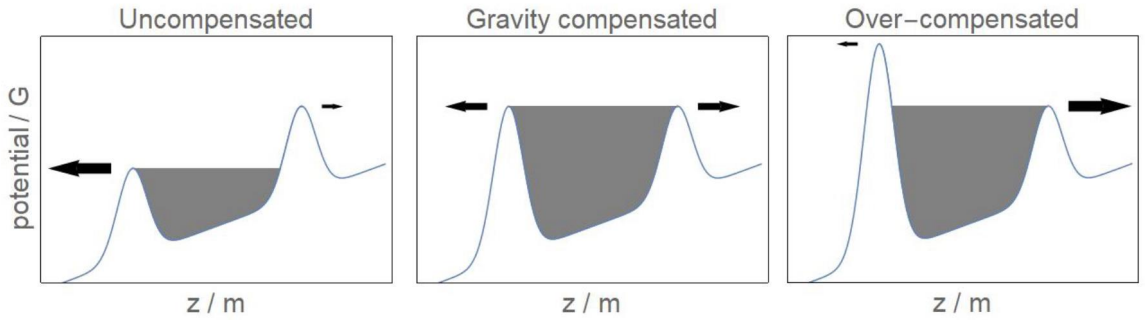
“up-down” measurement scheme

- Accumulate antihydrogen atoms
- Slowly ramp down the end mirror coils, maintaining bias
- Record annihilations going up or down
- Repeat for various bias values
- ECR field measurements at start and end of mirror ramp
- Extensive offline magnetometry measurements



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Simulated results

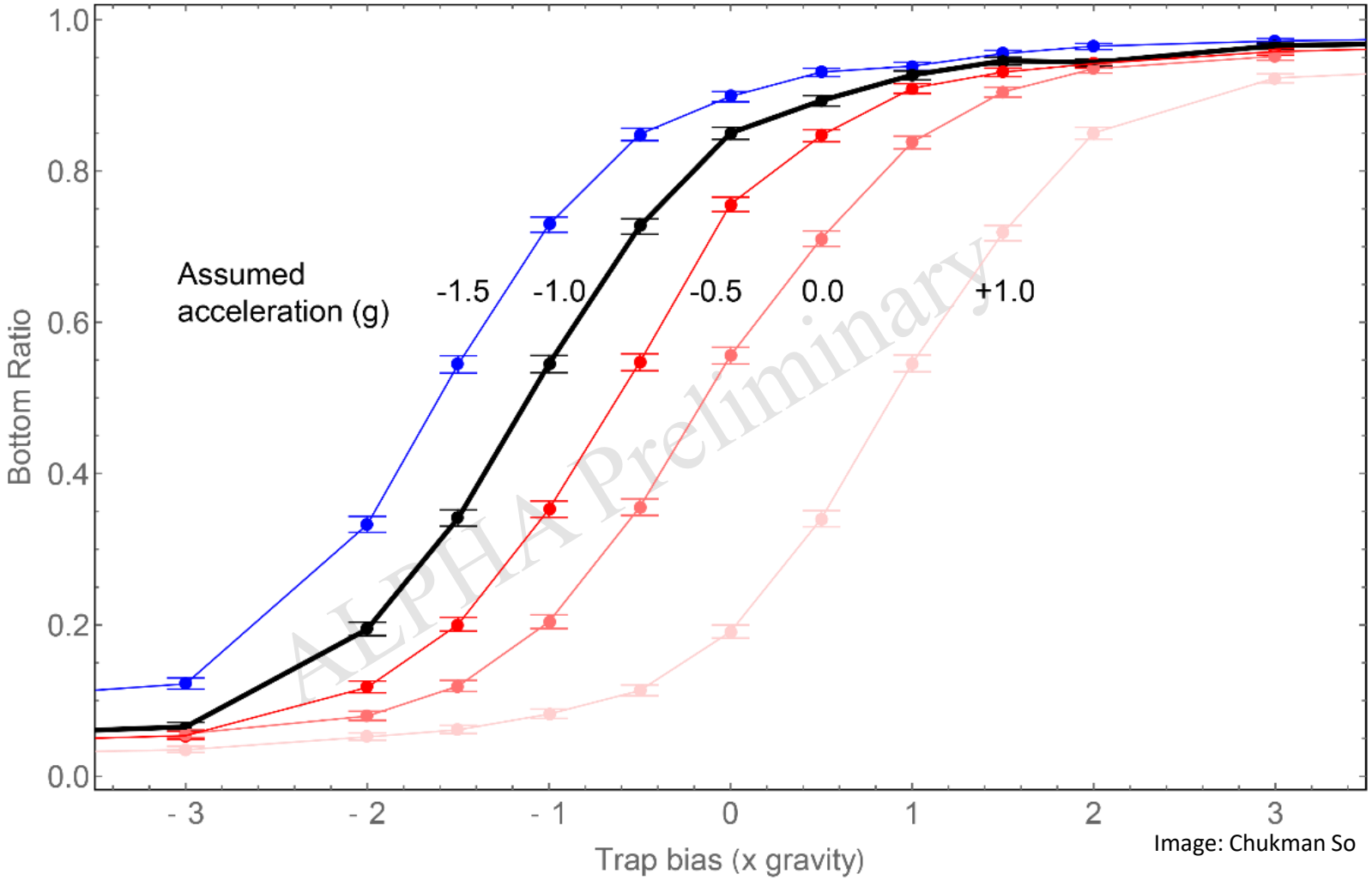

Image: Chukman So

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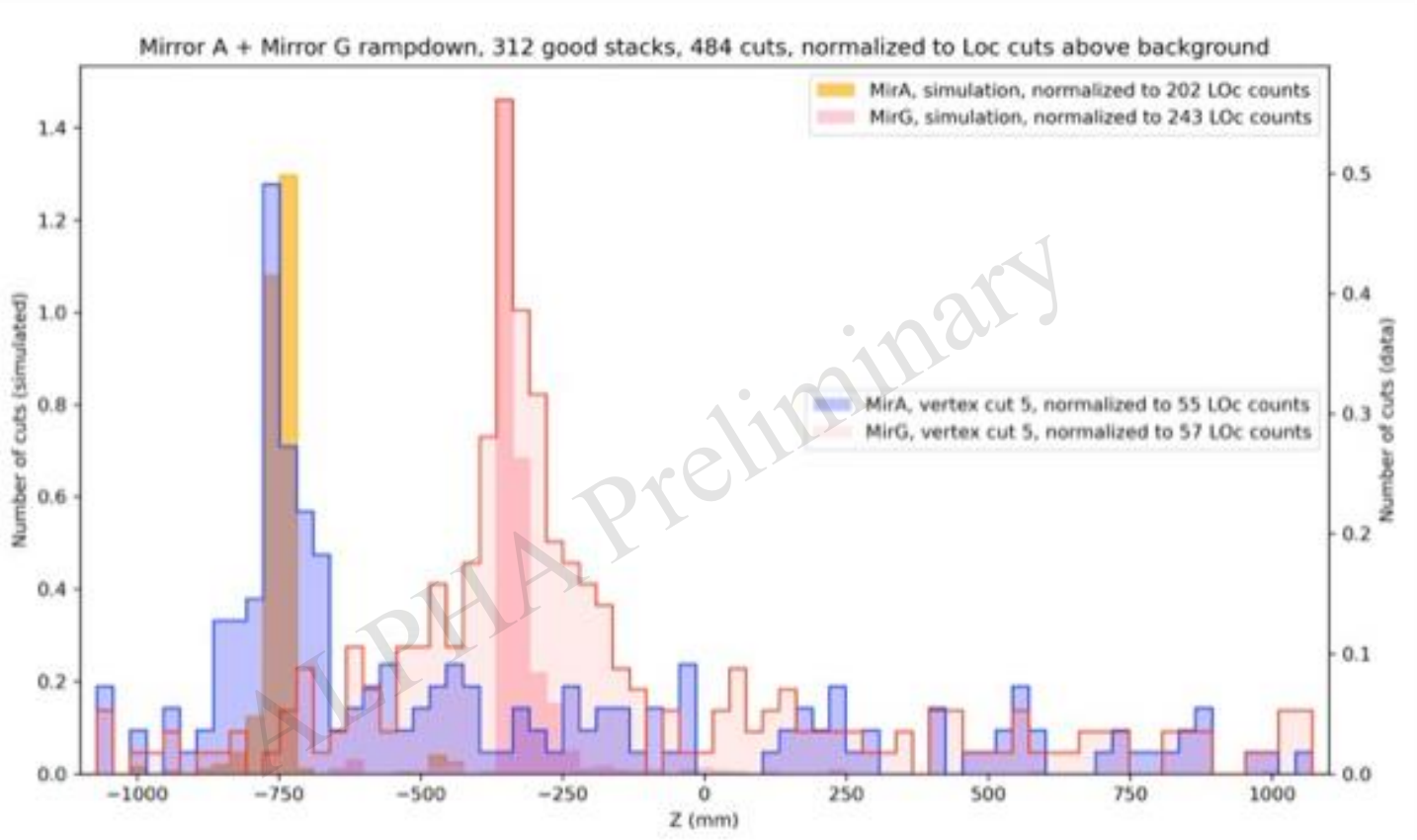
Proof of principle



DOWN

Blue: Trap bias 10x gravity

Red: Trap bias –10x gravity

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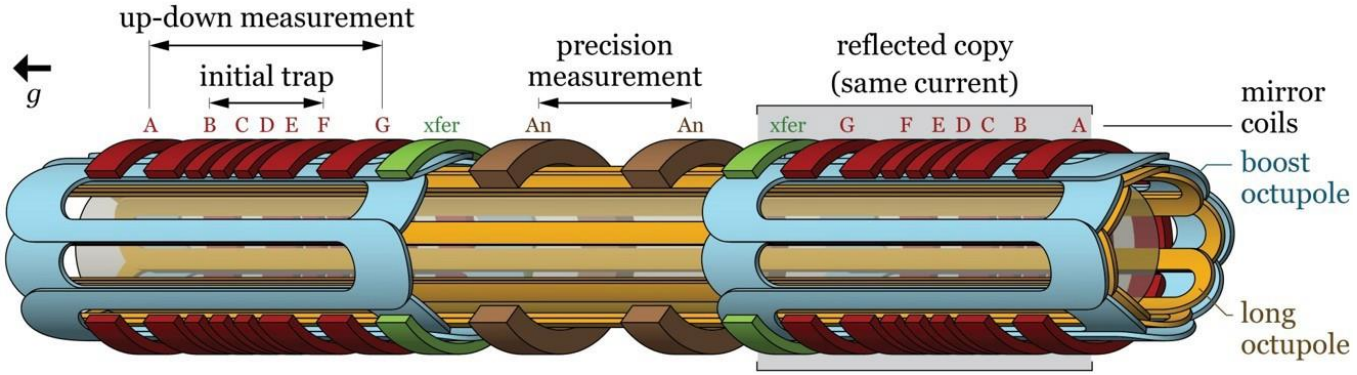
ALPHA-g status and prospects

- In 2022 we completed a set of experiments at various biases. Analysis in progress…
- Future precision:
  - Slower ramps
  - Improved background rejection
  - Improved magnetometry
  - Validation of simulations
  - Colder antihydrogen (laser cooling, adiabatic cooling)



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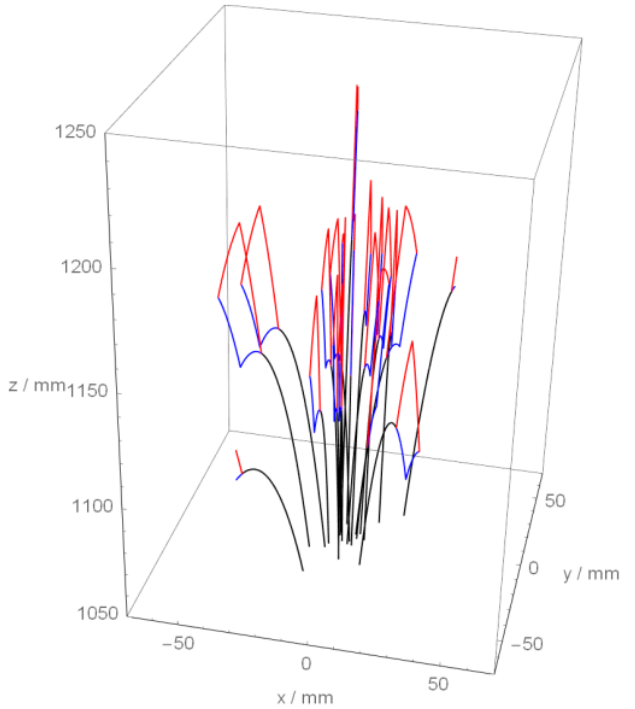
HAICU(俳句): Hydrogen-Antihydrogen Infrastructure at Canadian Universities

- R&D platform for development for "quantum sensing" techniques for anti-H
- Use H (and other cold atoms) as proxy
  - (Anti)atomic fountain
  - (Anti)Matter-wave interferometer

    With H. Mueller
  - Ramsey hyperfine spectroscopy
  - Optical trapping
  - Antimatter molecules
- Hydrogen difficult to handle
  - 1s-2p transition at 121 nm
  - Difficult to trap & detect
  - No fountain made with H

(Anti)Hydrogen Interferometer Simulation



- Techniques needed for anti-H could be useful to improve H measurements

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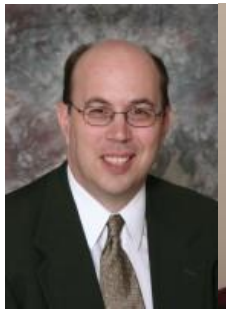
Thanks!

Tim Friesen
timothy.friesen@ucalgary.ca

Alberto Jesus Uribe Jimenez



Prof.
R.I. Thompson

Adam Powell

Pooja Woosaree

Jay Suh

Abbygale Swadling

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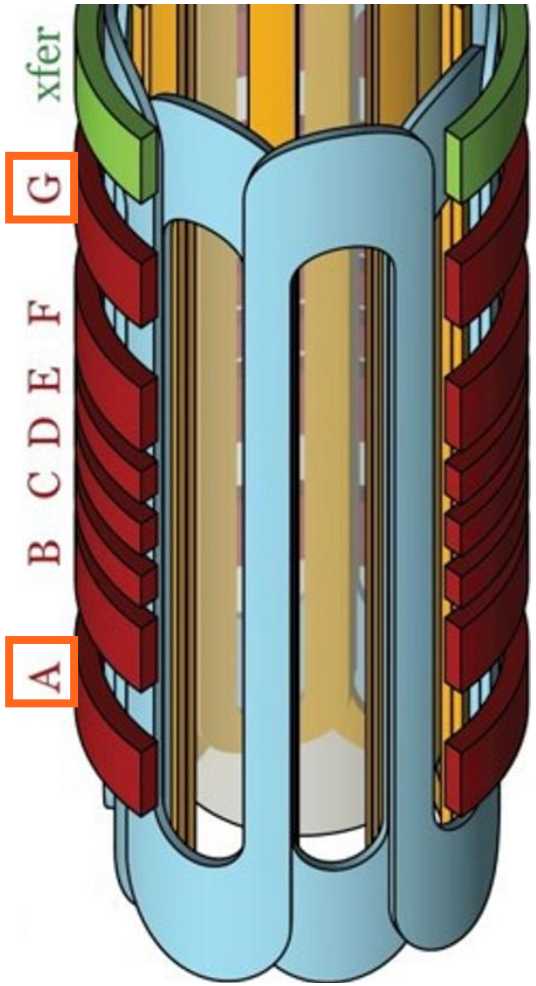
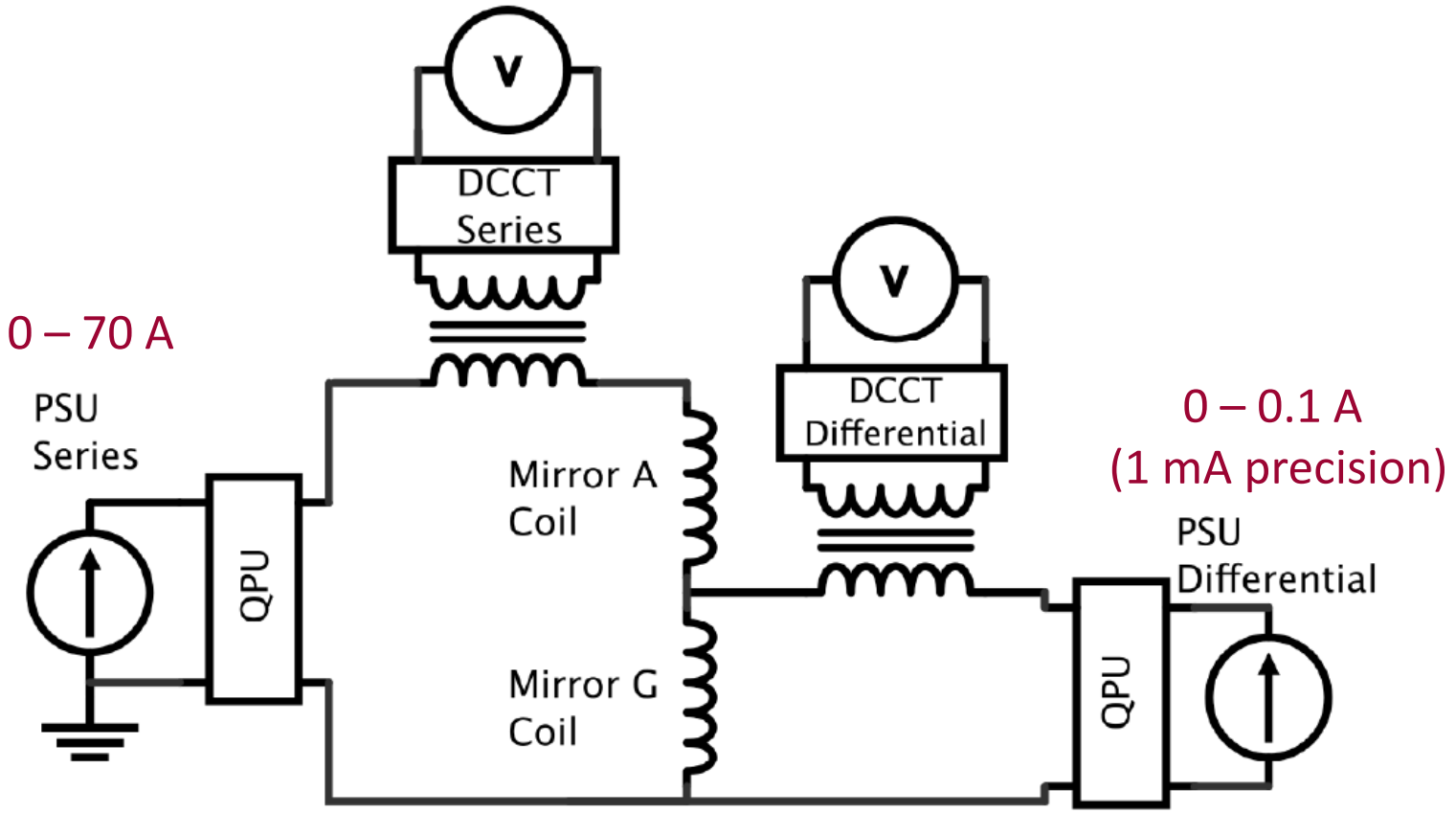
Magnet control





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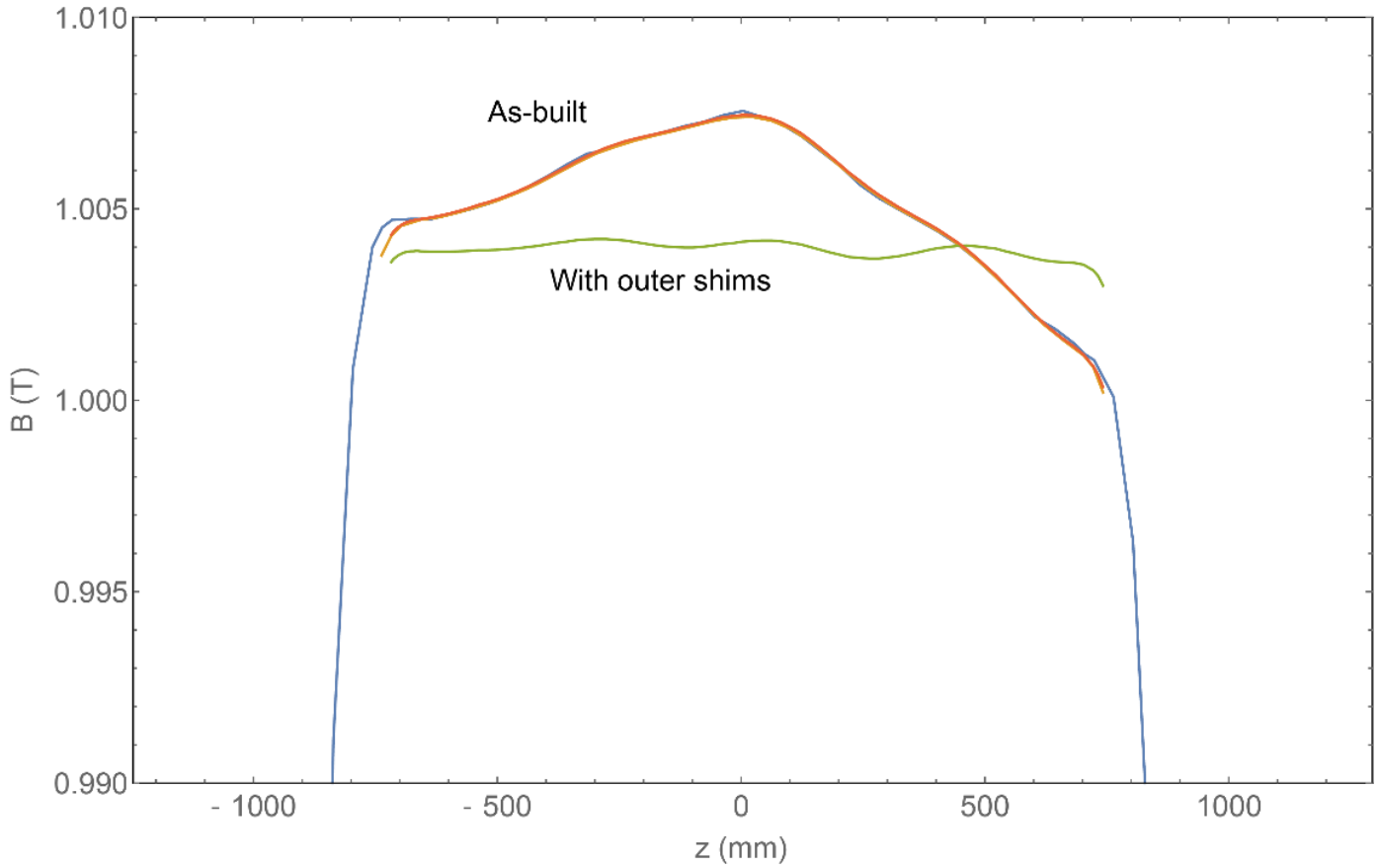
Background solenoid uniformity



As-built: 20 G non-uniformity

With outer shims: ~4 G non-uniformity

(As measured with hollow solenoid using NMR magnet probes)

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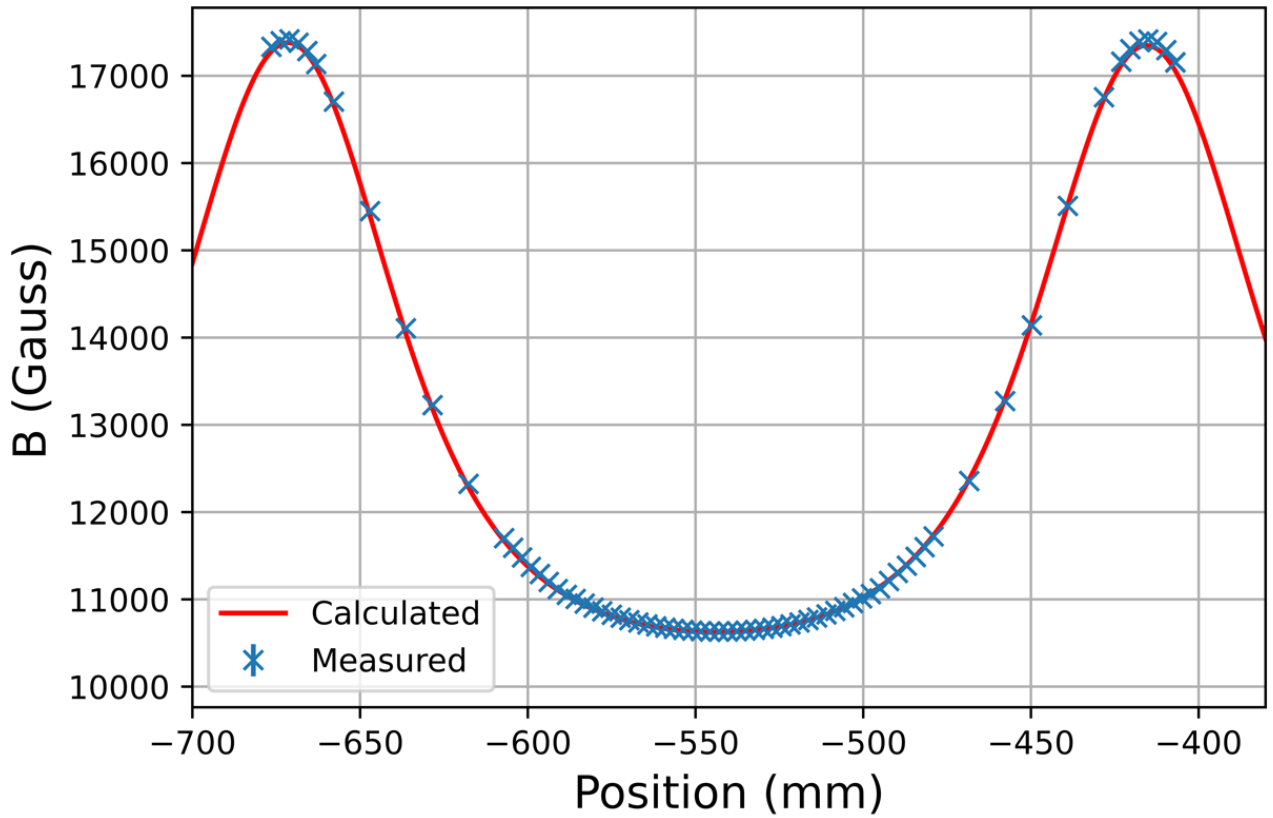
Electron cyclotron resonance



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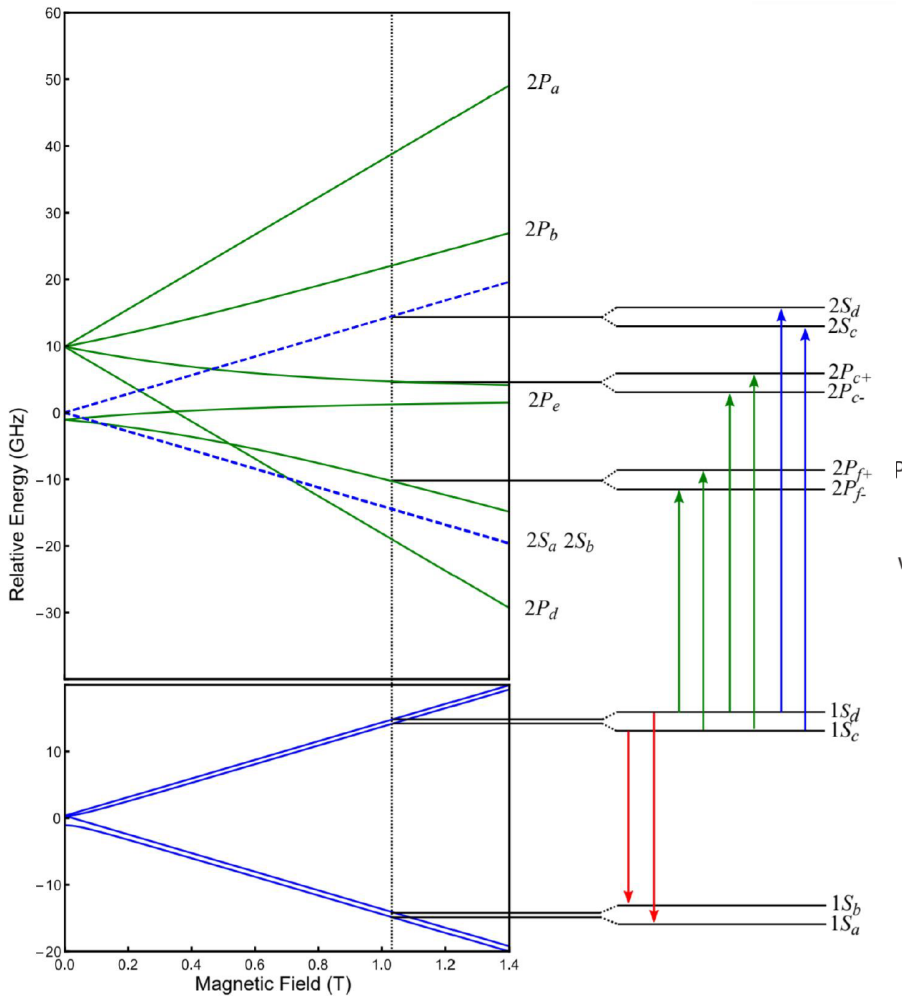
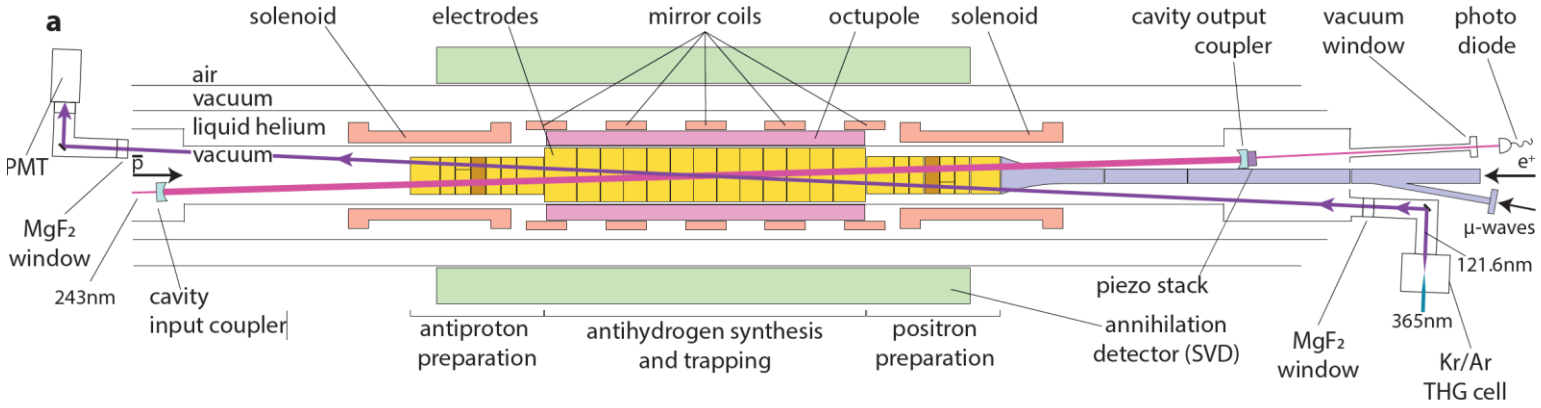
Antihydrogen spectroscopy





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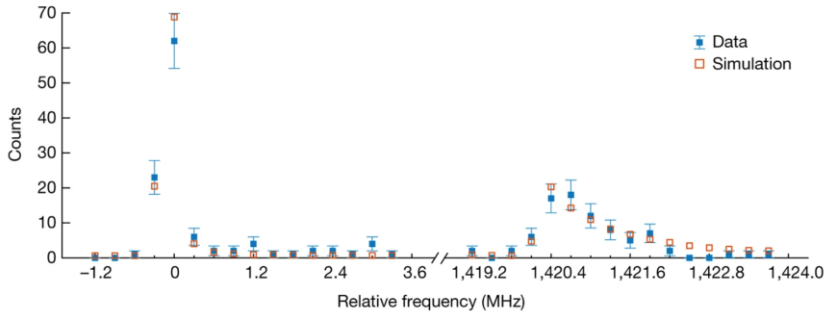
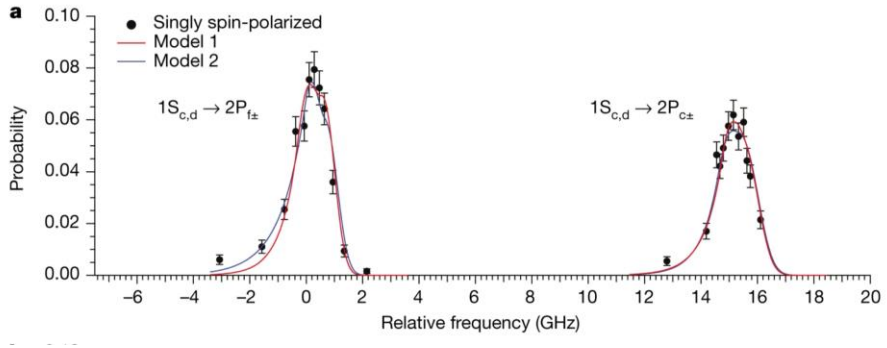
Antihydrogen spectroscopy

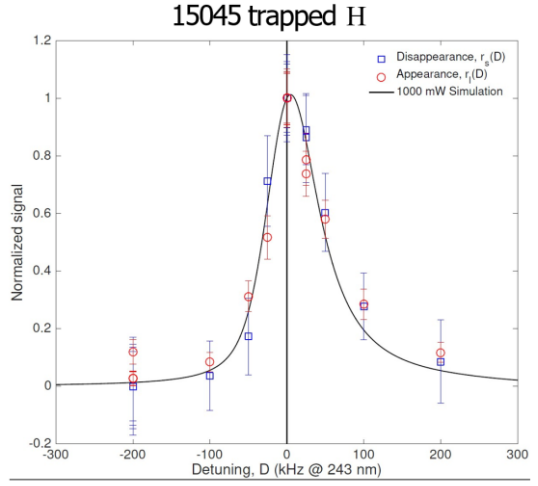
Hyperfine spectrum [M. Ahmadi et al, Nature 548, 66 (2017)]



Fine structure [M. Ahmadi et al, Nature 578, 375 (2020)]



1S – 2S spectroscopy [M. Ahmadi et al, Nature 557, 71 (2018)]



Result: f_{d-d} = 2, 466, 061, 103, 079.4 (5.4) kHz

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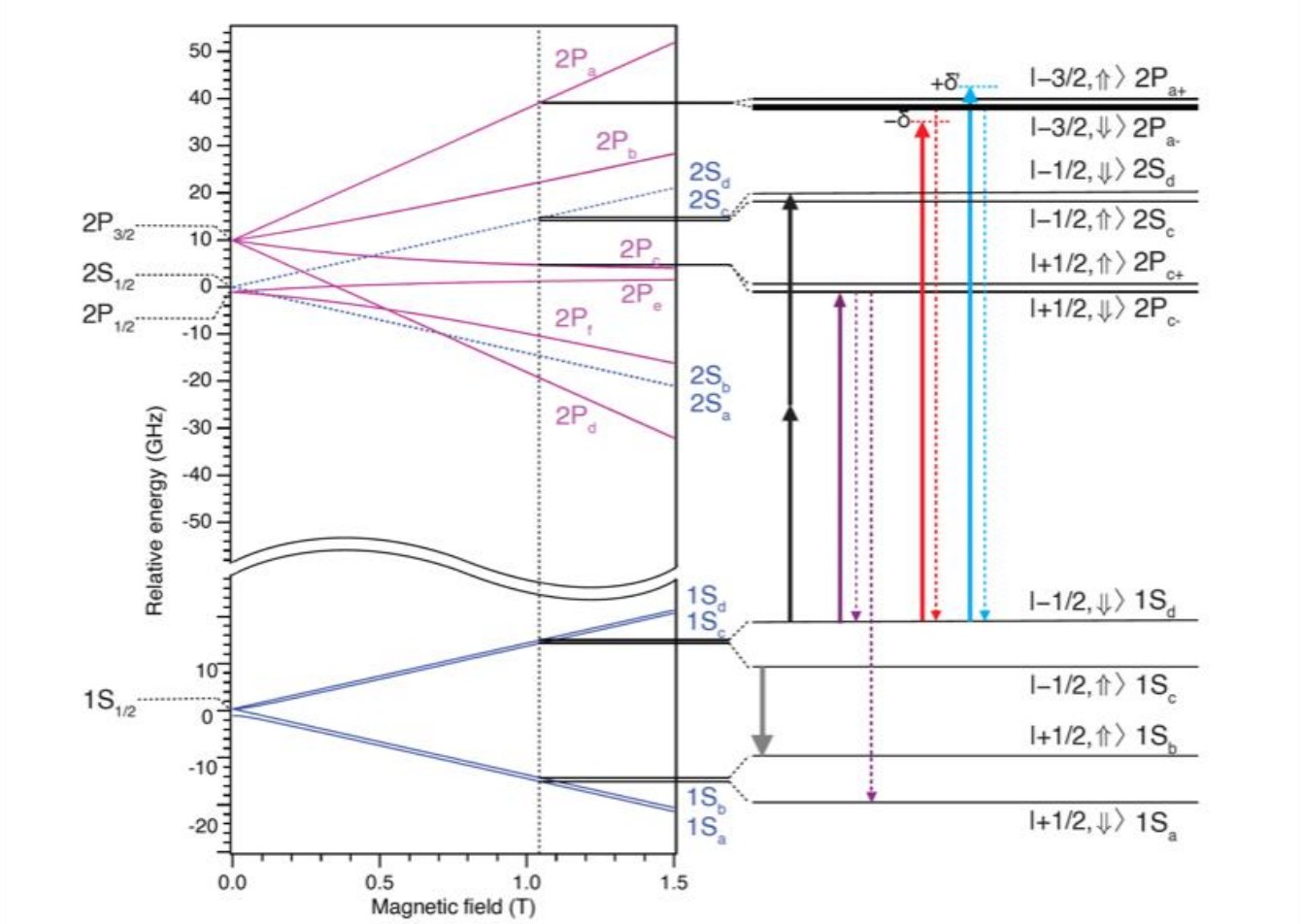
Laser cooling antihydrogen



Pulsed 121.6 nm generated by THG:

- Approx. 15 ns pulse length
- Approx. 2 - 10 nJ per pulse
- 10 Hz repetition rate
- Detuned -220 MHz for cooling

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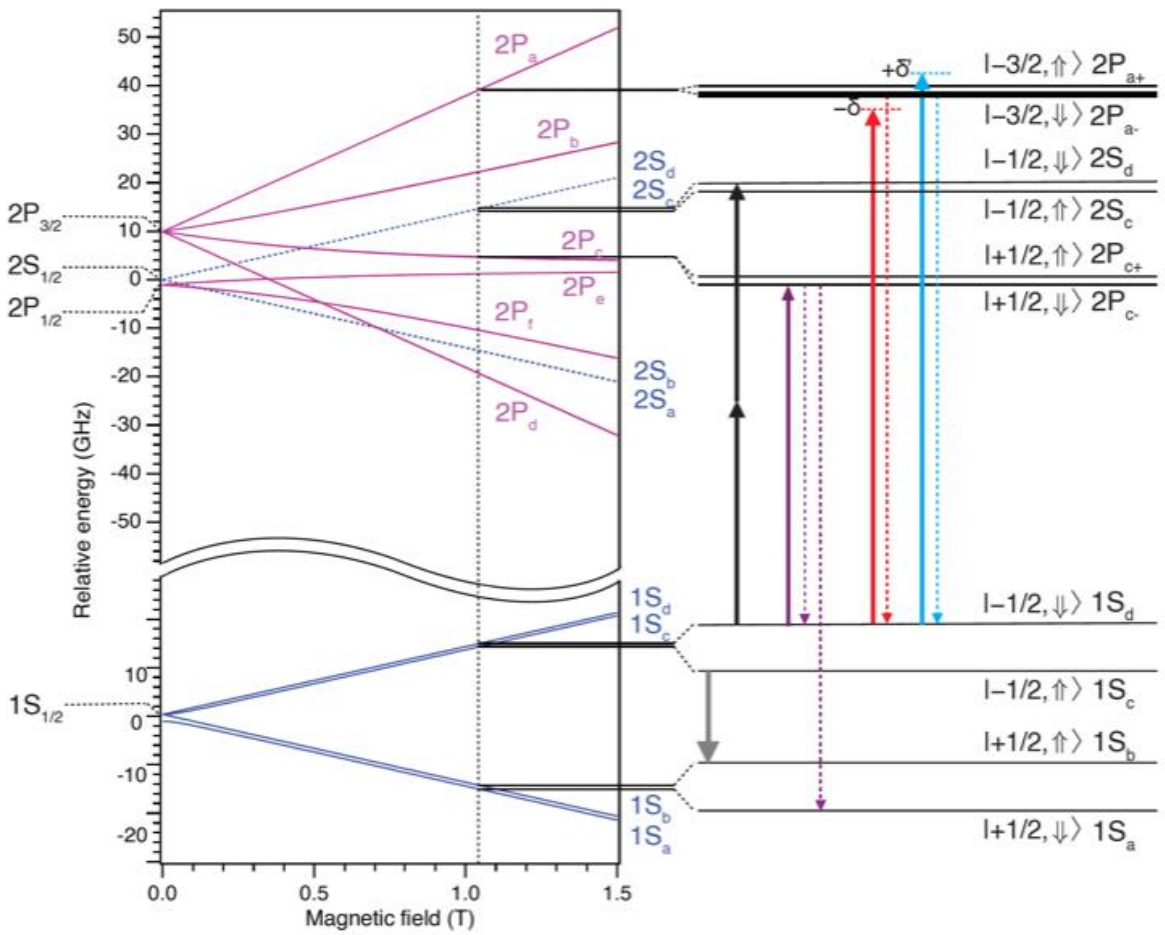
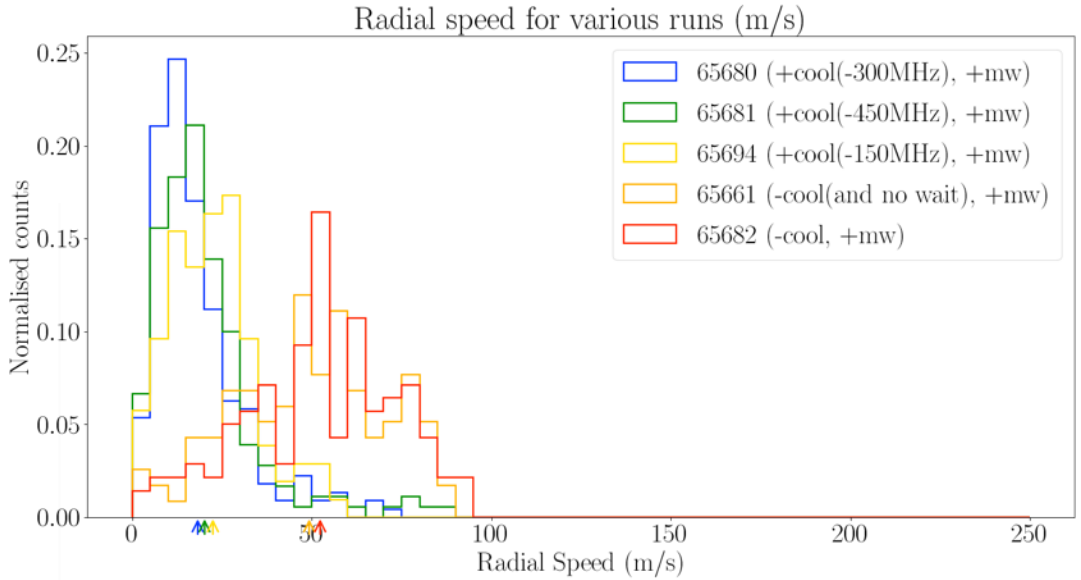
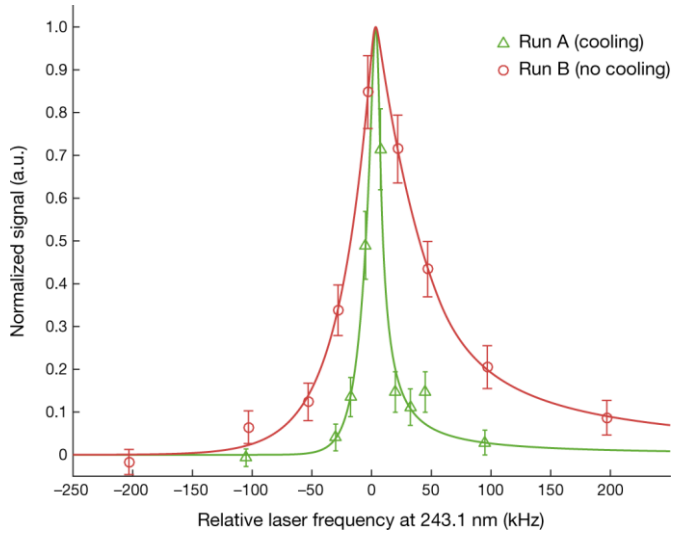
Laser cooling antihydrogen







C. J. Baker et al, Nature 592, 35 (2021)

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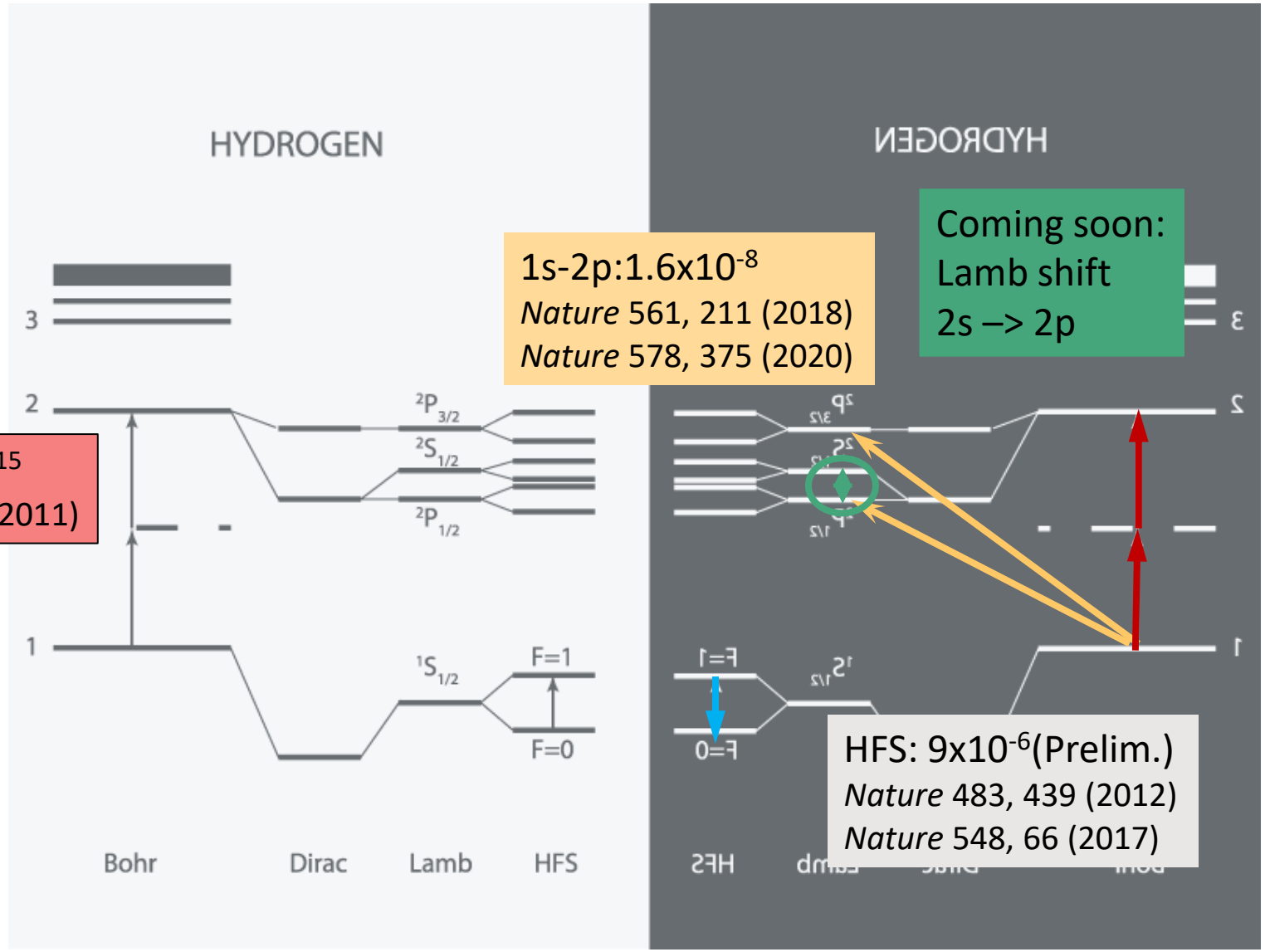
Antihydrogen spectroscopy



1s-2p:1.6x10^{-8}
Nature 561, 211 (2018)
Nature 578, 375 (2020)

Coming soon:
Lamb shift
2s –> 2p

1s-2s: 4x10^{-15}
PRL 107, 203001 (2011)

1s-2s: 2x10^{-12}
Nature 541, 506 (2017)
Nature 557, 71 (2018)

HFS: 9x10^{-6}(Prelim.)
Nature 483, 439 (2012)
Nature 548, 66 (2017)

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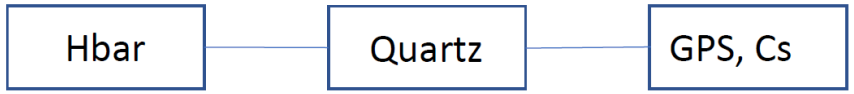
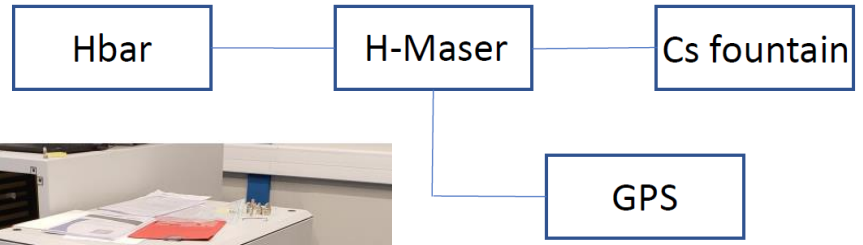
Toward higher precisions

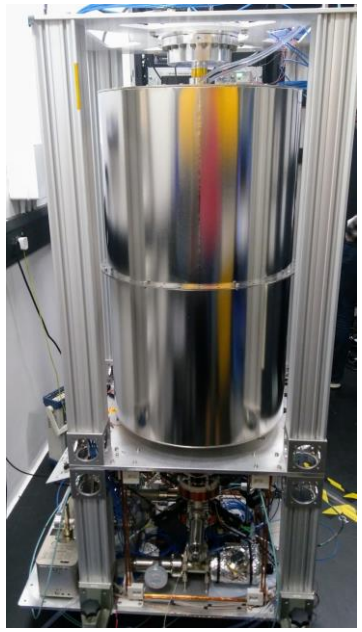
- **Laser cooling**: Upgraded 121 nm system (5x repetition rate, 4x pulse energy)
- **1S – 2S**: New frequency metrology

Previously (10^{-13})



Now (10^{-15})





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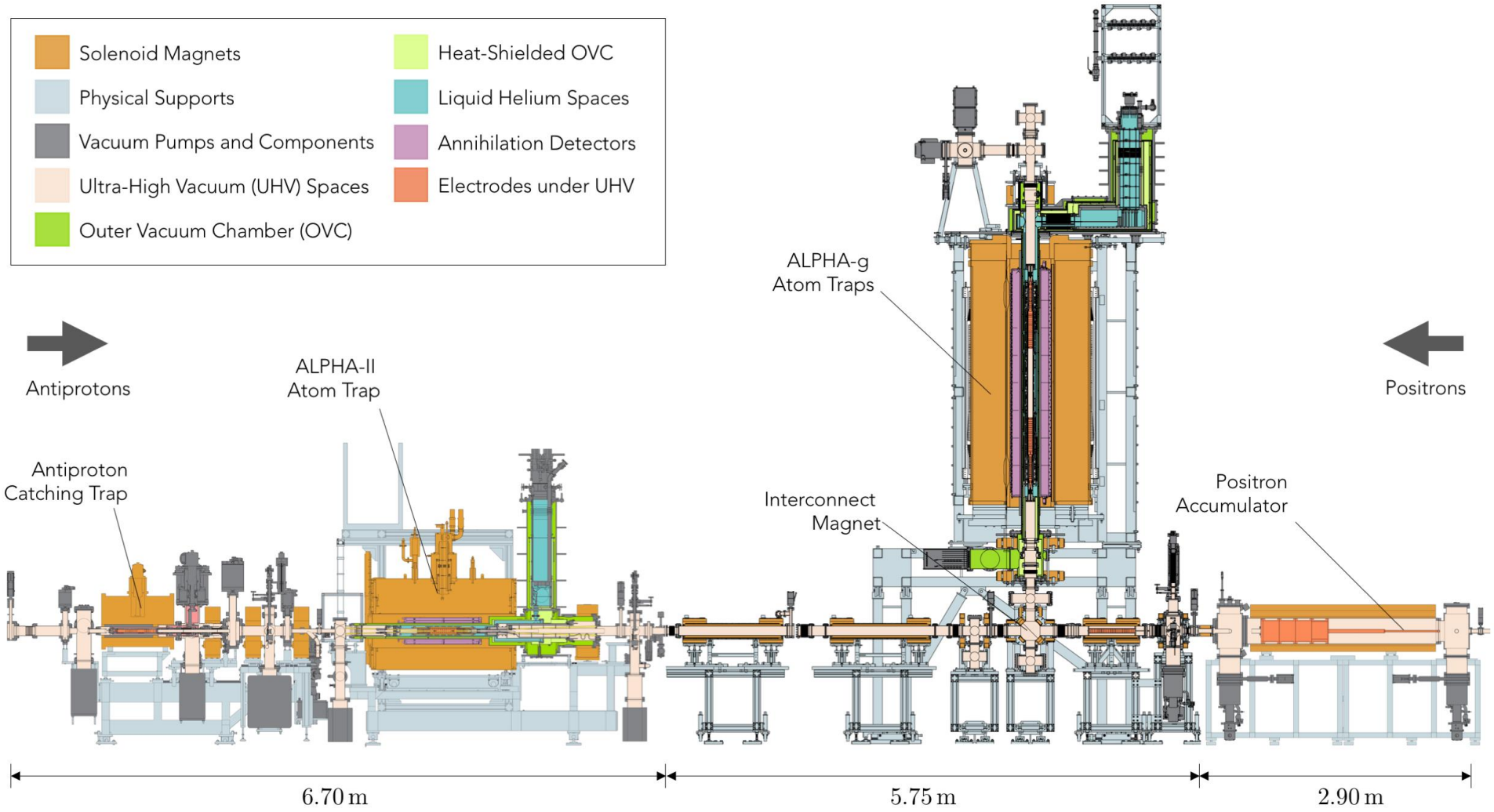
Toward higher precision spectroscopy

- **Laser cooling:** Upgraded 121 nm system (5x repetition rate, 4x pulse energy)
- **1S – 2S:** New frequency metrology, laser cooling
- **HFS:** Vastly improved magnetic field stability, improved magnetometry
- More antihydrogen!

ALPHA-g schematic



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