Testing fundamental physics with trapped antihydrogen

FFK2023

Tim Friesen (He/Him/His)
on behalf of the ALPHA collaboration
Assistant Professor
Department of Physics and Astronomy, University of Calgary

May 26, 2023

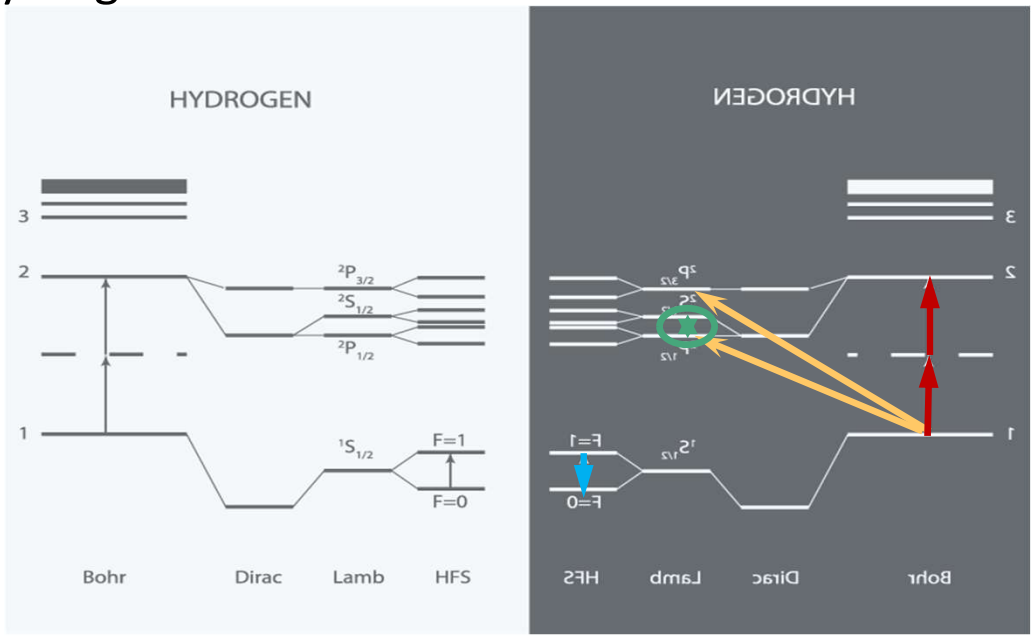
UNIVERSITY OF CALGARY

ALPHA

Goal: Precision measurements of antihydrogen atoms

Spectroscopy:

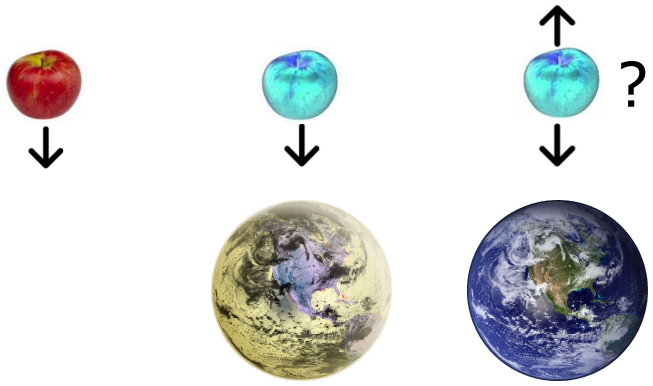
- 1S – 2S (4.2 x 10^{-15} in H)
- Ground state HFS (1.4 x 10^{-12} in H)
- Lamb shift (3 x 10^{-6} in H)
- nS – n'S/P ?



UNIVERSITY OF CALGARY

ALPHA

Goal: Precision measurements of antihydrogen atoms



Gravity:

- Test the Weak Equivalence Principle with free-fall experiments

UNIVERSITY OF CALGARY

ALPHA

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.

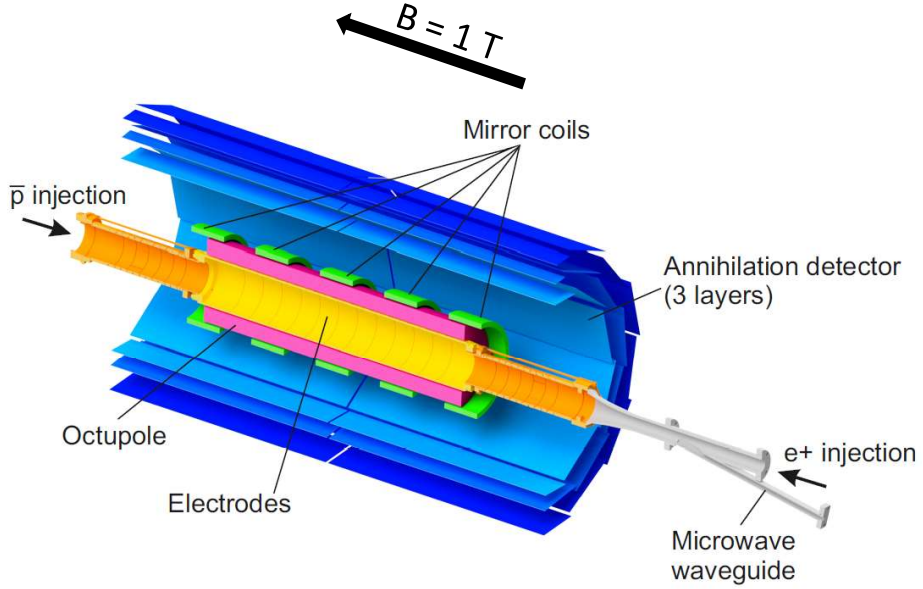
ALPHA experiment

AARHUS UNIVERSITET
CERN
PURDUE UNIVERSITY
UBC THE UNIVERSITY OF BRITISH COLUMBIA
UNIVERSITY OF CALIFORNIA BERKELEY 1868
BERKELEY LAB
ALPHA
UNIVERSITY OF CALGARY
UNIVERSITY OF LIVERPOOL
MANCHESTER 1824
The Cockcroft Institute of Accelerator Science and Technology
NRCN Nuclear Research Center Negev

UNIVERSIDADE DO PORTO
Stockholm University
SFU SIMON FRASER UNIVERSITY THINKING OF THE WORLD
Swansea University Prifysgol Abertawe
TRIUMF
YORK UNIVERSITÉ UNIVERSITY

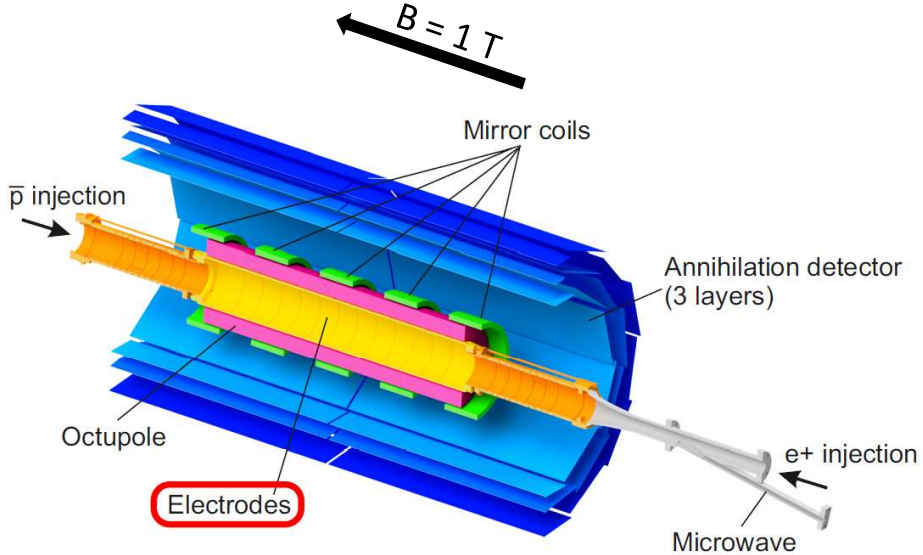
UNIVERSITY OF CALGARY

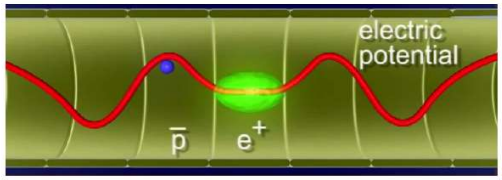
Producing and trapping antihydrogen

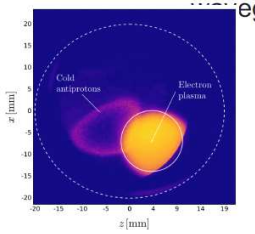


UNIVERSITY OF CALGARY

Producing and trapping antihydrogen



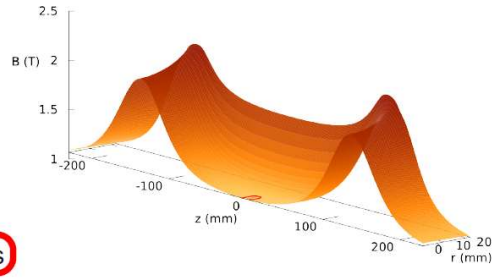




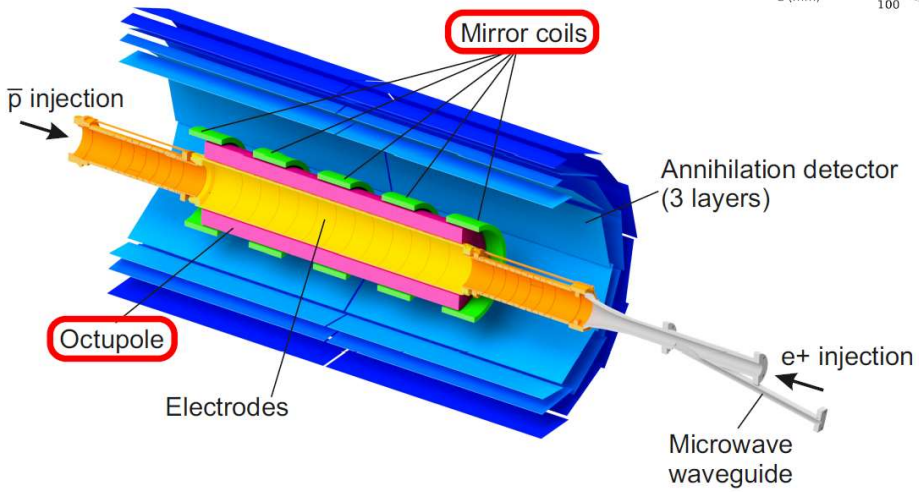
UNIVERSITY OF CALGARY

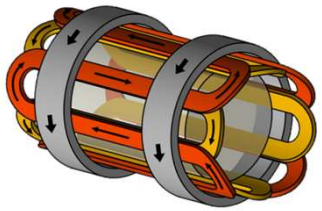
Producing and trapping antihydrogen

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



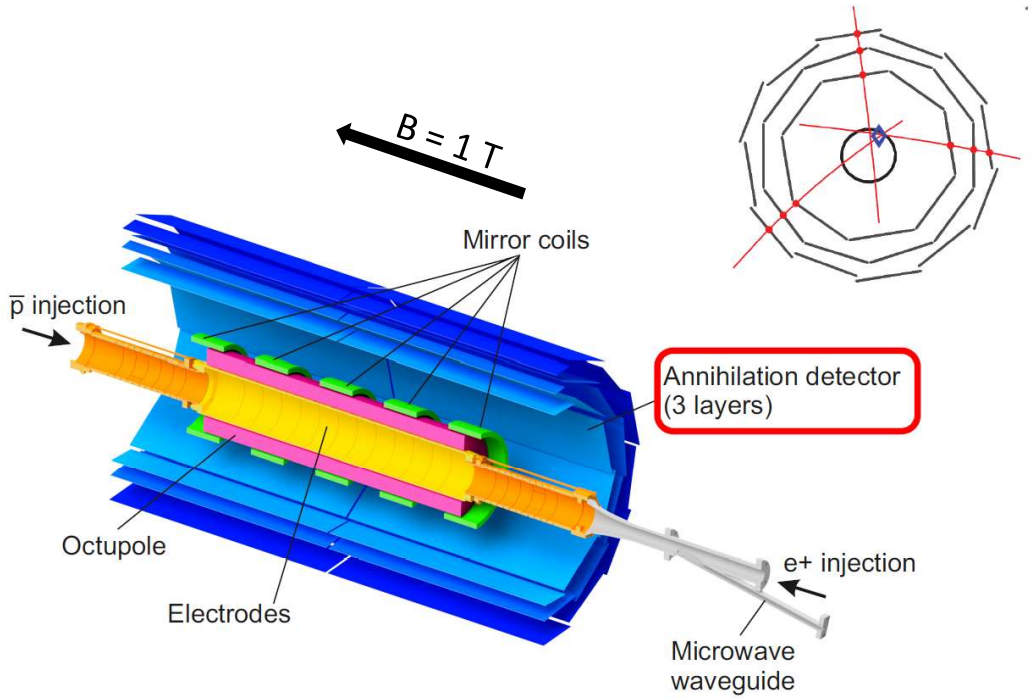
$\Delta U \approx 0.5$ K



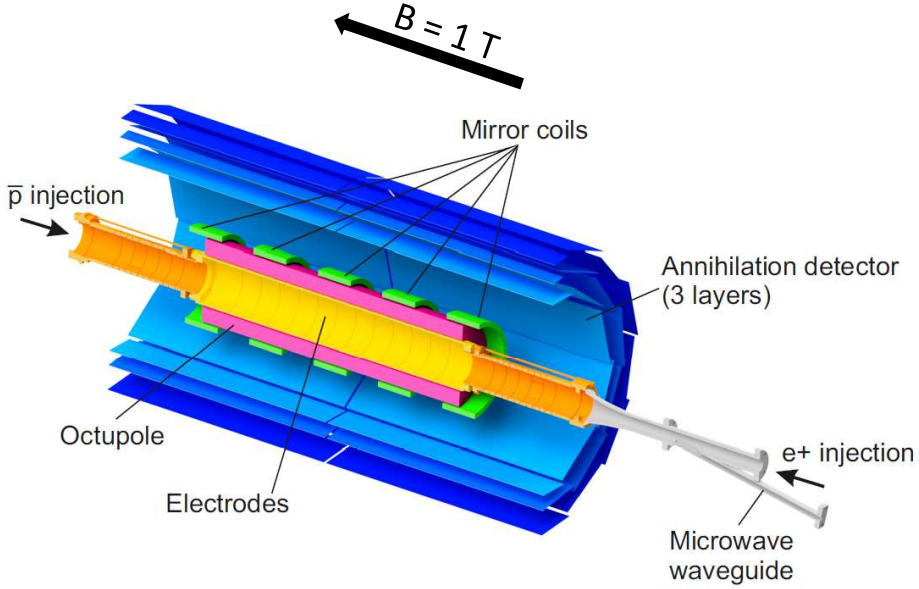


UNIVERSITY OF CALGARY

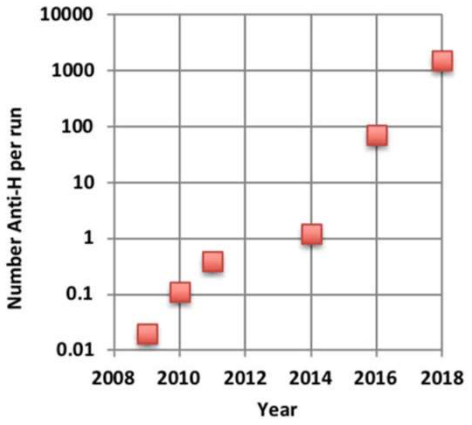
Producing and trapping antihydrogen



Producing and trapping antihydrogen



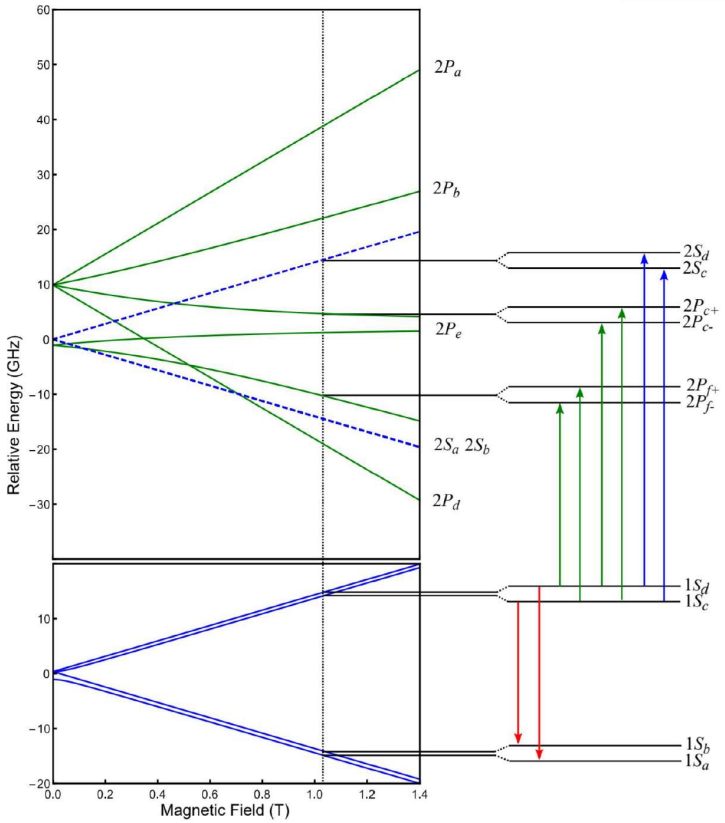
Improvements to antihydrogen trapping
[Nature Comm. 8, 681 (2017)]

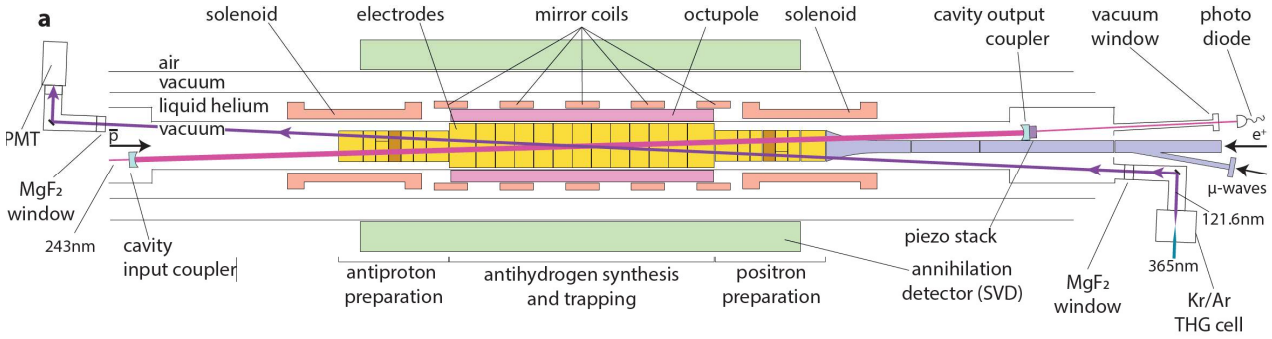


Can accumulate anti-atoms (~2500 over 17 hours)

UNIVERSITY OF CALGARY

Antihydrogen spectroscopy

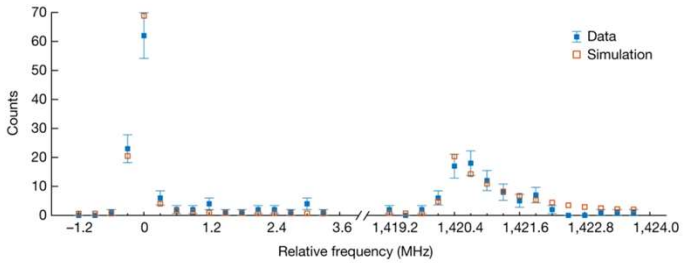




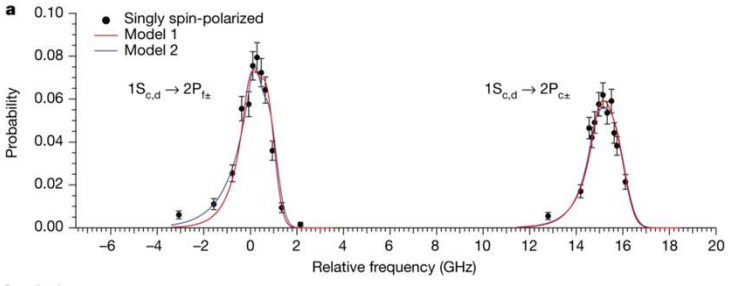
UNIVERSITY OF CALGARY

Antihydrogen spectroscopy

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

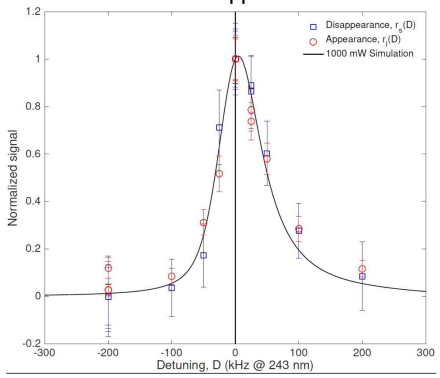


Fine structure [M. Ahmadi et al, Nature 578, 375 (2020)]



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

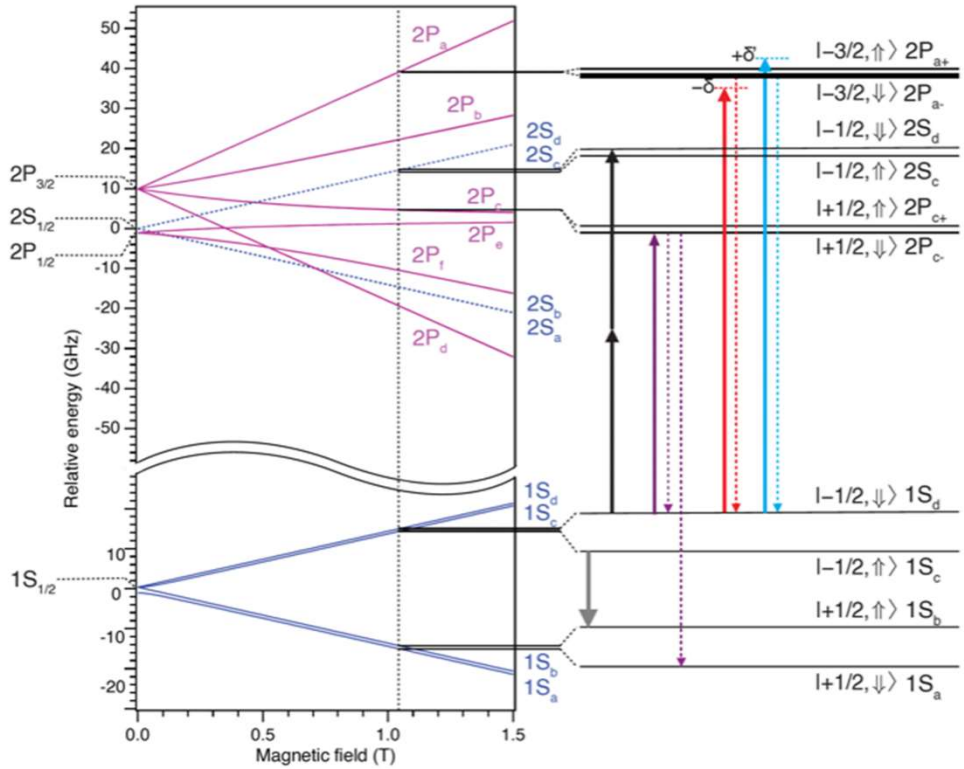
15045 trapped H



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

UNIVERSITY OF CALGARY

Laser cooling antihydrogen

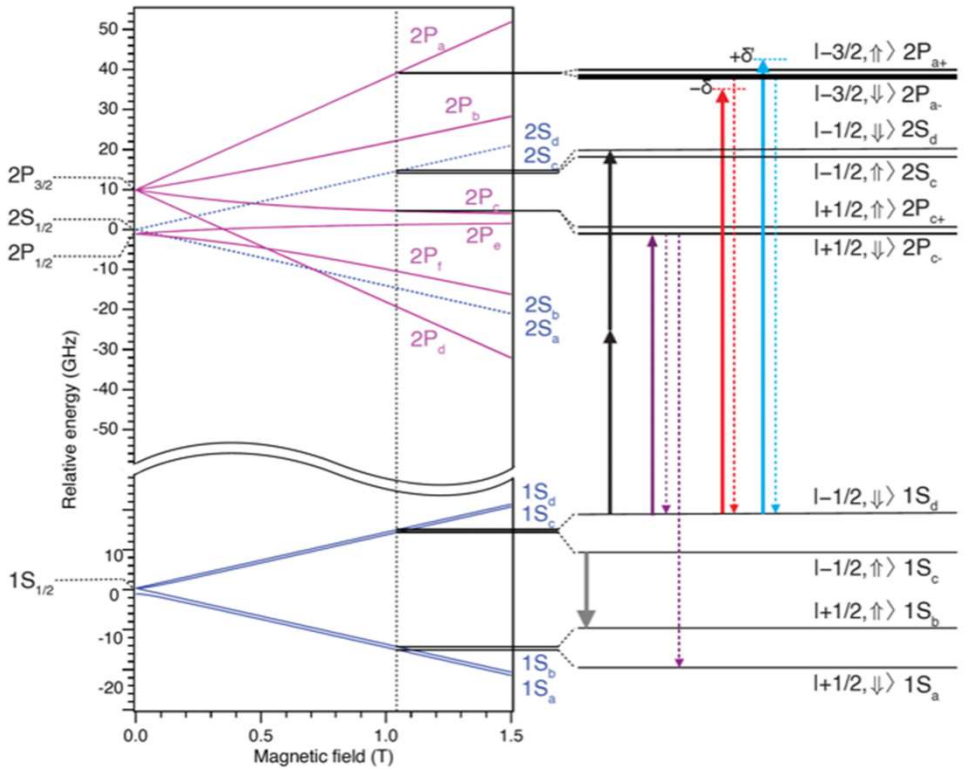


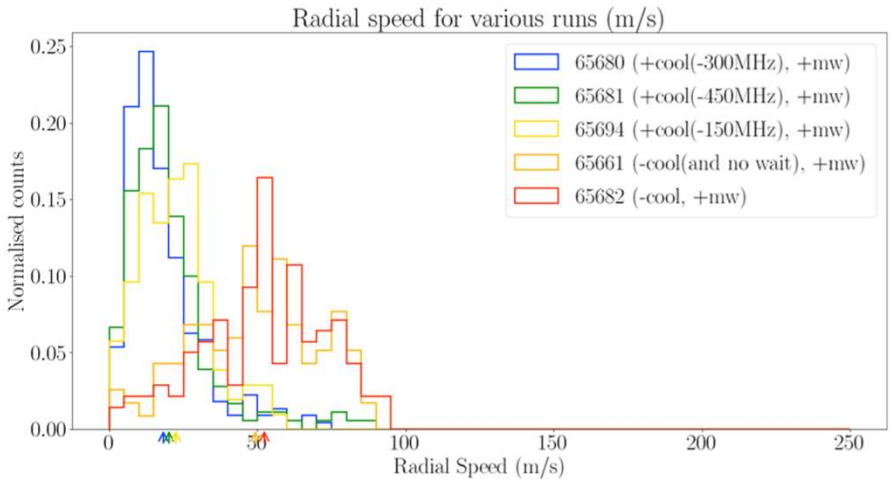
Pulsed 121.6 nm generated by THG:

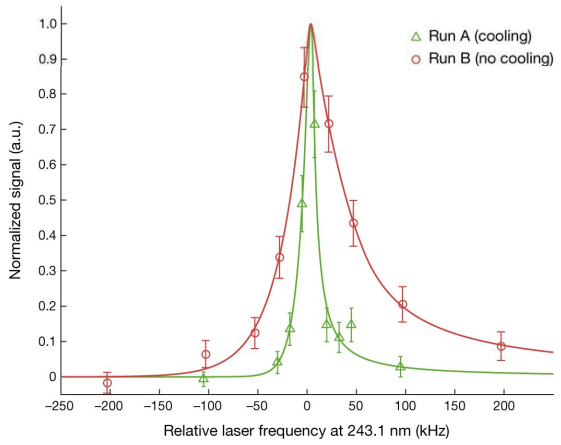
- Approx. 15 ns pulse length
- Approx. 2 - 10 nJ per pulse
- 10 Hz repetition rate
- Detuned -220 MHz for cooling

UNIVERSITY OF CALGARY

Laser cooling antihydrogen



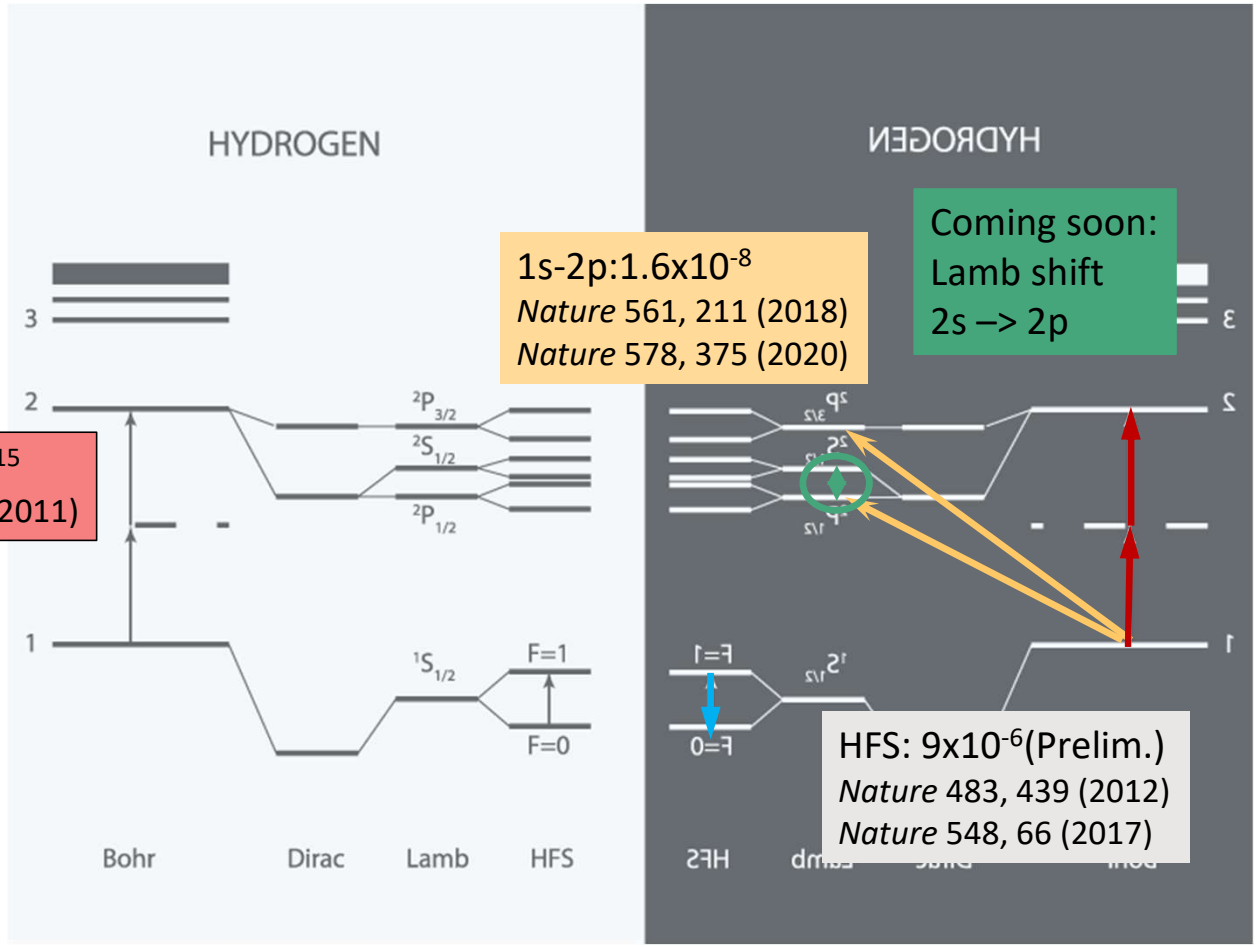




C. J. Baker et al, Nature 592, 35 (2021)

UNIVERSITY OF CALGARY

Antihydrogen spectroscopy



1s-2s: 4×10^{-15}
PRL 107, 203001 (2011)

1s-2p:1.6×10^{-8}
Nature 561, 211 (2018)
Nature 578, 375 (2020)

Coming soon:
Lamb shift
2s –> 2p

1s-2s: 2×10^{-12}
Nature 541, 506 (2017)
Nature 557, 71 (2018)

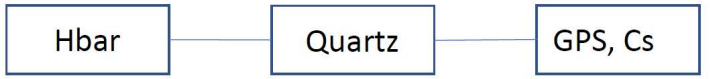
HFS: 9×10^{-6}(Prelim.)
Nature 483, 439 (2012)
Nature 548, 66 (2017)

UNIVERSITY OF CALGARY

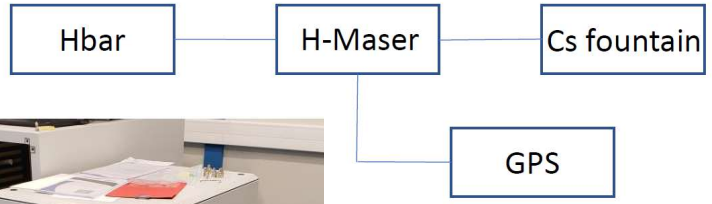
Toward higher precisions

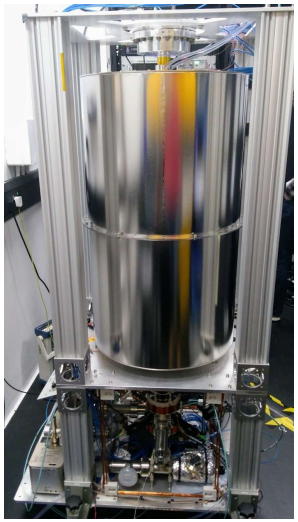
- **Laser cooling**: Upgraded 121 nm system (5x repetition rate, 4x pulse energy)
- **1S – 2S**: New frequency metrology

Previously (10^{-13})



Now (10^{-15})

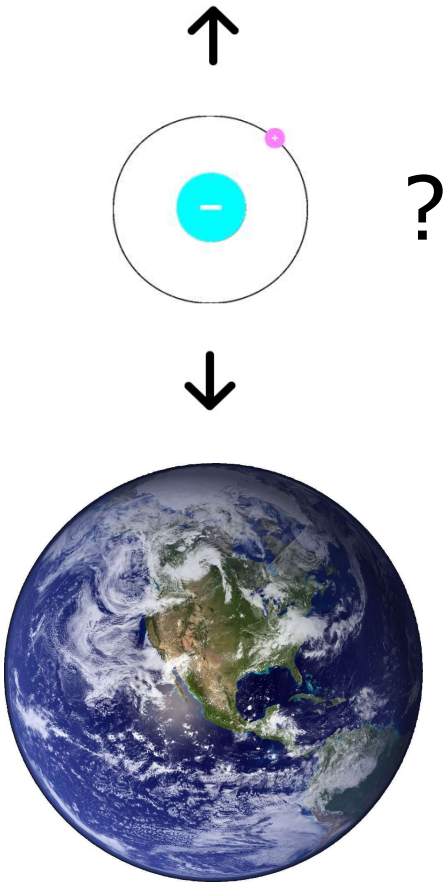




UNIVERSITY OF CALGARY

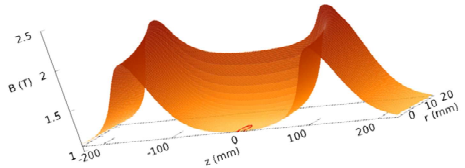
Toward higher precision spectroscopy

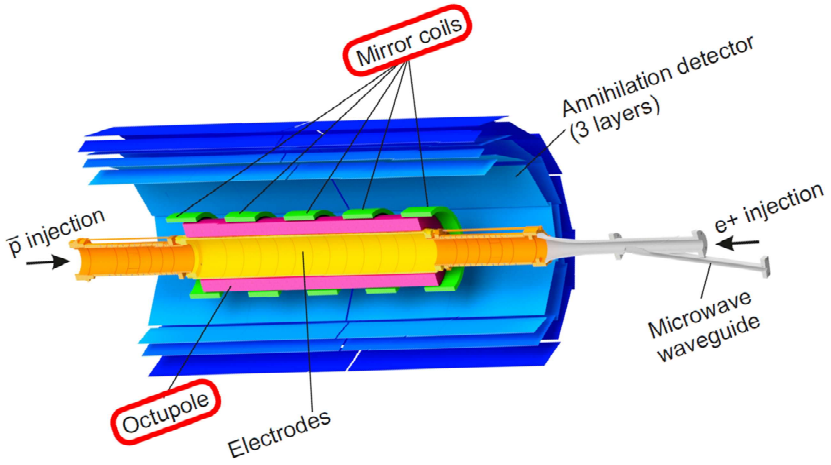
- **Laser cooling:** Upgraded 121 nm system (5x repetition rate, 4x pulse energy)
- **1S – 2S:** New frequency metrology, laser cooling
- **HFS:** Vastly improved magnetic field stability, improved magnetometry
- More antihydrogen!



Antihydrogen + gravity: ALPHA-g

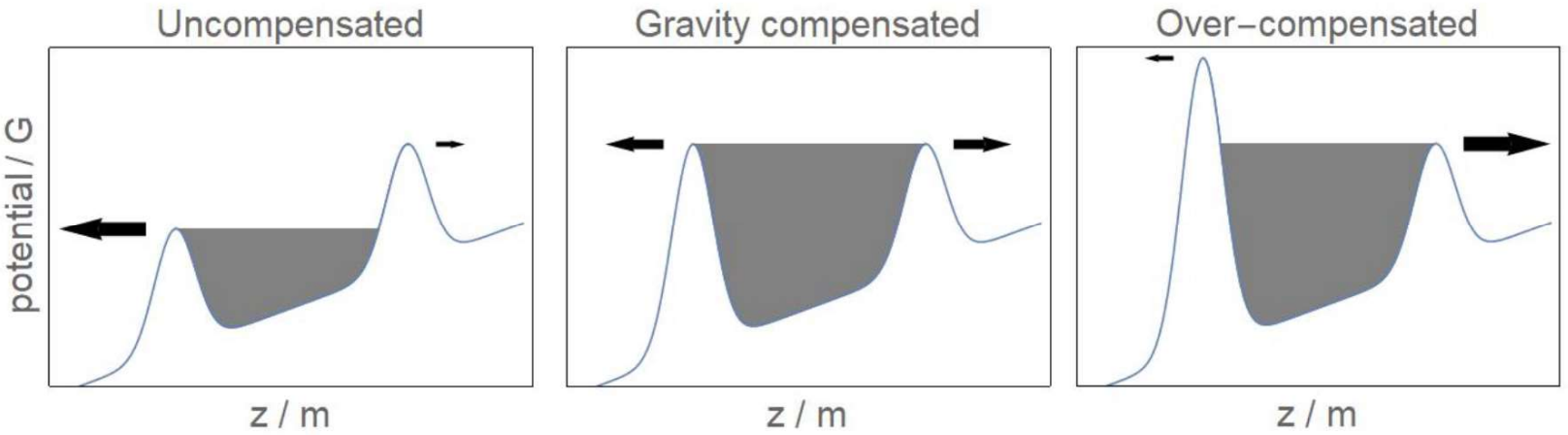
$$U = -\vec{\mu} \cdot \vec{B}$$





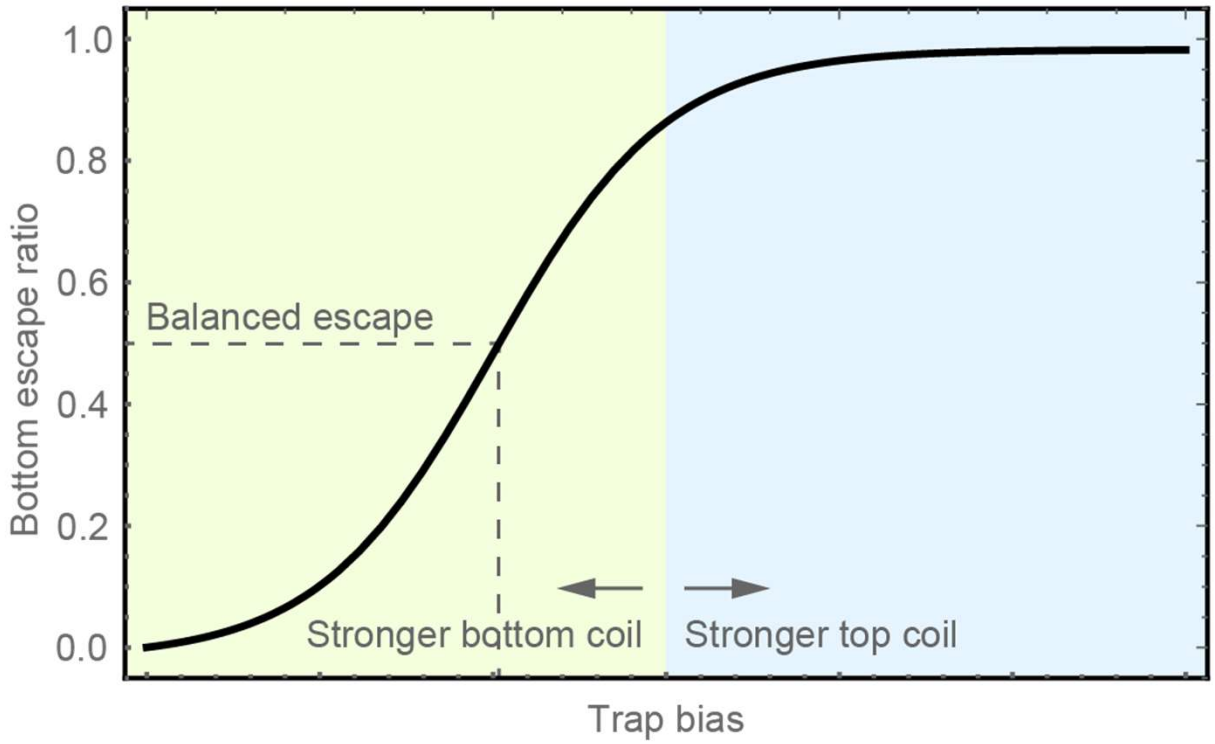
UNIVERSITY OF CALGARY

Measuring the effect of gravity



UNIVERSITY OF CALGARY

Measuring the effect of gravity



UNIVERSITY OF CALGARY

The challenge

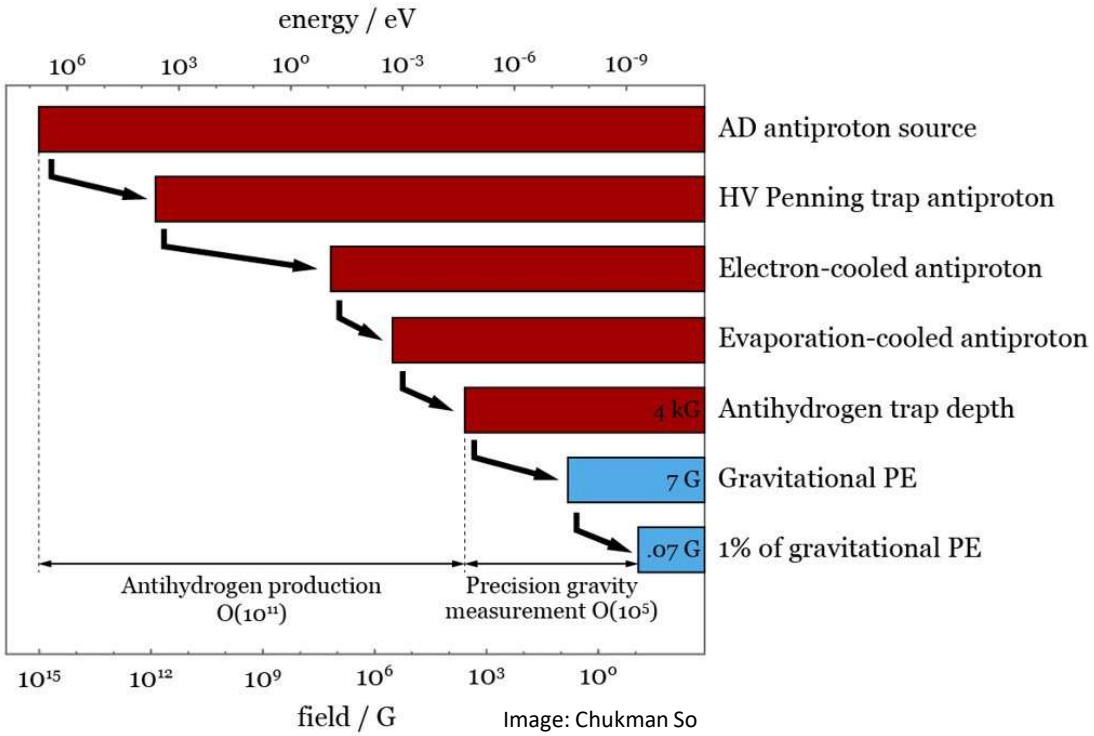


Image: Chukman So

UNIVERSITY OF CALGARY

Magnetic traps

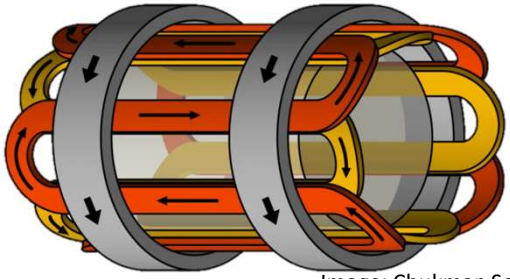


Image: Chukman So

Magnetic traps

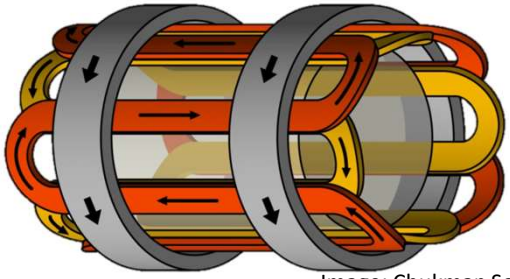


Image: Chukman So

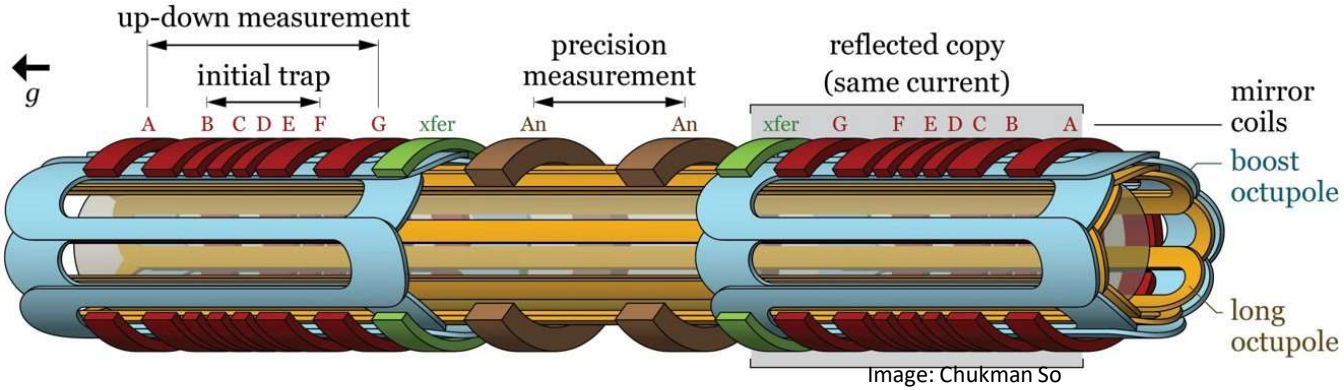
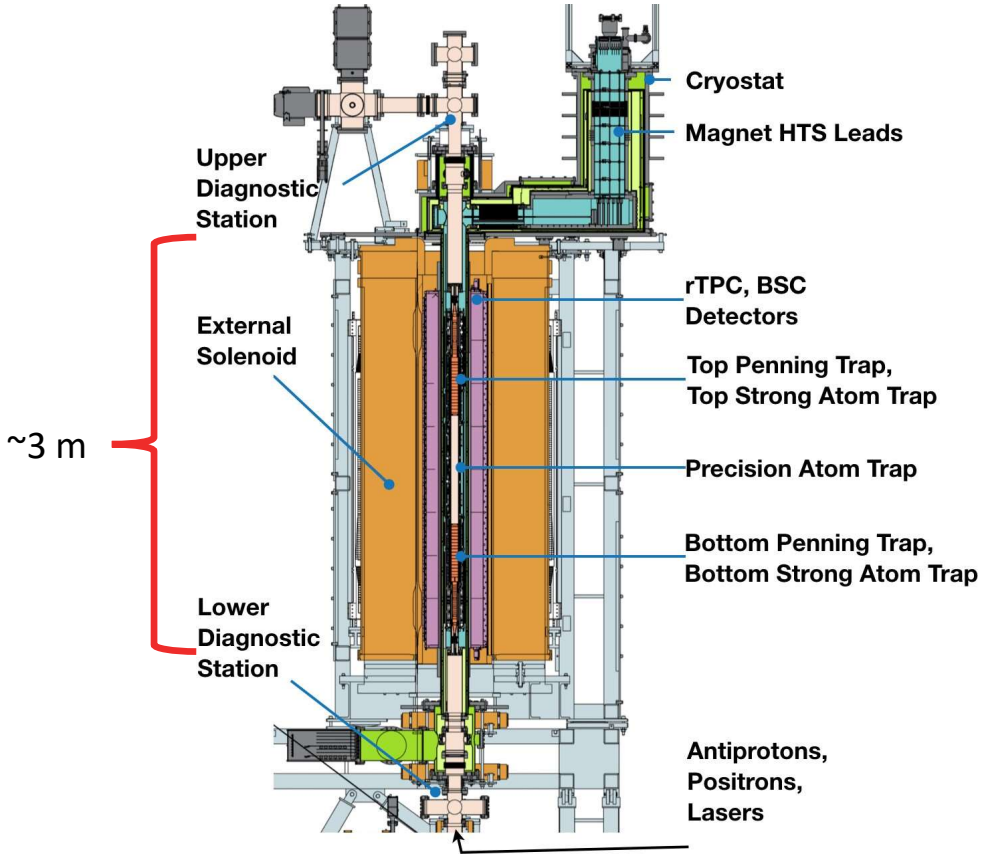


Image: Chukman So

17 superconducting circuits with 34 HTS current leads

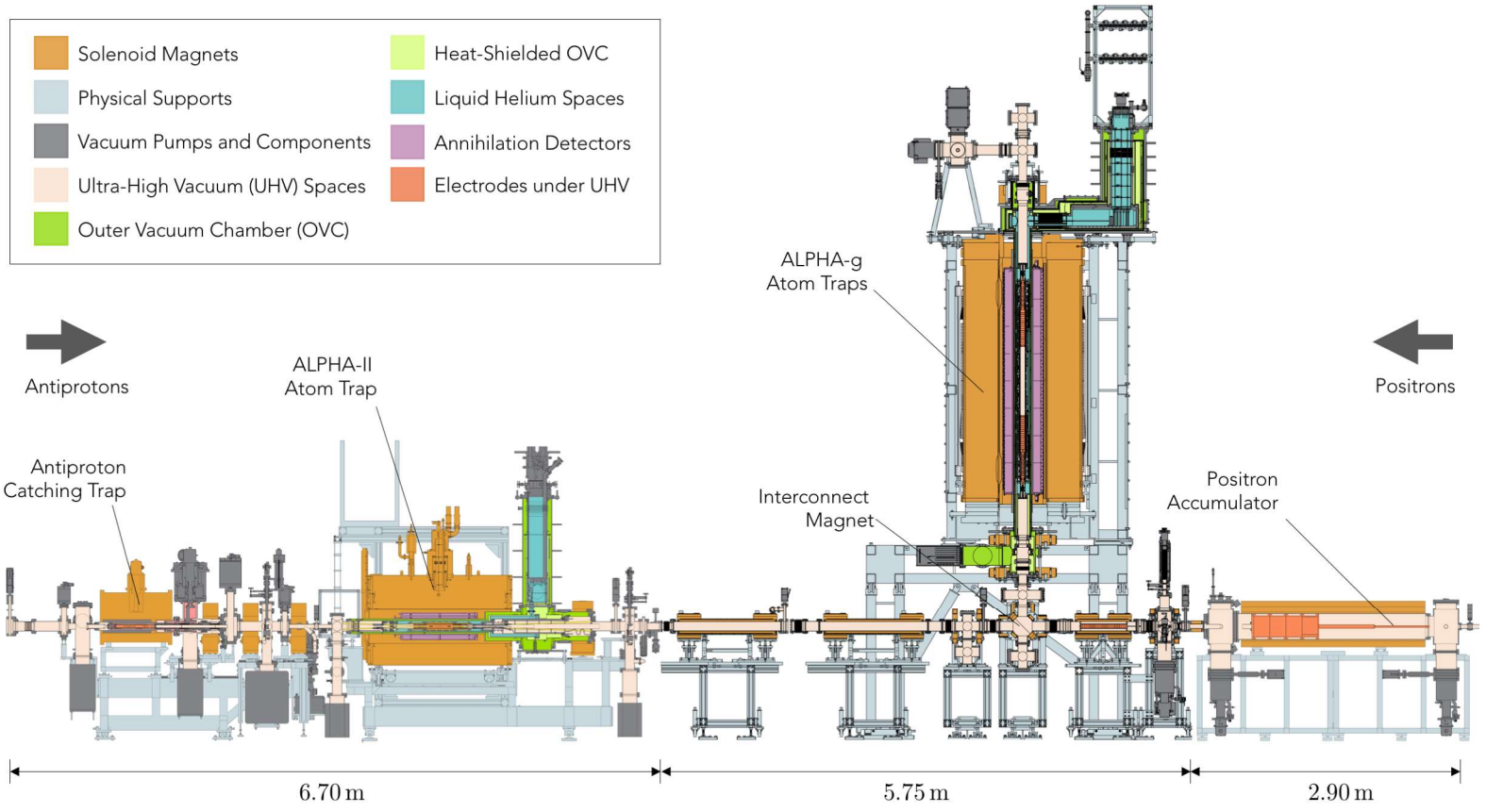
UNIVERSITY OF CALGARY

ALPHA-g schematic



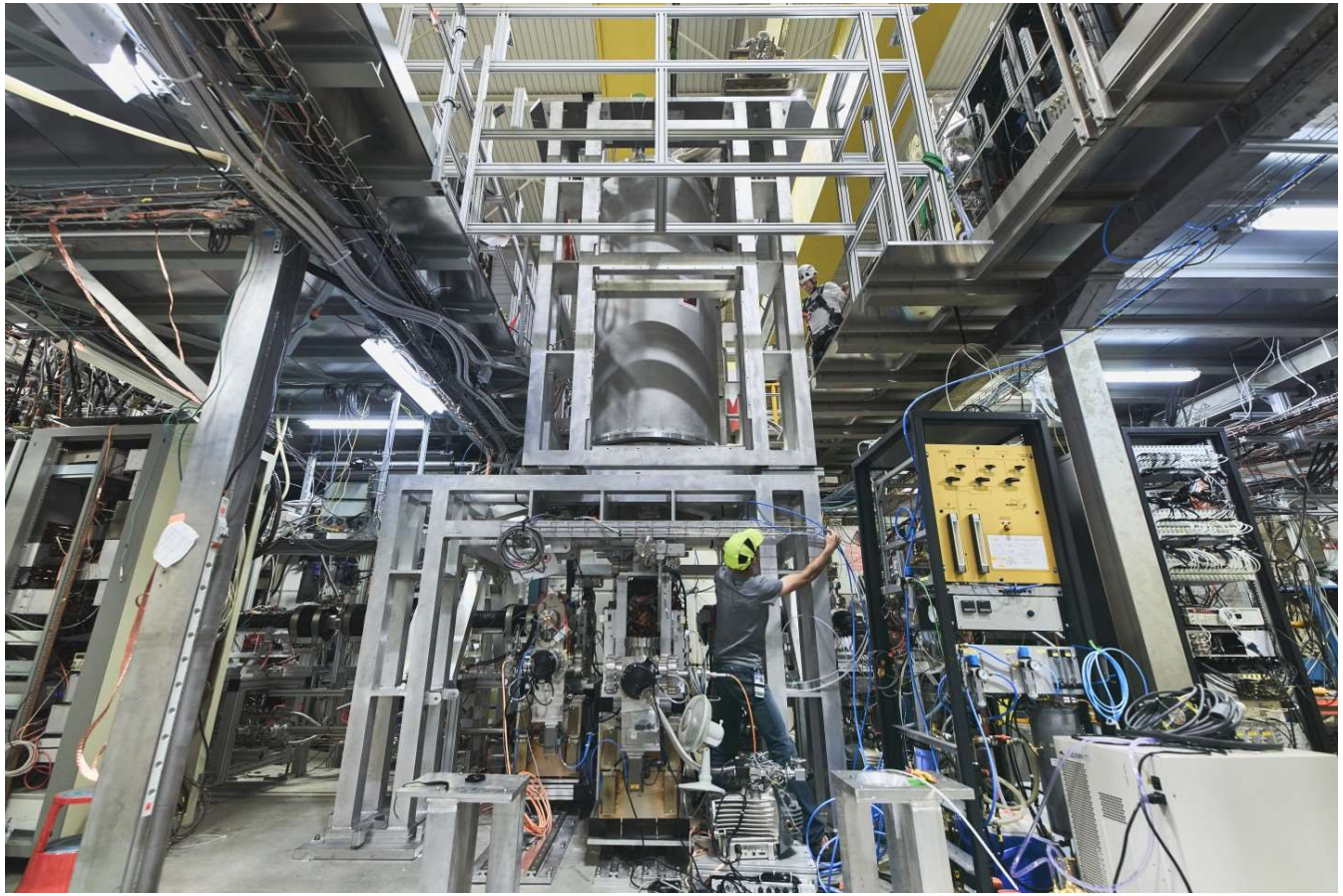
UNIVERSITY OF CALGARY

ALPHA-g schematic



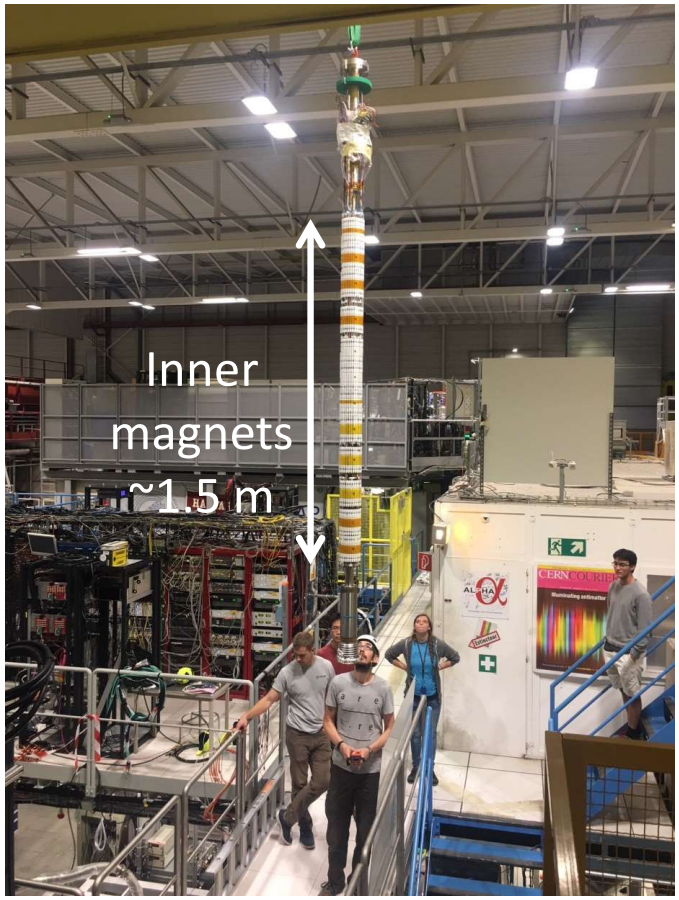
UNIVERSITY OF CALGARY

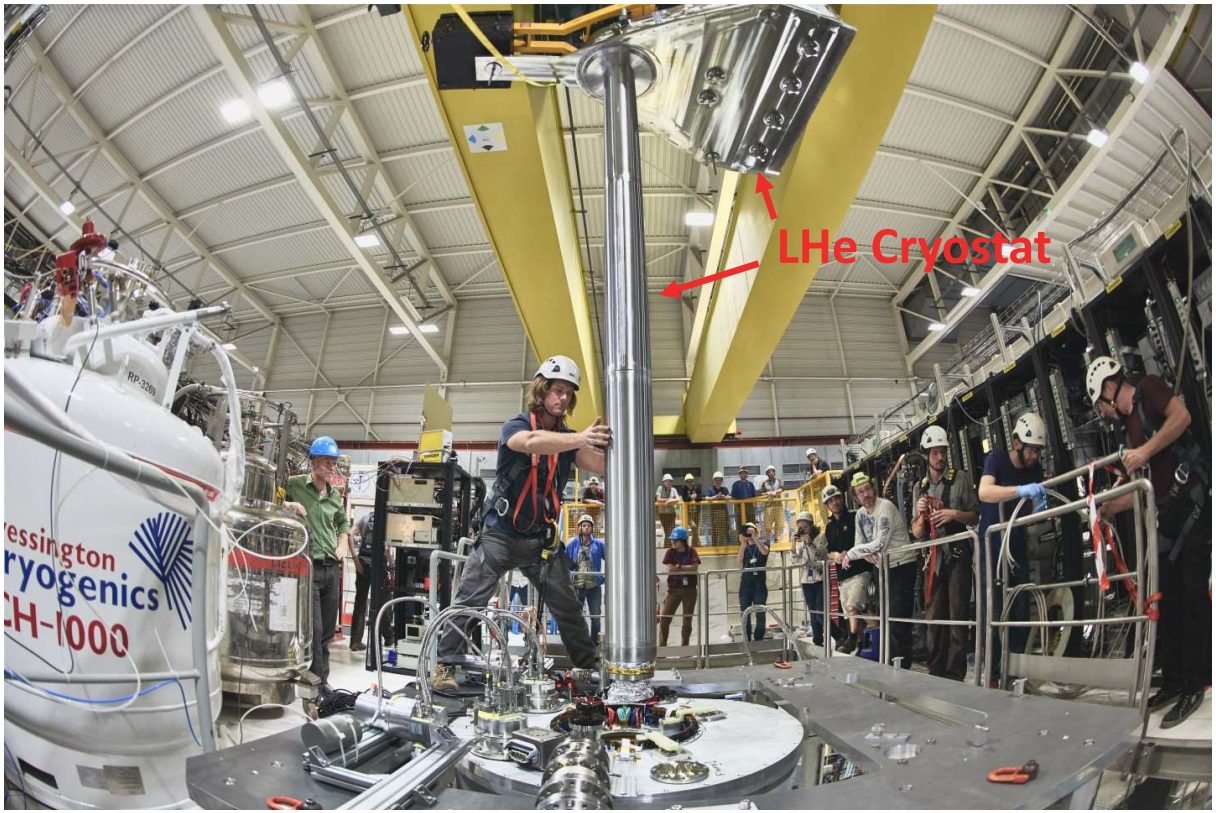
ALPHA-g reality



UNIVERSITY OF CALGARY

ALPHA-g reality

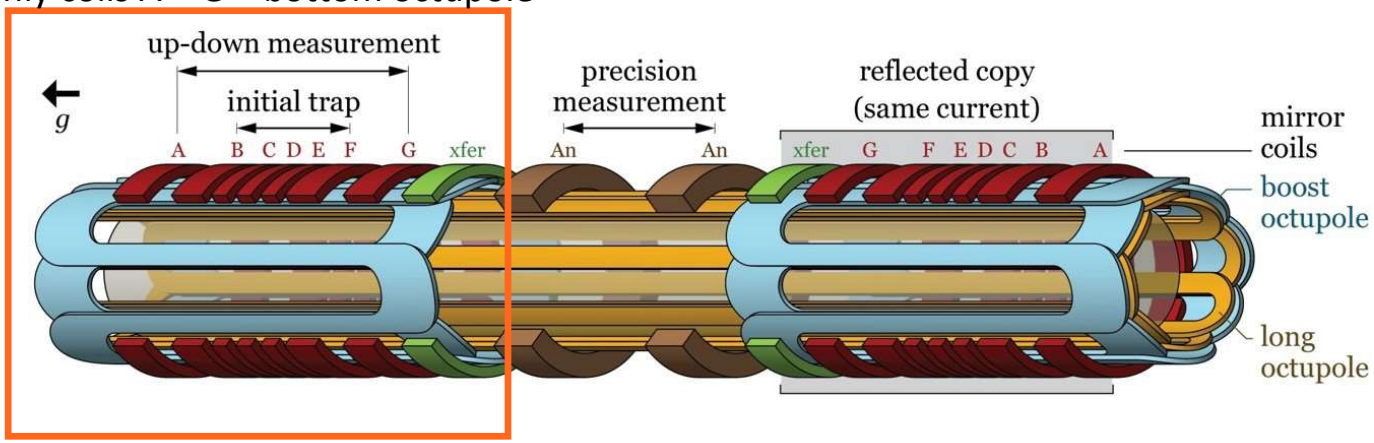




UNIVERSITY OF CALGARY

“up-down” measurement

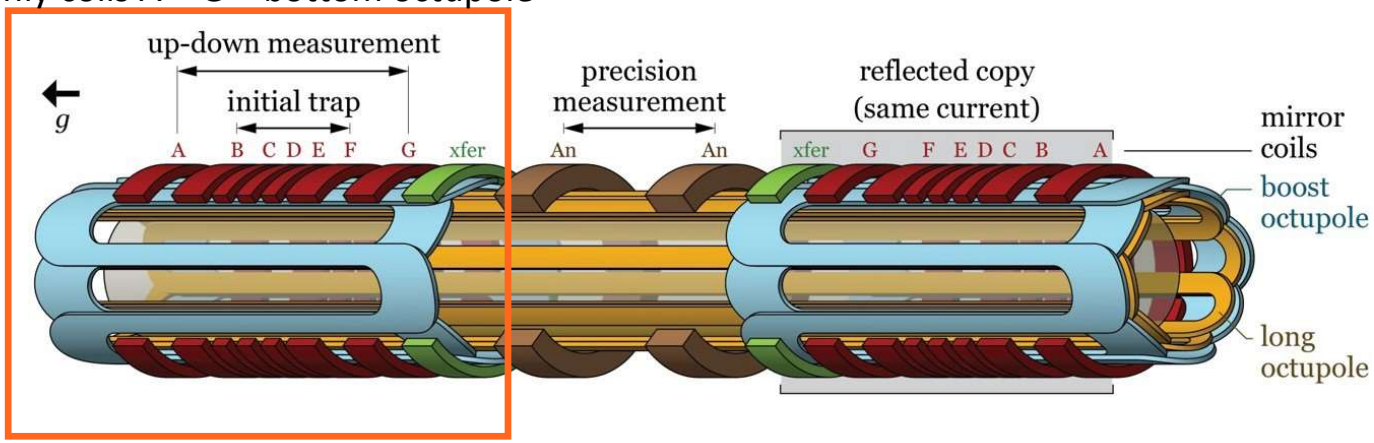
Only coils A + G + bottom octupole



UNIVERSITY OF CALGARY

“up-down” measurement

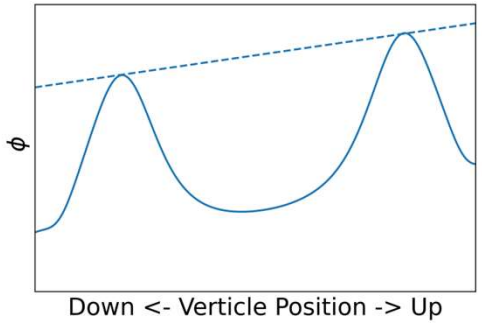
Only coils A + G + bottom octupole



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

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

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



UNIVERSITY OF CALGARY

Magnetic field measurements

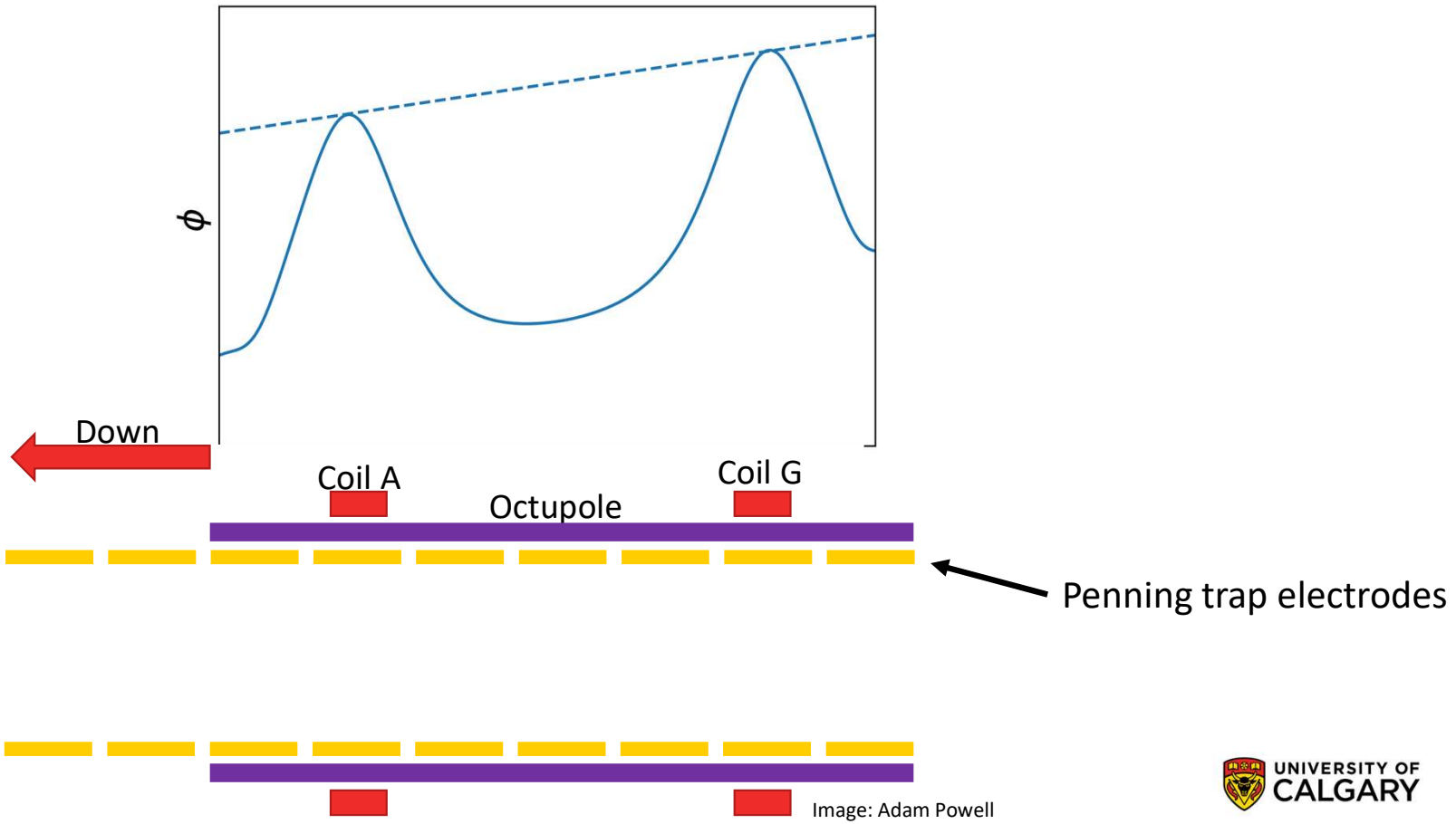
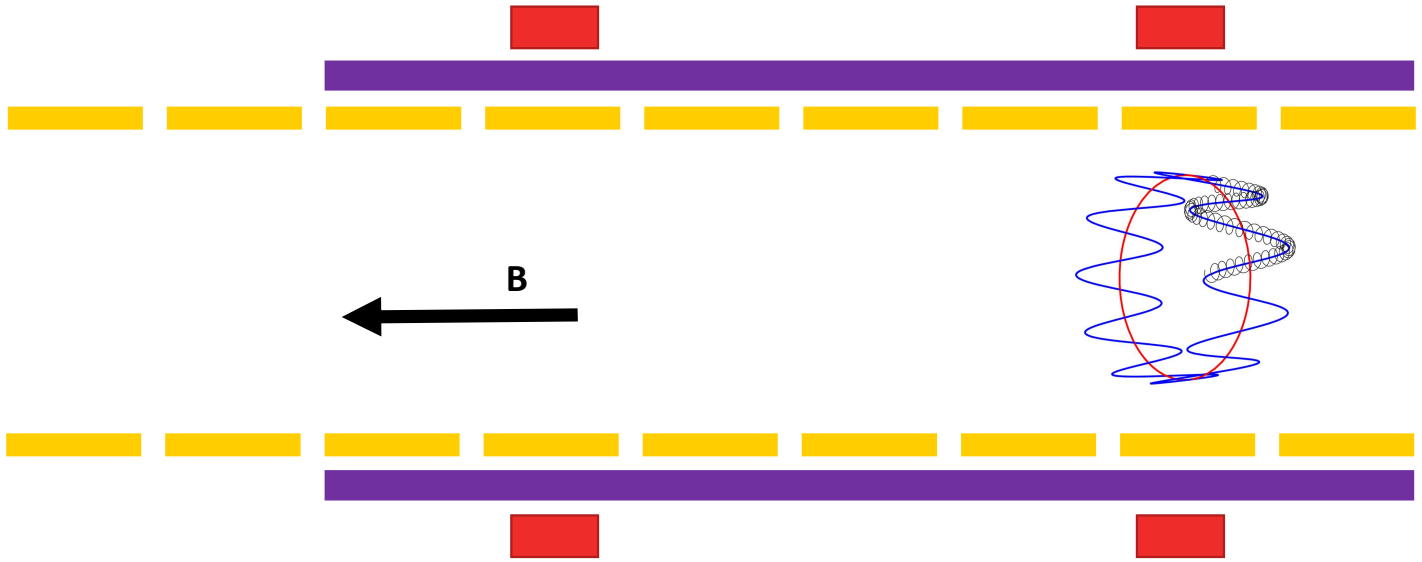


Image: Adam Powell

UNIVERSITY OF CALGARY

Electron cyclotron resonance magnetometry



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

At 1 T $f_c \approx 28$ GHz

Electron cyclotron resonance

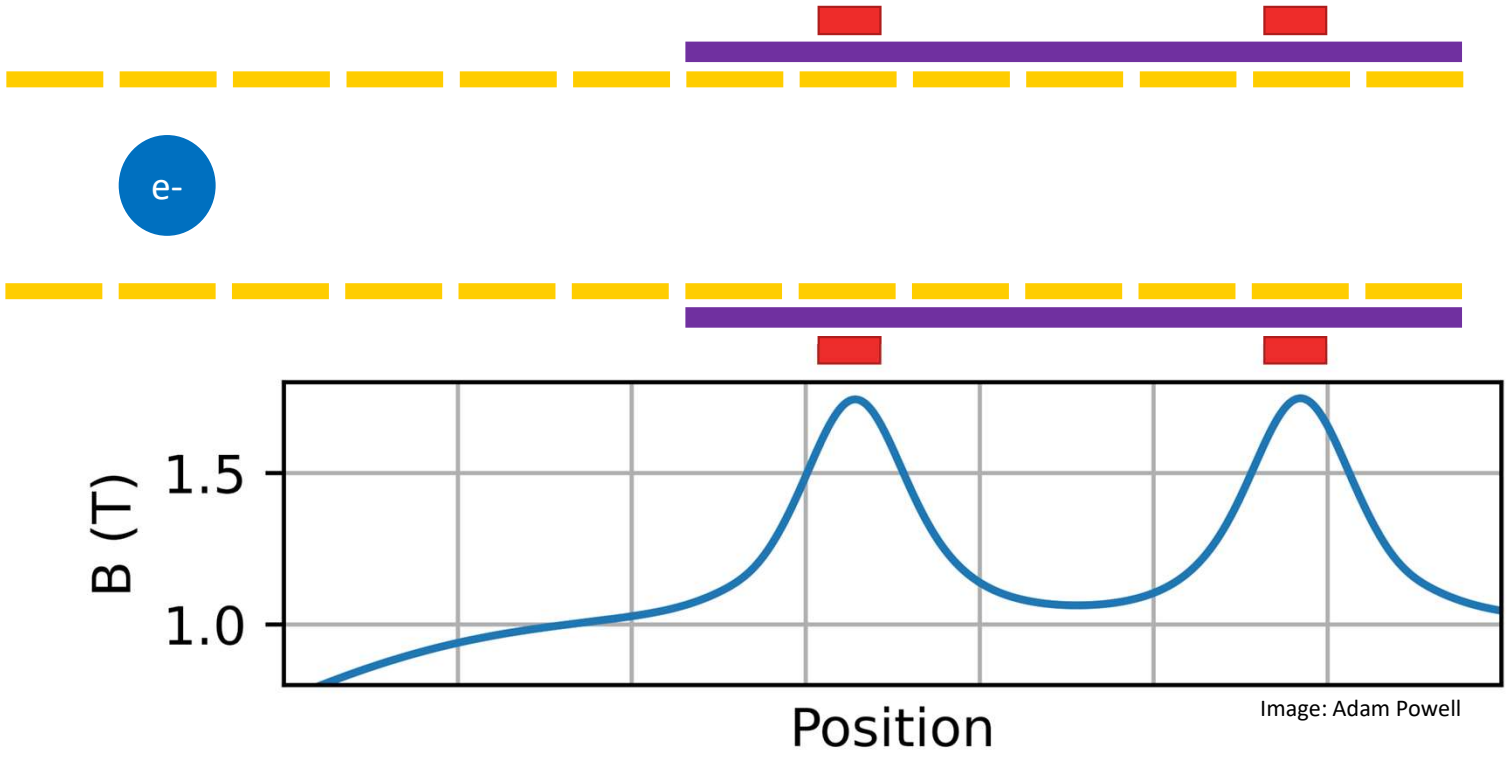


Image: Adam Powell

UNIVERSITY OF CALGARY

Electron cyclotron resonance

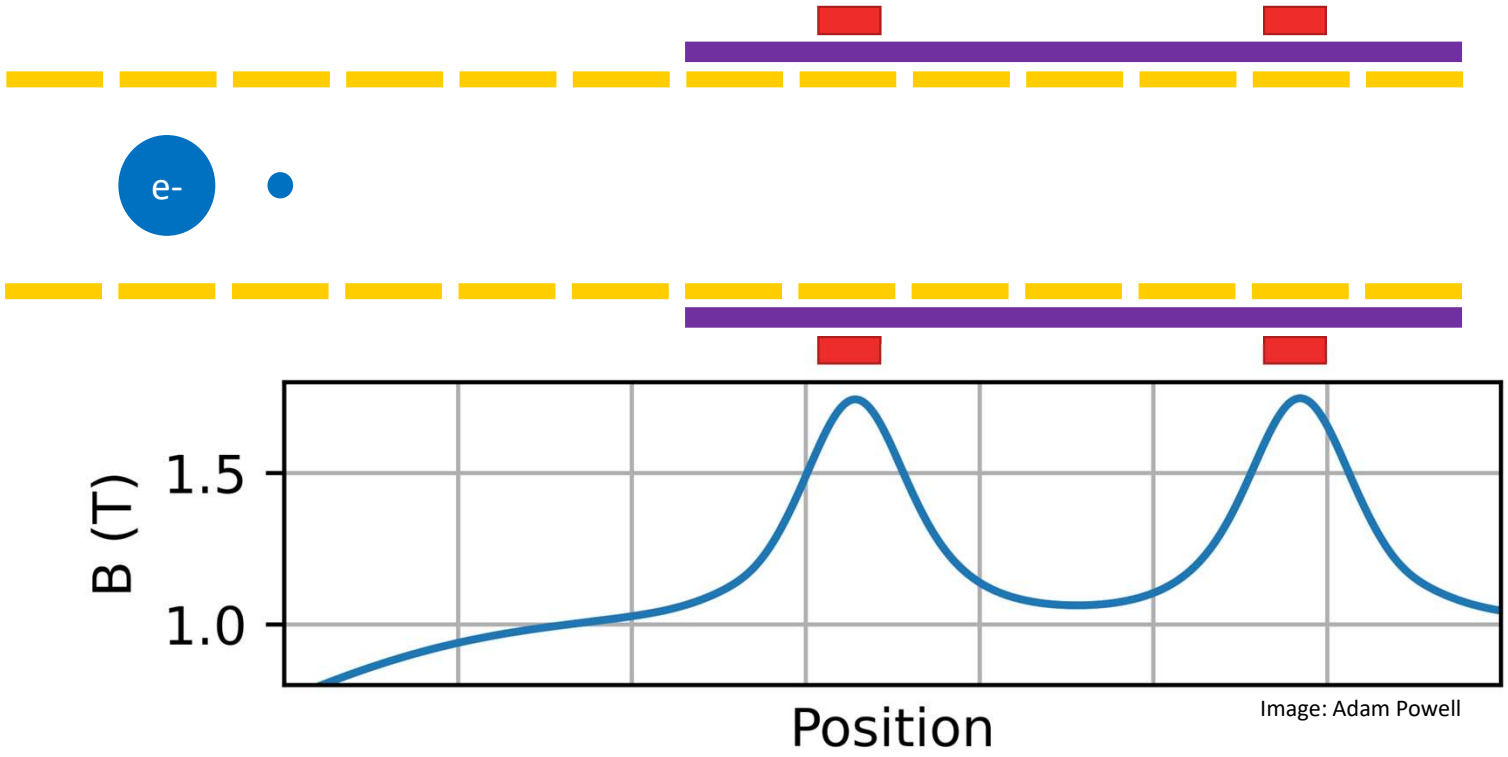


Image: Adam Powell

UNIVERSITY OF CALGARY

Electron cyclotron resonance

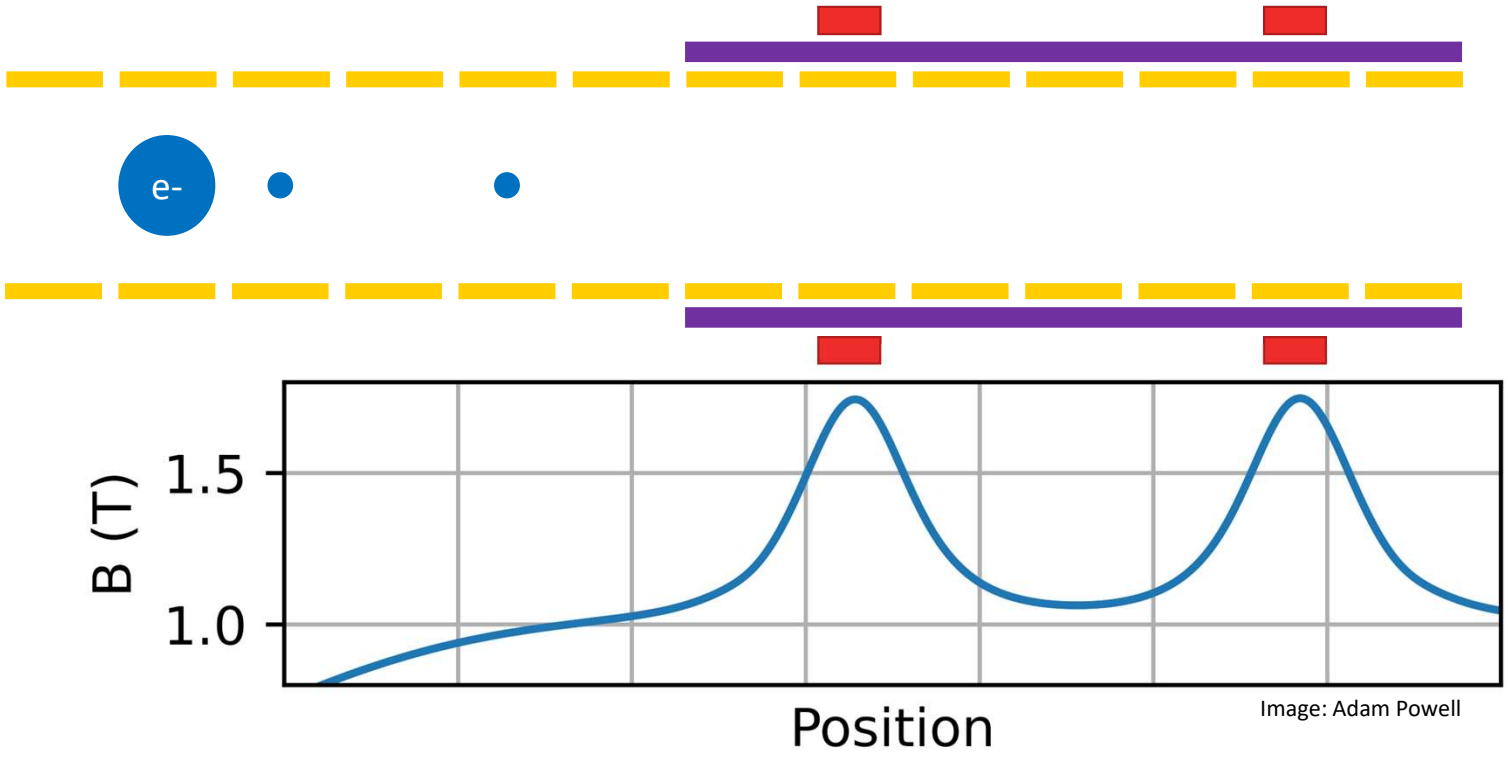


Image: Adam Powell

UNIVERSITY OF CALGARY

Electron cyclotron resonance

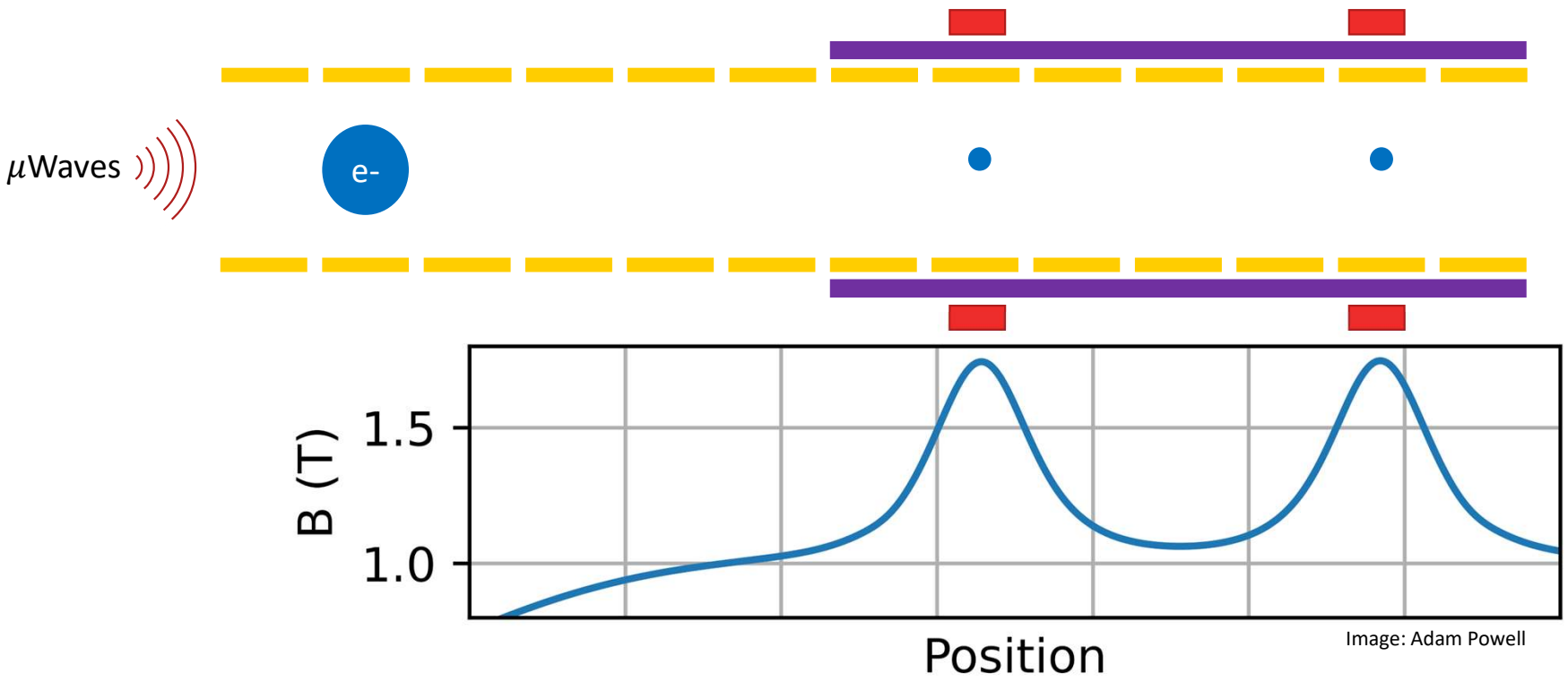


Image: Adam Powell

UNIVERSITY OF CALGARY

Electron cyclotron resonance

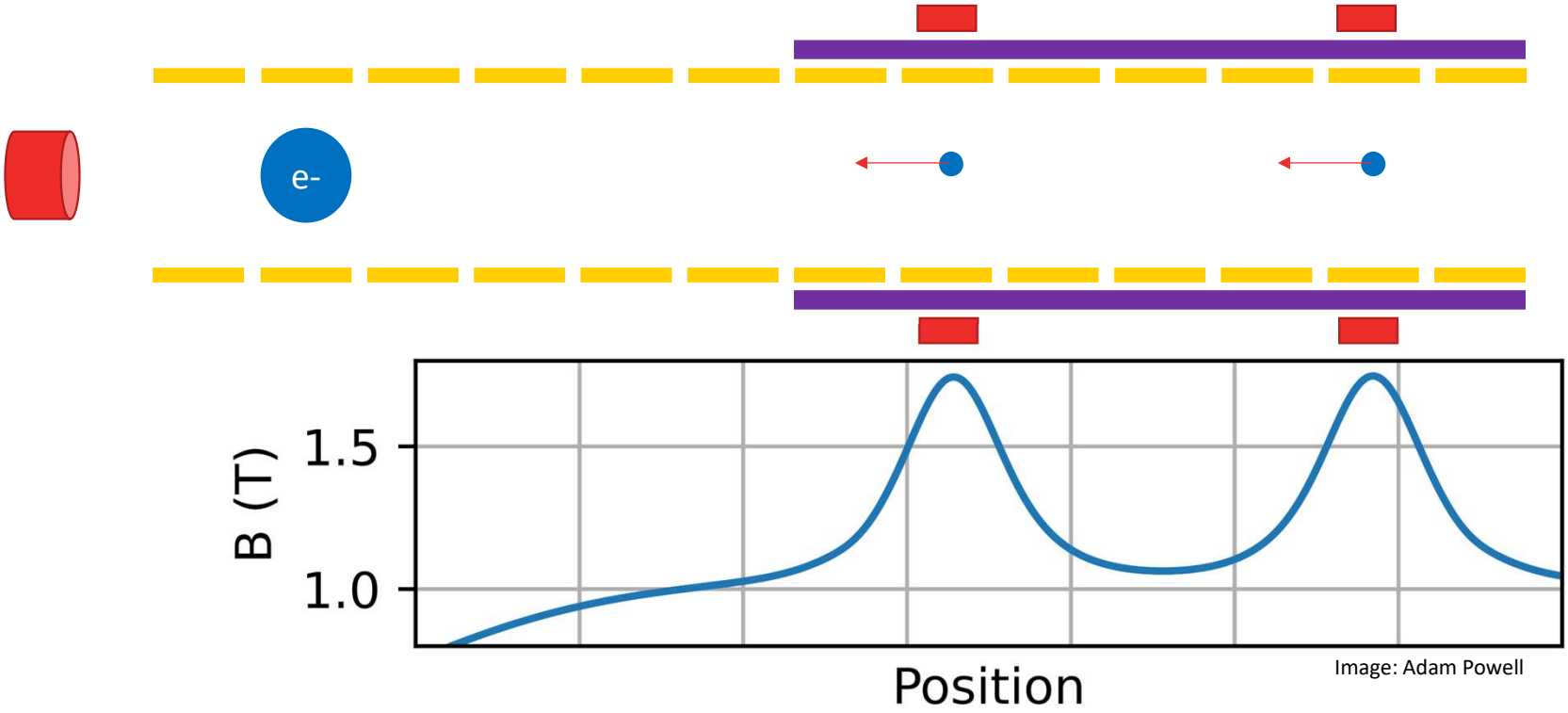
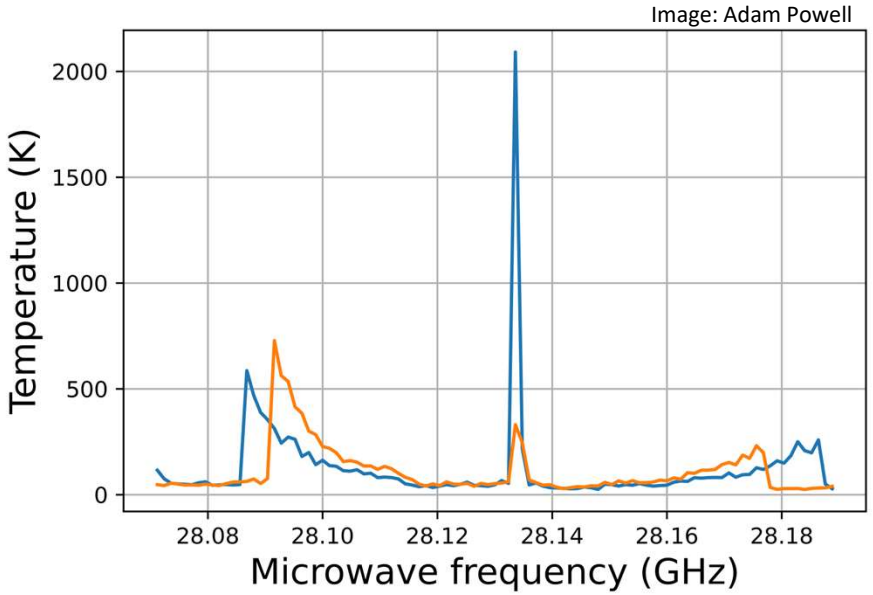


Image: Adam Powell

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



- 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

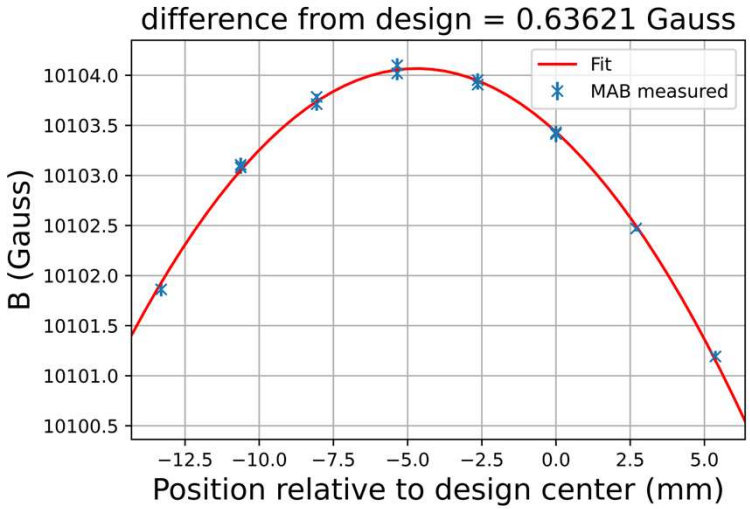
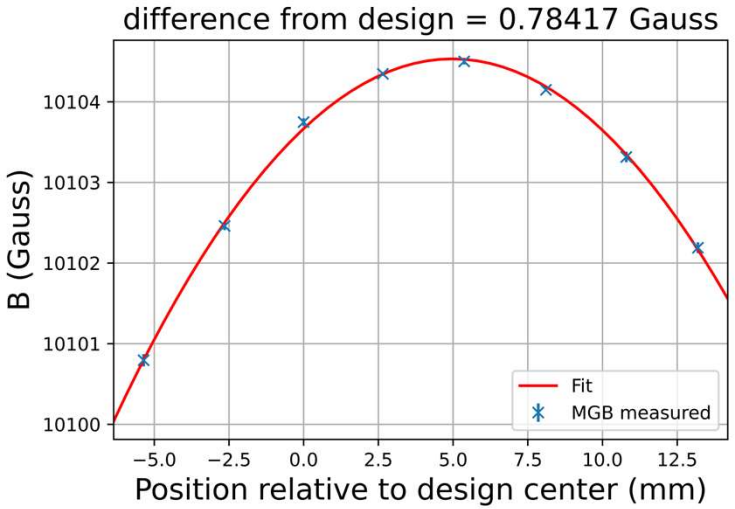
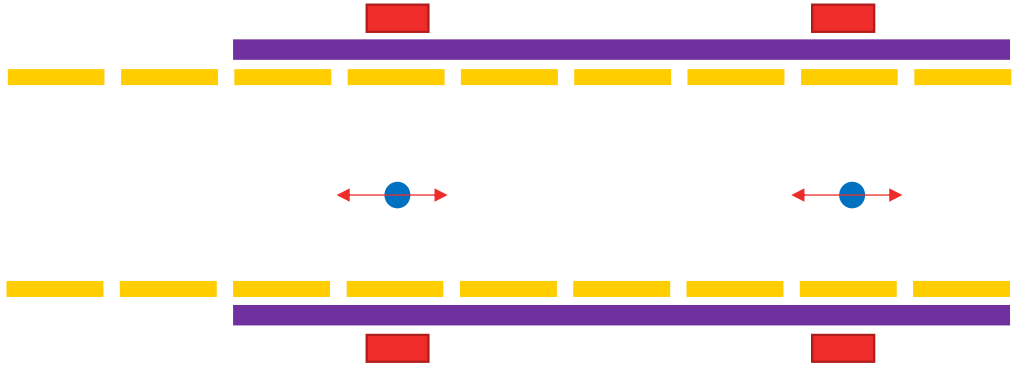


Image: Adam Powell

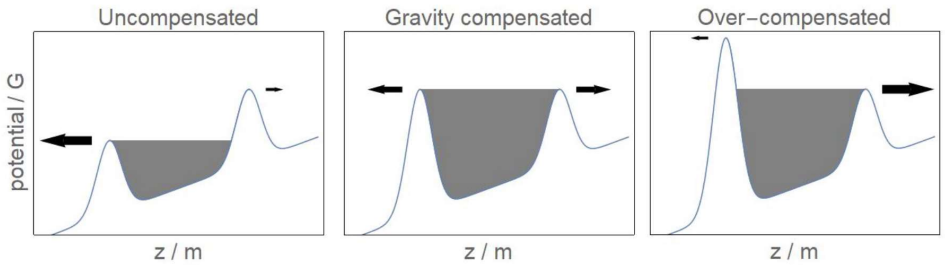




UNIVERSITY OF CALGARY

“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



UNIVERSITY OF CALGARY

Simulated results

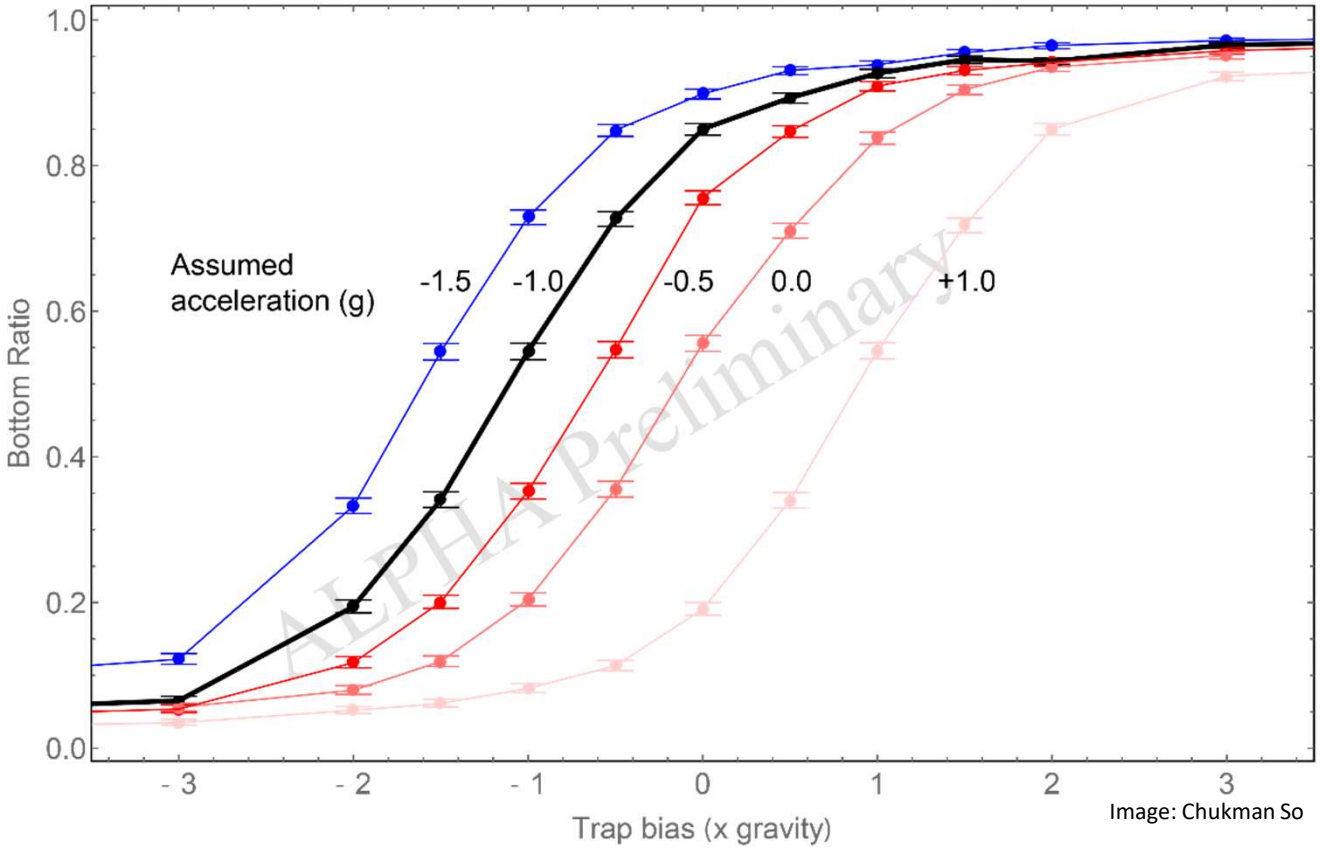
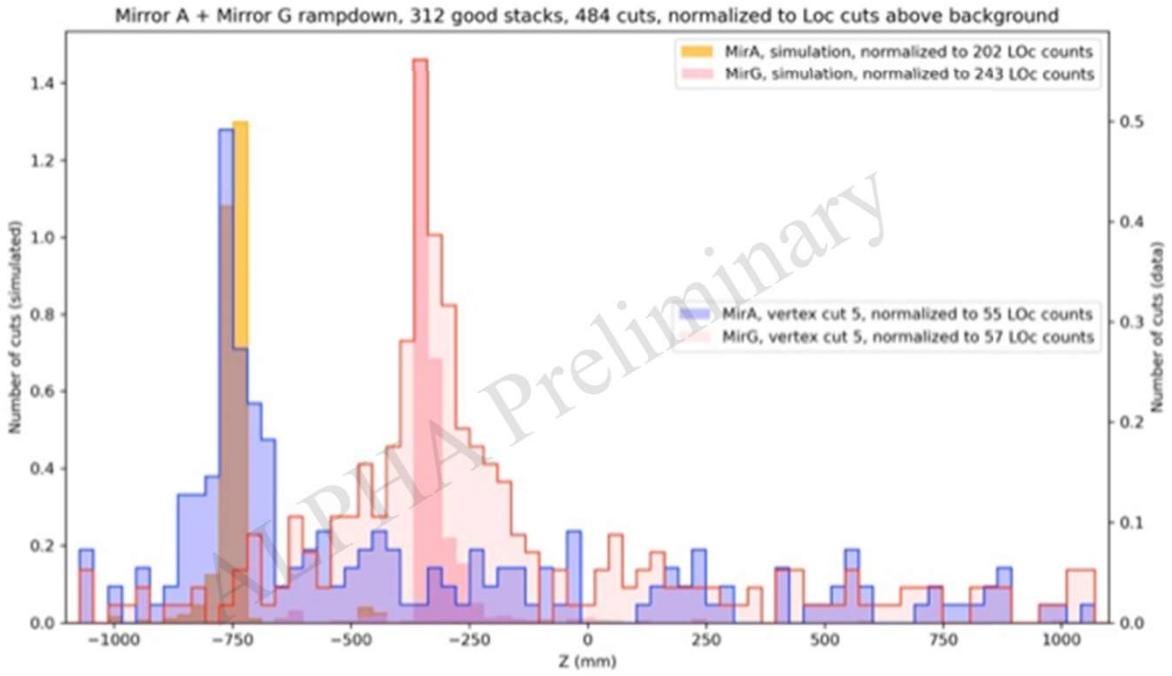


Image: Chukman So

UNIVERSITY OF CALGARY

Proof of principle



DOWN

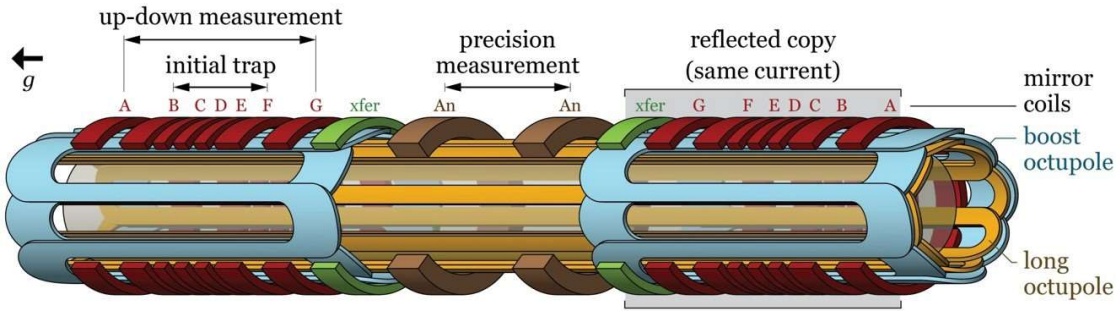
Blue: Trap bias 10x gravity

Red: Trap bias –10x gravity

UNIVERSITY OF CALGARY

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)



UNIVERSITY OF CALGARY

Thanks!

Tim Friesen
timothy.friesen@ucalgary.ca

Alberto Jesus Uribe Jimenez

Prof.
R.I. Thompson

Adam Powell

Pooja Woosaree

Jay Suh

Abbygale Swadling

UNIVERSITY OF CALGARY

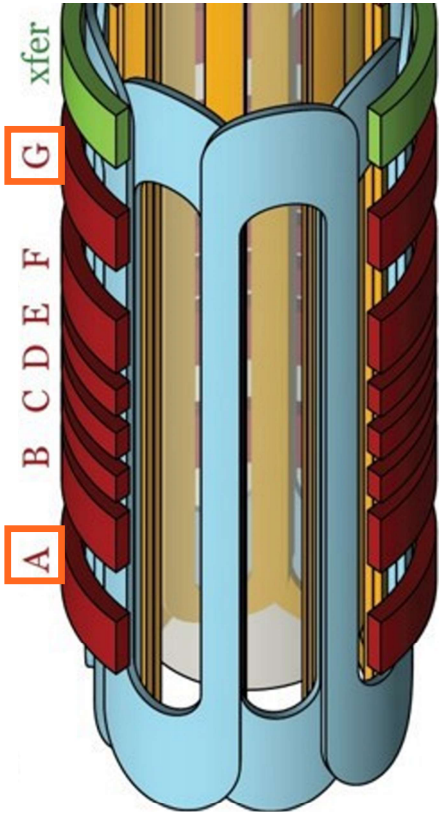
INNOVATION
Canada Foundation for Innovation
Fondation canadienne pour l'innovation

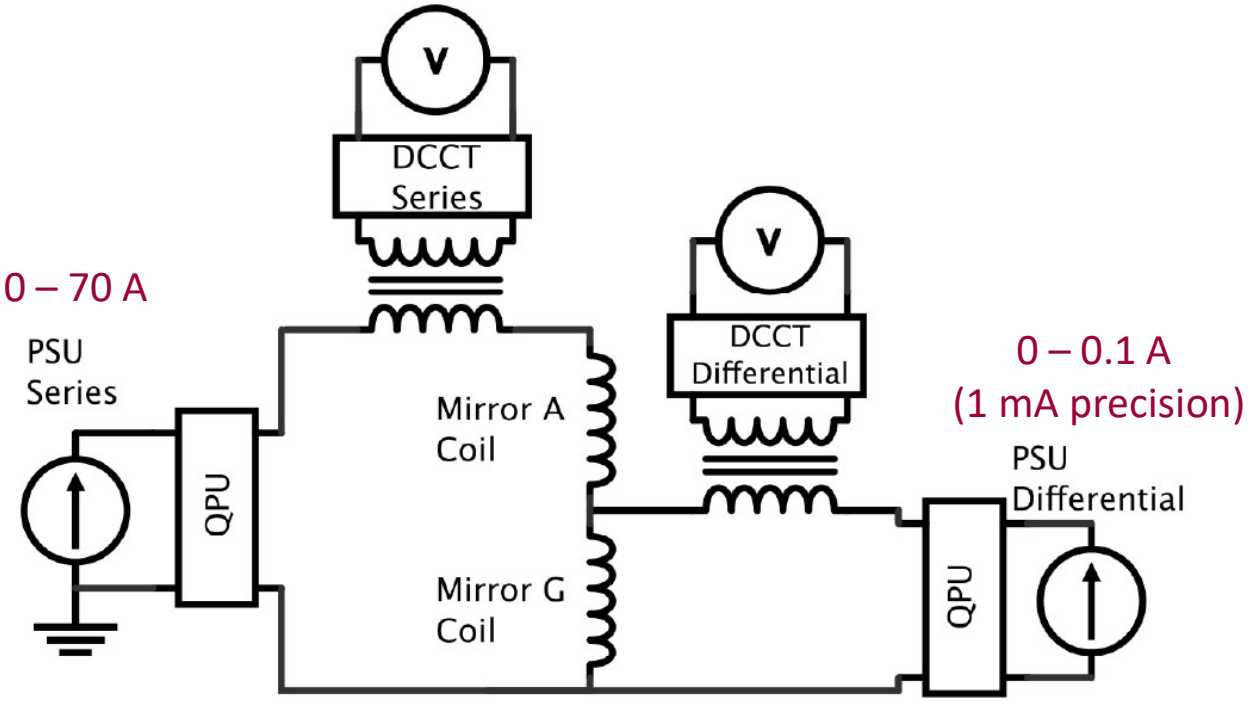
NSERC CRSNG

Alberta

UNIVERSITY OF CALGARY

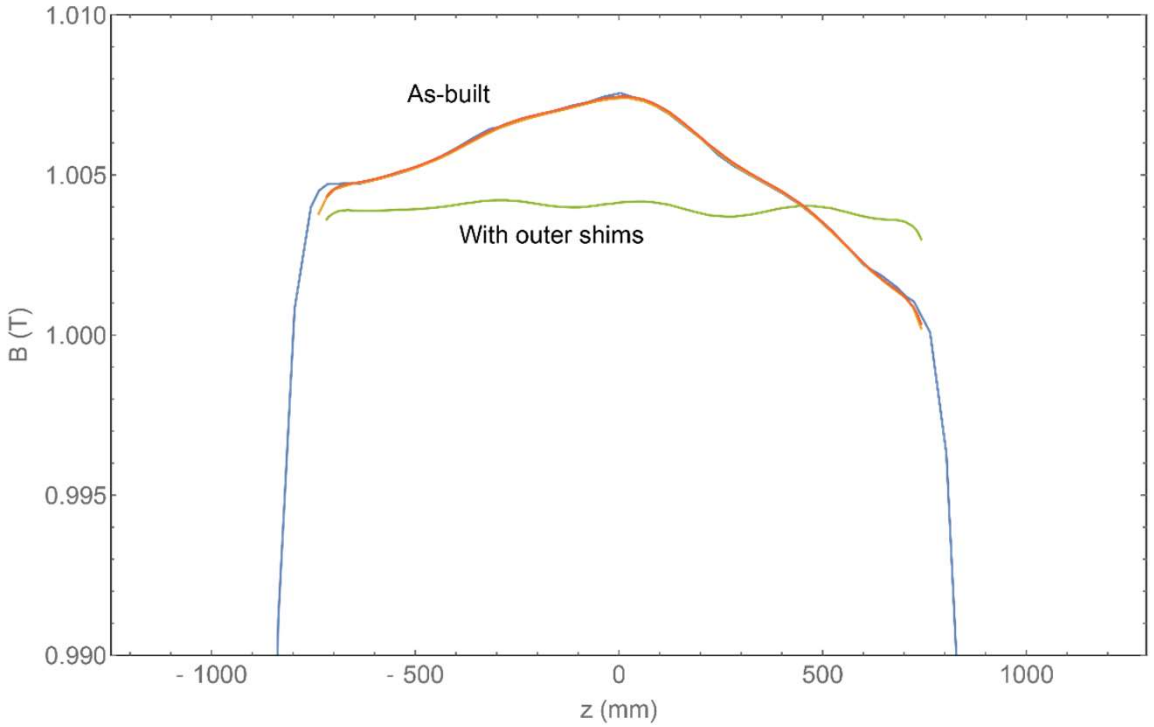
Magnet control





UNIVERSITY OF CALGARY

Background solenoid uniformity



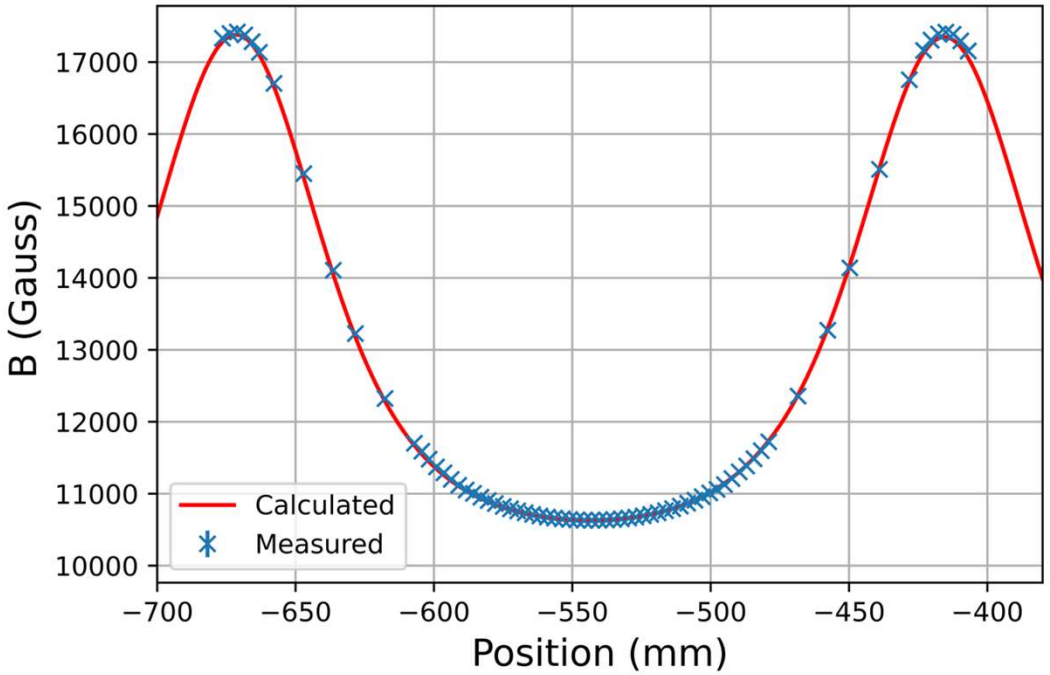
As-built: 20 G non-uniformity

With outer shims: ~4 G non-uniformity

(As measured with hollow solenoid using NMR magnet probes)

UNIVERSITY OF CALGARY

Electron cyclotron resonance

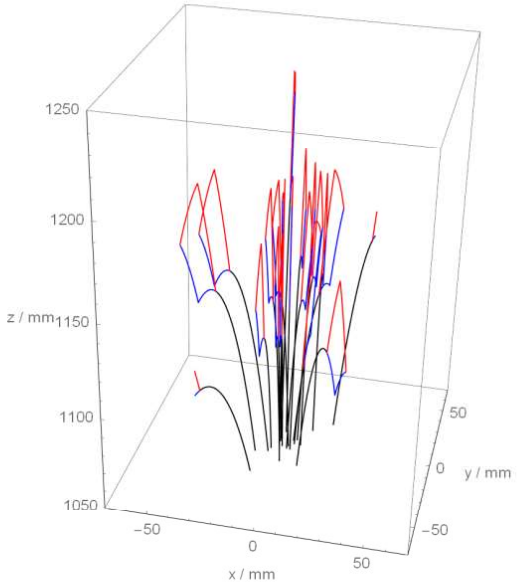


UNIVERSITY OF CALGARY

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

UNIVERSITY OF CALGARY