# Magnetic Fields Studies for Gravitational Experiments with Antihydrogen in ALPHAg

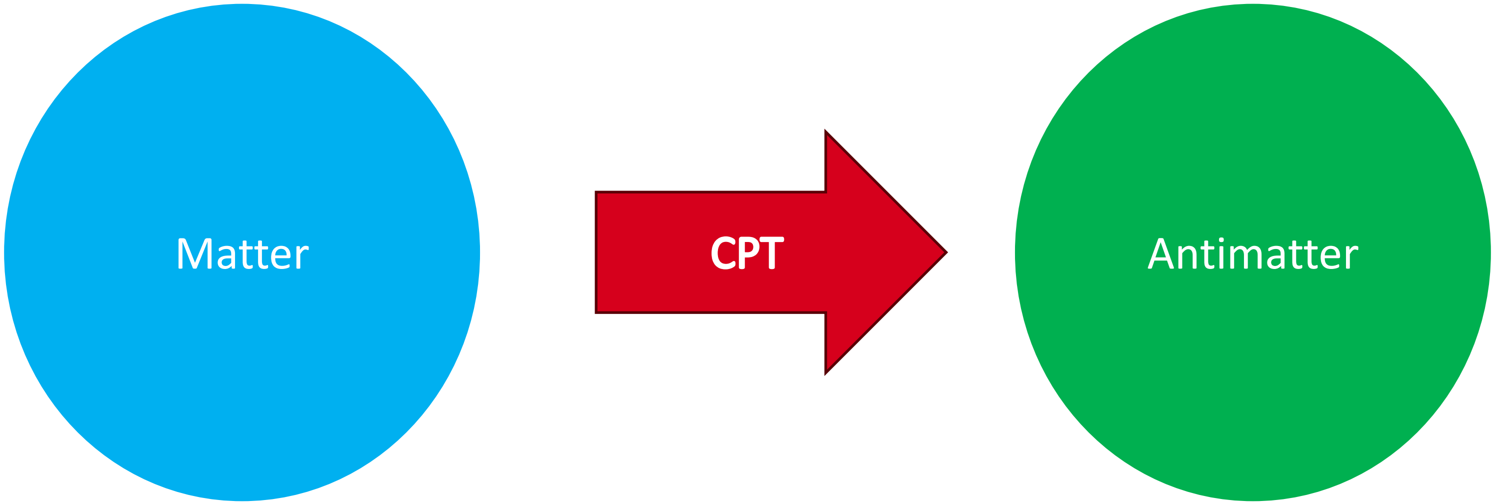
**Early Career Conference on Trapped Ions (ECCTI)**
**Innsbruck**

12th July 2024
Adam Powell

# Outline

- Introduction and ALPHAg
- Results of antihydrogen free fall experiment
- "ECR" magnetometry technique
- Example magnetic field measurements
- Summary of magnetic bias uncertainty

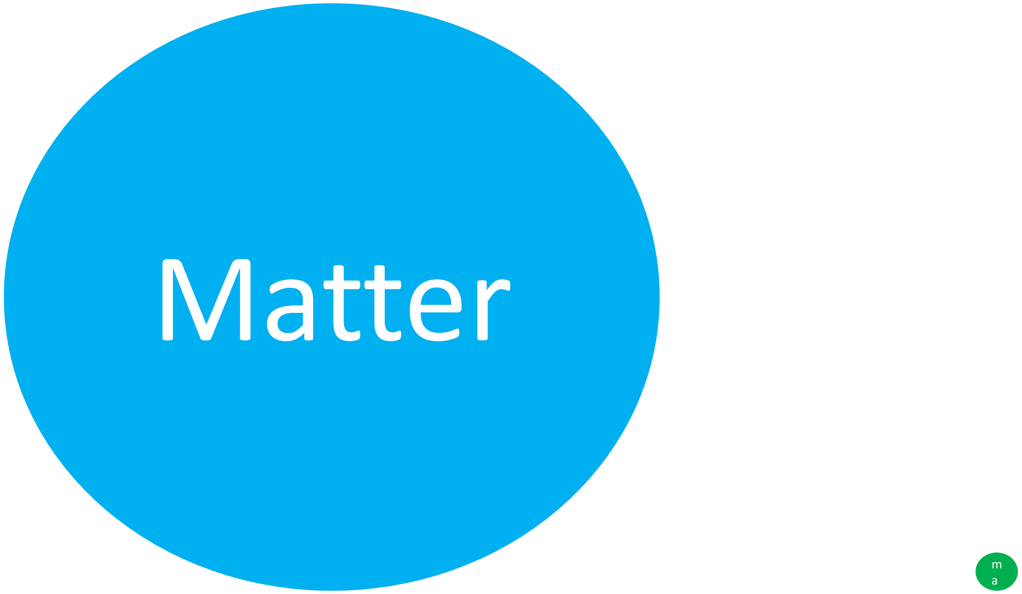
# Antimatter and fundamental symmetries




Since a system should be invariant under CPT transformation
**compare and look for differences**

# Where is all the antimatter?

There should be equal amounts of matter and antimatter…




…but we only see matter in the observable universe, why?

**compare and look for differences**

# Why do we use antihydrogen?

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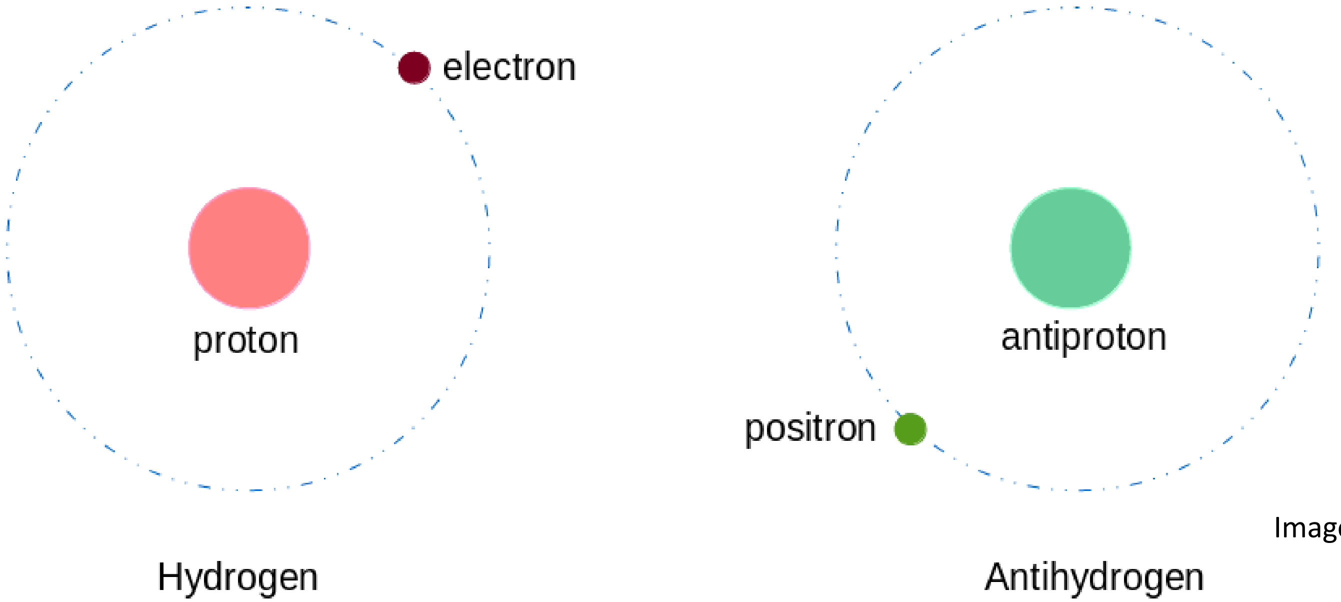


Image credit: P.Woosaree

- Hydrogen has been studied extensively through history, comparing to antihydrogen can test fundamental symmetries

- Electrically neutral and stable

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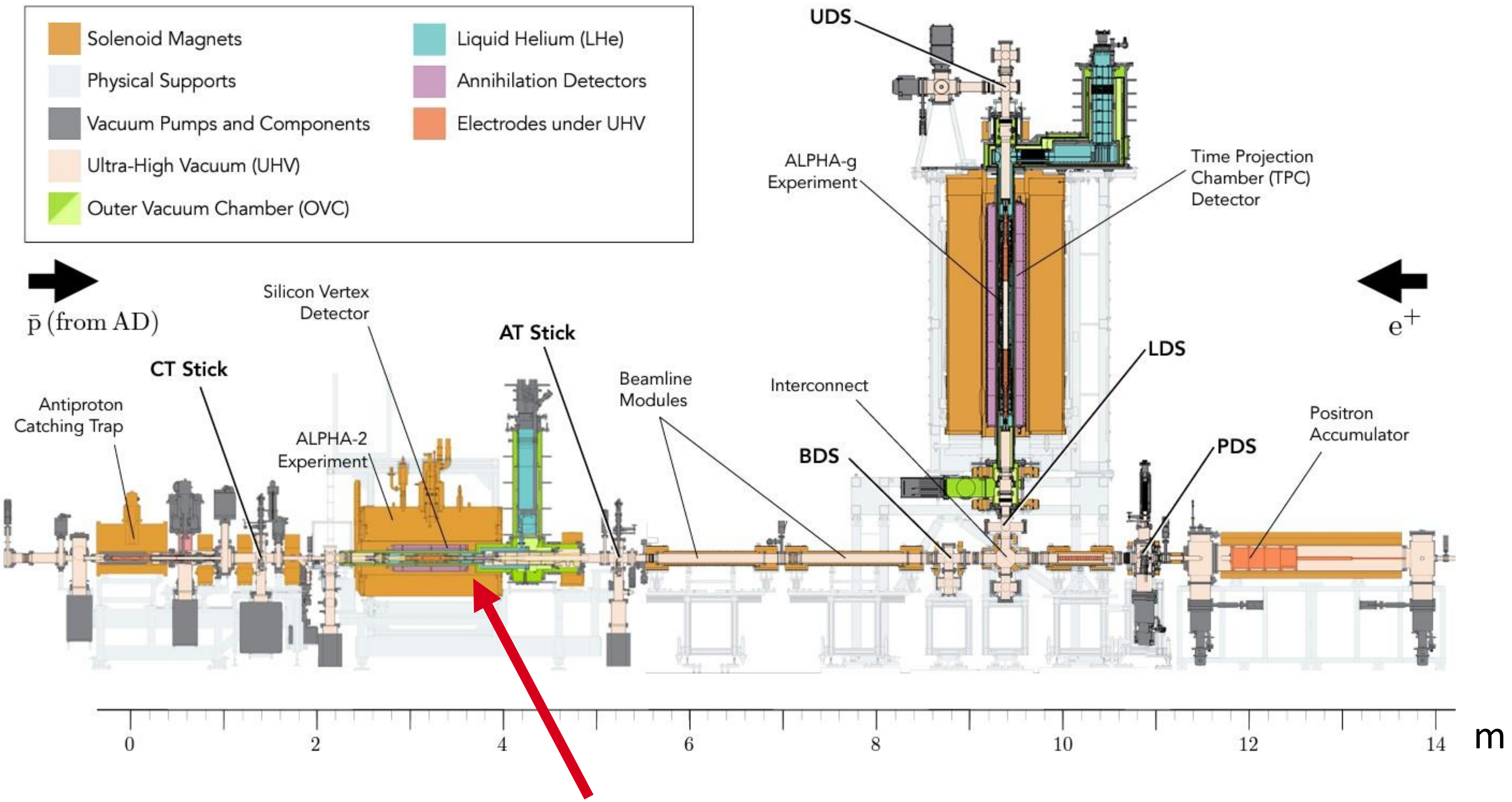
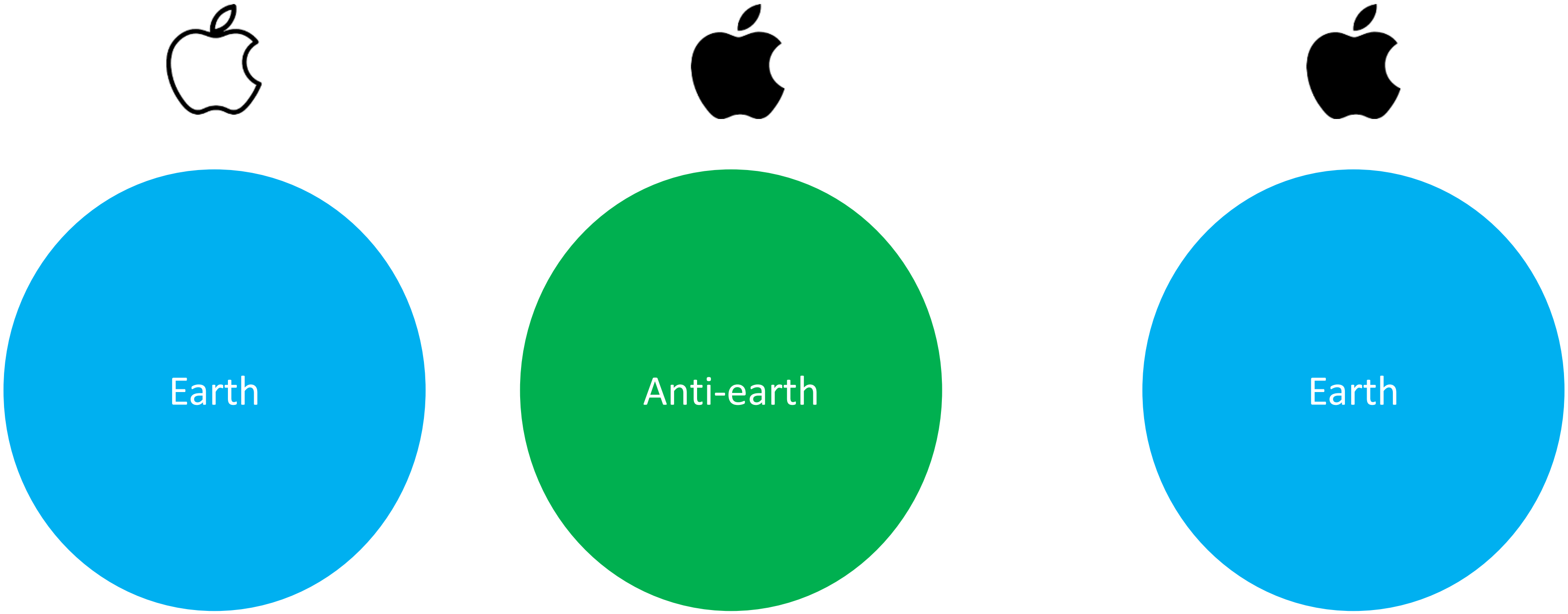
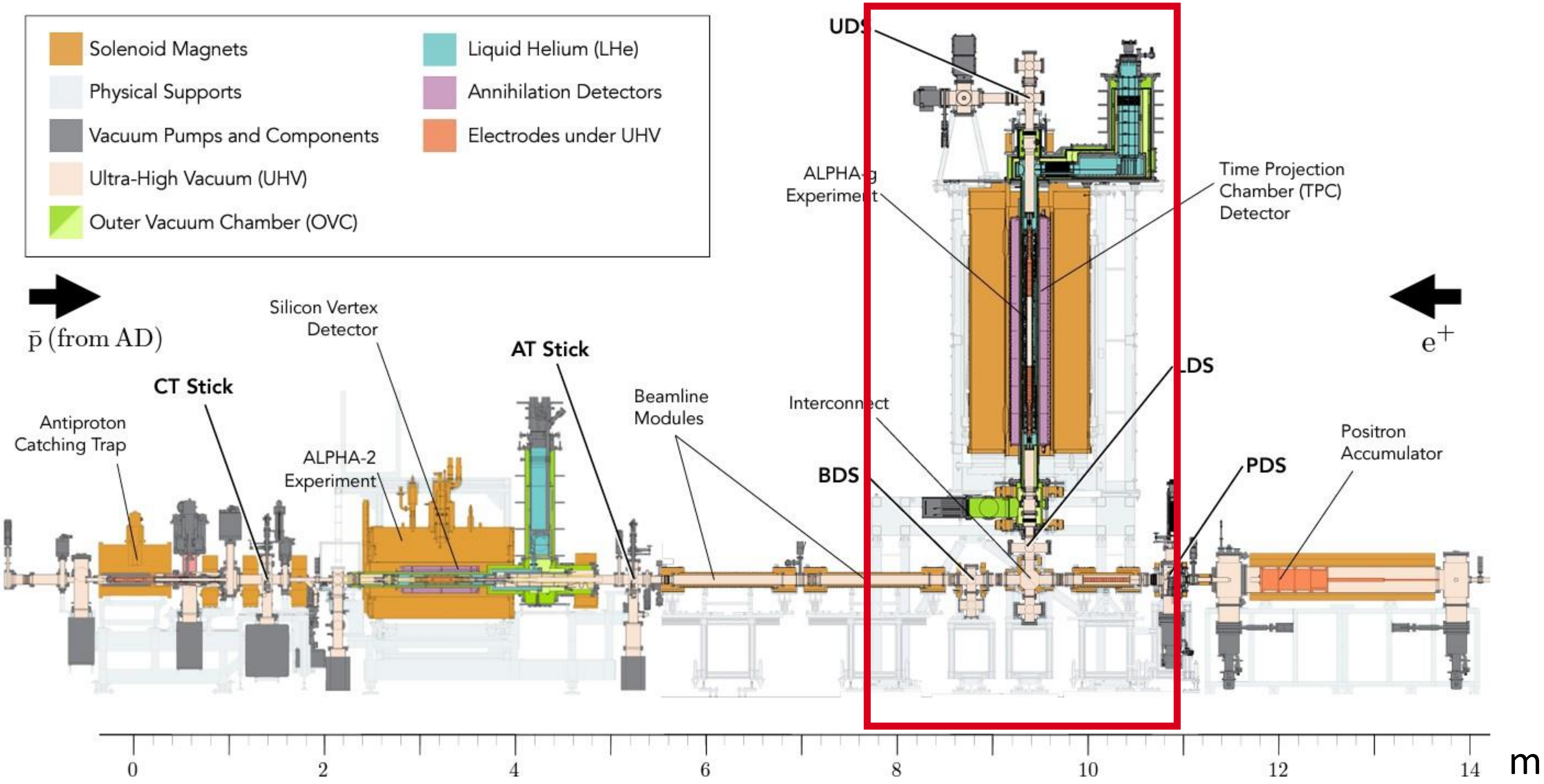



Dr. Alberto Jesus Uribe Jimenez talk next!

# Antimatter and fundamental symmetries




-> We can use free fall as a test of the equivalence principle



Solenoid Magnets
Physical Supports
Vacuum Pumps and Components
Ultra-High Vacuum (UHV)
Outer Vacuum Chamber (OVC)
Liquid Helium (LHe)
Annihilation Detectors
Electrodes under UHV
p̄ (from AD)
e+
UDS
ALPHA-g Experiment
Time Projection Chamber (TPC) Detector
Silicon Vertex Detector
AT Stick
CT Stick
Antiproton Catching Trap
ALPHA-2 Experiment
Beamline Modules
Interconnect
BDS
LDS
PDS
Positron Accumulator
0
2
4
6
8
10
12
14
m


ANTIMATTER
FACTORY
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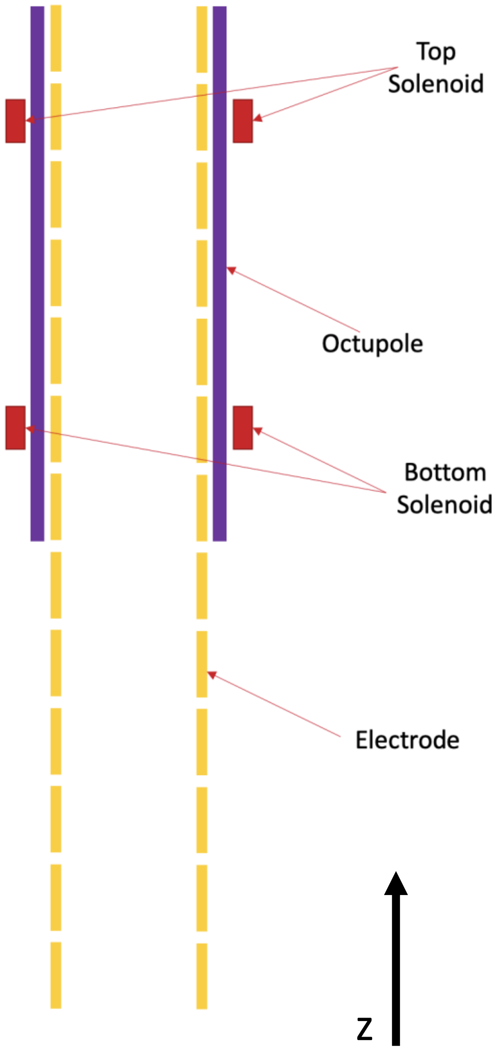
# ALPHAg simplified



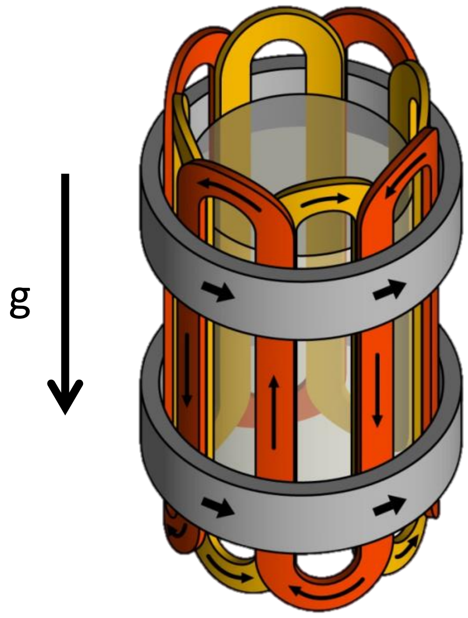
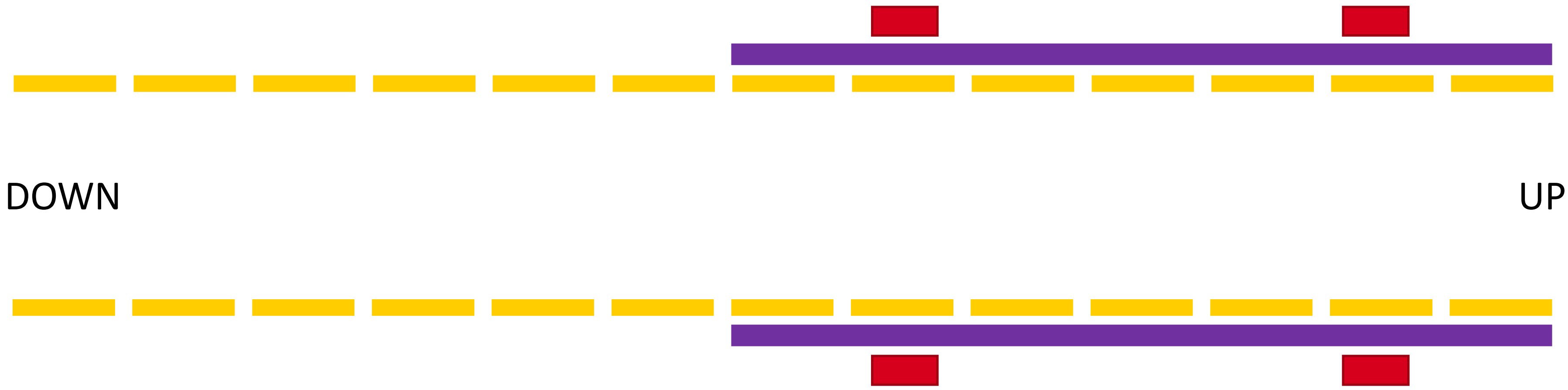




Image credit: Dr C.So, ALPHA member

# And put it in an easier orientation

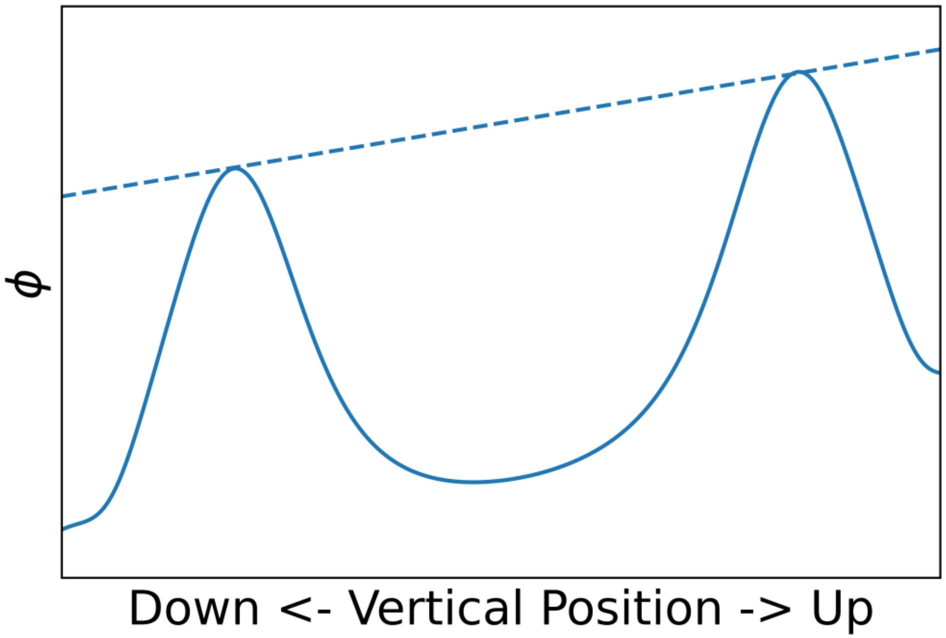


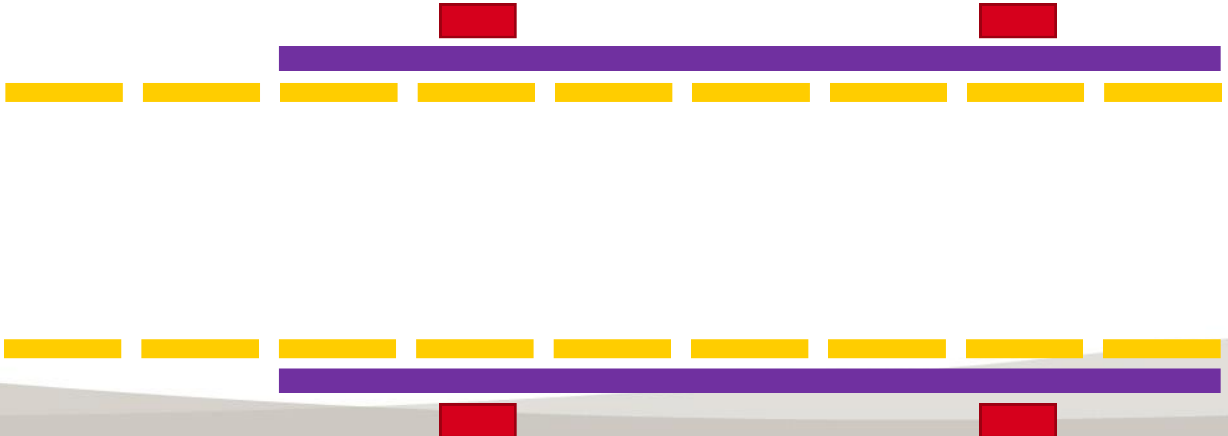
# Assuming gravity acts the same on matter and antimatter

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

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

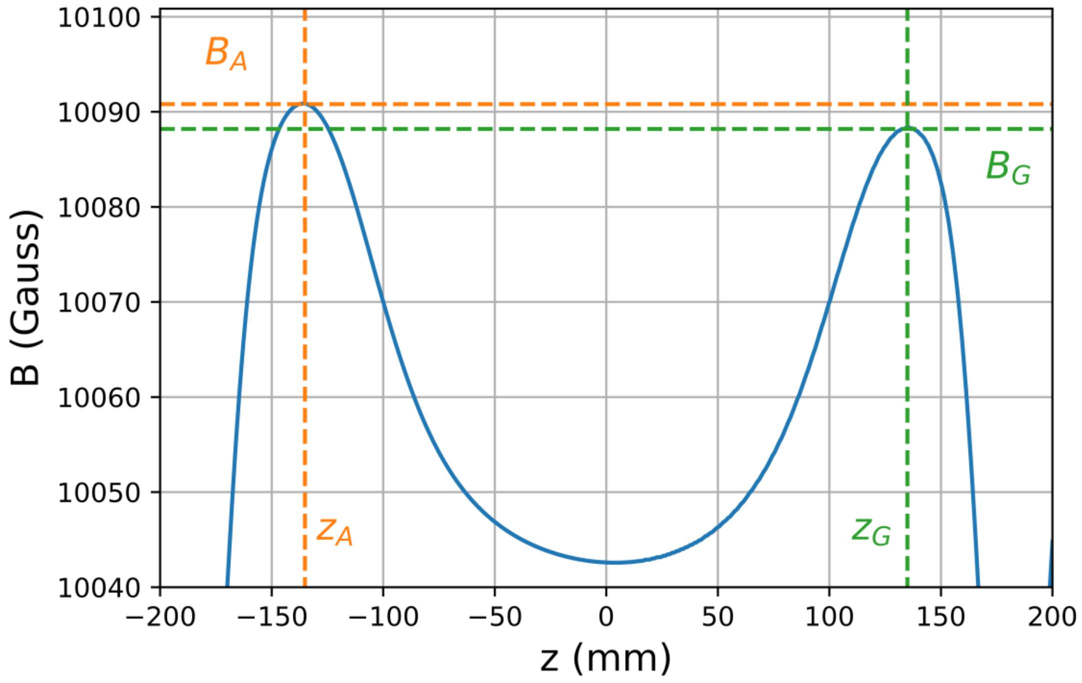
$$\equiv \Delta B \sim 5 \times 10^{-4}\ \mathrm{T}$$



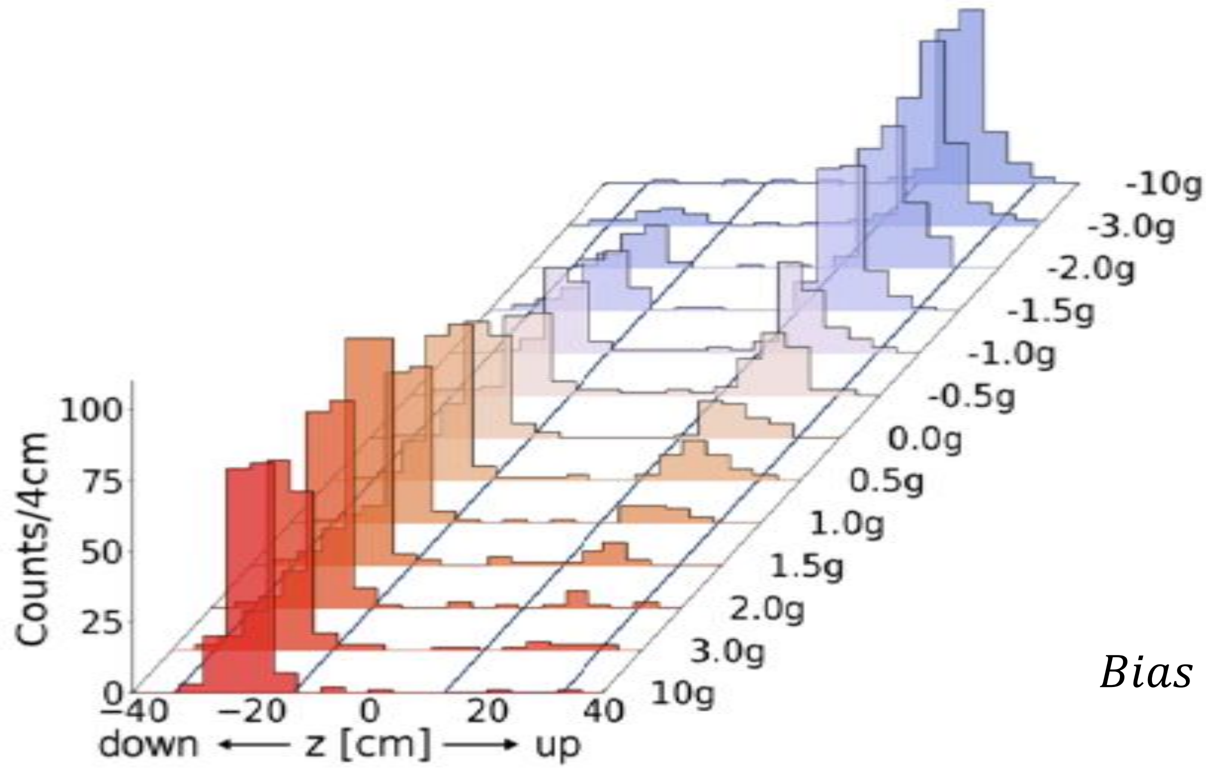

ANTIMATTER
FACTORY
ELENA

# Magnetic trap bias




$$Bias = \frac{\mu_B(B_G - B_A)}{m_H(z_G - z_A)}$$

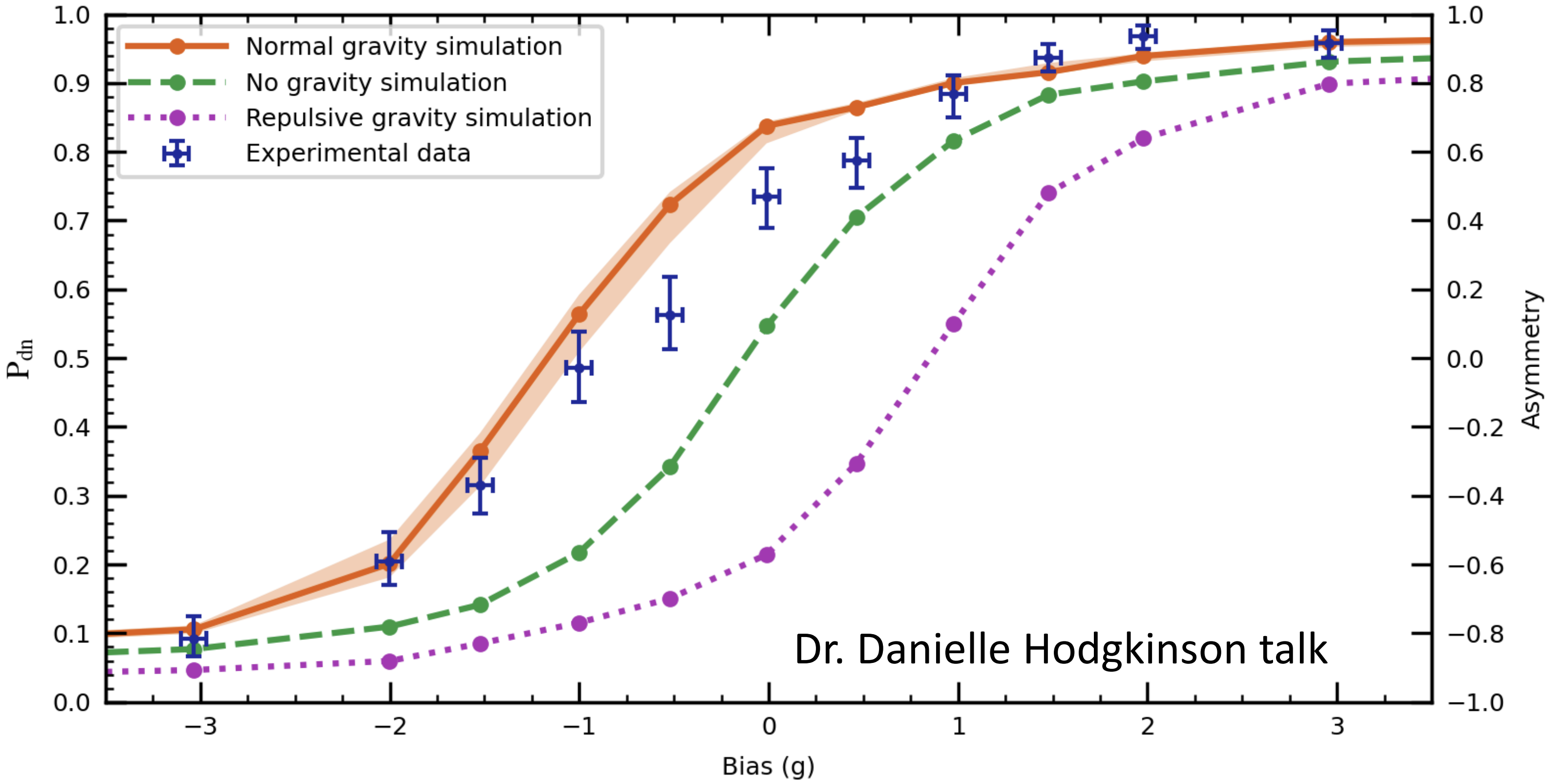
# Annihilation distributions per bias




$$Bias = \frac{\mu_B(B_G - B_A)}{m_H(z_G - z_A)}$$

Observation of the effect of gravity on the motion of antimatter
Nature volume 621, pages716–722 (2023)

# ALPHAg escape curve




$$\bar{g} = [0.75 \pm 0.13\,(statistical + systematic) \pm 0.16\,(simulation)]\; g$$

Observation of the effect of gravity on the motion of antimatter
Nature volume 621, pages716–722 (2023)

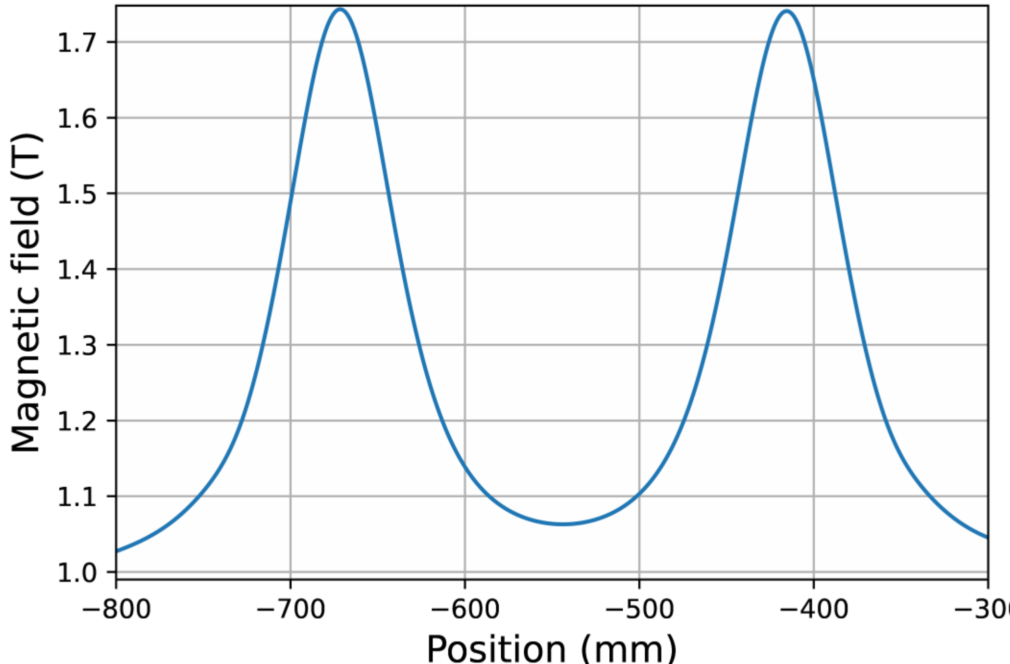
**"Adam, do you control and know the magnetic fields better than 5 Gauss?"**

# Assuming gravity acts the same on matter and antimatter

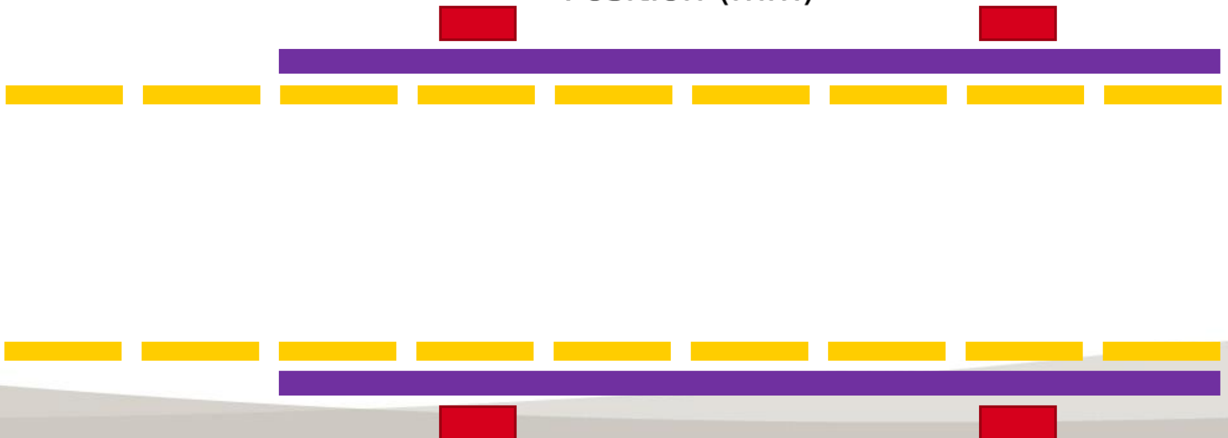
$$\phi = \mu_B B \; - \; mgh$$

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

$$\equiv \Delta B \sim 5 \times 10^{-4}\ \mathrm{T}$$




Field change from
1.7 T to 1 T in 20 s



# Using cyclotron frequency for magnetometry

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

$f_c$ for electrons at 1 T ~ 28 GHz

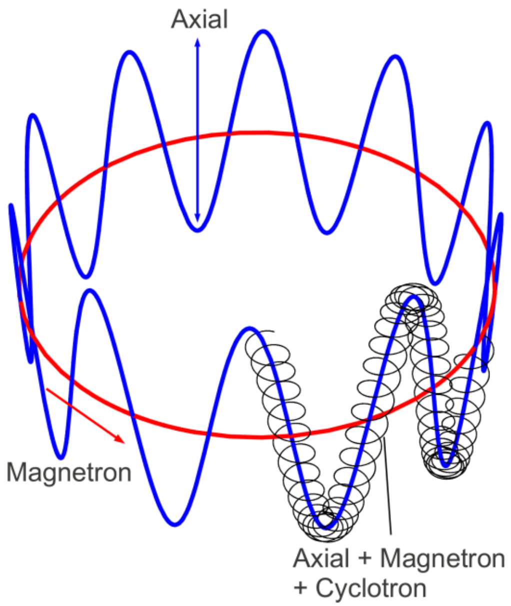


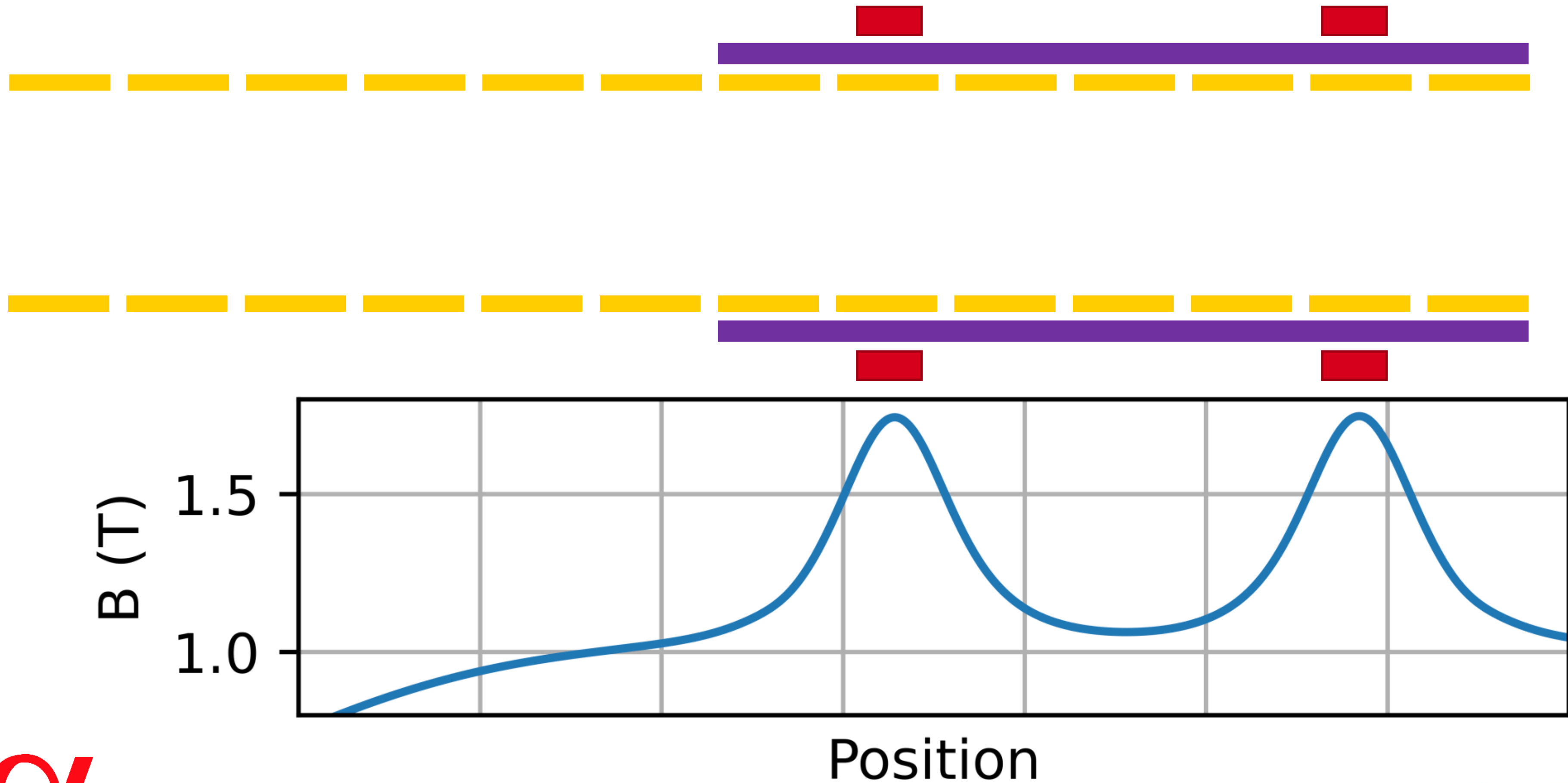

Image credit: T.Friesen

But…the cyclotron motion isn't all that happens in a Penning trap

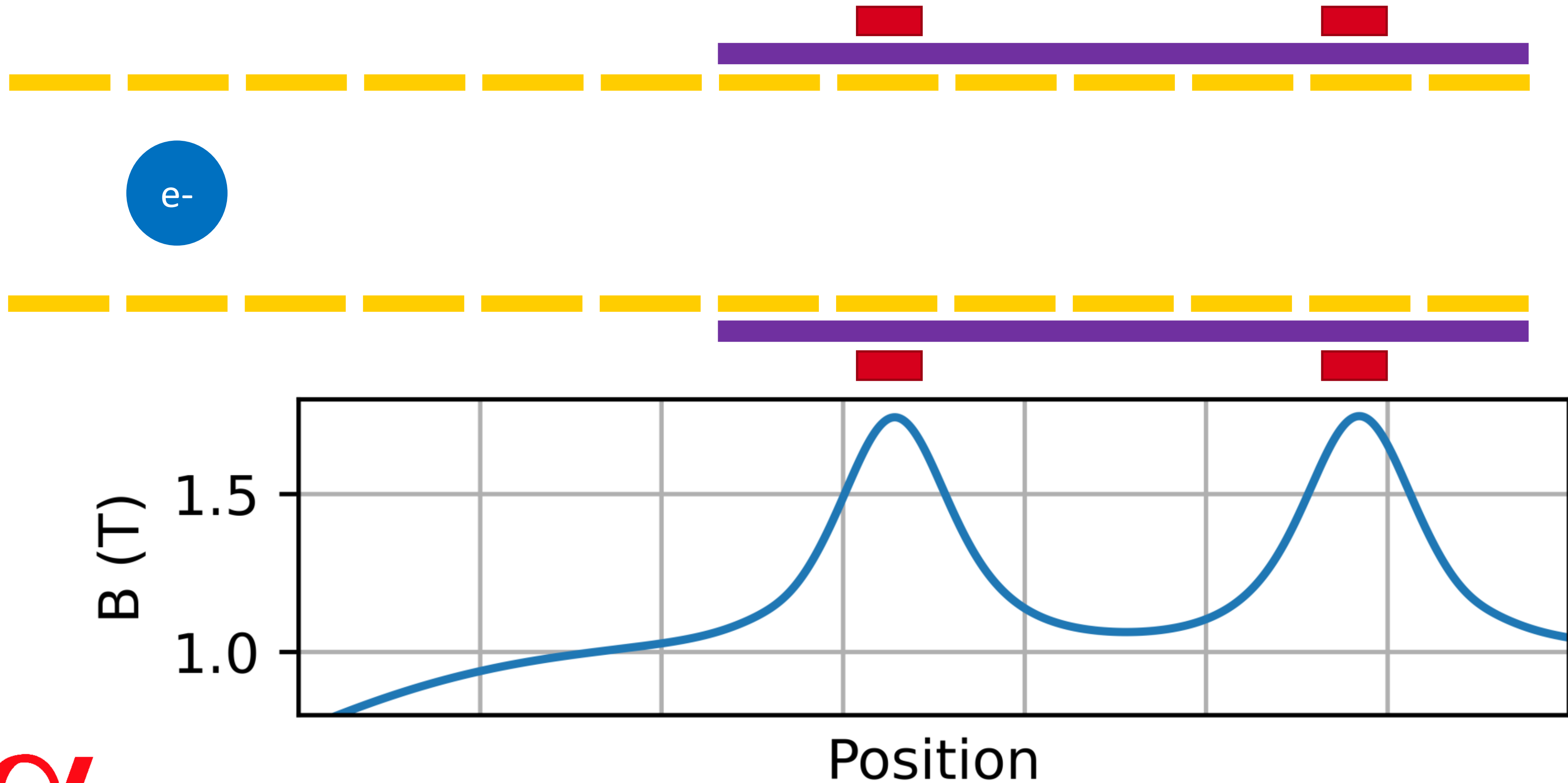
Axial frequency ~ 10 - 50 MHz

Magnetron frequency ~ 100 - 300 kHz

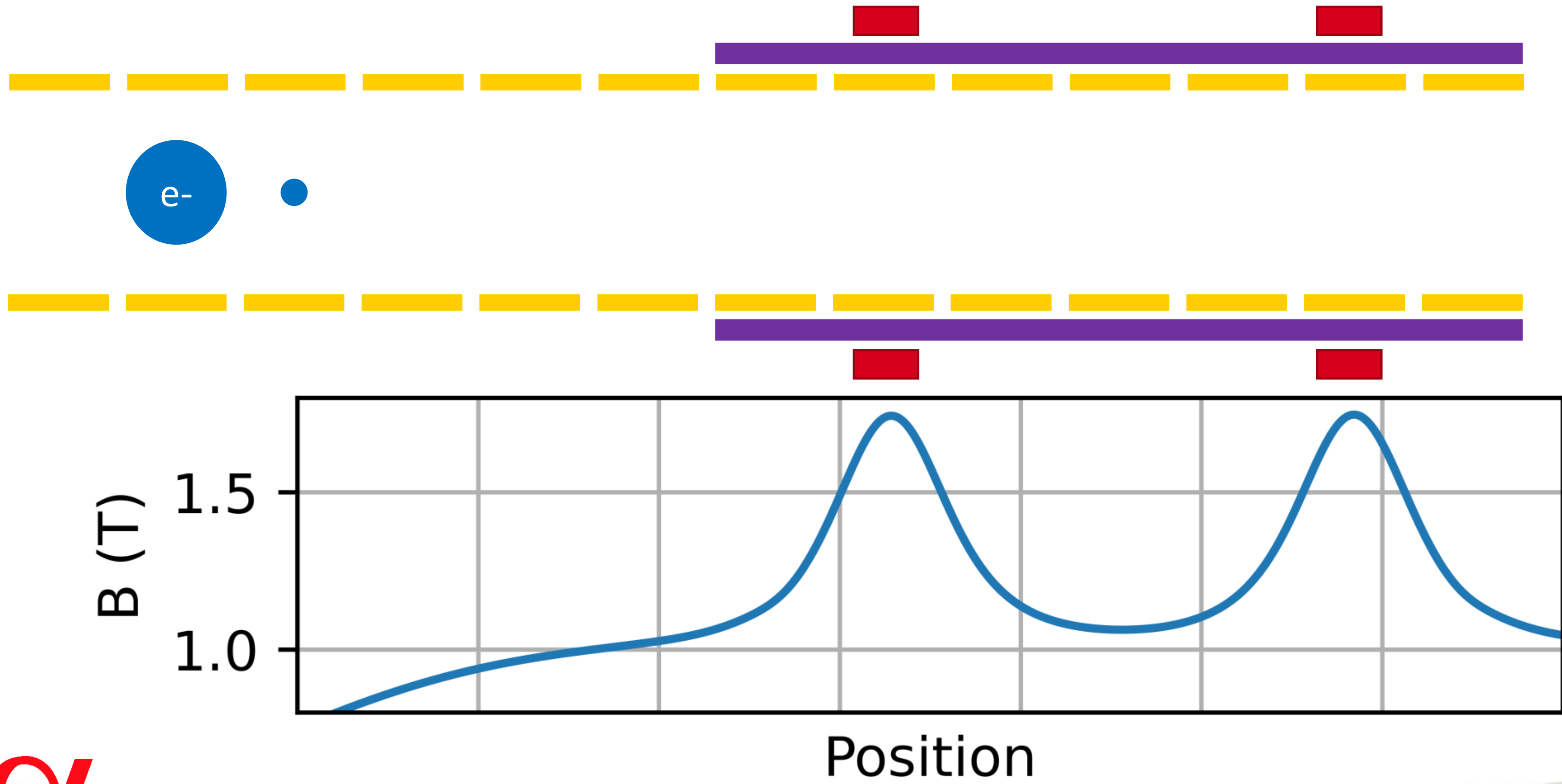
# What is Electron cyclotron resonance magnetometry?



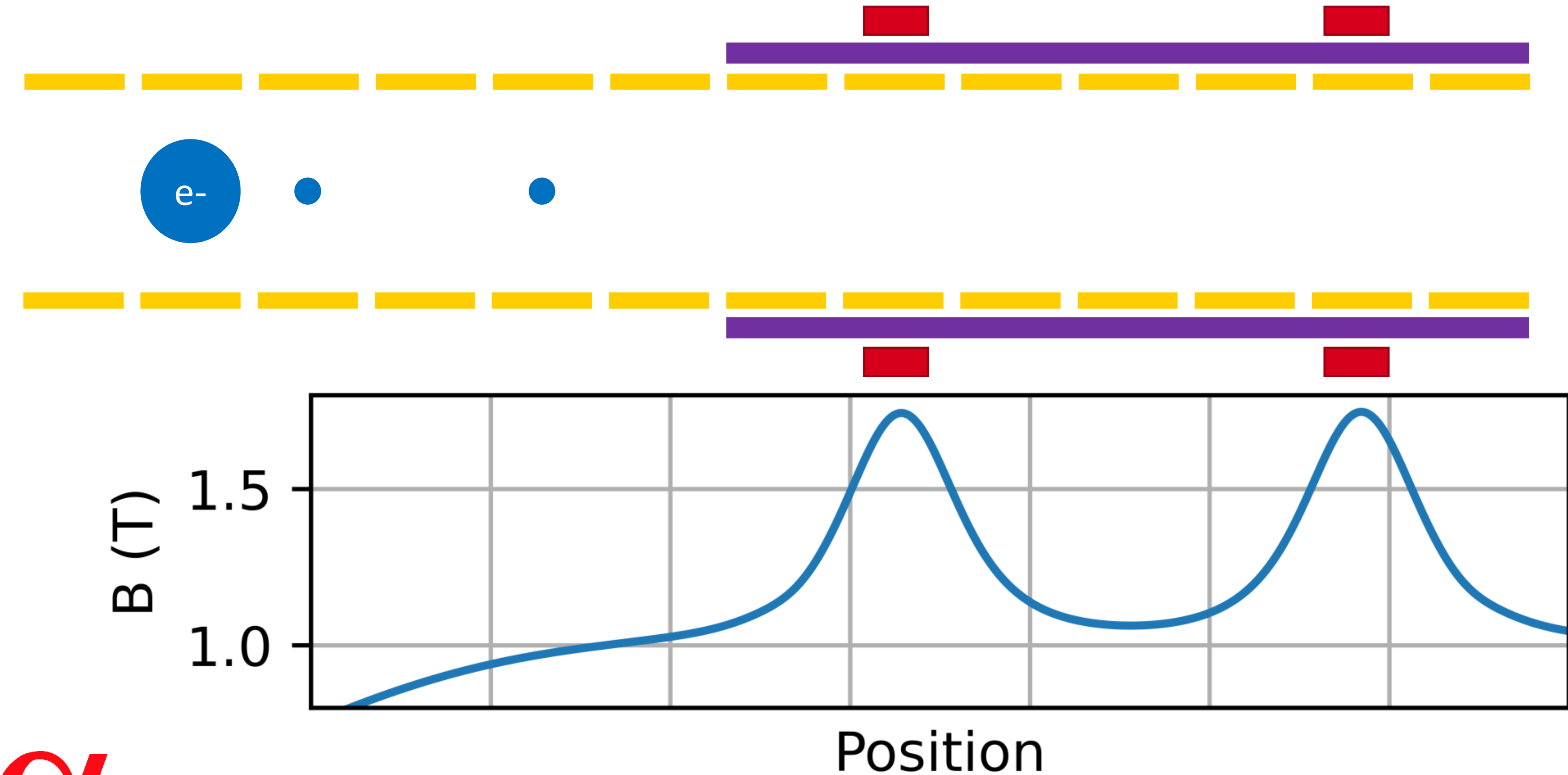
# Get an electron plasma



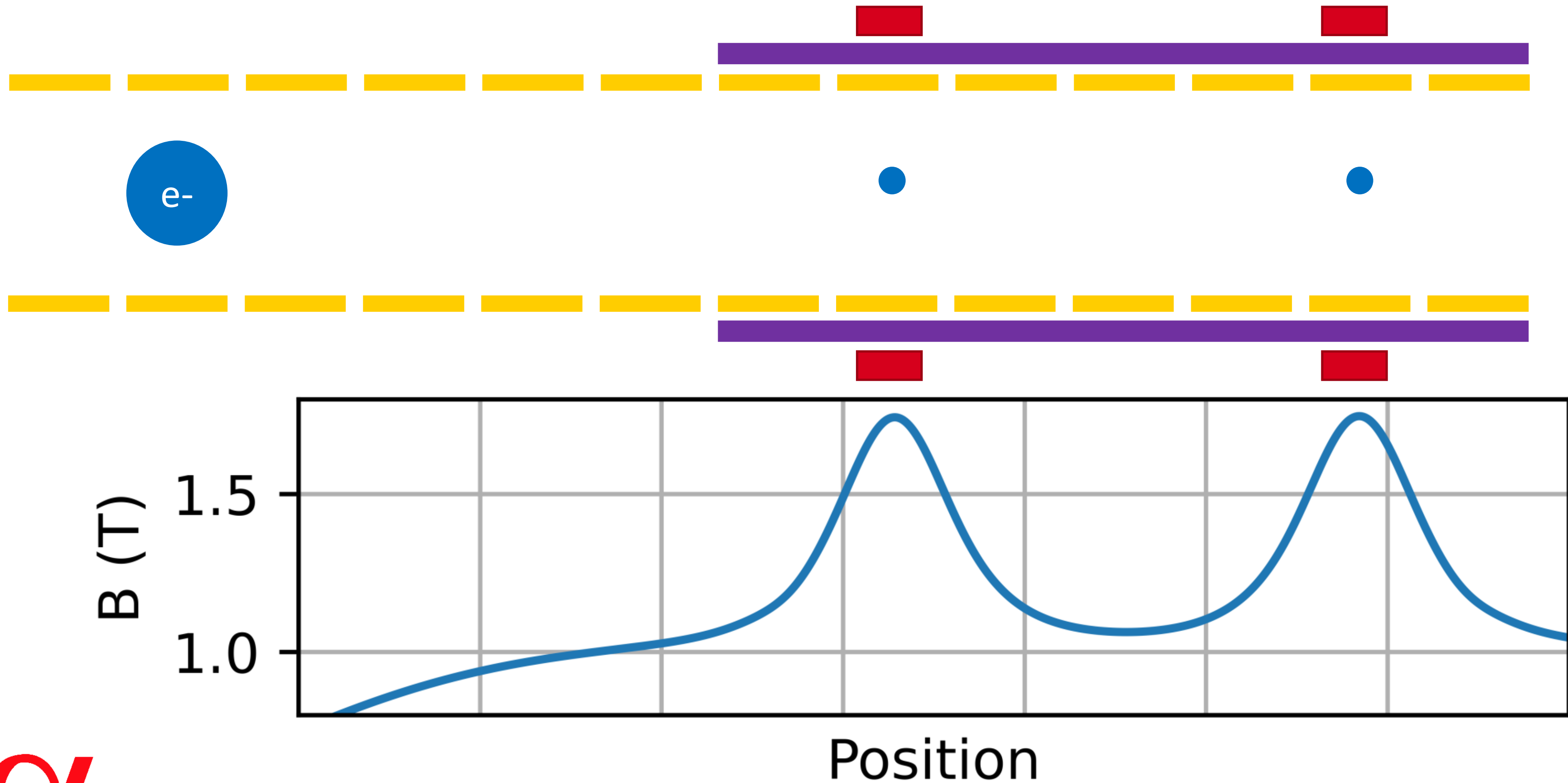
# Remove a small “scoop” of electrons



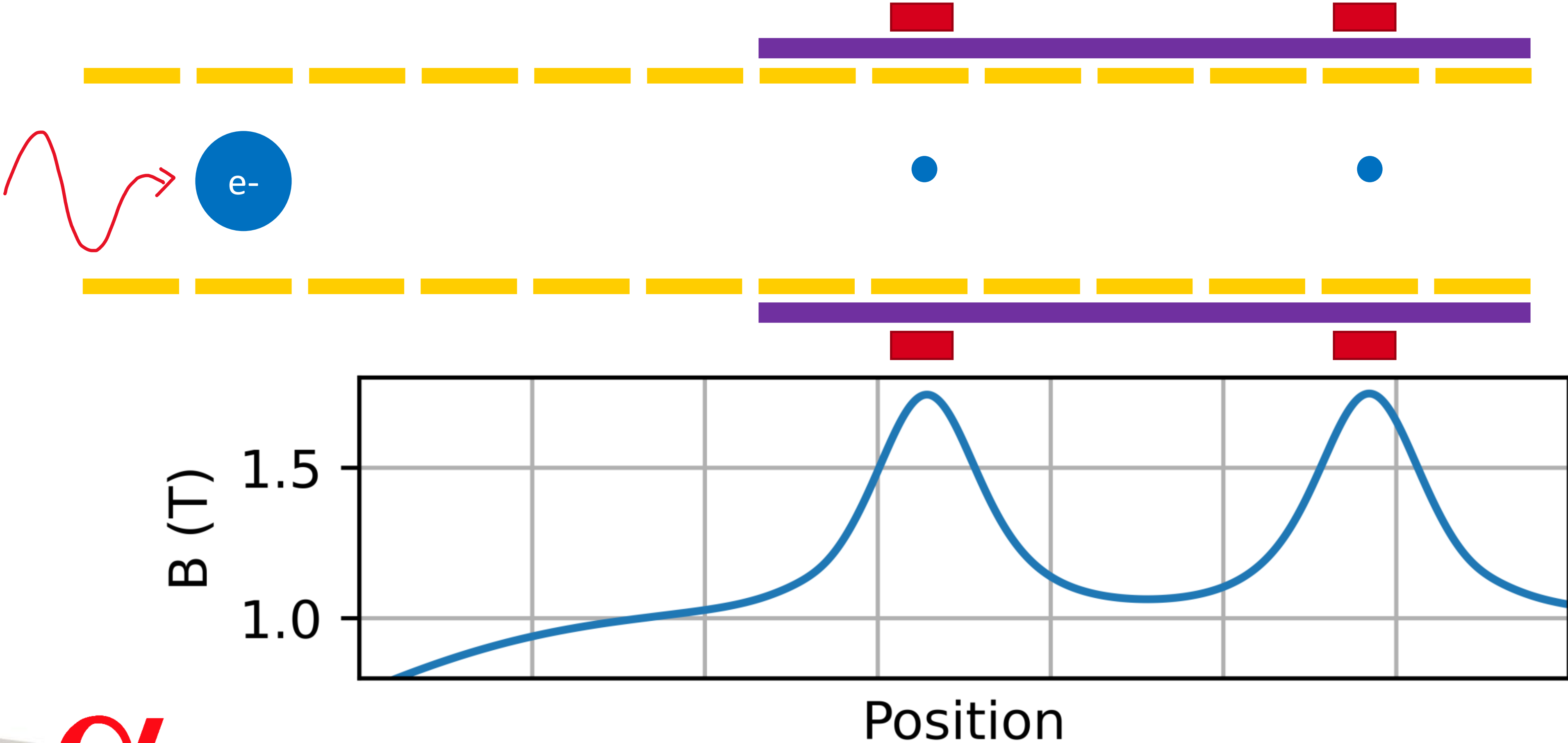
# And another



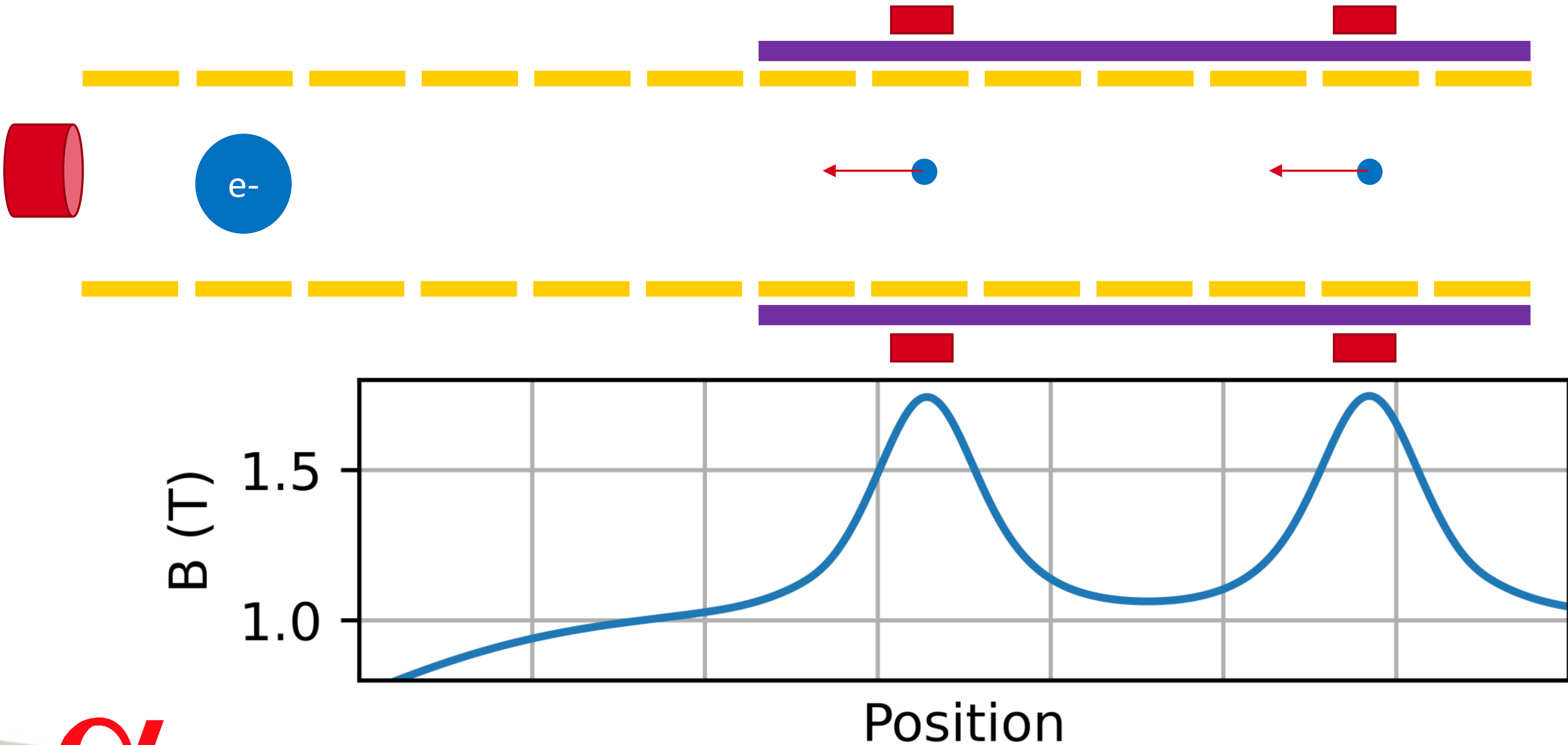
# Move to target location



# Irradiate with a microwave pulse



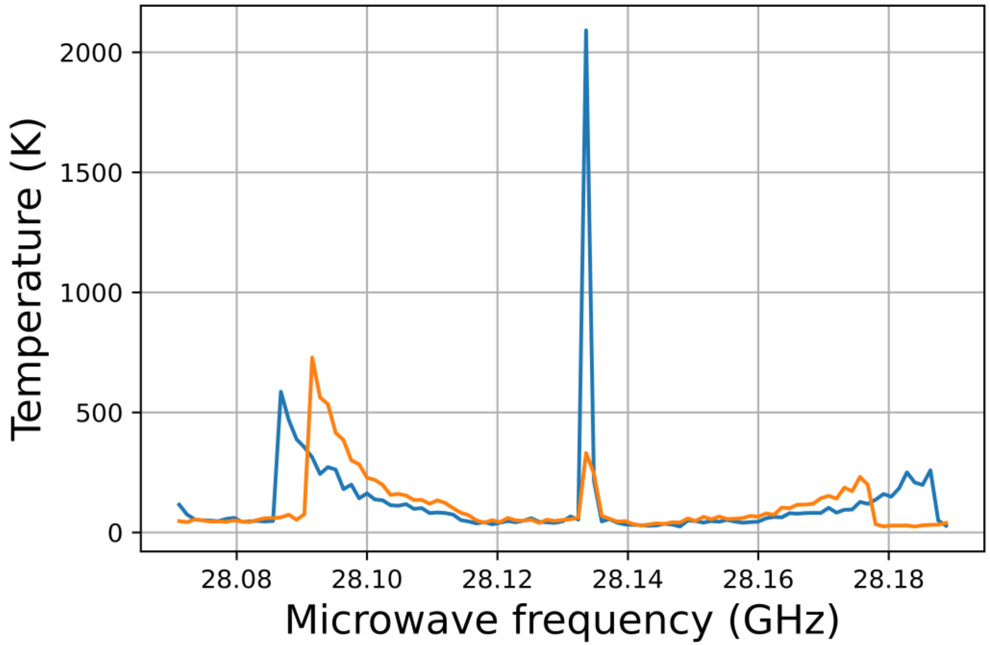
# Measure temperature of electron "scoops"



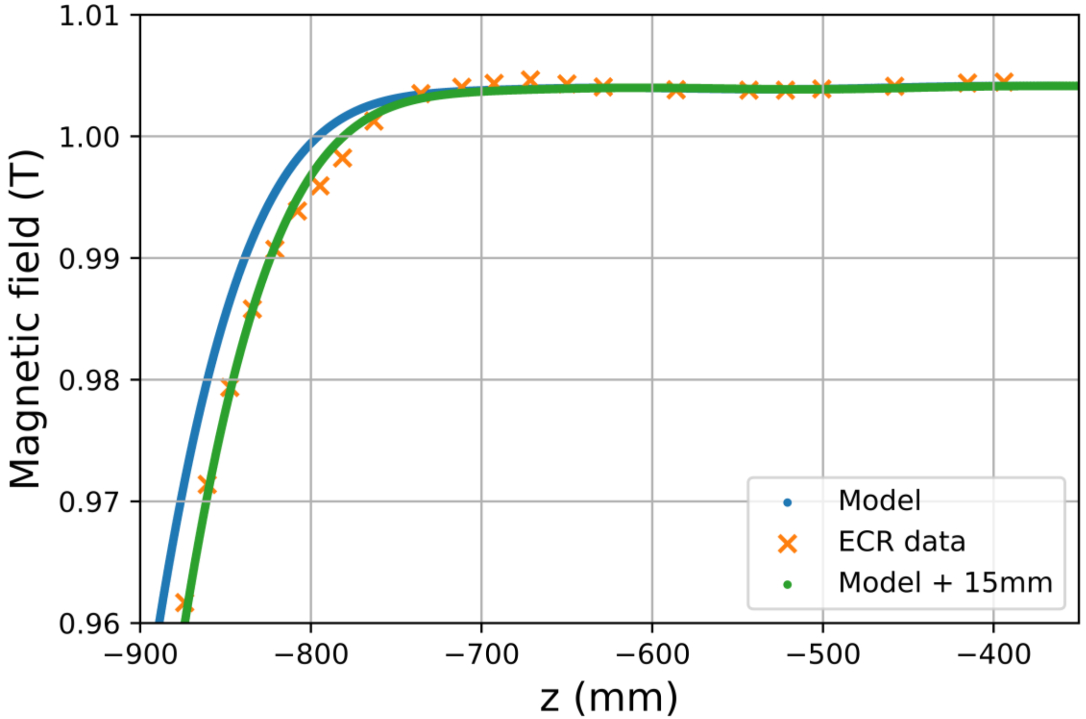

Electron Cyclotron Resonance (ECR) Magnetometry with a Plasma Reservoir
E. D. Hunter, A. Christensen, J. Fajans , T. Friesen, E. Kur, and J. S. Wurtele (2019)

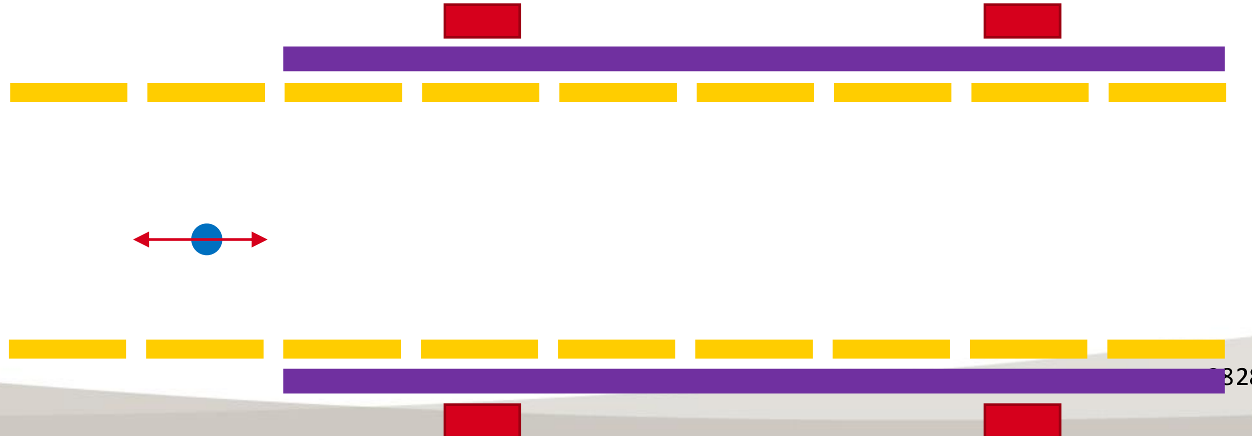
# An example of ECR spectra

- Narrow central peak = $f_c$
- Precision related to peak width
- Broad, asymmetric sidebands from electrons axial frequency



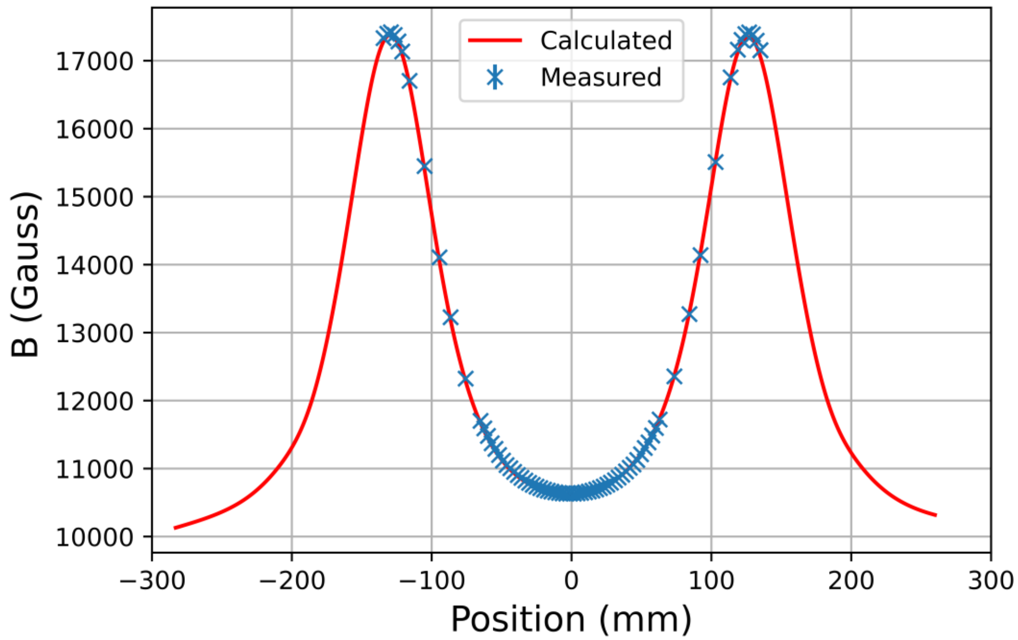
# Field mapping the background magnet

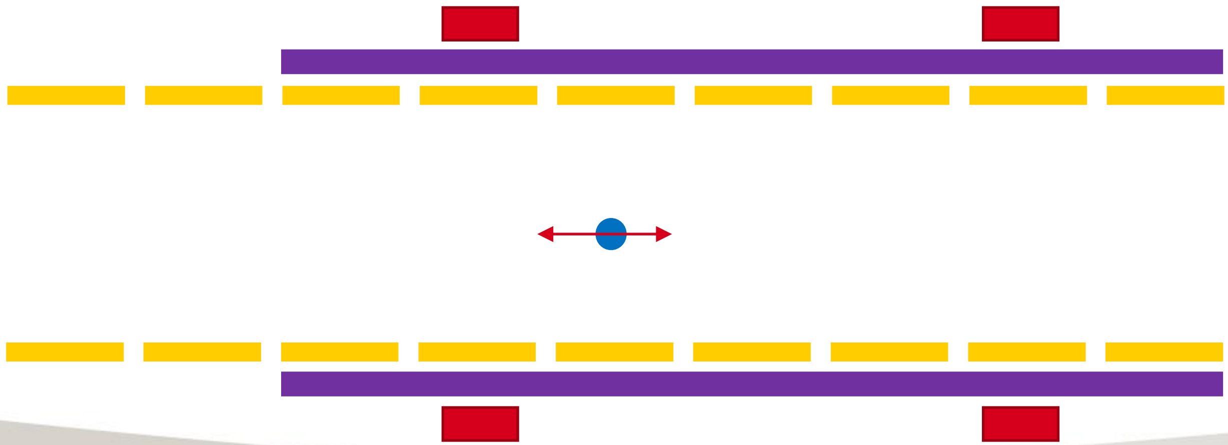


$10^{-4}$ T = 1 Gauss = 2.8 MHz

# Field mapping the magnetic trap

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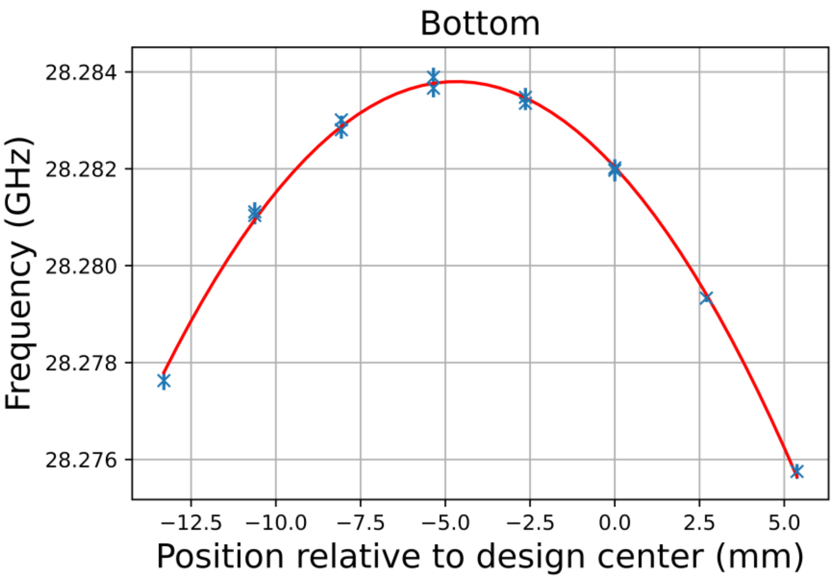
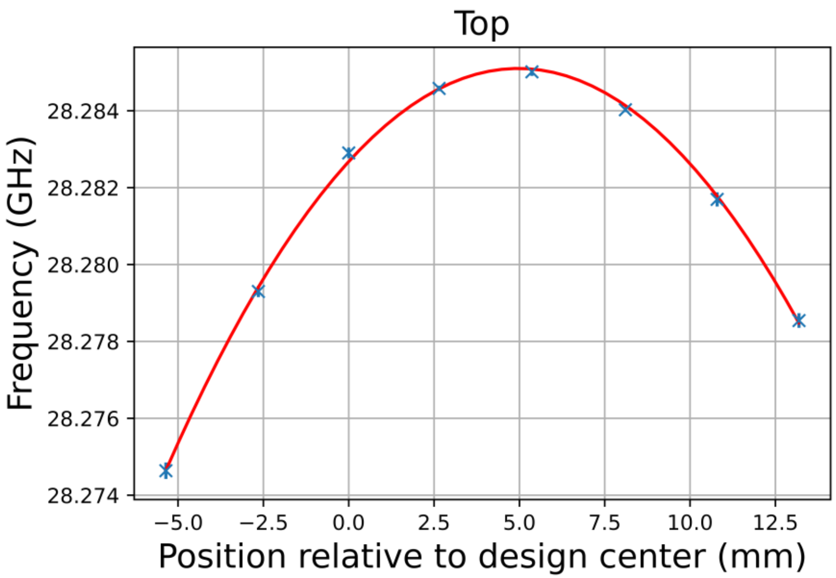
# Mapping out the on axis maxima of each solenoid

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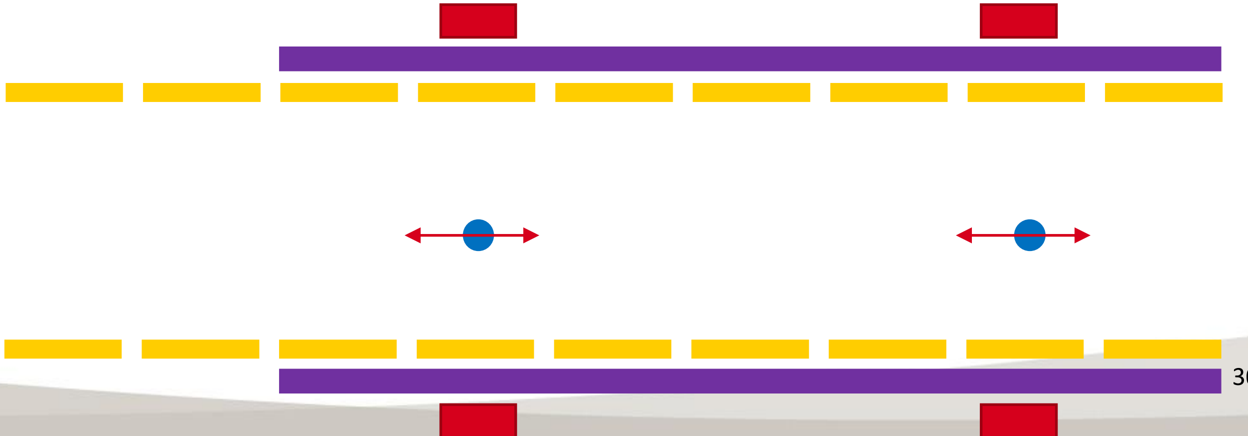

# Mapping out the on axis maxima of each solenoid

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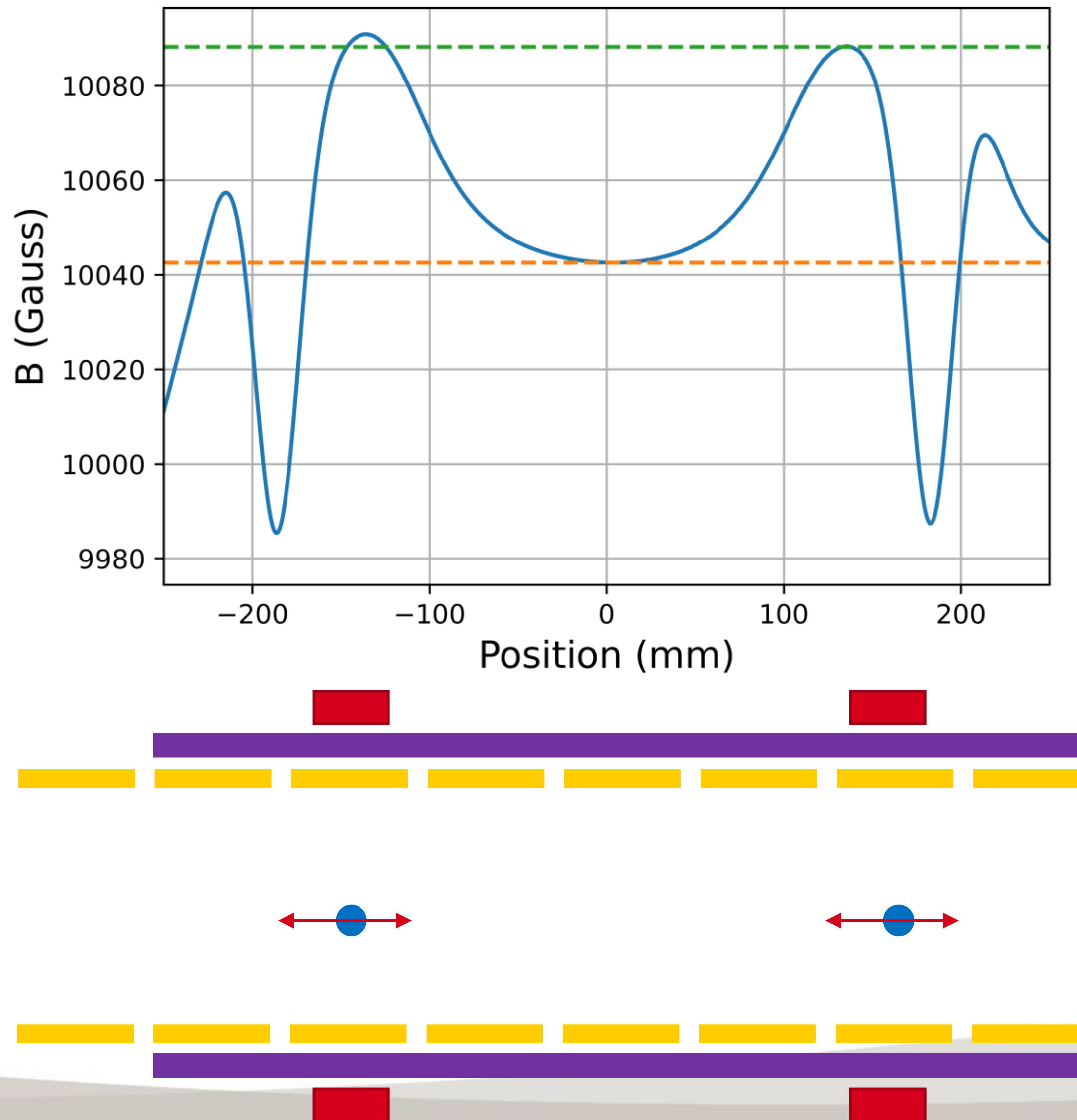


$10^{-4}$ T = 1 Gauss = 2.8 MHz

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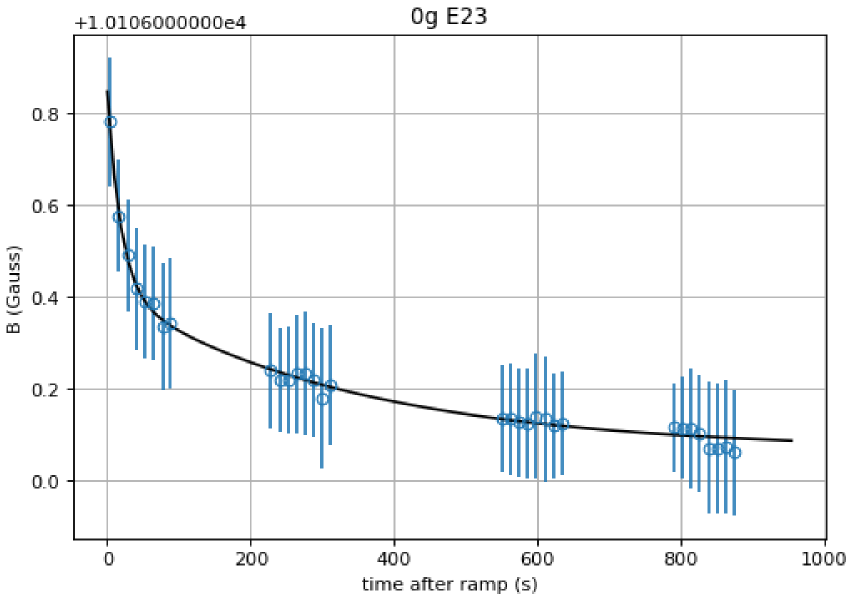
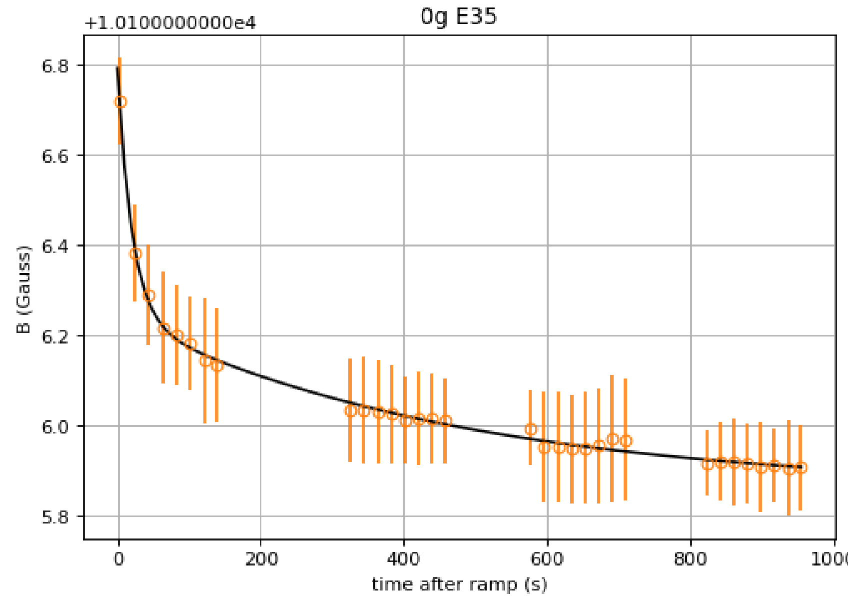
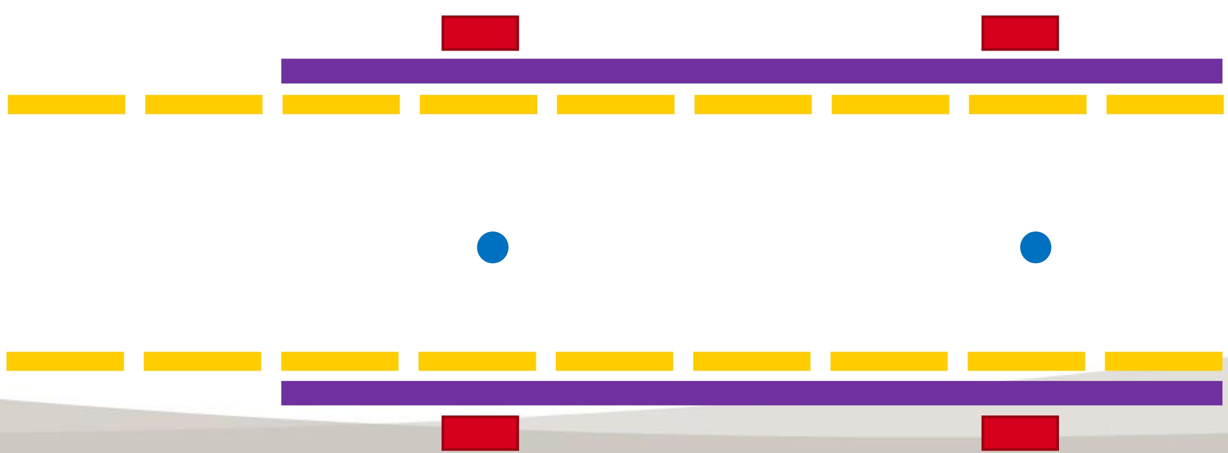
# Measure decaying induced fields

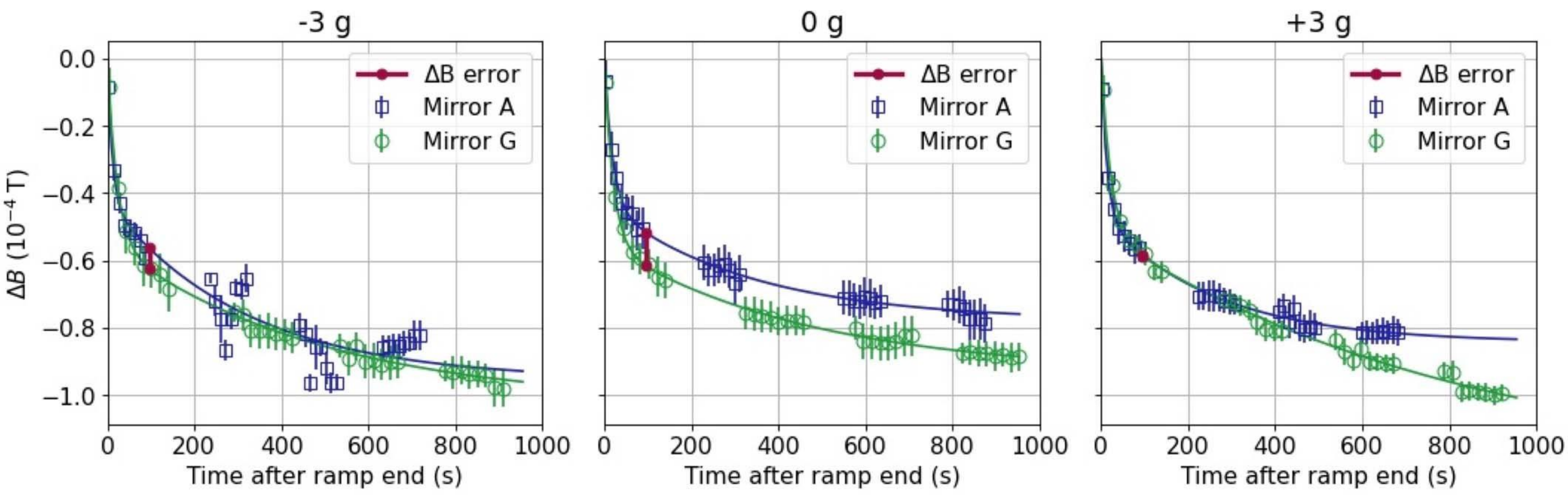


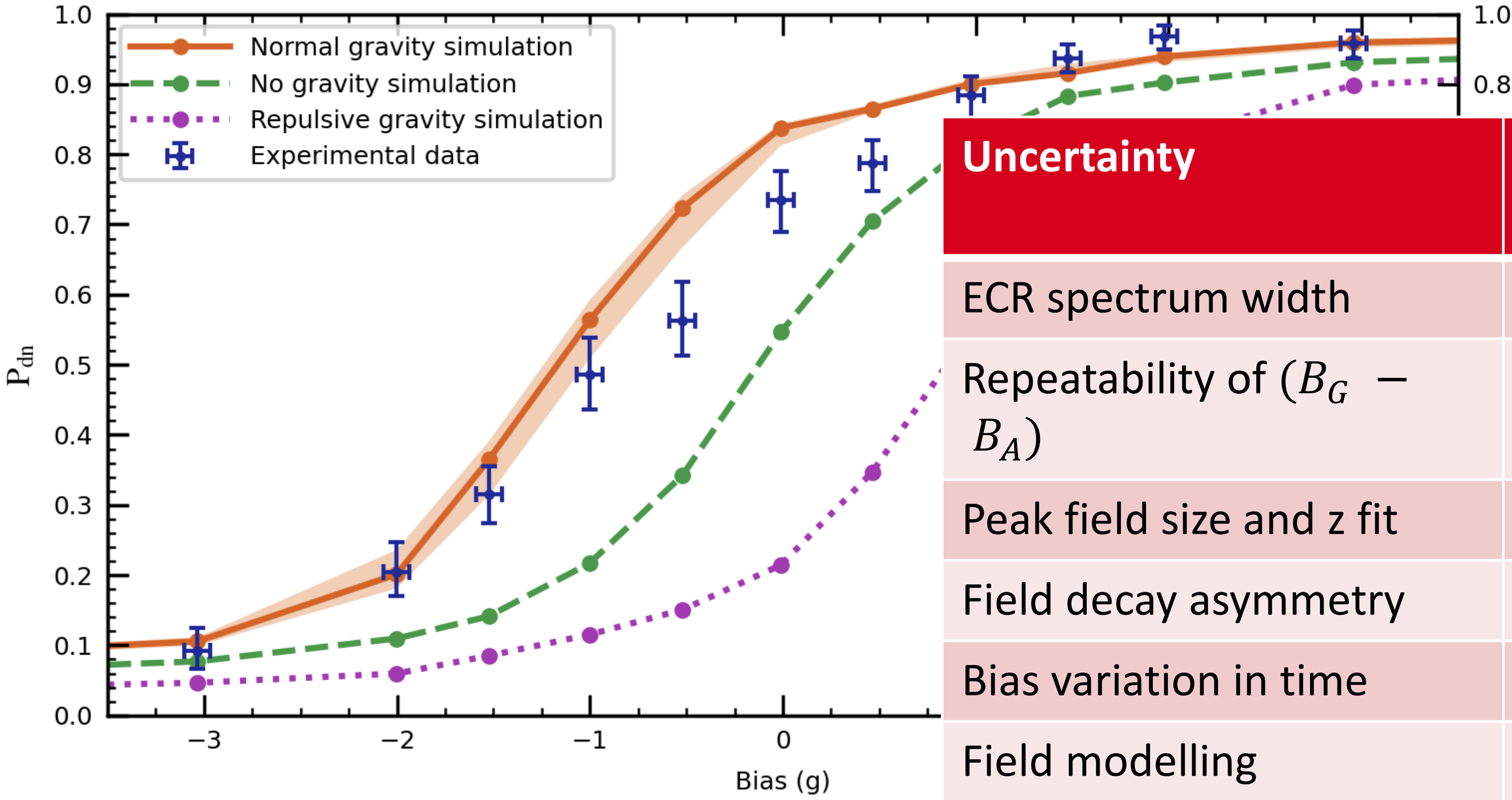

$10^{-4}$ T = 1 Gauss = 2.8 MHz



# Error from different decaying fields



# ALPHAg escape curve




| Uncertainty | Magnitude (g) |
|---|---|
| ECR spectrum width | 0.07 |
| Repeatability of $(B_G - B_A)$ | 0.014 |
| Peak field size and z fit | 0.009 |
| Field decay asymmetry | 0.02 |
| Bias variation in time | 0.02 |
| Field modelling | 0.05 |

$$\bar{g} = [0.75 \pm 0.13\,(statistical + systematic) \pm 0.16\,(simulation)]\,g$$

ECR data constrained

# Summary

- We have made the first observation of antihydrogen motion under the effect of Earth's gravity
- We have extensively studied magnetic fields in ALPHAg using ECR
- We have assigned uncertainty to the bias based on these magnetic field measurements

# Thank you for listening!

TRIUMF

KEK

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MO SHÙILE TOGAM SUAS

INNOVATION.CA
CANADA FOUNDATION FOR INNOVATION | FONDATION CANADIENNE POUR L'INNOVATION

NSERC CRSNG

CERN

CINP ICPN

LEVERHULME TRUST


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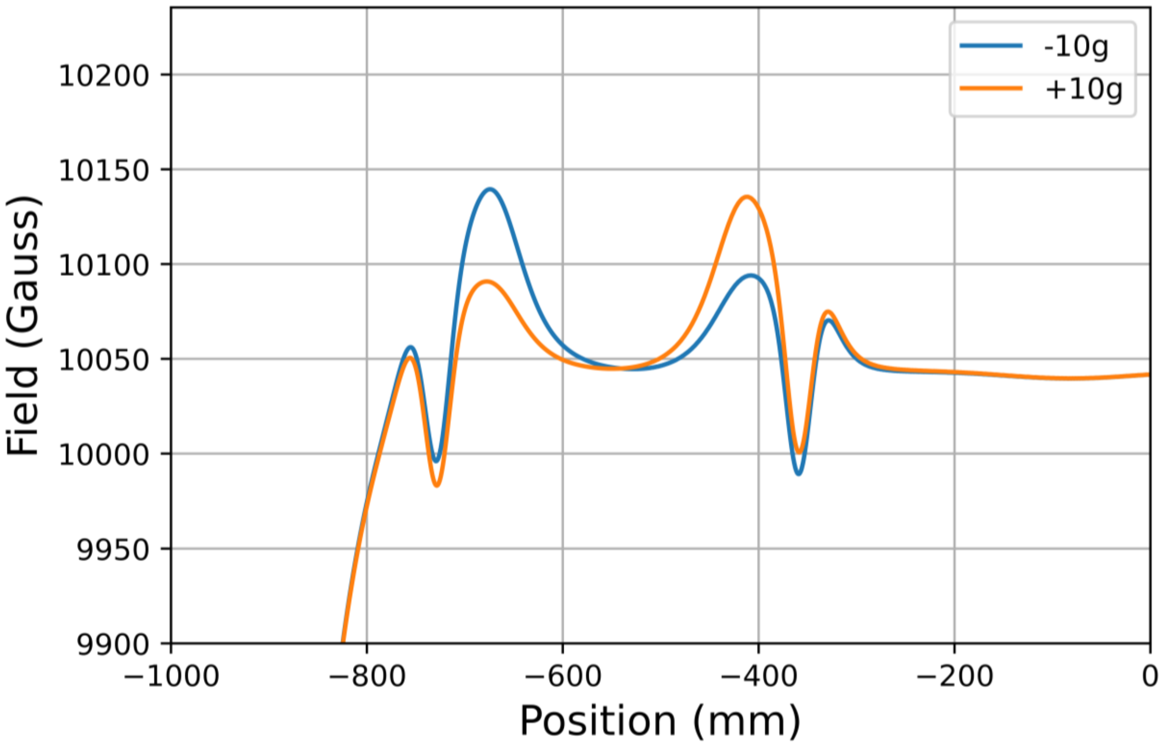
# Backup slides

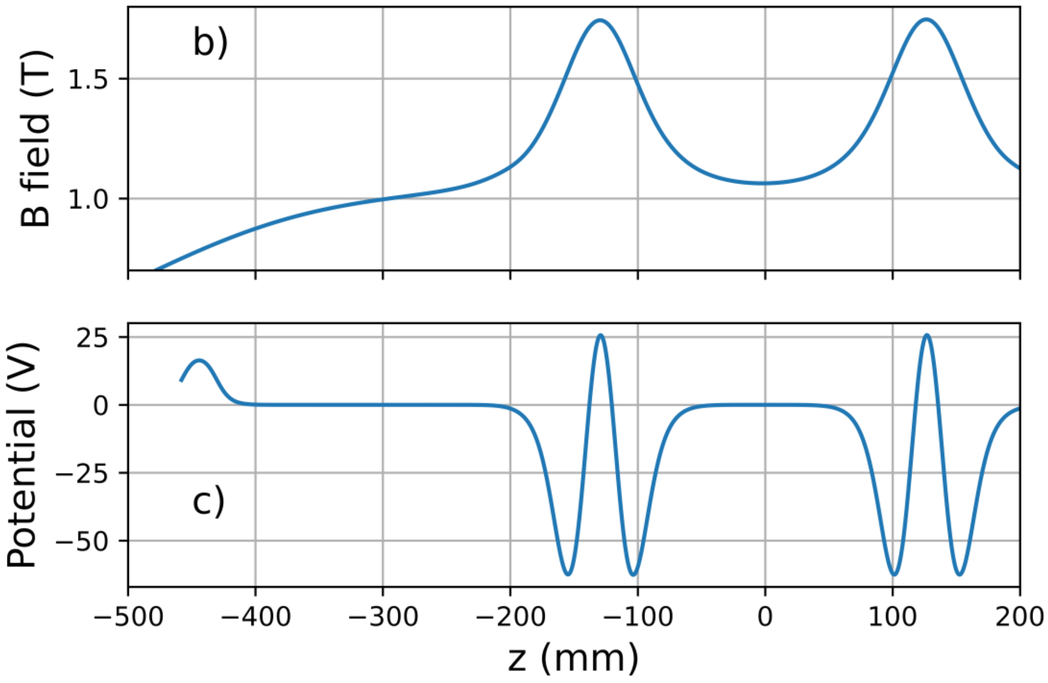
# Assuming gravity acts the same on matter and antimatter

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

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

$$\equiv \Delta B \sim 5 \times 10^{-4}\,\mathrm{T} \equiv 1\,\mathrm{g}$$




b)
B field (T)
1.5
1.0
c)
Potential (V)
25
0
−25
−50
−500
−400
−300
−200
−100
0
100
200
z (mm)

# How do you understand the magnetic environment?

- What is the background field?
- How does the field respond to applied current for each magnet?
- Where is the maxima of each magnet?
- Are there any uncontrolled fields?

Key point: We are always interested in the differences bottom/top

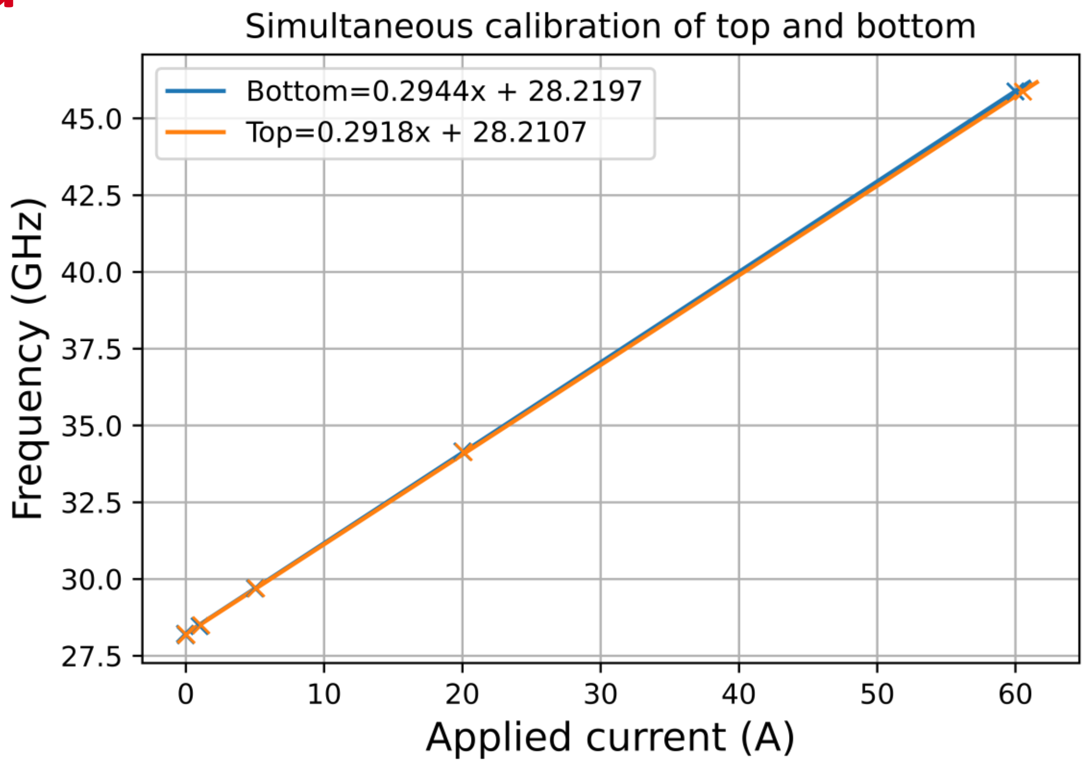
# Significant improvements to ECR capabilities

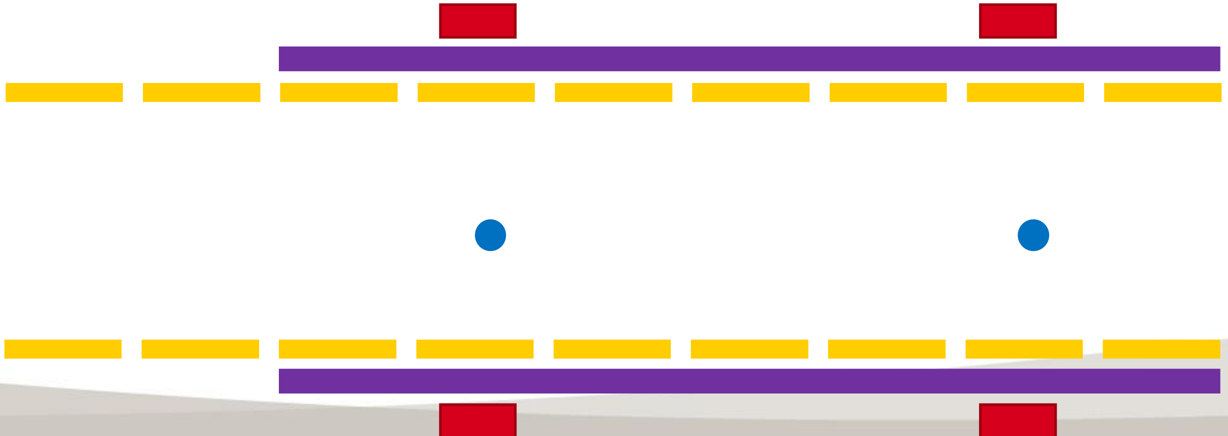
- Measure in multiple locations simultaneously
- Resolution better than $10^{-4}$ T (even in high field gradients of a few $10^{-4}$ T/mm)
- Stable plasmas for repeatable measurements over months
- On axis field mapping with resolution < 1mm
- Available range: 0.5 – 1.78 T (14 – 50 GHz)
  - Low frequency end not tested

# Non-neutral plasma requirements

- Debye length, $\lambda_D = \sqrt{\frac{\varepsilon_0 T}{n_0 e^2}}$
- $\lambda_D \ll L$
- $n_0 \lambda_D^3 \gg 1$

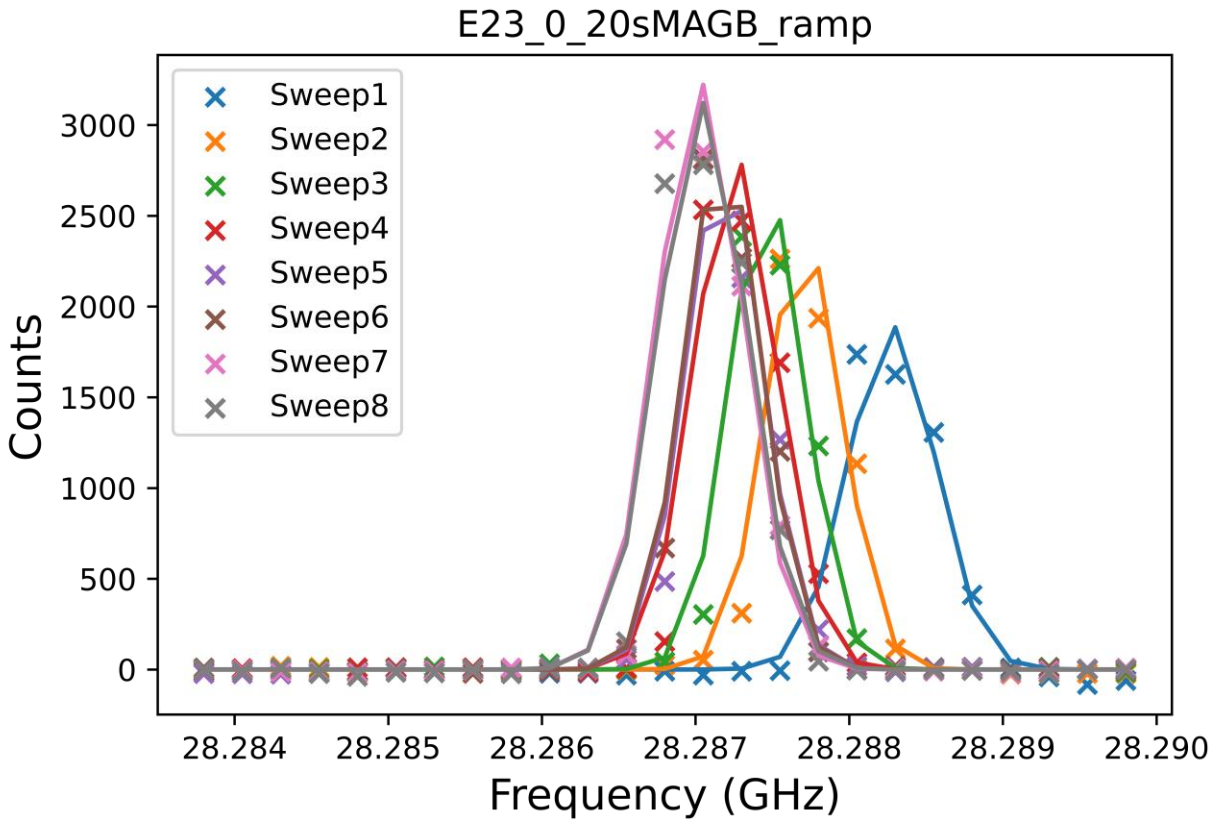
# Calibrating magnetic field to current applied



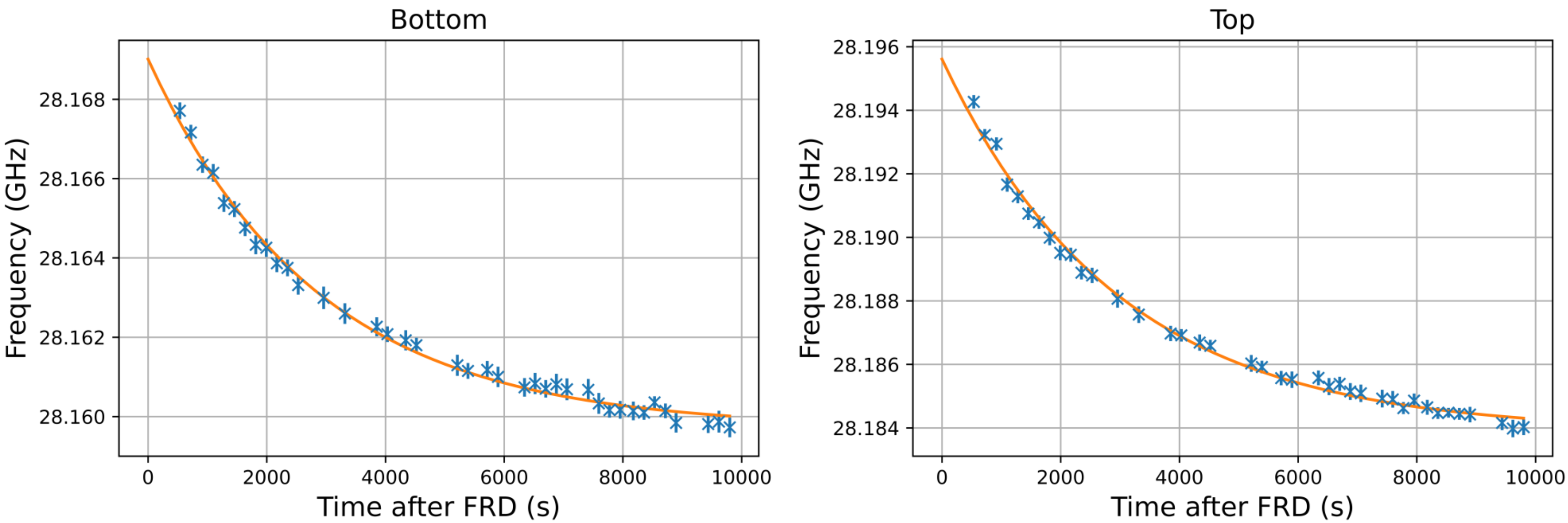



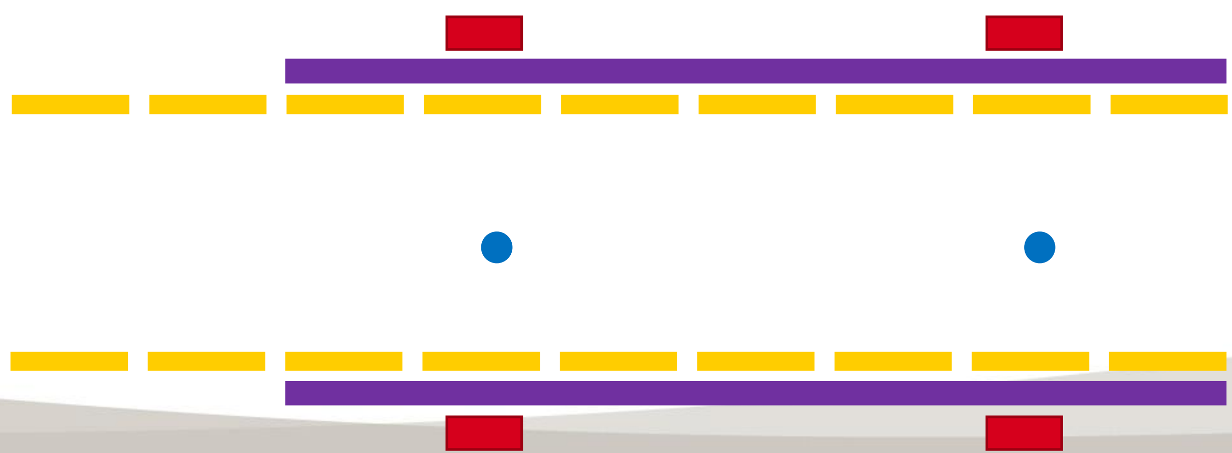
$10^{-4}$ T = 1 Gauss = 2.8 MHz

# Fast repeat ECR example



# Measure decaying induced fields



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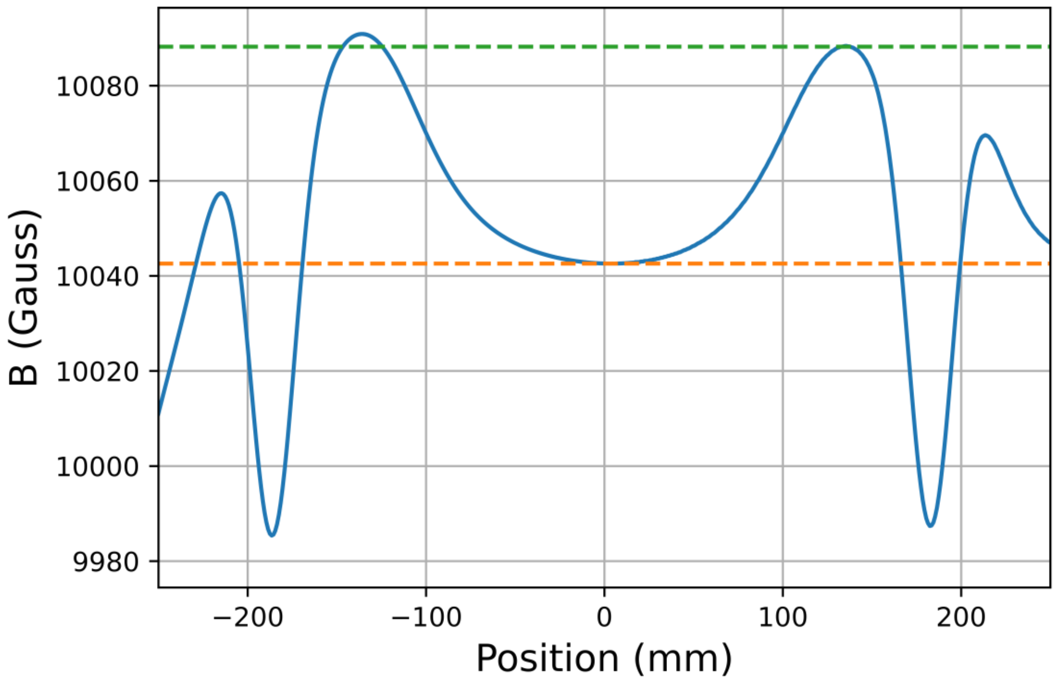
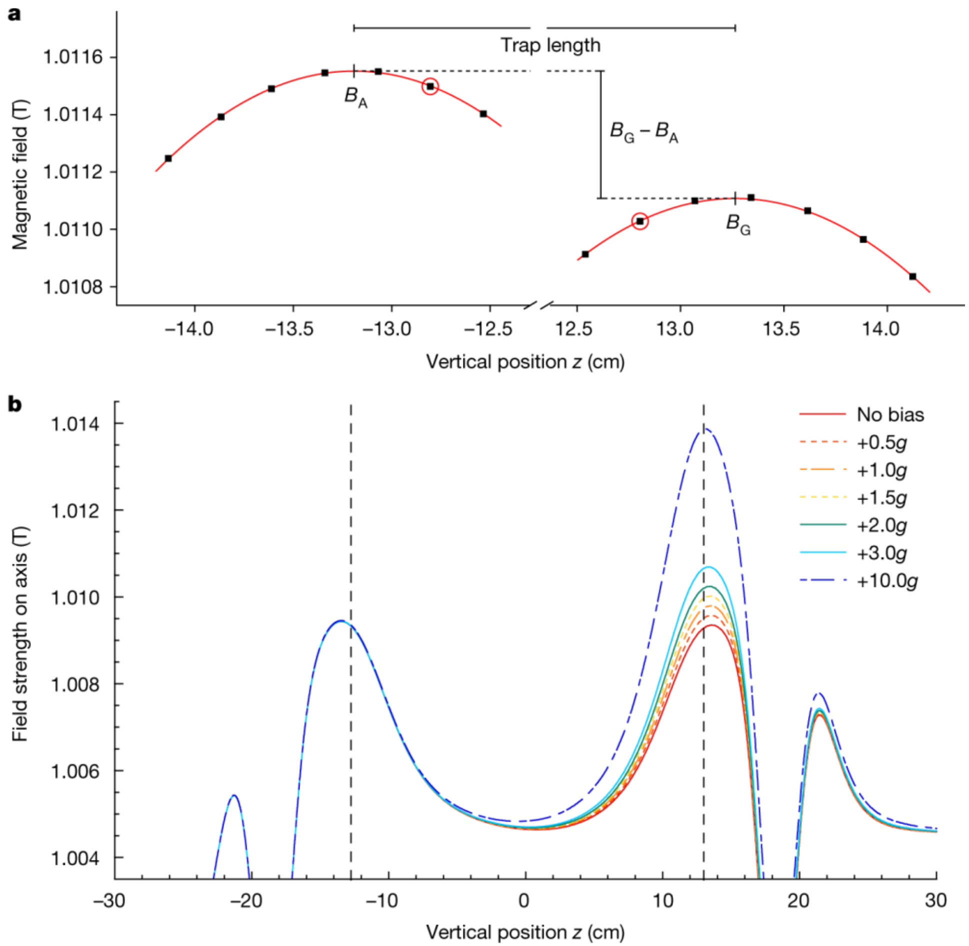
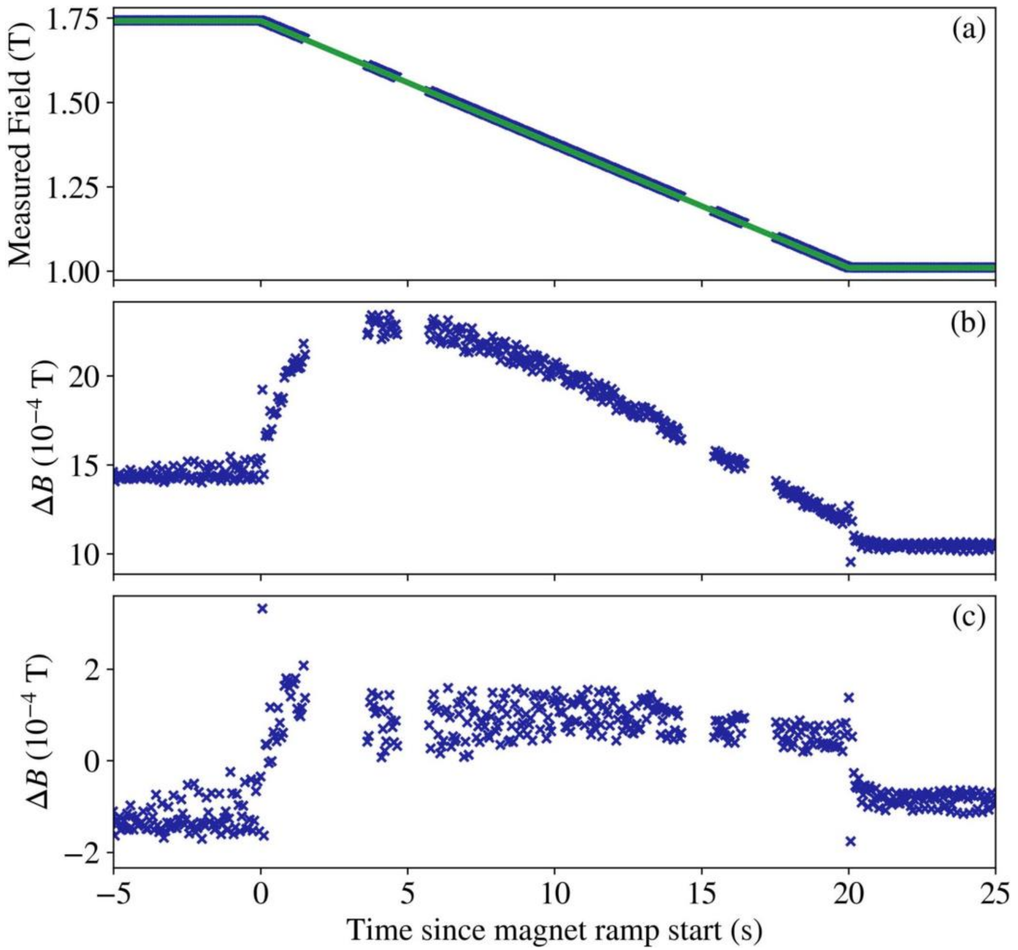
# Final well

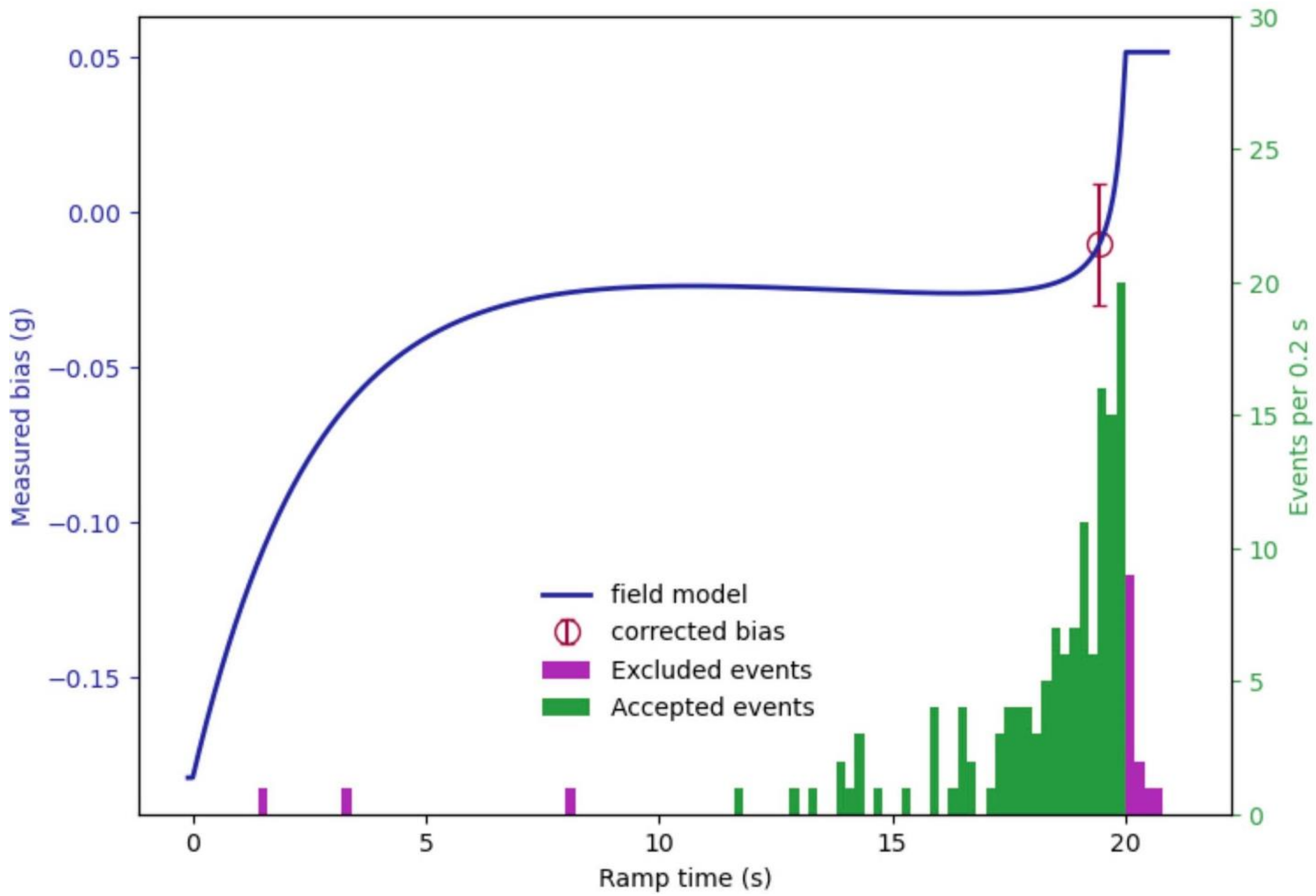



Aimed for 50 Gauss


a
Trap length
1.0116
1.0114
1.0112
1.0110
1.0108
Magnetic field (T)
$B_A$
$B_G - B_A$
$B_G$
−14.0
−13.5
−13.0
−12.5
12.5
13.0
13.5
14.0
Vertical position z (cm)
b
No bias
+0.5g
+1.0g
+1.5g
+2.0g
+3.0g
+10.0g
1.014
1.012
1.010
1.008
1.006
1.004
Field strength on axis (T)
−30
−20
−10
0
10
20
30
Vertical position z (cm)



Measured Field (T)
1.75
1.50
1.25
1.00
(a)
$\Delta B$ ($10^{-4}$ T)
20
15
10
(b)
$\Delta B$ ($10^{-4}$ T)
2
0
−2
(c)
−5
0
5
10
15
20
25
Time since magnet ramp start (s)



0.05
0.00
−0.05
−0.10
−0.15
Measured bias (g)
30
25
20
15
10
5
0
Events per 0.2 s
0
5
10
15
20
Ramp time (s)
field model
corrected bias
Excluded events
Accepted events

# Systematic effects studied with ECR

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- Induced currents from changing fields
- Long term stability
- Changing trap length during a ramp down
- Differences in magnet construction
- Errors in magnet winding positions

# Magnetic field uncertainties

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| Uncertainty | Magnitude (g) |
|---|---|
| ECR spectrum width | 0.07 |
| Repeatability of $(B_G - B_A)$ | 0.014 |
| Peak field size and z fit | 0.009 |
| Field decay asymmetry | 0.02 |
| Bias variation in time | 0.02 |
| Field modelling | 0.05 |

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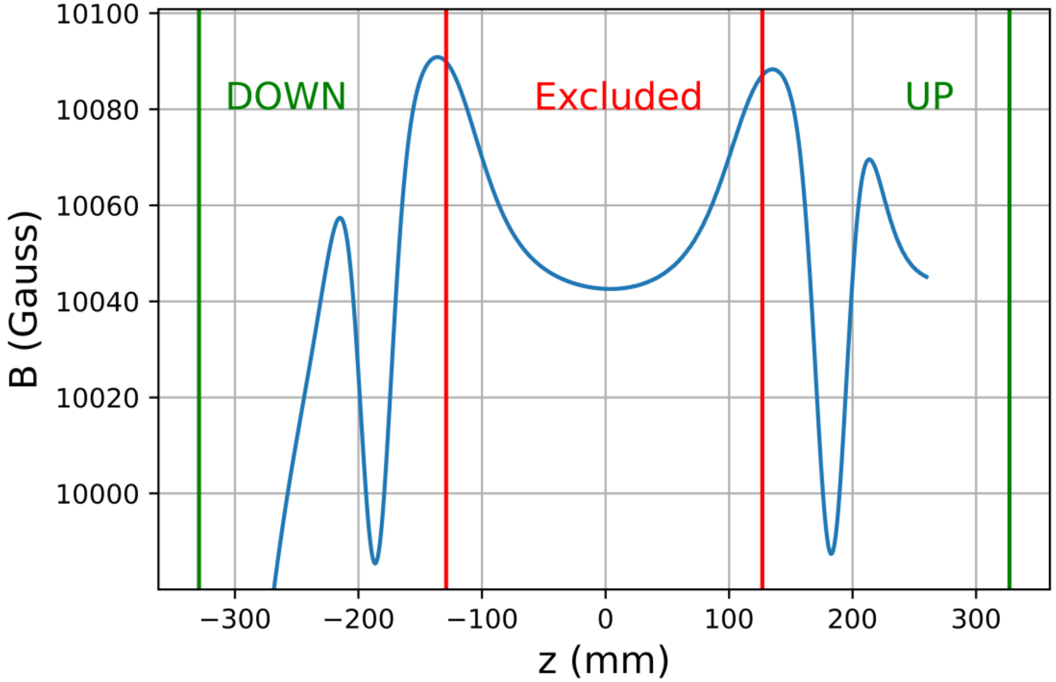
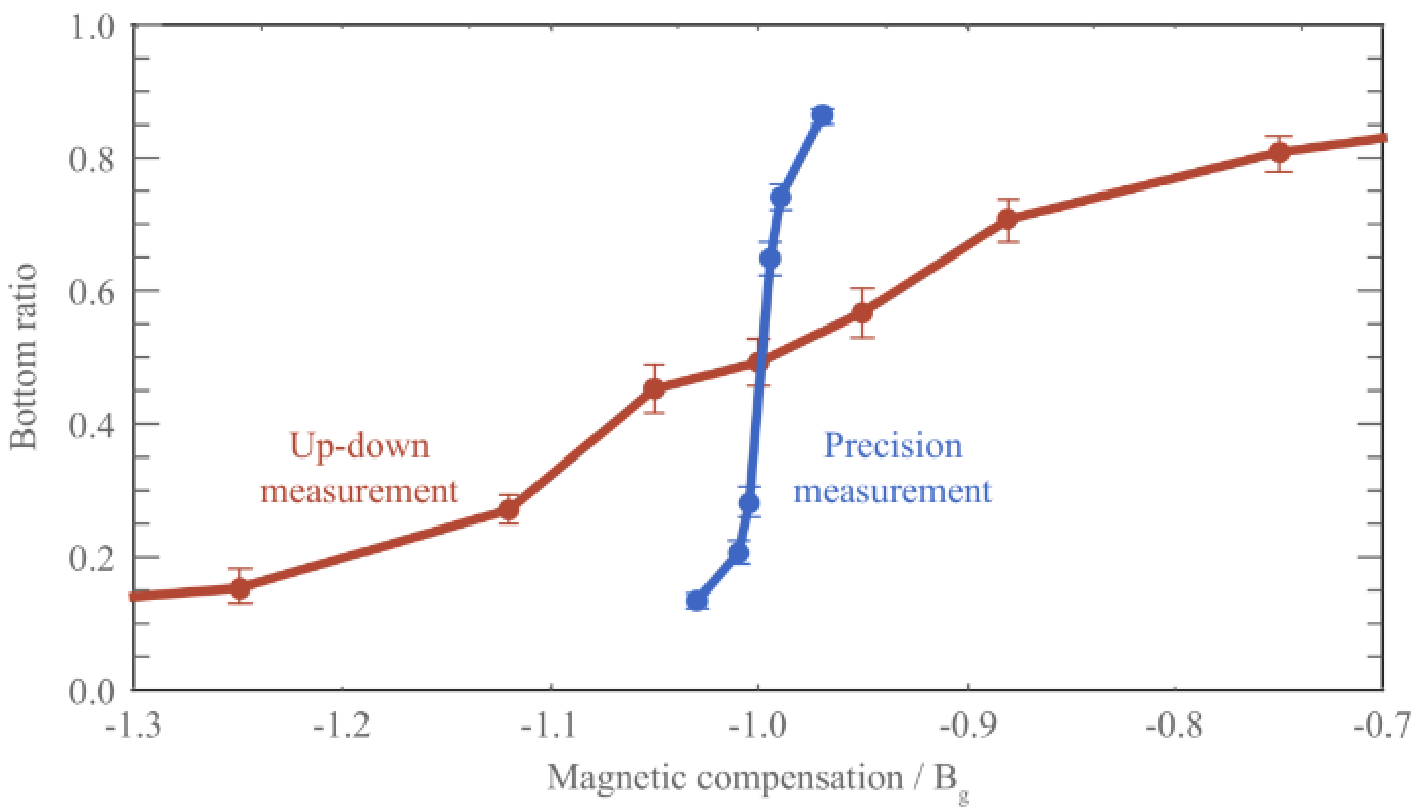
# Contributions to g uncertainty

| | Uncertainty | Magnitude (g) |
|---|---|---|
| Statistical and systematic | Finite data size | 0.06 |
| | Calibration of detector efficiencies (up vs down) | 0.12 |
| | Other minor sources | 0.01 |
| Simulation model | Modelling of magnetic fields | 0.16 |
| | Antihydrogen initial energy distribution | 0.03 |

# How to define up and down?



# Towards 1%



1.0
0.8
0.6
0.4
0.2
0.0
Bottom ratio
Up-down
measurement
Precision
measurement
-1.3
-1.2
-1.1
-1.0
-0.9
-0.8
-0.7
Magnetic compensation / $B_g$

# Control of coils

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