Investigating Energy Mixing Dynamics of Magnetically Trapped Antihydrogen

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Overview

1) Introduction to ALPHA and energy mixing
2) Why study energy mixing?
3) Experimental methods for energy mixing studies
4) Results
5) Conclusion and next steps

Antihydrogen Laser PHysics Apparatus

- ALPHA utilizes the ELENA (Extra Low ENergy Antiproton) ring at CERN
- ALPHA investigates the baryon asymmetry problem
- ALPHA produces and traps antihydrogen ($\bar{\mathbf{H}}$) for experimental use

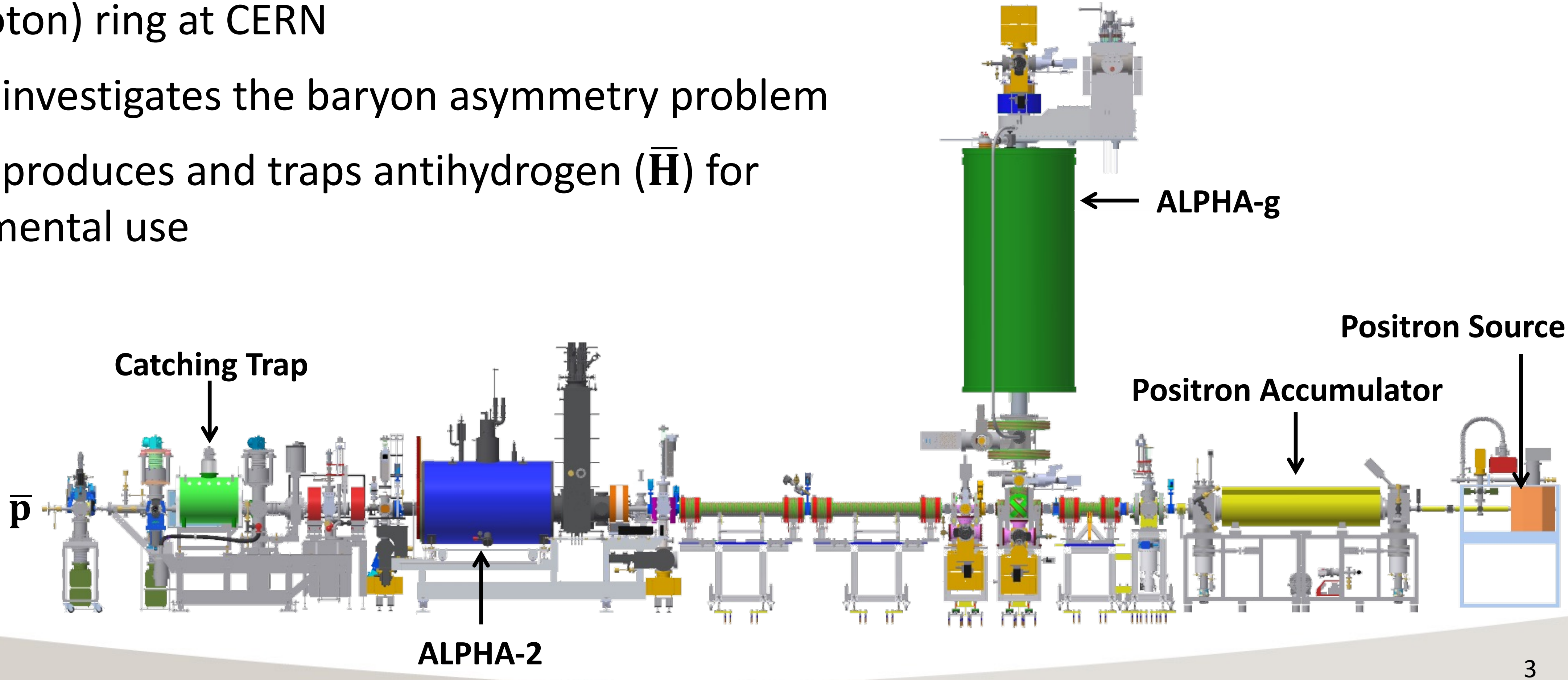

Image Credit: Prof. Steven Armstrong Jones and The ALPHA Collaboration

Magnetic Trapping of Antihydrogen

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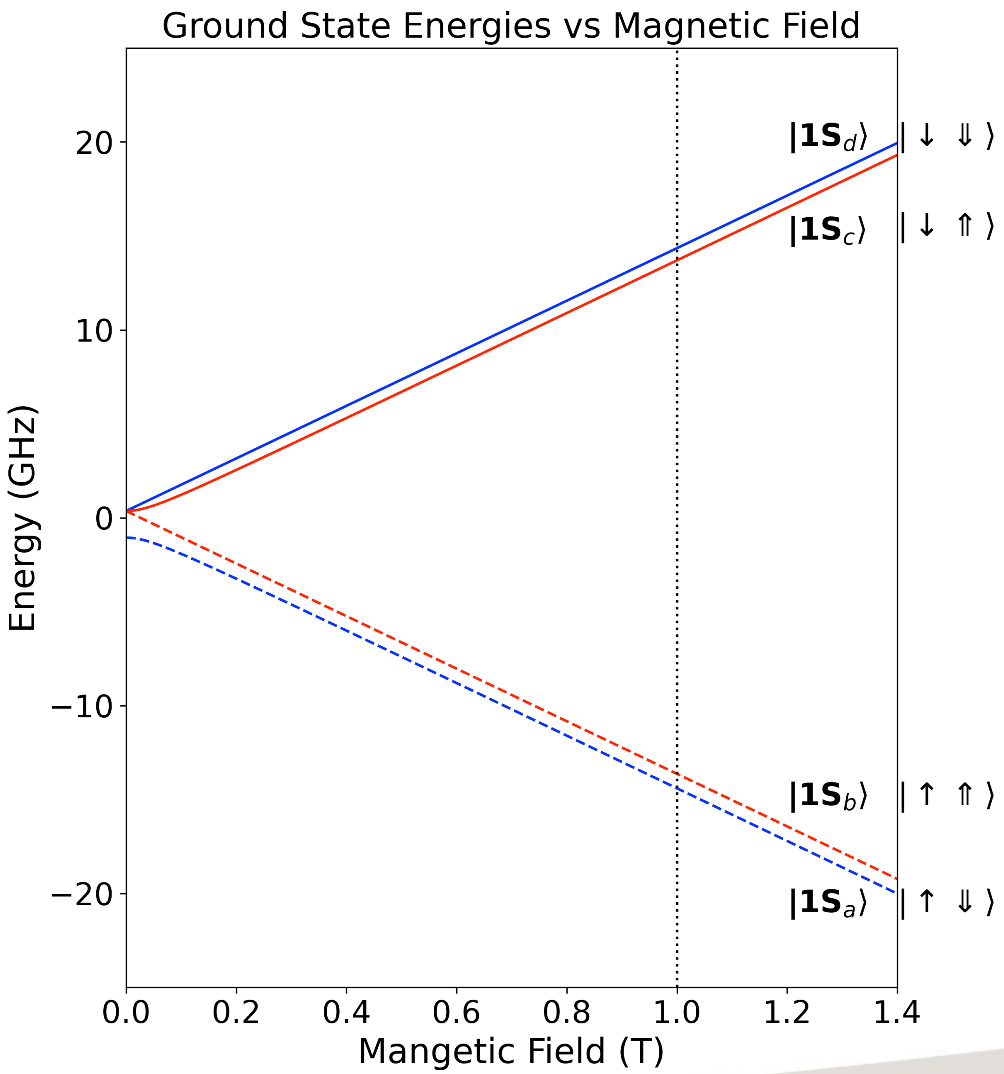
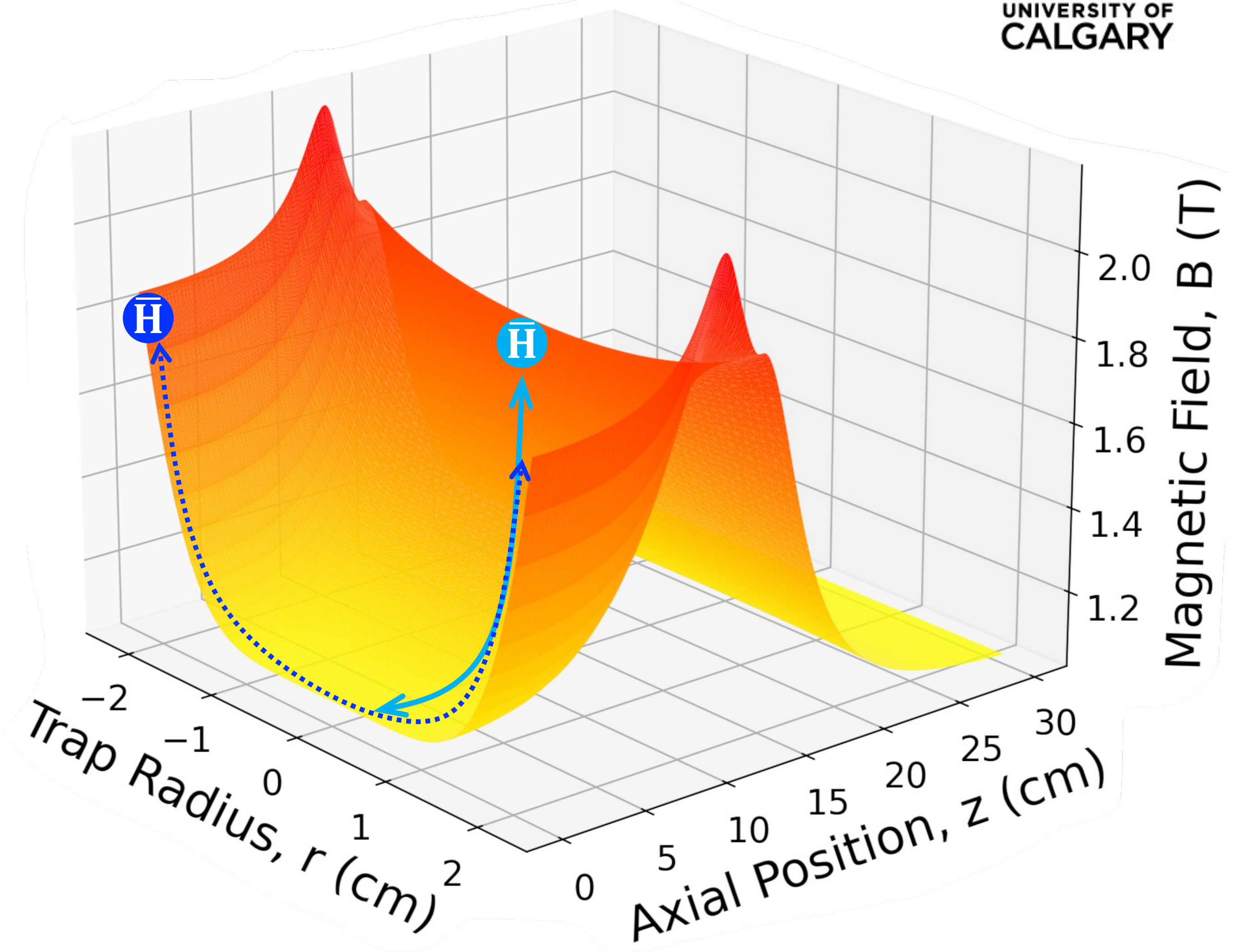
- The dipole moment ($\vec{\boldsymbol{\mu}}$) interacts with the magnetic field ($\mathbf{B}$)
  - $\mathbf{U} = -\vec{\boldsymbol{\mu}} \cdot \vec{\mathbf{B}}$
- If $\vec{\boldsymbol{\mu}}$ is anti-aligned with $\vec{\mathbf{B}}$ an atom will be “low-field seeking” and can be trapped



$\bar{H}$ Energy Components

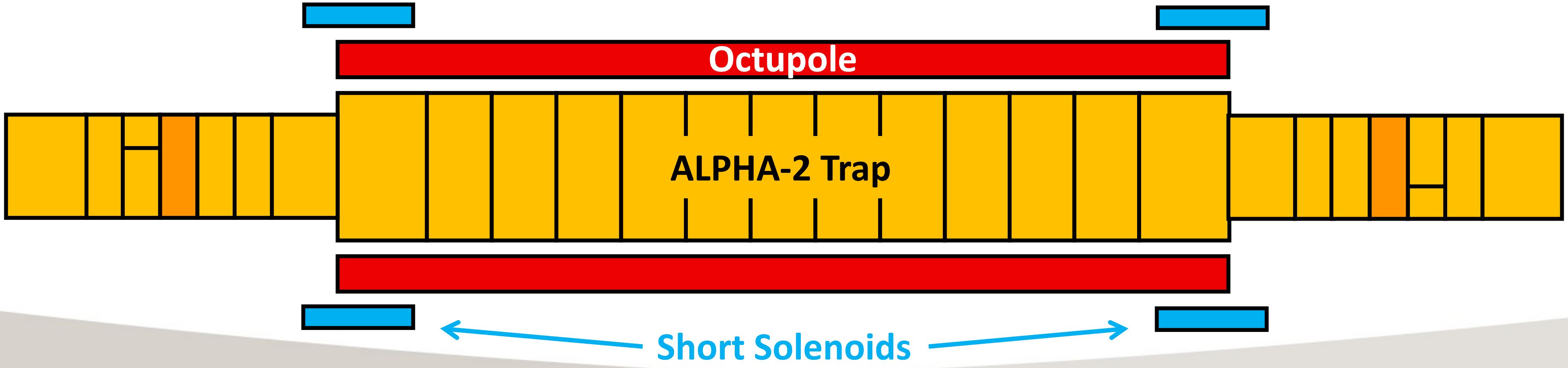
- $\bar{\mathbf{H}}$ atoms have axial ($E_{\parallel}$) and transverse energy ($E_{\perp}$)
  - $E_{total} = E_{\parallel} + E_{\perp}$



$\bar{H}$ atom with only transverse energy
$\bar{H}$ atom with only axial energy

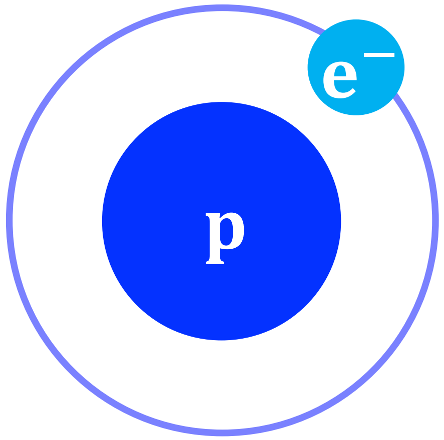
$\bar{\mathrm{H}}$ Energy Mixing

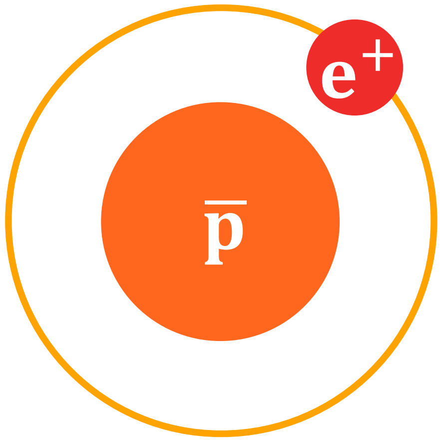
- Energy mixing is when $E_{\parallel}$ and $E_{\perp}$ are exchanged over an atom's trapped lifetime
- Energy mixing is caused by azimuthal field asymmetries
  - Radial components of solenoid fields add to the radial field of the octupole
  - Octupole end turns
- Simulations predict that some atoms will not mix energies
  - **This has never been experimentally verified**



Why investigate energy mixing?

- Studies can help ALPHA reach higher experimental precision
- Understanding the timescale is important for ALPHA experiments
  - Laser cooling of antihydrogen
  - Laser and microwave spectroscopy
  - Measuring the effects of gravity on antimatter
- Experimental studies are critical for simulations
  - All results in ALPHA require simulations to compare matter to antimatter





Simulated $\bar{\mathrm{H}}$ Energy Mixing

- Simulations predict the existence of two categories of atoms those that will mix energies and those that will not
- If atoms start with low axial energy they tend not to mix
- 1/3 of atoms are no-mix
  - Initial $\boldsymbol{\varepsilon}_{\parallel} < 0.1$
- 2/3 of atoms mix
  - Initial $\boldsymbol{\varepsilon}_{\parallel} > 0.1$

$$\boldsymbol{\varepsilon}_{\parallel} = \frac{\boldsymbol{E}_{\parallel}}{\boldsymbol{E}_{\parallel} + \boldsymbol{E}_{\perp}}$$

Time-averaged Normalized Axial Energy

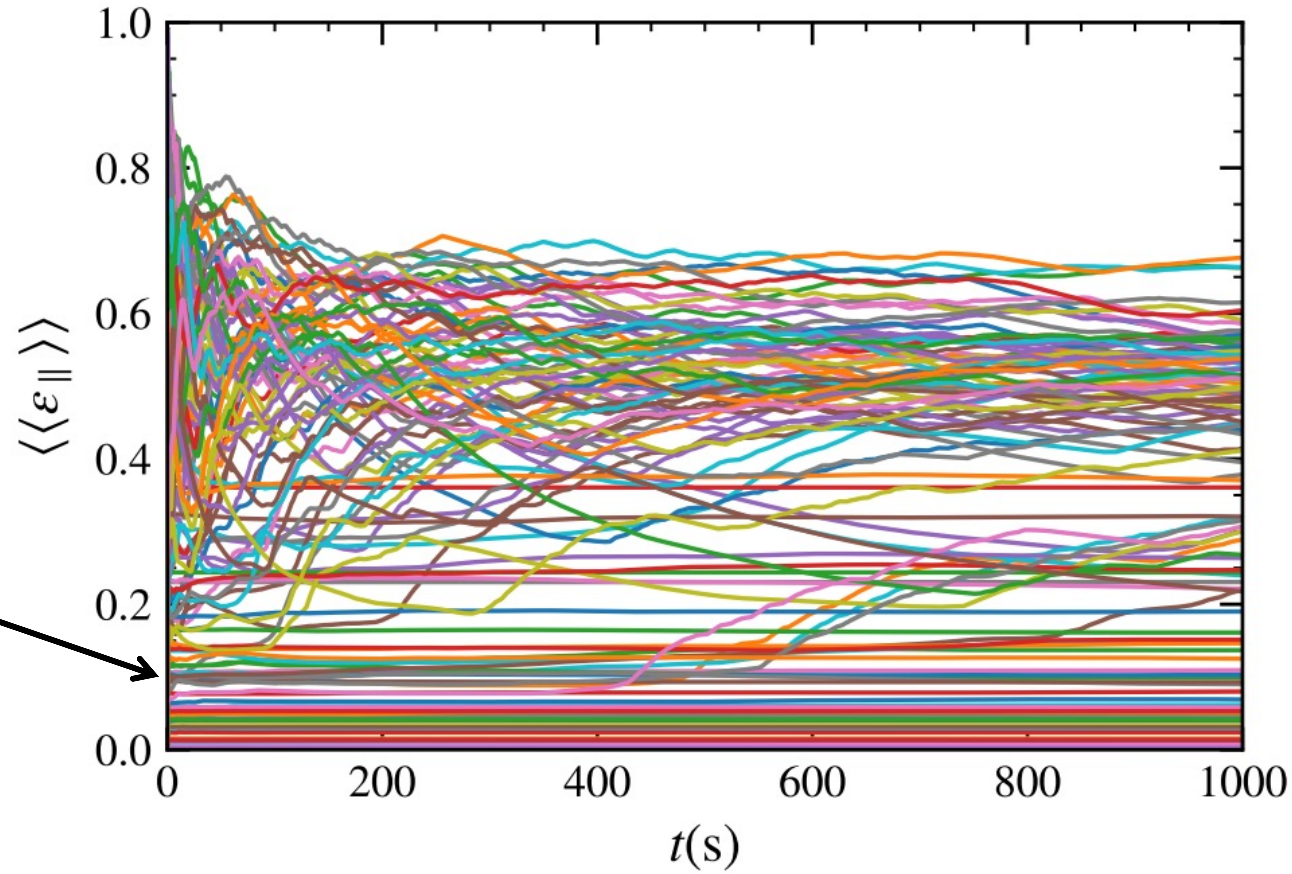
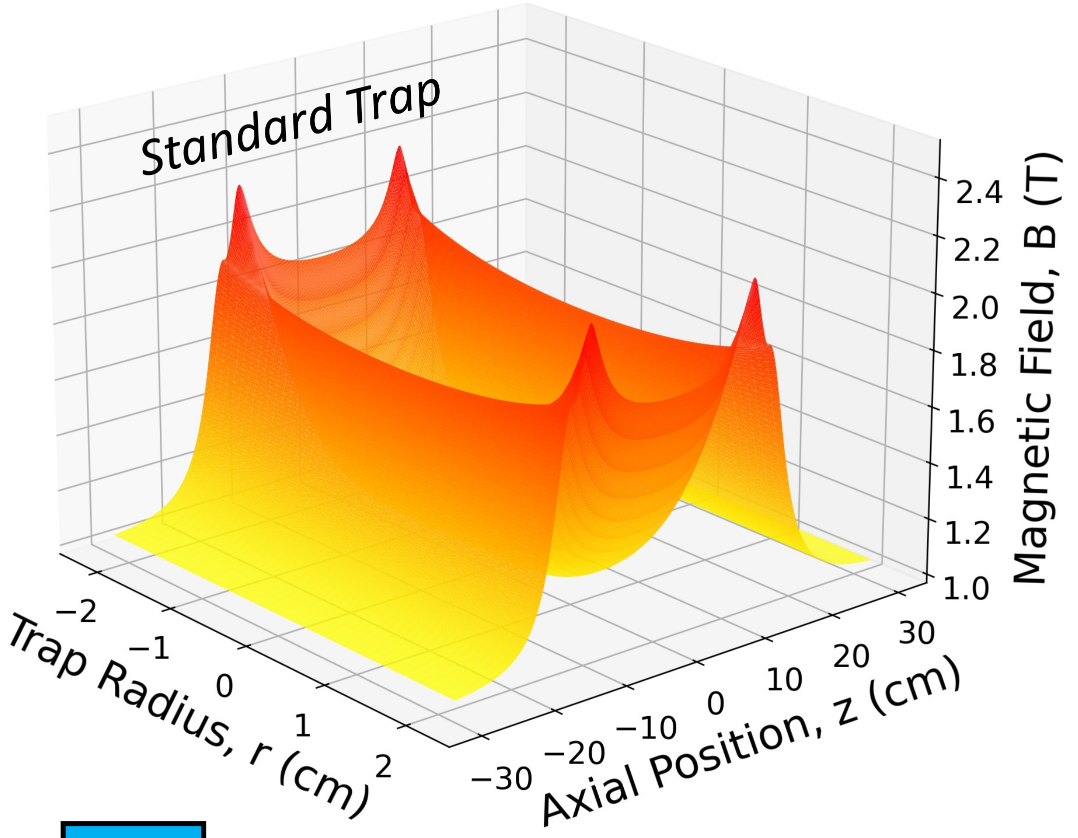
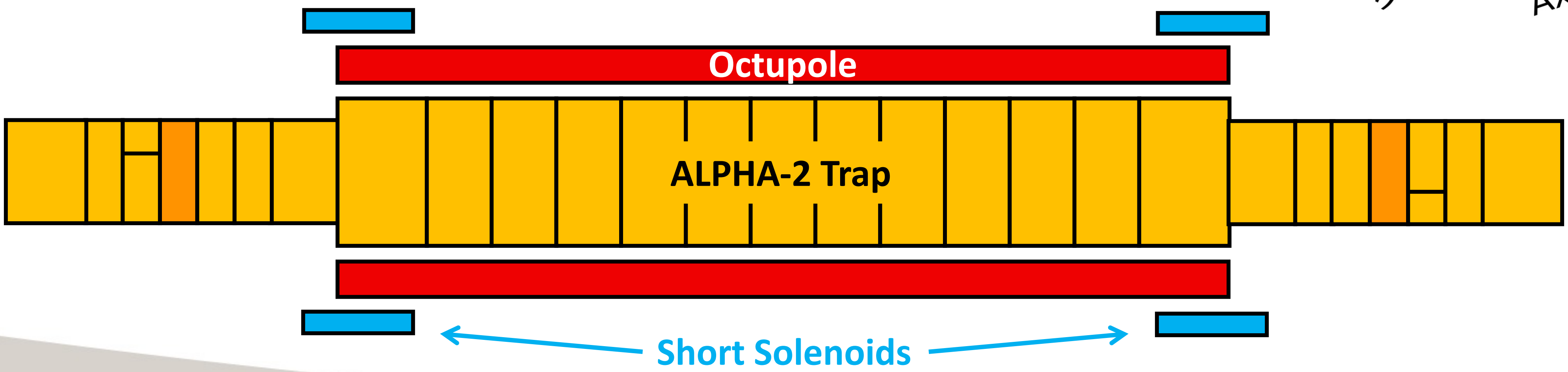


Image Credit: Dr. Danielle Hodgkinson, adapted from Zhong, A., Fajans, J., Zukor, A. F. Axial to transverse energy mixing dynamics in octupole-based magnetostatic antihydrogen traps. *New J. Phys.* **79**, 053003, (2018).

Experimental Procedure: Step 1

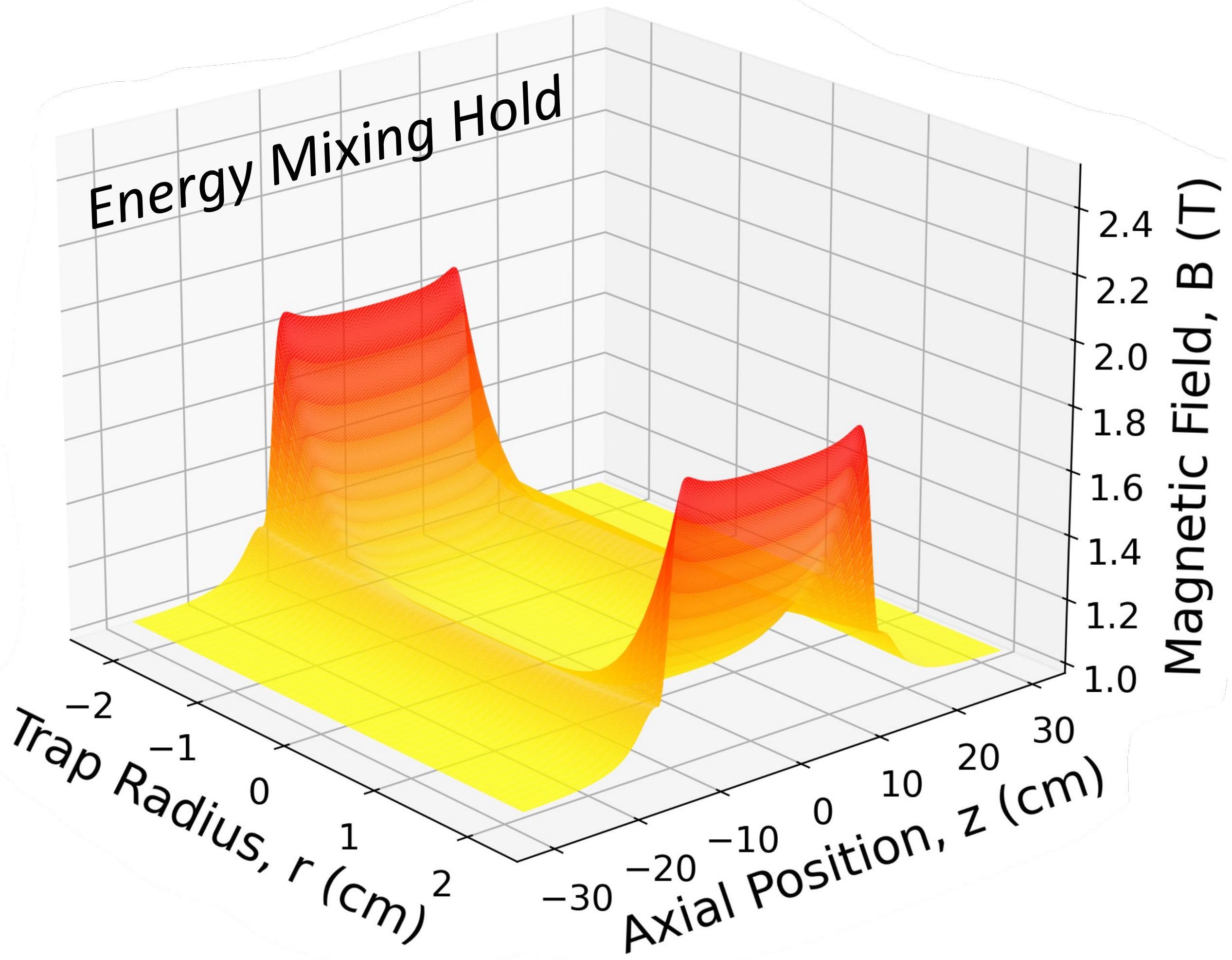
- $\bar{\mathbf{H}}$ is confined axially by short solenoids and radially by octupole magnet
- Axial trap depth is set by magnetic field of short solenoids





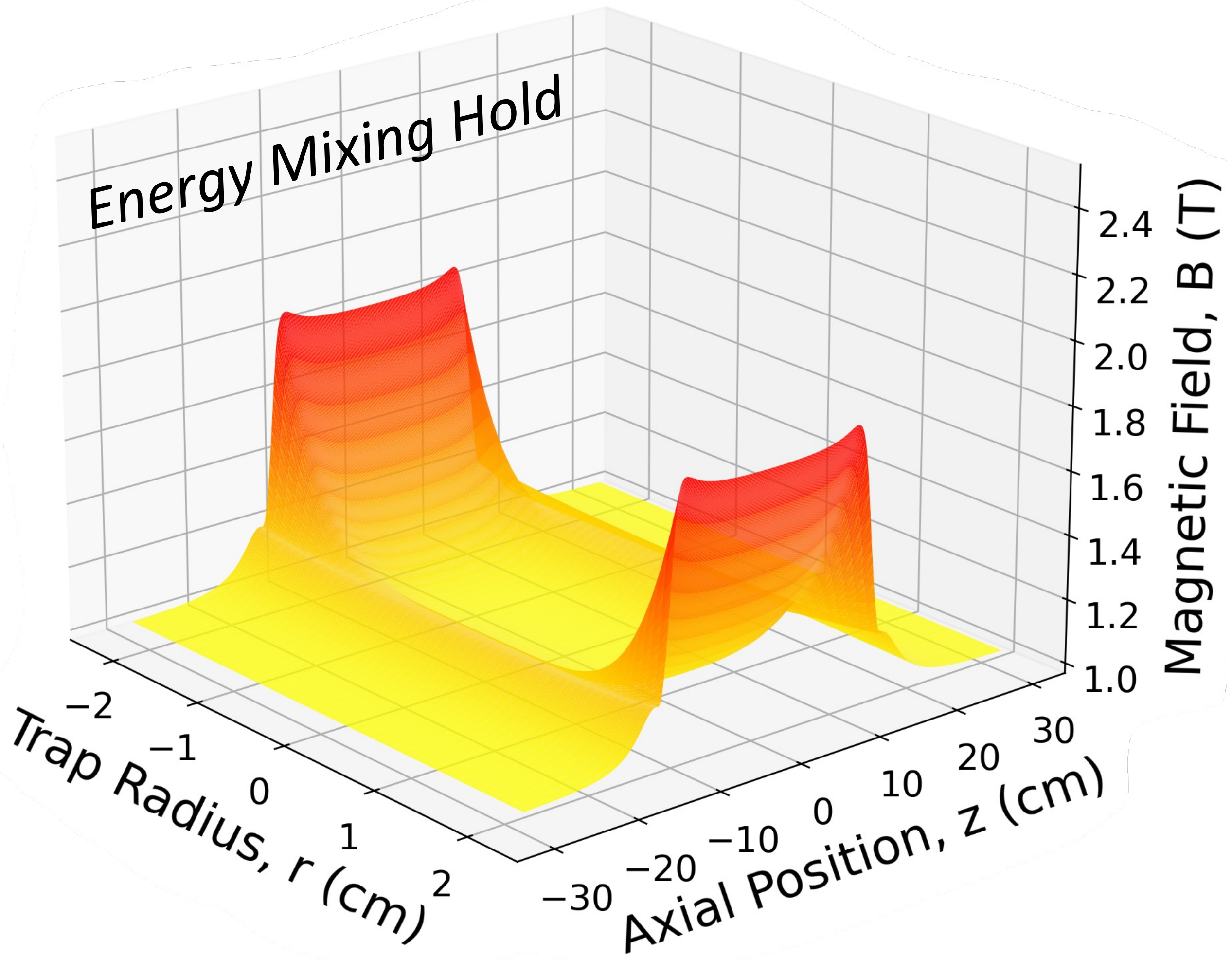
Experimental Procedure: Step 2

- Decrease $\mathbf{B}$ field at short solenoids, this decreases the axial trap depth
- Immediately $\bar{\mathbf{H}}$ with $E_{\parallel}$ > trap depth are lost
  - These are mostly mix atoms
- Hold atoms in this field
- Remaining $\bar{\mathbf{H}}$ with $E_{\parallel} + E_{\perp}$ > trap depth may escape if they mix energies
  - Atoms need to gain $E_{\parallel}$ from their $E_{\perp}$ component to overcome the axial trap depth



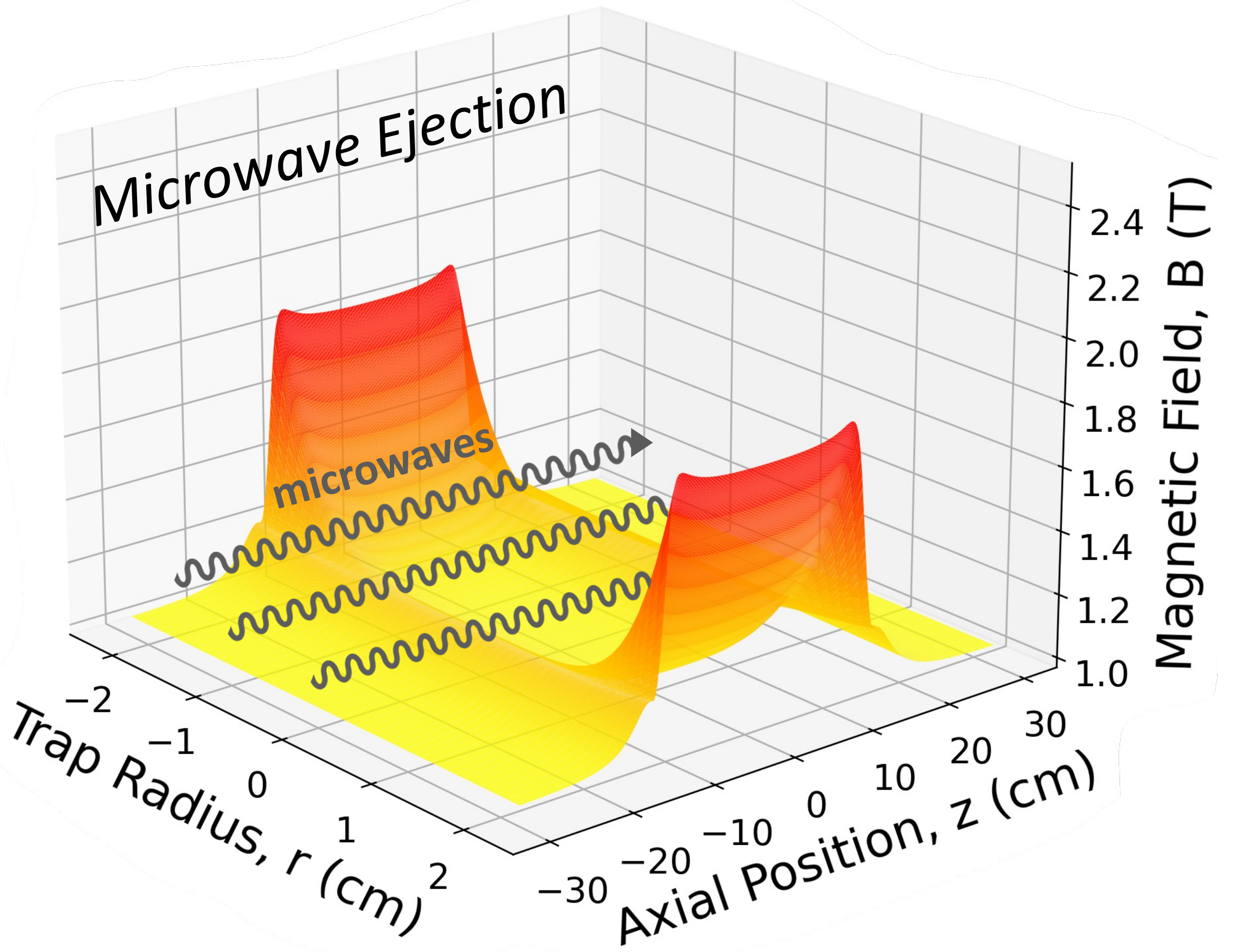
Experimental Procedure: Step 2

- After waiting two types of atom should remain trapped
  1) No mix atoms with $E_{\parallel}$ < trap depth
  2) Atoms with $E_{\parallel} + E_{\perp}$ < trap depth



Experimental Procedure: Step 3

- Inject microwaves at positron spin resonance for atoms sampling the $\mathbf{B}$ field just above the axial trap depth
- $\bar{\mathrm{H}}$ with $\mathrm{E}_{\perp}$ > trap depth will be ejected
  - These atoms must be no-mix



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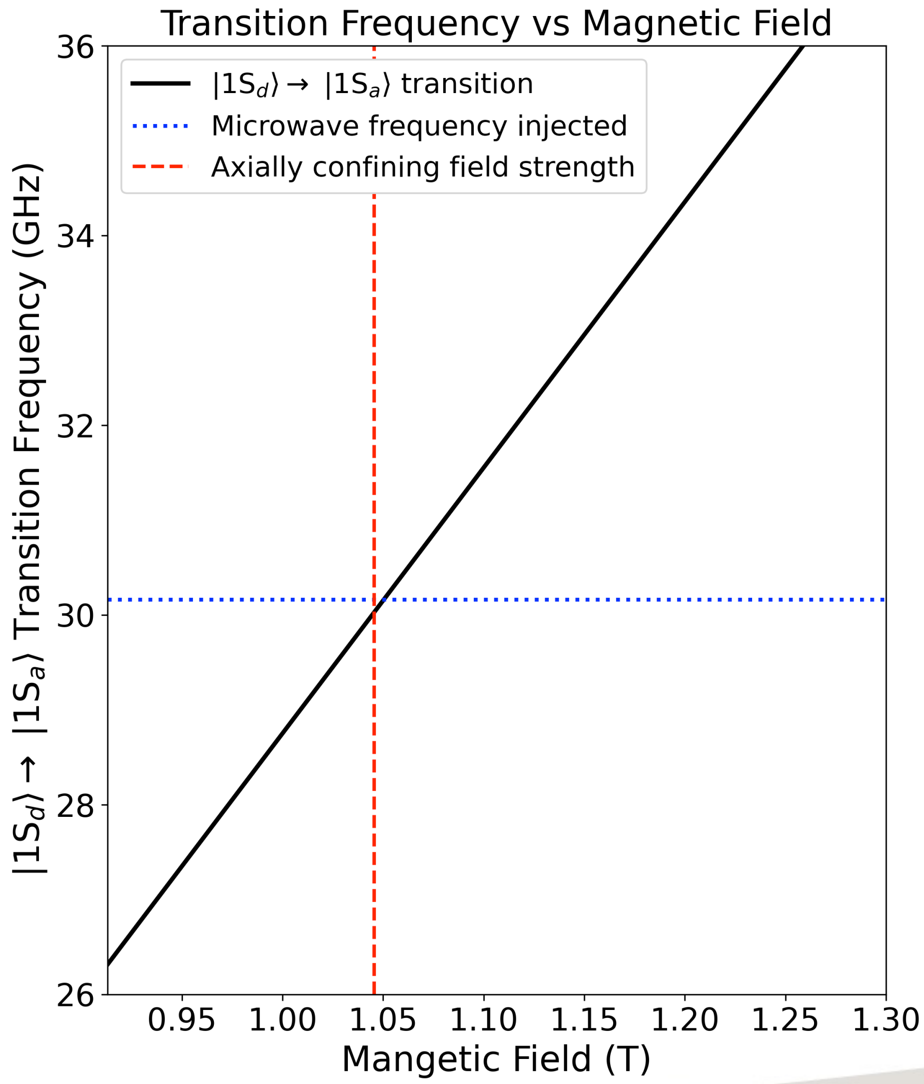
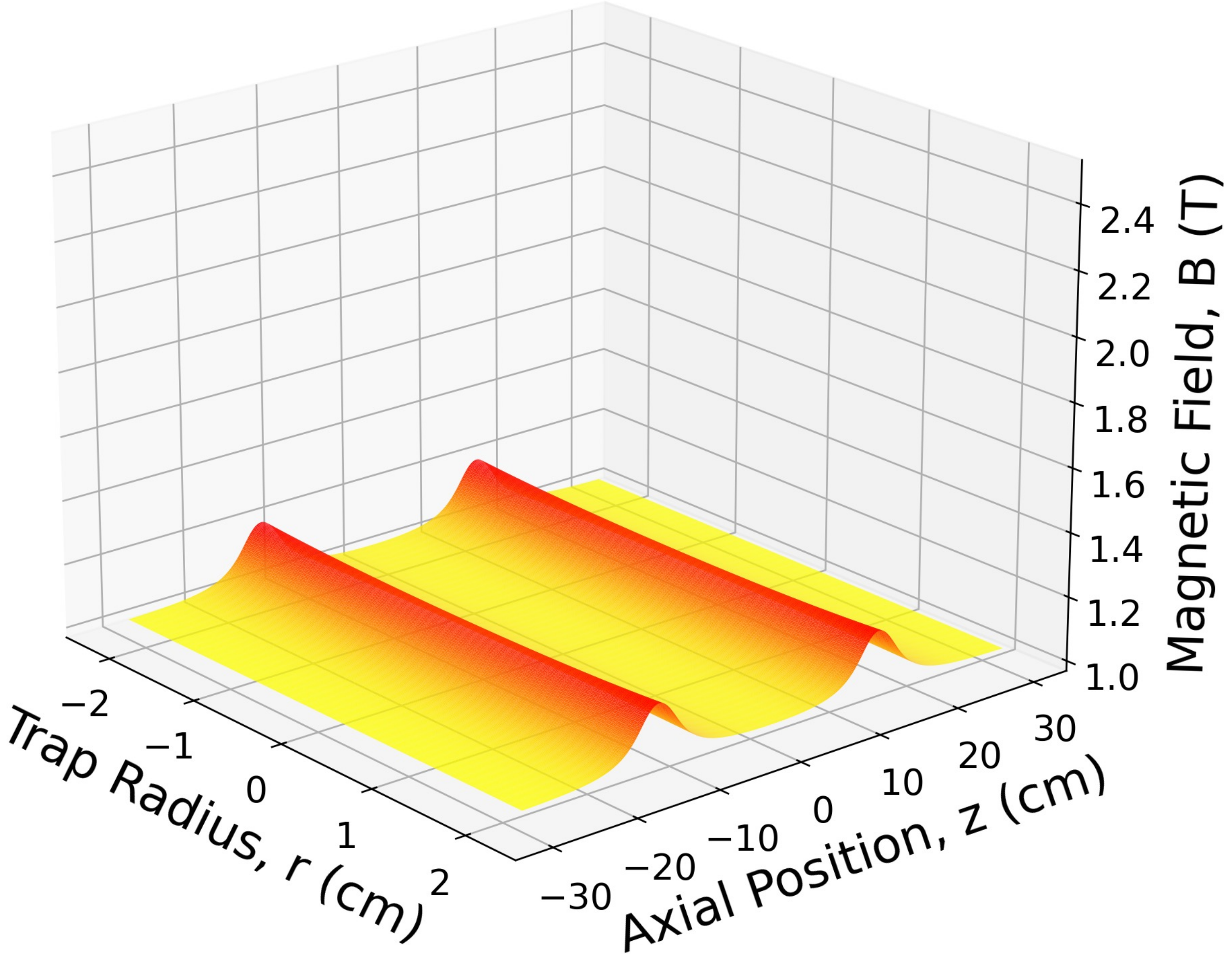
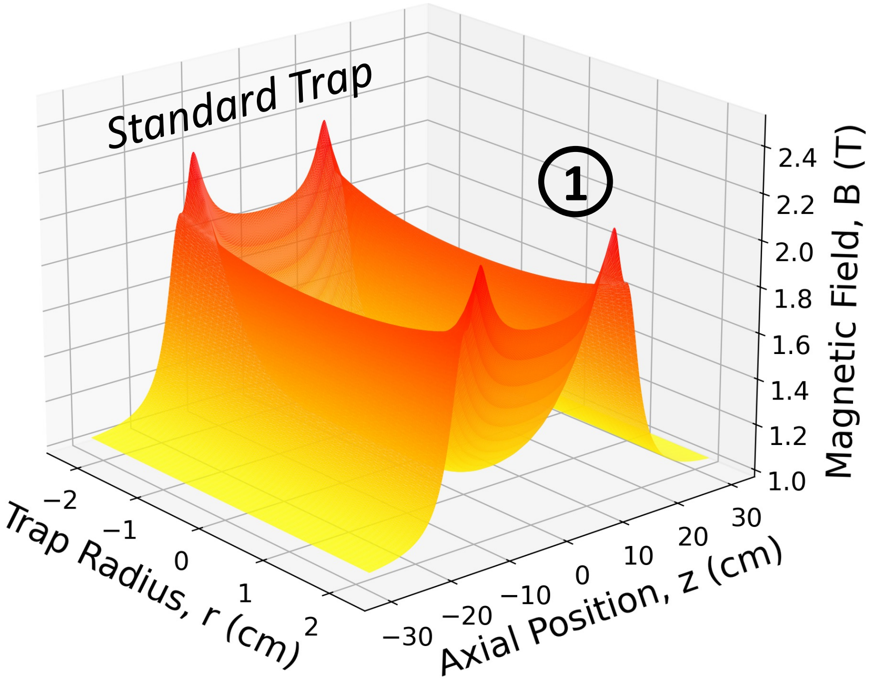


Experimental Procedure: Step 4

- There should only be one type of atom remaining
  - Atoms with $E_{\parallel} + E_{\perp}$ < trap depth (cold atoms, less than 86 mK)
- Remove radial confinement by ramp down octupole magnet
  - All trapped atoms remaining will be lost

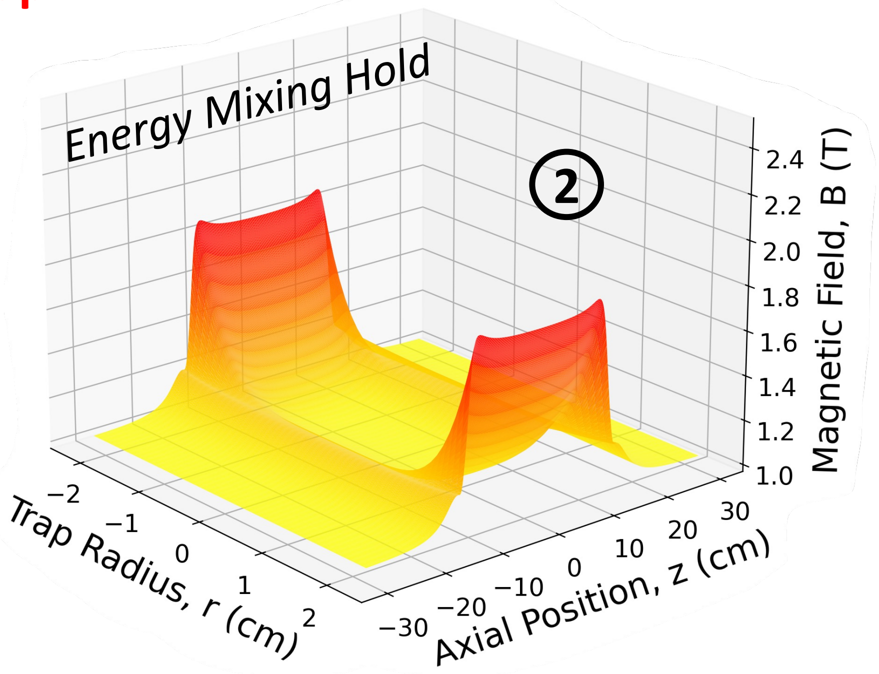


Step 1 to 2



At first $\overline{\mathrm{H}}$ with $\mathrm{E}_{\parallel}$ > trap depth will escape

→



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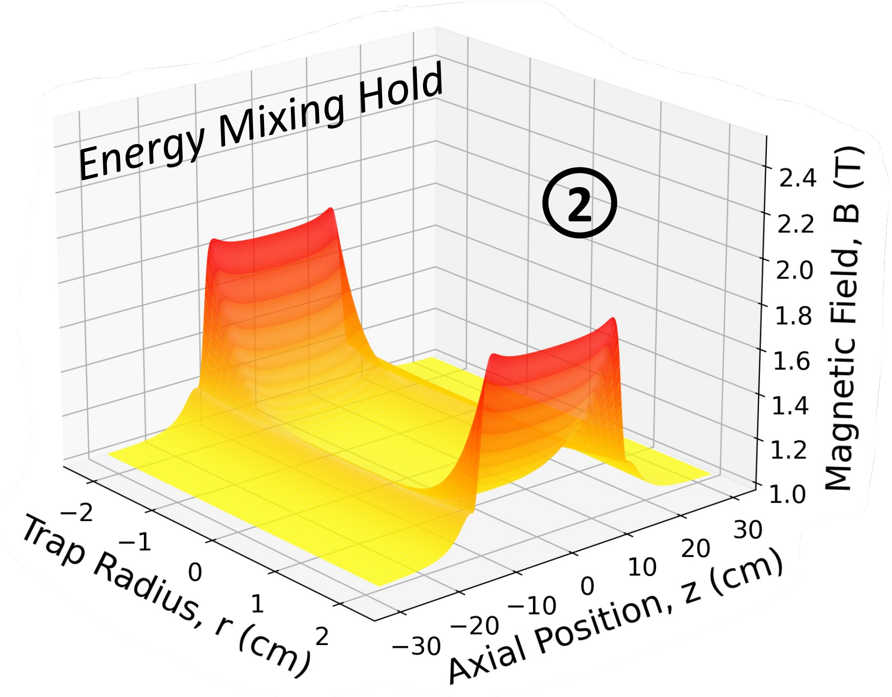
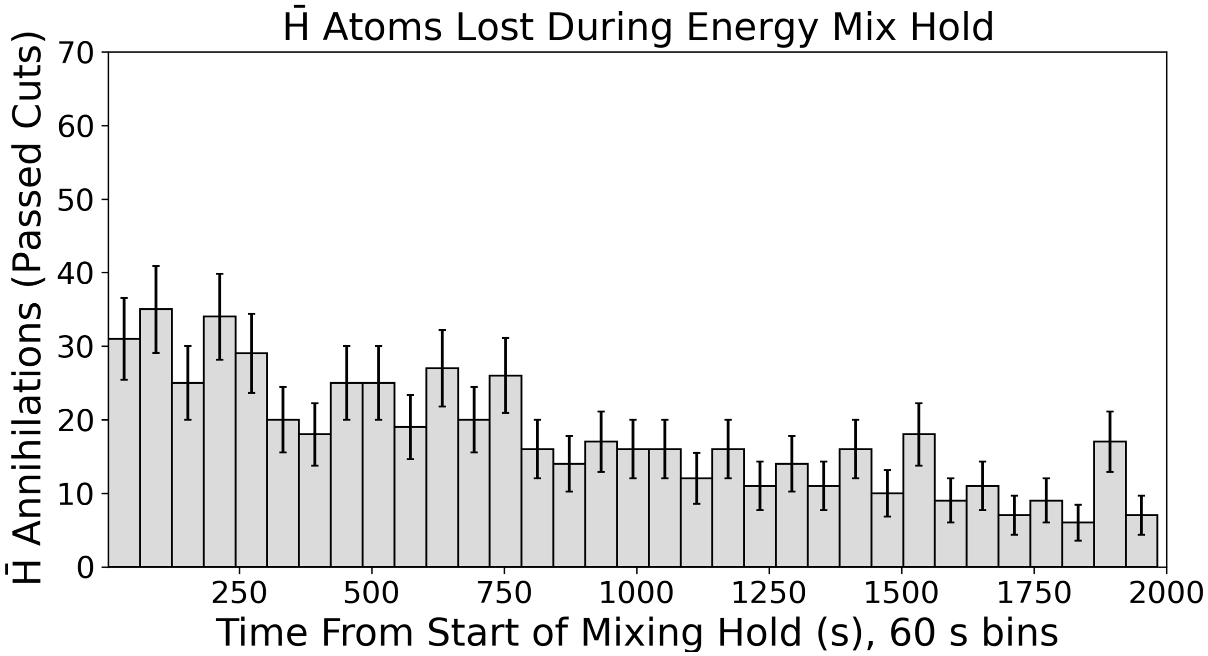
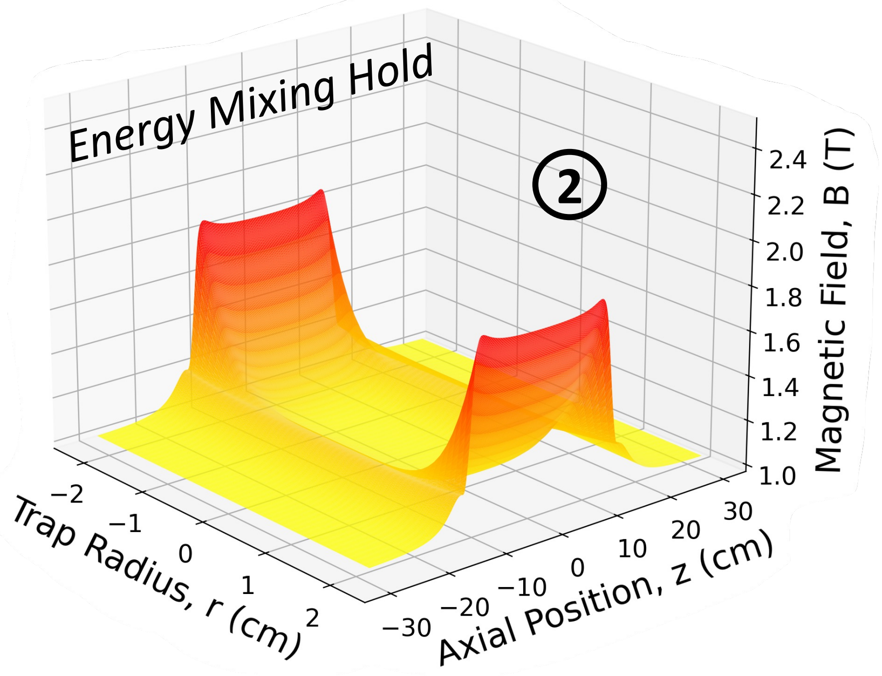
Experimental Results: $\bar{\mathrm{H}}$ Energy Mixing Evidence

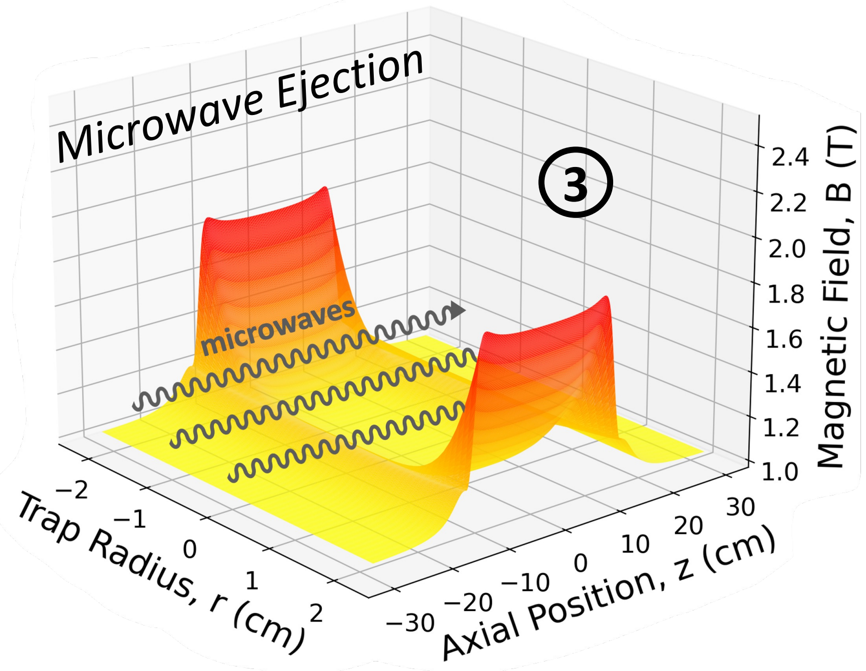




Over time $\bar{\mathrm{H}}$ will escape magnetic trap by exchanging $E_\perp$ with $E_\parallel$

Step 2 to 3


Energy Mixing Hold
2
Magnetic Field, B (T)
2.4
2.2
2.0
1.8
1.6
1.4
1.2
1.0
Trap Radius, r (cm)
−2
−1
0
1
2
Axial Position, z (cm)
−30
−20
−10
0
10
20
30


Microwave Ejection
3
microwaves
Magnetic Field, B (T)
2.4
2.2
2.0
1.8
1.6
1.4
1.2
1.0
Trap Radius, r (cm)
−2
−1
0
1
2
Axial Position, z (cm)
−30
−20
−10
0
10
20
30

Experimental Results: No Mix $\bar{\mathrm{H}}$ Evidence

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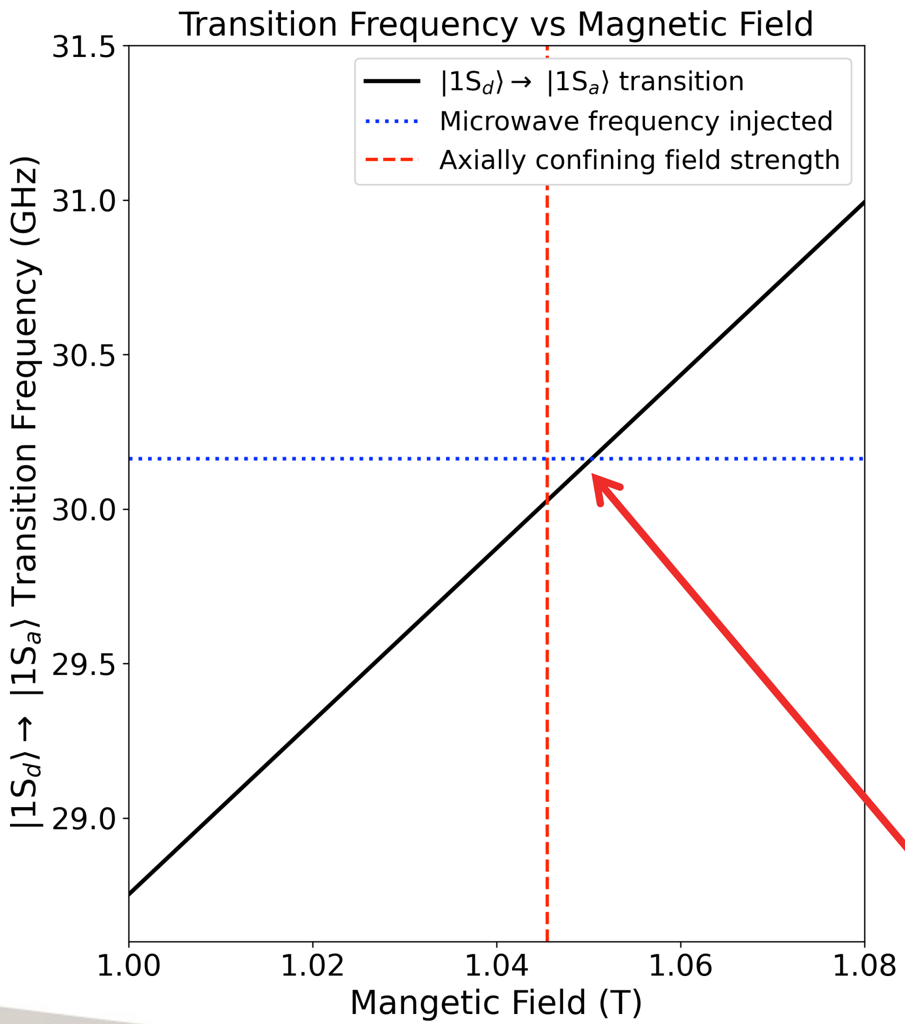
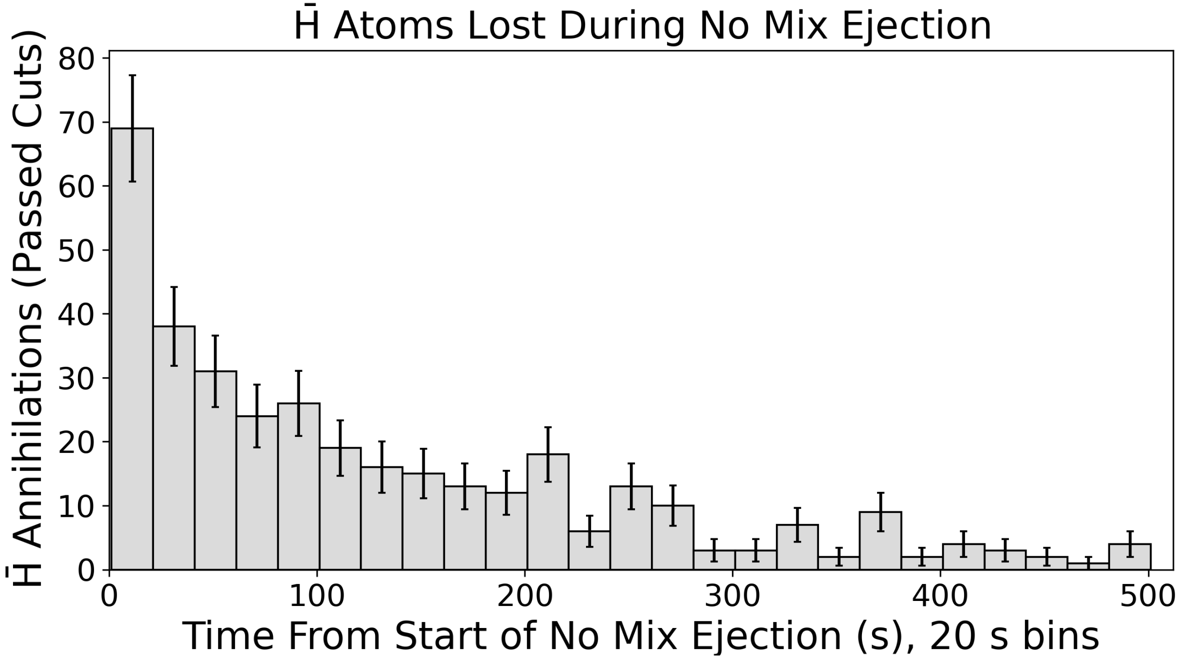
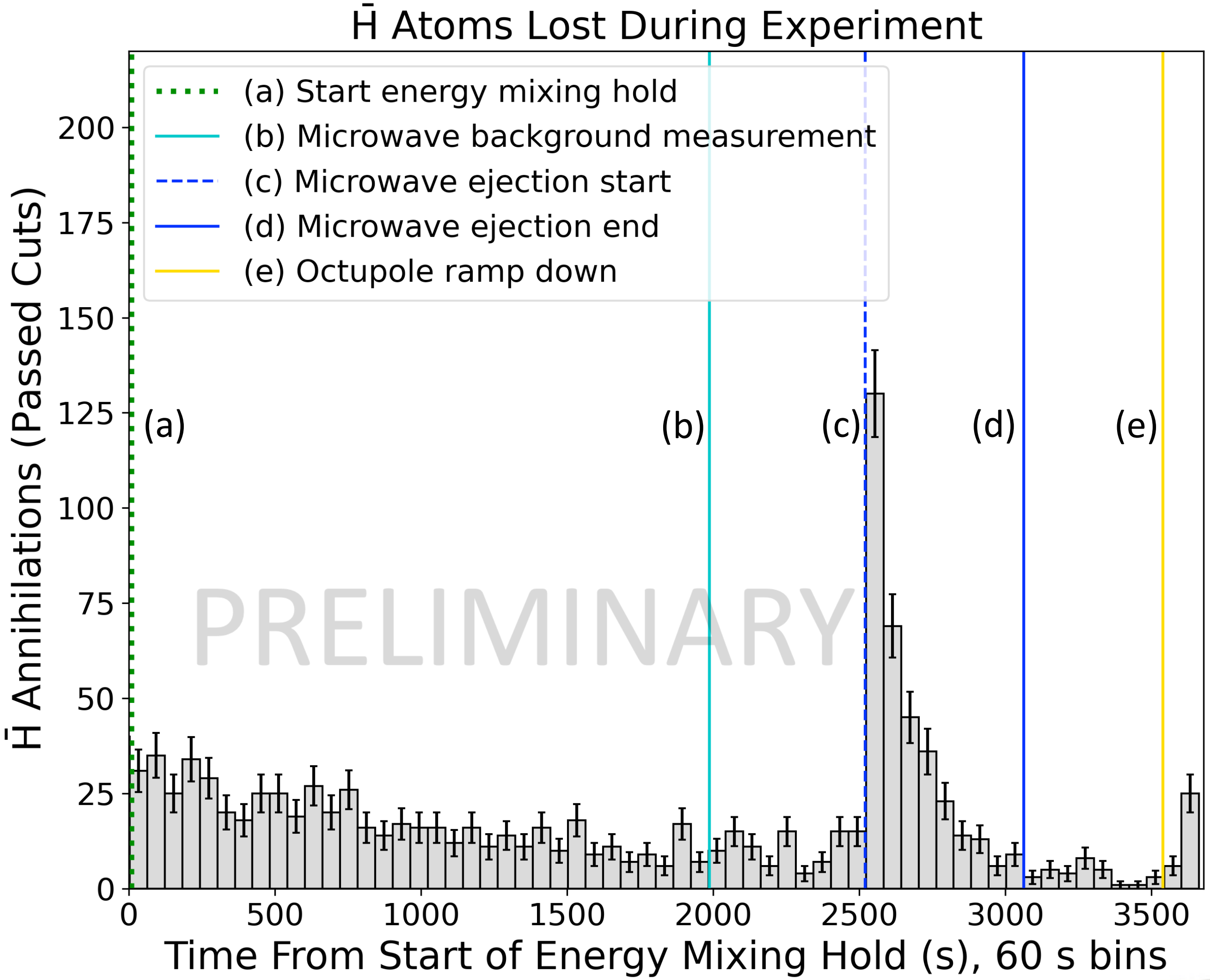




$\bar{\mathrm{H}}$ that samples B field just above the axial trap depth will transition to an untrappable state via microwave induced positron spin flip

Summary of Results

Stage	Losses*
Decrease short solenoids†	68.5%
Hold for atoms to mix energies	**12.6%**
Microwave background	**1.9%**
Microwave ejection of no-mix atoms	**7.6%**
Count cold atoms	**8.9%**



*Losses are represented as percentages of total population and are shown only in relevant experimental steps

† Not shown in plot

Conclusion and Next Steps

- No-mix $\overline{\mathbf{H}}$ atoms have been observed for the first time

- Analysis of the experiment is currently in progress
- Results will be used for future experiment design, analysis, and simulation in ALPHA
  - Improved cooling of antihydrogen
  - Higher precision gravity measurements on antimatter
  - Higher precision laser and microwave spectroscopy

Acknowledgements

- This experiment was proposed by Prof. Joel Fajans (UC Berkeley), Prof. Jonathan Wurtele (UC Berkeley), and Prof. Mike Hayden (Simon Fraser University).
- This experiment was designed and simulated by Dr. Danielle Hodgkinson (UC Berkeley).

ALPHA

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UC Berkeley

CERN

CINP ICPN

Canadian Institute of Nuclear Physics

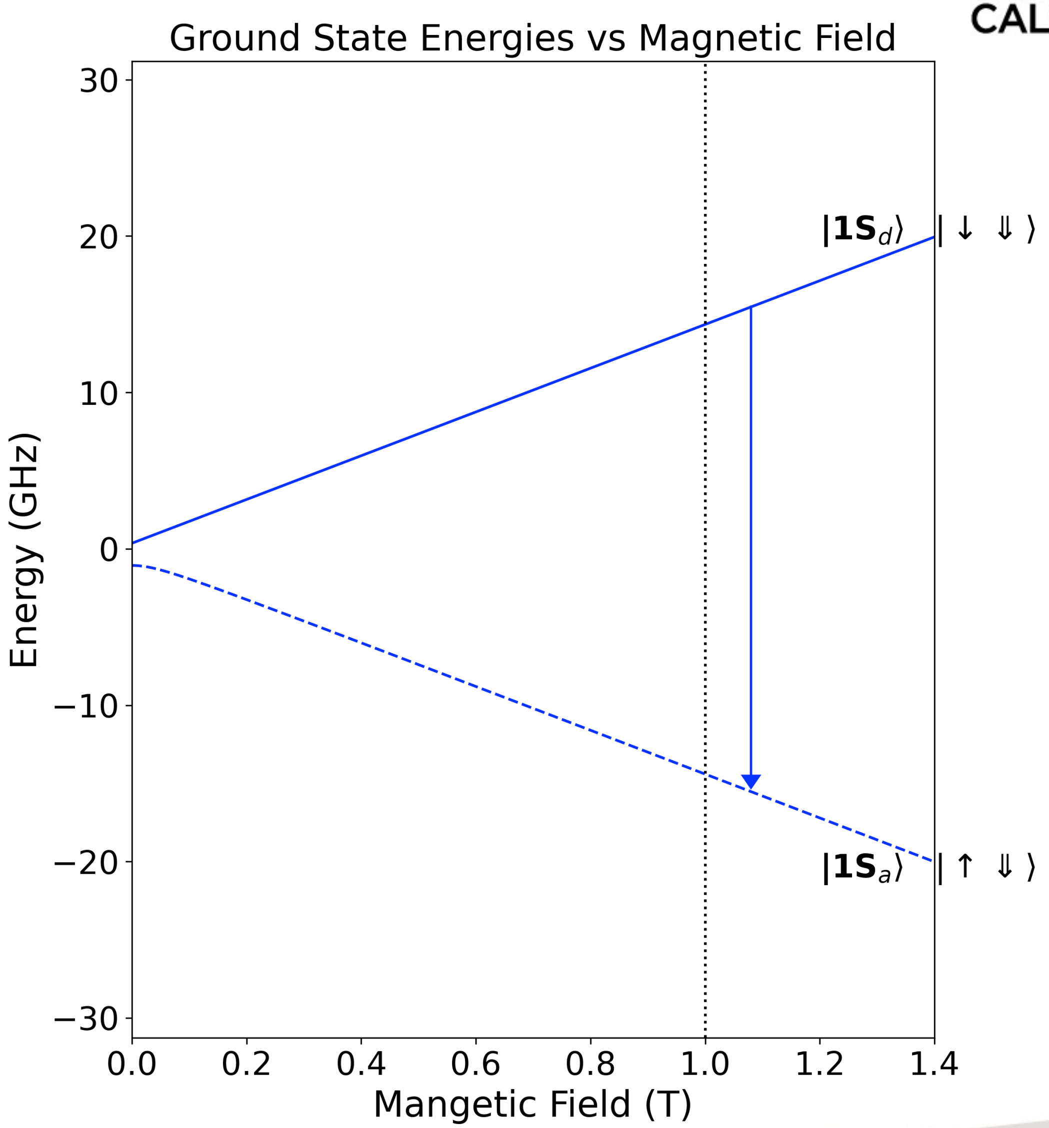
Institut canadien de physique nucléaire

ALBERTA INNOVATES

Extra slides

Ground State Hyperfine Transitions

- Trapped $\overline{\mathrm{H}}$ will be in $|1S_d\rangle$
- Microwave radiation can induce transitions from $|1S_d\rangle$ -> $|1S_a\rangle$
- If $\overline{\mathrm{H}}$ transitions to $|1S_a\rangle$ it will escape and annihilate on surrounding apparatus walls



The ALPHA experiment

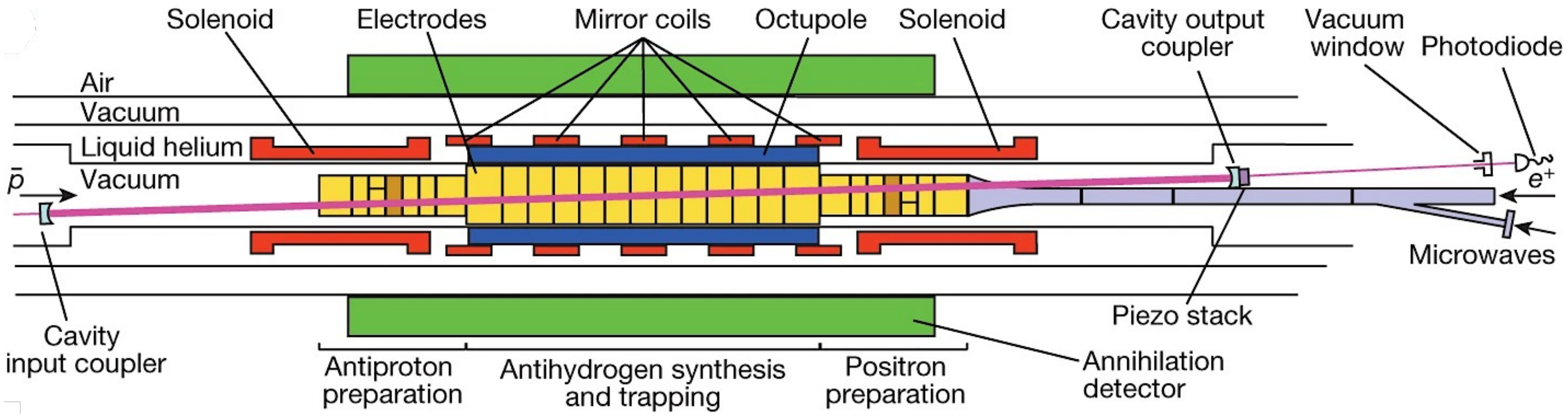
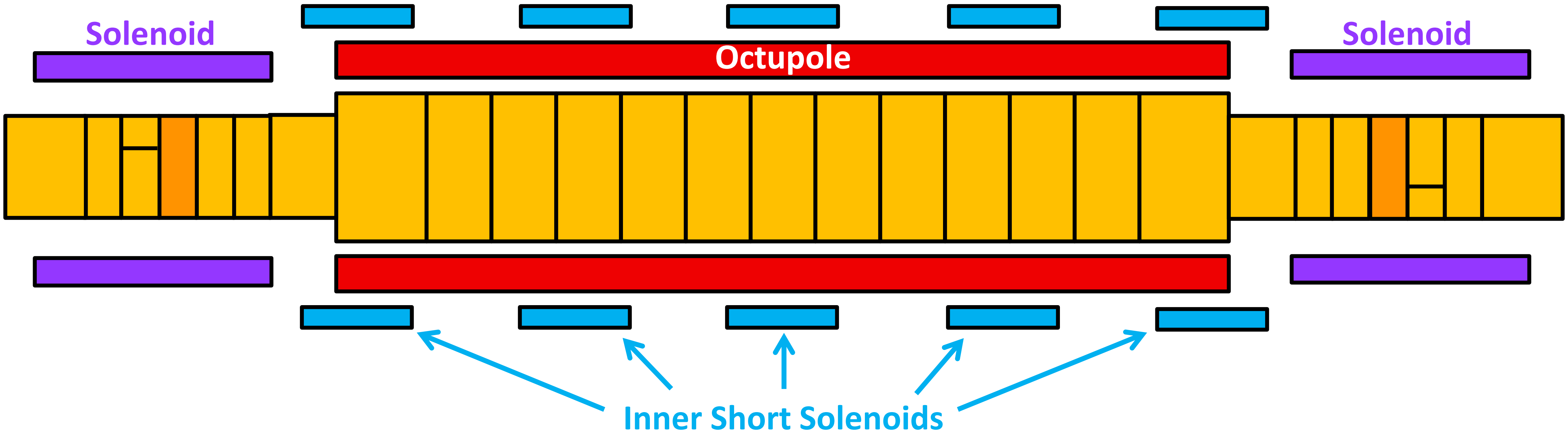


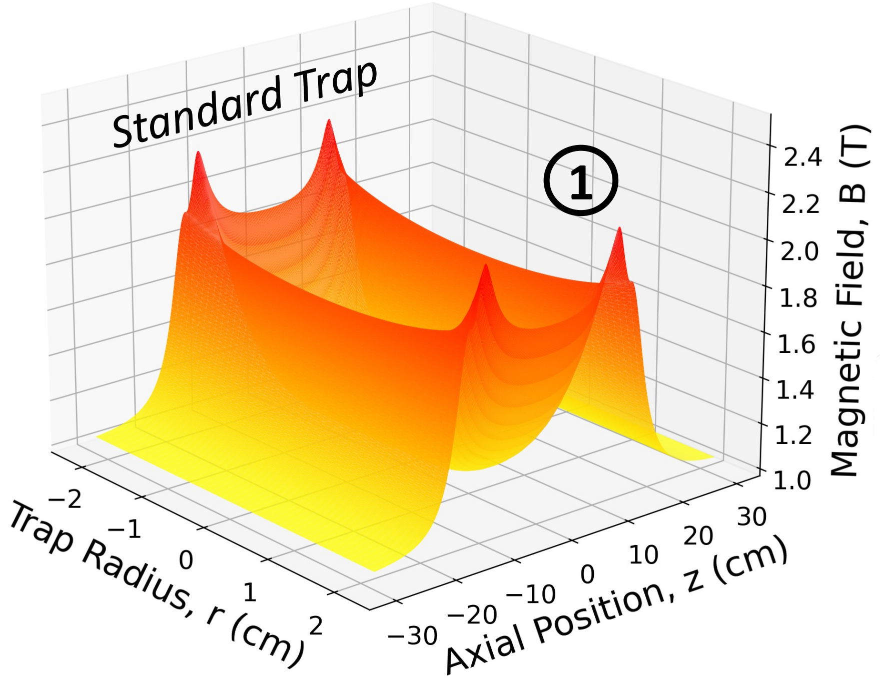
Image Credit: Ahmadi, M., Alves, B.X.R., Baker, C.J. *et al.* Characterization of the 1S–2S transition in antihydrogen. *Nature* **557**, 71–75 (2018).

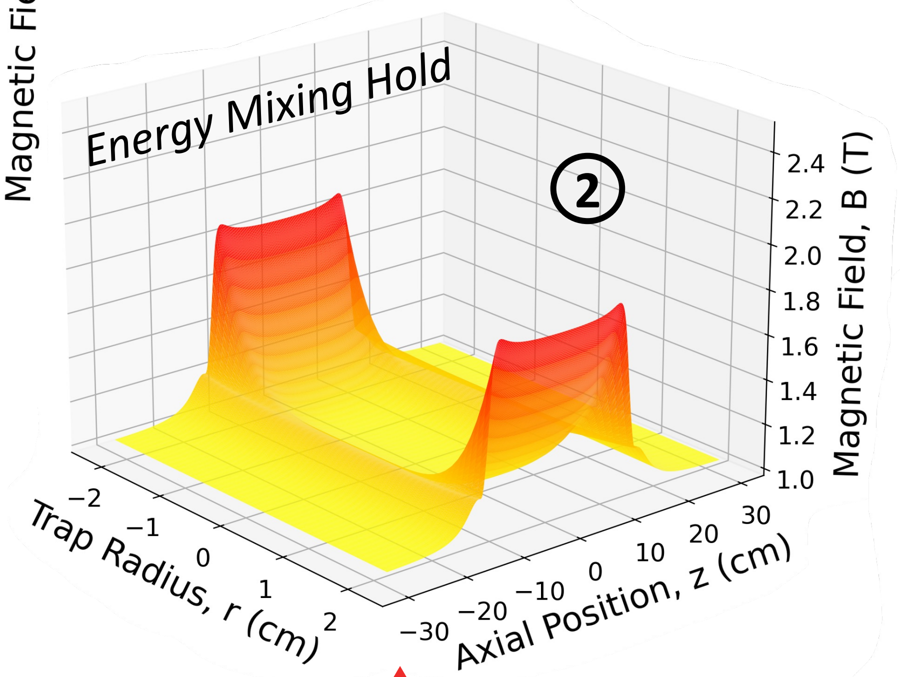
ALPHA-2 Magnets

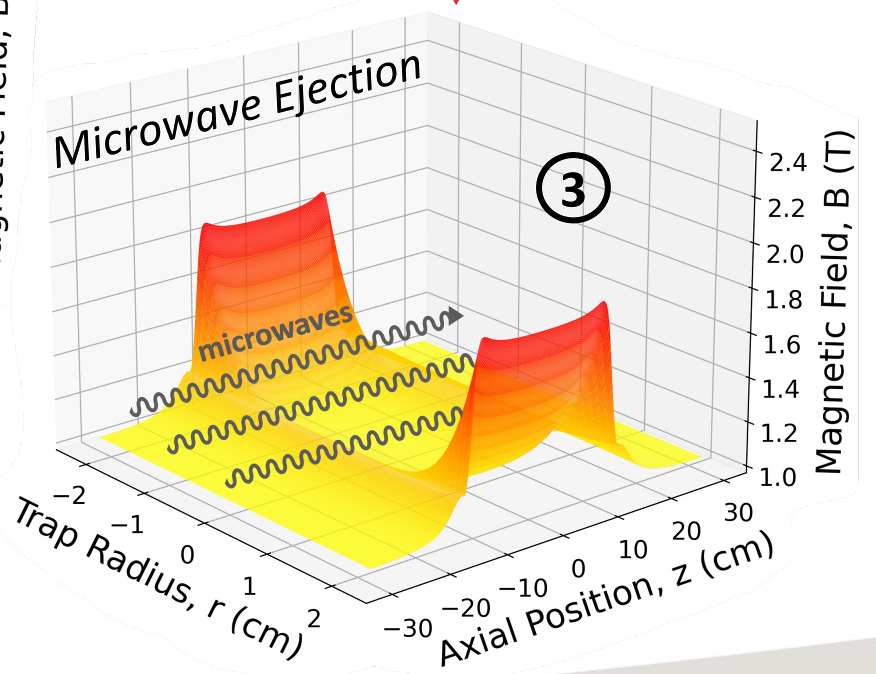


Key Steps of Experiment

$\bar{\mathrm{H}}$ that samples the B field just above the axial trap depth will transition to an untrappable state via microwave induced positron spin flip







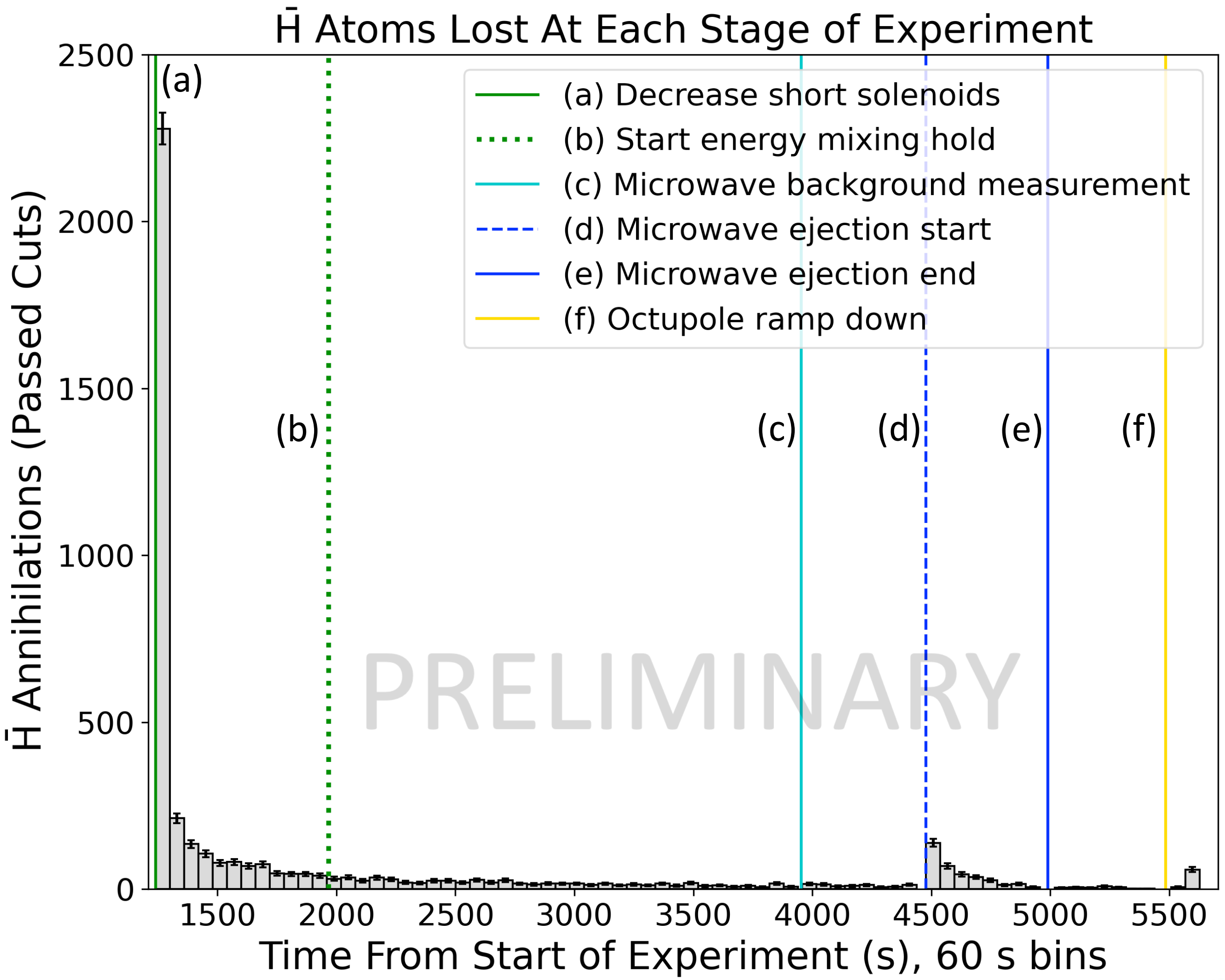
At first $\bar{\mathrm{H}}$ with $\mathrm{E}_{\parallel}$ > trap depth will escape

Over time $\bar{\mathrm{H}}$ will escape magnetic trap by exchanging $\mathrm{E}_{\perp}$ with $\mathrm{E}_{\parallel}$

Results Comparison

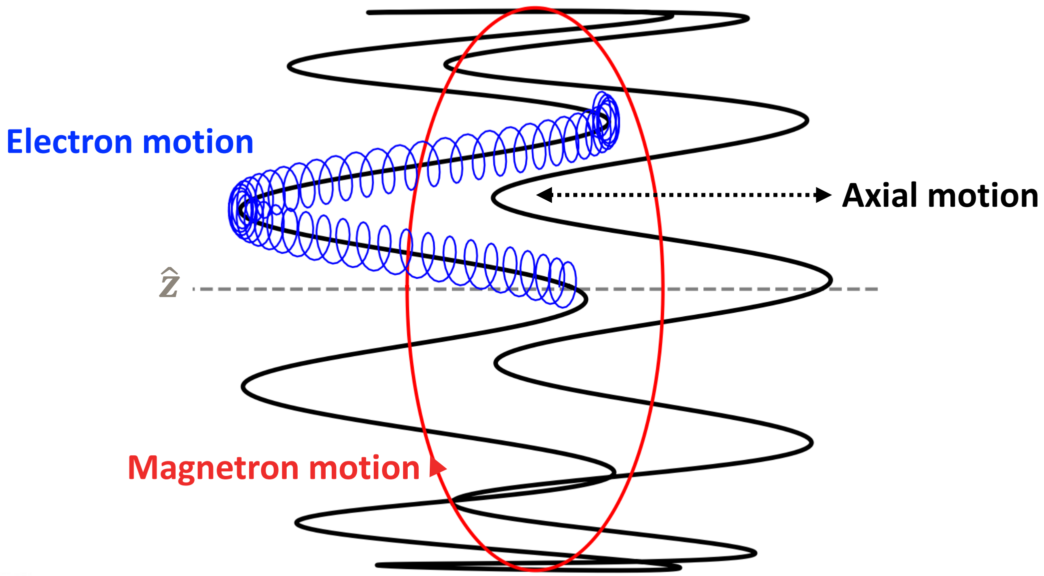
Stage	Losses*	Preliminary Simulated Losses*†
Decrease short solenoids	**68.5%**	**76.2%**
Hold for atoms to mix energies	**12.6%**	**15.4%**
Microwave background	**1.9%**	**--**
Microwave ejection of no-mix atoms	**7.6%**	**7.3%**
Count cold atoms	**8.9%**	**0.1%**

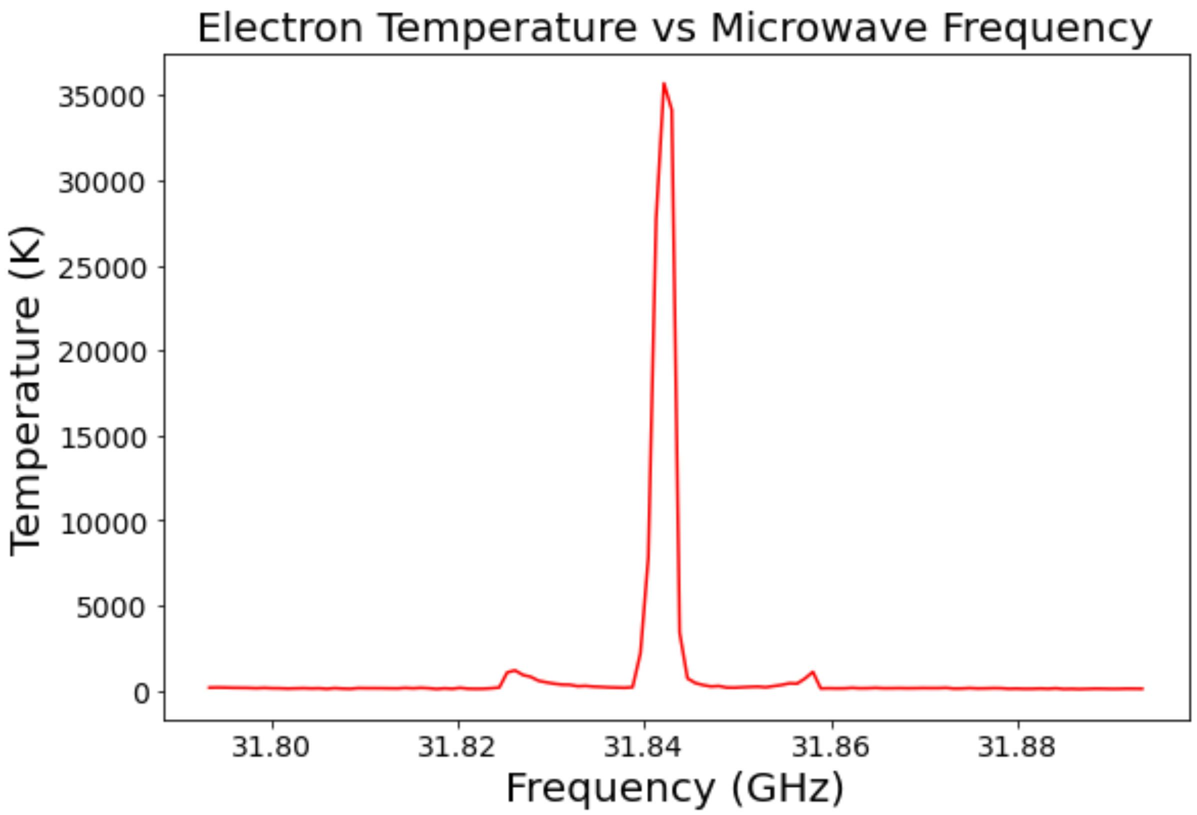
*Losses are represented as percentages of total population and are shown only in relevant experimental steps



Electron Cyclotron Resonance (ECR)

- $\mathbf{B} = \frac{\mathbf{m}\boldsymbol{\omega_c}}{\boldsymbol{q}}$
  - m = electron mass
  - q = electron charge
  - ω_c = angular frequency of cyclotron motion
  - B = magnetic field





Axial Trap Depth During Energy Mixing Hold

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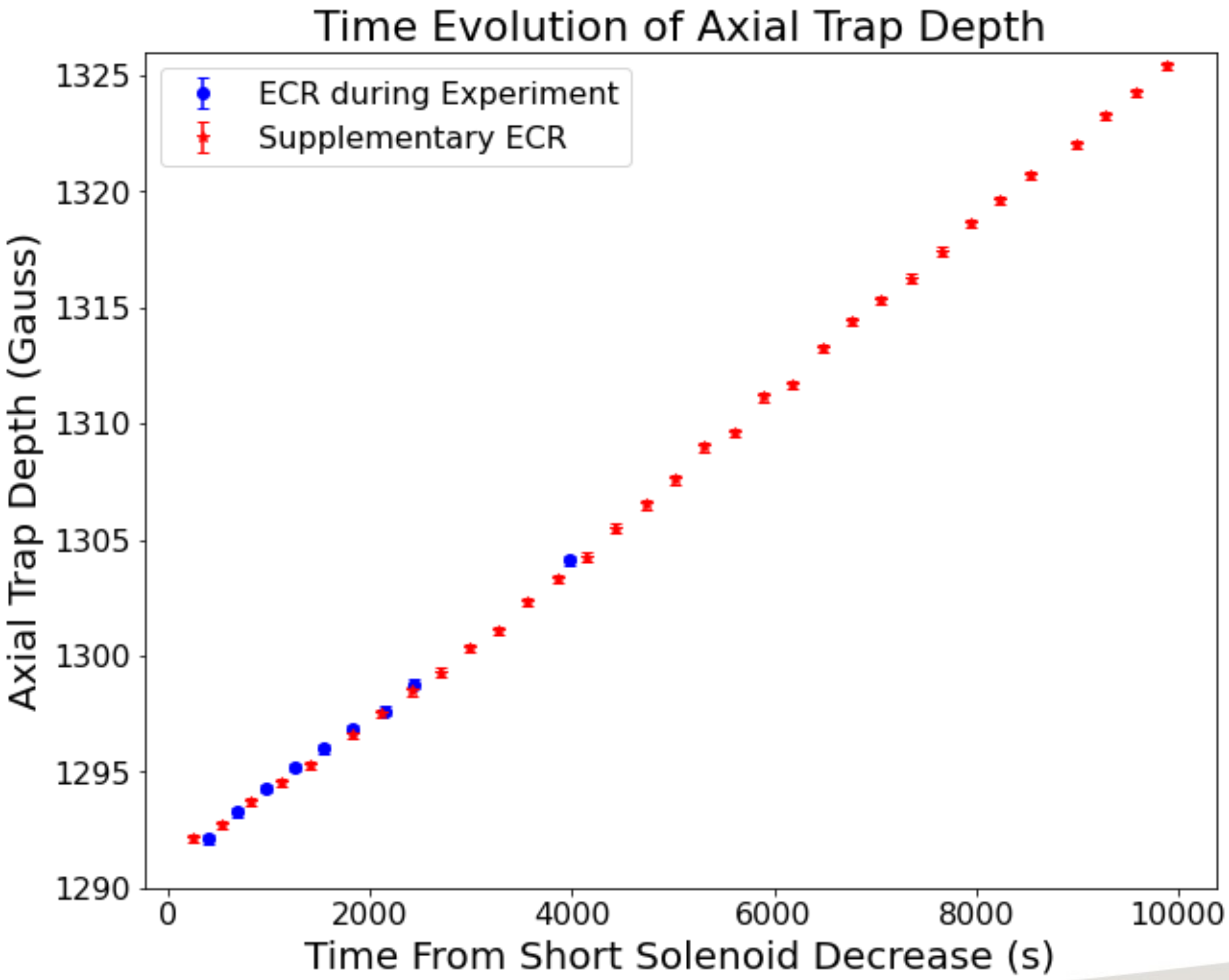
- The magnetic field was measured using Electron Cyclotron Resonance (ECR) techniques
- One of the short solenoid fields was slowly increased over time
  - This caused the axial trap depth to increase during the energy mixing hold
  - Trap depth = (maximum field at the short solenoid) – (magnetic minimum)



Hunter, E. D., Christensen, A., Fajans, J. *et al.* Electron cyclotron resonance (ECR) magnetometry with a plasma reservoir. *Phys. Plasmas* **27**, 032106 (2020).

Axial Magnetic Field During Energy Mixing Hold

- Axial magnetic field was always higher at the downstream solenoid
- It was necessary to increase the field only at the upstream solenoid to maintain an increasing trap depth