Hyperfine spectroscopy of antihydrogen in the ALPHA experiment

Tim Friesen on behalf of the ALPHA collaboration
Aarhus University
EXA2017 September 12, 2017

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European Research Council
Established by the European Commission

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UBC THE UNIVERSITY OF BRITISH COLUMBIA

THE UNIVERSITY OF CALIFORNIA BERKELEY 1868

BERKELEY LAB

UNIVERSITY OF CALGARY

ALPHA

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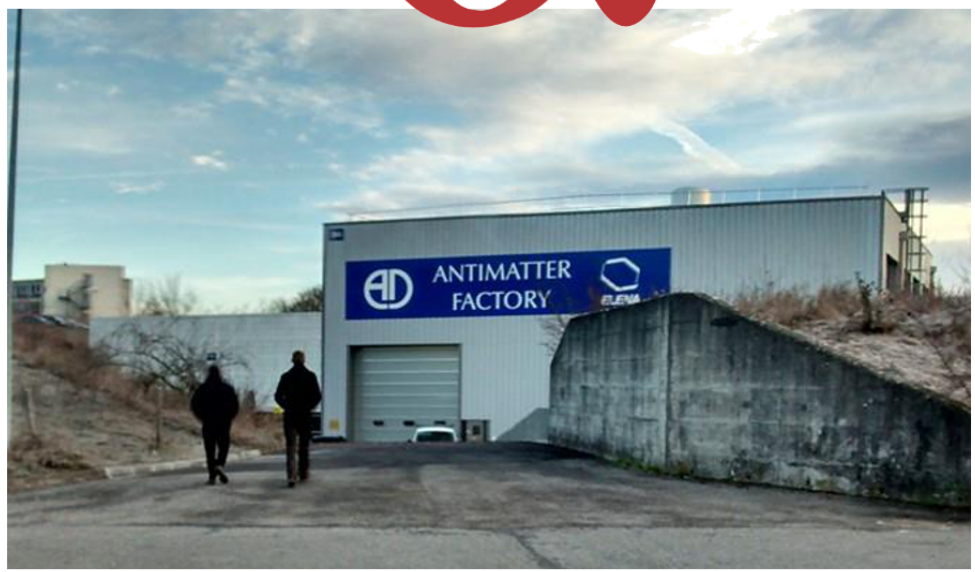

MANCHESTER 1824

The Cockcroft Institute of Accelerator Science and Technology

NRCN Nuclear Research Center Negev

UNIVERSIDADE DO BRASIL

Stockholms Universitet
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SIMON FRASER UNIVERSITY
THINKING OF THE WORLD

Swansea University
Prifysgol Abertawe

TRIUMF

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Antihydrogen **L**aser **PH**ysics **A**pparatus

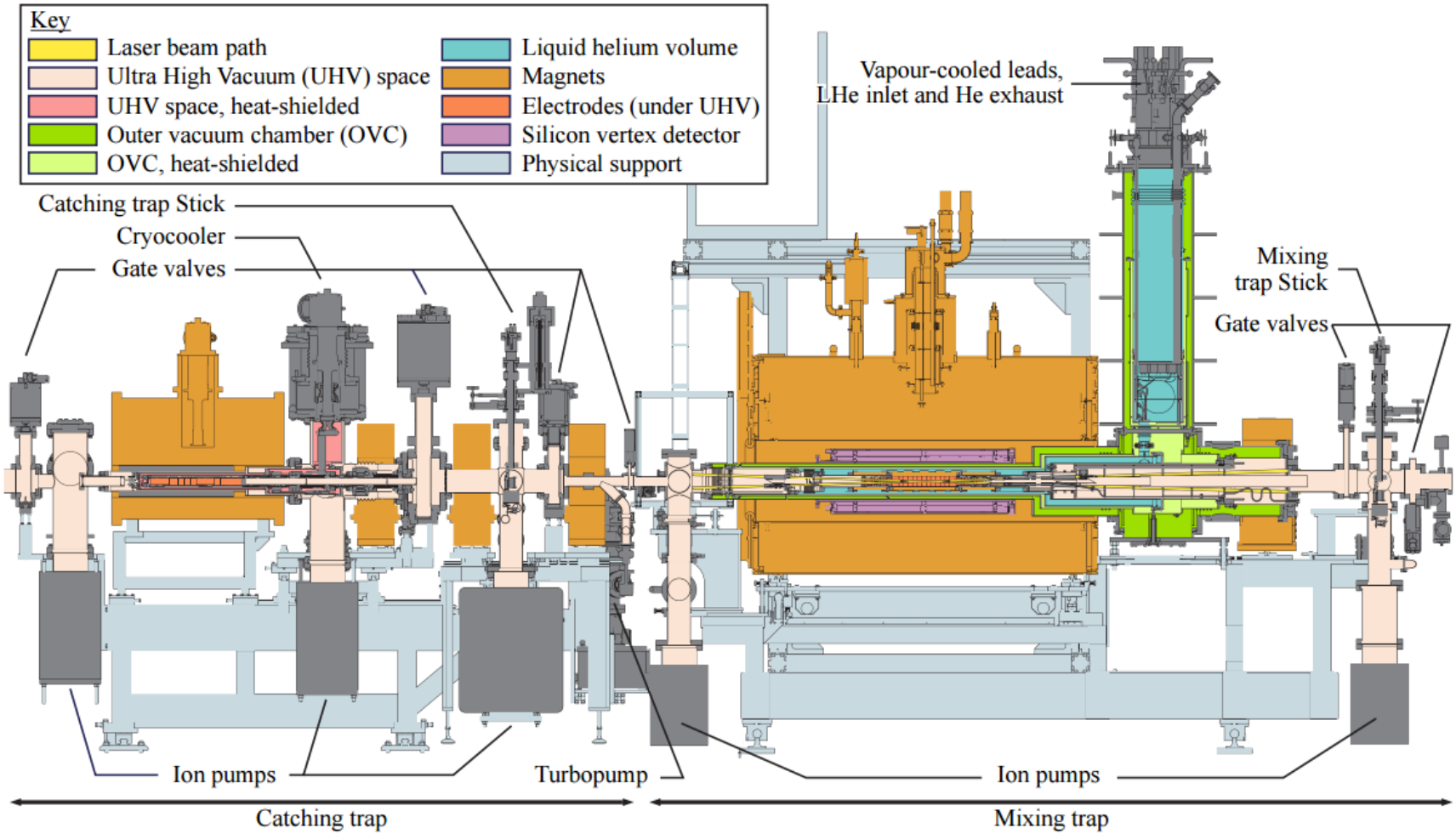
Goal: High precision studies of antihydrogen.

- 1S - 2S spectroscopy.
- Ground state hyperfine spectroscopy (known to $\sim$1 parts in 10^{12} in hydrogen[1]).
- Gravitational mass.

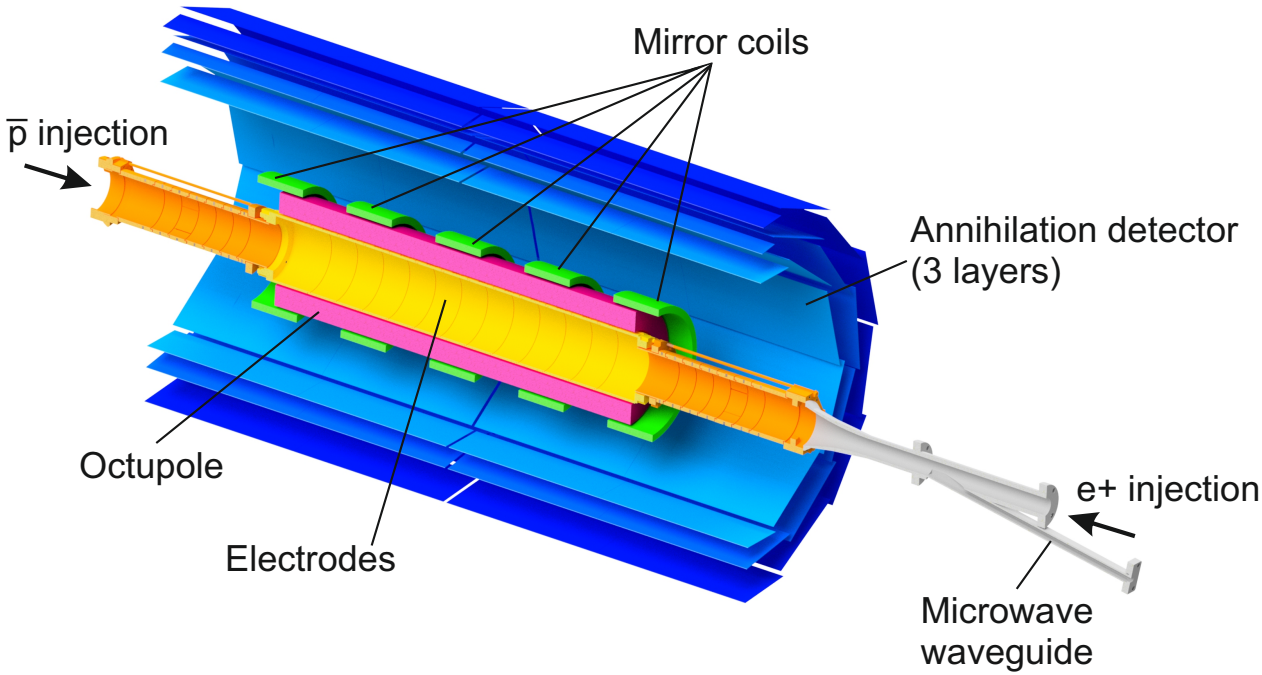
Approach: Trap antihydrogen in a magnetic minimum neutral atom trap for study.

[1] H. Hellwig et al. Instrumentation and Measurement, IEEE Transactions on 19, 200 (1970).

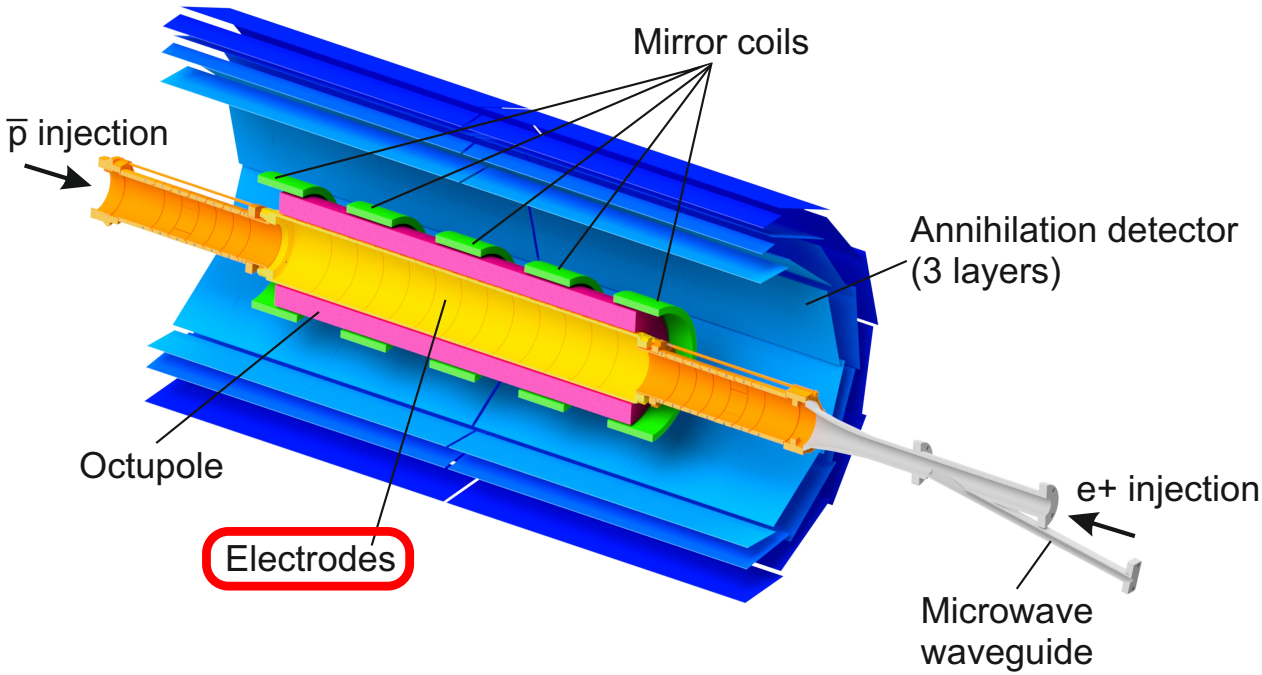
Apparatus


Key
Laser beam path
Ultra High Vacuum (UHV) space
UHV space, heat-shielded
Outer vacuum chamber (OVC)
OVC, heat-shielded
Liquid helium volume
Magnets
Electrodes (under UHV)
Silicon vertex detector
Physical support
Vapour-cooled leads,
LHe inlet and He exhaust
Catching trap Stick
Cryocooler
Gate valves
Mixing
trap Stick
Gate valves
Ion pumps
Turbopump
Ion pumps
Catching trap
Mixing trap

Apparatus


Mirror coils
p̄ injection
Annihilation detector
(3 layers)
Octupole
Electrodes
e+ injection
Microwave
waveguide

Apparatus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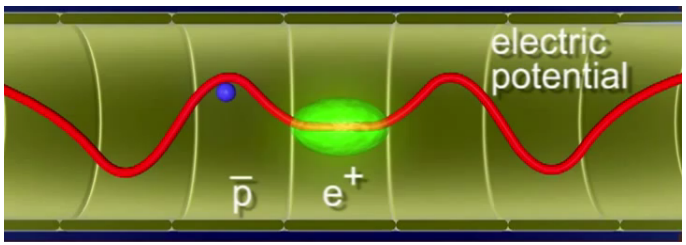
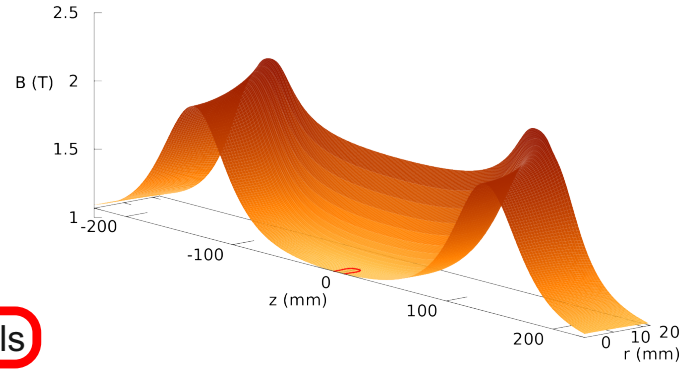
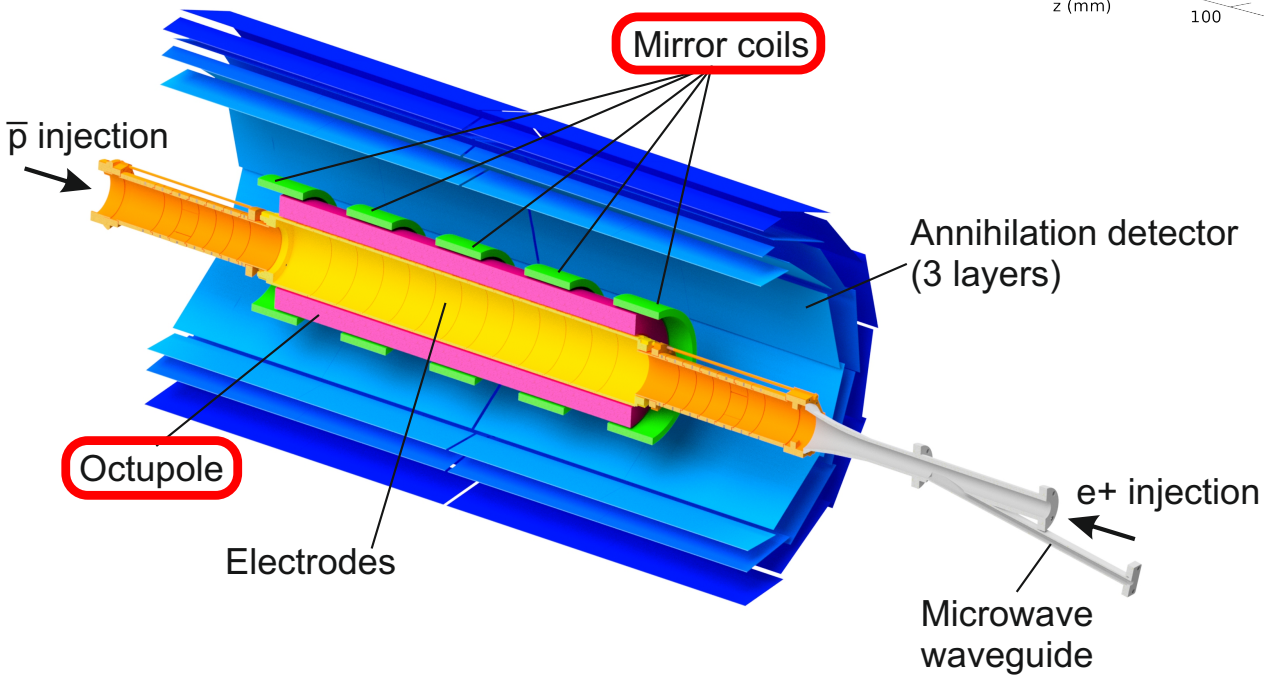

electric
potential
p̄
e+

Apparatus

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





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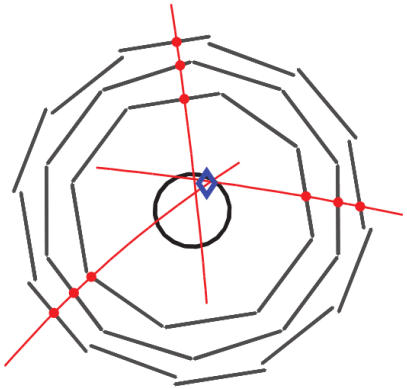
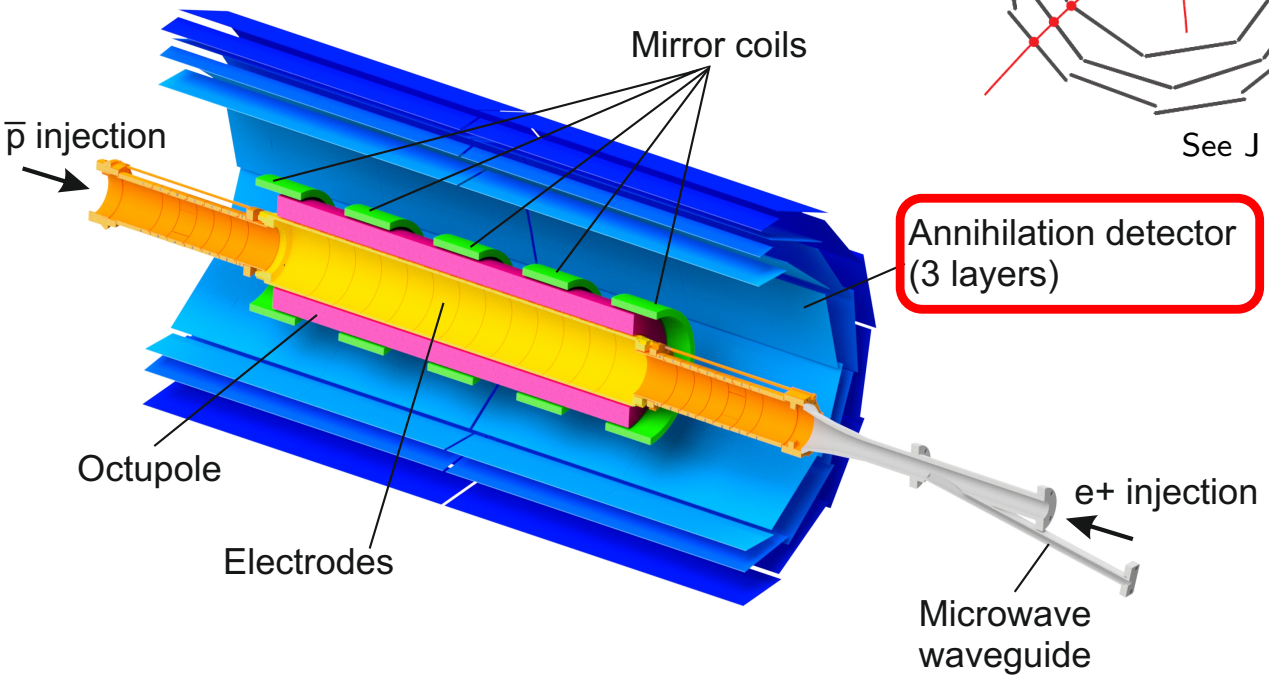
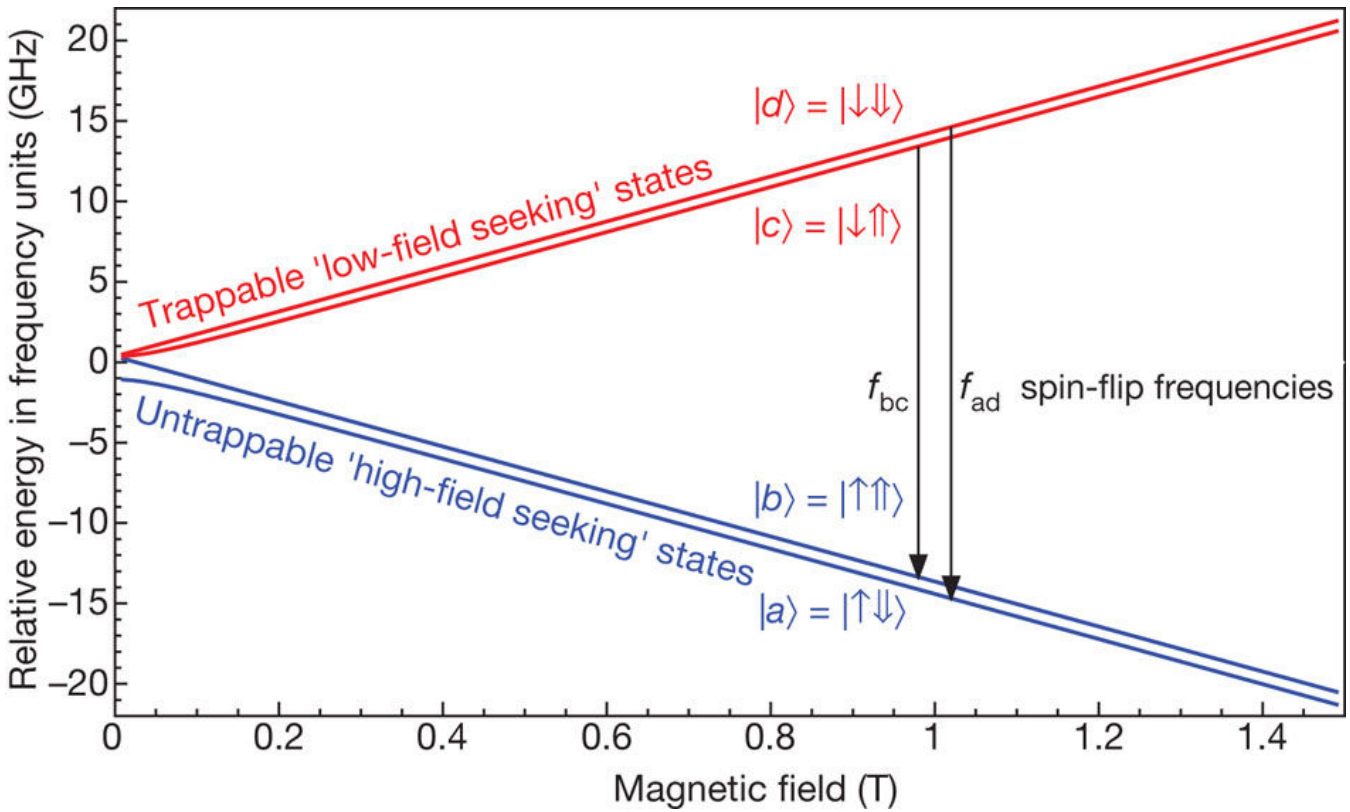


See J T K Mckenna's talk



Hyperfine spectroscopy of trapped antihydrogen

$H/\bar{H}$ Hyperfine levels



$$\Delta f_{HFS}(B = 0) = f_{ad} - f_{bc}$$

At 1 T:

$f_{bc} \approx 28.0$ GHz

$f_{ad} \approx 29.42$ GHz

Hyperfine spectroscopy of trapped antihydrogen

Challenges:

- Few trapped antihydrogen atoms ($\sim 31 \times 10^4$ $\bar{\mathrm{H}}$ formed $\rightarrow$ $\sim$8 trapped and detected).

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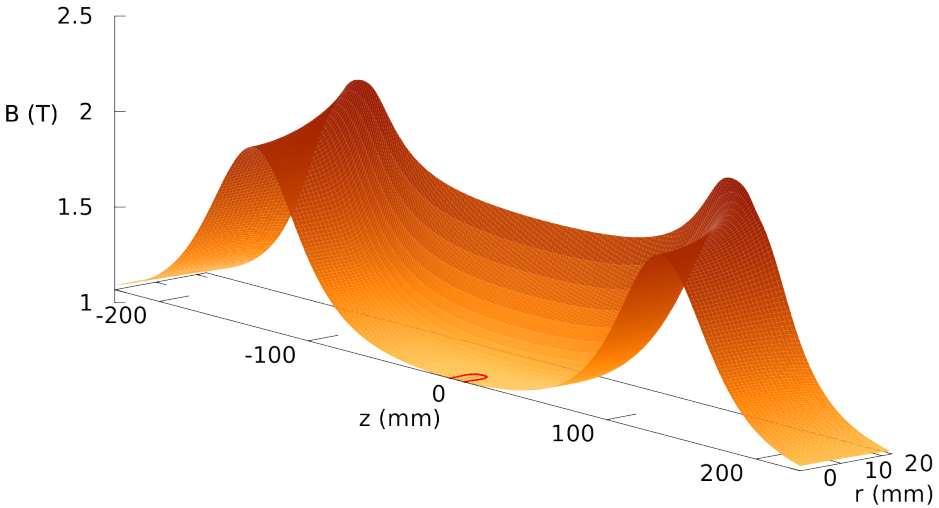
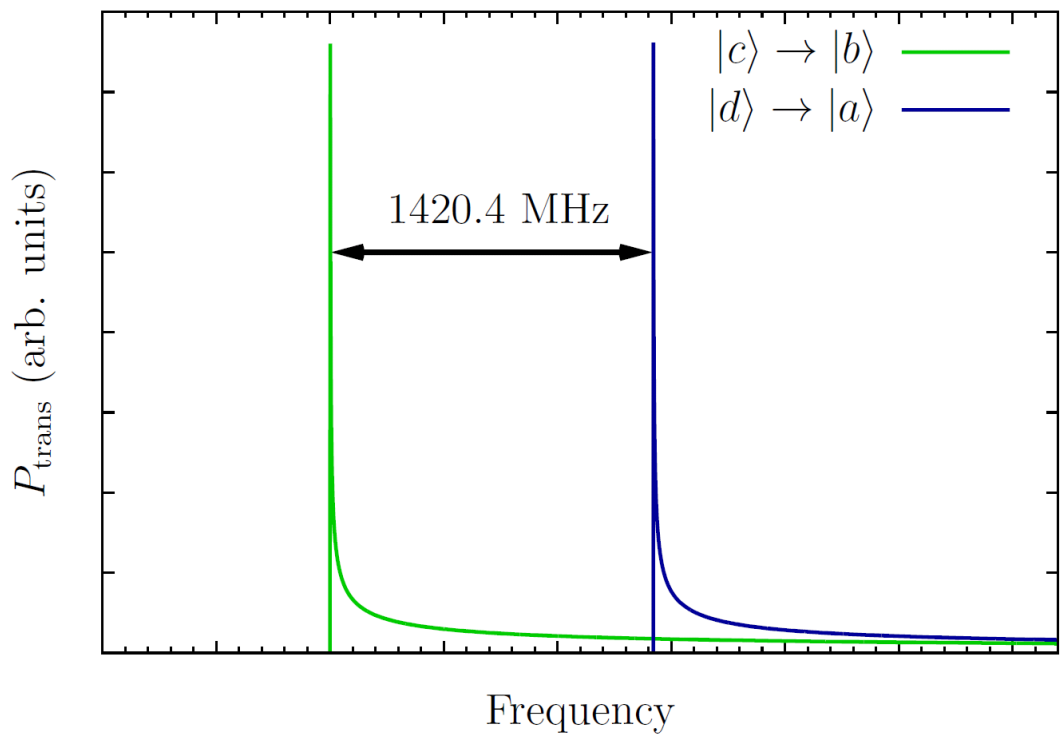
Advantage:

- Trapped antihydrogen is in ground state.

Hyperfine levels





Microwave hardware

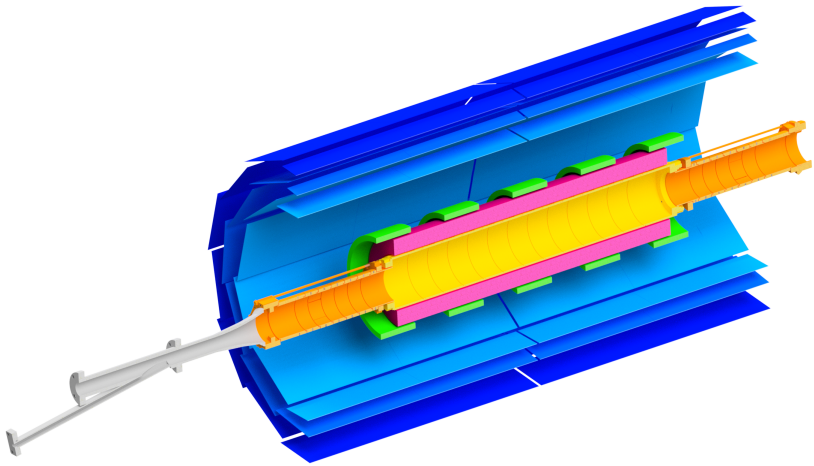
Agilent 8257D PSG synthesizer

↓

Miteq AMF-4B amplifier

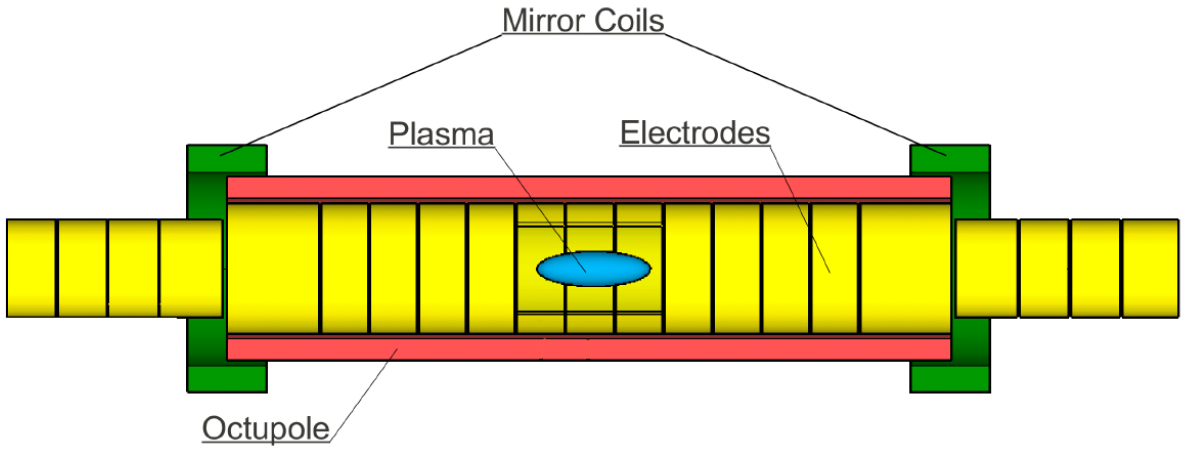
↓

Vacuum feedthrough →

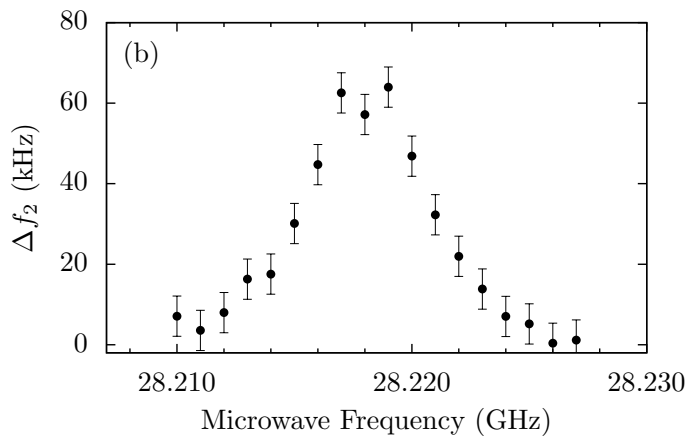


- Can inject up to ~ 1 W at feedthrough.
- Mode structure in Penning trap unknown. *In situ* power varies strongly with frequency and position.

In situ field diagnostics



- Electron plasma can be loaded in centre of neutral trap.
- Microwave radiation at cyclotron frequency ($f_c = qB/(2\pi m)$) excites cyclotron motion of electrons, heating plasma.
- Amplitude of heating allows us to estimate microwave field strength



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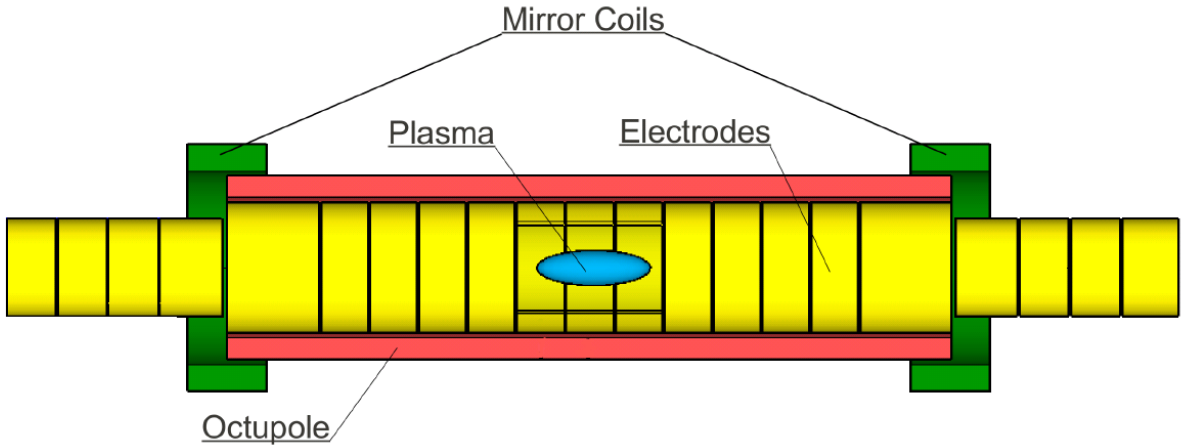
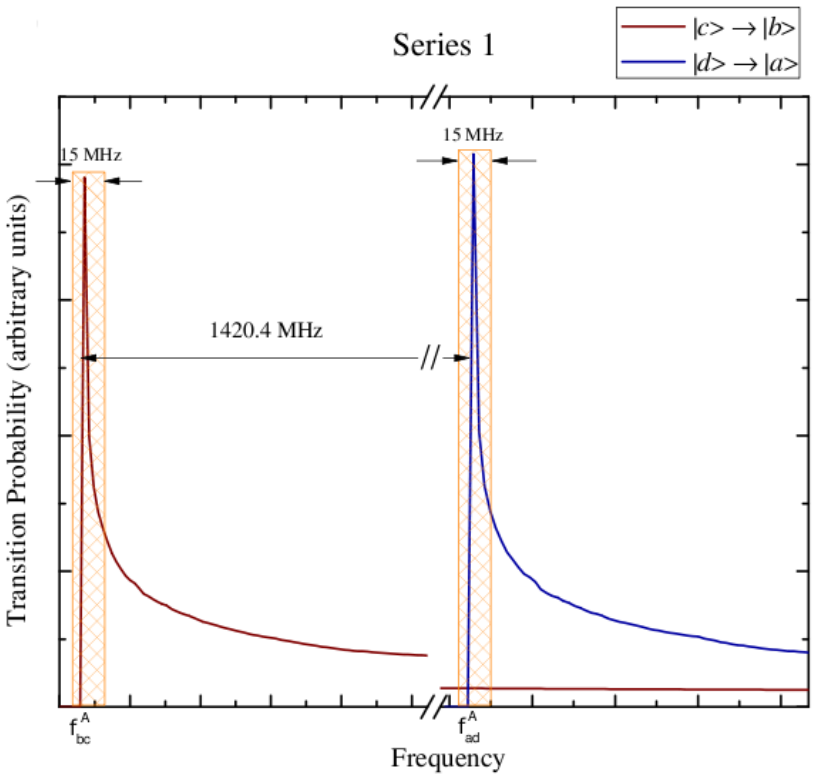


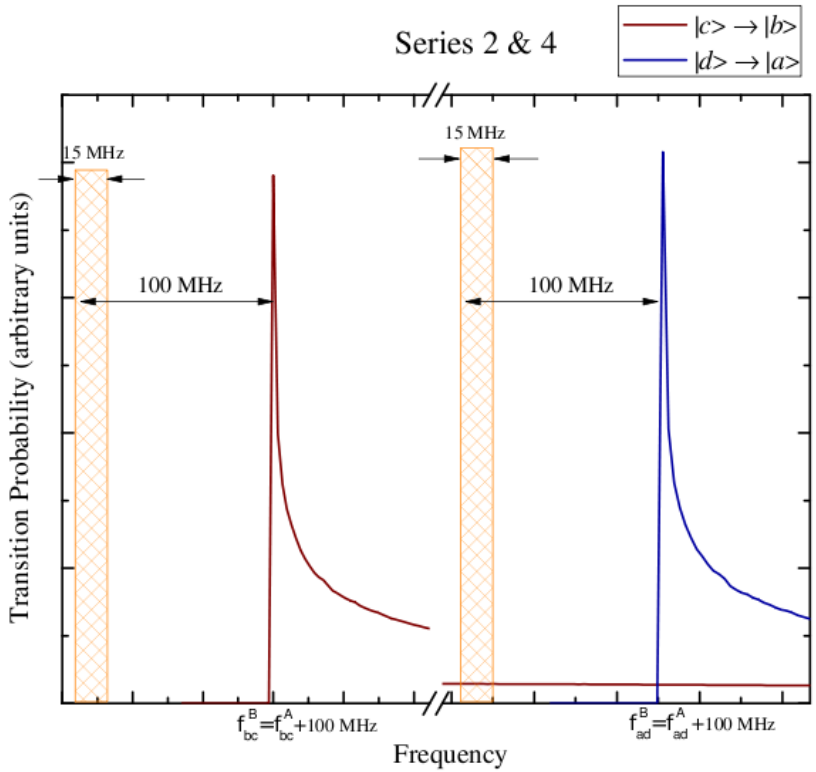
- Chose magnetic field that gave pair of frequencies with low reflected power to protect amplifier.
- At chosen frequencies $B_{MW}(f_{cb})/B_{MW}(f_{da}) \approx 7$.
- Double power at f_{da} such that $B_{MW}(f_{cb})/B_{MW}(f_{da}) \approx 5$.
- Injected 160 mW at f_{cb} and 320 mW at f_{da}.
- Limited by heating of internal surfaces.

2012 Hyperfine measurement

On Resonance:



Off Resonance:



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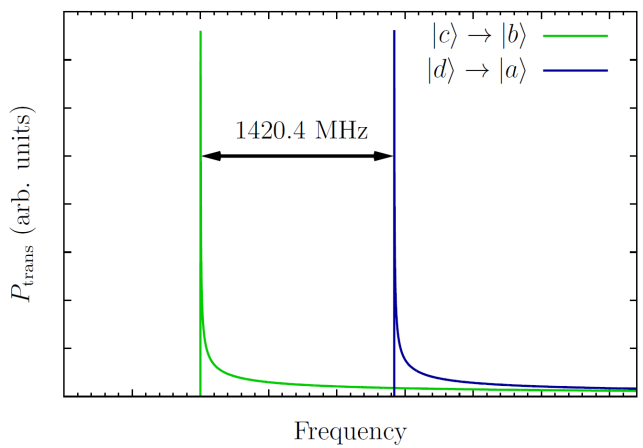

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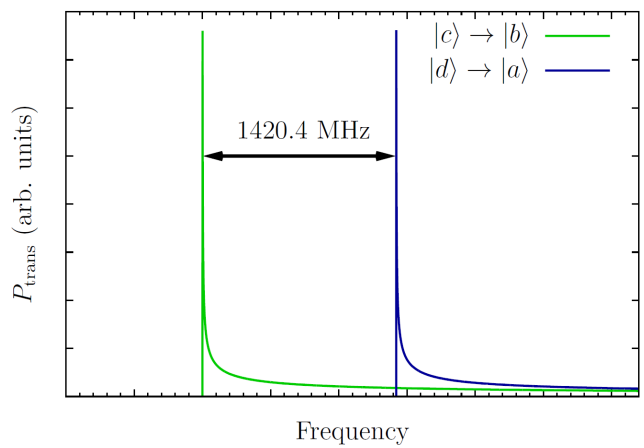
  - Increase frequency in 16, 300 kHz steps.
  - Sit at each frequency for 4 s.



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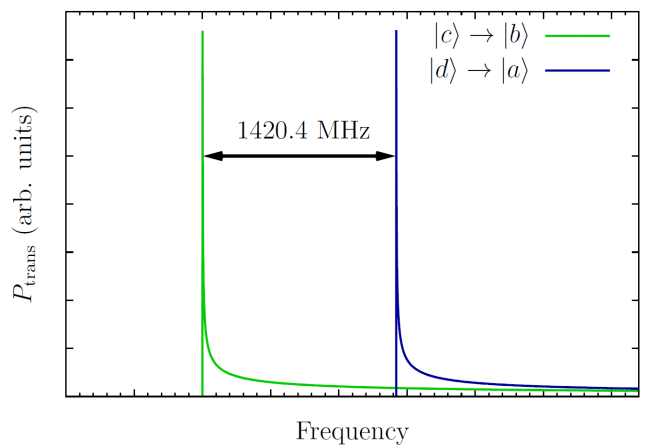
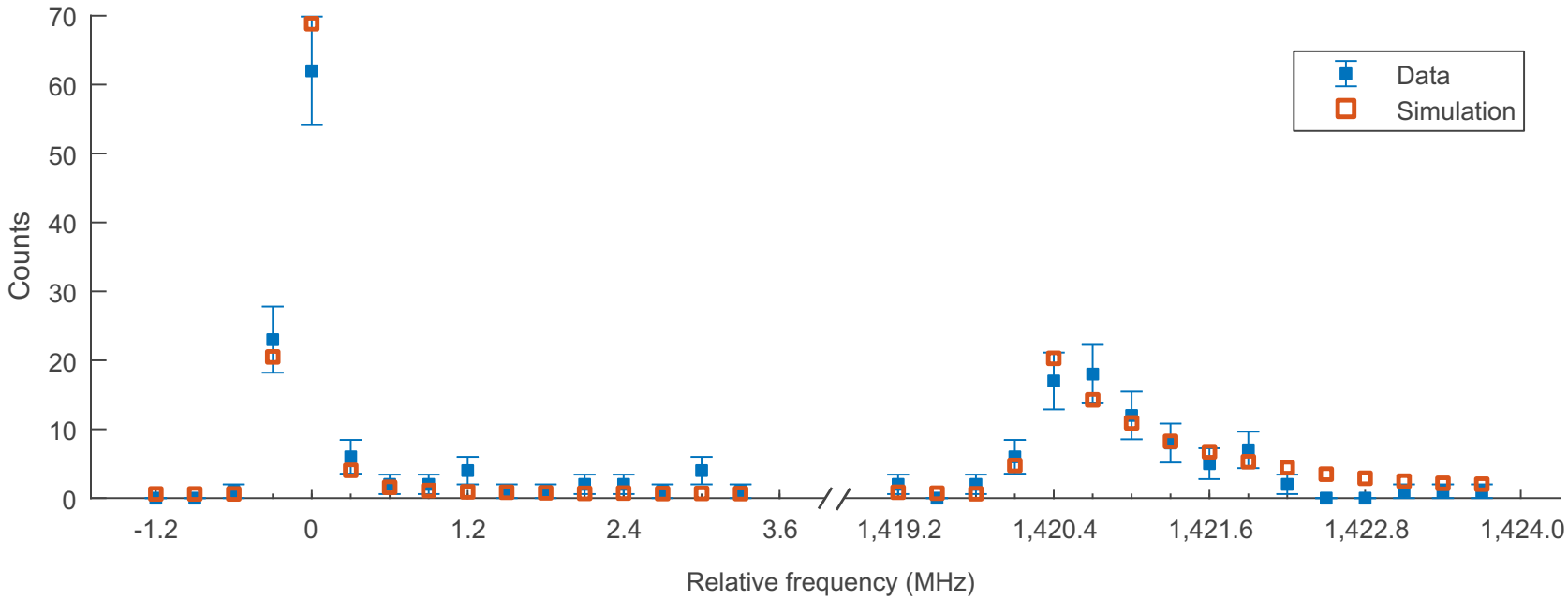
- Introduce microwaves:
  - Starting below $|c\rangle \rightarrow |b\rangle$ transition frequency.
  - Increase frequency in 16, 300 kHz steps.
  - Sit at each frequency for 4 s.
  - Increase frequency by 1420.4 MHz and repeat 16 more steps (driving $|d\rangle \rightarrow |a\rangle$).



Results



NRuns: 22
Total counts: 194
Counts in $|c\rangle \rightarrow |b\rangle$ window: 112
Counts in $|d\rangle \rightarrow |a\rangle$ window: 82
Not spin flipped: 9
Expected background per bin: 0.5

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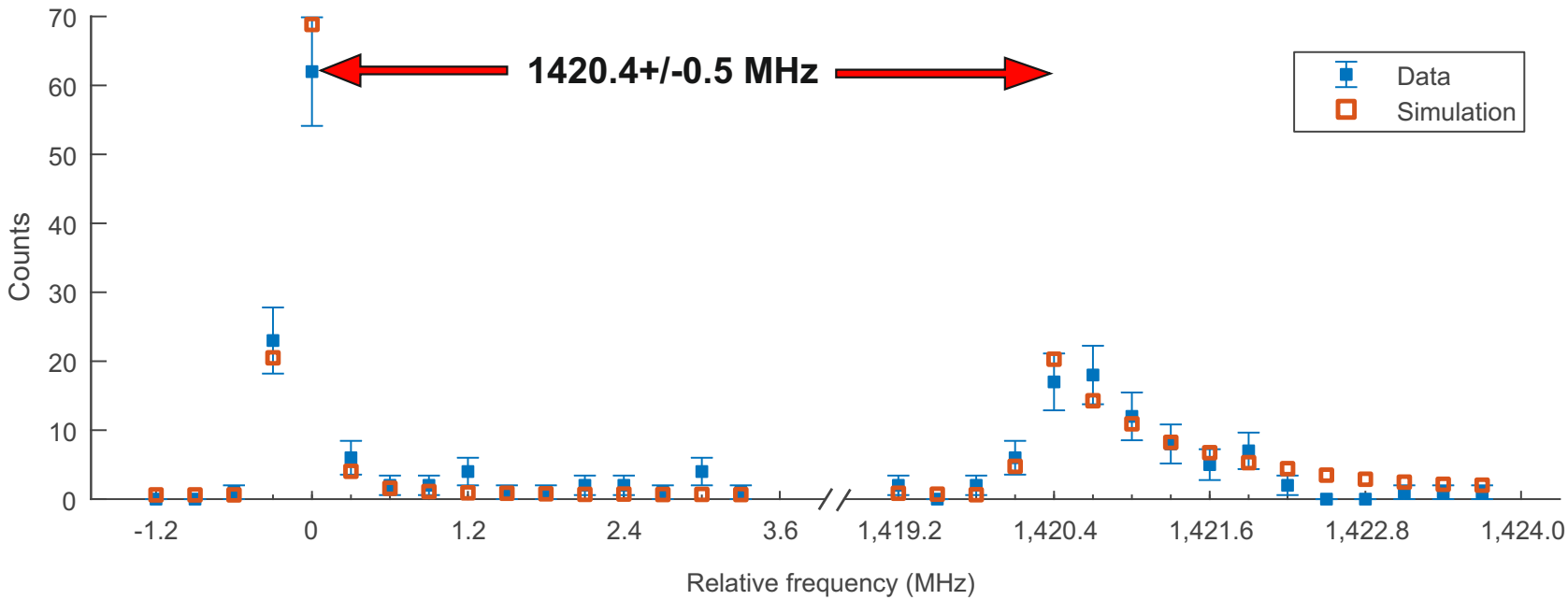

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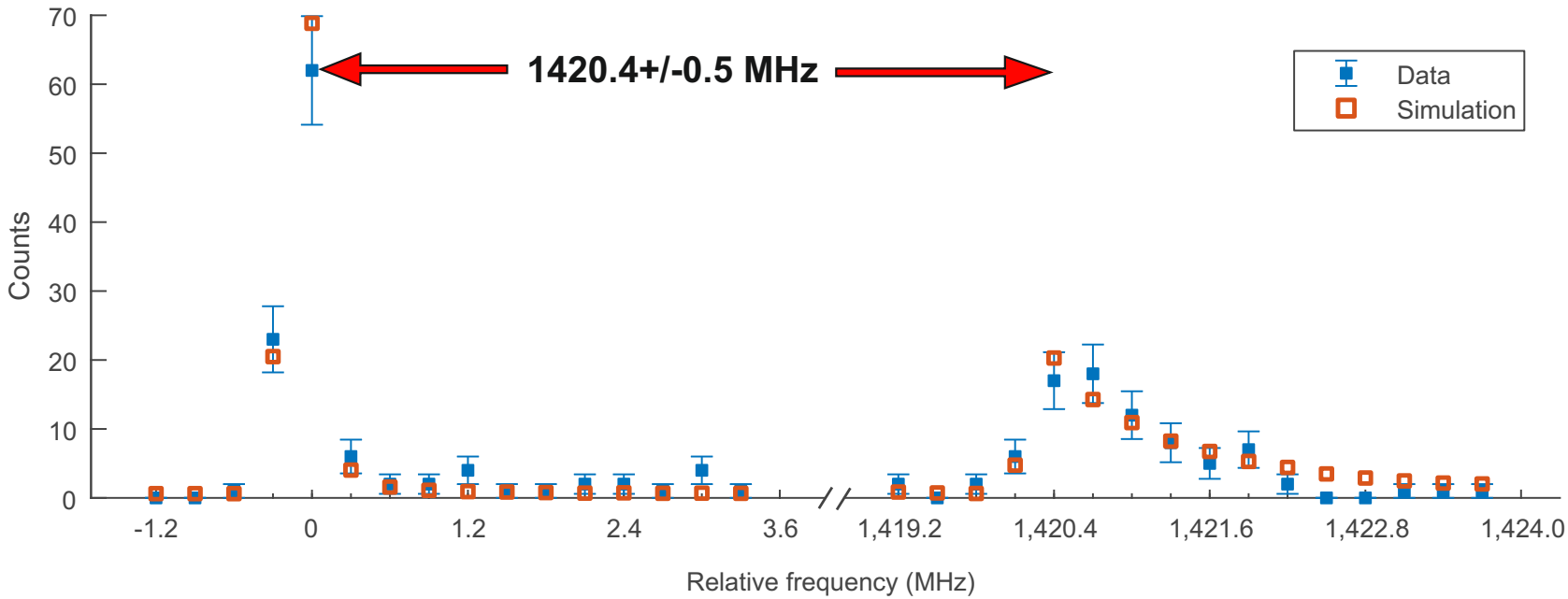
Errors:

- Magnetic field drifts - 0.3 MHz
- Adding of data - 0.3 MHz
- Determination of onset - 0.3 MHz

Results



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Simulation inputs:

- Microwave powers (from ECR heating estimate)
- Run-to-run B-field fluctuations (based on measured magnet currents)
- B-field drift (based on measured magnet currents)
- Absolute B-field (rough fit by eye)

Hyperfine spectrosopy in 2017+

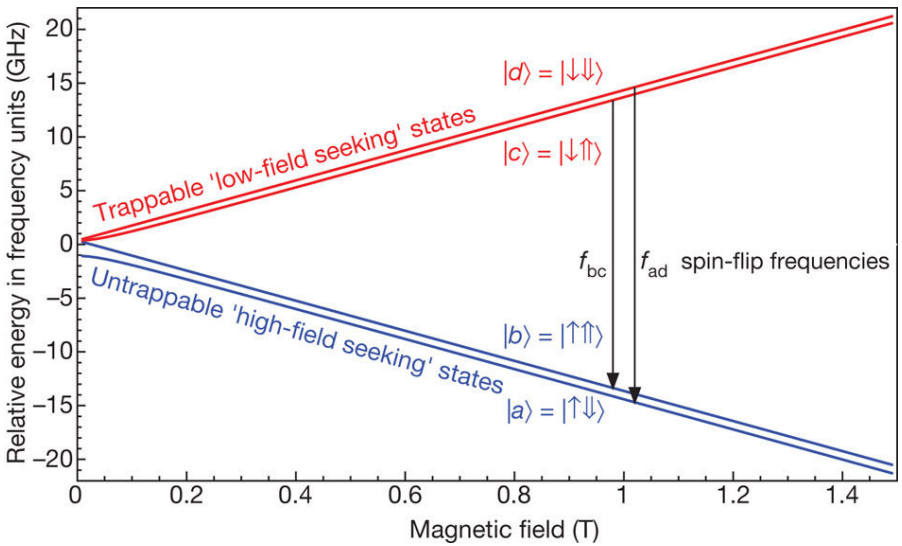
Improvements:

- Improved magnetic field stability and control.
- With current trapping rates we can observe 300+ spin flips in an 8hr shift.
- External impedance matching.

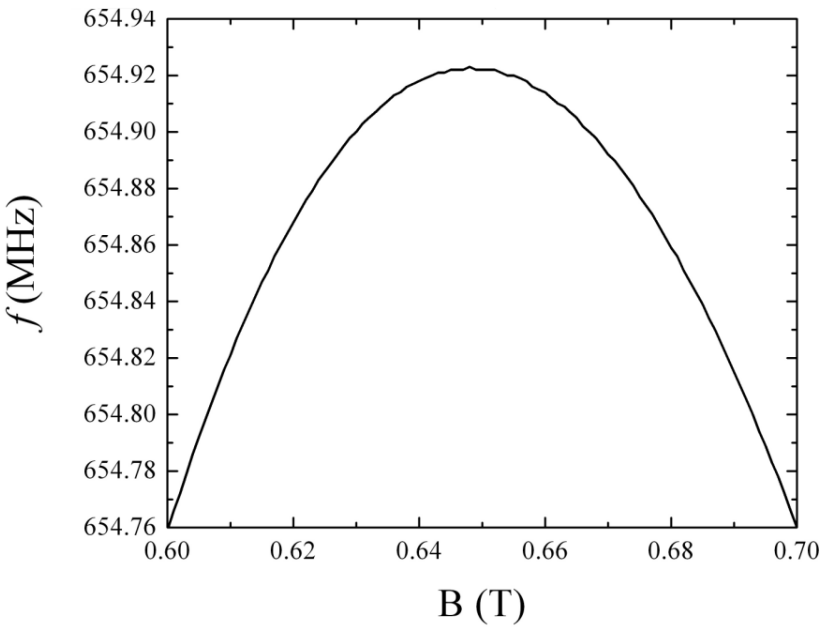
Challenges:

- Magnetic field stability.
- Unknown mode structure in Penning trap.

Looking ahead



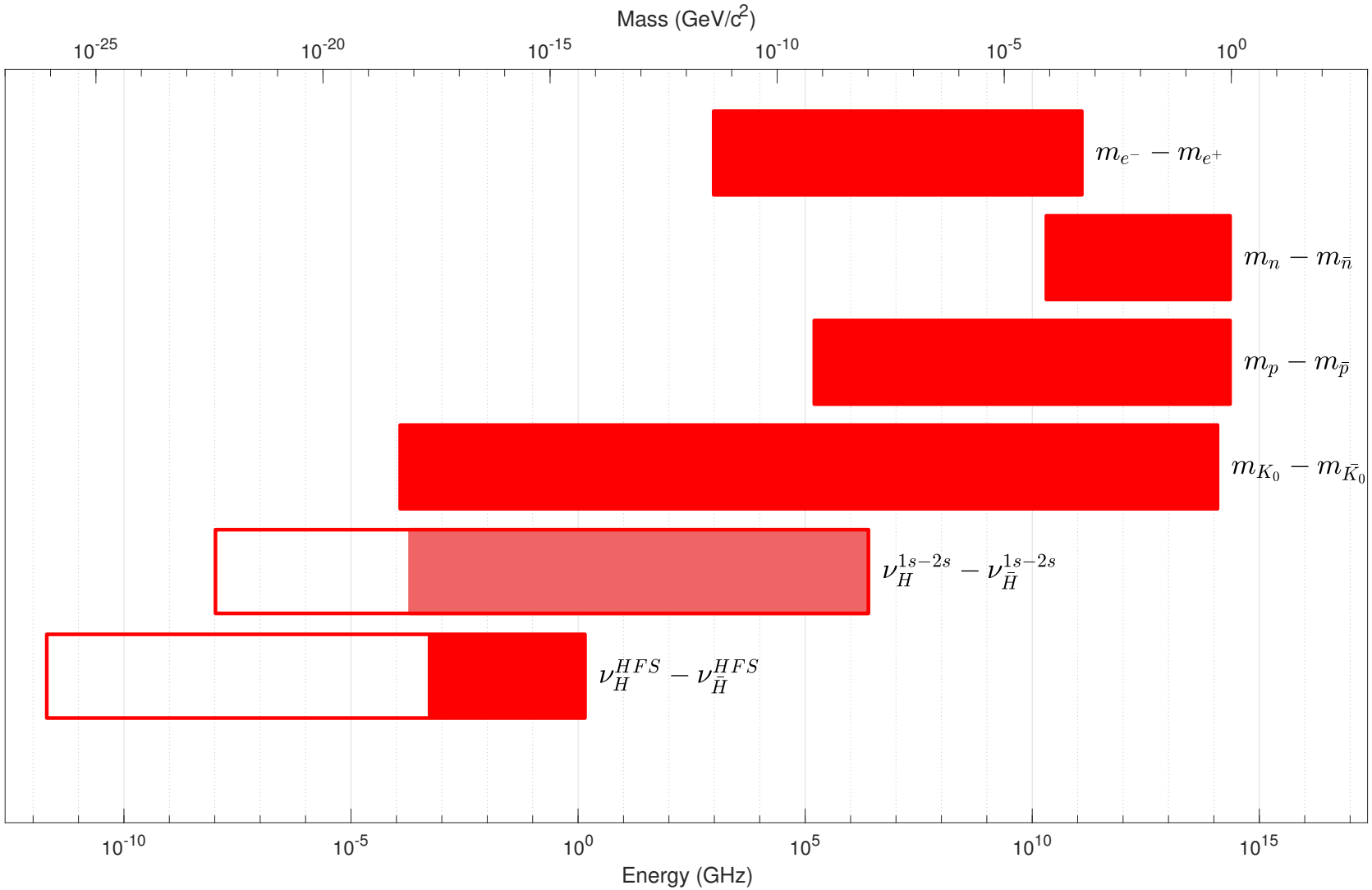
Measure $f_{cd} + (f_{cb}$ or $f_{da})$



[2] W. N. Hardy, A. J. Berlinsky, L. A. Whitehead. Magnetic Resonance Studies of Gaseous Atomic Hydrogen at Low Temperatures. PRL 42, 1042, 1979.

Appendix

Hyperfine spectroscopy CPT test



Trapping antihydrogen: Antiprotons

Antiprotons:

- Antiprotons from CERN's Antiproton Decelerator (AD) are captured in the catching trap at 3 T.

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- Sympathetically cooled by preloaded electrons.
- Compressed with the rotating wall technique.
- Electrons removed and pbars are sent to the atom trap.
- Another round of electron cooling, compression, and electron ejection leaves a pbar cloud with:

$$N = 60 \times 10^4,\ r = 1\ \text{mm},\ T = 100\ \text{K}$$

Trapping antihydrogen: Positrons

Positrons:

- ^{22}Na source feeds a Surko-type buffer-gas accumulator.

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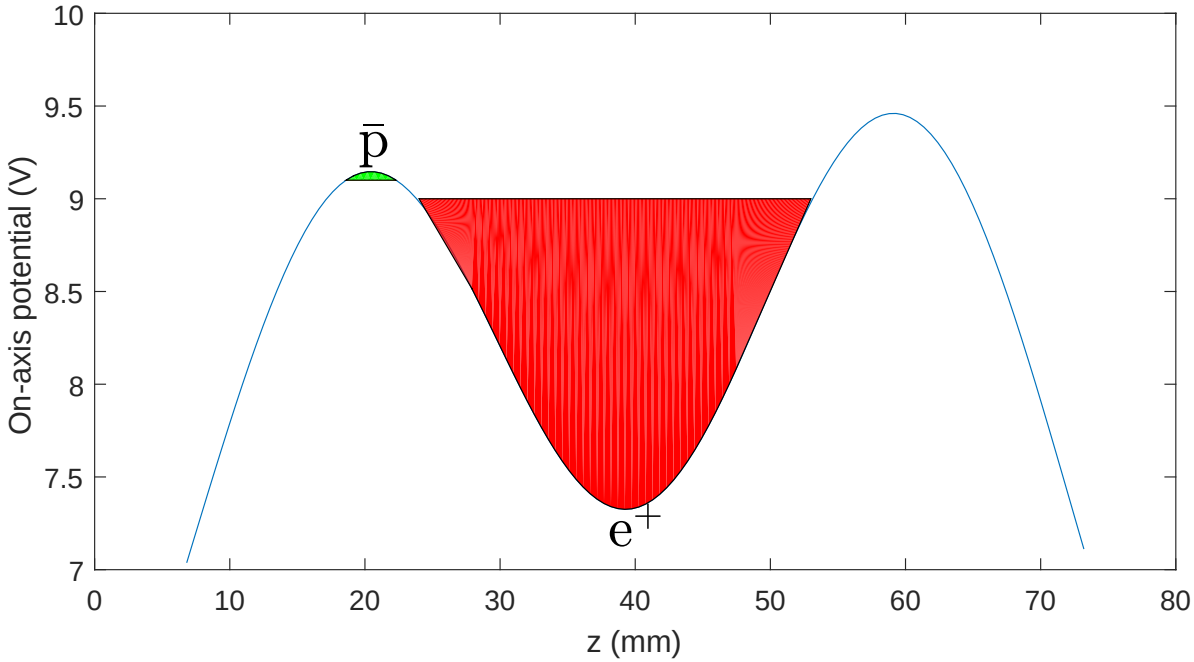
- ^{22}Na source feeds a Surko-type buffer-gas accumulator.
- e^+ are then transfered to the atom trap.
- Thermalize in a short deep well before being transferred to a longer shallow well before mixing.

$$N = 3 \times 10^6,\ r = 0.5\ \text{mm},\ T = 30\ \text{K}$$

Trapping antihydrogen: Mixing



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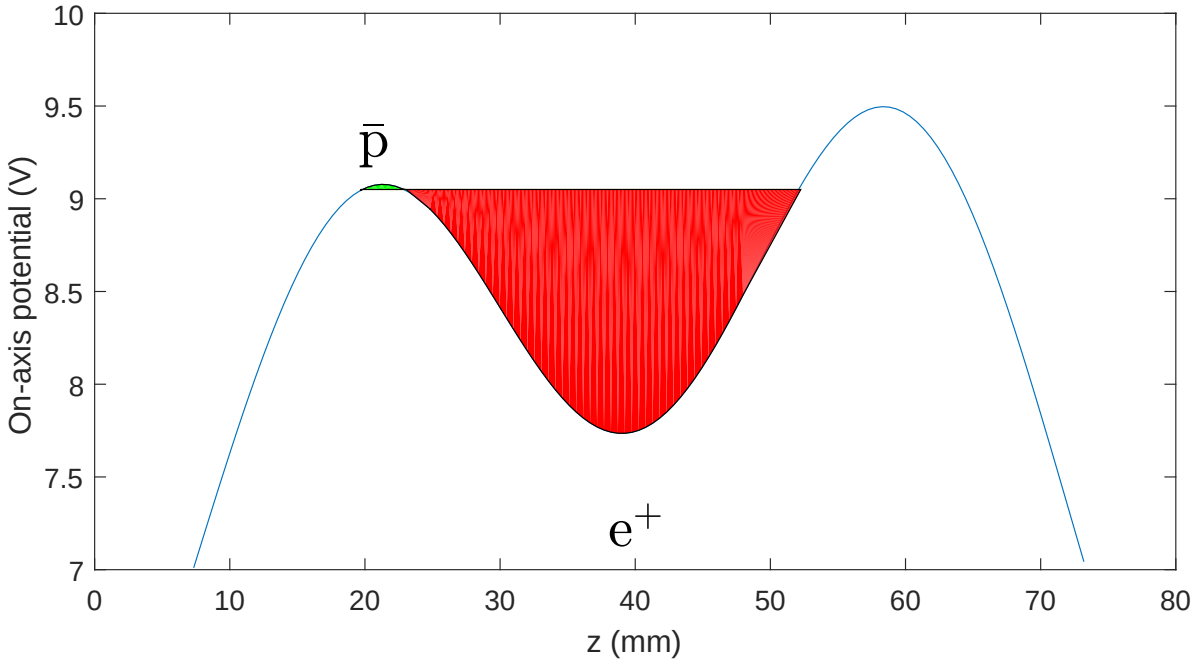

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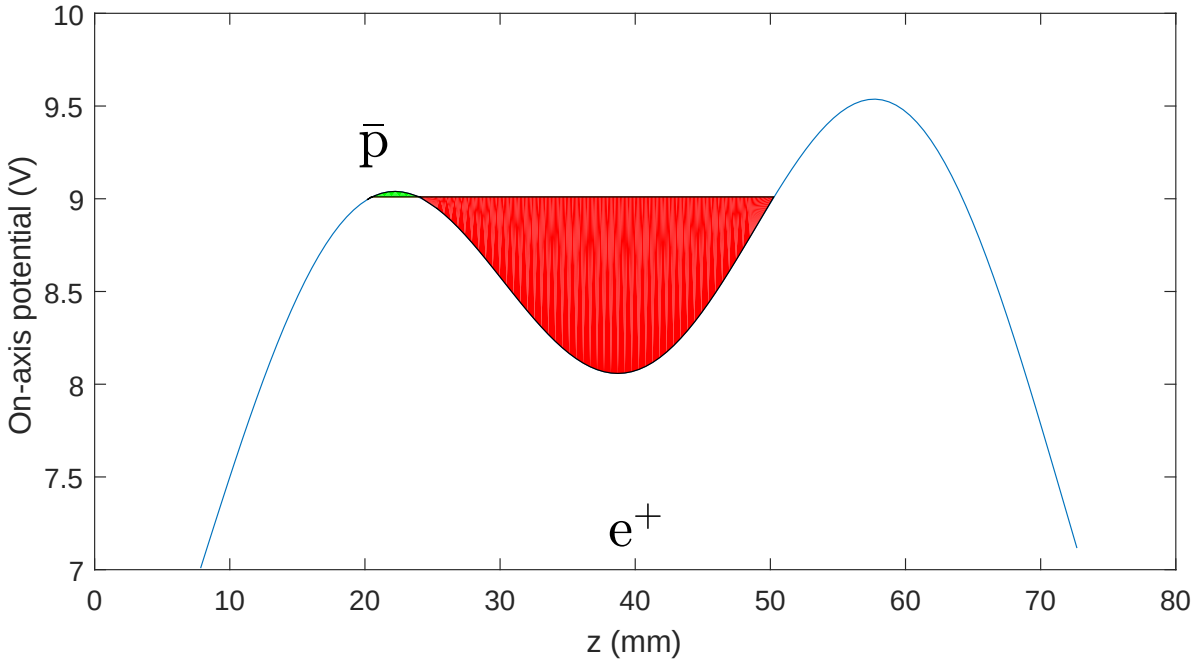

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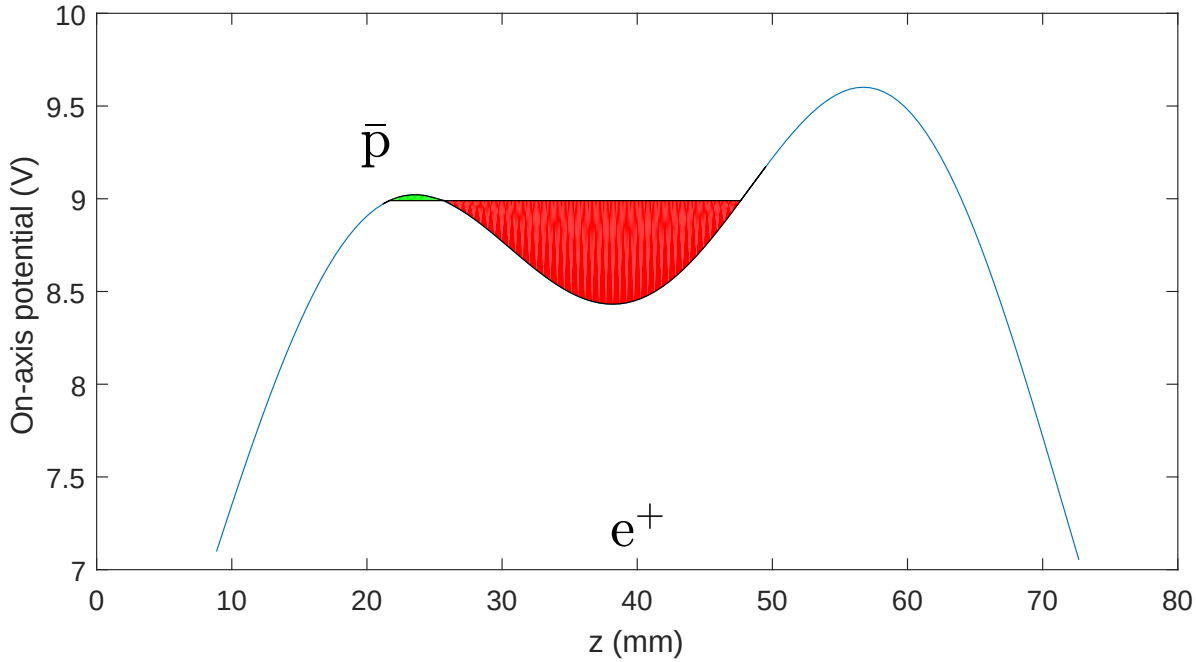

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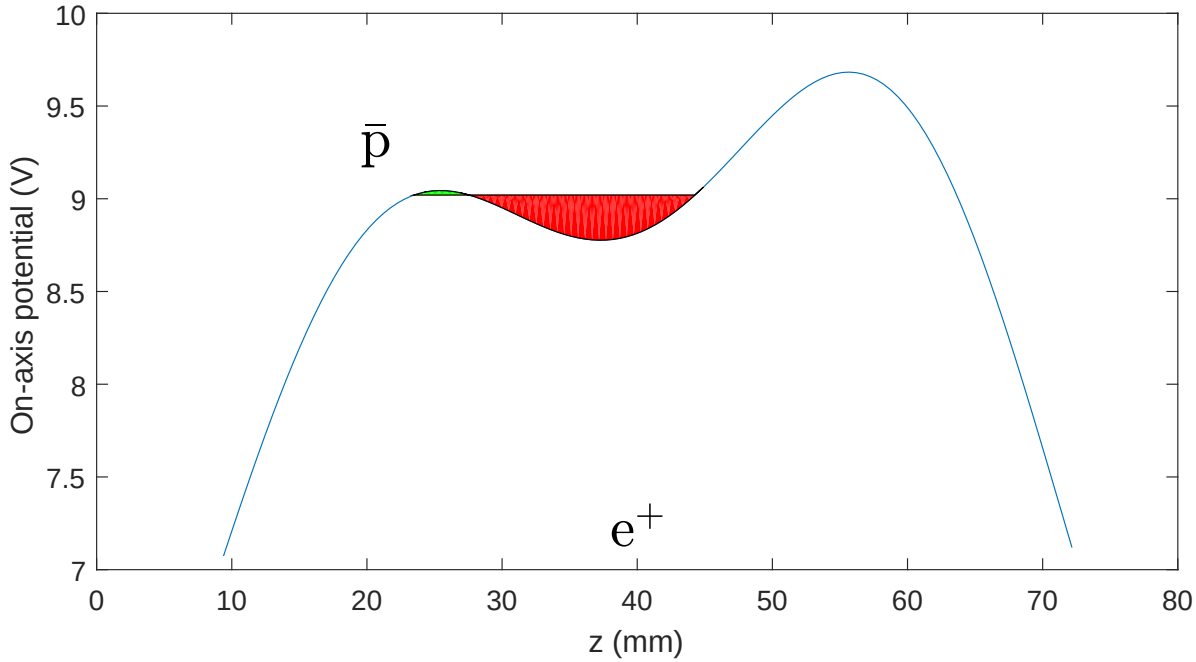

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Trapped $\bar{\mathrm{H}}$ can be accumulated with consecutive mixing cylces

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Trapping Antihydrogen

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The challenge

Atom trap depth: **45 μeV ($\sim$0.5 K)**

vs

$\bar{p}$ energy after injection:	$\sim$ **5 keV**
$\bar{p}$ after electron cooling:	$\sim$ **100 K**
Electrode potentials:	$>$ **10 V**
e^+ space charge:	$>$ **1 V**

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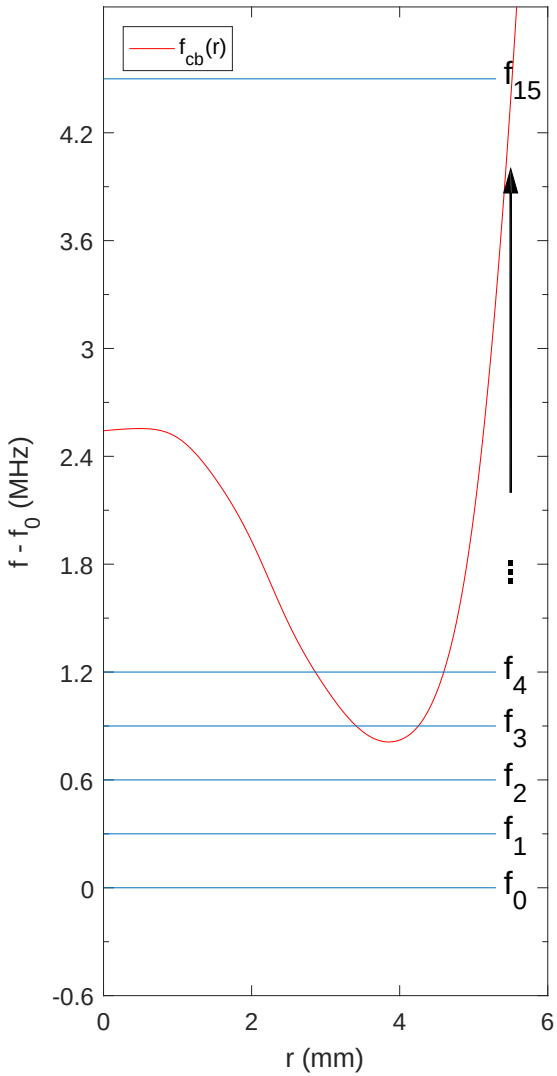

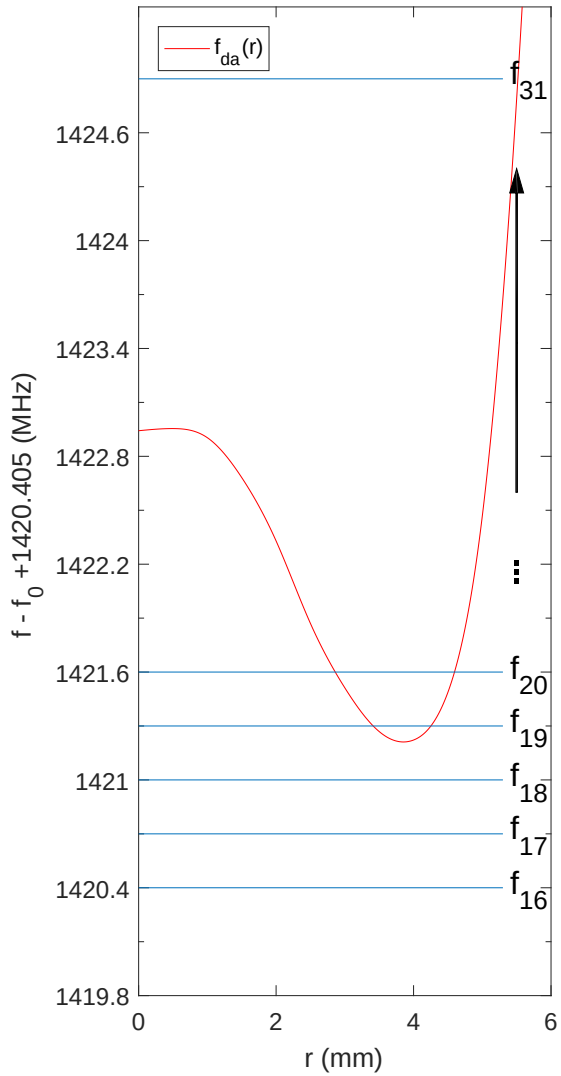

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