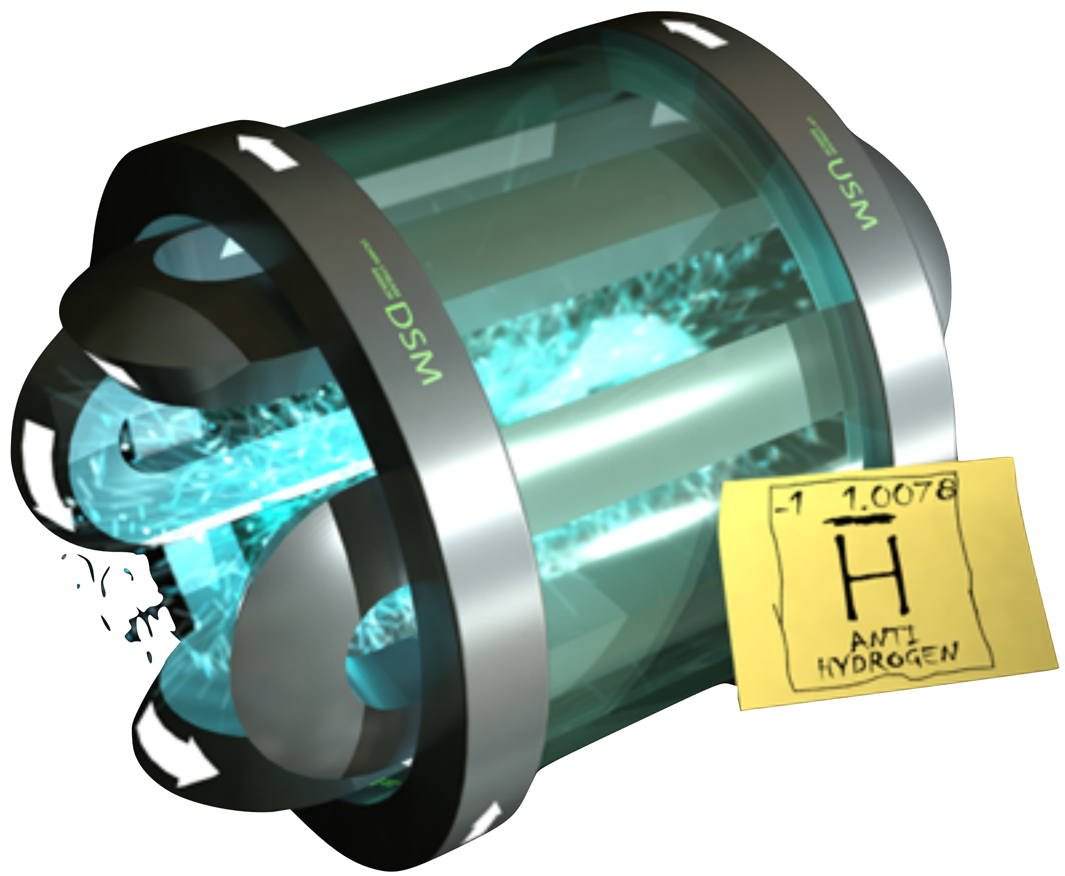
Observation of the 1S-2S Transition in Antihydrogen



Dirk van der Werf
Swansea University
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ALPHA

What do we want to do

Check CPT conservation

Baryon asymmetry

Standard model extension (SME):

Assume some violation, i.e. Lorentz symmetry is broken in a particular way, then in a number of cases there will be a difference between the some of the properties between matter and antimatter (see e.g. V.A. Kostelecký and S. Samuel, Phys. Rev. D 39 (1989) 683)

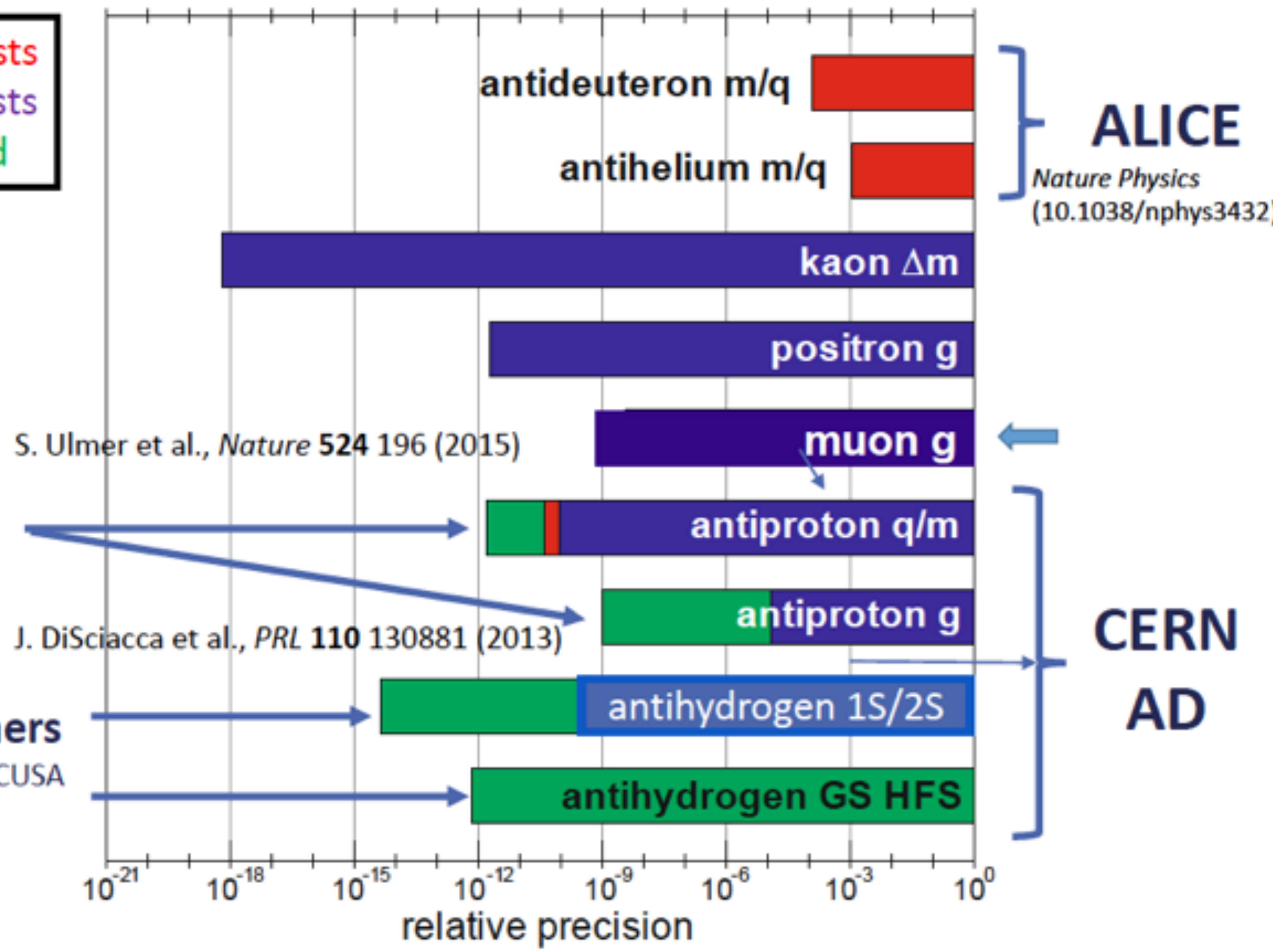
Goals

CPT theorem -> particles and antiparticles must have equal energy levels of bound states

- Compare the spectra of H and $\overline{\text{H}}$, testing CPT.
  - Records for Hydrogen
    - 1S-2S transition known to 4.2 parts in 10^{15}.
      C.G. Parthey *et al.* Phys. Rev. Lett. **107**, 203001 (2011)
    - Ground state hyperfine transition known to 1.4 parts in 10^{12}.
      H. Hellwig *et al*. Instrumentation and Measurement, IEEE Transactions **19**, 200 (1970).

Different CPT tests

Red: Recent tests
Purple: Past tests
Green: Planned



Planned by others
ALPHA / ATRAP / ASACUSA

CPT test with fractional precision of 10^{-18} available... why continue measuring?

Energy Resolution

$$< \psi^* | \Delta V | \psi > = \Delta E$$

$$\mathcal{L}_p = \frac{\lambda}{M} \langle T \rangle \bar{\psi} \Gamma (i\partial)^k \psi$$

Kostelecky et al.

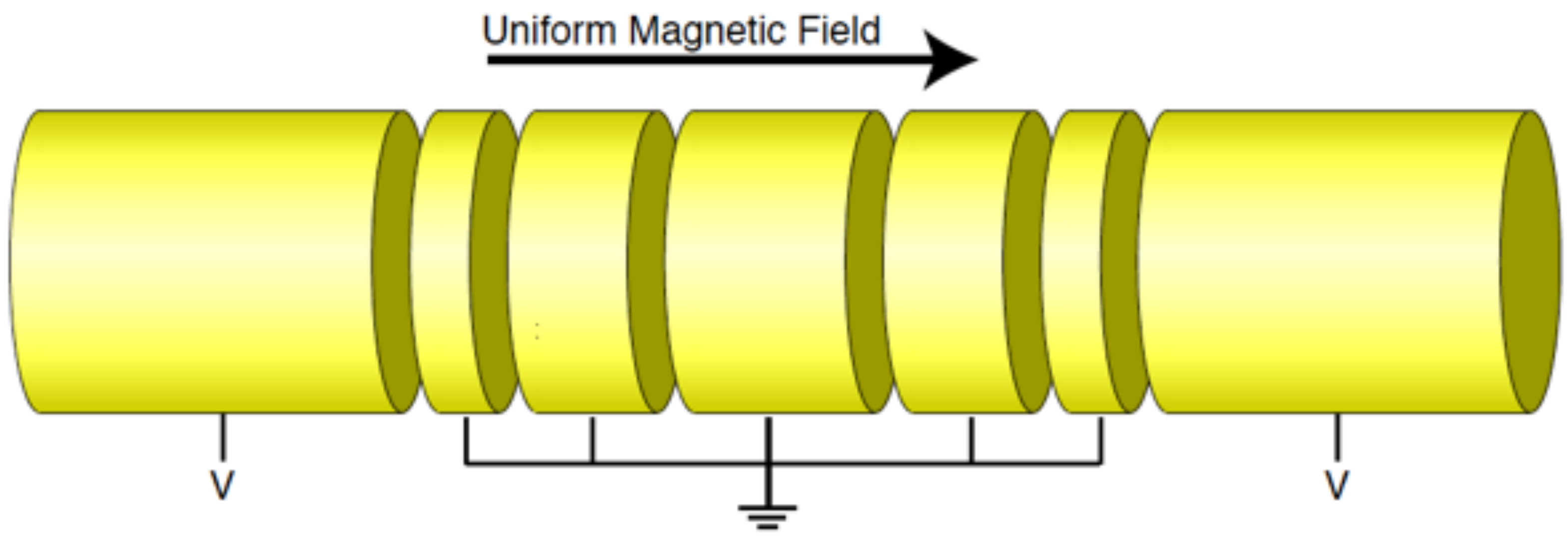
- Absolute energy resolution (normalized to m-scale) might be a more appropriate measure to characterize the sensitivity of an experiment with respect to CPT violation.
- Single particle measurements in Penning traps give high energy resolution.

	Relative precision	Energy resolution	SME Figure of merit
Kaon Δm	$\sim 10^{-18}$	$\sim 10^{-9}$ eV	$\sim 10^{-18}$
p-$\bar{p}$ q/m	$\sim 10^{-11}$	$\sim 10^{-18}$ eV	$\sim 10^{-26}$
p-$\bar{p}$ g-factor	$\sim 10^{-6}$	$\sim 10^{-12}$ eV	$\sim 10^{-21}$

Borrowed from Stefan Ulmer

Penning Trap

Trap for charged particles

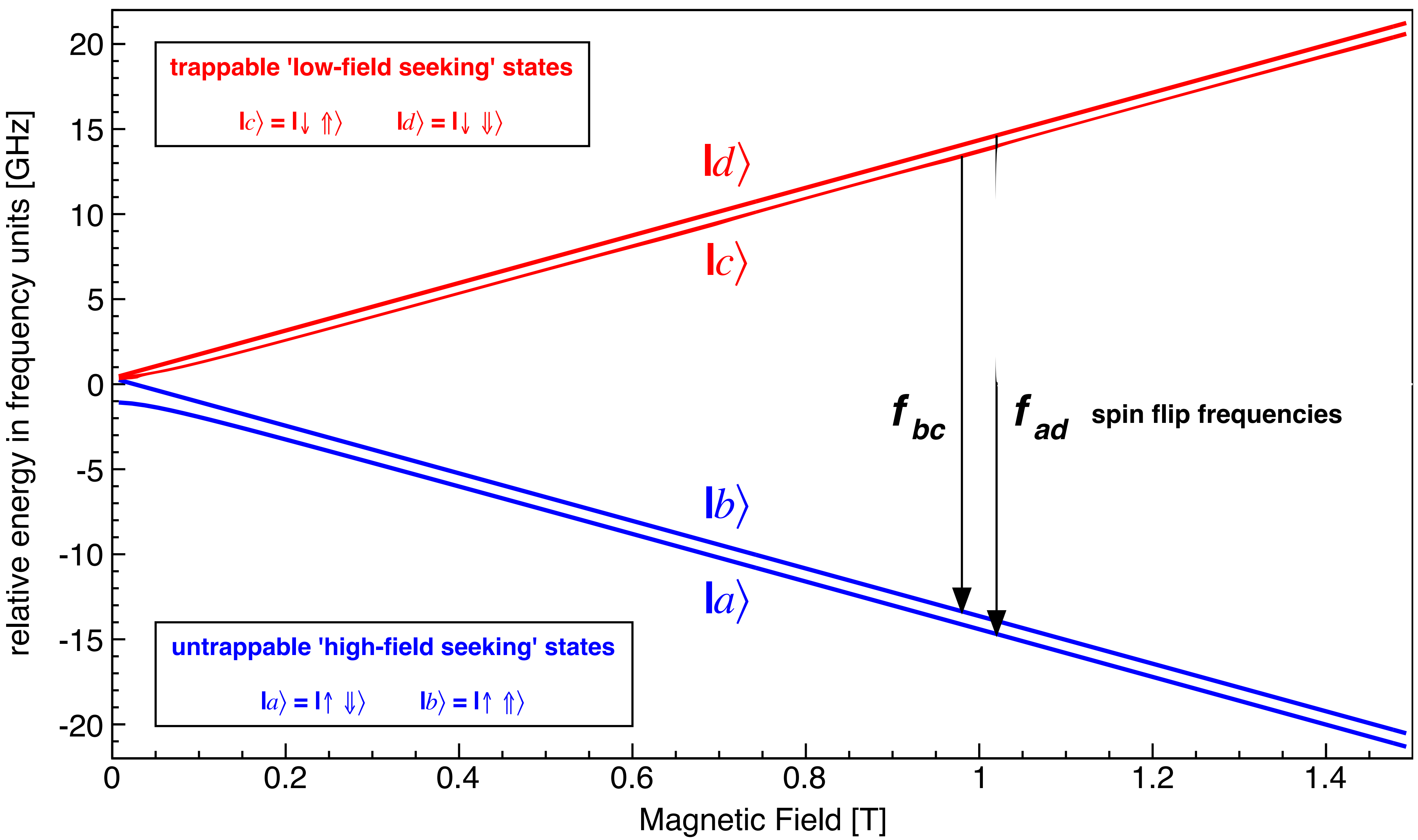


Particle clouds mostly in non-neutral plasma regime, i.e. the Debye Length

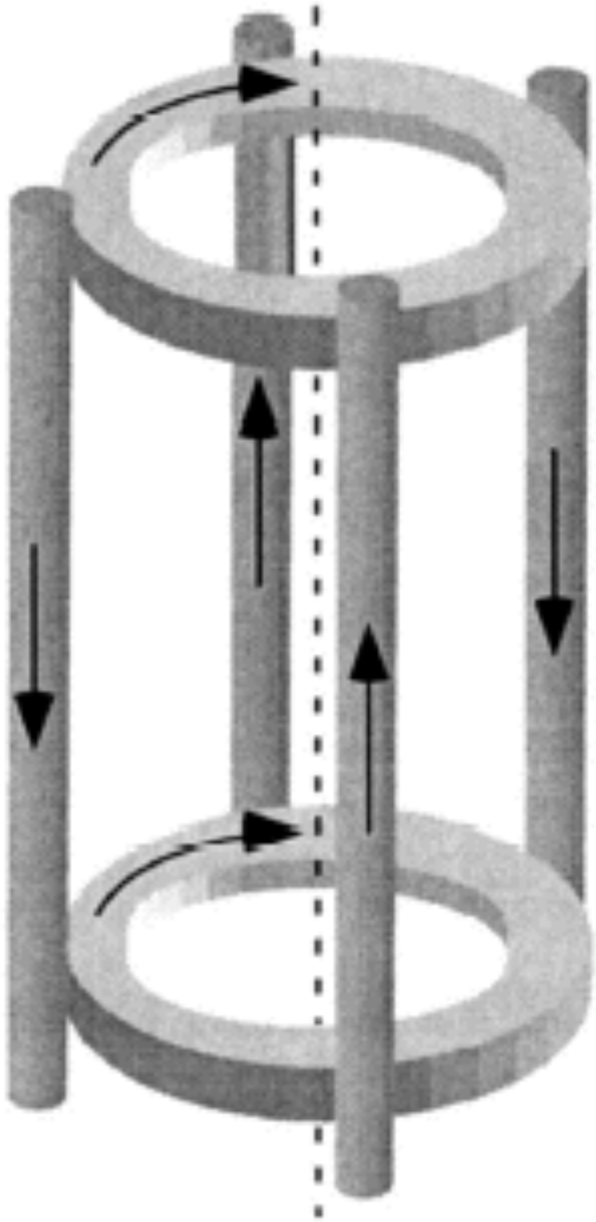
$$\lambda_D = \left(\frac{kT_e\varepsilon_o}{n_e q^2}\right)^{1/2} << \text{cloud size}$$

$\overline{\text{H}}$ Breit-Rabi Diagram

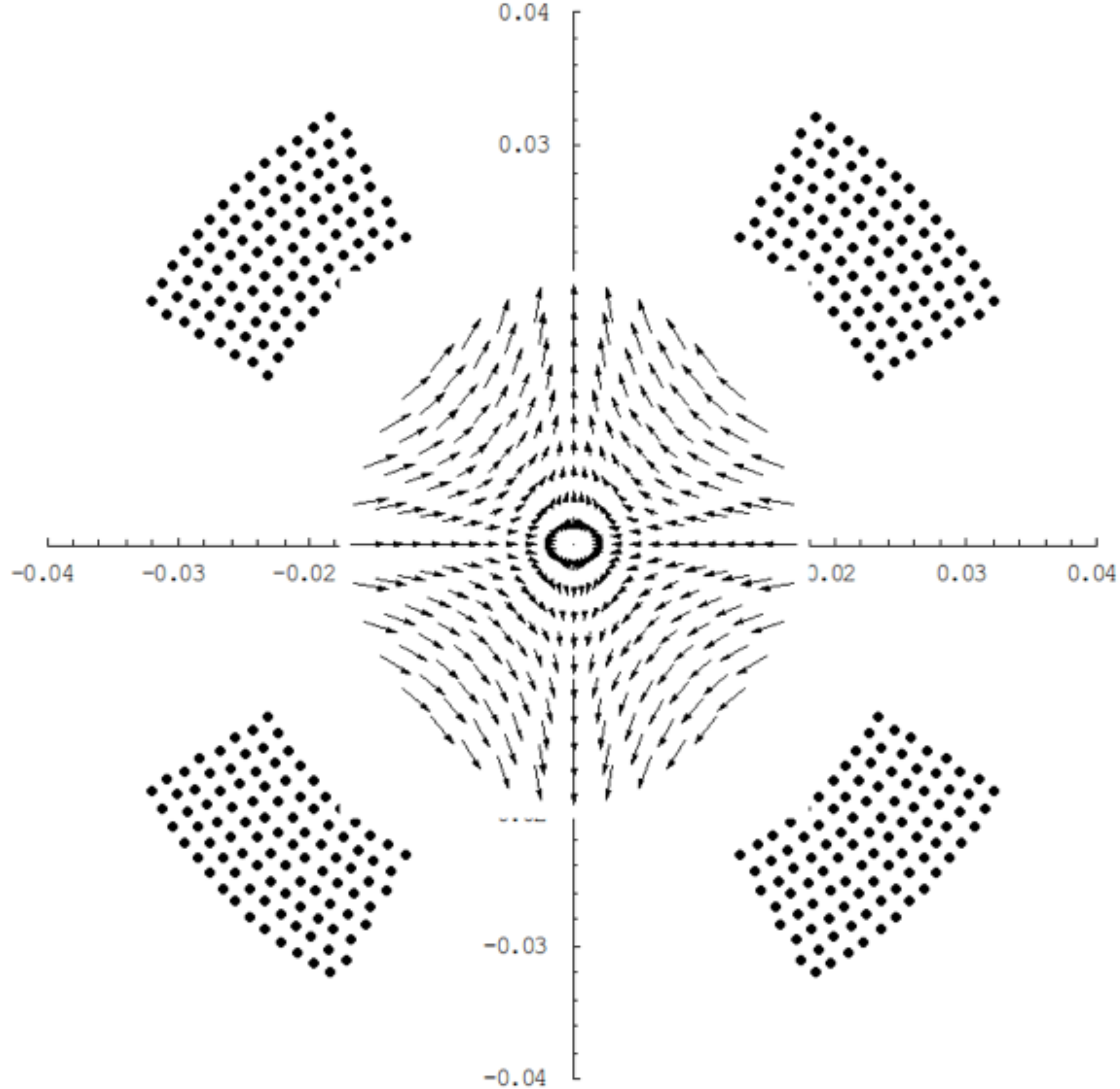
To measure accurately electronic transition a trap for neutral atoms is necessary: use the spin state of the antihydrogen atom



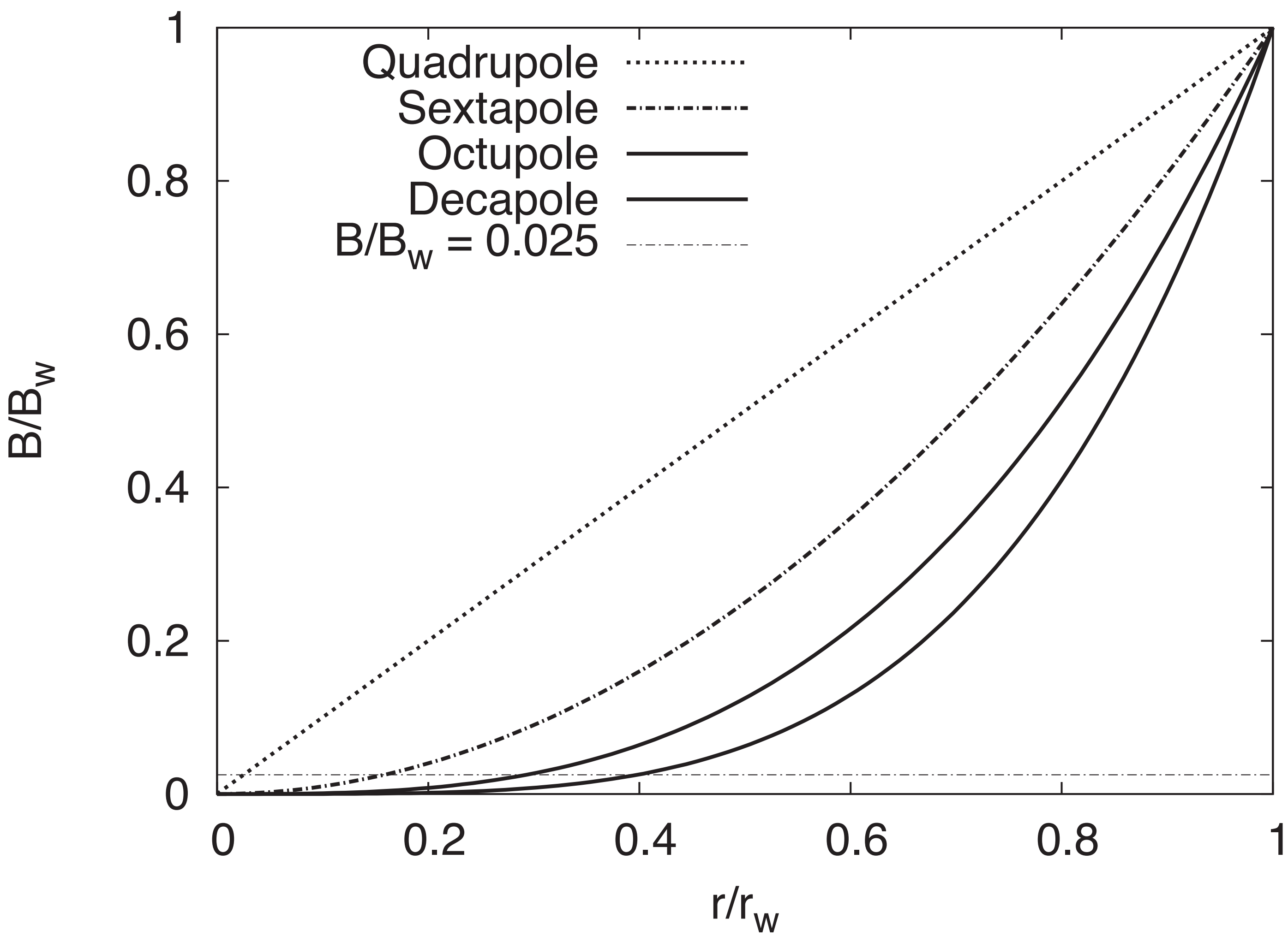
Magnetic trap

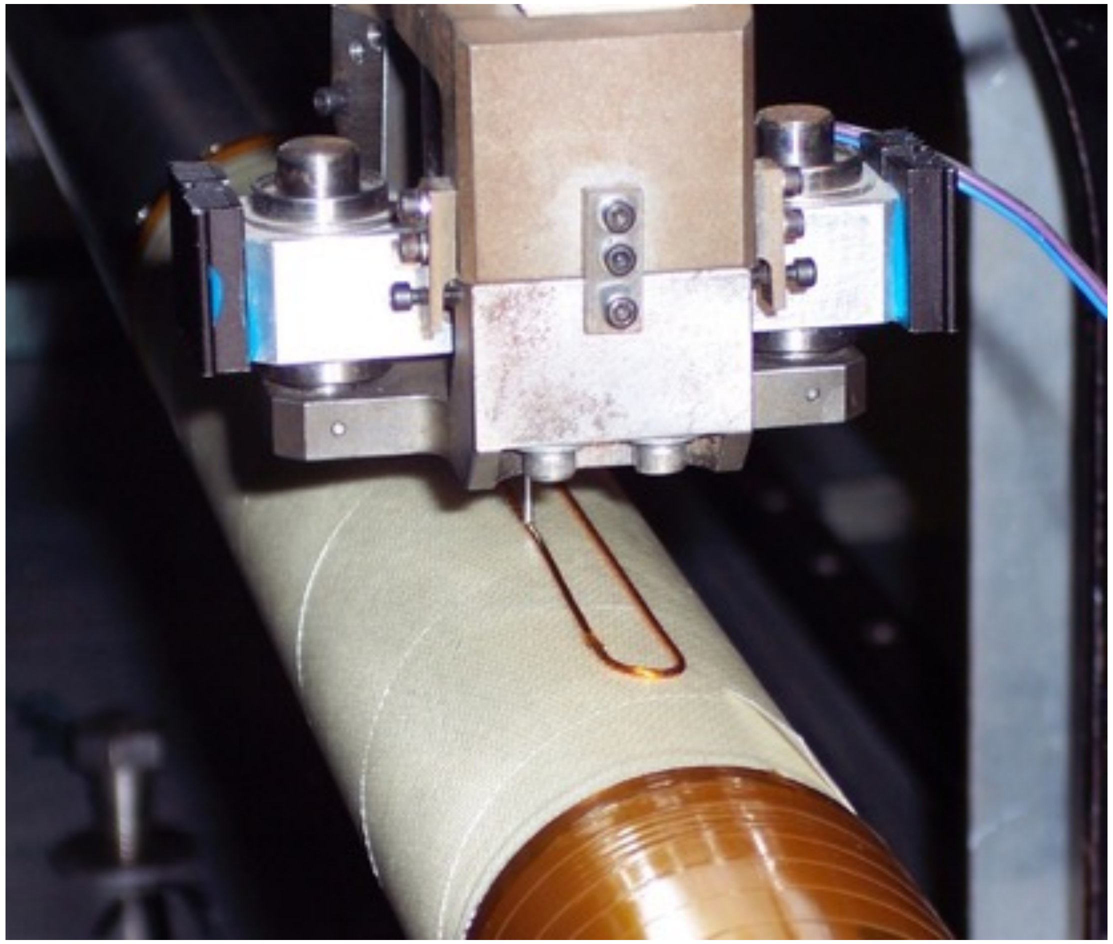


Ioffe-Pritchard trap

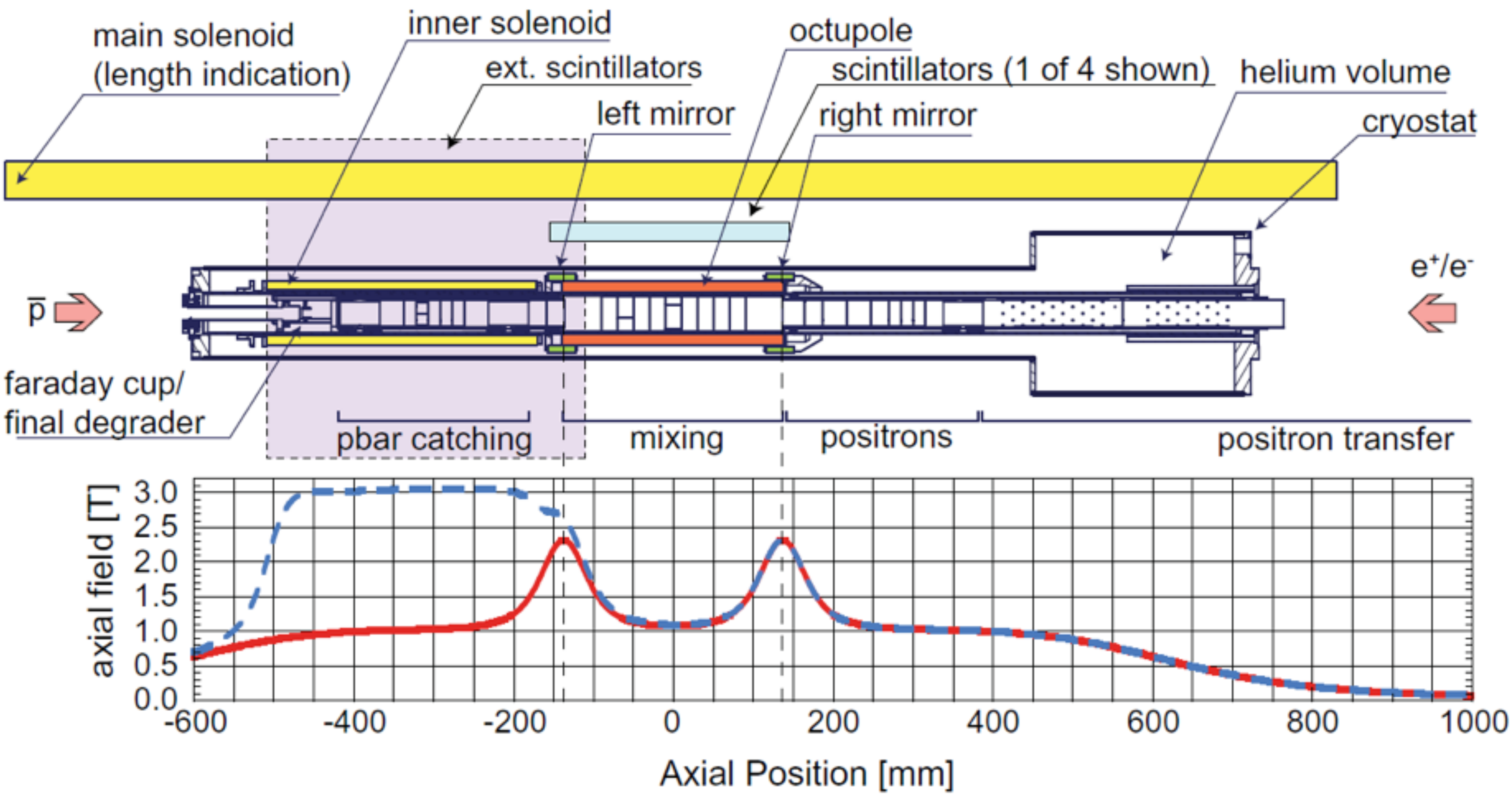


Magnetic trap





Alpha Apparatus



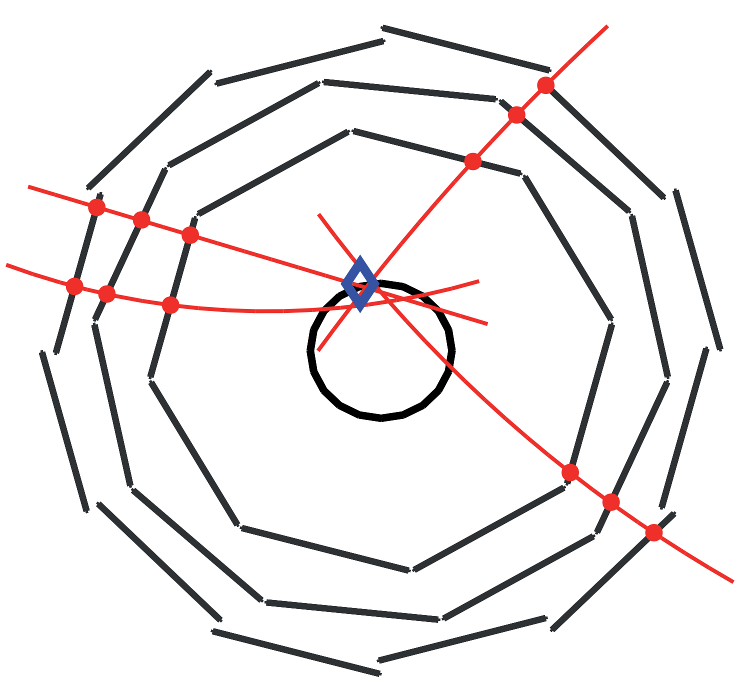
Well depth is ~0.8 T equivalent 0.54 K for ground state (anti)hydrogen

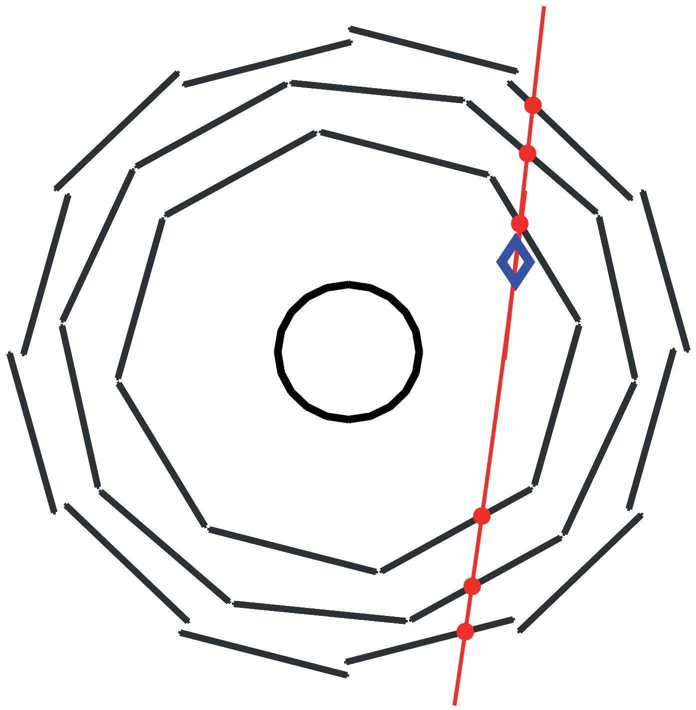
Ramp down/Quench of trap $\tau = 9$ ms

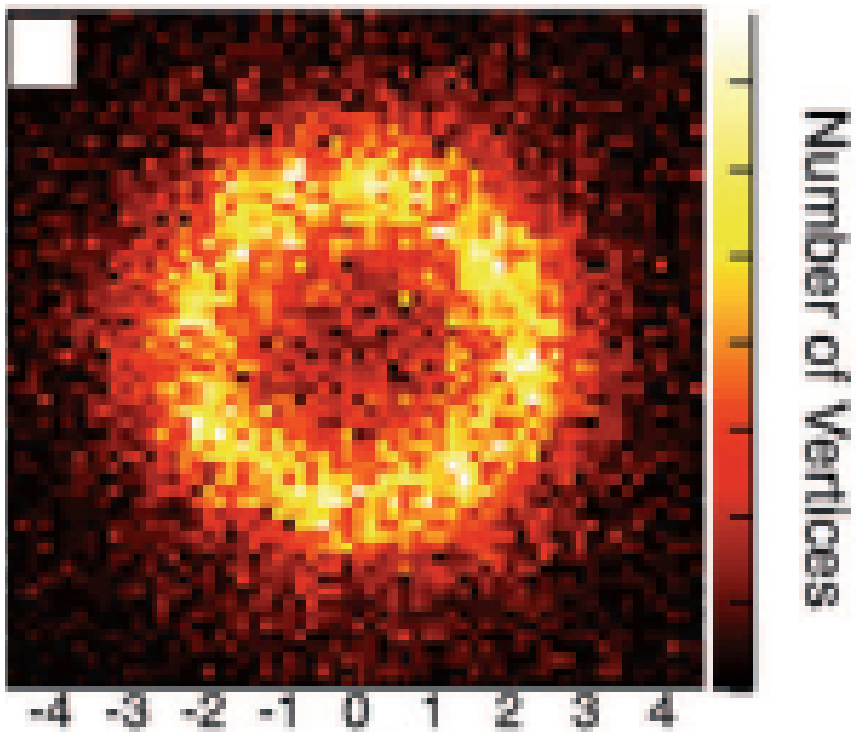
Number of quenches: a couple of thousands

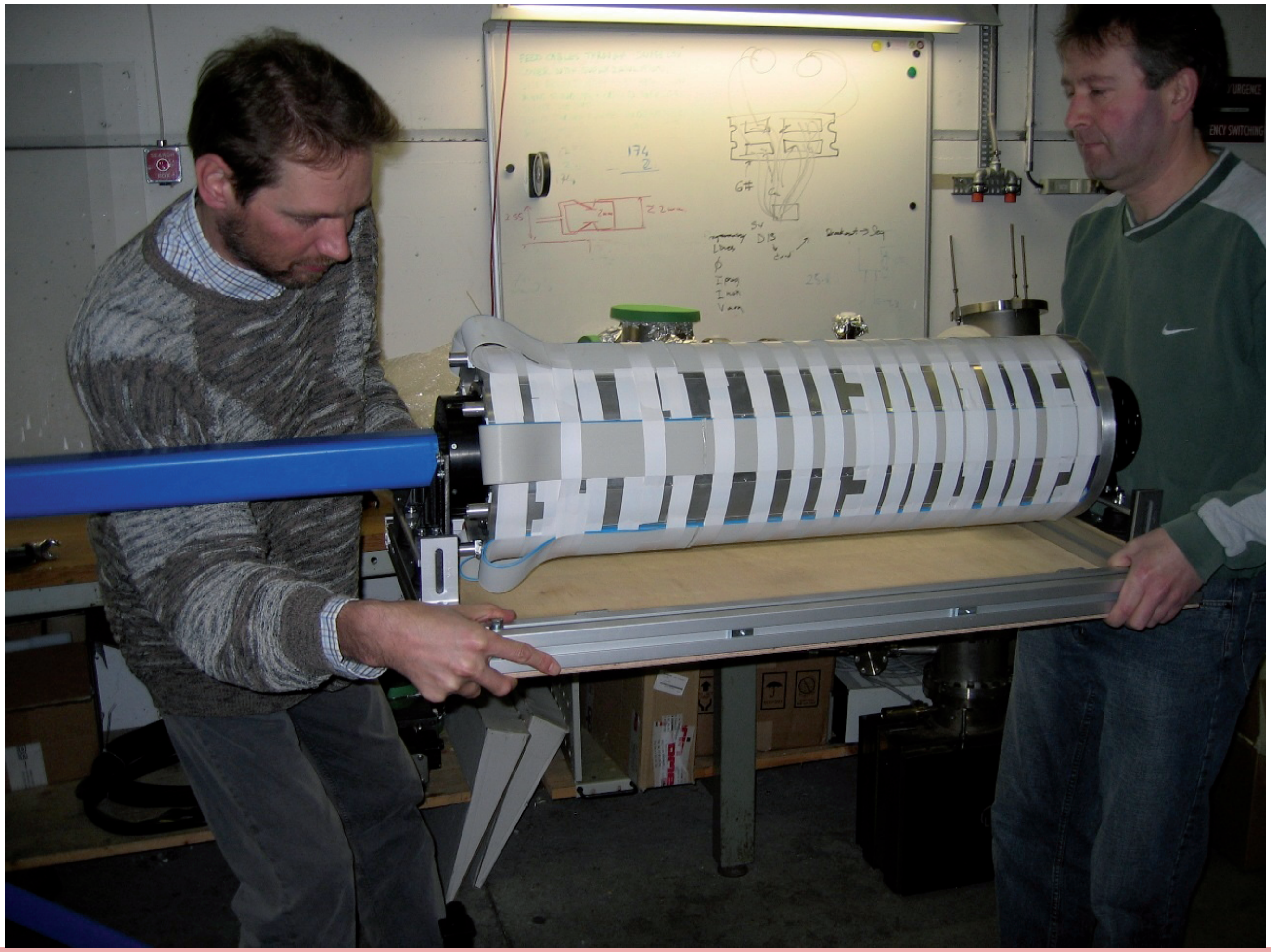
W. Bertsche et al (ALPHA collaboration)
Nucl. Instr. Meth. Phys. Res. A **56**, 746 (2006)

Detector

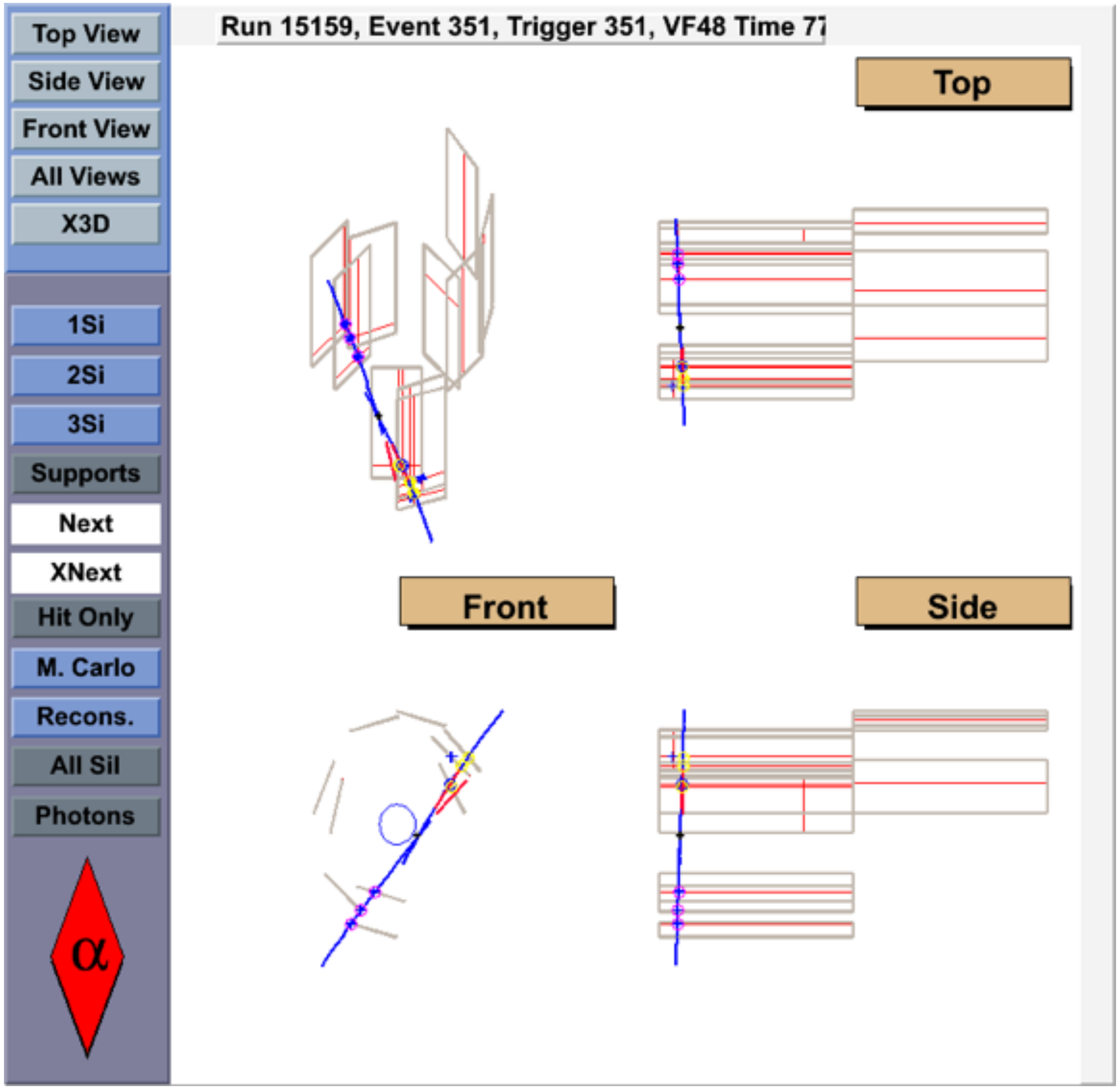




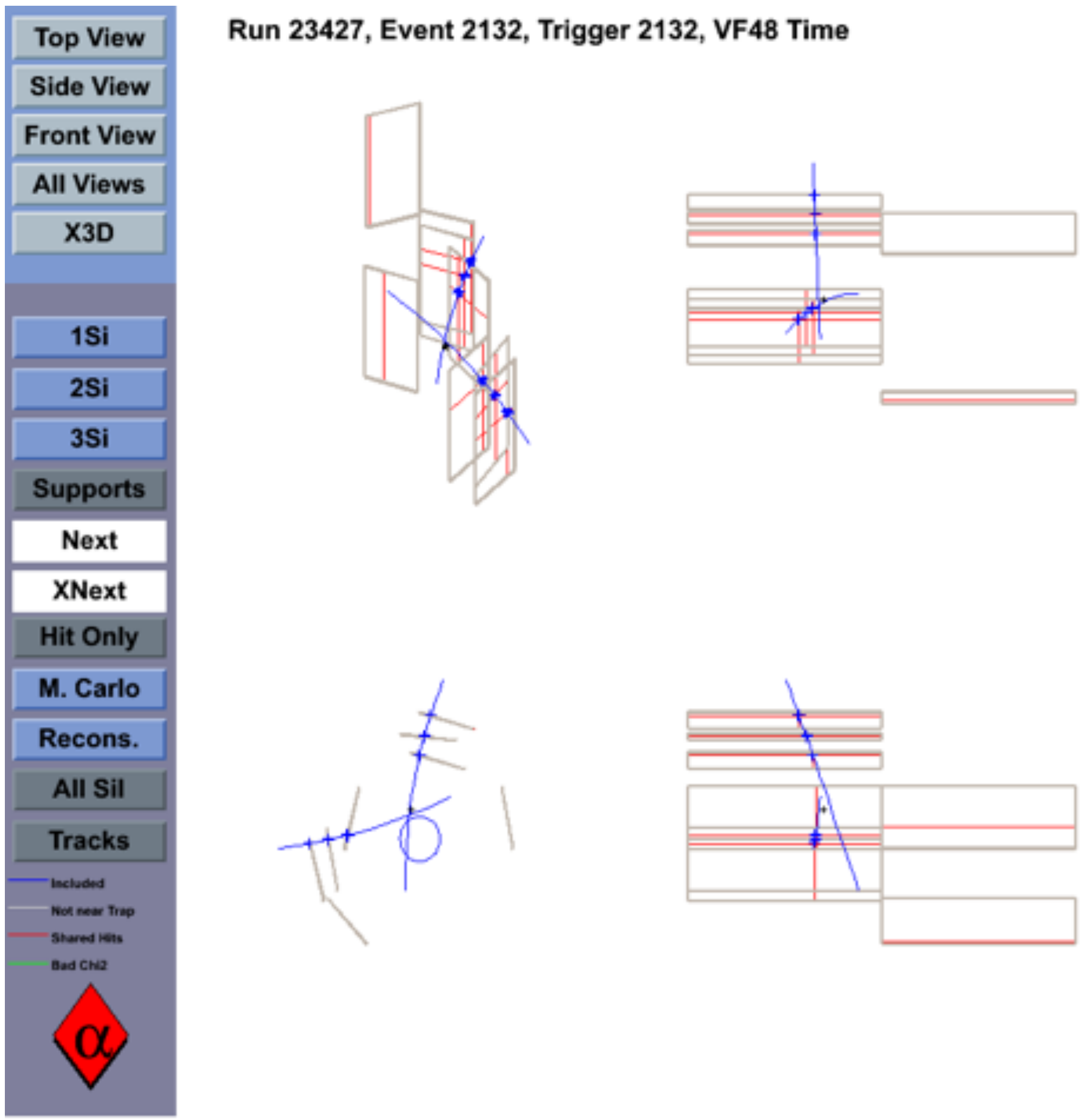


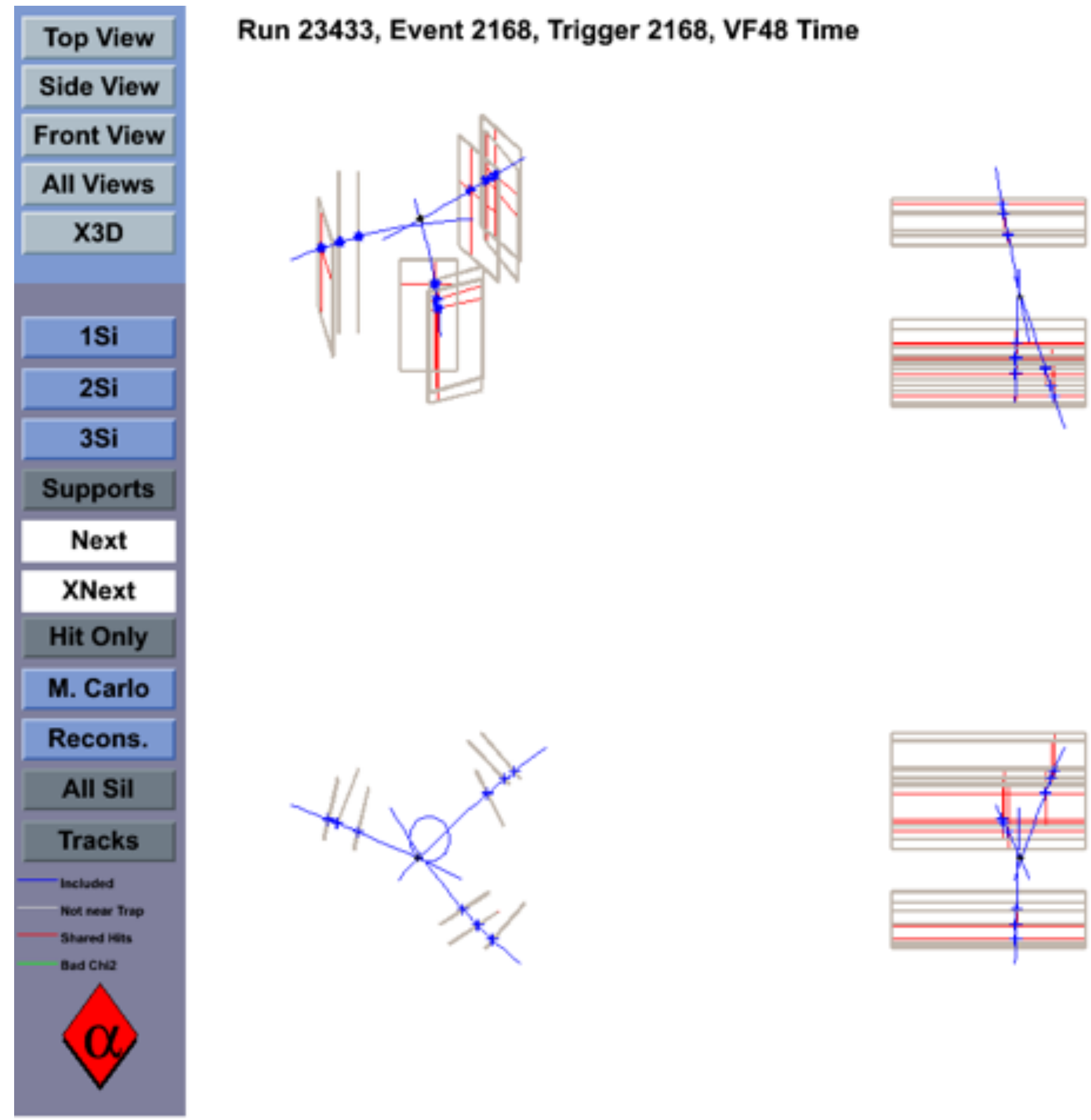


Cosmic event

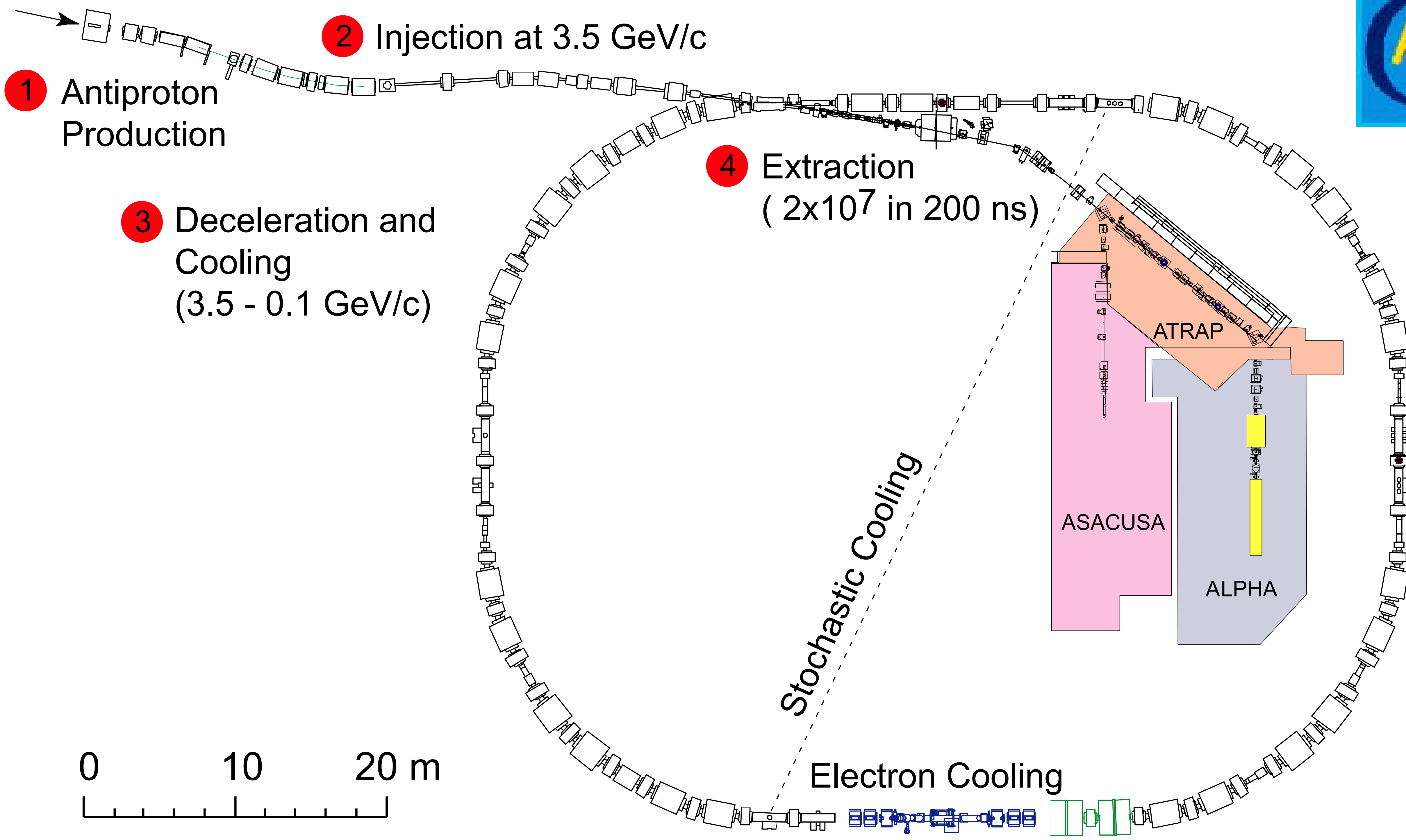


$\bar{p}$ annihilation

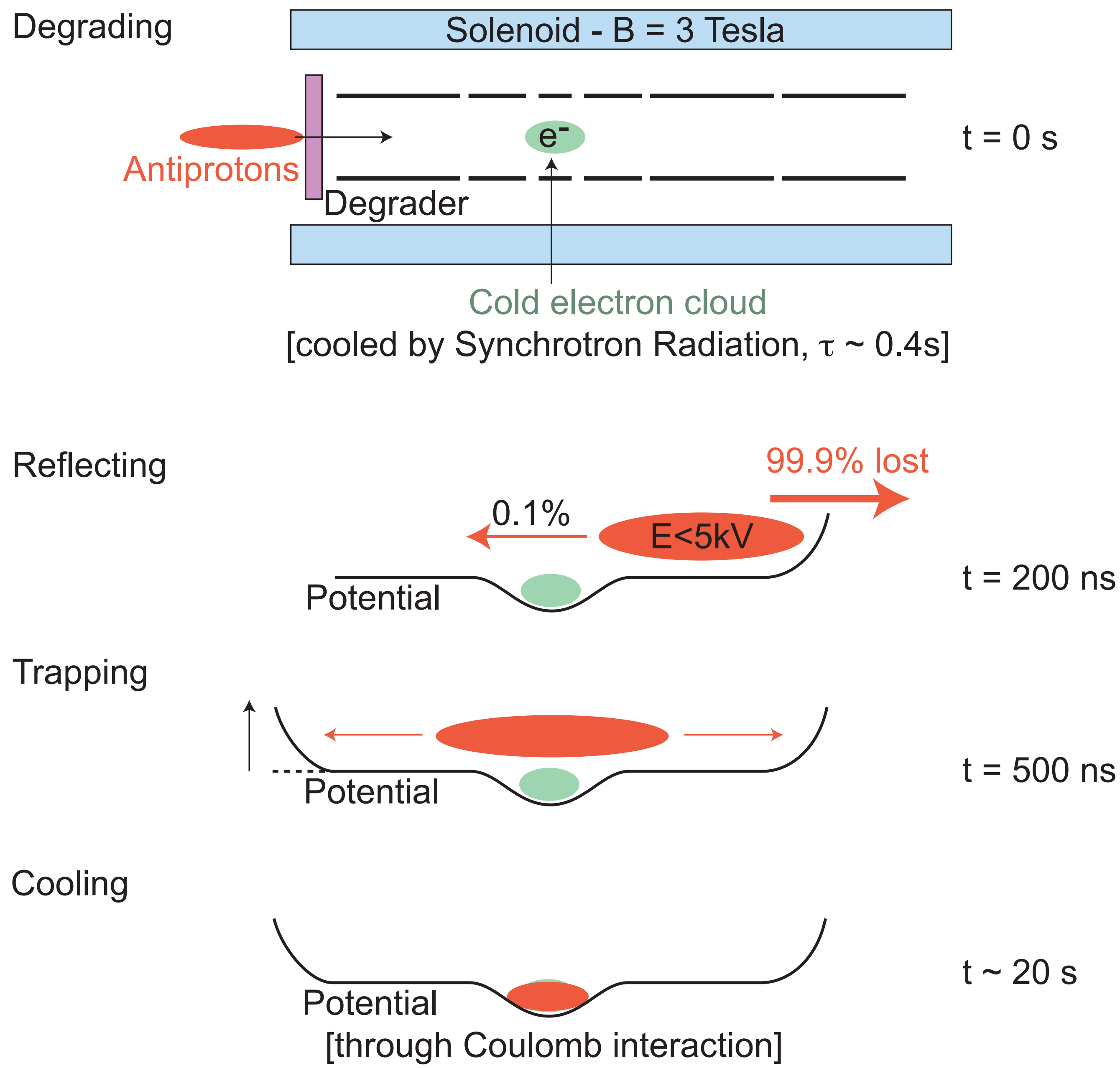




Antiproton Decelerator



$\bar{p}$ trapping



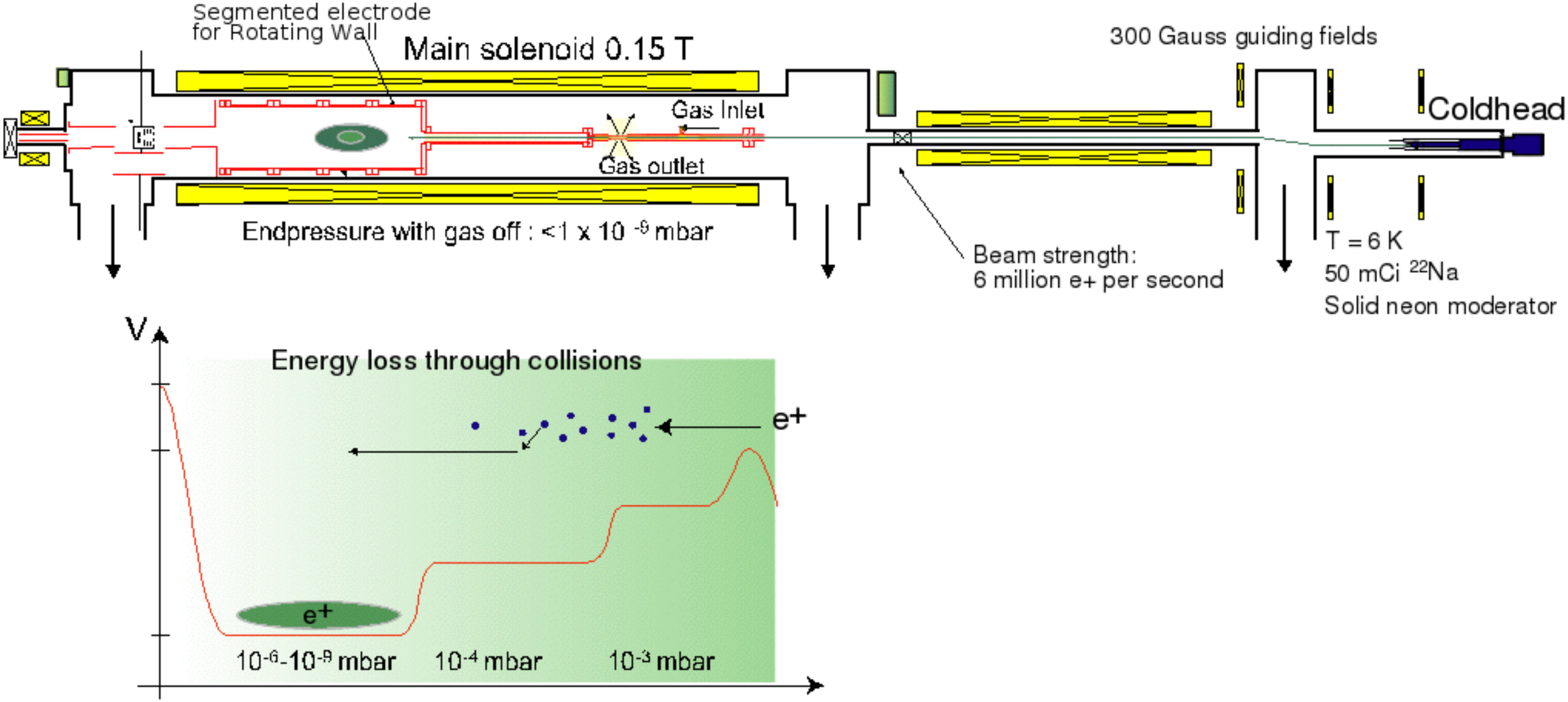
Cooling rate :

$$\Gamma_c = \frac{2q^4B^2}{9\pi\epsilon_0 m^3 c^3}$$

Cooling time at 5 T :

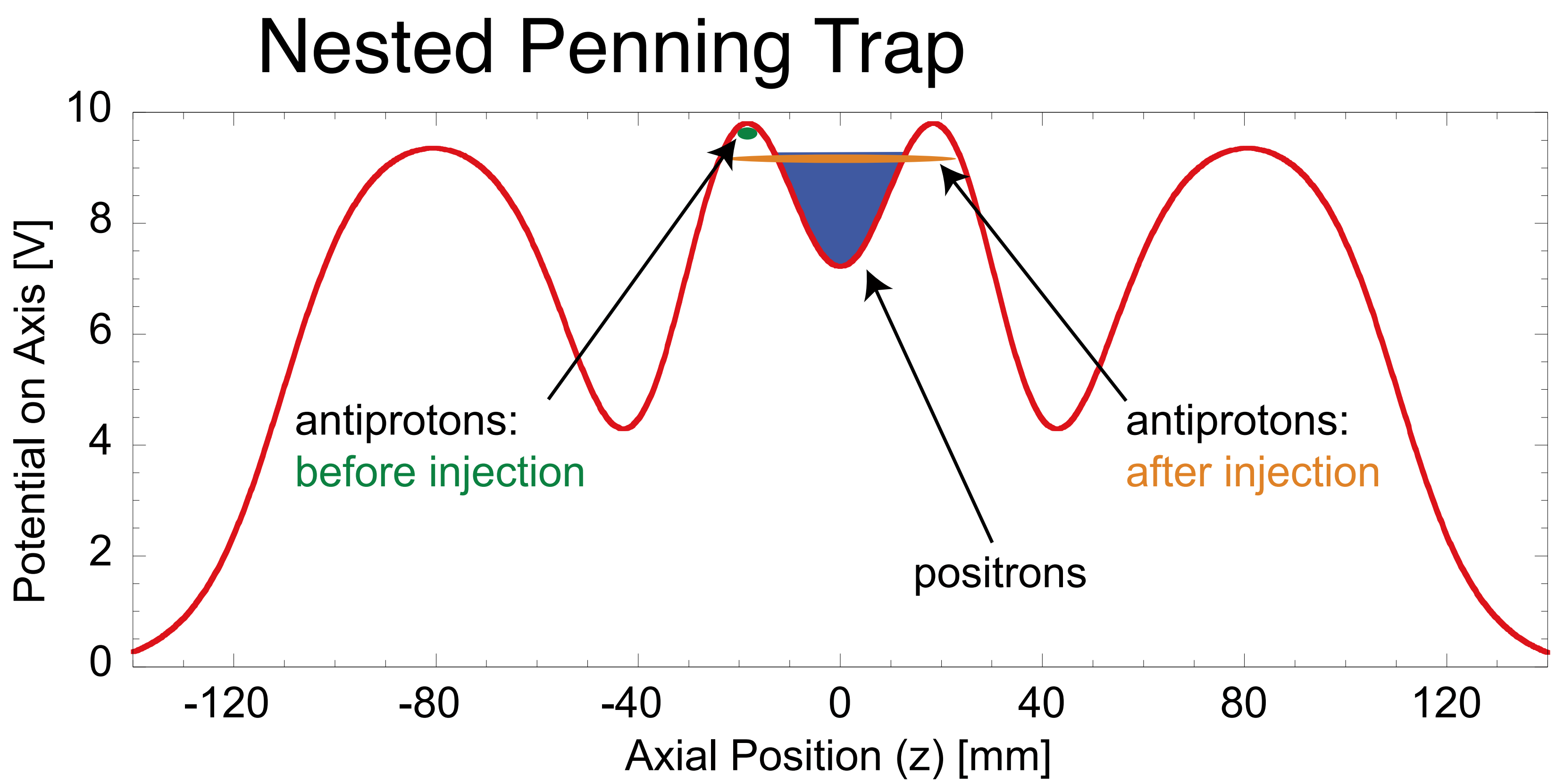
$$\tau_c = 1/\Gamma_c \approx 32 \text{ y for } \bar{p}$$
$$\approx 0.16 \text{ s for } e^+$$

e^+ trapping



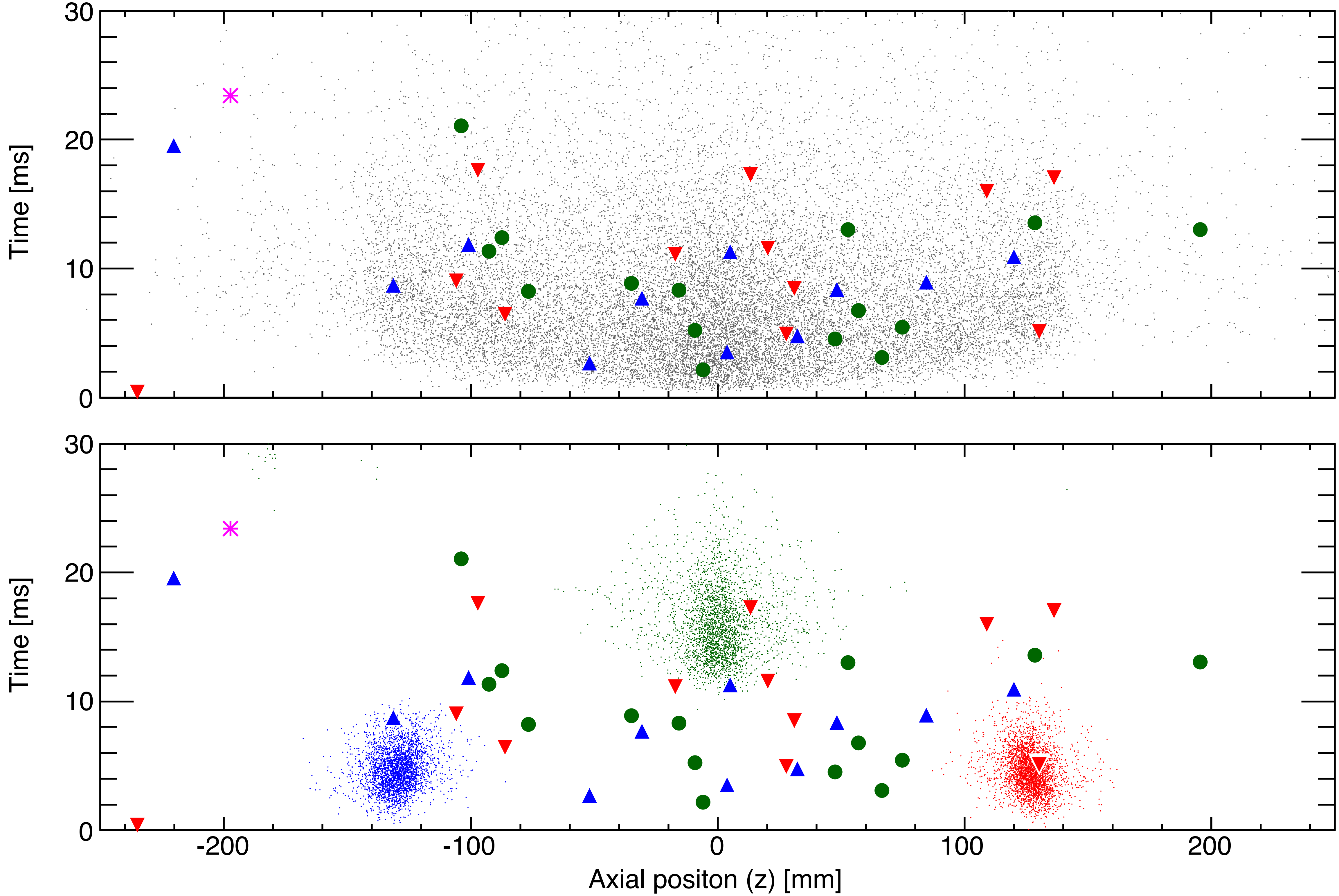
T. J. Murphy and C. M. Surko, *Phys. Rev. A* **46**, 5696 (1992)

Mixing



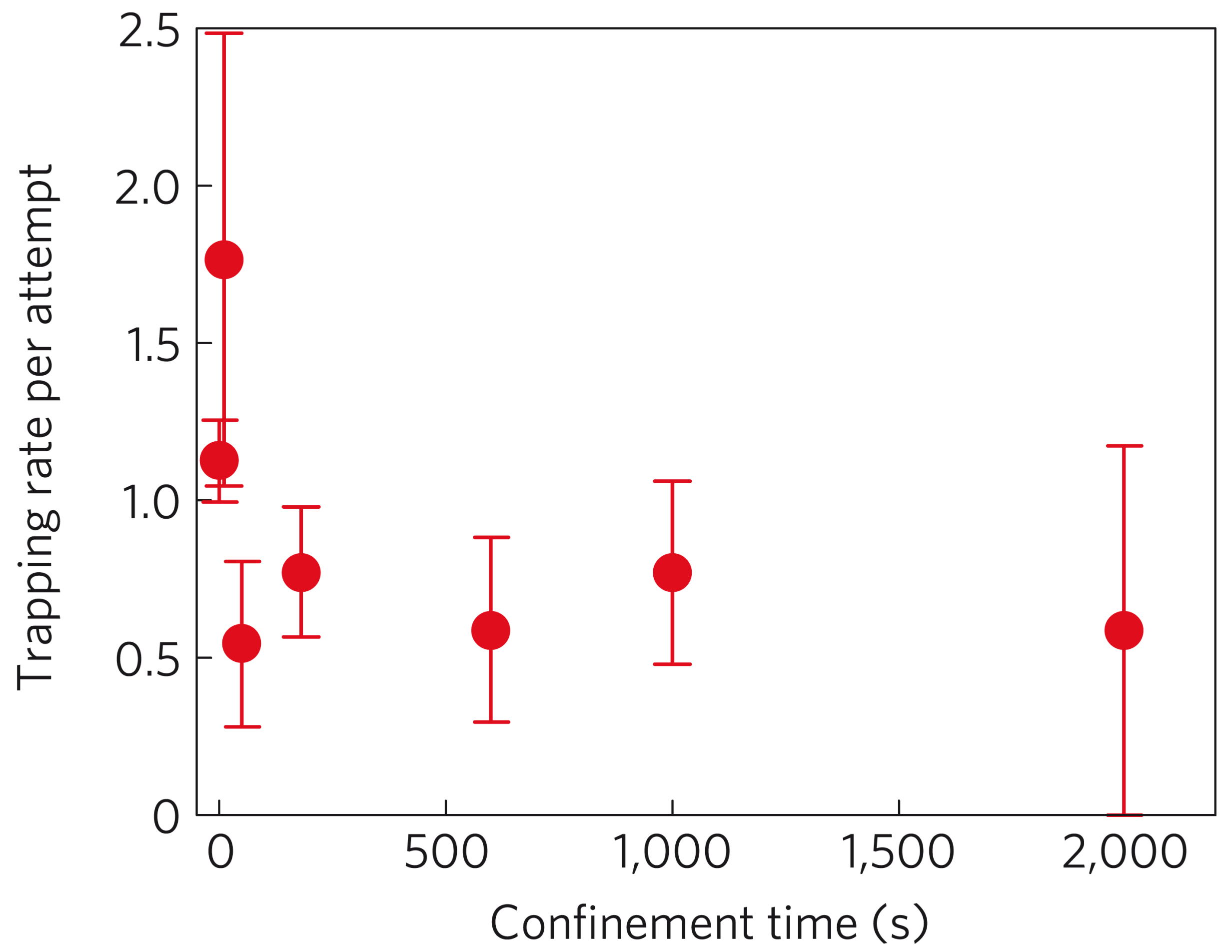
G. Gabrielse *et al. Phys. Lett. A* **129**, 38 (1988)

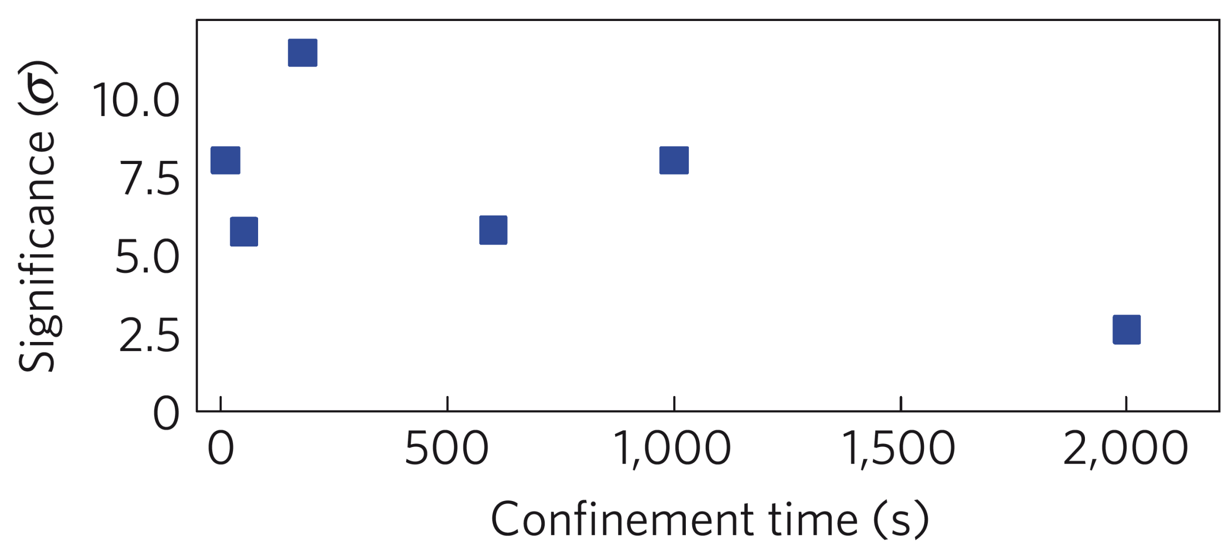
Trapping



G. B. Andresen et al (ALPHA collaboration)
Nature **468**, 673 (2010)

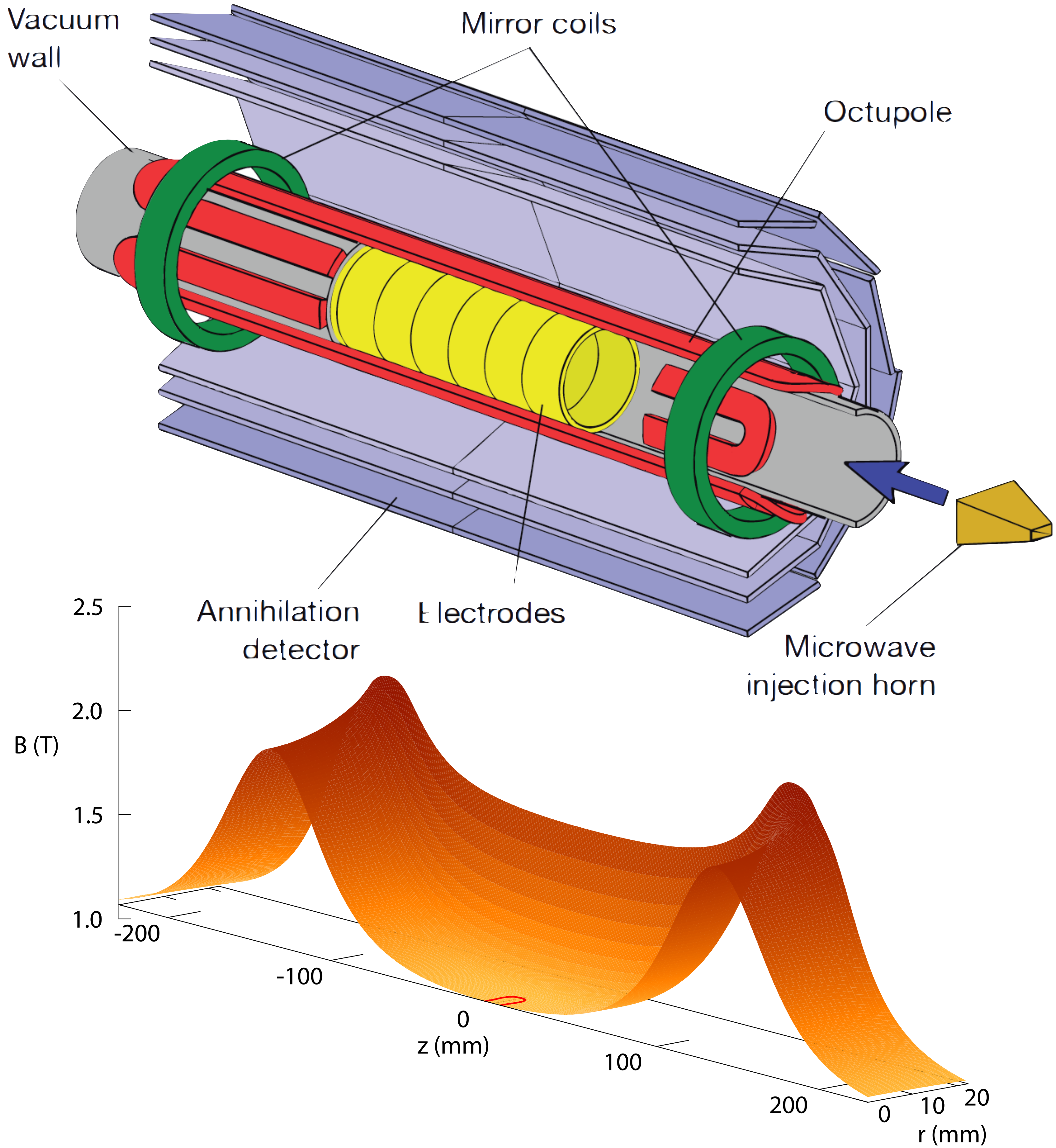
1000 Confinement



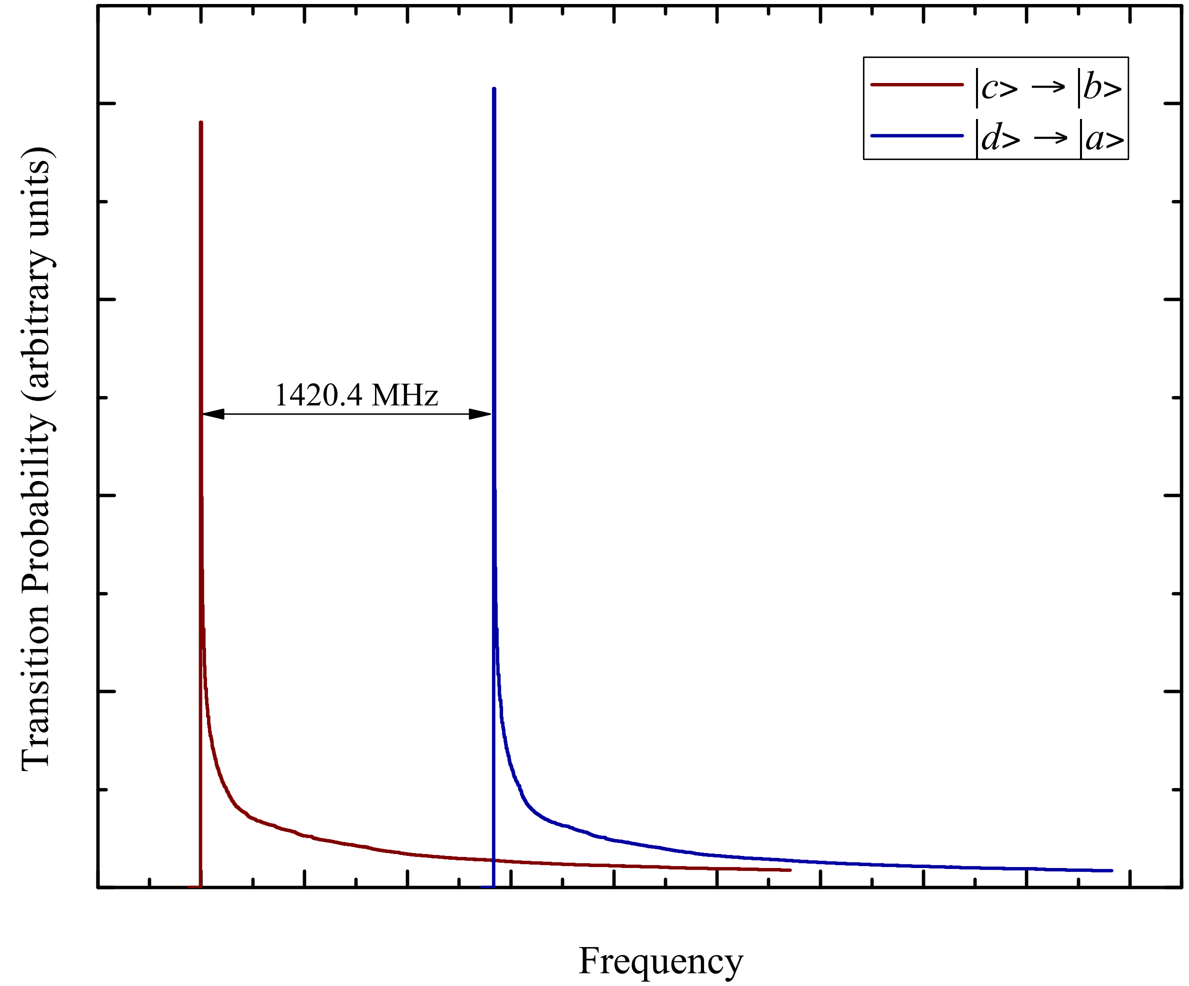


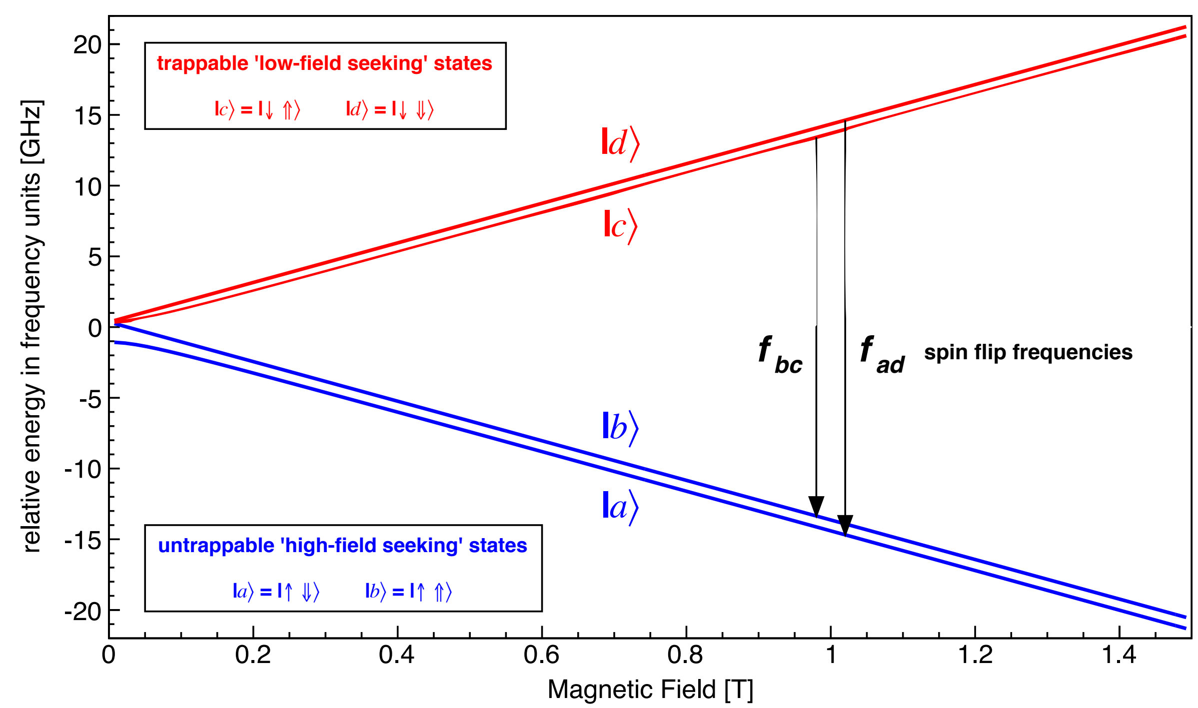
G. B. Andresen et al. (ALPHA collaboration)
Nature Physics **7**, 558 (2011)

Resonant Quantum Transitions



Simulation of the transition probability





Transition measurements

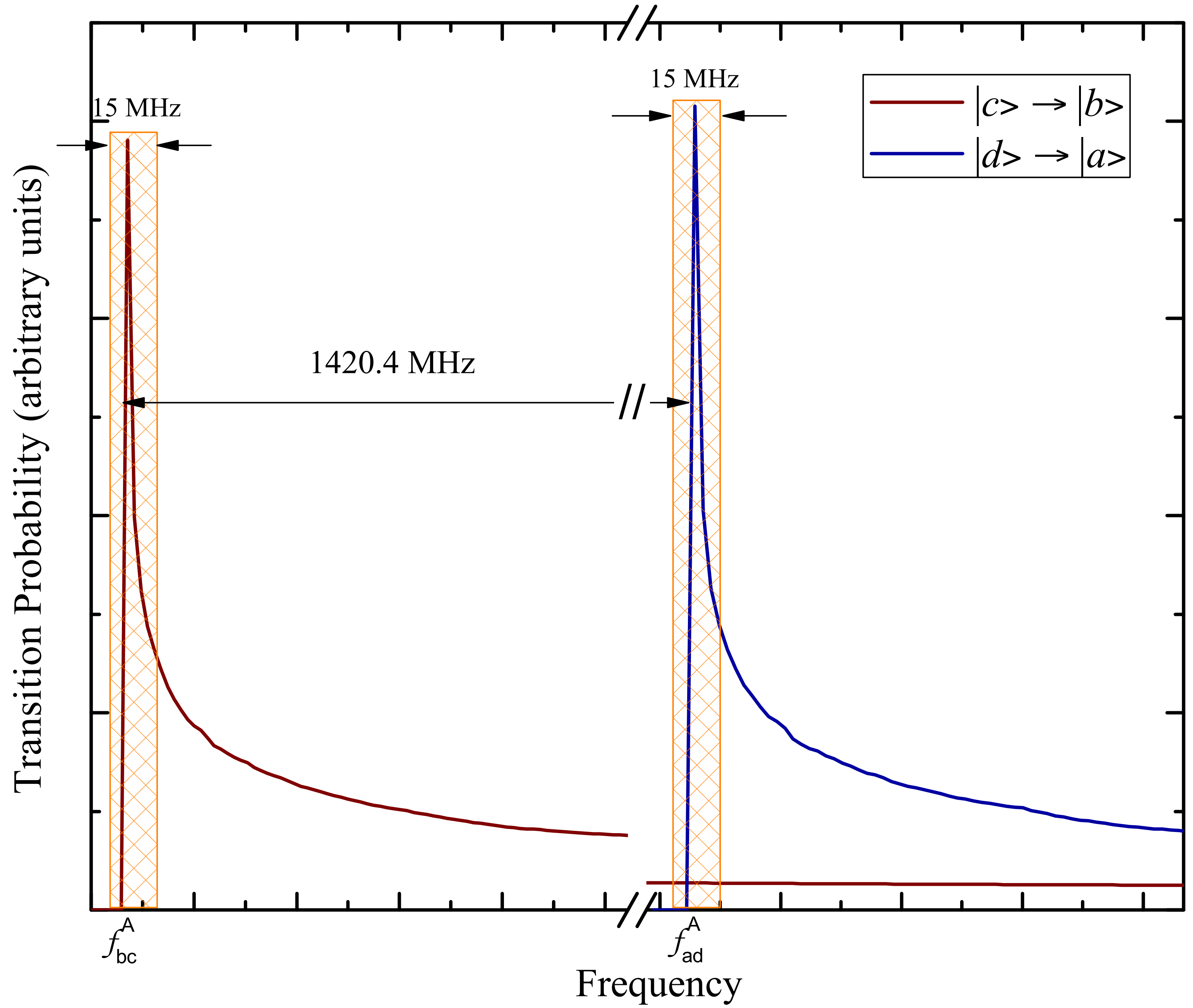
- Produce and trap Antihydrogen
- Wait 60 s and maybe change B
- Microwave for 180 s
- Quench trap

Two data sets

Count the remaining antihydrogen atoms when quenching the magnets

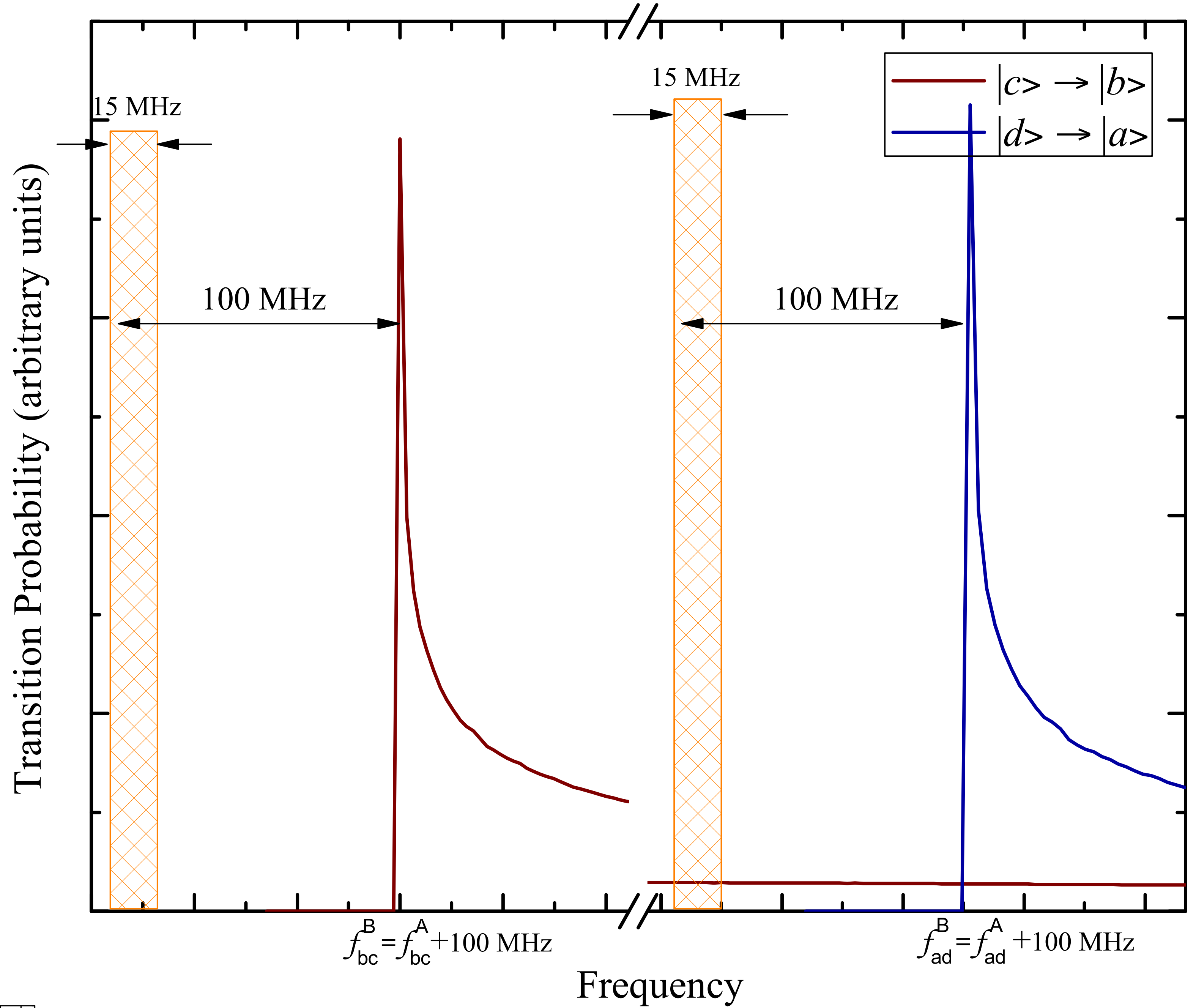
Count the escaping antihydrogen atoms during the microwave injection

Series 1

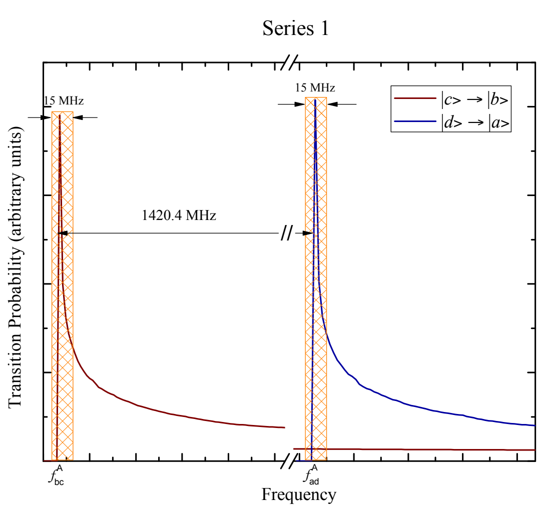


15 MHz
15 MHz
|c> → |b>
|d> → |a>
1420.4 MHz
Transition Probability (arbitrary units)
f_{bc}^{A}
f_{ad}^{A}
Frequency

Series 2 & 4

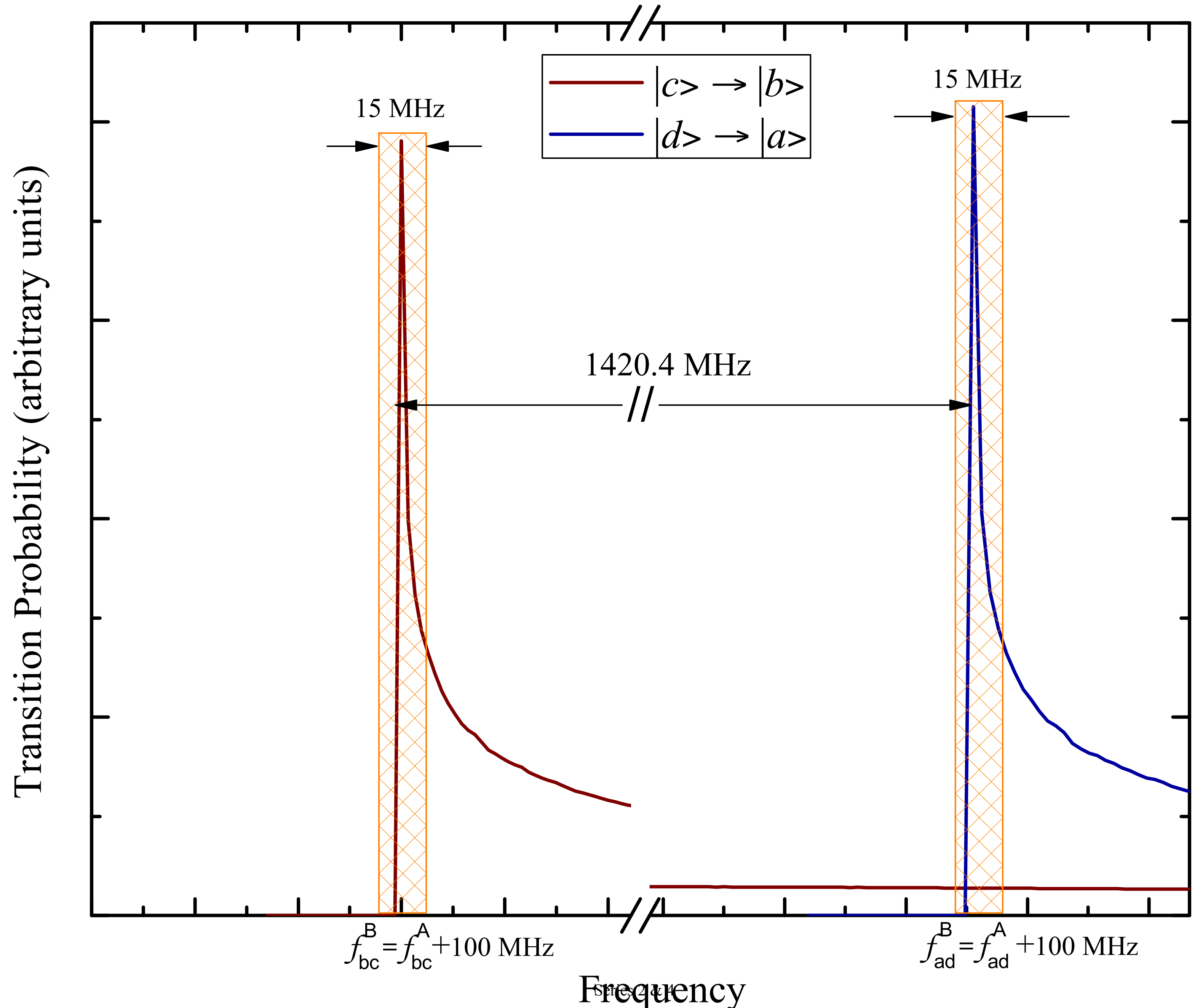


15 MHz
15 MHz
100 MHz
100 MHz
|c> → |b>
|d> → |a>
Transition Probability (arbitrary units)
$f_{bc}^{B}=f_{bc}^{A}$+100 MHz
$f_{ad}^{B}=f_{ad}^{A}$ +100 MHz
Frequency

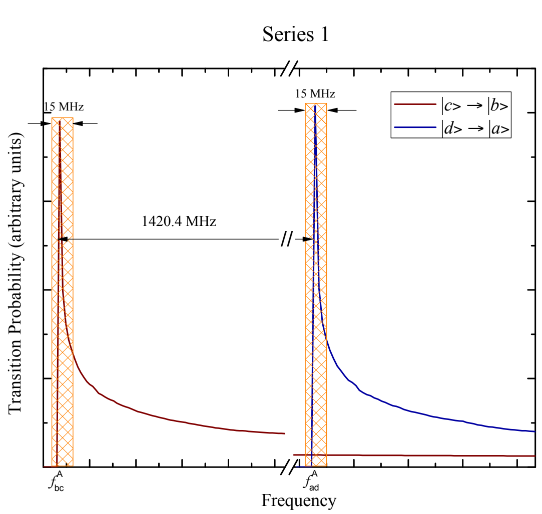


Series 1
15 MHz
15 MHz
1420.4 MHz
|c> → |b>
|d> → |a>
Transition Probability (arbitrary units)
Frequency

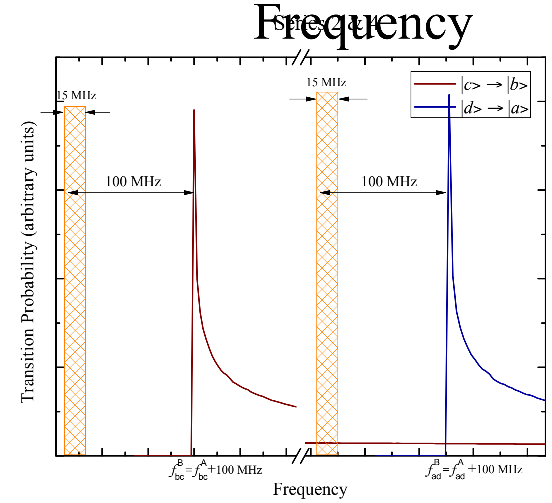
Series 3



15 MHz
|c> → |b>
|d> → |a>
15 MHz
1420.4 MHz
Transition Probability (arbitrary units)
$f_{bc}^{B}=f_{bc}^{A}$+100 MHz
$f_{ad}^{B}=f_{ad}^{A}$ +100 MHz
Frequency



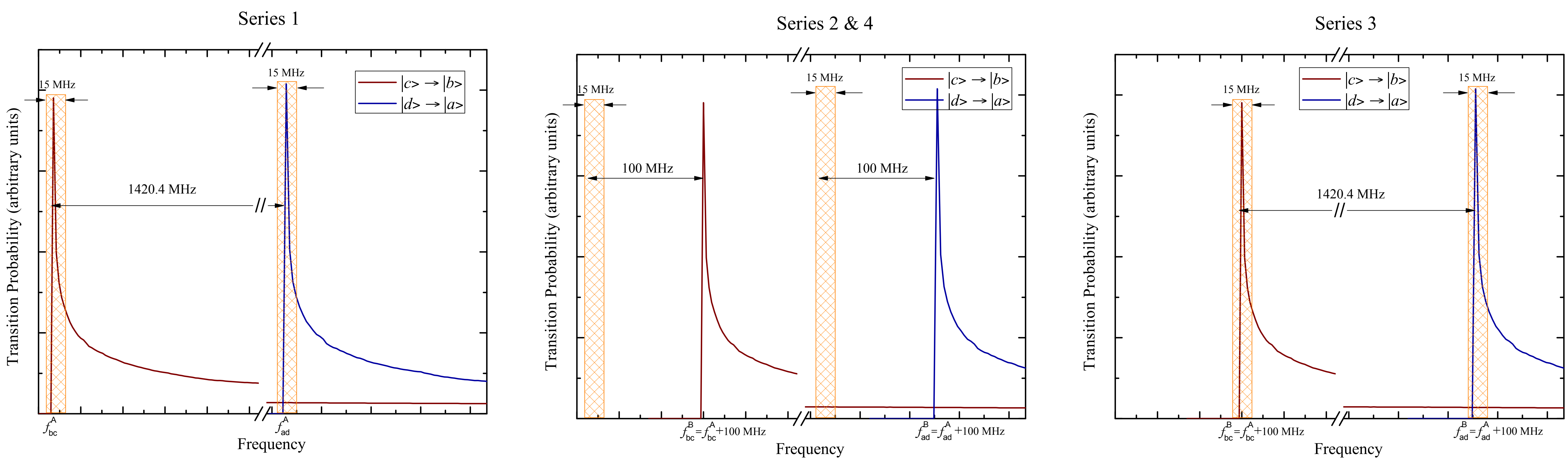
Series 1
15 MHz
15 MHz
|c> → |b>
|d> → |a>
1420.4 MHz
Transition Probability (arbitrary units)
Frequency



15 MHz
15 MHz
|c> → |b>
|d> → |a>
100 MHz
100 MHz
Transition Probability (arbitrary units)
Frequency

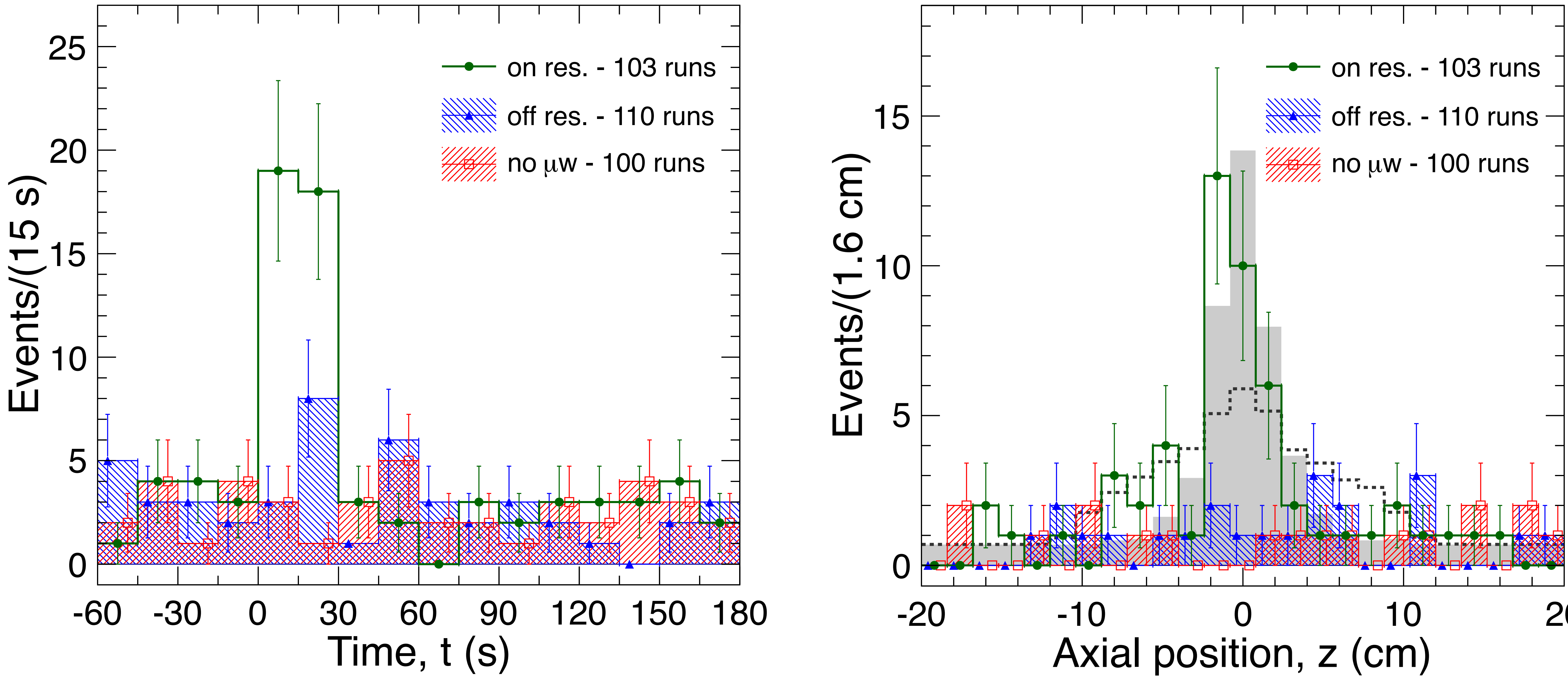
Totals for all ‘disappearance mode’ series

	Number of attempts	Detected antihydrogen	Rate
On resonance (1 + 3)	103	2	0.02 ± 0.01
Off resonance (2 + 4)	110	23	0.21 ± 0.04
No microwaves (5 + 6)	100	40	0.40 ± 0.06

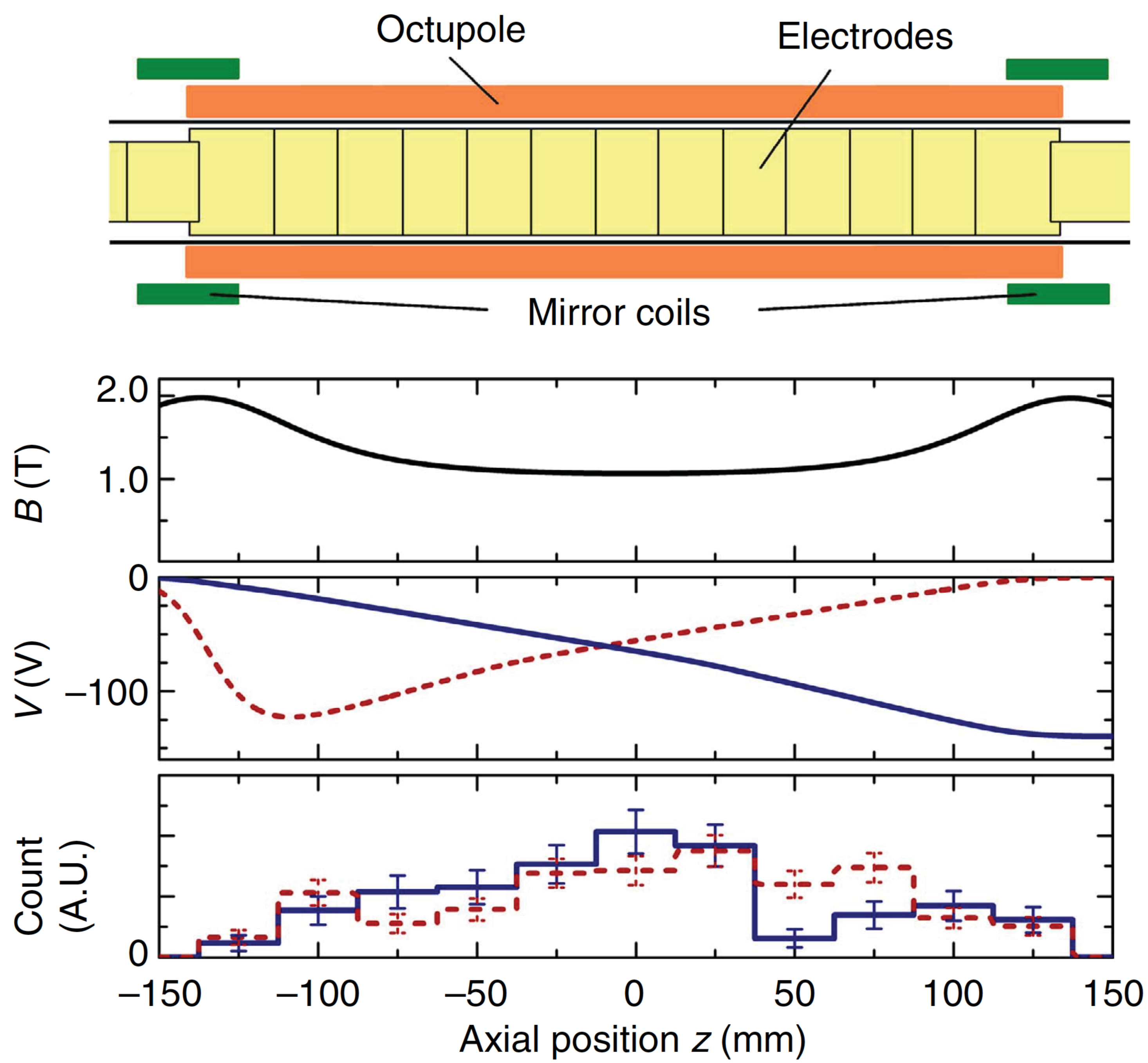


C. Amole et al. (ALPHA collaboration)
Nature **483**, 439 (2012)

Appearance measurements



Charge neutrality

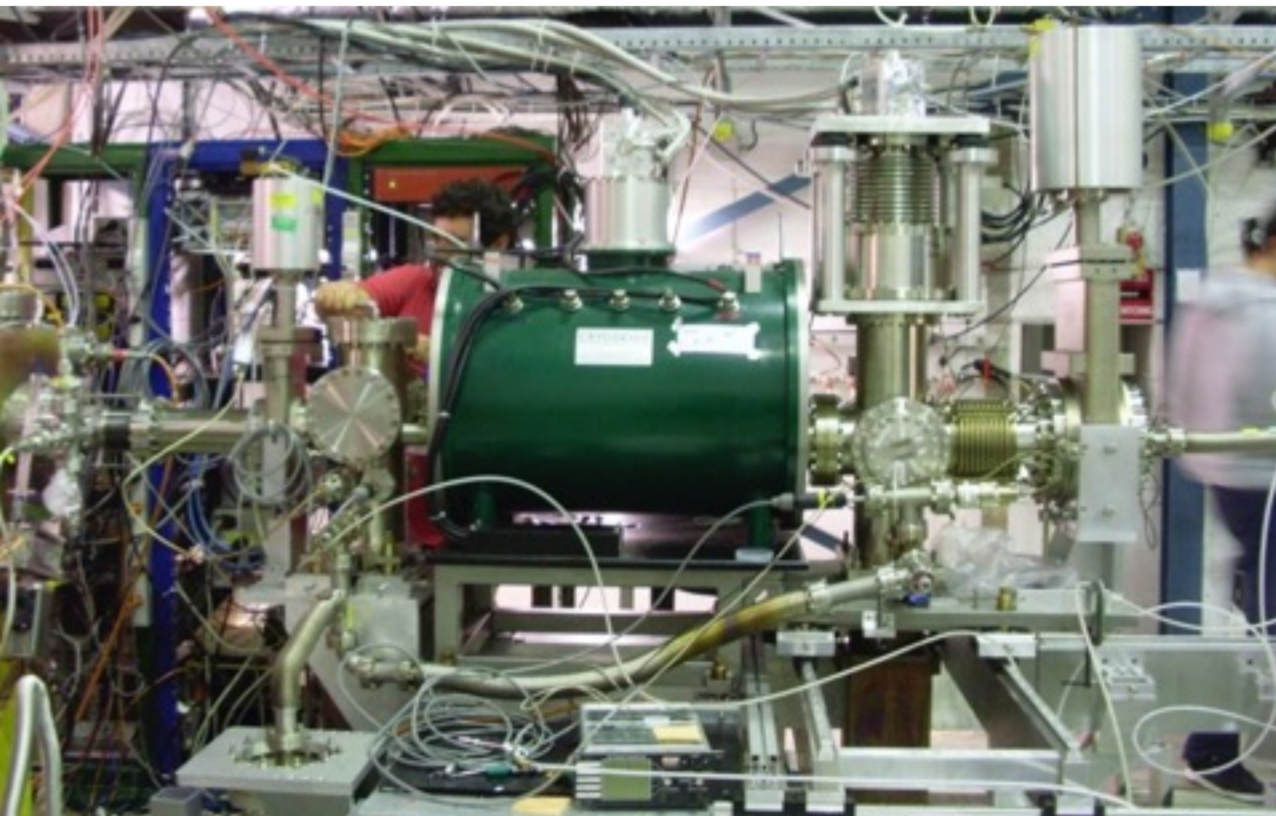


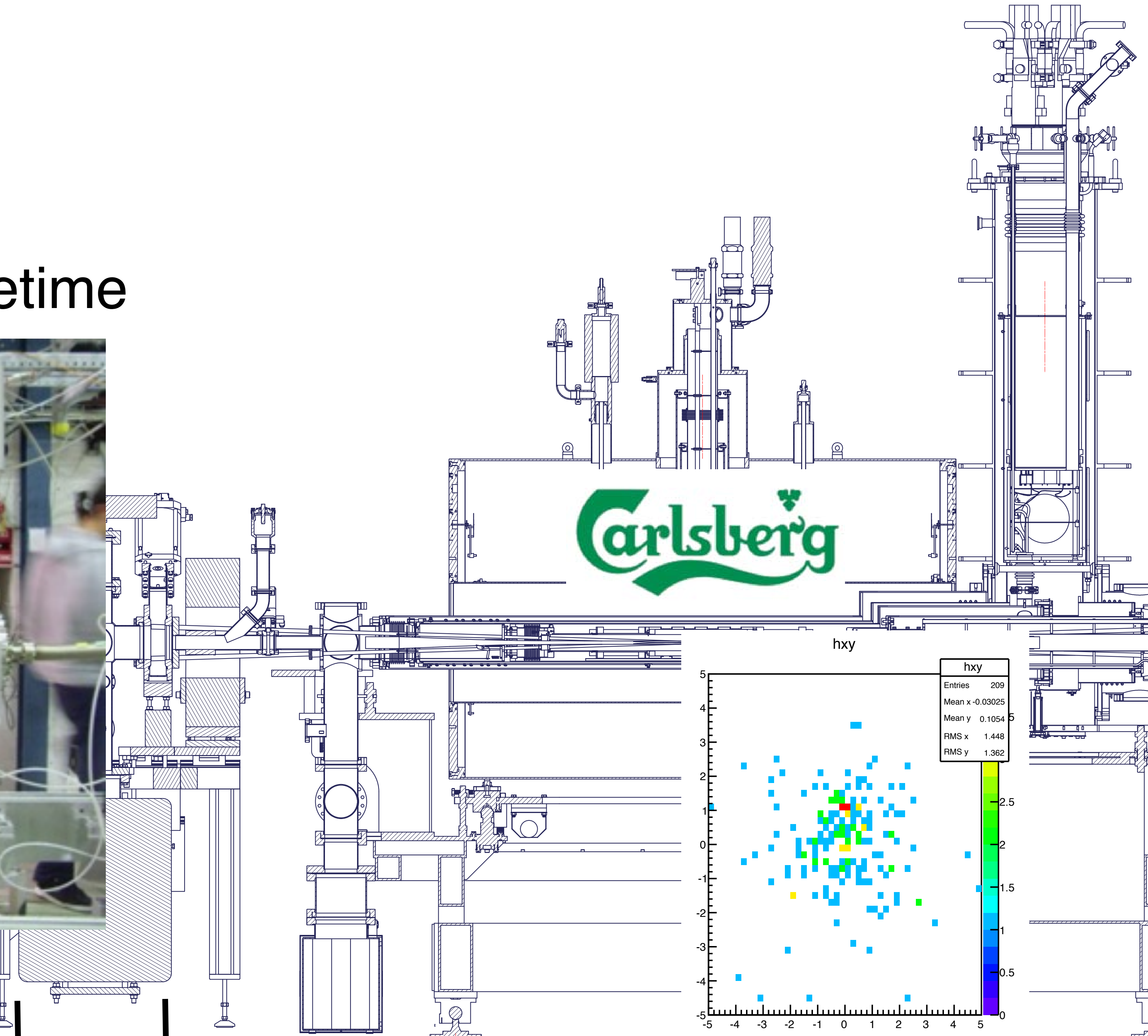
$$Q = (1.3 \pm 1.1 \pm 0.4) \times 10^{-8} \quad (1\sigma \text{ confidence level})$$

C. Amole et al. (ALPHA collaboration)
Nature Communications **5,** 3955 (2014)

ALPHA-2

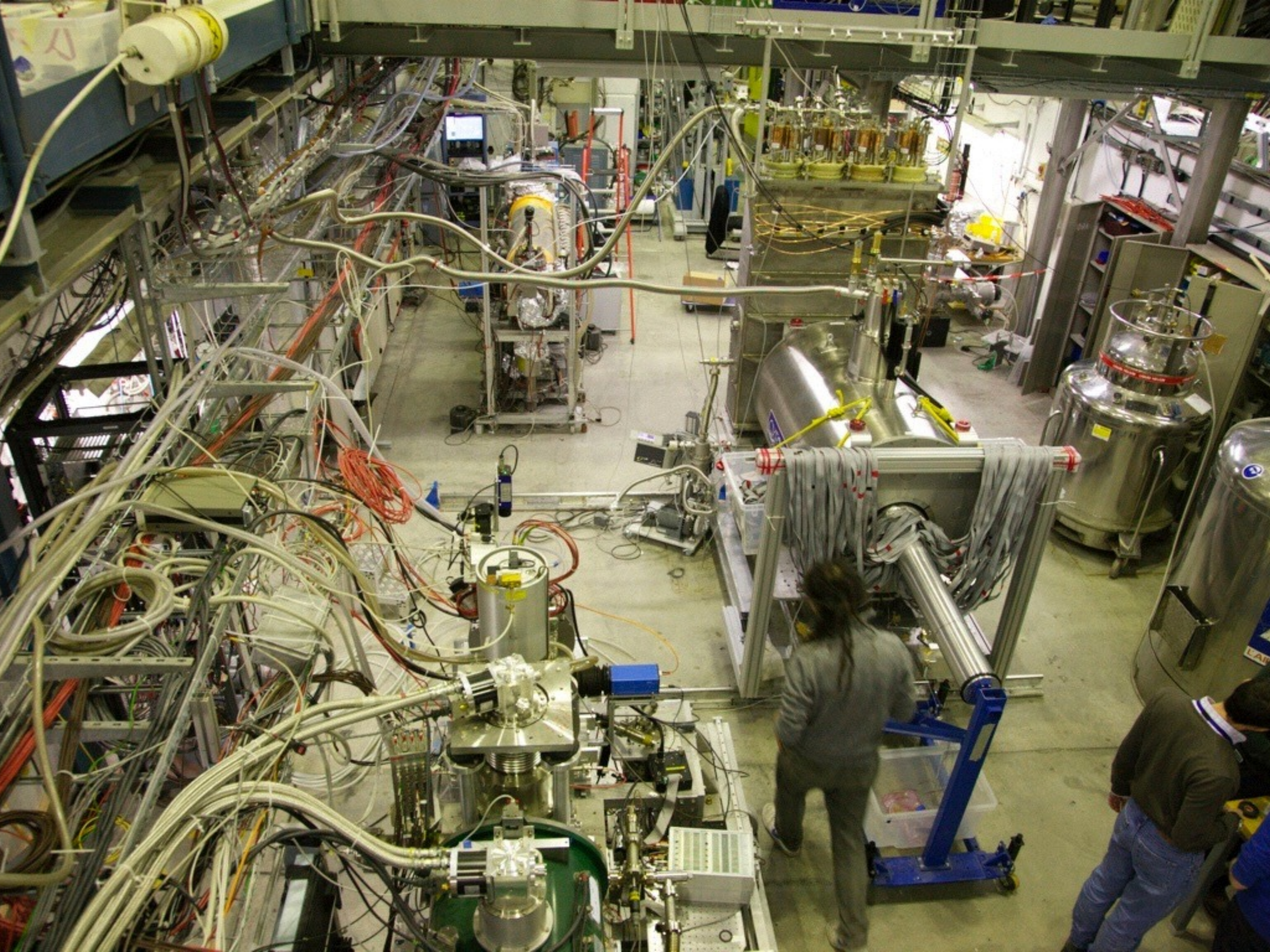
Installed: ~150k p/shot, >10h lifetime

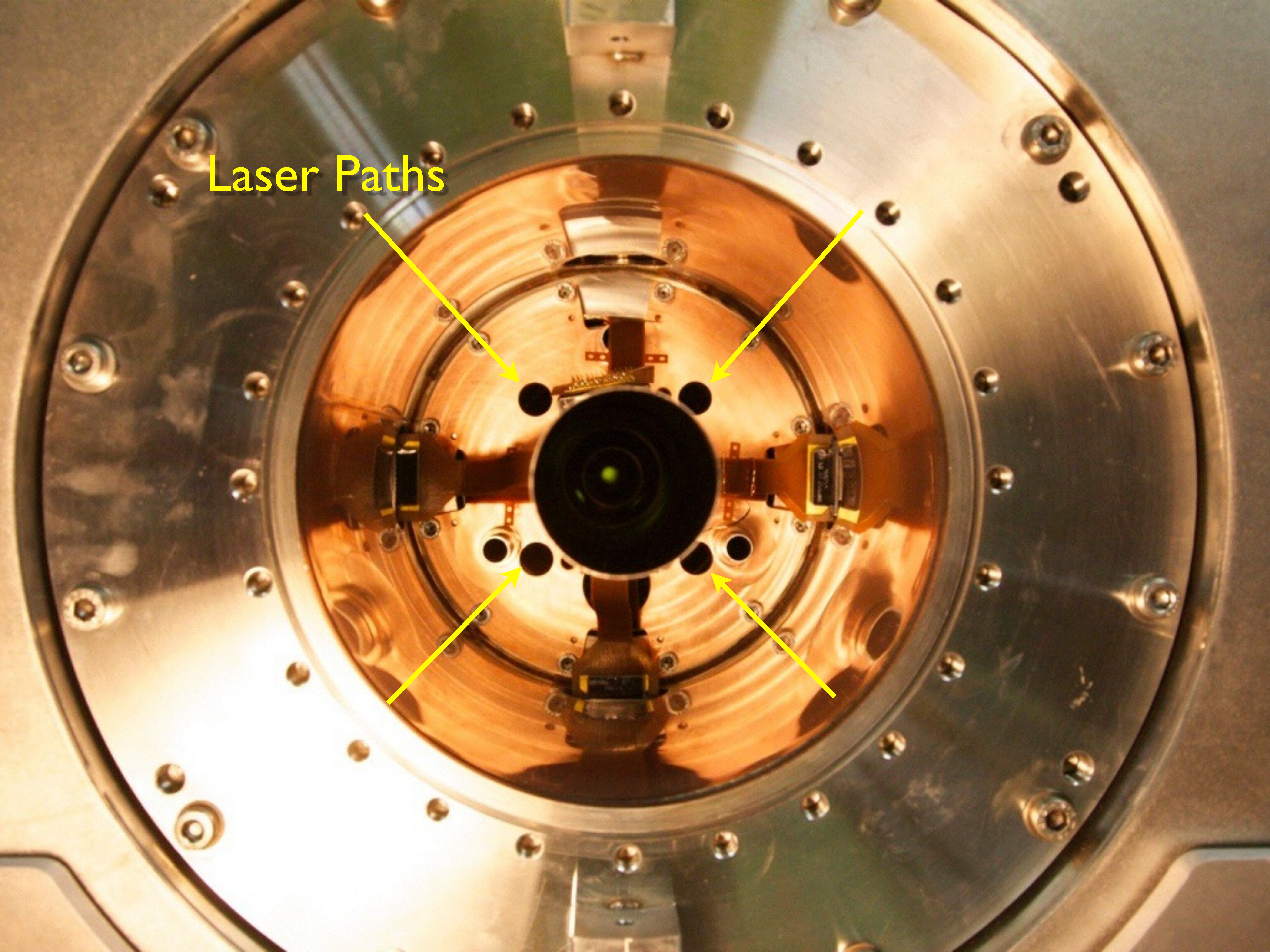




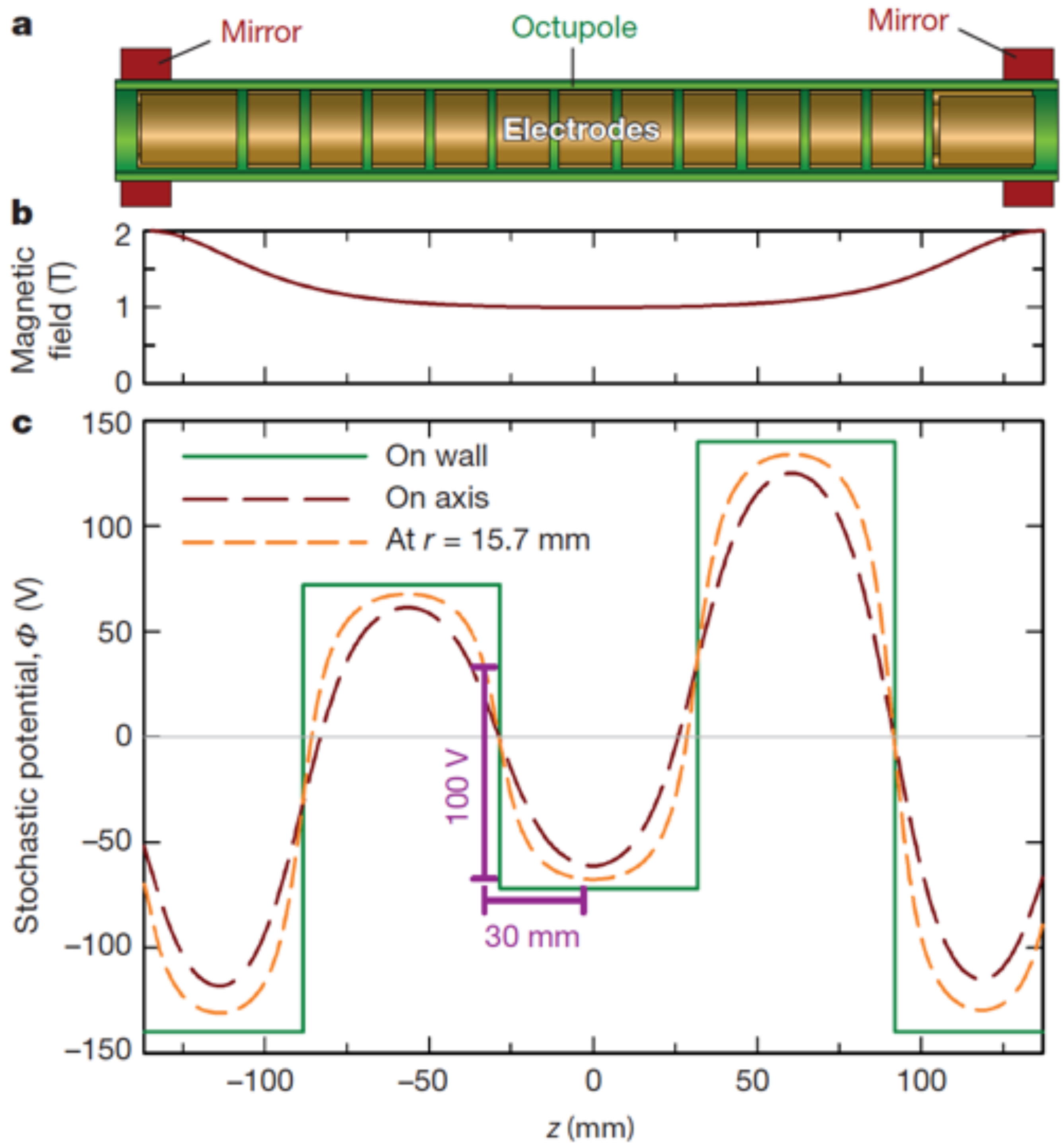
$\bar{p}$ catch and accumulation

$\overline{H}$ formation, trap and spectroscopy




Laser Paths

Charge neutrality 2

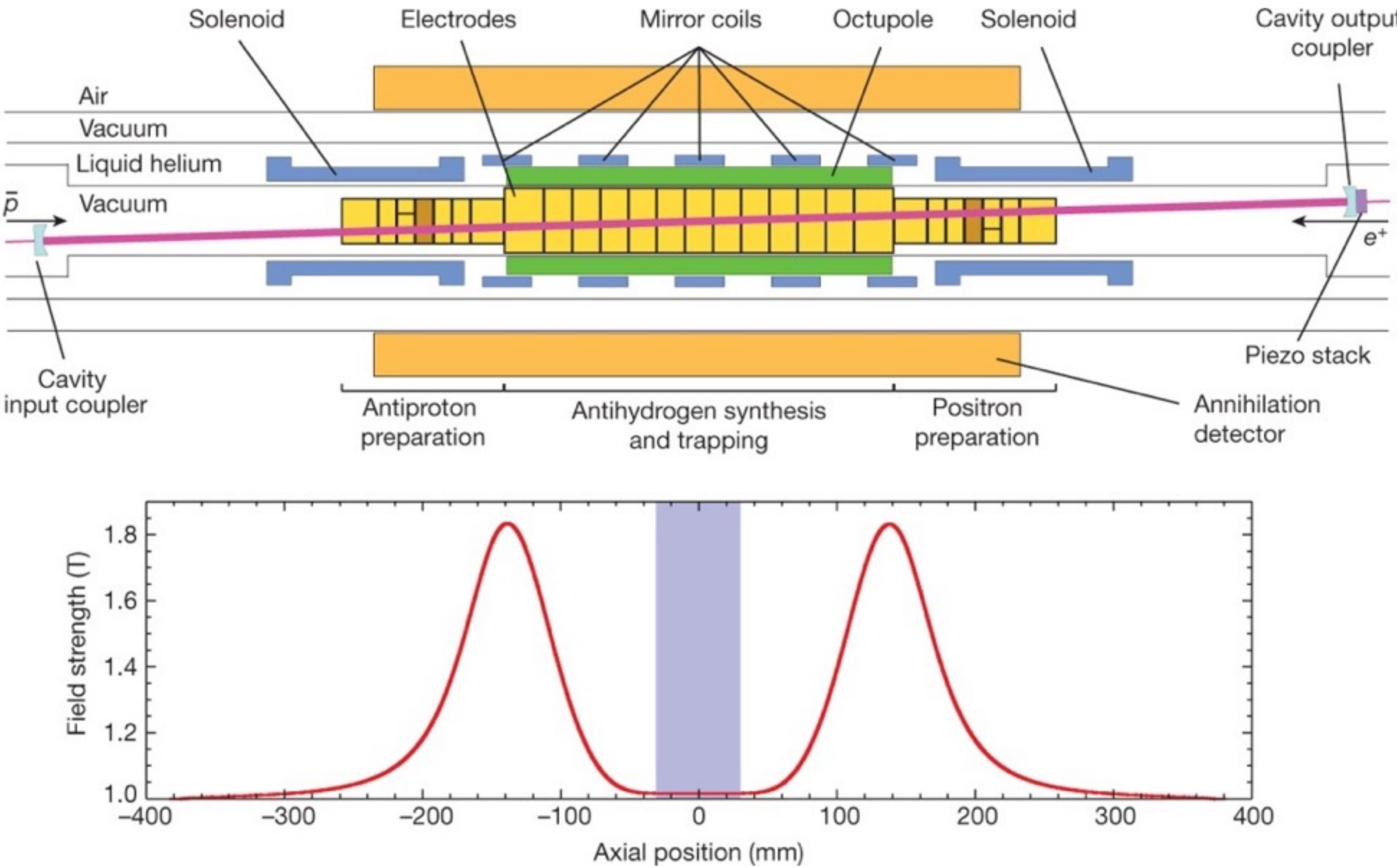


stochastic acceleration

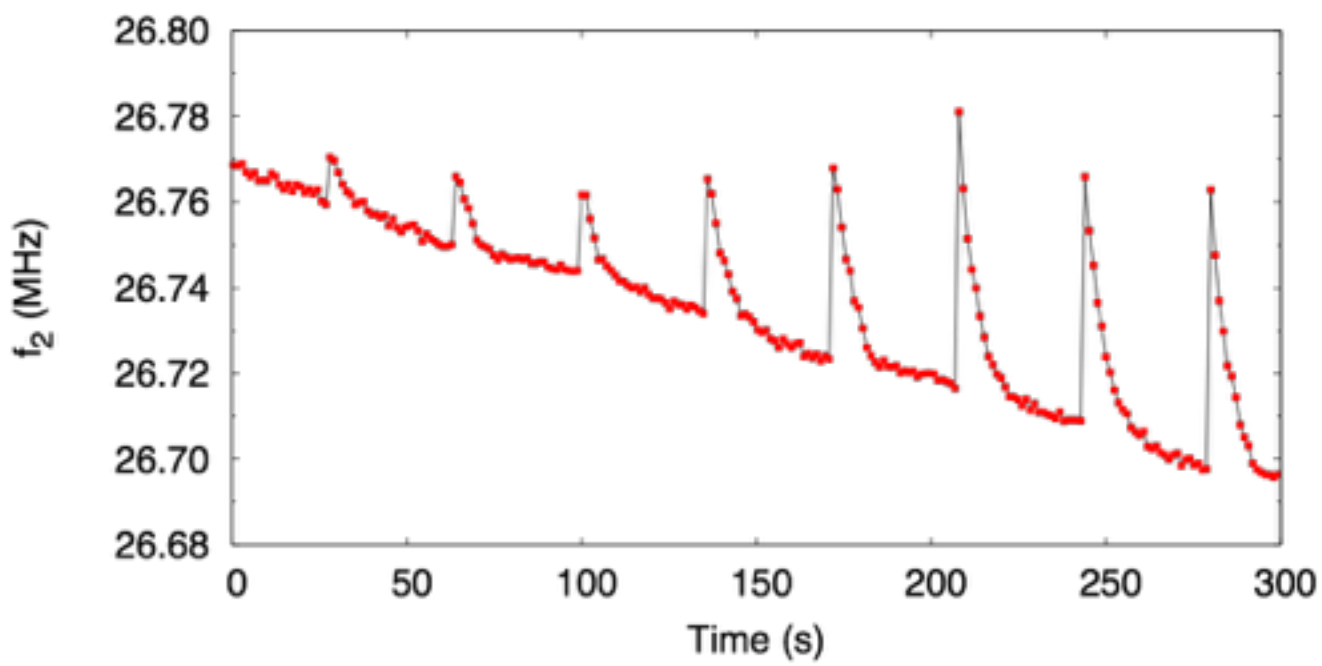
$$|Q| < 0.71 \text{ ppb}$$

M. Ahmadi et al. (ALPHA collaboration)
Nature **529,** 373 (2016)

Schematic Overview



Magnetic field measurements



Cyclotron excitation

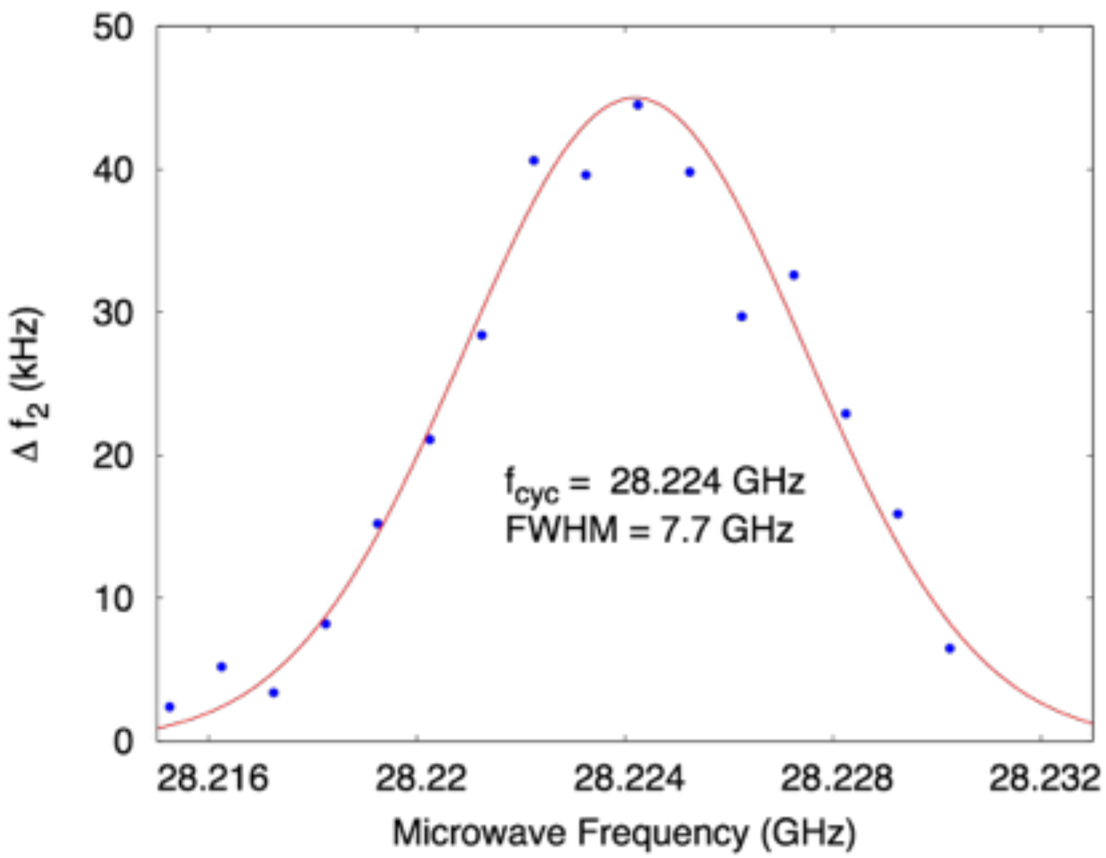
↓

Heat non-neutral electron plasma

↓

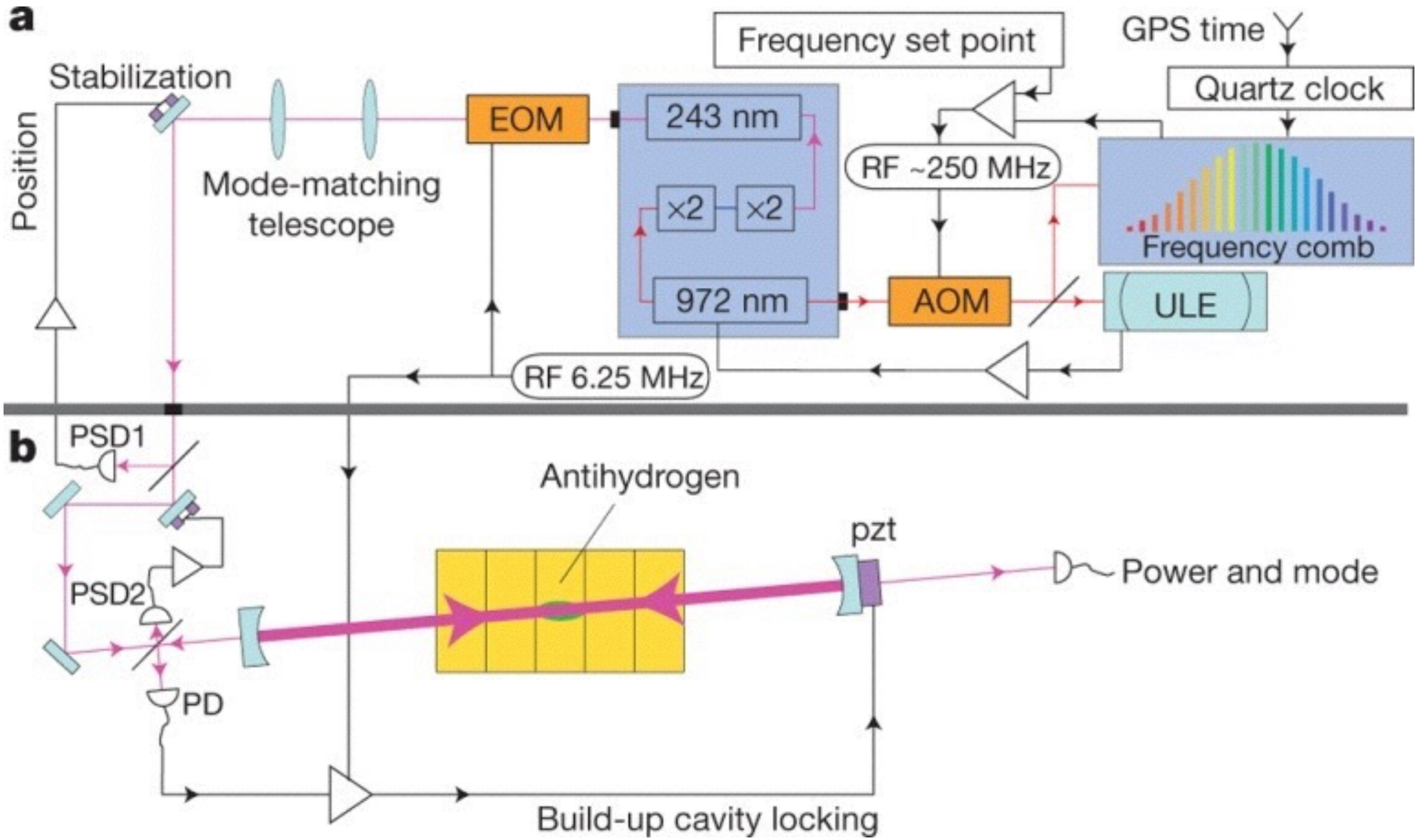
Change quadrupole mode frequency f_2

Typical measurement



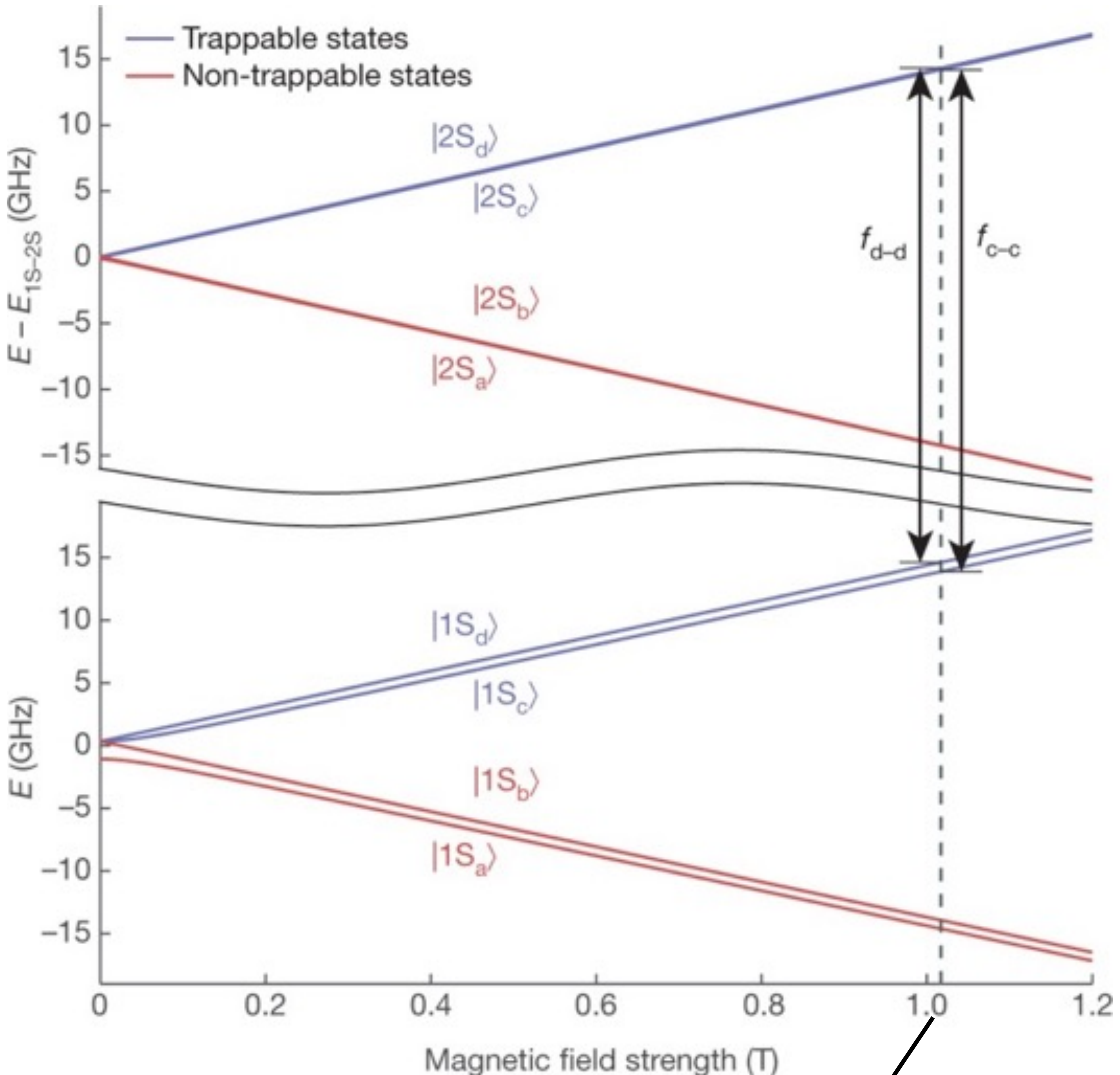
M. Amole et al. (ALPHA collaboration)
New J. Phys. **16**, 013037 (2014)

Laser Setup



The long-term average laser frequency at 972 nm is determined to a relative accuracy of 8×10^{-13}

1S-2S Experiment



f_{c-c} = 2,466,061,707,104(2) kHz

f_{d-d} = 2,466,061,103,064(2) kHz

Procedure:

1. Make and Trap antihydrogen
2. Pulsing axial electric fields to remove antiprotons
3. Holding the trapped anti-atoms for 600 s
4. ramping down the trapping fields

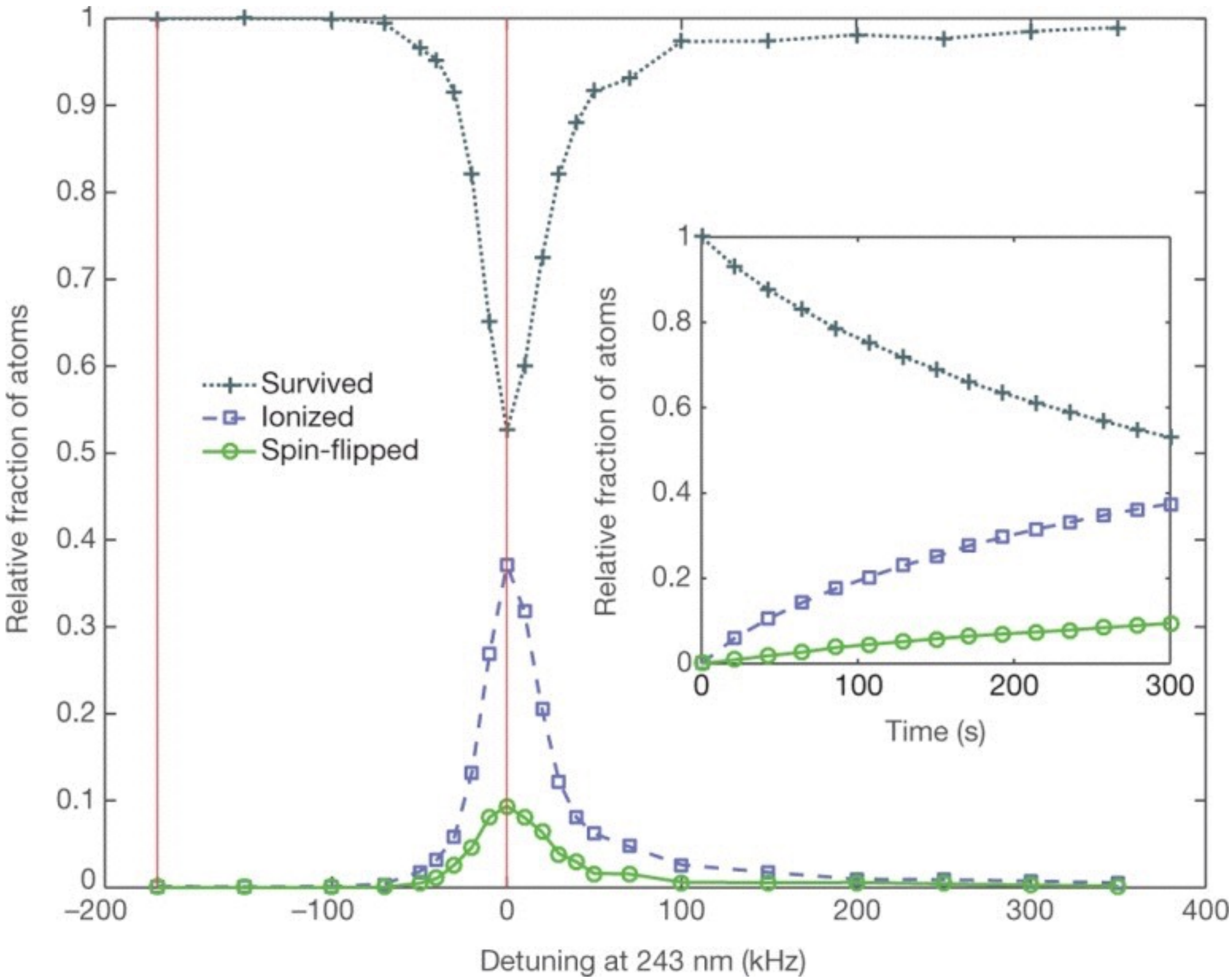
Three types of trials

1. ‘On resonance’: d–d transition and then the c–c transition are driven for 300 s each.
2. ‘Off resonance’: same as above, but the laser is detuned 200 kHz down
3. ‘No laser’: no laser radiation is present during the 600-s hold time.

During hold times, electrostatic blocking potentials so that anti- protons can only radially escape.

11 sets, change of measurement order between sets.

Simulation for 1 W laser power



Result 1

Table 1 | Detected events during the 1.5 s ramp down of the trap magnets

Type	Number of detected events	Background	Uncertainty
Off resonance	159	0.7	13
On resonance	67	0.7	8.2
No laser	142	0.7	12

The MVA used for the 1.5-s shutdown window yields a cosmic ray background rate of $0.042 \pm 0.001\ s^{-1}$

Reconstruction efficiency: 0.688 ± 0.002

Off - On = 92 ± 15

Resonant laser light removes a fraction of 0.58 ± 0.06 of the antihydrogen atoms

Result 2

Table 2 | Detected events during the 300 s hold times for each transition, and their sum

Type	Number of detected events	Expected Background	Uncertainty
d-d off res.	15	14.2	3.9
d-d on res.	39	14.2	6.2
No laser	22	14.2	4.7
c-c off res.	12	14.2	3.5
c-c on res.	40	14.2	6.3
No laser	8	14.2	2.8
d-d + c-c off res.	27	28.4	5.2
d-d + c-c on res.	79	28.4	8.9
No laser (sum)	30	28.4	5.5

The MVA used for the 1.5-s shutdown window yields a cosmic ray background rate of $0.0043 \pm 0.0003\ s^{-1}$

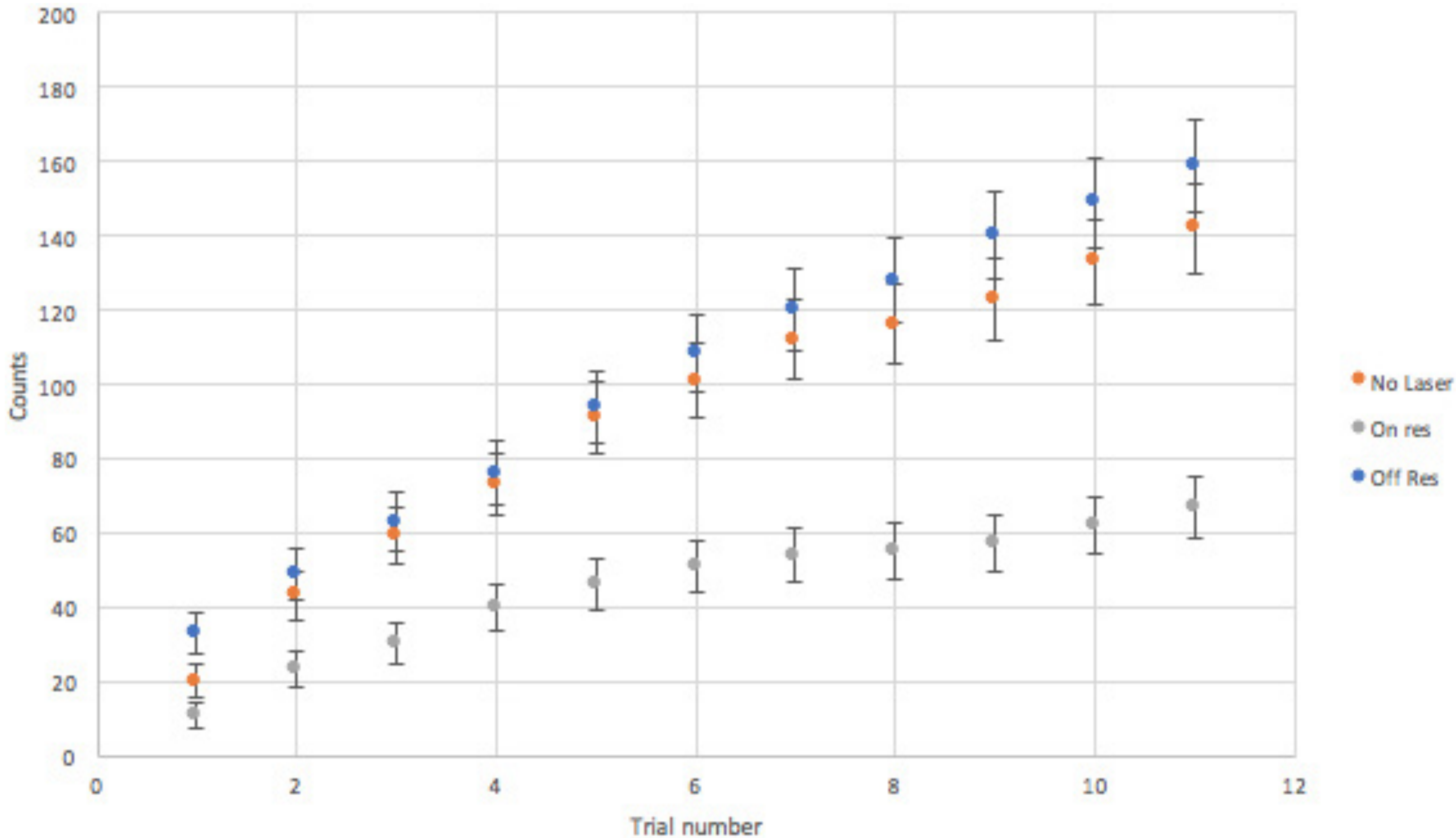
Off - On = 52 ± 10

Reconstruction efficiency: 0.376 ± 0.002

Budget: 52/0.376 ~ 138 92/0.688 ~ 134

M. Ahmadi et al. (ALPHA collaboration)
Nature **541,** 506 (2017)

Time evolution of the dataset.



Conclusion + Outlook

- Reduction of antihydrogen atoms by 58% when on-resonance
- Result consistent with CPT invariance at a relative precision of about 2×10^{-10},assuming the same line shape as for hydrogen
- Sensitivity ~ 2×10^{-18} GeV
- This year full line shape measurement

Funding

The Leverhulme Trust

THE ROYAL SOCIETY

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Engineering and Physical Sciences Research Council

U.S. DEPARTMENT OF ENERGY

NSF

Alberta Innovates Technology Futures

Fonds de recherche Nature et technologies Québec

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