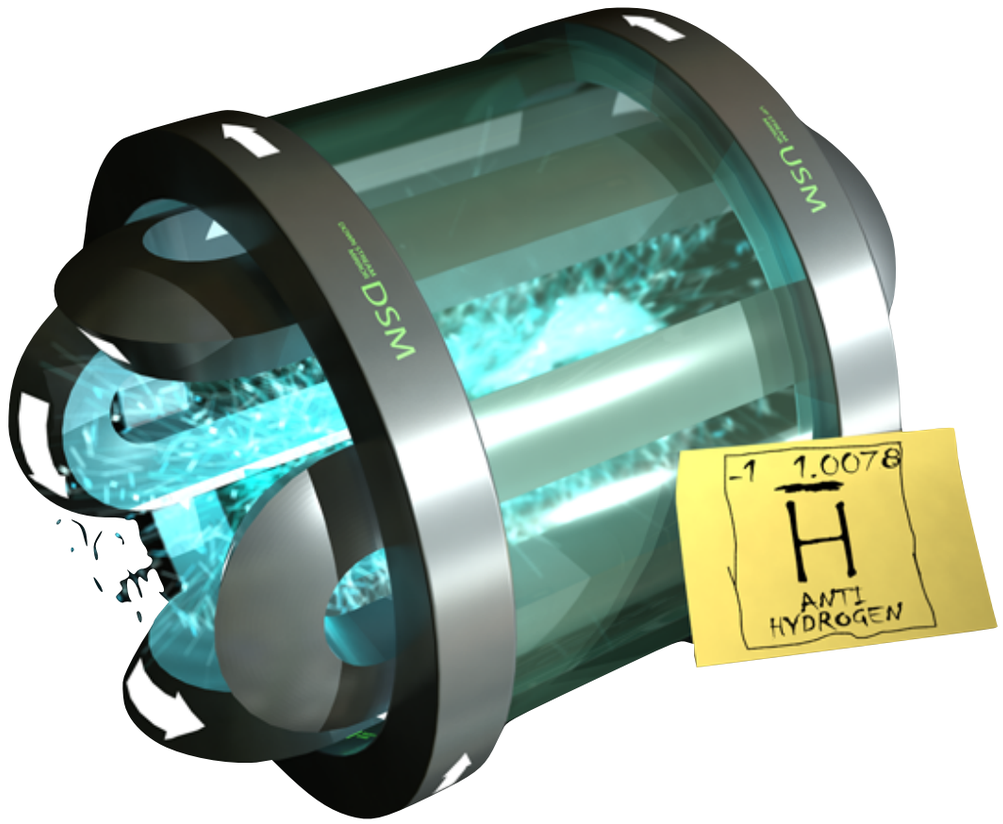
The ALPHA Experiment



Dirk van der Werf
Swansea University
CEA-Saclay

Swansea University
Prifysgol Abertawe

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)

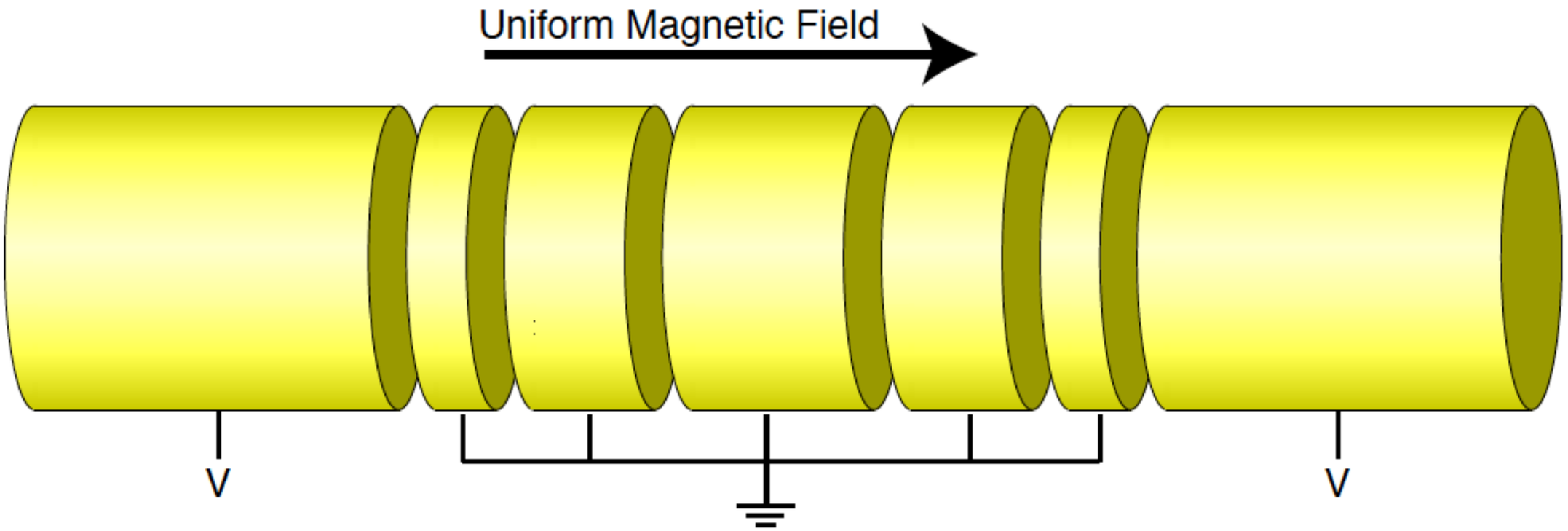
Goals

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).

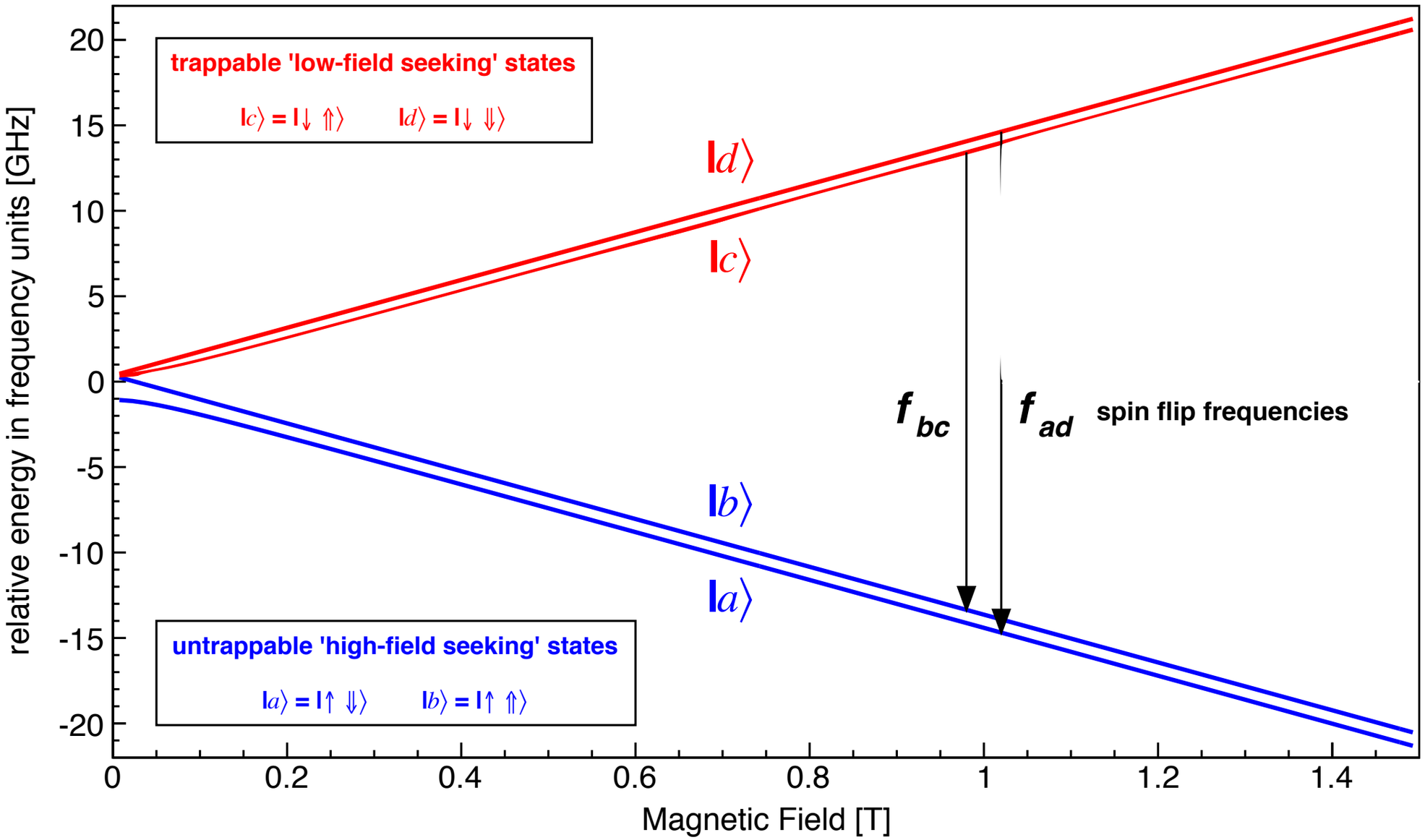
Penning Trap

Trap for charged particles



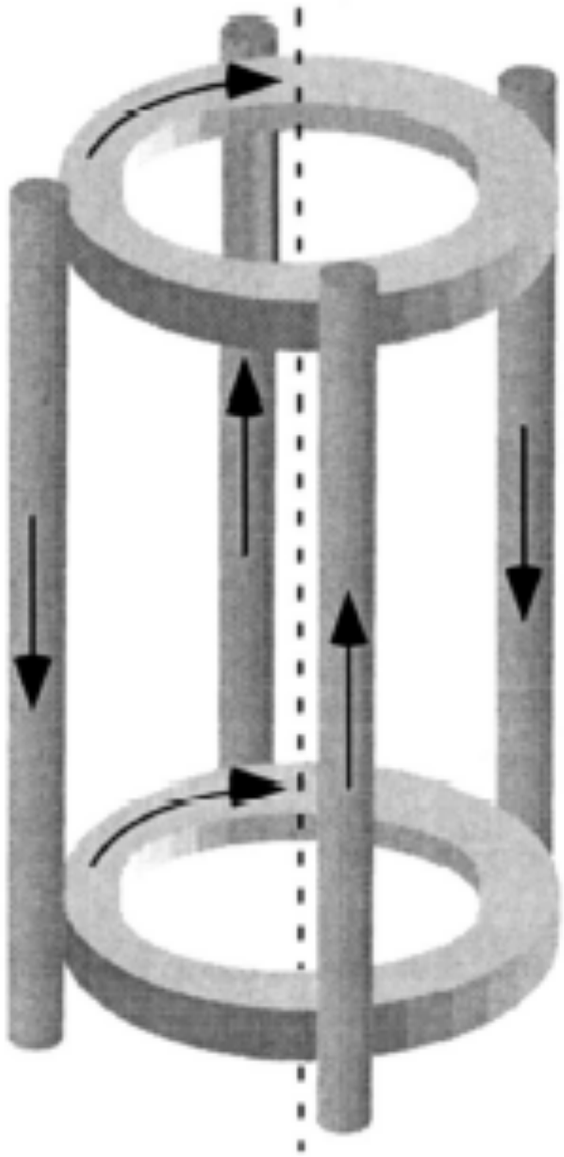
$\overline{\mathrm{H}}$ Breit-Rabi Diagram

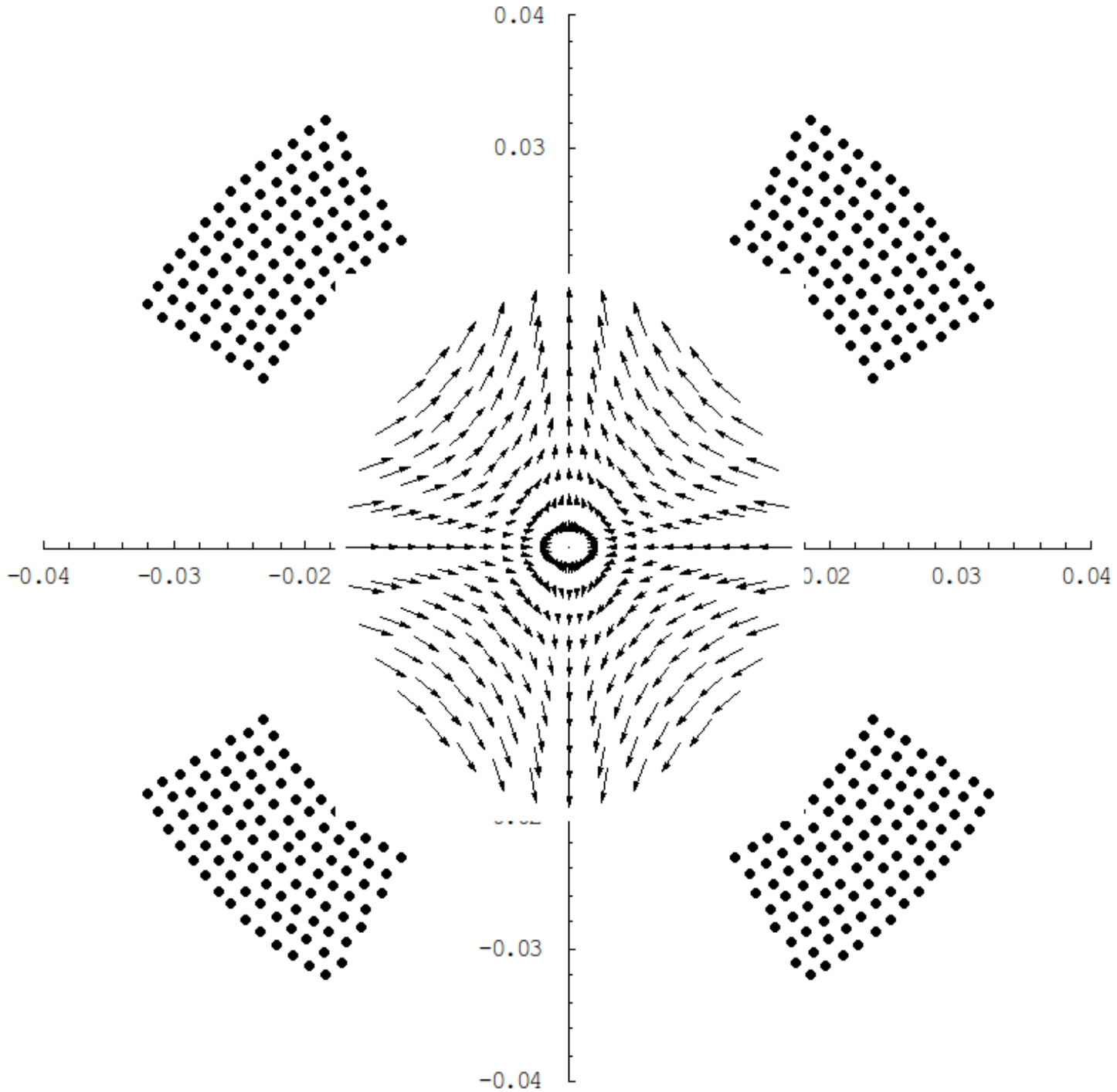
To measure accurately electronic transition a trap for neutral atoms is necessary: use the spin state of the antihydrogen atom



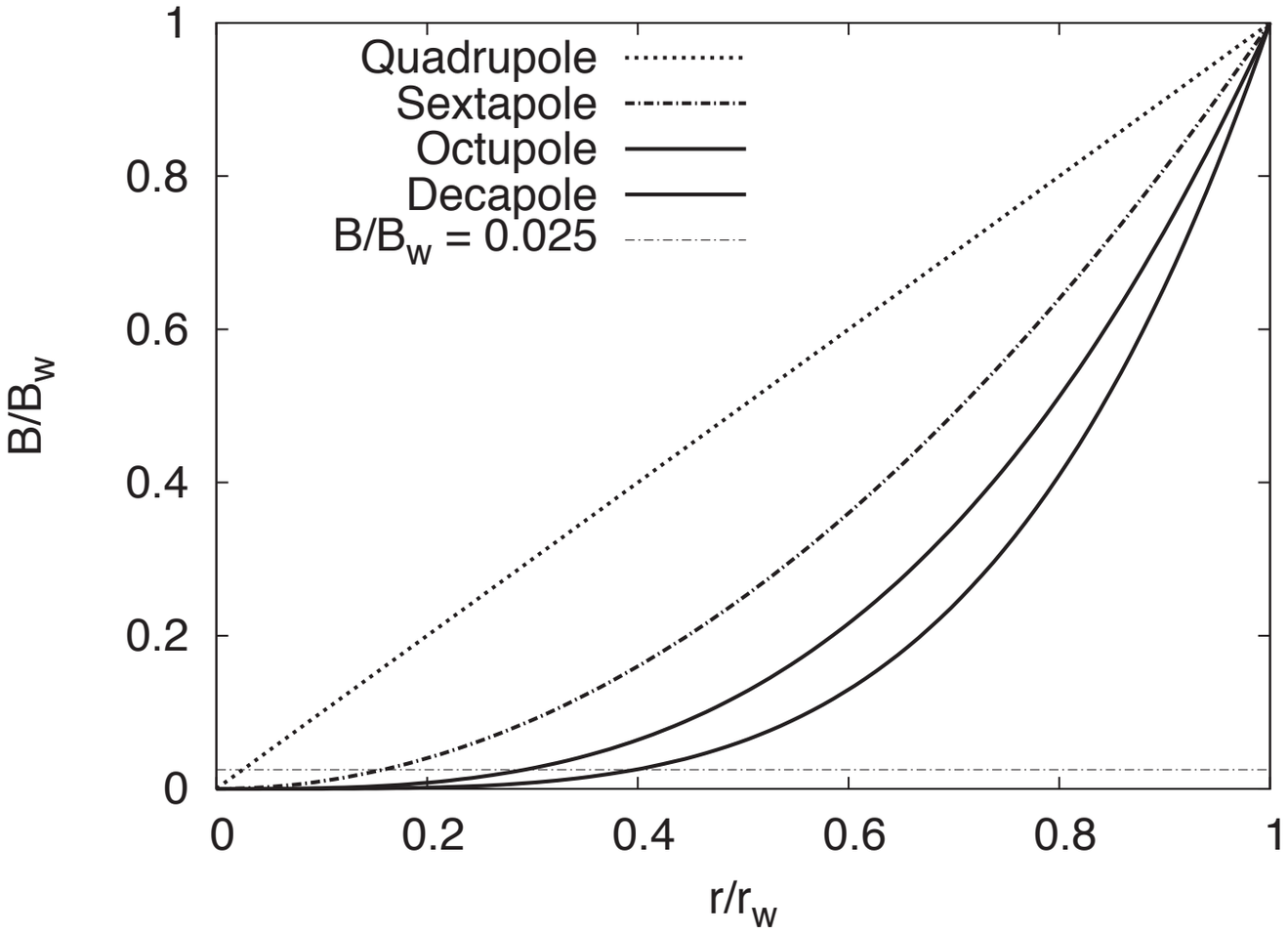
Magnetic trap

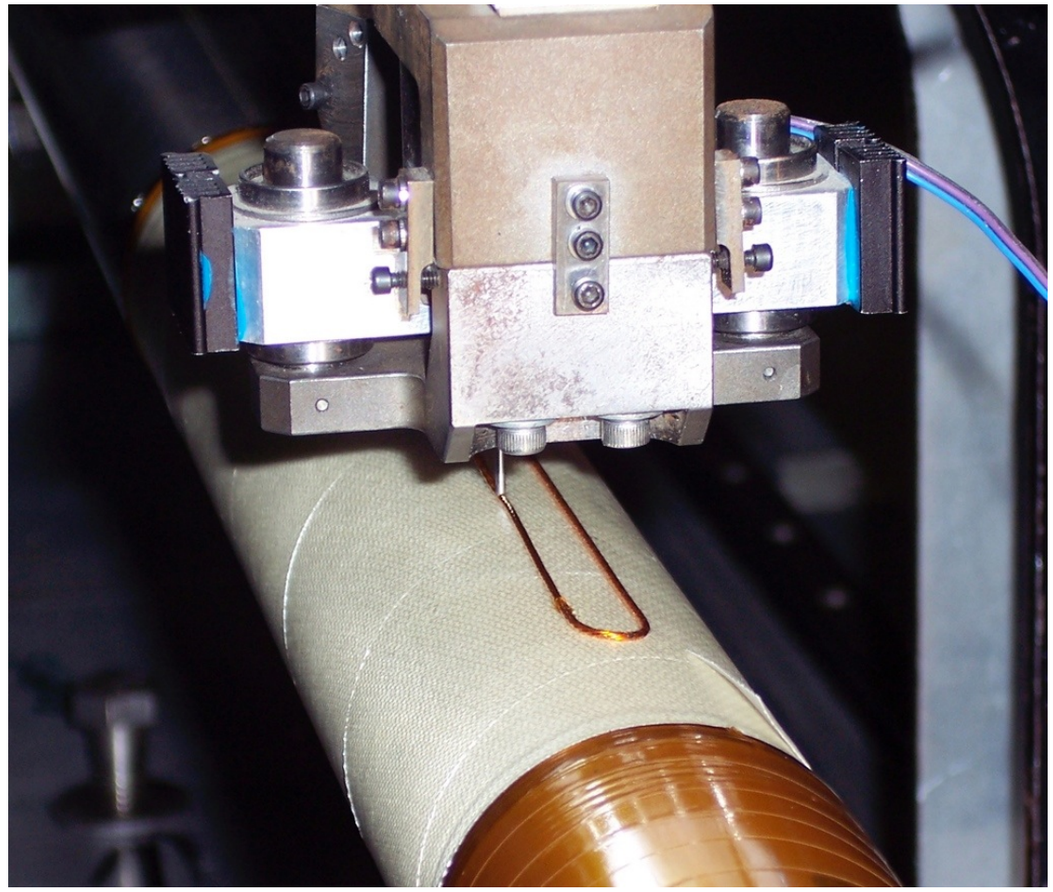
Trap for neutral particles

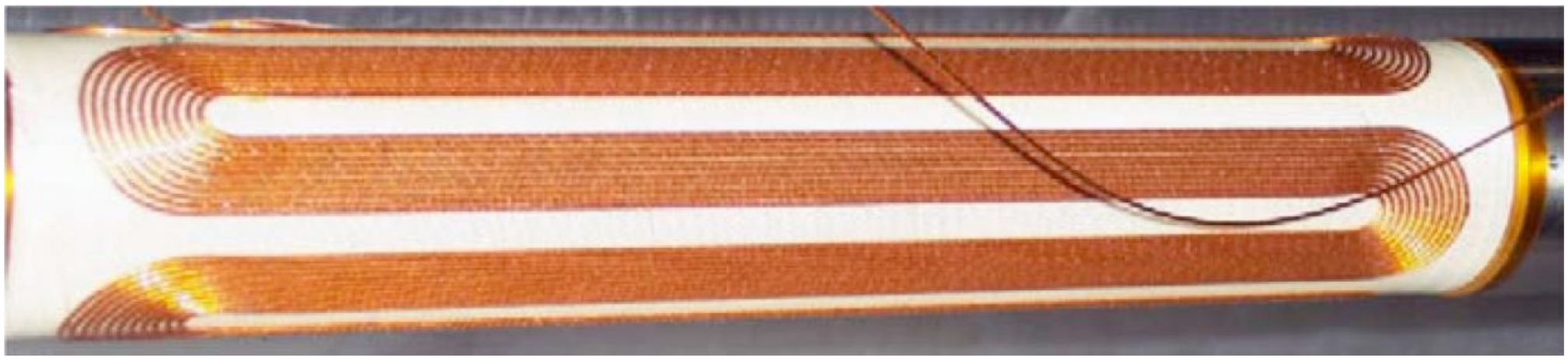




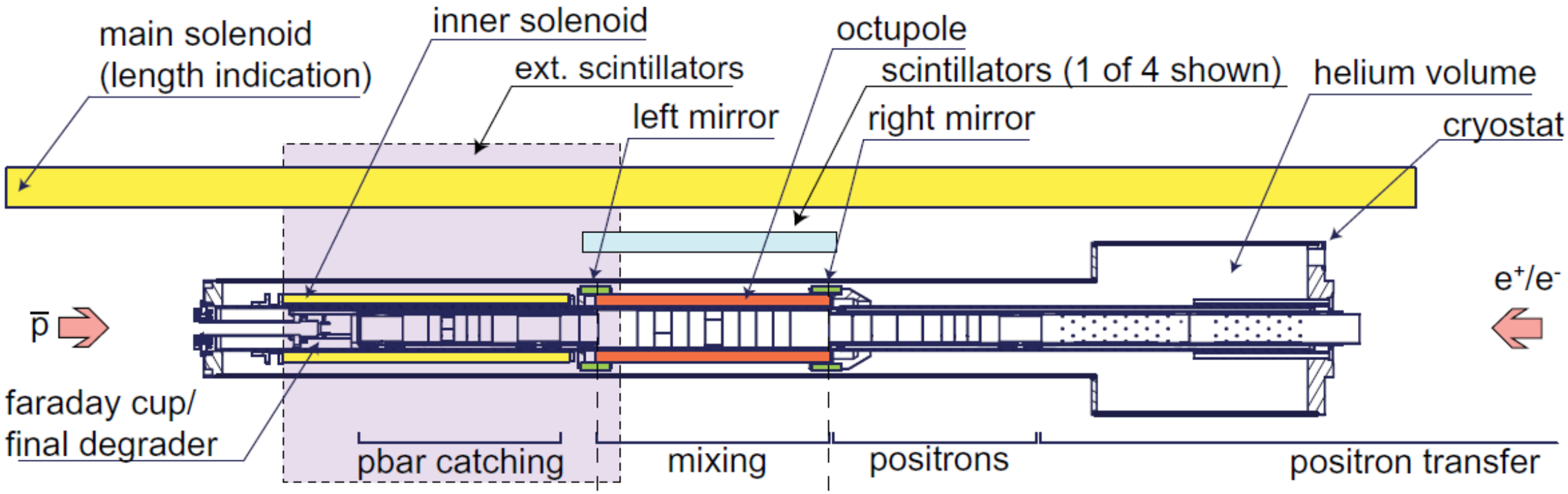
Magnetic trap

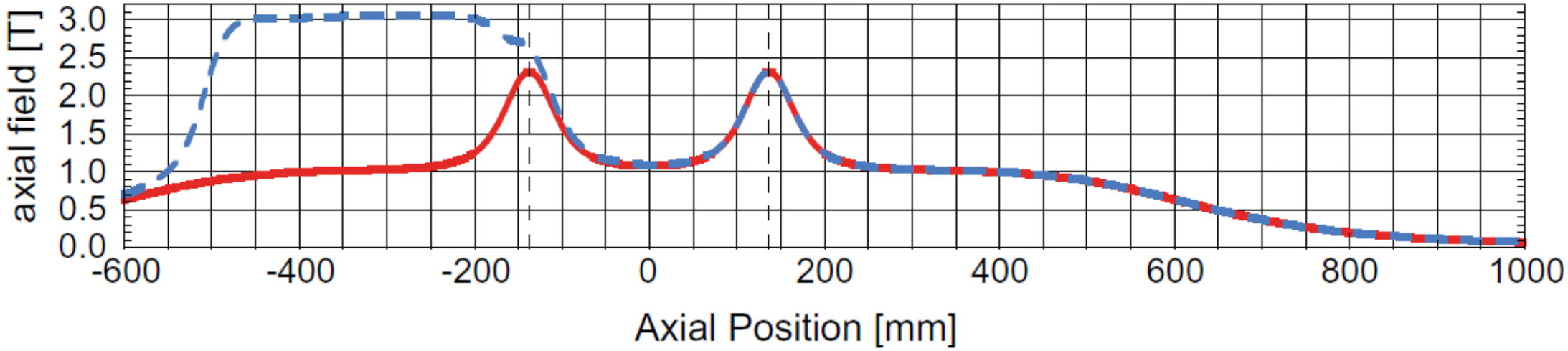






Alpha Apparatus





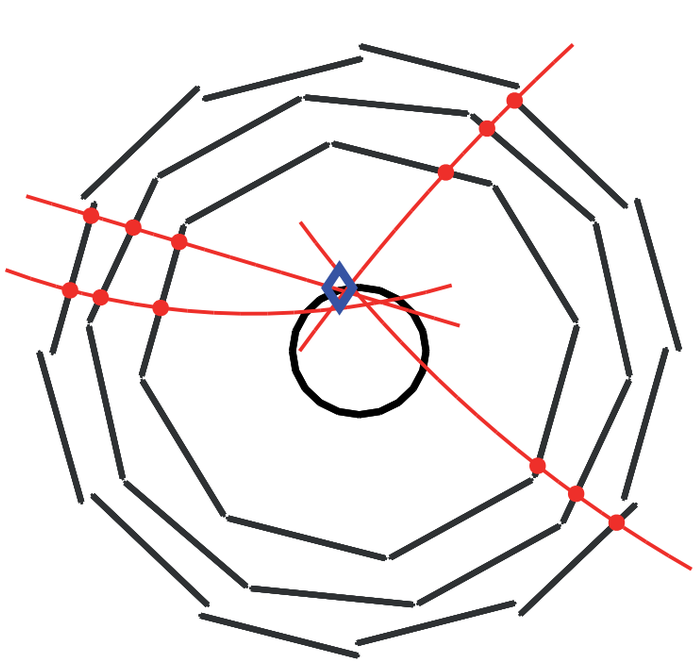
Well depth is ~0.8 T equivalent 0.54 K for ground state (anti)hydrogen

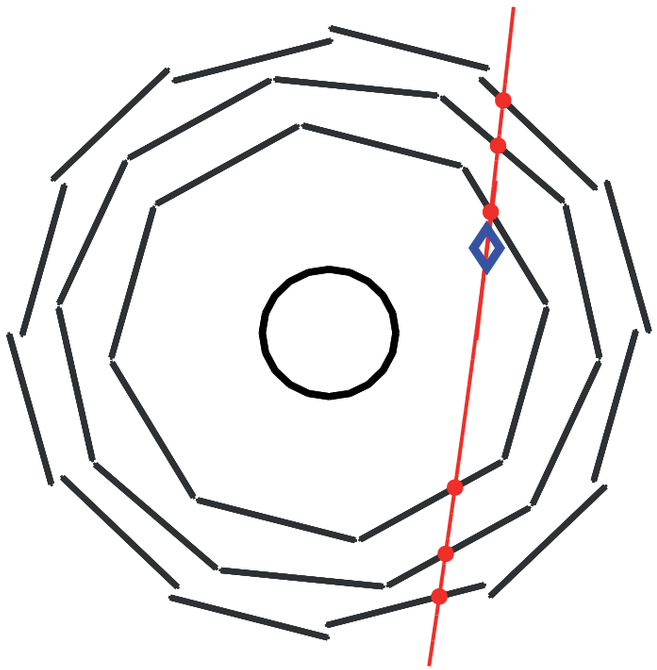
Ramp down/Quench of trap $\tau = 9$ ms

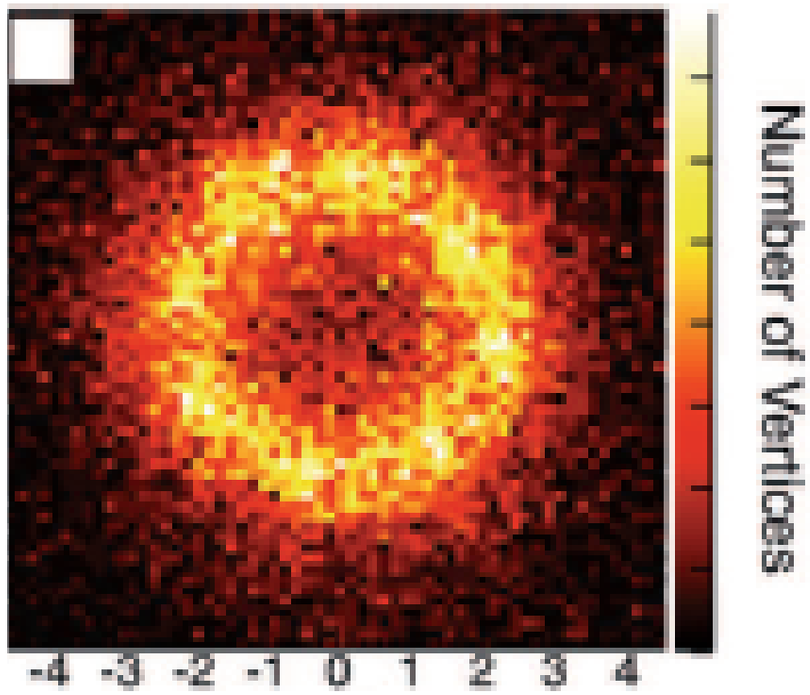
Number of quenches: a couple of thousands

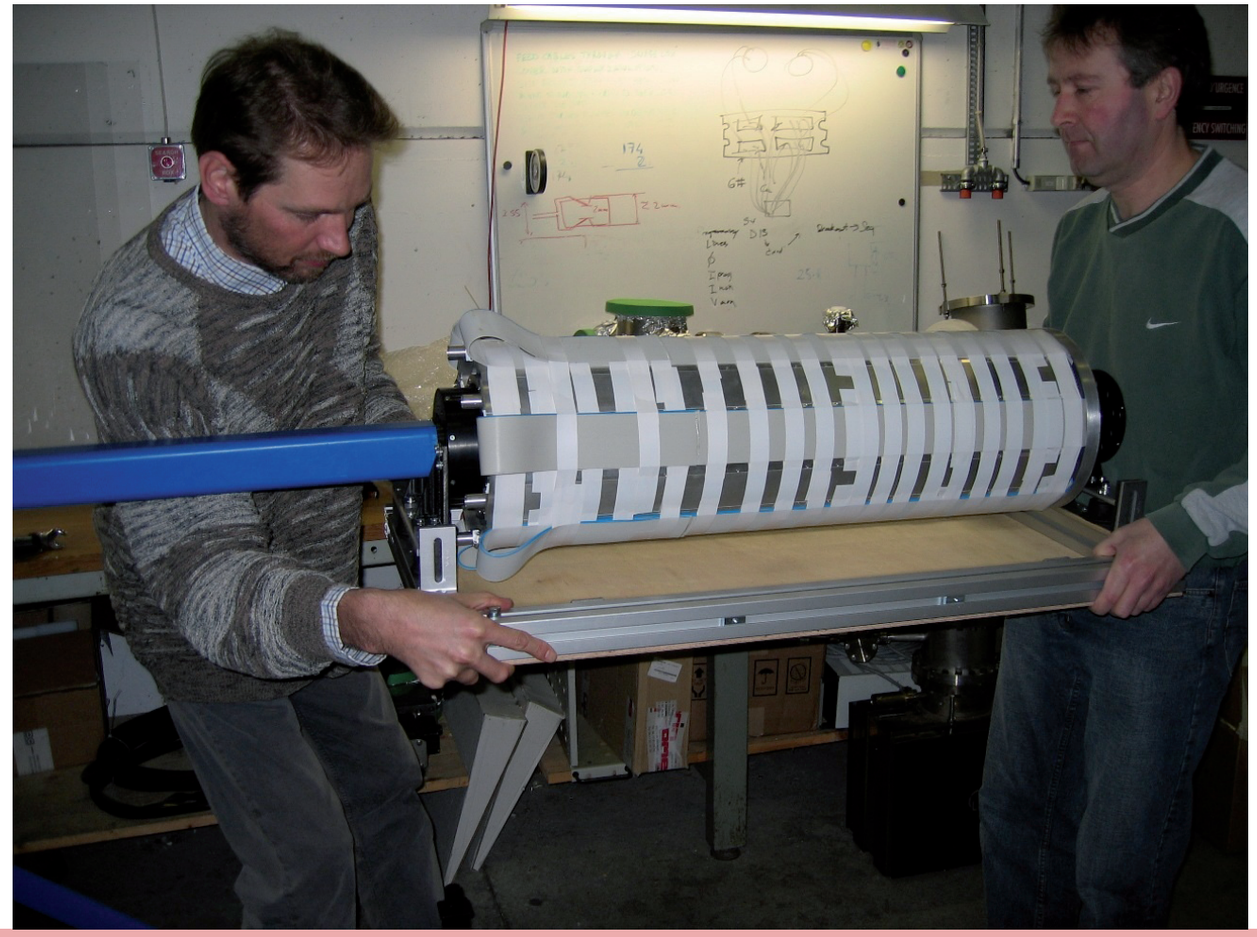
W. Bertsche et al (ALPHA collaboration)
Nucl. Instr. Meth. Phys. Res. A **56**, 746 (2006)

Detector

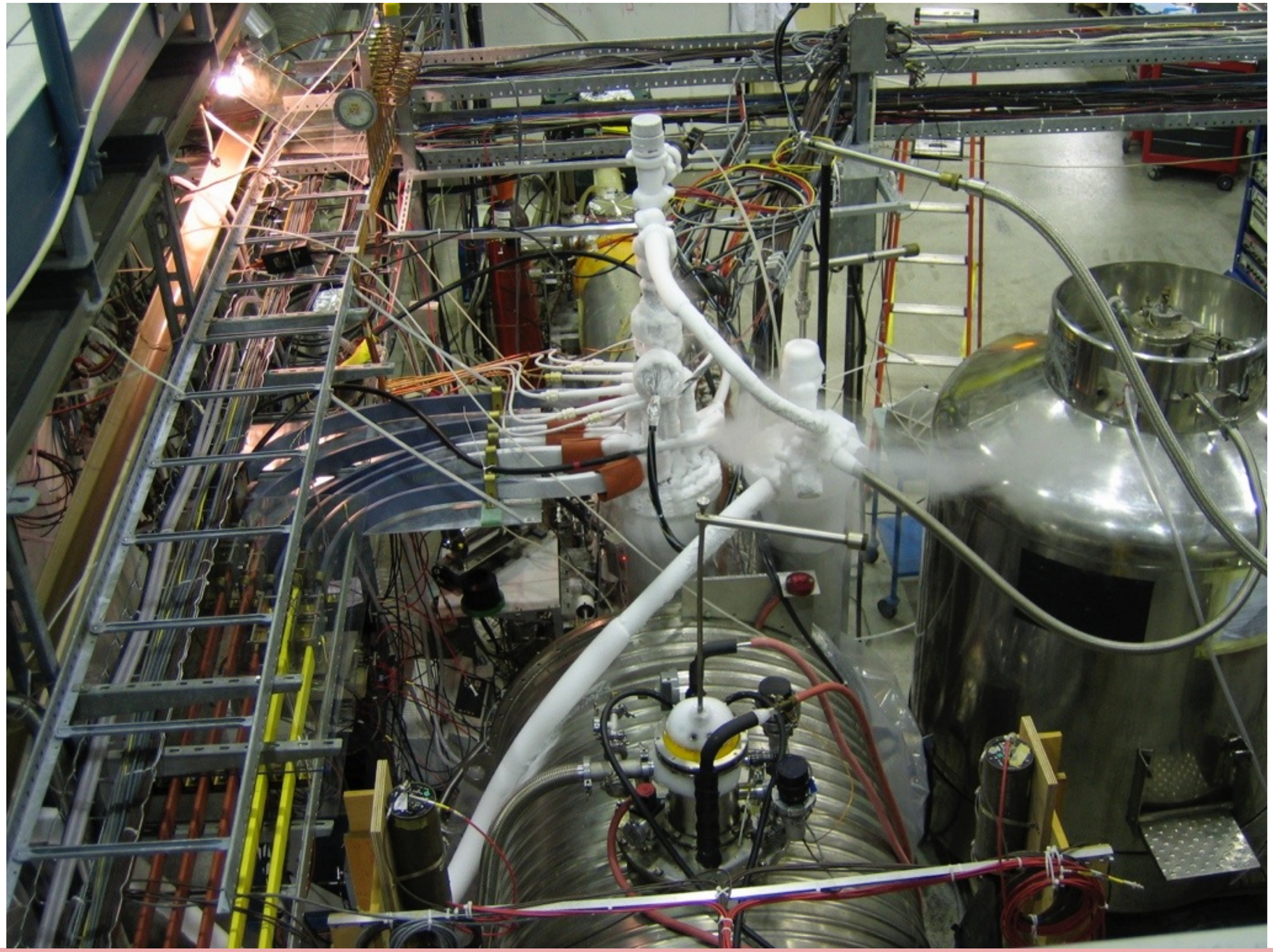




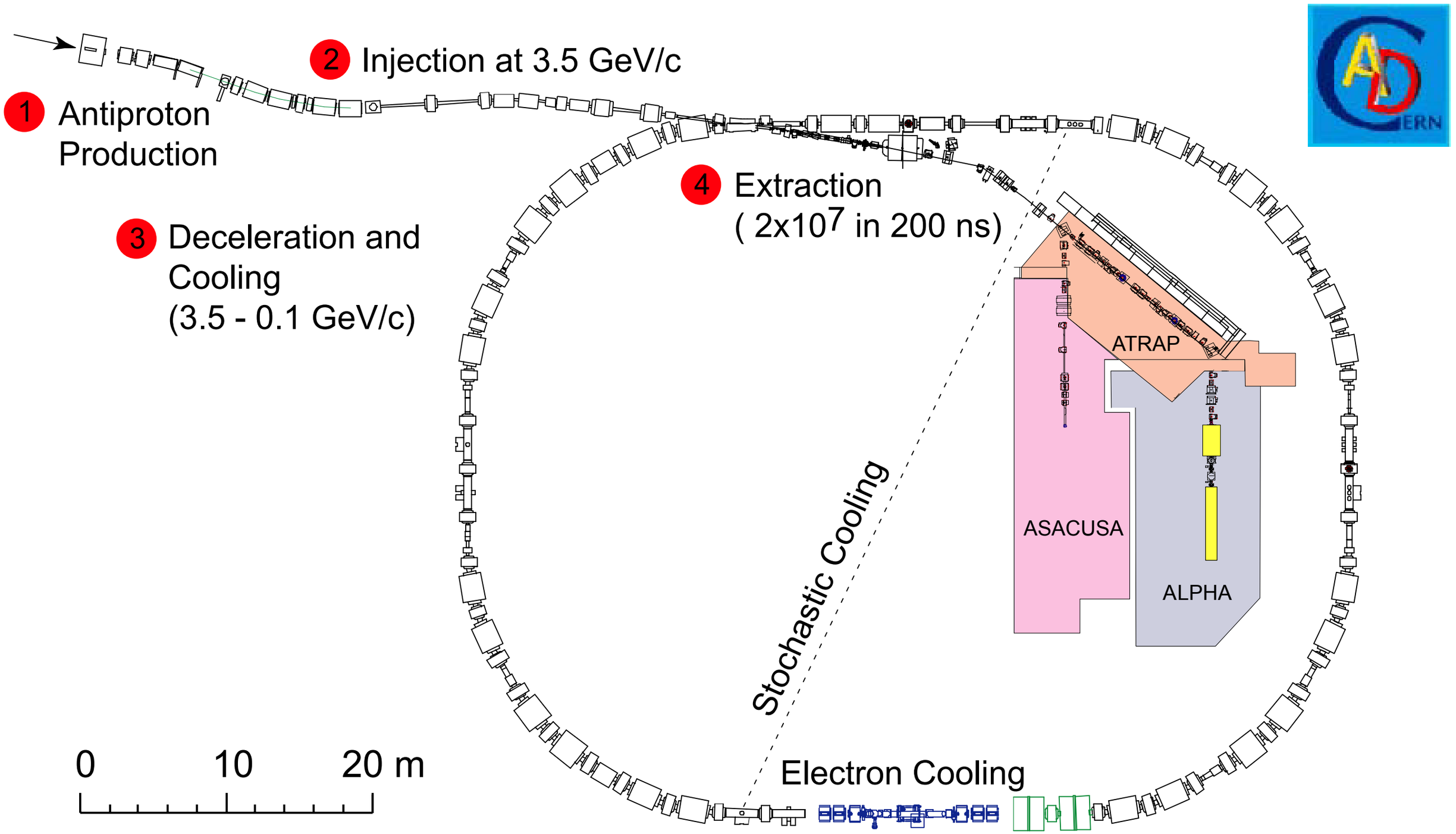




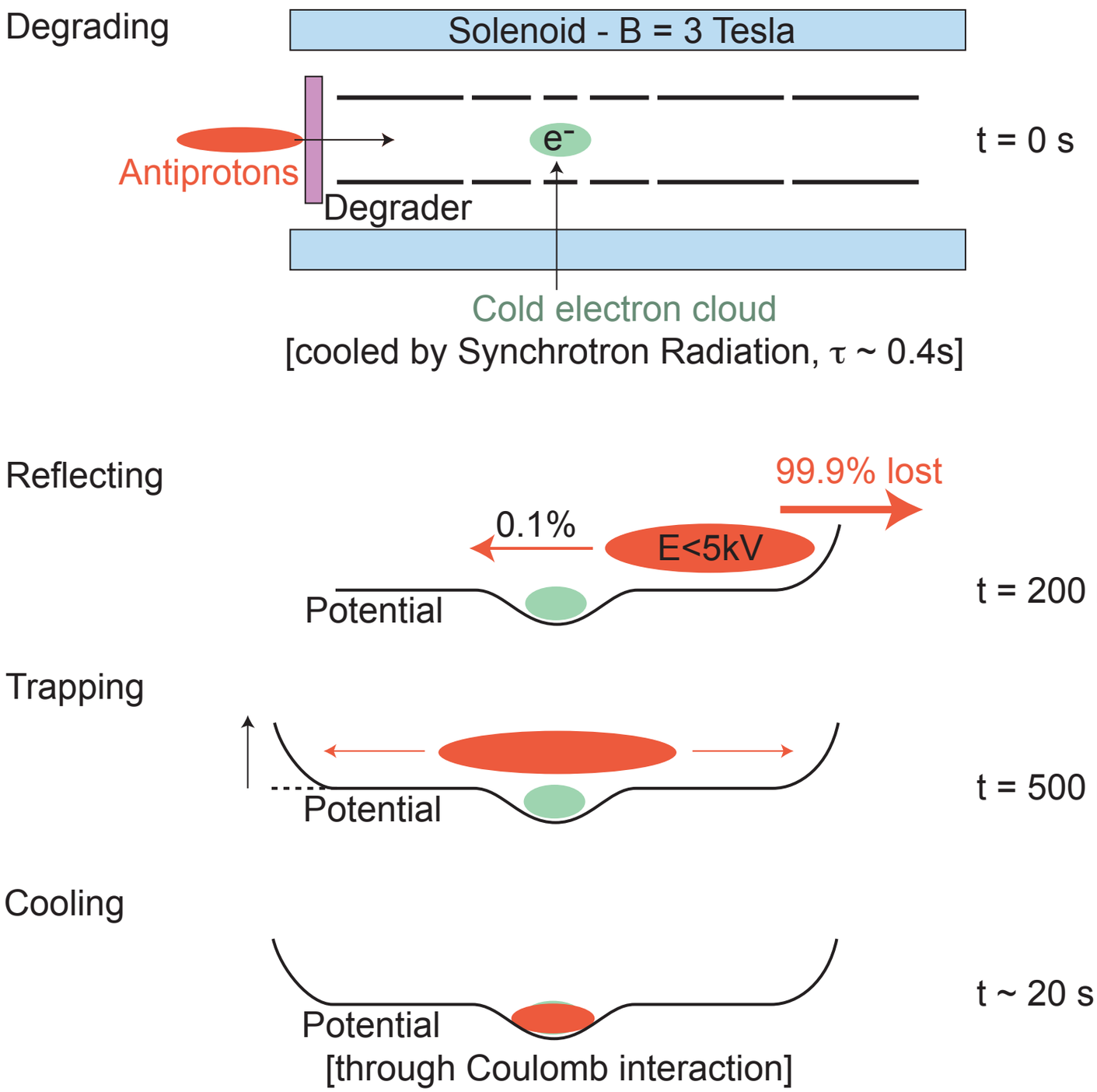
Alpha Apparatus



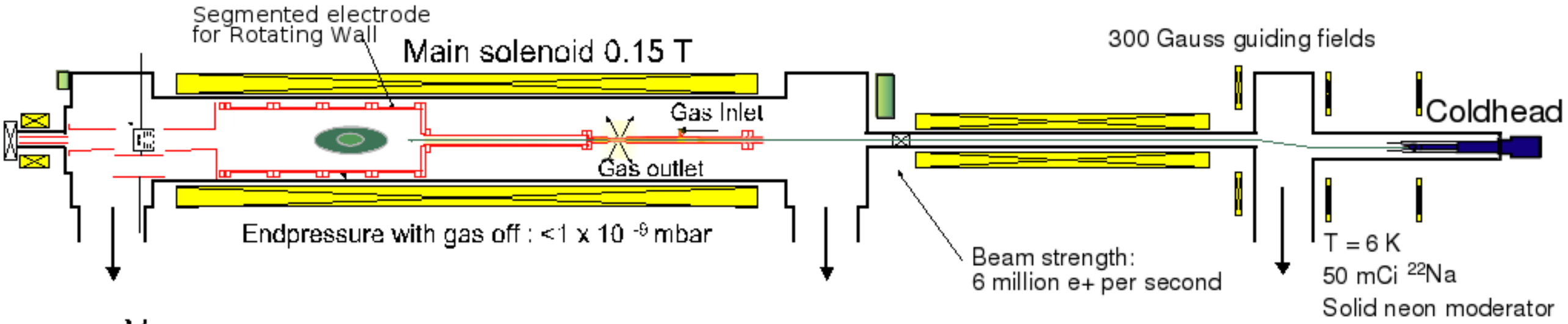
Antiproton Decelerator

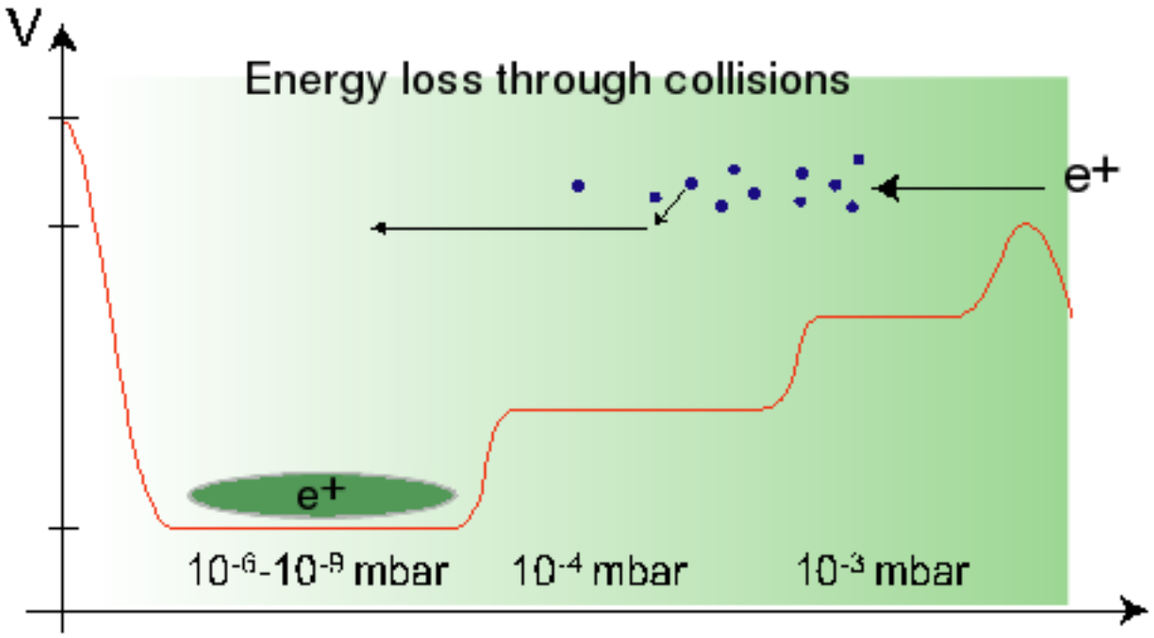


$\bar{p}$ trapping



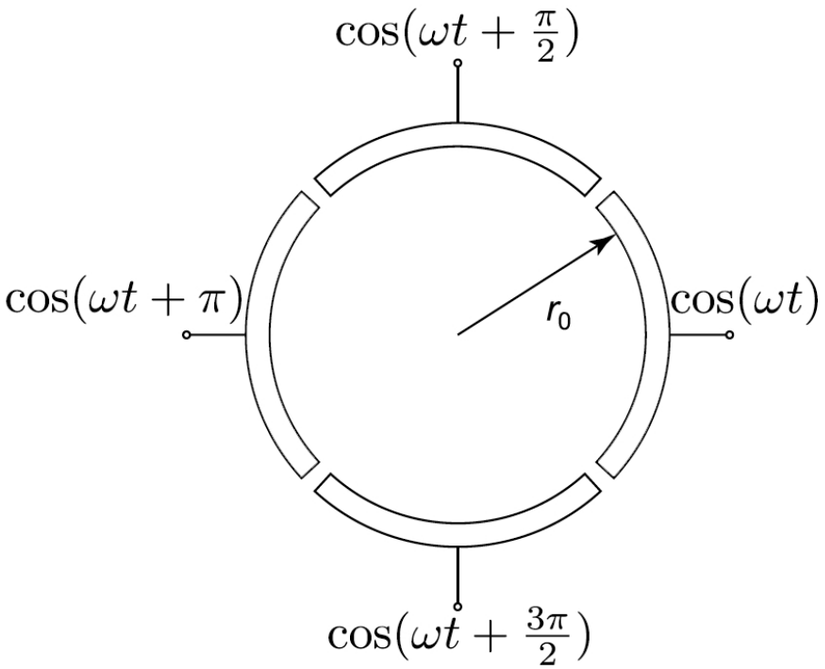
e^+ trapping



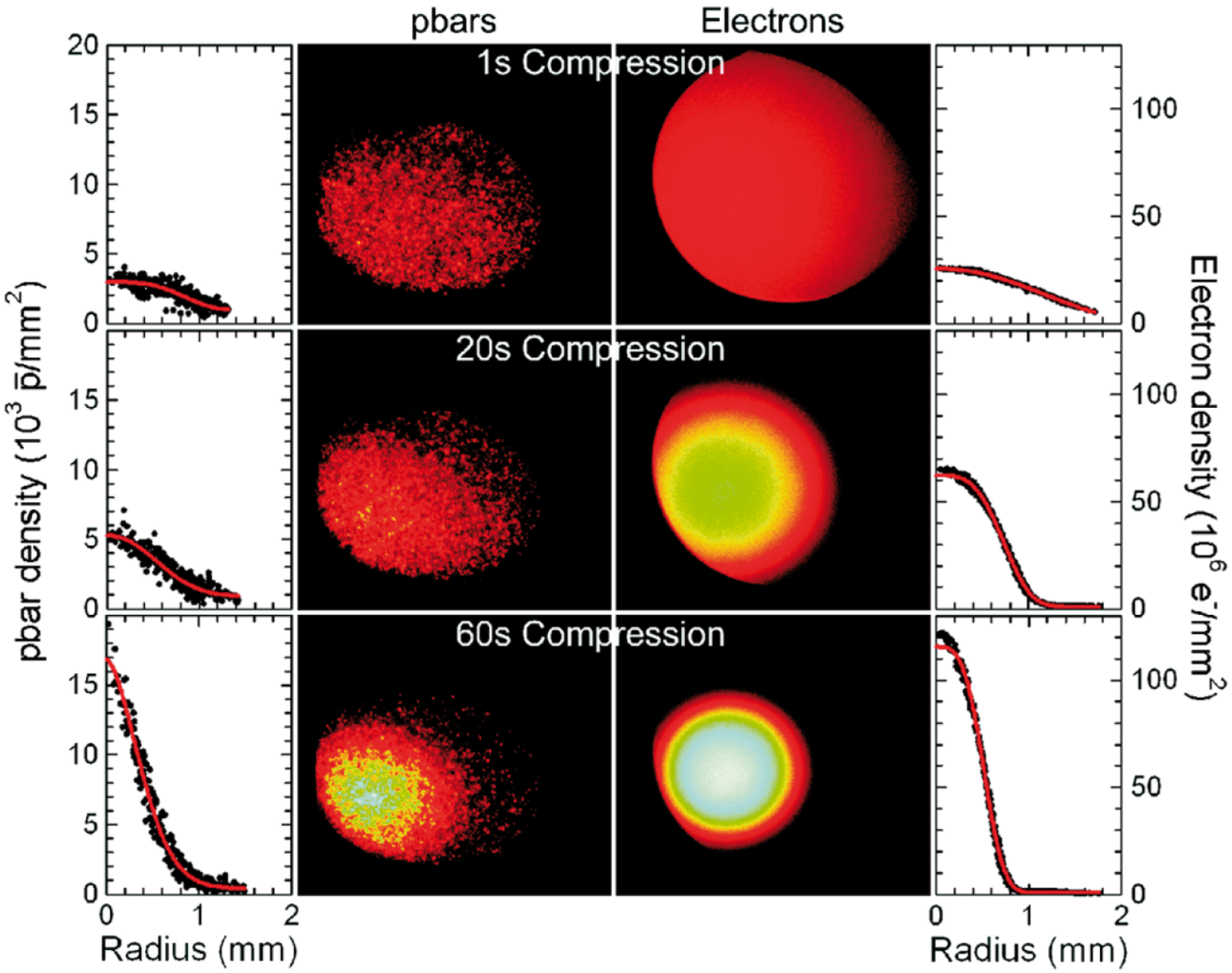


T. J. Murphy and C. M. Surko, *Phys. Rev. A* **46**, 5696 (1992)

Compression using a Rotating Wall Electric Field



X.-P. Huang *et al.*, *Phys. Rev. Lett.* **78**, 875 (1997)

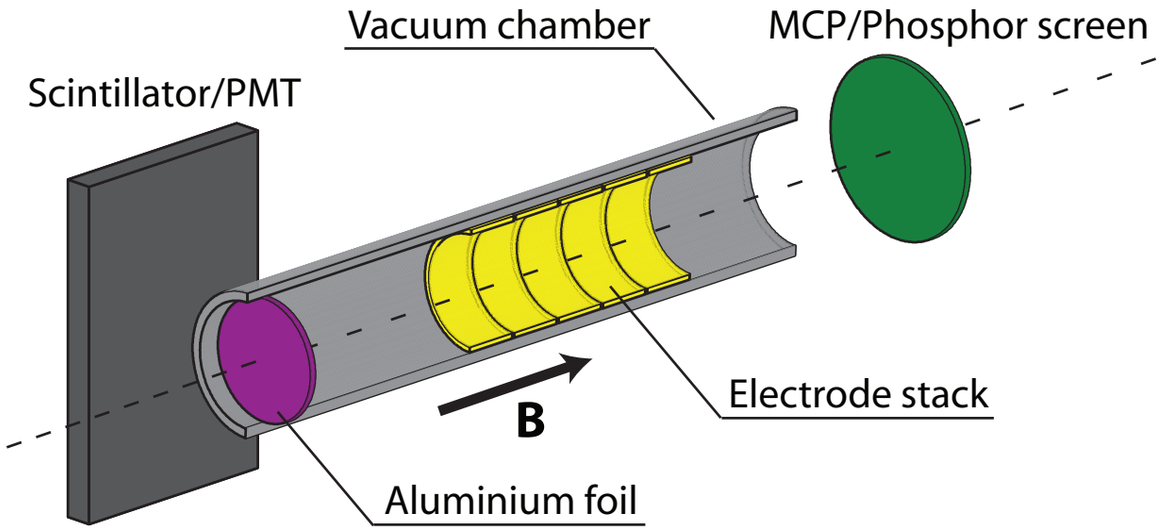


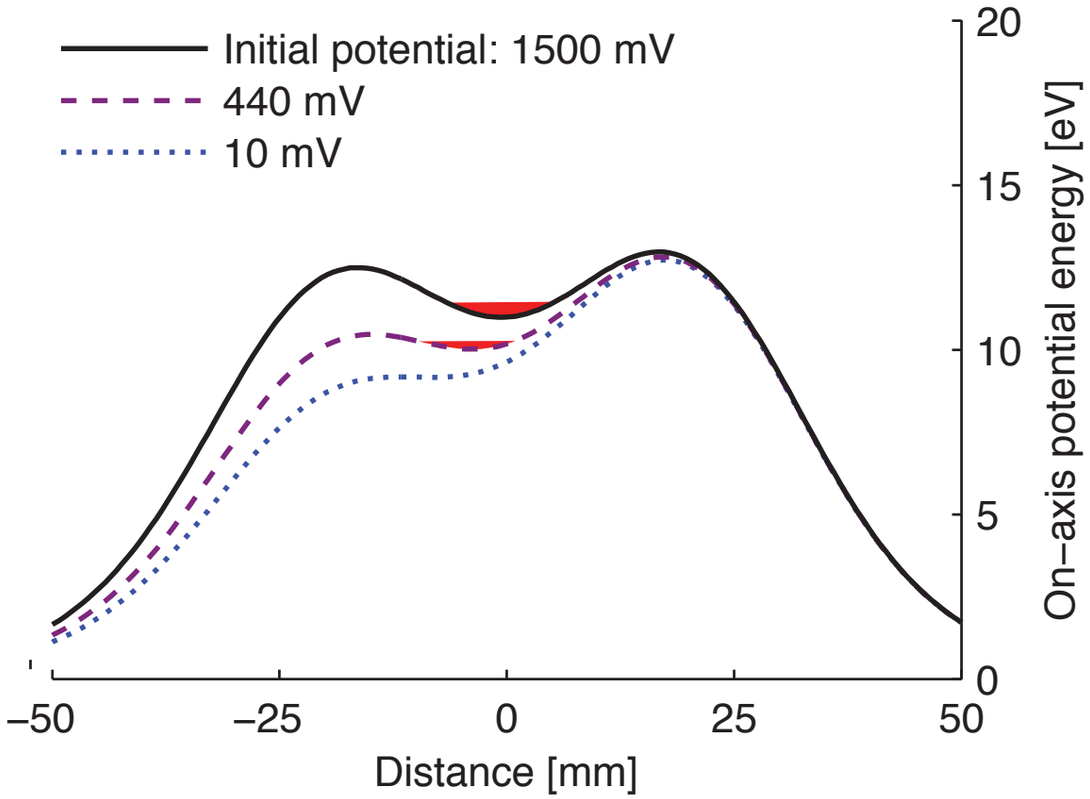
G. B. Andresen *et al.* (ALPHA collaboration)
Phys. Rev. Lett. **100**, 203401 (2008)

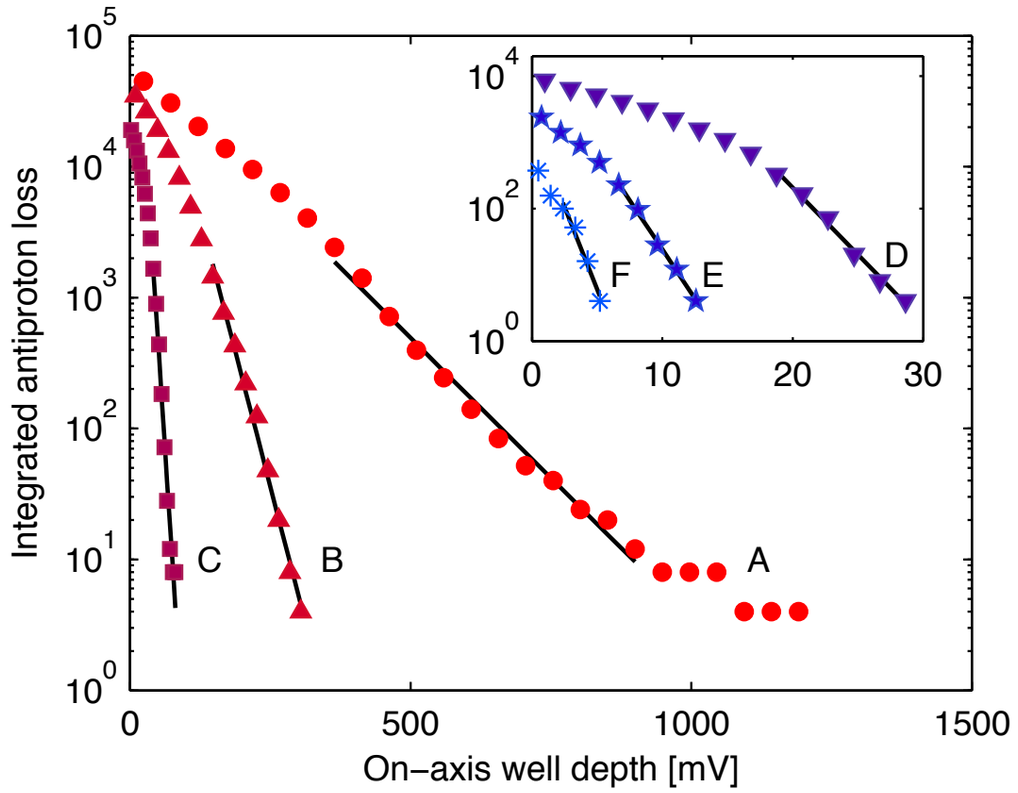
Without electrons

N. Kuroda *et al* (ASACUSA collaboration)
Phys. Rev. Lett. **100**, 203402 (2008)

Evaporative Cooling



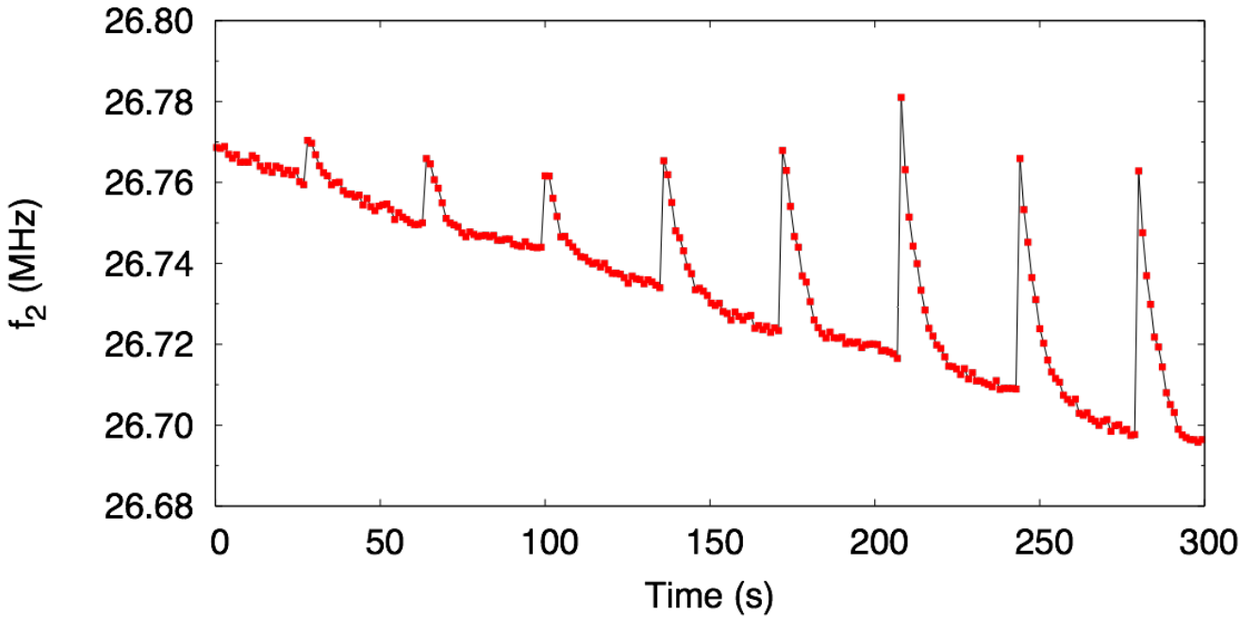




A: 1040 K
B: 325 K
C: 57 K
D: 23 K
E: 19 K
F: 9 K

G. B. Andresen et al. (ALPHA collaboration)
Phys. Rev. Lett. **105**, 013003 (2010)

Magnetic field measurements



Cyclotron excitation

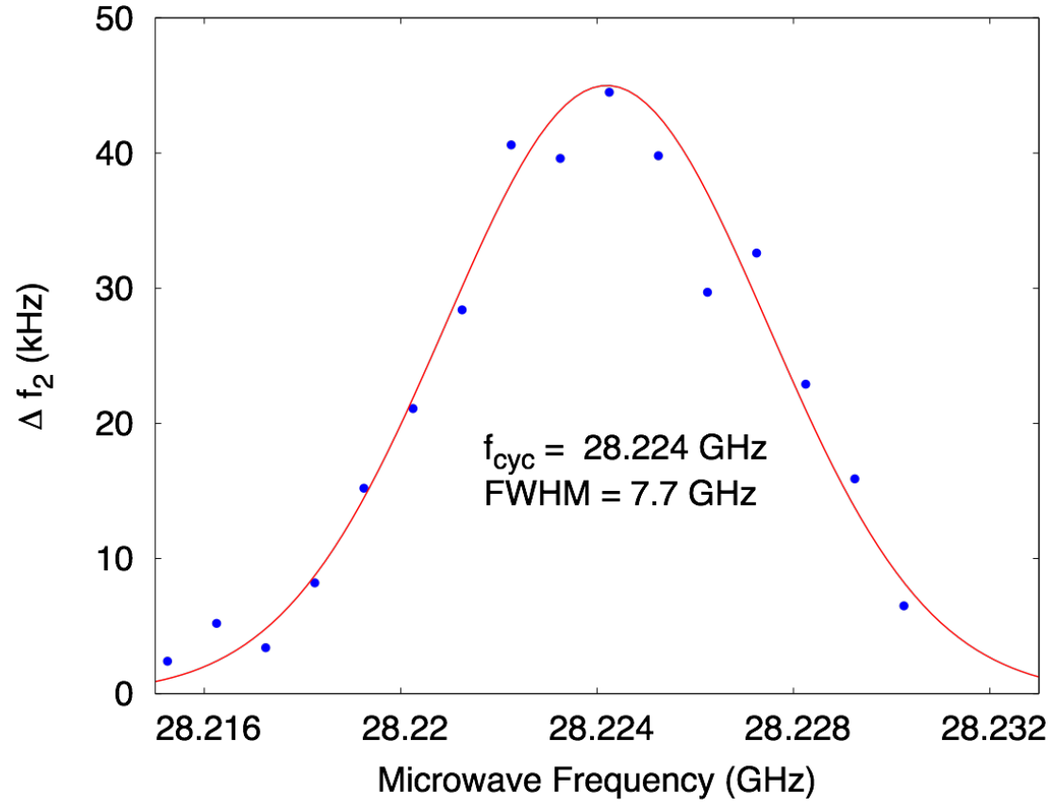
↓

Heat non-neutral electron plasma

↓

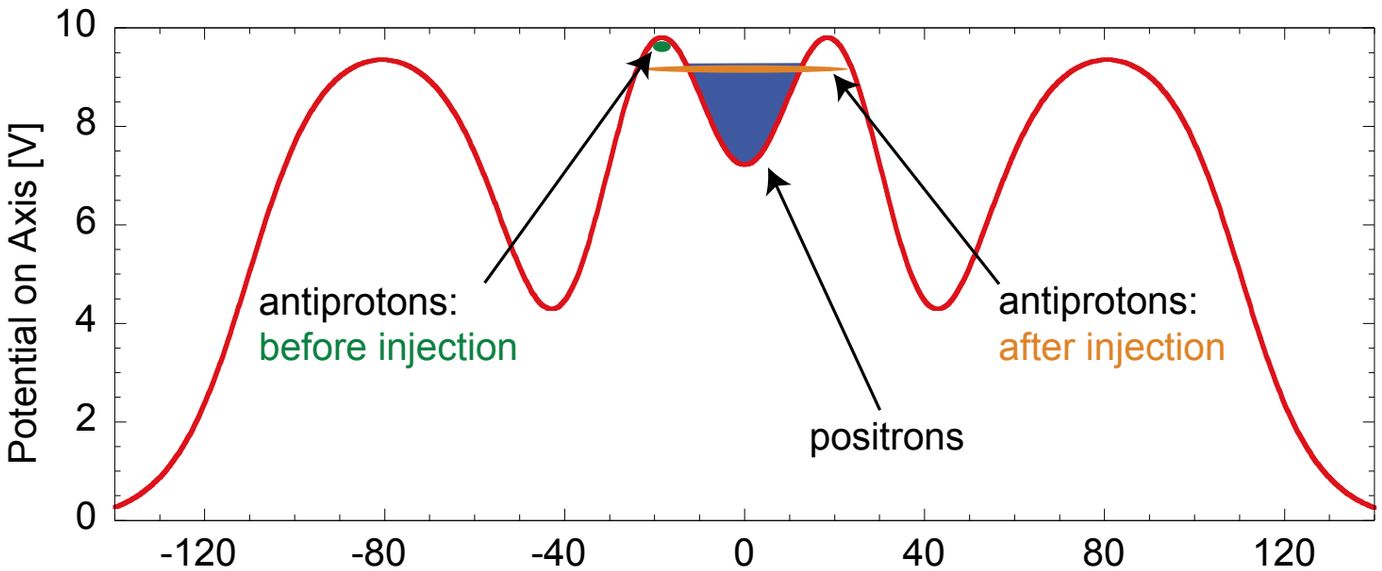
Change quadrupole mode frequency f_2

Typical measurement



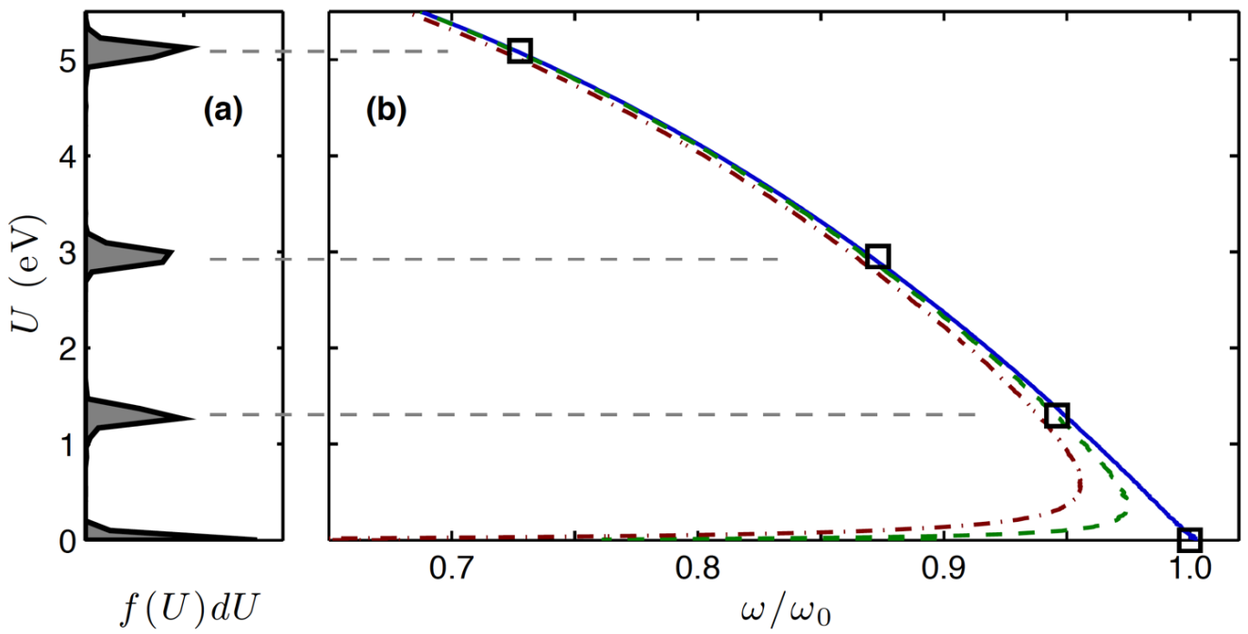
Mixing

Nested Penning Trap



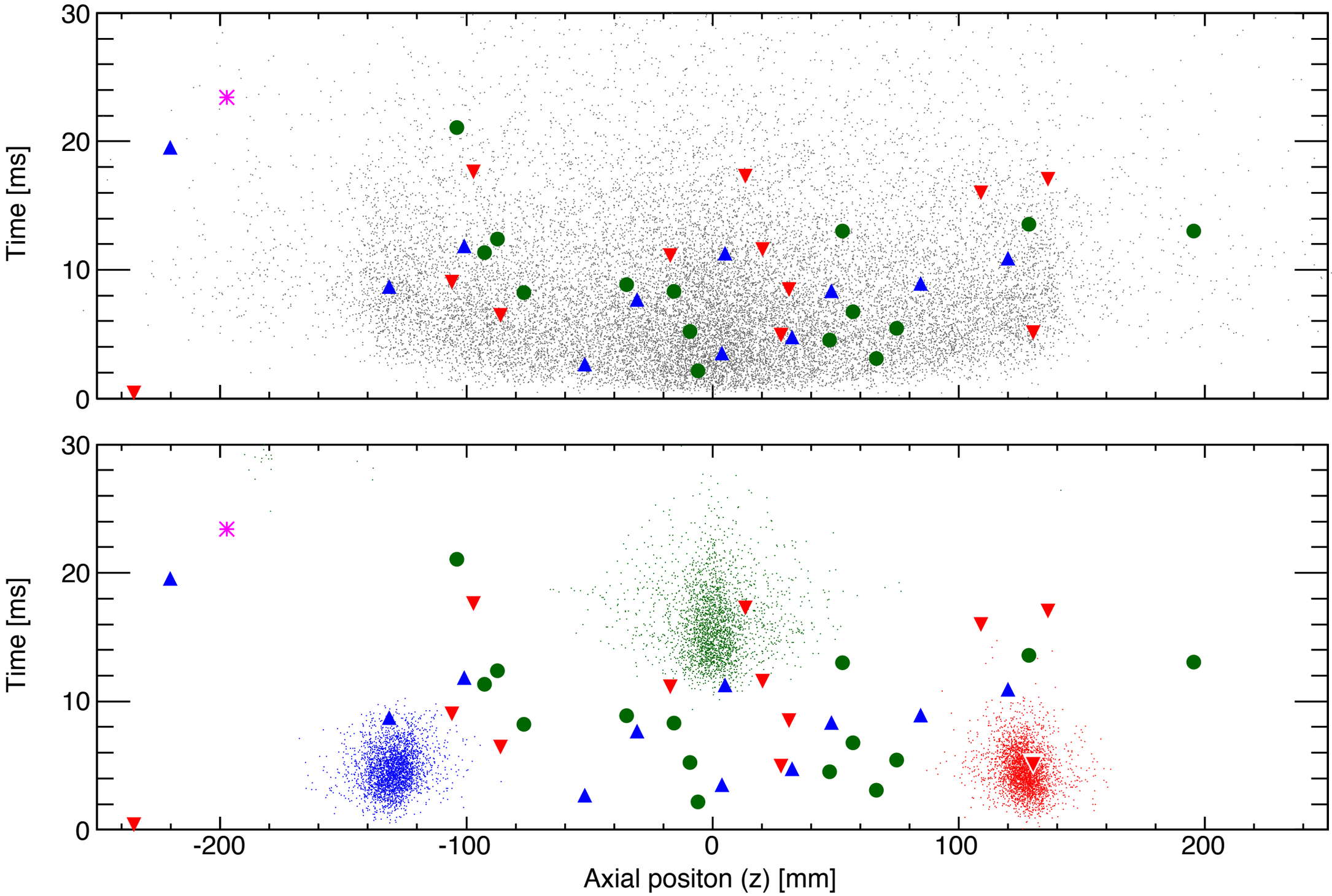
G. Gabrielse *et al. Phys. Lett. A* **129**, 38 (1988)

Autoresonance



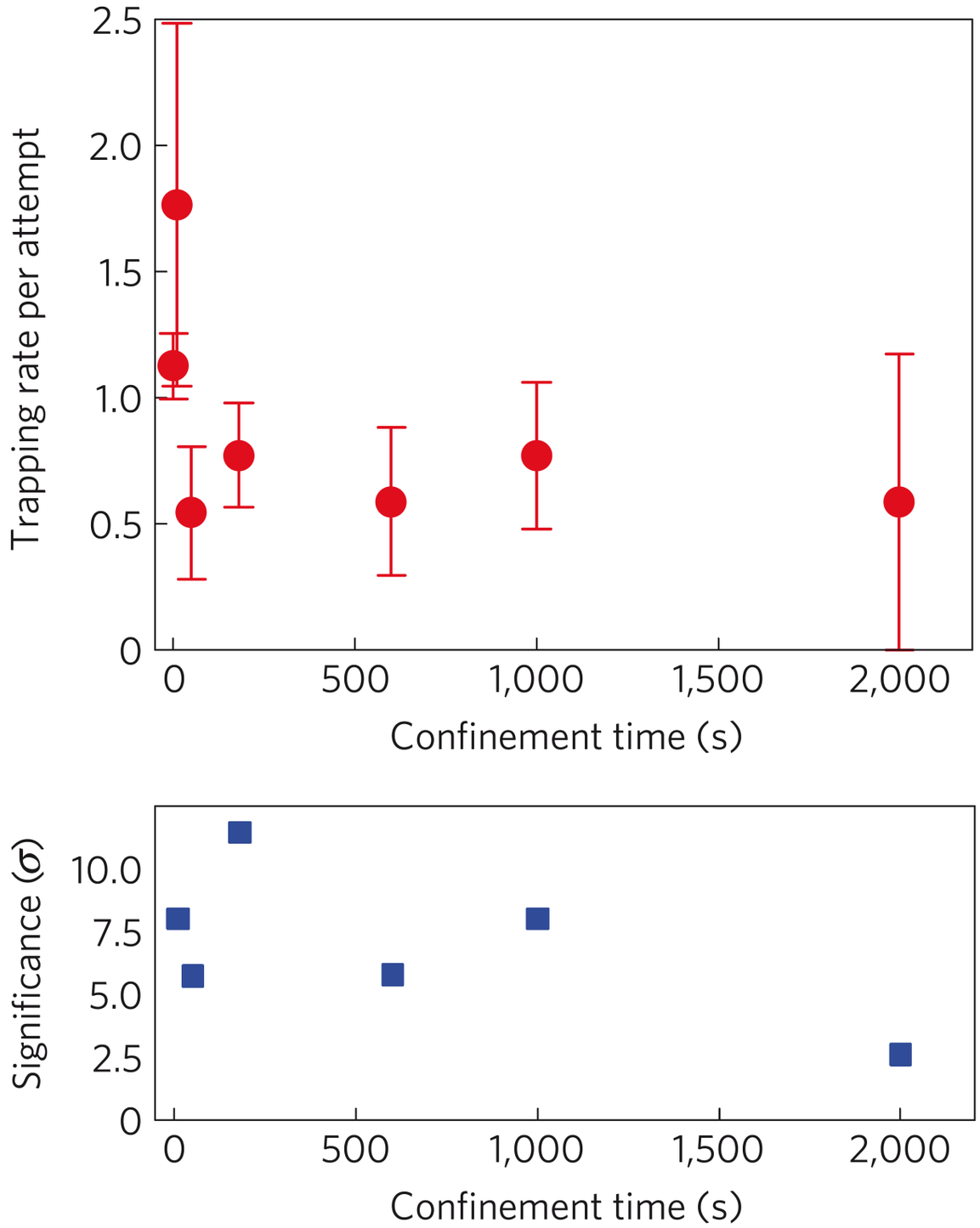
G.B. Andresen *et al.* (ALPHA collaboration) *Phys. Rev. Lett.* **106**, 025002 (2011)

Trapping



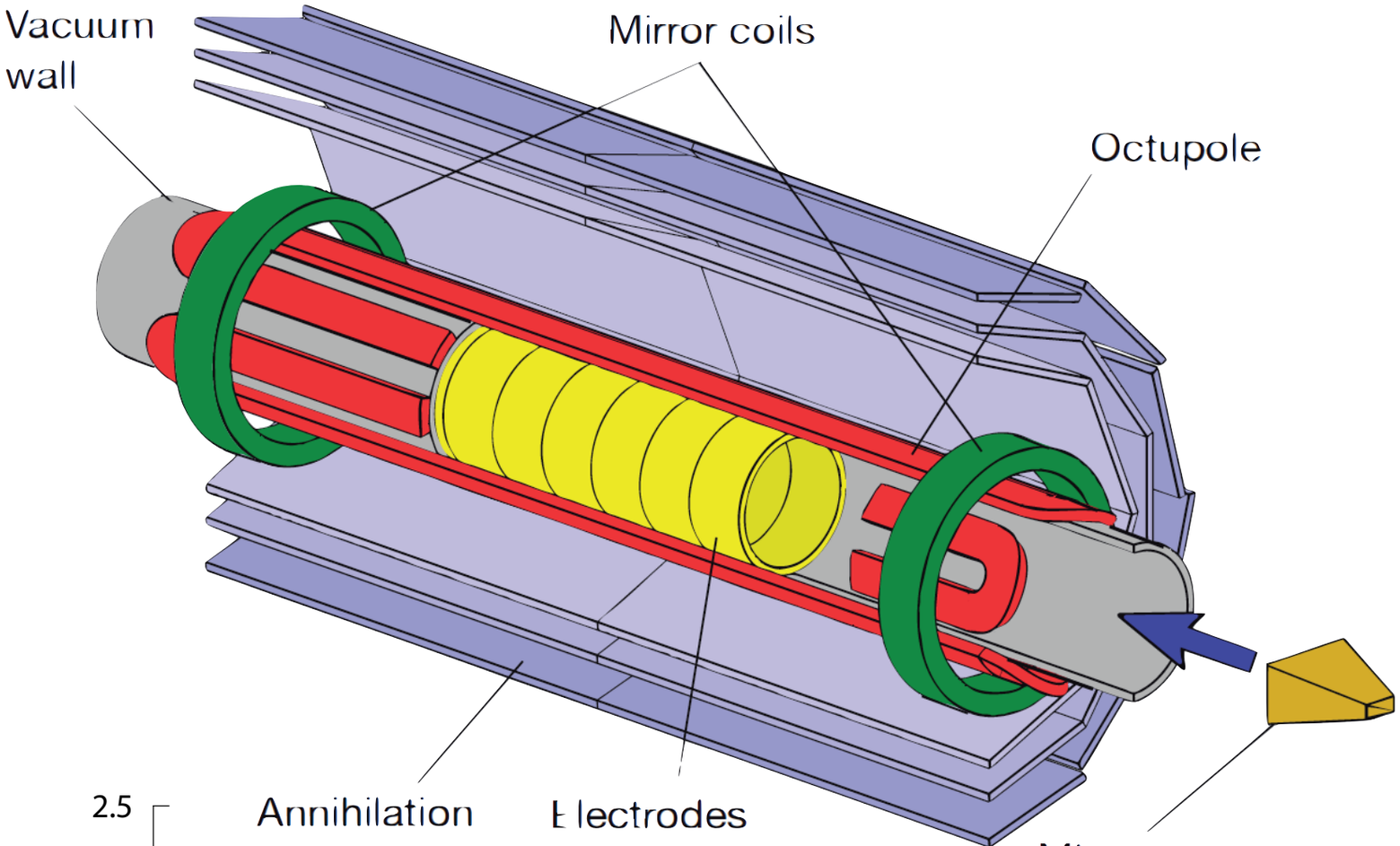
G. B. Andresen et al (ALPHA collaboration)
Nature **468**, 673 (2010)

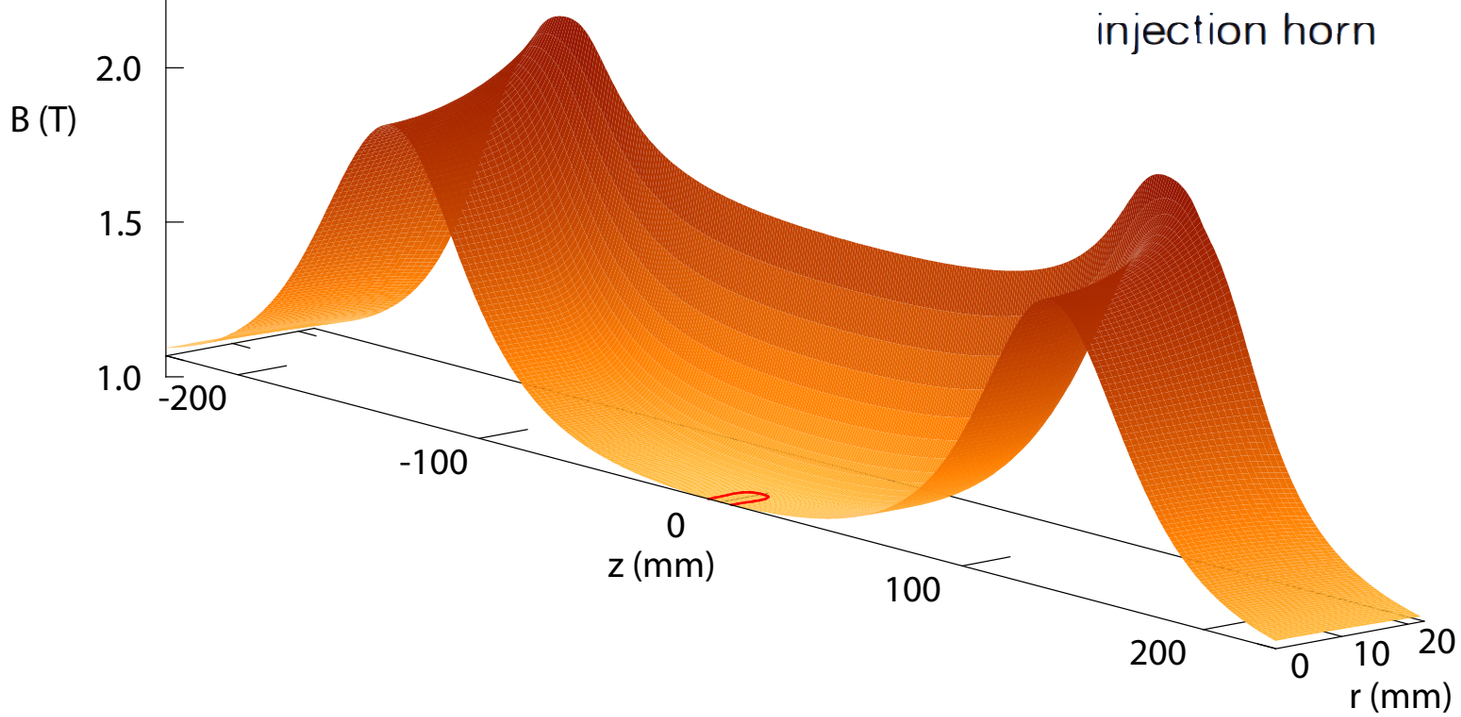
1000 Confinement



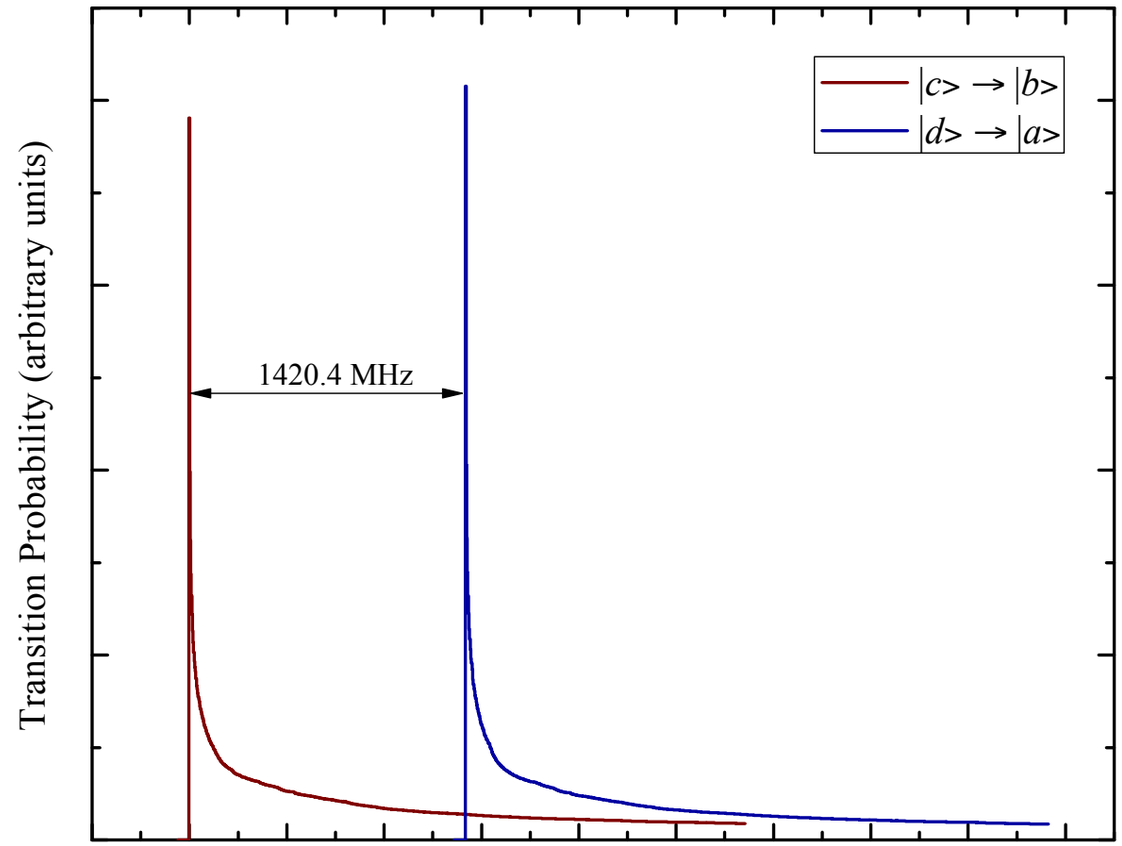
G. B. Andresen et al. (ALPHA collaboration)
Nature Physics **7**, 558 (2011)

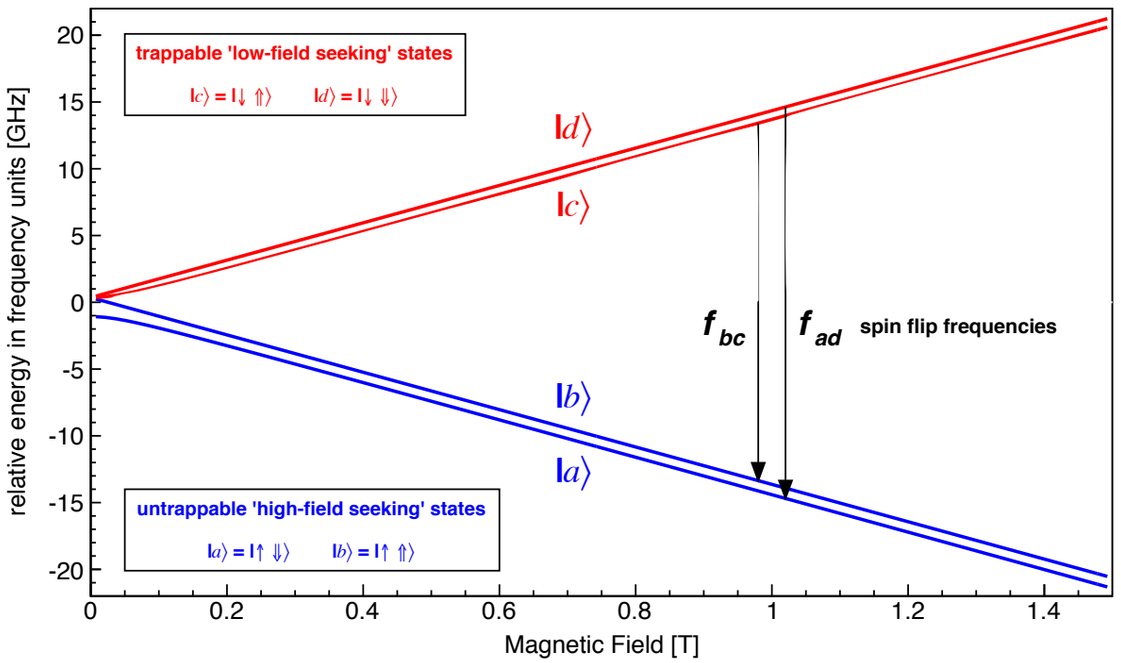
Resonant Quantum Transitions





Simulation of the transition probability





Transition measurements

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

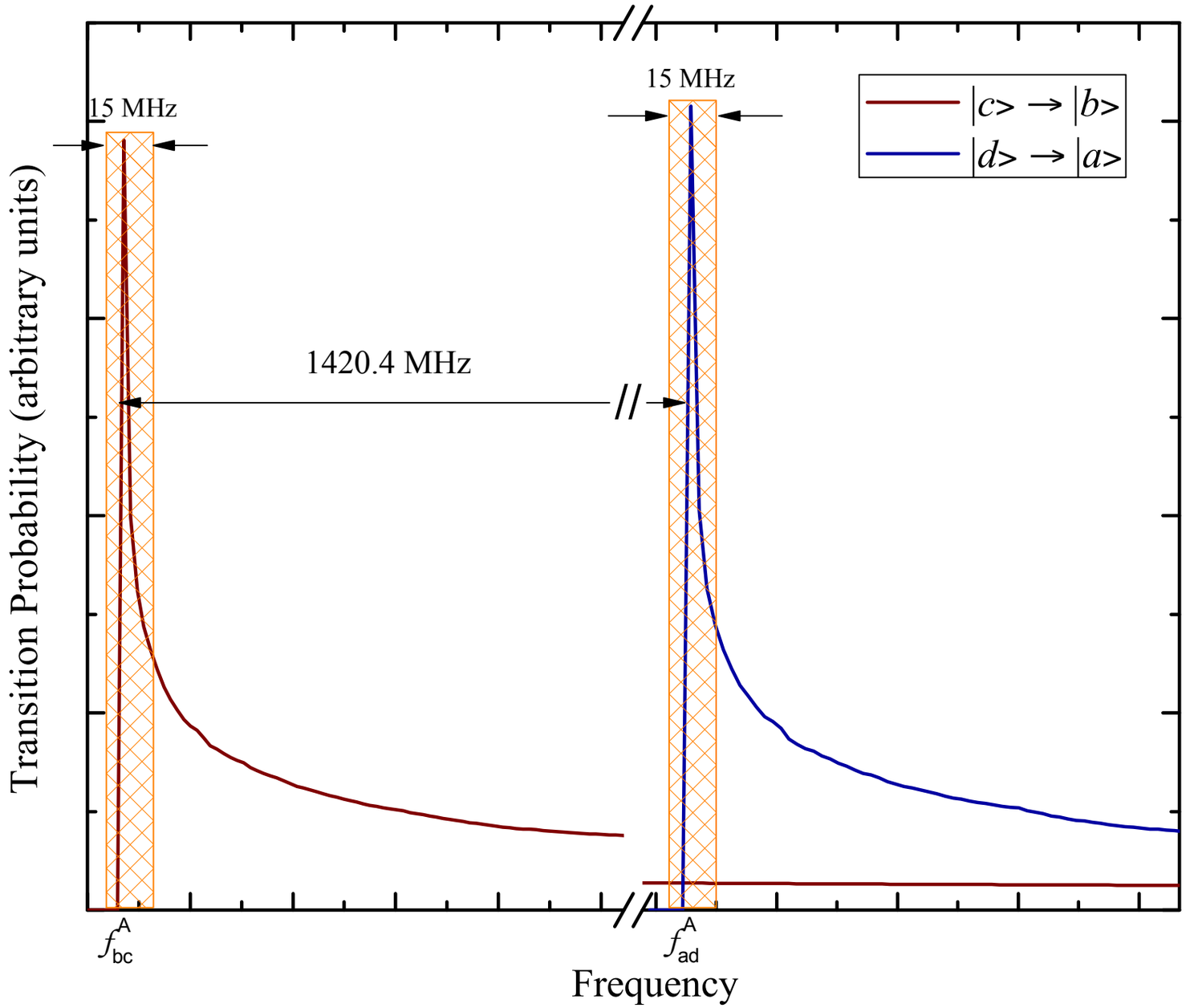
Two data sets

Disappearance mode:

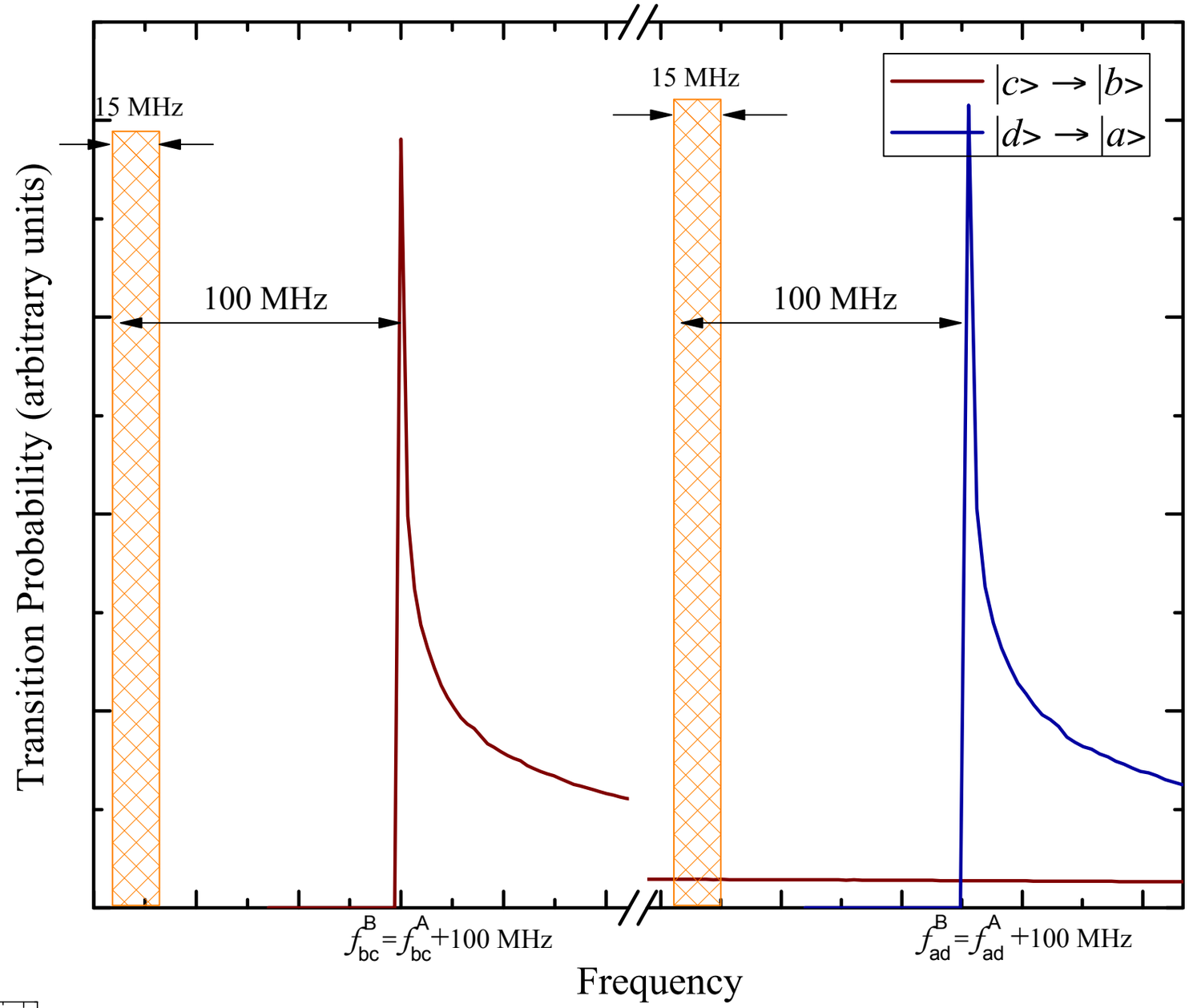
Count the remaining antihydrogen atoms when quenching

Appearance mode:

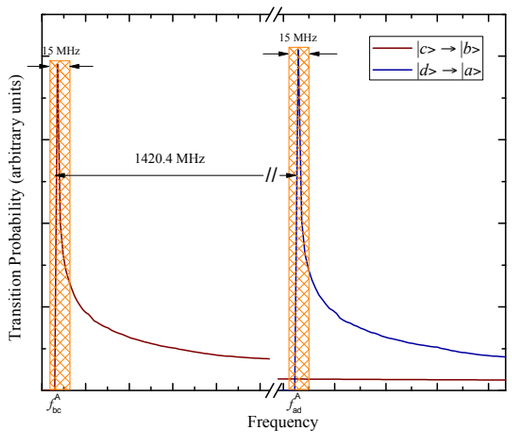
Count the escaping antihydrogen atoms during the microwave injection


Series 1
15 MHz
15 MHz
1420.4 MHz
|c> → |b>
|d> → |a>
Transition Probability (arbitrary units)
f^{A}_{bc}
f^{A}_{ad}
Frequency

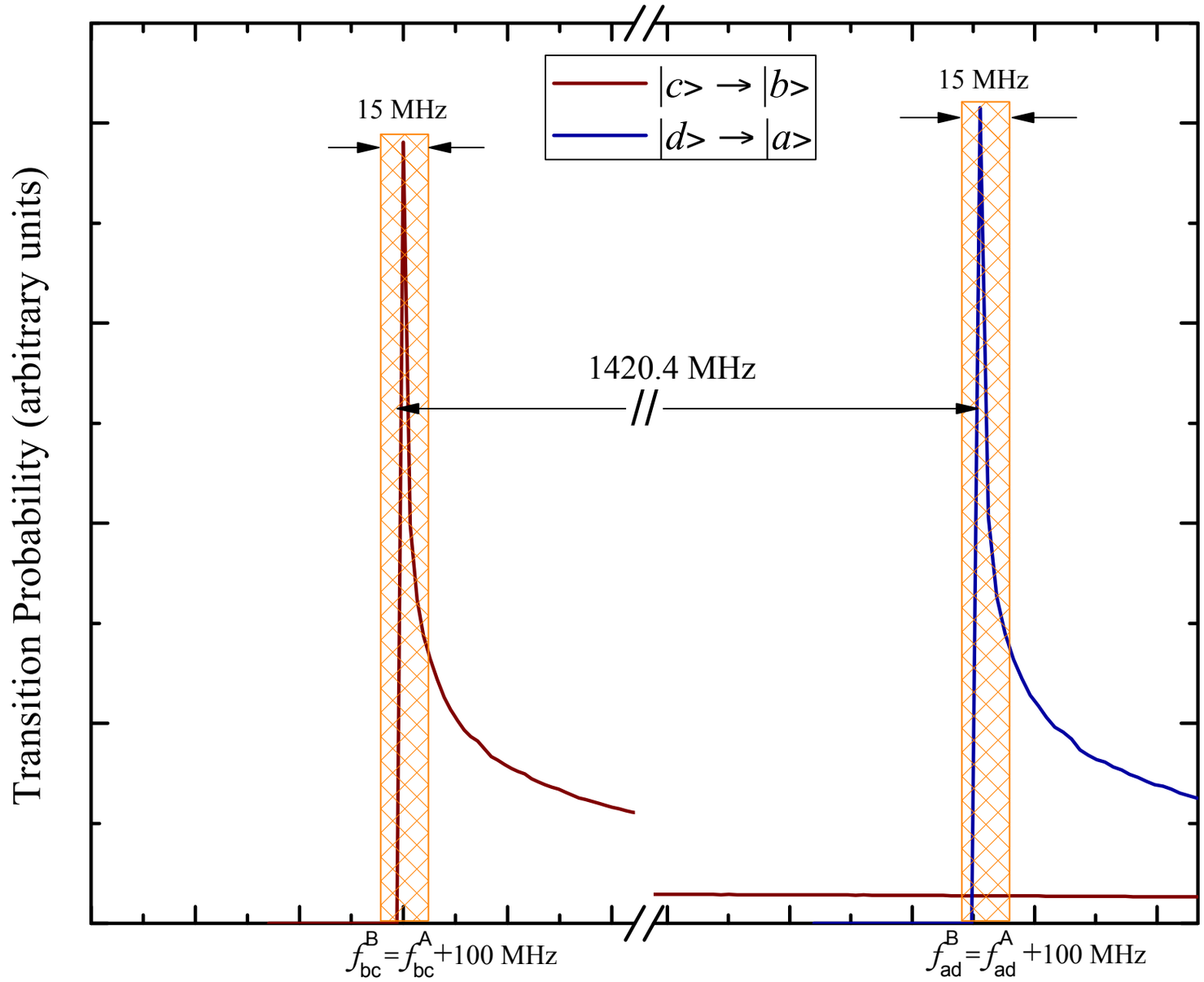
Series 2 & 4



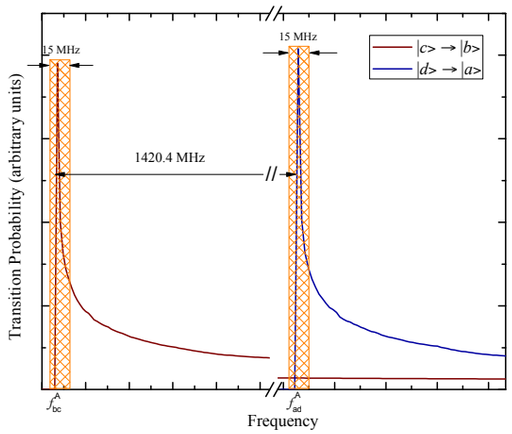
Series 1



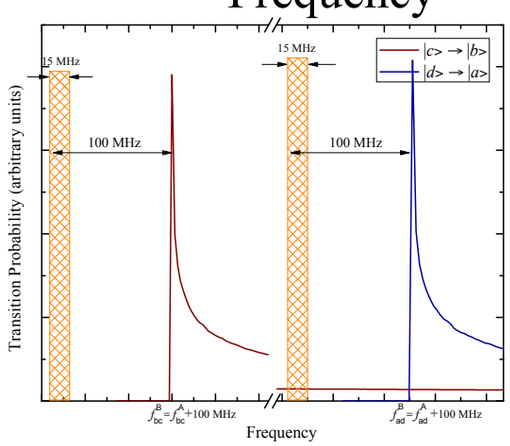
Series 3



Series 1



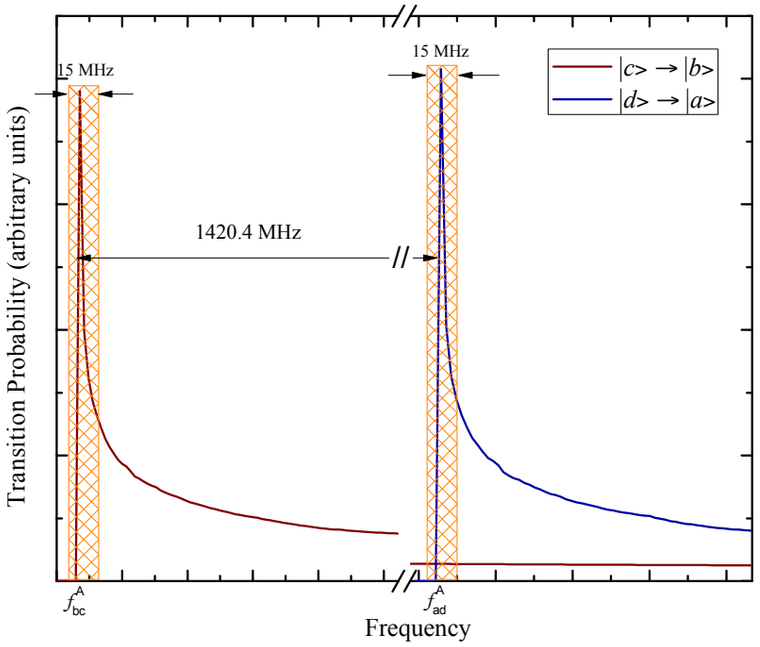
Series 2



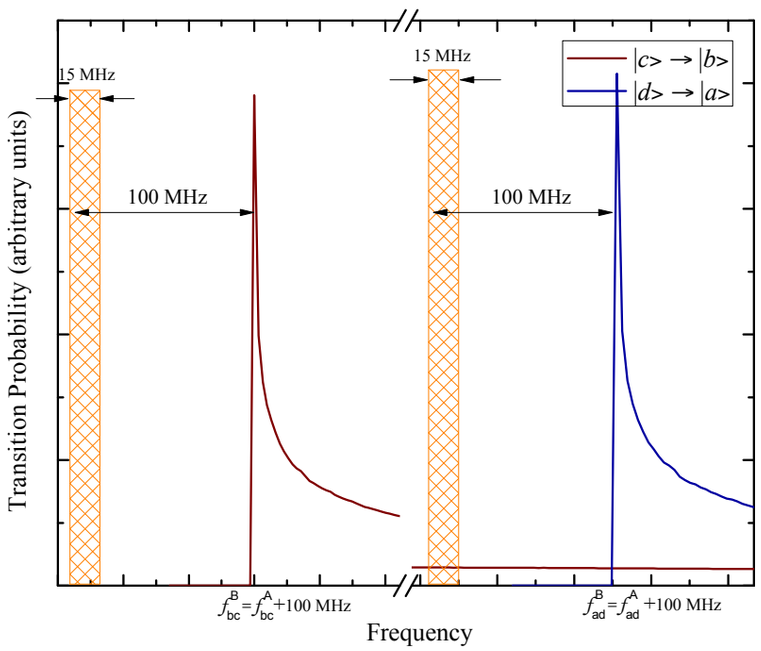
Totals for all ‘disappearance mode’ series

	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

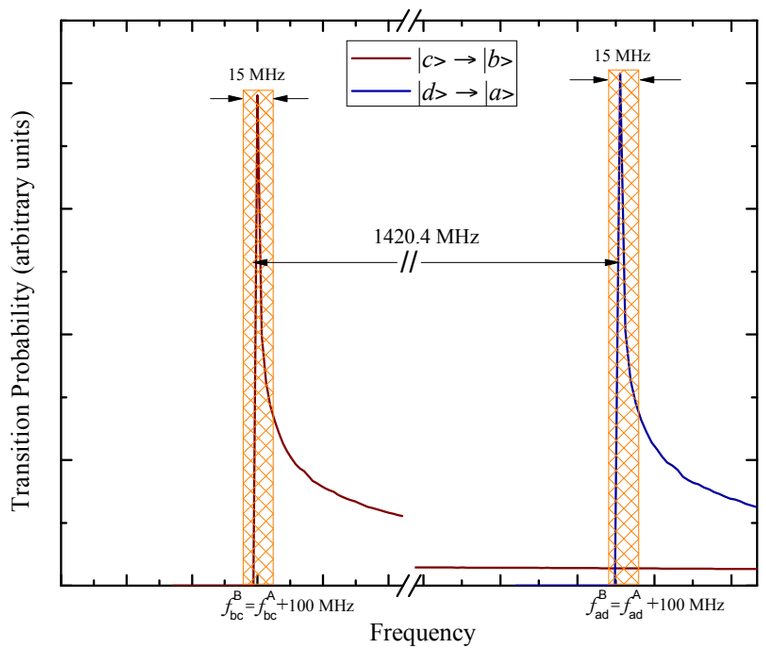
Series 1



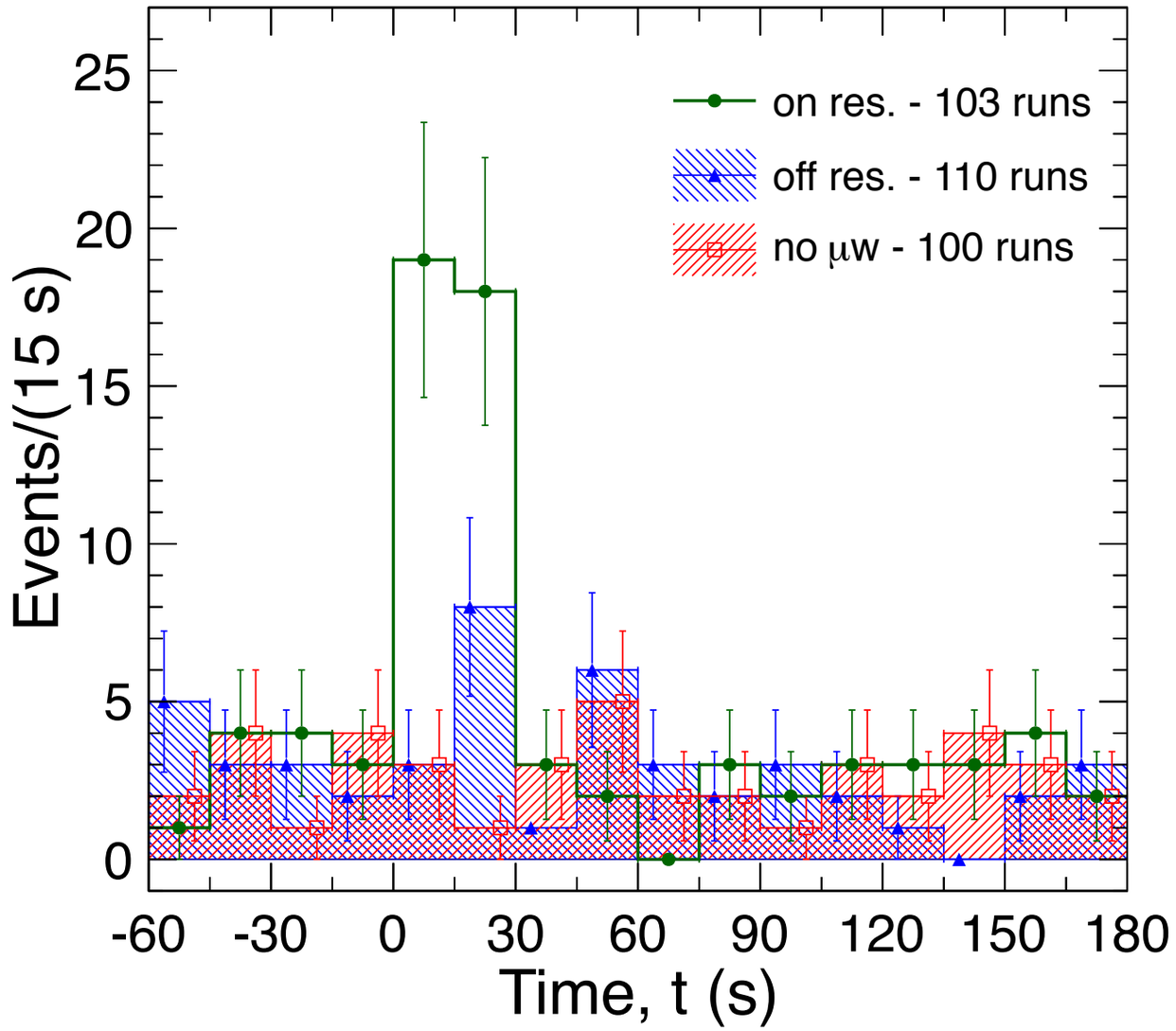
Series 2 & 4

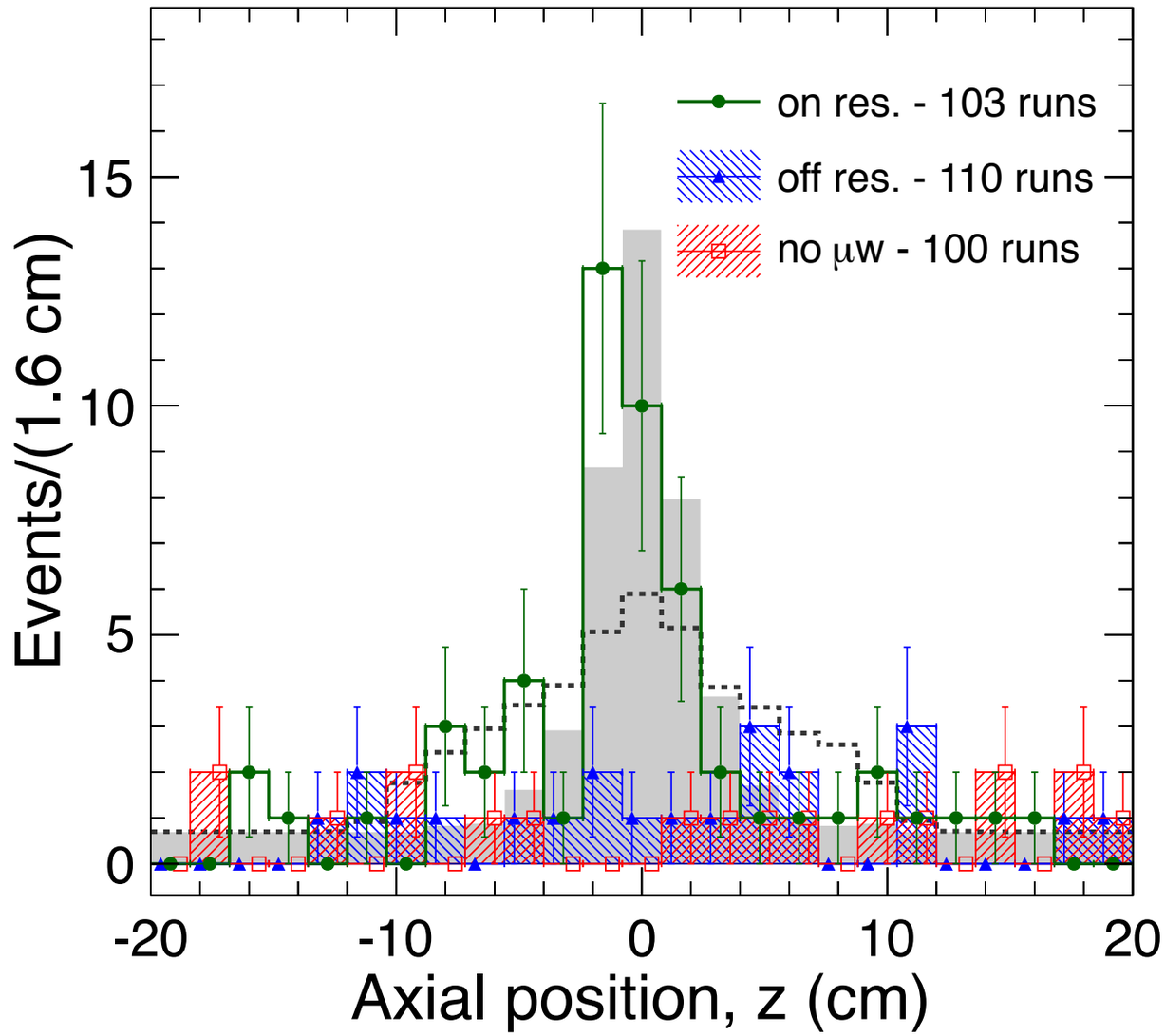


Series 3



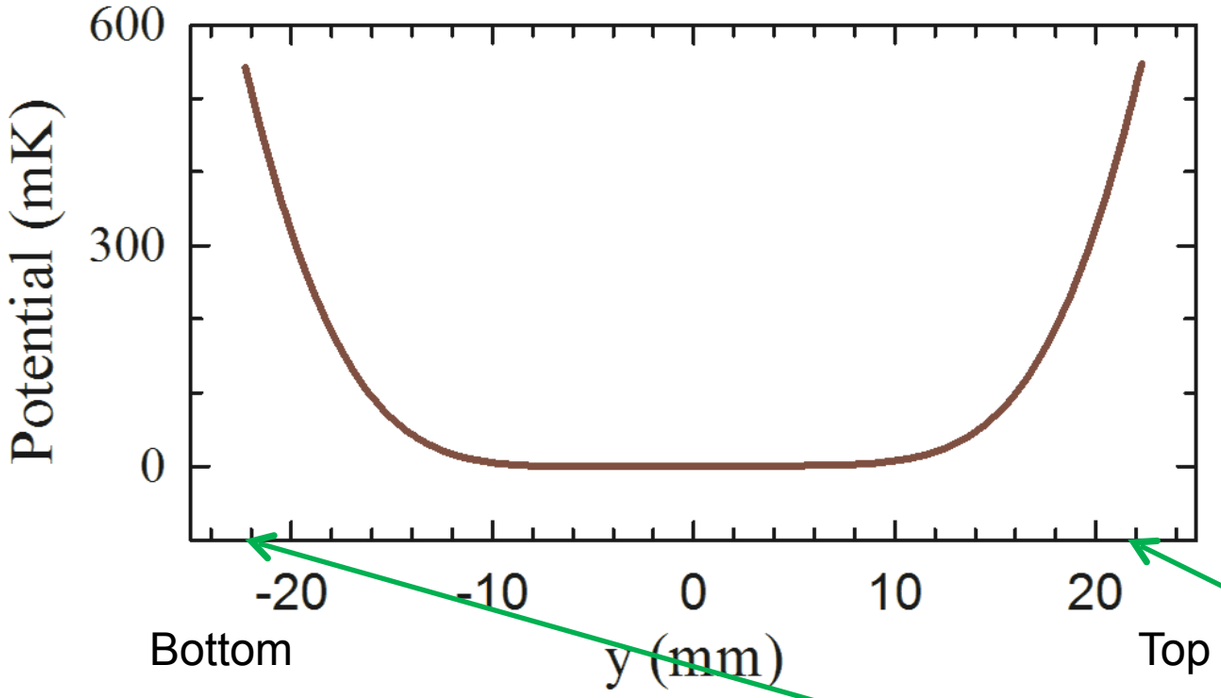
Appearance measurements



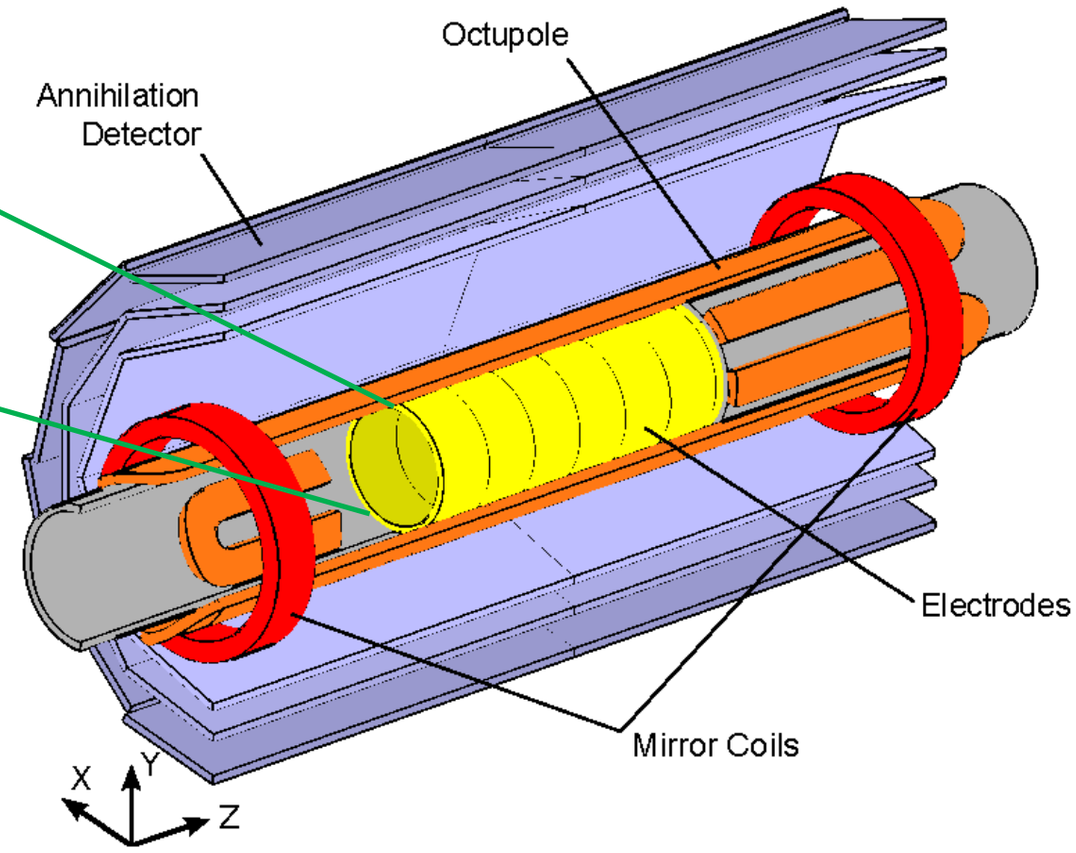


C. Amole et al. (ALPHA collaboration)
Nature **483**, 439 (2012)

Gravity measurements

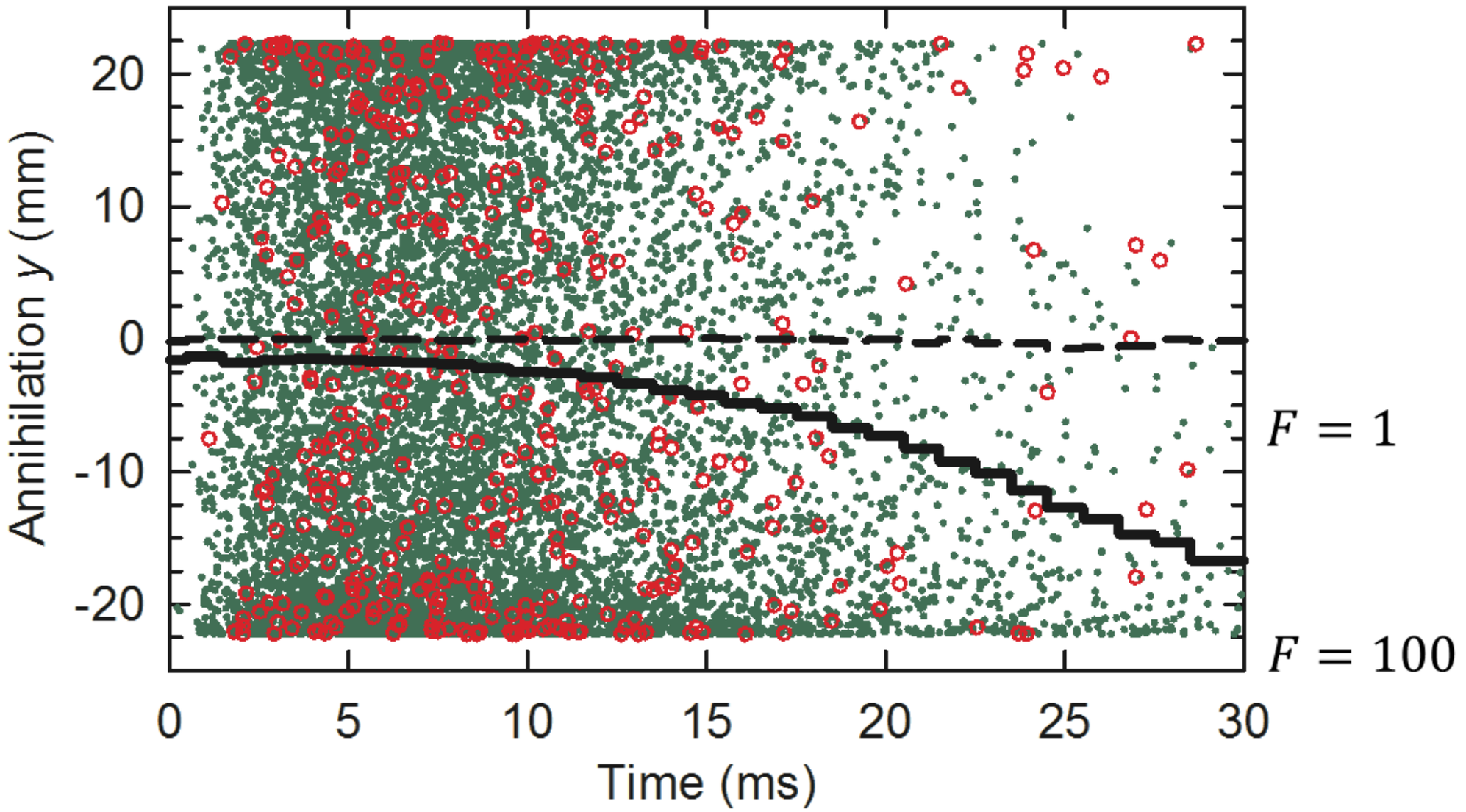


- F is the ratio of the gravitational mass to the inertial mass of antihydrogen.
- "Normal" gravity is $F = 1$.



- Potential includes effect from both the magnet system and gravity.
- The trap diameter is 44.55mm.

Gravity measurements

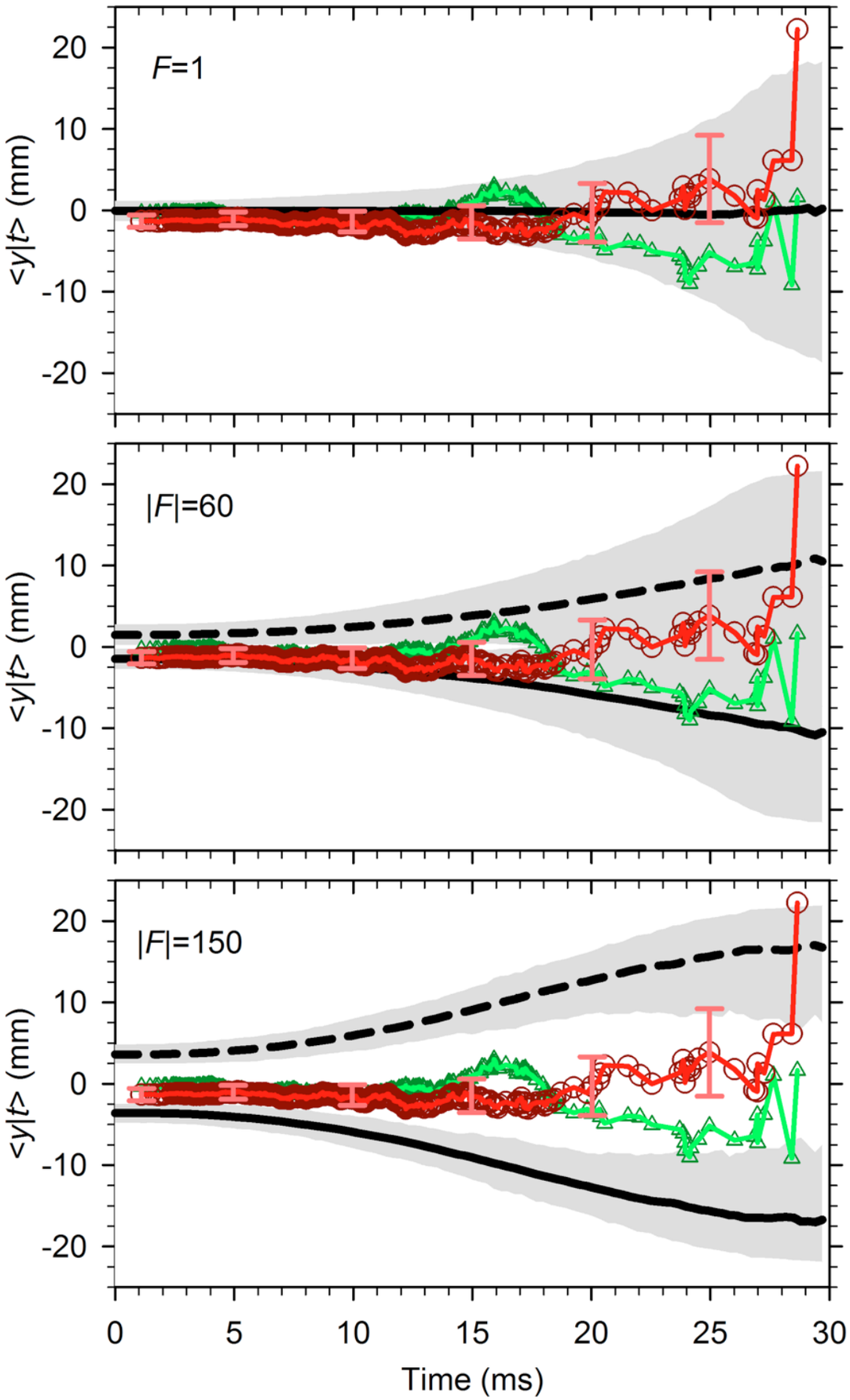


Green dots---simulated annihilations

Red circles---434 Observed annihilations

Basic Dilemma:

- The late escaping anti-atoms are most sensitive to gravity…
- But there are relatively few late escaping particles, so the statistics for these anti-atoms are poor



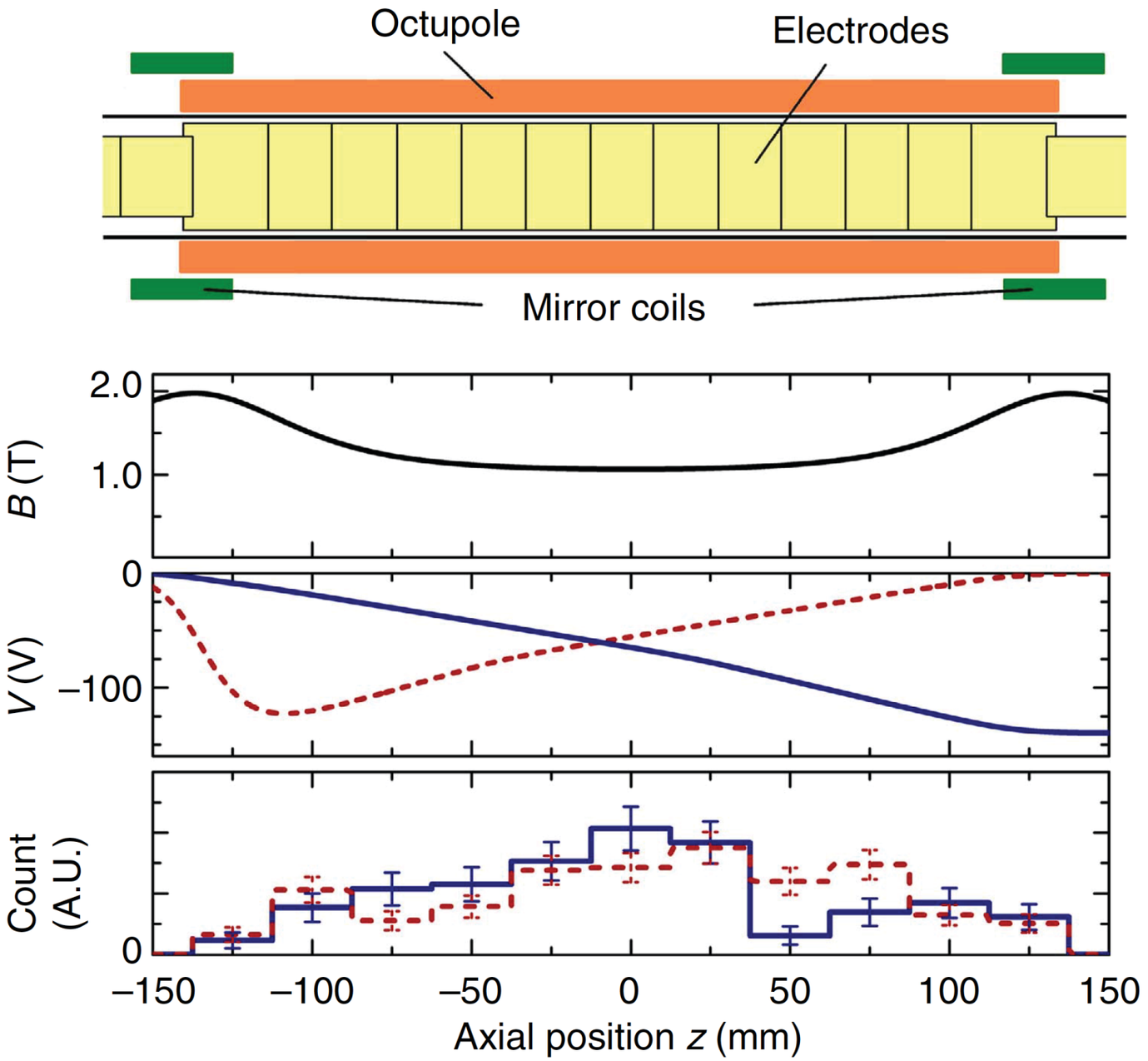
Reverse cumulative Average

$$\bar{y}_j = \frac{\sum_{i=j}^{N} y_i}{N - j + 1}$$

$$-75 < F < 110$$
$$(1\sigma \text{ confidence level})$$

C. Amole et al. (ALPHA collaboration)
Nature Communications 4 (2013) 1785

Charge neutrality 1

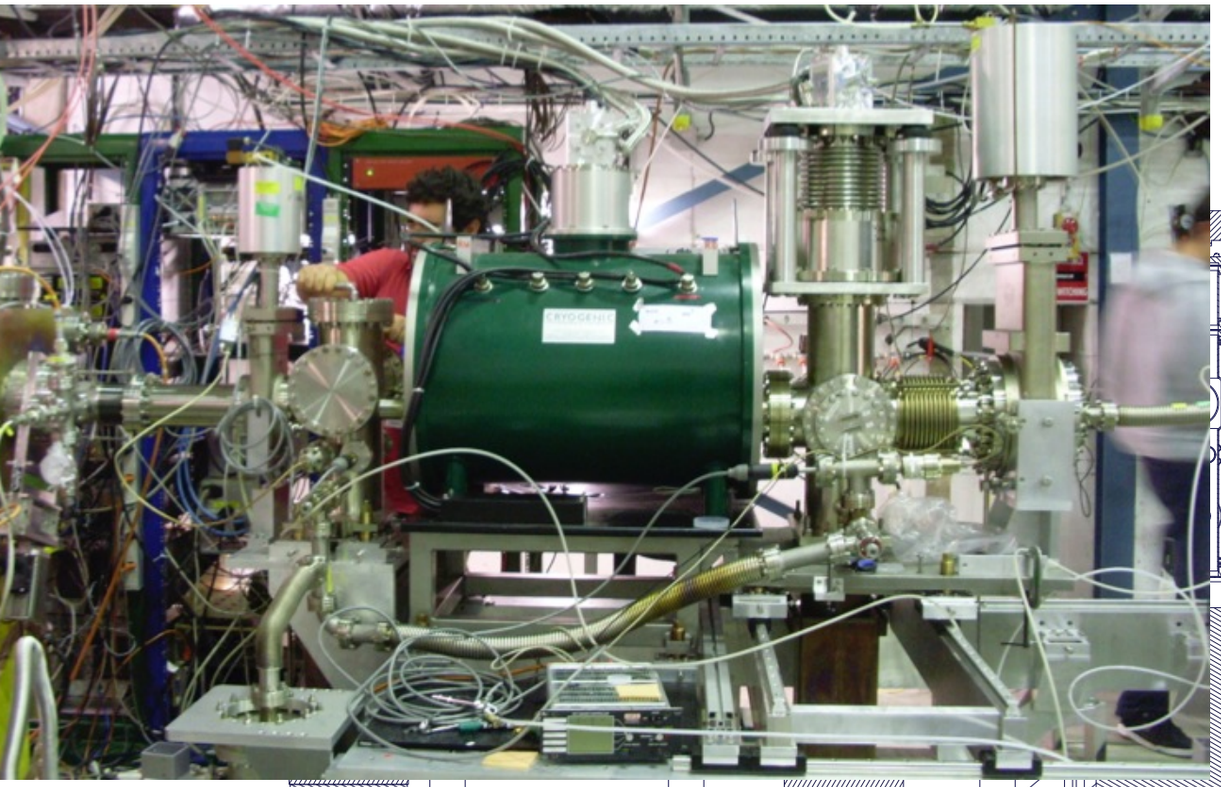


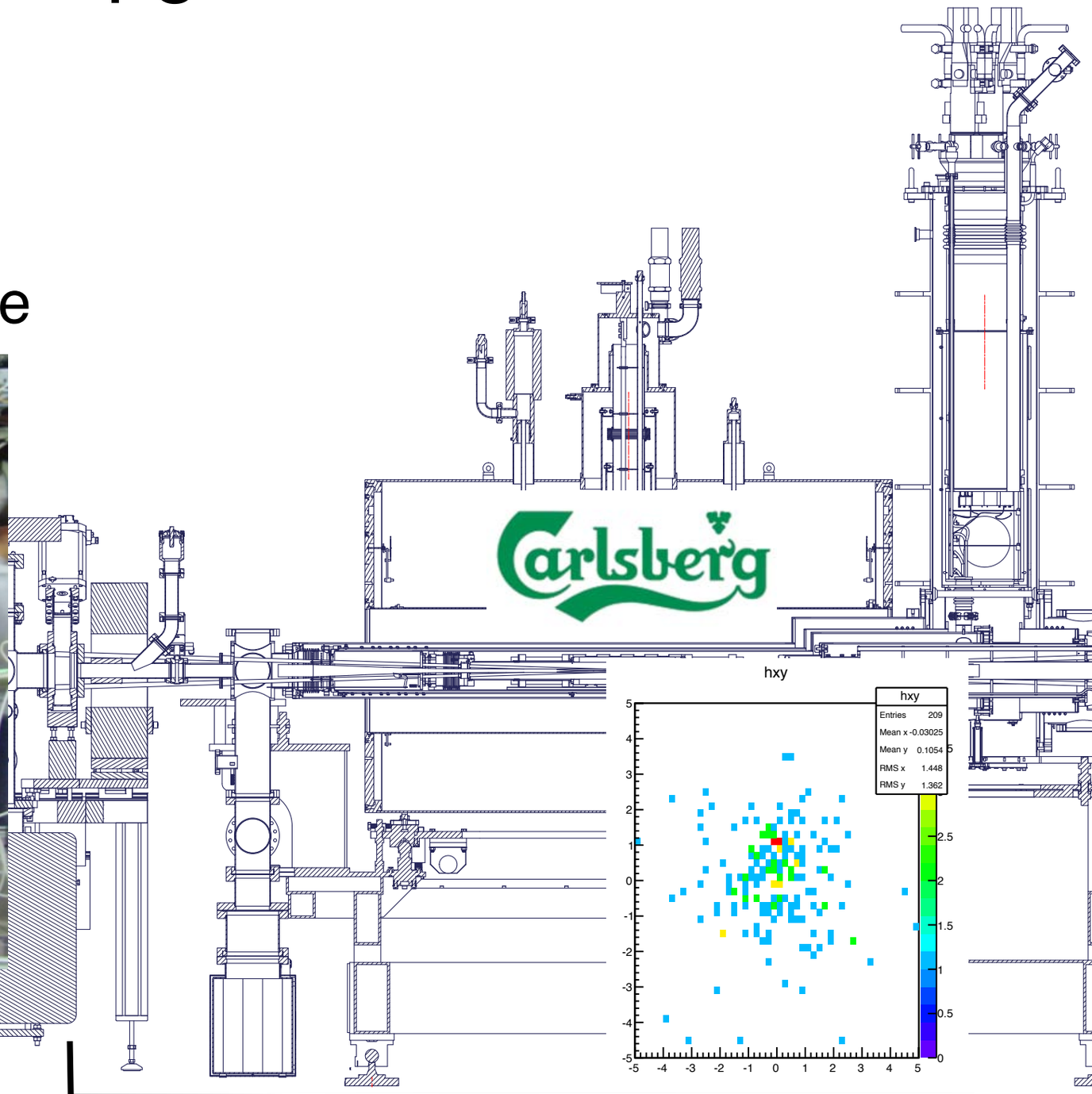
$$Q = (1.3 \pm 1.1 \pm 0.4) \times 10^{-8} \quad (1\sigma \text{ confidence level})$$

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

ALPHA upgrade

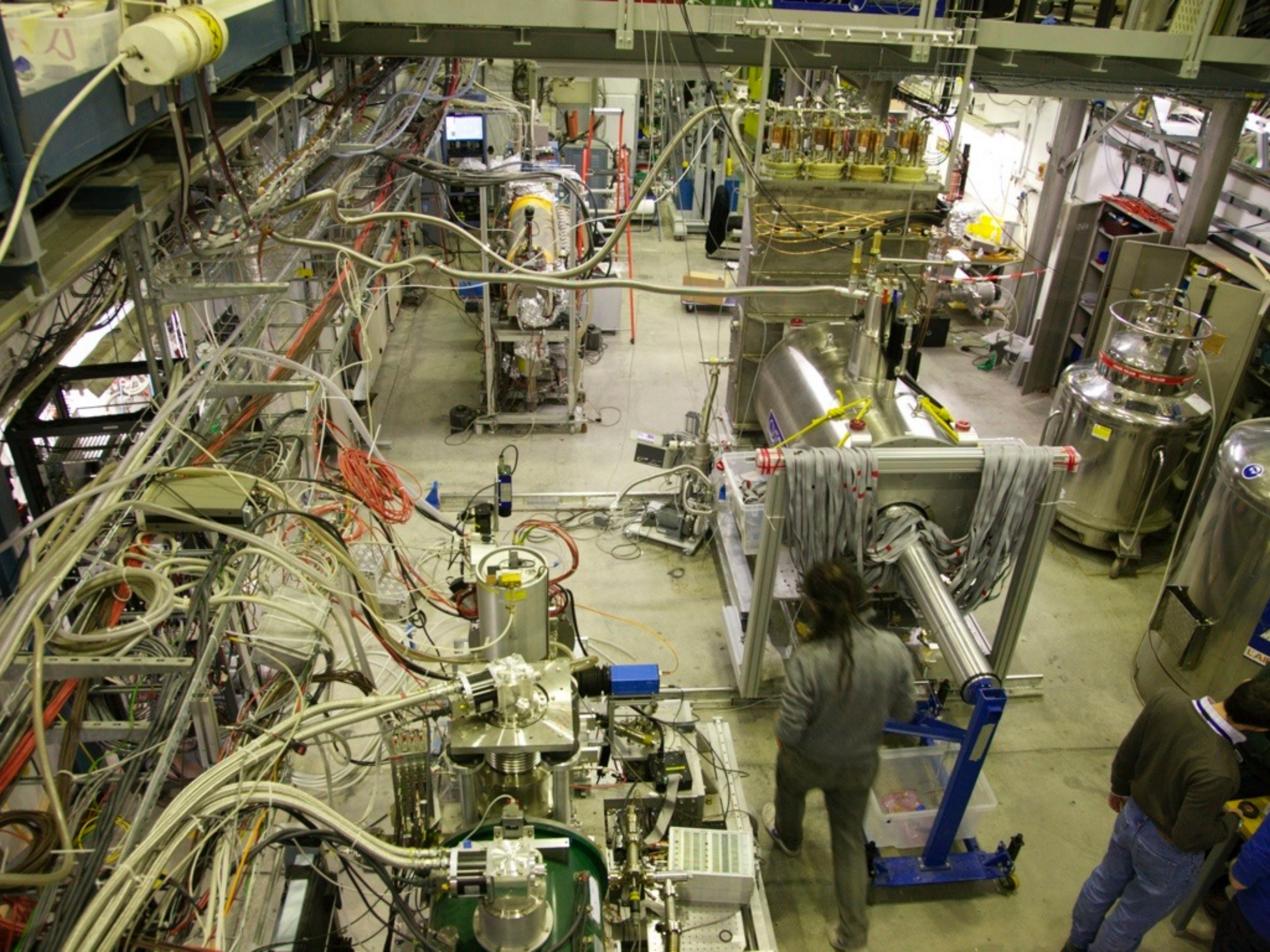
Installed: ~150k p/shot, >10h lifetime

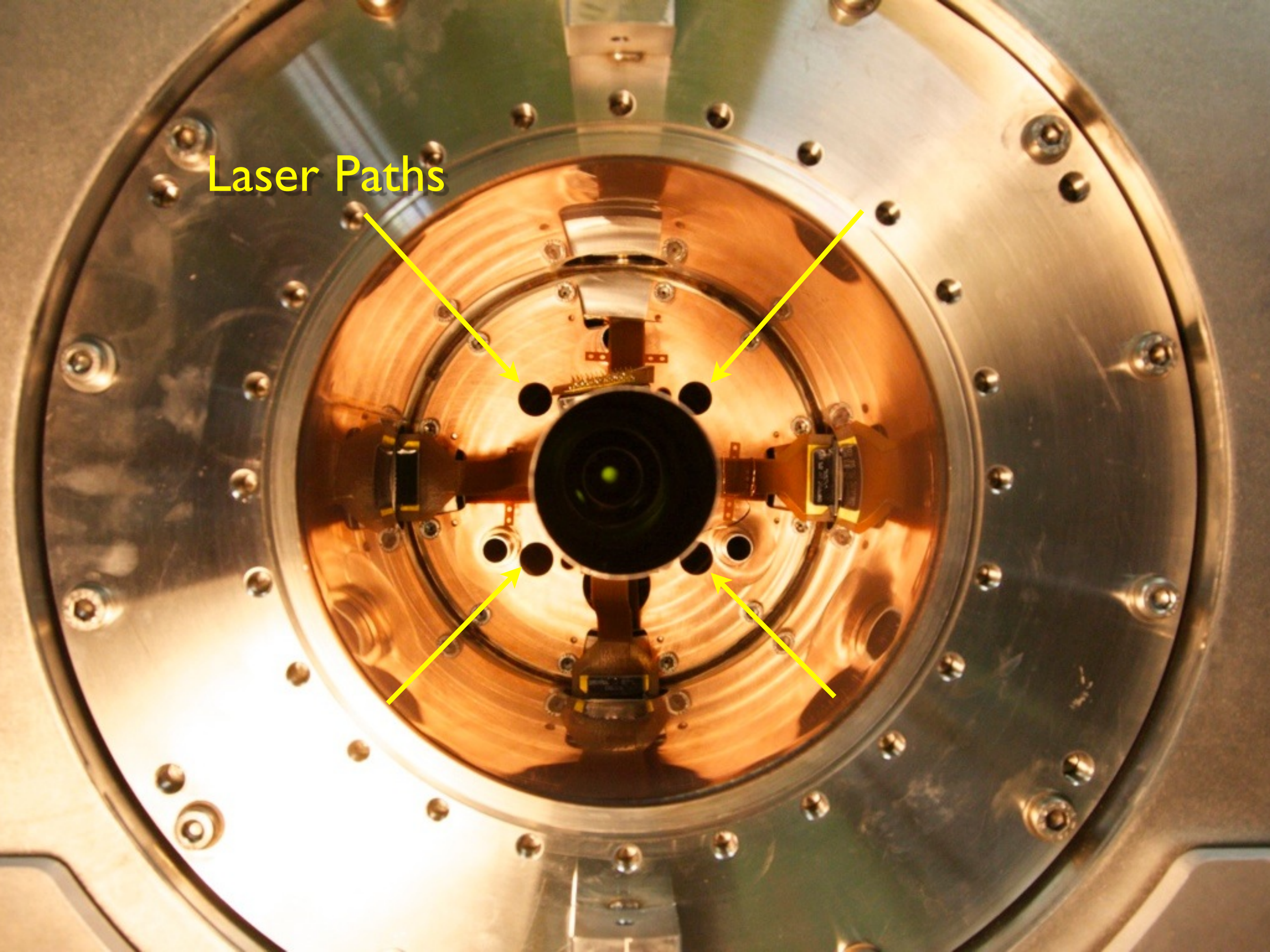




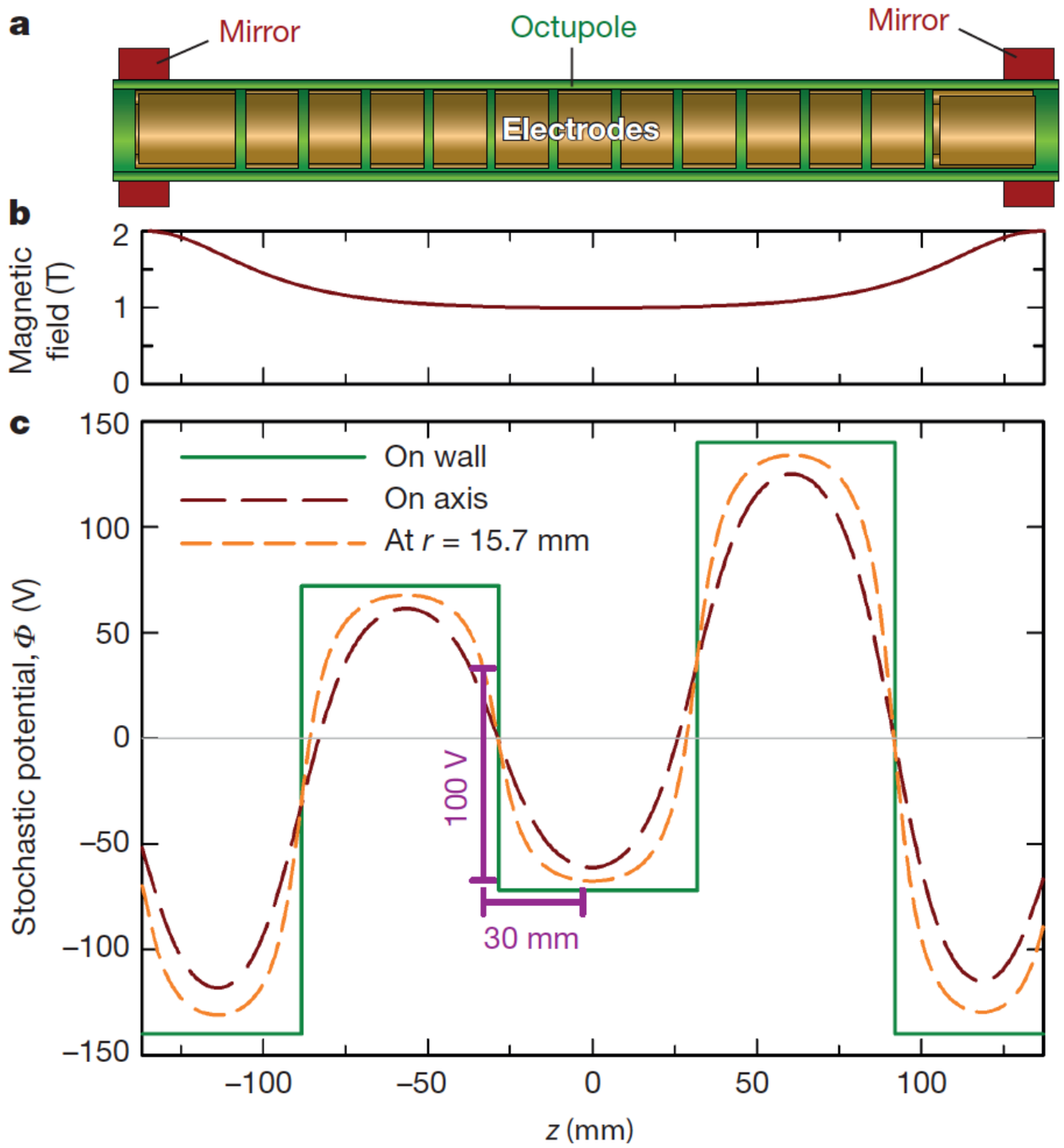
$\bar{p}$ catch and accumulation

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




Laser Paths

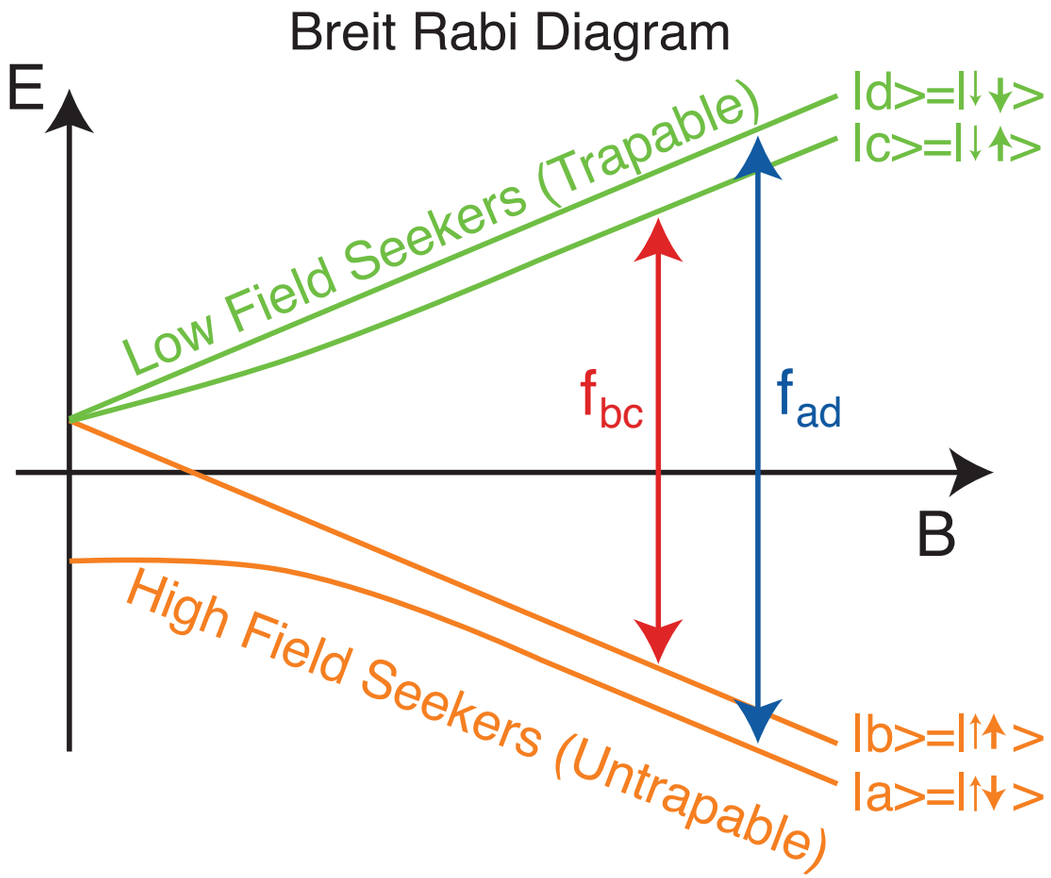
Charge neutrality 2

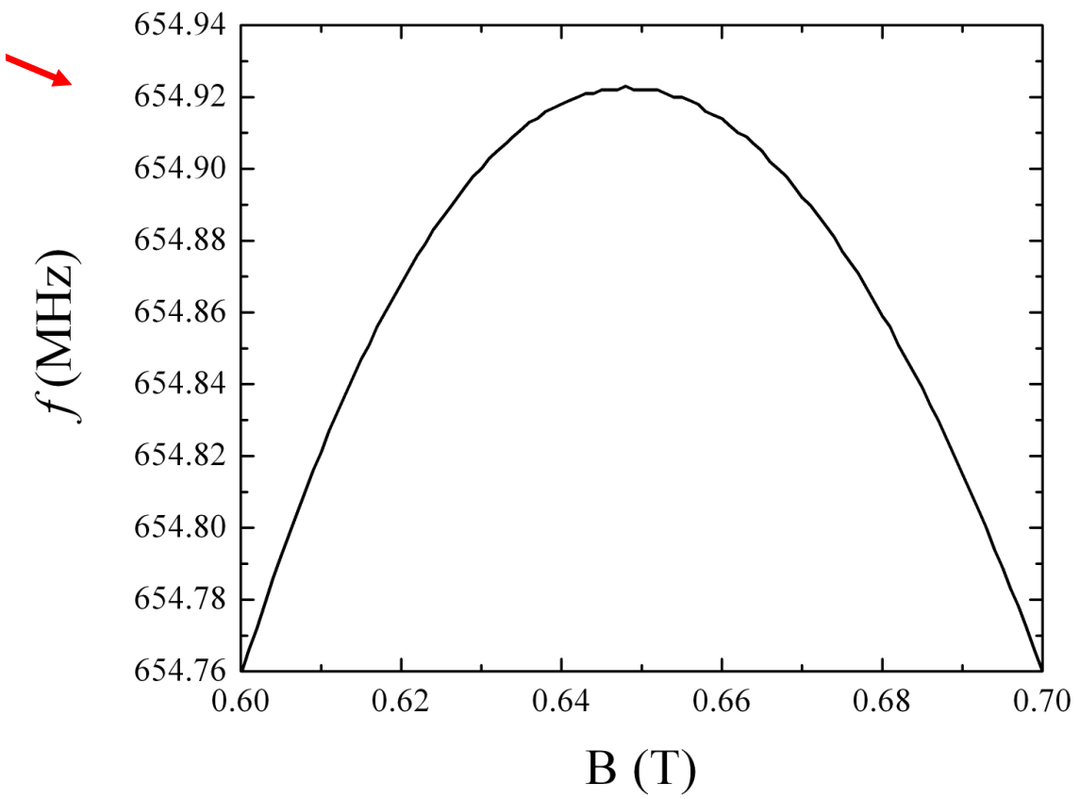


$$|Q| < 0.71 \text{ ppb}$$

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

μ-waves revisited





- We can also measure the Hyperfine splitting (f_{ad}-f_{bc}) w
- Upgrade includes μ-waves, 10^{-6} -> 10^{-8} potential

Conclusion + Outlook

- Trapped Antihydrogen, Quantum transition, Charge neutrality, Gravity
- Upgraded equipment for laser and improved microwave access
- We re-established Hydrogen formation and trapping and are presently shining a 243 nm (for two photon 1S-2S excitation) into the system while antihydrogen is present
- First spectroscopy results soon …

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THE ROYAL SOCIETY

EPSRC
Engineering and Physical Sciences Research Council

U.S. DEPARTMENT OF ENERGY

NSF

Alberta Innovates Technology Futures

Fonds de recherche Nature et technologies Québec

הקרן הלאומית למדע

MEXT MINISTRY OF EDUCATION, CULTURE, SPORTS, SCIENCE AND TECHNOLOGY-JAPAN

NSERC CRSNG

Danish Agency for Science Technology and Innovation
Ministry of Science, Innovation and Higher Education

Vetenskapsrådet

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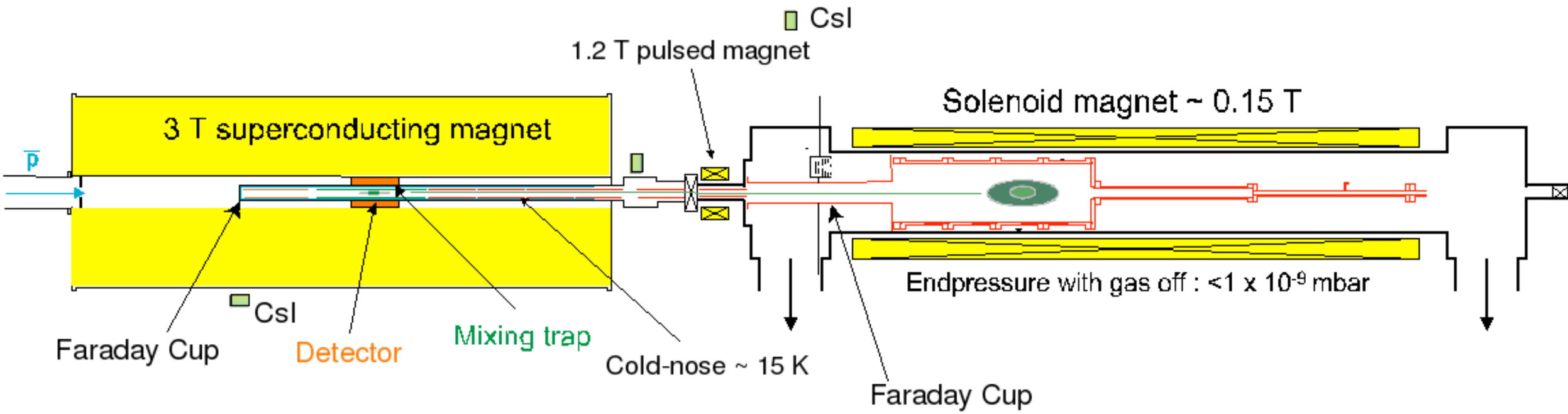
Universidade Federal do Rio de Janeiro
BRASIL

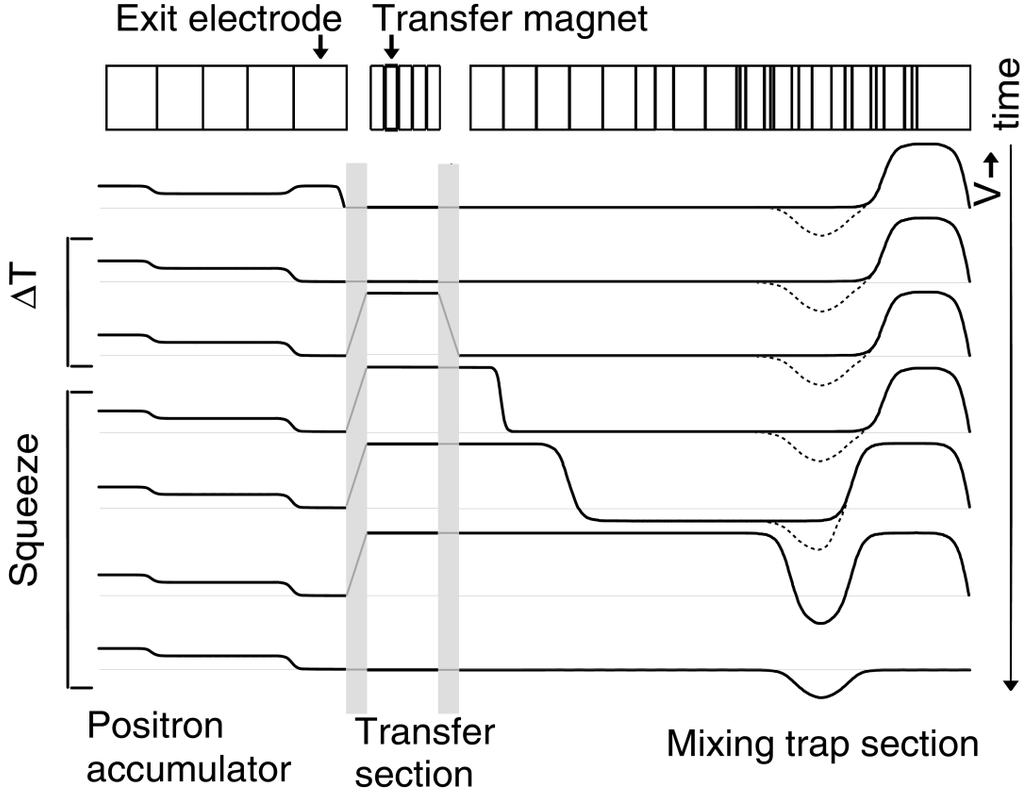
TRIUMF

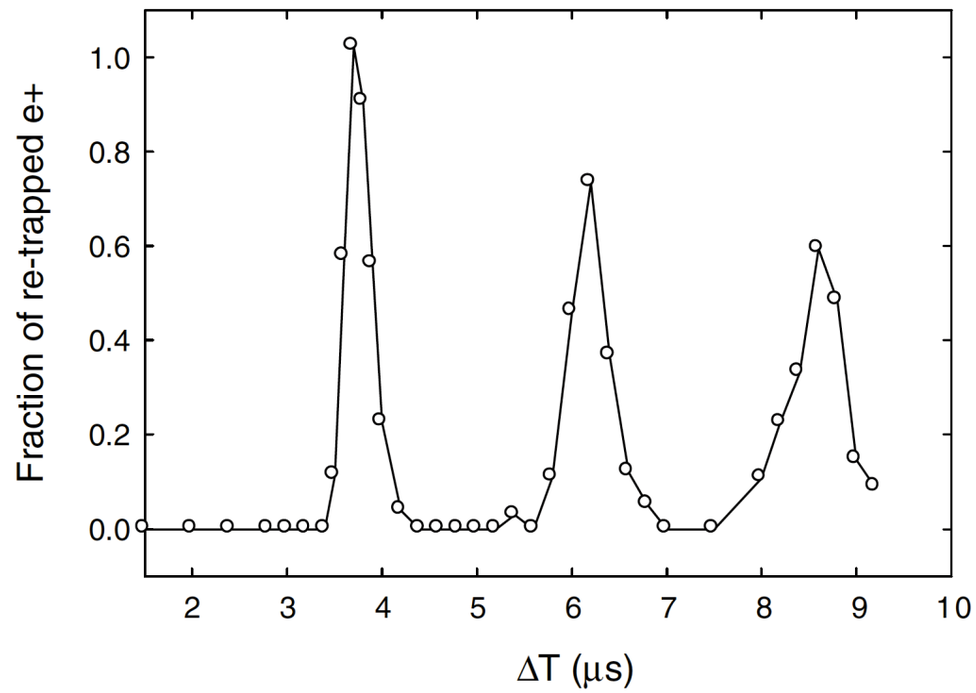
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e+ transfer







L. V. Jørgensen, *et al.* (ATHENA collaboration) *Phys. Rev. Lett.* **95,** 025002 (2005)

Table 1 | Systematic errors.

Error source	Normalized variation s Category A (10^{-9}/mm)	$\langle z \rangle_\Delta$ Category B (mm)	Time invariant $\langle z \rangle$ Category D (mm)	Q error net (10^{-8})
10 s Hold time.	–	–	±0.04*	–
Improved $\mathbf{B}(\mathbf{r},t)$, dB/dt terms, adaptive Runge-Kutta propagator.	±0.01 [±0.01]*	±0.09 [±0.03]†	±0.20†	±0.03†
Degraded $\mathbf{E}(\mathbf{r},t)$.	±0.01 [±0.01]*	±0.10 [±0.03]†	±0.24†	±0.03†
$\|c>$ Space $\mu_{\bar{H}}$ included.	±0.01 [±0.01]*	–	±0.07*	±0.01*
±1% Differential mirror drift.	–	±0.13 [±0.04]‡	±0.29‡	±0.05‡
±1% Common mode mirror drift.	±0.01 [±0.01]‡	±0.02 [±0.00]‡	±0.03‡	±0.02‡
2 mrad Solenoid tilt.	±0.01 [±0.02]*	±0.07 [±0.02]*	±0.15*	±0.03*
±1% Octupole drift.	–	±0.01 [±0.00]*	±0.03*	±0.01*
External magnet.	–	±0.06 [±0.02]‡	±0.11‡	±0.02‡
3 × Radius, 2 × length.	±0.01 [±0.02]*	±0.07 [±0.02]*	±0.15*	±0.03*
Initial energy distribution.	±0.22 [±0.29]‡	±0.04 [±0.01]‡	±0.05‡	±0.31‡
Anisotropic initial distribution.	±0.08 [±0.11]†	±0.17 [±0.06]†	±0.23†	±0.12†
Detector z-centre relative to electrode z-centre.	–	±0.17 [±0.06]‡	±0.2‡	±0.06‡
Mirror z-centre relative to electrode z-centre.	–	–	±0.5‡	–
Detector efficiency.	±0.03 [±0.04]‡	±0.02 [±0.01]‡	±3.6‡	±0.04‡
Long-term detector drift.	–	±0.04 [±0.01]‡	±0.09‡	±0.01‡
Cosmic background.	–	±0.25 [±0.08]§	–	±0.08§
Antiproton background.	–	±0.13 [±0.04]‡	–	±0.04‡

Entries in [] are the induced Q error associated with the adjacent entries, scaled by 10^{-8}. (These entries do not always sum to the corresponding entries in the Q Error Net column because of rounding and because the entries in the sum are sometimes known to have opposite sign.) The normalized variation in the sensitivity $s = dQ/d\langle z \rangle_\Delta$ is defined to be $s/s_{\mathrm{Nom}} - 1$, where s_{Nom} is the sensitivity evaluated with nominal parameters. Entries that are zero to two digits are designated with a '–'.

*Effects for which the 1σ sampling errors in the simulations used to study the effects are larger than the size of the effect predicted by the simulation; thus, we cannot determine whether these effects would cause an actual change in the experimental observations. More precisely, the simulations generally predict an effect of size $a \pm b$. For these entries, $|a| < b$; to give an estimate of the worst case errors possible for these effects, we report the value of b, not that of a. For all other entries, we report a.

†Comparisons between simulations where $|a| > b$.

‡The potential effect caused by some independently measurable parameter $c \pm d$ is real, that is, the simulations or calculations predict $|a(c)| > b(c)$, but the 1σ errors in the measurement of the relevant parameter are compatible with zero, that is, $|c| < d$. Consequently, we do not know whether these error sources cause an actual change in our data.

§An effect based on an independently measured parameter that is not compatible with zero; this effect is likely to have caused a change to our data.