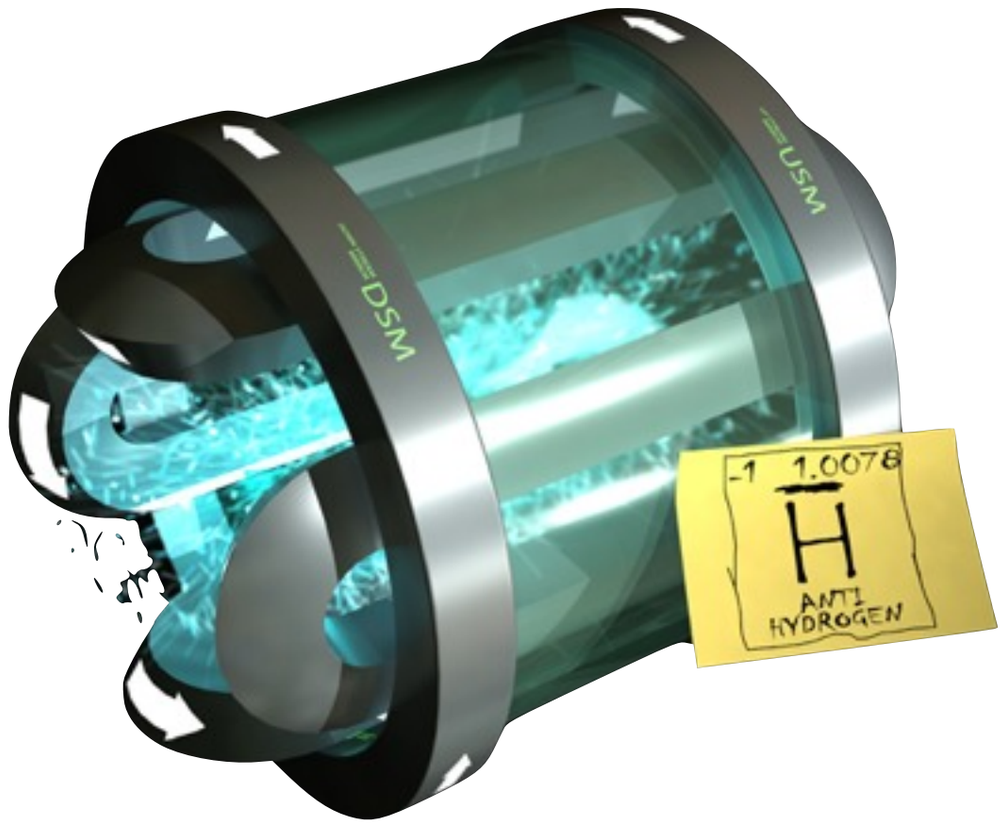
Resonant Quantum Transitions in Trapped Antihydrogen



Dirk van der Werf
Swansea University

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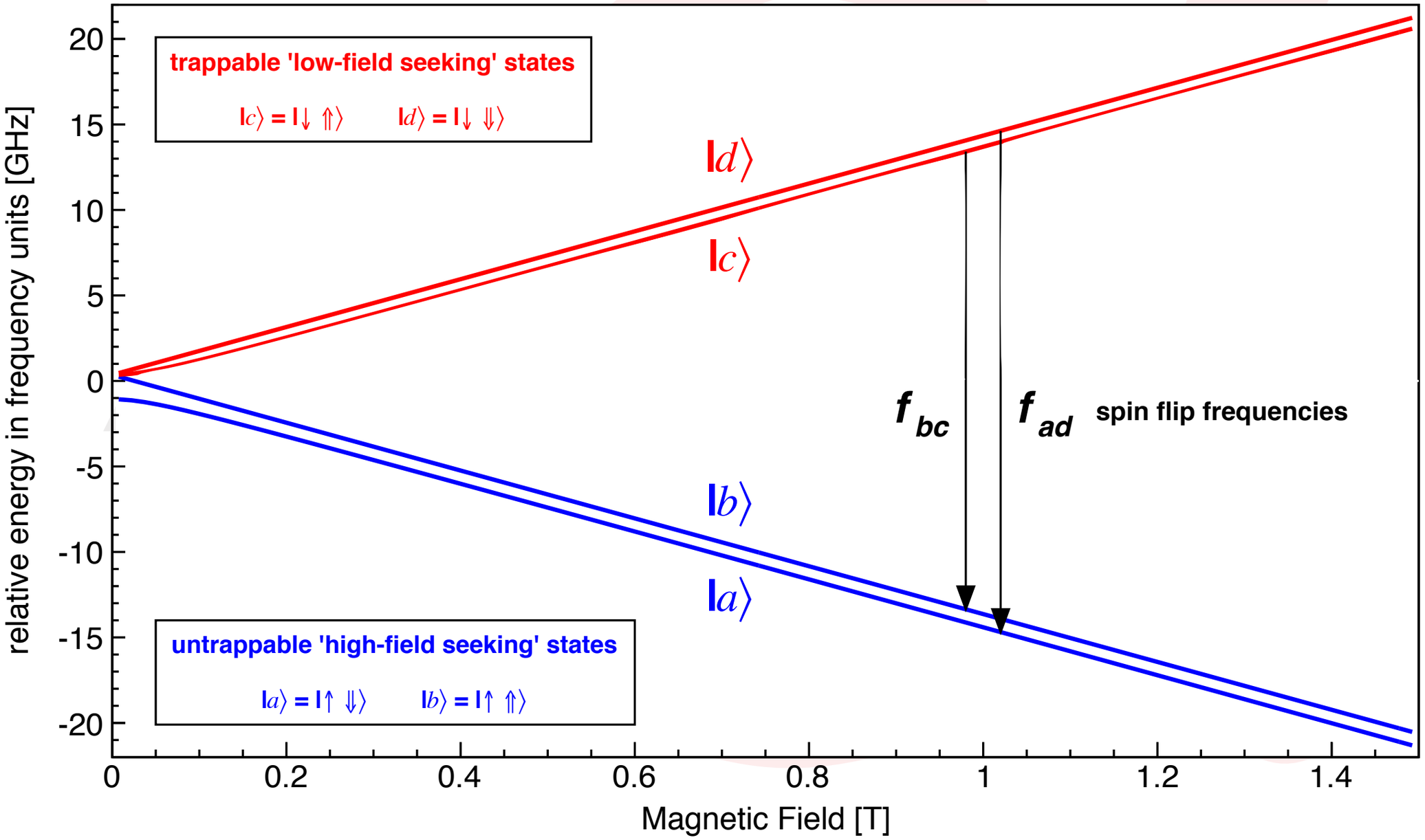
Prifysgol Abertawe

ALPHA

Goals

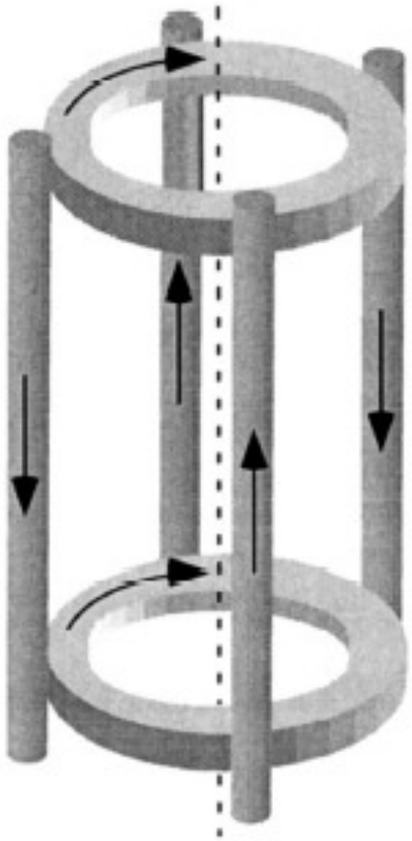
- Compare the spectra of H and $\overline{\text{H}}$.
  - Records for Hydrogen
    - 1S-2S transition known to 4.2 parts in 10^{15}.
      C.G. Parthey *et al.* Phys. Rev. Lett. 107, 203001 (2011)
    - Ground state hyperfine transition known to 1.4 parts in 10^{12}.
      H. Hellwig *et al*. Instrumentation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

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

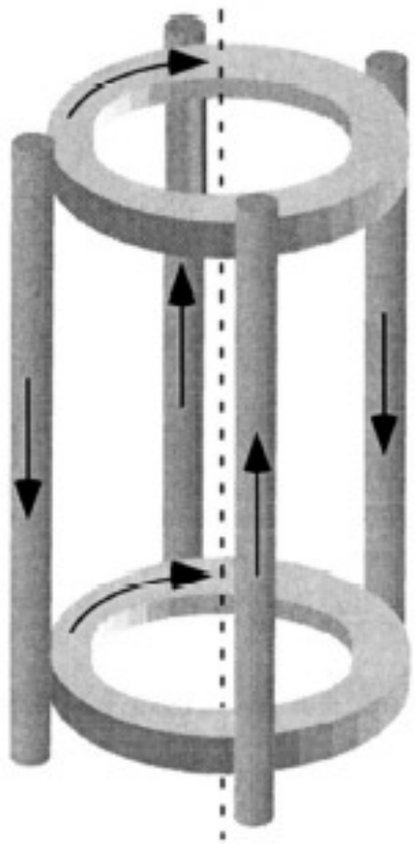


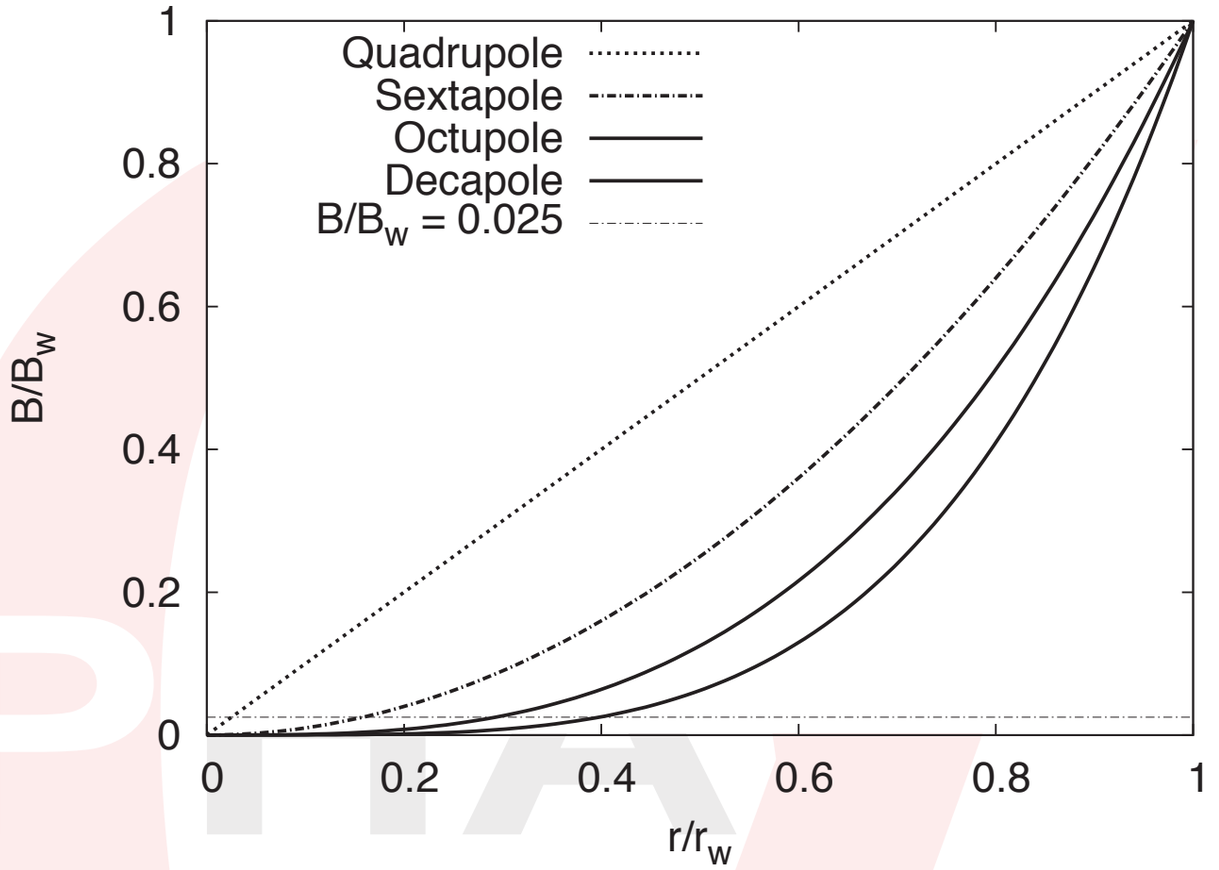
Magnetic trap

Magnetic trap

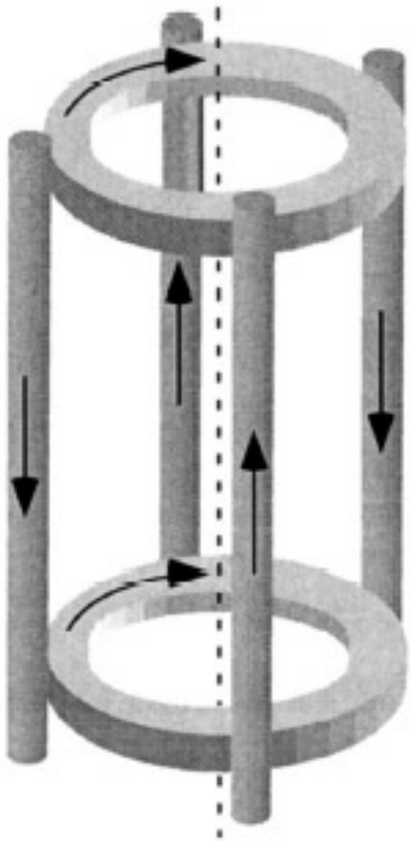


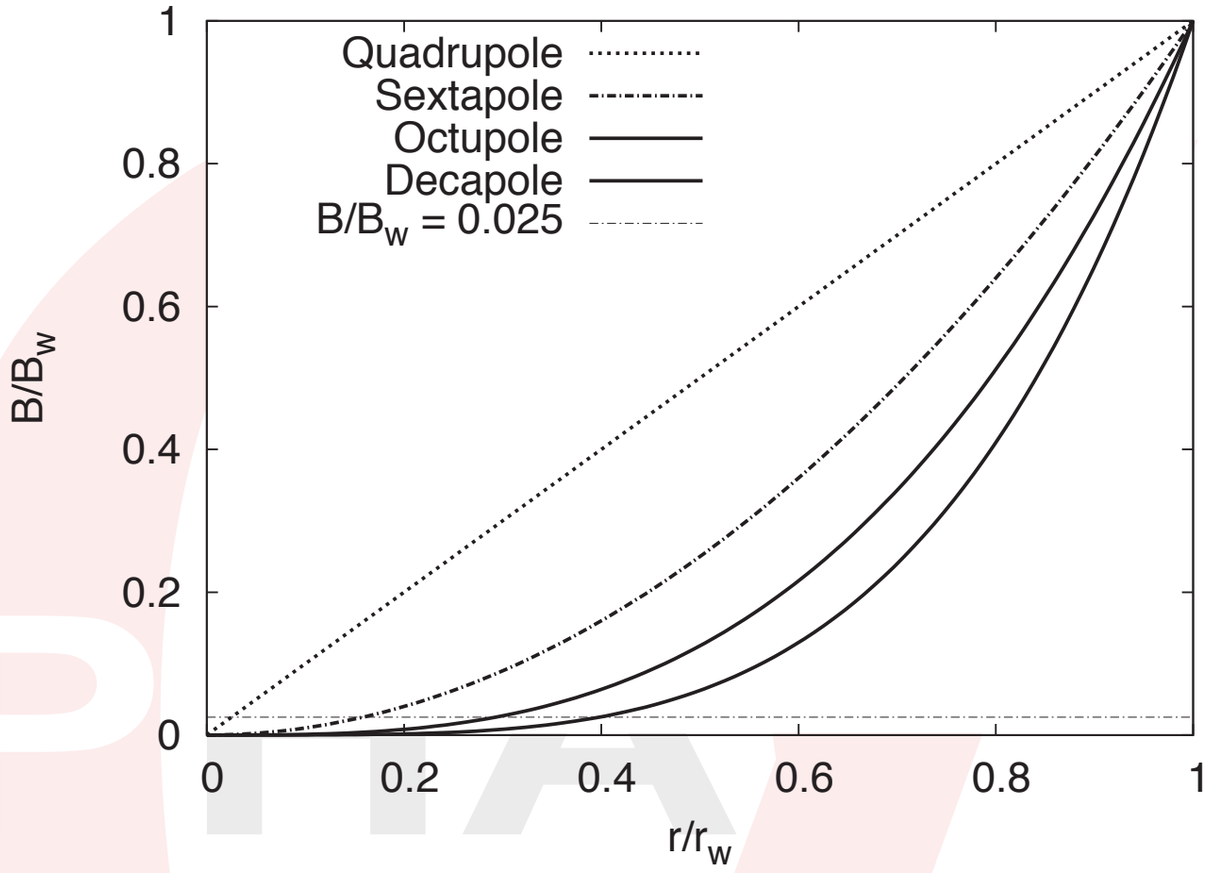
Magnetic trap

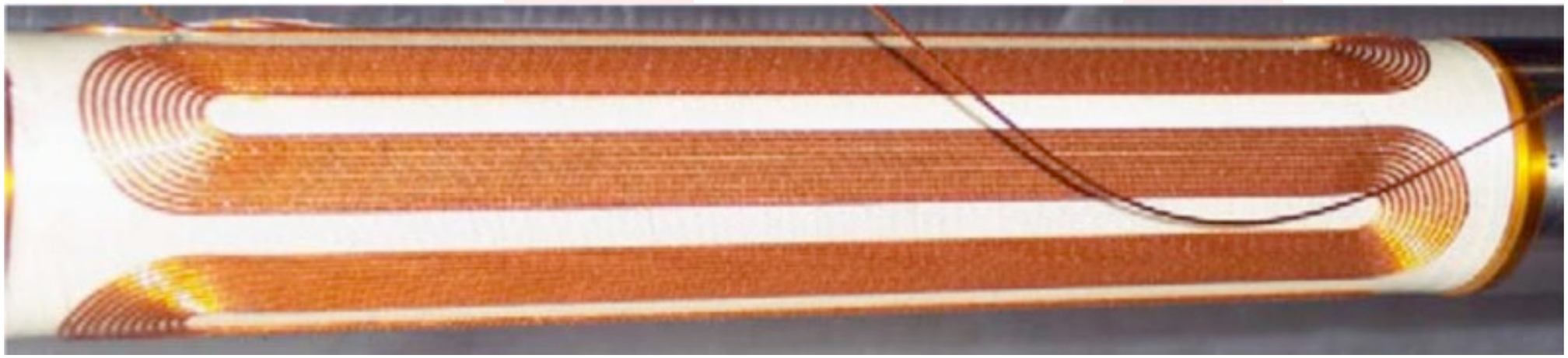




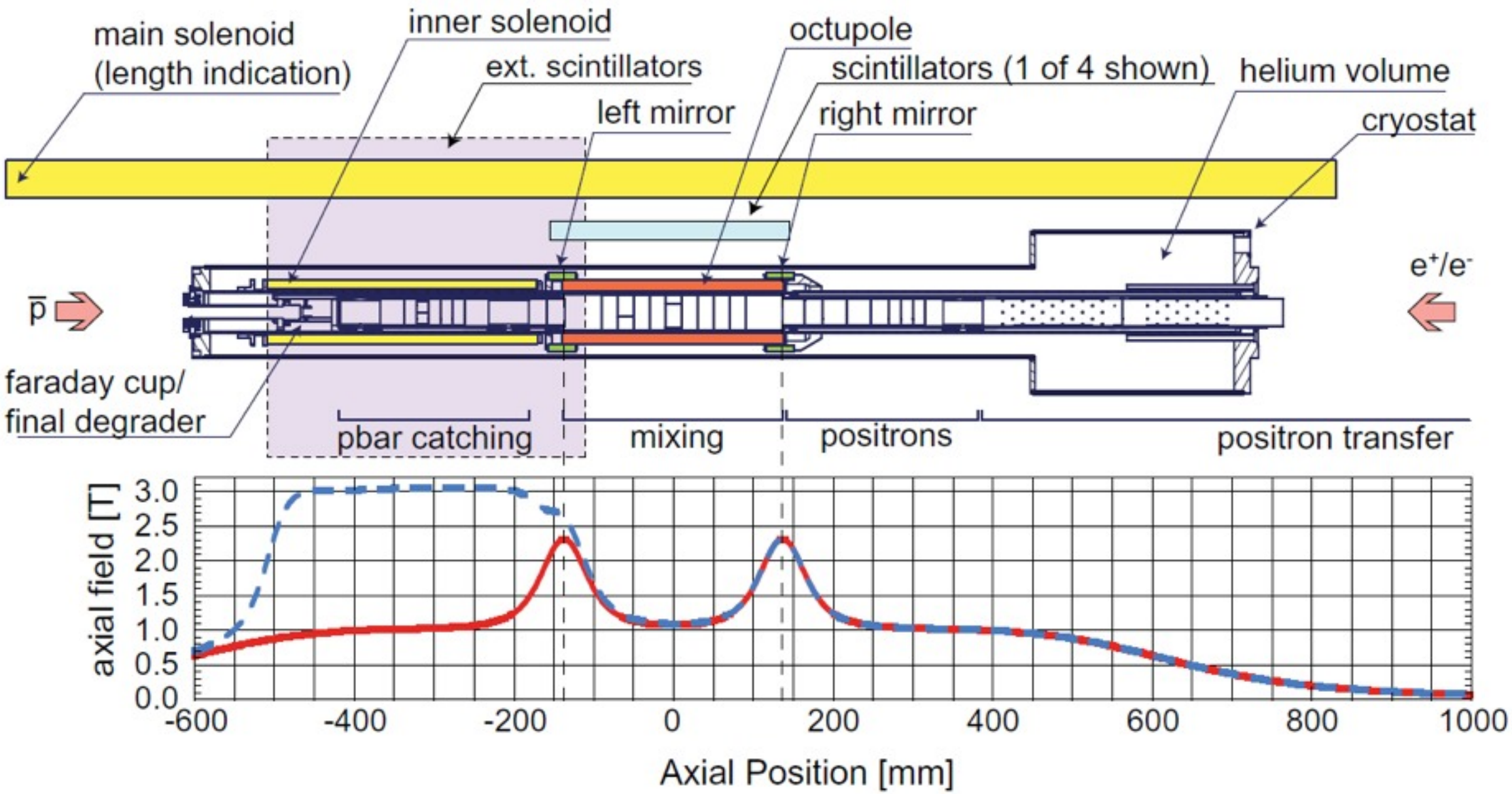
Magnetic trap







Alpha Apparatus



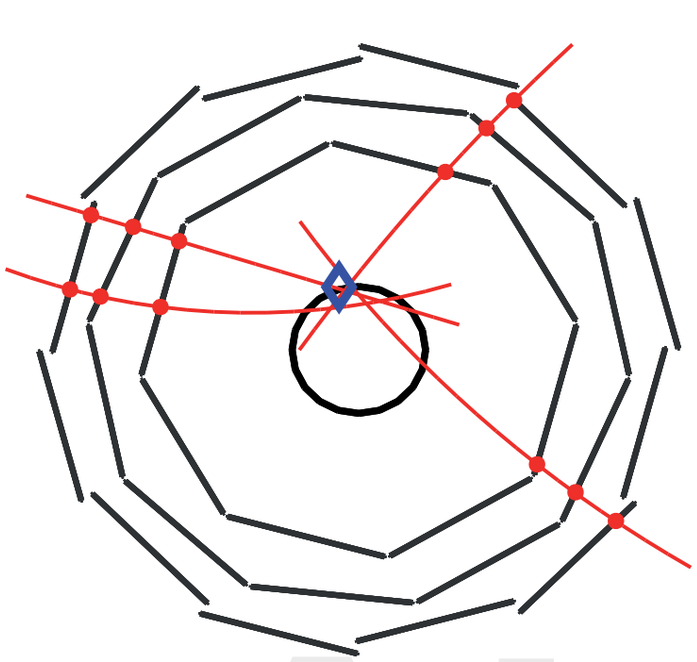
Well depth is ~0.8 T equivalent 0.54 K for ground state (anti)hydrogen

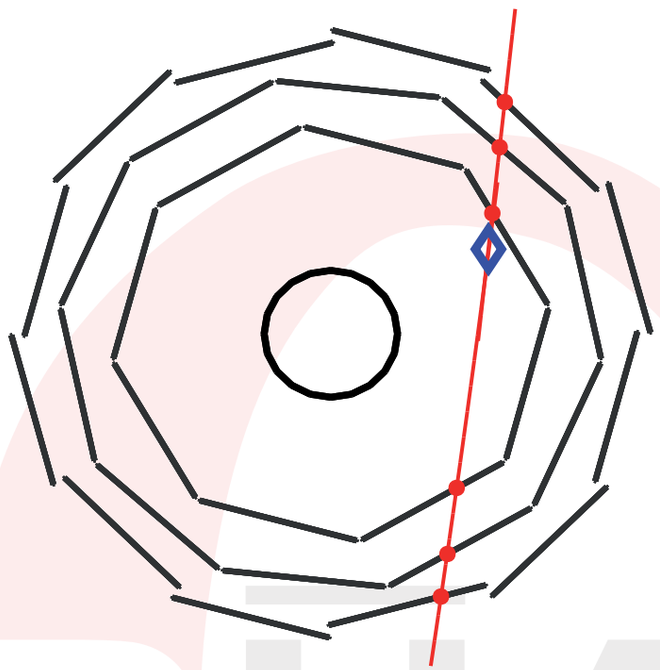
Ramp down/Quench of trap: τ = 9 ms

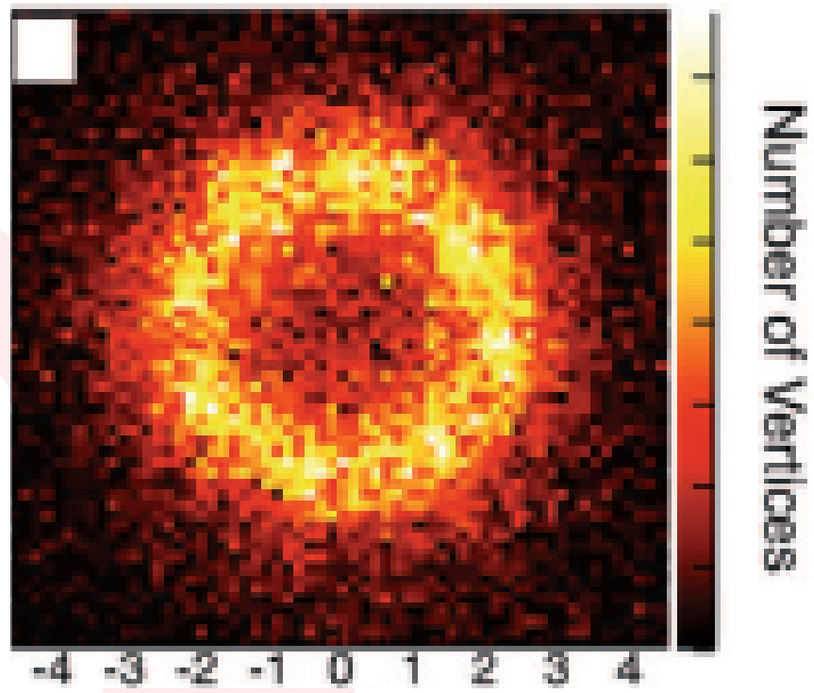
Number of quenches: a couple of thousands

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

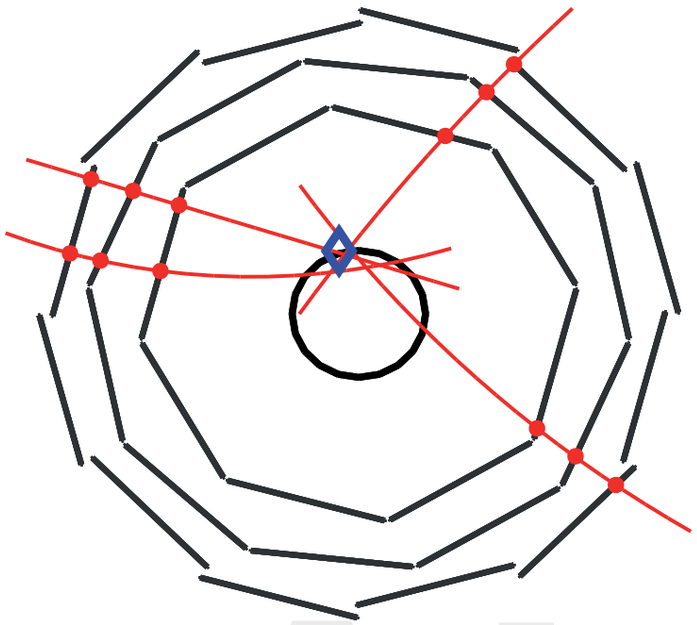
Detector

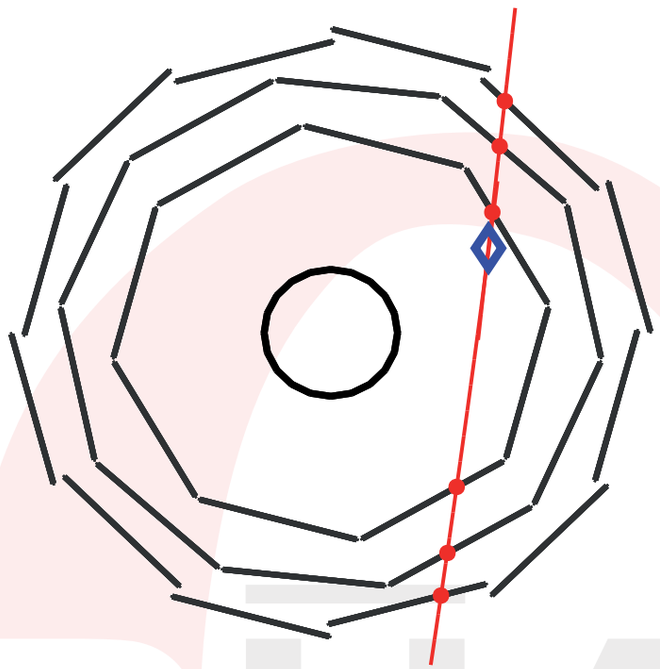


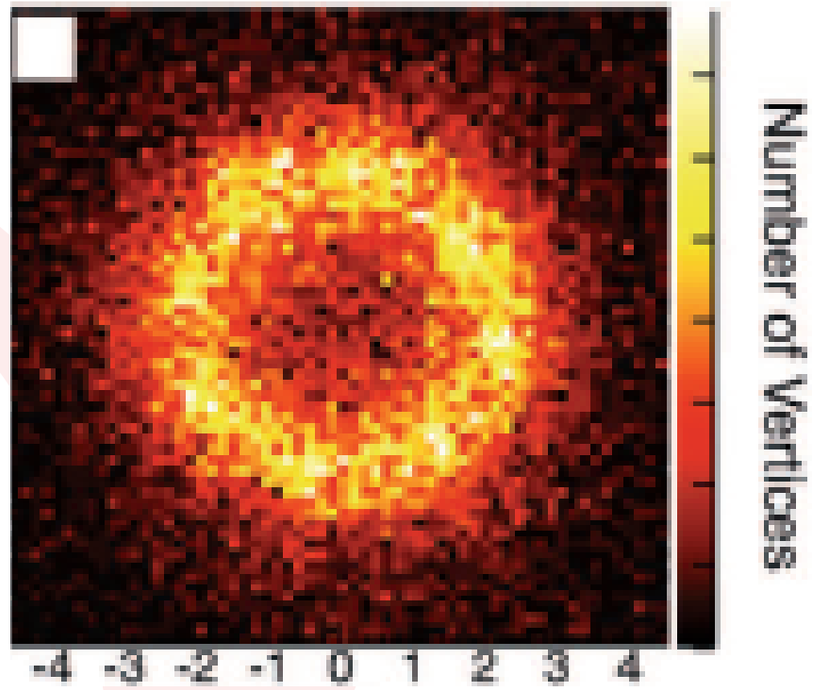


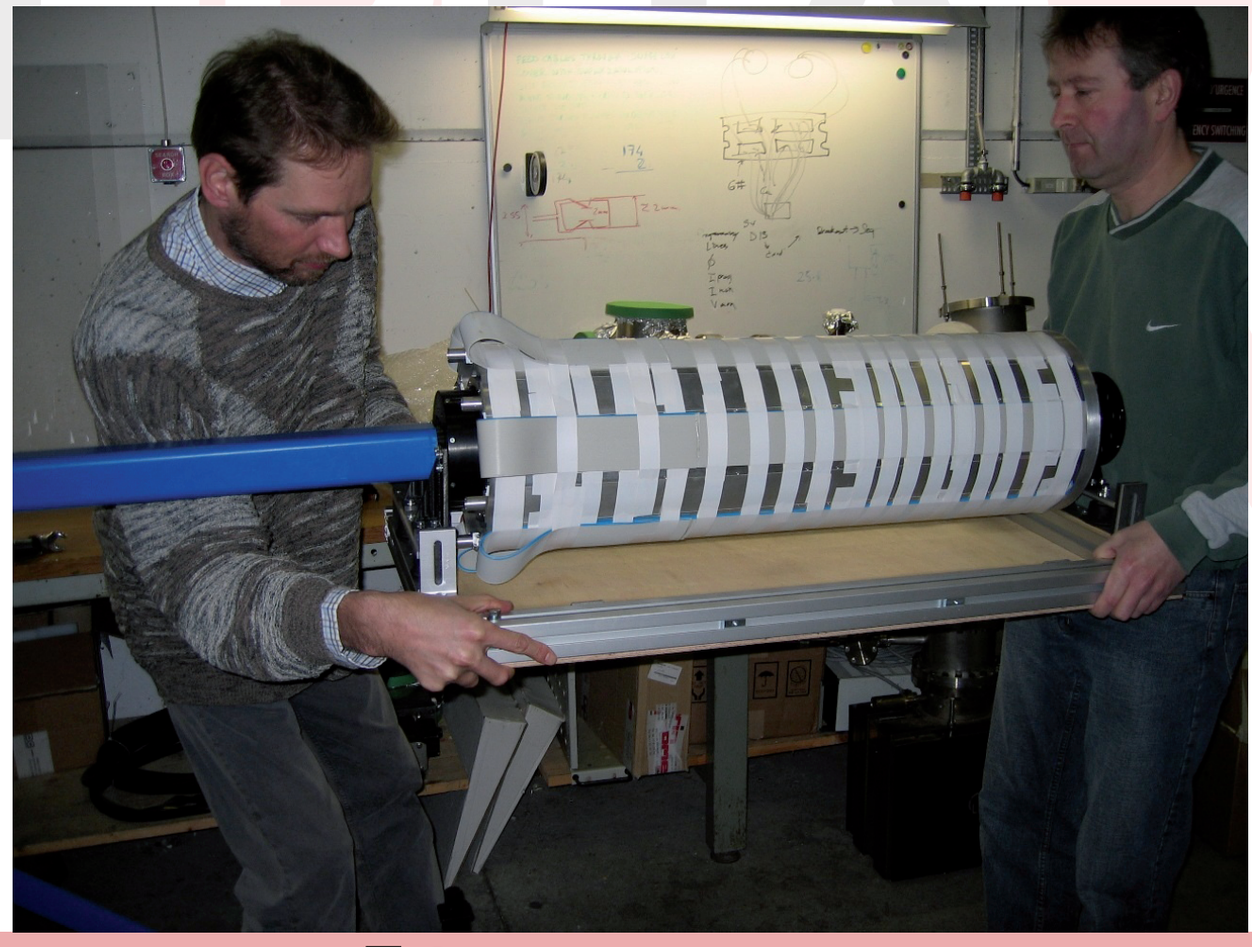


Detector

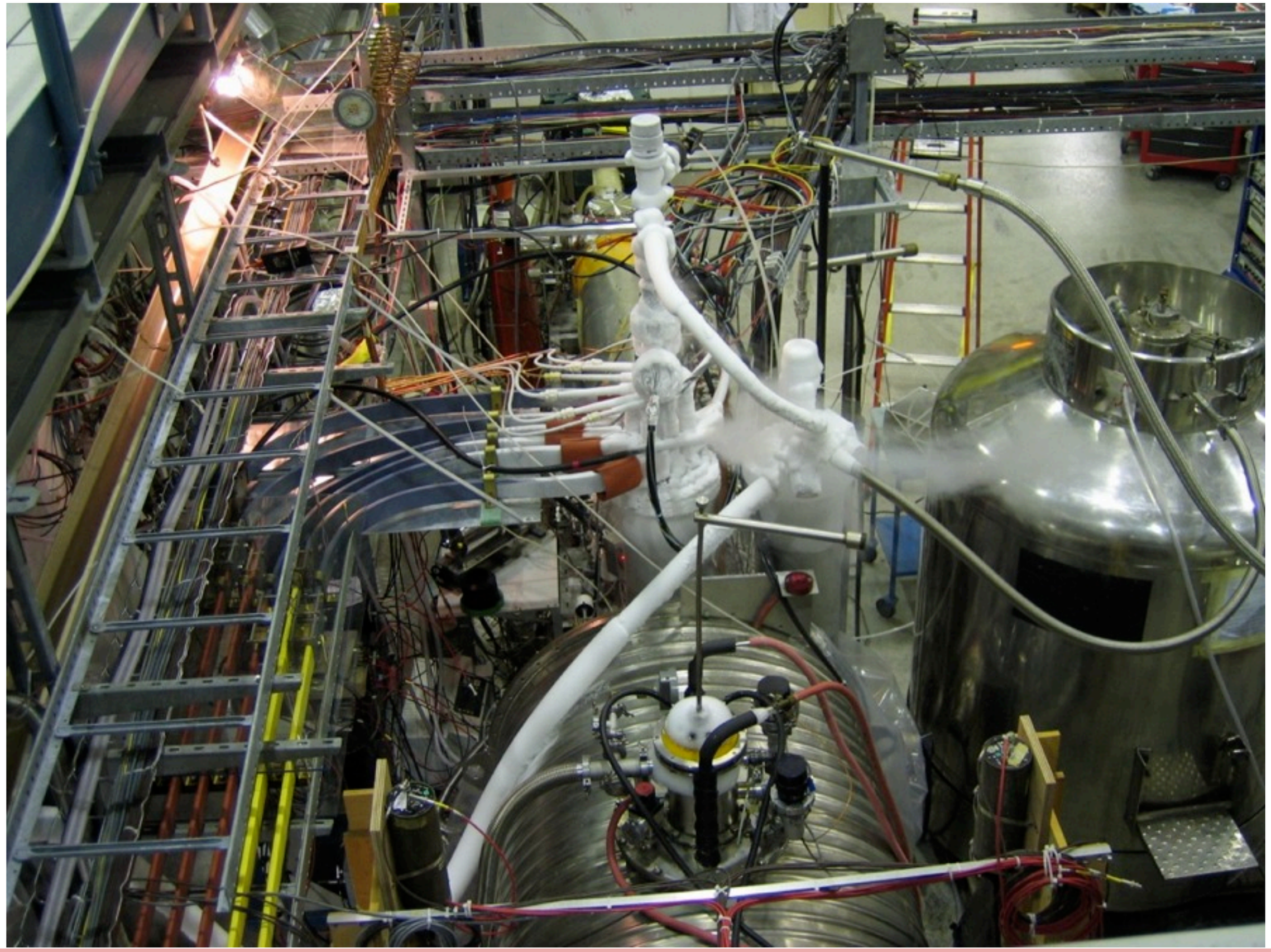


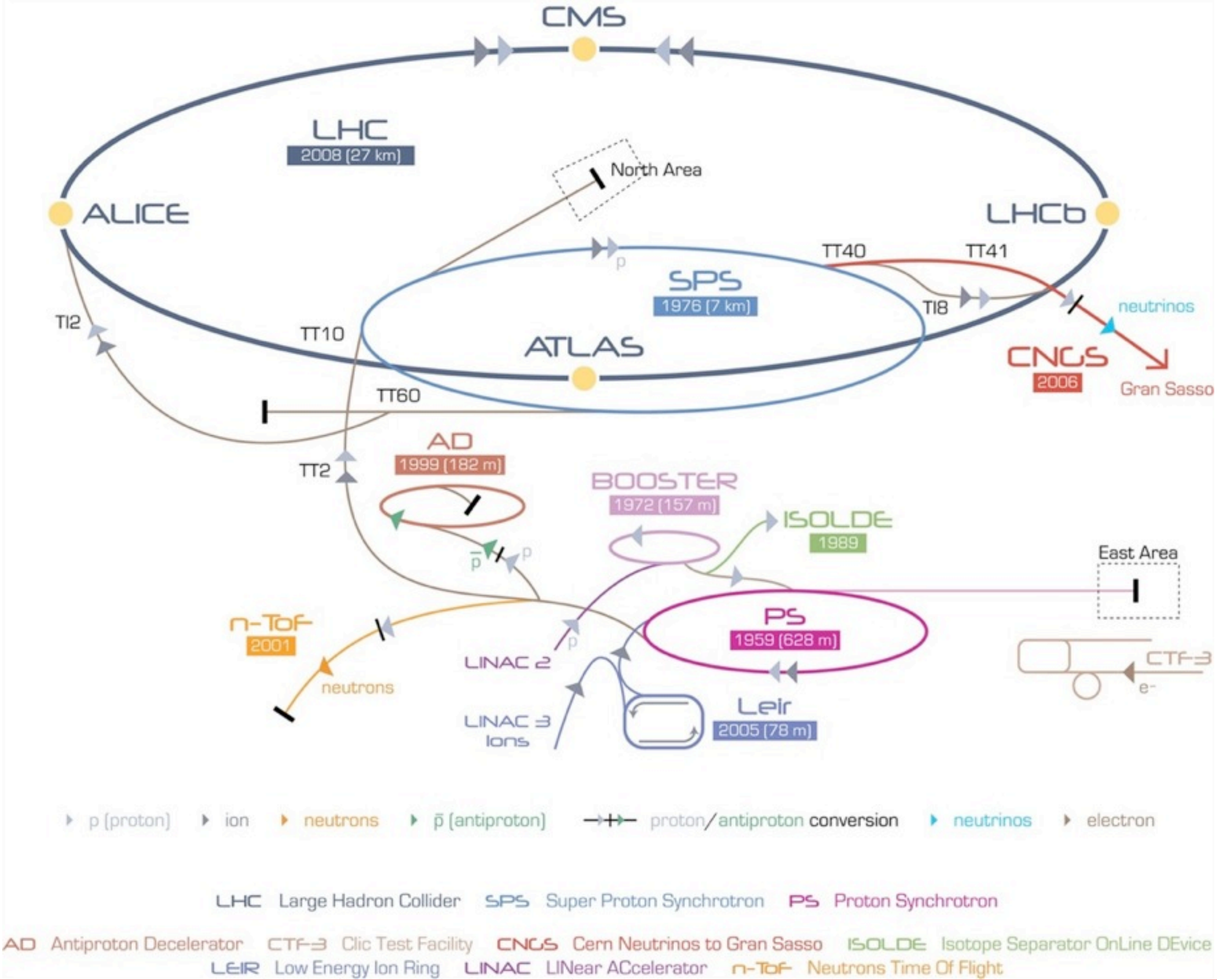




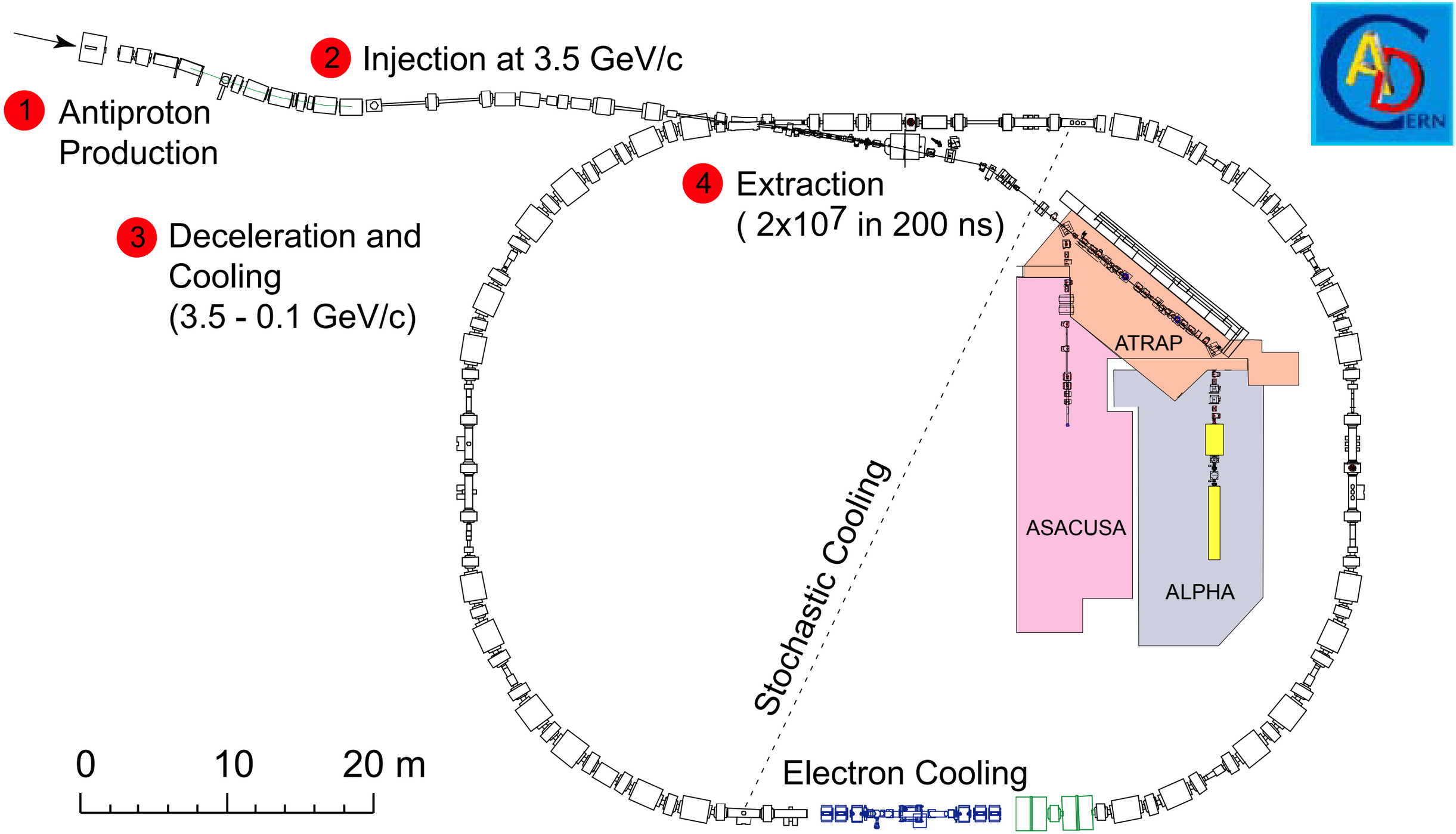


Alpha Apparatus

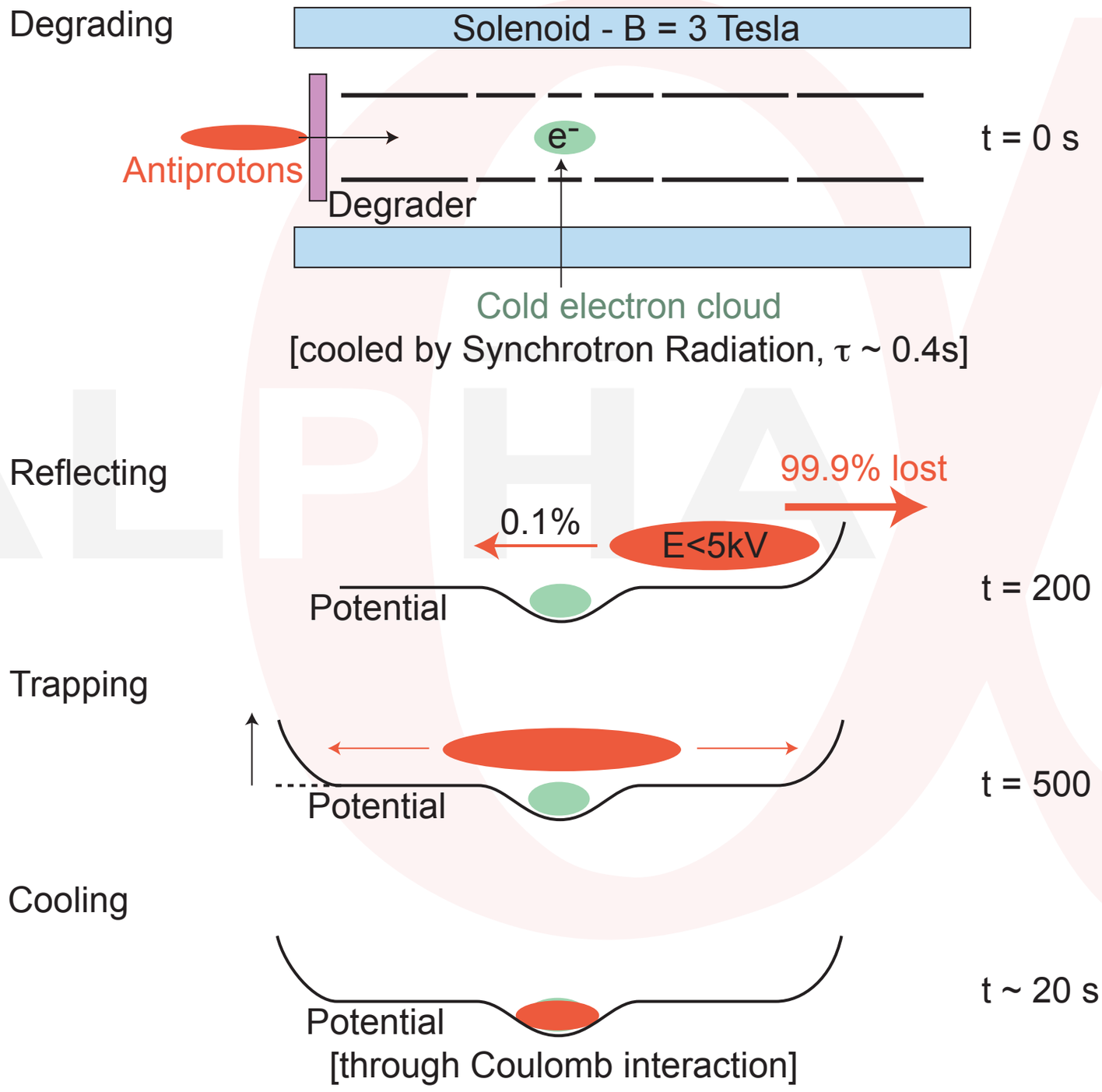



CMS
LHC
2008 (27 km)
North Area
ALICE
LHCb
TT40
TT41
p
SPS
1976 (7 km)
TI8
neutrinos
TI2
TT10
ATLAS
CNGS
2006
Gran Sasso
TT60
AD
1999 (182 m)
TT2
BOOSTER
1972 (157 m)
ISOLDE
1989
East Area
n-ToF
2001
PS
1959 (628 m)
CTF-3
LINAC 2
neutrons
LINAC 3
Ions
Leir
2005 (78 m)
p (proton)
ion
neutrons
p̄ (antiproton)
proton/antiproton conversion
neutrinos
electron
LHC Large Hadron Collider
SPS Super Proton Synchrotron
PS Proton Synchrotron
AD Antiproton Decelerator
CTF-3 Clic Test Facility
CNGS Cern Neutrinos to Gran Sasso
ISOLDE Isotope Separator OnLine DEvice
LEIR Low Energy Ion Ring
LINAC LINear ACcelerator
n-ToF Neutrons Time Of Flight

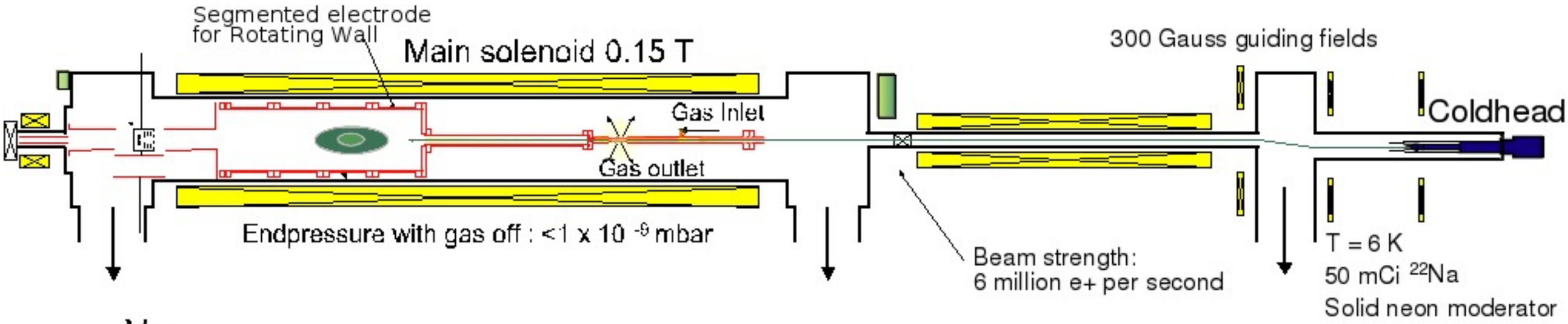
Antiproton Decelerator

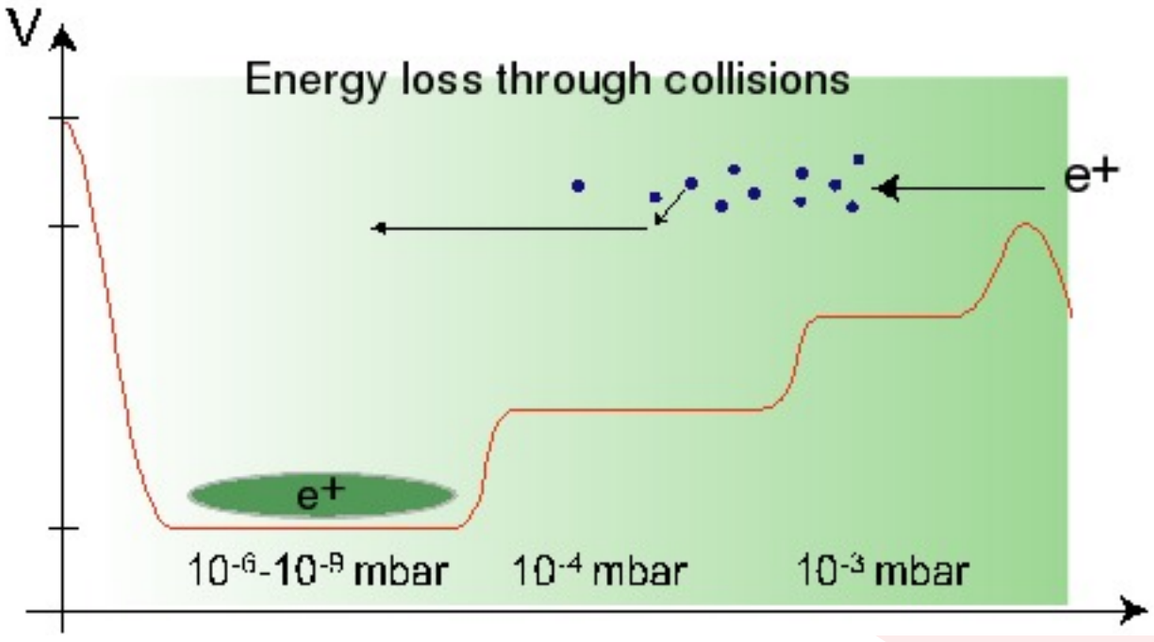


$\bar{p}$ trapping



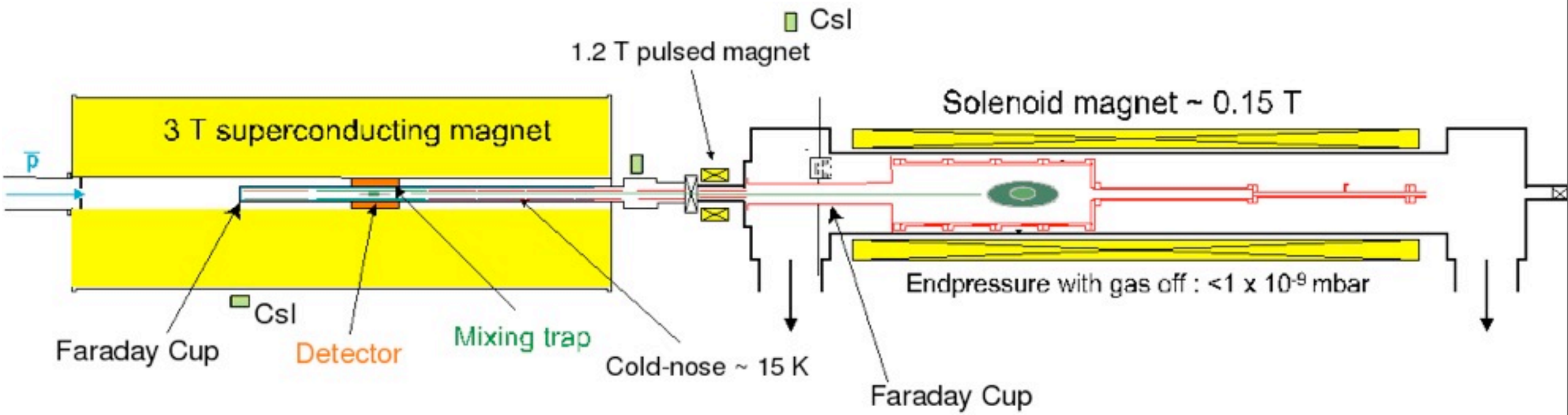
e+ trapping

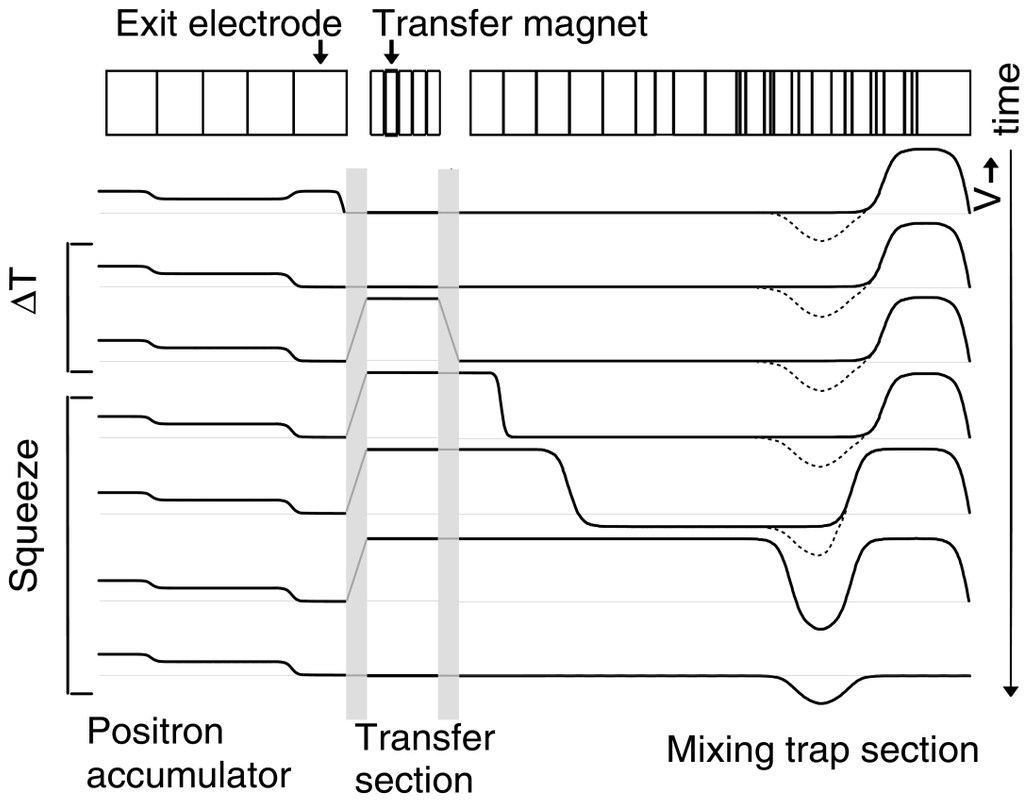


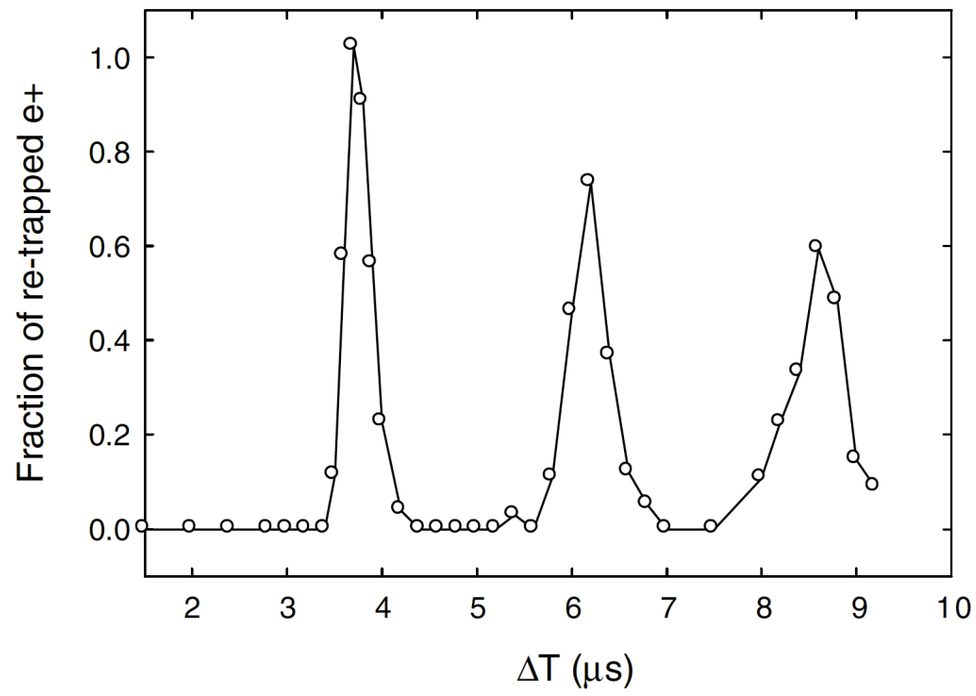


T. J. Murphy and C. M. Surko, *Phys. Rev. A* **46**, 5696 (1992)

e+ transfer



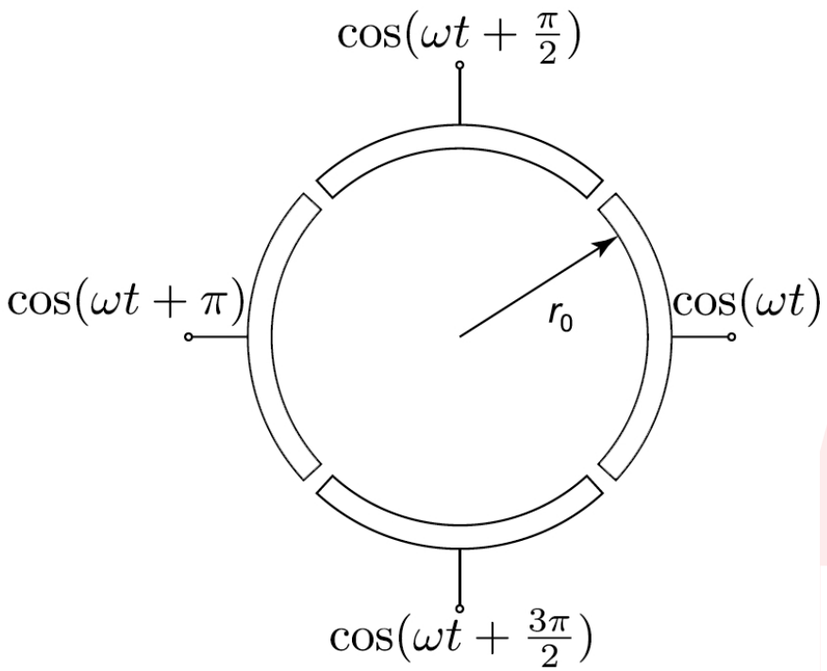




L. V. Jørgensen, *et al.* (ATHENA collaboration) *Phys. Rev. Lett.* **95,** 025002 (2005)

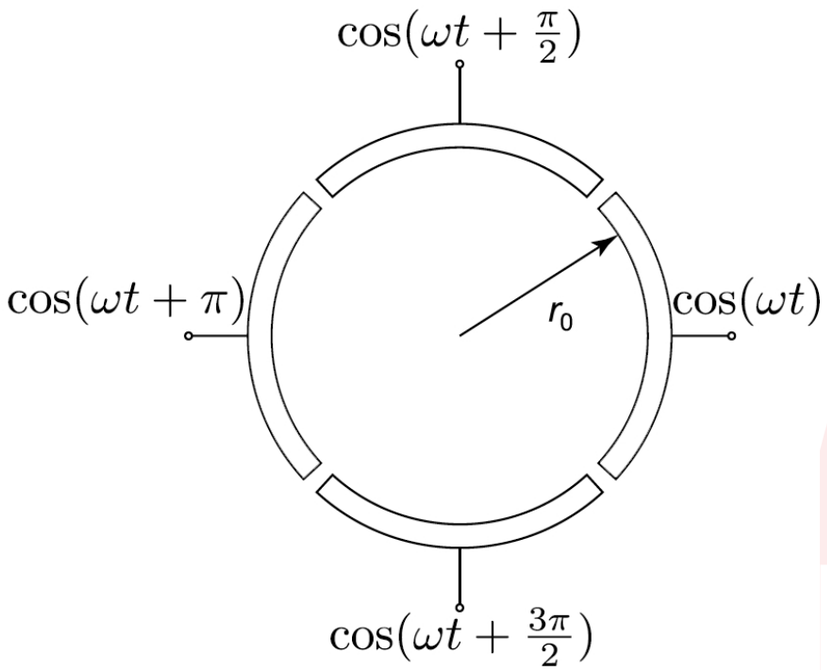
Compression using a Rotating Wall Electric Field

Compression using a Rotating Wall Electric Field

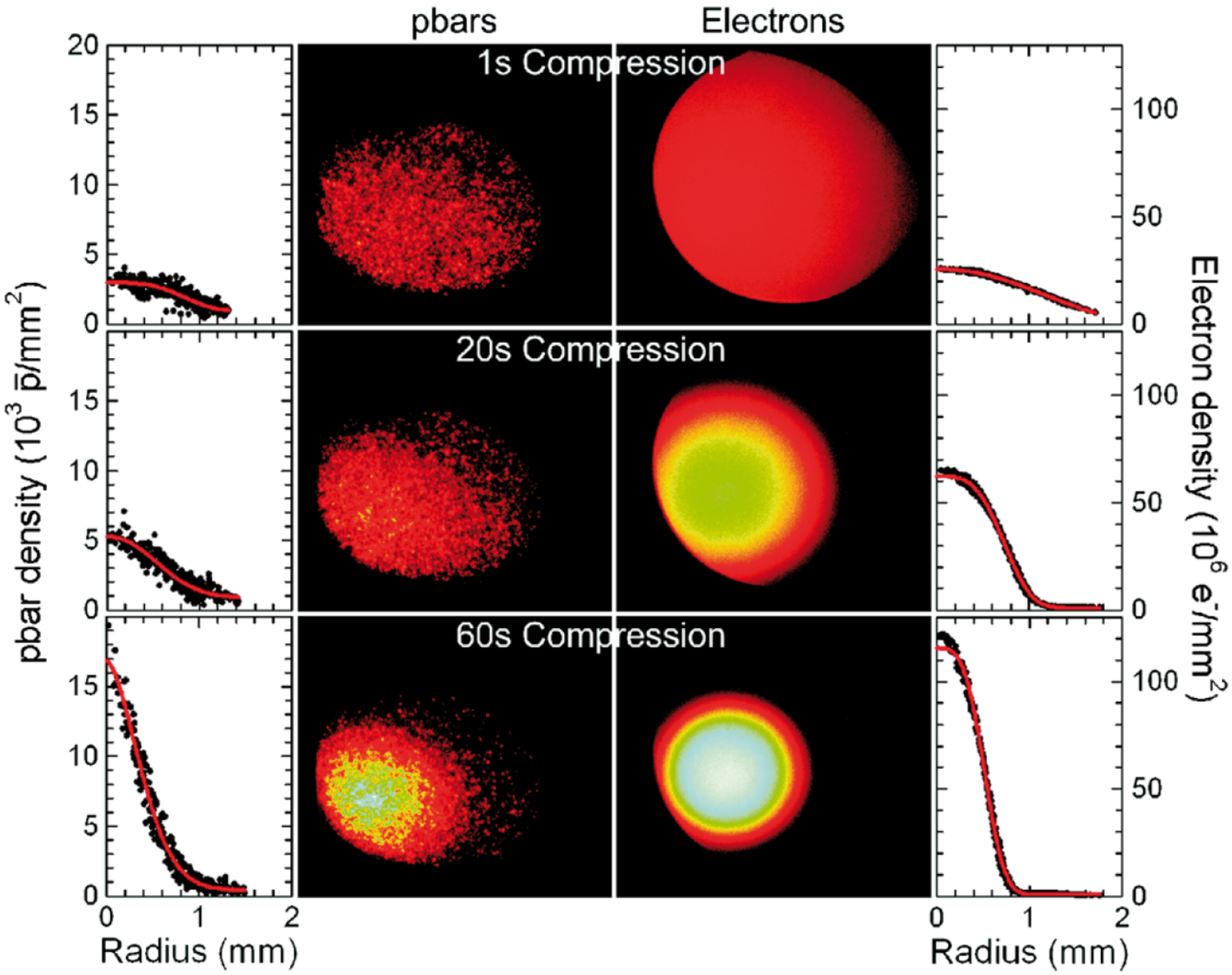


X.-P. Huang *et al.*, *Phys. Rev. Lett.* **78**, 875 (1997)

Compression using a Rotating Wall Electric Field

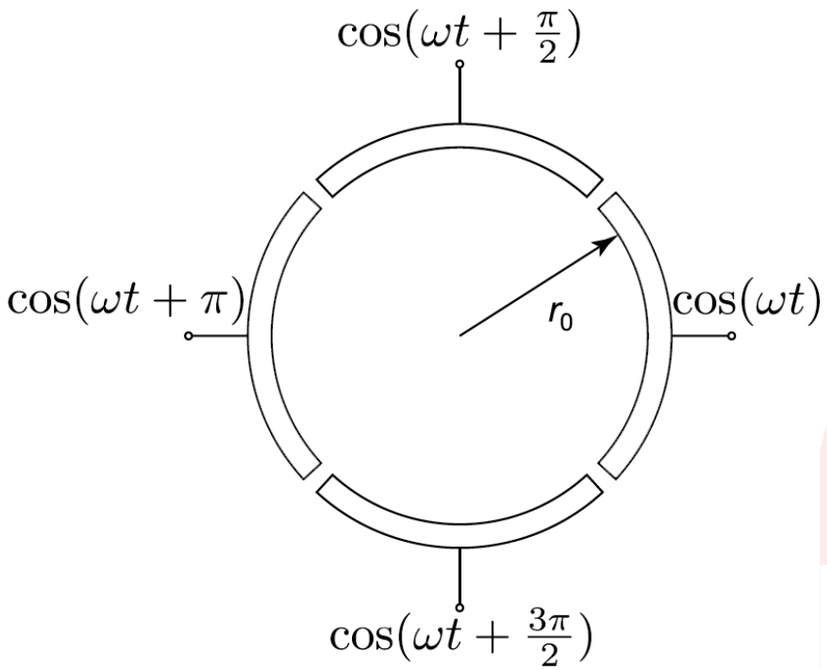


X.-P. Huang *et al.*, *Phys. Rev. Lett.* **78**, 875 (1997)

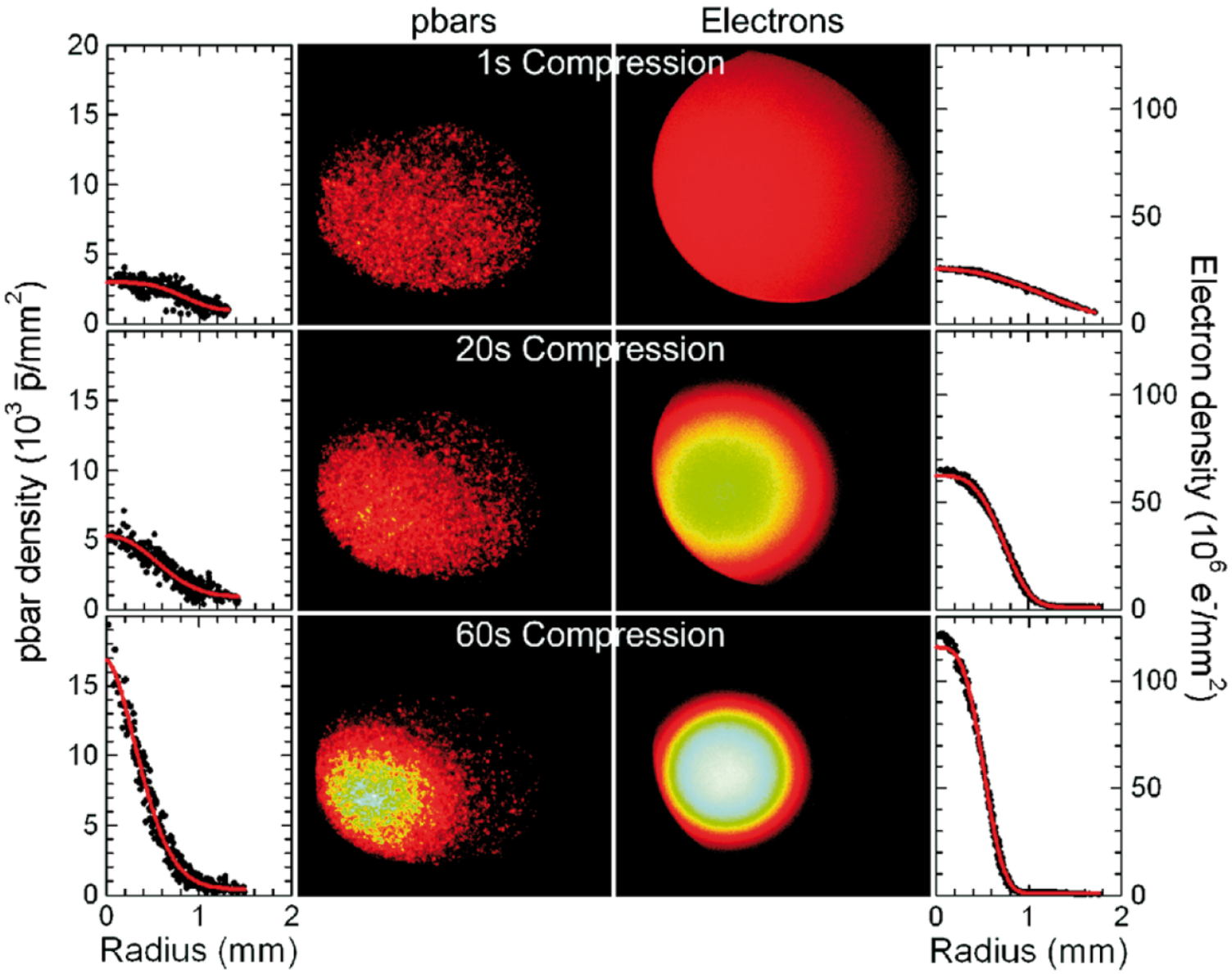


G. B. Andresen *et al.* (ALPHA collaboration)
Phys. Rev. Lett. **100**, 203401 (2008)

Compression using a Rotating Wall Electric Field



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

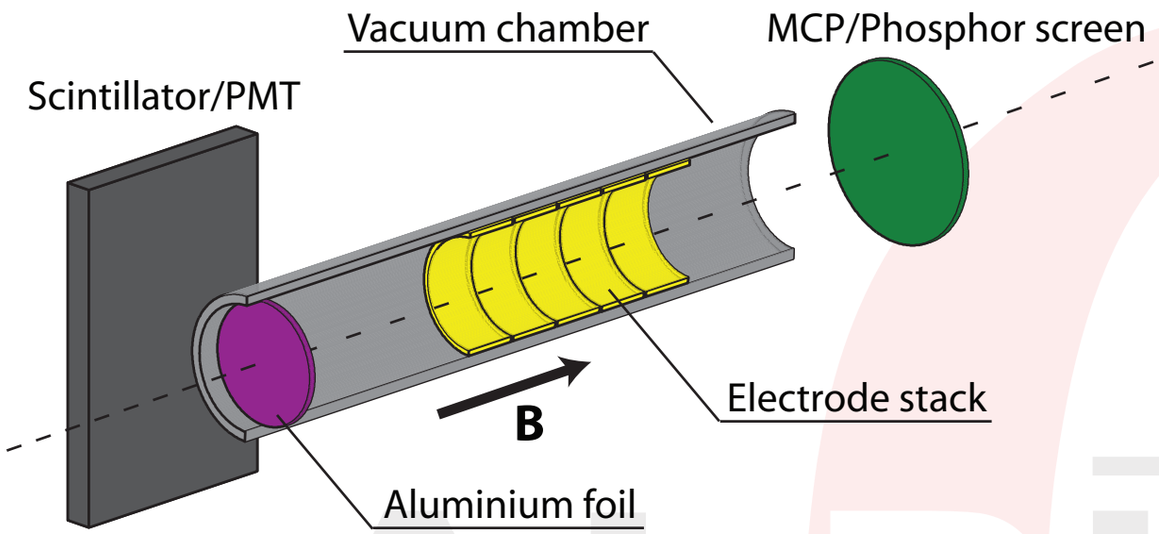


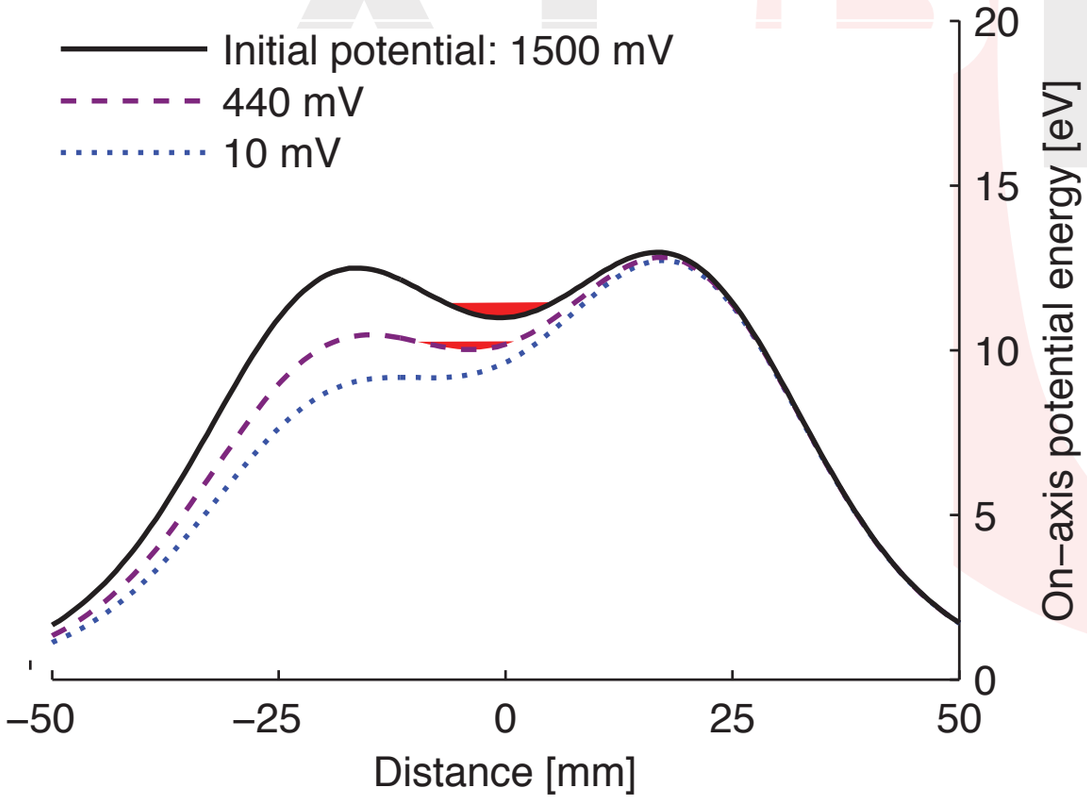
G. B. Andresen *et al.* (ALPHA collaboration)
Phys. Rev. Lett. **100**, 203401 (2008)

Without electrons

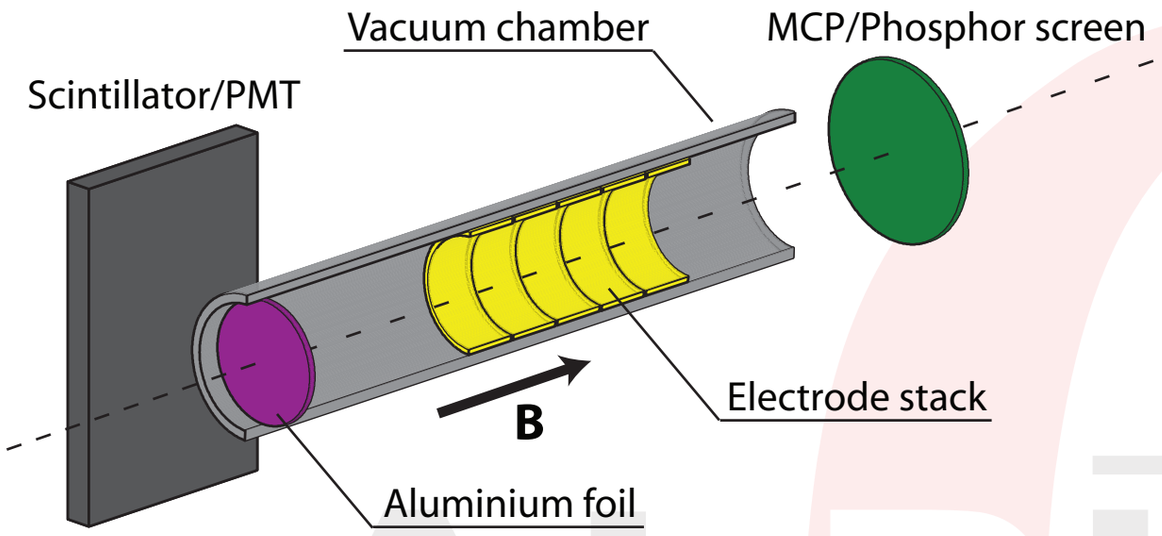
N. Kuroda *etal* (ASACUSA collaboration)
Phys. Rev. Lett. 100, 203402 (2008)

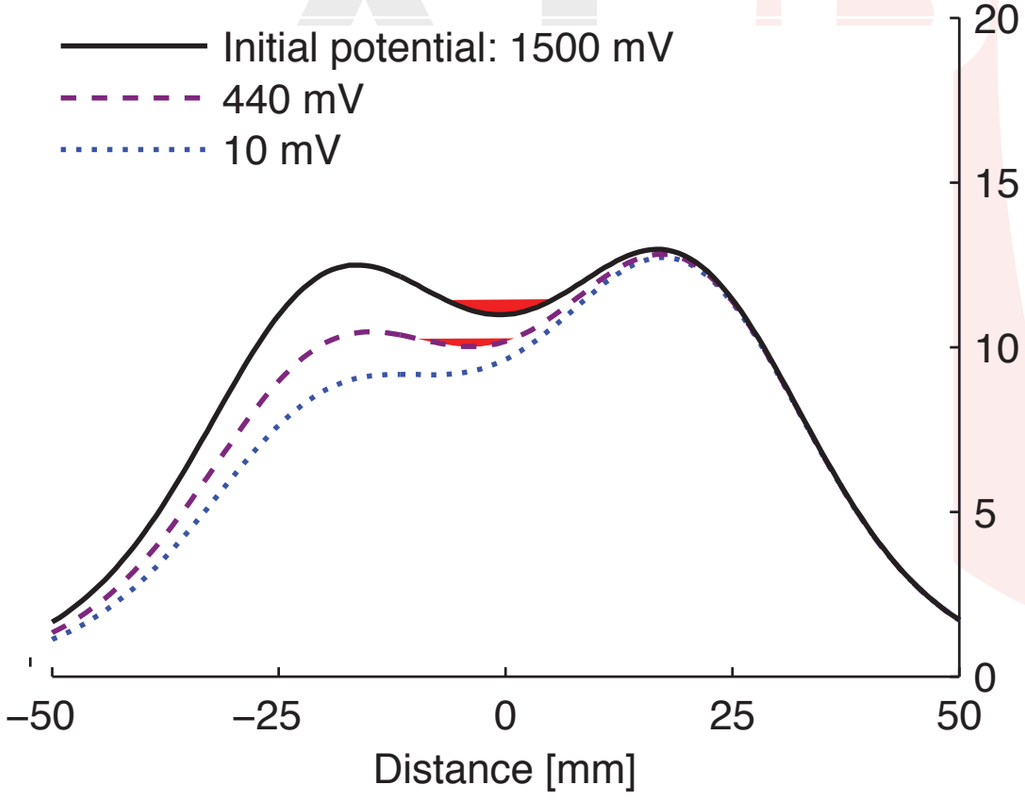
Evaporative Cooling

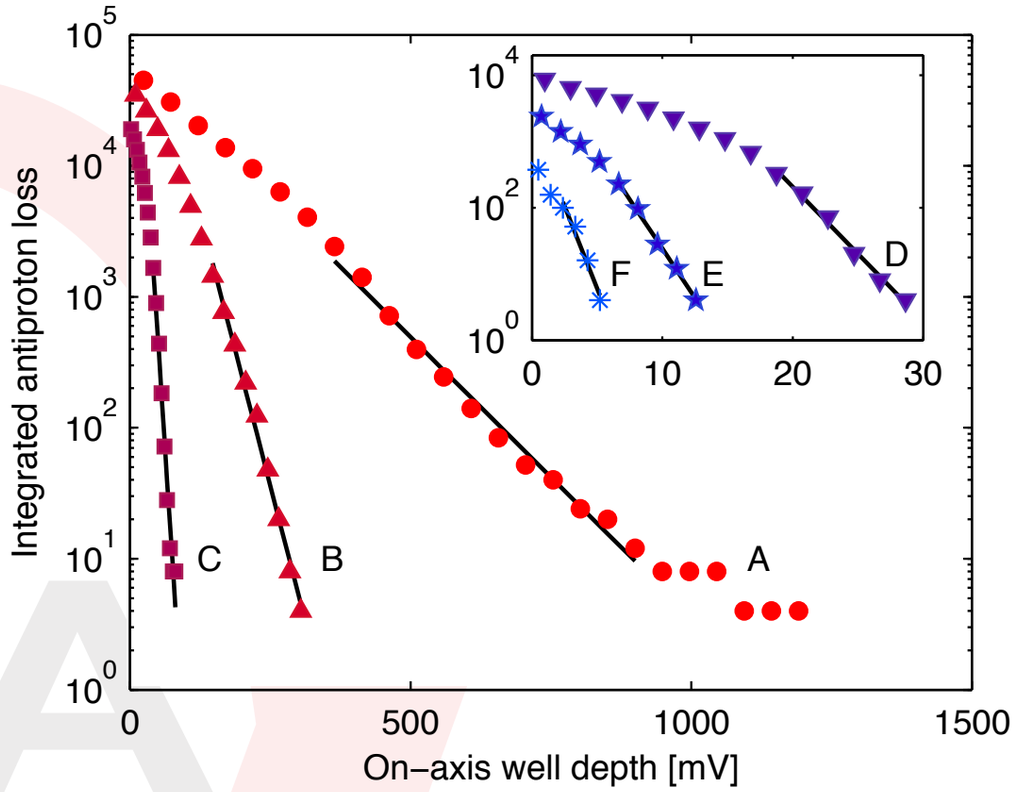




Evaporative Cooling





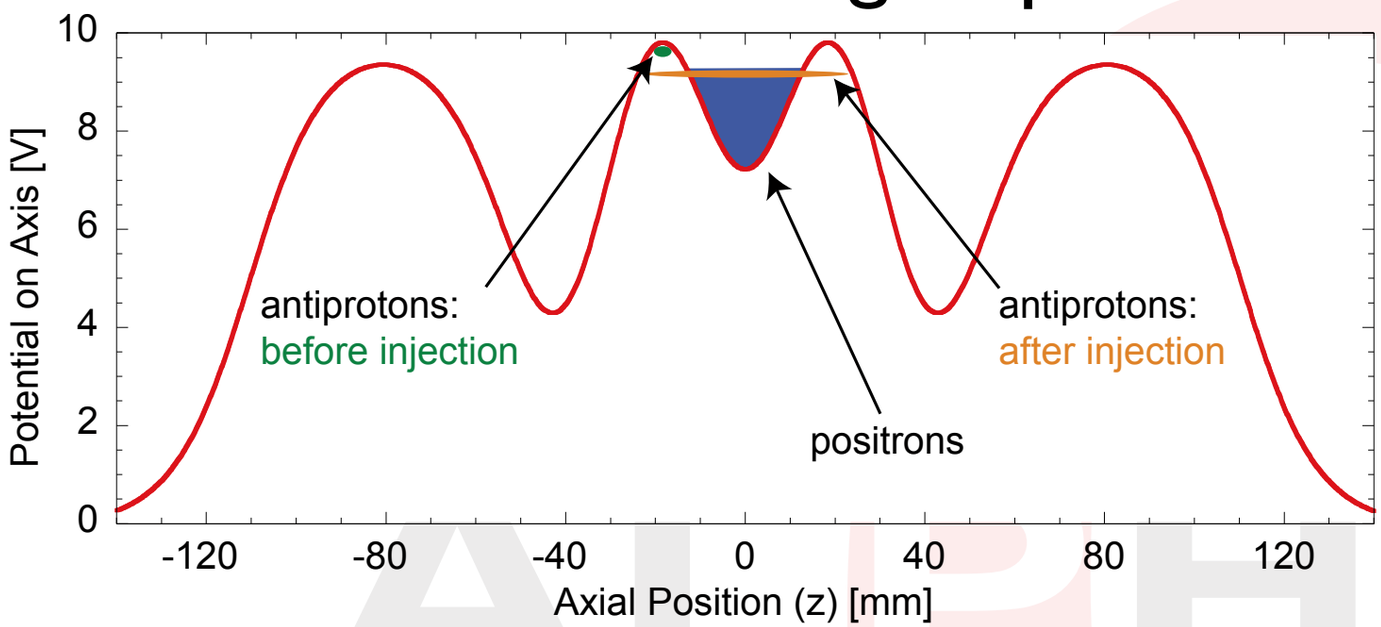


A: 1040 K
B: 325 K
C: 57 K
D: 23 K
E: 19 K
F: 9 K

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

Mixing

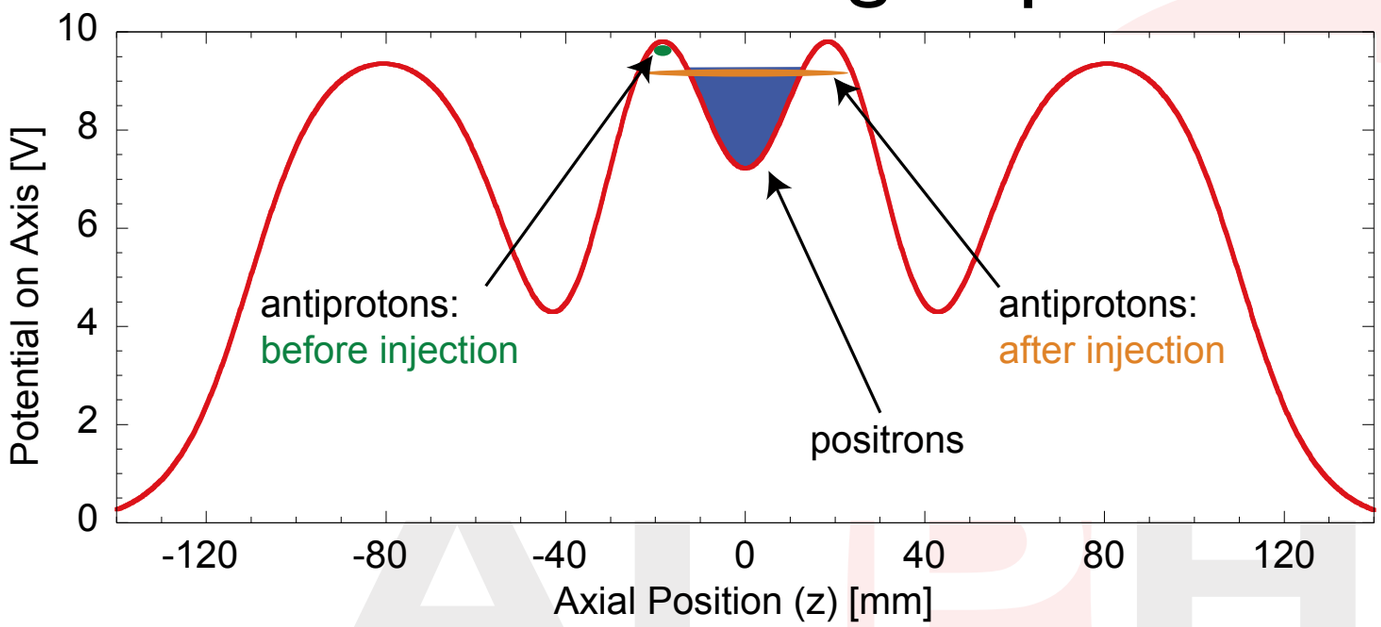
Nested Penning Trap



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

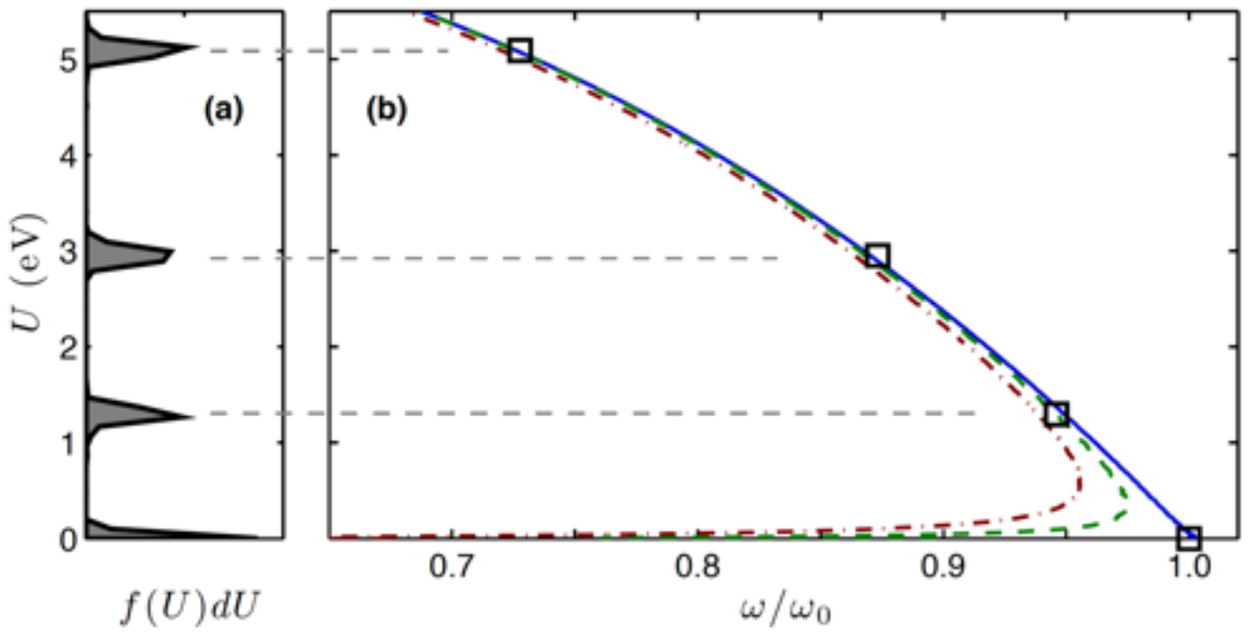
Mixing

Nested Penning Trap



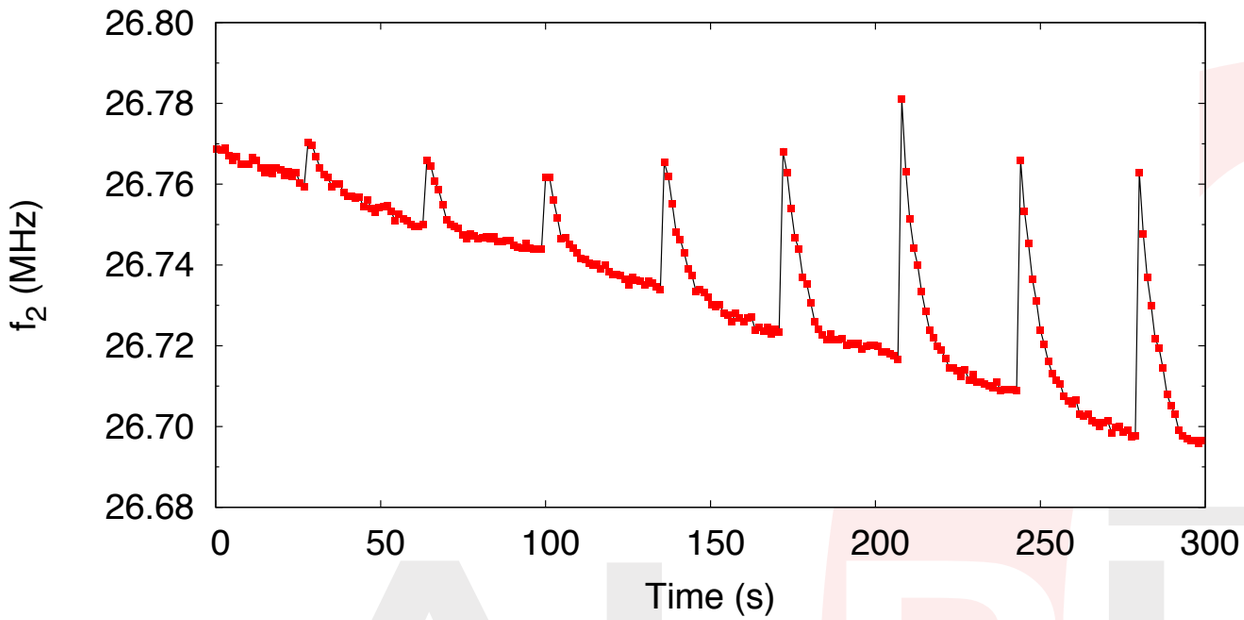
G. Gabrielse *et al. Phys. Lett. A* **129**, 38 (1988)

Autoresonance



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

Magnetic field measurements



Cyclotron excitation

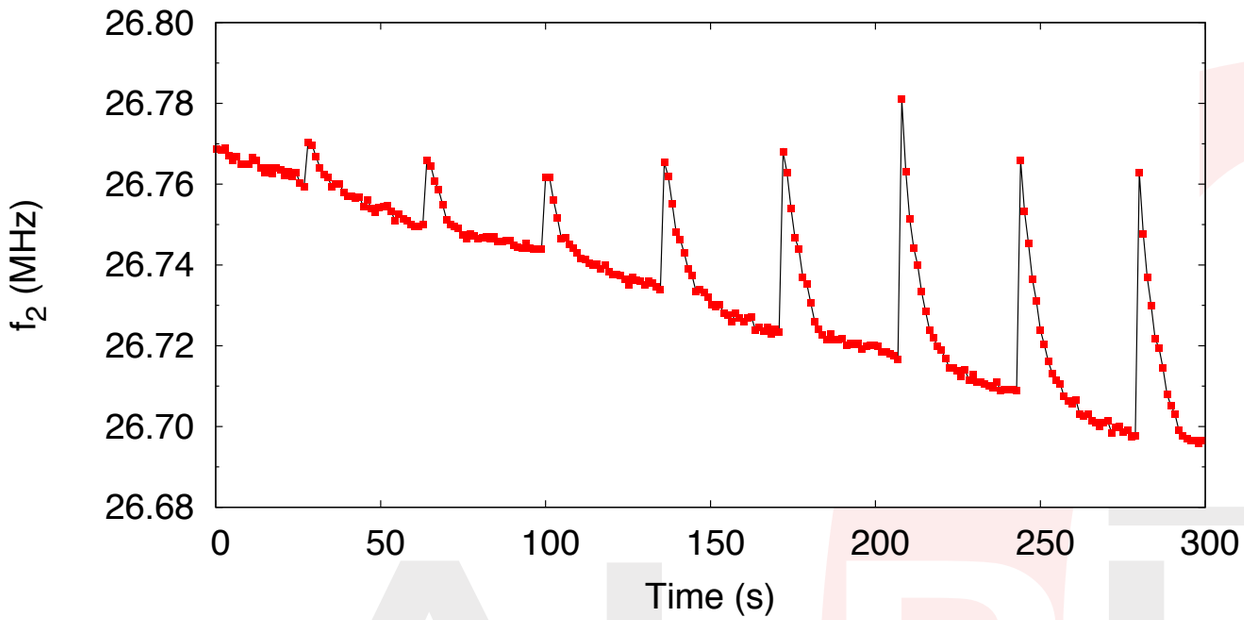
↓

Heat non-neutral electron plasma

↓

Change quadrupole mode frequency f_2

Magnetic field measurements



Cyclotron excitation

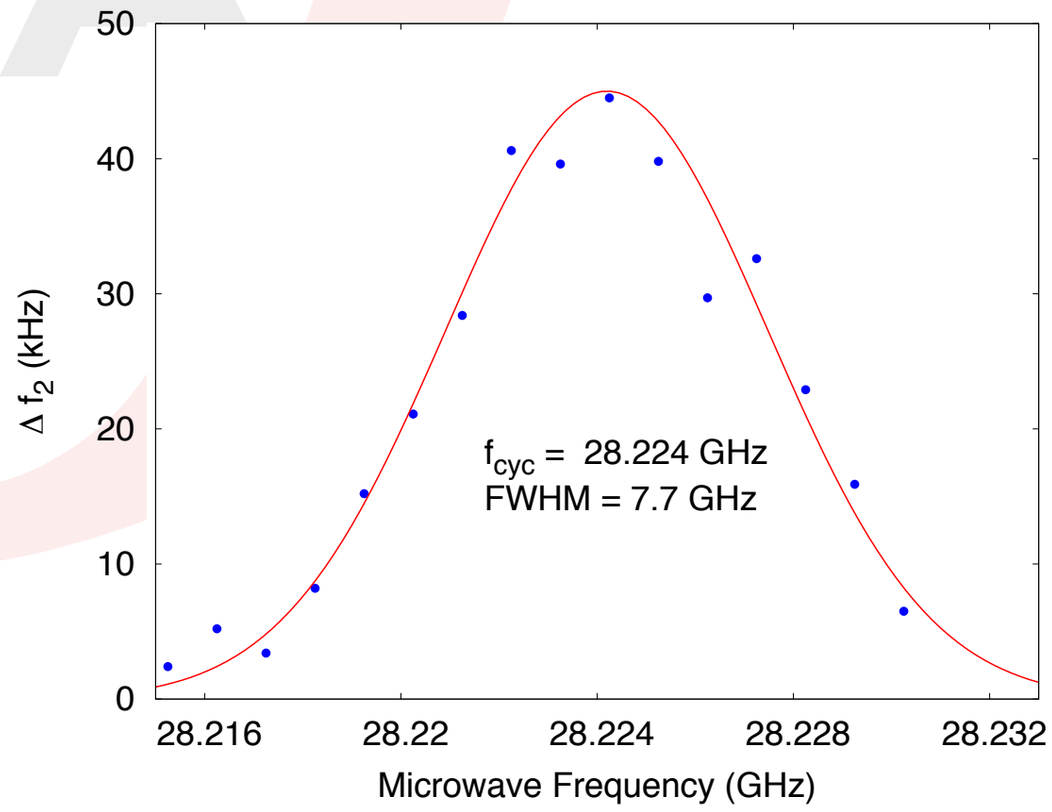
↓

Heat non-neutral electron plasma

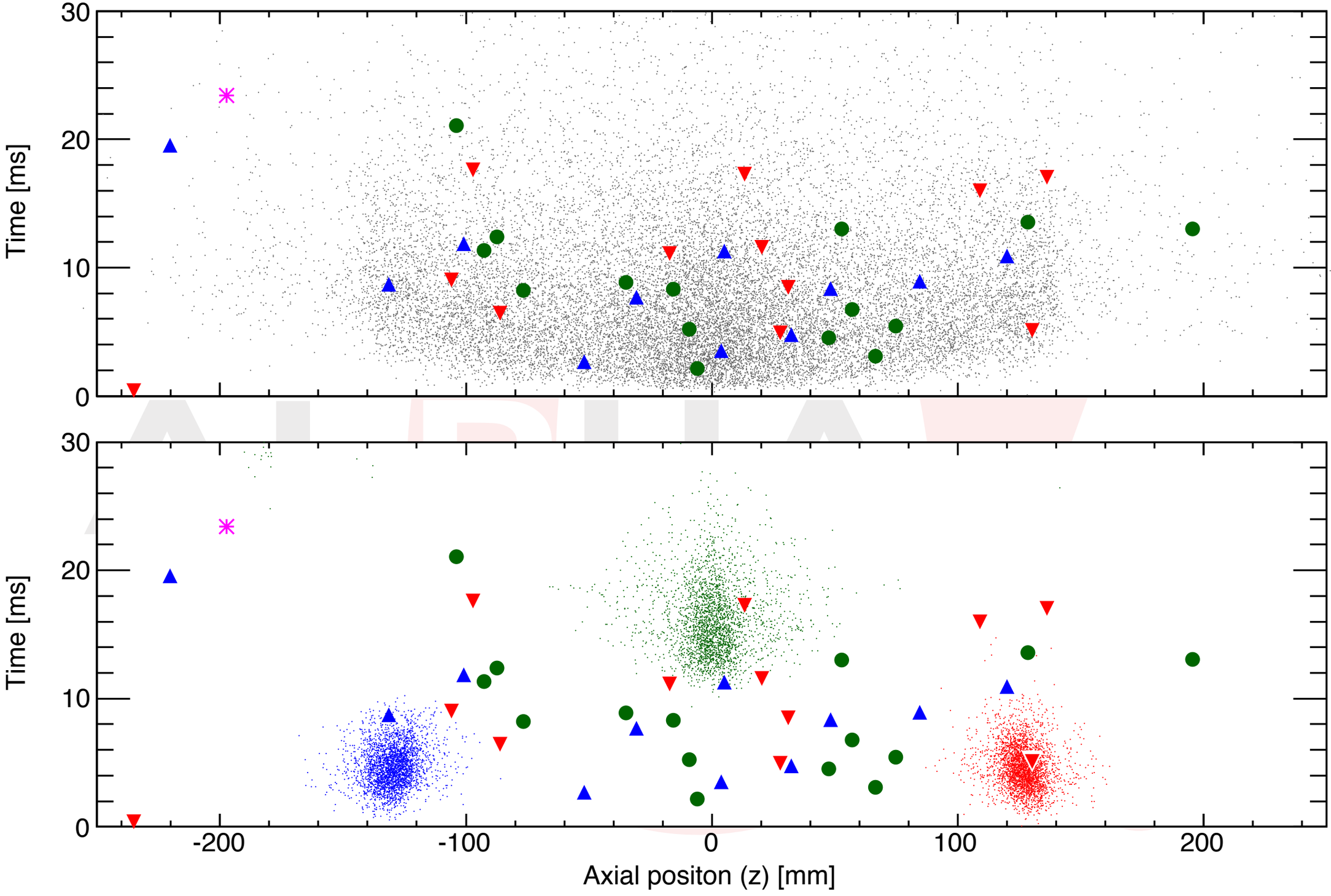
↓

Change quadrupole mode frequency f_2

Typical measurement

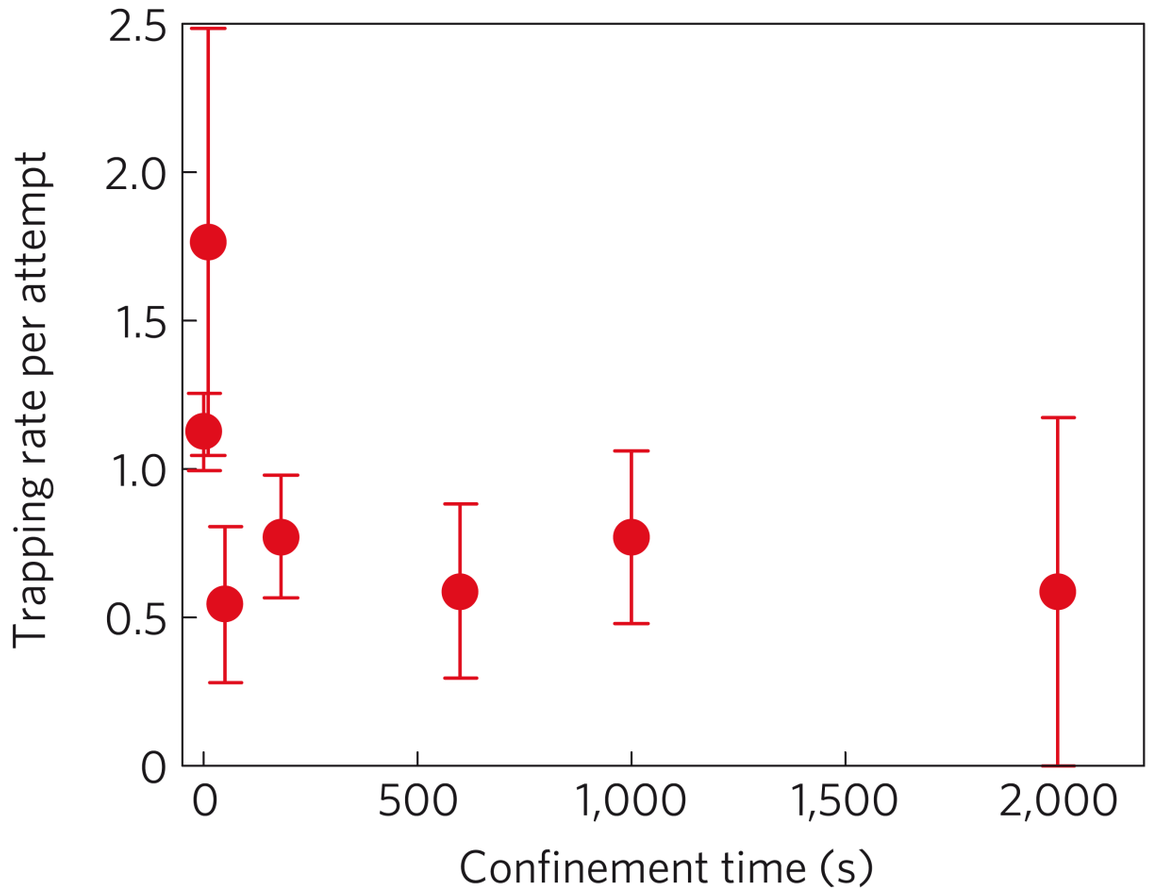


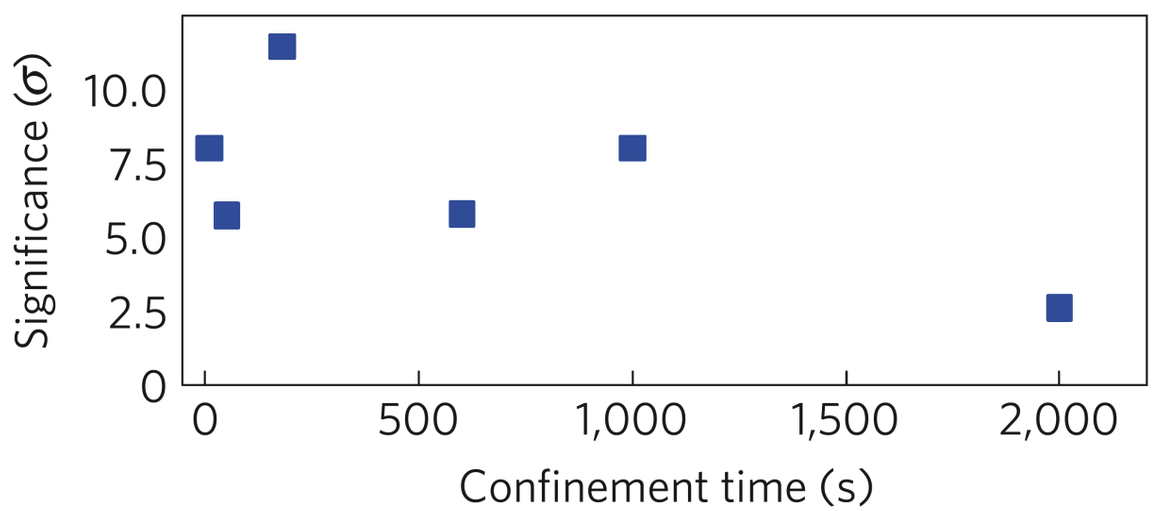
Trapping



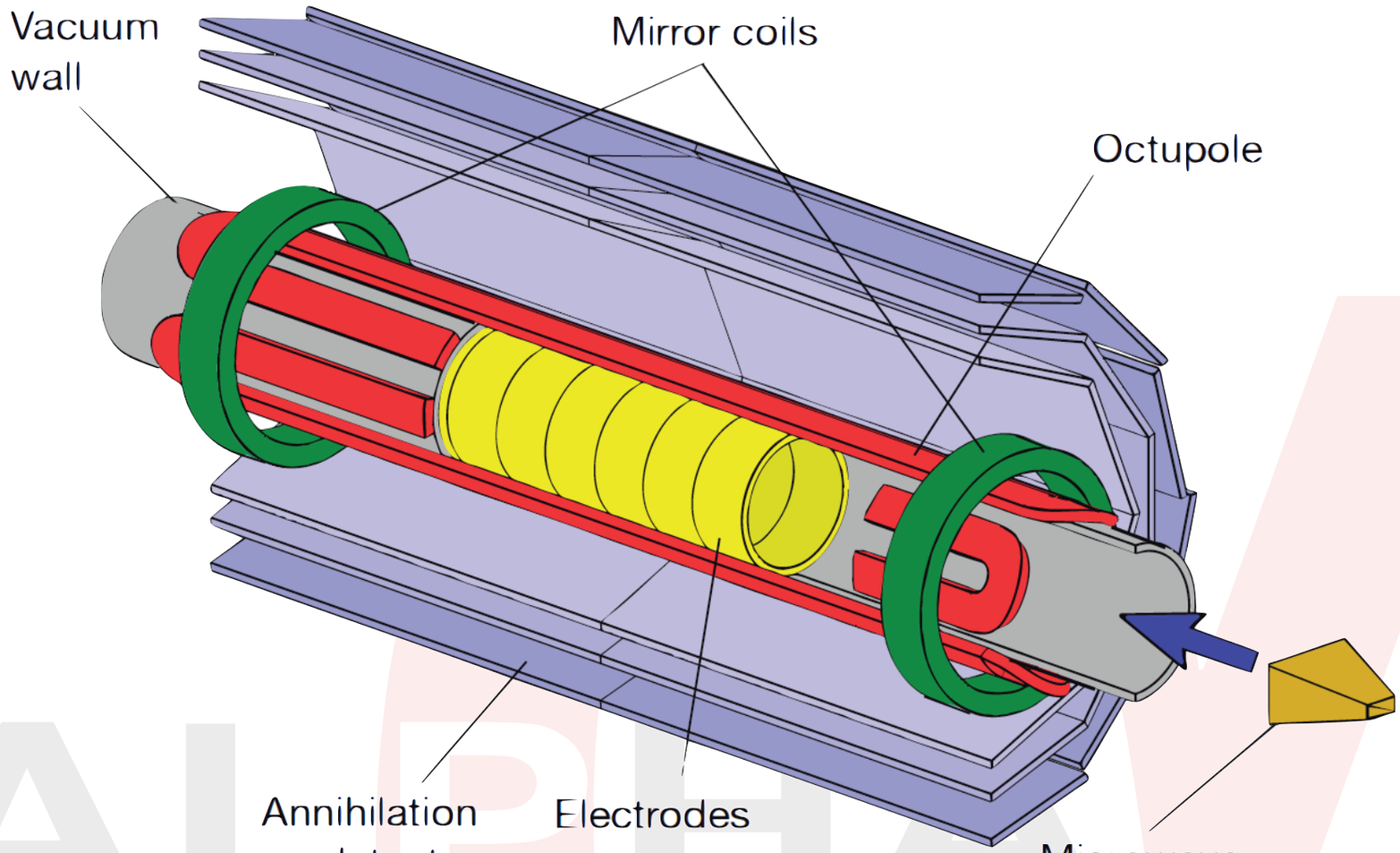
G. B. Andresen et al (ALPHA collaboration)
Nature **468**, 673 (2010)

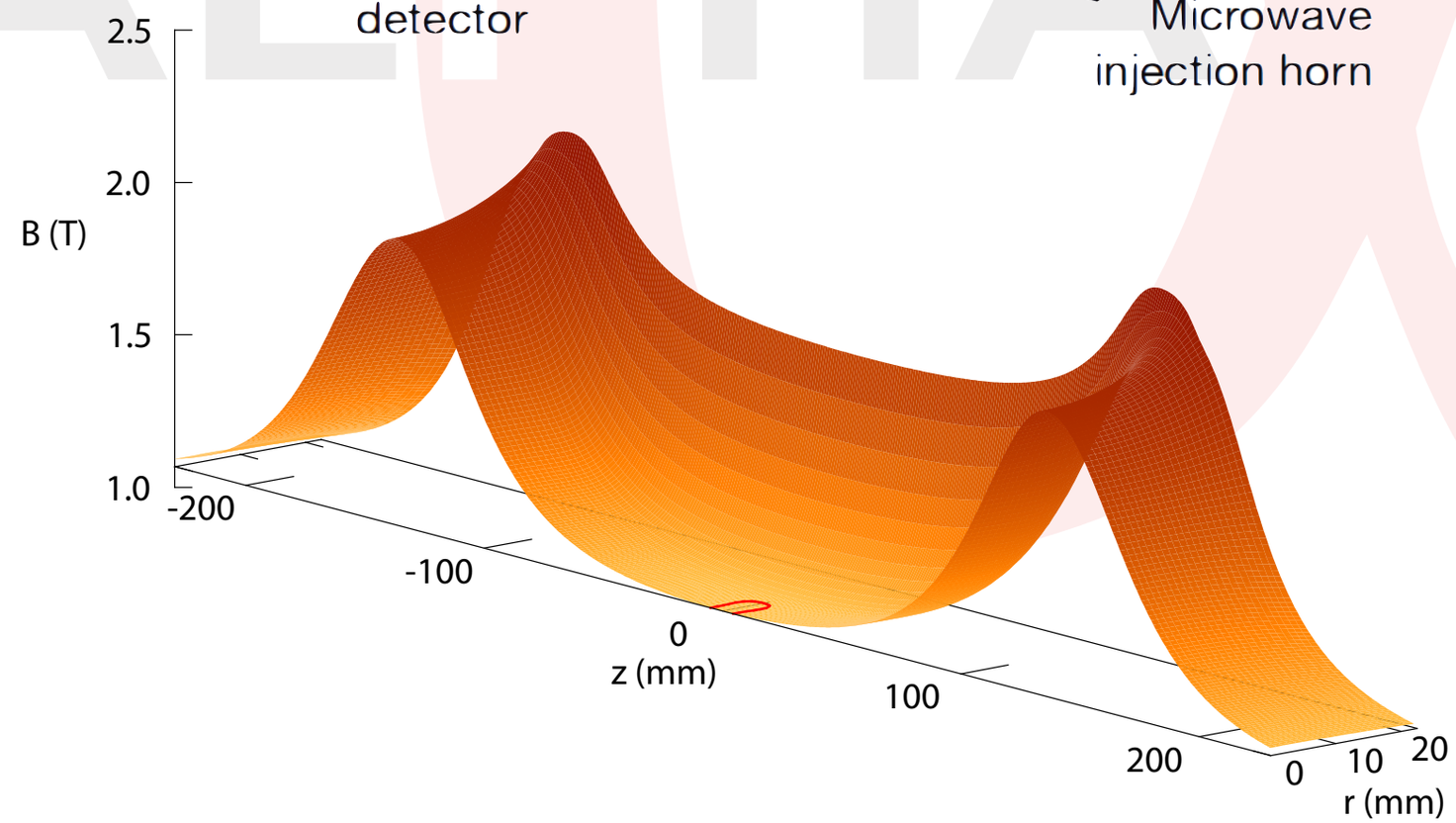
1000 Confinement





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


Vacuum wall
Mirror coils
Octupole
Annihilation detector
Electrodes
Microwave injection horn


B (T)
2.5
2.0
1.5
1.0
-200
-100
0
z (mm)
100
200
0
10
20
r (mm)

Transition measurements

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

Transition measurements

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

Two data sets

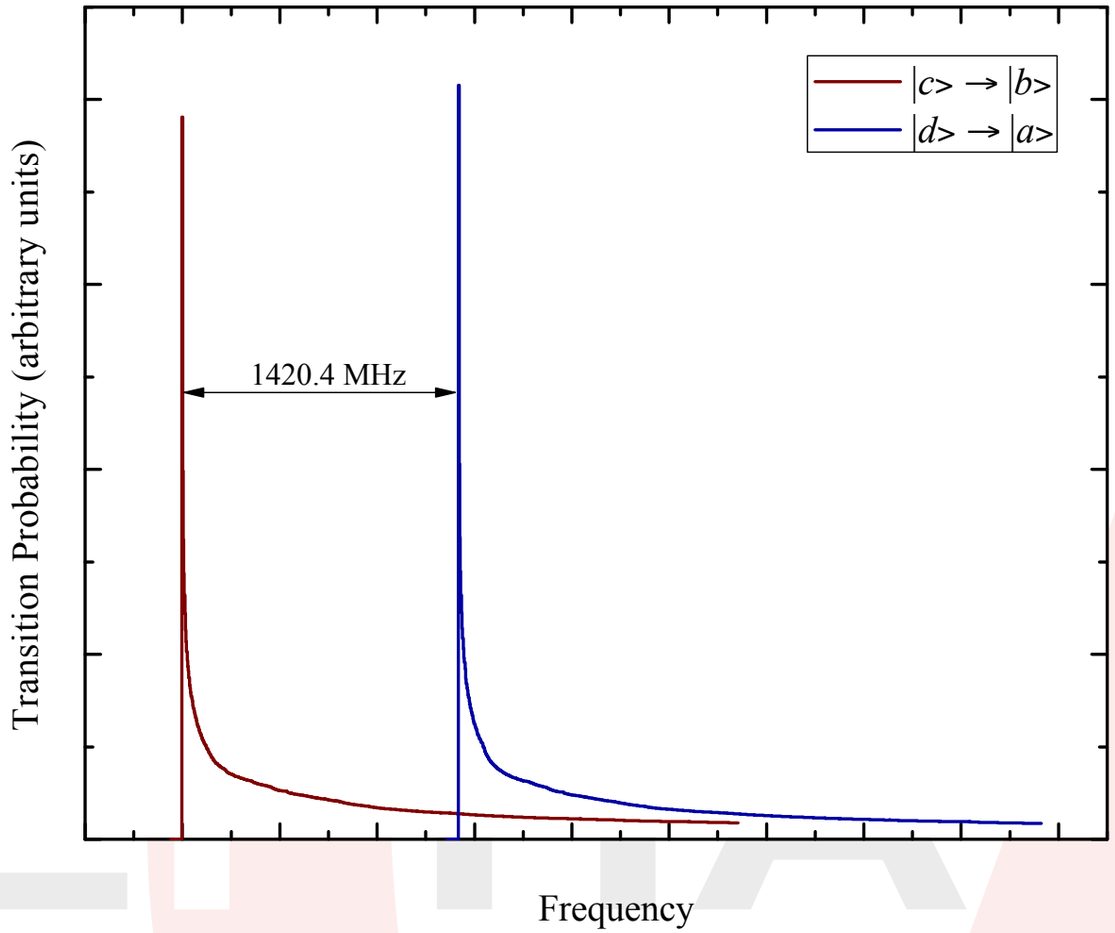
Disappearance mode:

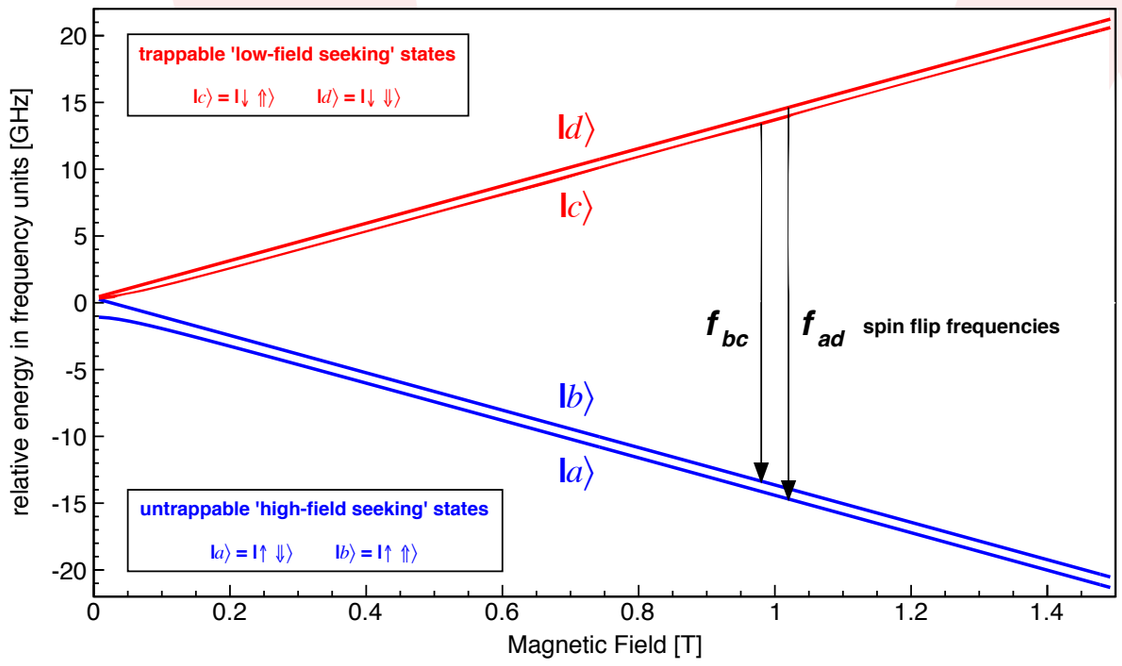
Count the remaining antihydrogen atoms when quenching

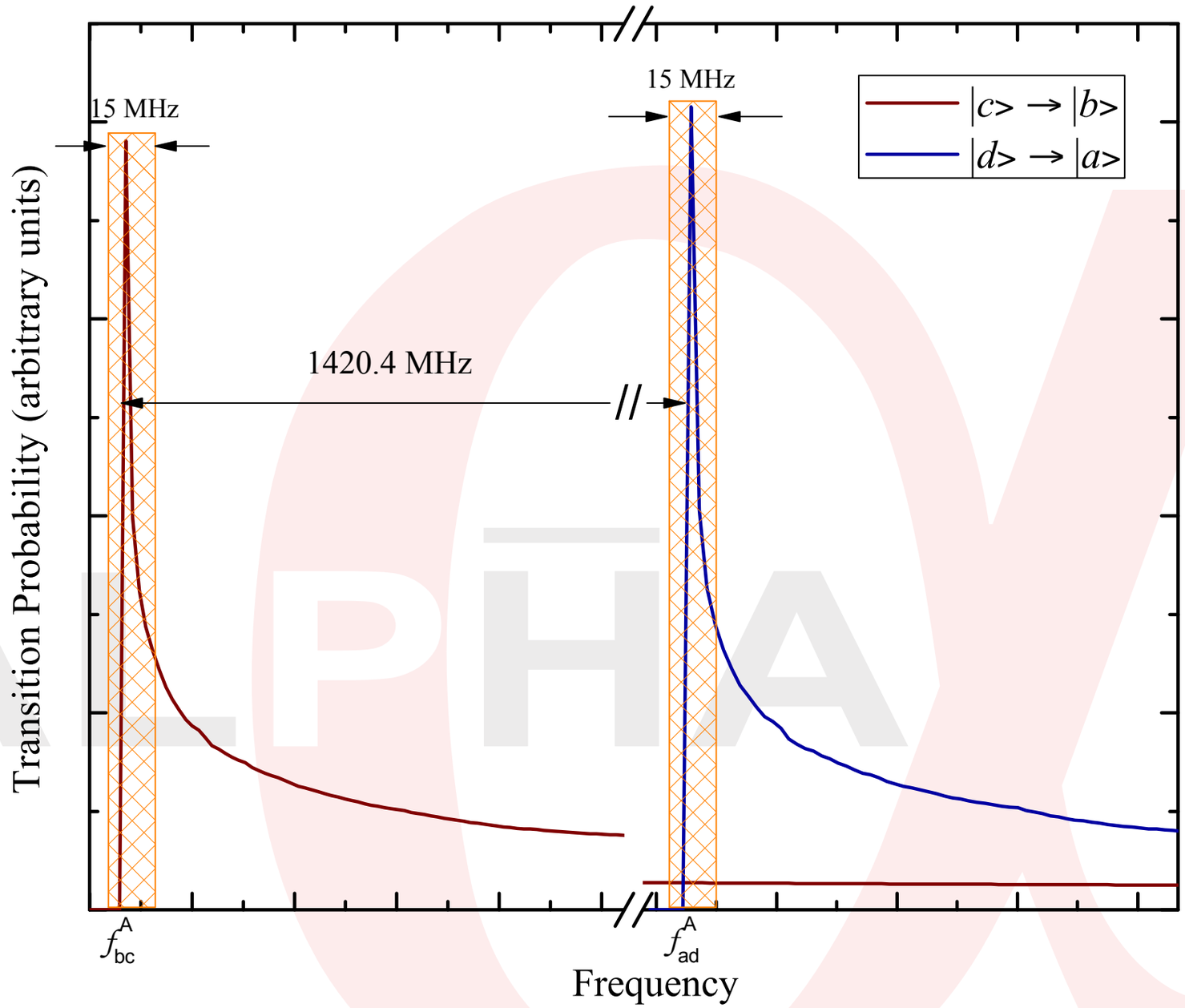
Appearance mode:

Count the escaping antihydrogen atoms during the microwave injection

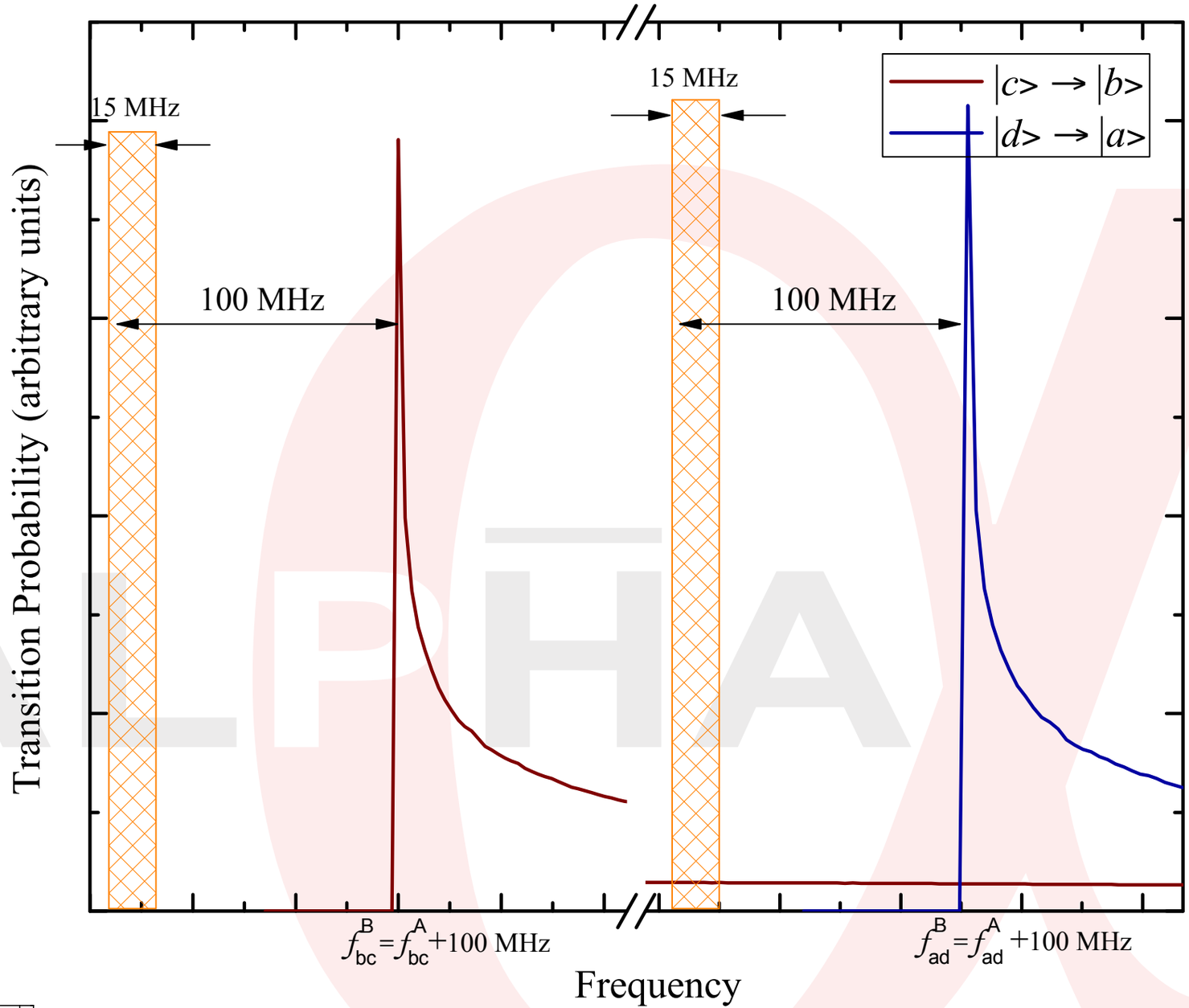
Simulation of the transition probability



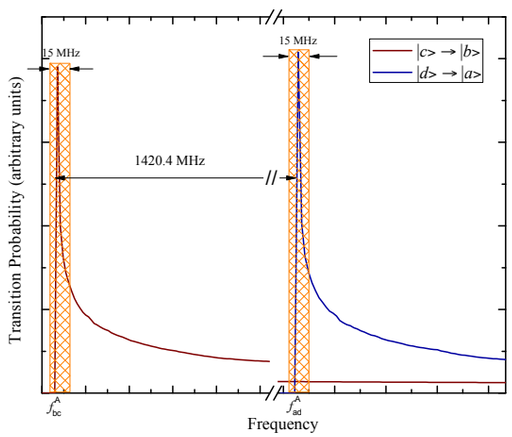



Series 1
15 MHz
15 MHz
1420.4 MHz
|c> → |b>
|d> → |a>
Transition Probability (arbitrary units)
f_{bc}^{A}
f_{ad}^{A}
Frequency

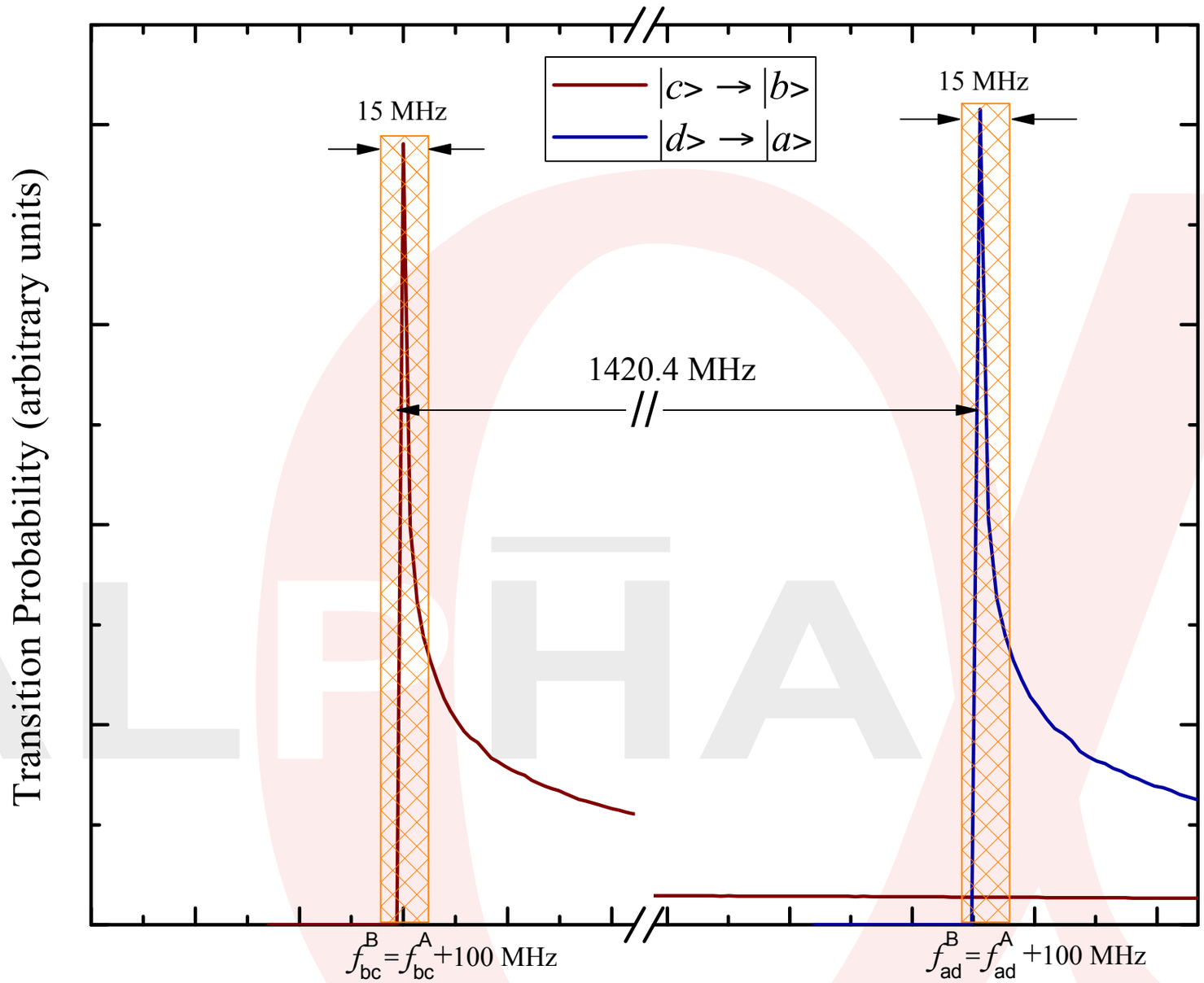
Series 2 & 4



Series 1



Series 3



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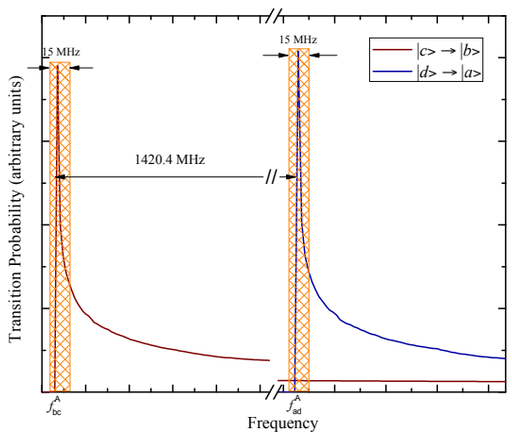
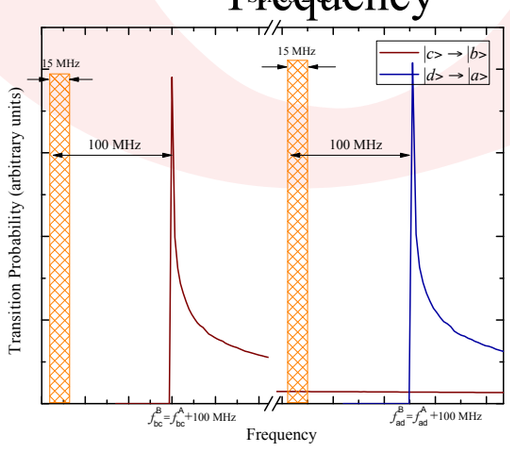
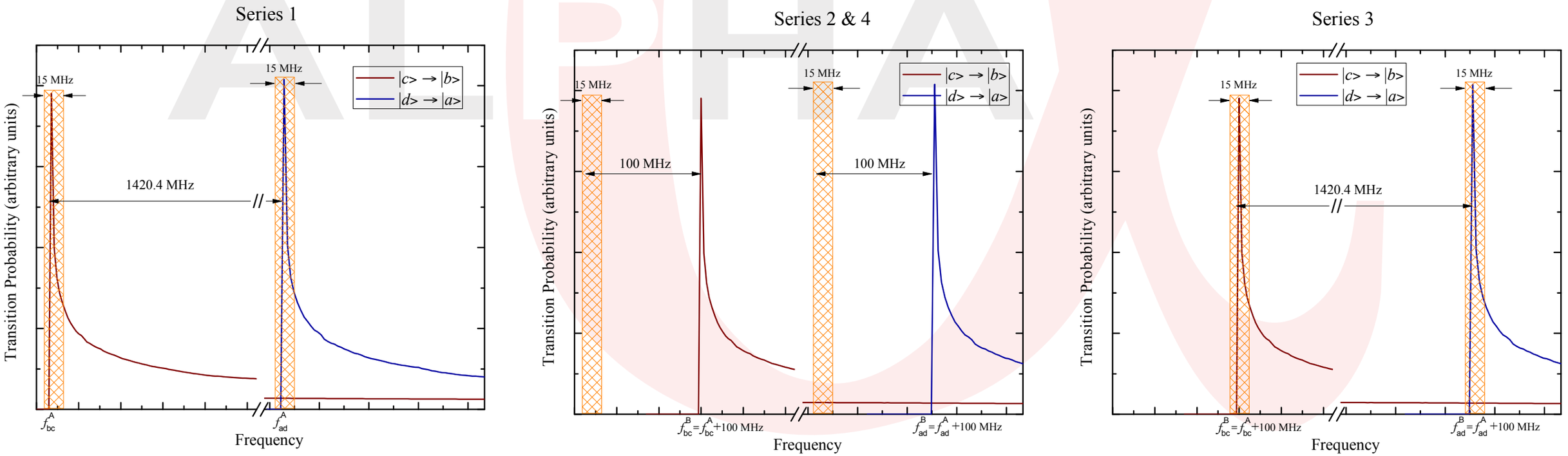


Series 2 & 4



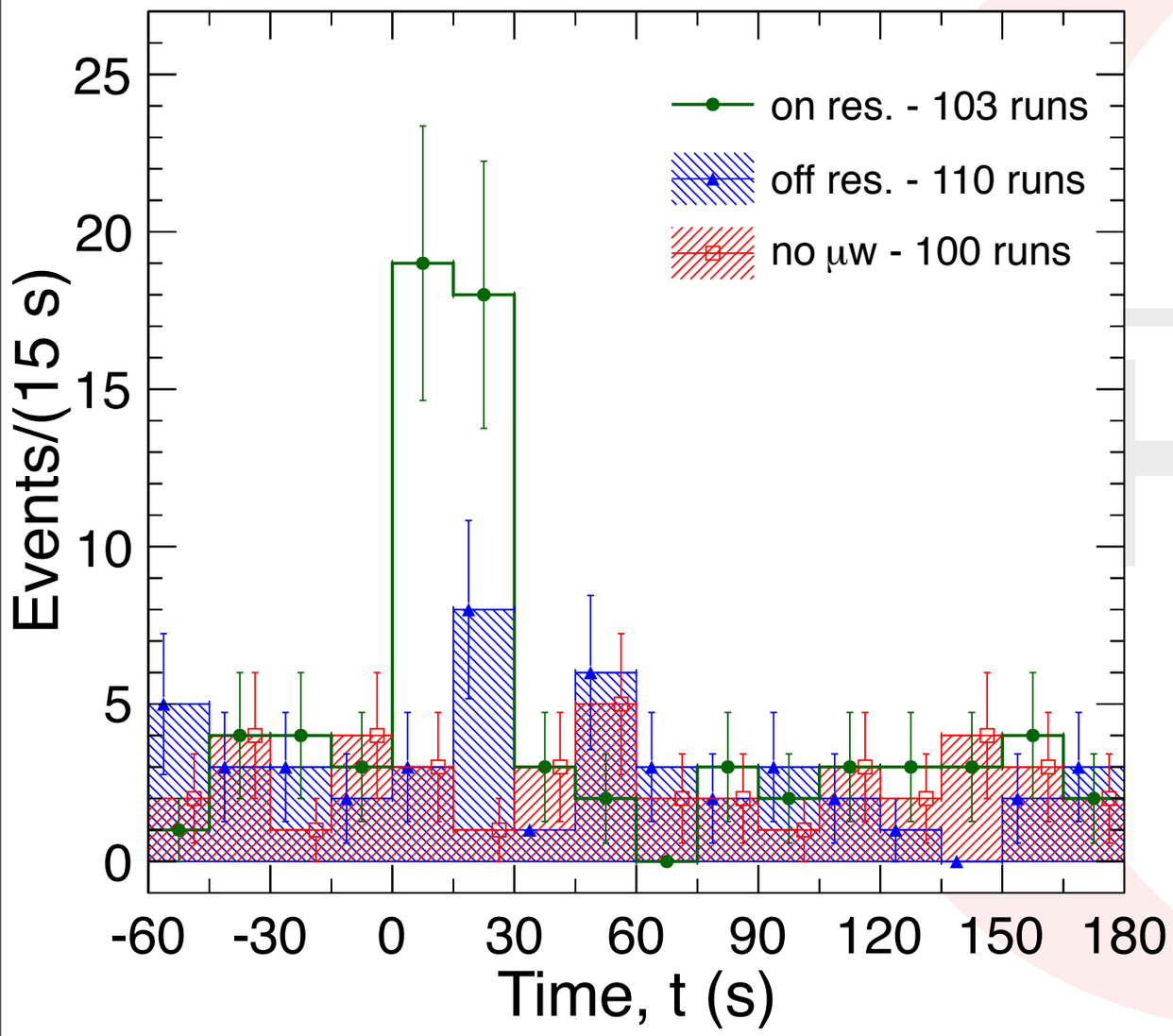
Totals for all ‘disappearance mode’ series

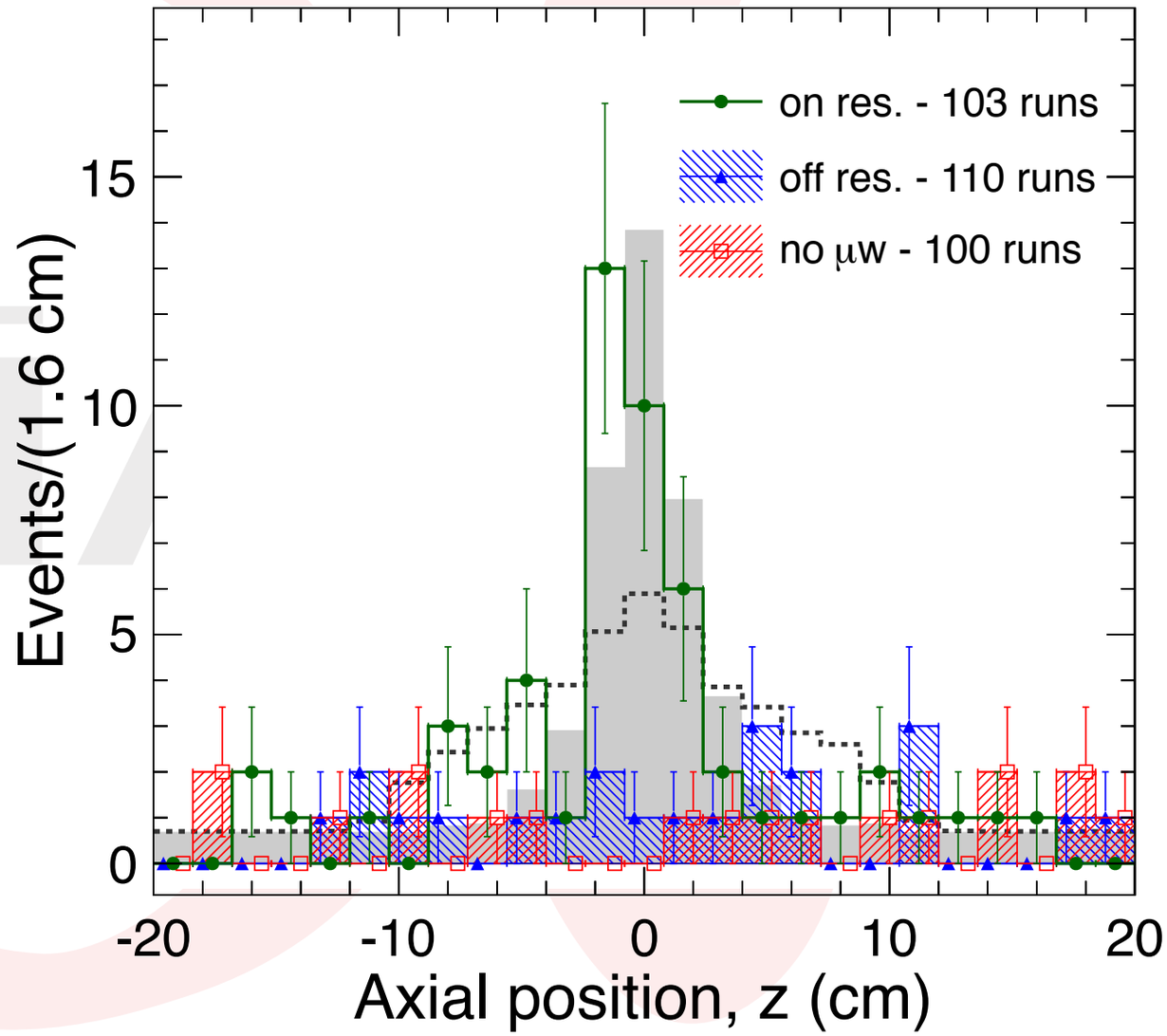
	Number of attempts	Detected antihydrogen	Rate
On resonance (1 + 3)	103	2	0.02 ± 0.01
Off resonance (2 + 4)	110	23	0.21 ± 0.04
No microwaves (5 + 6)	100	40	0.40 ± 0.06



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

Appearance measurements





Conclusion + Outlook

- We trapped antihydrogen and were able to make quantum transitions using microwaves
- Presently, we are upgrading the equipment for laser and improved microwave access
- There are no antiprotons in 2013. This time will be used for ironing out problems encountered and improving lasers and measurement techniques
- First spectroscopy in 2014?
- Further away:
  - Devise a realistic scheme to measure "g" for antihydrogen.

Funding

The Leverhulme Trust

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

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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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