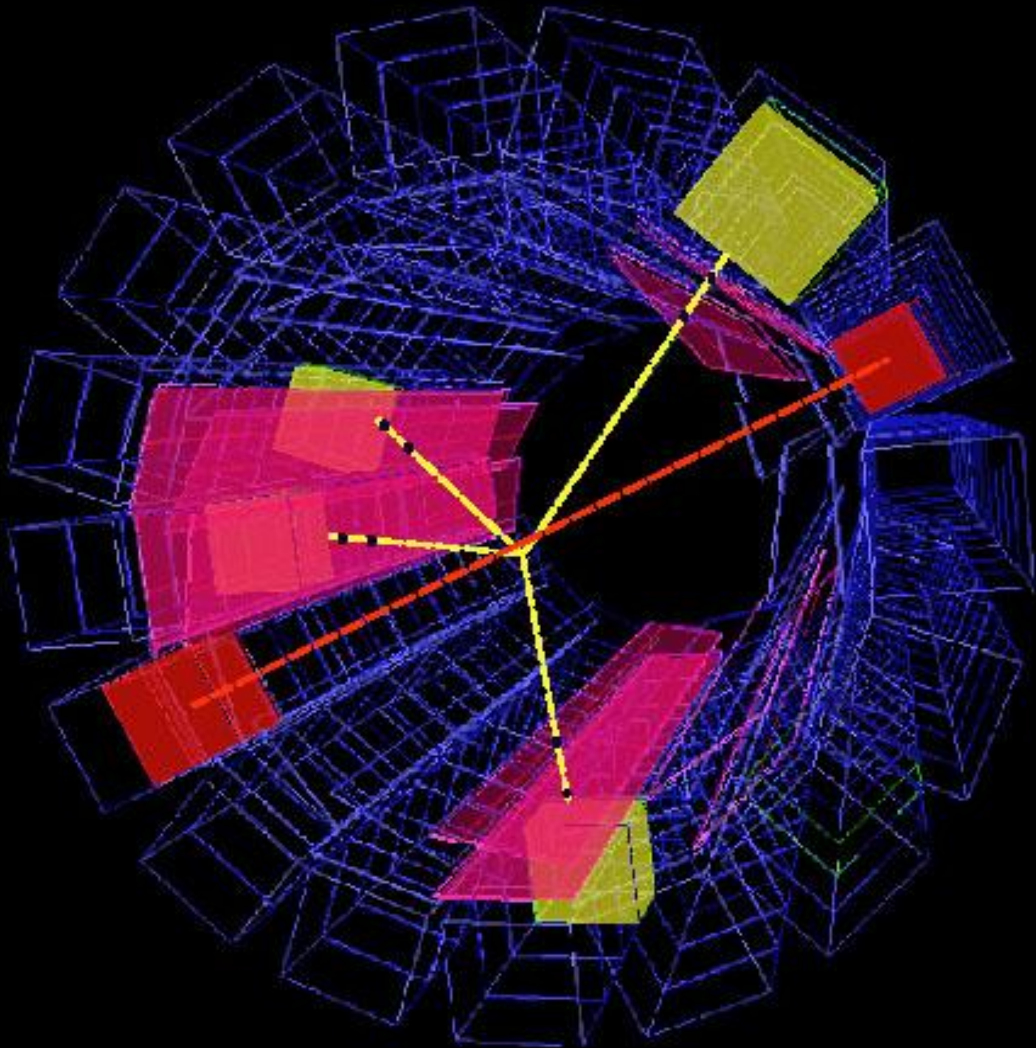
Trapped Antihydrogen

Swansea University Prifysgol Abertawe



**Mike Charlton, Physics,
Swansea University
UK**

Summary of the Talk

Motivation for Antihydrogen Experiments

Processes and Some Insights from Simulations

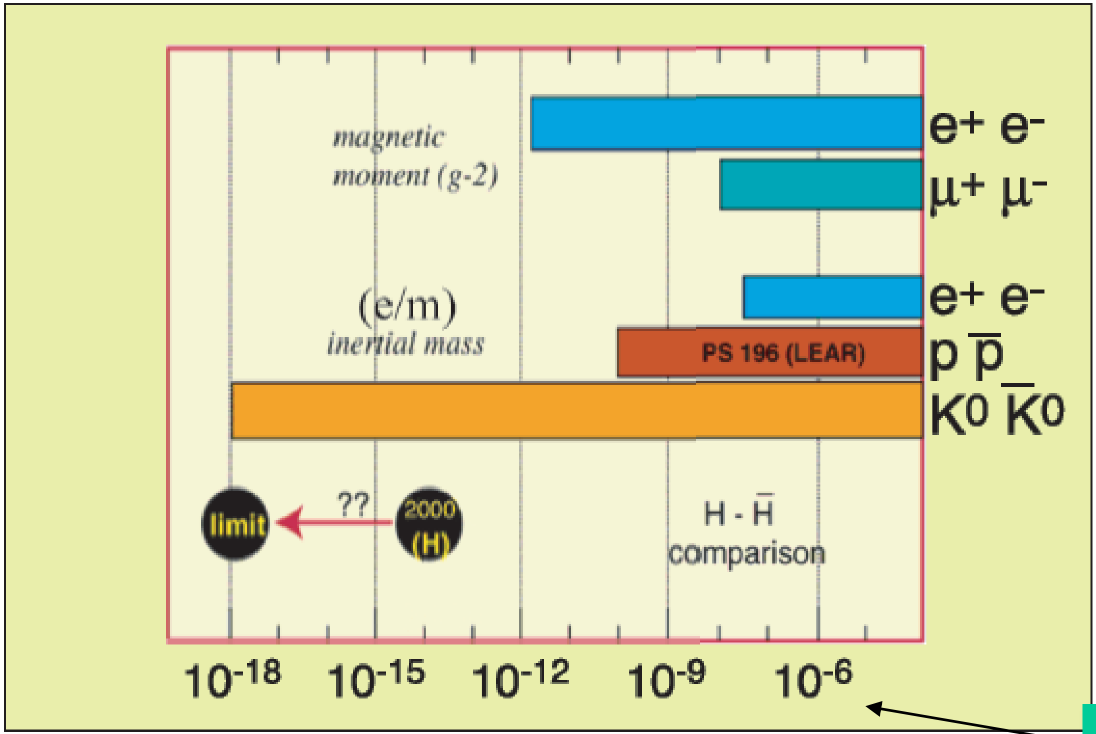
Positron and Antiproton Clouds - Collection and Manipulation

Antihydrogen Production

The ALPHA Antihydrogen Trapping Experiment

| Antihydrogen | = | Hydrogen | ?

CPT Theorem. **(Based upon Lorentz Invariance, spin-statistics and locality)**



Relative precision

Some of the most precise tests of CPT

Motivation for Antihydrogen Experiments

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An outside view …?

Quote from John Ellis (CERN Theory Division) writing in his article "Antimatter matters" a "news and views feature" from *Nature* 424 (2003) 631-4

" But CERN has recently embarked on an experimental programme … to look for any differences between the structure (…) of hydrogen and antihydrogen down to one part in 10^{12} or 10^{15}. Admittedly we theorists do not really expect that CPT violation will show up in these experiments ….. – but we have been wrong before."

Motivation for Antihydrogen Experiments

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1S-2S transition in H; Niering *et al.* PRL 84 (2000) 5496

2 466 061 413 187 103(46) Hz, or 1.8 parts in 10^{14}

Ground State Hyperfine transition in H; Essen *et al.* Nature 229 (1971) 110

1 420 405 751.7667(9) Hz, or 6.4 parts in 10^{13}

Motivation for Antihydrogen Experiments

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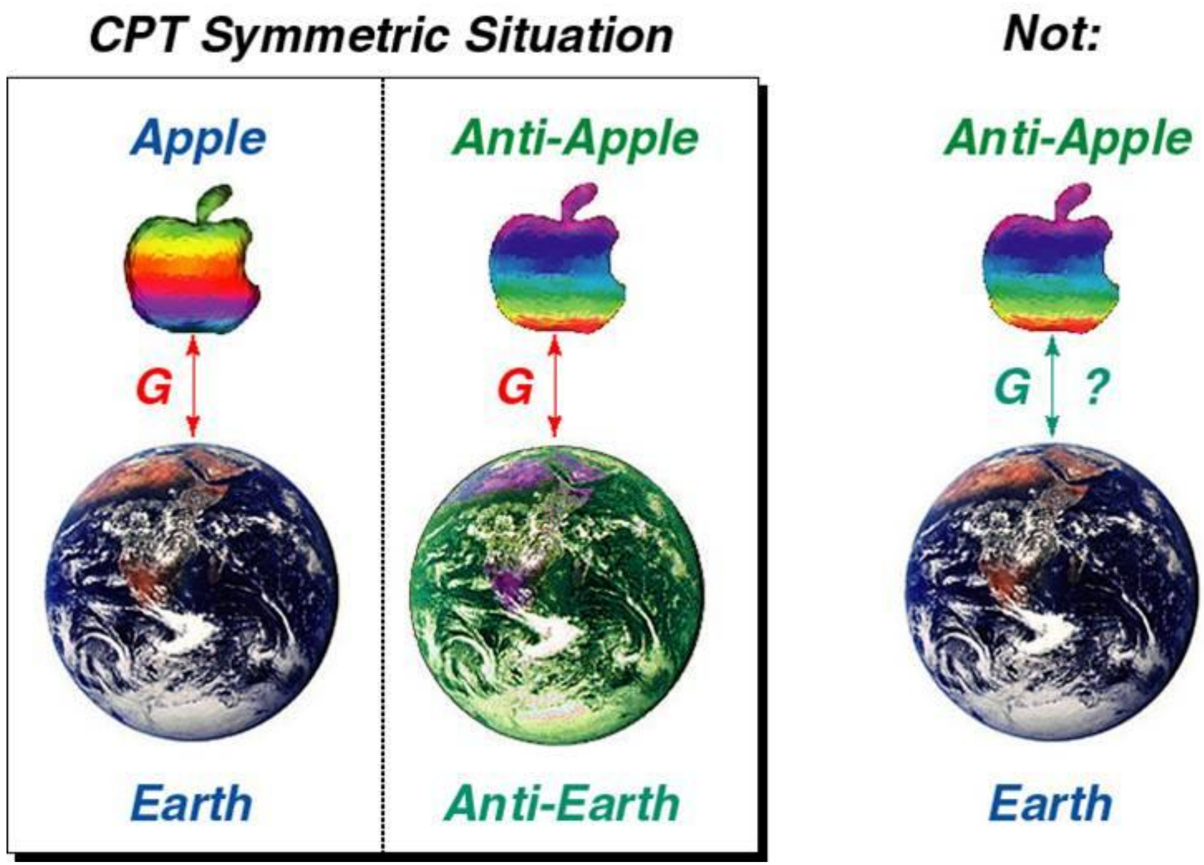
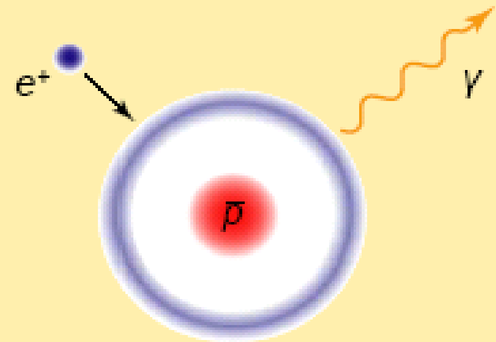
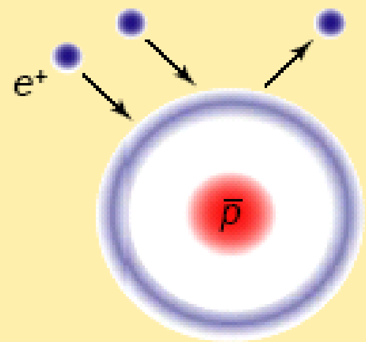
| Antihydrogen | = | Hydrogen | ?

Gravity



Antihydrogen Production: Formation Processes

	Radiative Recombination	Three-Body Recombination
Principle		
Temperature depend.	$\propto T^{-2/3}$	$\propto T^{-9/2}$
e^+ density dependence	$\propto n_e$	$\propto n_e^2$
Final internal states	$n < 10$	$n >> 10$
Expected rates	few 10 Hz	unknown

[J. Stevefelt *et al.*, PRA **12** (1975) 1246] [M. E. Glinsky *et al.*, Phys. Fluids B **3** (1991) 1279]

Antihydrogen Production: Formation Processes

The TBR is a quasi-elastic encounter of 2 positrons in the vicinity of an antiproton. Energy exchange ~ $k_B T_e$, which will be the same order of the binding energies.

Thus, these are very weakly bound states which are strongly influenced by the ambient fields

Electric and magnetic fields of the Penning trap

AND

The plasma self electric field $$E_r(r) = n_e e r / 2\varepsilon_0$$

The combination of E_r and B_z results in a tangential drift speed, which to 2nd order is given by:

$$v_d = -E(r)/B + mE(r)^2 / eB^3 r$$

Antihydrogen Production: Insights from Simulations

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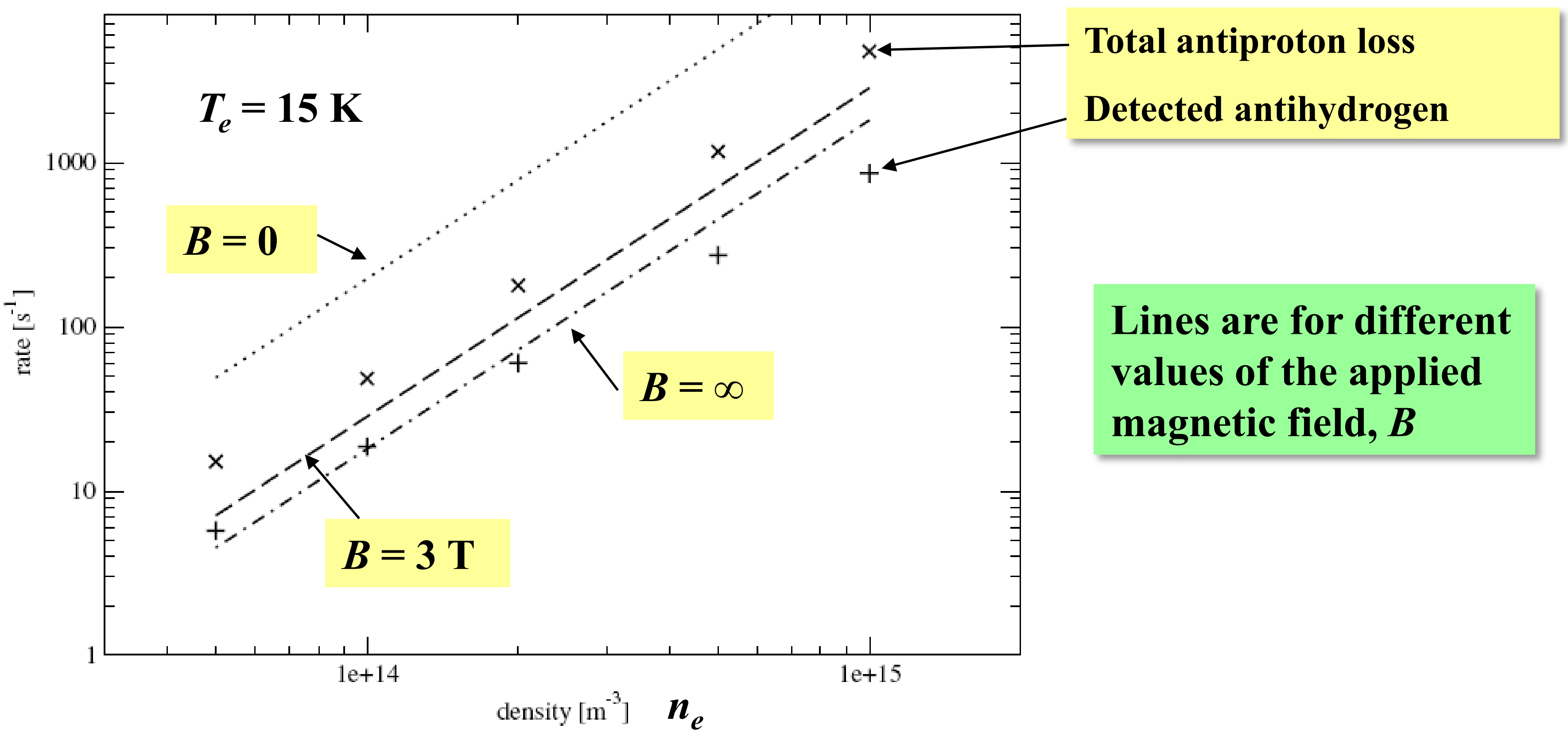
$$e^+ + e^+ + \bar{p} \rightarrow \bar{H} + e^+$$

Work of Jonsell *et al.*, J.Phys.B 42 (2009) 215002



Lines are for different values of the applied magnetic field, *B*

Antihydrogen Production: Insights from Simulations

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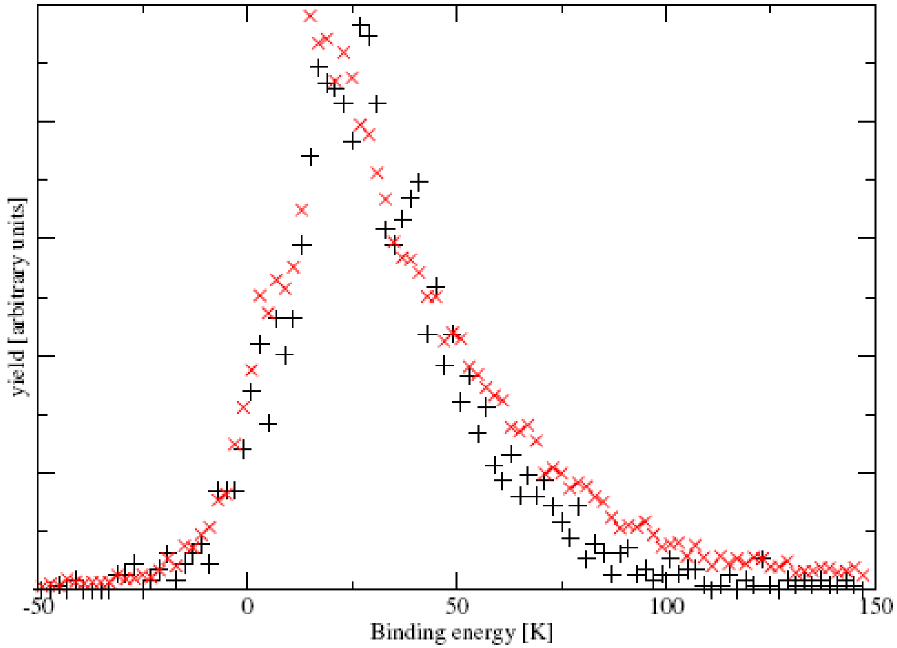
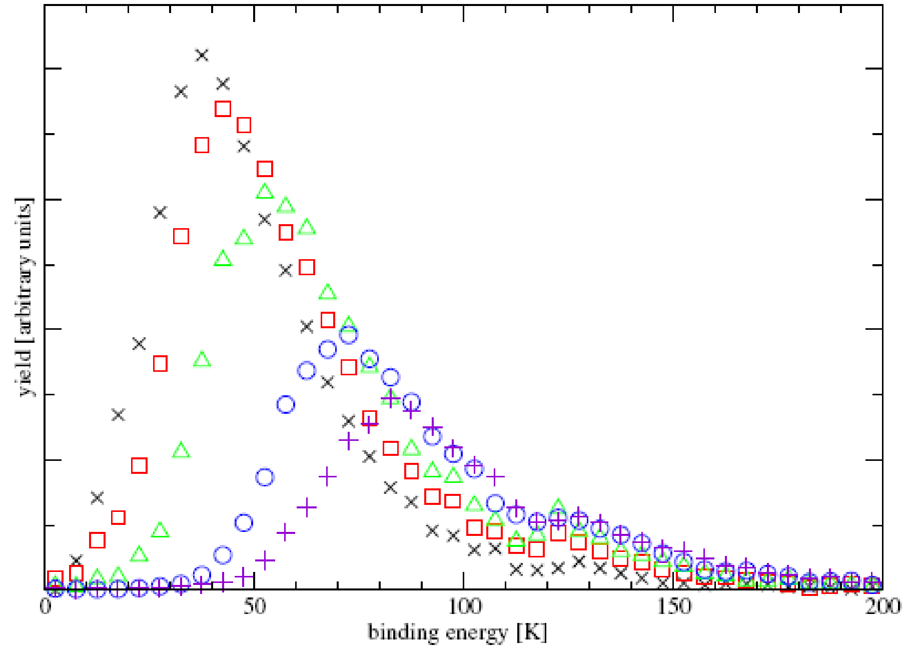
Prifysgol Abertawe

T_e = 15 K





Antihydrogen binding energies as the atoms leave the positron plasma

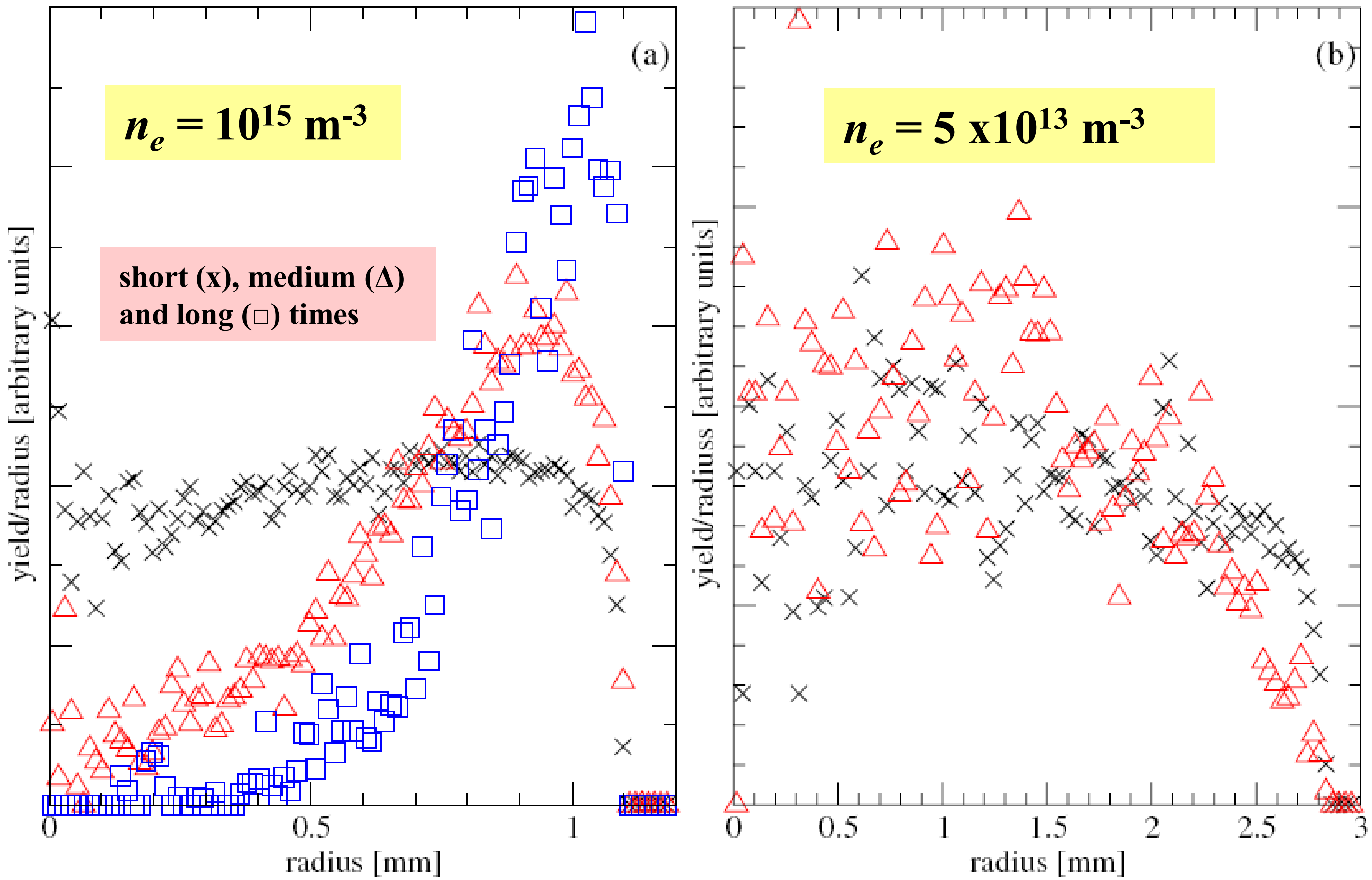
$n_e = 10^{15}$ m^{-3} (x); $n_e = 5 \times 10^{13}$ m^{-3} (+)

Antihydrogen binding energies on detection

$n_e = 10^{15}$ m^{-3} (+); 5 (○), 2 (Δ) and 1 (□) x 10^{14} m^{-3} and 5 x 10^{13} m^{-3} (x)

Antihydrogen Production: Insights from Simulations

Radial distribution of antihydrogen formation positions at different time intervals



$T_e = 15$ K

NB at 10^{15} m^{-3} a "long" time is > 1ms

Positron Accumulation

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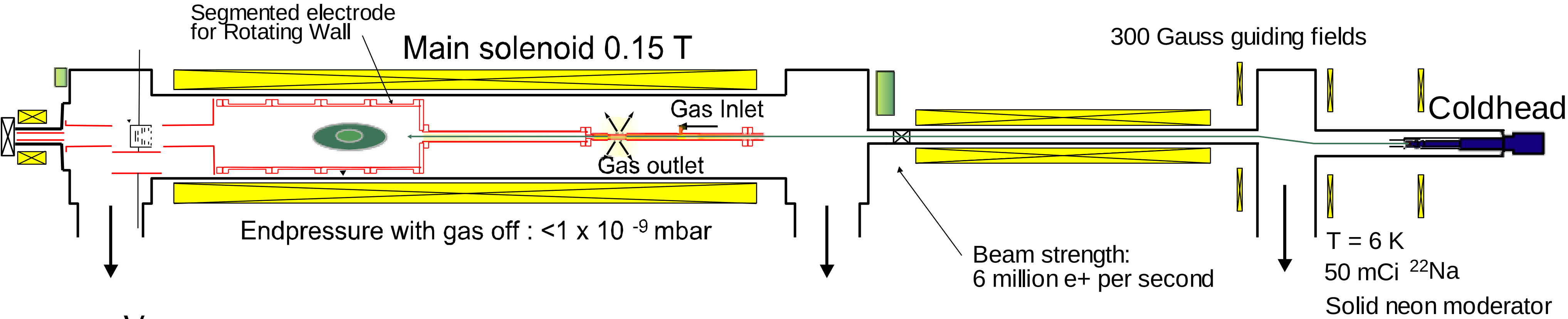
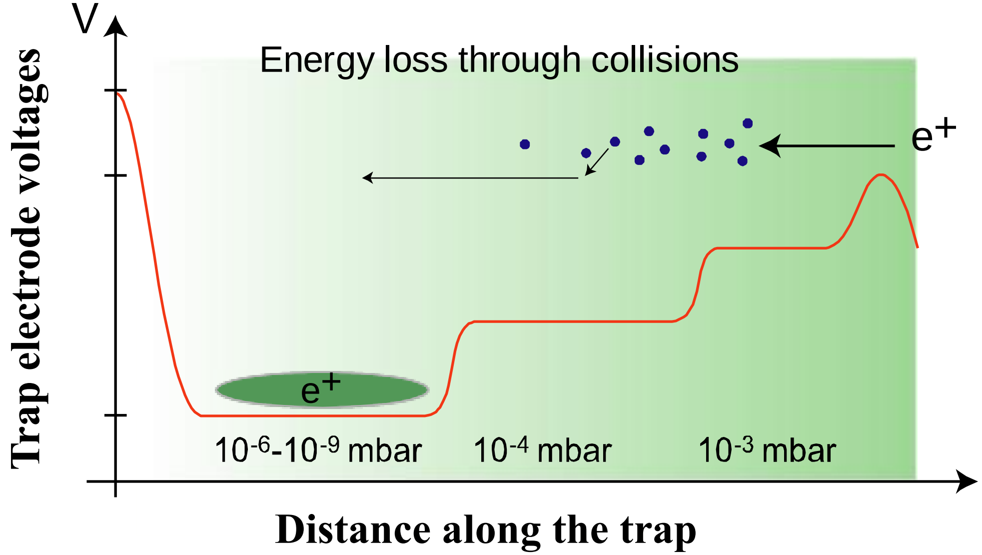
Prifysgol Abertawe





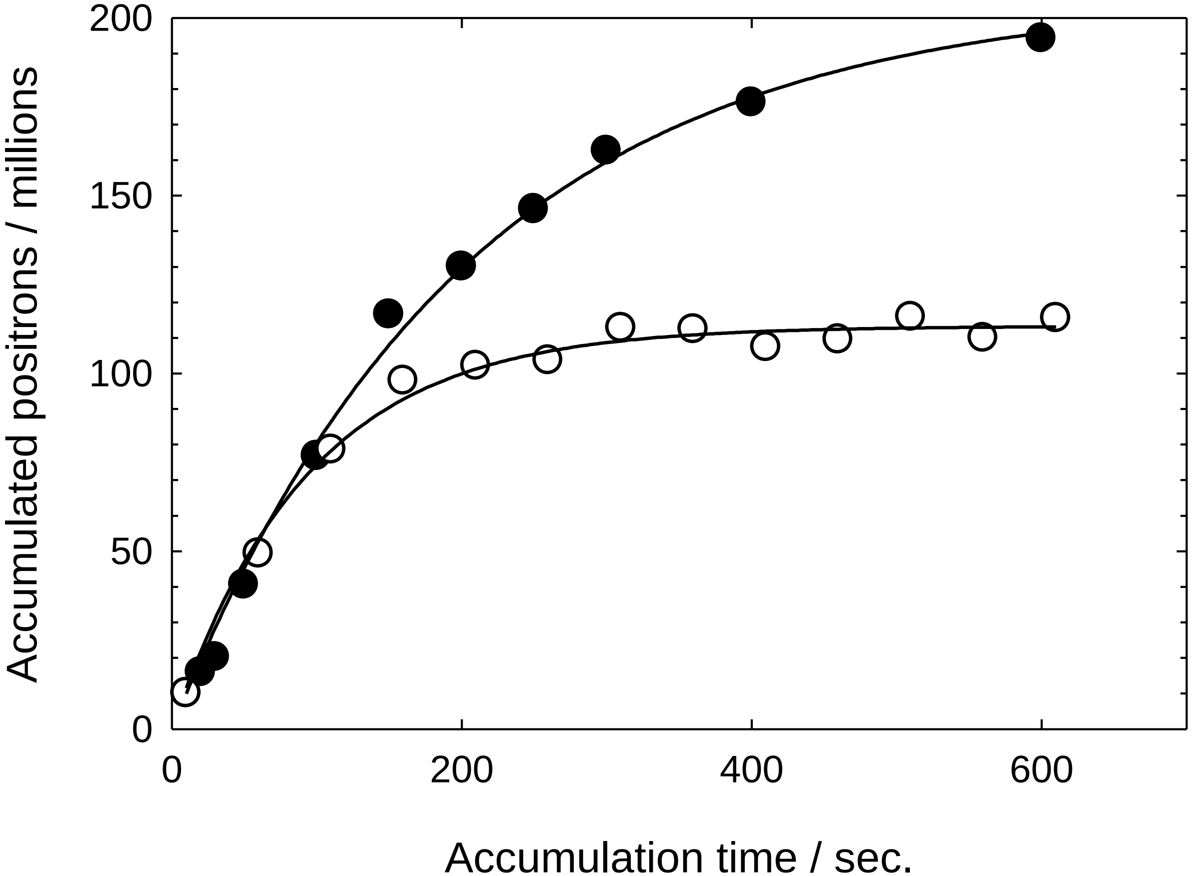
Based upon the industry standard …

{Solid-Ne moderator -plus - UCSD Penning Malmberg buffer gas trap: Surko and co-workers}

$$e^{+}(E_i) + N_2 \rightarrow e^{+}(E_f) + N_2^{*}$$

Positron Accumulation

Swansea University
Prifysgol Abertawe



**Open circles:
no rotating electric field**

**Closed circles:
rotating field applied**

Plasma formed after
about 10-15 s

Positron Accumulator – 3rd stage

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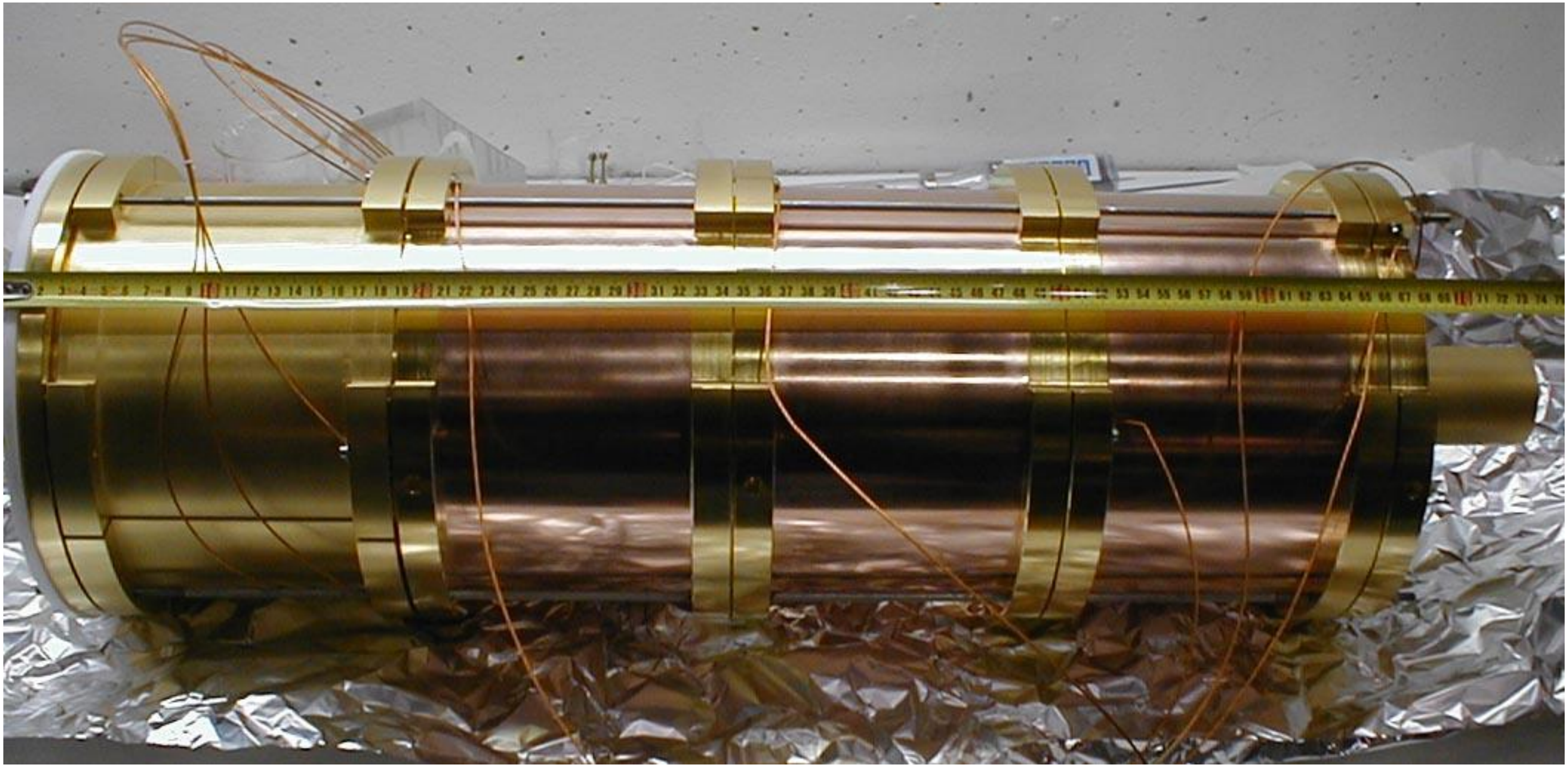
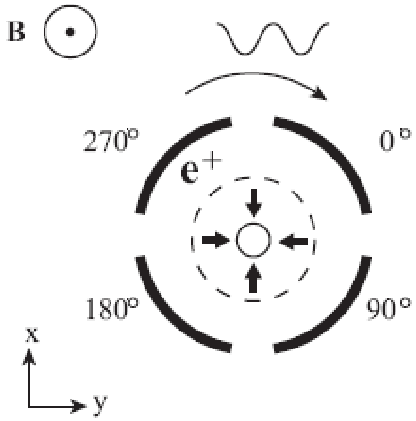
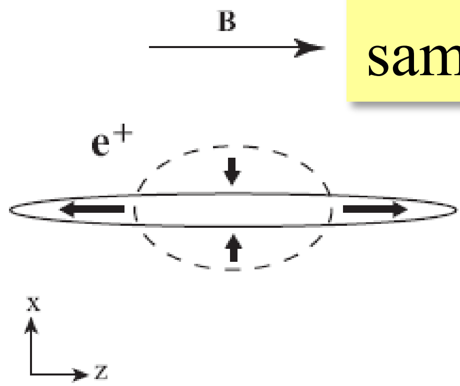
Prifysgol Abertawe

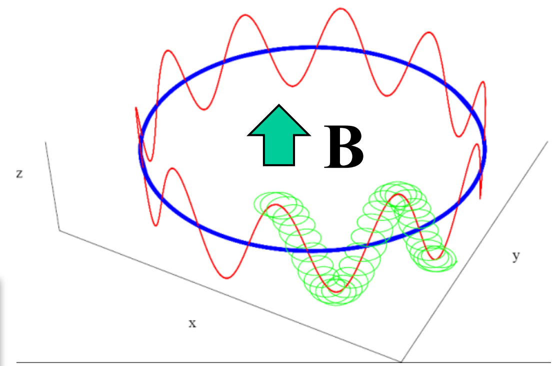


Positron Plasma Rotating Wall Compression

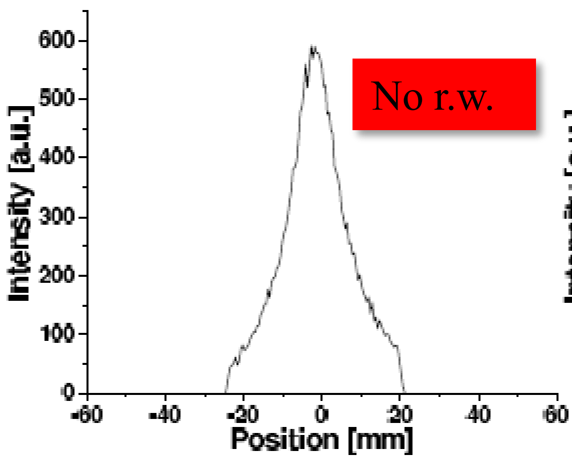




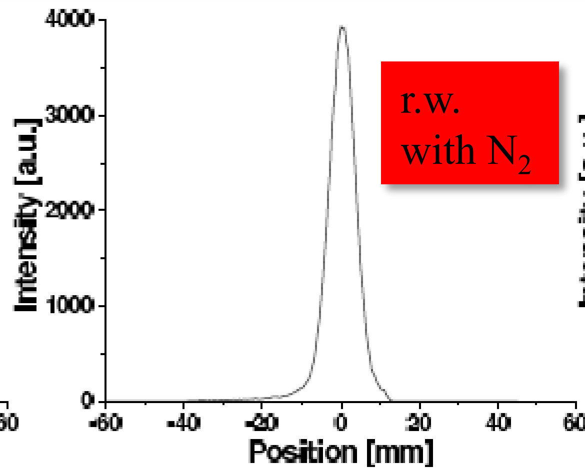
Rotating electric field in same sense as ExB drift



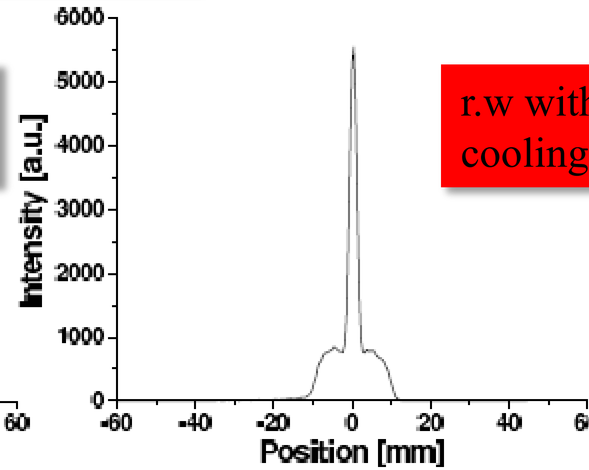
Positron plasma radial distributions



No r.w.

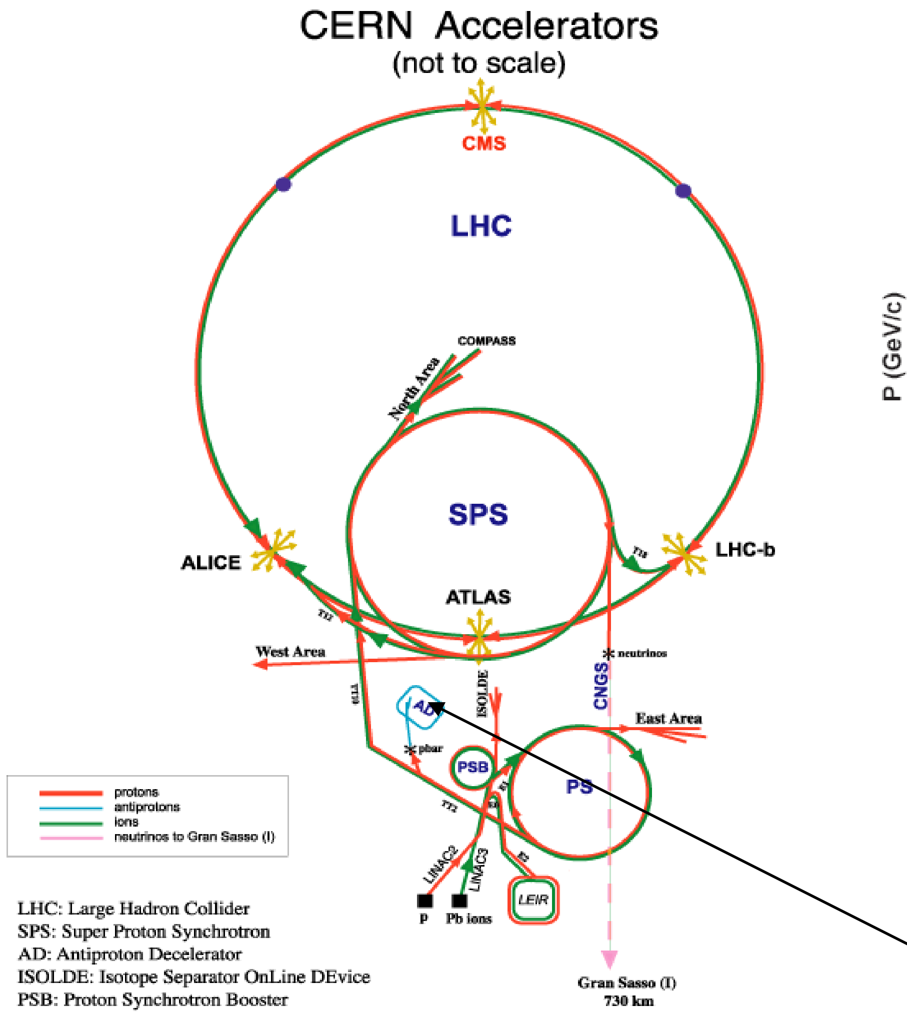


r.w. with N_2



r.w with added cooling gas

Antiprotons: CERN's "Accelerators"



LHC: Large Hadron Collider
SPS: Super Proton Synchrotron
AD: Antiproton Decelerator
ISOLDE: Isotope Separator OnLine DEvice
PSB: Proton Synchrotron Booster
PS: Proton Synchrotron
LINAC: LINear ACcelerator
LEIR: Low Energy Ion Ring
CNGS: Cern Neutrinos to Gran Sasso

Rudolf LEY, PS Division, CERN, 02.09.96
Revised and adapted by Antonella Del Rosso, ETT Div.,
in collaboration with B. Desforges, SL Div., and
D. Manglunki, PS Div. CERN, 23.05.01

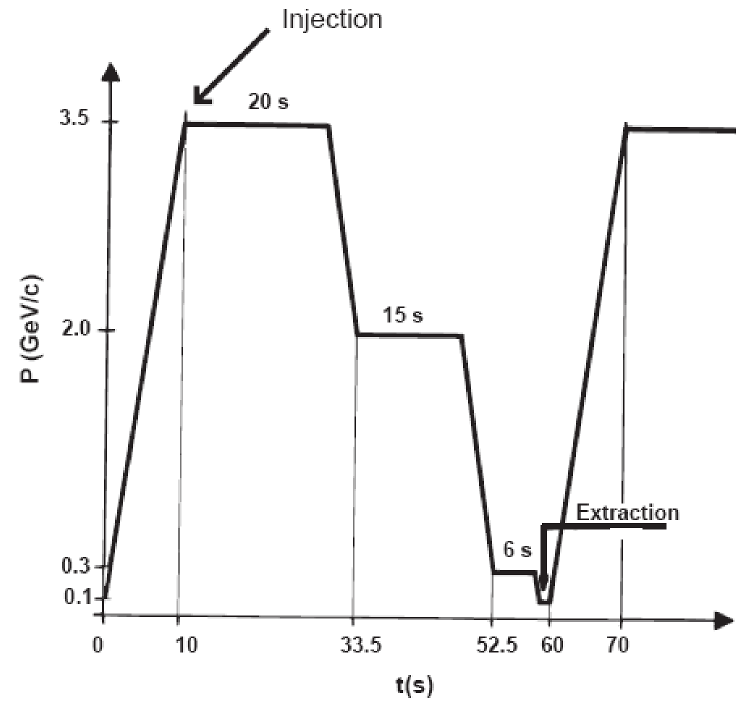
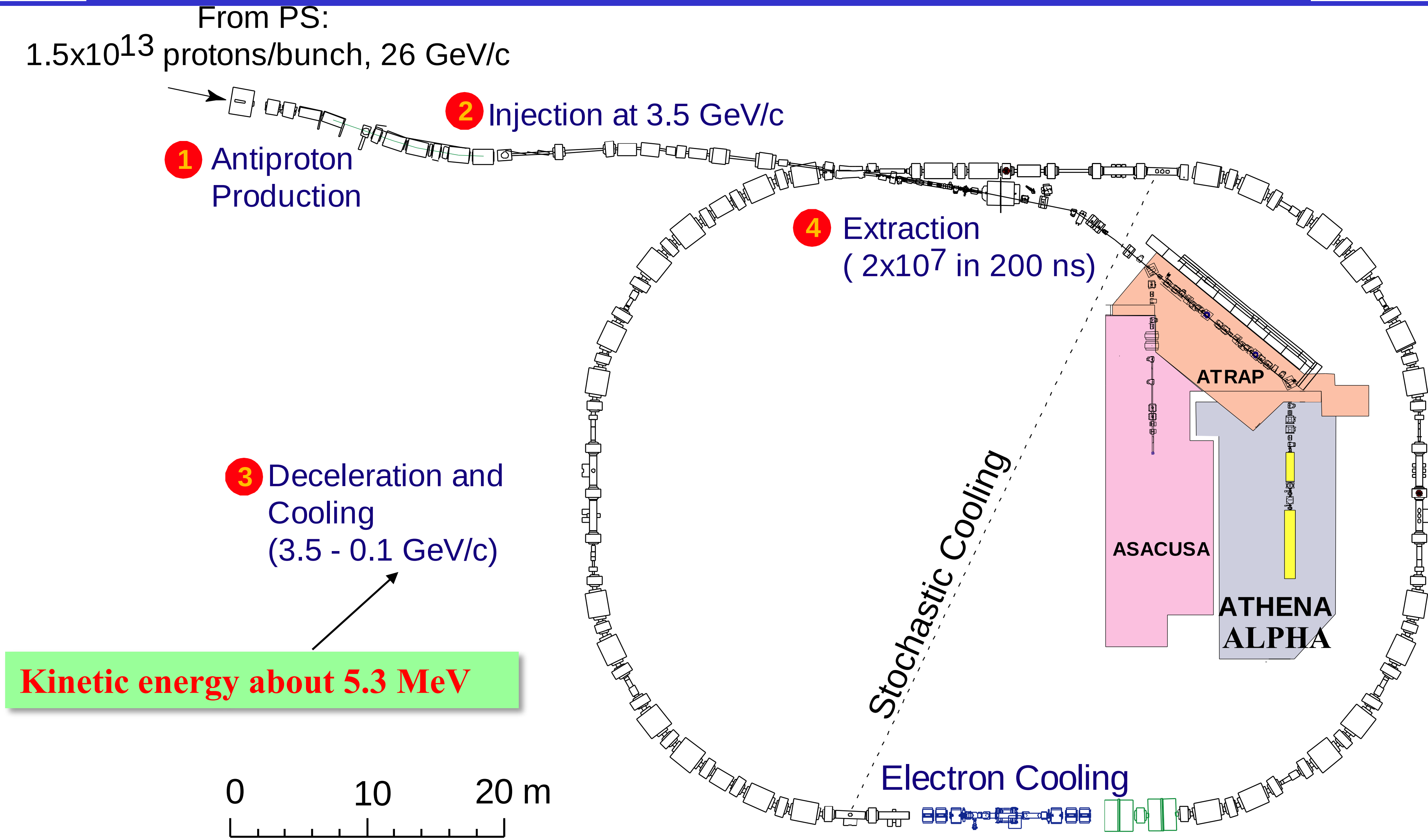


Fig. 6. Machine cycle for the AD operation (from [109]).

The AD, or

Antiproton Decelerator

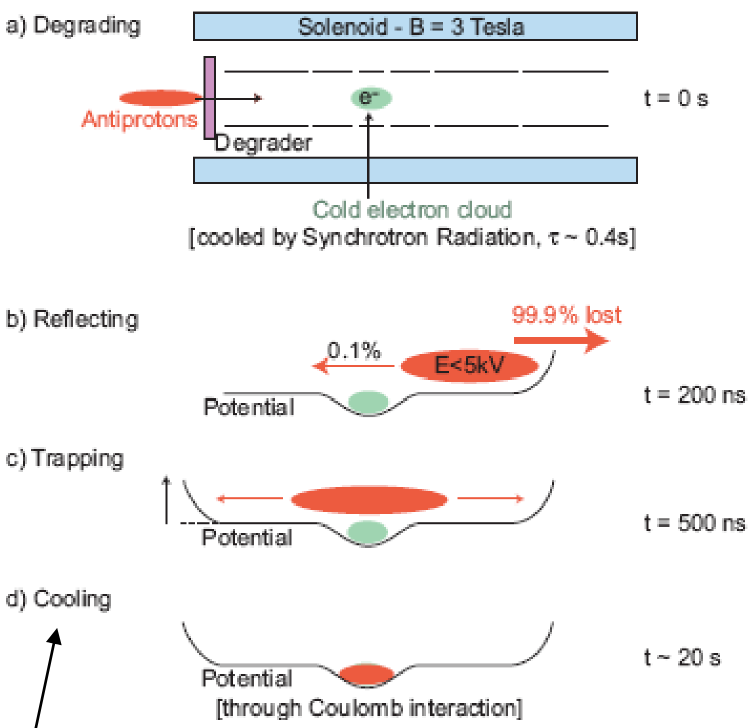
Antiprotons: the AD, Antiproton Decelerator



Antiprotons: Capture and Cooling

Swansea University Prifysgol Abertawe

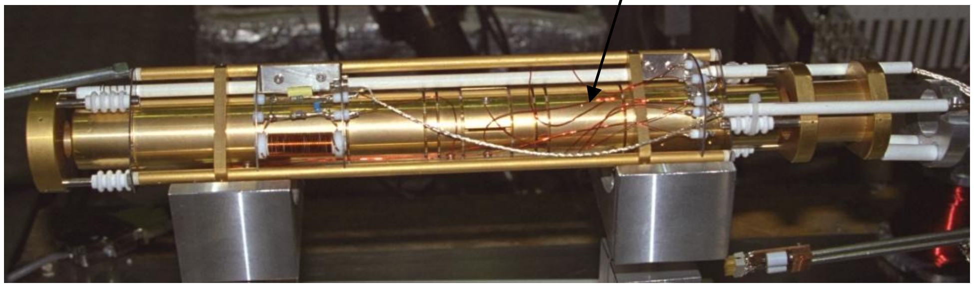
Method devised by Gabrielse and co-workers: PRL, 57, 2504 (1986) and PRL ,63, 1360 (1989)



To (or close to) the trap temperature

The trap walls are cooled to 15 K

ATHENA

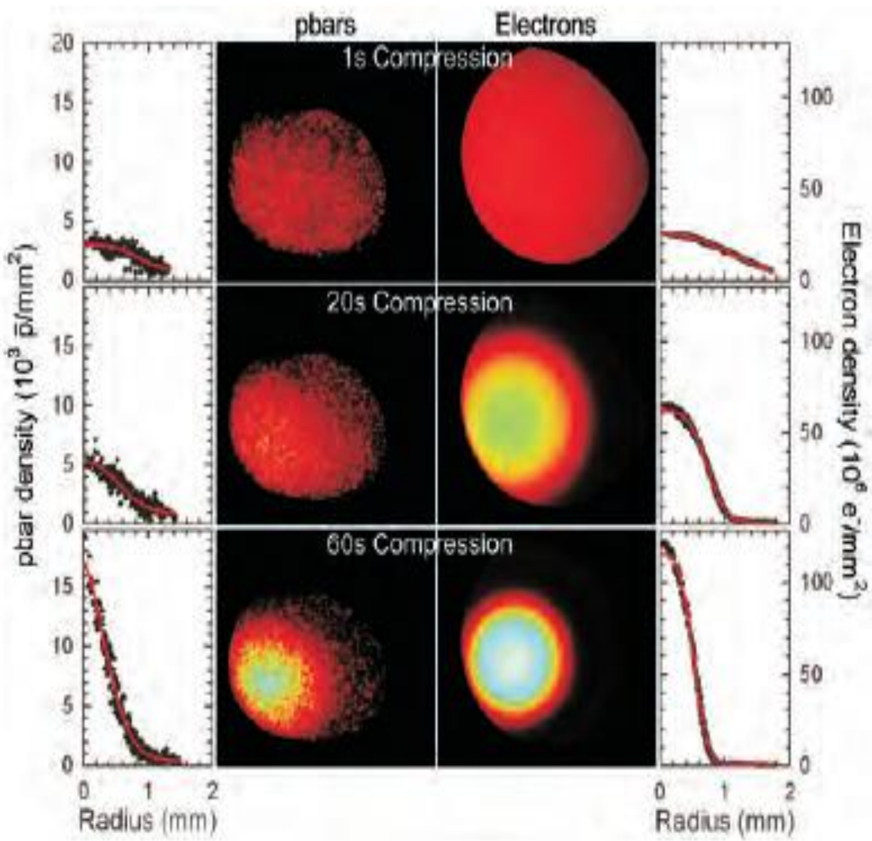


Antiproton Capture Trap

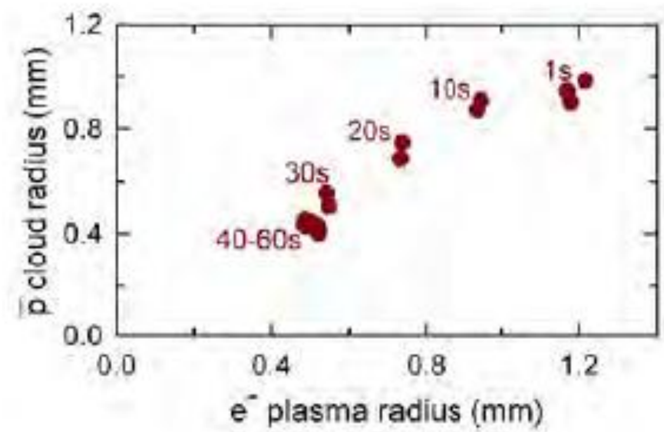
Similar apparatus used currently in ALPHA

ALPHA will routinely stack up to 8 shots from the AD to provide ~ 2 x 10^5 antiprotons into mixing

Antiprotons: ALPHA-Sympathetic Compression using Electrons



Sympathetic compression of an antiproton cloud by electrons

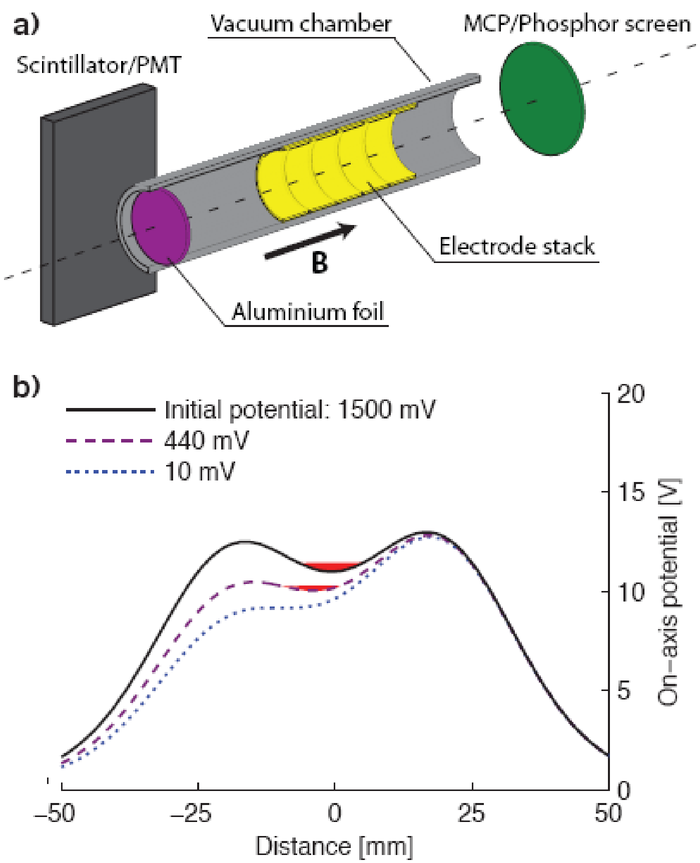


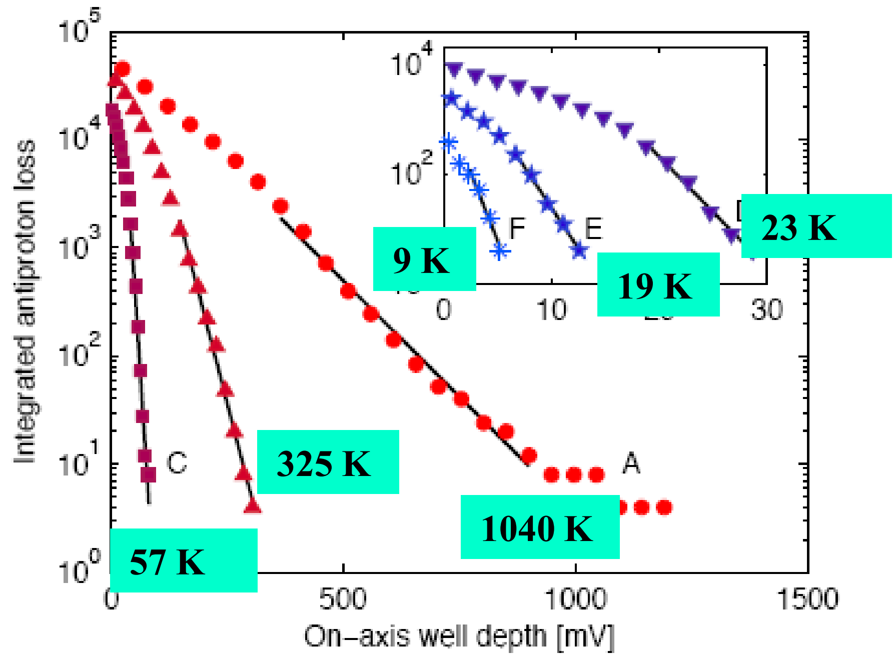
G. Andresen et al, PRL, 101 (2008) 203401

Typically use a fixed frequency rotating wall technique at 10 MHz

Antiprotons: ALPHA – Evaporative Cooling

Andresen *et al*. PRL (2010) 105 013003





Typically (9 ± 4) K is lowest achievable at the lowest well available at which (6 ± 1) % of the initial antiprotons remain

Antiprotons: So far …

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Antiprotons into the AD at ~ 3.5 GeV (~3×10^7 from 1.5×10^{13} protons at 26 GeV)

~ 100 s of cooling in the AD to 5.3 MeV; ejection in a 100 ns burst

Capture and electron cooling in a Penning Malmberg trap for ~ 20 s ($\varepsilon \sim 10^{-3}$)

Stacking of up to 8 AD shots. Takes ~ 1000 s for ~ 2×10^5 cold antiprotons

Shuffle to 1 T region. Recool and sympathetic radial compression for about 60 s

Evaporative cooling if desired to very low temperatures. Takes ~ 10 s

… Now ready for mixing with positrons …

ALPHA

Antihydrogen Production: ATHENA

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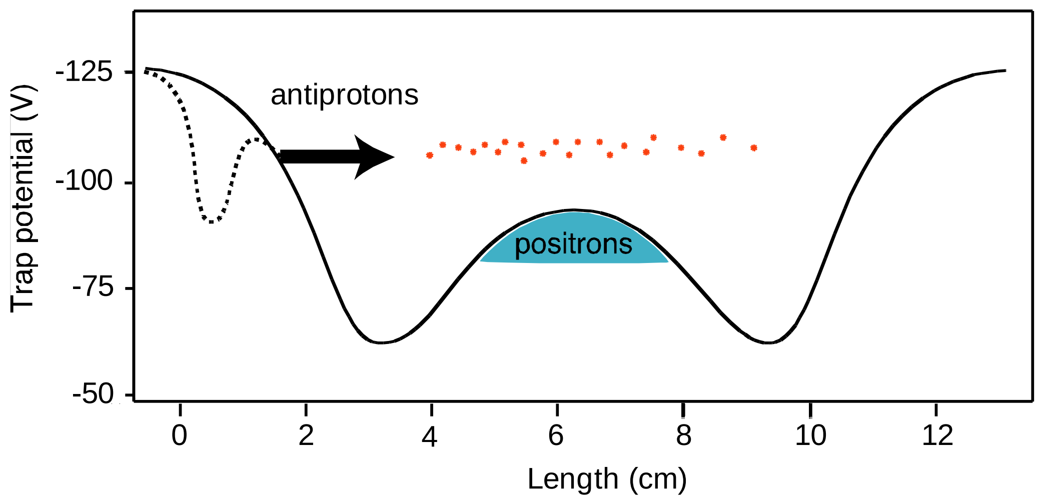
1. Fill positron well in mixing region with $75 \cdot 10^6$ positrons; allow them to cool to ambient temperature (15 K)
2. Launch 10^4 antiprotons into mixing region
3. Mixing time 190 sec - continuous monitoring by detector
4. Repeat cycle every 5 minutes



For comparison:

"hot" mixing = continuous RF heating of positron cloud

(suppression of formation of antihydrogen)

Antihydrogen Detection: ATHENA

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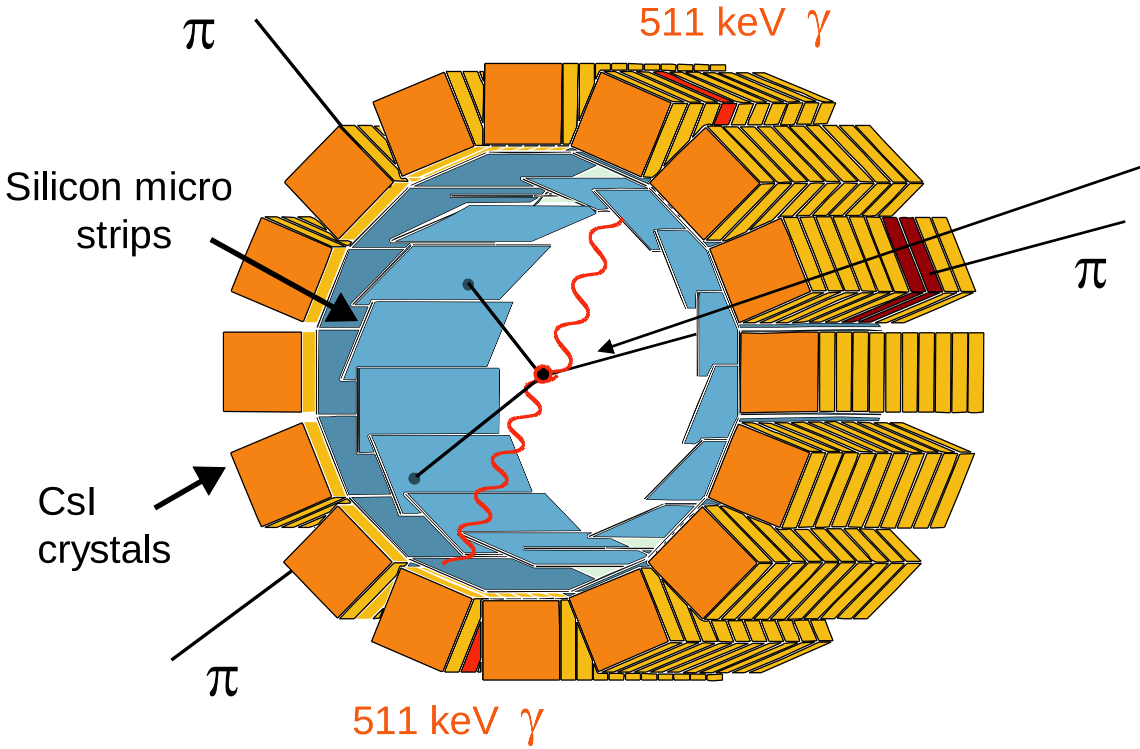
- Charged tracks to reconstruct antiproton annihilation vertex.
- Identify 511 keV photons from e^+-e^- annihilations.
- Identify space and time coincidence of the two.



Two annihilation events from antihydrogen which strikes the wall of the charged particle traps

- Compact (3 cm thick)
- Solid angle > 70%
- High granularity
- Operation at 140K, 3 T

Antihydrogen Production: ATHENA

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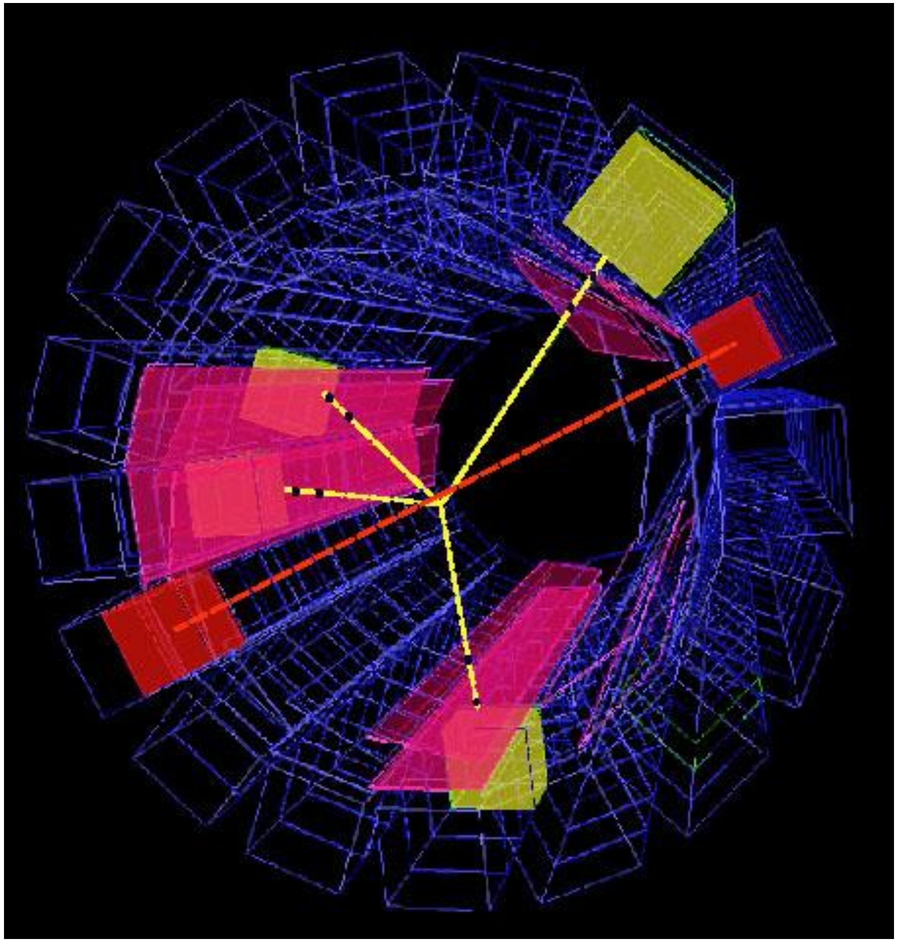

- Reconstruct annihilation vertex
- Search for ‘clean’ 511 keV-photons:
  - exclude crystals hit by charged particles
  - + its 8 nearest neighbours
- ‘511 keV’ candidate =
  - 400… 620 keV
  - no hits in any adjacent crystals
- Select events with two ‘511 keV’ photons
- Reconstruction efficiency ≤ 0.25 %

Antihydrogen Production: ATHENA

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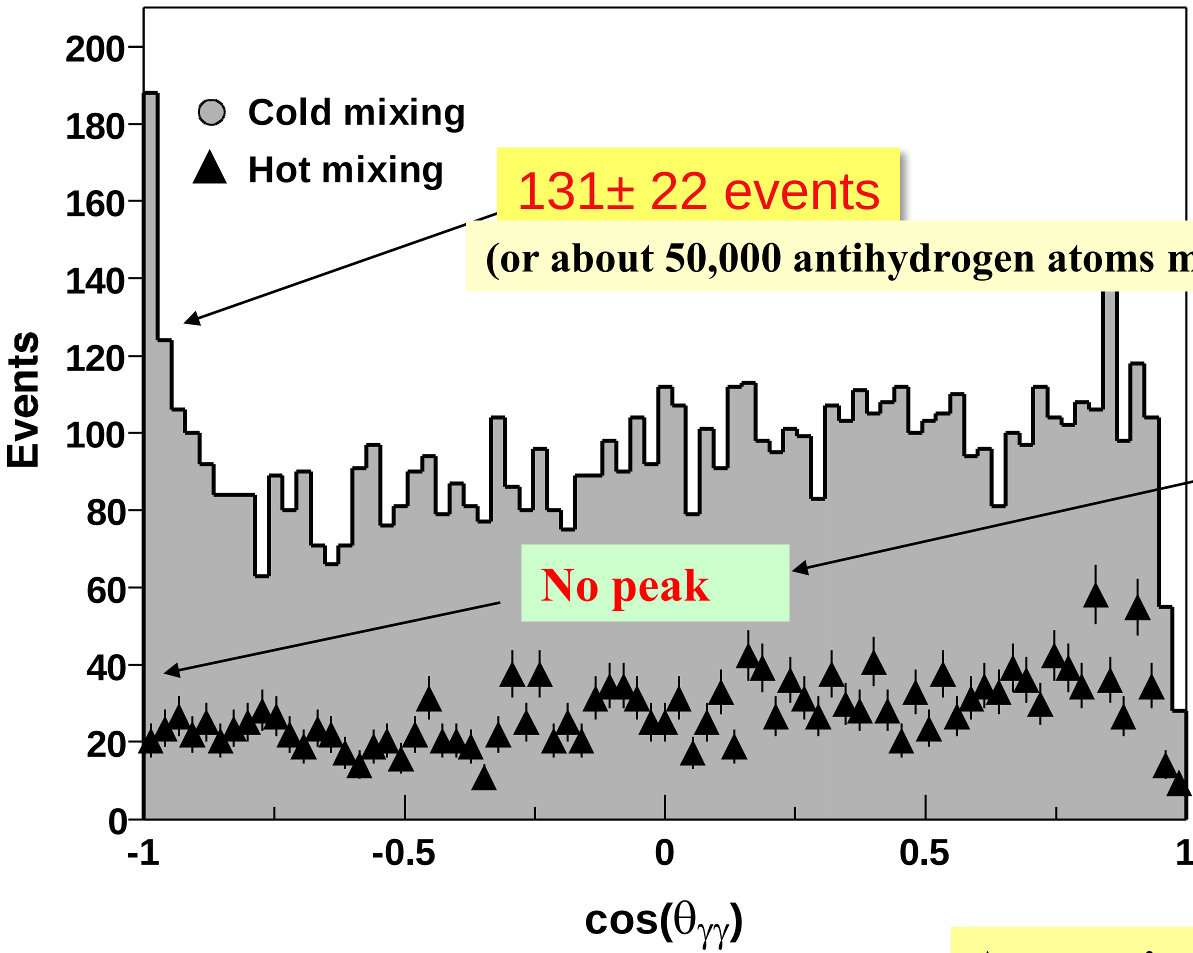


131± 22 events

(or about 50,000 antihydrogen atoms made)

No peak

Cold Mixing :
103270 vertices,
7125 2x511keV events

Antihydrogen suppressed

Hot Mixing :
Scaled (x1.6) to 165 mixing cycles.

Amoretti et al., Nature 419 456 (2002)

ALPHA Collaboration – 2011

University of Aarhus: *G.B. Andresen, P.D. Bowe, J.S. Hangst*

Auburn University: *F. Robicheaux*

University of British Columbia: *A. Gutierrez, W.N. Hardy*

University of Calgary: *T. Friesen, R. Hydomako, R.I. Thompson*

University of California, Berkeley: *M. Baquero-Ruiz, J. Fajans, C. So, J.S. Wurtele*

CERN: *E. Butler*

University of Liverpool: *P. Nolan, P. Pusa*

NRCN, Negev: *E. Sarid*

Riken: *D. M. Silveira, Y. Yamazaki*

Federal University of Rio de Janeiro: *C.L. Cesar*

Simon Fraser University : *M.D. Ashkezari, M.E. Hayden*

York University, Toronto : *S. Menary*

Swansea University: *W. Bertsche, M. Charlton, A. Deller, S.J. Eriksson, A. Humphries, N. Madsen, D.P. van der Werf*

Stockholm University : *S. Jonsell*

University of Tokyo: *R.S. Hayano*

TRIUMF: *M. C. Fujiwara, D.R. Gill, L. Kurchaninov, K. Olchanski, A. Olin, J.W. Storey*

Main Aim

To superimpose a magnetic well neutral trap onto an antihydrogen production and detection apparatus. Thus, to trap antihydrogen to promote spectroscopic comparisons with hydrogen.

Complexities are many including;

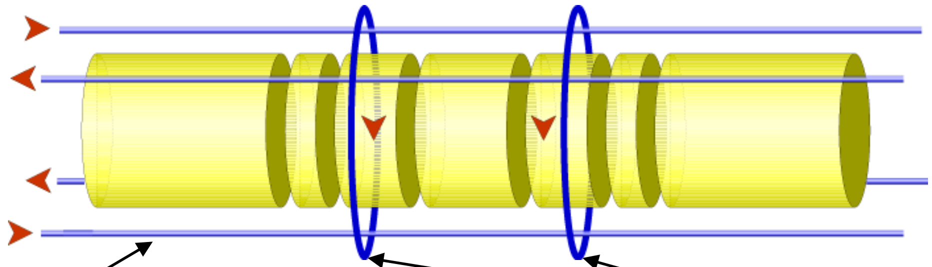
Effect of neutral trap fields on stability of charged particle clouds

Detection involves pion trajectory detection and vertex reconstruction …

Cryogenic traps …

Laser access …

Ioffe-Pritchard Geometry



$\mathbf{B} \longrightarrow$

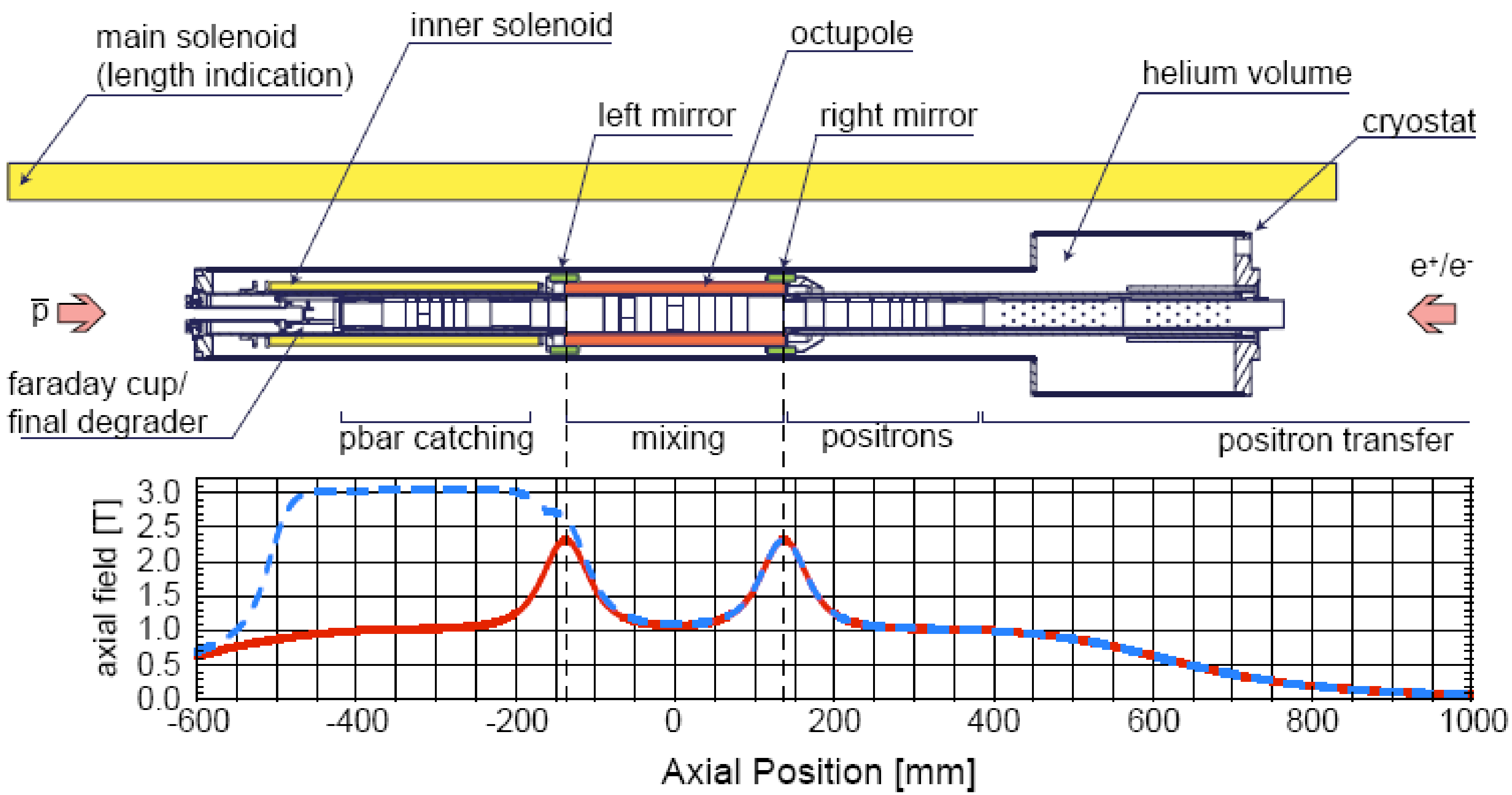
Solenoid field is the minimum in B

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

N.B.
Well depth ~ 0.7 K/T

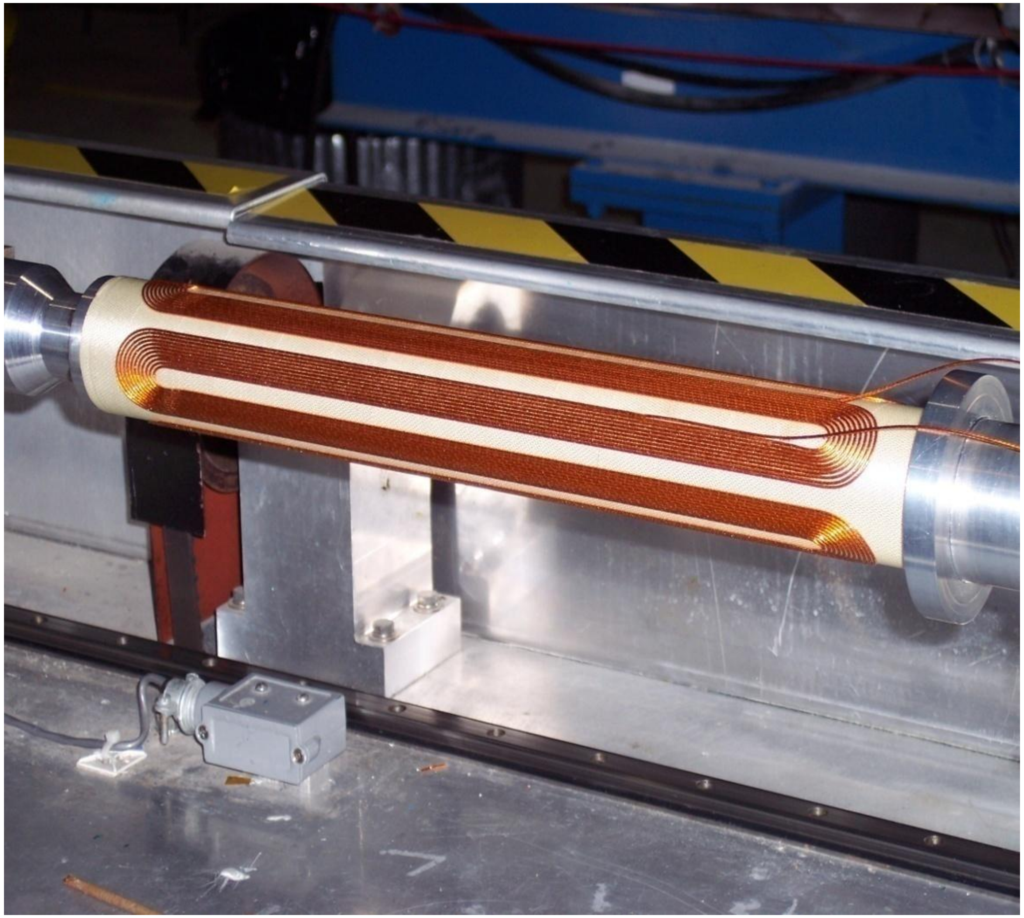
Based on Berkeley/Swansea results: standard quadrupole arrangement was rejected by ALPHA as the magnetic field gradient across charged plasmas is too great;
see Fajans et al., Phys. Rev. Lett. 95 155001 (2005)

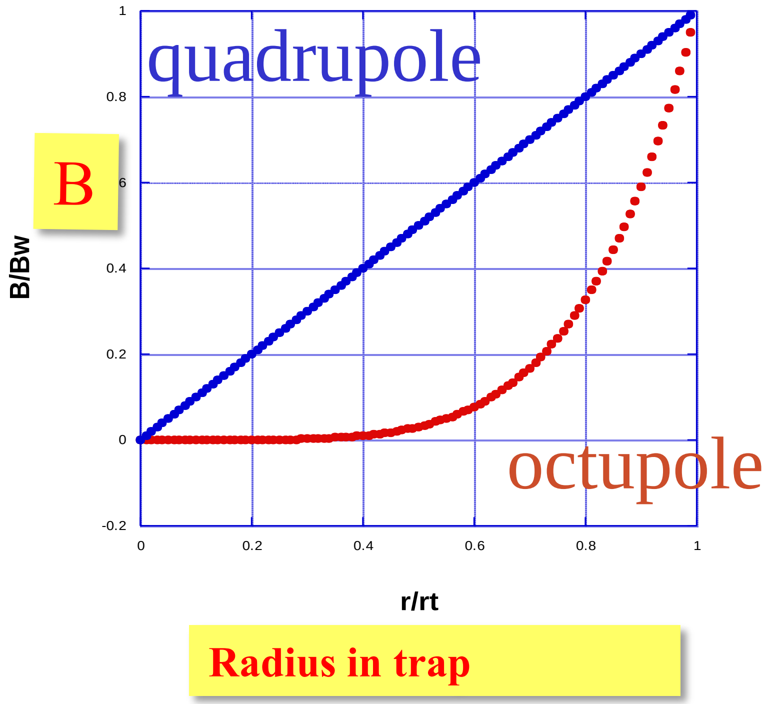
Plasma lifetimes may be reduced in the presence of quadrupolar field



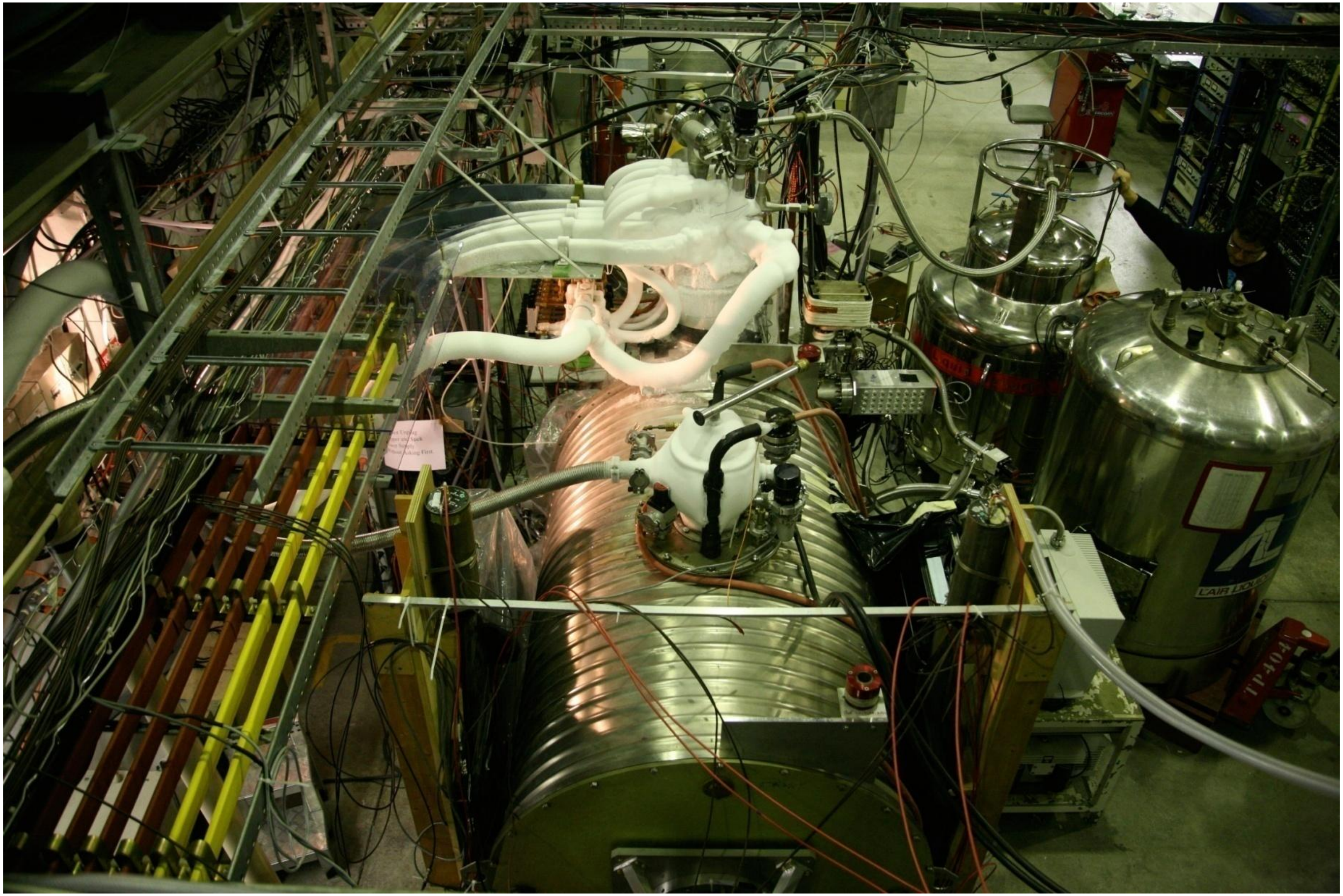
3-layer silicon antiproton annihilation vertex detector surrounding the mixing region is not shown

ALPHA: An Antihydrogen Trapping Experiment





ALPHA: An Antihydrogen Trapping Experiment



ALPHA: An Antihydrogen Trapping Experiment

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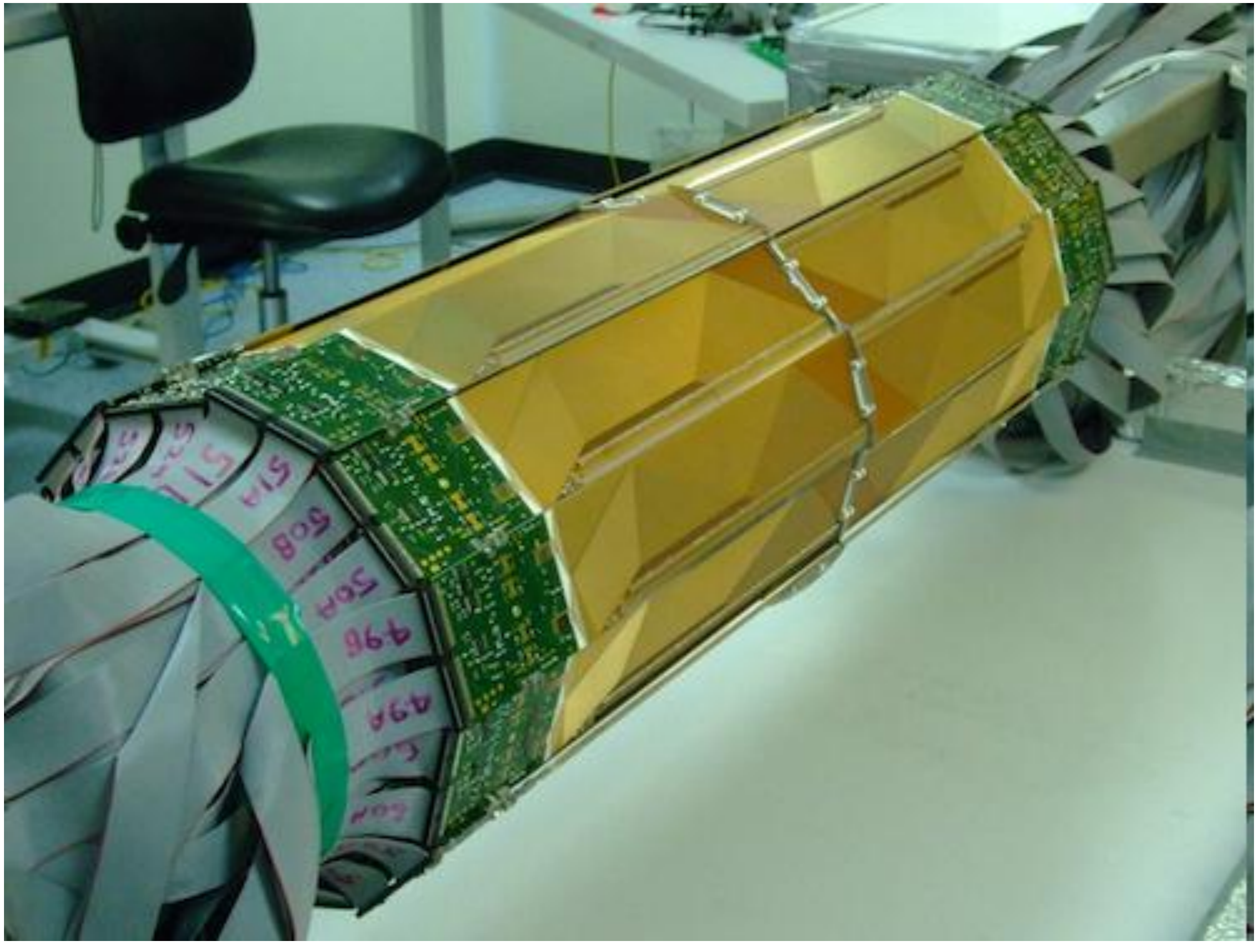

ALPHA: An Antihydrogen Trapping Experiment

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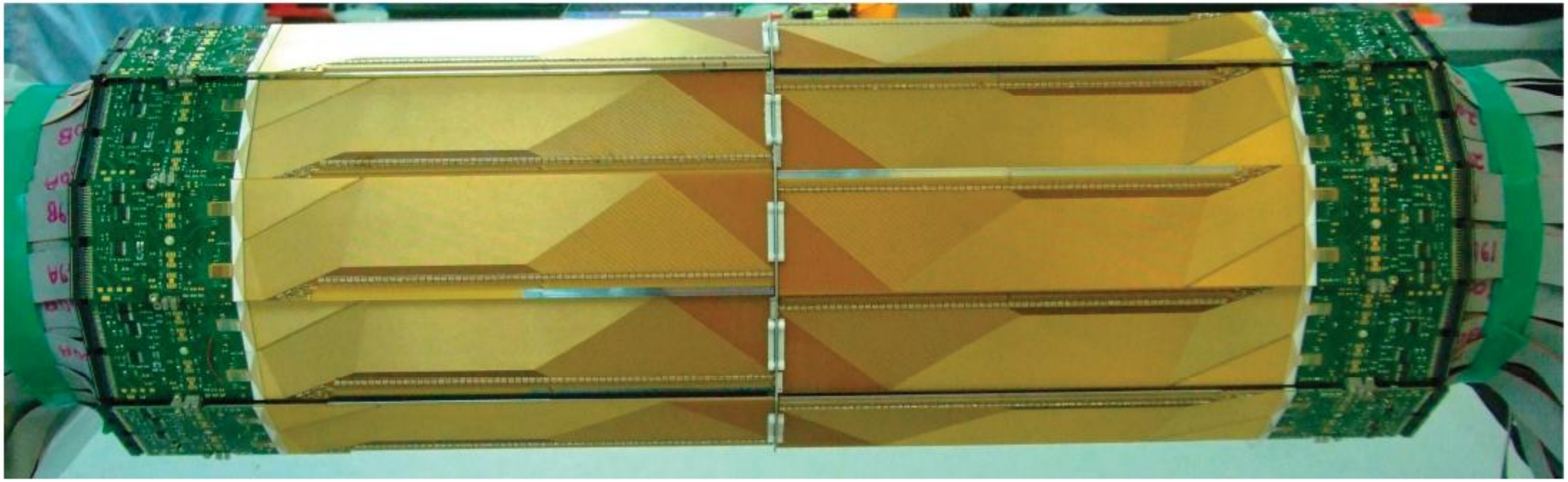

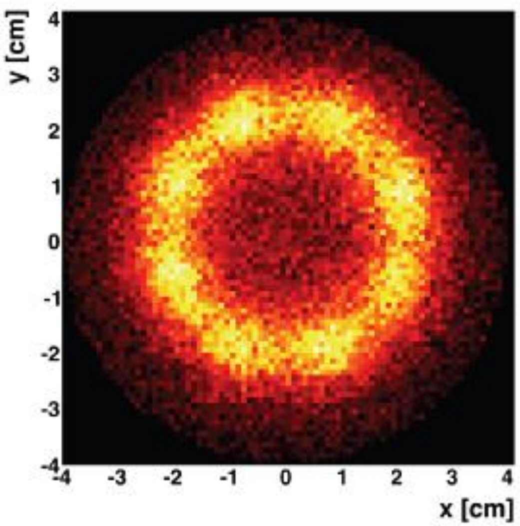

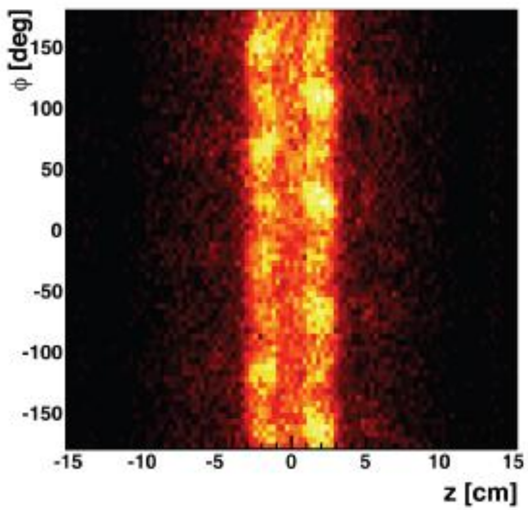

LETTER

doi:10.1038/nature09610

Trapped antihydrogen

G. B. Andresen[1], M. D. Ashkezari[2], M. Baquero-Ruiz[3], W. Bertsche[4], P. D. Bowe[1], E. Butler[4], C. L. Cesar[5], S. Chapman[3], M. Charlton[4], A. Deller[4], S. Eriksson[4], J. Fajans[3,6], T. Friesen[7], M. C. Fujiwara[8,7], D. R. Gill[8], A. Gutierrez[9], J. S. Hangst[1], W. N. Hardy[9], M. E. Hayden[2], A. J. Humphries[4], R. Hydomako[7], M. J. Jenkins[4], S. Jonsell[10], L. V. Jørgensen[4], L. Kurchaninov[8], N. Madsen[4], S. Menary[11], P. Nolan[12], K. Olchanski[8], A. Olin[8], A. Povilus[3], P. Pusa[12], F. Robicheaux[13], E. Sarid[14], S. Seif el Nasr[9], D. M. Silveira[15], C. So[3], J. W. Storey[8]†, R. I. Thompson[7], D. P. van der Werf[4], J. S. Wurtele[3,6] & Y. Yamazaki[15,16]

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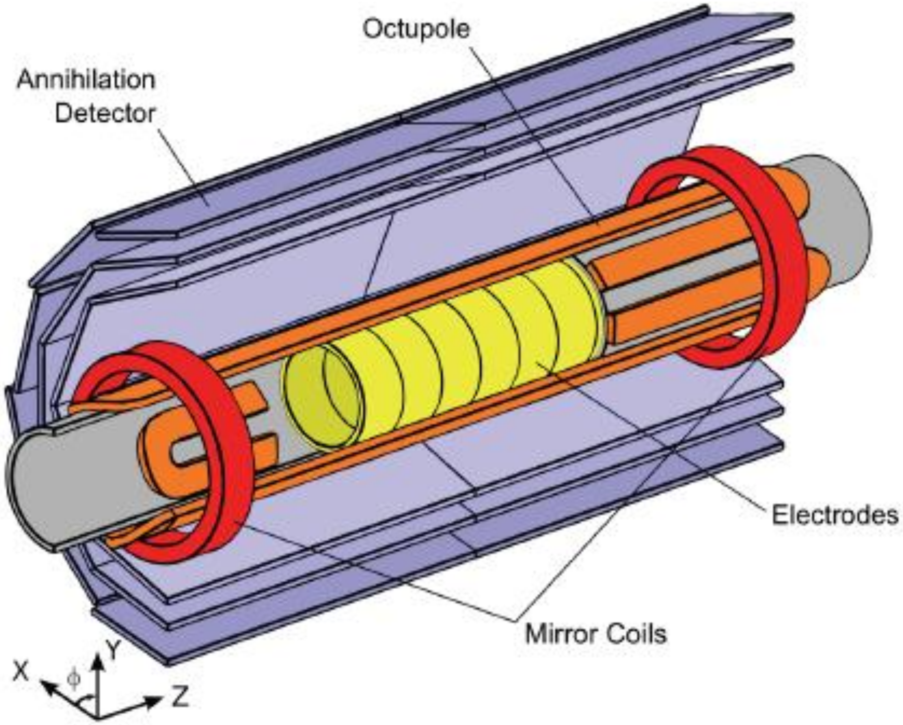
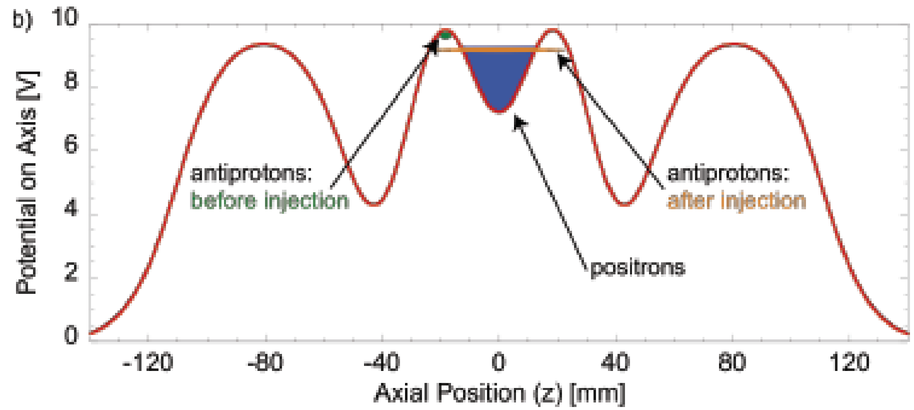
ALPHA: An Antihydrogen Trapping Experiment





Neutral trap
depth ~ 0.5 K

30,000 pbars at 200K

2M positrons at 40 K (evaporatively cooled)

Auto-resonant injection and mix for 1 sec.

Clear the charge particles

Turn off the neutral trap (1/e time ~ 9 ms)

Search for pbar annihilations from Hbar (bias fields to eject any charged particles still trapped)

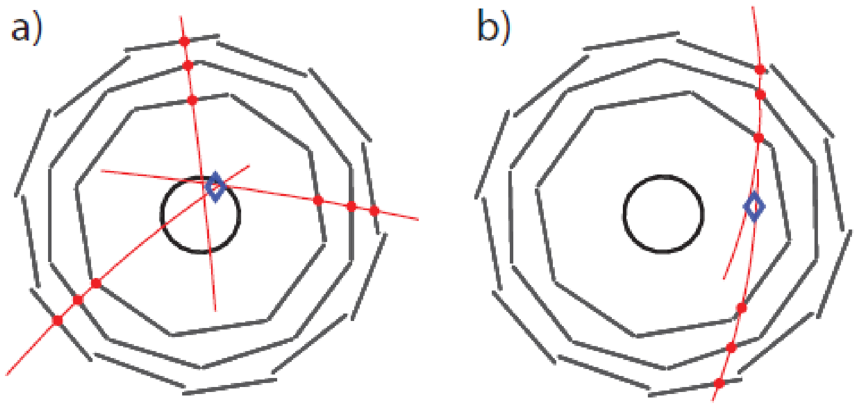
Searching for trapped antihydrogen

Shut off magnetic minimum trap (1/e time ~ 9 ms)

Interrogate output of vertex detector in 30 ms time window after the shut off

Apply cuts to data to reject cosmic ray events

a) Antiproton annihilation



b) Cosmic ray

ALPHA: An Antihydrogen Trapping Experiment

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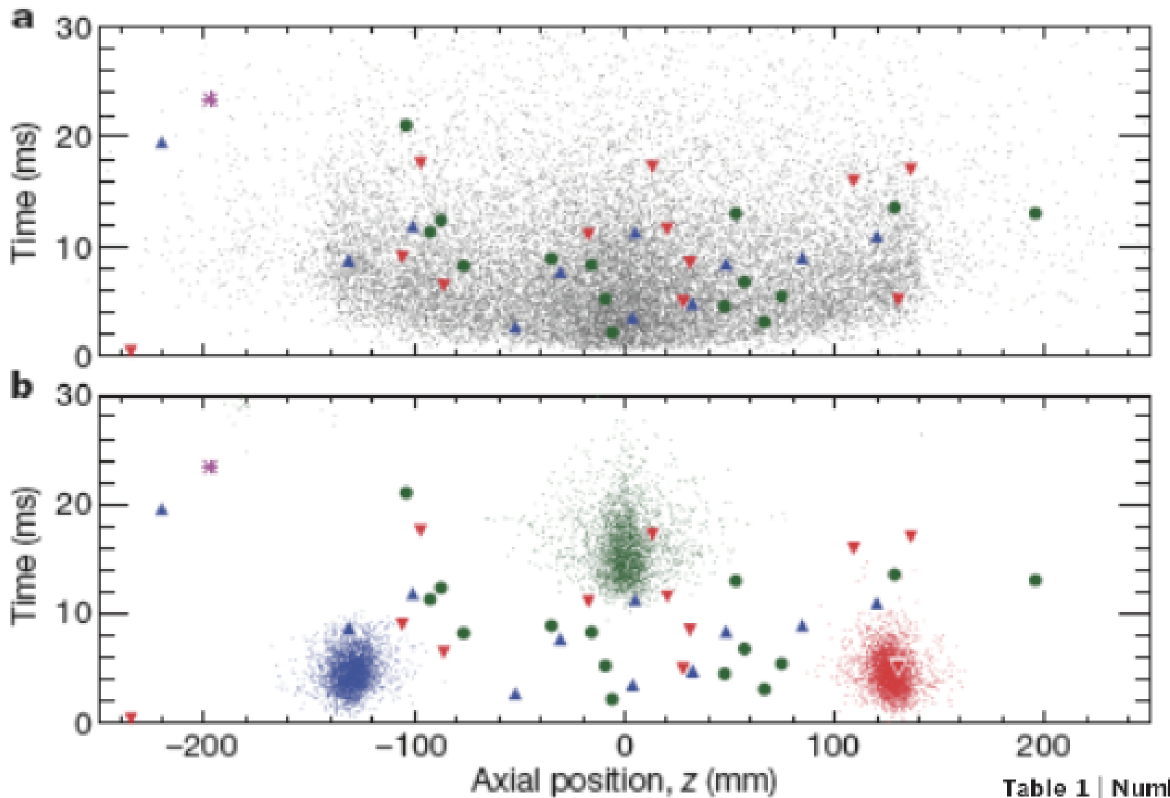

HBAR simulation

left bias
right bias
no bias

PBAR simulations

1 event with heated positrons

Initial publication – 38 events

Table 1 | Number of annihilations identified in the 30 ms following the trap shutdown

Type of attempt	Number of attempts	Antiproton annihilation events
No bias	137	15
Left bias	101	11
Right bias	97	12
No bias, heated positrons	132	1
Left bias, heated positrons	60	0
Right bias, heated positrons	54	0

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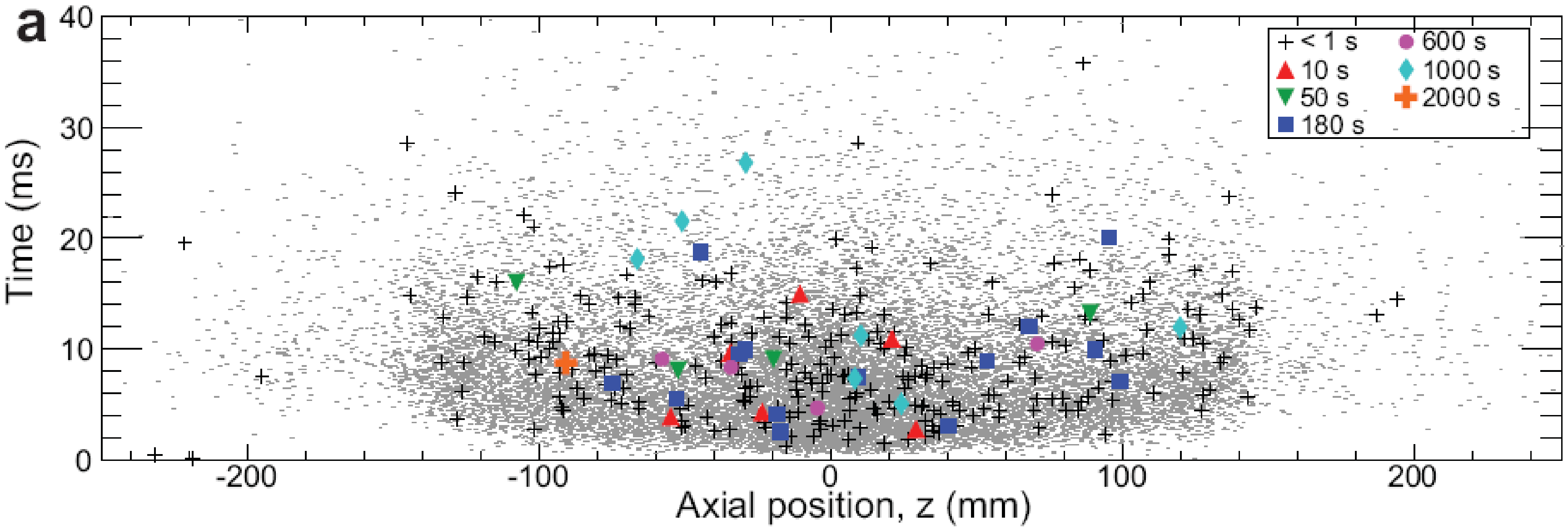

309 events

Nature Physics – June 2011

ALPHA: An Antihydrogen Trapping Experiment

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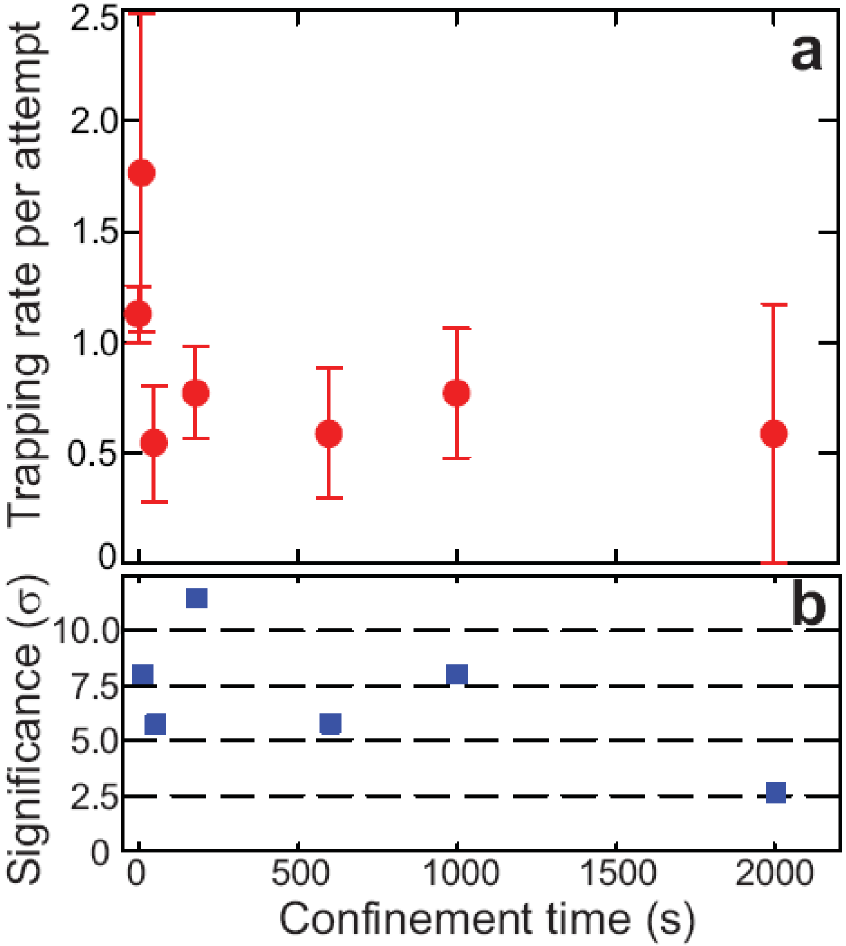
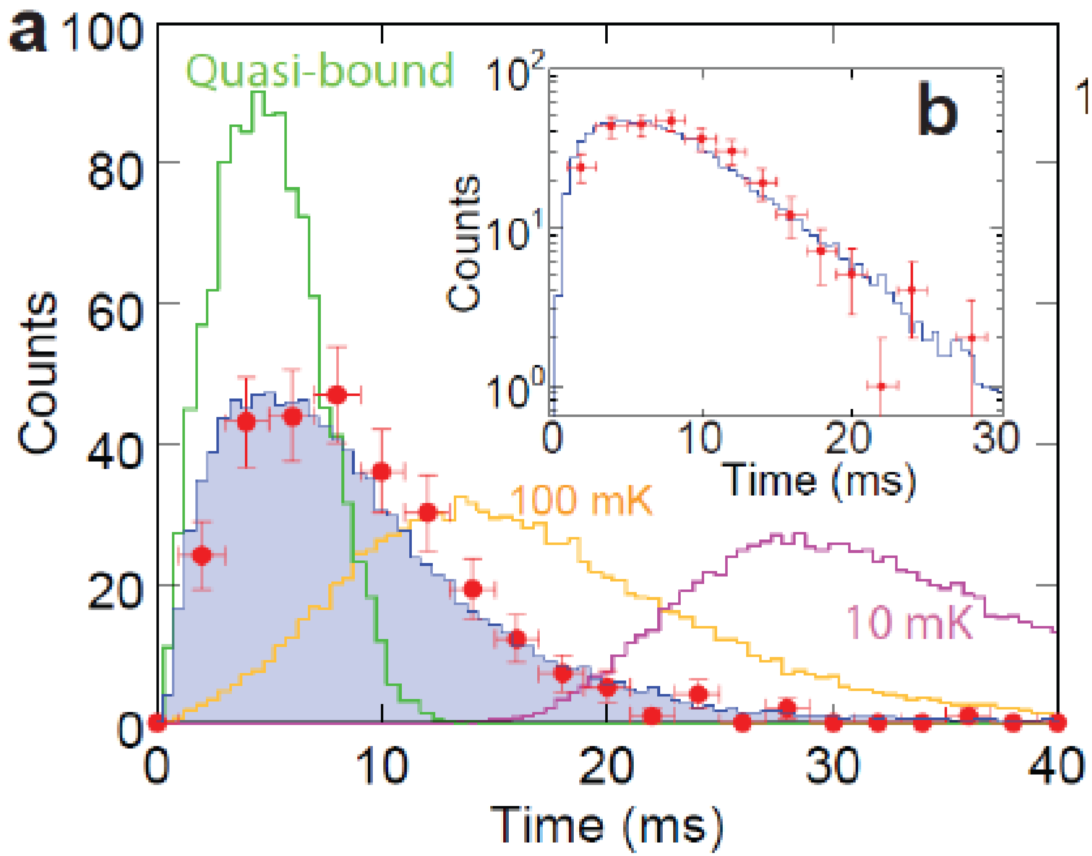


Confinement Time (s)	0.4	10.4	50.4	180	600	1000	2000
Number of attempts	119	6	13	32	12	16	3
Detected events	76	6	4	14	4	7	1
Estimated background	0.17	0.01	0.02	0.05	0.02	0.02	0.004
Statistical significance (σ)	>>20	8.0	5.7	11	5.8	8.0	2.6
Trapped antihydrogen per attempt	1.13 ±0.13	1.76 ±0.72	0.54 ±0.26	0.77 ±0.21	0.59 ±0.29	0.77 ±0.29	0.59 ±0.59

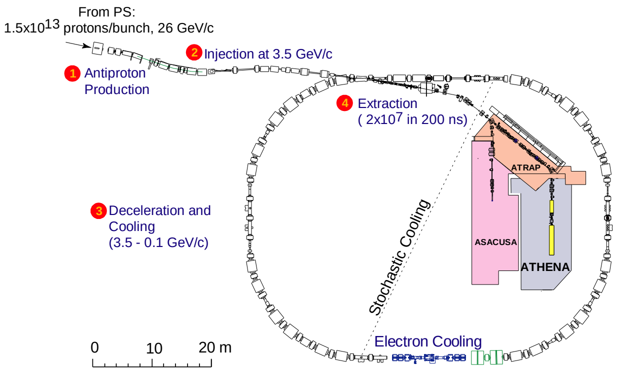

a
Quasi-bound
100 mK
10 mK
Counts
Time (ms)
b
Counts
Time (ms)

ALPHA – what's next?

2011 beamtime – try microwave positron spin flip experiment as a first probe of the ground state hyperfine structure

In parallel, work on new apparatus to allow laser access for 1S-2S 2-photon transition

CERN has recently approved the "ELENA" project and will construct an extra ring to further decelerate antiprotons to about 100 keV – this will increase our capture efficiency for low energy antiprotons by a factor of around 100! (About 5 years from now …)



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Members of the ALPHA collaboration

Colleagues at Swansea

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