THE ALPHA COLLABORATION

Aarhus University, Denmark

Auburn University, USA

University of British Columbia, Canada

University of California Berkeley, USA

University of Calgary, Canada

CERN

University of Liverpool, UK

NRCN - Nucl. Res. Center Negev, Israel

RIKEN, Japan

Federal University of Rio de Janeiro, Brazil

Stockholm University, Sweden

Simon Fraser University, Canada

TRIUMF, Canada

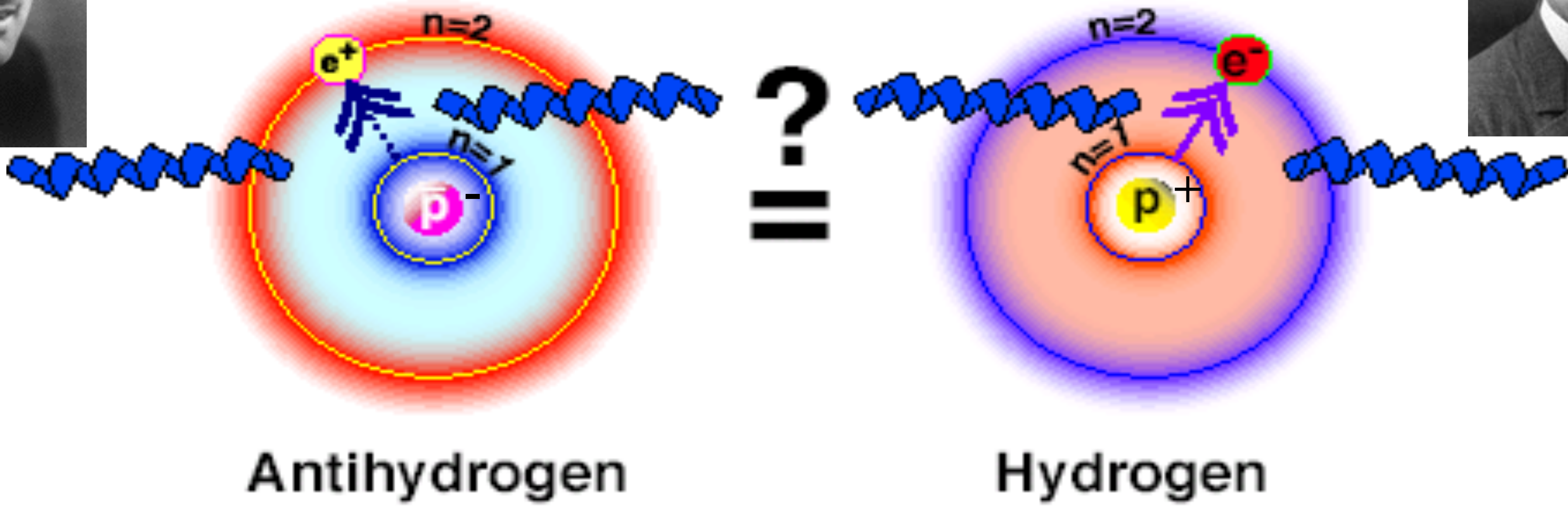
University of Wales Swansea, UK

University of Tokyo, Japan

York University, Canada

THE ALPHA COLLABORATION

The Question



How could I possibly work in Denmark and *not* want to know the answer to this?

Motivations in Brief

•Tests of fundamental symmetries by applying ***precision*** atomic physics techniques to anti-atoms:

- •CPT violation?
- •Lorentz invariance violation?

Physics beyond the Standard Model?

The initial physics goal of ALPHA was to TRAP antihydrogen atoms, so that they can be studied in detail.

•(Anti)-Gravity - no current experimental effort in ALPHA, but success in ALPHA suggests possibilities for long-term work – see Makoto's talk tomorrow

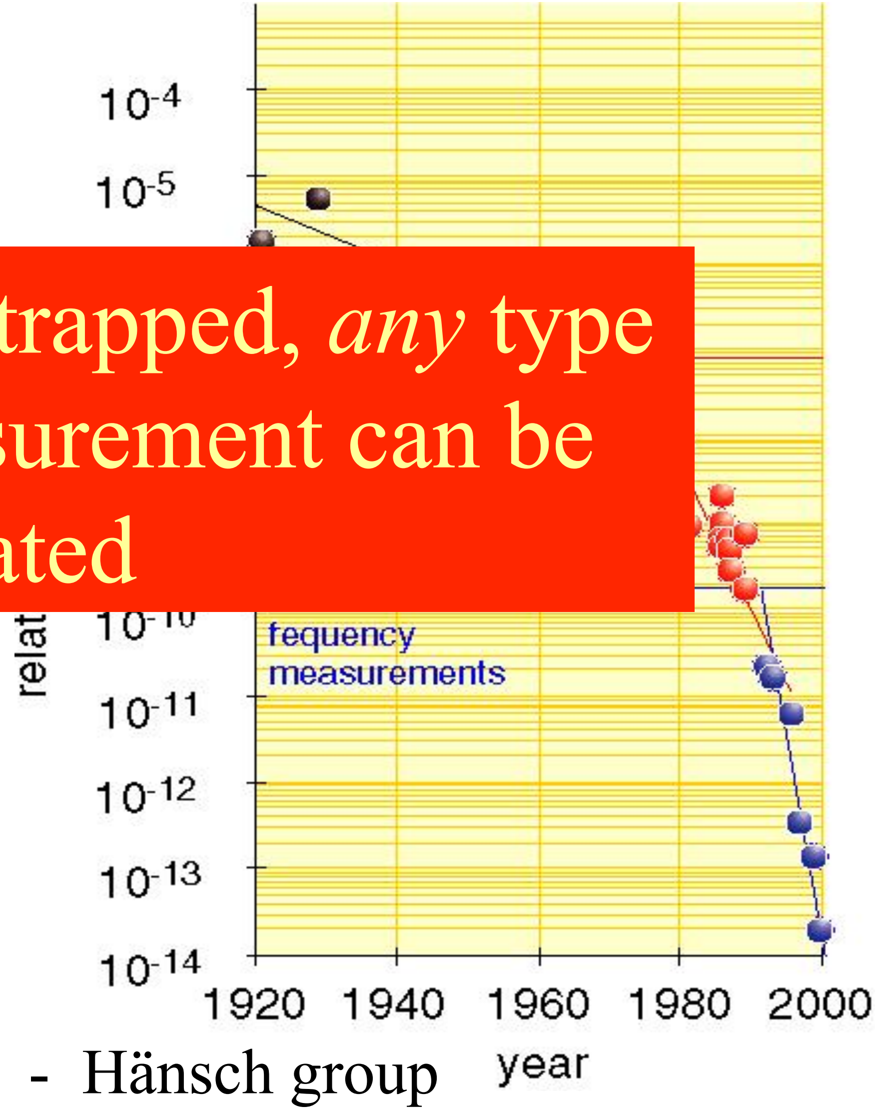
The dream - Antihydrogen Spectroscopy

1s-2s two-photon spectroscopy

If antihydrogen can be trapped, *any* type of spectroscopic measurement can be contemplated

- **Doppler effect cancels**
- **High precision in matter sector**
- **test of CPT theorem**

“Hänsch Plot”



f(1S-2S) = 2 466 061 102 474 851(34) Hz - Hänsch group

A Brief History of Antihydrogen

- CERN (LEAR-TRAP Collaboration): pioneering work on trapping, cooling of antiprotons; proton/antiproton mass comparison (to 1996, LEAR closed)

- CERN (LEAR-PS210): Baur et al., 1996, gas-jet experiment in LEAR

$\bar{p} + Xe -> \bar{H} + e^{-} + Xe$ $\gamma = 2.3$ 11 atoms observed

- Fermilab (E862): Blanford et al., 1998, gas-jet experiment at FNAL Accumulator

$\bar{p} + H -> \bar{H} + e^{-} + H$ $\gamma = 9.5$ 57 atoms observed

- CERN (AD-1): Amoretti et al., Sept. 2002

ATHENA produces and observes first cold (< eV) antihydrogen atoms by mixing cold antiprotons and positrons in a Penning trap.

~50000 atoms produced

M. Amoretti et al., Nature 419, 456 (3 Oct 2002)

- CERN (AD-2): Gabrielse et al., Oct. 2002

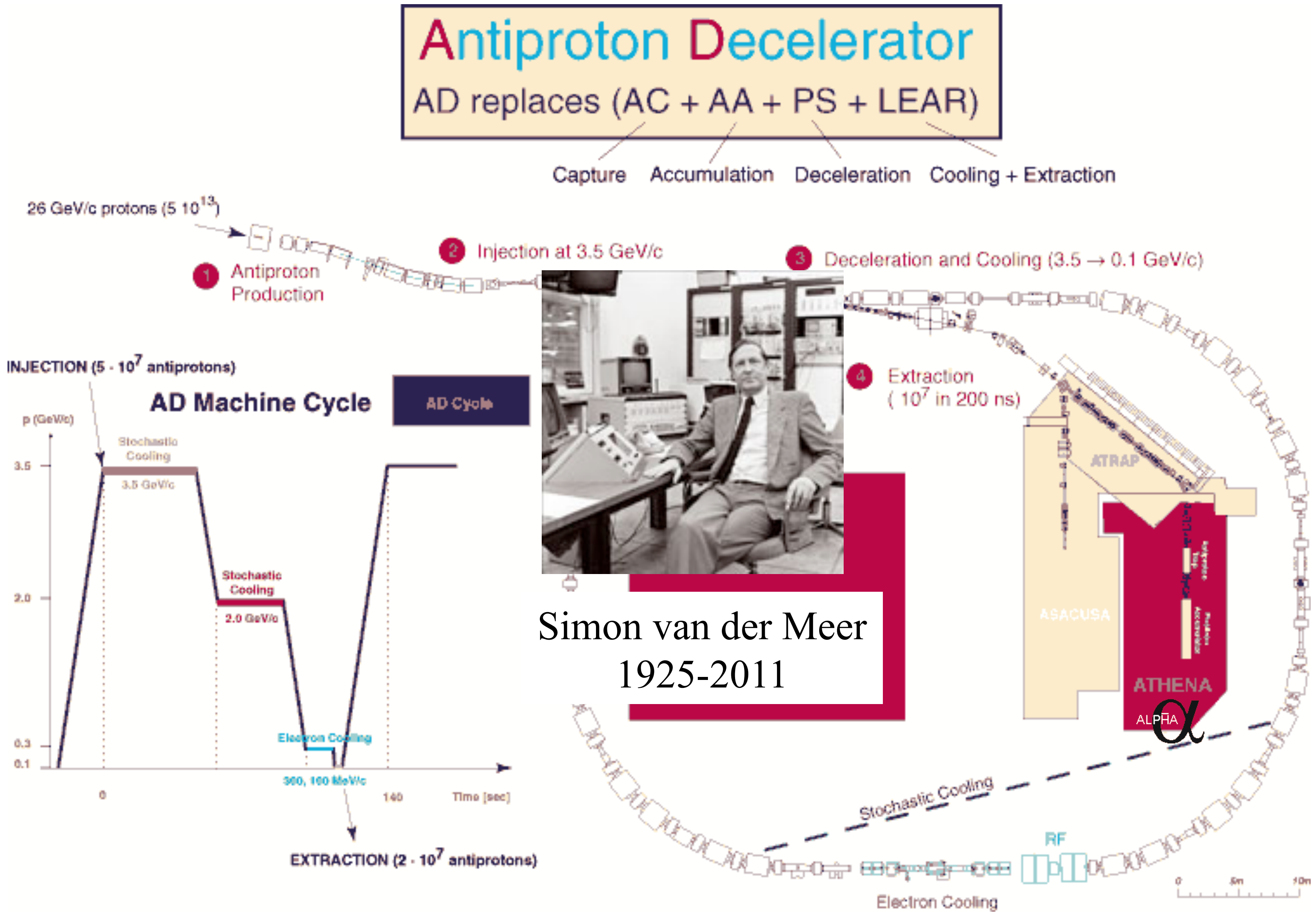
ATRAP confirms observation of antihydrogen atoms, indirect detection.

~170000 atoms produced

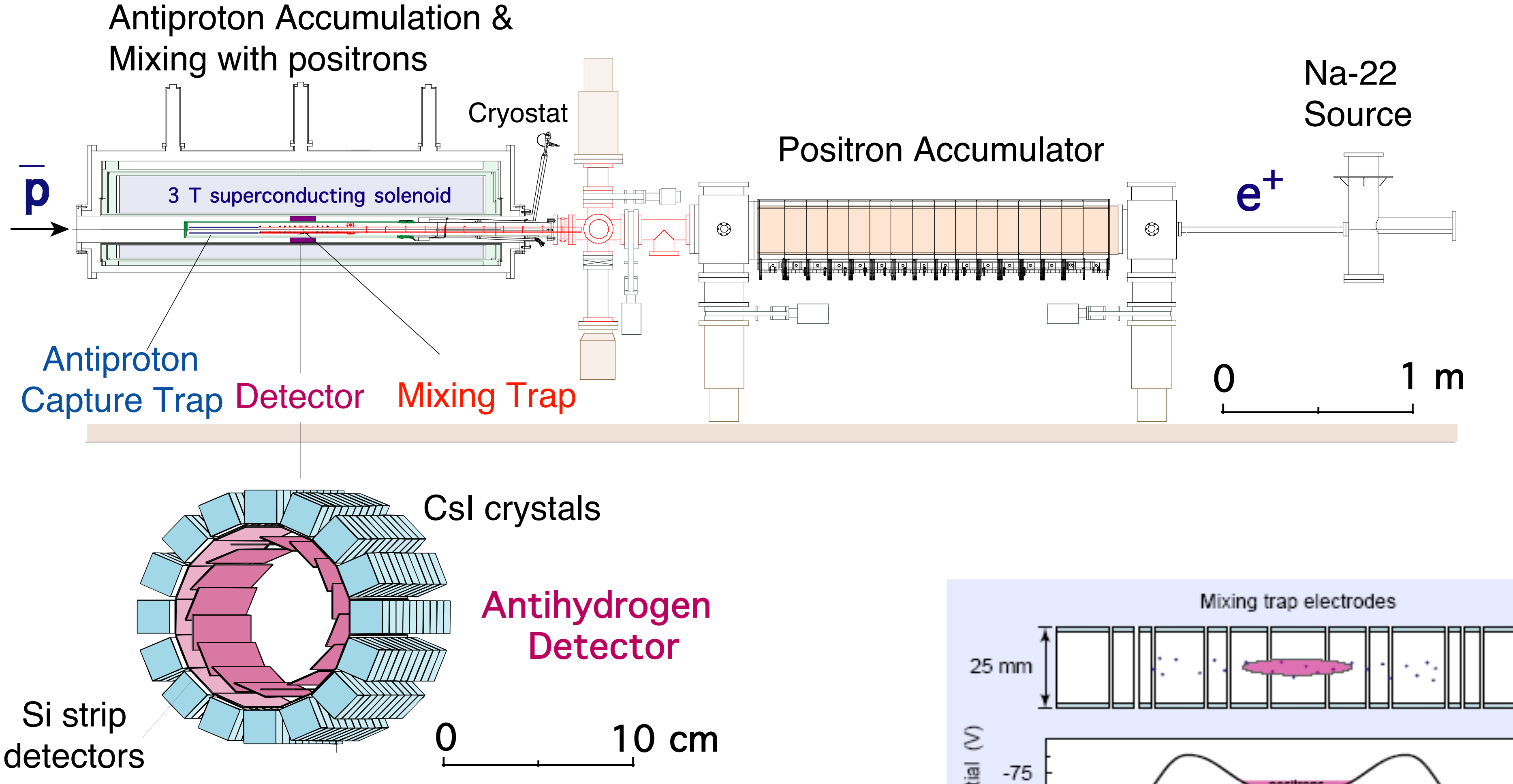
A Brief History of Antihydrogen II

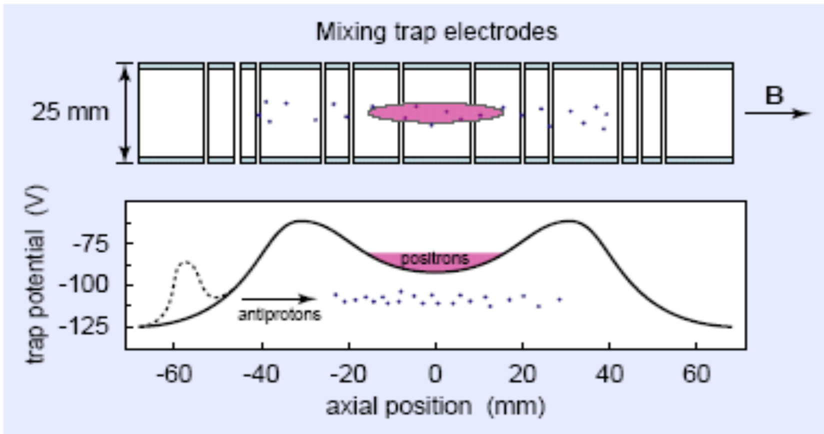
- CERN closes AD for 1.5 years because of LHC construction: November 2004 (ATHENA dissolved and ATRAP I finishes operation)
- ALPHA proposed (former ATHENA groups + new partners): January 2005
- ALPHA approved by CERN: June 2005
- AD restarts, ALPHA operational: June 2006
- First ALPHA PRL: January 2007
- ALPHA first to trap antihydrogen: November 2010
- ALPHA confines antihydrogen for 1000 s: June 2011

The CERN AD

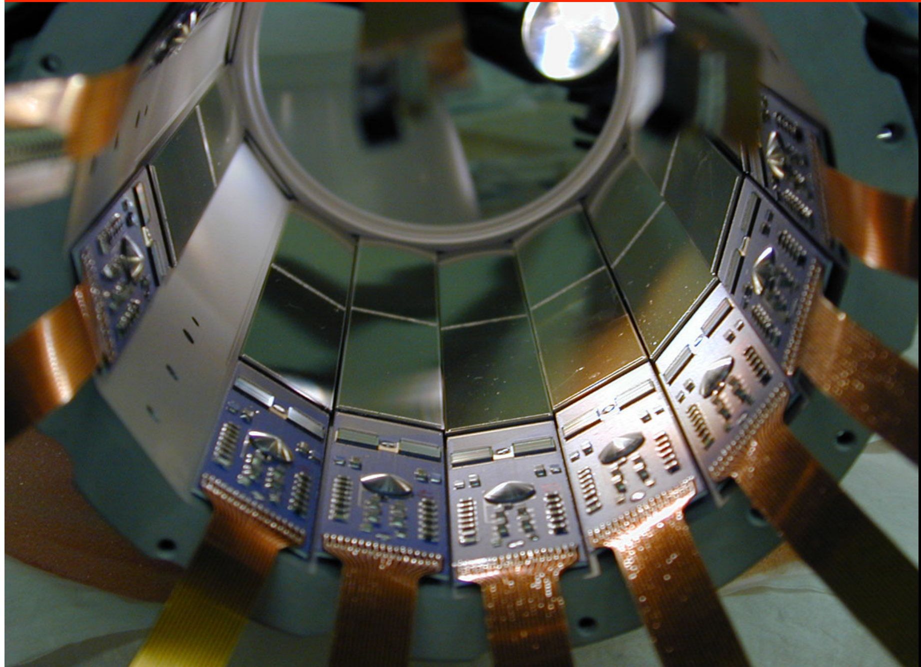

Antiproton Decelerator
AD replaces (AC + AA + PS + LEAR)
Capture
Accumulation
Deceleration
Cooling + Extraction
26 GeV/c protons (5 10^13)
1 Antiproton Production
2 Injection at 3.5 GeV/c
3 Deceleration and Cooling (3.5 → 0.1 GeV/c)
4 Extraction (10^7 in 200 ns)
INJECTION (5 · 10^7 antiprotons)
AD Machine Cycle
AD Cycle
p (GeV/c)
Stochastic Cooling
3.5 GeV/c
Stochastic Cooling
2.0 GeV/c
Electron Cooling
300, 100 MeV/c
3.5
2.0
0.3
0.1
0
140
Time [sec]
EXTRACTION (2 · 10^7 antiprotons)
Simon van der Meer
1925-2011
ATRAP
ASACUSA
ATHENA
ALPHA
Stochastic Cooling
RF
Electron Cooling

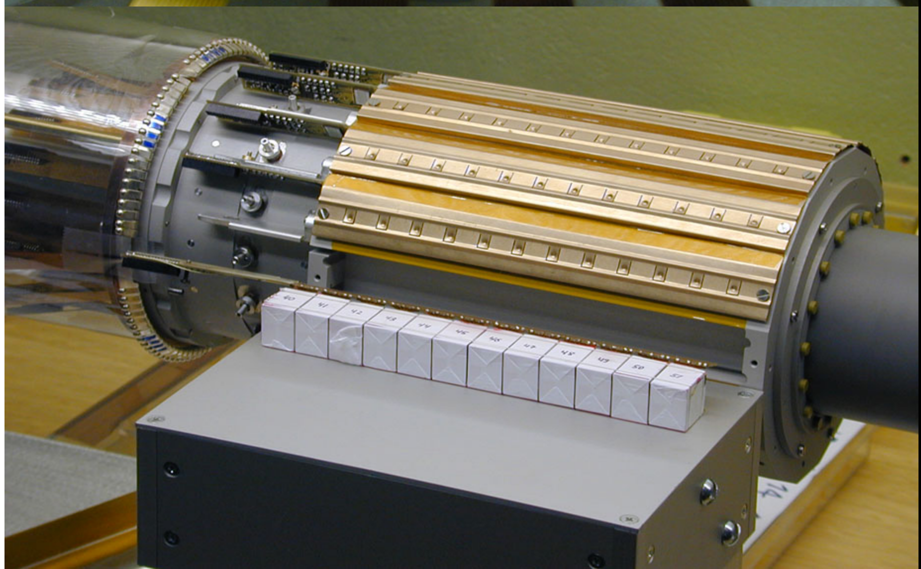
How do you make antihydrogen? : ATHENA 2002

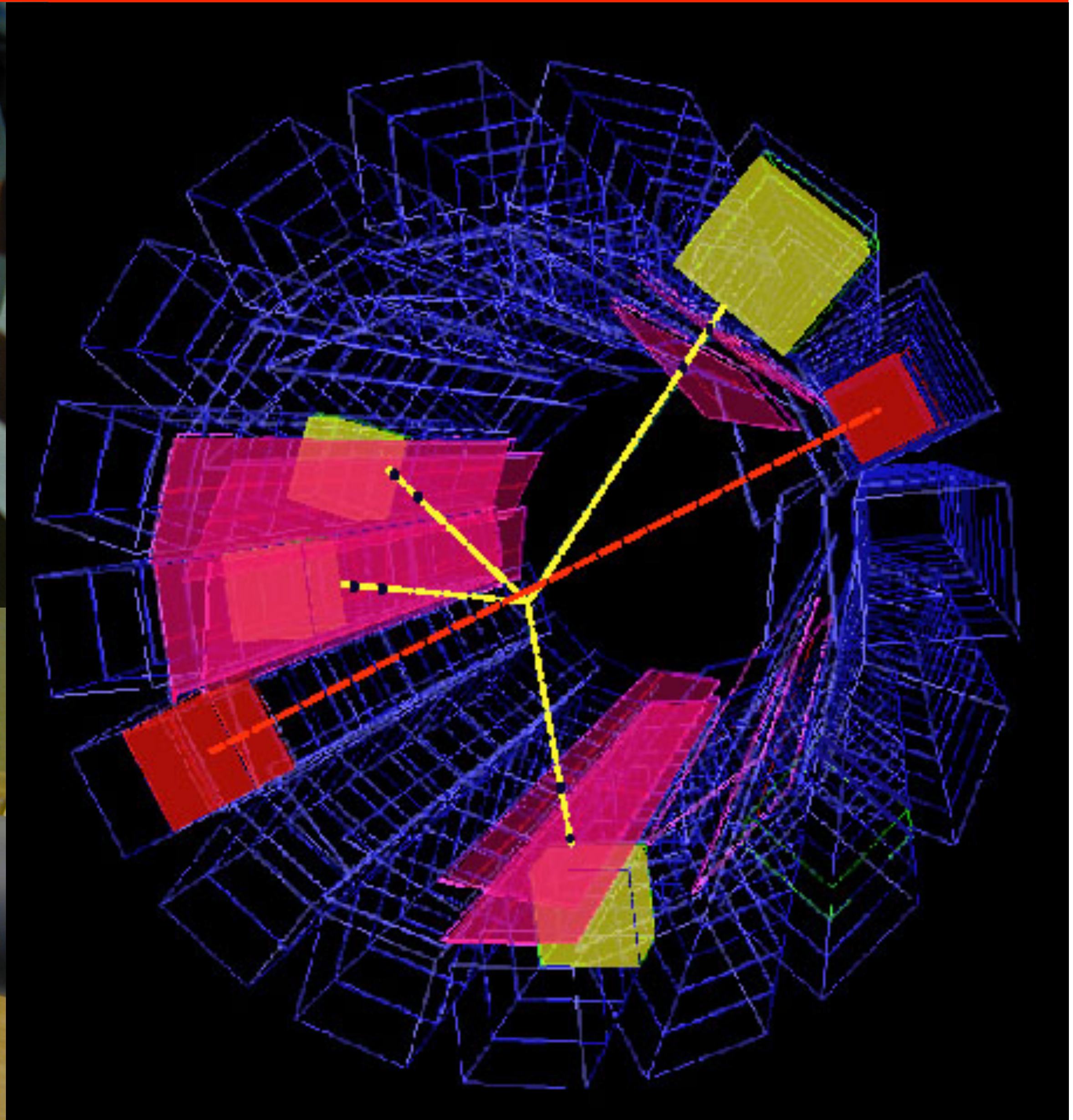




ATHENA Detector

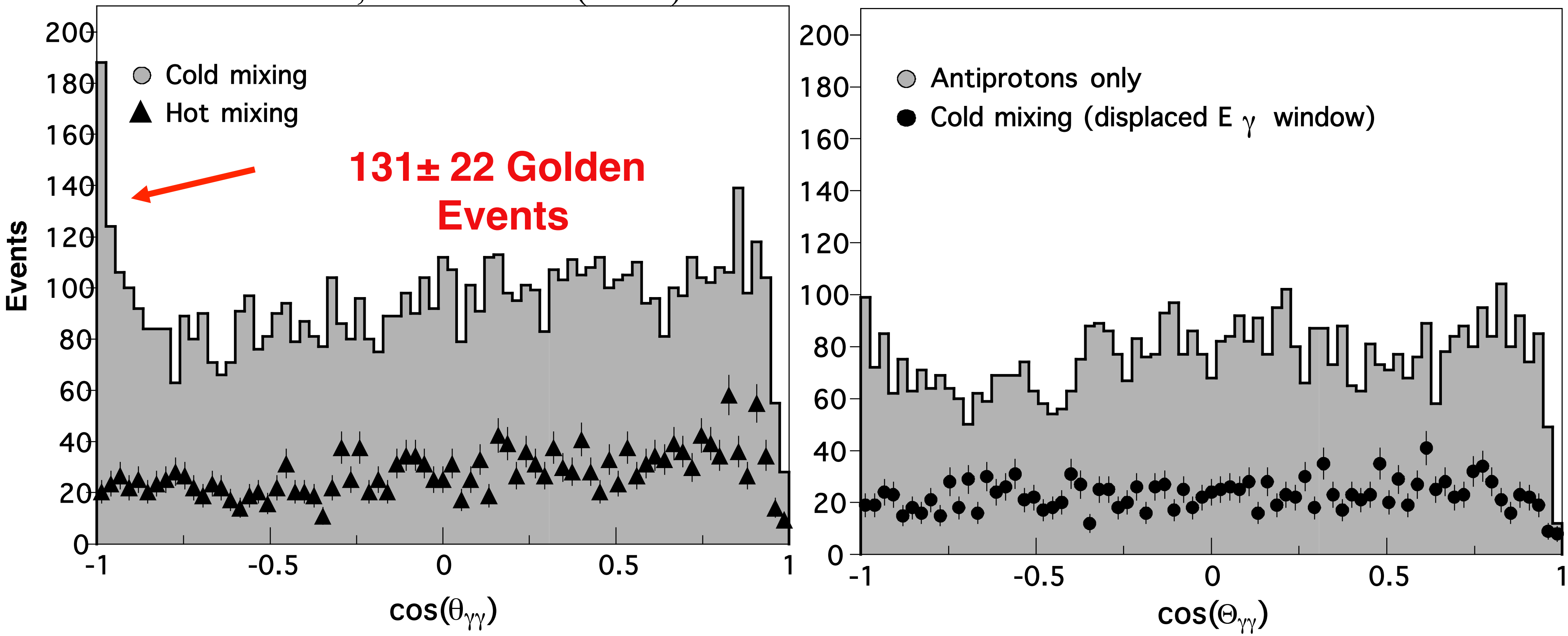






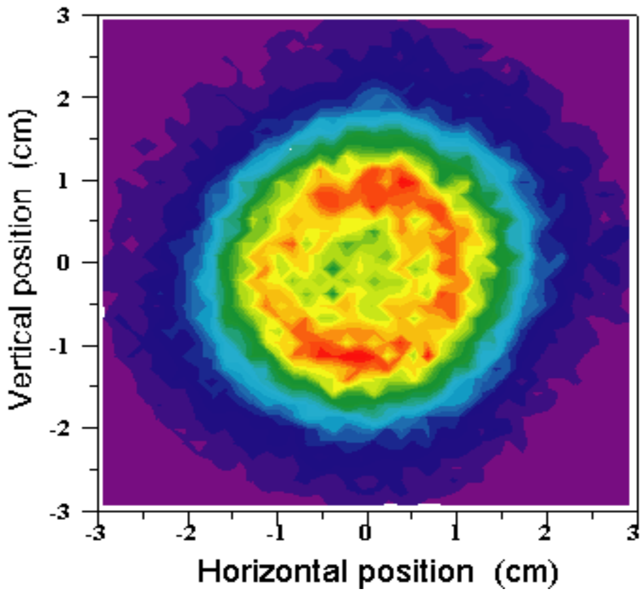
Antihydrogen Signal August 2002 *ATHENA*

Amoretti et al., ***Nature*** 419 (2002) 456

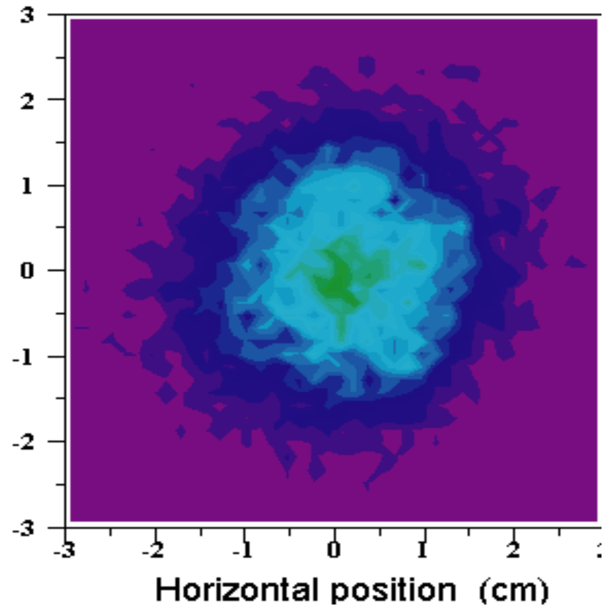


>50000 Cold Antihydrogen

Cold Antihydrogen Signal - Vertices



Cold Mix



Hot Mix

Amoretti et al., ***Nature*** 419 (2002) 456

ALPHA Strategy (from 2005)

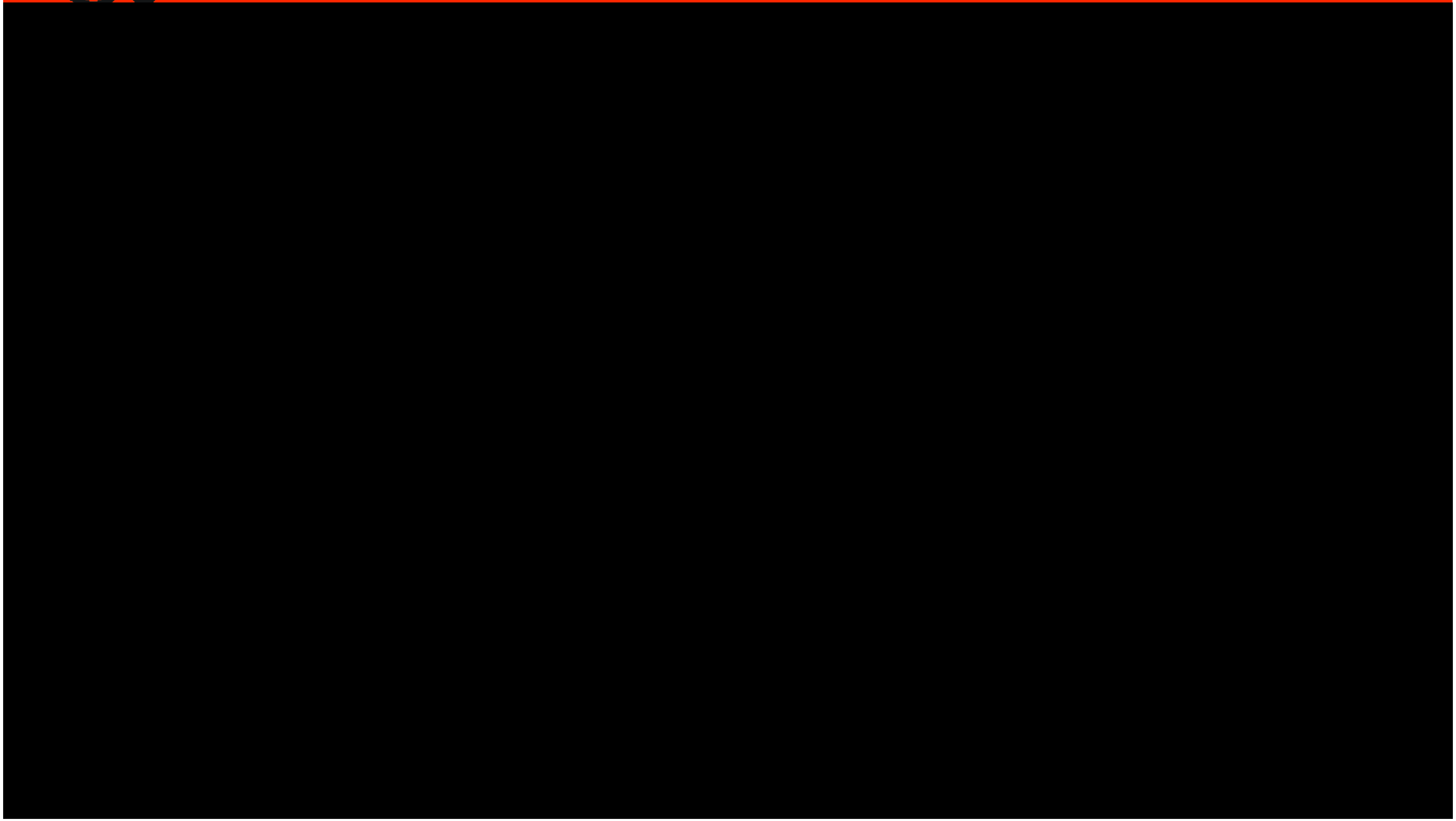
•Produce cold antihydrogen at the minimum of a minimum-B trap

•Get rid of the remaining charged particles

•Shut off the atom trap as quickly as possible

•Detect the antiproton annihilation from released antihydrogen with a *position sensitive annihilation detector*

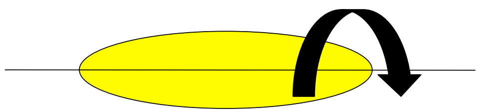
•Use event topology to reject cosmic rays



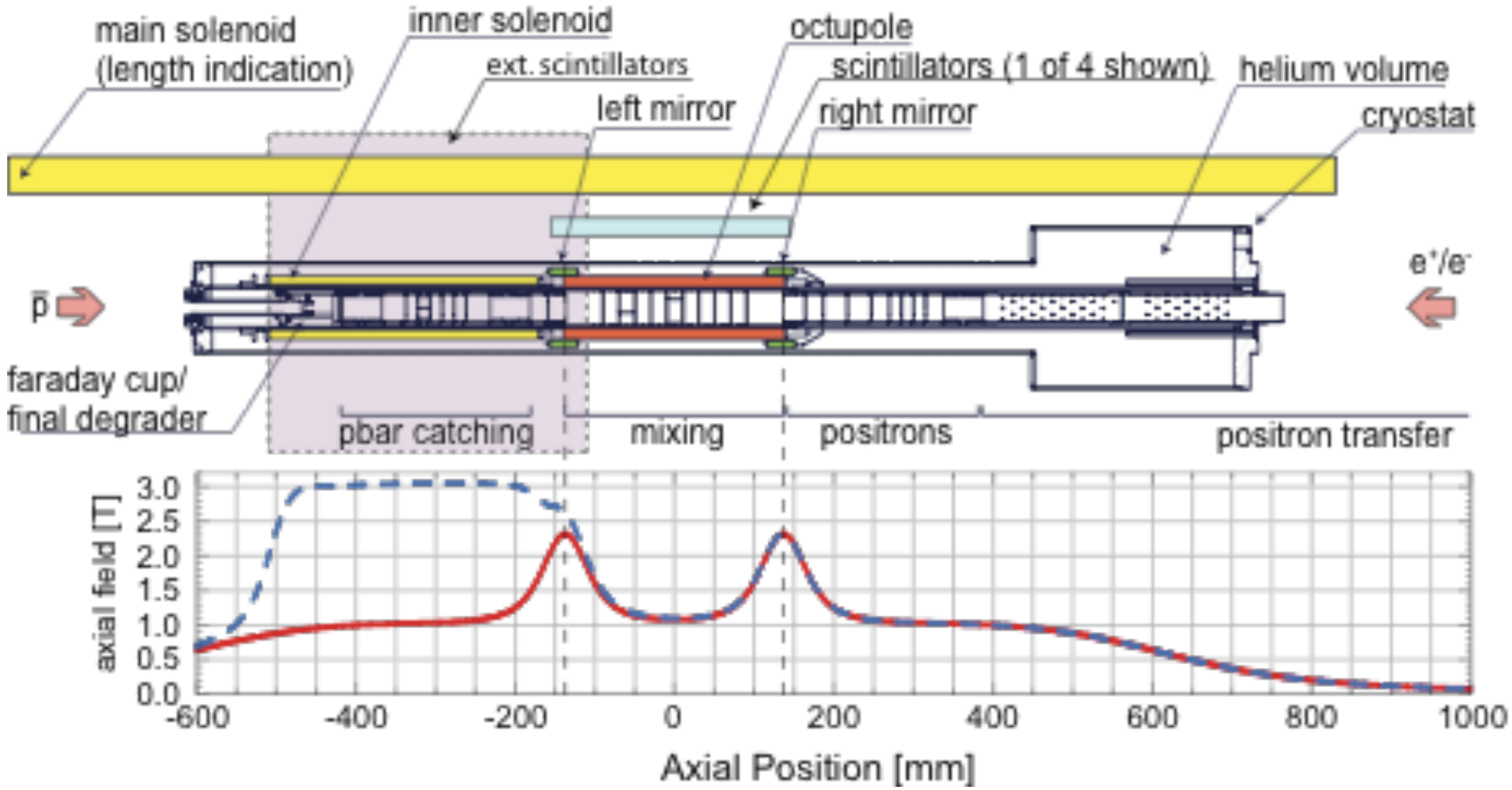
Why is this difficult?

- **Keep in mind: 1eV of kinetic energy is about *12000 K***
- **The antiprotons are captured at 5 keV**
- **Typical spacecharge energies of plasmas are a few eV**
- **The trap for neutral antihydrogen is *0.5 K deep***

One-component plasmas in equilibrium rotate at a constant angular frequency. The velocities associated with this rotation are of just as much concern as thermal velocities, as far as trapping is concerned. Not obvious that high positron number and density desirable - sometimes less is more.



ALPHA Apparatus -antihydrogen trapping



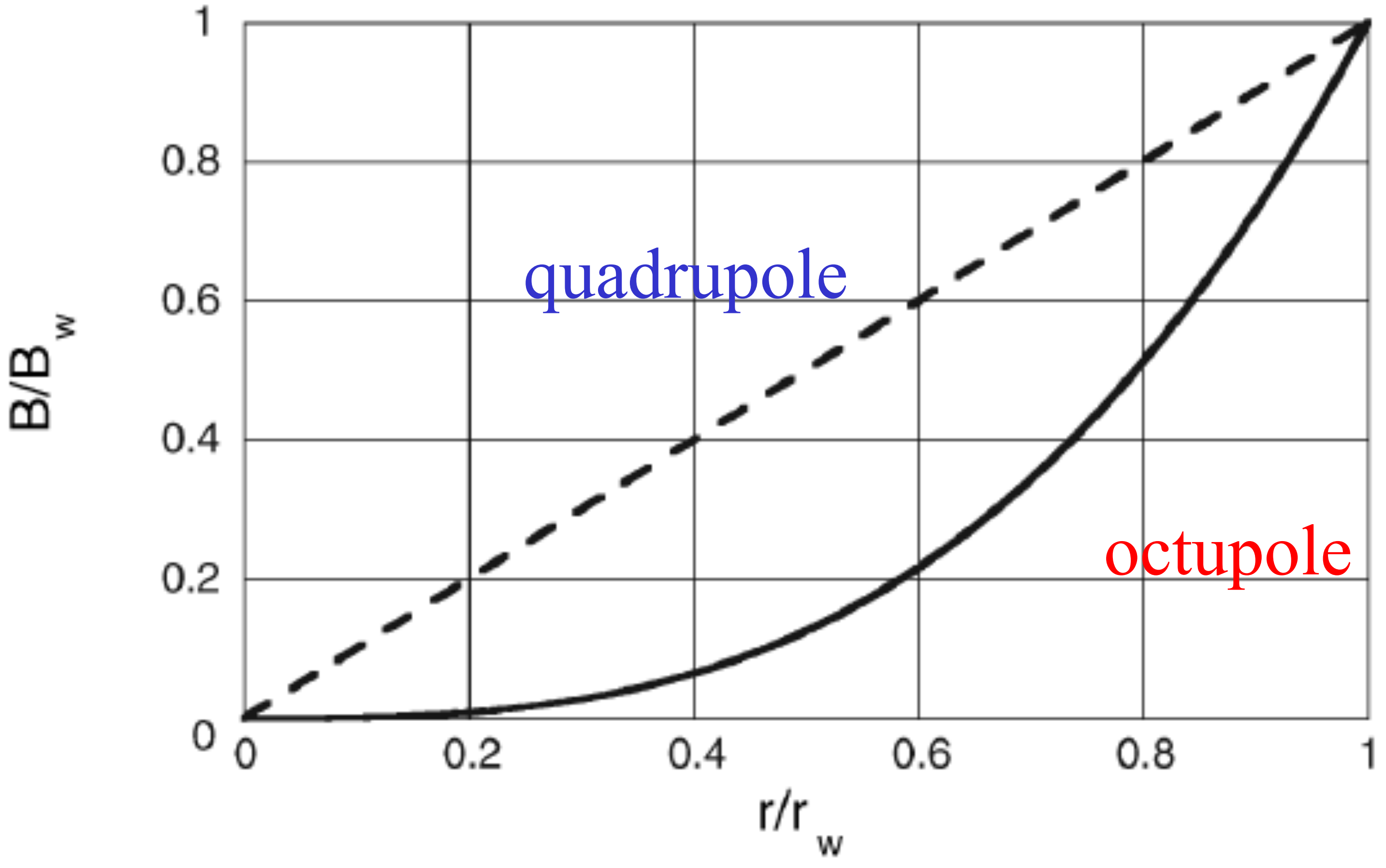
Successor to ATHENA

Flexible magnetic design: catch antiprotons at 3 T; mix with positrons at 1 T to allow deeper neutral trap depth

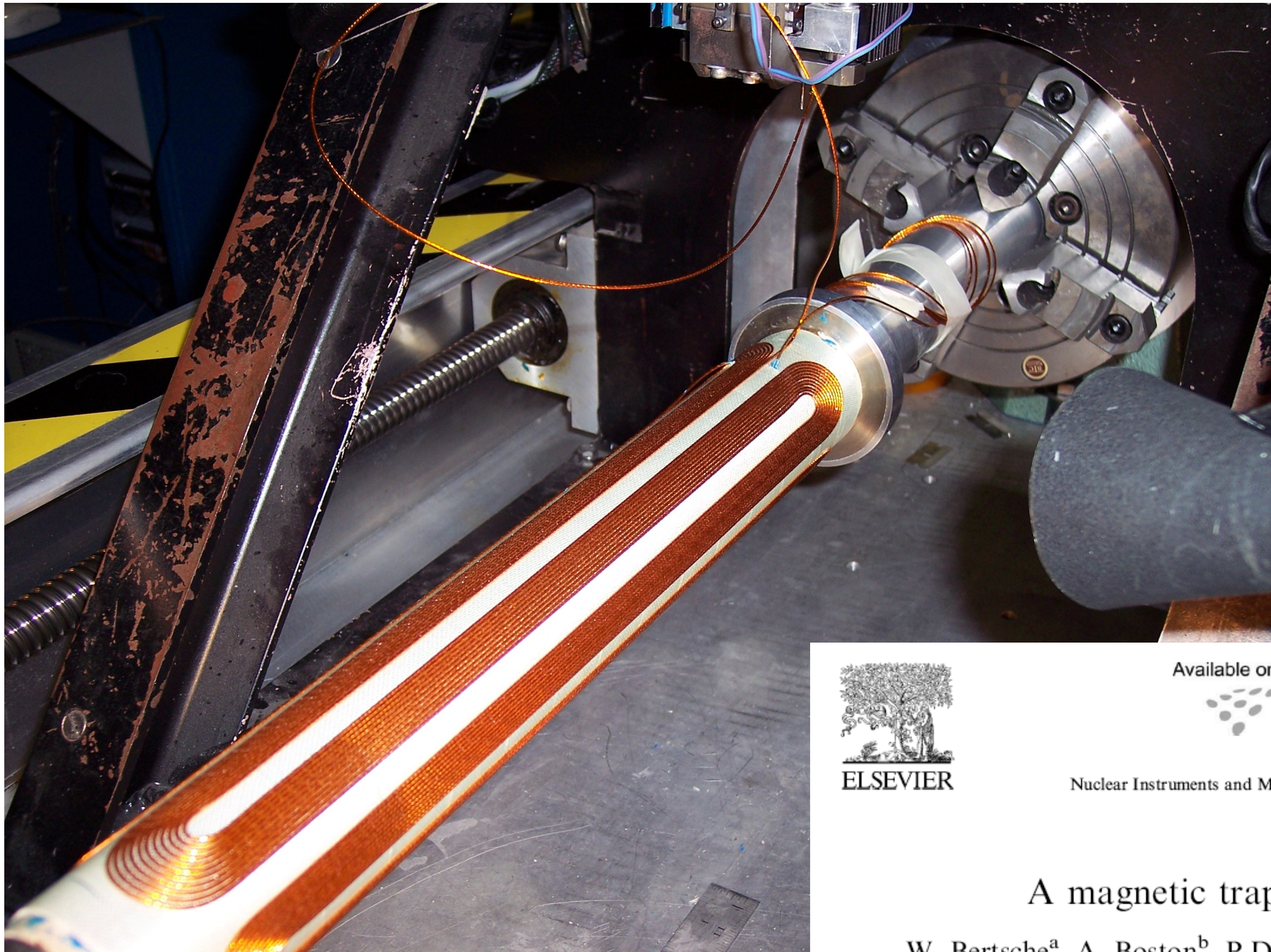
Octupole transverse field for minimum perturbation of trapped charged plasmas (antiprotons and positrons)

Silicon vertex detector *a la* ATHENA (2007/2008)

The ALPHA Approach: higher-order multipole



Octupole Fabrication at BNL



- Magnets wound directly on vacuum chamber (1.25 mm wall)
- No metals in support structure: epoxy/fiber
- High SC/copper ratio cable

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ScienceDirect

Nuclear Instruments and Methods in Physics Research A 566 (2006) 746–756

NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH Section A

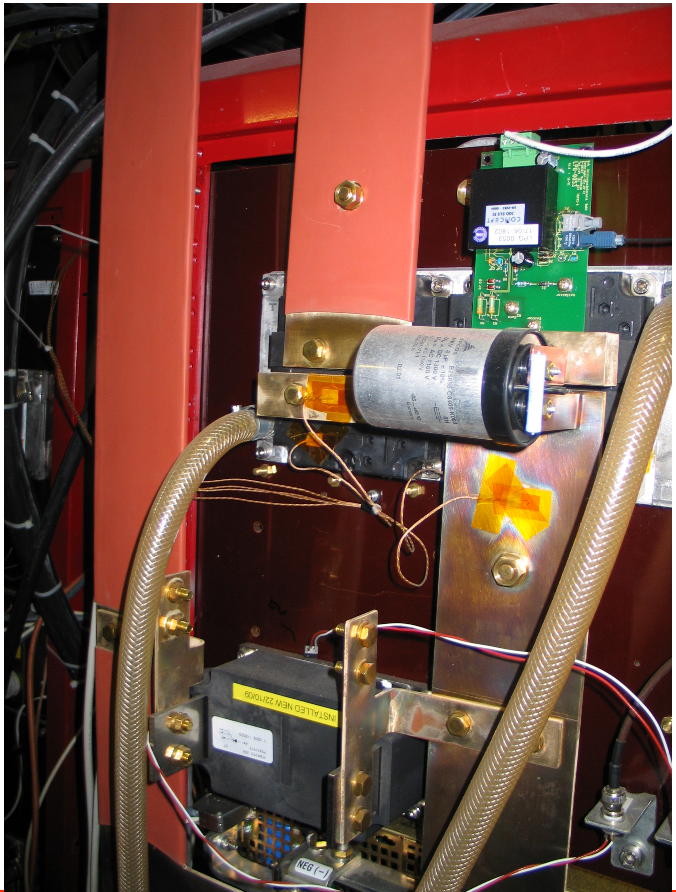
www.elsevier.com/locate/nima

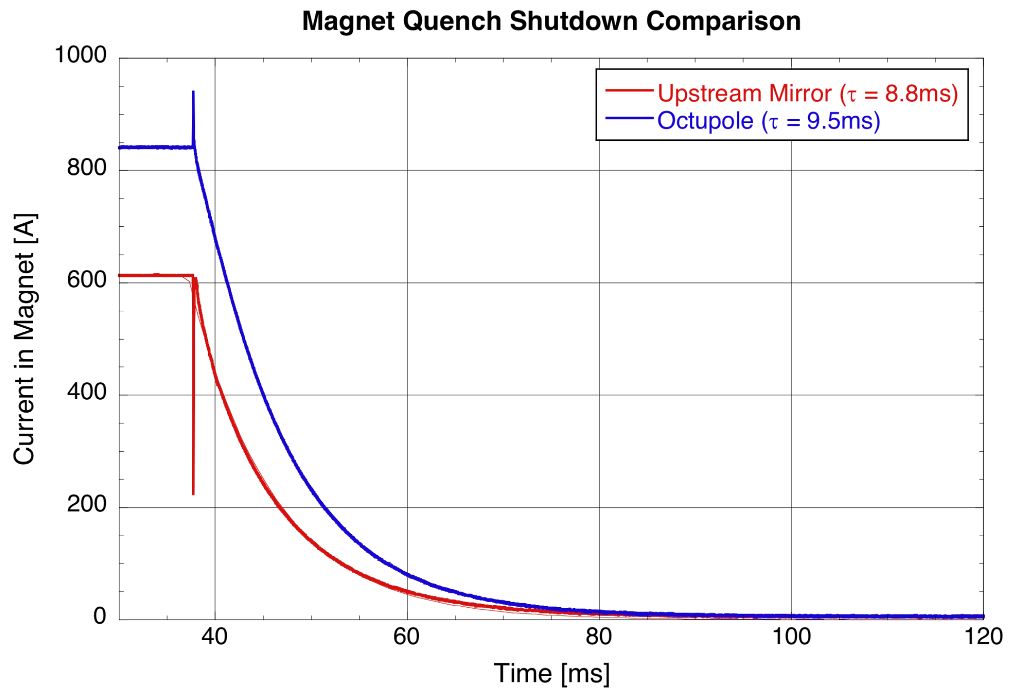
A magnetic trap for antihydrogen confinement

W. Bertsche[a], A. Boston[b], P.D. Bowe[c], C.L. Cesar[d], S. Chapman[a], M. Charlton[e], M. Chartier[b], A. Deutsch[a,f], J. Fajans[a,f], M.C. Fujiwara[g], R. Funakoshi[h], K. Gomberoff[a,f], J.S. Hangst[c], R.S. Hayano[h], M.J. Jenkins[e], L.V. Jørgensen[e], P. Ko[a], N. Madsen[e], P. Nolan[b], R.D. Page[b], L.G.C. Posada[h], A. Povilus[a], E. Sarid[i], D.M. Silveira[d], D.P. van der Werf[e,*], Y. Yamazaki[j] (ALPHA Collaboration) , B.Parker[k], J.Escallier[k], A.Ghosh[k]

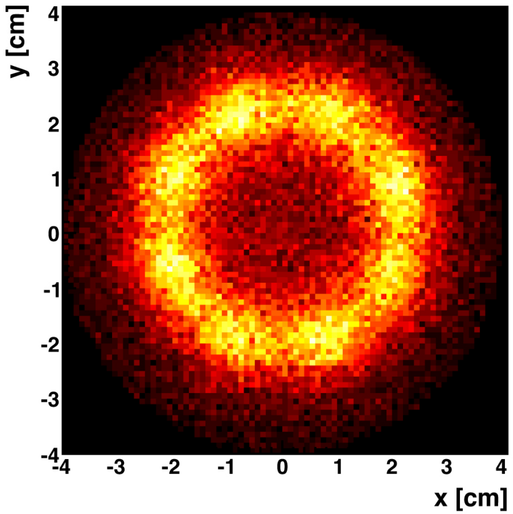
QPS and Rapid Shutdown

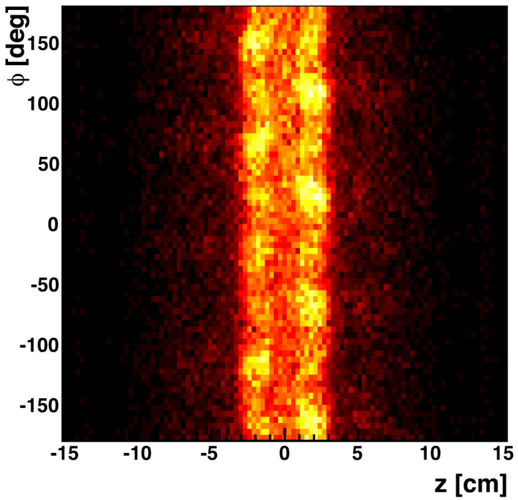
- Hardware patterned after G. Ganetis – IGBT switch to dump resistors
- Signal conditioning hardware from CERN LHC test chain
- Home-made FPGA QPS
- Taps on magnets, vapor cooled leads, and SC leads
- Magnets quench when shutting down – have survived several 10^3 cycles of this





ALPHA Silicon Vertex Detector

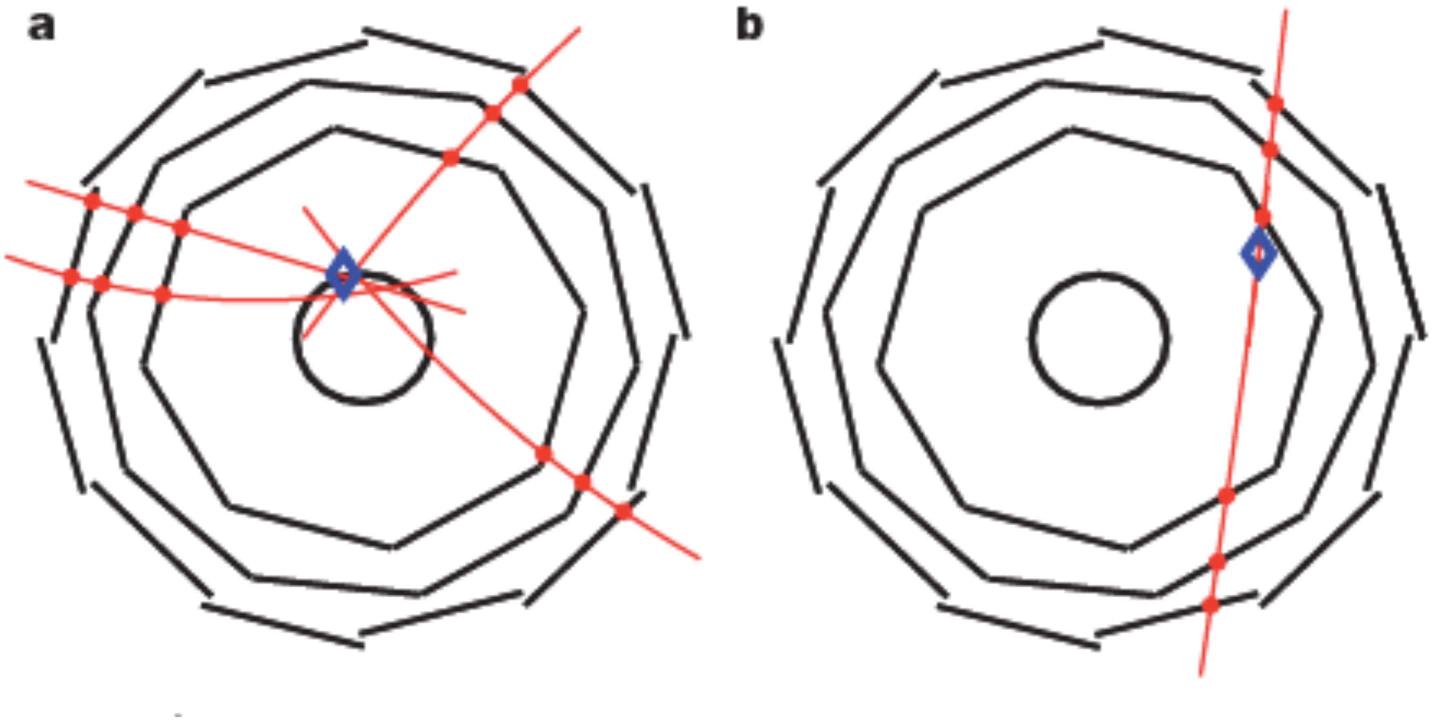




3-layer, double-sided modules
Detect antiproton anihilation (not e^+)
Fabricated by U. Liverpool

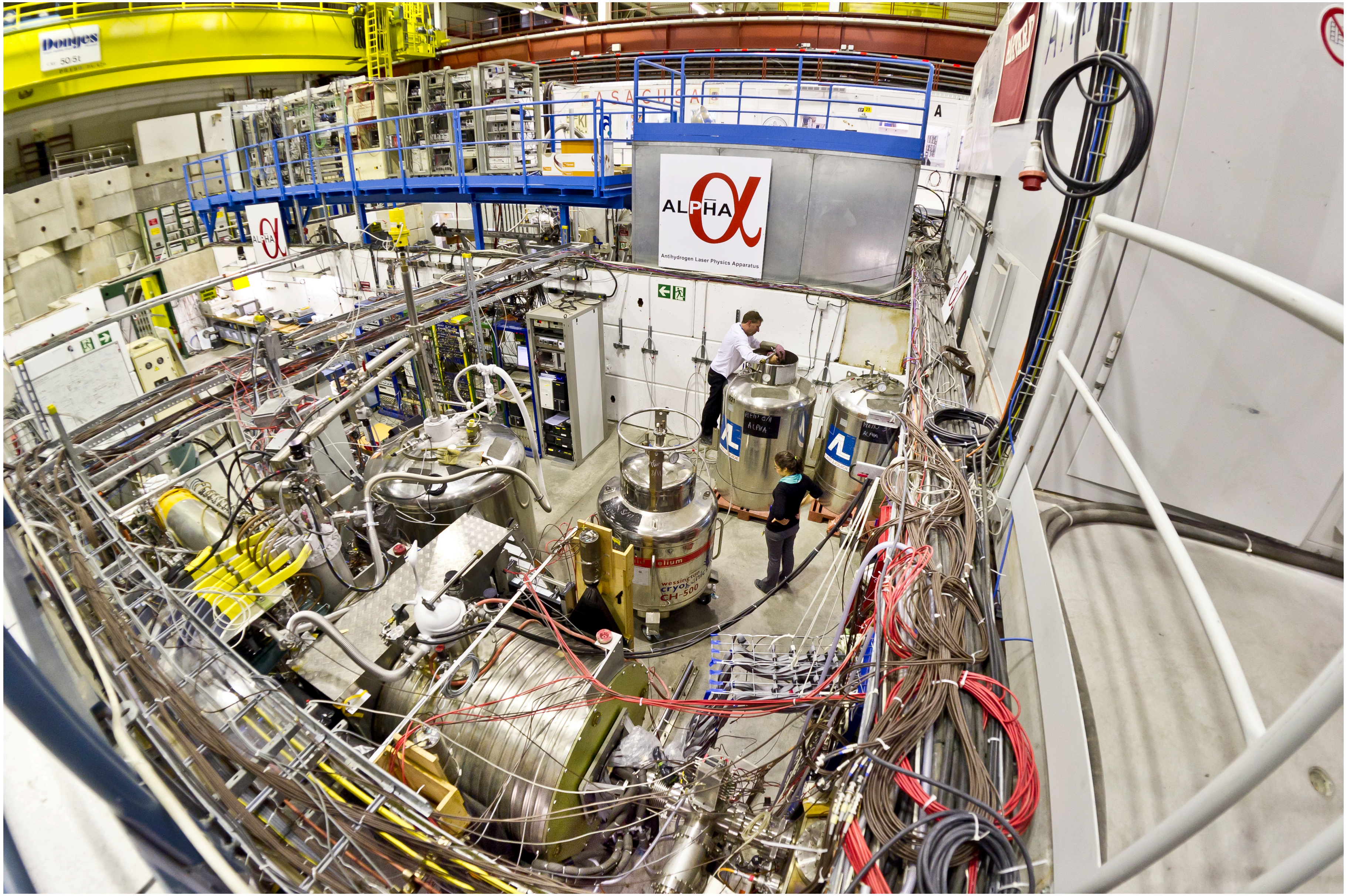
Topology

Typical antiproton annihilation **Typical cosmic ray**

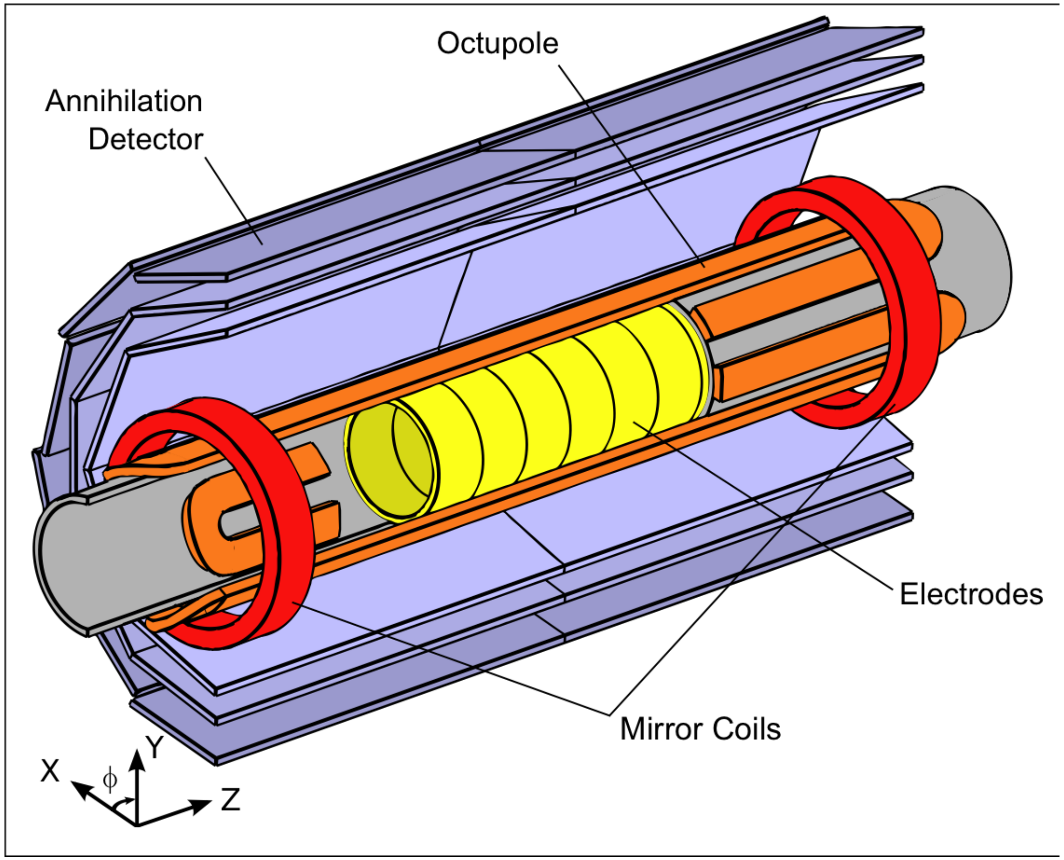


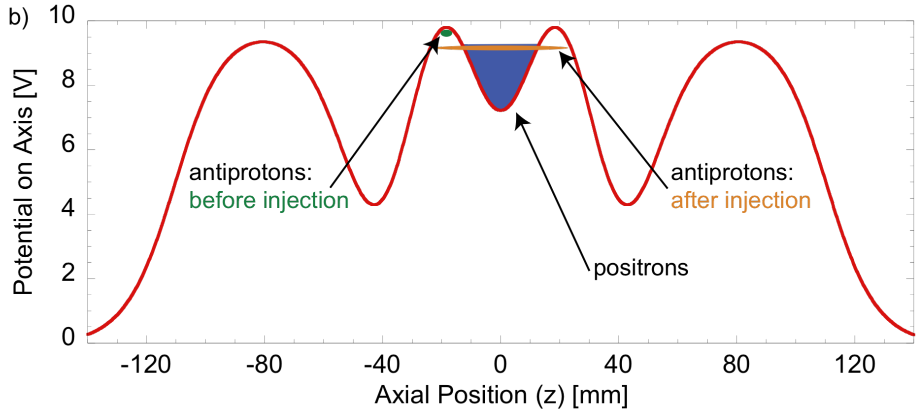
… not much going on here

ALPHA


ALPHA
Antihydrogen Laser Physics Apparatus
ASACUSA
Demag

The Experiment -2009



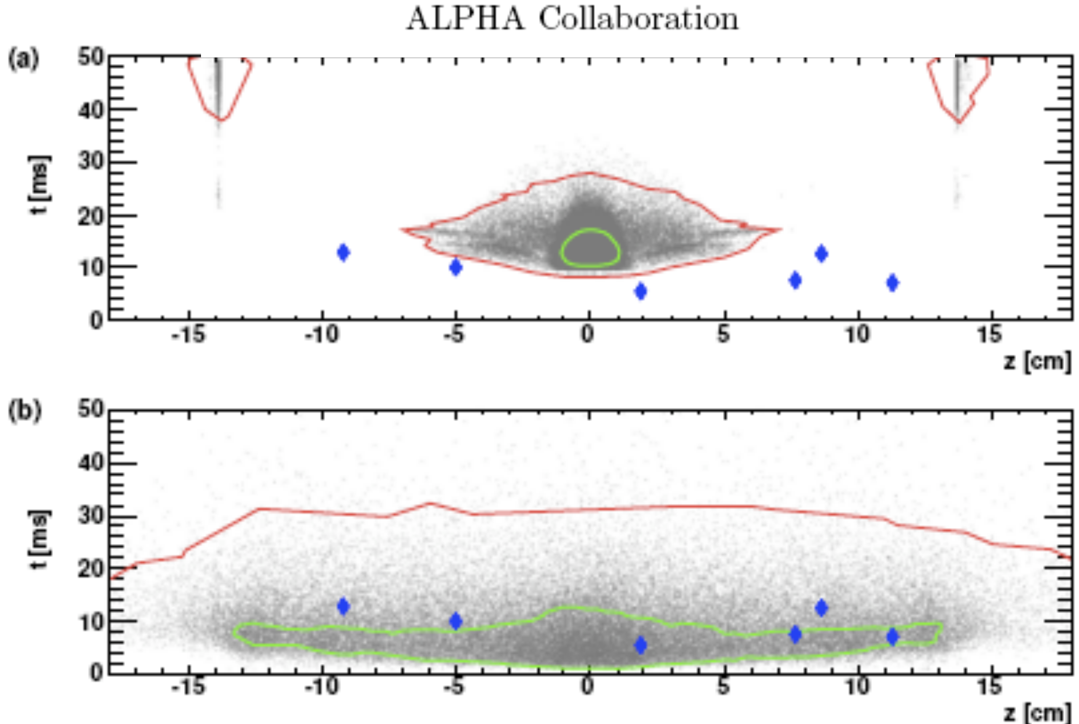


- 30000 antiprotons at 360 K
- 2 M positrons at 70 K
- Inject antiprotons autoresonantly
- Mix for 1 s
- Eject trapped charged particles
- Pulsed fields to clear any mirror-trapped pbars
- Fast shutdown of trap magnets (9 ms)
- Look for annihilating pbar from hbar
- Was it really a neutral? Compare to simulations

Trap antihydrogen in magnetic minimum trap
Trap depth ~ 0.5 K

2009 Data

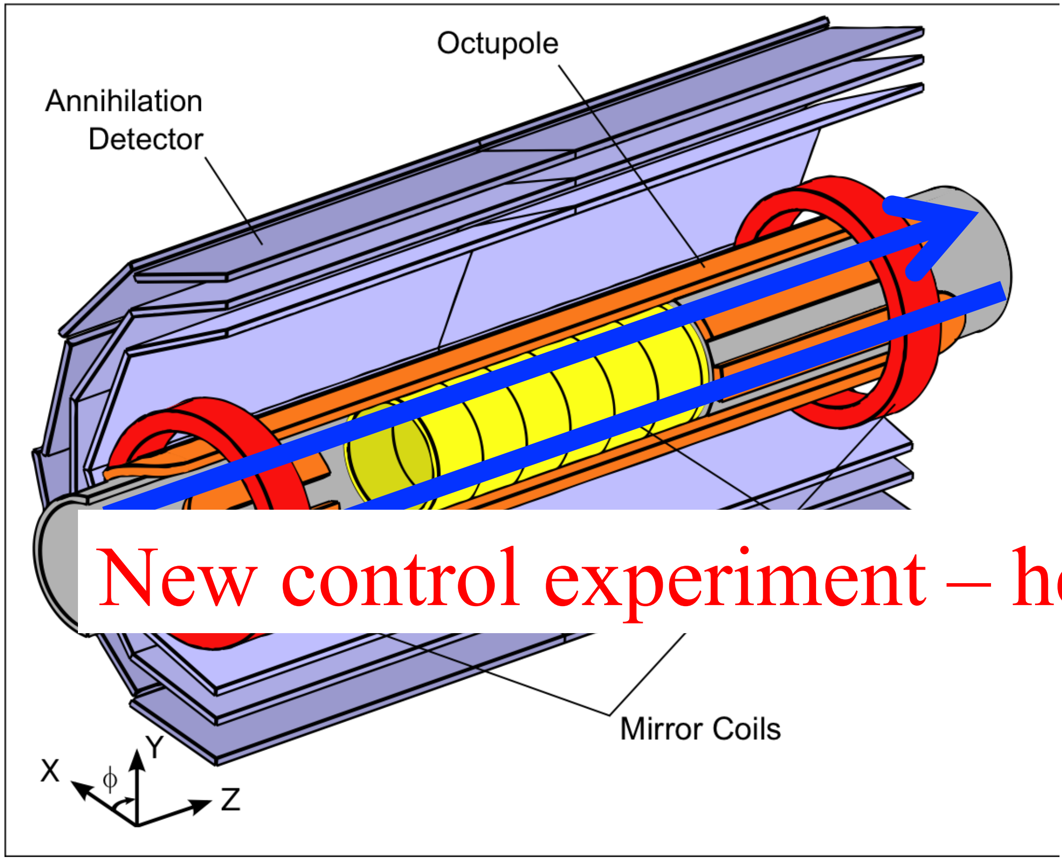
Search for Trapped Antihydrogen

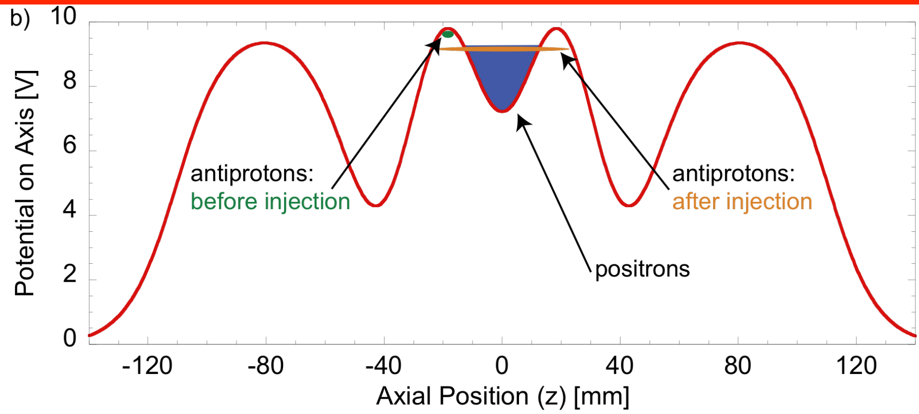


In 212 trials, six events consistent with trapped antihydrogen and inconsistent with mirror trapping simulations – but more experimental work needed.

PLB article deals with pbar identification, cosmic background, and mirror trapping physics

The Experiment -2010





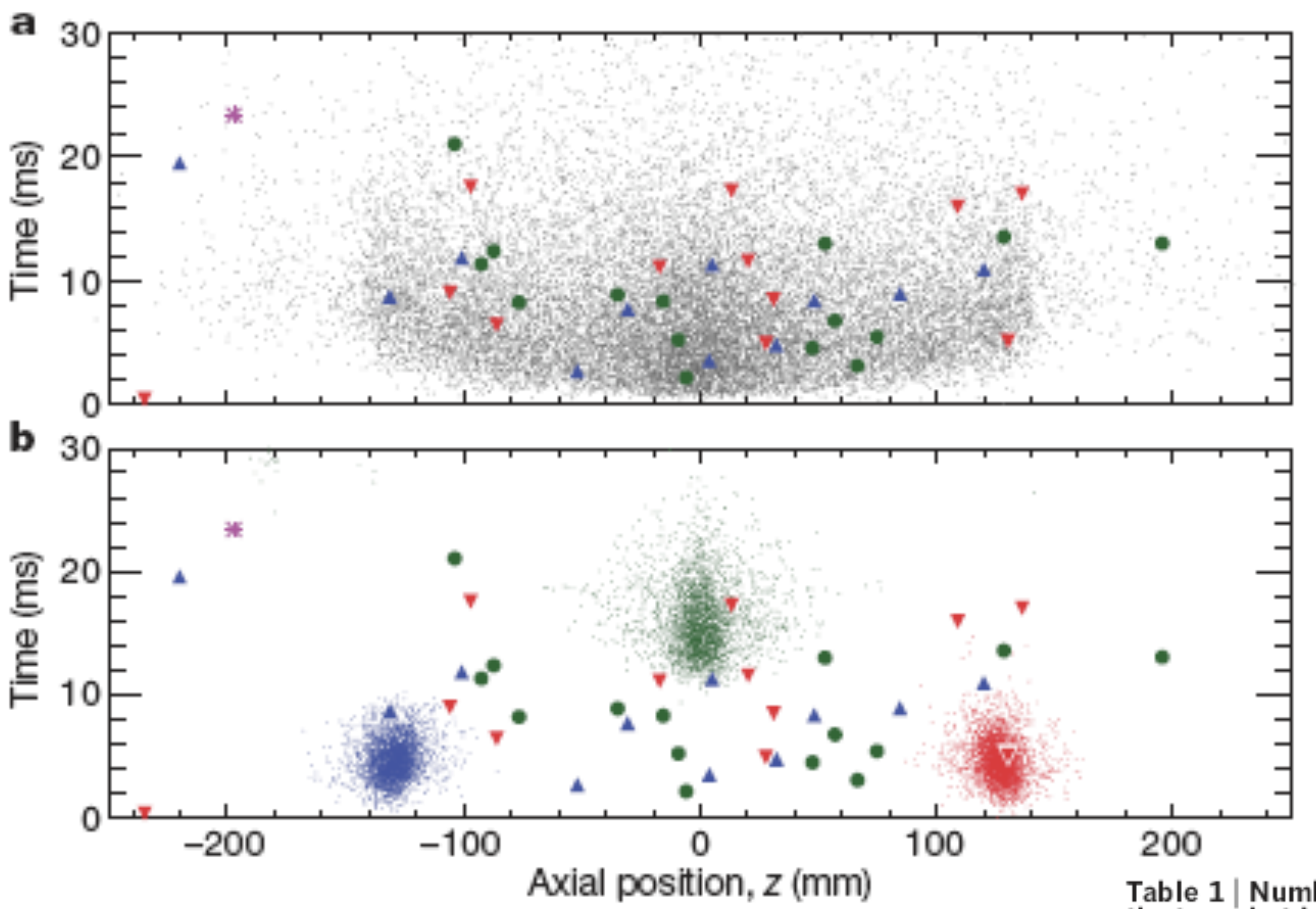
- 30000 antiprotons at 200 K
- 2 M positrons at 40 K, evaporatively

New control experiment – heated positrons (ATHENA)

- Inject antiprotons autoresonantly
- Mix for 1 s
- Eject trapped charged particles
- Pulsed fields to clear any mirror-trapped pbars
- Fast shutdown of trap magnets (9 ms)
- Look for annihilating pbar from hbar
- Was it really a neutral? Apply bias electric fields during shutdown.

Trap antihydrogen in magnetic minimum trap
Trap depth ~ 0.5 K

The Result



HBAR simulation

left bias
right bias
no bias

PBAR simulations

1 event with heated positrons

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

Conclusion from 2010 Run

38 annihilations in 335 attempts

Total background 1.4±1.4 events, including cosmic of 0.46±0.01 events – heated positrons

Bias fields prove that the annihilations are not mirror trapped pbars

Trapped antihydrogen for at least 172 ms.

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]

Published online in *Nature*, 17 November 2010

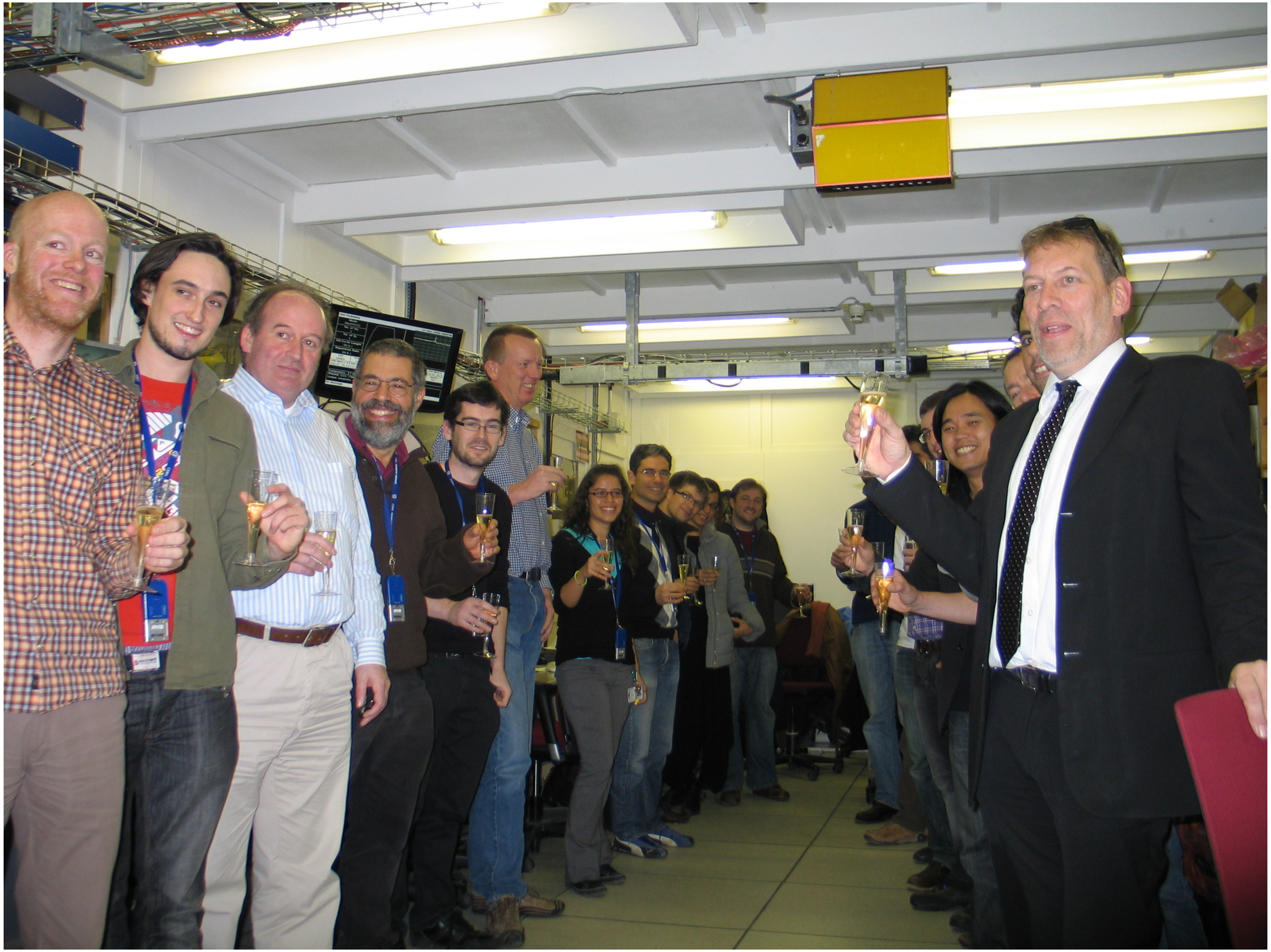
Physics Breakthrough of the Year, 2010 *Physics World* (UK)

One of the top ten physics stories of 2010 - American Institute of Physics

Most clicked-on story on *Nature* website for all of 2010

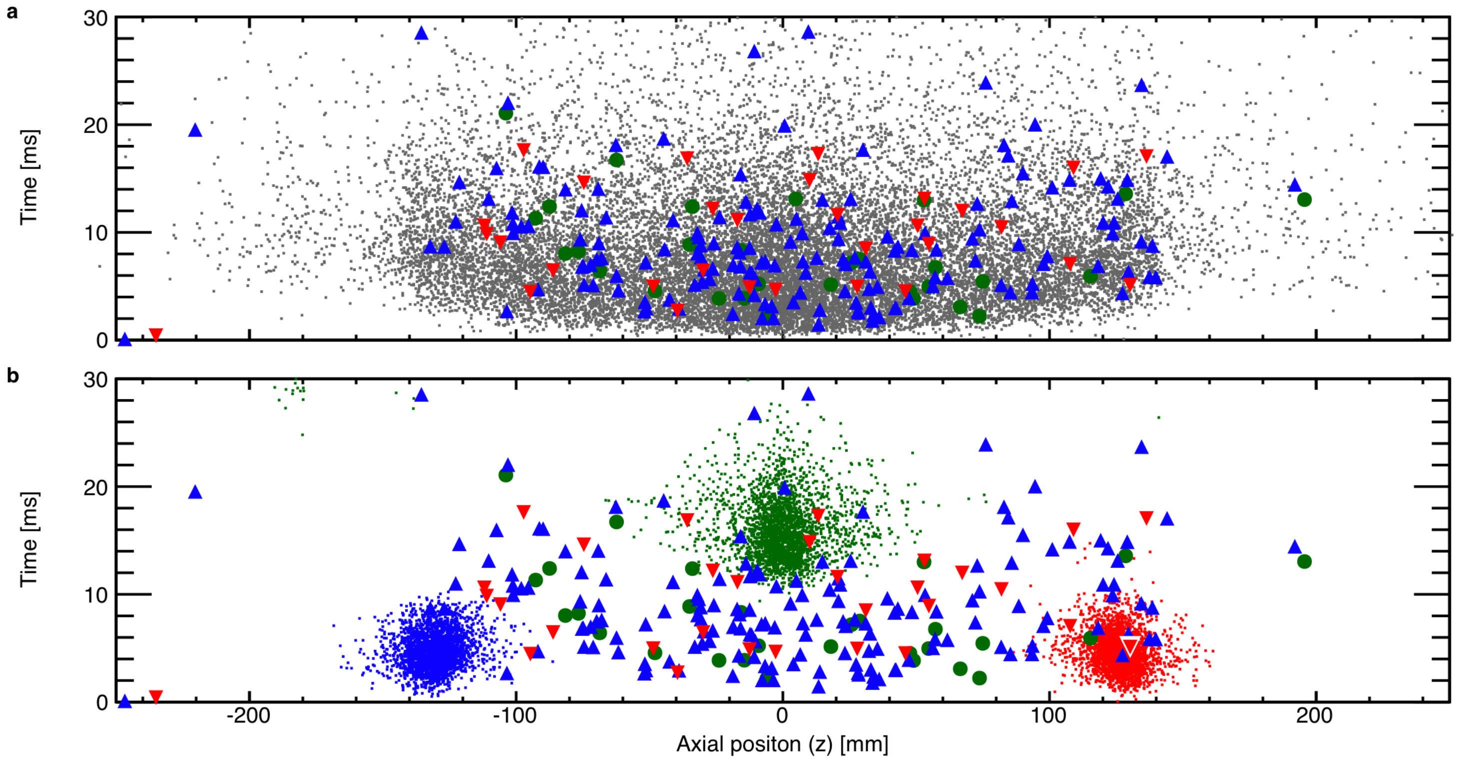
"The very fact of a proof-of-principle demonstration of wall-free confinement of even a small number of antimatter atoms has an intrinsic philosophical value."

ALPHA



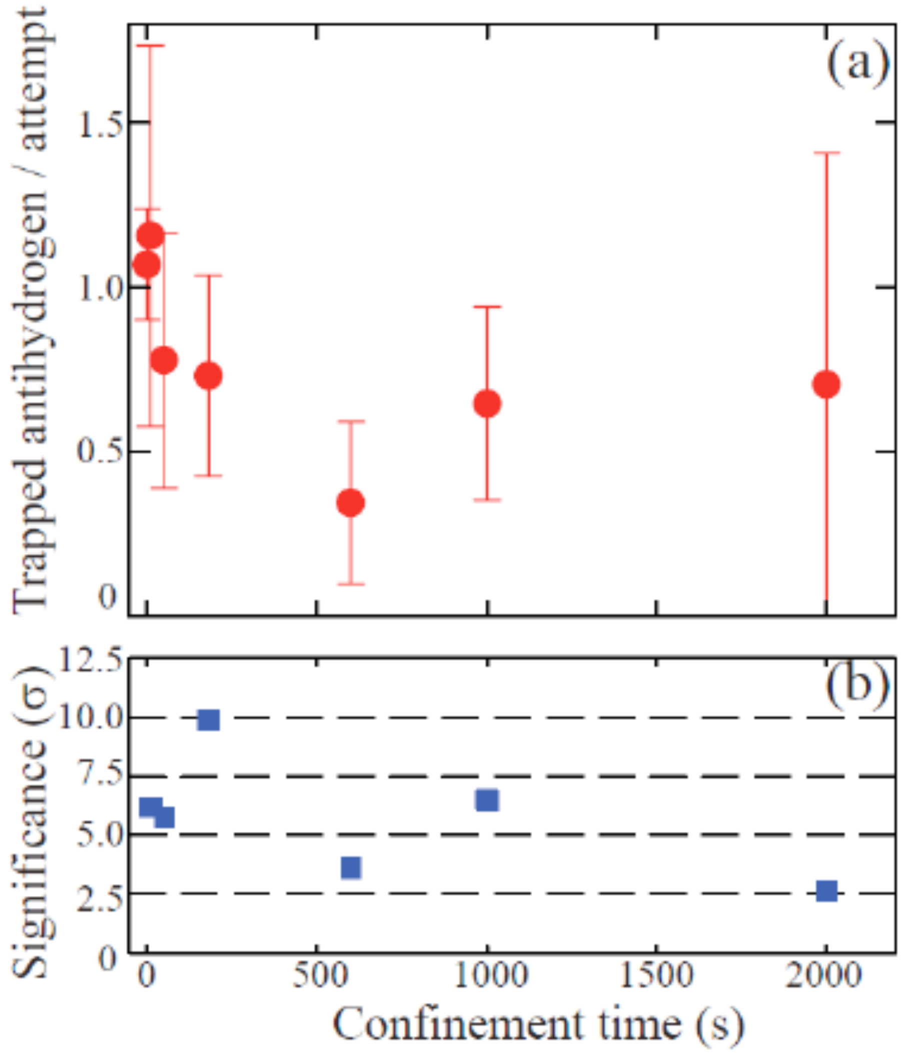

CERN COURIER
Antihydrogen gets caught in the act
FACET
ICECUBE
WOMEN IN SCIENCE

TOTAL SAMPLE – 2010 – you can tweak 38



(300+ annihilation events)

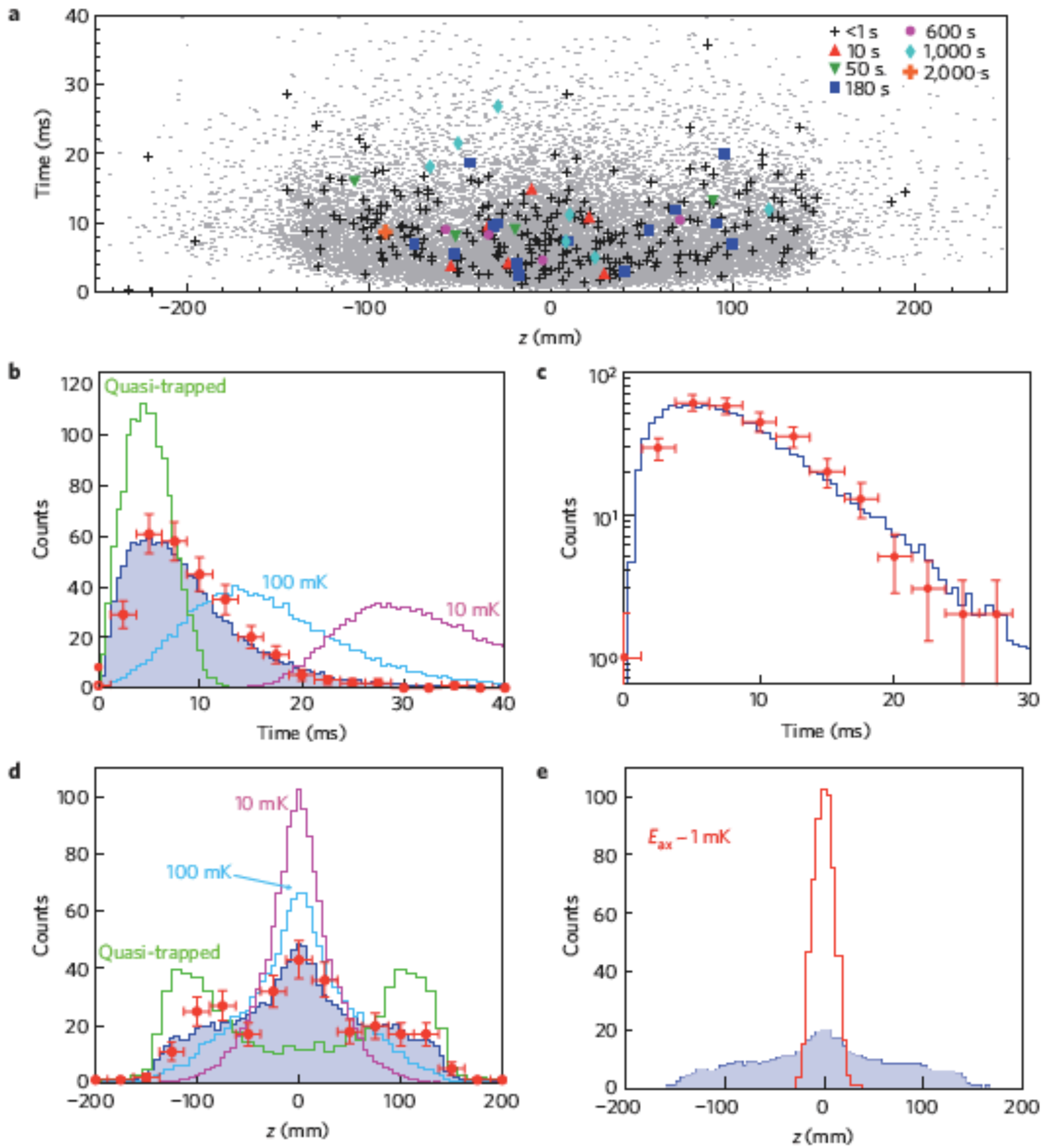
Latest result: ANTIHYDROGEN STORAGE TIME



Confinement Time (s)	0	10	50	180	600	1000	2000
Number of attempts	119	7	13	32	12	16	3
Detected events (counts)	60	4	4	11	2	5	1
Estimated back-ground (counts)	0.16	0.01	0.02	0.04	0.02	0.02	0.004
Statistical significance (σ)	24	6.2	5.8	9.9	3.6	6.5	2.6
Trapping rate per attempt	1.1 ±0.17	1.2 ±0.6	0.78 ±0.39	0.73 ±0.30	0.34 ±0.25	0.65 ±0.29	0.70 ±0.70

Nature Physics, 5 June 2011

Release dynamics of trapped antihydrogen



•Working assumption is that trappable hbar is formed from pbars in equilibrium with the positron plasma

•Energy scales:

	pbars	~200 K
	positrons	~ 40 K
	trap depth	~ 0.5 K

•Much can be learned from position-sensitive detection – listen to Makoto's talk

nature physics

ARTICLES

PUBLISHED ONLINE: XX MONTH XXXX | DOI: 10.1038/NPHYS2025

Confinement of antihydrogen for 1,000 seconds

The ALPHA Collaboration*

Atoms made of a particle and an antiparticle are unstable, usually surviving less than a microsecond. Antihydrogen, made entirely of antiparticles, is believed to be stable, and it is this longevity that holds the promise of precision studies of matter–antimatter symmetry. We have recently demonstrated trapping of antihydrogen atoms by releasing them after a confinement time of 172 ms. A critical question for future studies is: how long can anti-atoms be trapped? Here we report the observation of anti-atom confinement for 1,000 s, extending our earlier results by nearly four orders of magnitude. Our calculations indicate that most of the trapped anti-atoms reach the ground state. Further, we report the first measurement of the energy distribution of trapped antihydrogen, which, coupled with detailed comparisons with simulations, provides a key tool for the systematic investigation of trapping dynamics. These advances open up a range of experimental possibilities, including precision studies of charge–parity–time reversal symmetry and cooling to temperatures where gravitational effects could become apparent.

- Published online 5 June 2011
- First ***ground state*** antihydrogen
- Important implications for future spectroscopy and gravitational studies, laser cooling?
- More press circus…

Cover of Nature Physics – July 2011

What's Next?

- Improve trapping efficiency: as high as ~1 event per attempt now

- Continue to investigate storage lifetime: but rather boring

- Try to interact with hbar using microwaves – focus for 2011 – first resonant interaction with antihydrogen; run started May 9th

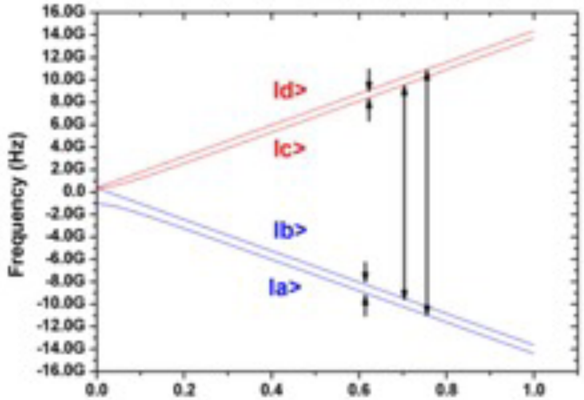
- Working on design of next-generation device (laser and microwave spectroscopy) for 2012 run – ALPHA 2

- CERN will close the accelerator chain in 2013 for an indeterminate amount of time

- CERN Research Board recently approved a new project, ELENA, to decelerate further, to 100 keV

ALPHA – present and future

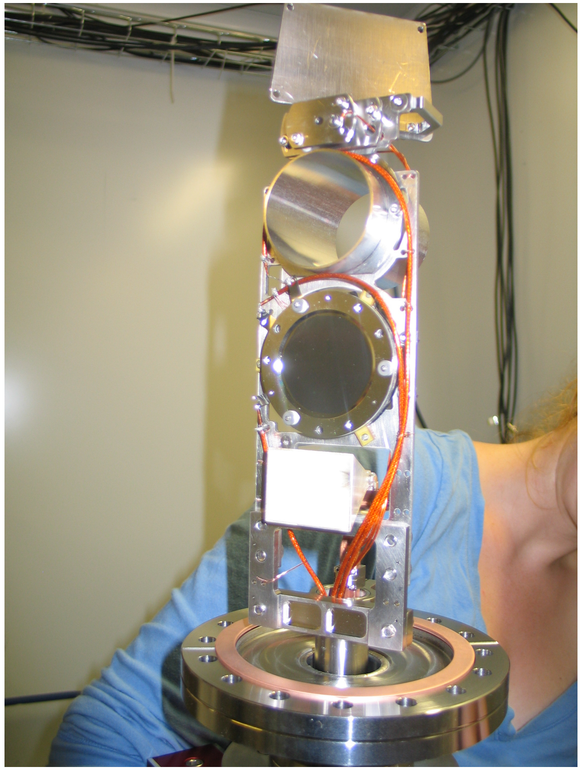
2011 Run



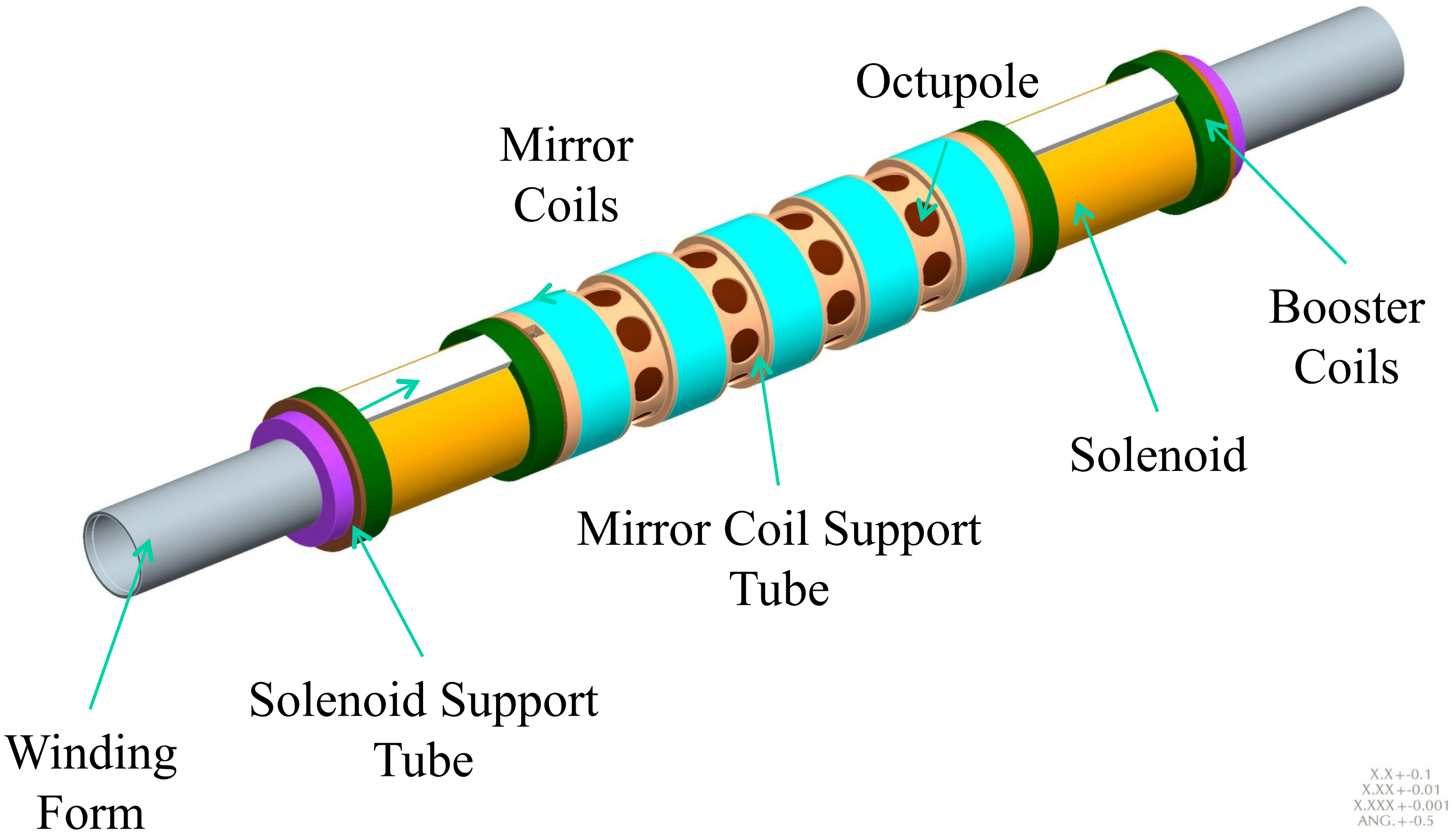
- studies of trapped antihydrogen (rate, plasma parameter dependence, stability, etc.)
- attempt to interact *resonantly* with antihydrogen: positron spin flip driven by microwaves

- 2012 and beyond: a completely new device – ALPHA-2

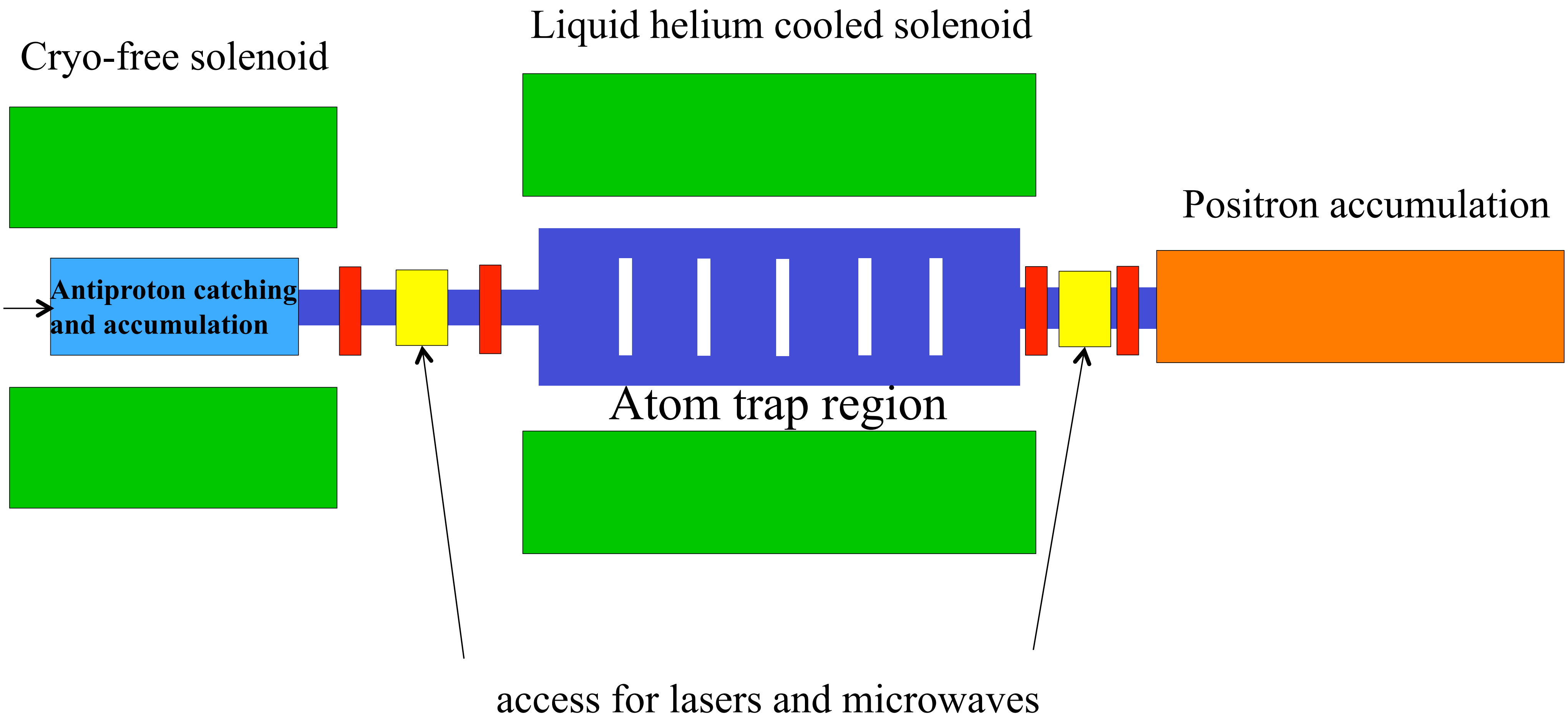
- CERN will close the accelerator chain in 2013 for an indeterminate amount of time
- CERN Research Board recently approved a new project, ELENA, to decelerate further, to 100 keV



The ALPHA-2 Atom Trap



ALPHA-2 : separation of functions



ALPHA-2 Features

•Modular design: separate antiproton catching region from the "atomic physics" section

•Capable of accumulating antiprotons whenever they are available; use them when needed – possible 24 hour operation with pbars even before ELENA

•Could feed two devices – ALPHA-3?; ELENA will only require mods to one section when she arrives

•Magnets again from BNL – octupole, five mirror coils, and two solenoids – in progress

•Utilize LHC HTSC leads to minimize helium usage

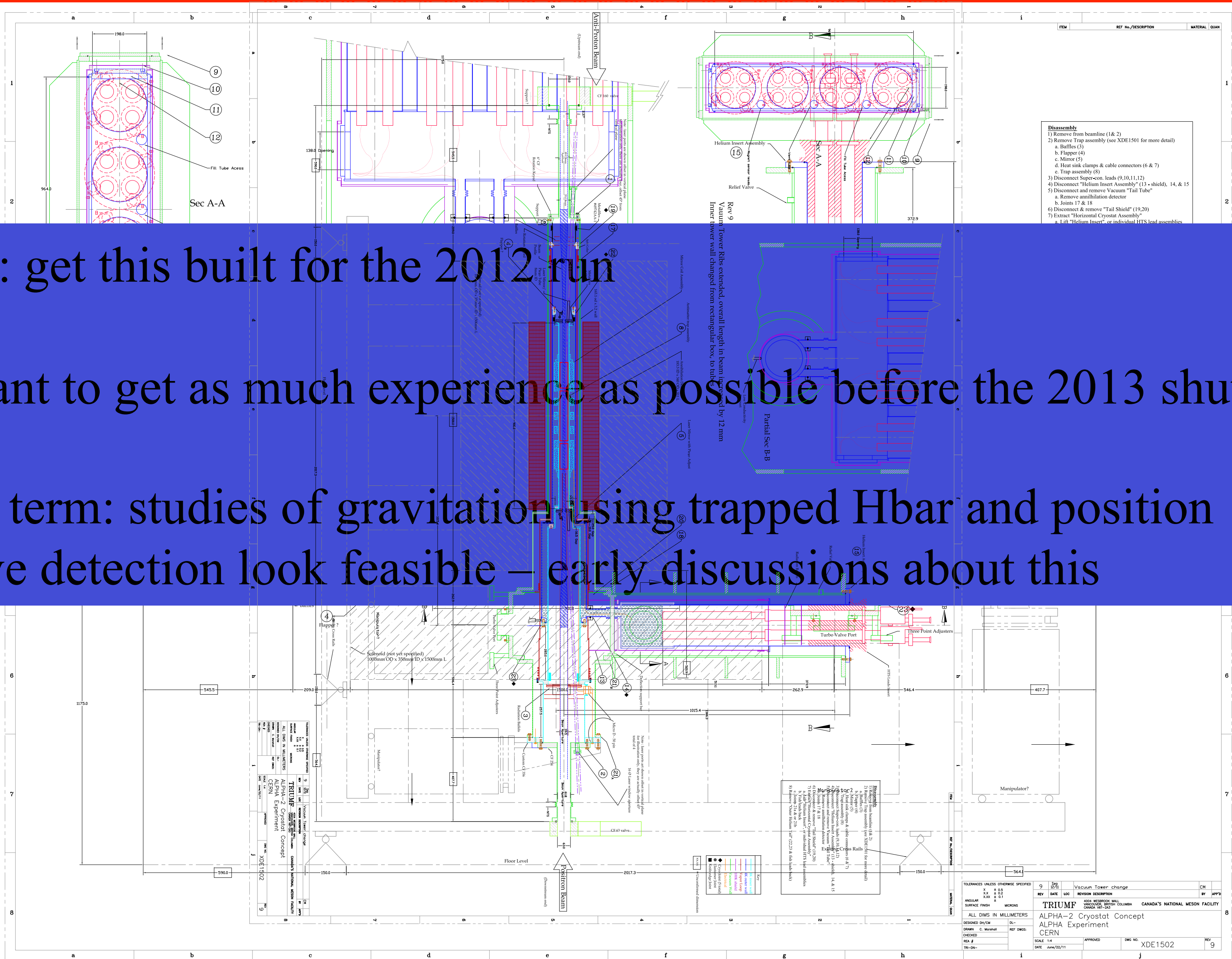
•Multiple mirror coils for Hbar manipulation, field tailoring

•Access for multiple lasers; buildup cavity *in vacuo*

•Rapid charging solenoid for microwave experiments

•New positron source end

•Reconfigured silicon detector; added scintillator layer, cosmic veto



Timing: get this built for the 2012 run

Important to get as much experience as possible before the 2013 shutdown

Longer term: studies of gravitation using trapped Hbar and position sensitive detection look feasible – early discussions about this

Antihydrogen Physics Summary

•More than 20 years of effort – no physics yet…

•Trapped neutral antimatter in 2010 – lots of fun, great relief

•First precision spectroscopy of antihydrogen in ~ 5 years

•I have been telling funding agencies this for ~ 15 years

•One front-page story in the *New York Times*, one best-selling novel, one hit movie (what's the impact factor?), physics story of the year twice (various outlets); live on *Al Jazeera*…; cover of *Nature Physics*

•No matter what Dan Brown, Hollywood (or CERN, or Fermilab, etc.) may tell you, the trapped antimatter at CERN is at the Antiproton Decelerator, and has *nothing at all* to do with the LHC