Detection of trapped antihydrogen in ALPHA

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UNIVERSITY OF CALGARY

NSERC CRSNG

ALBERTA INGENUITY FUND

Les Fiducies Killam Trusts

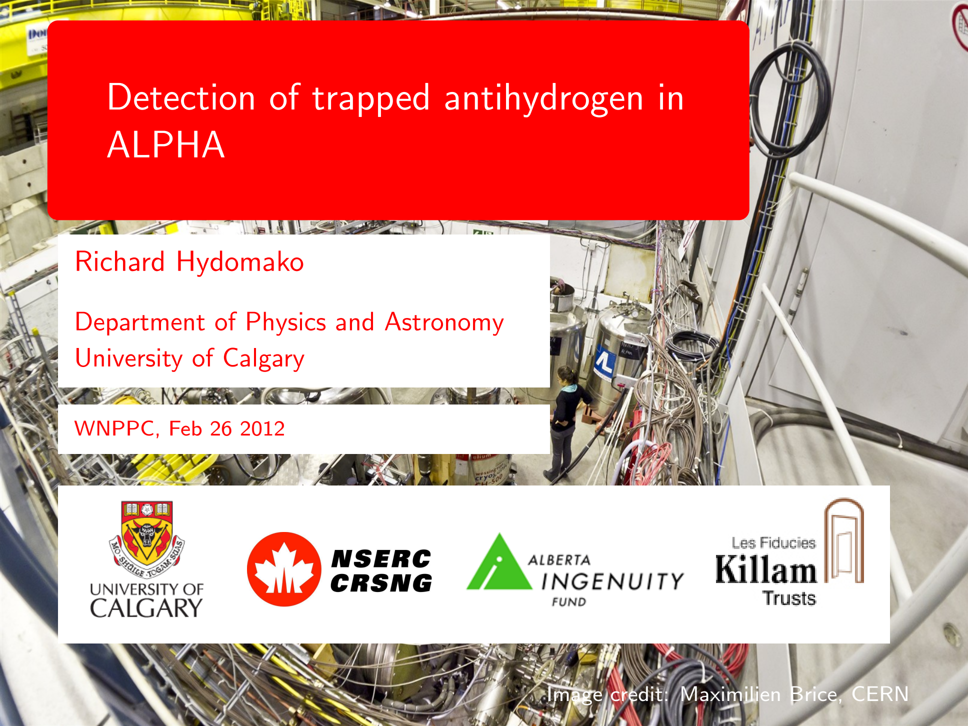
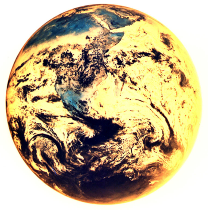


Image credit: Maximilien Brice, CERN

Physics motivation for antihydrogen

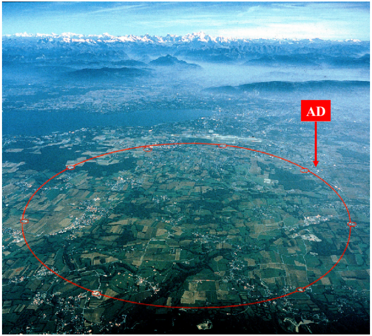
Comparison of matter and antimatter:

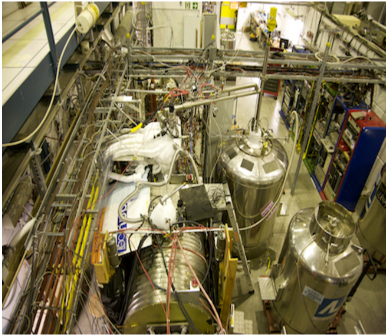
$\overset{?}{\Longleftrightarrow}$



- Antihydrogen is the simplest antiatomic system
- The comparison of antihydrogen to hydrogen is a stringent CPT test
  - $1S$ - $2S$ transition in atomic hydrogen is known to parts in 10^{14}
- Gravitational interaction measurements

The ALPHA experiment





- ALPHA is an international experimental effort (located at the Antiproton decelerator at CERN) to produce, trap, and perform precision measurements on antihydrogen

The ALPHA collaboration

University of Aarhus	G. B. Andersen, P. D. Bowe, J. S. Hangst
Auburn University	F. Robicheaux
University of British Columbia	A. Gutierrez, W. N. Hardy, S. Seif el Nasr
University of California, Berkeley	M. Baquero-Ruiz, S. Chapman, J. Fajans, A. Povilus, J. S. Wurtele
University of Calgary	T. Friesen, R. Hydomako, R. I. Thompson
CERN	E. Butler
University of Liverpool	P. Nolan, P. Pusa
Nuclear Research Center, 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
Stockholm University	S. Jonsell
Swansea University	W. Bertsche, M. Charlton, S. Eriksson, A. Humphries, L. V. Jørgensen, N. Madsen, D. P. van der Werf
University of Tokyo	R. Hayano
TRIUMF	M. C. Fujiwara, D. R. Gill, L. Kurchaninov, K. Olchanski, A. Olin, J. W. Storey
York University	C. Amole, S. Menary

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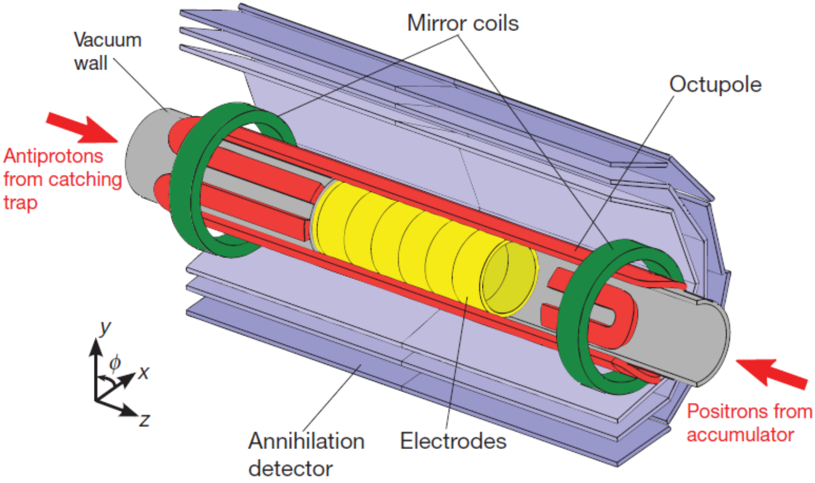
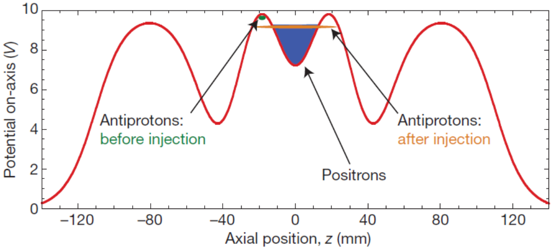
HARVARD
SFU
RADIATION

The ALPHA apparatus



Antihydrogen formation



- Positrons and antiprotons are mixed together to form antihydrogen
- Antiprotons are excited into the positron plasma autoresonantly (axial frequency locked to rf drive)
- The resulting neutral antiatom is no longer confined by the Penning trap fields

Trapping experiment

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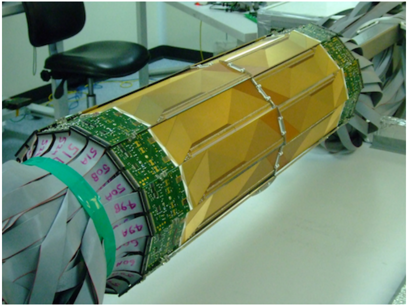
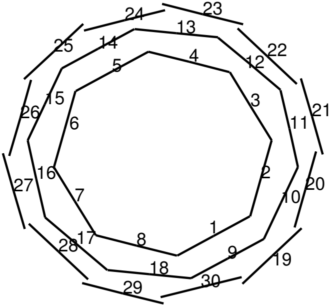
7. Look for annihilations in the silicon detector during, and immediately after, the magnet rampdown

Silicon detector



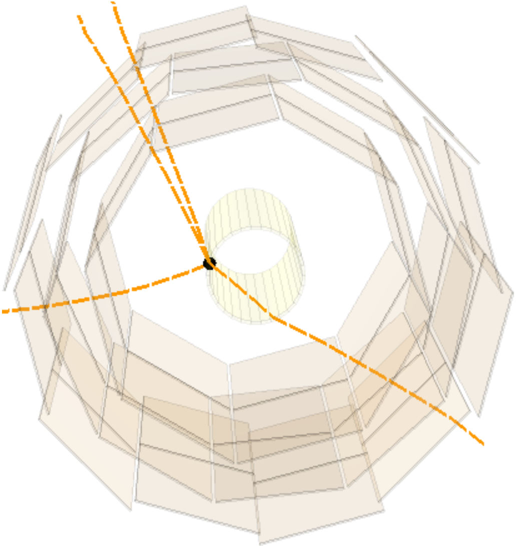
(a) At University of Liverpool



(b) Module arrangement

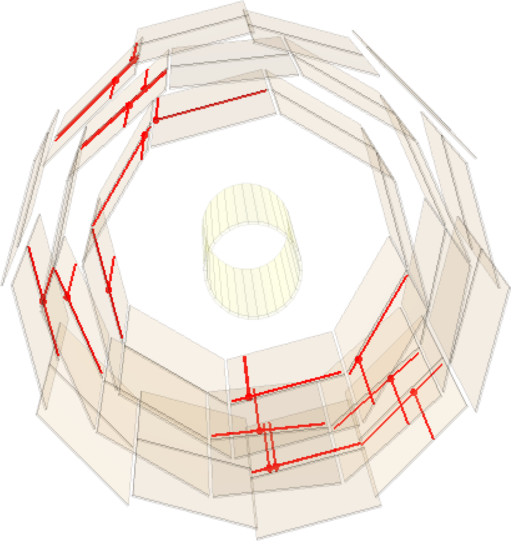
- 60 double-sided silicon microstrip detector modules, arranged in three concentric layers
- 30 720 strips with pitch widths of 875 μm in the $\hat{z}$ direction, and 227 μm in the $\hat{\phi}$ direction

Event reconstruction in the ALPHA detector



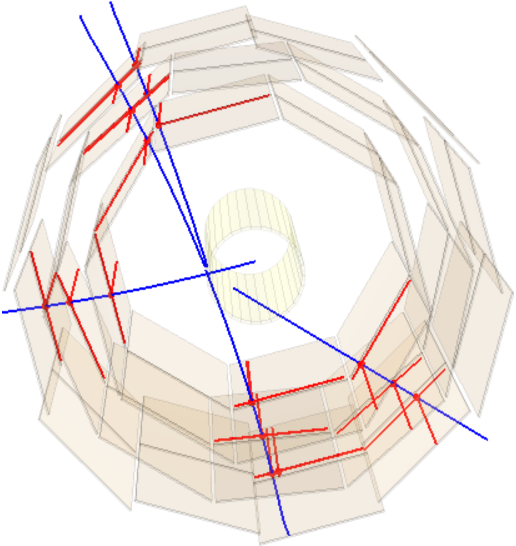
- Example Monte Carlo event
- Annihilation on the electrode surface produces several charged pions

Event reconstruction in the ALPHA detector



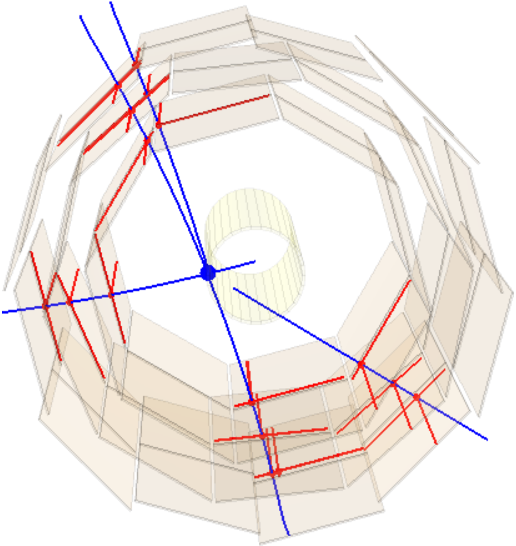
- The detector modules record energy deposition within the silicon wafers (in this case, by the passage of charged pions)
- Orthogonal signal strips give the hit positions in the plane of the silicon module

Event reconstruction in the ALPHA detector



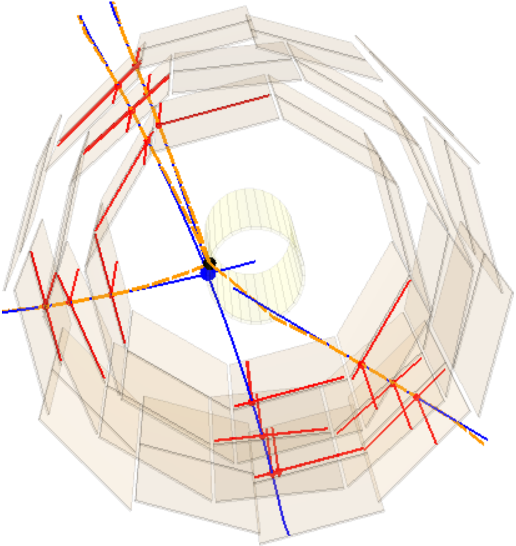
- The charged particle tracks can be identified and extrapolated back into the apparatus
- Tracks are modeled as helices in an uniform magnetic field

Event reconstruction in the ALPHA detector



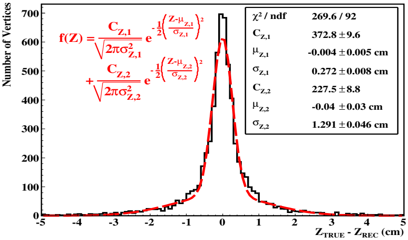
- The annihilation vertex is determined as the point where the tracks converge

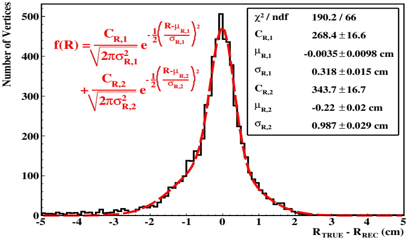
Event reconstruction in the ALPHA detector



- The performance of the reconstruction algorithms can be evaluated using prior knowledge from the Monte Carlo simulation

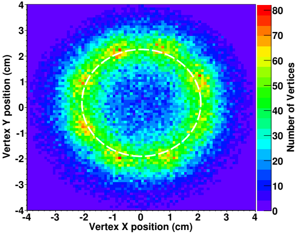
Reconstructed vertex resolution





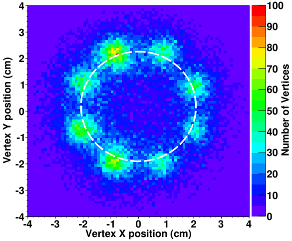
- The vertex position resolution can be estimated using the Monte Carlo simulation
- Broadening dominated by multiple scattering
- Example estimates from Monte Carlo:
  - Axial resolution (top): (0.67 ± 0.04) cm
  - Radial resolution (bottom): (0.68 ± 0.02) cm

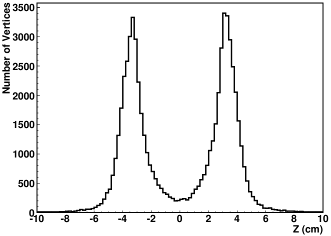
Annihilation imaging



Vertex distributions provide information about the physics

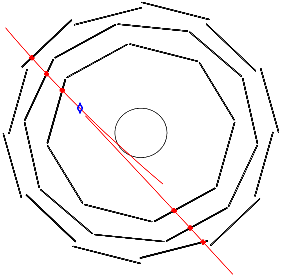
- Top left: Antihydrogen formation in the neutral-atom traop
- Bottom right/left: Antiproton annihilation in the octupole magnetic field



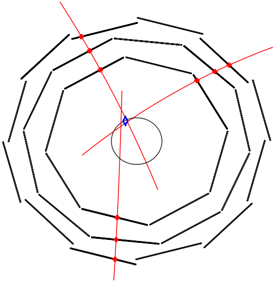


Cosmic ray background

- Cosmic muons can leave tracks through the detector (top right)
- Unsuppressed rate of ~ 10 event/s
- Need to discriminate between signal and background events, especially for the detection of rare events
- Focused on the topological differences between cosmic and annihilation events

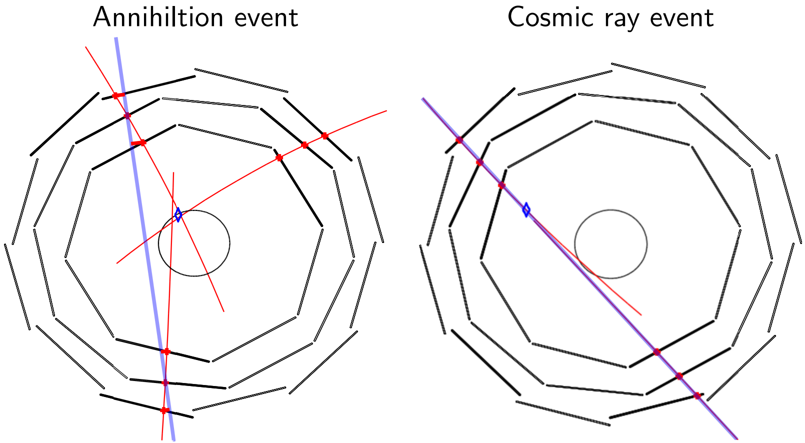


(c) Example cosmic event



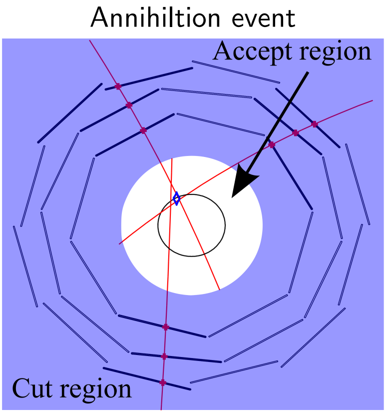
(d) Example annihilation

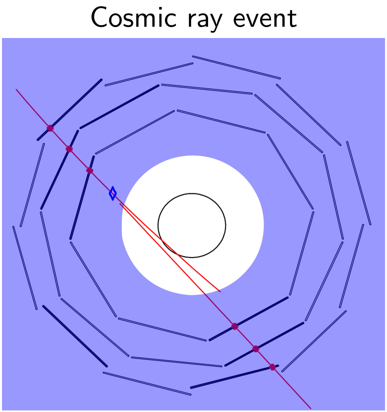
Discriminating variable (linear residual, δ)



- Cosmic events will conform to a straight line fit
- Slight curvature in the strong axial magnetic field

Discriminating variable (vertex radius, R)



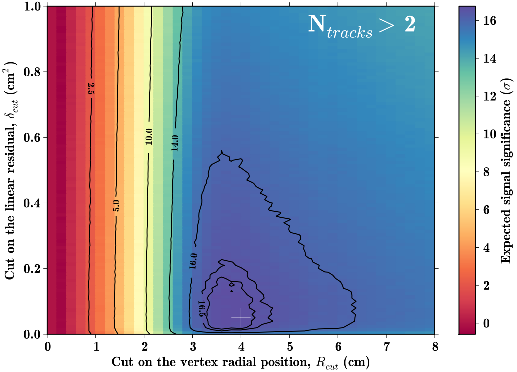


- Cosmic events are unconstrained in radius, while annihilations occur withing the trap region of the apparatus

Background rejection analysis

- Analysis focused on detecting rare events during the trapping experiments
- Studies performed on auxiliary datasets to avoid optimizing on the trapping events (blind analysis):
  - Signal: antihydrogen annihilation during mixing
  - Background: apparatus operating without antiparticles
- Find cuts that optimize the expected signal

Cut optimization



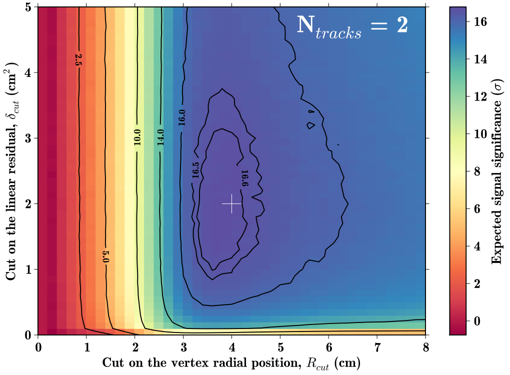
- Performed 5000 pseudoexperiments for each cut configuration
- Figure of merit, the expected p-value:

$$\alpha = \sum_{n=n_0}^{\infty} \frac{b^n e^{-b}}{n!},$$

n_0: expected number of events

b: background rate

Cut optimization



- $N_{tracks} = 2$ events are considered separately
- White crosses indicate the cut choices

Cosmic background rejection results

N_{tracks}	Vertex radius, R_{cut} (cm)	Linear residual, δ_{cut} (cm^2)
$= 2$	< 4	> 2
> 2	< 4	> 0.05

Table: Final background rejection cuts. Events that satisfy these conditions are accepted as signal.

- Results of the cut optimization:
  - $(99.55 \pm 0.02)\%$ cosmic background rejection
  - $(64.4 \pm 0.1)\%$ signal acceptance
  - $(47 \pm 2) \times 10^{-3}$ event/s background acceptance rate

Summary of 2010 experiments

Type	Number of cycles	Vertices passing all cuts
Normal trapping experiments	335	48
Heated positron plasma	246	1

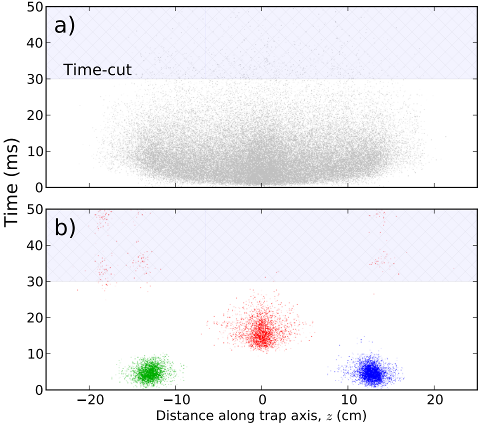
- For readouts less than 30 ms after neutral-trap magnets shutdown

Summary of 2010 experiments

Type	Number of cycles	Vertices passing all cuts
No bias	137	20
Left bias	101	14
Right bias	97	14
No bias, heated positrons	132	1
Left bias, heated positrons	60	0
Right bias, heated positrons	54	0

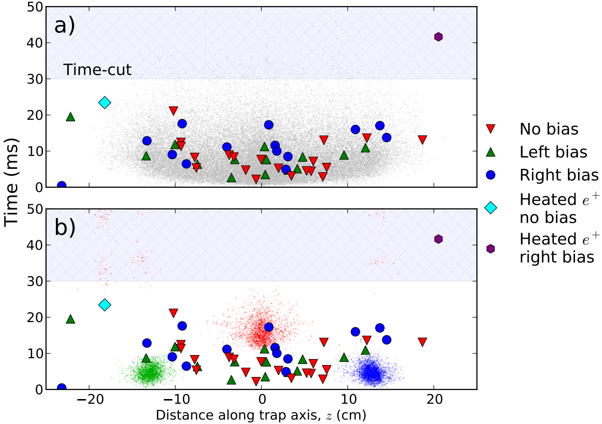
- For readouts less than 30 ms after neutral-trap magnets shutdown

Experimental observation of trapped antihydrogen



a) Simulated antihydrogen signal in grey
b) Coloured dots are simulated bare antiprotons

Experimental observation of trapped antihydrogen



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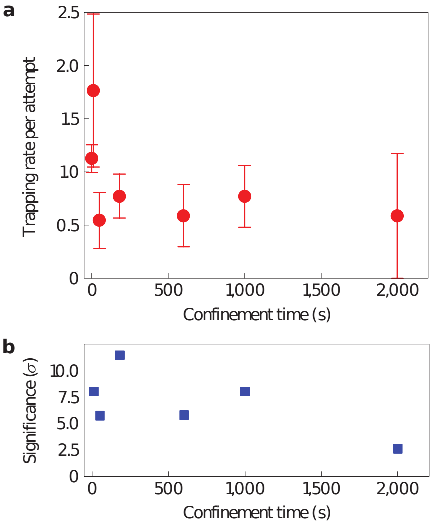
Extended confinement



- Neutral trap engaged for longer
- Trapped atoms for up to 1000 s (low significance at 2000 s)
- More than enough time for the antihydrogen atom to radiate to the ground state

What's next for ALPHA

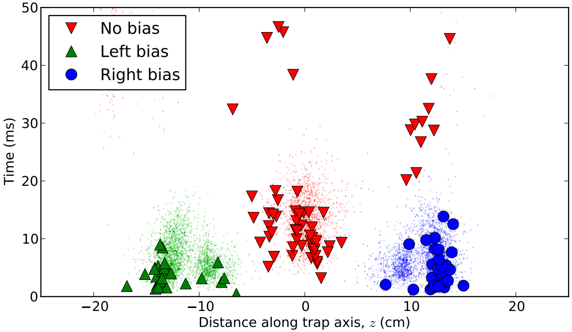
- 2011 Run: introduced microwaves into the apparatus
- Currently: a new apparatus with laser access is being constructed

Conclusion

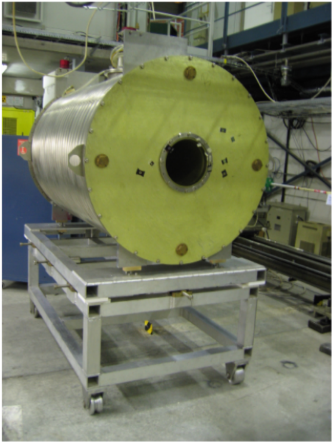
- ALPHA has successfully demonstrated the magnetic confinement of antihydrogen for as long as 1000 s
- The silicon detector and annihilation reconstruction routines played a large role in this effort
- The cosmic background rejection analysis enabled a sensitive identification of annihilation events
- The position-sensitive reconstruction allowed for discrimination against mirror-trapped antiprotons and cosmic-ray muons
- Long-time magnetic confinement of antihydrogen atoms will allow for precision studies of this anti-atomic system

Backup slides

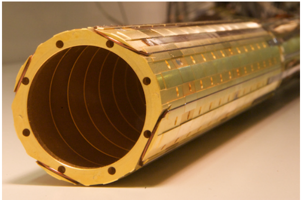
Intentially mirror-trapped antiprotons



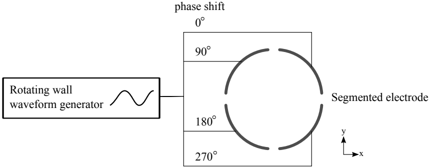
Penning-Malmberg trap for charged particles/plasmas

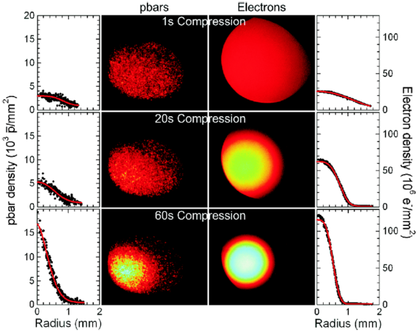


- Strong external solenoidal magnetic field for radial confinement
- Electric potential for axial confinement and manipulation
- Provides excellent confinement of non-neutral plasmas



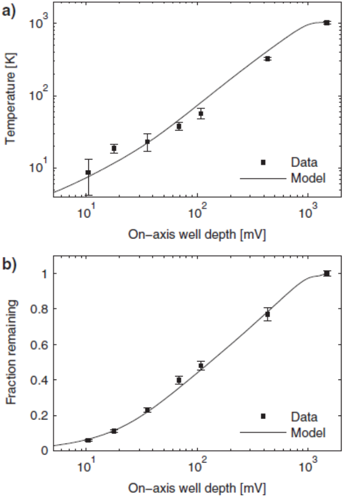
Radial compression using the Rotating Wall technique





- Rotating electric field applies a torque to the rotating plasma
- The mean-squared plasma radius is related the canonical angular momentum (e. g. electron plasma): $P_\theta = (-eB/2c)\left\langle r^2 \right\rangle$
- An applied torque $\mathcal{T} = dP_\theta/dt$ can then be used to increase or decrease the plasma radius
- The rotating wall is typically driven as a dipole with 0.5-2.5 V, 0.5-20 MHz, with optional sweeping frequency

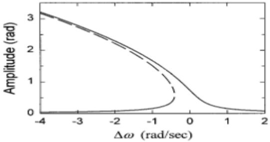
Evaporative cooling of charged plasmas



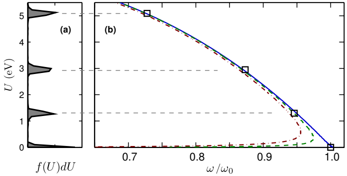
- Demonstrated evaporative cooling of antiprotons to temperatures as low as 9 K
- Energetic particles escape as the confining potential is lowered, leaving the remaining particles at a lower temperature
- Also can be applied to the positrons plasma, resulting in a positron temperature of about 40 K

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

Autoresonant excitation of the antiproton plasma



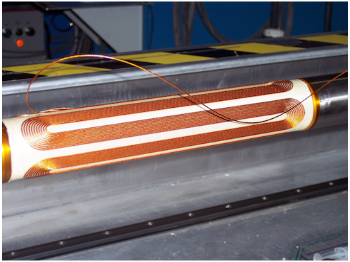
Response of a driven nonlinear oscillator (J. Fajans and L. Friedland, *Am. J. Phys.* **69**, 1096 (2001))



Response of a driven antiproton plasma

- The electrostatic confining wells we use have anharmonic components
- The oscillation amplitude (parallel energy) is a function of the bounce frequency
- Equation of motion: $\ddot{\theta} + \omega_0^2 \sin\theta = \bar{\epsilon}\cos(\omega_i t - \alpha t^2/2)$
- A drive with a decreasing frequency can result in an increase in the oscillation amplitude
- Typical drive: 200 μs, 55 mV, 350-200 kHz

Magnetic neutral-atom trap



- Antihydrogen has a small magnetic moment, which interacts with the field, $U = -\vec{\mu} \cdot \vec{B}$
- The ALPHA neutral trap consists of a superconducting octupole (left) for the radially increasing field, and two mirror coils for the axial field
- Shallow trap depth: ~ 0.5 K