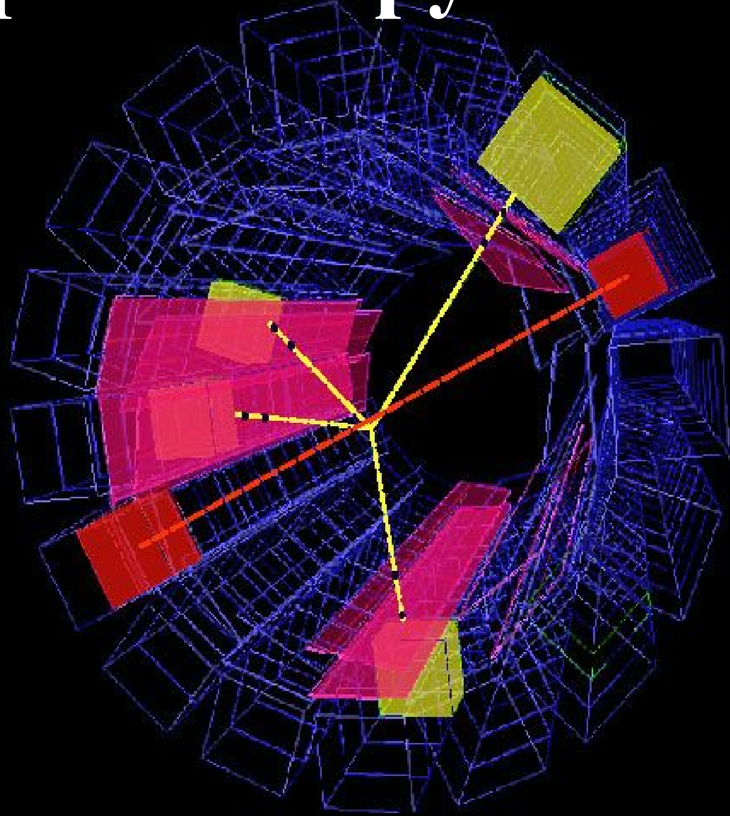
From ATHENA to ALPHA: Towards trapping and spectroscopy of antihydrogen atoms



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for Particle and Nuclear Physics

μCF-07

June 18-21, 2007, Dubna, Russia

Motivations

CPT Symmetry

Gravity

Cosmology

Cold Antihydrogen

Nuclear Particle

Atomic

Plasma

Laser

MC/Software

Cryogenics

Traps

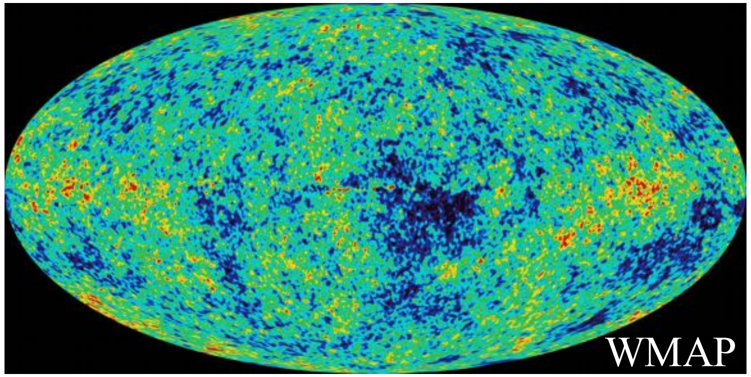
Detectors

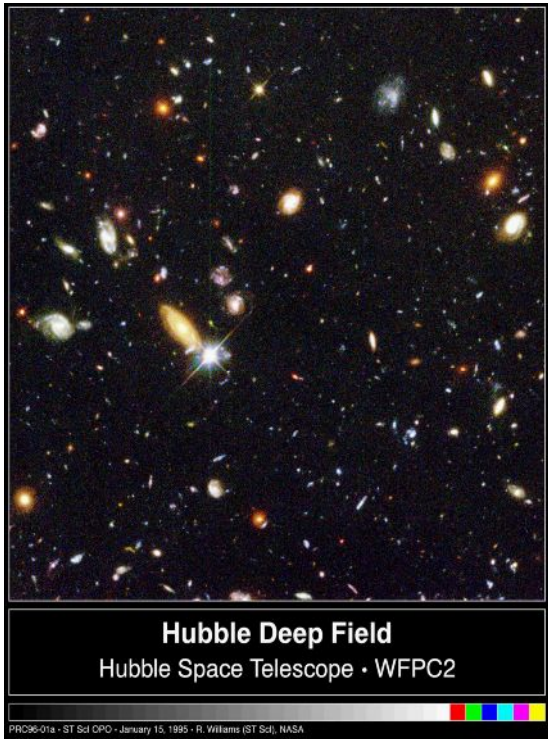
Muonic Hydrogen vs Antihydrogen

- Energy scales
  - keV vs. ***eV***
  - Standard atomic experimental techniques applicable
- Detection
  - Decay, fusion, X-rays vs. ***Annihilation***
    - Pbar → several pions
    - e+ → 2 x 511 keV gamma
  - 3D imaging possible!
- Lifetime
  - 2 μs vs. ***Infinite***
  - Pbar cooling in AD (100 sec), in trap (10 sec)
  - Pbar (Hbars) can be trapped for days for precision studies
- Theory
  - Armour, Froelich, etc.

Where is Antimatter?

- Baryon Asymmetry in Universe (Matter-antimatter asymmetry)
- No evidence for antimatter in Universe





Cosmology, Gravity

- Baryogenesis
  - Sakharov's conditions involving CP violation
  - Baryogenesis via CPT violation (e.g. Zeldovich)

Cosmology, Gravity

- Baryogenesis
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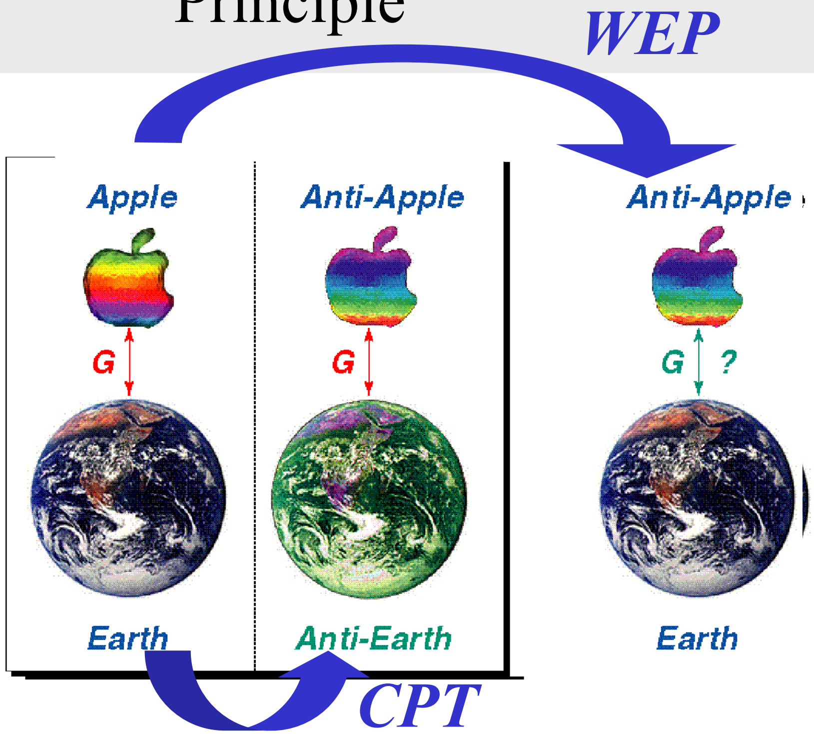
- Gravity
  - Never measured with antimatter
  - Test of Weak Equivalence Principle



Fundamental Symmetries with Antihydrogen

- CPT invariance
  - Foundation of Field Theory
  - Valid in Strings, Planck scale?
  - Precision comparison with hydrogen: competitive with other tests, e.g. neutral kaons

Possible CPT violation scale

$$\text{if } L = L_{SM} + L_{CPTV}$$

$$\text{where } L_{CPTV} \sim \frac{m^2}{\Lambda_{CPTV}} O$$

$$\text{for } m = 1\,\text{GeV}, \ \Lambda_{CPTV} = M_{pl} \approx 10^{19}\,\text{GeV}$$

$$E_{CPTV} \approx 10^{-19}\,\text{GeV}$$

In frequency, this is E_{CPTV} ~10 kHz

Hänsch: Δf~1 kHz with 10^3 trapped Hbars

→ reaching Planck Scale sensitivity !

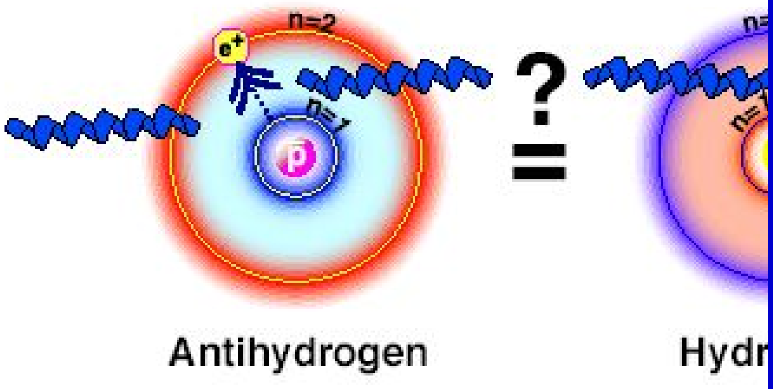
→ improve e^+ mass, charge by 10000

Neutral K: $\Delta(m_K - m_{Kbar}) \sim 100$ kHz

See also: Kobayashi, Sanda, PRL 69, 3139 (1992)

Antihydrogen Spectroscopy

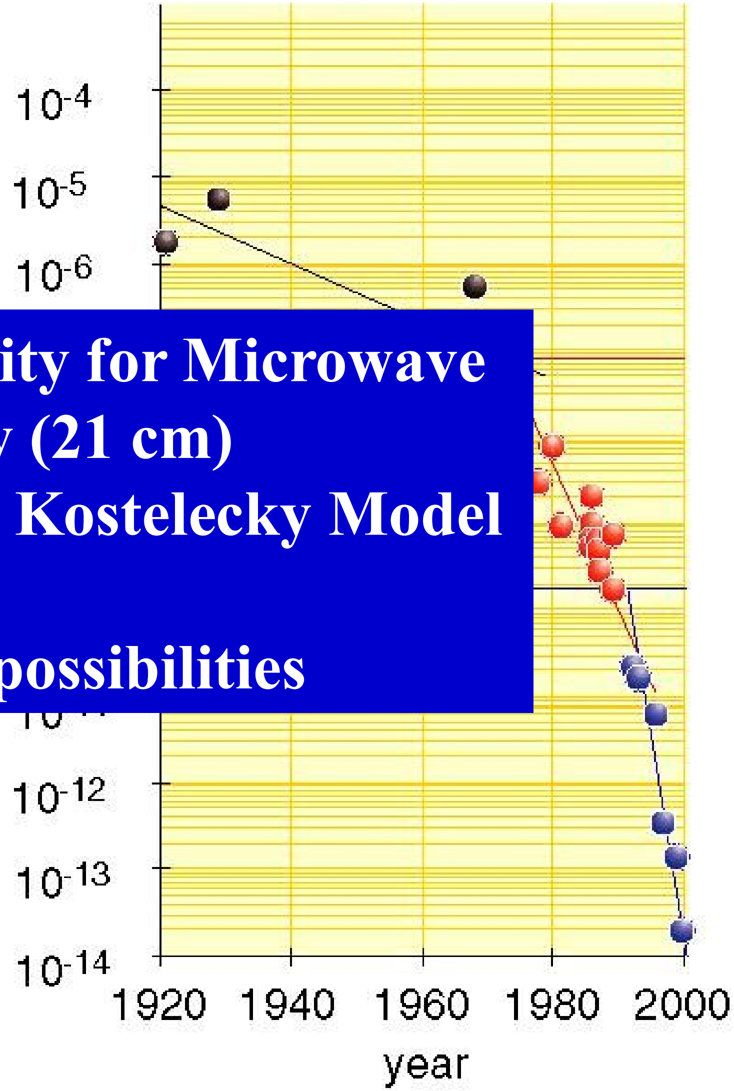
1s-2s two-photon spectroscopy



Also Possibility for Microwave Spectroscopy (21 cm)
Favoured by Kostelecky Model

Many other possibilities

“Hänsch Plot”



- **Doppler effect cancels**
- **High precision in matter sector**

Cold Antimatter: Opening Up New Possibilities

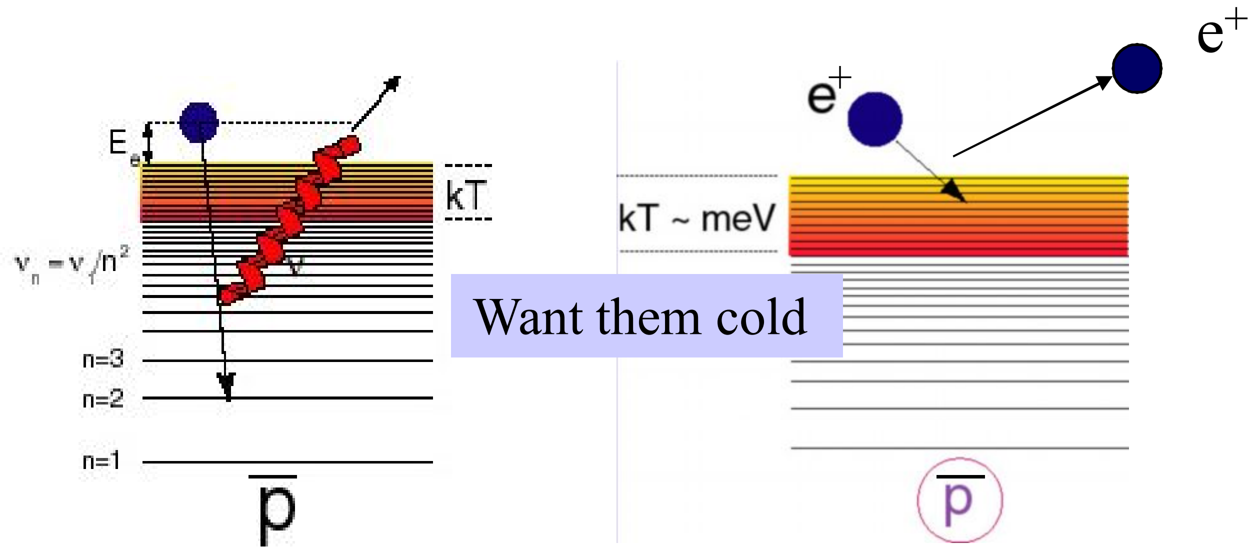
- Other spectroscopic measurements
  - e.g. Lamb Shift
- Charge neutrality of antimatter
  - No explanation in SM (except anomaly cancellation)
  - Indirect limit ~ 10^{-8}
- Hydrogen-antihydrogen collisions
  - Interactions at antimatter “domain”?
- Antimatter Matter (bulk):
  - Ions, Ion Crystals, Molecules, BEC?
- Gravity measurements
  - Probably need laser cooling of antihydrogen (121 nm)
- <u>Most Important: “Not yet thought of”s</u>

Some Basics

Antihydrogen formation process

How we trap antiparticles

Antihydrogen formation processes

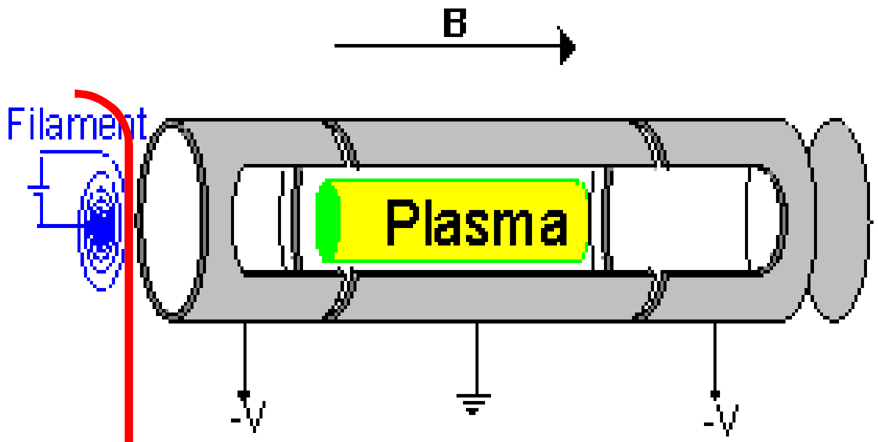


Energy-momentum conservation requires 3rd body

	Radiative	Three-body
Cross-section [cm^2]	10^{-16} (1 K)	10^{-7} (1 K)
Temp dependence	**$T^{-0.5}$**	**$T^{-4.5}$ → stabilization**
Final quantum state	n < 10	n >> 100
Stability (re-ionization)	high	low
Expected rates	<50s Hz	???

Trapping Antiparticles

- (Anti)particle traps: suspend in vacuum
  - Confinement force
  - Loading mechanism
- Charged antiparticles (pbar, e+, e-)
  - Penning trap
  - B and E field
  - Depth up to keV
- Neutral (anti)hydrogen atoms
  - Magnetic trap
  - B field gradient on magnetic moment
  - Depth ~1K (0.1 meV): need cold atoms
- Loading
  - Dissipative
  - Dynamical
  - Born to be trapped
- Particle manipulations (moving&shaking): non-trivial!



Challenge:
Combining Charged/Neutral Traps

Production of Cold Antihydrogen

10^{-12}

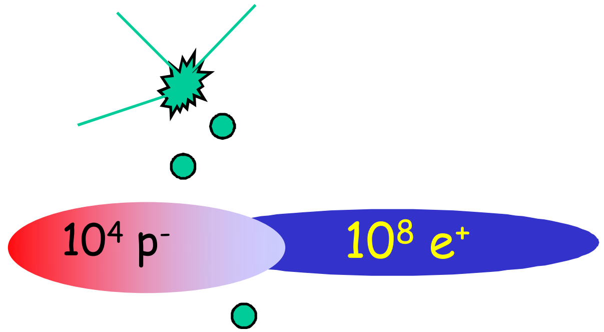
AD

p- Production (GeV)

Deceleration (MeV)

Trapping (keV)

Cooling (~ meV)



Plasma diagnosis/manipulation

p^- and e^+ in mixing trap

Antihydrogen formation

Detection of annihilation

10^{-9}

Na-22

e^+ Production (MeV)

Moderation

Accumulation (eV)

Cooling (~ meV)

Making Cold Antihydrogen with ATHENA

Hot Race for Cold Antihydrogen

Where we were at μCF01 (April, 2001)

- **ATHENA**
  - Pbar catching
  - Electron cooling

- **ATRAP**
  - Pbar catching
  - Electron cooling
  - Stacking
  - Positron
  - Pbar-positron interaction
  - Positron cooling of pbars

Milestones since μCF01

<u>June 2001</u>
Pbar lifetime >10 hours

<u>July 2001</u>
Pbar transfer between traps

<u>Sept 2001</u>
Pbar Vertex Imaging

<u>Dec 2001</u>
25M positrons in 3T

<u>July 2002</u>
First indications

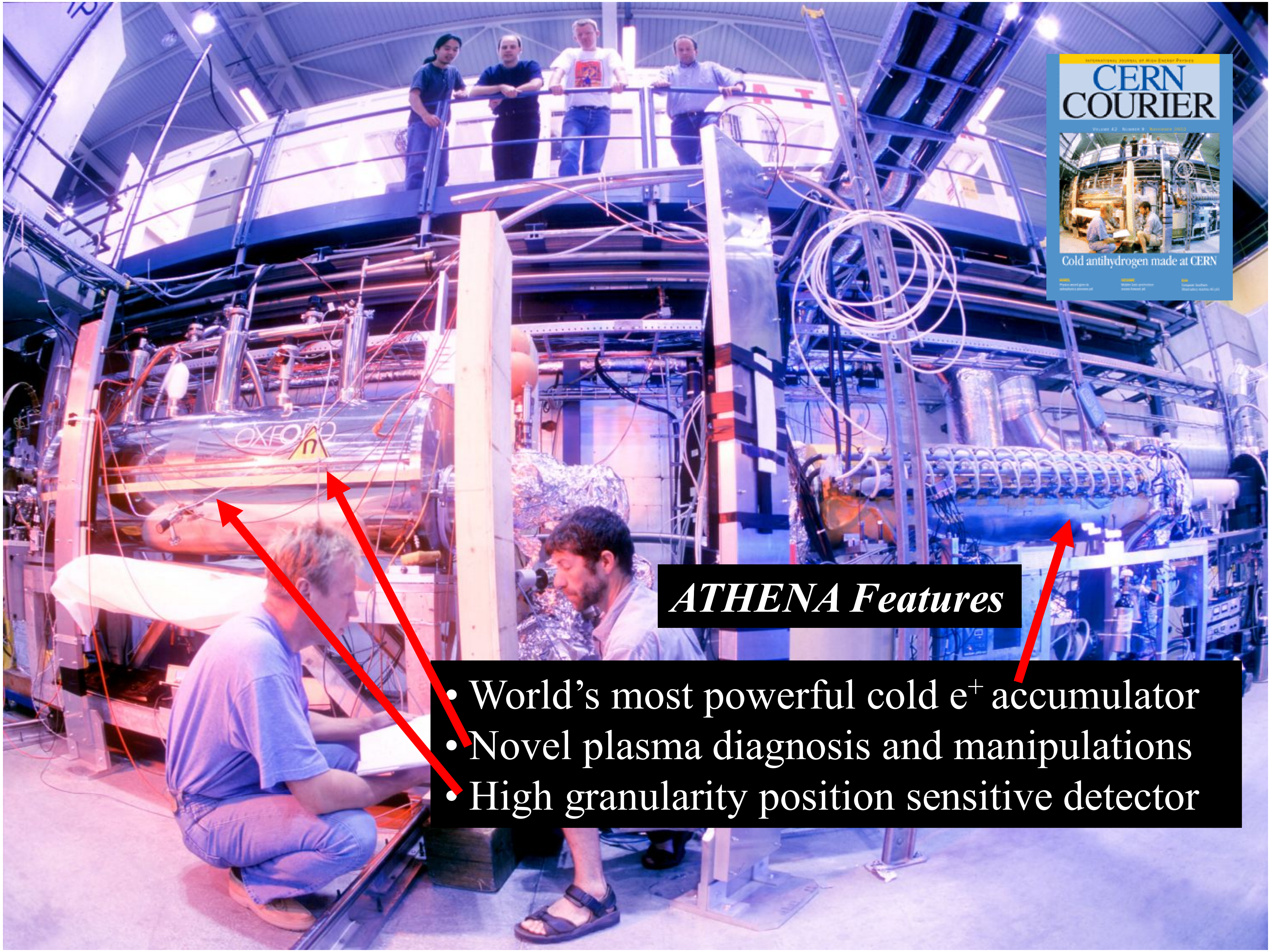
Detailed studies

<u>Aug 27</u>
Hbar paper submitted

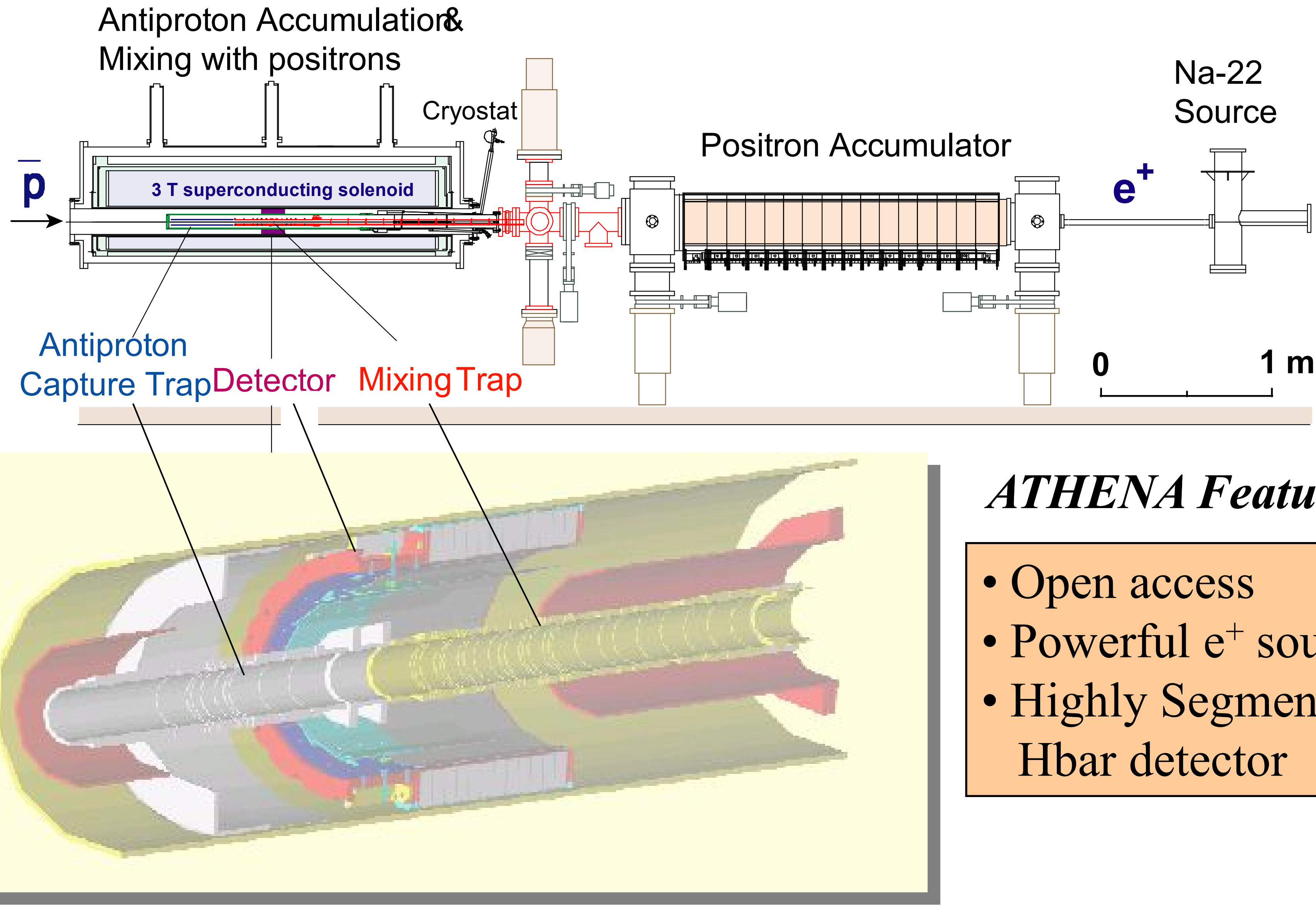
<u>Sep 3</u>
Hbar paper accepted

<u>Sep 18 2002</u>
Published in ***Nature*** on-line

<u>Oct 31</u>
ATRAP published


CERN COURIER
Cold antihydrogen made at CERN
ATHENA Features
• World's most powerful cold e+ accumulator
• Novel plasma diagnosis and manipulations
• High granularity position sensitive detector

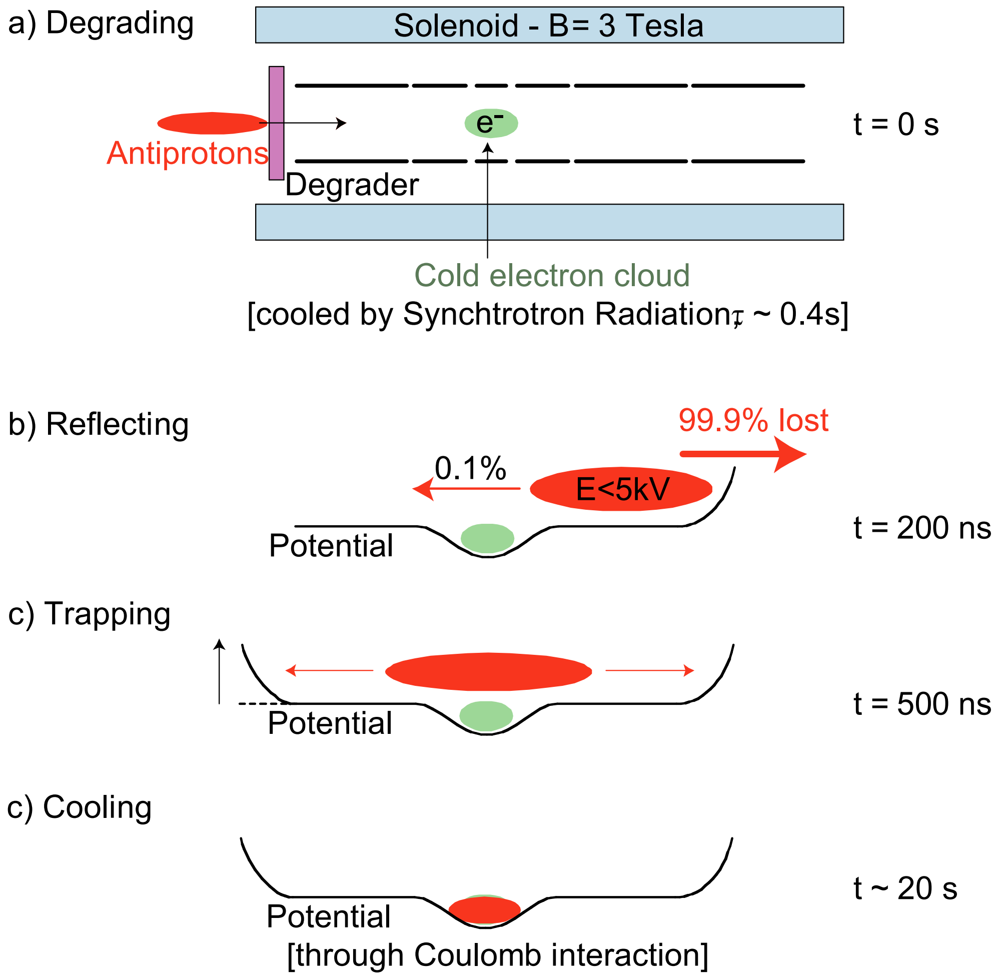
ATHENA Antihydrogen Apparatus



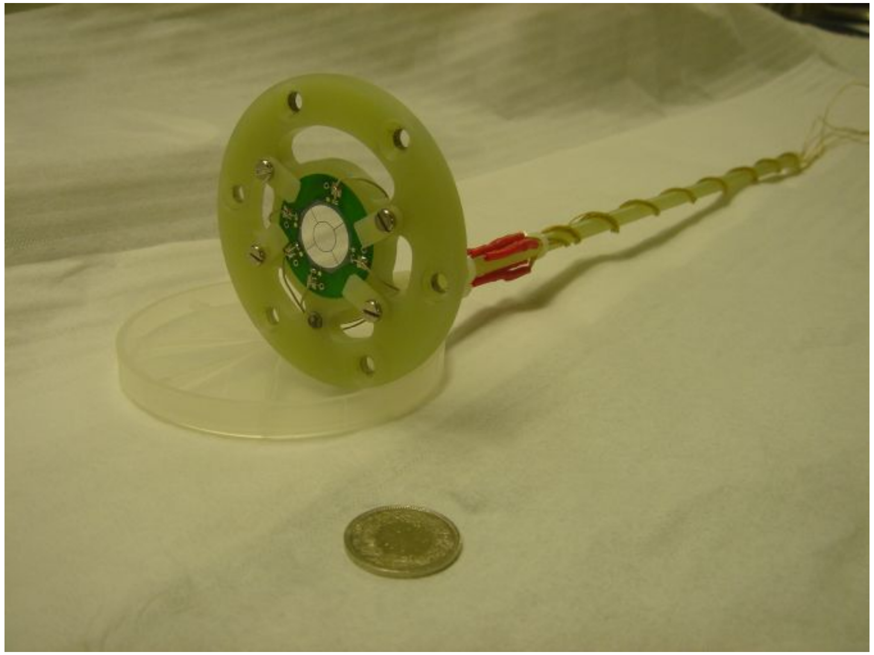
ATHENA Features

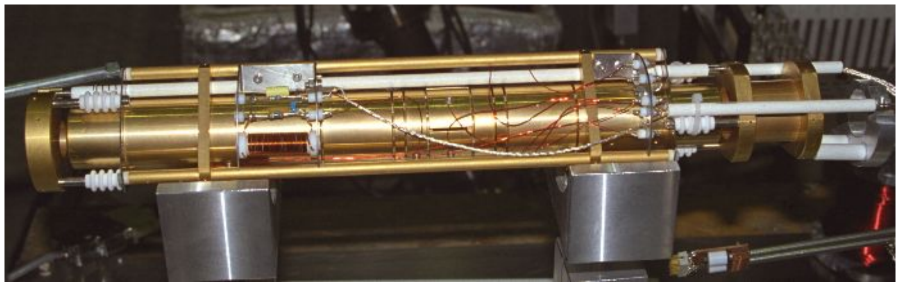
- Open access
- Powerful e^+ source
- Highly Segmented Hbar detector

Antiproton Catching & Cooling



Gabrielse et al. 1986, MCF et al. 2001



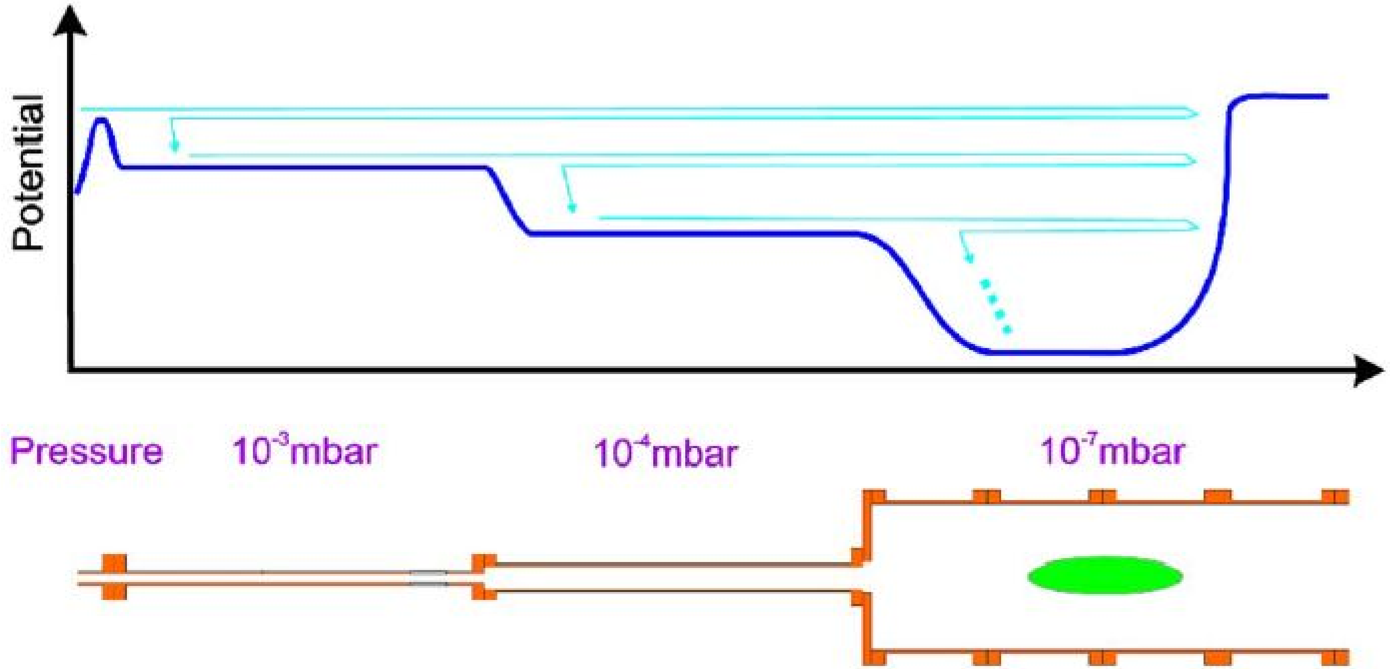


Antiproton Capture Trap

About 10^4 antiprotons captured from an AD shot (every 80 s)

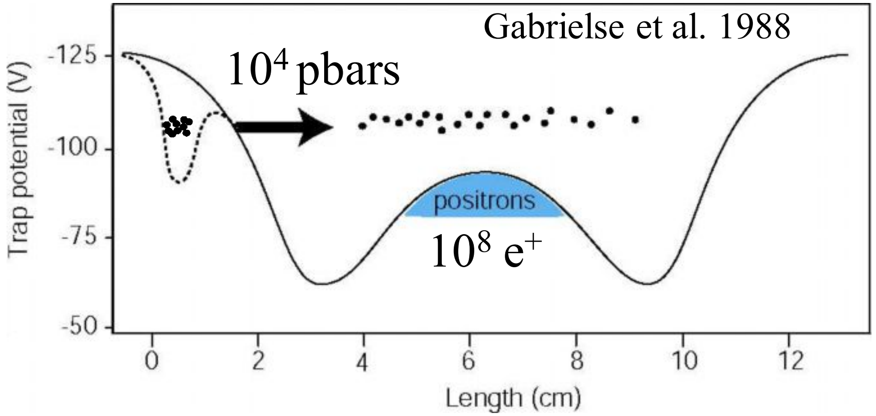
Accumulating Positrons

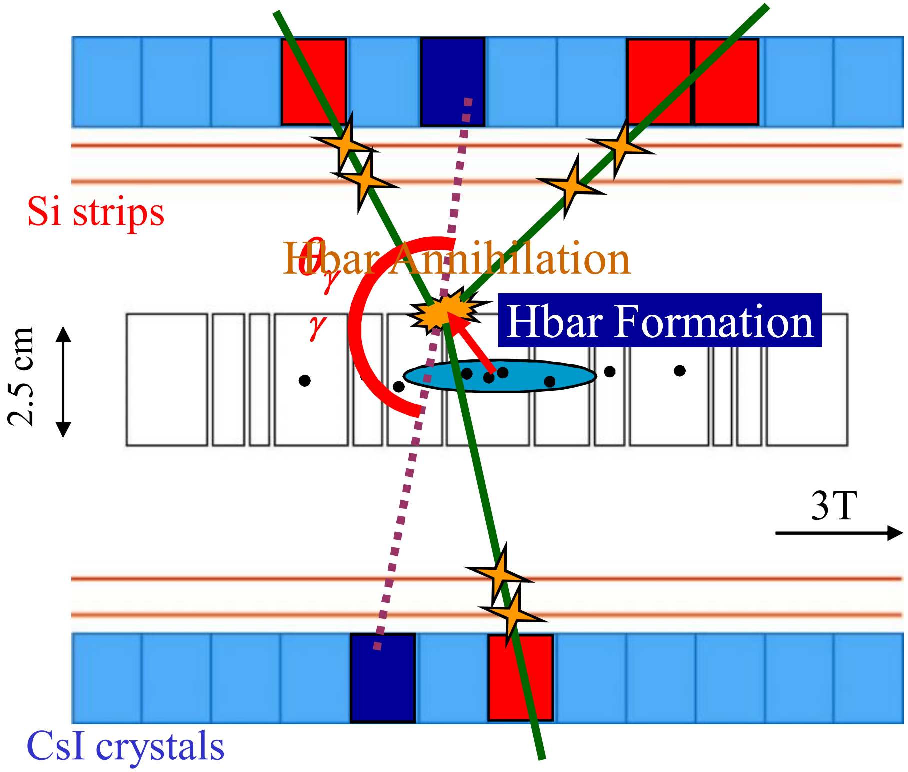
Dissipative trapping with N_2 buffer gas_



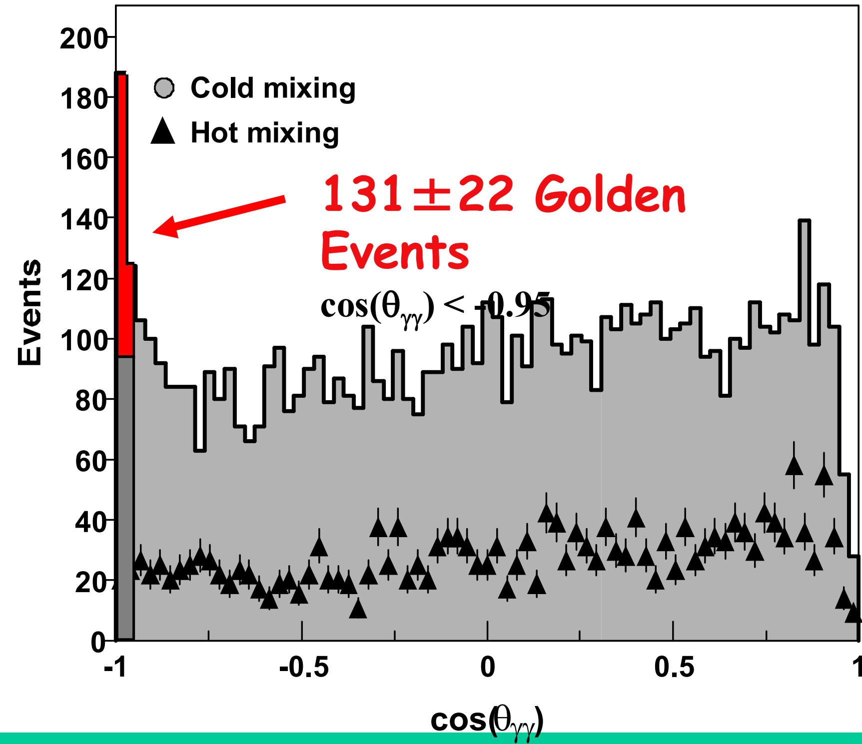
(concept by C. Surko et al., Non-neutral plasmas Vol. 3, 3-12; AIP 1999)

First Cold Antihydrogen — August 2002 *ATHENA*





- 10^4 pbars & 10^8 e^+ mixed for 190 sec
- Hbar forms, annihilates on electrode
- pbar annihilates into charged pions
- e^+ annihilates into back-to-back γs
- $\cos(\theta_{\gamma\gamma})$, opening angle of two 511keV γs, seen from the vertex, is plotted
- Neutral pions give uncorrelated background



First Cold Antihydrogen

***Nature*, September 18, 2002**

advance online publication — letters to nature

TOP SCIENCE NEWS in 2002

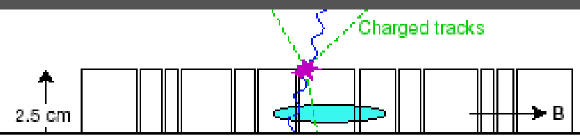
AIP *Physics News Update*
(Top 2 physics stories of the year, with SNO)
IOP *Physics World* (Number 1 Highlight of the year)
Discover Magazine (Top 4 Science News of the year)
Nature (Highlight of the year)
Science (Watch for 2003 or later)
…

60040-531, Brazil
 # Department of Physics, University of Wales Swansea, Swansea SA2 8PP, UK

protons for interaction experiments.

Wired Magazine, Annual Rave Award Nomination
(with Eminem, Spielberg, Hayao Miyazaki et al.)

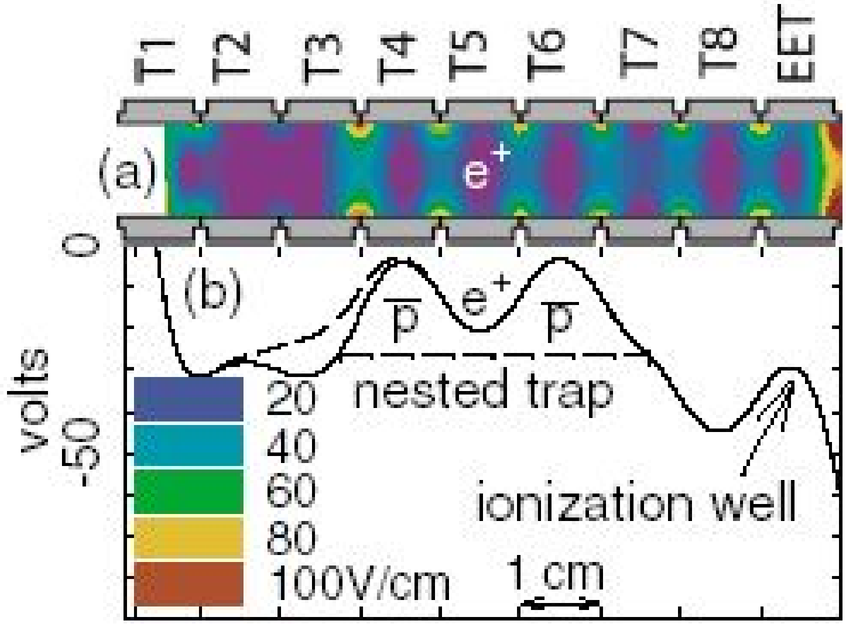
operations of charge conjugation, parity and time reversal. Antimatter, the existence of which was predicted by Dirac, can be used to test the CPT theorem—experimental investigations involving comparisons of particles with antiparticles are numer-



ATRAP corroborates Cold Hbar

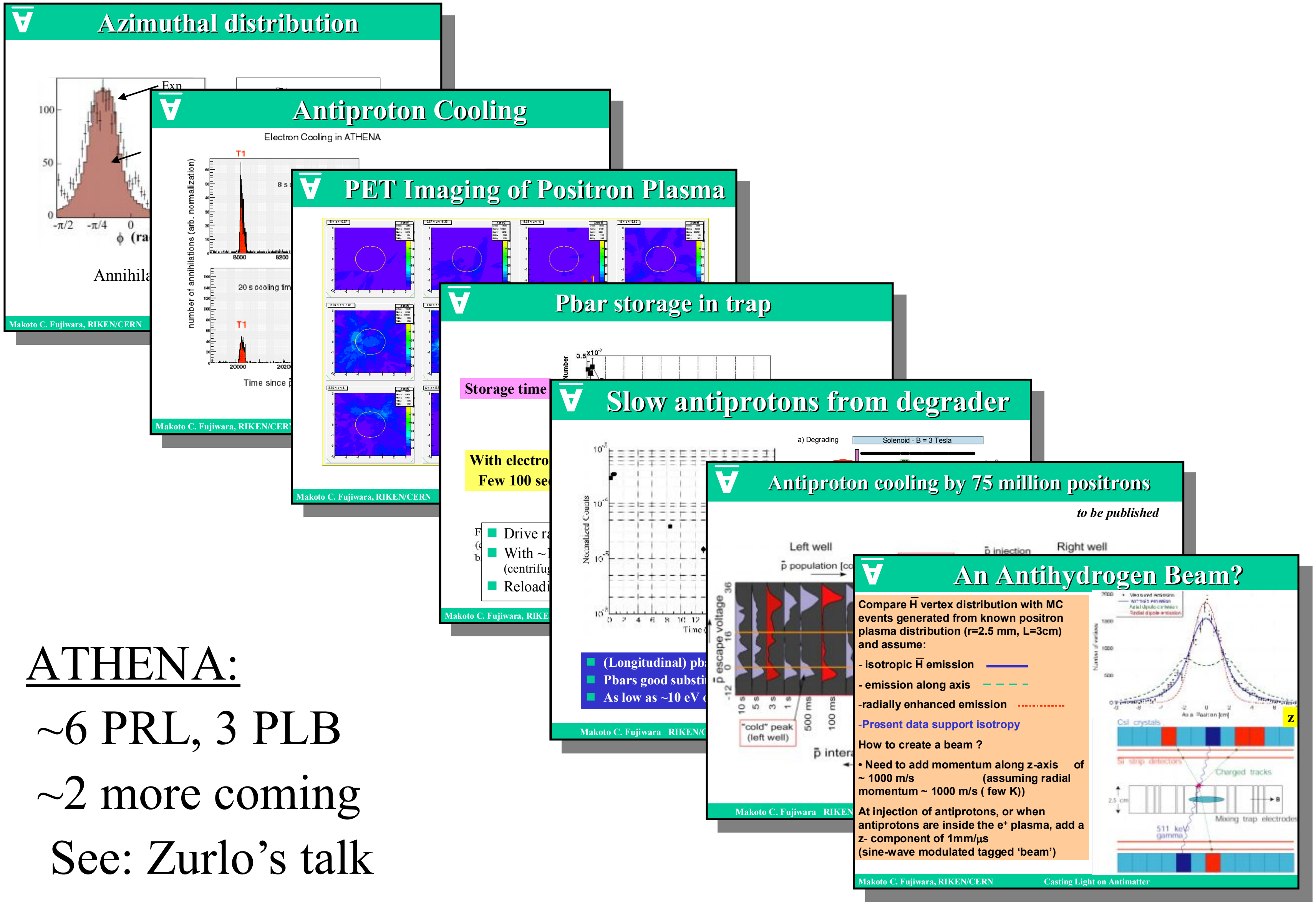
- Challenges
  - No vertex detector, small number of e^+ (~1/600)
- Elegant detection:

  Field ionization of loosely bound Hbars
  - no e+ detected
  - *n* measurements
- Velocity Measurements
- Double Charge Exchange



ATRAP, PRL **89** 233401; **90** 043001 (2002)

Physics with Pbars, Positrons, Hbars



ATHENA:

~6 PRL, 3 PLB

~2 more coming

See: Zurlo's talk

Selected ATHNEA papers since 2002

Production and Detection of Cold Antihydrogen Atoms
Nature **419**, 456 (2002)

Positron Plasma Diagnostic and Temperature Control for Antihydrogen Production
Phys. Rev. Lett. **91**, 055001 (2003)

Complete Nondestructive Diagnostic of Nonneutral Plasmas Based on the Detection of Electrostatic Modes
Phys. Plasmas **10**, 3056 (2003)

The ATHENA Antihydrogen Apparatus
Nucl. Inst. Meth. Phys. Res. A **518,** 679-711 (2004)

High Rate Production of Antihydrogen
Phys. Lett. B **578**, 23-32 (2004)

Antihydrogen Production Temperature Dependence
Phys. Lett. B **583**, 59-67 (2004)

Three-Dimensional Annihilation Imaging of Trapped Antiprotons
Phys. Rev. Lett. **92**, 065005 (2004)

Dynamics of Antiproton Cooling in a Positron Plasma During Antihydrogen Formation
Phys. Lett. B **590,** 133-142 (2004)

Spatial Distribution of Cold Antihydrogen Formation
Phys. Rev. Lett. **94**, 033403 (2005)

New Source of Dense, Cryogenic Positron Plasmas
Phys. Rev. Lett. **95**, 025002 (2005)

Search for laser induced formation of antihydrogen
Phys. Rev. Lett. **97**, 213401 (2006)

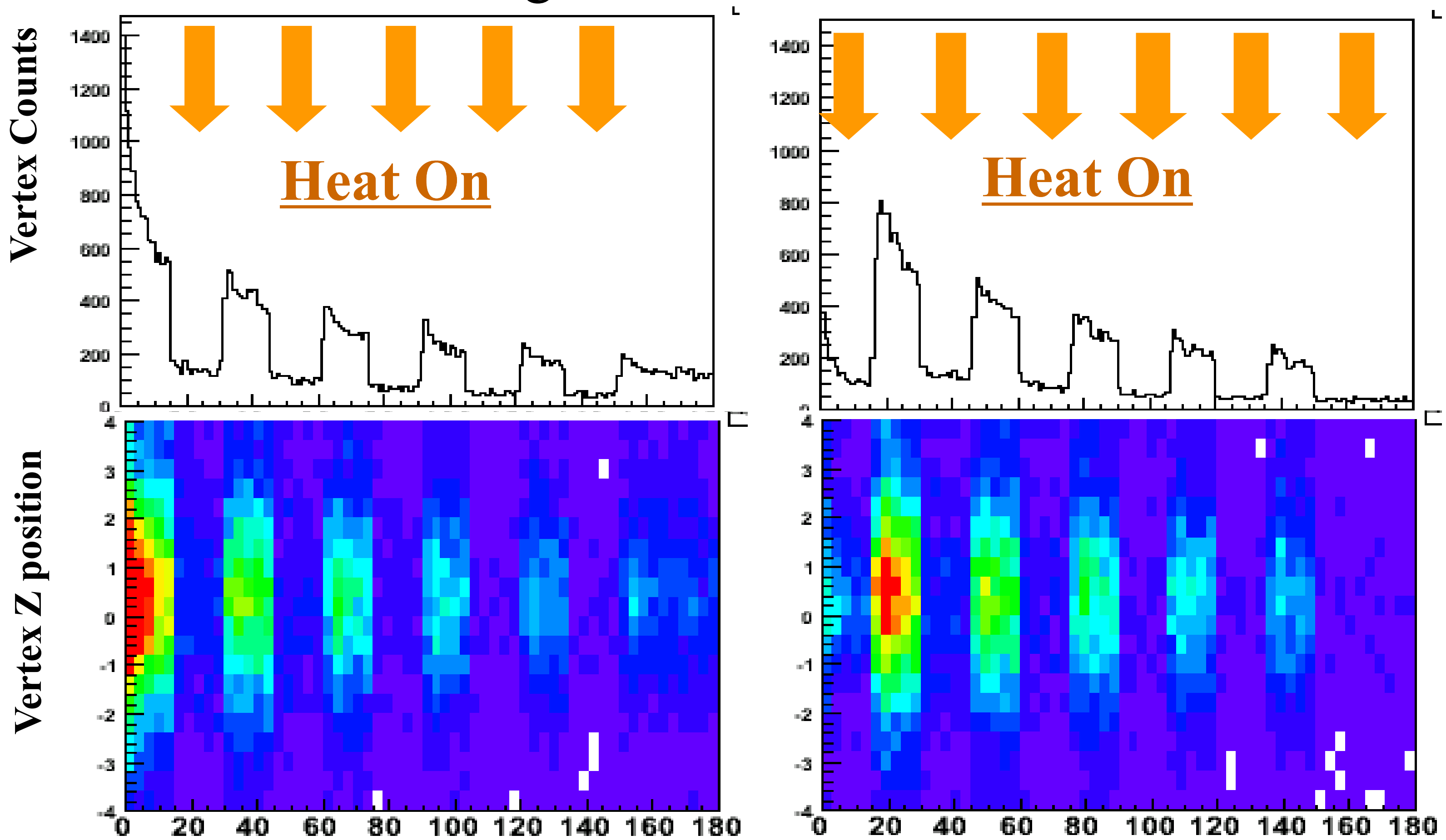
1 Nature, 6 PRL, 3 PLB, 4 full papers; a few more in preparation

Temporal Modulation

Temporal Modulation of Hbar Production

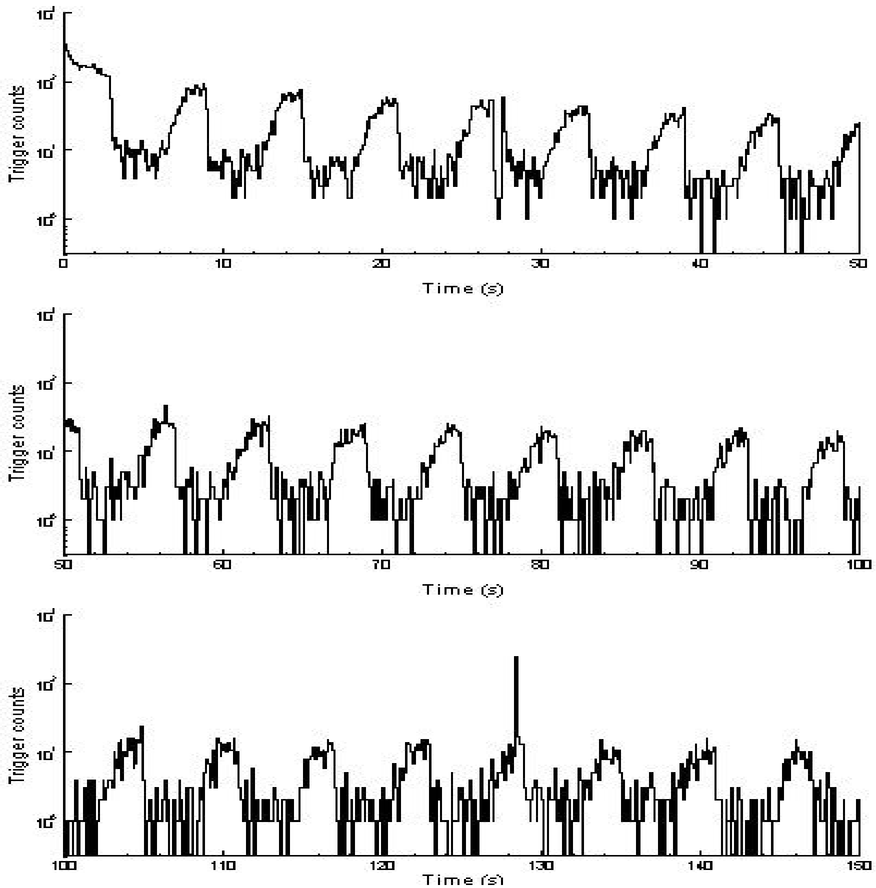
MCF et al, in preparation

RF heating of e^+ to switch off formation

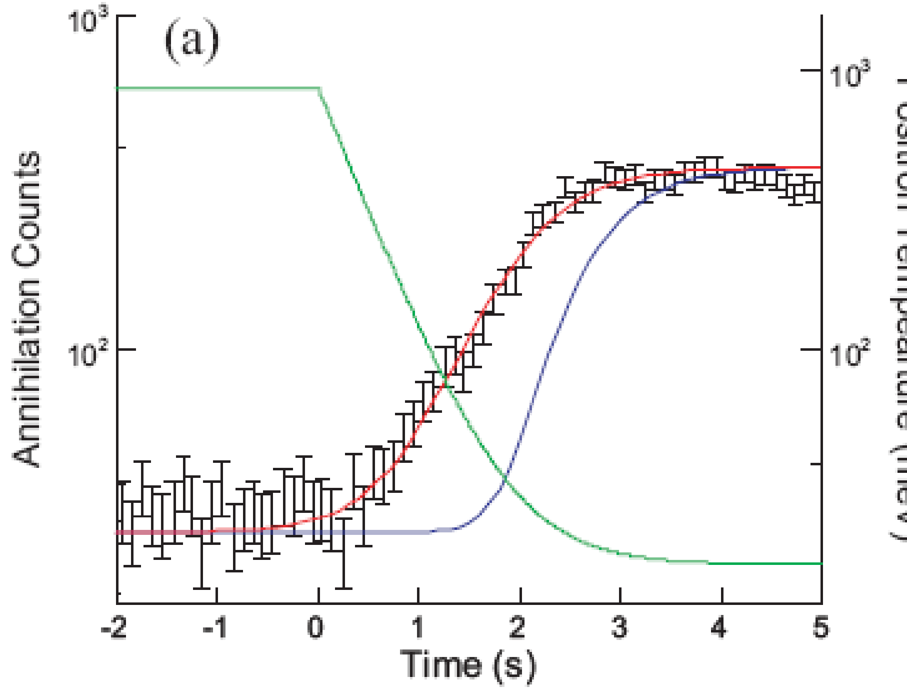


A Pulsed Source on Cold Antihydrogen !

Modulation of Hbar Production



Heat On/Off every 3 sec



Rise time contains Physics

- Positron Plasma Cooling time
- Hbar formation temperature dependence

$$R(t) \sim \left(\Delta T_{Heat} \cdot \exp\left(-\frac{t}{\tau_c} \right) + T_o \right)^P$$

Present and Future

From ATHENA to ALPHA

- ATHENA data taking ended in 2004 (analysis will continue for some years)
- Developed into a new experiment

~~**<u>ALE</u>**~~

~~Antihydrogen Laser Experiment~~

$\bar{\text{A}}$LPHA

Antihydrogen Laser Physics Apparatus

Project ALPHA Collaboration

University of Aarhus: G. Andersen, P.D. Bowe, J.S. Hangst

RIKEN: Y. Yamazaki

Federal University of Rio de Janeiro: C.L. Cesar, D. Miranda

University of Tokyo: R. Funakoshi, R.S. Hayano

University of Wales, Swansea: M. Charlton, N. Madsen, L. V. Jørgensen, M. Jenkins, H.H. Telle, D.P. van der Werf

Auburn University: F. Robicheaux

University of California, Berkeley: W. Bertsche, S. Chapman, J. Fajans, A. Povilus, J. Wurtele

Nuclear Research Centre, Negev, Israel: E. Sarid

University of Liverpool: A. Boston, M. Chartier, P. Nolan, R.D. Page, P. Pusa

University of British Columbia: S. Seif El Nasr, D.J. Jones, W.N. Hardy

University of Calgary: R. Hydomako, R.I. Thompson

Université de Montréal: J.-P. Martin

Simon Fraser University: M. Hayden

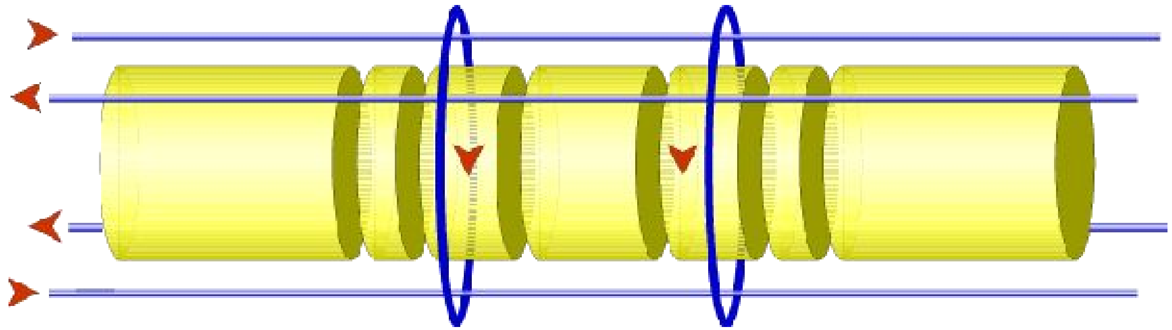
TRIUMF: P. Amaudruz, M. Barnes, M.C. Fujiwara, D.R. Gill, L. Kurchaninov, K. Olchanski, A. Olin, J. Storey + Professional Support

York University: H. Malik, S. Menary

Supported by NSERC, TRIUMF

Goal: Trapping Neutral Antihydrogen

- Magnetic trap (Ioffe-Prichard)



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

<u>Many Challenges</u>:

- Need very cold Hbar: Well depth ~0.7 K/T
- Need ground state Hbars
- Plasma stability in inhomogeneous B field:
  - Can charged and neutral traps co-exist?

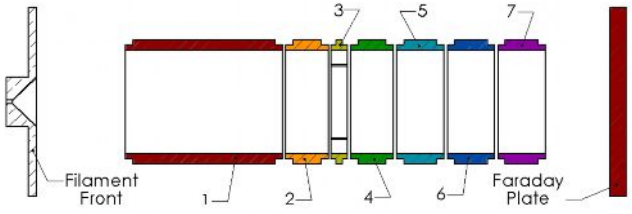

ALPHA

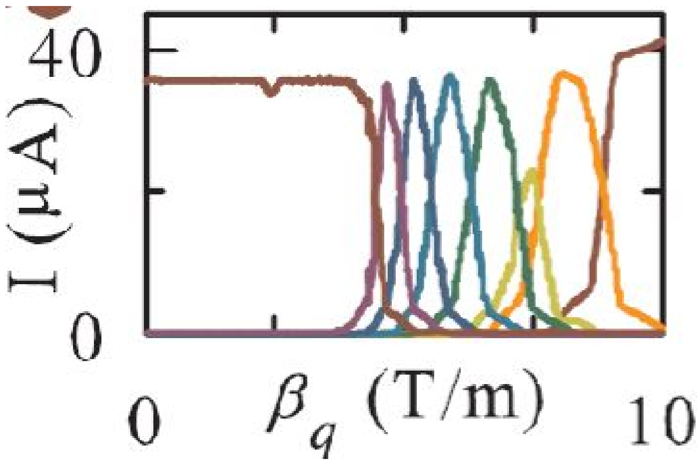


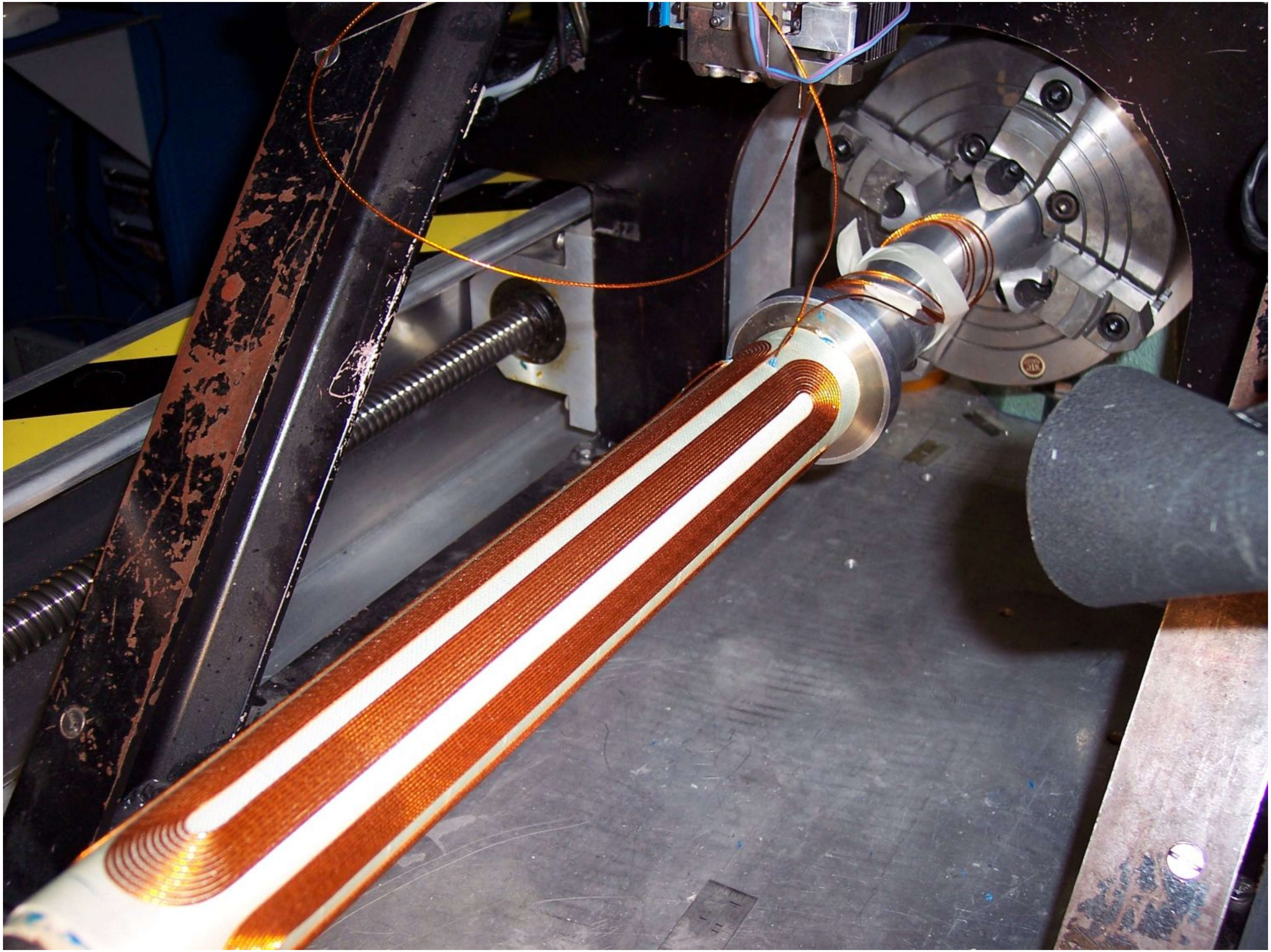
DANGER
LASER
DANGER
MAGNETIC FIELD
ALPHA

Quadrupoles - Why not?

Field lines diverge rapidly to the wall; particles making axial excursions (transfer, mixing) are easily lost [Fajans et al., PRL 2005]



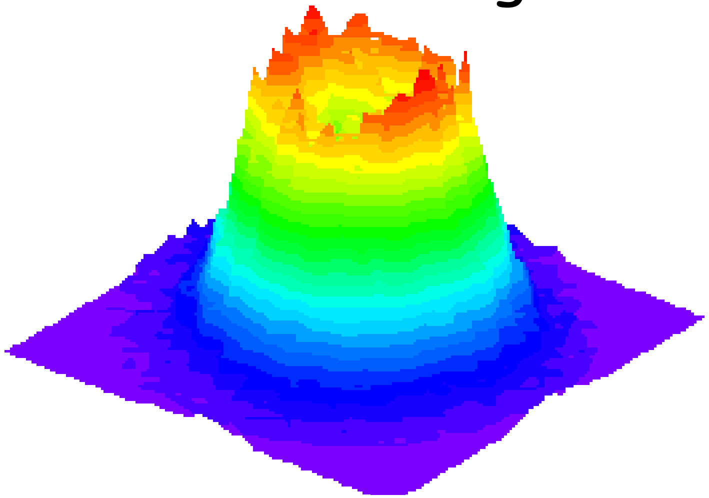




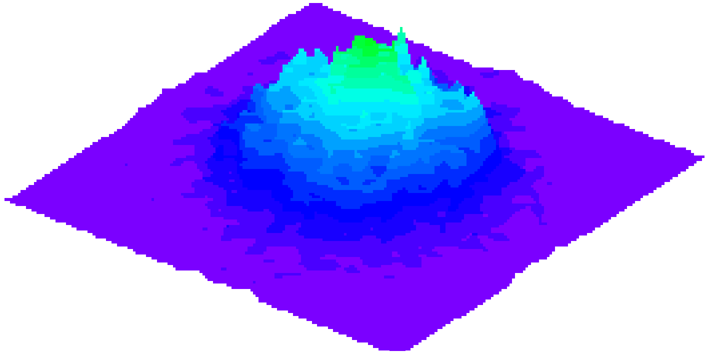
Antiproton Imaging with Si Vertex Detector

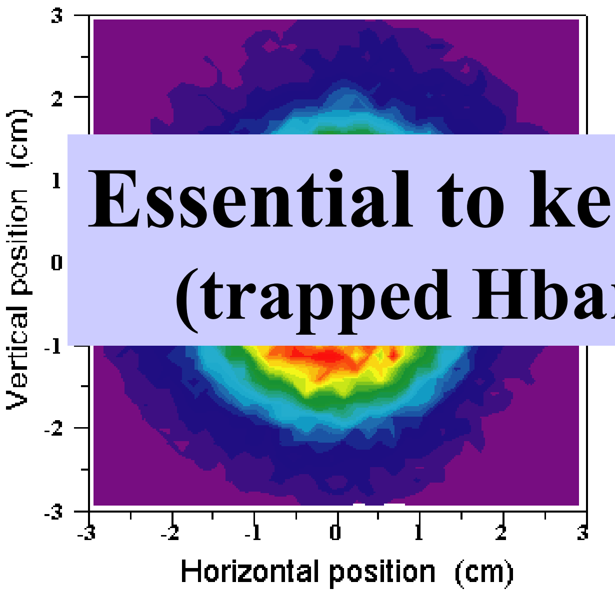
Amoretti et al Nature (2002), MCF et al PRL (2004)

Cold Mixing

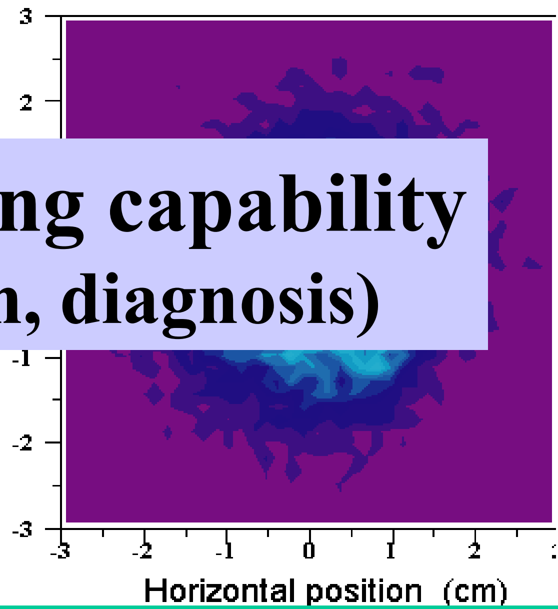


Hot Mixing (Bkgd)





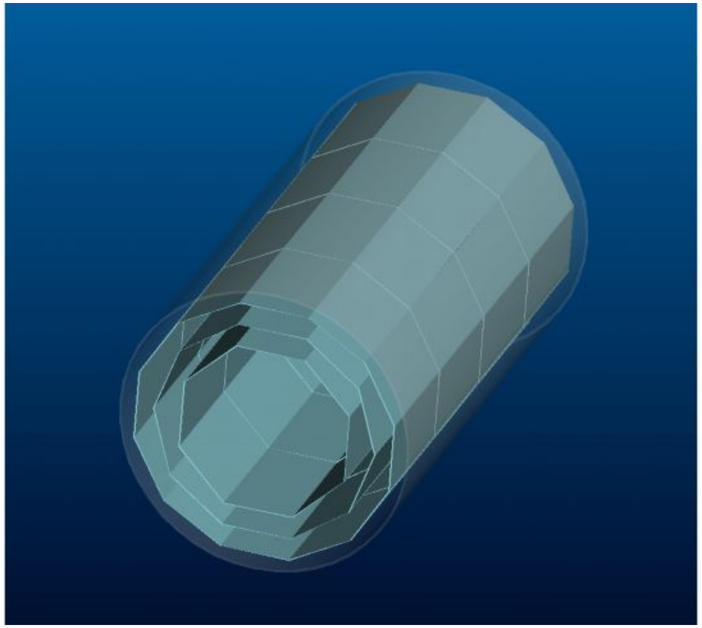
Essential to keep imaging capability
(trapped Hbar detection, diagnosis)

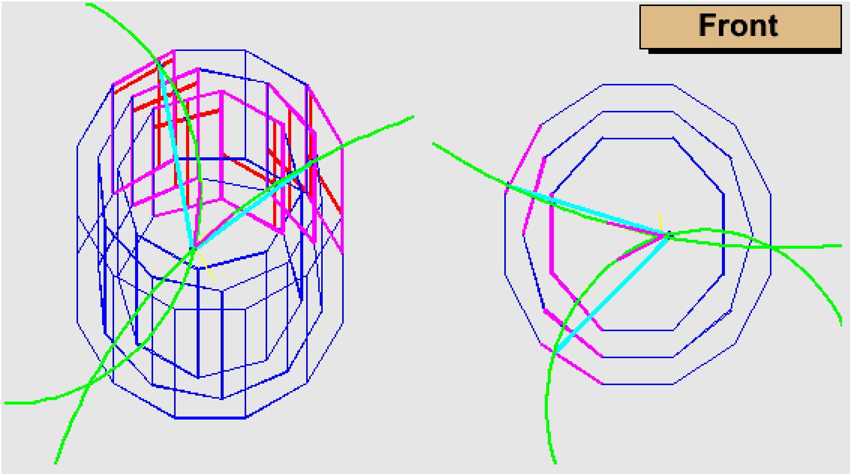


Hot Mix

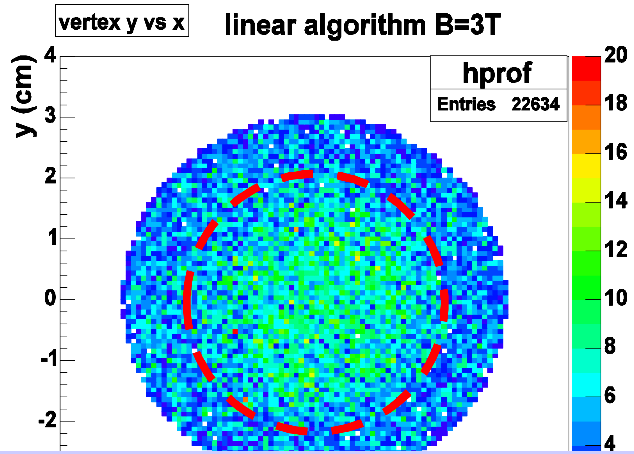
ALPHA Detector Design Challenge

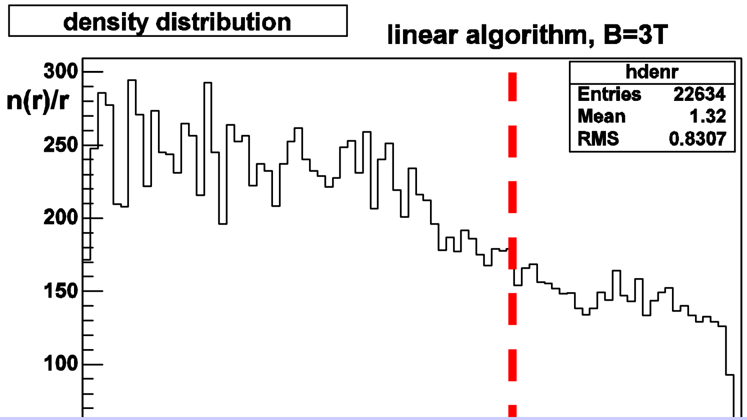
- Detector: Essential
- Trap requirements:
  - Thick magnet material (up to 1 X_0 of metal)
  - 1st layer far from interaction region
- Crazy to try vertex detection?
- Initial study was promising (MCF: hep/ex:0507082)





GEANT Simulations TRIUMF





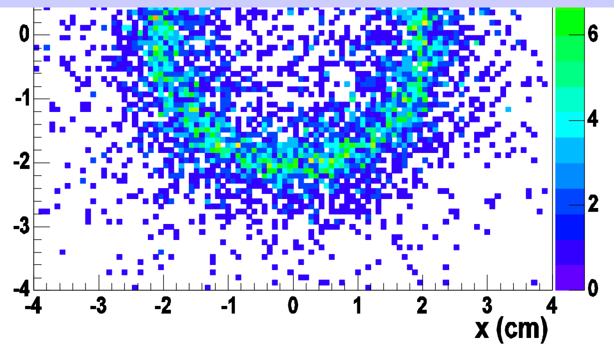
Straight track fit

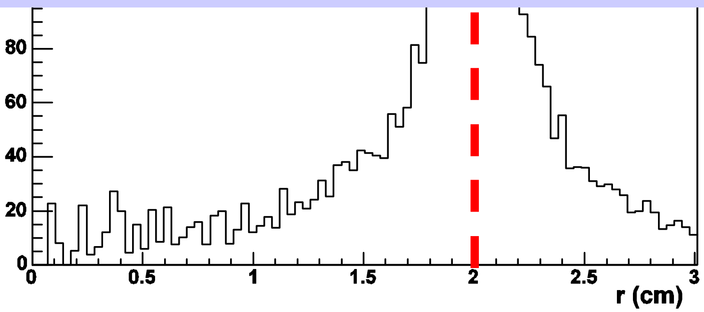
Accurate track curvature measurement essential

→3 Si layers (0.8 m^2)

→More than 30000 ch

(pattern recognition non-trivial)



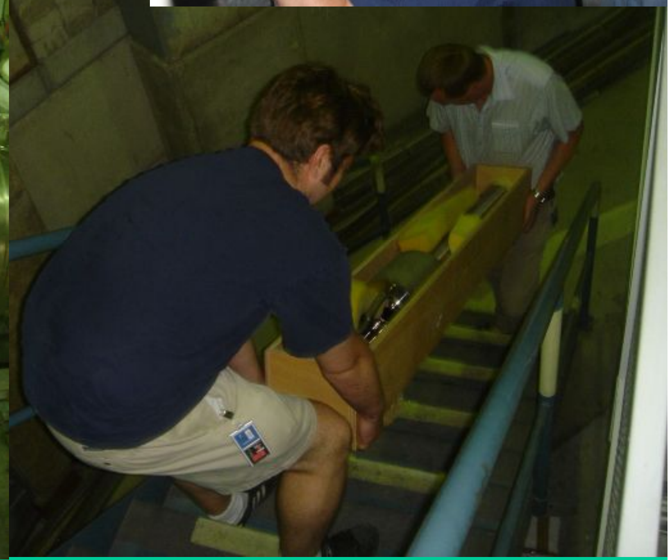


lix track fit

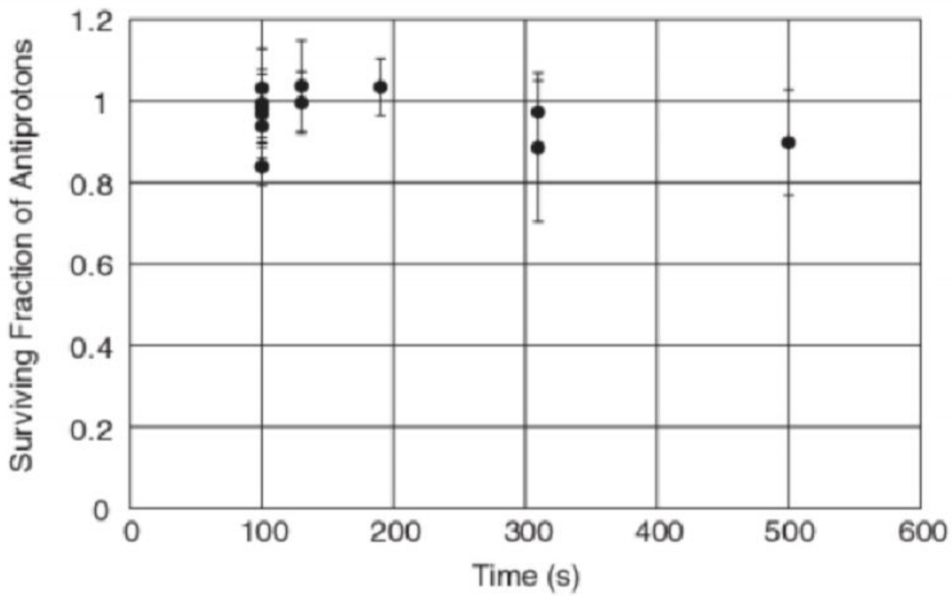
ALPHA Milestones

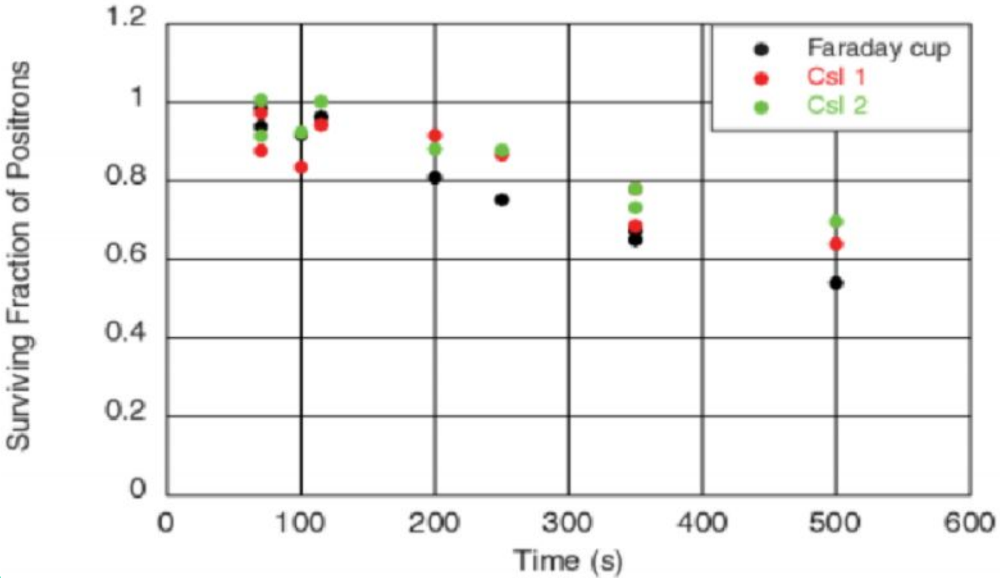
- Proposal – Jan, 2005, Approval – May 2005
  - Constructed a new apparatus from scratch
- First Beam – Aug -Nov, 2006
  - Trap pbars – Sep 12, 2006
  - Electron cooling – Sep 17, 2006
  - Antihydrogen production – Sep 30, 2006
- Entering unexplored territories: Oct – Nov 2006
  - Mirror magnets commission, Oct 8
  - Octupole magnets commission, Oct 20
  - Pbar/positron stability in octupole:
    PRL submitted Nov 10, 2006, published Jan 11, 2007
  - Hbar production in mirror field: (submitted)
  - Pbar/positron mixing in mirror/octupole: (in preparation)

ALPHA construction 2006



First Results with ALPHA

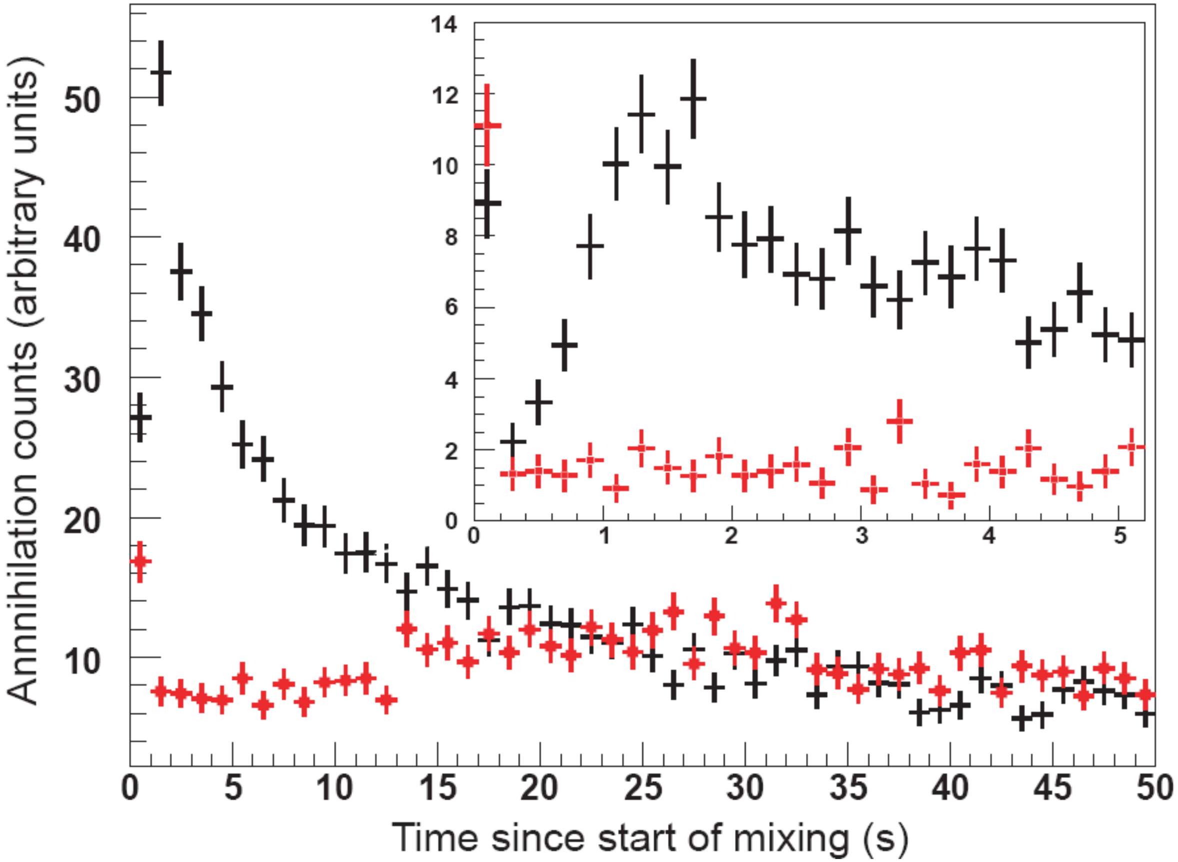




Phys. Rev. Lett. 98 023402 (2007)

- Results already from first beam!
- Pbars, e+ stored separately
- Survival fraction with/ without octupole (1.2 T)
- Sufficient number of pbars and positrons survive in a neutral trap
- Co-existence seems feasible!

Hbar production in mirror field



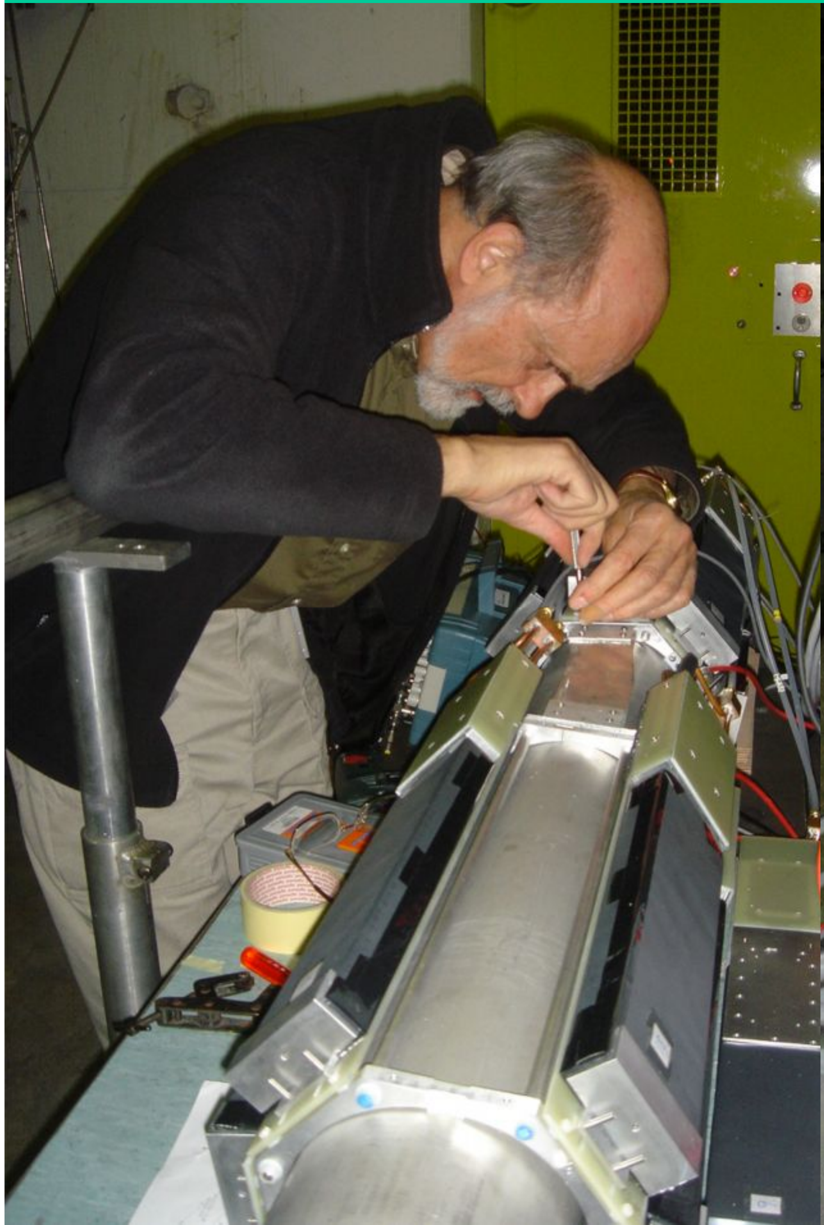
Submitted for publication (2007)

- Reduced background B field (1T)
  - Detected with scintillator + APD
  - Cold mixing versus hot mixing
- Other results in preparation

ALPHA Status

- This year's Run just started
  (June – Oct 2007)
  - Major upgrade external detector (APD)
  - Improved e+ source, pbar trapping, cryostat
  - Installing Si detector
- Antiproton-positron interactions, antihydrogen formation in a magnetic trap
- Attempts for antihydrogen trapping

Annihilation Detector Upgrade, June 2007



Antihydrogen Laser Experiment Roadmap

ATHENA 2002

First Production

ATHENA 1st attempt 2004

Quantum State Manipulations

ALPHA Initial GOAL

Stable Trapping

py

?

Planck Scale Physics
CPT Violation
Gravity

Steps Along on the Way

Laser induced formation
- First laser-antiatom interaction
- e+ temperature measurement
- 3-body plasma effects

Two-step laser induced formation
- First bound-to-bound spectroscopy
- Hbar velocity via Doppler width
- Resonant velocity selection

Non-neutral plasma stability studies
- Resonant particle transport
- Ballistic loss
- Quadrupole vs. multipole effect

1s-2s spectroscopy
- Comparison with hydrogen
- Resonant ionization
- Low field measurement

Strengths and Expertise

- Strong cold e+ sourc
- Precision and high-p
- Sophisticated detect
- Non-neutral plasma

Ultimate goals ambitious, Many intermediate physics results on the way

Summary

- Cold Antihydrogen: exciting emerging field
- ATHENA: made important contributions
- ALPHA: ambitious projects with aggressive schedule; important results coming out
- Still long way to precision measurements of matter-antimatter symmetry, but we are having lots of fun on the way!
- Participation of μCF friends will be welcome!!

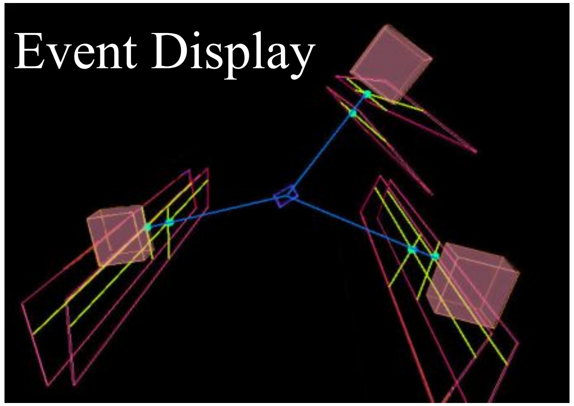
Antihydrogen Detection

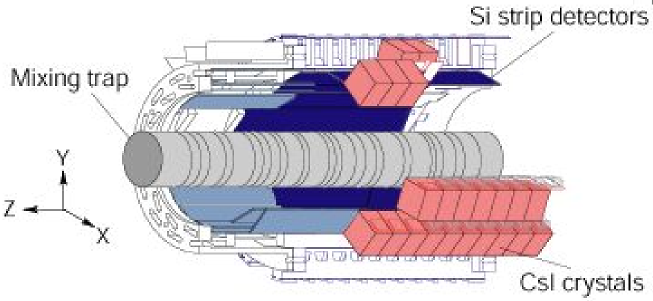
•Need to confirm and optimize Hbar production w/o trapping fields: reproduce ATHENA or ATRAP operation

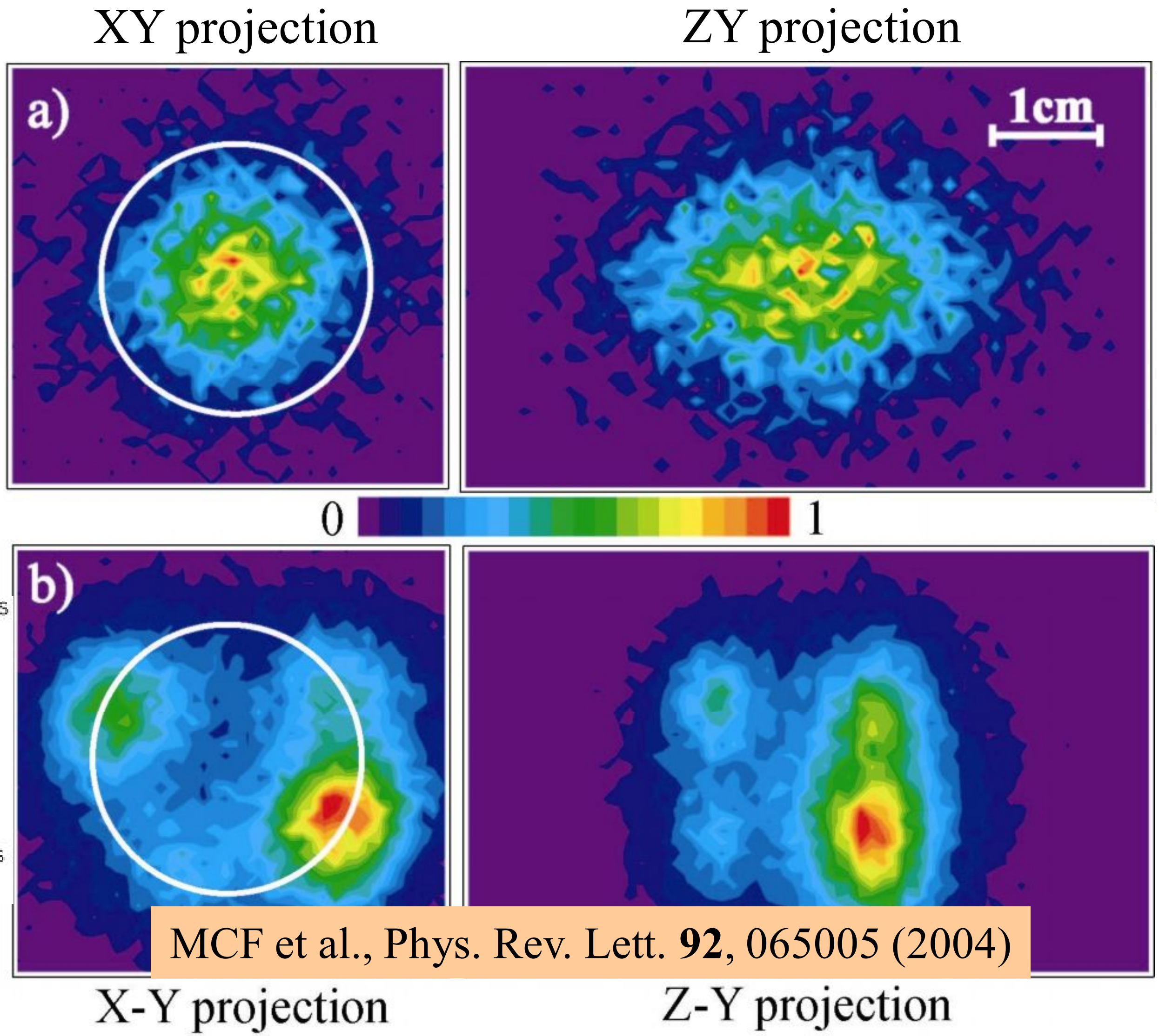
•Need to confirm and optimize Hbar production w/ trapping fields

•Need to verify trapping: probably by fast release of trapping fields

3D Imaging of Trapped Antiprotons

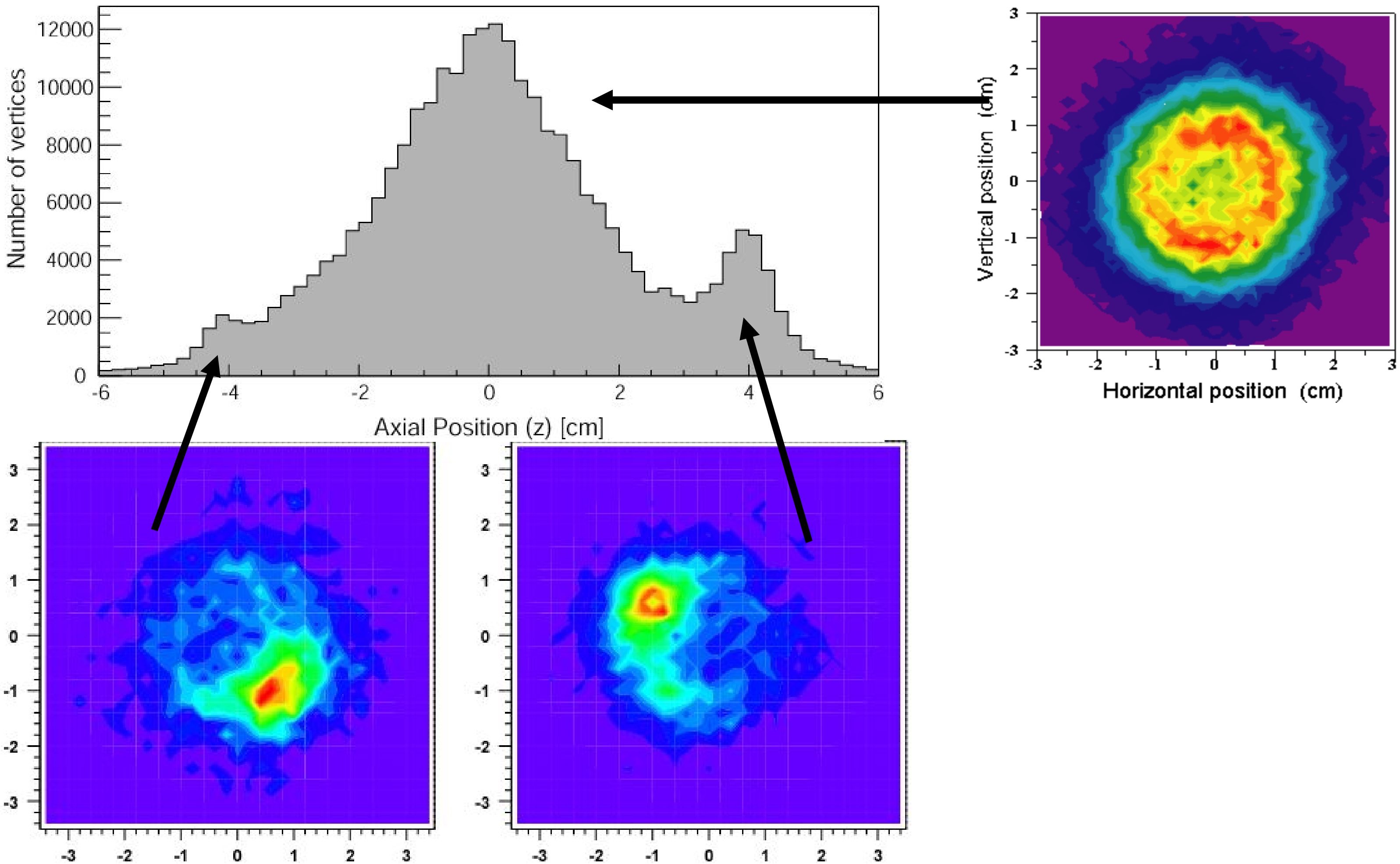






MCF et al., Phys. Rev. Lett. **92**, 065005 (2004)

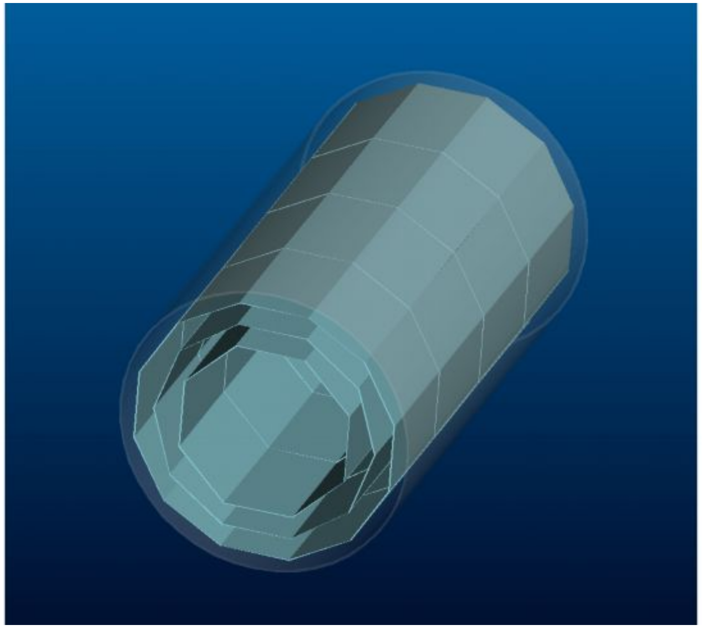
Implications for Hbar detection

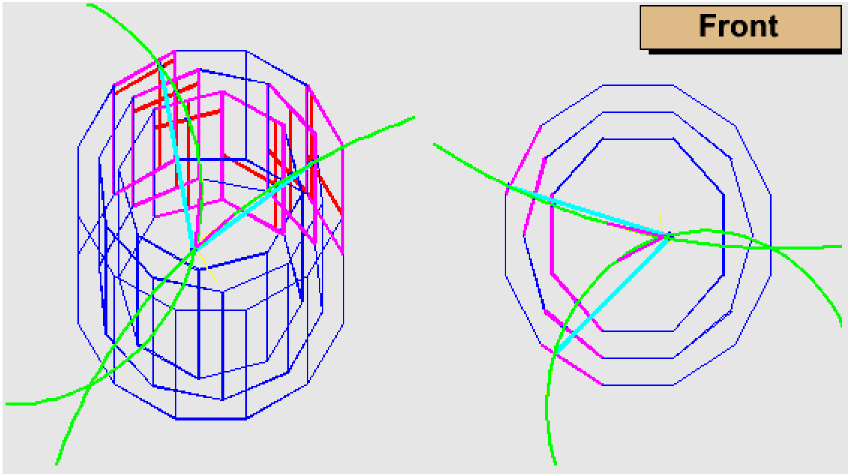


Hbar (neutral) and Pbars (charged) can be distinguished

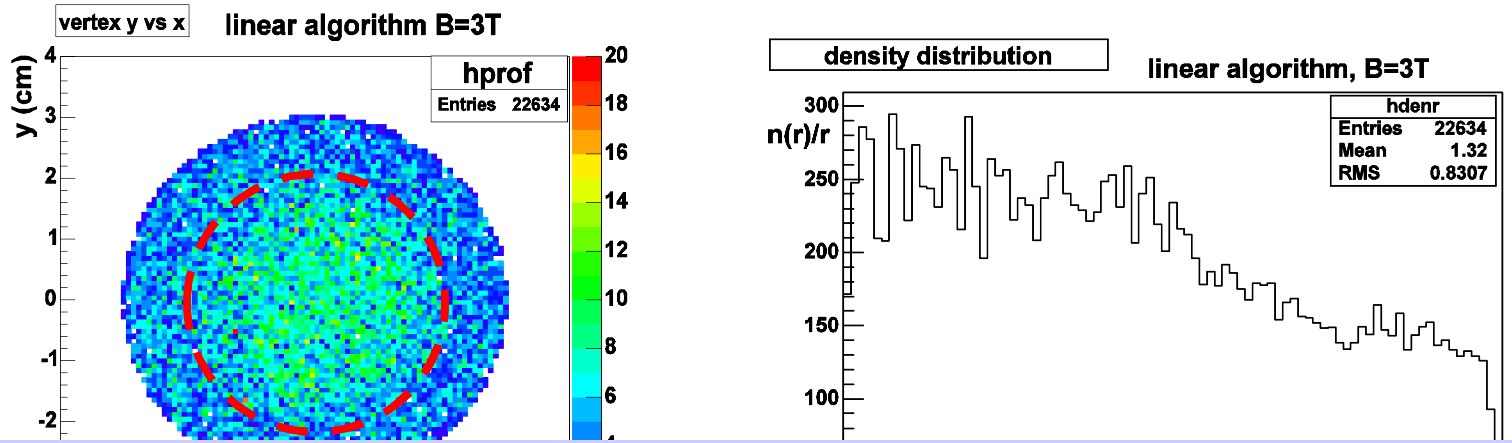
ALPHA Detector Design Challenge

- Trap requirements:
  - Thick magnet material (up to 1 X_0 of metal)
  - 1^{st} layer far from interaction region
- Crazy to try vertex detection?
- Initial study promising (MCF: hep/ex:0507082)





GEANT Simulations

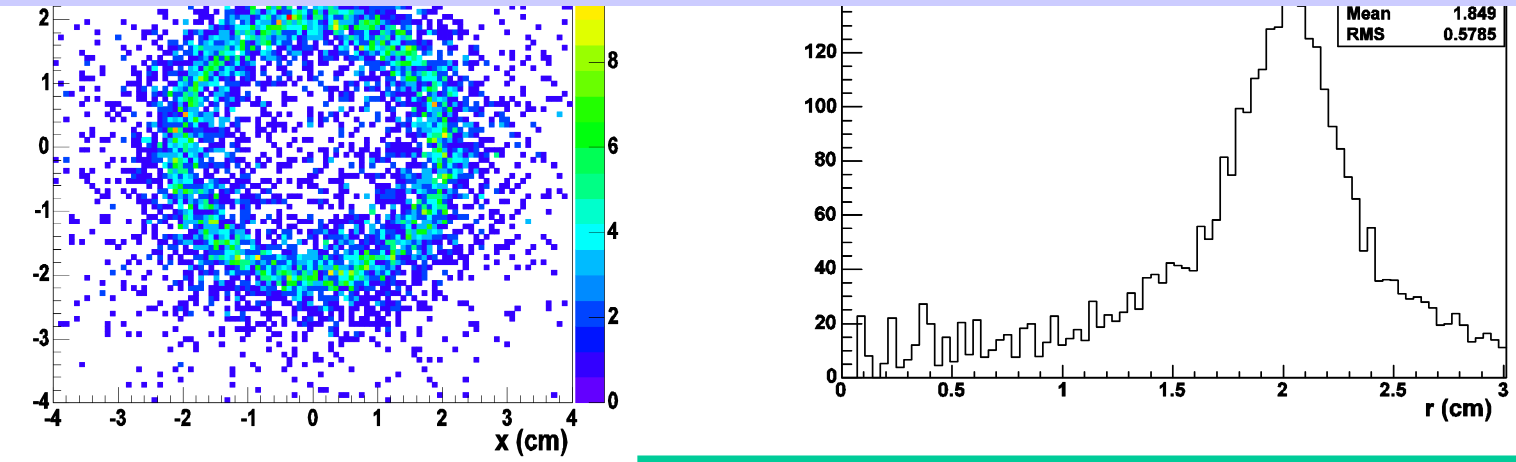


Straight track fit

Accurate track curvature measurement essential

→3 Si layers (0.8 m^2)

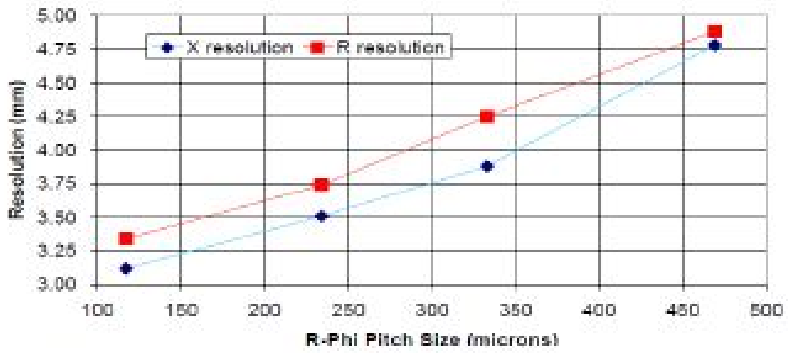
(pattern recognition non-trivial)

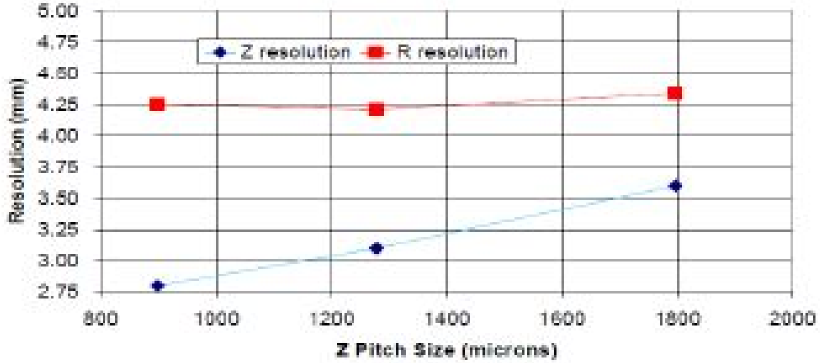


Helix track fit

Si vertex design studies at TRIUMF

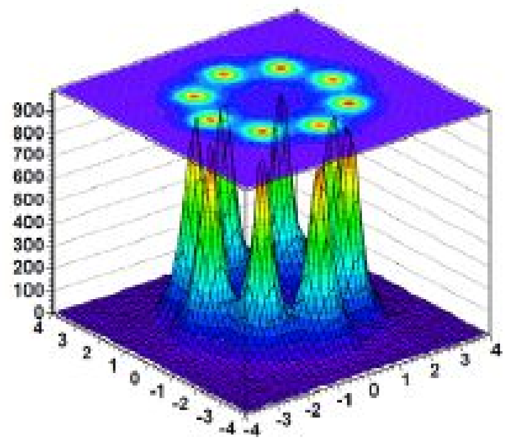
with P. Genova (Pavia), L. Posada (Tokyo), B. Jacobson (Berkeley

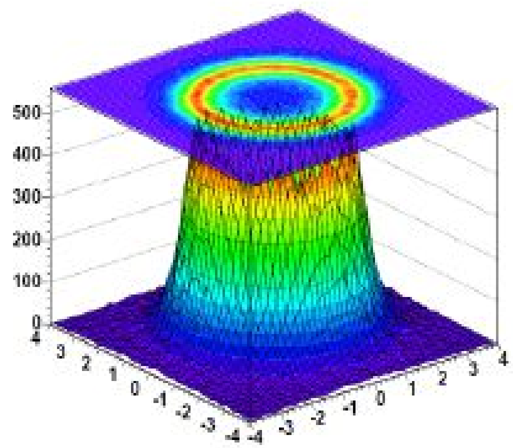




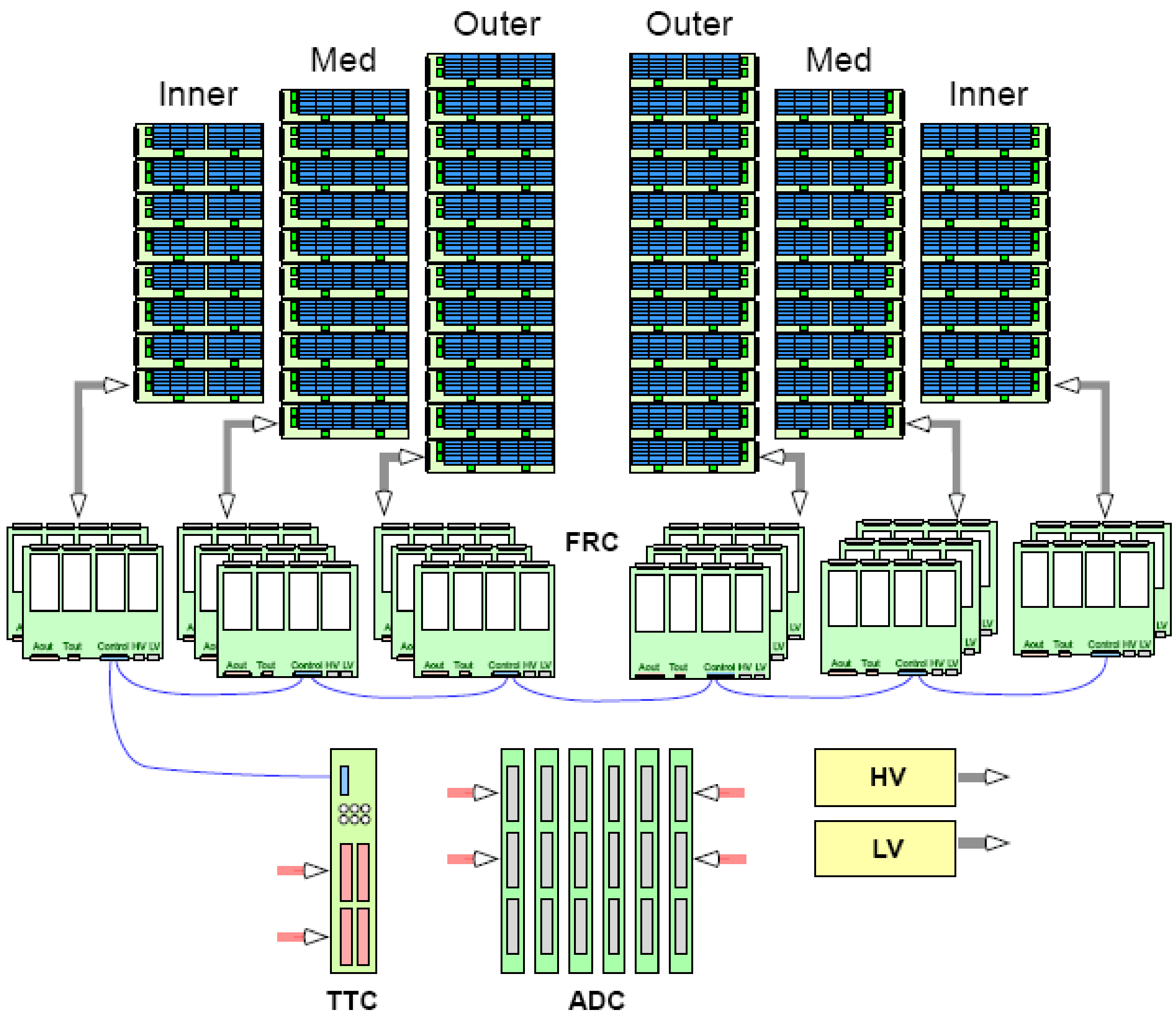
- 3 layers, 0.8 m^2
- 60 mm x 230 mm
- R-phi pitch : 230 micro, Z pitch: 900 micron
- > 30000 channels

Simulated annihilation images
X-Y Projection





Si Vertex Detector Read Out

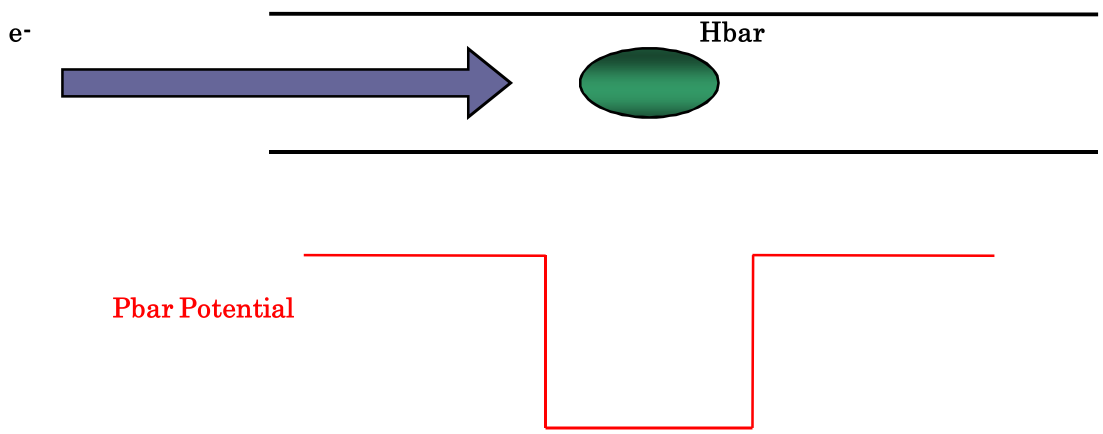


- TRIUMF-Montreal
- 48 channel FADCs
- Level 1.5 triggering capability with FPGA
- Much improvement over ATHENA in performance & cost

Detecting trapped Hbars

- Fast ramping of the SC magnet?
- Electron impact ionization of Hbars

  (MCF, AIP Conf Proc 2005)



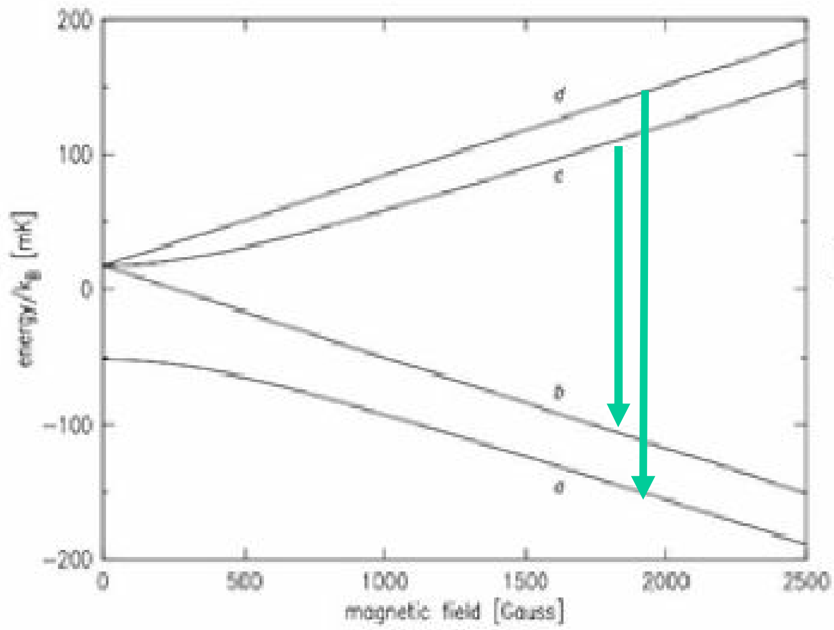
- Trap neutrals → get rid of charged → prepare pbar trap → shoot e beam → catch ionized pbar → dump

Electron impact ionization

- Nearly "back ground free"
  - Can detect one trapped Hbars
- Cross section for electron on normal H ($e^- + H^+ \rightarrow e^- + e^- + p^+$): ~ 10^{-16} cm^{-2} @50 eV [NIST]
- If trapped within 1 cm^2, an electron beam 1mA ionizes Hbar in 1 sec
- Positron impact on hydrogen? (CPT equiv)
- Other detection schemes, eg microwave resonance (Hardy, Kleppner)

Antihydrogen Microwave Spectroscopy

- Maser experts: Walter Hardy, Mike Hayden
- Theoretically favoured for CPT violations
- PSR: Positron Spin Resonance
- Pbar magnetic moment (poorly known ~0.3%)



Low field seeker (trappable)

Microwave 28GHz/T

High field seeker (escape trap)

$$\nu_{ad} = \frac{\Delta\nu}{2} + \frac{\mu_B g_{e+}}{h} B$$

$$\nu_{bc} = -\frac{\Delta\nu}{2} + \frac{\mu_B g_{e+}}{h} B$$

Initial studies in ~ 1 year