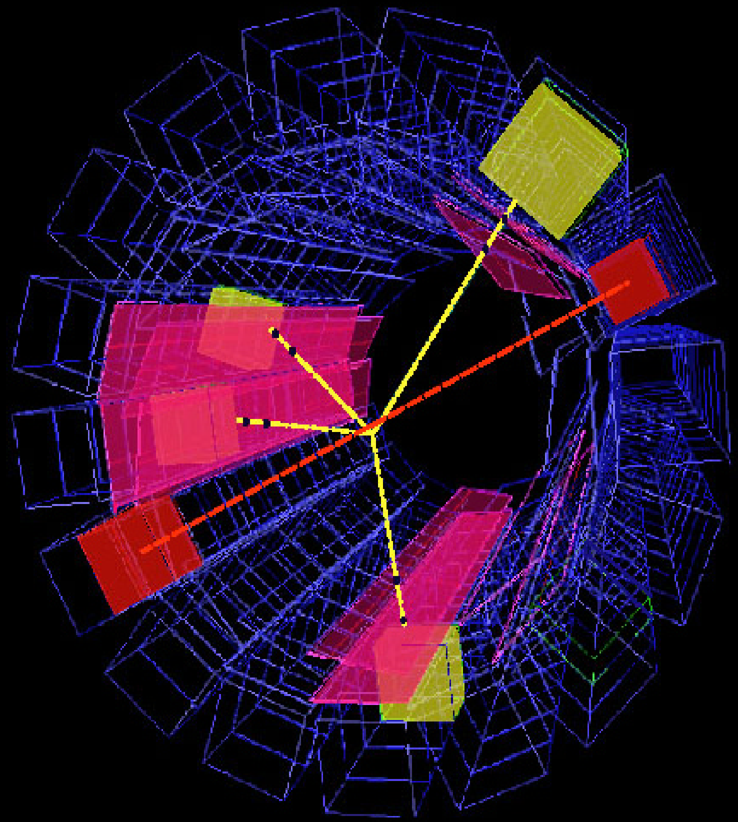
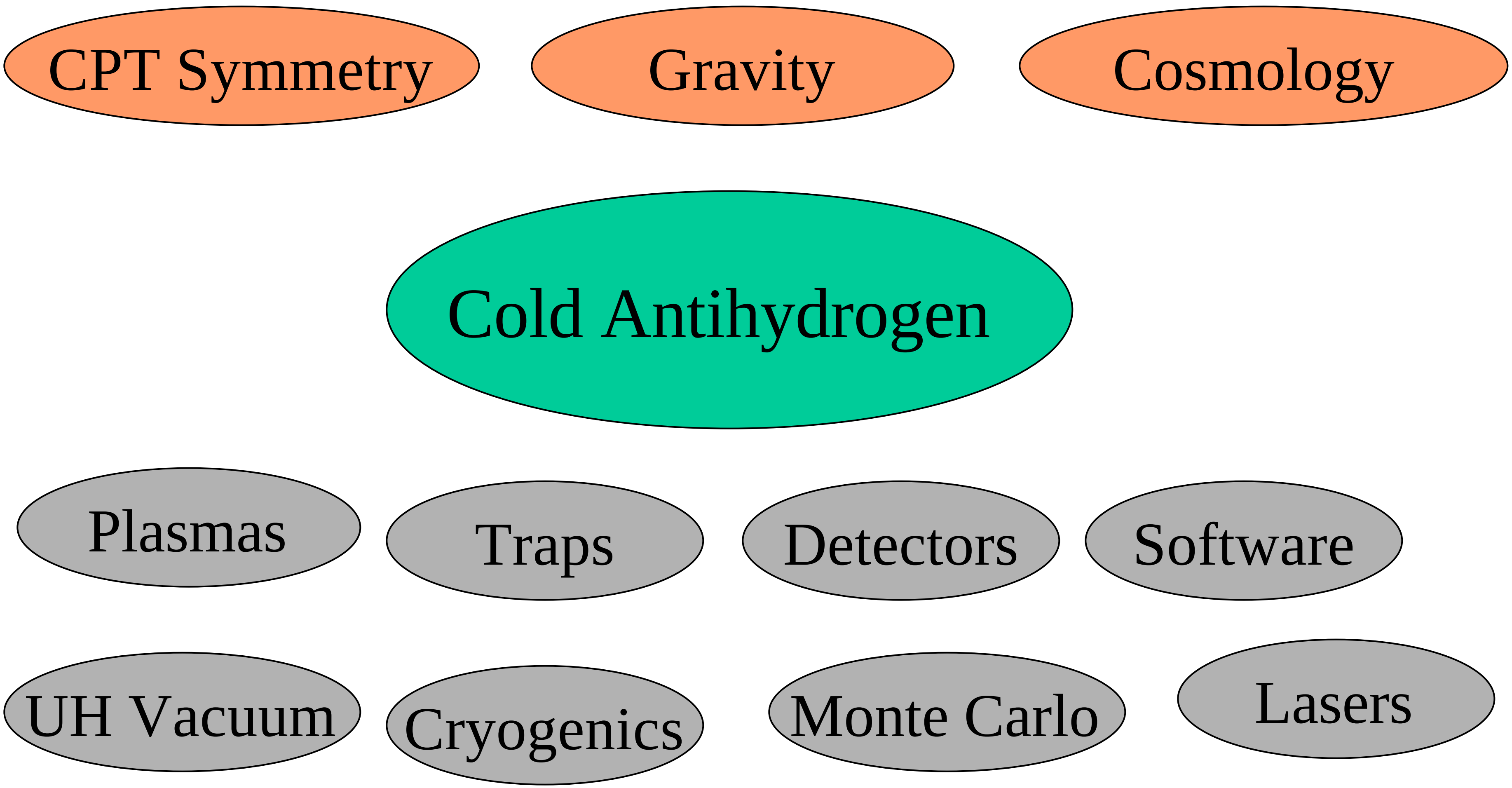
Production and Detection of Cold Antihydrogen



Makoto C. Fujiwara
University of Tokyo / CERN

KEK Physics Seminar March 26, 2003

Motivations



Test of CPT Invariance

- CPT theorem
  - Assumptions:

    Local Quantum Field Theory, Lorenz Invariance, Unitary
  - Consequences for particles and antiparticles:
    - Equal mass, lifetime
    - Equal and opposite charge and magnetic moment
    - Identical energy levels
- Not necessarily valid at Planck Scale
  - Gravity (curved space-time) → Unitarity?
  - Strings (non-local) → Field Theory?
  - Higher dimensions, Non-commutative geometry → Lorentz violation?
- Many recent theories ~~CPT~~ (Kostelecky, Ellis, Yanagida etc.)

Recent CPT and Lorentz violating theories

- **Robert Bluhm, V. Alan Kostelecký, Charles D. Lane, and Neil Russell**
  Clock-comparison tests of Lorentz and CPT symmetry in space, Phys. Rev. Lett. **88,** 90801 (2002)
- **V. Alan Kostelecký, Charles D. Lane, and Austin G.M. Pickering**
  One-loop renormalization of Lorentz-violating electrodynamics, Phys. Rev. D **65,** 56006 (2002)
- **Sean M. Carroll, Jeffrey A. Harvey, V. Alan Kostelecký, Charles D. Lane, and Takemi Okamoto**
  Noncommutative field theory and Lorentz violation, Phys. Rev. Lett. **87**, 141601 (2001)
- **V. Alan Kostelecký and Matthew Mewes**
  Cosmological constraints on Lorentz violation in electrodynamics, Phys. Rev. Lett. **87,** 251304 (2001)
- **V. Alan Kostelecký and Robertus Potting**
  Analytical construction of a nonperturbative vacuum for the open bosonic string, Phys. Rev. D **63,** 46007 (2001)
- **V. Alan Kostelecký and Ralf Lehnert** Stability, causality, and Lorentz and CPT violation, Phys. Rev. D **63,** 65008 (2001)
- **V. Alan Kostelecký and Ágnes Roberts** Analogue models for T and CPT violation in neutral-meson oscillations, Phys. Rev. D **63,** 96002 (2001)
- **V. Alan Kostelecký** CPT, T, and Lorentz violation in neutral-meson oscillations, Phys. Rev. D **64,** 76001 (2001)
- **V. Alan Kostelecký** Signals for CPT and Lorentz violation in neutral-meson oscillations, Phys. Rev. D **61,** 16002 (2000)
- **Robert Bluhm, V. Alan Kostelecký, and Charles D. Lane** CPT and Lorentz tests with muons, Phys. Rev. Lett. **84,** 1098 (2000)
- **Robert Bluhm and V. Alan Kostelecký** Lorentz and CPT tests with spin-polarized solids, Phys. Rev. Lett. **84,** 1381 (2000)
- **V. Alan Kostelecký and Charles D. Lane** Constraints on Lorentz violation from clock-comparison experiments, Phys. Rev. D **60,** 116010 (1999)
- **Robert Bluhm, V. Alan Kostelecký, and Neil Russell** CPT and Lorentz tests in hydrogen and antihydrogen, Phys. Rev. Lett. **82,** 2254 (1999)
- **R. Jackiw and V. Alan Kostelecký** Radiatively induced Lorentz and CPT violation in electrodynamics, Phys. Rev. Lett. **82,** 3572 (1999)
- **V. Alan Kostelecký** Sensitivity of CPT tests with neutral mesons, Phys. Rev. Lett. **80,** 1818 (1998)
- **Robert Bluhm, V. Alan Kostelecký, and Neil Russell** CPT and Lorentz tests in Penning traps, Phys. Rev. D **57,** 3932 (1998)
- **D. Colladay and V. Alan Kostelecký** Lorentz-violating extension of the standard model, Phys. Rev. D **58,** 116002 (1998)

Recent CPT and Lorentz violating theories (cont'd)

- **Robert Bluhm, V. Alan Kostelecký, and Neil Russell**
  Testing CPT with anomalous magnetic moments, Phys. Rev. Lett. **79,** 1432 (1997)
- **Don Colladay and V. Alan Kostelecký**
  CPT violation and the standard model, Phys. Rev. D **55,** 6760 (1997)
- **V. Alan Kostelecký and R. Van Kooten**
  Bounding CPT violation in the neutral B system, Phys. Rev. D **54,** 5585 (1996)

  ….

Recent CPT and Lorentz violating theories, tests

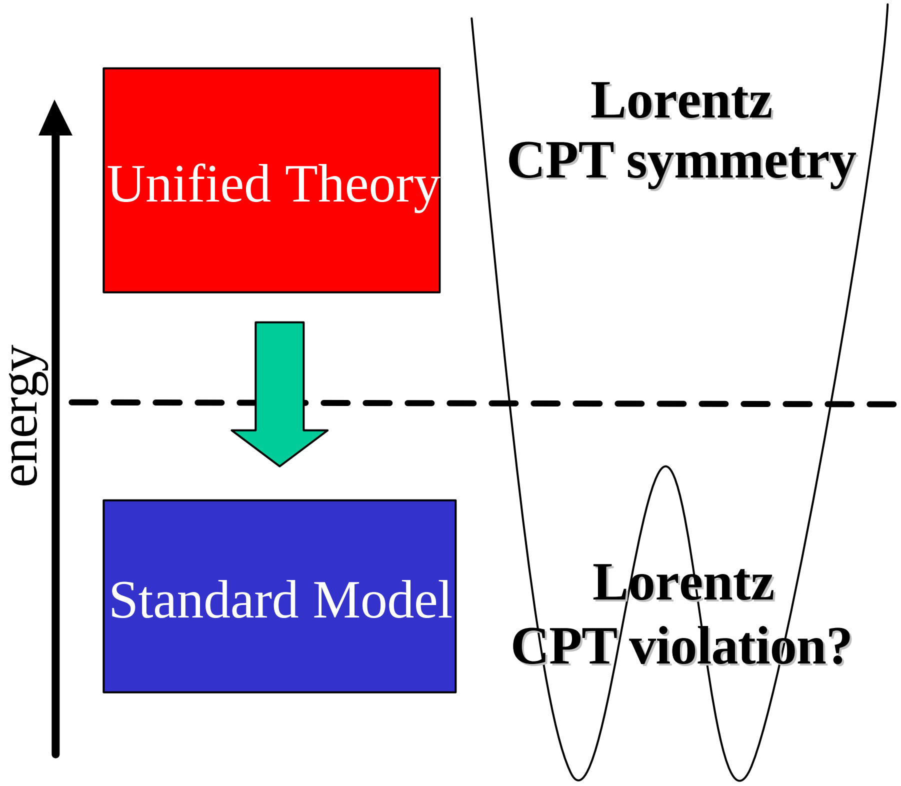
Other Theory

- **J. Bachall et al.** How accurately can one test CPT conservation with reactor and solar neutrino experiments**?** hep-ph/0201211 (2002)
- **H. Murayama and T. Yanagida** LSND, SN1987A, and CPT violation, Phys. Lett. **520B** 263 (2001)
- **N. Isger et al**. Background enhancement of CPT reach at an asymmetric phi factory, Phys. Lett. **515B** 333 (2001)
- **S. Coleman and S. Glashow** High energy tests of Lorentz invariance, Phys. Rev. D **59** 116008 (1999)
- **J. Ellis et al.** Phys. Lett. **293B** 142 (1992)
- **P. Huet and M. E. Peskin** Nucl. Phys. B **434** 3 (1995)
- **S. Hawking** Phys. Rev D **14** 2460 (1975)
- **I. Mocioiu et al.,** Breaking CPT by mixed non-commutability hep-ph/0108136

Experimental Tests

- **M. Hori et al.** ASACUSA: anti-protonic helium
- **V. Hughes et al.** Muonium hyperfine structure
- **H. Dehmelt et al.** electron and positron in penning trap
- **G. Gabrielse et al.** proton and antiproton in penning trap
- **CPLEAR** neutral kaon mass difference

Probing Planck-scale physics with CPT violation



Unitarity violation

Planck Scale M_{Pl}

~~CPT~~ effects suppressed by

$$\left(\frac{m}{M_{Pl}^{\;n}}\right)$$

Low energy scale m

Normally $M_{Pl} \sim 10^{19}$ GeV

If Large Extra Dimension with M_{Pl}* ~10^3 GeV

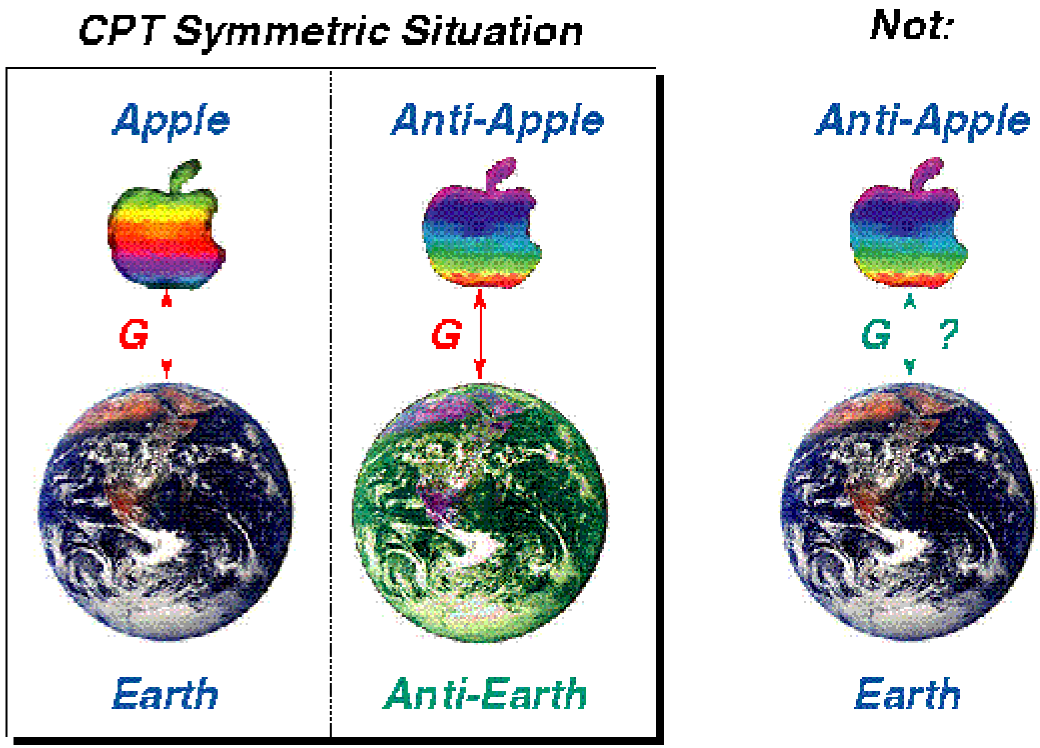
→ Possibly "large" CPTV at low energy?

Gravitational acceleration of antimatter

Possible Non-Newtonean gravity with vector coupling

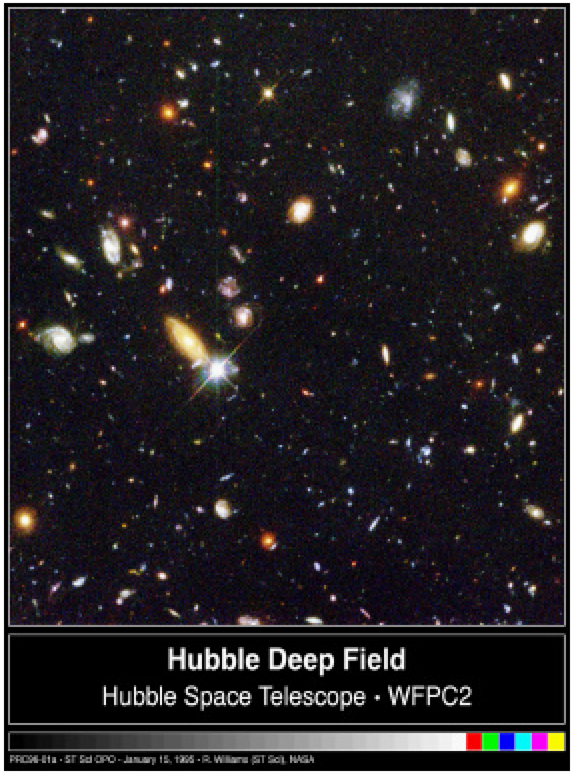
No direct measurements

CPT theorem does not help



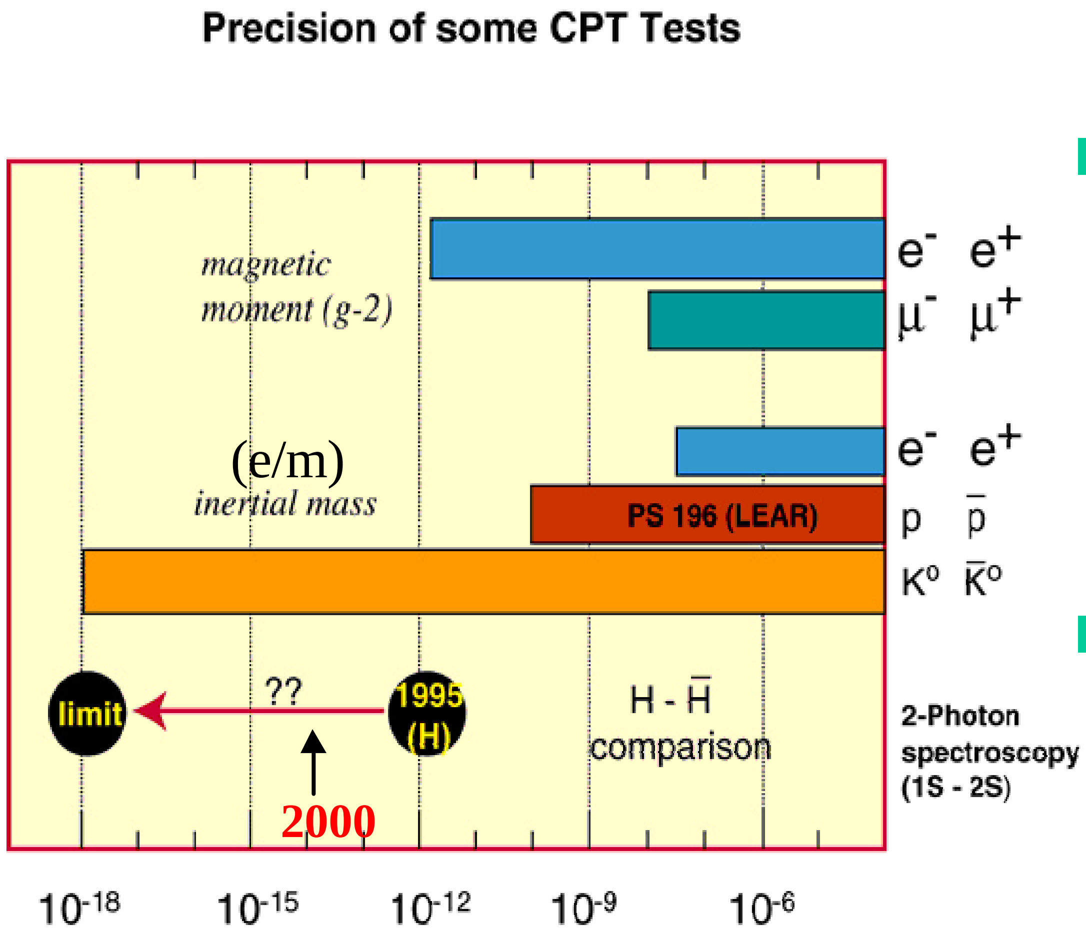
Baryogenesis: Where Do We Come From?

- Baryon asymmetry:
  no anti-universe observed
- Standard scenario:
  Sakharov's conditions
  - Baryon number violation
  - C, and CP violation
  - Out of thermal equilibrium
- New physics beyond SM required
  - CPV from CKM not large enough
  - Problems with vacuum phase transitions
- Other source of baryon asymmetry
  →CPT violation?



A.D. Dolgov, Ya.B. Zeldovich, Rev. Mod. Phys. 53, 1 (1981)
O. Bertolami et al., Phys. Lett. B 395, 178 (1997)

Previous CPT Tests

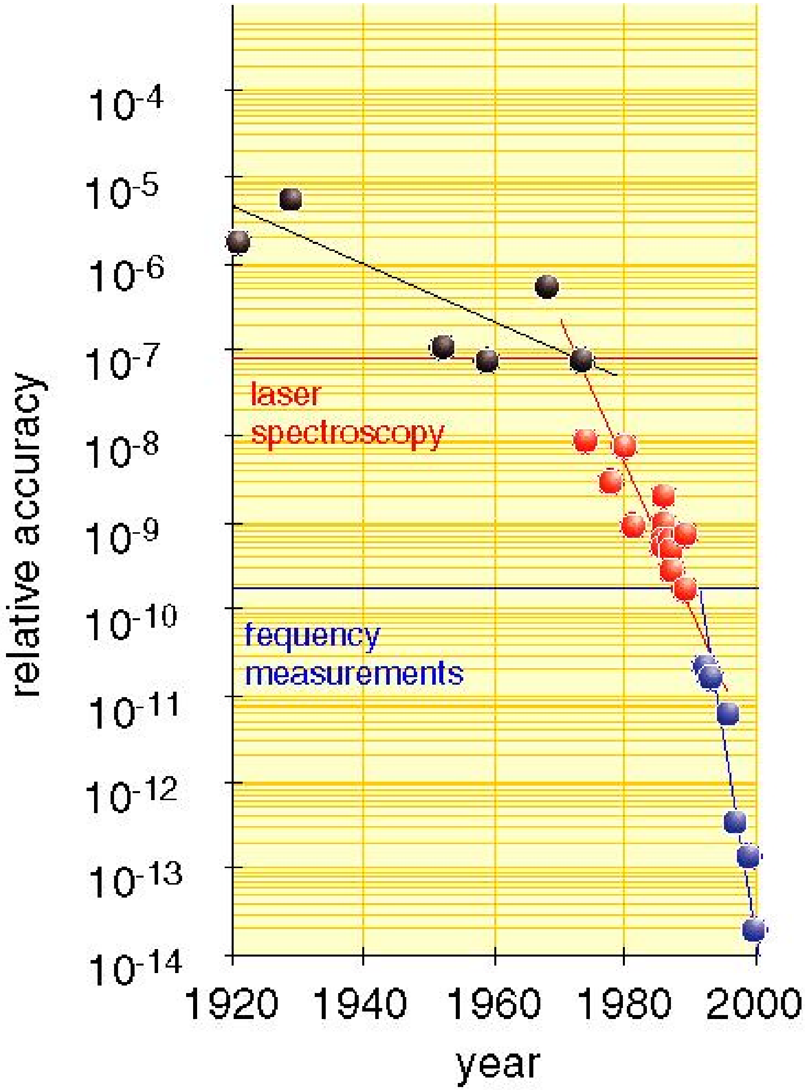


- Neutral Kaon analysis model dependent
  - Possible CPTV suppressed M_{KL}-M_{KS} (10^{-15})
  - 10% test of CPTV interact. (Kobayashi and Sanda)
- Pattern of CPTV totally unknown

All sectors should be tested

(Anti)hydrogen Spectroscopy

- Comparison with hydrogen would allow high precision tests
- Progress in 1s-2s measurements impressive over the years (now at 10^{-14} level)
- Hyperfine levels, Lamb shift



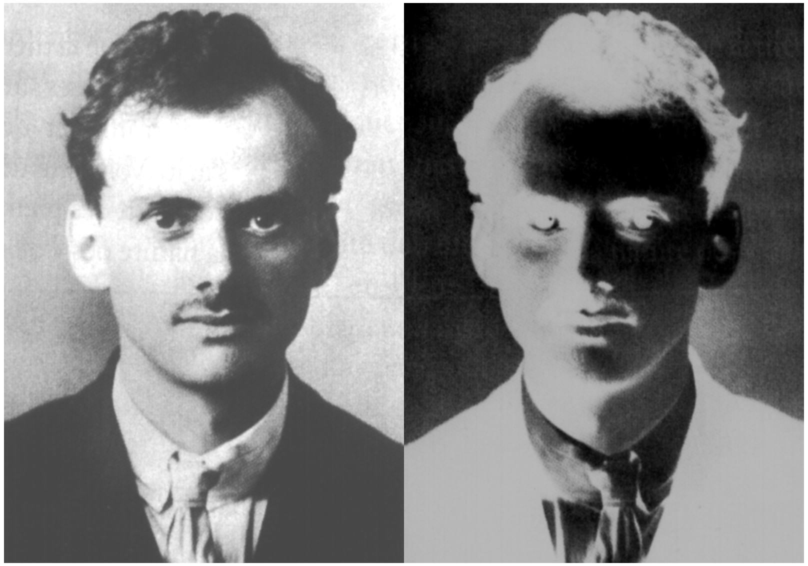
Antimatter Brief History

Antiparticles:

1927 Dirac predicts the anti-electron

1931 Anderson registers positrons from cosmic rays

1955 Discovery of the Antiproton at the Bevatron

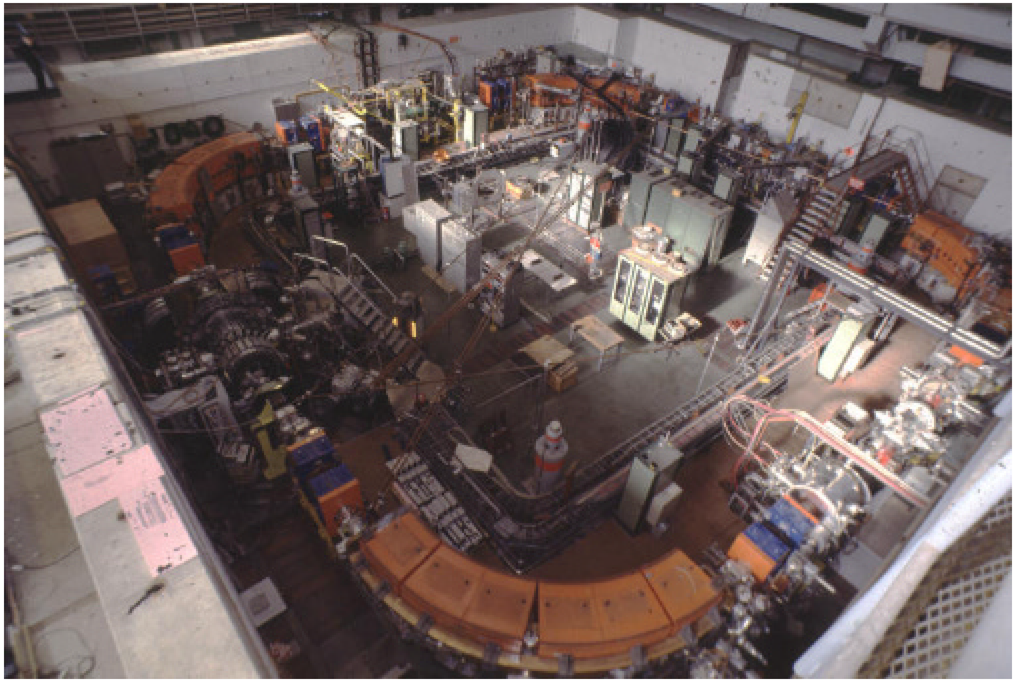


Paul Dirac

Emilio Segre, Clyde Wiegand, Edward Lofgren
Owen Chamberlain, Tom Ypsilantis

Relativistic Antihydrogen

- 1992 Suggestion by Munger et al: pbar + Z $\rightarrow$ hbar
- 1996 Production of 9 antihydrogen atoms reported at LEAR



LEAR
1986-1996

No precision studies could be performed

ATHENA - I : GOAL

FIRST PRODUCTION OF COLD ANTIHYDROGEN (hbar)

10^{-12}

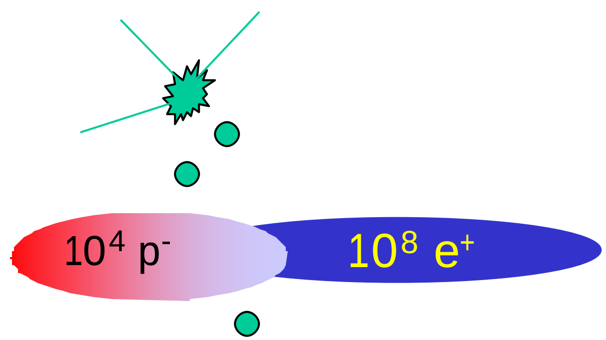
AD

p- Production (GeV)

Deceleration (MeV)

Trapping (keV)

Cooling (~ meV)



10^{-9}

Na-22

e^+ Production (MeV)

Moderation

Accumulation (eV)

Cooling (~ meV)

Plasma diagnosis/manipulation

p^- and e^+ in mixing trap

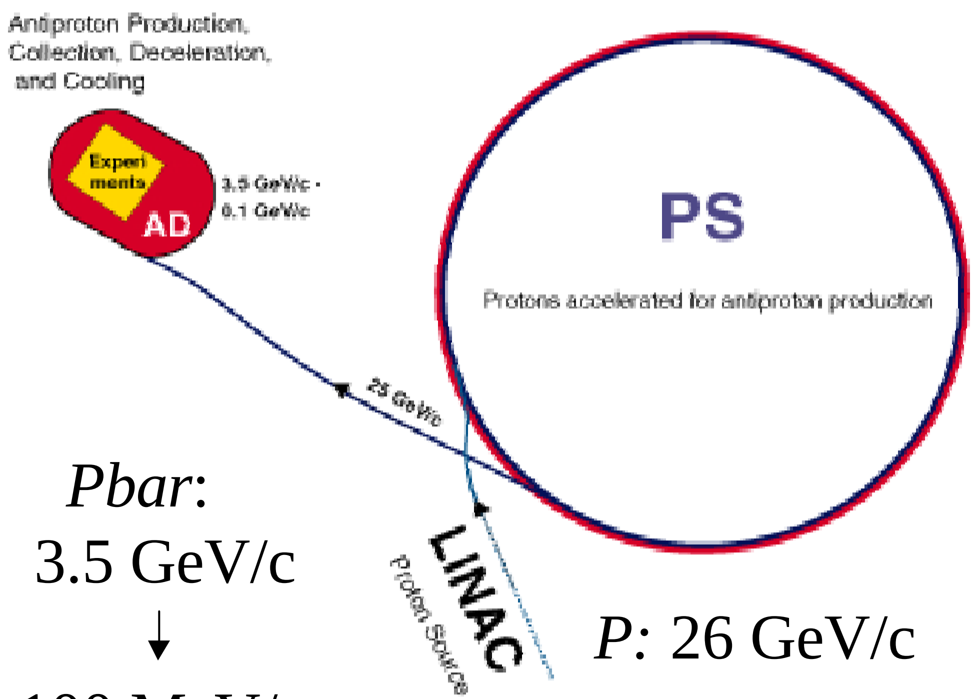
Antihydrogen formation

Detection of annihilation

CHALLENGES

- Making everything work at same time
- Competition

Antiproton Decelerator Complex at CERN

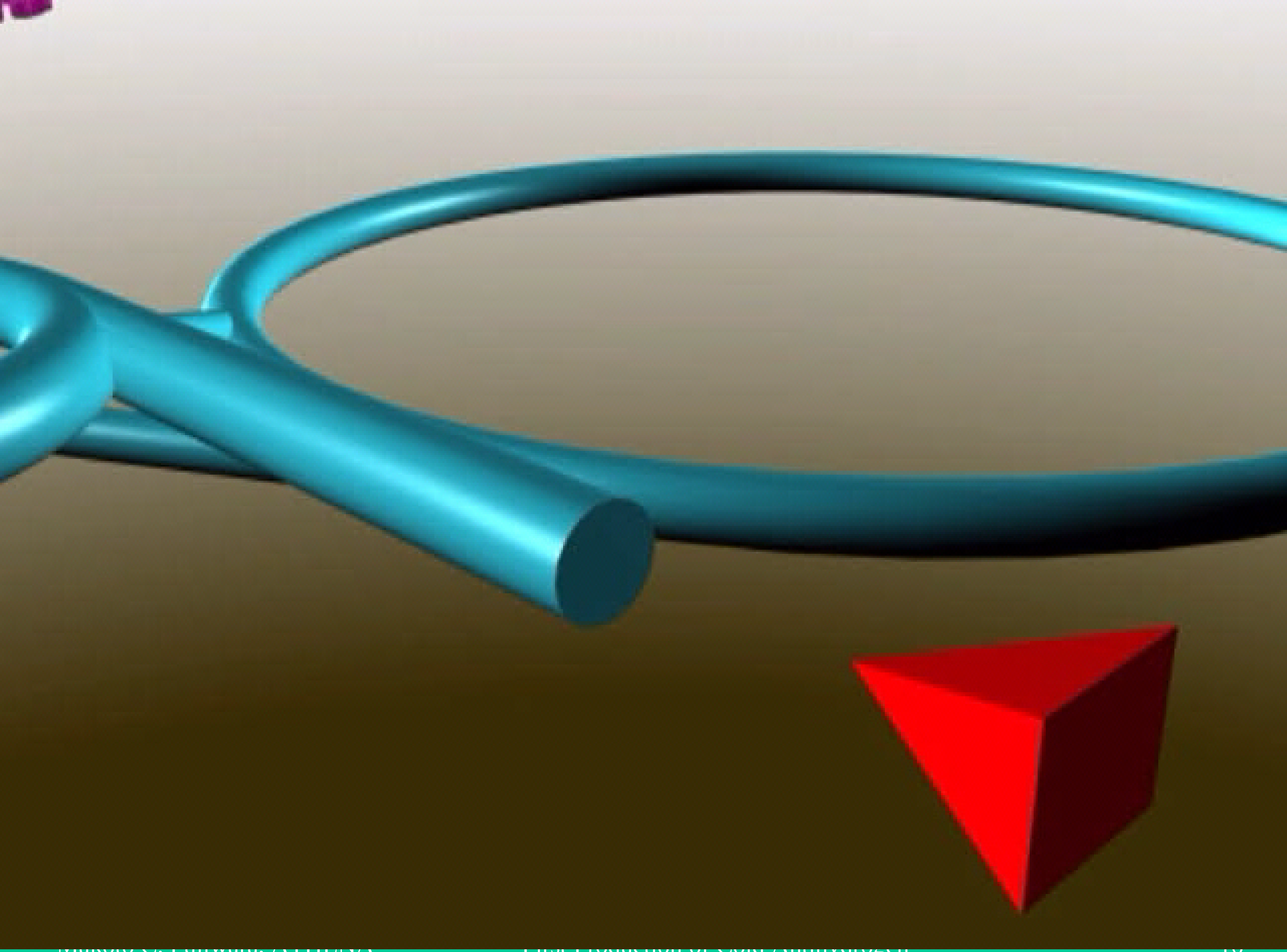


Pbar:
3.5 GeV/c
↓
100 MeV/c

P: 26 GeV/c

- Economical successor of LEAR
- Made possible by large financial contribution from Japan

- **Pulsed beam**:
  4×10^7 /pulse, every 100 sec
- **3 experiments at AD**:
  Asacusa --- pbar-He, collisions
  Athena --- antihydrogen
  Atrap --- antihydrogen



CERN-AD Experiments

Making of First Cold Antihydrogen

Hot Race for Cold Antihydrogen

Where we were in 2000 (LEAP00)

- ATHENA
  - Pbar catching
  - Electron cooling

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

Milestones since LEAP 2000

June 2001
Pbar lifetime >10 hours

July 2001
Pbar transfer between traps

Sept 2001
Pbar Vertex Imaging

Dec 2001
25M positrons in 3T

July 2002
First indications

Detailed studies

Aug 27
Hbar paper submitted

Sep 3
Hbar paper accepted

Sep 18 2002
Published in ***Nature*** on-line

Oct 31
ATRAP published

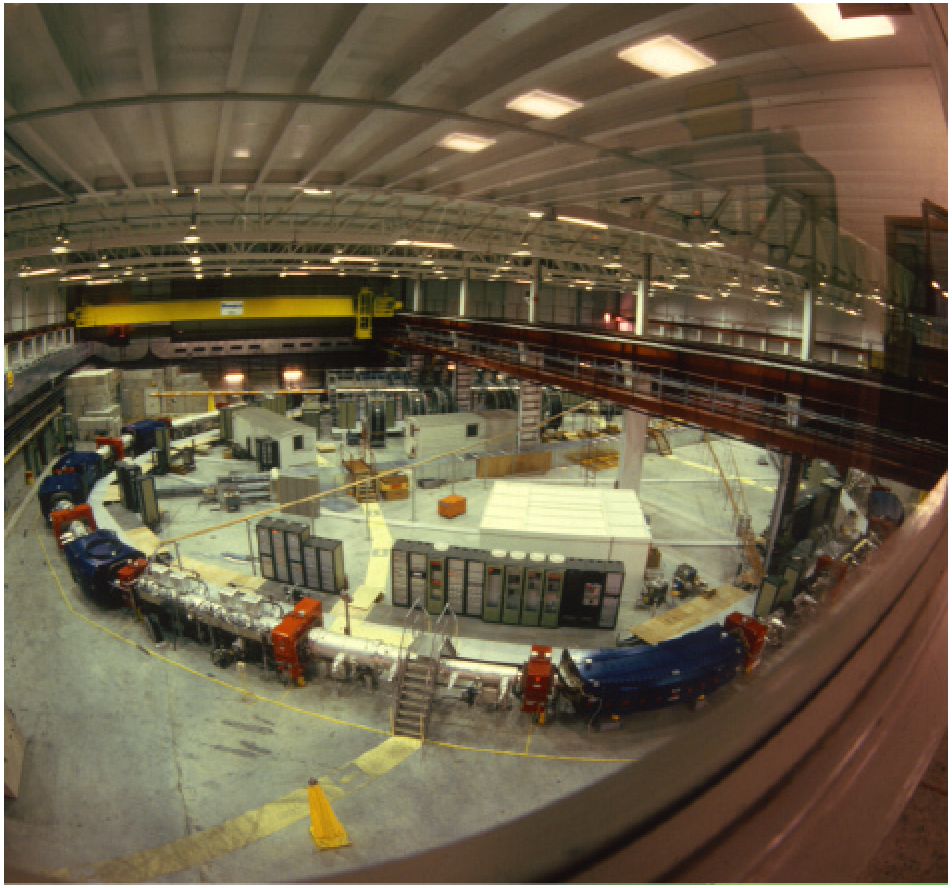
This Talk

- First cold antihydrogen with 131 ± 22 golden events
  →more than 50000 antihydrogen
- Apologies: we were too conservative
- Preliminary results: production of ~1 million antihydrogen with high initial rate >100 Hz
- Many other measurements
- Future Prospects

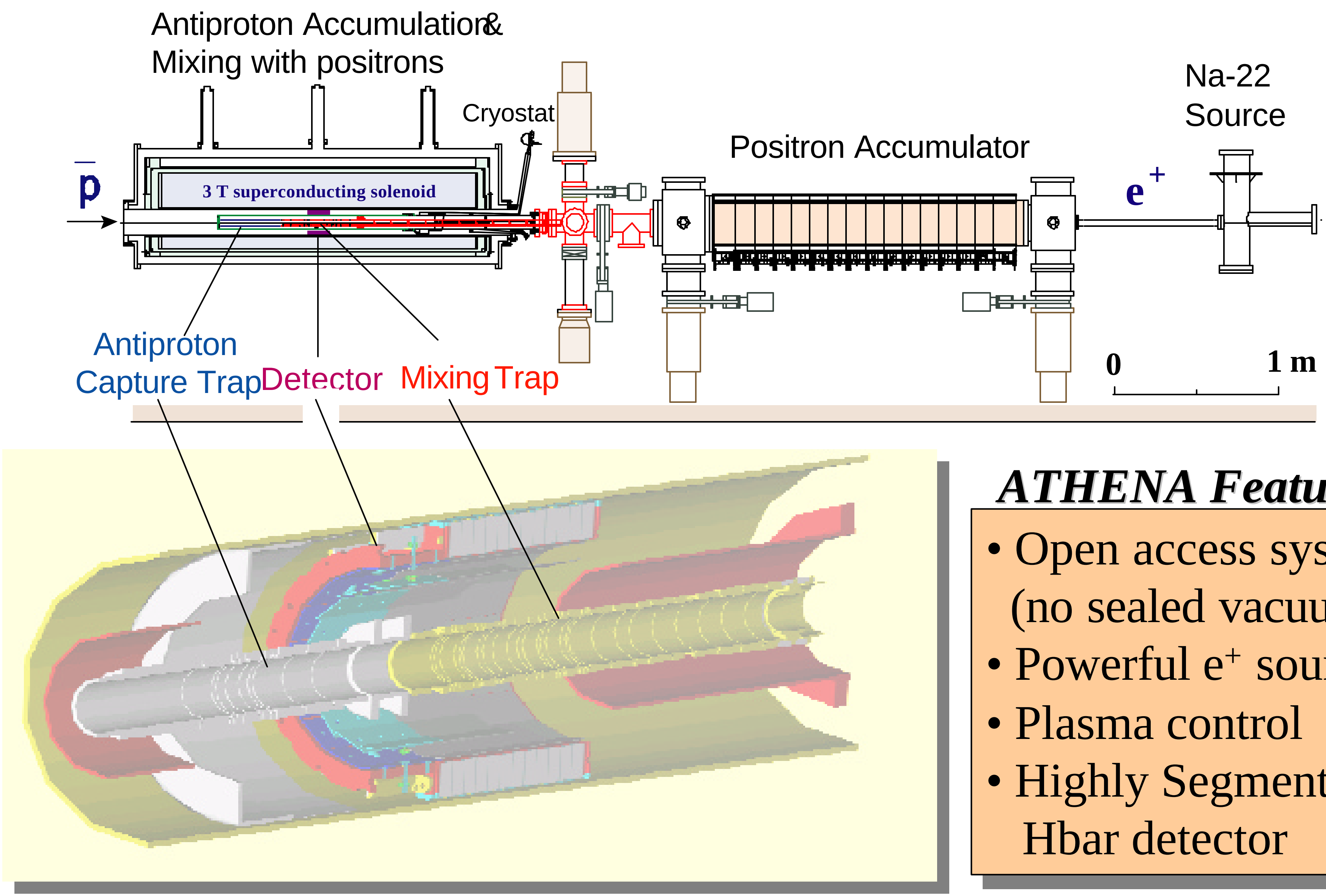
Antiproton Decelerator

1996	Design Report
1996	3 collaborations form
1997	Feb: CERN approval of AD
1997	Jun: SPSC approves EXPTs
2000	July: First data taking at AD

- Economical successor of LEAR
- Made possible by large financial contribution from Japan

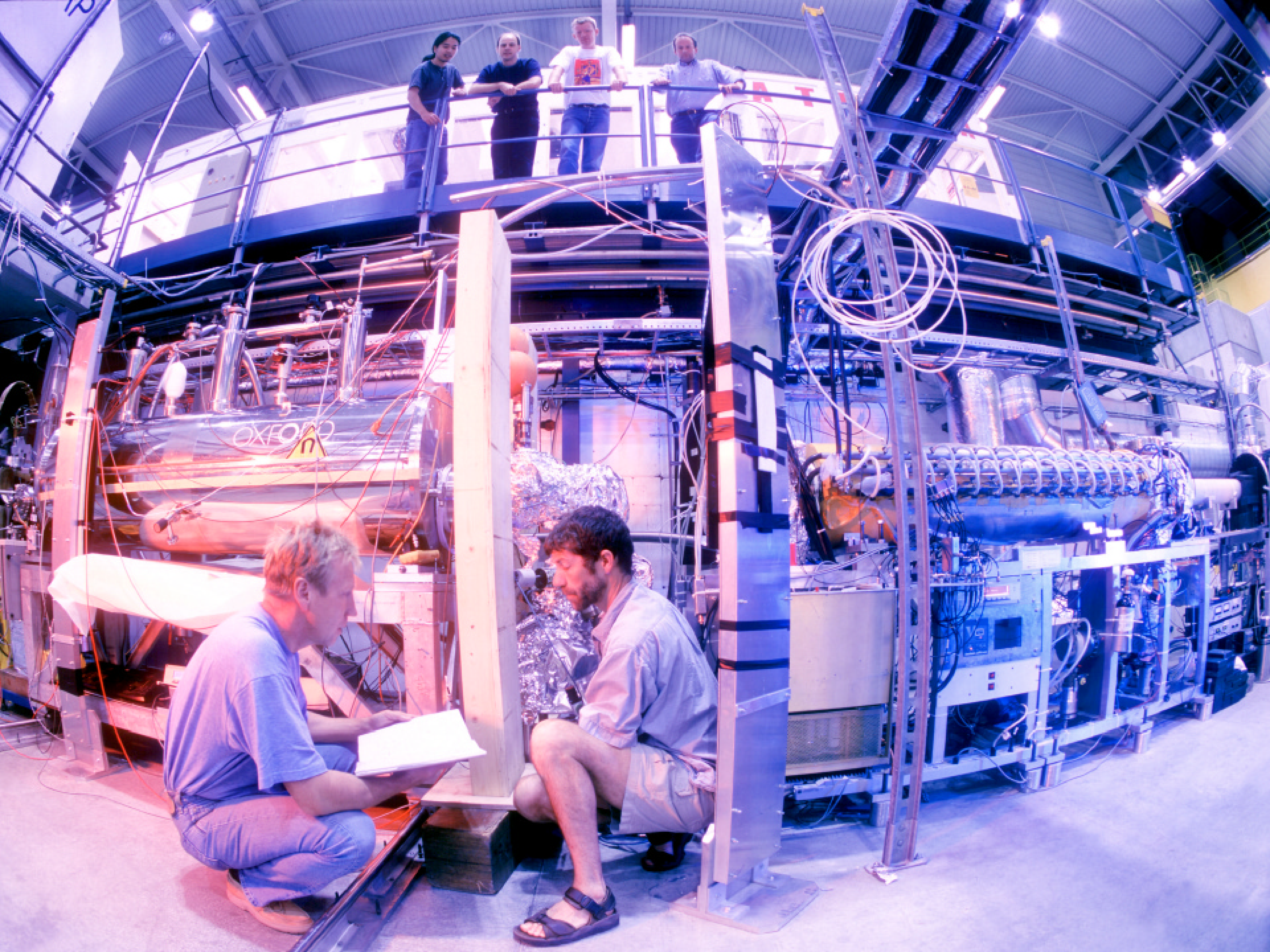


ATHENA Antihydrogen Apparatus



ATHENA Features

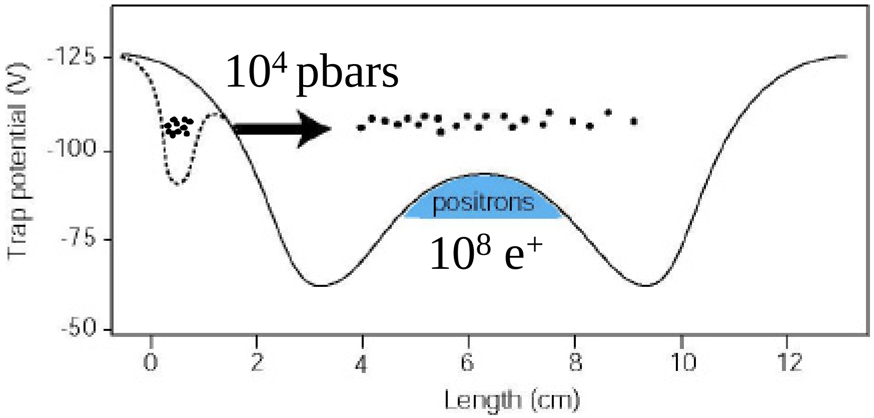
- Open access system (no sealed vacuum)
- Powerful e^+ source
- Plasma control
- Highly Segmented Hbar detector


OXFORD

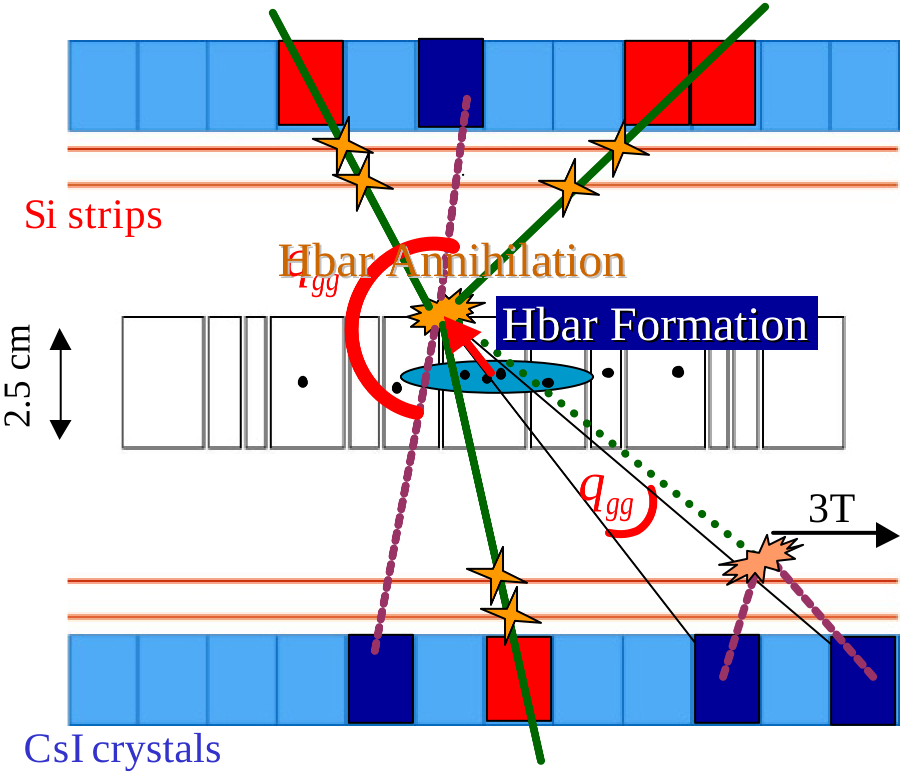
Making of Cold Antihydrogen

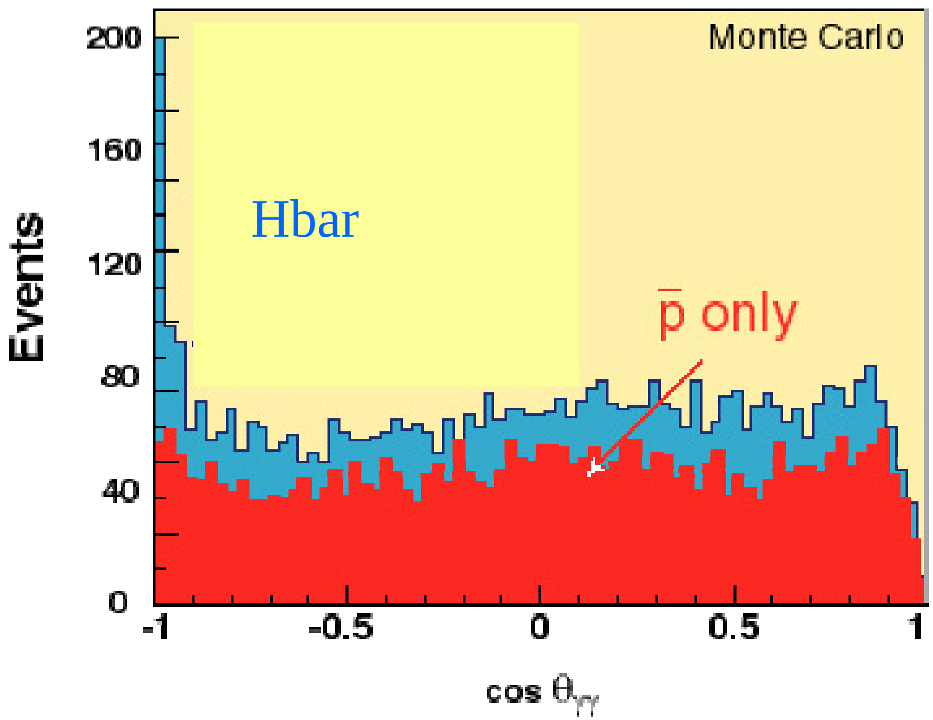
movie

First Cold Antihydrogen August 2002 *ATHENA*

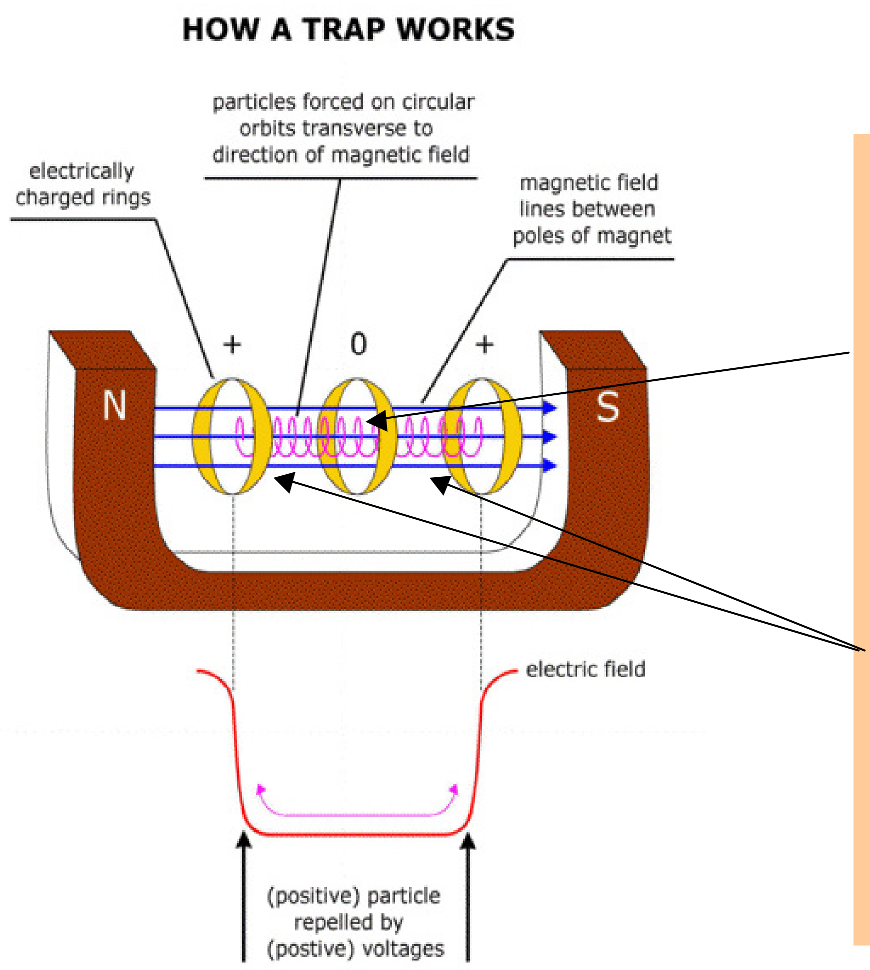


- 10^4 pbars & 10^8 e^+ mixed in Penning trap
- Hbar forms, annihilates on electrode
- pbar annihilates into charged pions
- e^+ annihilates into back-to-back γs
- $\cos(\theta_{\gamma\gamma})$, opening angle of two 511keV gs, seen from the vertex, is plotted
- Neutral pions give uncorrelated background





Trapping charged particles in Penning trap



Example:

Trapped electron at B = 3 T, E = 1 eV, U ~ 10 V

1) **Cyclotron motion** (perpendicular to B)

f = 84 GHz, r ~ 1 µm

Emission of synchrotron radiation + cooling

t_{cool} ~ 0.3 s

2) **Axial motion** (along B)

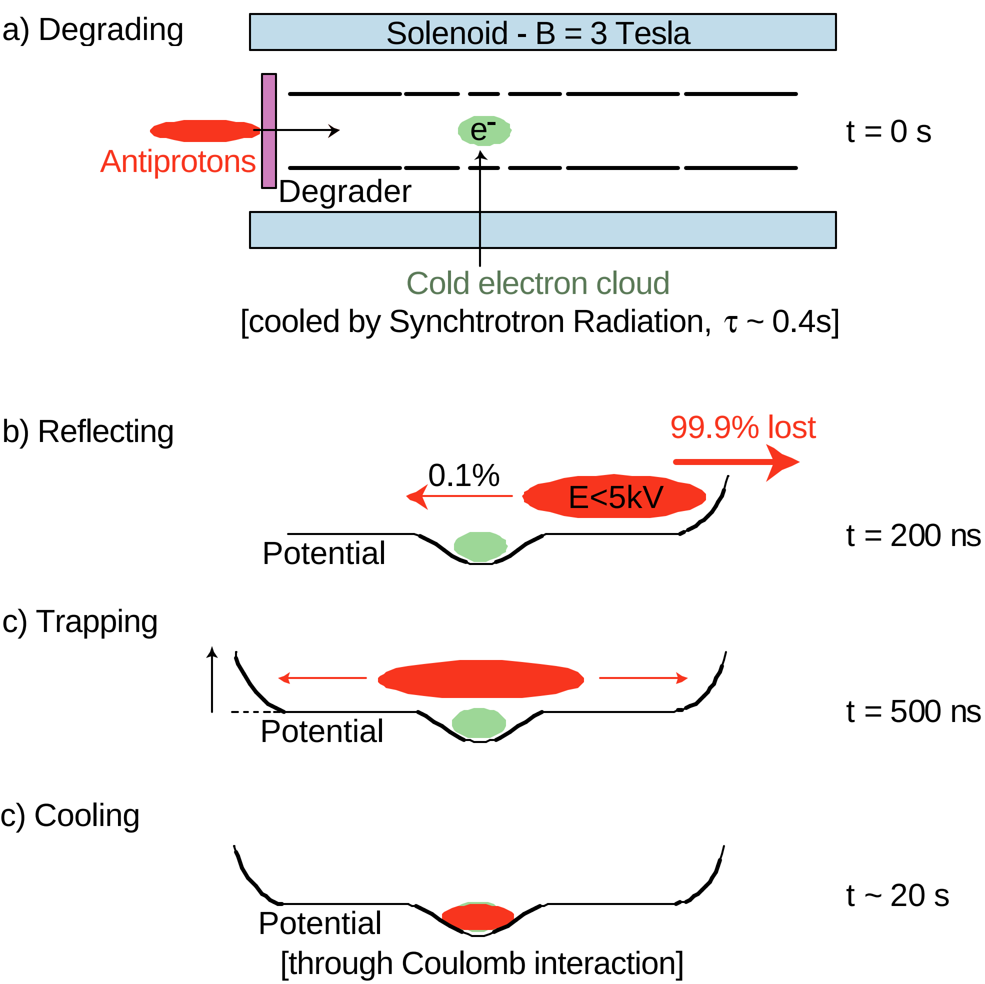
f ~ 7 MHz, d ~µm … cm

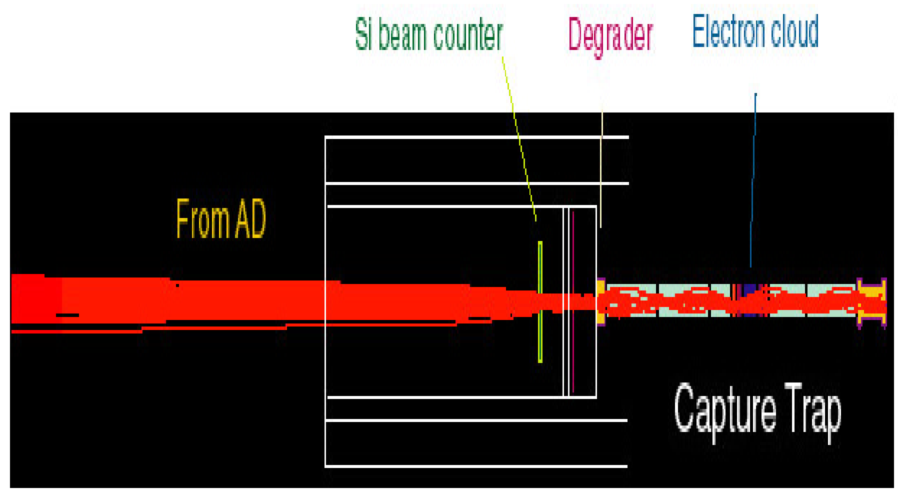
3) **E x B drift** (‘magnetron’)

f ~ kHz, r ~ mm

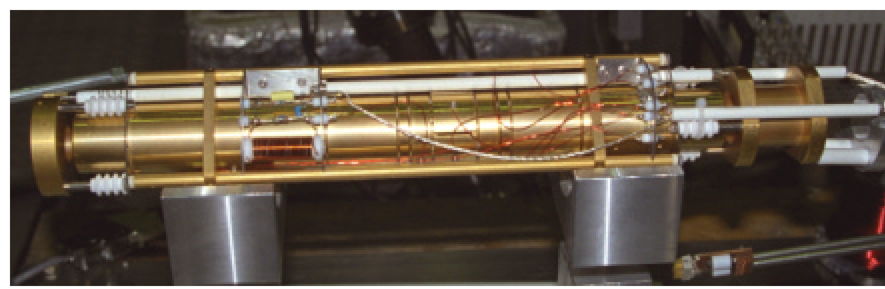
Dissipative vs dynamical trapping

Antiproton Catching & Cooling





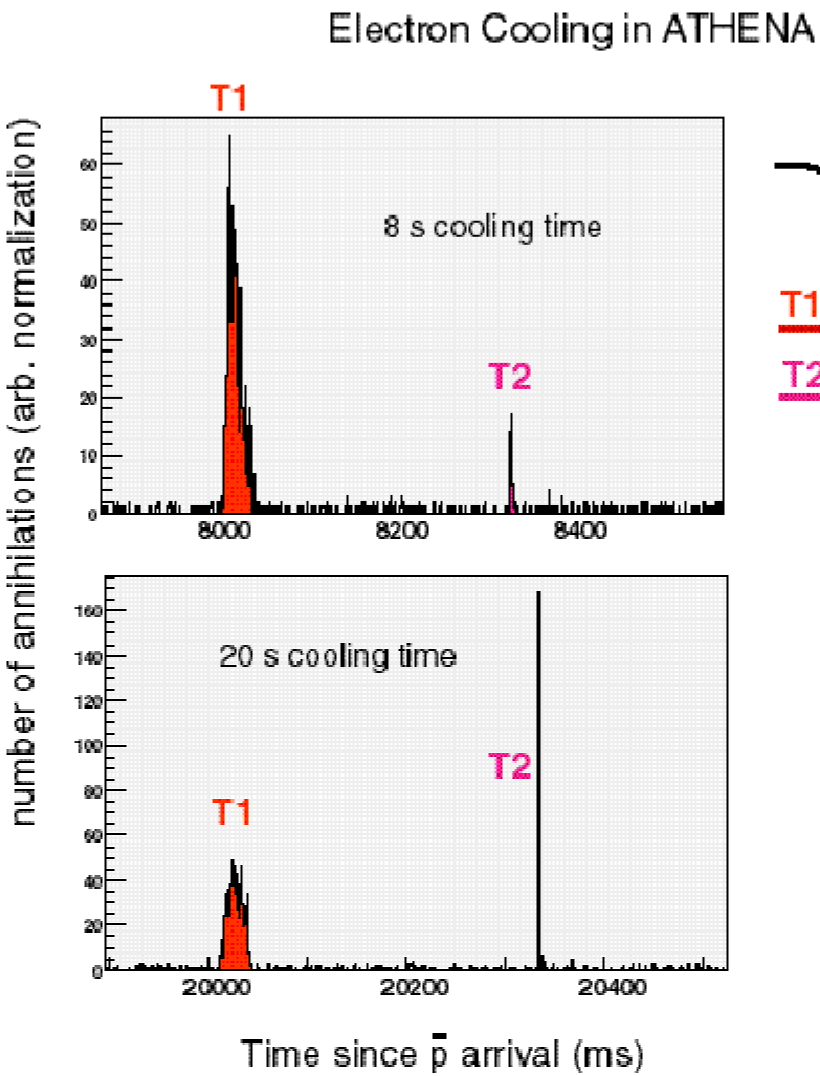
Segmented Si (67 μ) beam counter

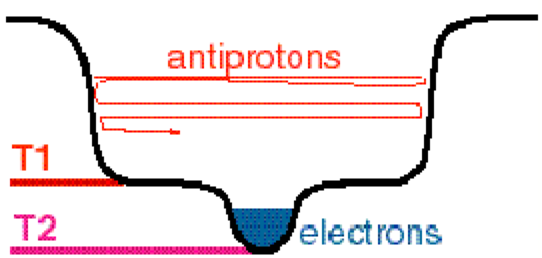


Antiproton Capture Trap

About 10000 antiprotons are captured from an AD shot.

Antiproton Cooling

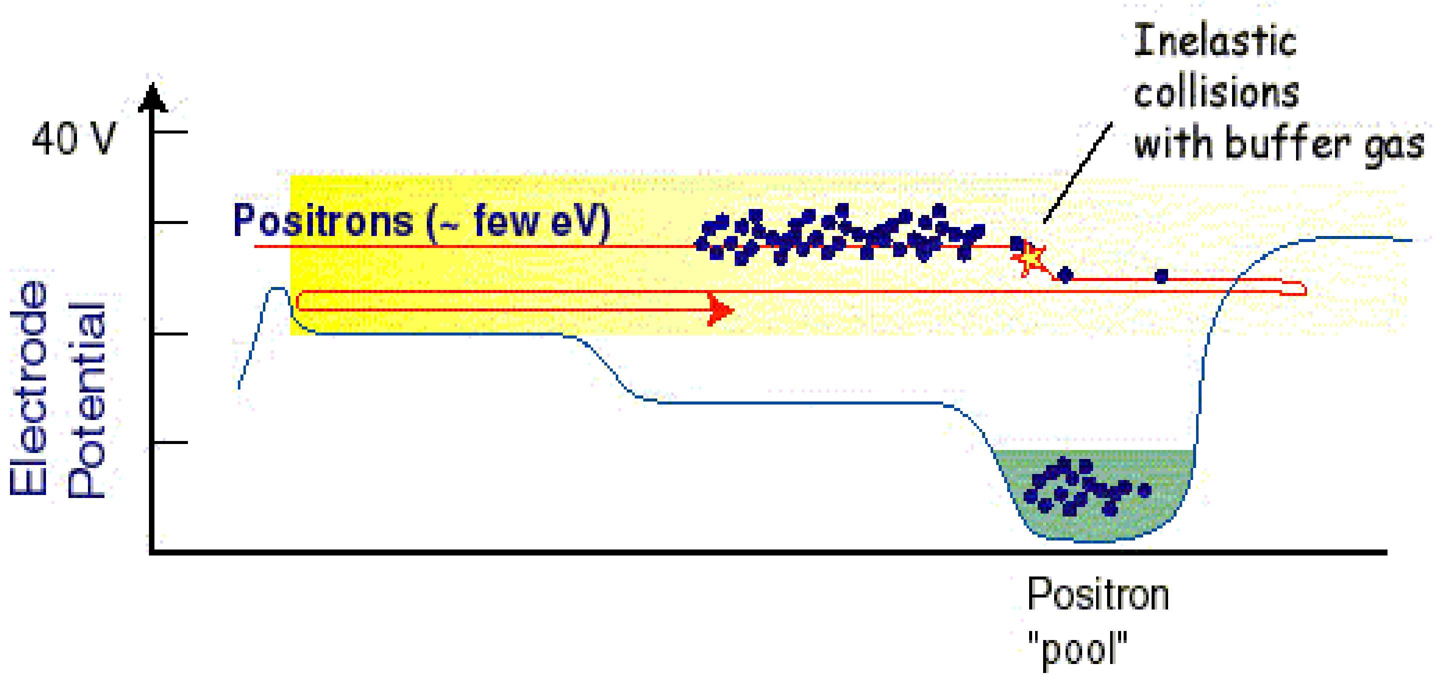




- Cooling time ～20-40 sec
- Cooling efficiency>80%
- Lifetime > 10 h
- Transfer pbars into mixing trap
- Remove electrons

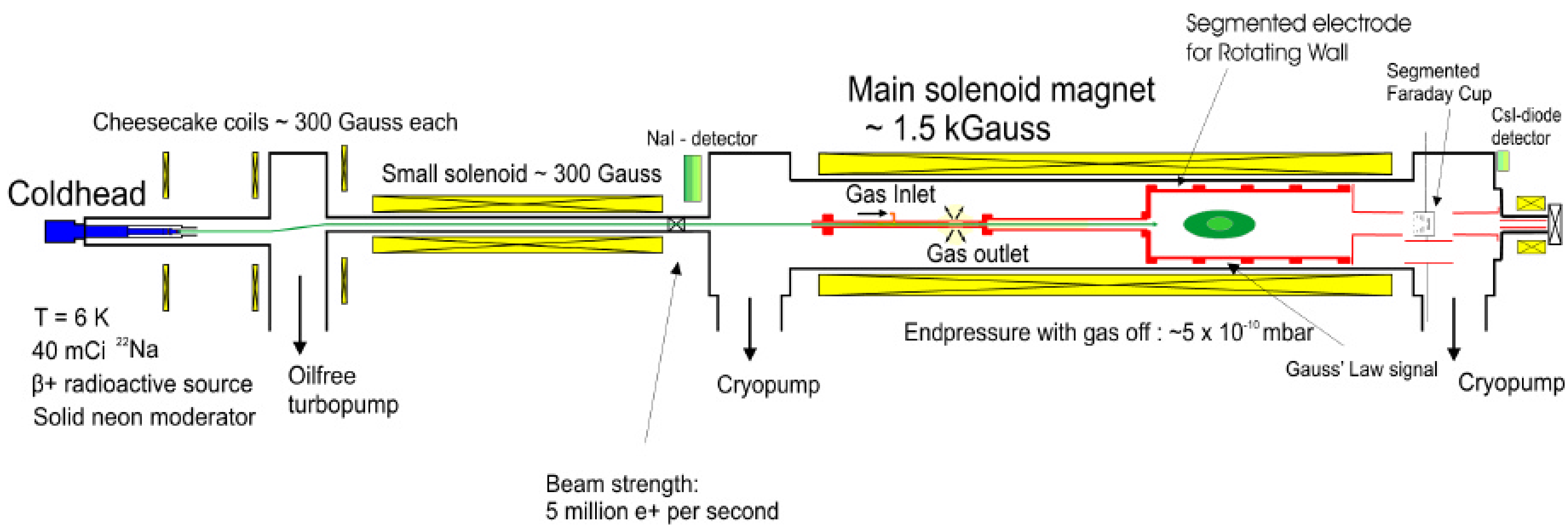
Accumulating Positrons

Dissipative trapping with N_2 buffer gas



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

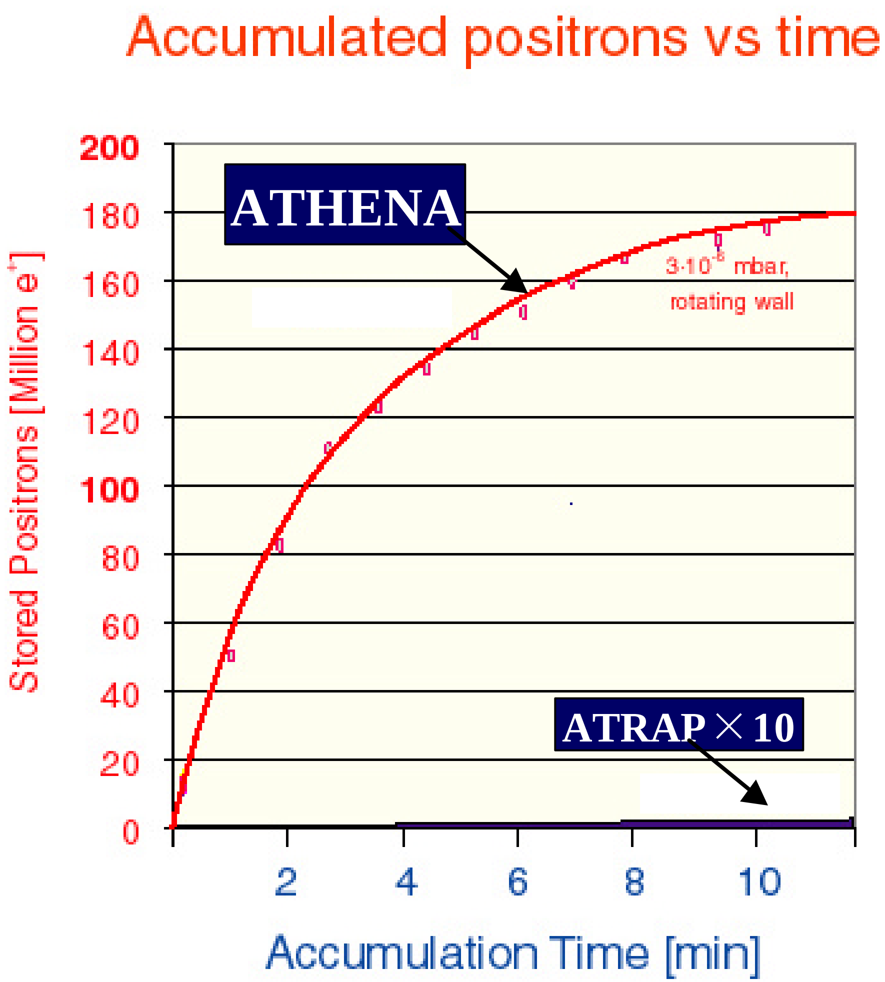
Accumulating Positrons



^{22}Na Source → Solid Ne Moderator → N_2 Buffer Gas Cooling → Plasma Compression → Transfer into 3T magnet

ATHENA Positron Accumulator

Based on buffer gas accumulation method by Surko (Non-neutral plasmas Vol. 3, 3-12; AIP 1999)



Accumulation rate ~ 10^6 e^+/sec

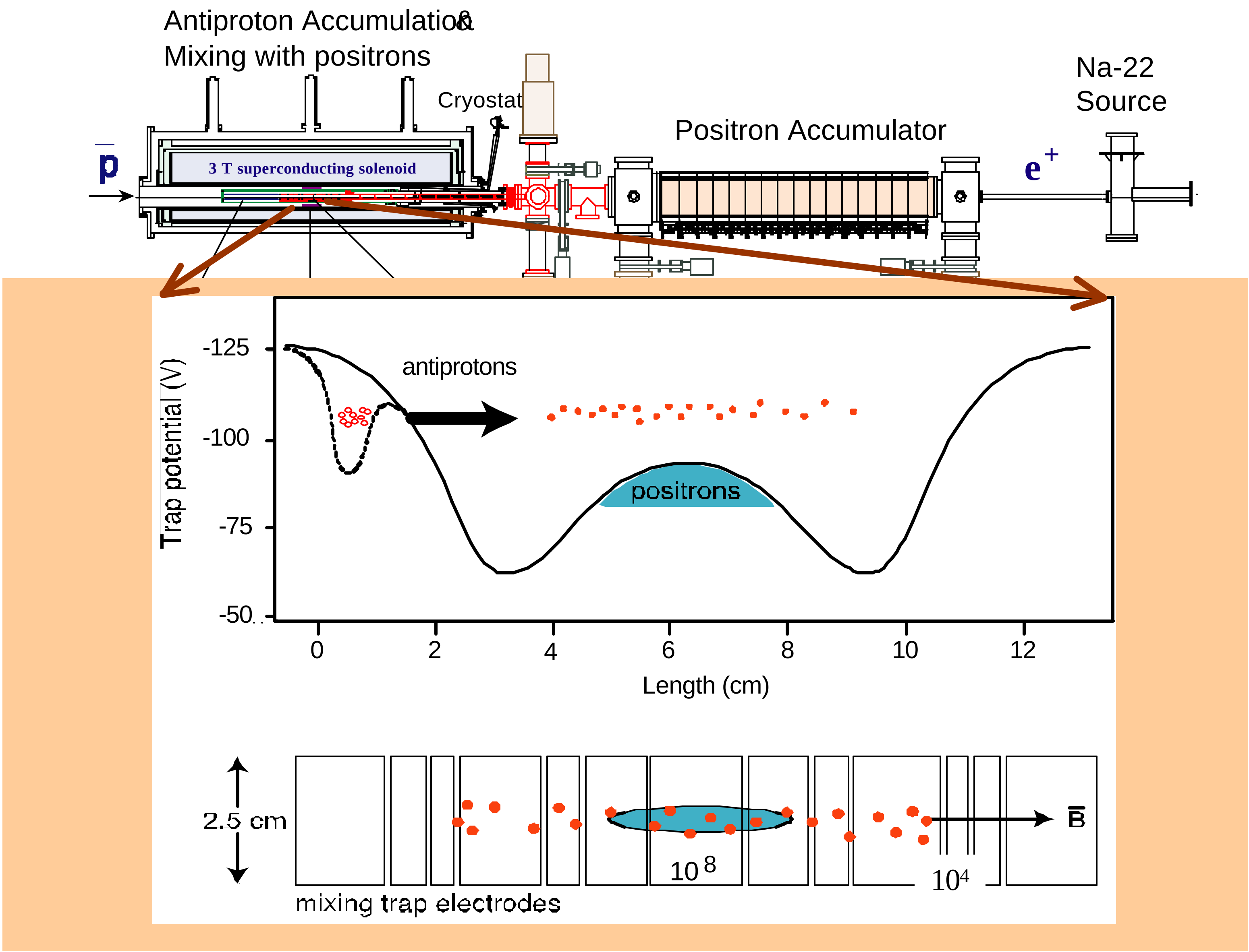
150 million positrons / 5 min

~50% transfer efficiency into 3T

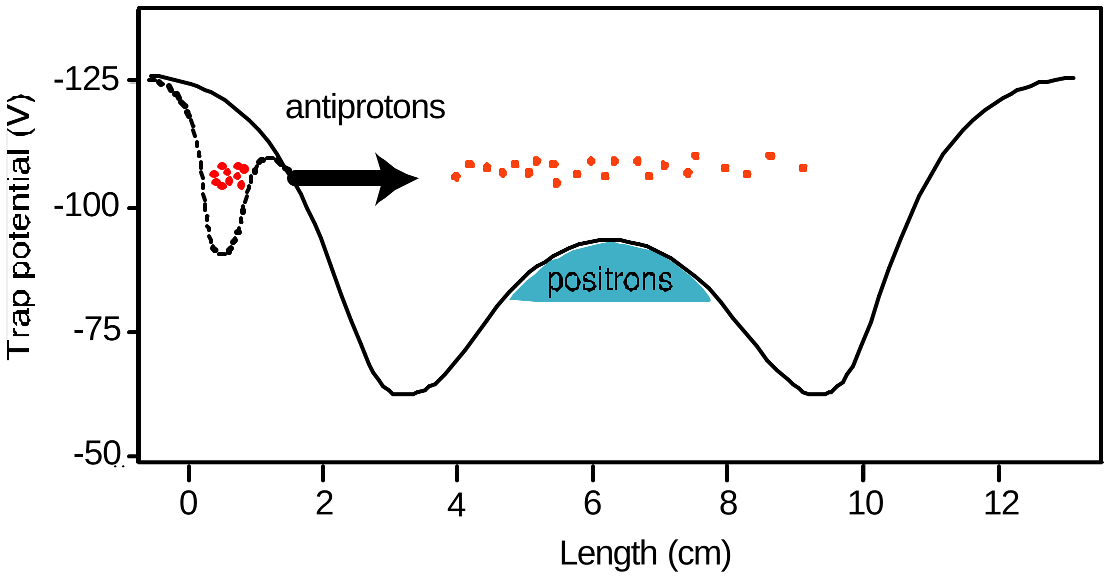
75 million cold e^+ for mixing / 5 min

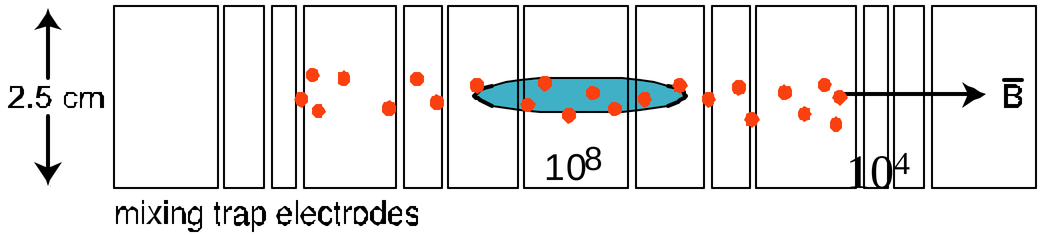
<u>Lifetime: many hours</u>

ATHENA Antihydrogen Apparatus



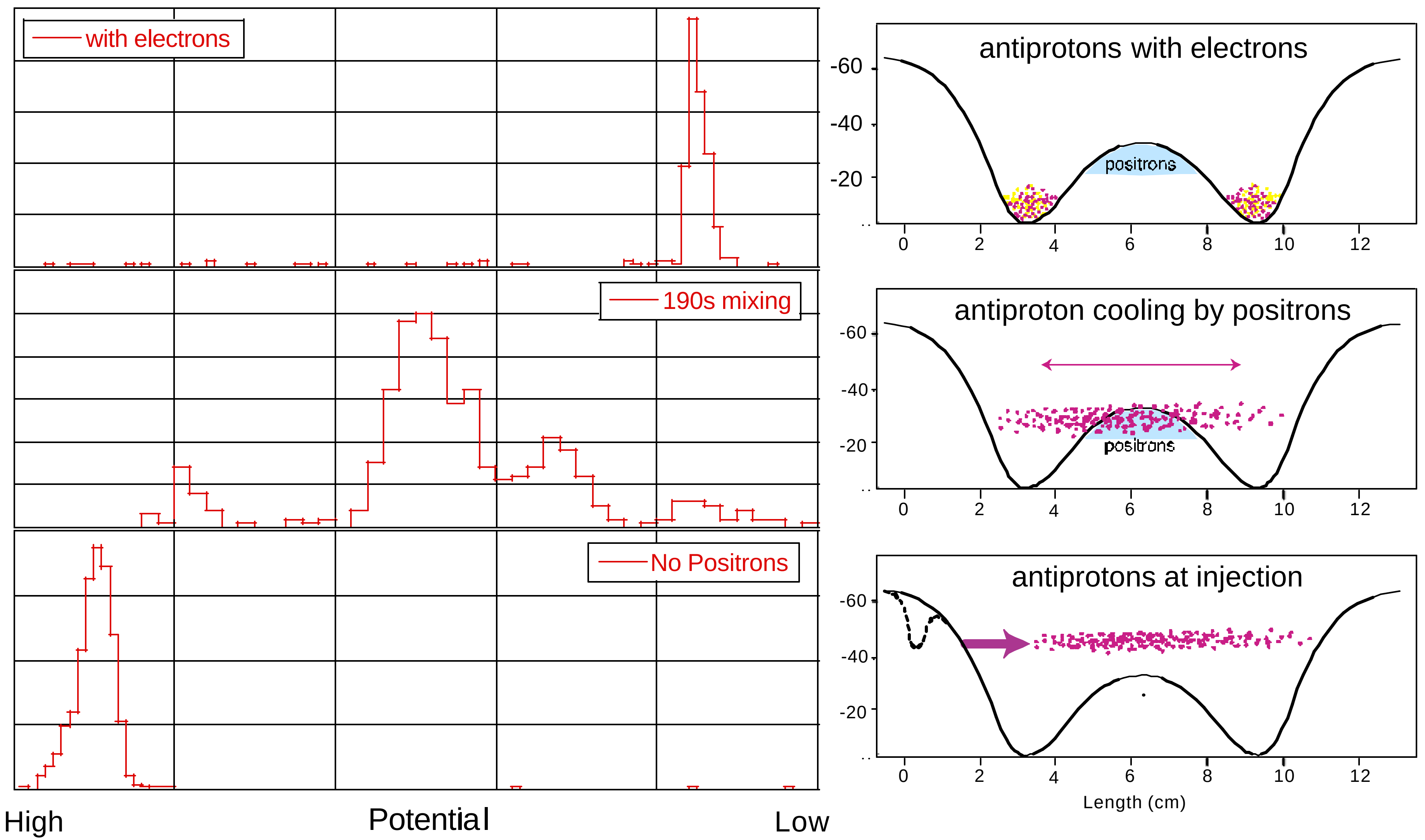
Pbar-Positron Mixing



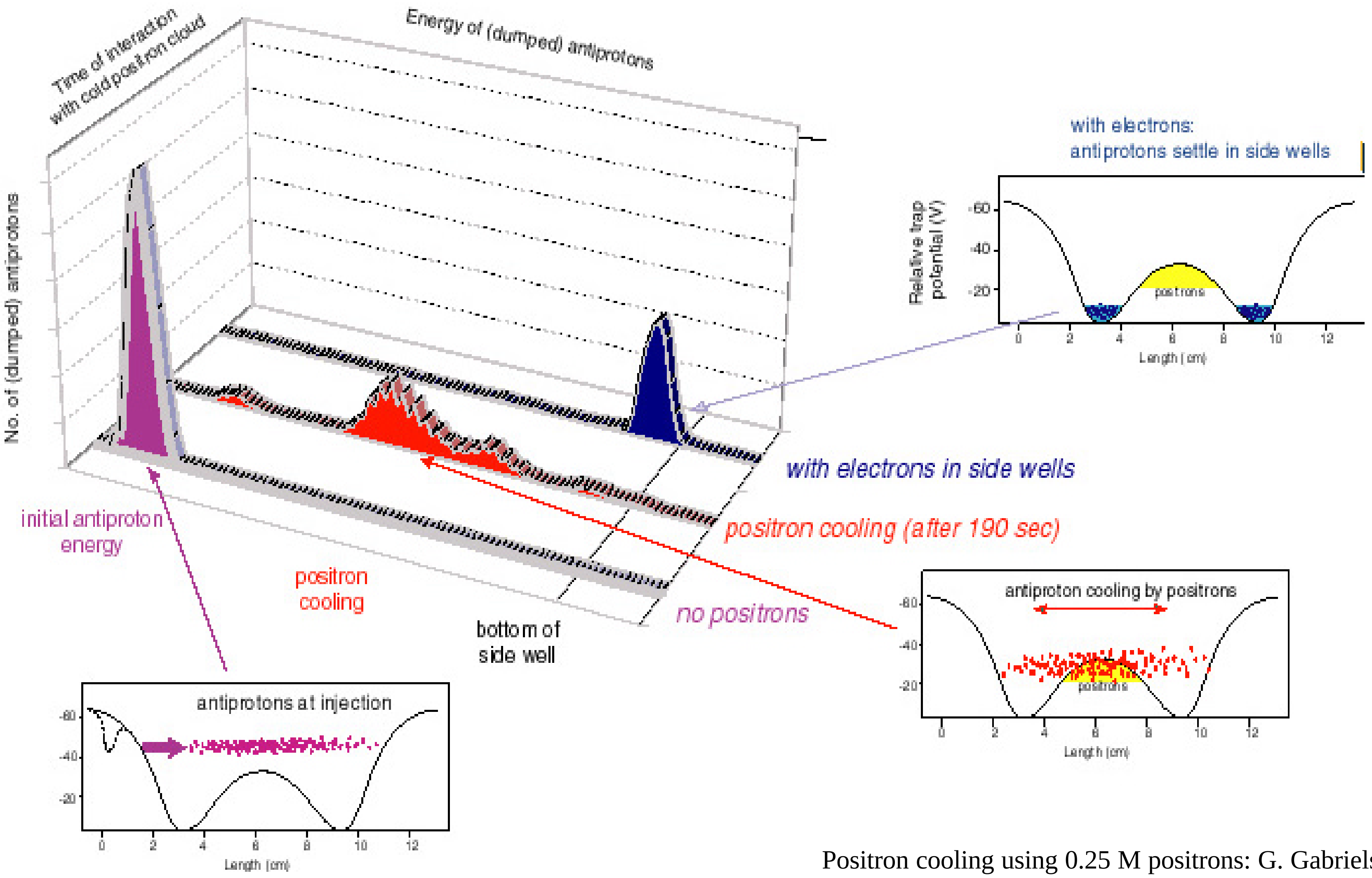


10^4 antiprotons are mixed with 10^8 positrons in a double trap configuration

Antiproton-Positron Interaction



Antiproton-Positron Interactions



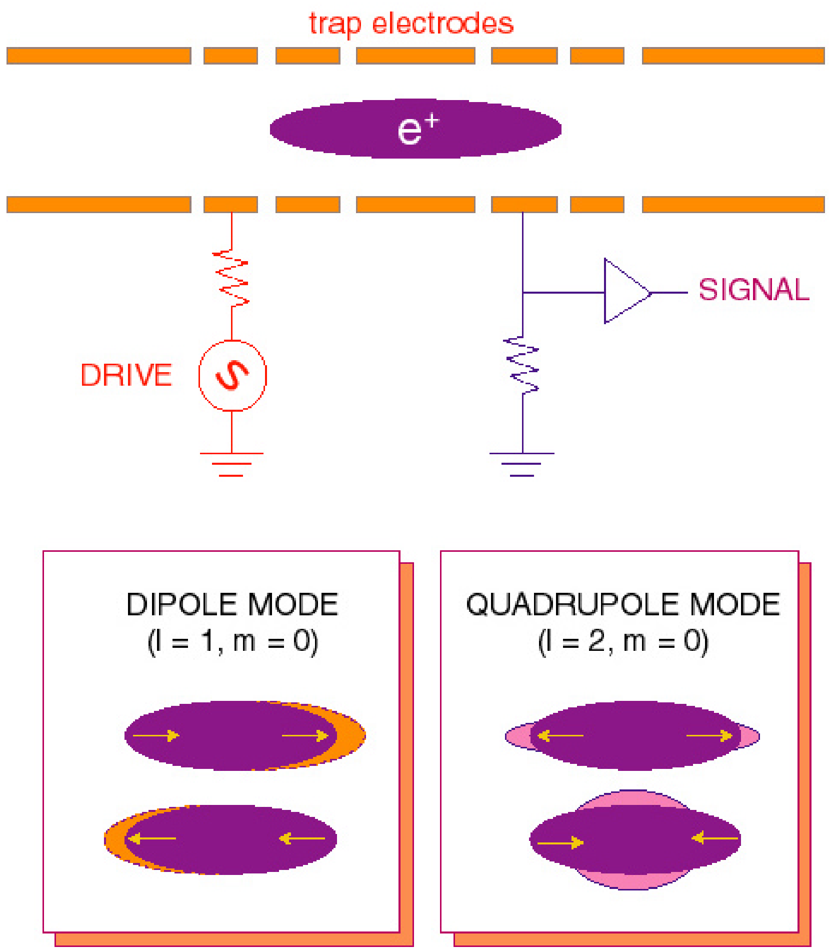
Positron cooling using 0.25 M positrons: G. Gabrielse et al.

Phys.Lett. B507,1 (2001)

Novel Plasma Diagnosis and Control

PLASMA MODES DIAGNOSTICS

Submitted to *Phys. Rev. Lett.*



Equivalent Circuit Model

Resonant RF Plasma Heating

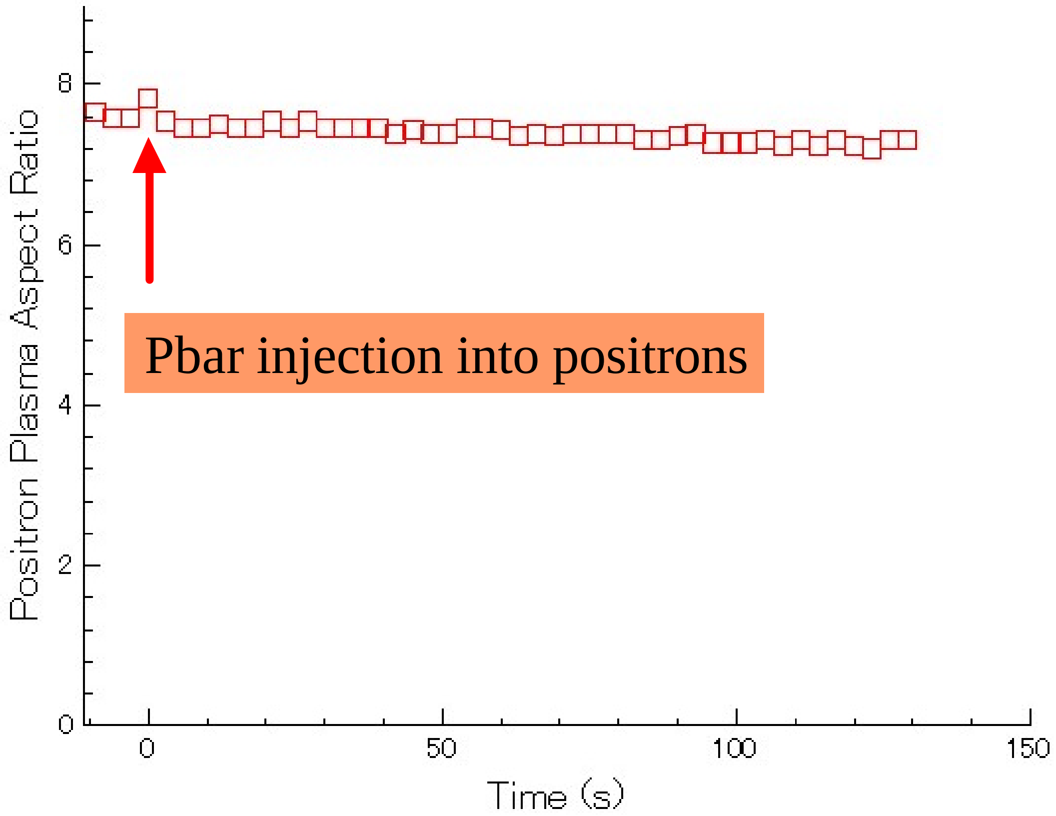
Non-destructive
Simultaneous
determination

Plasma Shape, Density,
Particle Number,
Temperature

Monitoring of plasma → no change due to pbars

10^4 pbars: small perturbation to 10^8 e^+

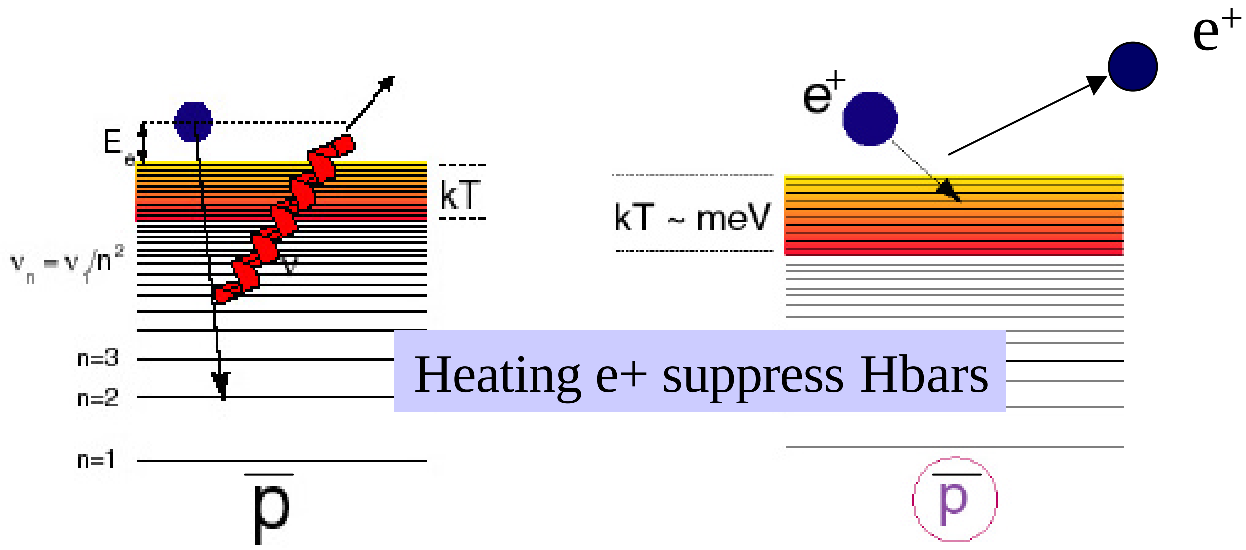
Plasma Modes Measurement during Mixing



- **No significant changes in e+ plasma shape due to pbar injection**
- **gamma detector rates consistent with hbars**

- **No evidence for anomalous plasma transport due to pbars**

Formation Processes

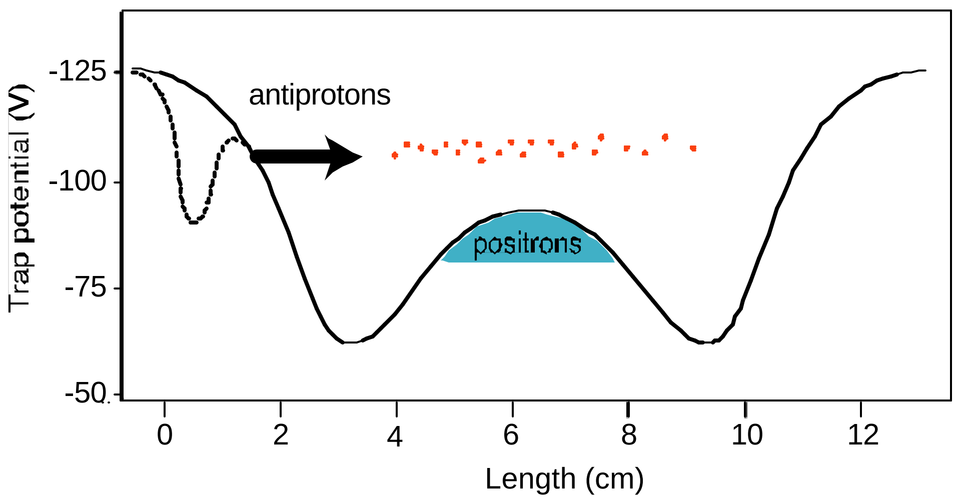


Energy-momentum conservation requires 3rd body

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

Antihydrogen Production

1. Fill positron well in mixing region with $75 \cdot 10^6$ positrons
2. Launch 10^4 antiprotons into mixing region
3. Mixing time 190 sec - continuous monitoring by detector
4. Repeat cycle every 5 minutes (data for 165 cycles)



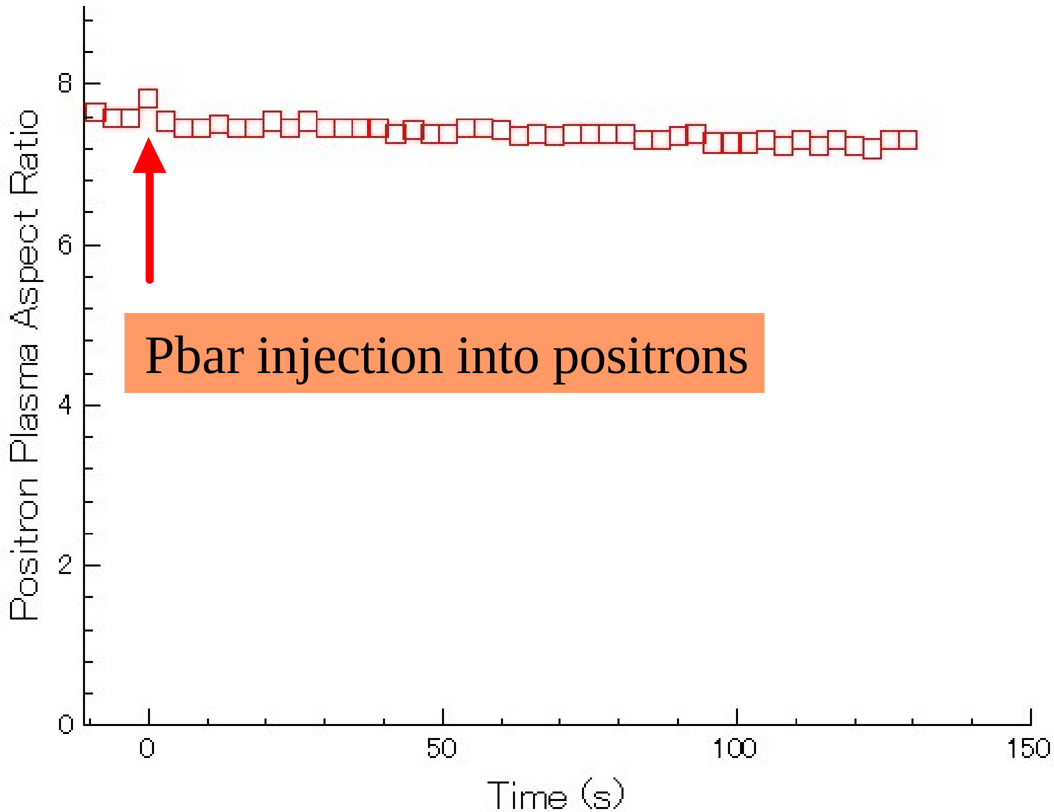
For comparison:

“hot” mixing = continuous RF heating of positron cloud

(suppression of formation)

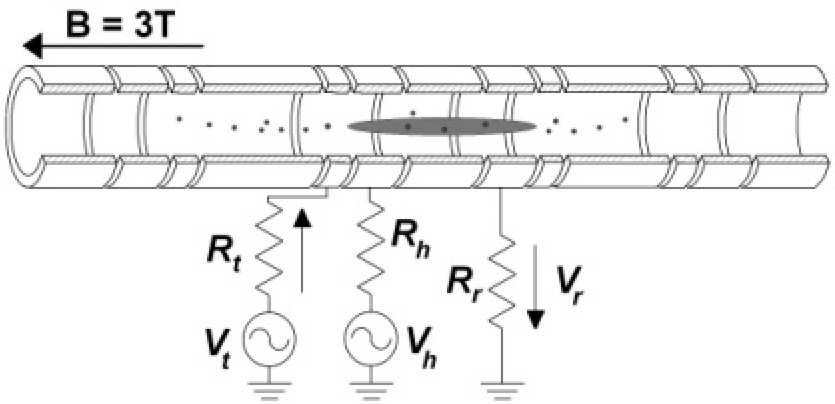
10^4 pbars: small perturbation to 10^8 e^+

Plasma Modes Measurement during Mixing



- No significant changes in e+ plasma shape due to pbar injection
- gamma detector rates consistent with hbars
- No evidence for anomalous plasma transport due to pbars

Novel Plasma Diagnosis and Control



Submitted to *Phys. Rev. Lett.*

Equivalent Circuit Model

Resonant RF Plasma Heating

Non-destructive
Simultaneous
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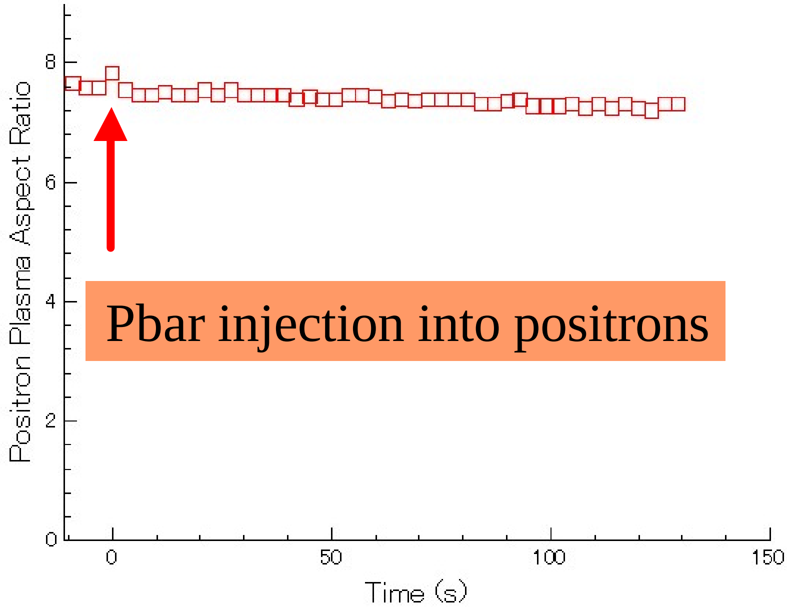
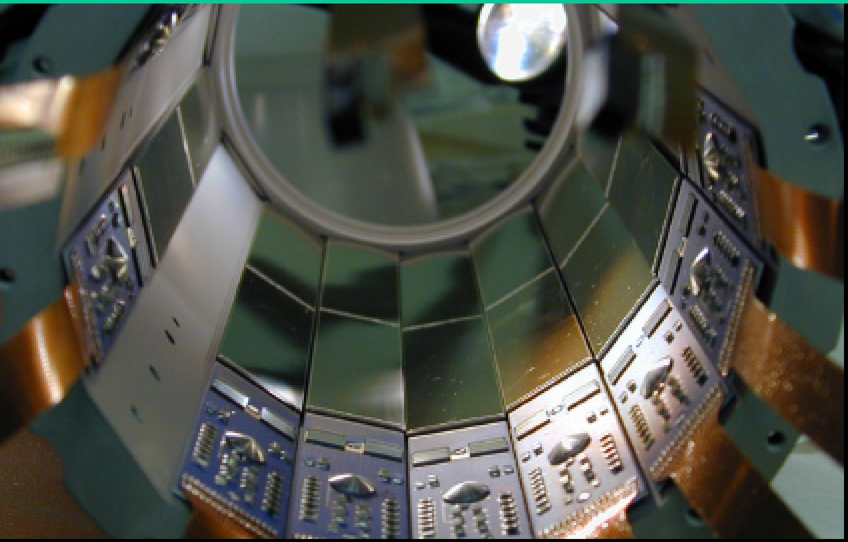
Plasma Shape, Density, Particle Number, Temperature



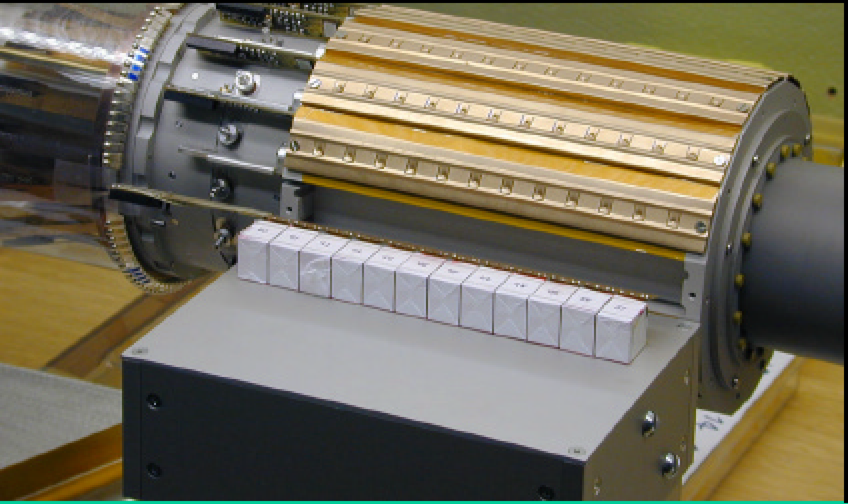
Monitoring of plasma → no change due to pbars

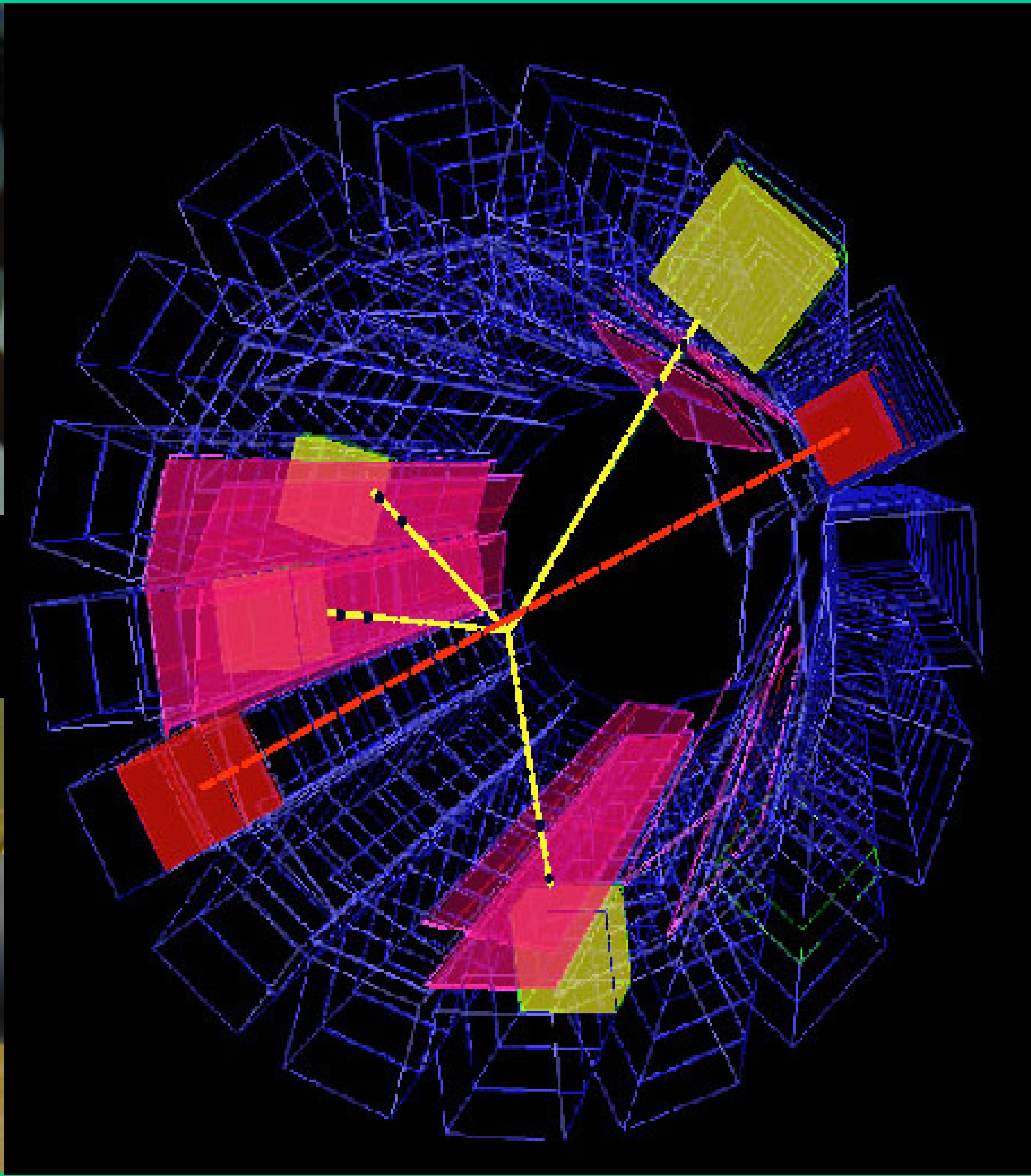
See Poster by Ryo Funakoshi

ATHENA Antihydrogen Detector

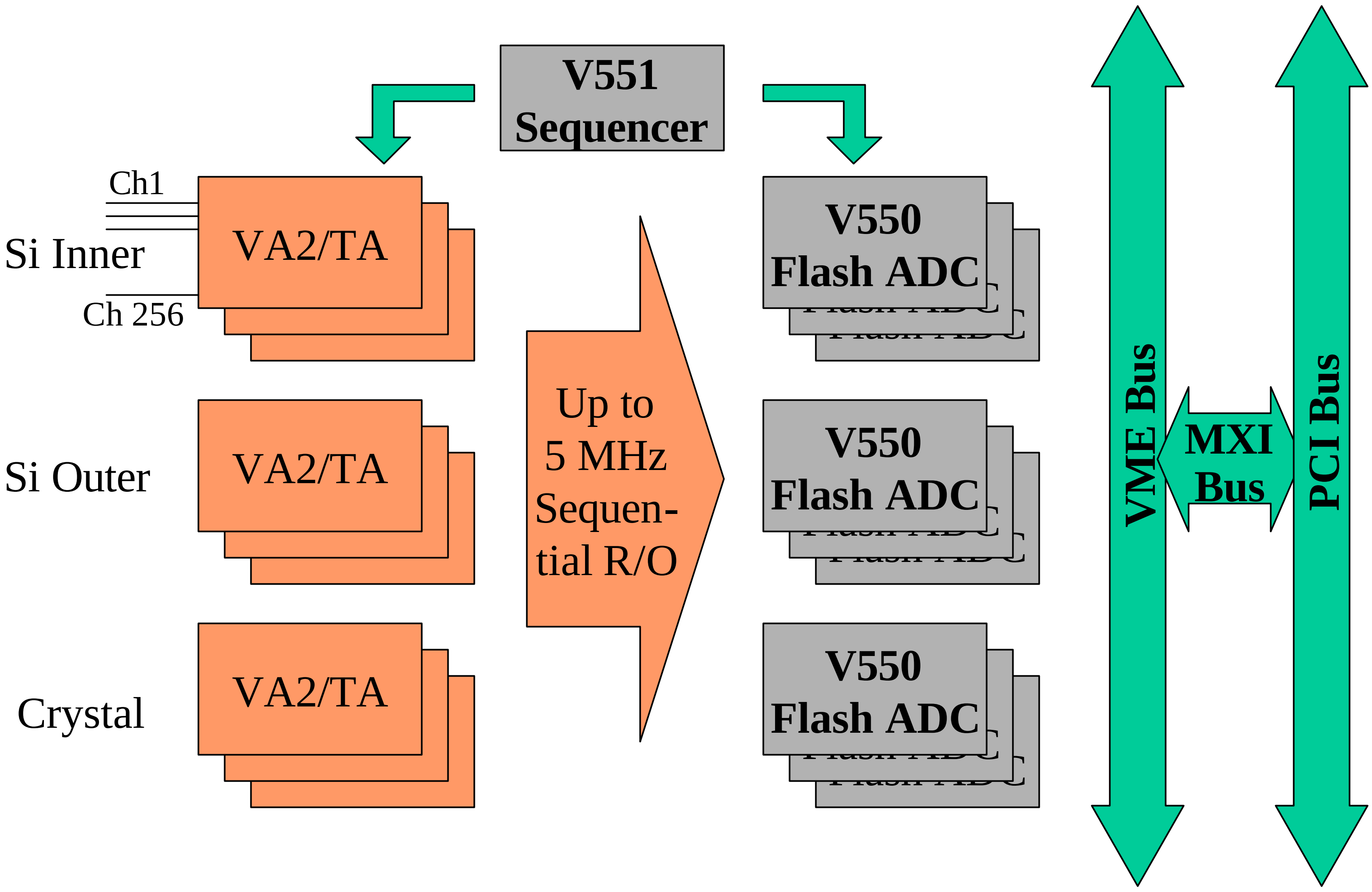


Operated at 140K, 3T, small space
- Si microstrips: 2 layers ~8000 ch
- CsI read out by APD: 192 ch

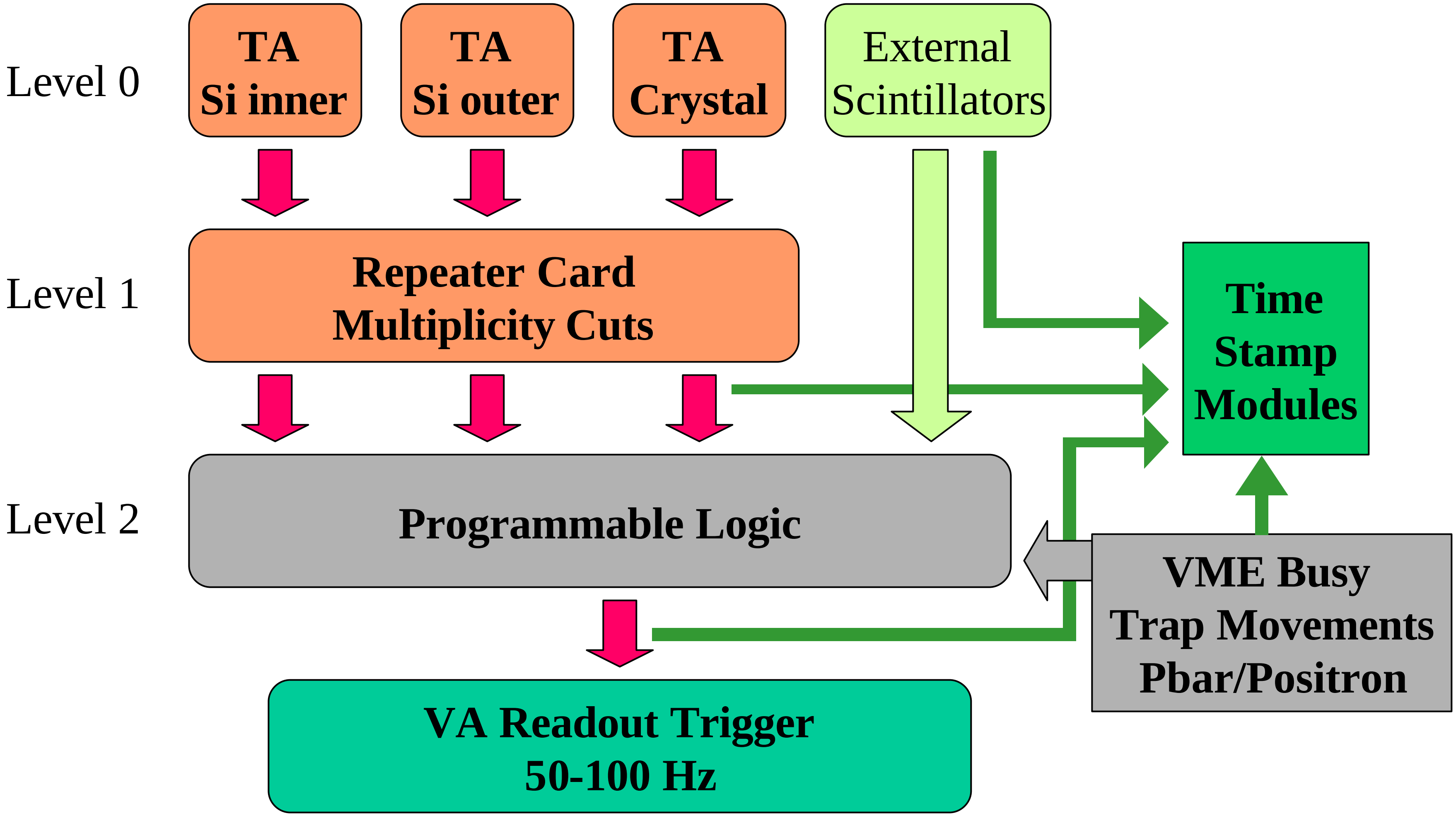




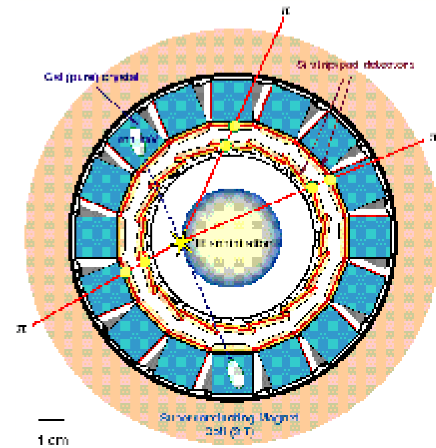
Detector Readout Scheme



Main Trigger Scheme

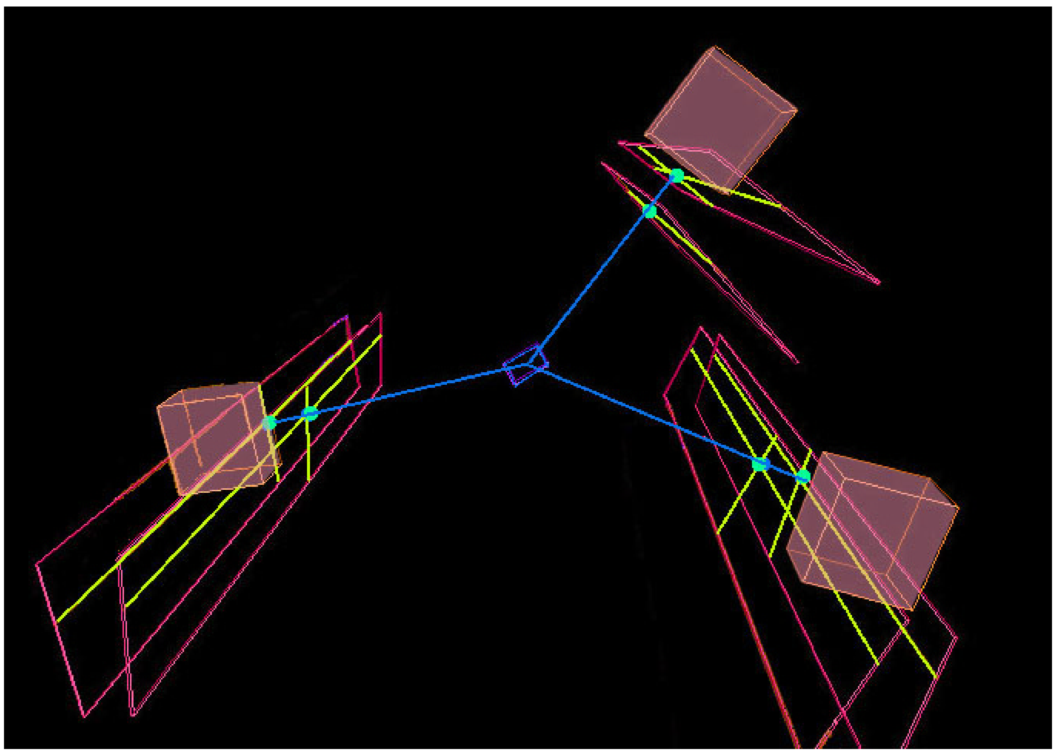


Antihydrogen Detector – Antiprotons Vertex

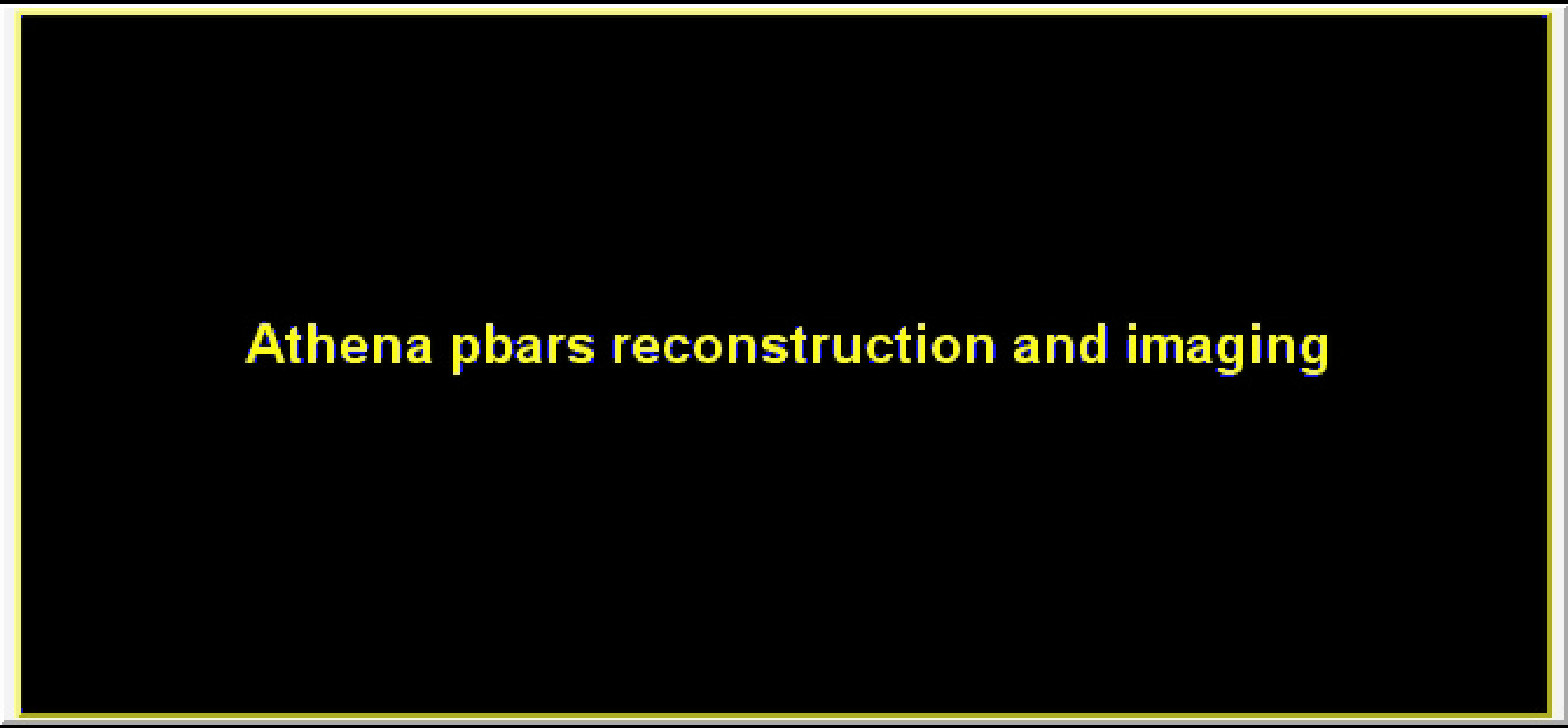


Antiproton Annihilation (example)

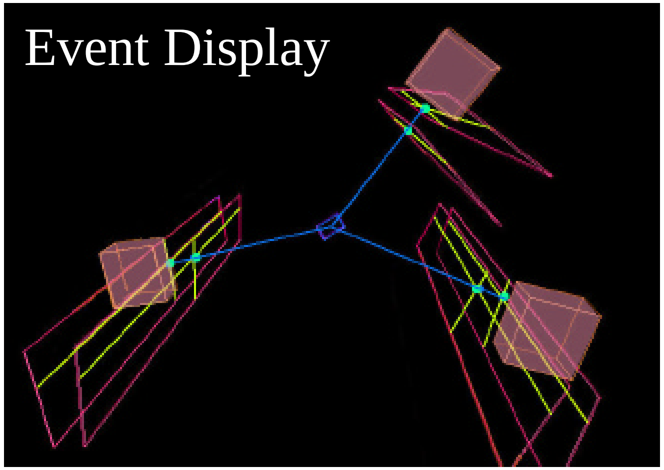
- into three charged particles
- hits on strips (r-phi) and pads (z) , inner/outer layer
- 3 crystals hit by tracks
- vertex reconstruction s ~ 3-4 mm (curvature @ 3 T)



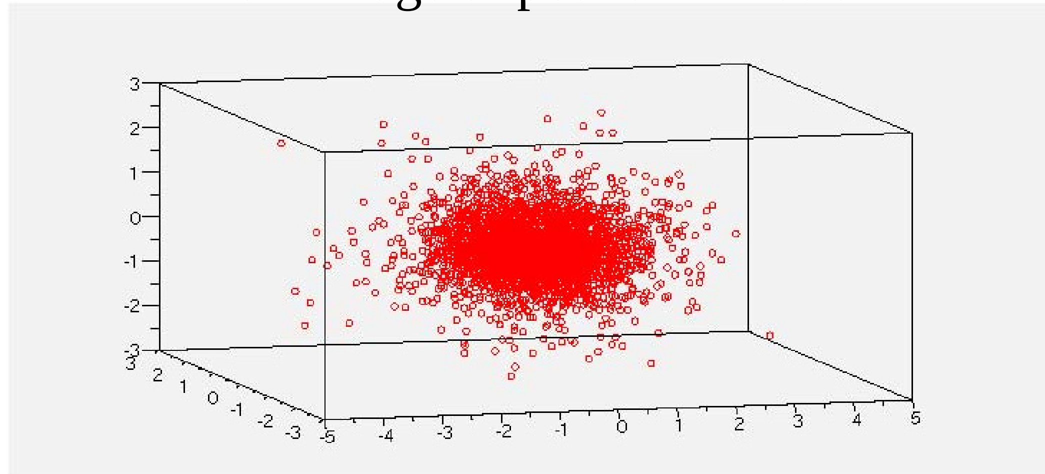
Real-time pbar annihilation imaging



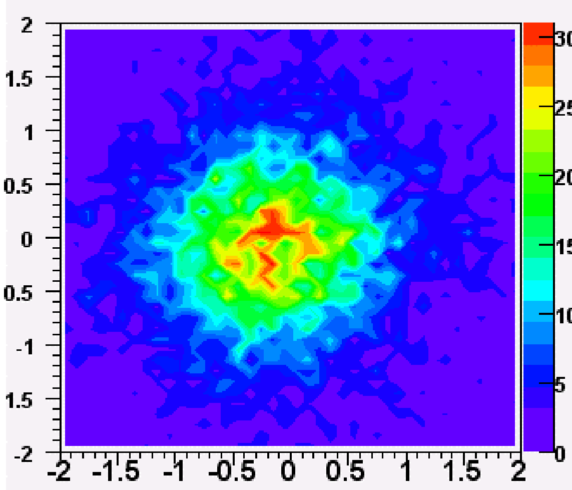
Real-time Antiproton Imaging *to be published*



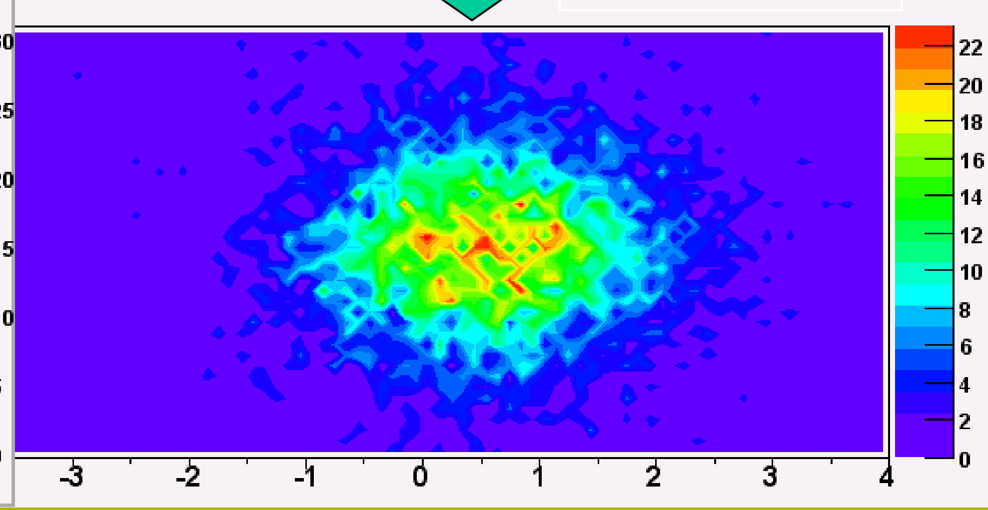
3D Image of pbar annihilation



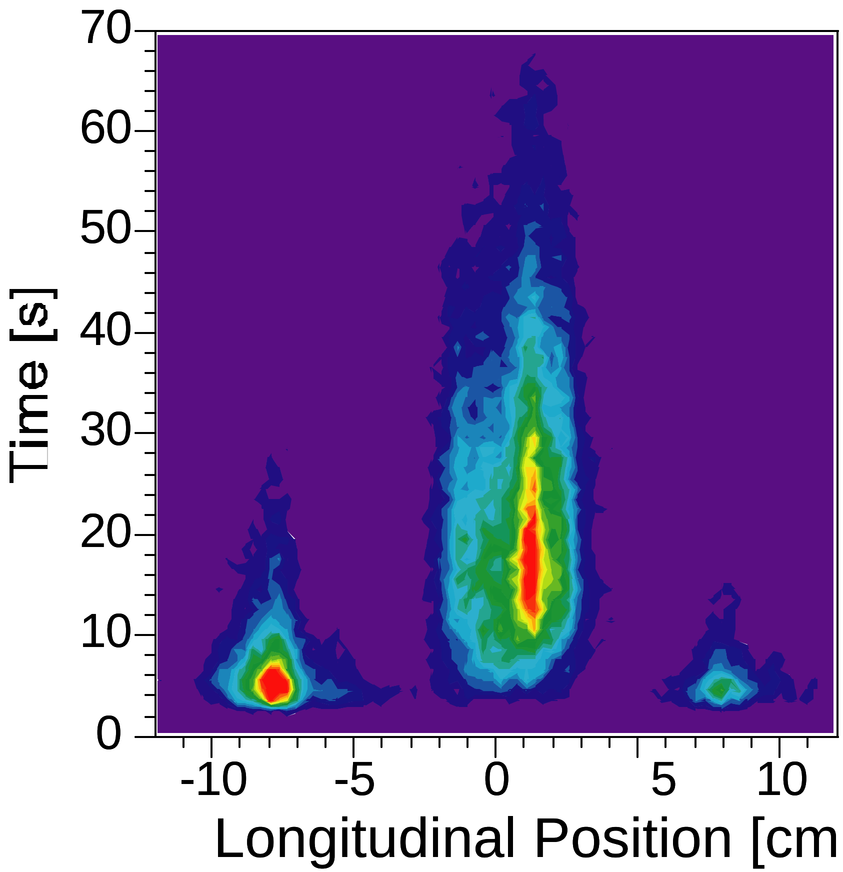
XY projection

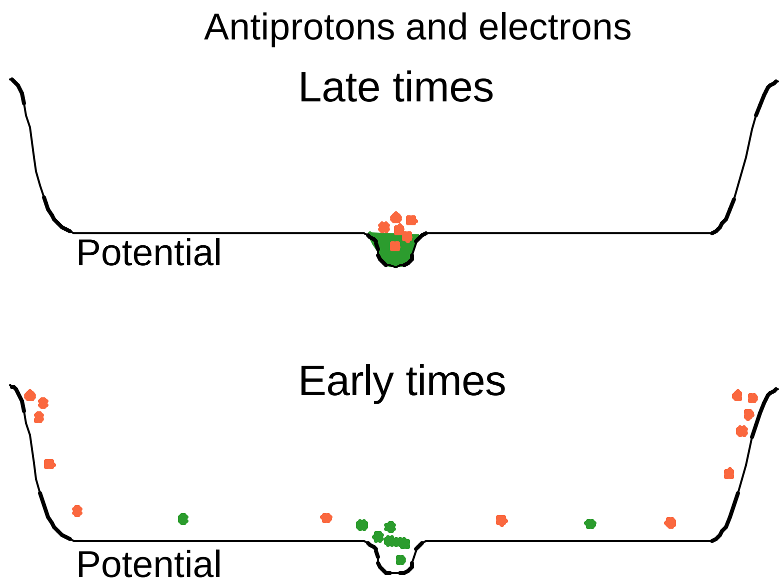


YZ projection



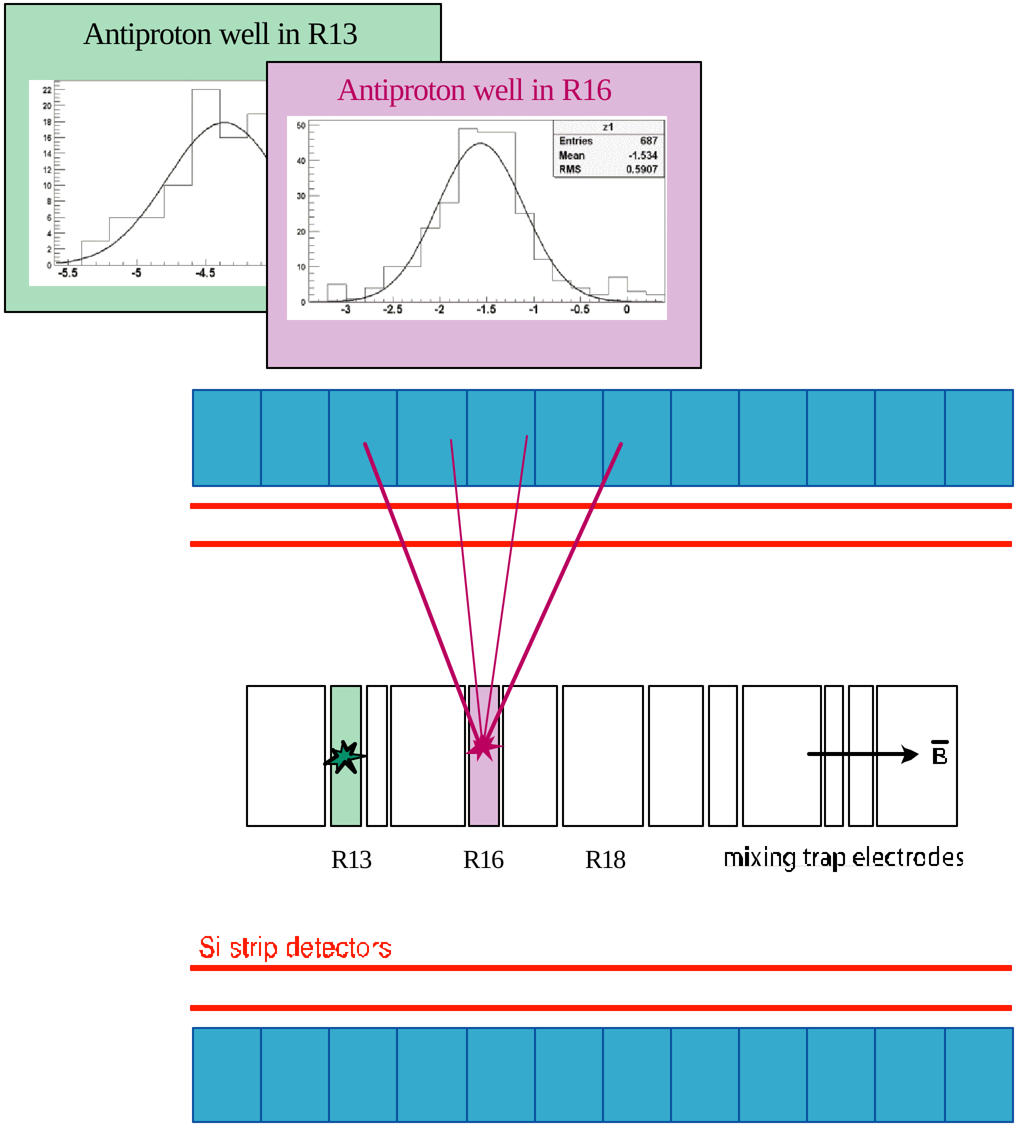
Time-Dependent Plasma Visualization

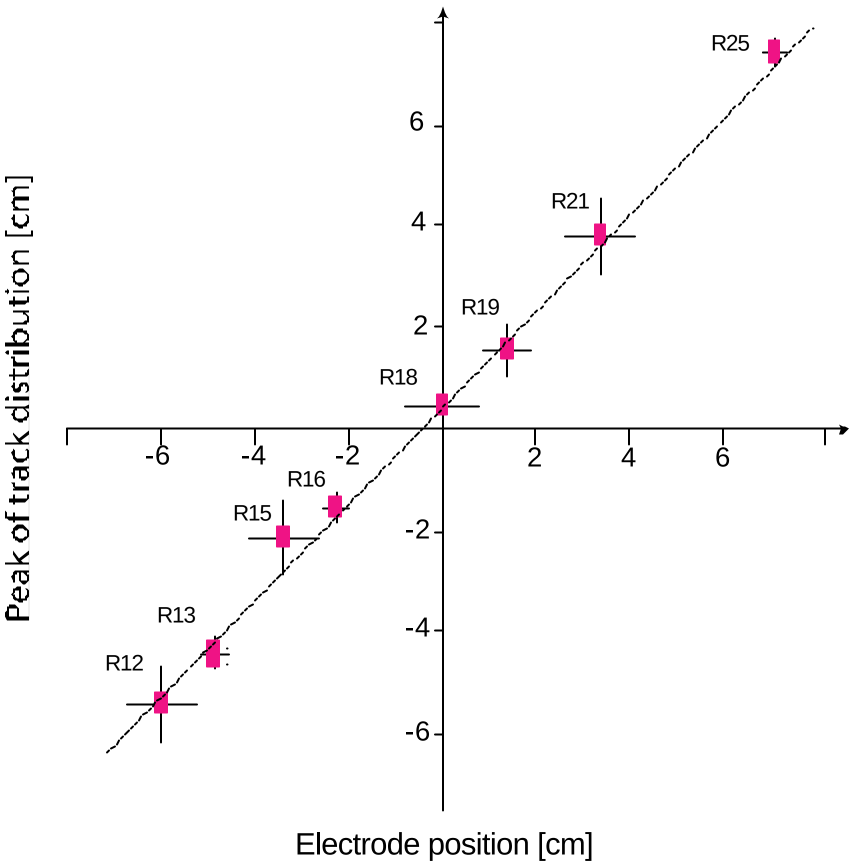




Powerful plasma and loss diagnostics !

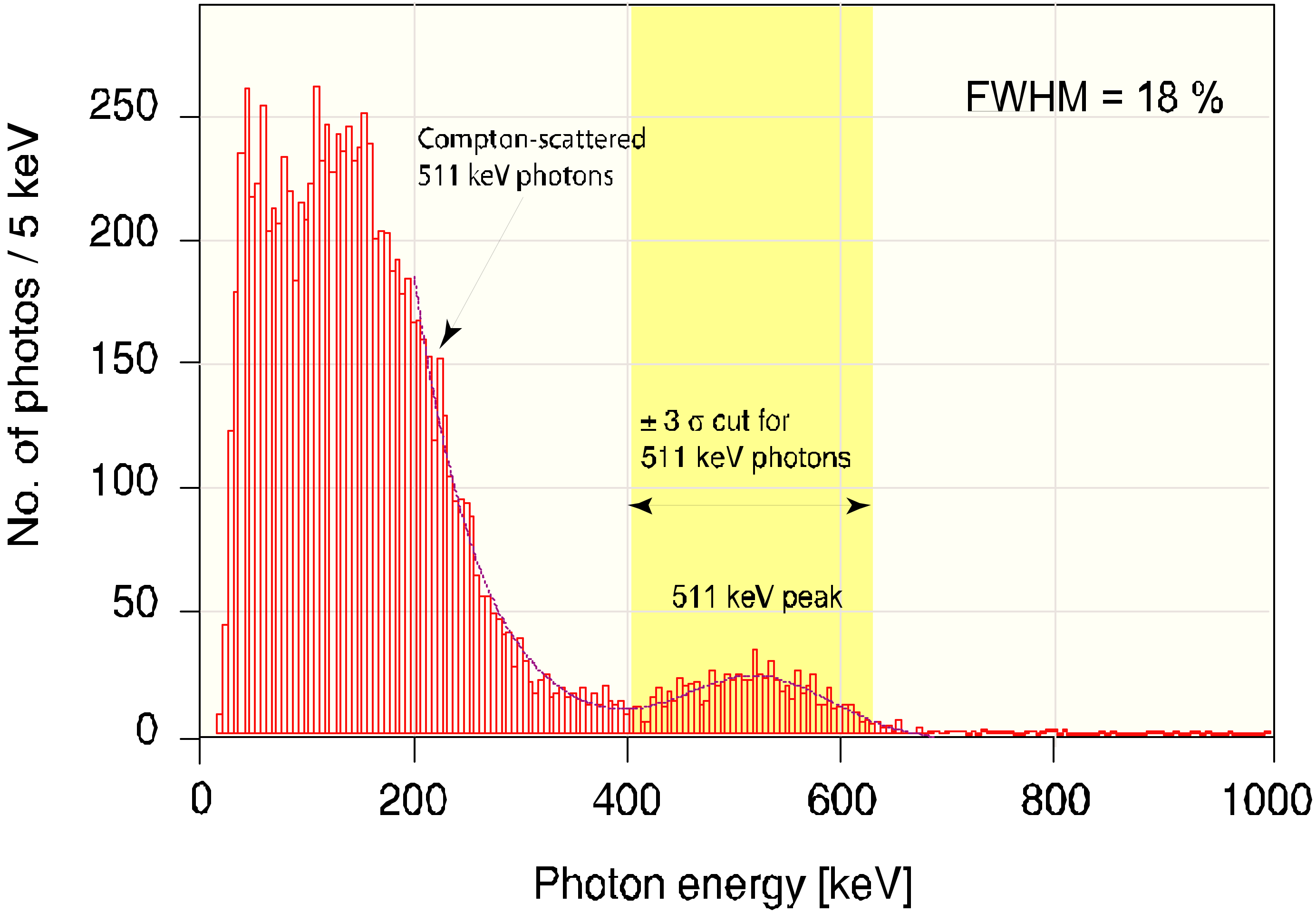
Z Calibration via pbar annihilation





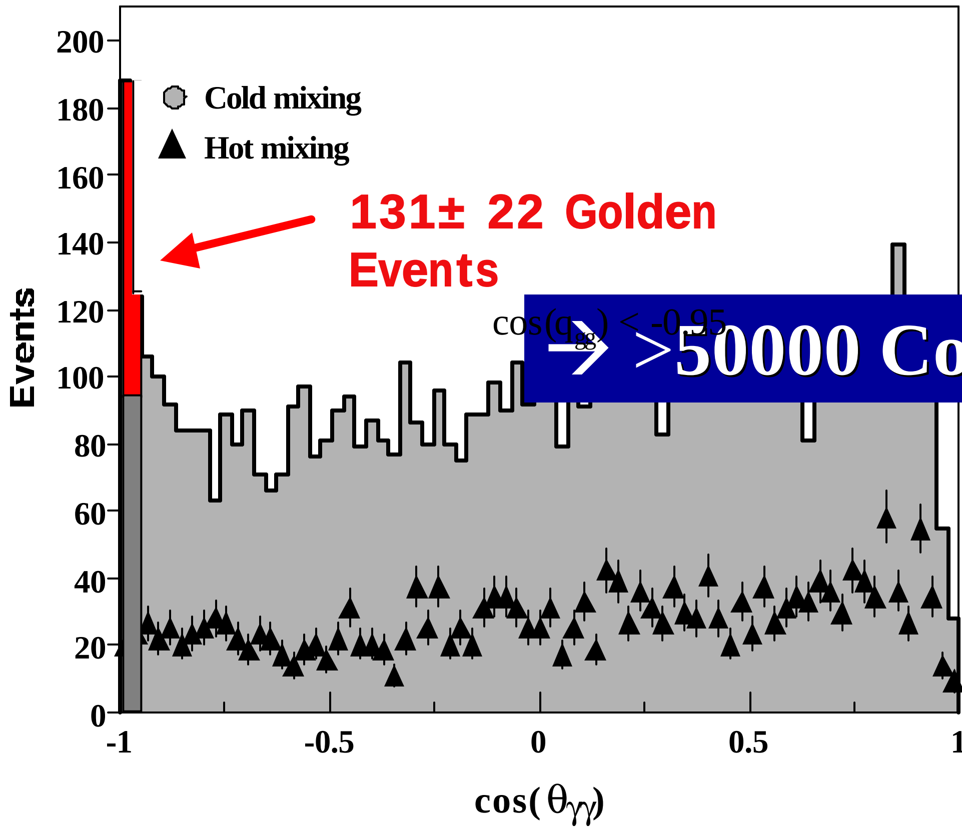
CsI spectrum for 511 keV gamma

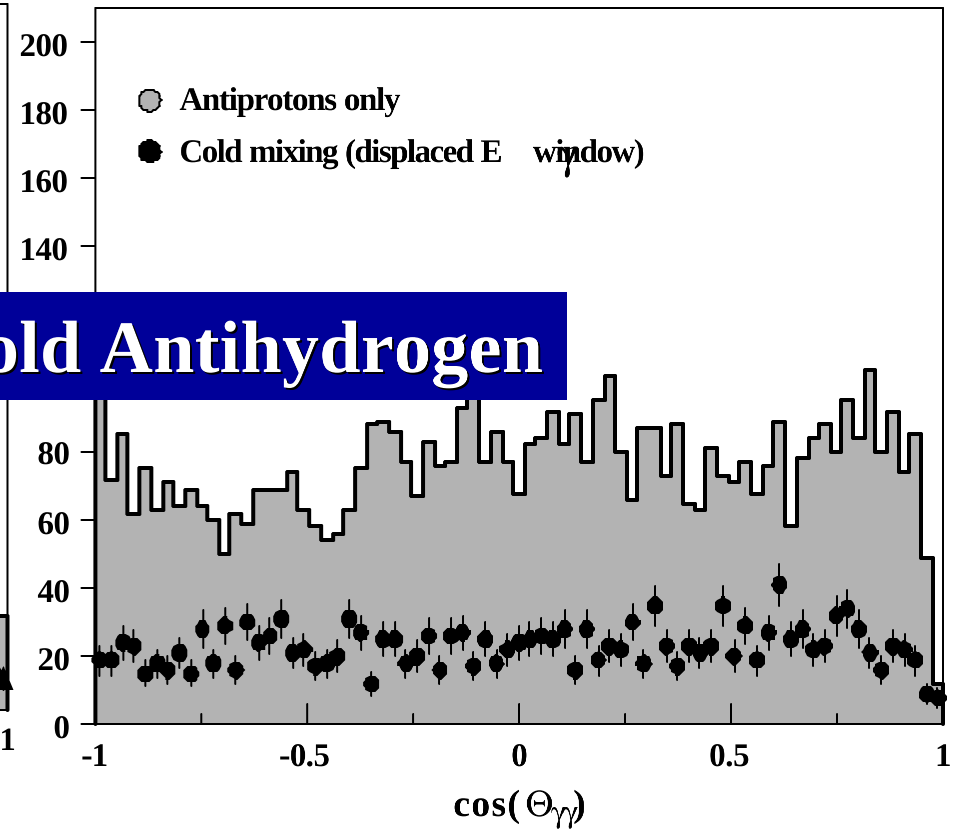
192 Pure CsI read out via APD



Cold Antihydrogen Signal August 2002 *ATHENA*

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





→ >50000 Cold Antihydrogen

Background Measurements

1. Hot-Mix: mixing with RF heated e^+ (~3000K): →turning off Hbar formation

2. Pbar-Only annihilation in interaction region
3. Displaced Eg window

ATHENA in the News

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)

  …
- *Wired* Magazine, Annual Rave Awards Nomination

  (with Eminem, Spielberg, Hayao Miyazaki et al.)

Future Prospects

Future Prospects

- **Antihydrogen Formation Studies**
  - Understanding the dynamics
  - Optimization of various processes
- **Towards Laser Spectroscopy**
  - Try first “in-beam”
  - Several options being considered
- **Hyperfine Splitting Measurement**
  - ASACUSA LoI
- **Other “Exotics” Studies**
  - Antihydrogen Charge Neutrality Test

Summary

- **First production and detection of cold antihydrogen**
  - Powerful e^+ accumulator, position sensitive detector
- **Preliminary New Results**:
  - In 2002 we produced ~1 Million Hbars
  - High initial rate production > 100 Hz
  - Modulation of Hbar formation: A Pulsed Hbar Source
  - Temperature dependence
  - Many measurements: plasma modes, mixing processes, Hbar emission angles
- **ATHENA Antihydrogen Apparatus:**

  High rate, High duty cycle (5 min^{-1}), Versatile
- **Exciting Future Ahead**

Stay Tuned!

Collaboration

Athena / AD-1

Particle Traps + Control

Genoa
Amoretti M. Carraro C. Lagomarsino V.
Macri M. Manuzio G. Testera G. Variola A.

CERN
Bonomi G. Bouchta A. Doser M. Holzscheiter M.
Landua R. Riedler P. Rouleau G.

Tokyo
Fujiwara M. Funakoshi R. Hayano R.

Precision lasers

Aarhus
Bowe P. Hangst J.S.

Rio de Janeiro (UFRJ)
Lenz Cesar C.

Positron Plasma

Swansea
Charlton M. Collier M. Jorgensen L.
Watson T. Van der Werf D.P.

Detector + Analysis

Zurich Univ.
Amsler C. Glauser A. Grögler D.
Lindelof D. Madsen N. Pruys H.
Regenfus C.

Pavia
Filippini V. Fontana A. Genova P.
Marchesotti M. Montagna P. Rotondi A.

Brescia
Lodi-Rizzini E. Venturelli L.