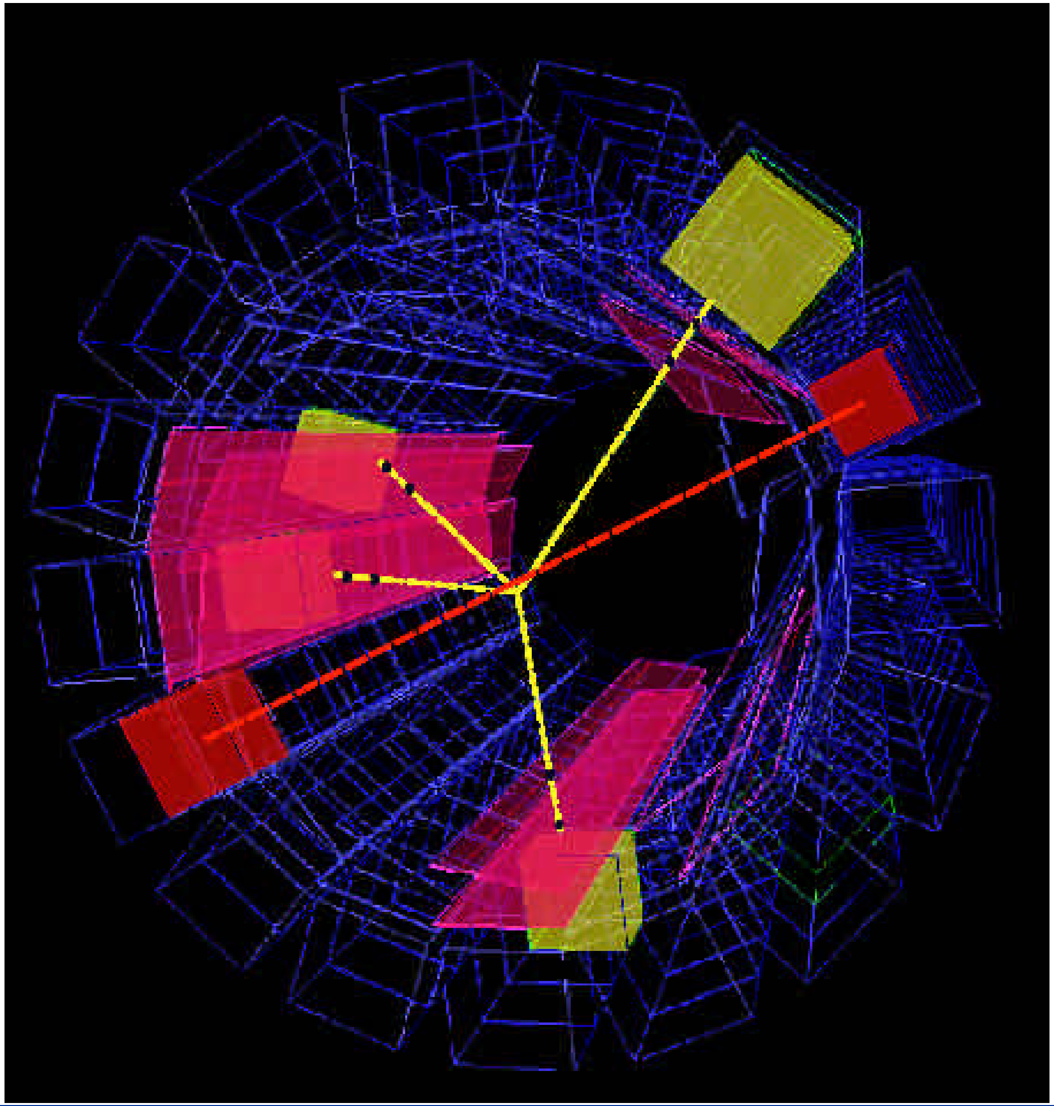
ATHENA / AD-1



First production and detection of cold antihydrogen atoms

ATHENA Collaboration

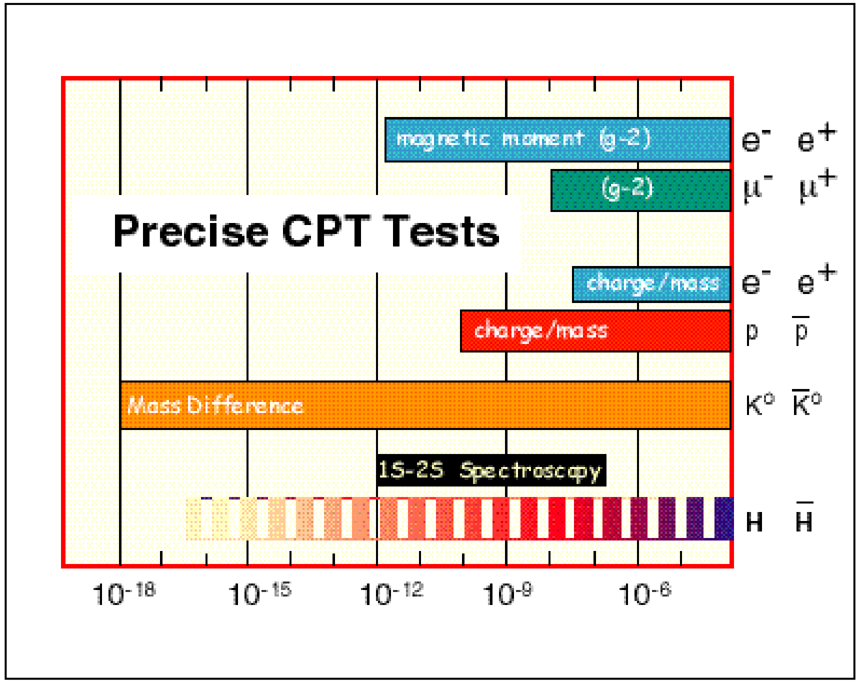
Rolf Landua

CERN

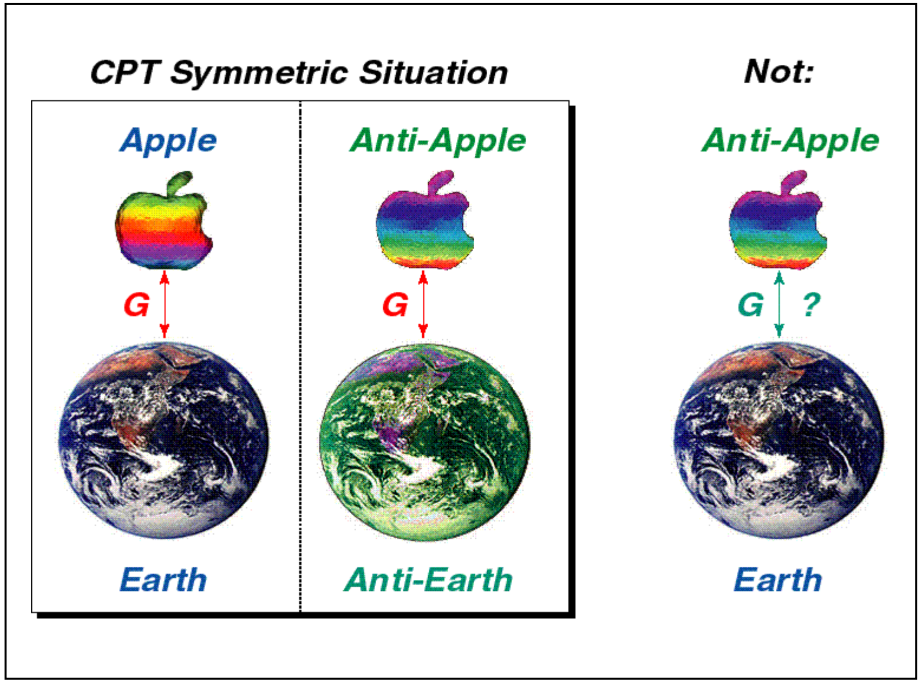
LONG TERM PHYSICS GOALS

| Antihydrogen | = | Hydrogen | ?

CPT



Gravity



But ...

FIRST GOAL

PRODUCTION AND DETECTION OF
COLD ANTIHYDROGEN

AD

p- Production (GeV)

Deceleration (MeV)

Trapping (keV)

Cooling (~ meV)

Na-22

e^+ Production (MeV)

Moderation

Accumulation (eV)

10^8 e^+

p^- and e^+ in mixing trap (cooling)

Antihydrogen formation

Detection of annihilation

A multi-disciplinary team :

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.

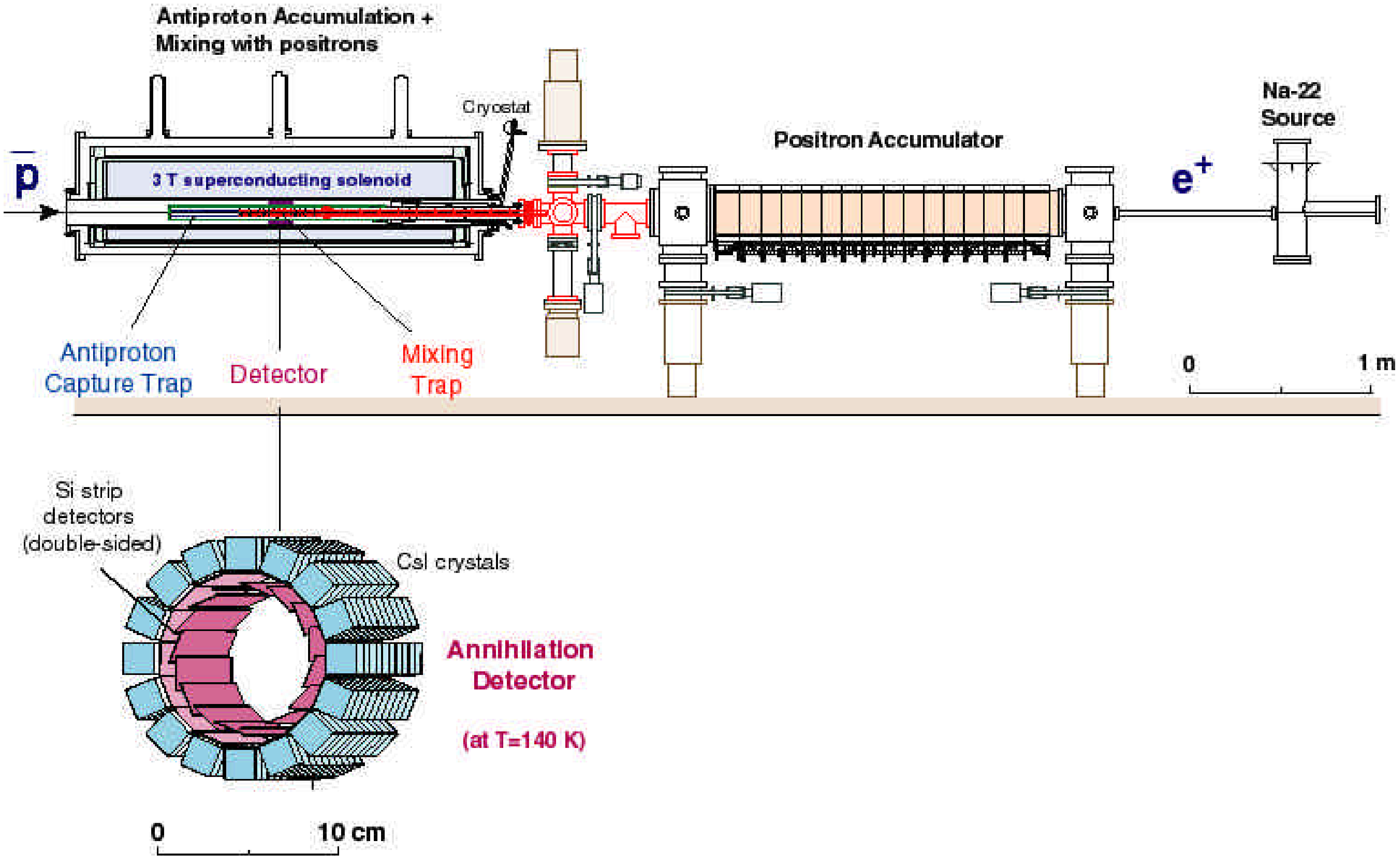
Detector + Analysis

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

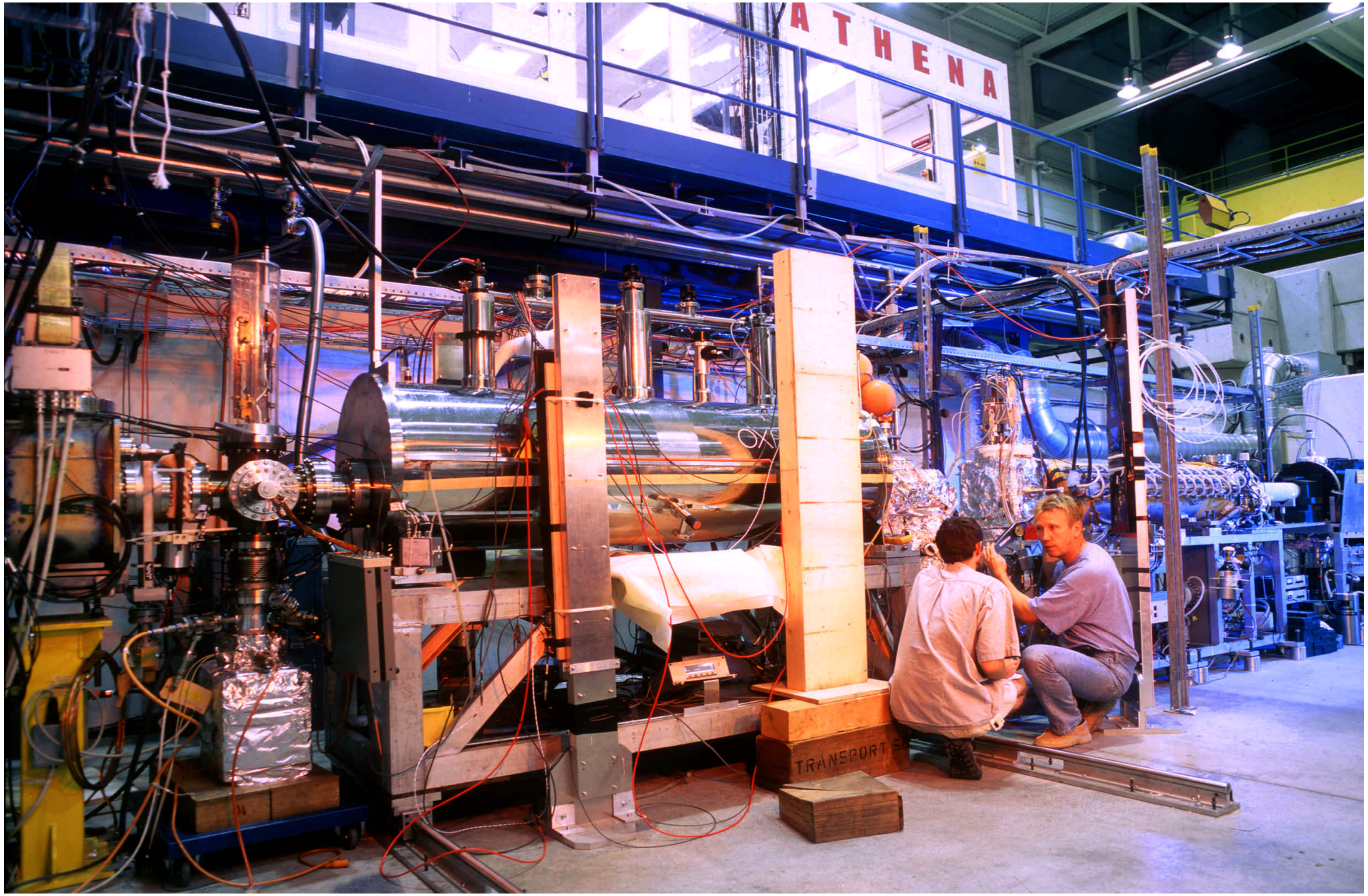
Pavia
Filippini V. Fontana A. Genova P.
Marchesotti M. Montagna P. Rotondi A.

Brescia
Lodi-Rizzini E. Venturelli L.

Overview - ATHENA / AD-1



ATHENA - Photo



Principal achievements before Summer 2002

Ingredients for 'cold antihydrogen' production ready:

10^4 antiprotons captured, cooled and transferred to mixing trap

150 million positrons accumulated per 5 minute cycle

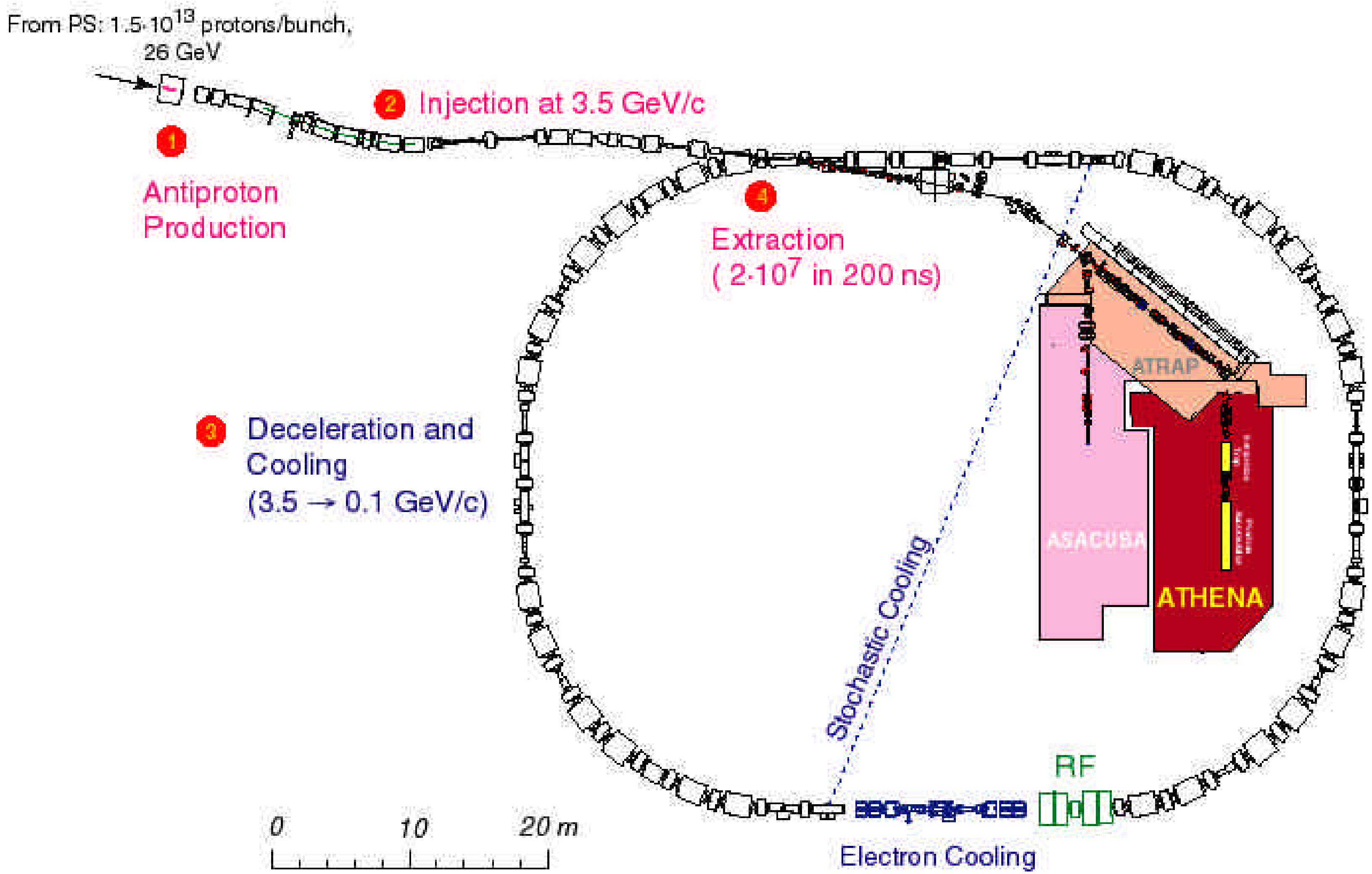
75 million positrons transferred to mixing trap and stored for several hours

Antihydrogen detector fully commissioned and working

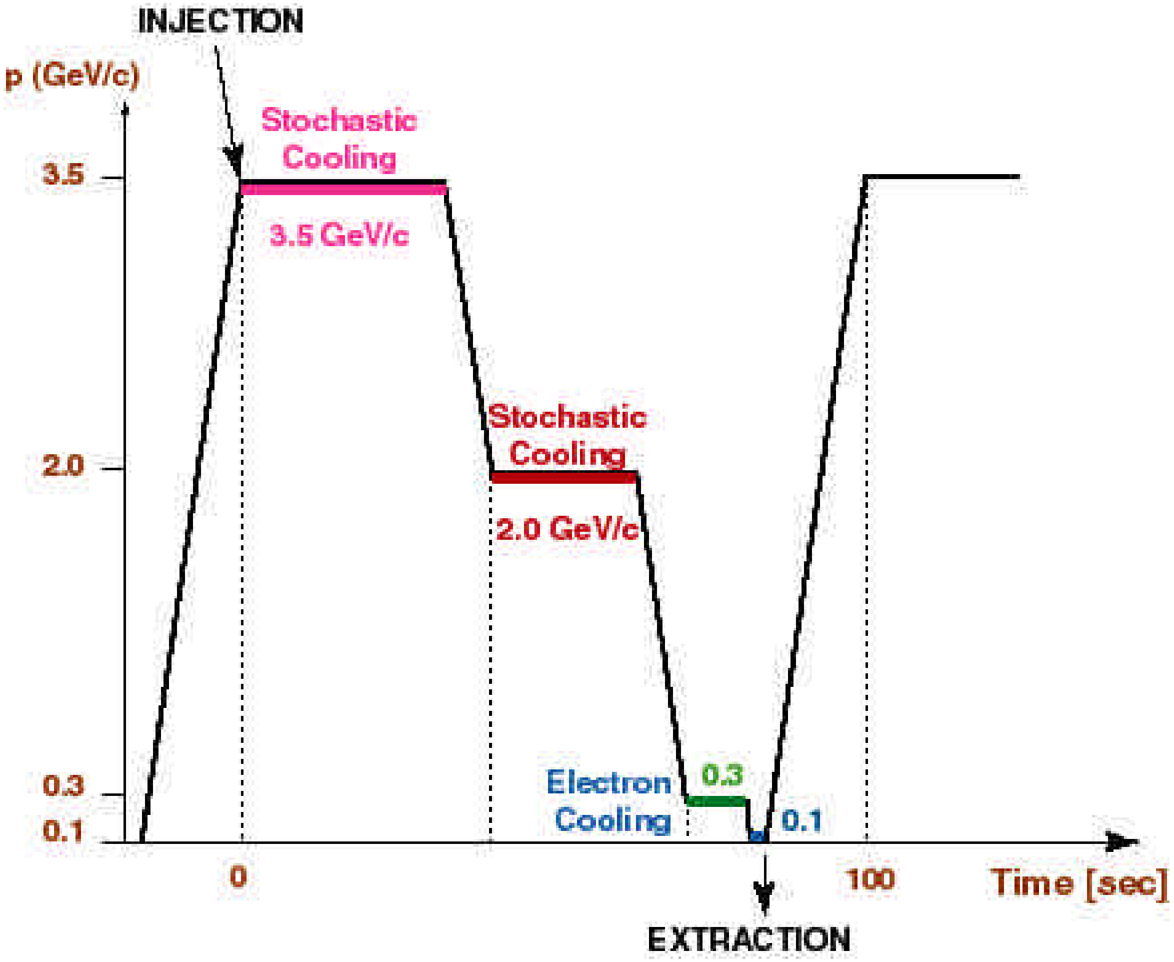
Antiproton vertex resolution $\sigma \sim$ 3-4 mm ("antiproton tomography")

511 keV peak from positrons observed *in situ*

Antiproton Decelerator (1)



Antiproton Decelerator (2)

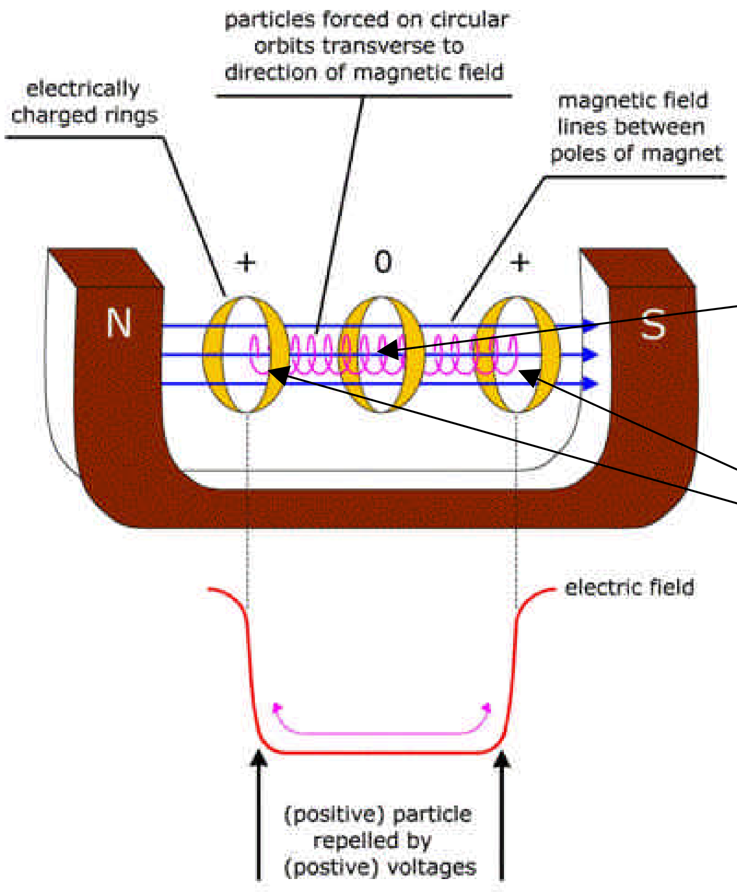


$2 \cdot 10^7$ antiprotons / cycle

P = 100 MeV/c (E = 5 MeV)

Interlude: Trapped Particles

HOW A TRAP WORKS



Particles fired into such a ring system are completely trapped by the electric and magnetic fields applied.

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

$t_{cool} \sim 0.3$ s

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

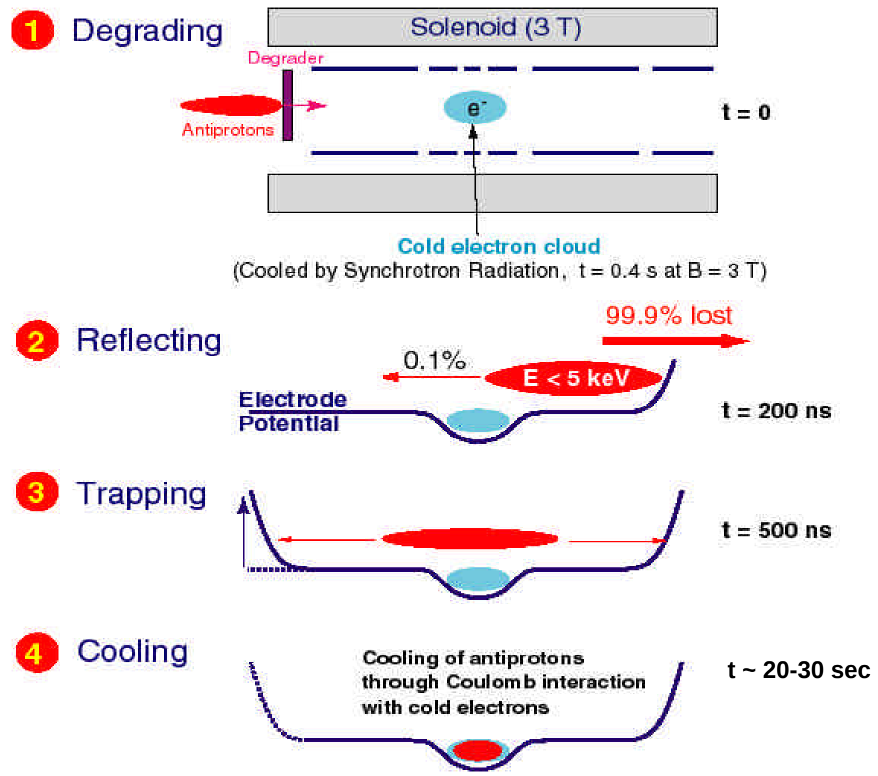
f ~ 7 MHz, d ~µm … cm

3) **E x B drift** (‘magnetron’)

f ~ kHz, r ~ mm

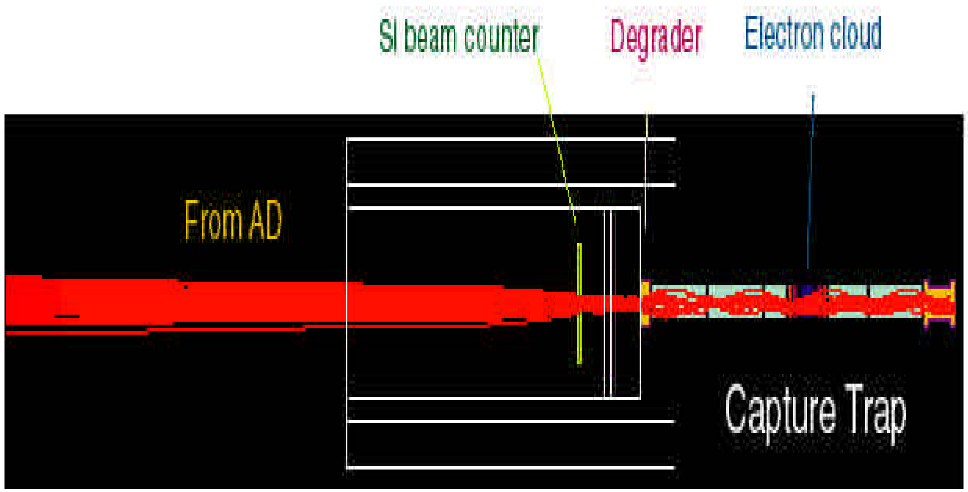
Antiprotons - Capture and Cooling

5.0 MeV antiproton bunch ($2 \cdot 10^7$) from AD

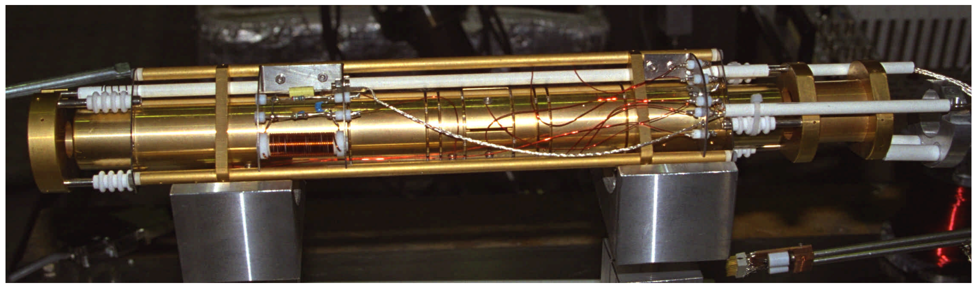


5. Transfer to mixing trap:

10,000 cold antiprotons / AD shot



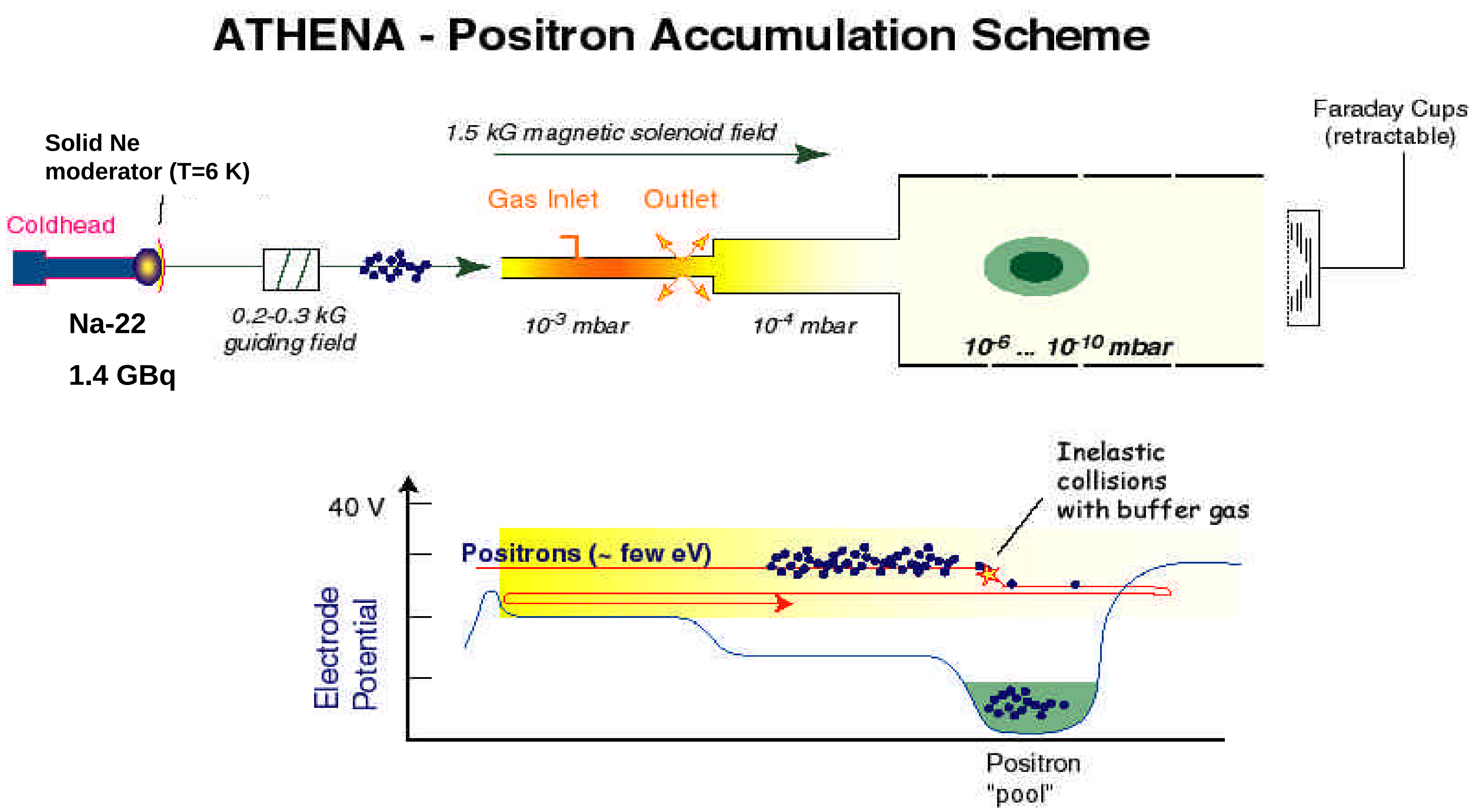
Segmented Si (67 μ) beam counter



Antiproton Capture Trap

Technique developed by TRAP collaboration at LEAR (1985)

Positron Accumulation (1)

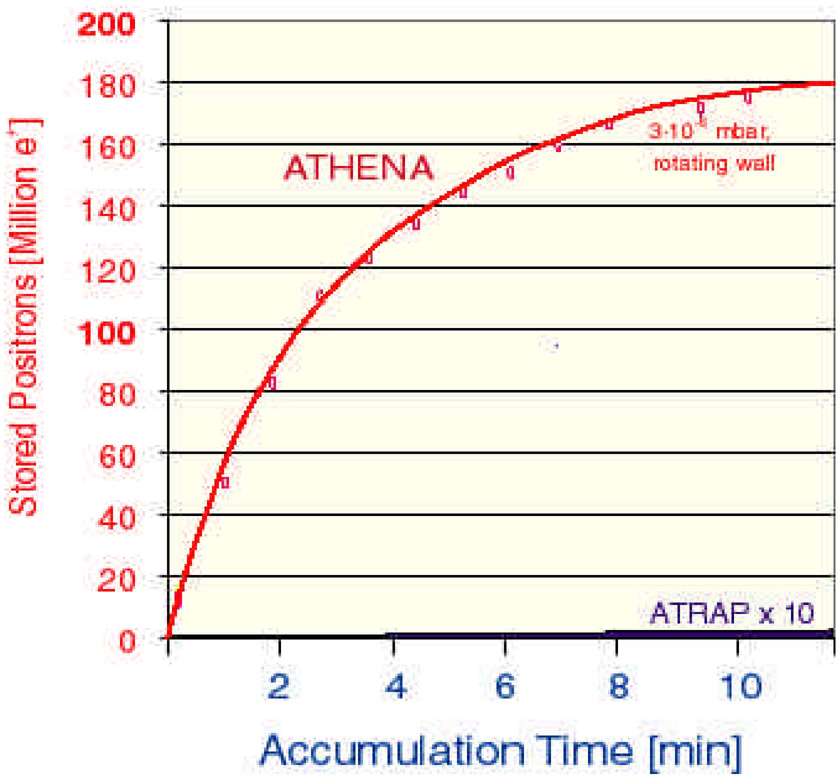


Scheme of ATHENA Positron Accumulator

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

Positron Accumulation (2)

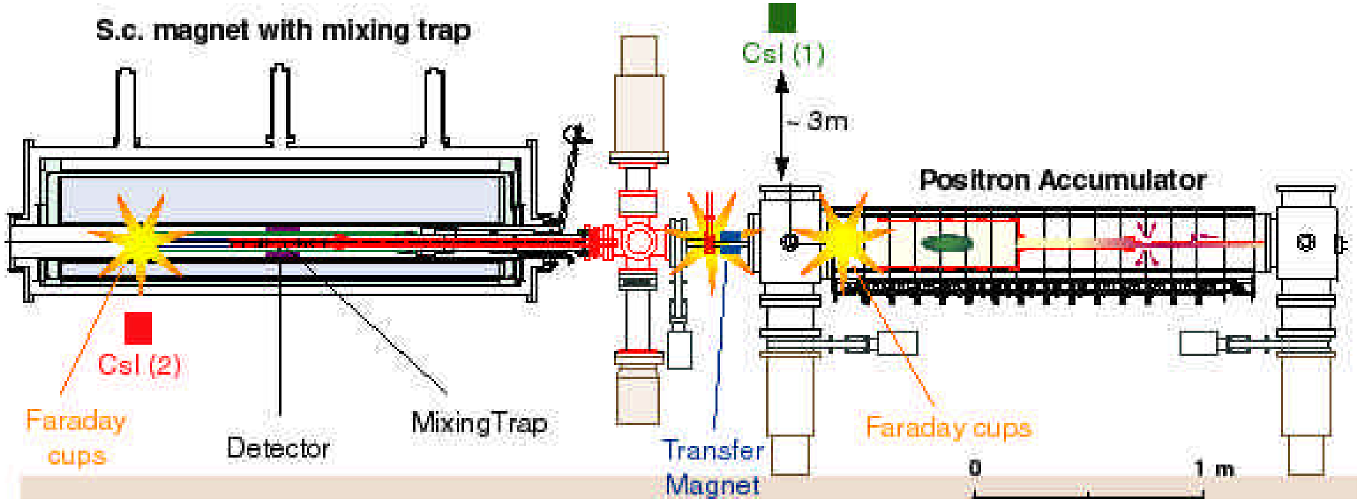
Accumulated positrons vs time



Accumulation rate ~ 10^6 e^+/sec

- **150 million positrons / 5 min**

Positron Transfer



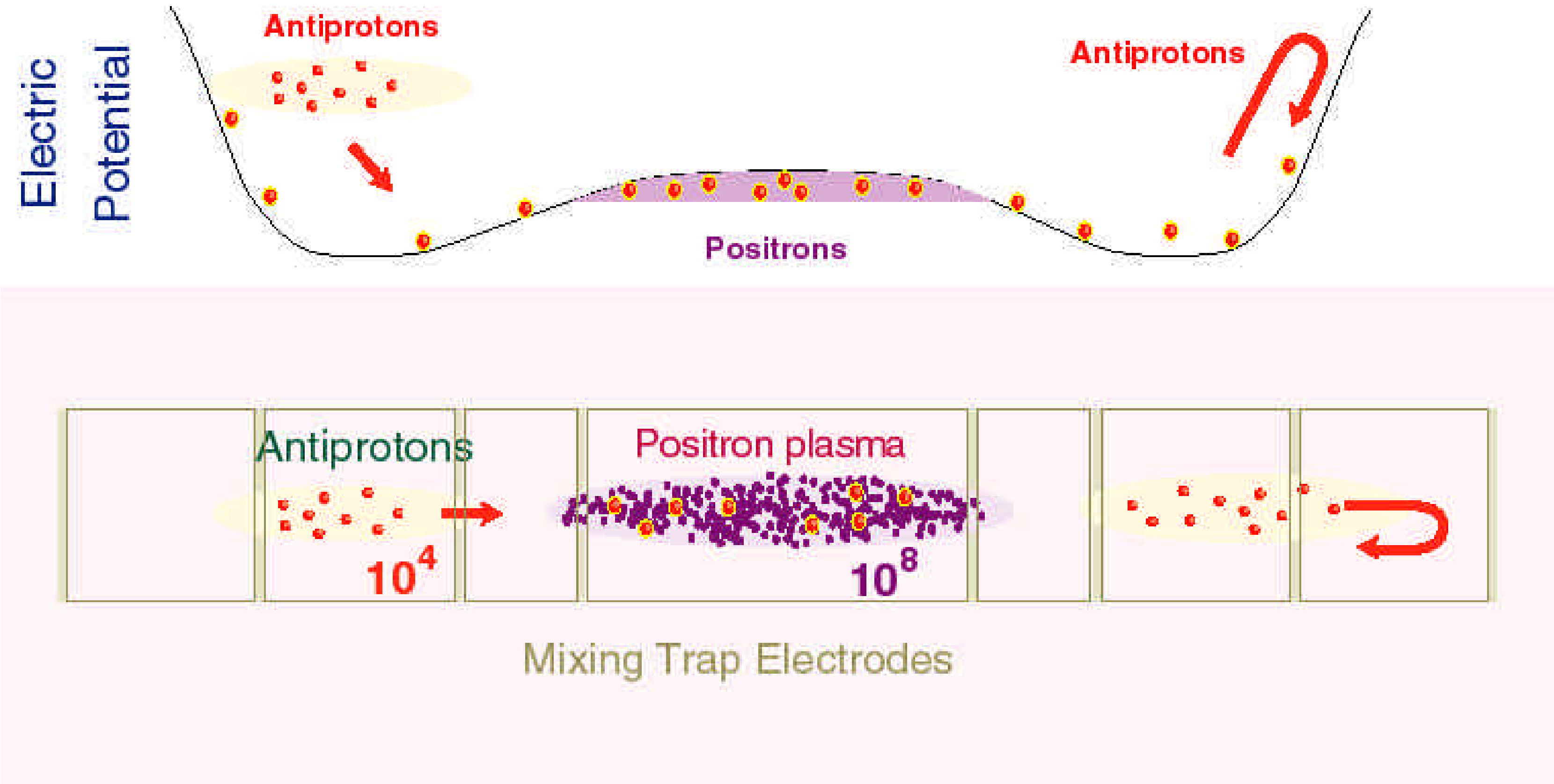
- Transfer positrons from accumulator into mixing trap (ε ~ 50 %)
- Positrons cool by synchrotron radiation at B=3T: 75 million cold positrons
- Non-destructive diagnostics gives plasma parameters:

  $R = 2.0$ mm

  $L = 32$ mm

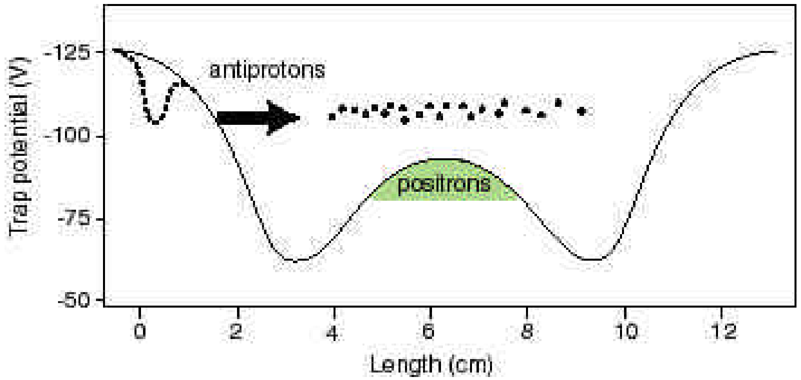
  $n = 2.5 \cdot 10^8$ cm^{-3}
- Life time ~ many hours

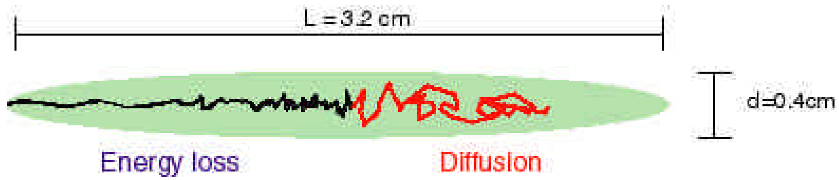
Mixing procedure



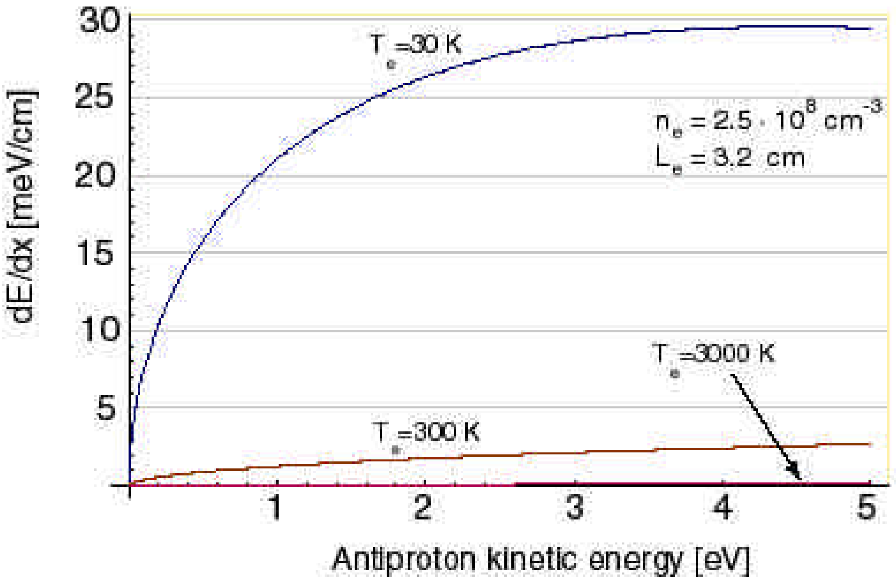
Scheme proposed by G. Gabrielse et al. - Phys.Lett. A129, 38 (1988)

Antiproton-Positron Interaction - dE/dx



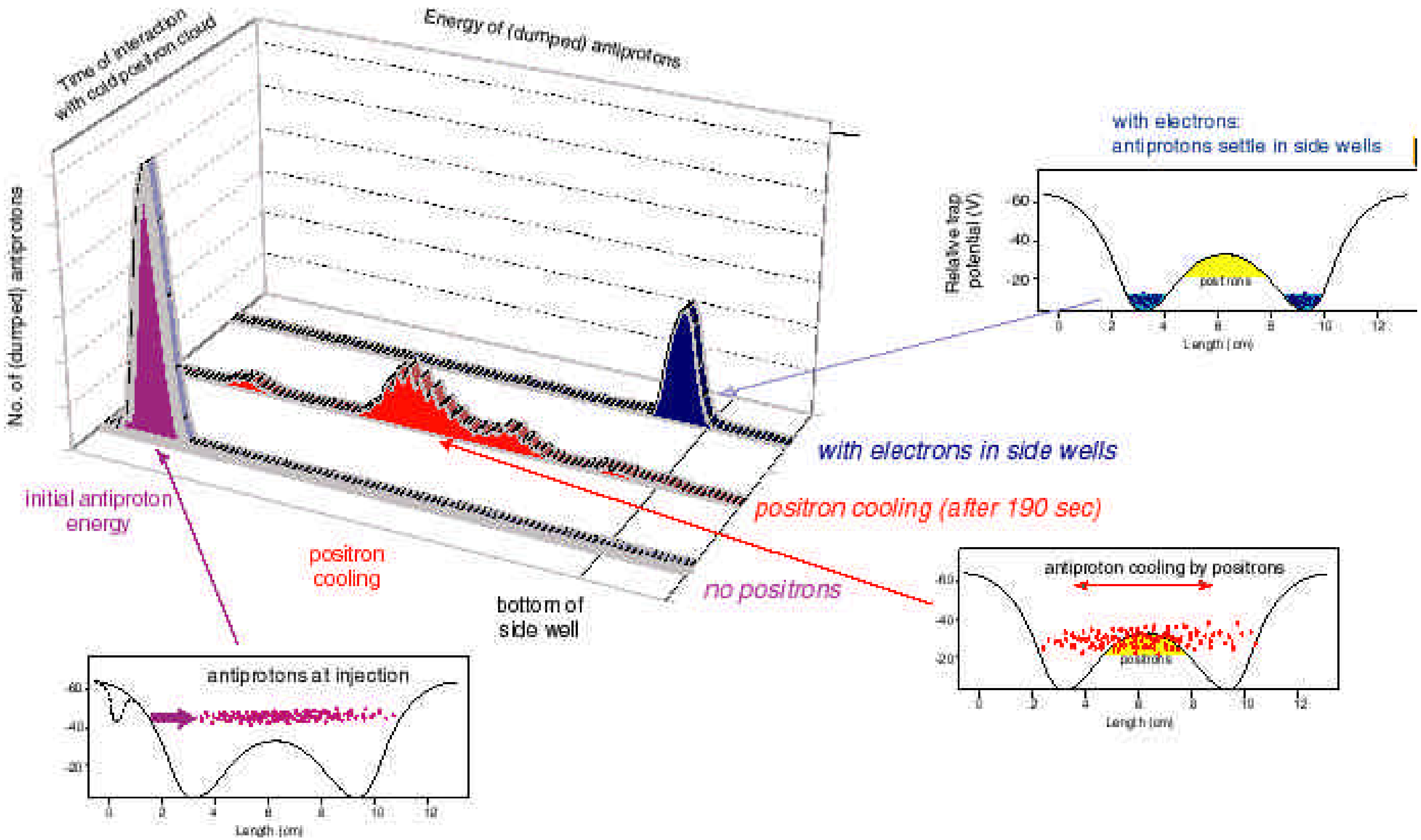


Specific energy loss [meV/cm] of antiprotons in positron plasma



From: Spitzer, Physics of fully ionized gases (1953); for non-magnetized plasmas

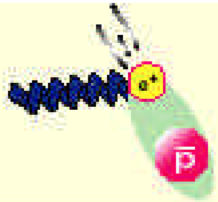
Antiproton cooling by 75 million positrons



Positron cooling using 0.25 M positrons: G. Gabrielse et al. - Phys.Lett. B507,1 (2001)

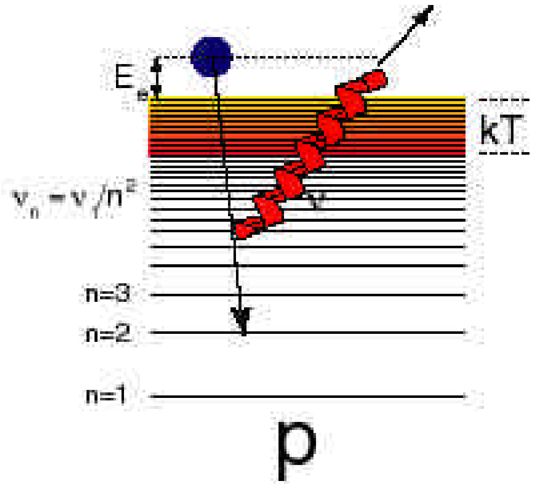
Combination processes (1)

Spontaneous Radiative Recombination (SRR)



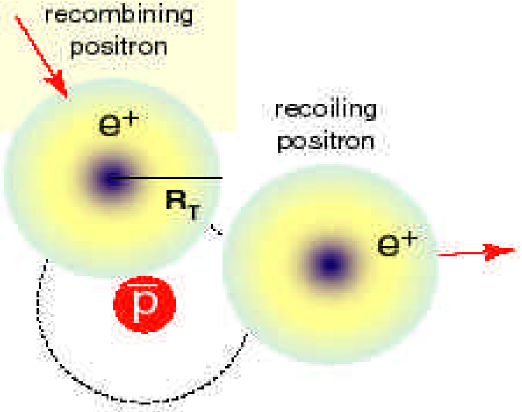
$$\sigma_{RR}(n, E_e) \sim 2.1 \cdot 10^{-22}\,cm^2 \;\frac{1}{n \cdot \frac{E_e}{13.6\,eV}}$$

$n = 1 \ldots 10$: $\quad \sigma \sim 1.0 \cdot 10^{-16} \frac{1}{T[K]}\,cm^2$



Combination processes (2)

Three-Body Recombination (TBR)



Thomson radius: $R_T = e^2 / kT$

(~ few µm at meV energies)

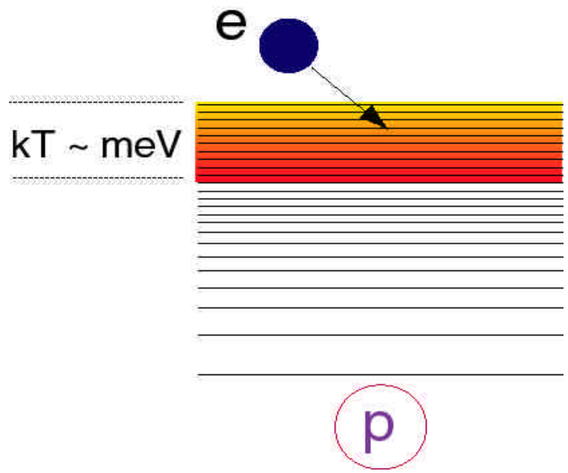
(Repulsion = kinetic energy)

Collision frequency e-p: $f_c = n_e \cdot v_e \cdot R_T^{\ 2}$

Probability for second e^+: $p_2 = n_e \cdot R_T^{\ 3}$

$\sigma_{TBR} = K\, n_e \cdot R_T^{\ 5}$ (K ~ 0.07 .. 0.7)

$$\sigma_{TBR} \sim 10^{-7}\ \mathrm{cm}^2 \ \frac{n_e}{[10^8\ \mathrm{cm}^{-3}]} \ \frac{[1\mathrm{K}^5]}{T^5}$$



Small energy transfer (~ meV)

→ E(final states) ~ - kT

→ n >> 100 ($\sigma \sim n^{4 \ldots 6}$)

→ long lifetime (> 0.1 s)

→ **unstable (re-ionization for n > 50)**

Comparison

	Radiative	Three-body
Cross-section [cm^2]	10^{-16} (1 K)	10^{-7} (1 K)
T dependence	T^{-1}	T^{-5}
Final state	n < 10	n >> 100
Stability (re-ionization)	high	low
Expected rates	~ Hz	???

Antihydrogen Detector

GOAL

Vertex from tracking of charged particles

Identification of 511 keV gammas

Time- and space coincidence of tracks + gammas

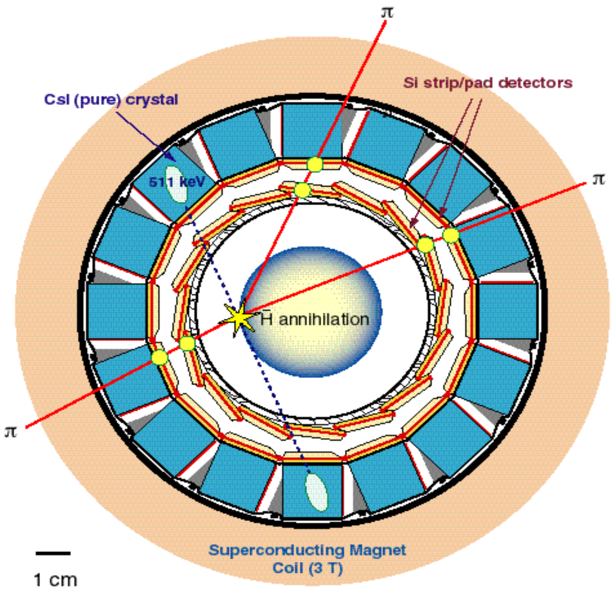
DESIGN

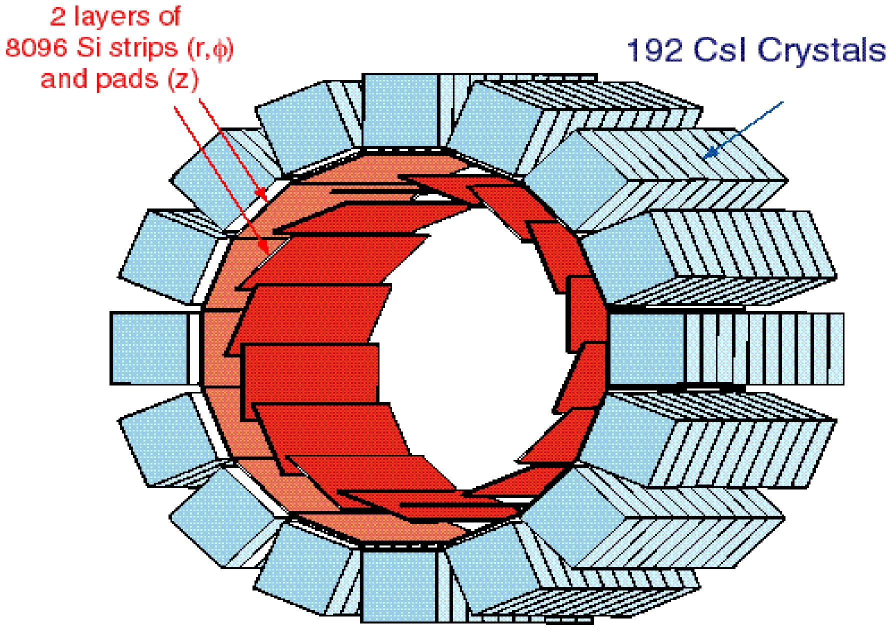
Compact (radial thickness ~ 3 cm)

Large solid angle (> 70 %)

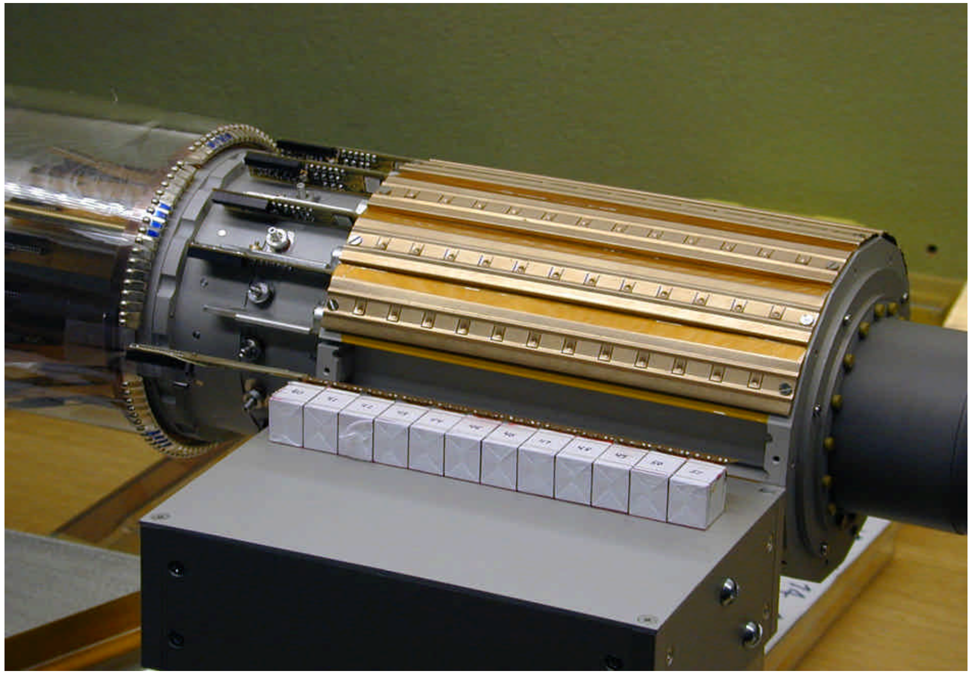
High granularity (8 K strips, 192 crystals)

Operation at T ~ 140 K, B = 3 Tesla





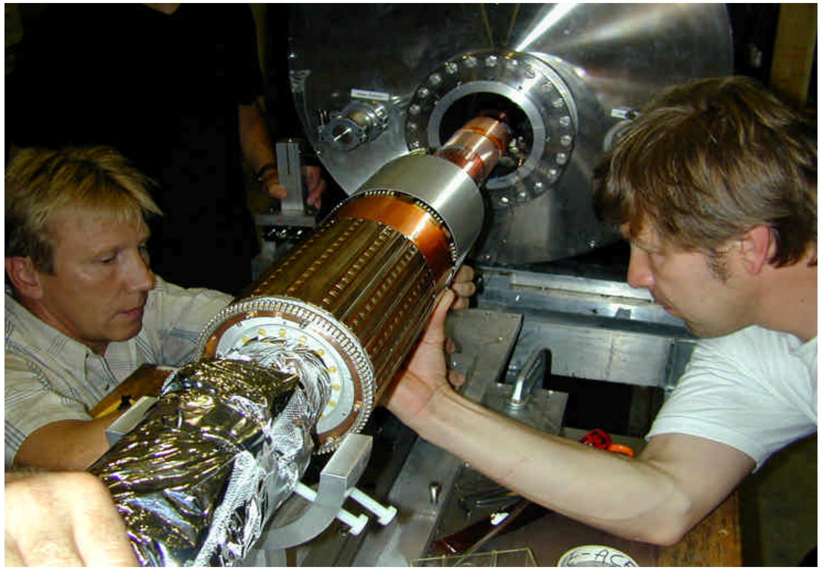
Antihydrogen Detector - R&D, Installation



Much effort into R&D, because :

- low temperature (~ 140 K)
- high magnetic field (3 T)
- low power consumption

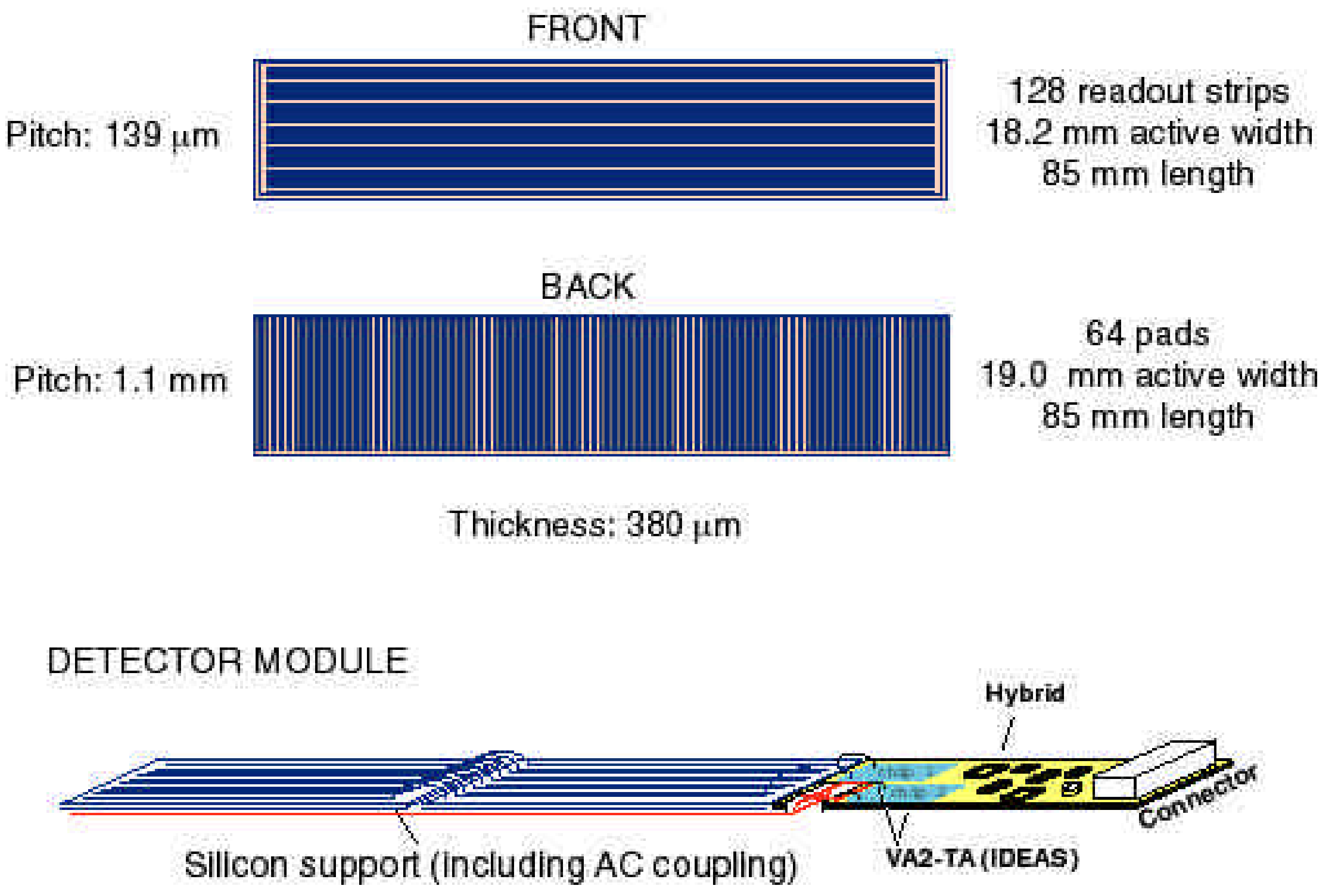
- Light yield of pure CsI crystals ?
- expansion coefficients (kapton, silicon, ceramics)
- electronic components (capacitors, amplifiers)



Full detector installed: August 2001

All photodiodes replaced with APDs: Spring 2002

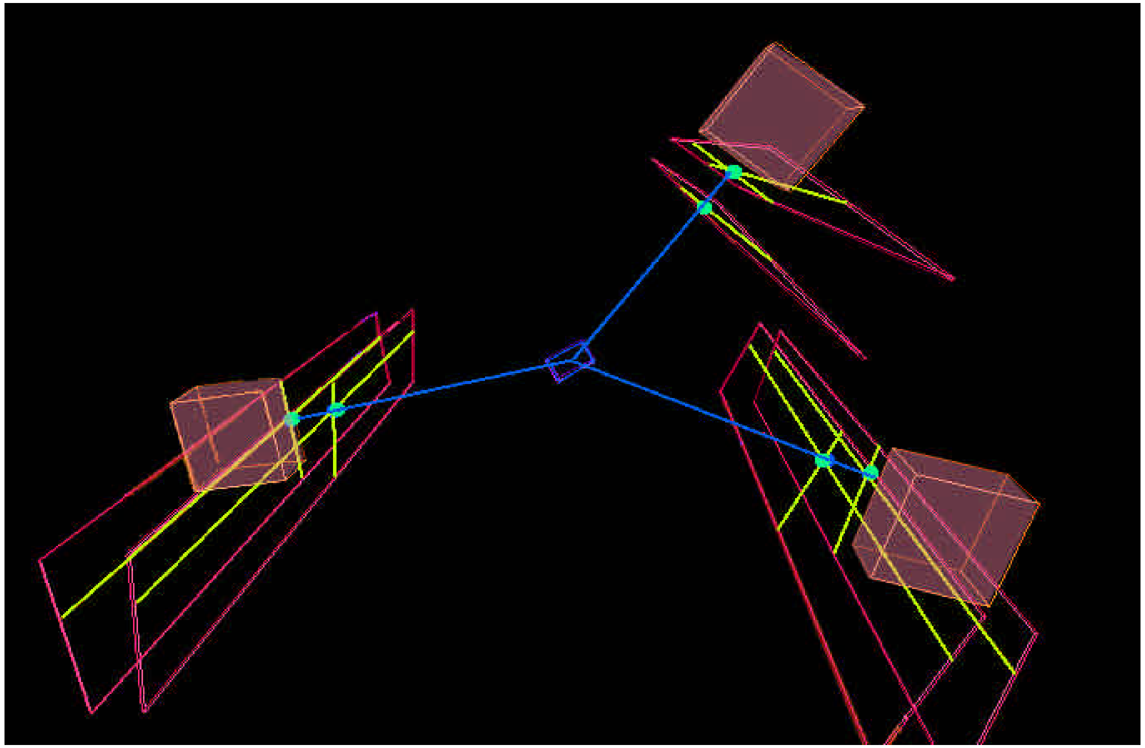
Si strips

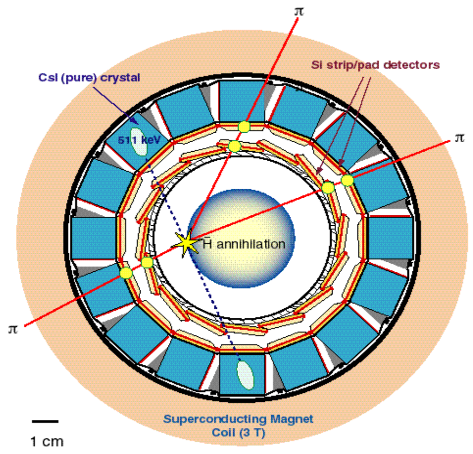

FRONT
Pitch: 139 µm
128 readout strips
18.2 mm active width
85 mm length
BACK
Pitch: 1.1 mm
64 pads
19.0 mm active width
85 mm length
Thickness: 380 µm
DETECTOR MODULE
Hybrid
Connector
Silicon support (including AC coupling)
VA2-TA (IDEAS)

Antihydrogen Detector - Antiprotons only

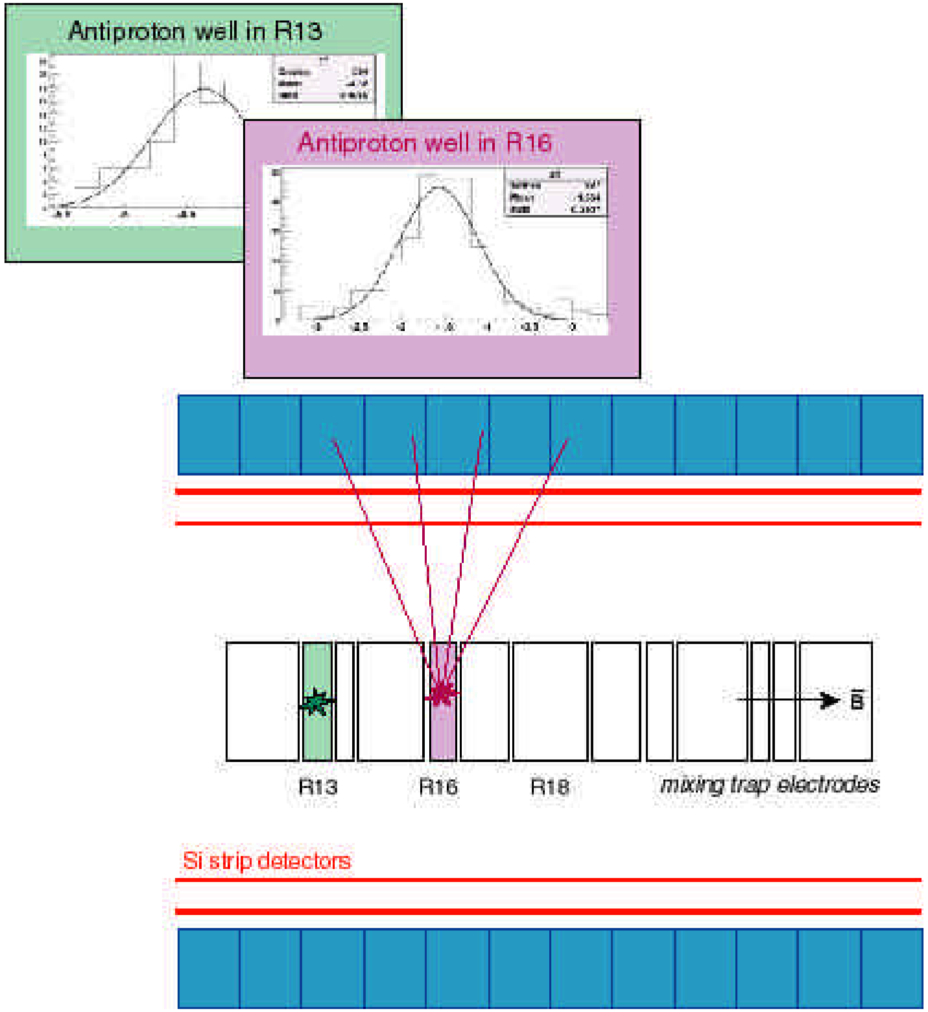
Antiproton Annihilation (example)

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

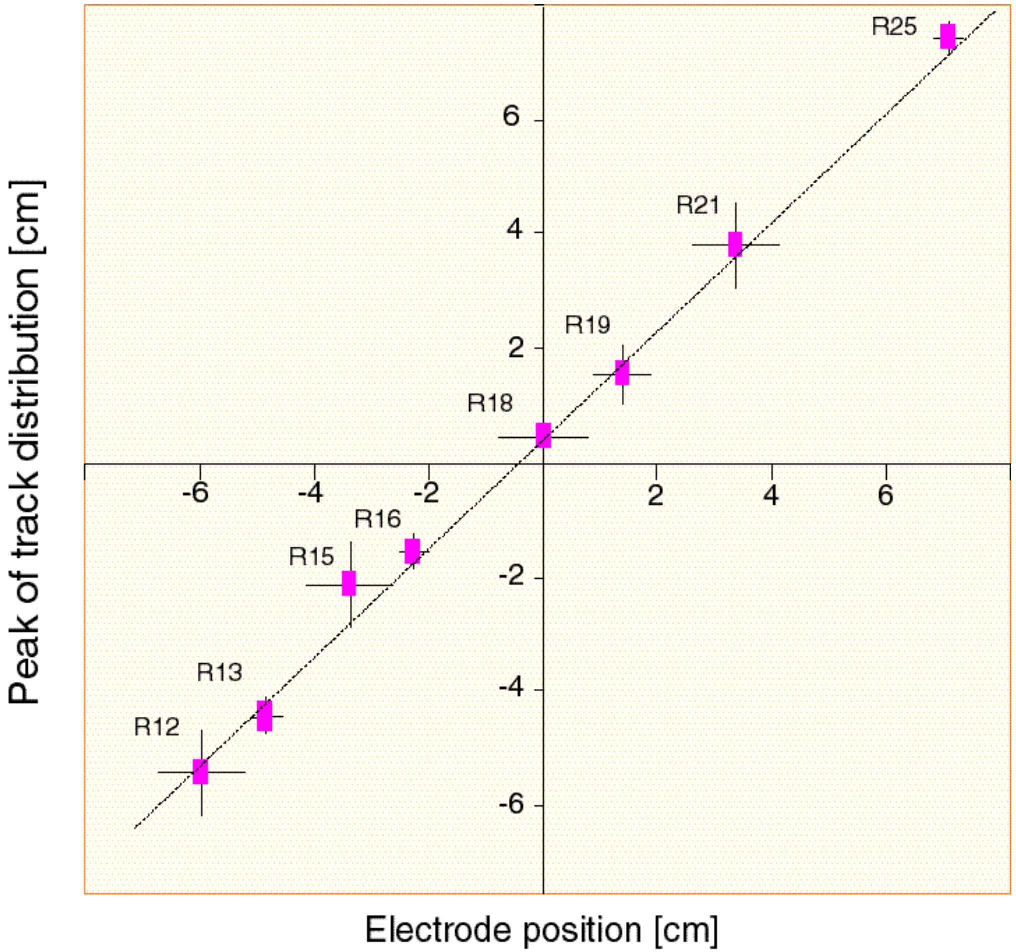




Z Position Calibration Method



Z Position Calibration

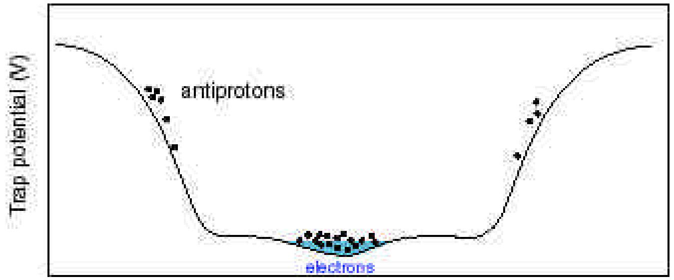


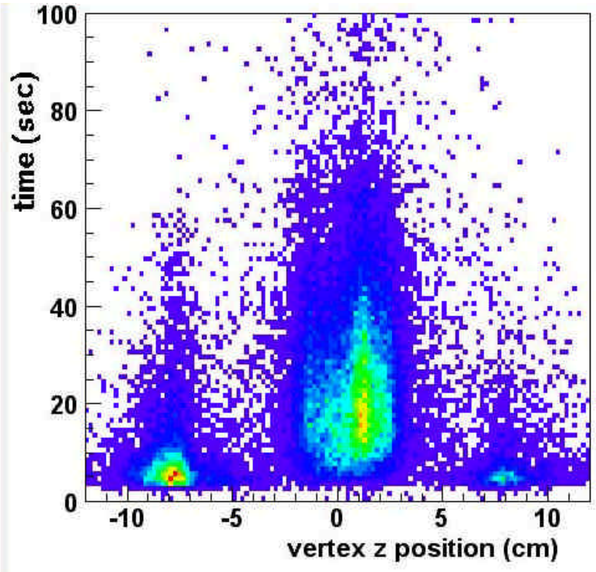
Evolution of Antiproton Annihilation

Capture antiprotons + electrons:

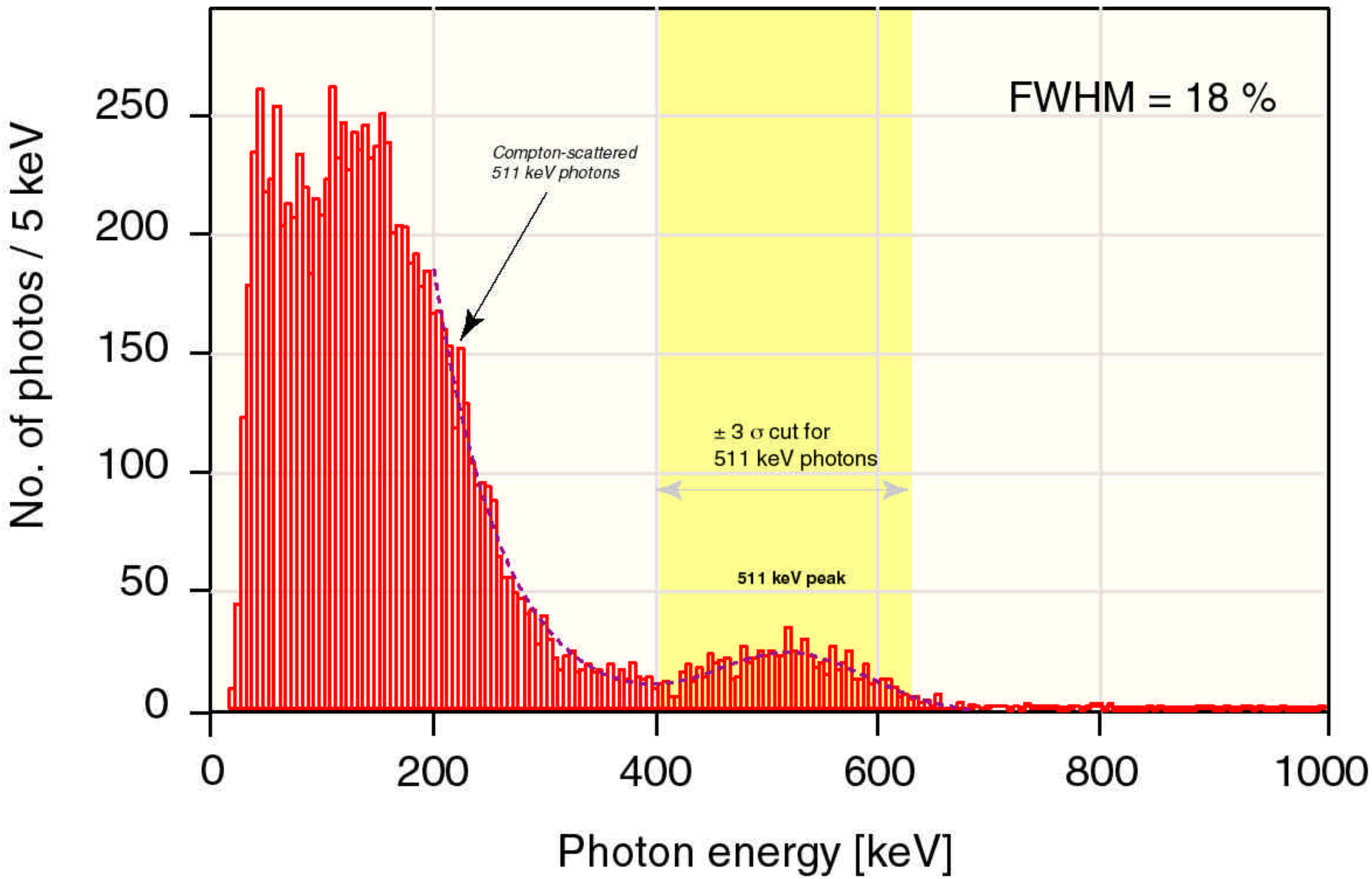
Tracking of antiproton annihilations ->

Real-time imaging of plasma dynamics

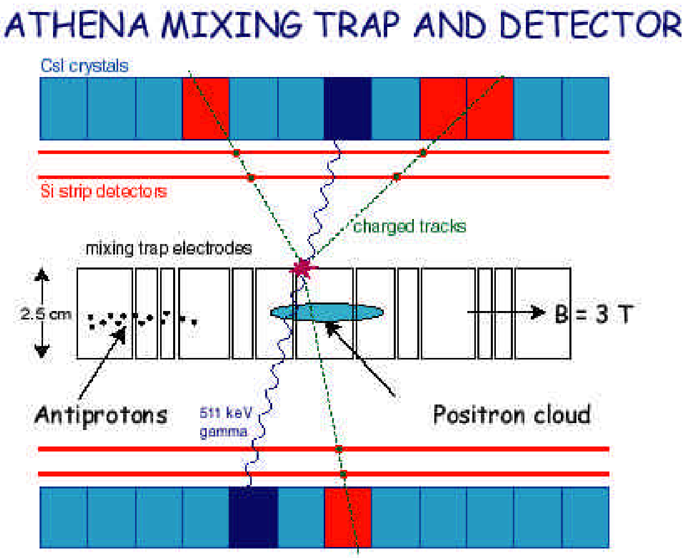


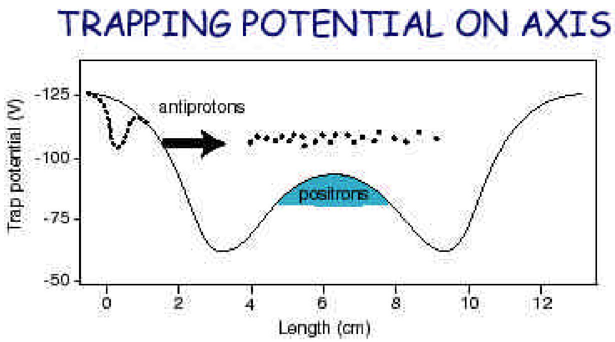


CsI - Photon Energy Resolution



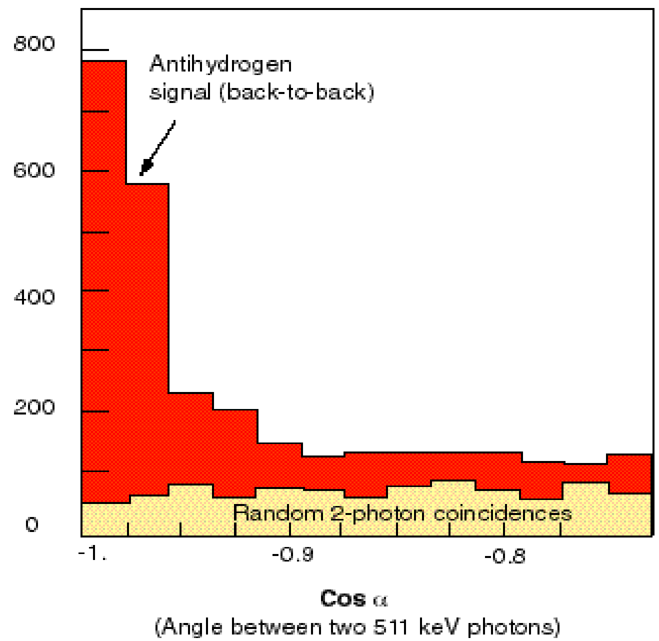
Antihydrogen Annihilation



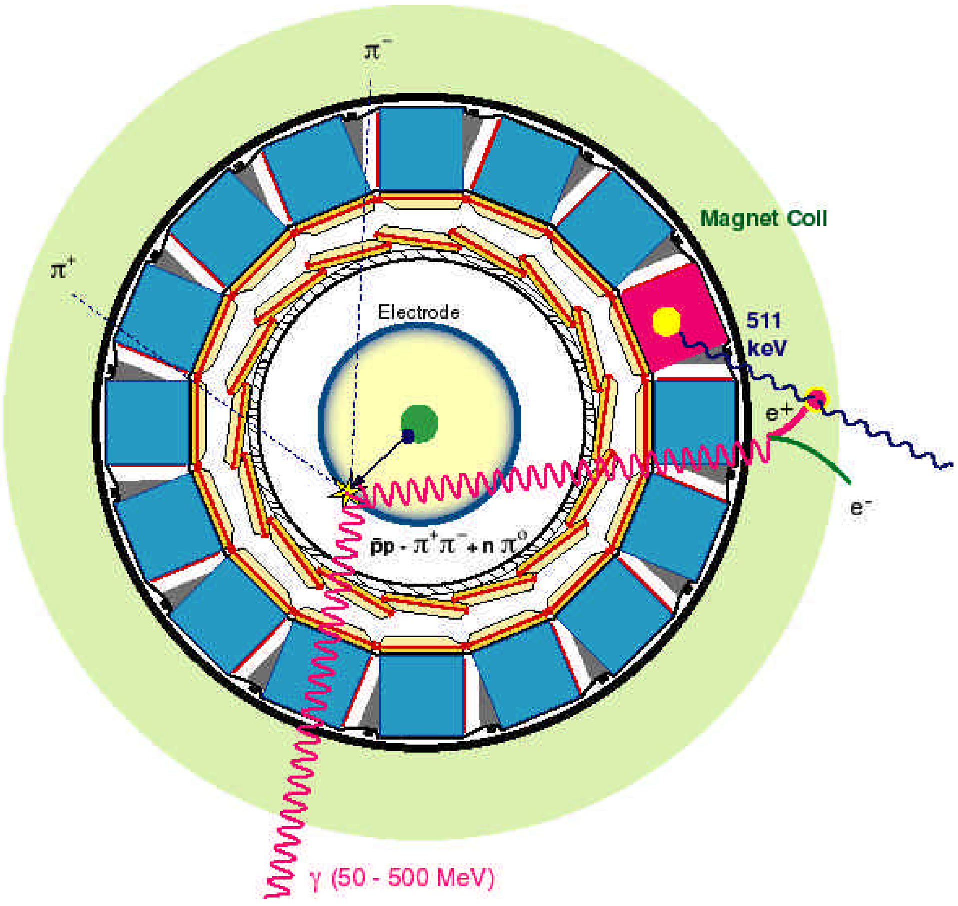


Antihydrogen signal

- within time resolution ~ few μsec:
- charged vertex, determine position
- identify two converted 511 keV gammas
- plot cos Θ between 2 photons as seen from vertex
- identify peak at cos Θ = -1



511 keV background



511 keV background

from antiproton annihilation

- Antiproton annihilation produces neutral pions
- Decay gammas (5-500 MeV) convert in magnet
- Secondary positrons stop and annihilate
- Homogeneous 511 keV photon background
- Can produce (fake) 2 x 511 keV photon events
- BUT: No angular correlation!

Production of Antihydrogen

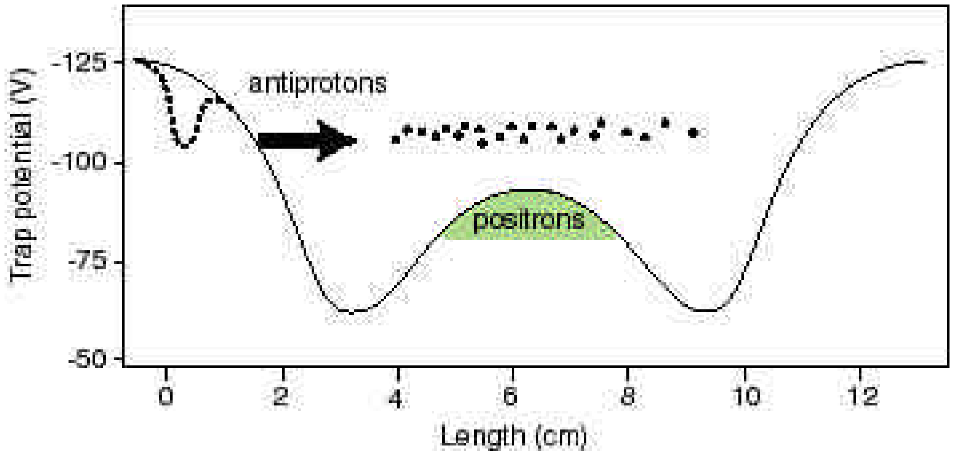
1. Fill positron well in mixing region with $75 \cdot 10^6$ positrons;

   allow them to cool to ambient temperature (15 K)

2. Launch 10^4 antiprotons into mixing region

3. Mixing time 190 sec - continuous monitoring by detector

4. Repeat cycle every 5 minutes - take data for 165 cycles

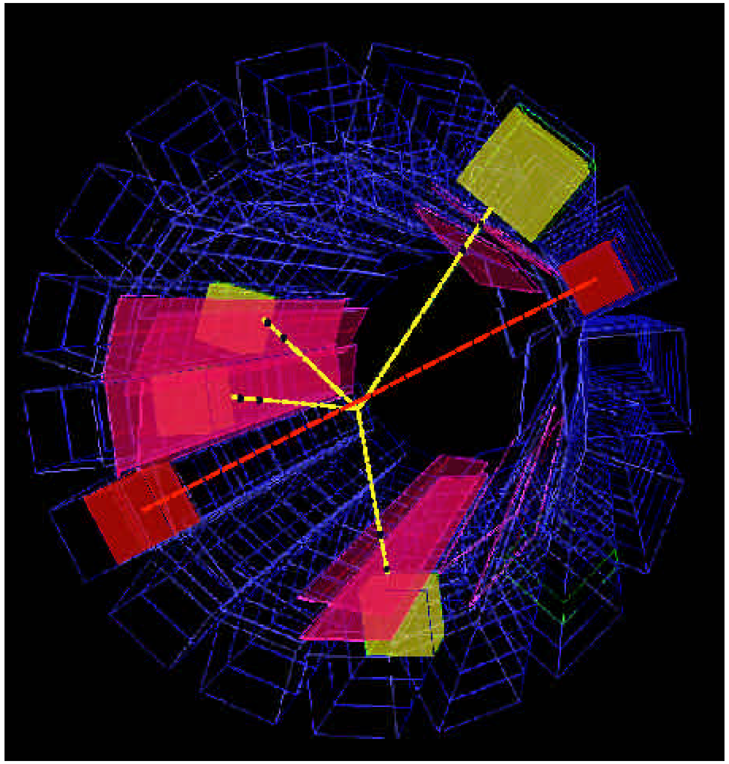


For comparison:

"hot" mixing = continuous RF heating of positron cloud

(suppression of recombination)

Analysis Procedure



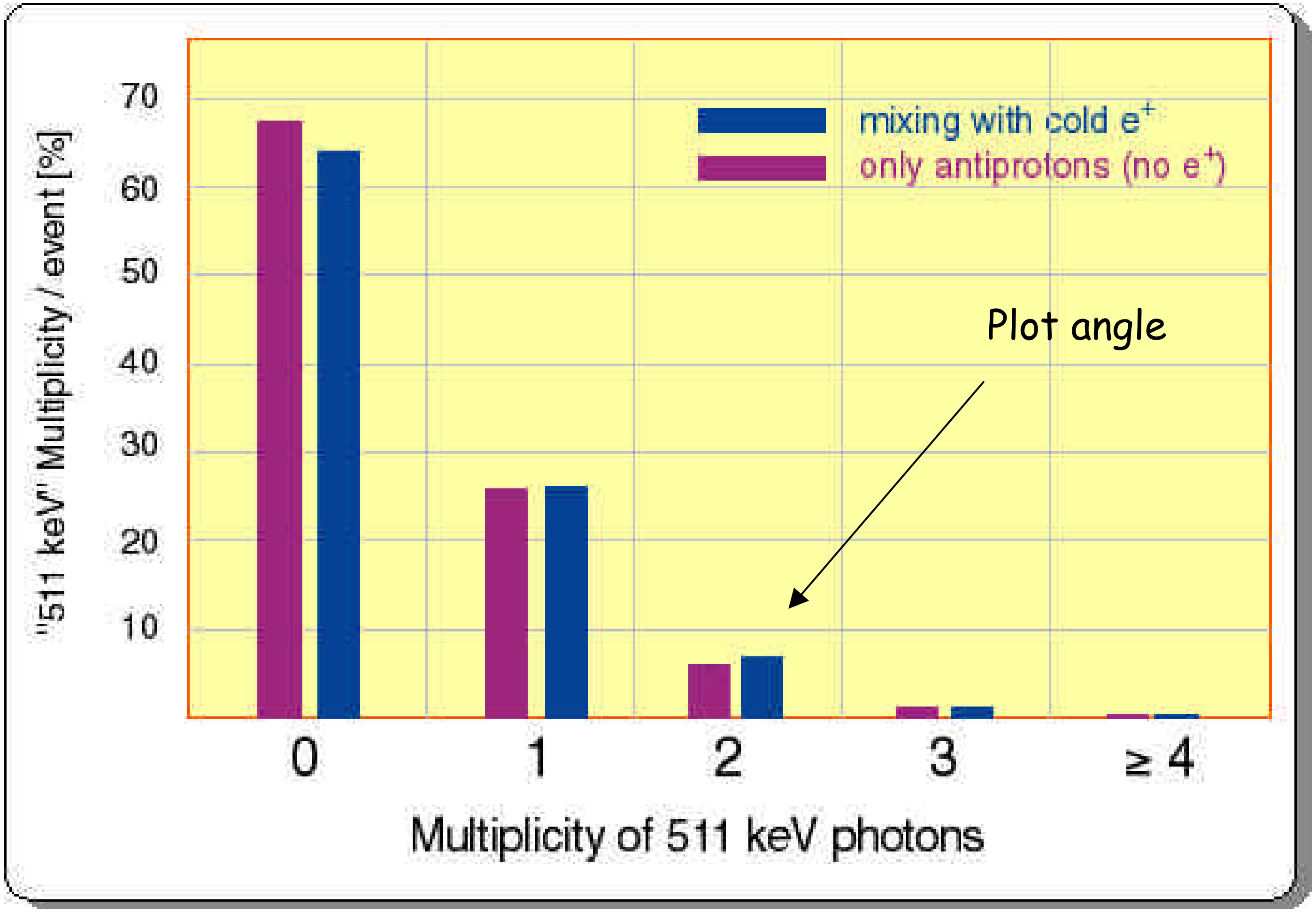
- Reconstruct annihilation vertex
- Search for ‘clean’ 511 keV-photons:

  exclude crystals hit by charged particles
  + its 8 nearest neighbours
- ‘511 keV’ candidate =

  400… 620 keV
  no hits in any adjacent crystals
- Select events with two ‘511 keV’ photons

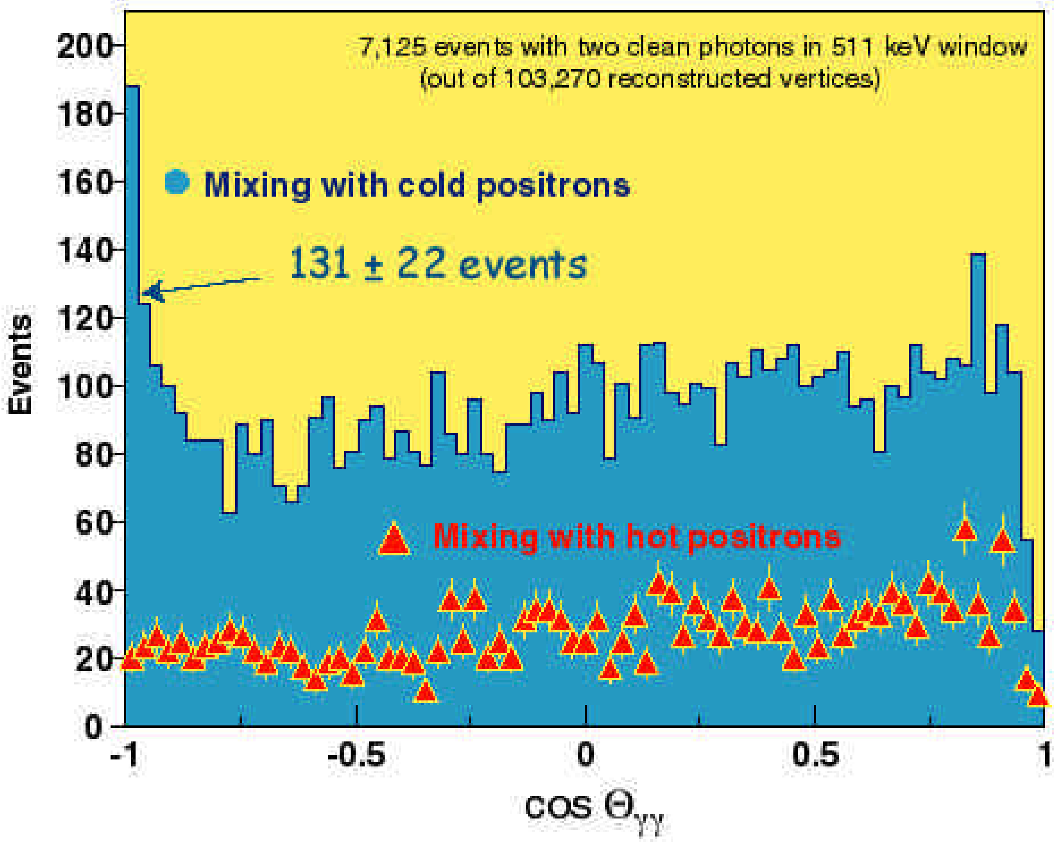
- Reconstruction efficiency ~ 0.25 %

511 keV Multiplicity Distribution

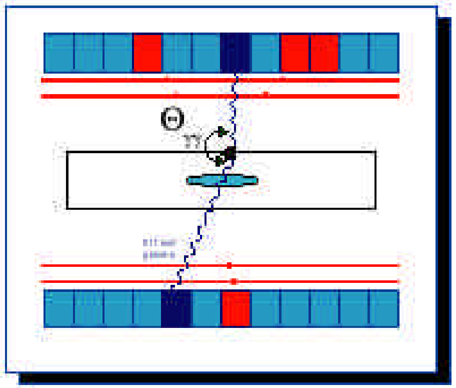


Antihydrogen Signal

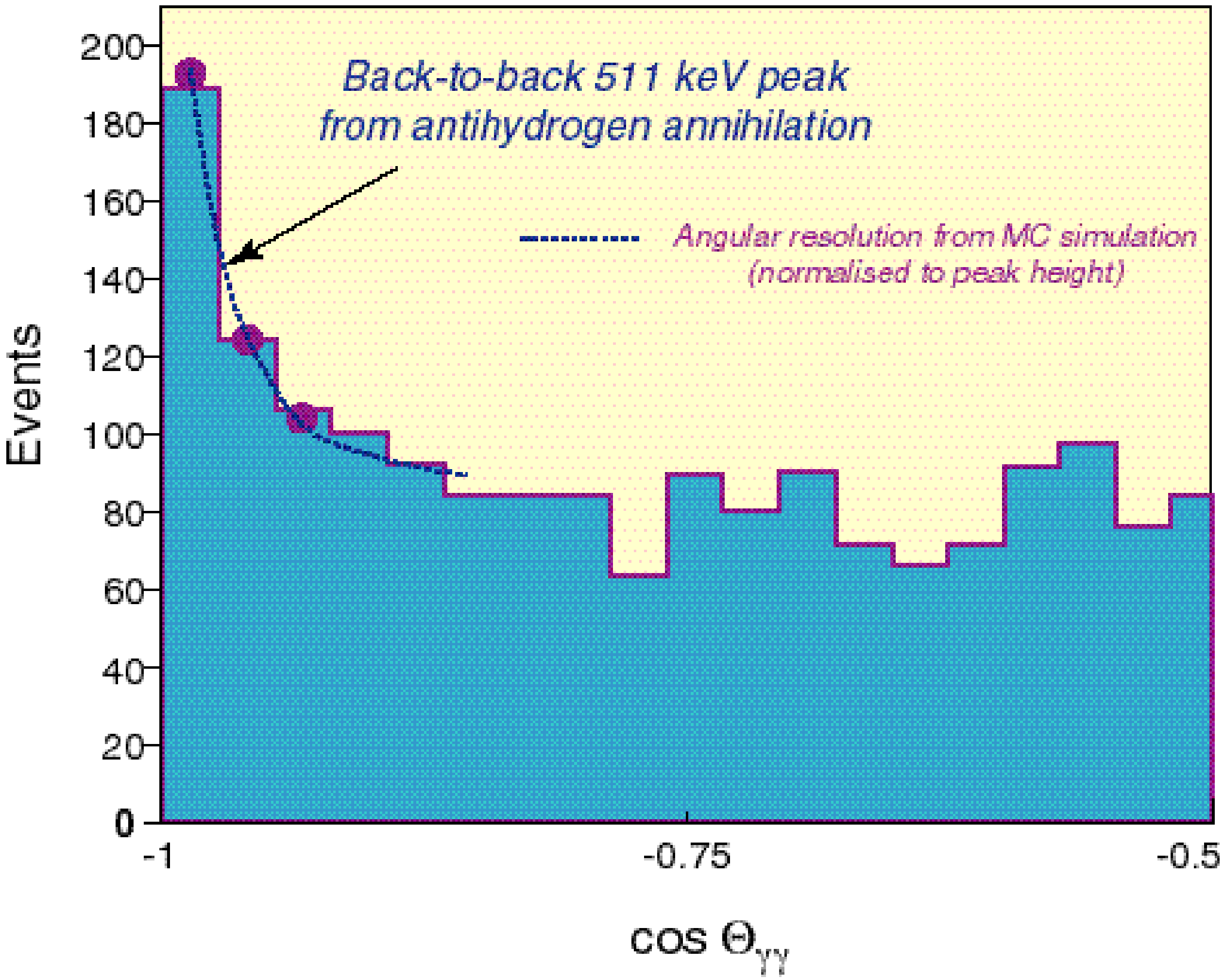
Opening angle between two 511 keV photons
(seen from charged particle vertex)



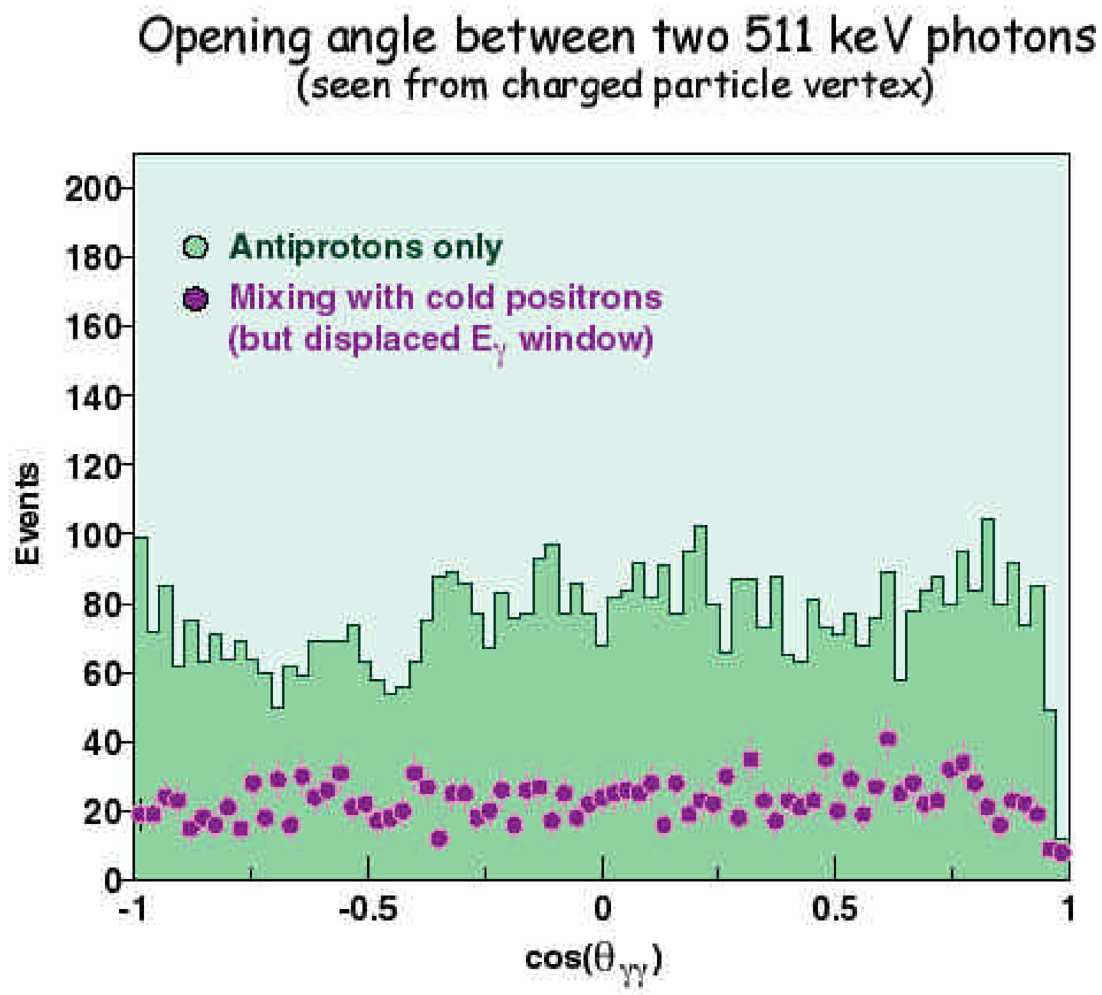
Definition of $\Theta_{\gamma\gamma}$



Comparison of width with MC



Background measurements



Histogram:

Antiproton-only data (99,610 vertices, 5,658 clean 2-photon events plotted).

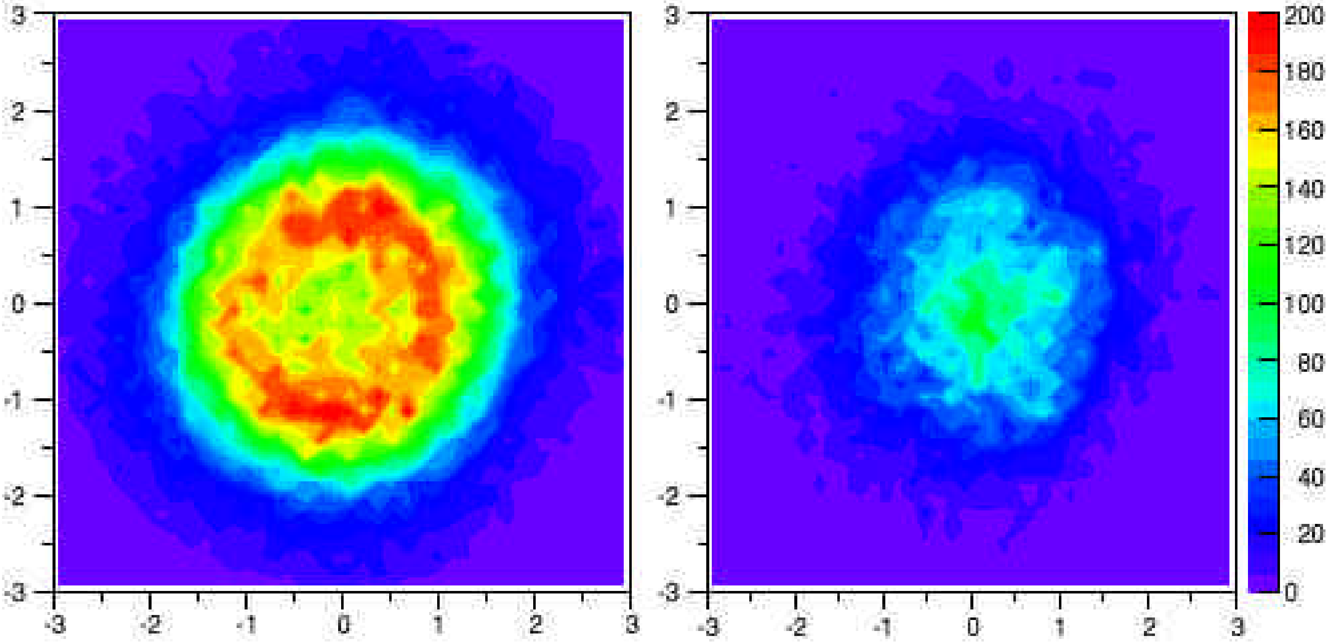
Dots:

Antiproton + cold positrons, but analyzed using an energy window displaced upward so as not to include the 511 keV photo-peak

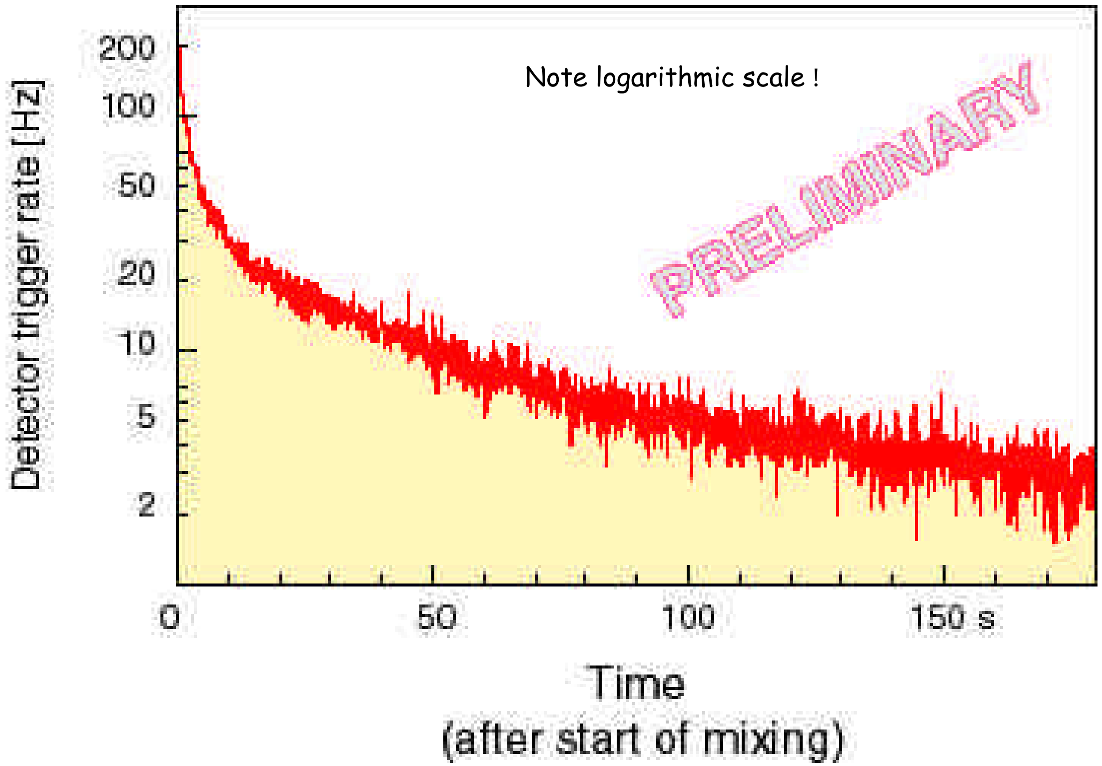
Distribution of annihilation points

Distribution of annihilation vertices
when antiprotons are mixed with ...

cold positrons hot positrons



Annihilation rate versus time

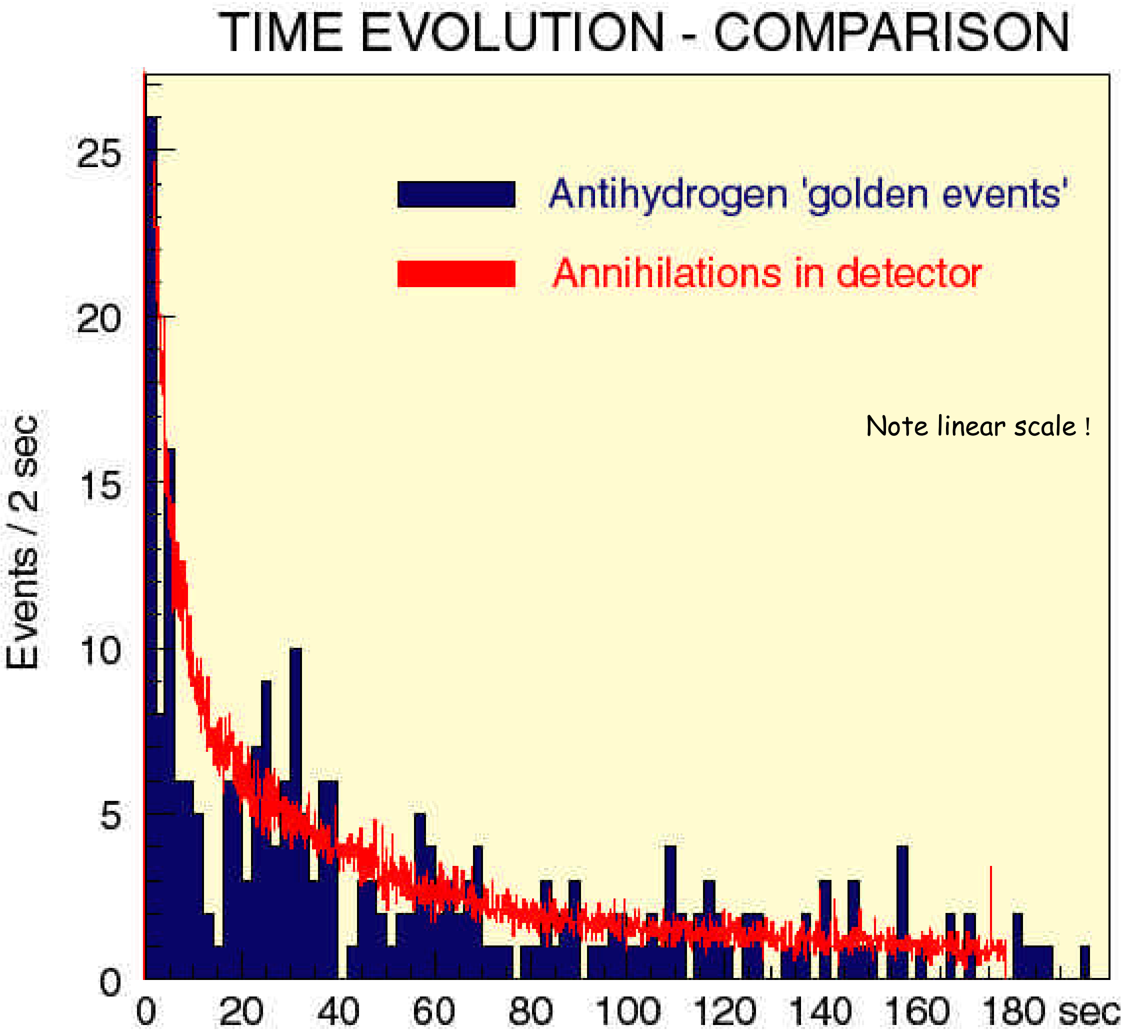


Very high initial rate (t < 10 sec), then exponential decrease

Rate is dominated by antihydrogen annihilation

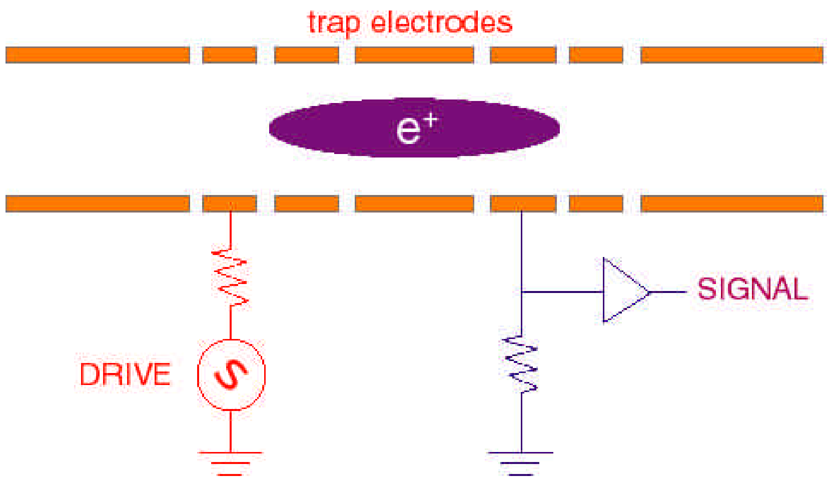
Ionizing field at positron plasma boundary: antihydrogen in n ≤ 55

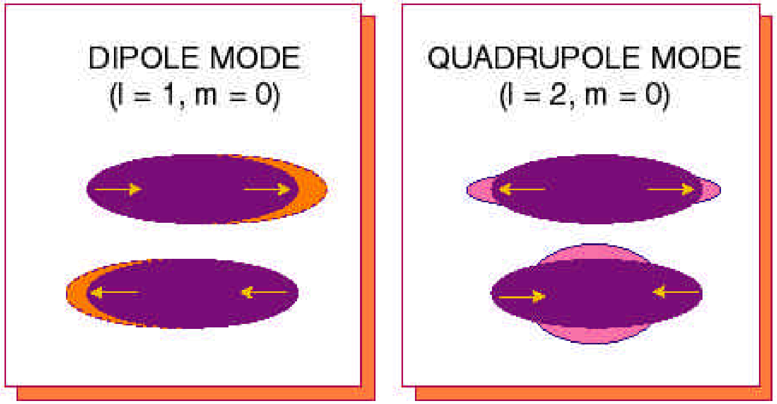
Time dependence of signal events



Positron temperature

PLASMA MODES DIAGNOSTICS





Non-destructive measurement:

$\omega(1,0)$, $\omega(2,0)$, line shape $\rightarrow$

Plasma parameters: n, α, r, z

ΔT from frequency shifts

Summary

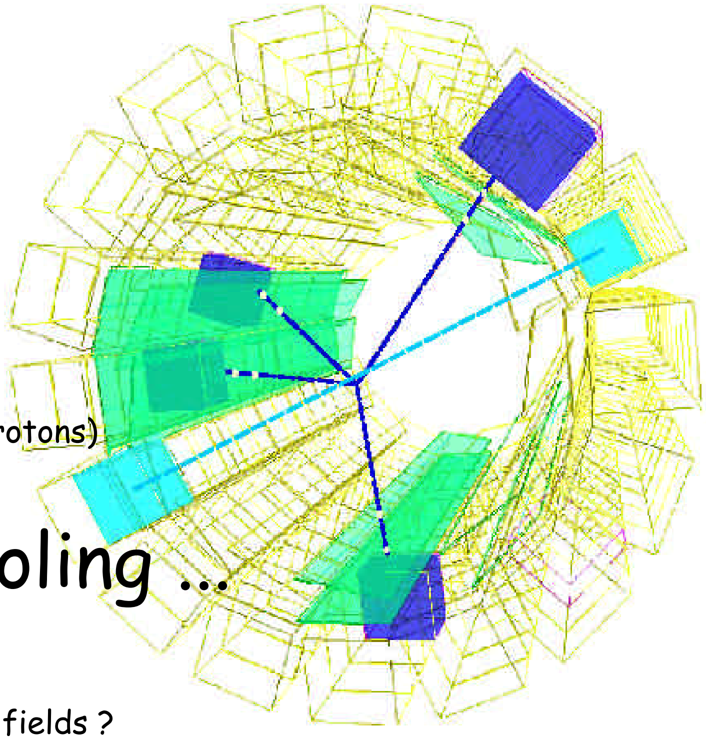
- 1 cycle = 10^4 antiprotons mixed with ~10^8 cold positrons (every 5 minutes)
- 131± 22 “golden” antihydrogen events reconstructed (~ 1 / cycle)
- Annihilation events are mostly antihydrogen (> 1000 / cycle)
- Antihydrogen production rate initially > 100 Hz
- Back-to-back signal not present when

  positrons are hot

  only antiprotons in mixing trap (annihilating on wall)
- Antihydrogen production can be switched off by RF heating of positrons
- ANTIHYDROGEN PRODUCTION AT T > 300 K CLEARLY OBSERVED

Outlook

Antihydrogen



Study …

Formation process

More …

Increase formation rate (more antiprotons)

Trapping and cooling …

Anti-Hydrogen at E < 0.05 meV ?

Dense plasmas in magnetic multipole fields ?

Laser cooling? Collisions with ultra-cold hydrogen atoms?

Spectroscopy

High precision comparison 1S-2S

Hyperfine structure

Gravitational effects

E ~ 0.000 1 meV

A new precision tool for science