Cold Antihydrogen

Status and Prospects

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ATHENA Collaboration

CERN

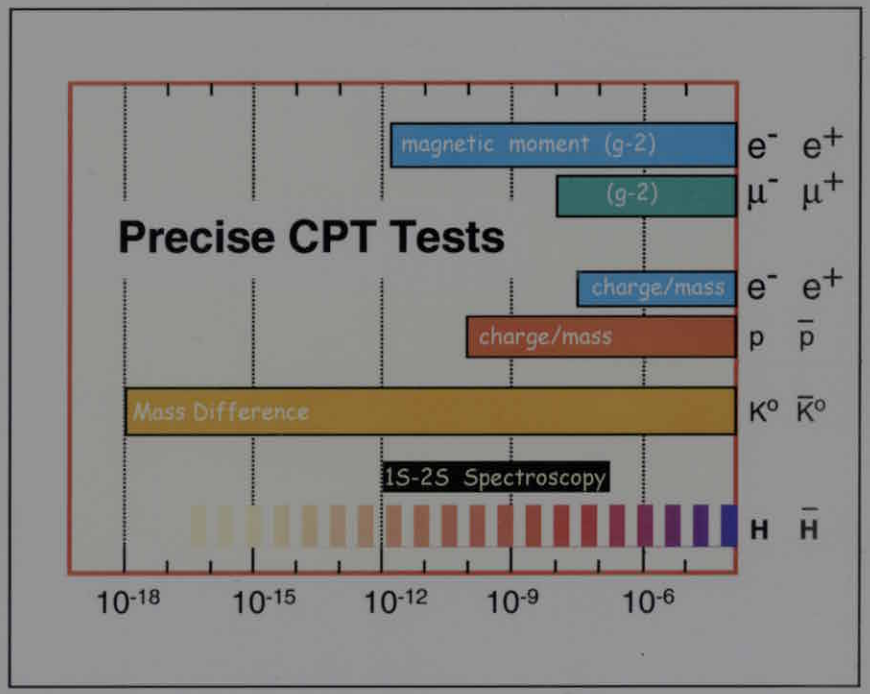
10.12.2002

GSI Future Workshop

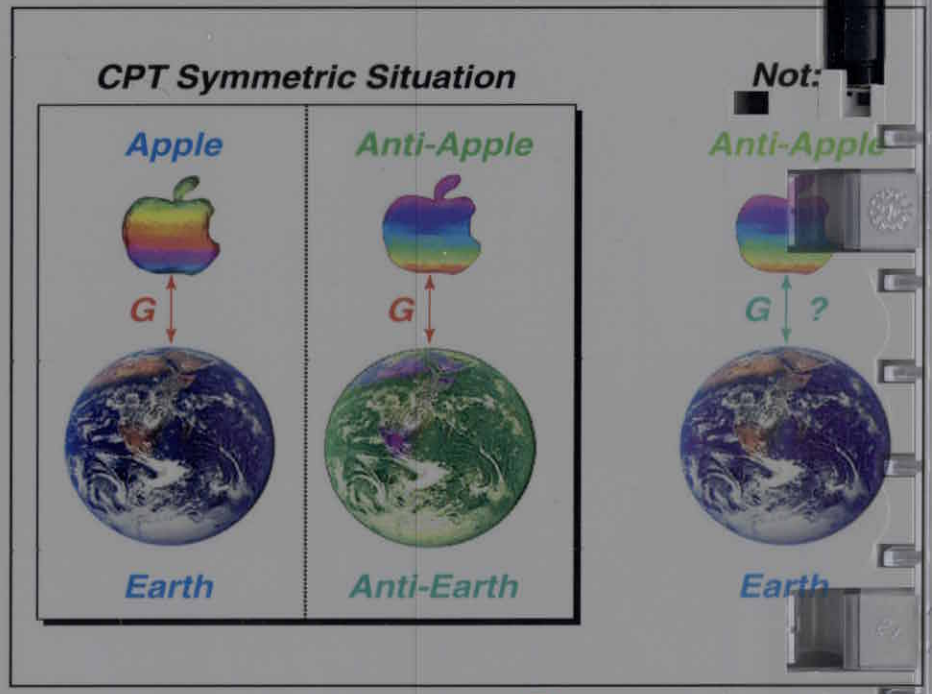
LONG TERM PHYSICS GOALS

| Antihydrogen | = | Hydrogen | ?

CPT



Gravity



But . . .

FIRST GOAL

PRODUCTION AND DETECTION OF COLD ANTIHYDROGEN

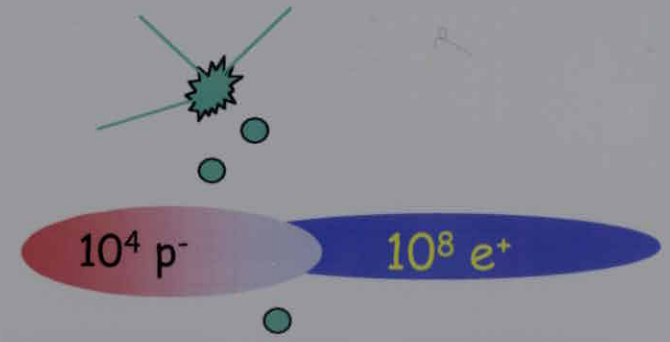
AD

p- Production (GeV)

Deceleration (MeV)

Trapping (keV)

Cooling (~ meV)



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

Antihydrogen formation

Detection of annihilation

Na-22

e^+ Production (MeV)

Moderation

Accumulation (eV)

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.

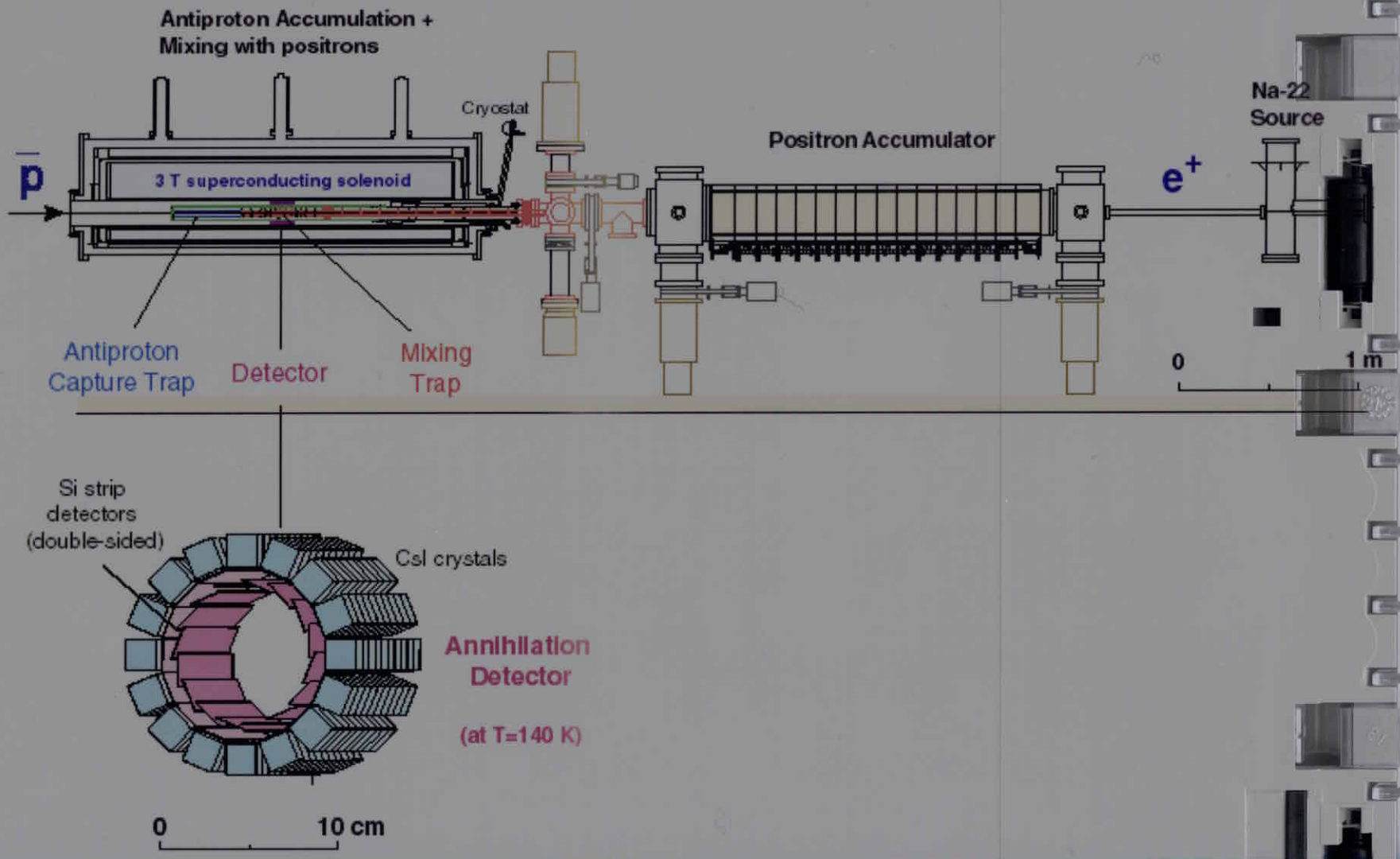
Detector + Analysis

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.

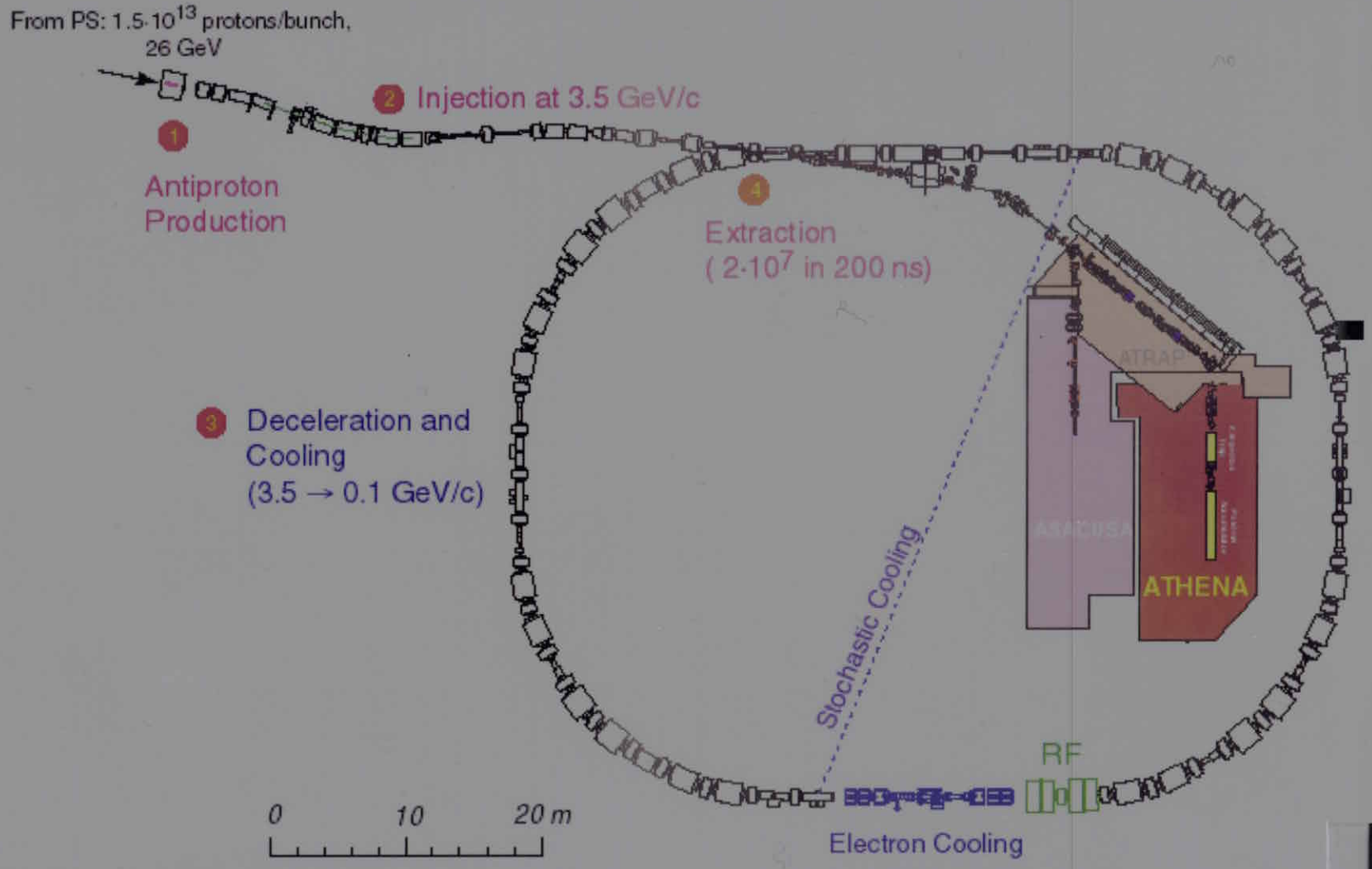
Brescia
Lodi-Rizzini E. Venturelli L.

Overview - ATHENA / AD-1



ATHENA - Photo

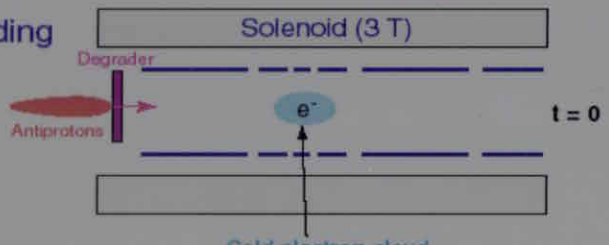
Antiproton Decelerator (1)



Antiprotons - Capture and Cooling

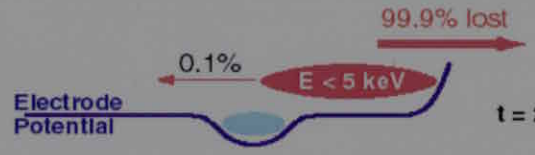
5.0 MeV antiproton bunch $(2 \cdot 10^7)$ from AD

1. Degrading

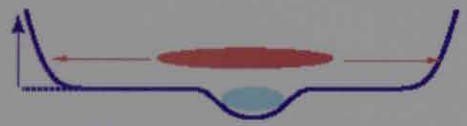


(Cooled by Synchrotron Radiation, t = 0.4 s at B = 3 T)

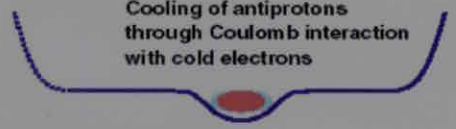
2. Reflecting



3. Trapping

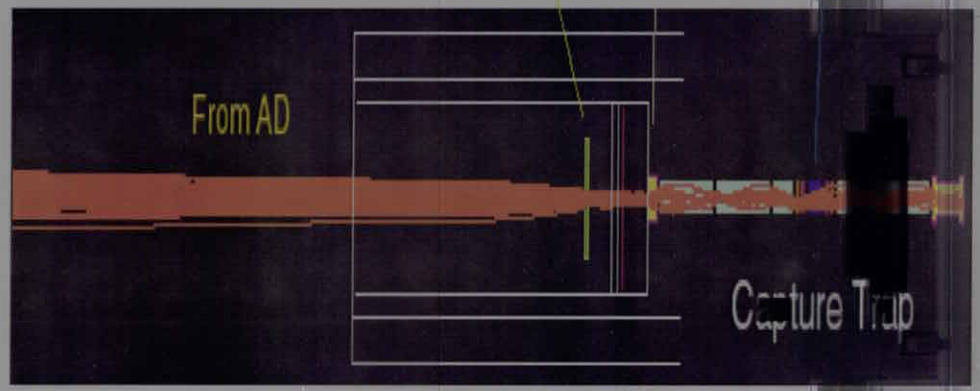


4. Cooling

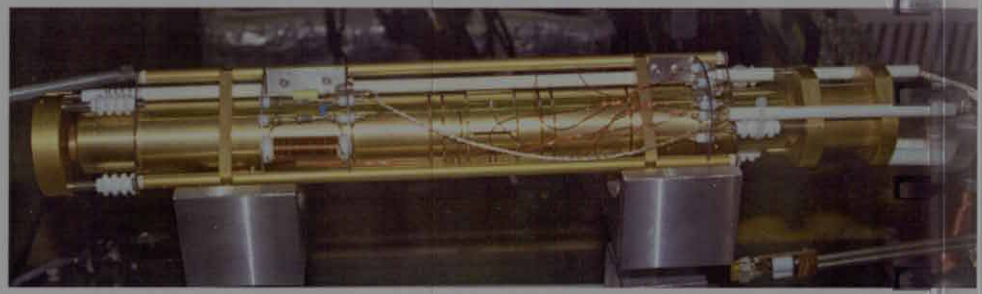


5. Transfer to mixing trap:

10,000 cold antiprotons / AD shot (~100")



Segmented Si (67 μ) beam counter

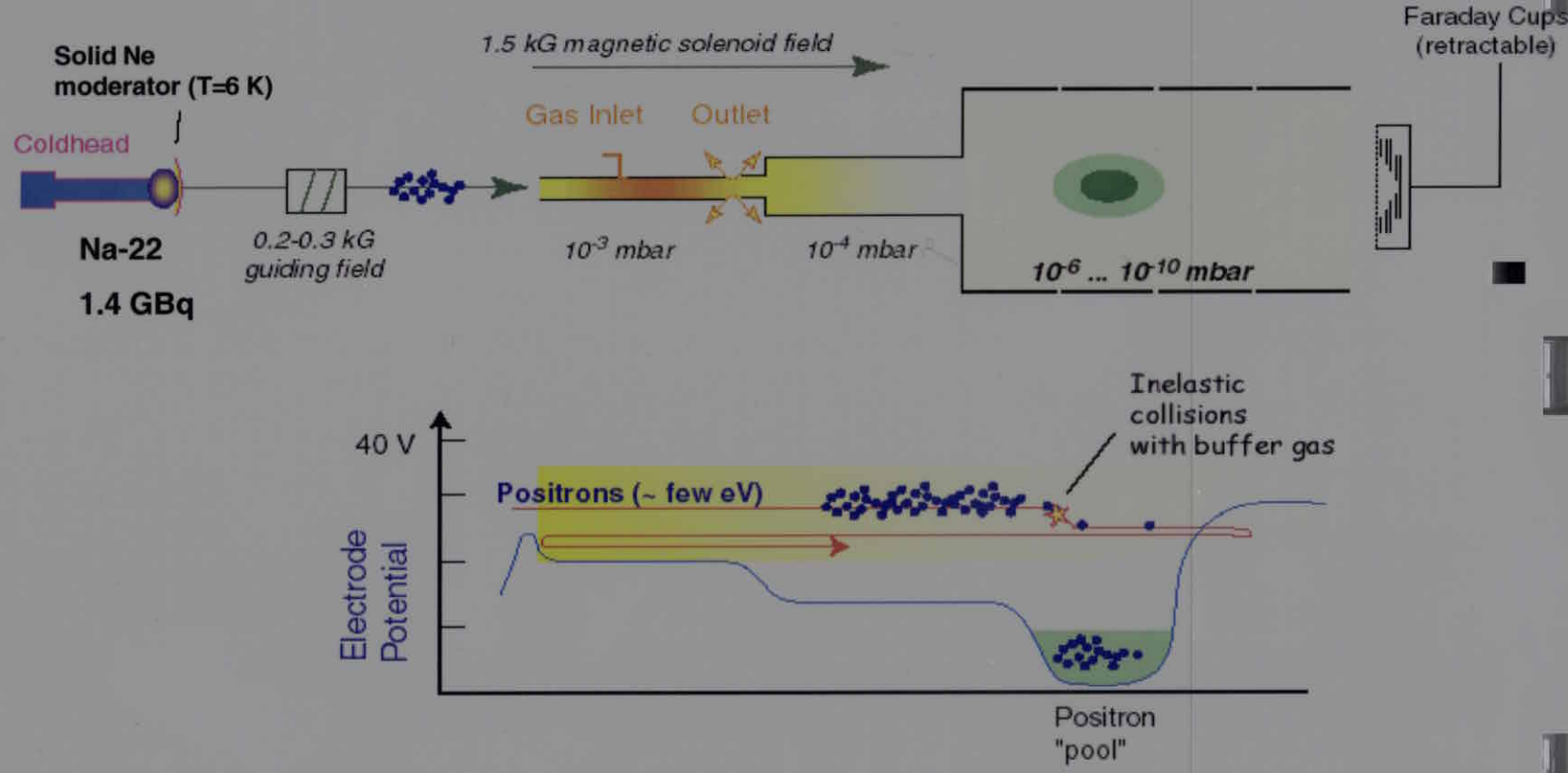


Antiproton Capture Trap

Technique developed by TRAP collaboration at LEAR (1985)

Positron Accumulation (1)

ATHENA - Positron Accumulation Scheme

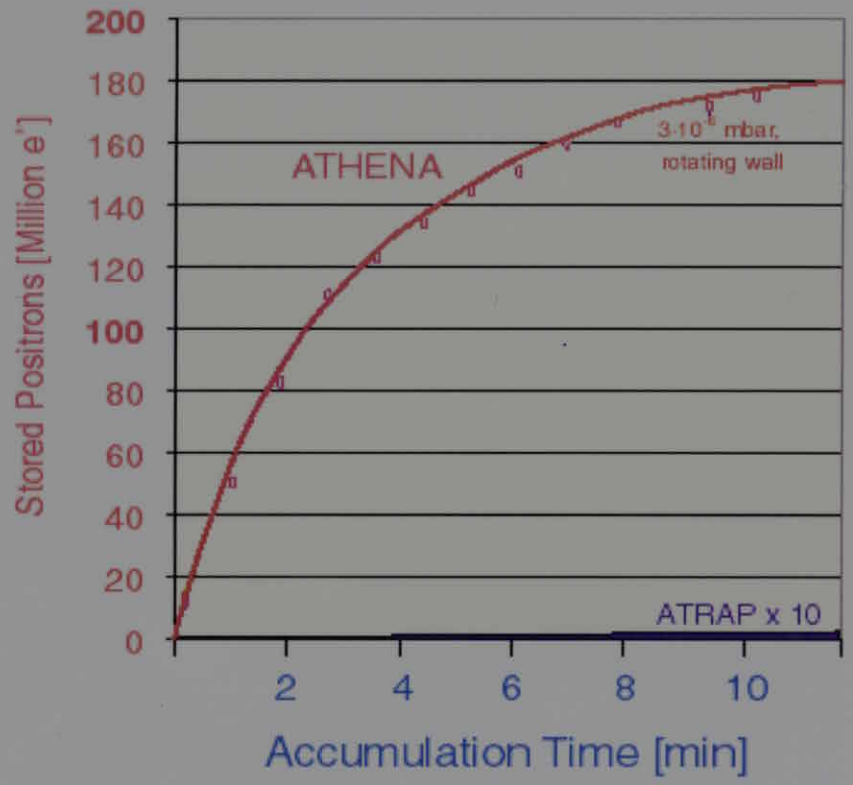


Scheme of ATHENA Positron Accumulator

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

Positron Accumulation (2)

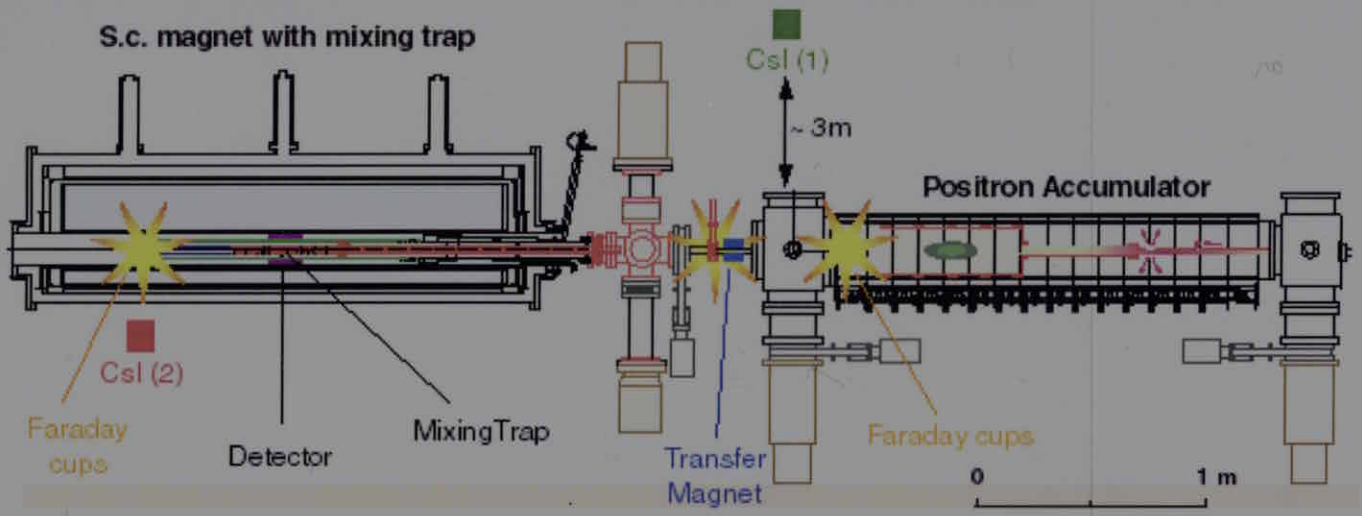
Accumulated positrons vs time



Accumulation rate ~ 10^6 e^+/sec

- 150 million positrons / 5 min

Positron Transfer



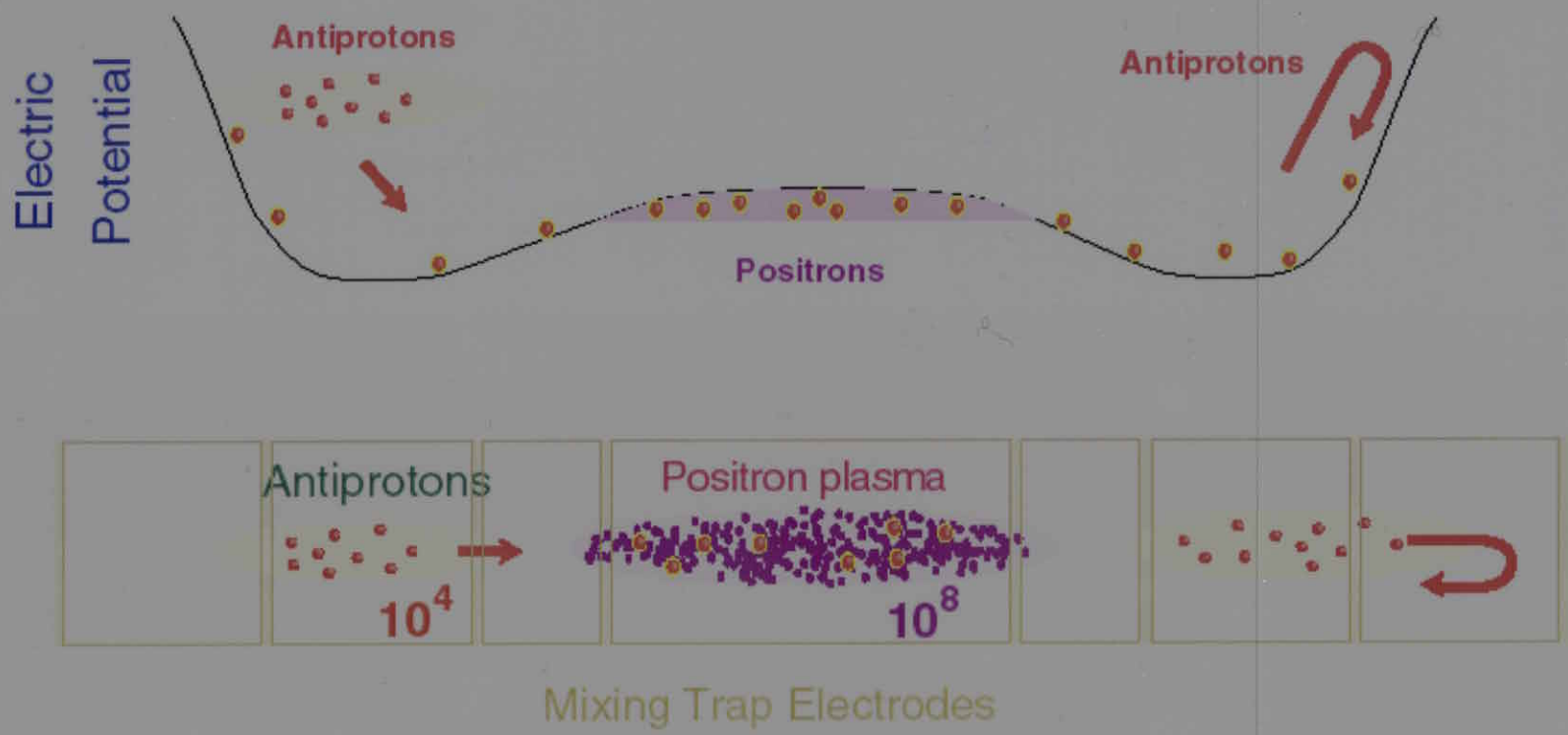
- Transfer positrons from accumulator into mixing trap (ε ~ 50 %)
- Positrons cool by synchrotron radiation at B=3T: 75 million cold positrons
- Non-destructive diagnostics gives plasma parameters:

  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)

Antihydrogen Detector

GOAL

Vertex from tracking of charged particles

Identification of 511 keV gammas

Time- and space coincidence of tracks + gammas

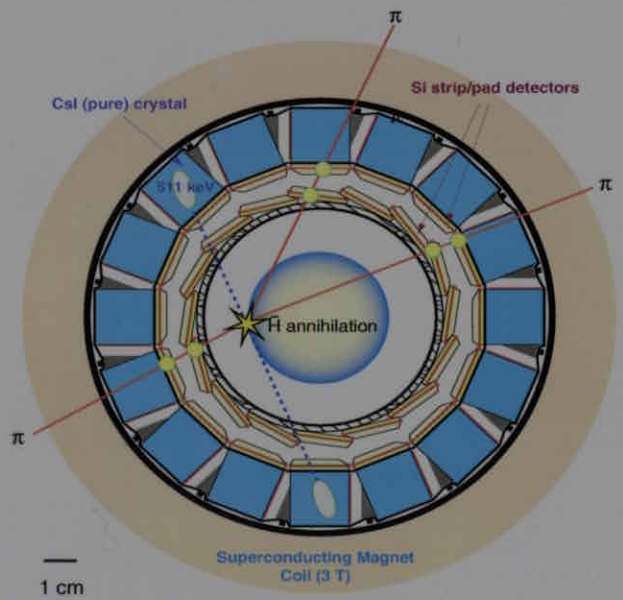
DESIGN

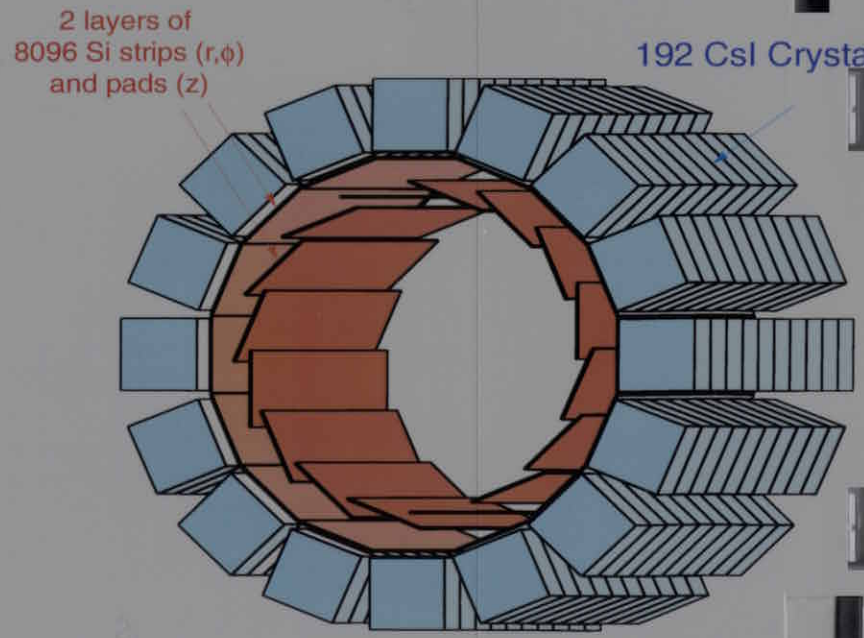
Compact (radial thickness ~ 3 cm)

Large solid angle (> 70 %)

High granularity (8 K strips, 192 crystals)

Operation at T ~ 140 K, B = 3 Tesla

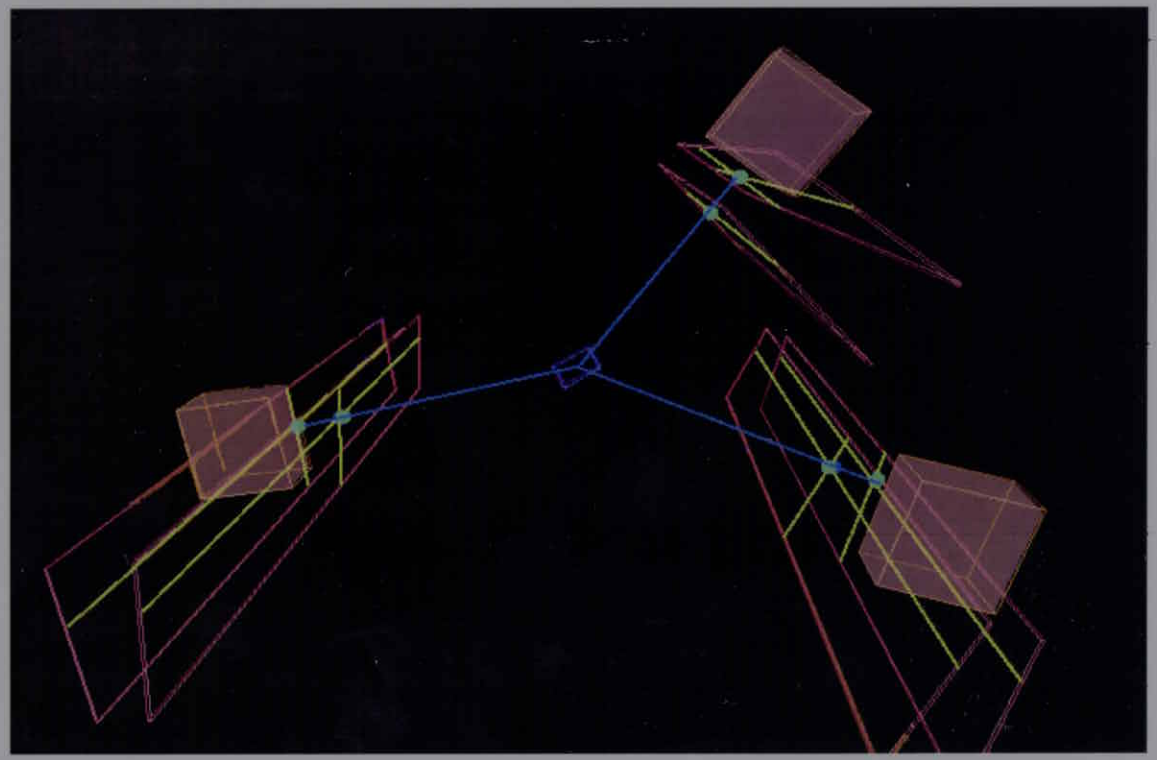


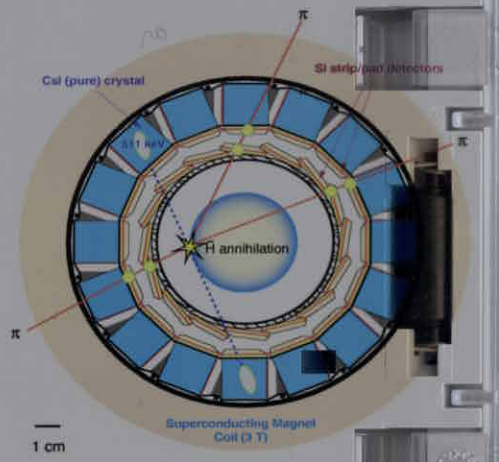


Antihydrogen Detector - Antiprotons only

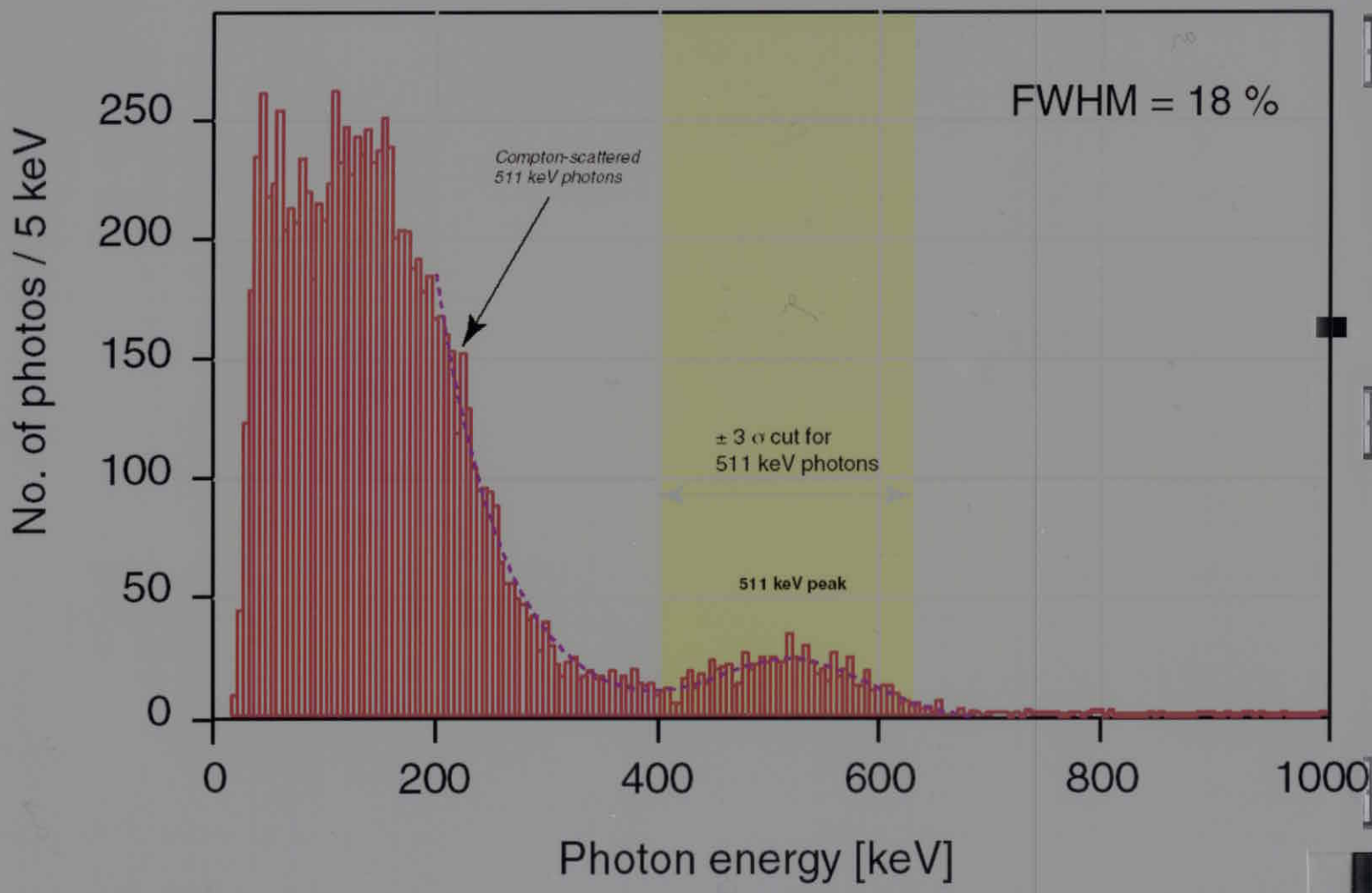
Antiproton Annihilation (example)

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

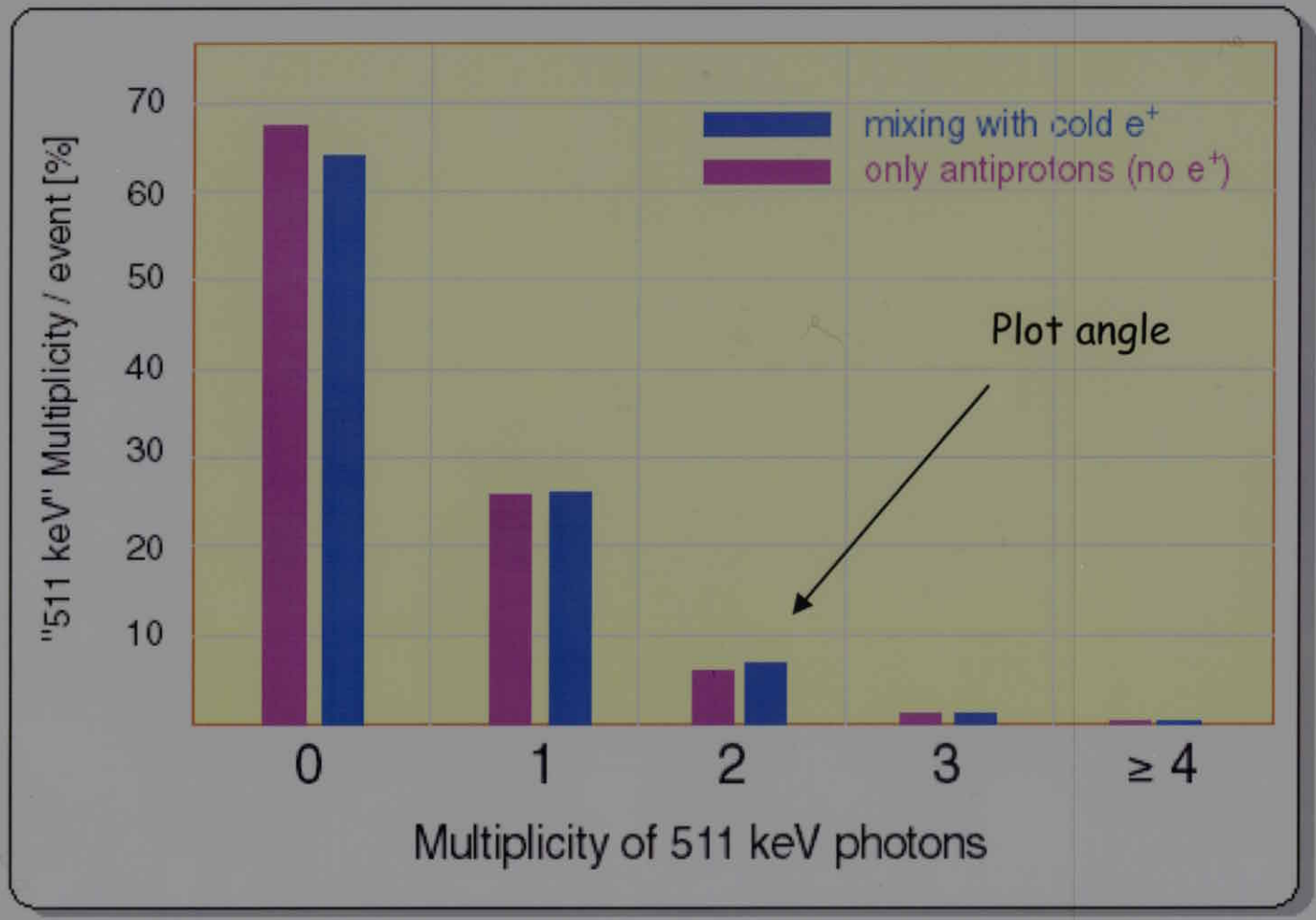




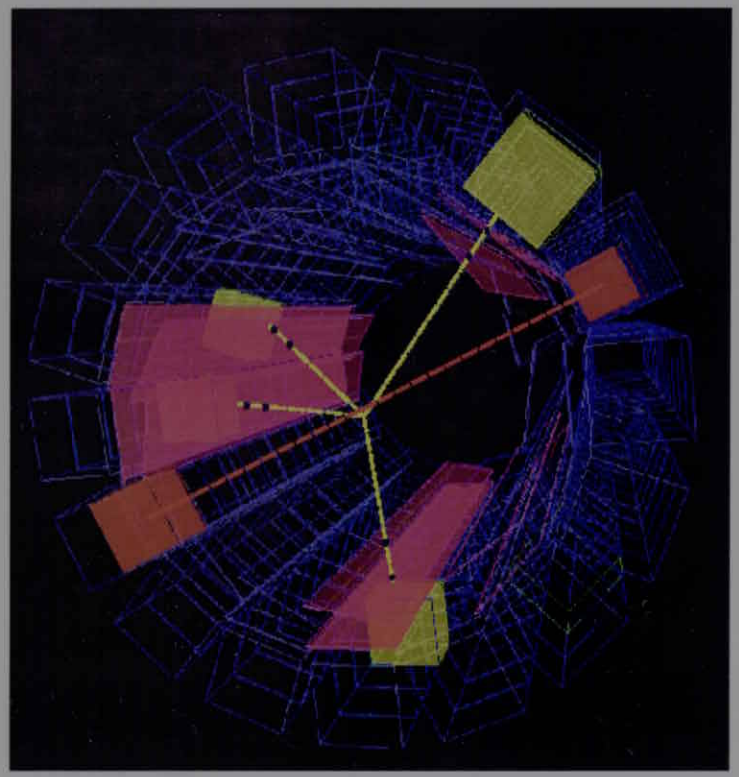
CsI - Photon Energy Resolution



511 keV Multiplicity Distribution

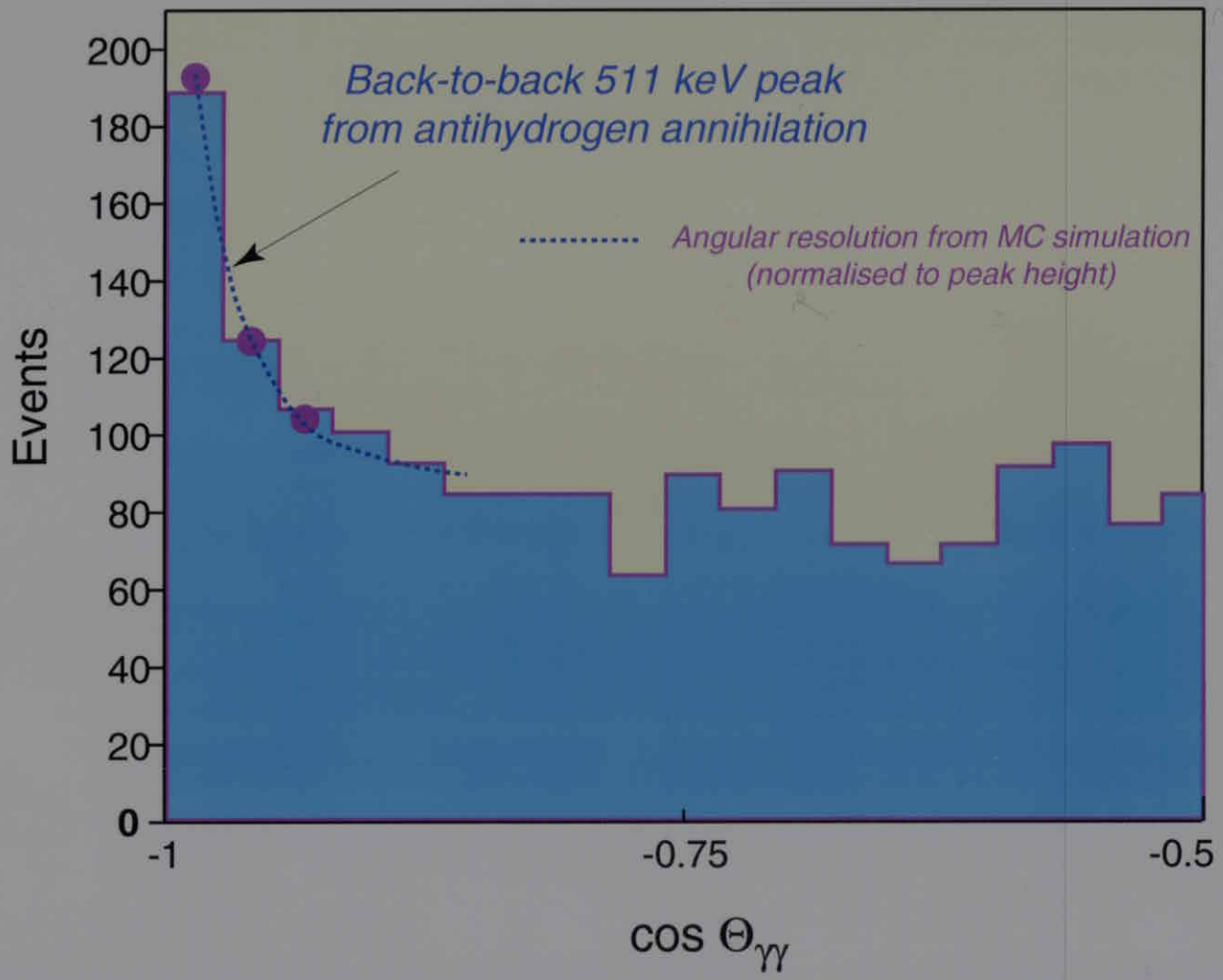


Analysis Procedure



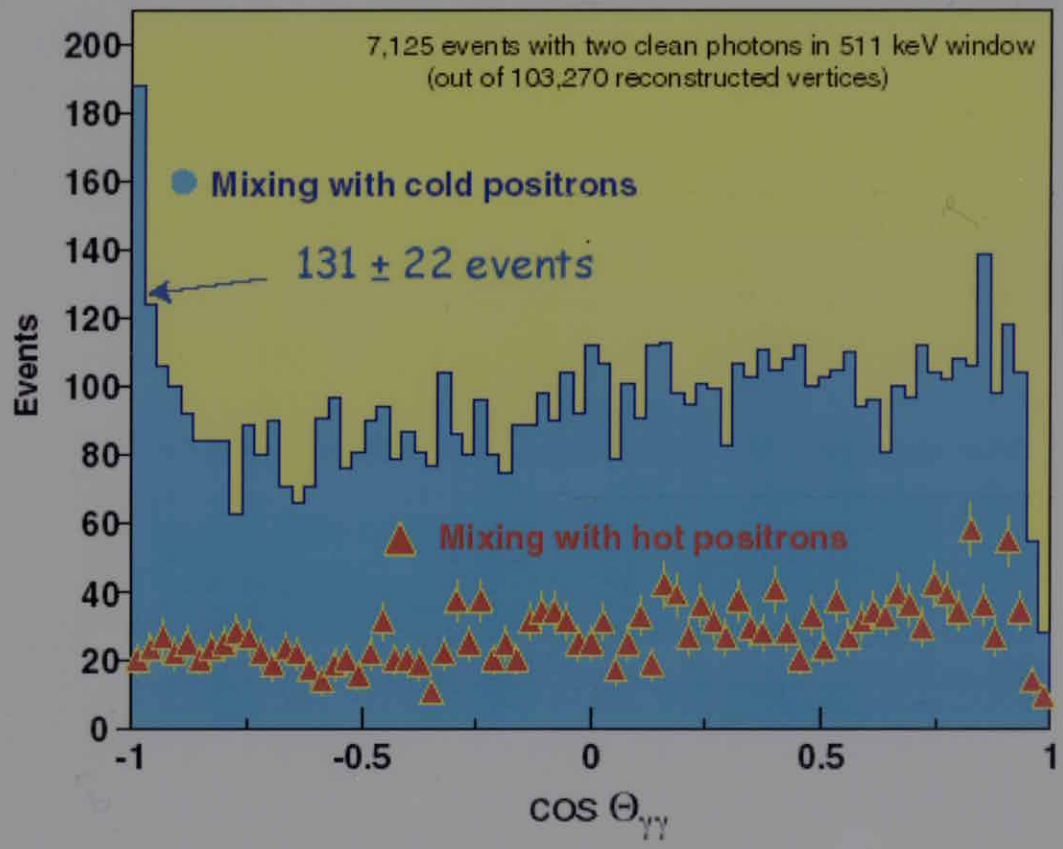
- Reconstruct annihilation vertex
- Search for 'clean' 511 keV-photons:
  - exclude crystals hit by charged particles
  - + its 8 nearest neighbours
- '511 keV' candidate =
  - 400... 620 keV
  - no hits in any adjacent crystals
- Select events with two '511 keV' photons
- Reconstruction efficiency ~ 0.25 %

Comparison of width with MC

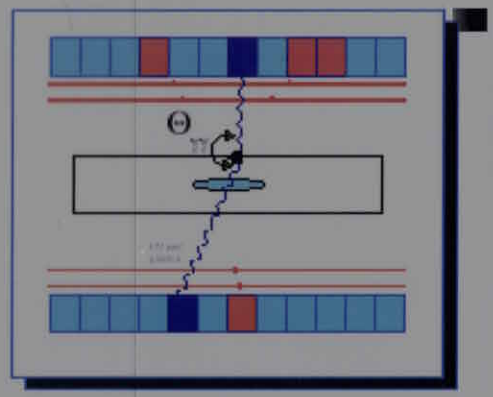


Antihydrogen Signal

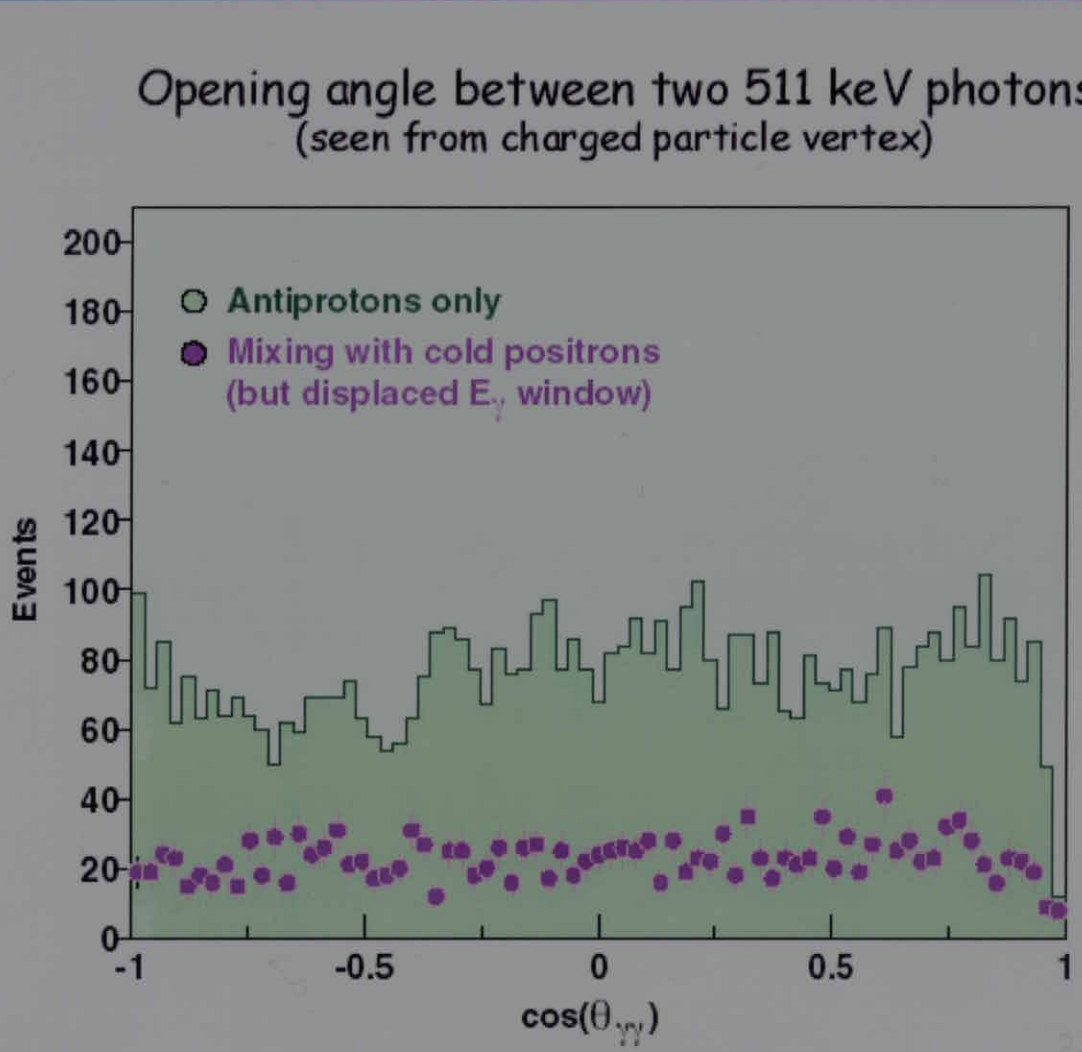
Opening angle between two 511 keV photons
(seen from charged particle vertex)



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



Background measurements



Histogram:

Antiproton-only data (99,610 vertices, 5,658 cl[illegible]2-photon events plotted).

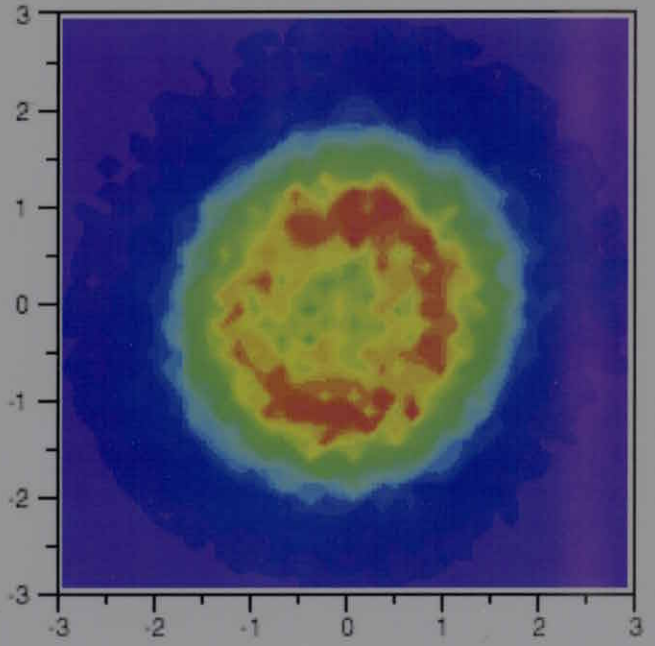
Dots:

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

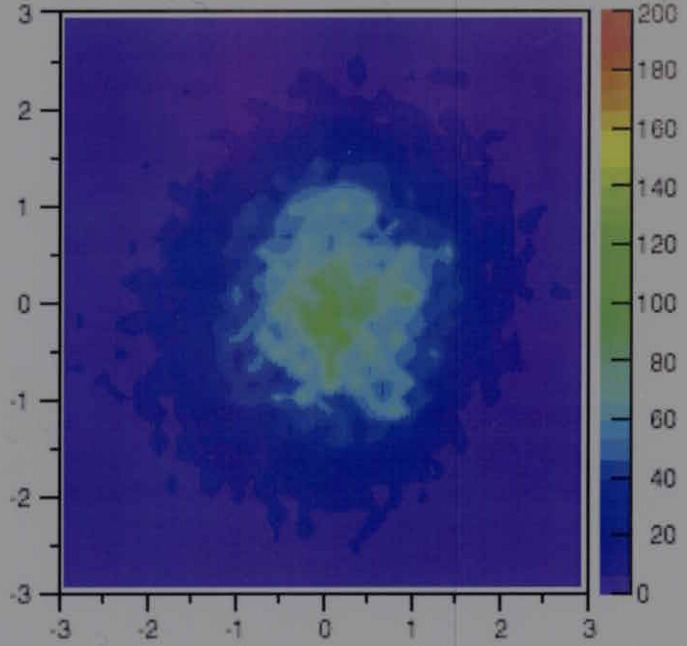
Distribution of annihilation points

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

cold positrons

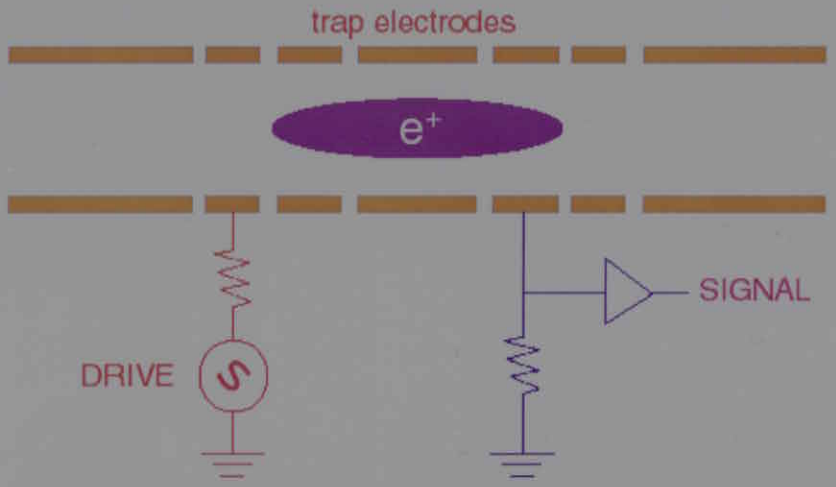


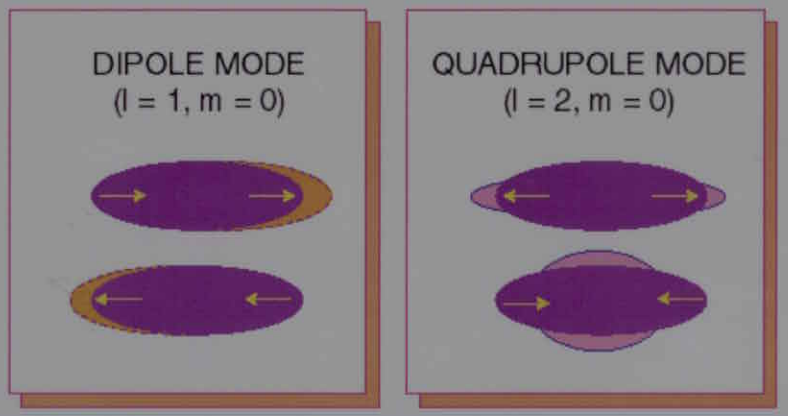
hot positrons



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

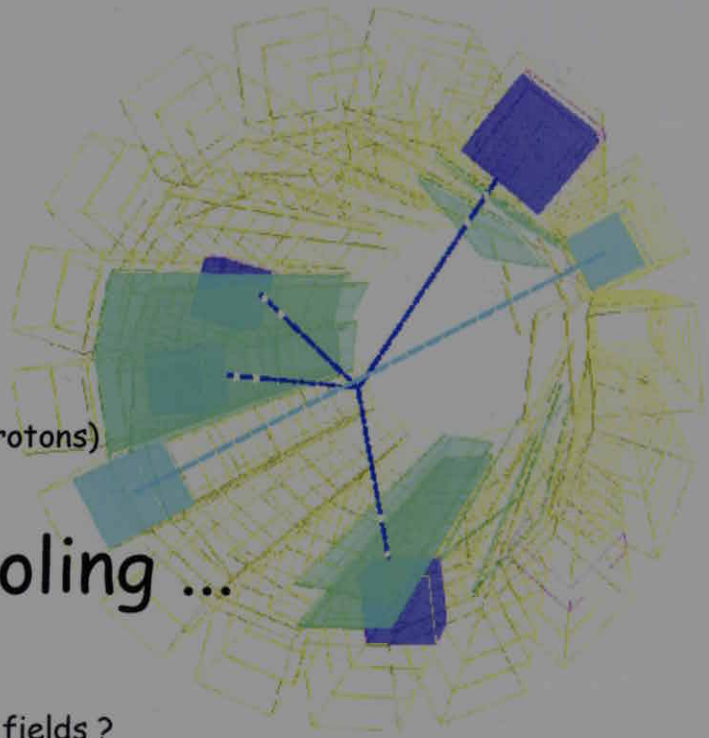
- 1 cycle = 10^4 antiprotons mixed with ~10^8 cold positrons (every 5 minutes)
- 131± 22 "golden" antihydrogen events reconstructed (~ 1 / cycle)
- Annihilation events are mostly antihydrogen (> 1000 / cycle)
- Antihydrogen production rate initially > 100 Hz
- Back-to-back signal not present when

  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
- Radiative recombination !! n < 60 (field ionization). Three-body process ?

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-

Hyperfine structure

Gravitational effects

E ~ 0.000 1 meV

A new precision tool for science

AD - PHASE 2 (?)

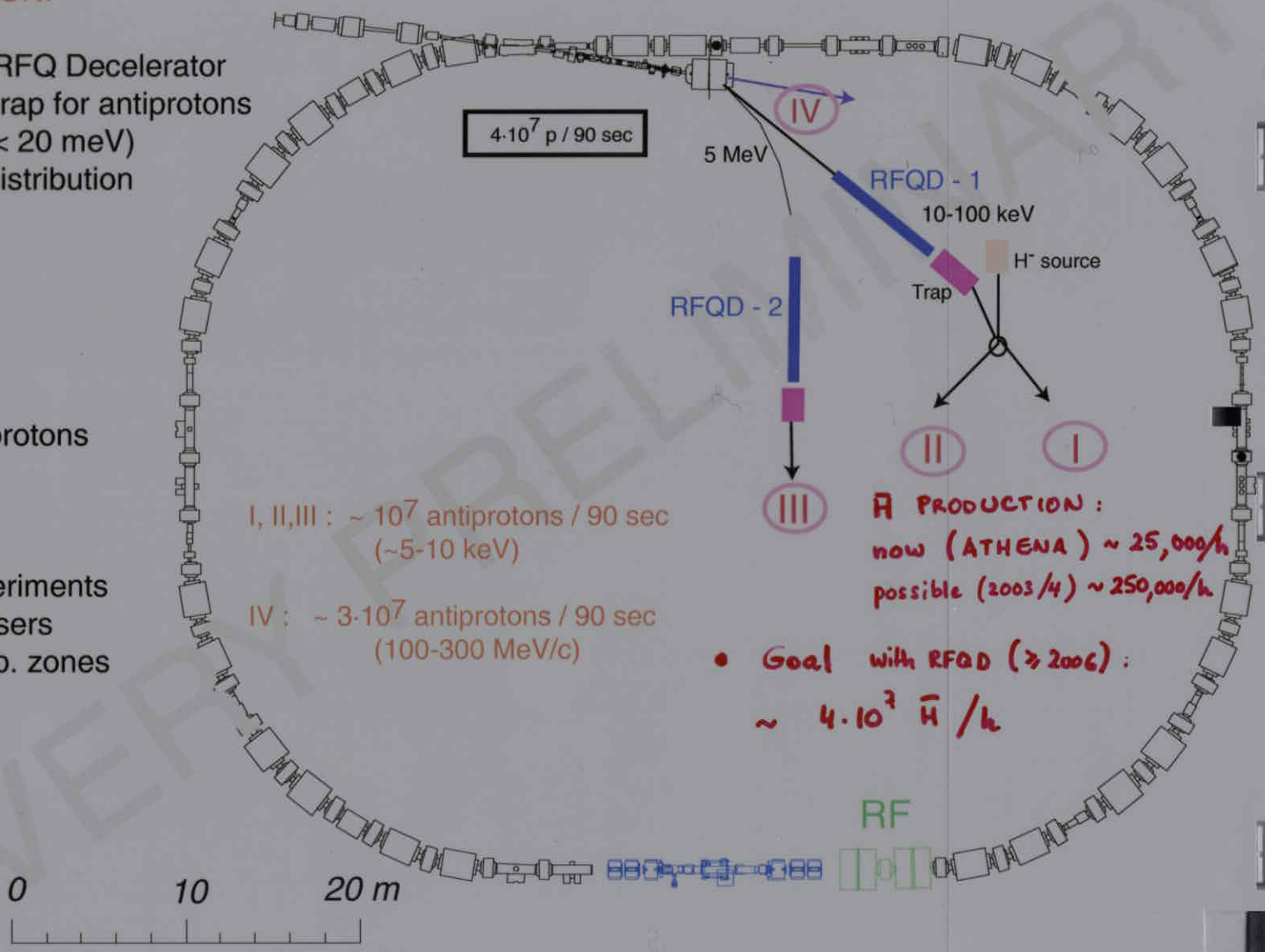
NDER DISCUSSION:

General purpose RFQ Decelerator
General purpose trap for antiprotons
Electron cooling (< 20 meV)
keV extraction + distribution

DVANTAGES:

Better use of antiprotons
Now: ~ 0.1 %
Then: ~ 10-30 %

antihydrogen experiments
other antiproton users
possibly more exp. zones



$\bar{H}$ PRODUCTION :
now (ATHENA) ~ 25,000/h
possible (2003/4) ~ 250,000/h

- Goal with RFQD (≥ 2006) :
  ~ $4 \cdot 10^7$ $\bar{H}$ /h