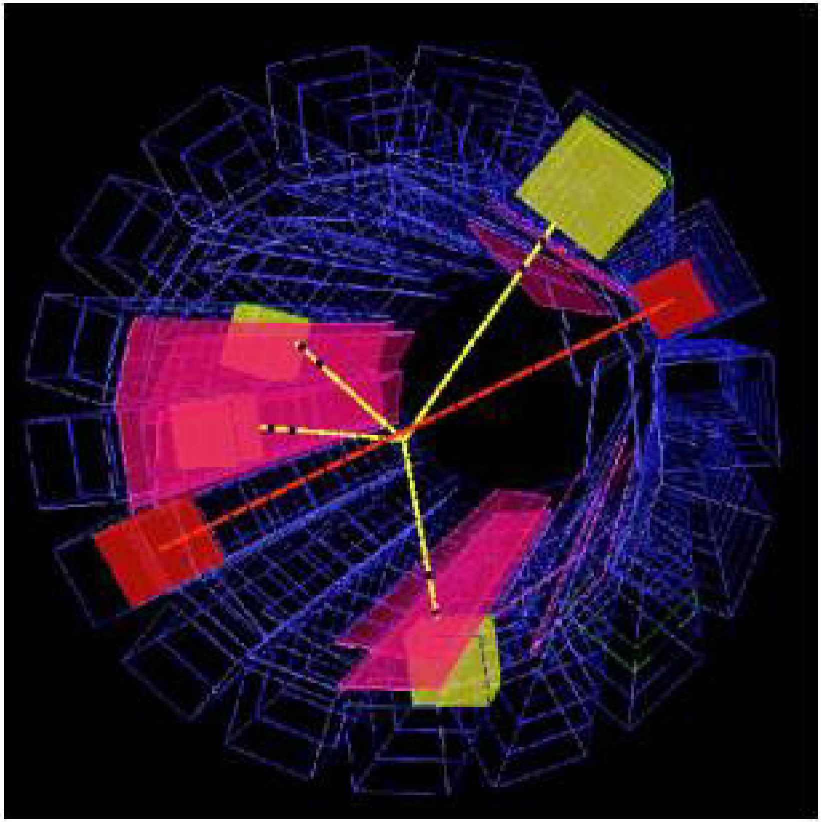

Produzione e rivelazione di atomi di antidrogeno a bassa temperatura

Production and detection of cold antihydrogen atoms

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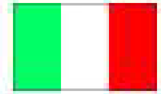
letters to nature

Gemma Testera
a nome della collaborazione
ATHENA

19 settembre 2002 advance online publication

INFN and University of Genoa,Pavia,Brescia -Italy



Genoa:

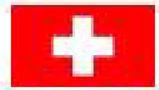
M. Amoretti, C. Carraro, V. Lagomarsino, M. Macri, G.Manuzio,G.Testera, A.Variola

Pavia

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

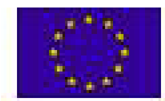
Brescia

G. Bonomi, E.Lodi Rizzini



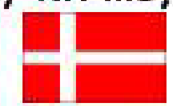
Physik-Institute -Zurich (Switzerland)

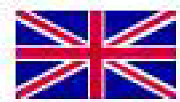
C.Amsler, D.Lindelof, N.Madsen, H.Pruys, C.Regenfus, P.Riedler



CERN

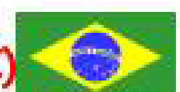
A.Boutcha, M.Doser, R.Landua, M.Holtzscheiter, K.Fine, G.Rouleau





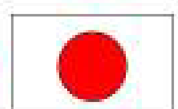
Dep. of Phys. And Astronomy Aarhus (Denmark)

P.Bowe,J.Hangst



Dep. Of Phys. Univ. of Swales Swansea (UK)

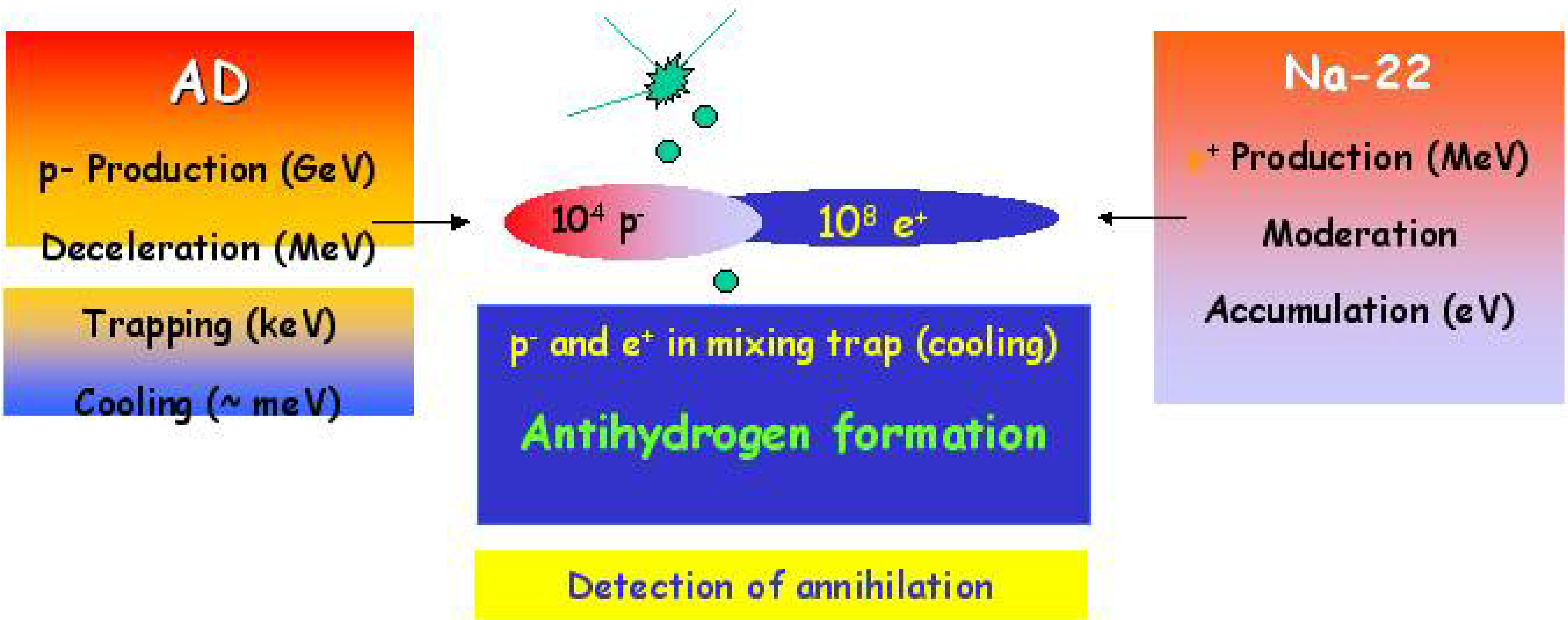
M.Charlton, M.Collier, L.V.Jorgensen, J.Rochet, T.Watson, D.P.van der Werf



Instituto de Fisica -Rio de Janeiro (Brasil)

C.L. Cesar

How to make cold antihydrogen



Antihydrogen before the ATHENA production

CERN G.Baur et. al. PL B 368 251 (1996)

$\bar{p} + Xe \rightarrow \bar{H} + e^- + Xe \quad \gamma = 2.3 \quad 11 \pm 2$ events

Fermilab G.Blanford et al.,PRL 80 14 (1998)

$\bar{p} + H \rightarrow \bar{H} + e^- + H \quad \gamma = 9.5 \quad 57 \pm 13$ events

$$\sigma = Z^2 \ln(\gamma) \ \ pb \qquad E_{\bar{H}} \approx E_{\bar{p}} \rightarrow GeV$$

ATHENA (and now also ATRAP):
- antihydrogen source
- production rate >>Hz
- energy in the submeV region (Kelvin - tenths of Kelvin)

Physics with Antihydrogen at subKelvin temperature

Anthydrogen Spectroscopy — CPT test ⟷ — **Hydrogen Spectroscopy**

1S-2S transition 243 nm, natural width 1.3Hz : 1 10^{-15} ➡ 10^{-18}

Resolution 1.5 10^{-14} (A. Huber et al., PRA 59 1844(1999)

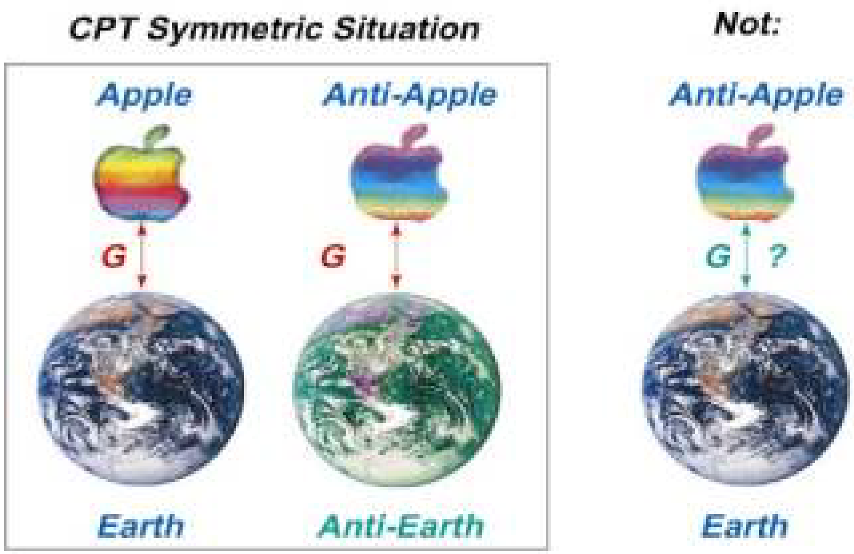
neutral atom traps - cold atomic beam - laser techniques

..near future:hydrogen laser cooling....

CPT precise tests:

$(m_{e+}-m_{e-})/m_{e-}$	$< 4\ 10^{-8}$
$(q_{e+}-q_{e-})/\ q_{e-}$	$< 4\ 10^{-8}$
$(g_{m+}-g_{m-})/\ g_{aver}$	$= (-2.6 \pm 1.6)\ 10^{-8}$
$(q/m)_{pbar}/(q/m)_p$	$= (1.5 \pm 1.1)\ 10^{-9}$
$(g_{e+}-g_{e-})/\ g_{aver}$	$= (-0.5 \pm 2.1)\ 10^{-12}$
$(m_{K0}-m_{K0})/m_{K0}$	$< 10^{-18}$

Test of the Weak Equivalence Principle (WEP) for antimatter



Gravity measur. on cold pbars
PS200 At CERN
V. Lagomarsino, V. Lia, G. Manuzio, G. Testera
Phys. Rev. A 50 2977 (1994)
"Using a Penning trap to weigh antiprotons"

Laser cooled atoms-atomic fountain-atom interferometry

Precision (Delta g)/g = $3\ 10^{-9}$ S. Chu, Nature Vol 400 849 (1999)

Gravitational red shift

10^{-18} → 10^{9} for positrons
10^{5} for pbars

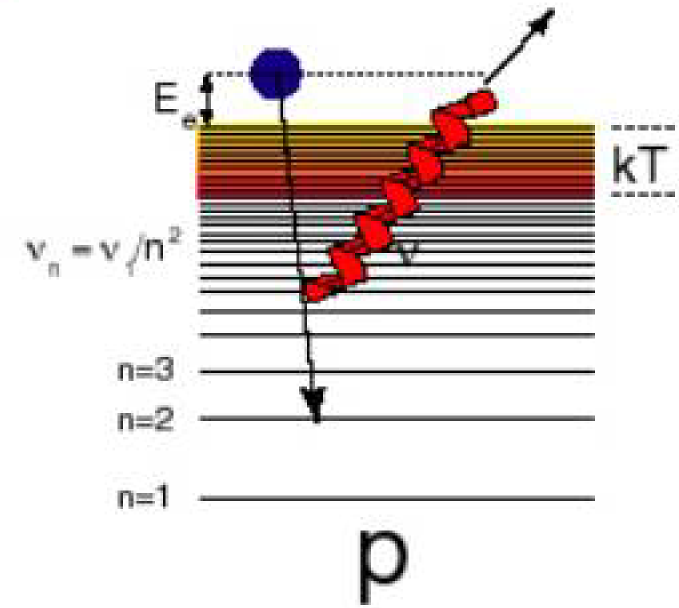
$$\frac{\Delta\nu}{\nu} = \frac{\Delta U}{c^2}$$

Spontaneous Radiative Recombination (SRR)

Pbar + e⁺ = Hbar + hν

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

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



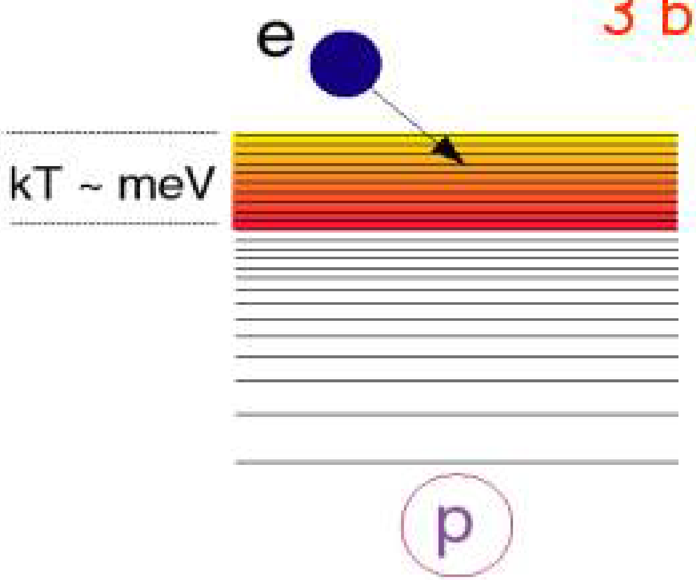
$$\tilde{A}_{rad}(s^{-1}) = 3\,10^{-11}\sqrt{\frac{4.2}{T(K)}}\, n_{e^+}(cm^{-3})$$

$$\frac{dN_{Hbar}}{dt} = N_{pbar}\,\Gamma_{rad}$$

……… Laser stimulated recombination

Pbar + e⁺ + m hν = Hbar + (m + 1) hν

3 bodies recombination



Pbar + e⁺ + e⁺ = Hbar + e⁺

$$\tilde{A}_{3bodies}(s^{-1}) = 6\ 10^{-12}\left(\frac{4.2}{T(K)}\right)^{9/2}\left(n_{e+}(cm^{-3})\right)^2$$

$$\frac{dN_{Hbar}}{dt} = N_{pbar}\,\Gamma_{3bodies}$$

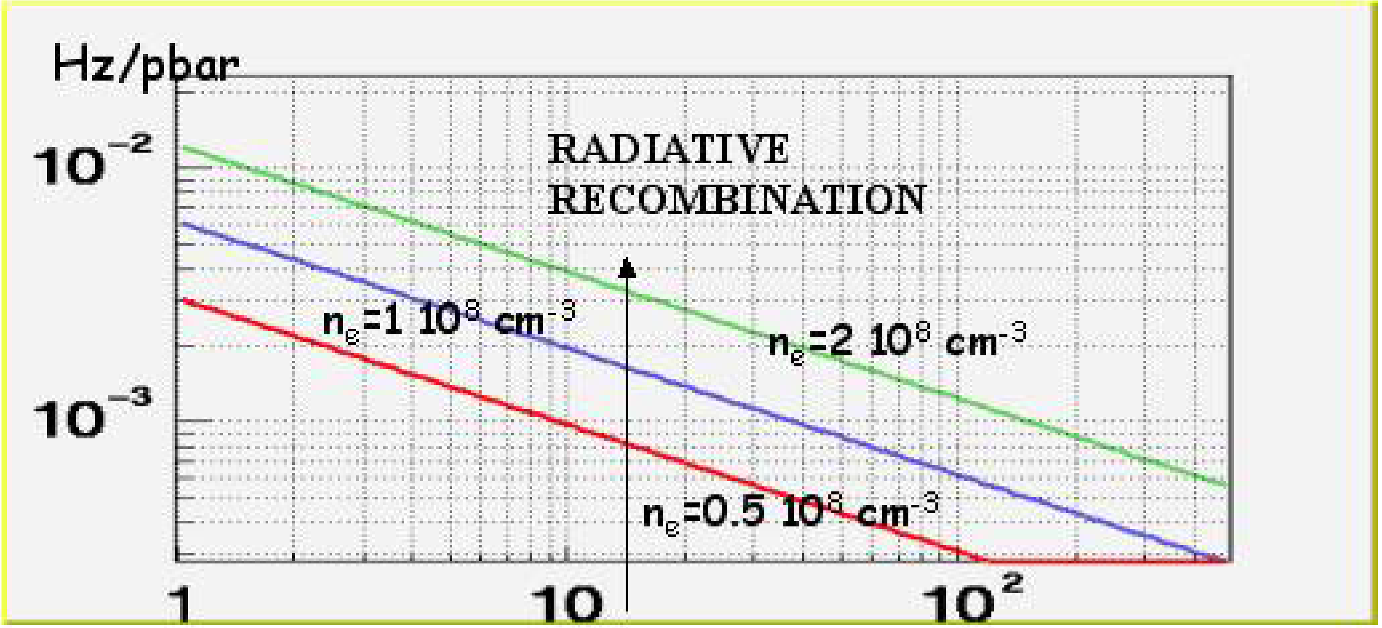
Small energy transfer (~ meV)

∅ E(final states) ~ - kT

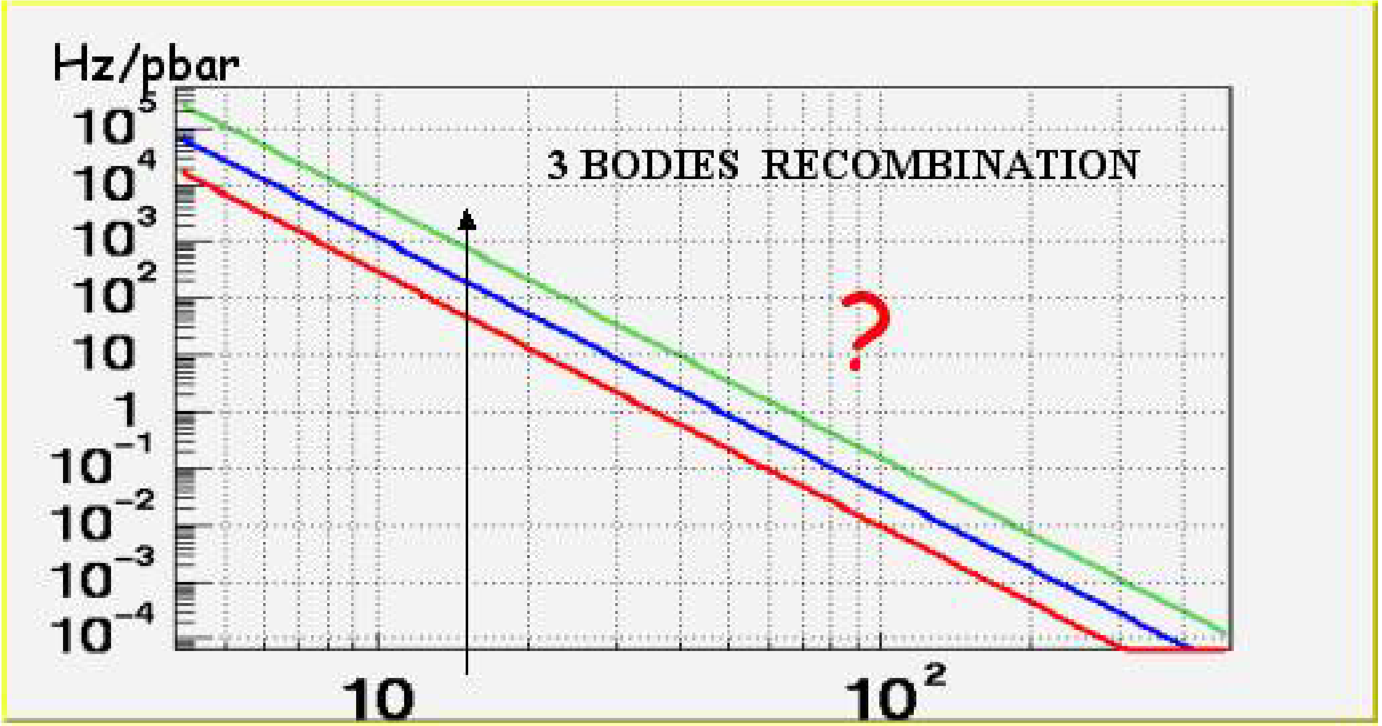
∅ n >> 100 ($\sigma \sim n^{4\ldots6}$)

∅ long lifetime (> 0.1 s)

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



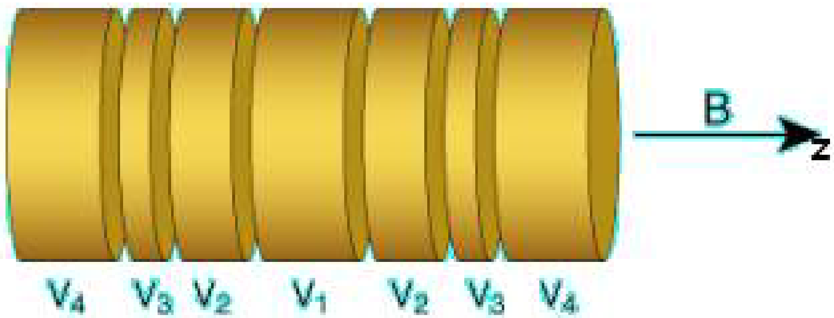
Γ= rate /pbar

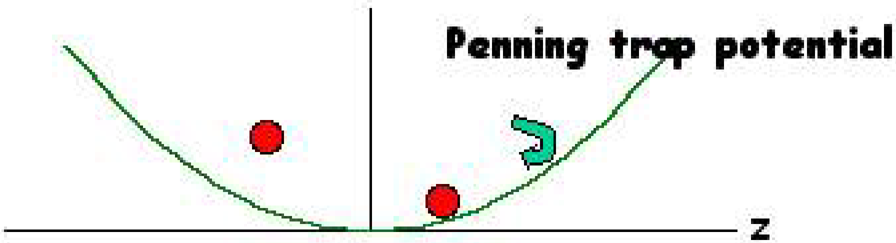


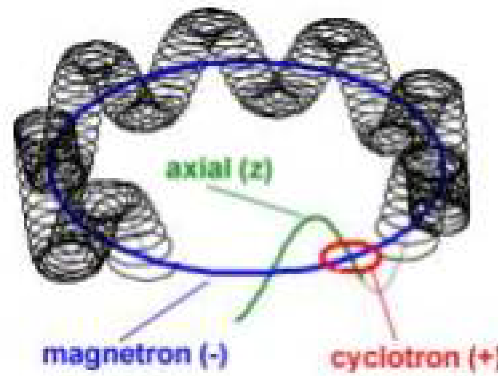
Traps for charged particles : Penning and Malmberg type

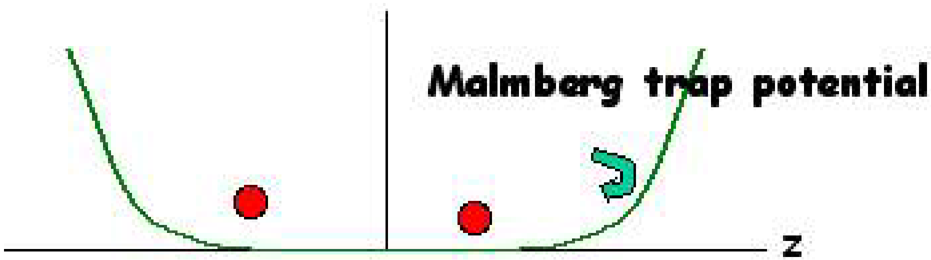
Axial confinement: electric field Ez

Radial confinement: uniform magnetic field Bz (3T)









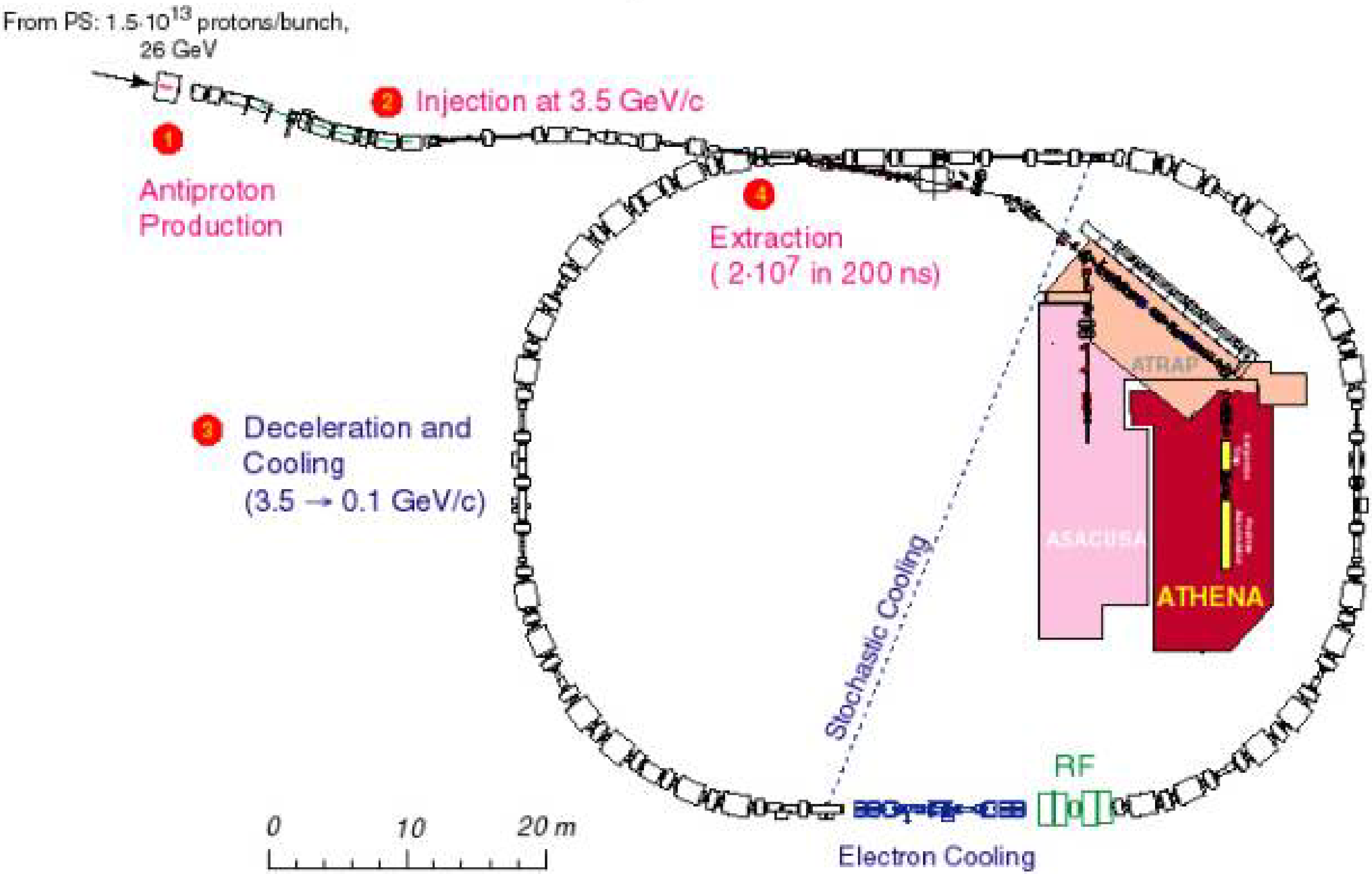
a) single particles classical motion (antiprotons)

b) non neutral cold plasma regime (electrons, positrons)

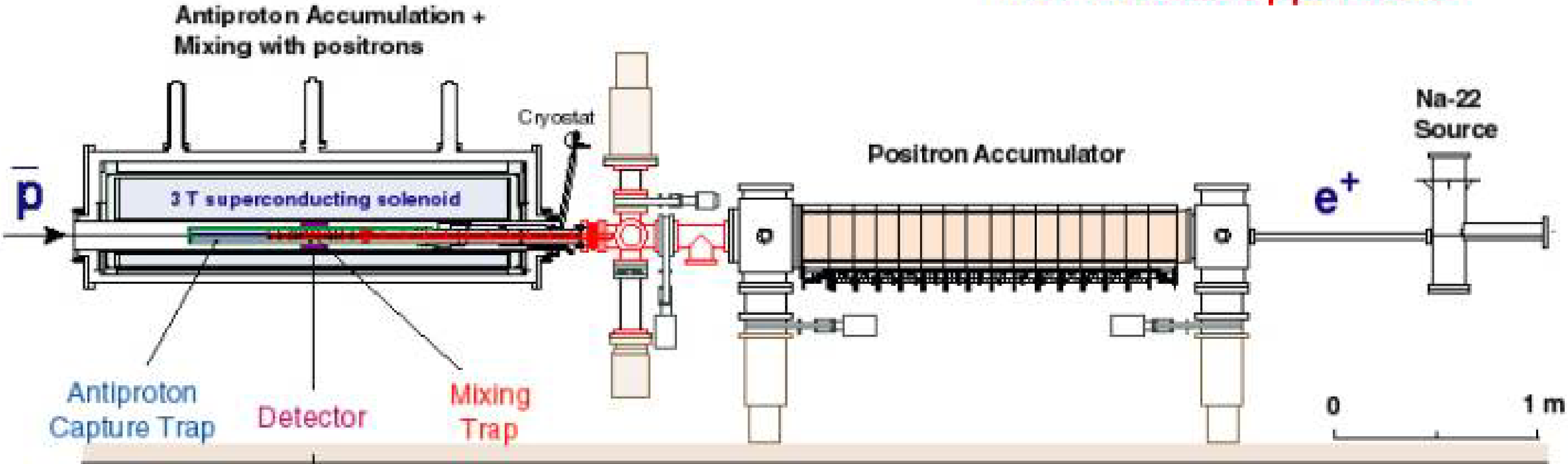
Athena trap system:

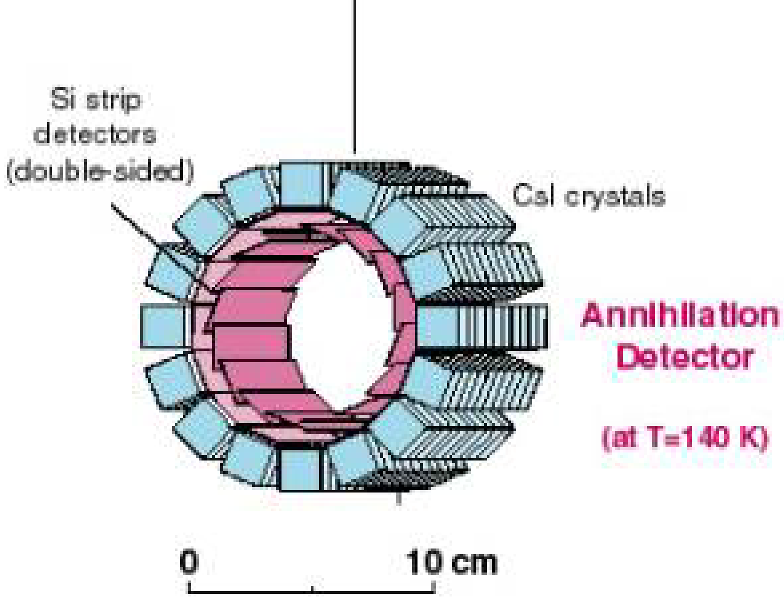
Pbar Catching trap, positron trap, recombination trap (nested)

Antiproton Decelerator : pulses of 2 10^7 pbars-200 ns - 5 MeV
repetition time: 100 sec



The Athena apparatus

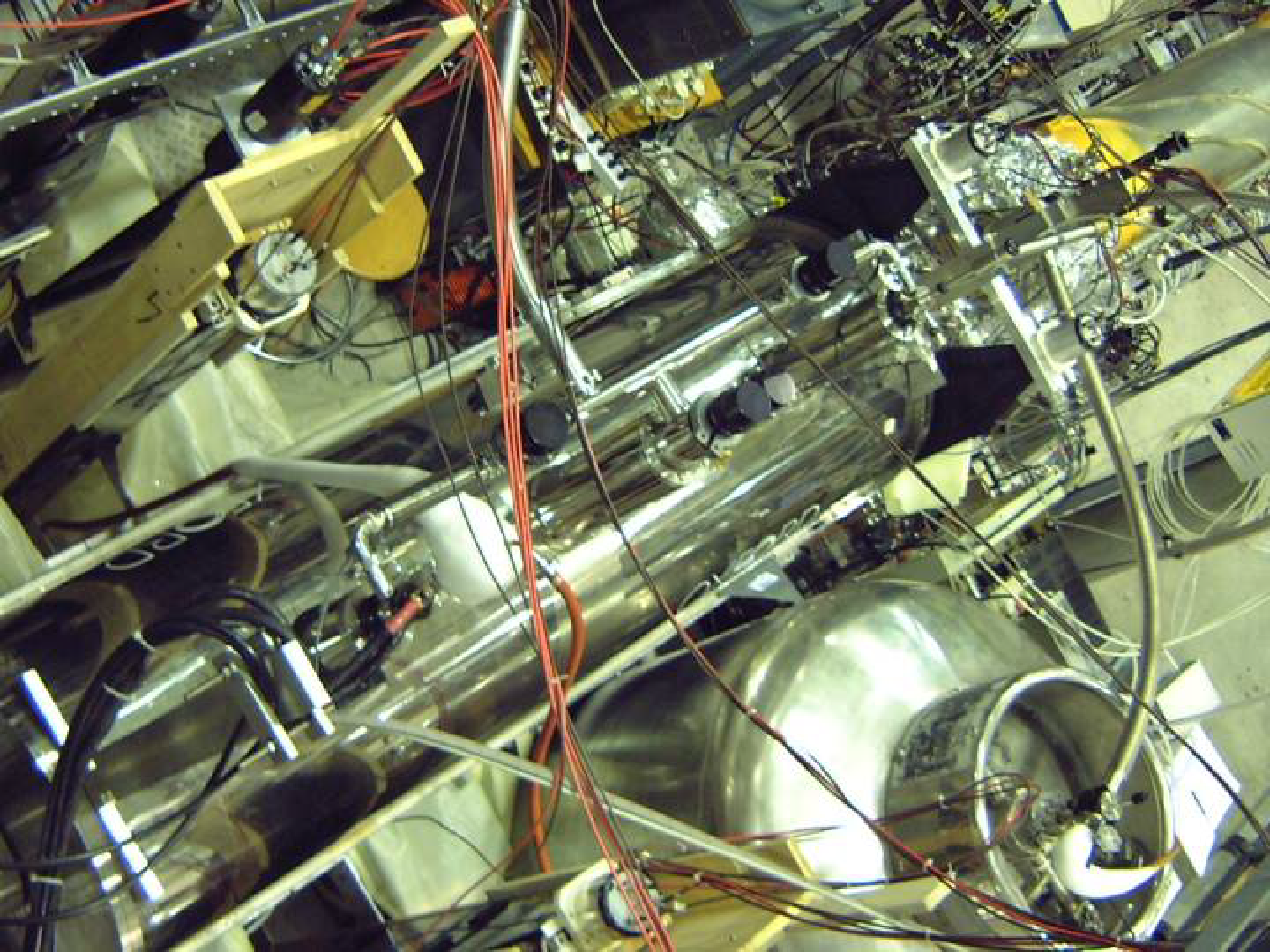




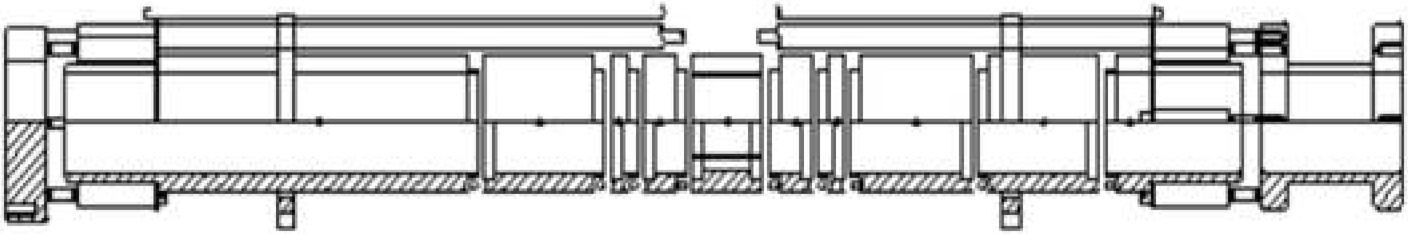
Trap Temperature: about 15 Kelvin

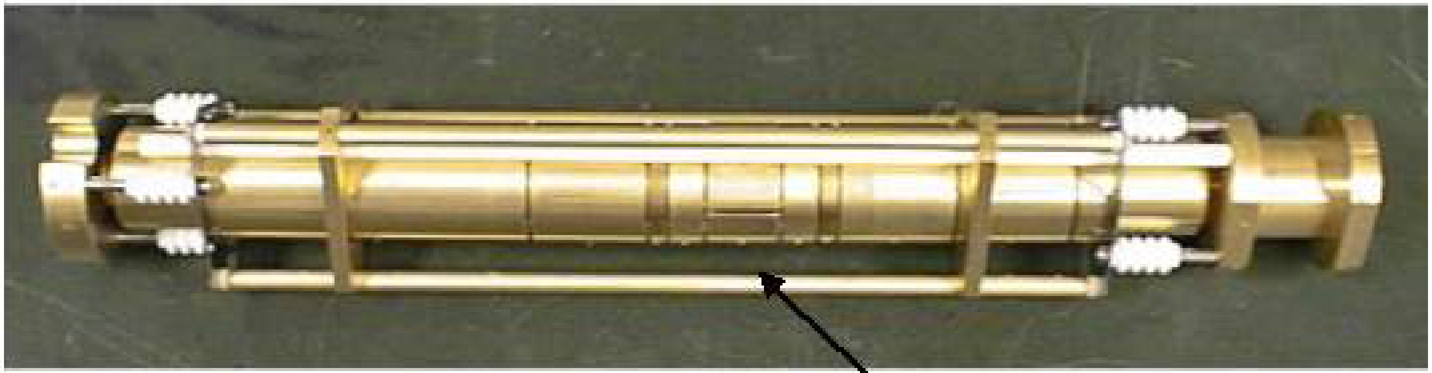
Pressure (room temp. region)$<10^{-11}$ mb


OXFOR



The pbar catching trap





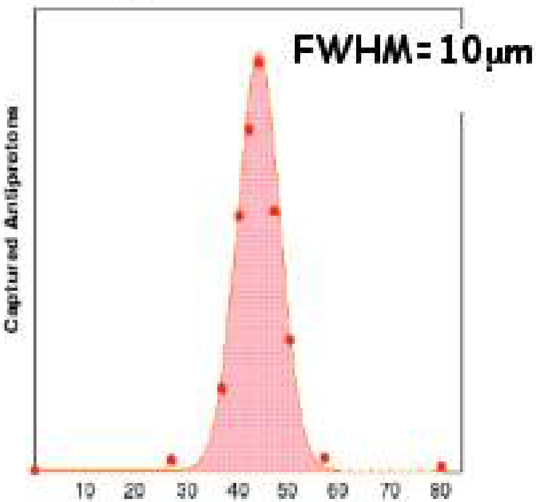
Penning trap

L=40 cm
r=1.25 cm

Catching and cooling antiprotons

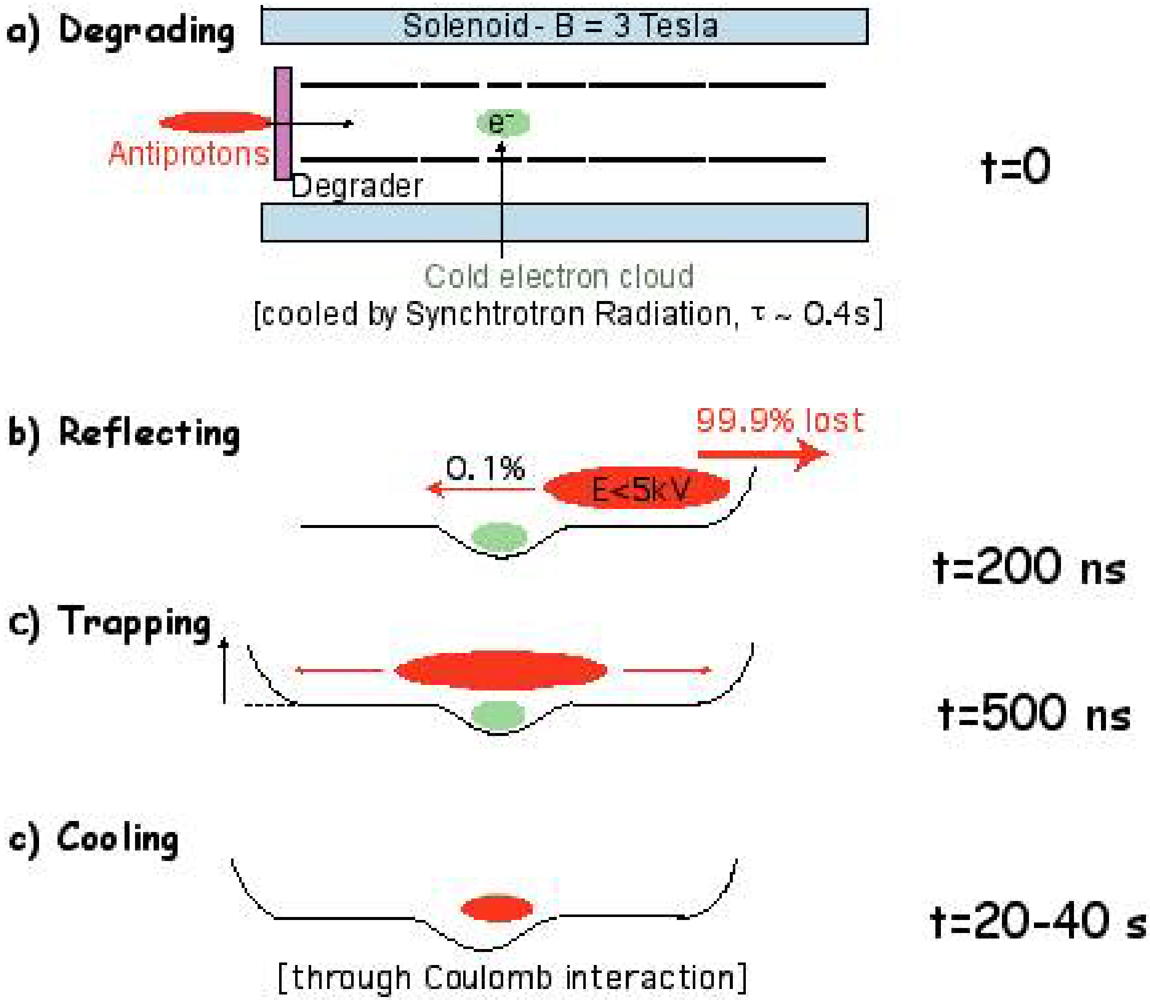
$3\ 10^8$ electrons preloaded in the catching trap
storage time: thousands of sec

Pbar capture versus degrader thickness

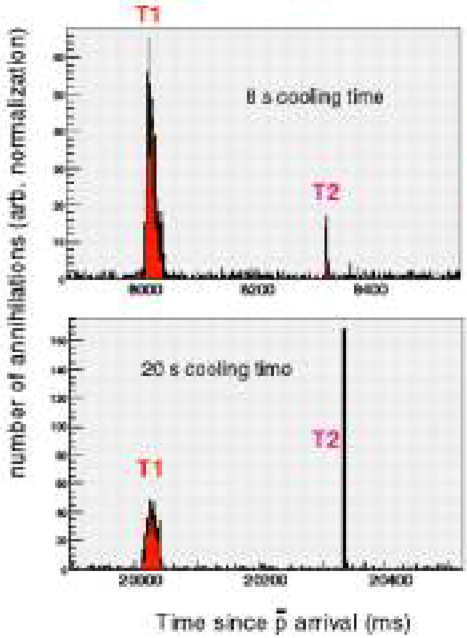


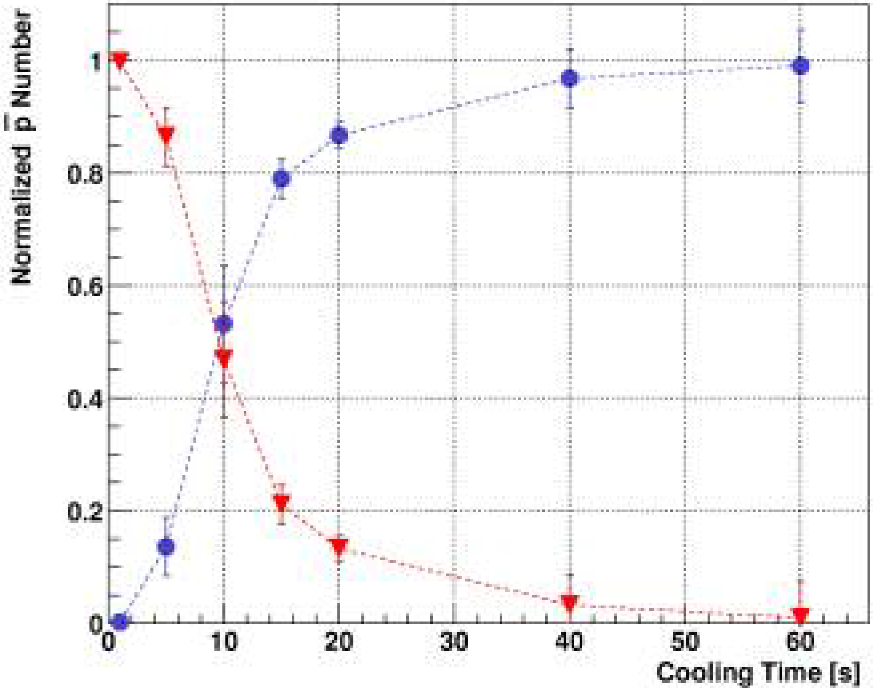
Additional Al thickness µm

Degrading materials:
67 µm silicon beam monitor
25 µm Stainless steel
130 µm Al foil (last degrader)

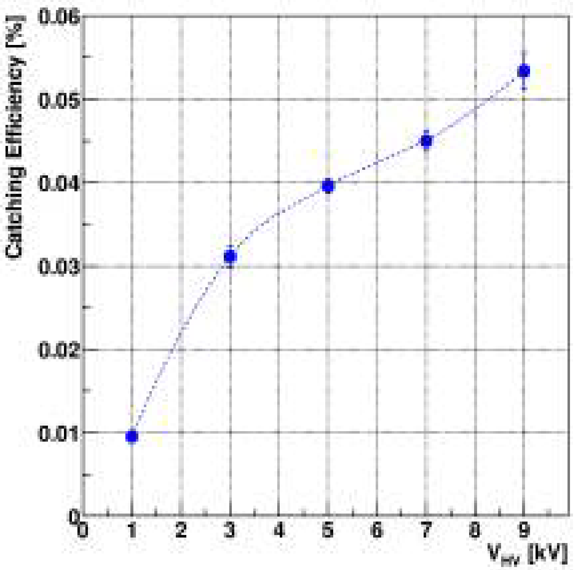


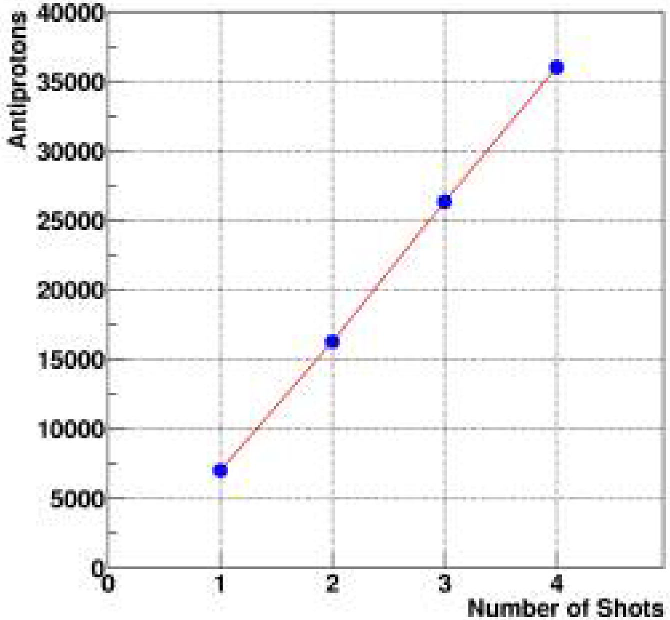
Catching trap results: summary



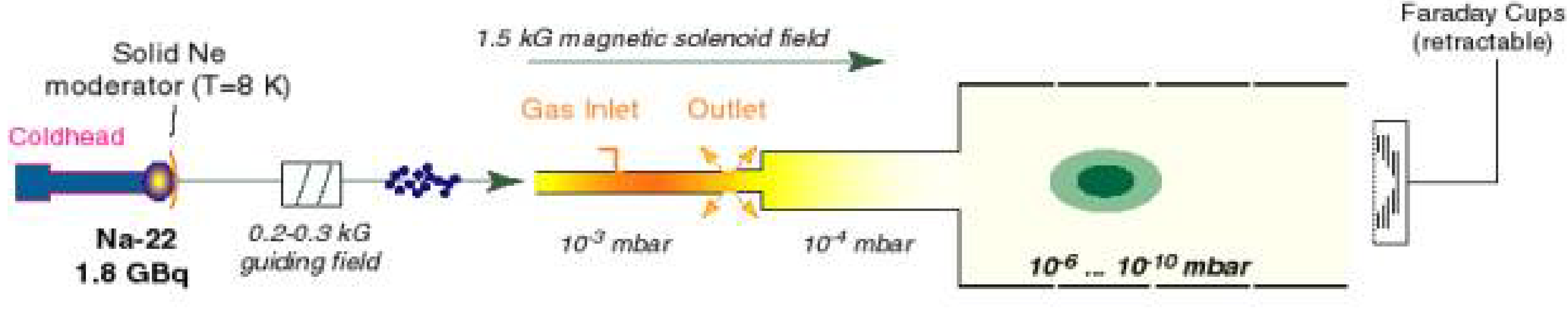


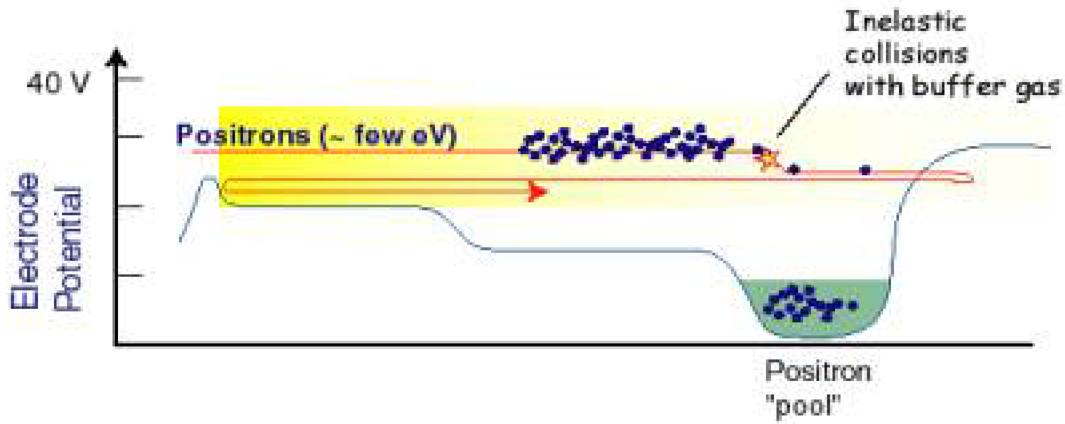
About 10^4 cold pbars transferred in the recombination trap

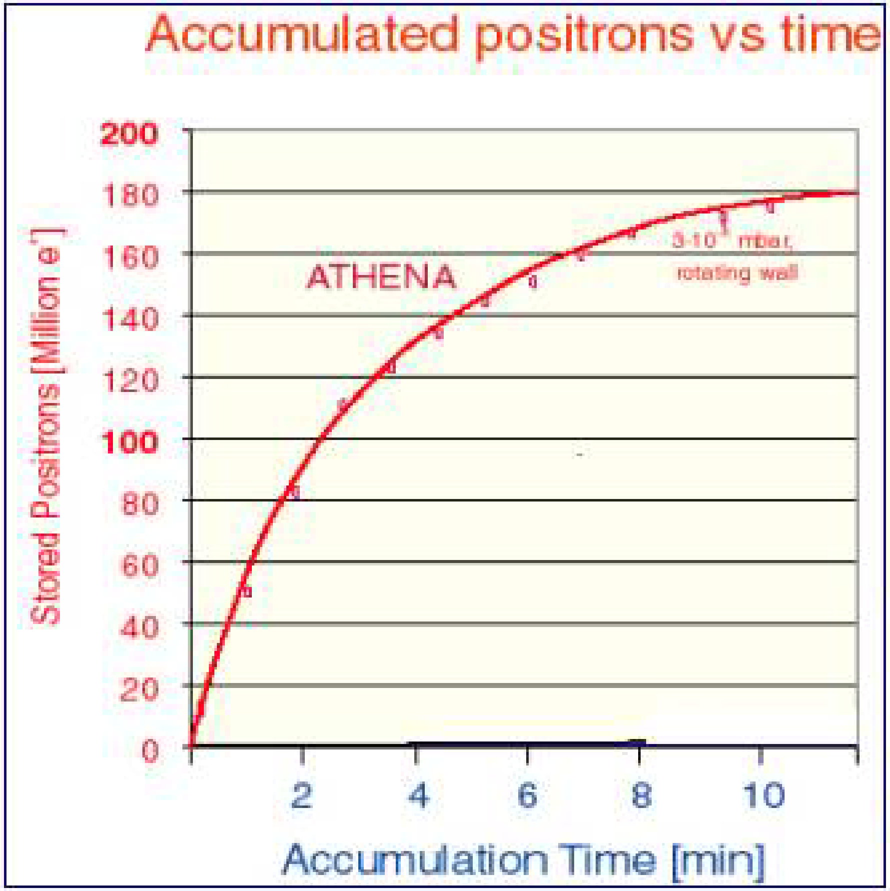




ATHENA - Positron Accumulation Scheme







Accumulation rate ~ 10^6 e^+/sec

- **150 million positrons / 5 min**

- 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.$\cdot$ 10^8 cm^{-3}

- Life time ~ many hours

Detectors in Athena

- Silicon Beam Monitor
- External scintillators with HPD readout and PMT readout
- Main Antihydrogen Detector
- Non destructive plasma modes (positrons,electrons)
- Faraday cup (last degrader)
- CsI and Farady cup on the positron accumulator

Plasma mode detection

e+ and e- lose energy by cyclotron radiation $\tau < 1$ sec and they reach an equilibrium temperature related to that of the ambient

(15 Kelvin + contribution of electronics noise)

The Debye length $\lambda_D \propto \sqrt{\frac{T}{n}}$

results to be tenths of μm and it is shorter than the cloud dimensions (mm or cm) → the cloud behaves as a non neutral plasma

The space charge energy (eV) is greater than the temperature (meV)

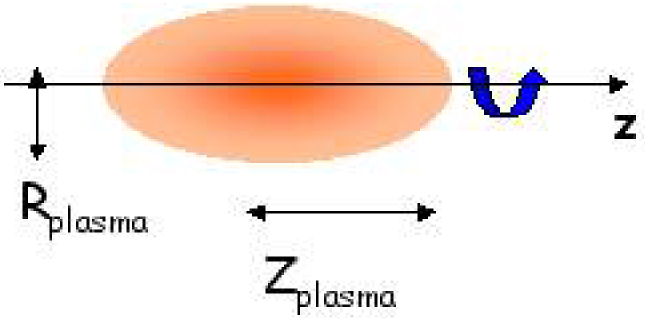
→ zero temperature non neutral plasma in equilibrium

The density is constant

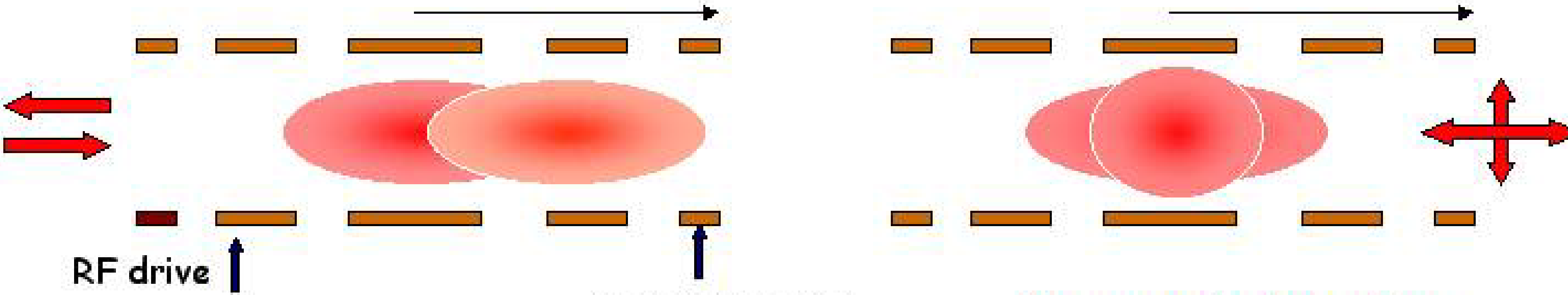
The space charge electric field exactly balance the axial (parallel to B) applied field

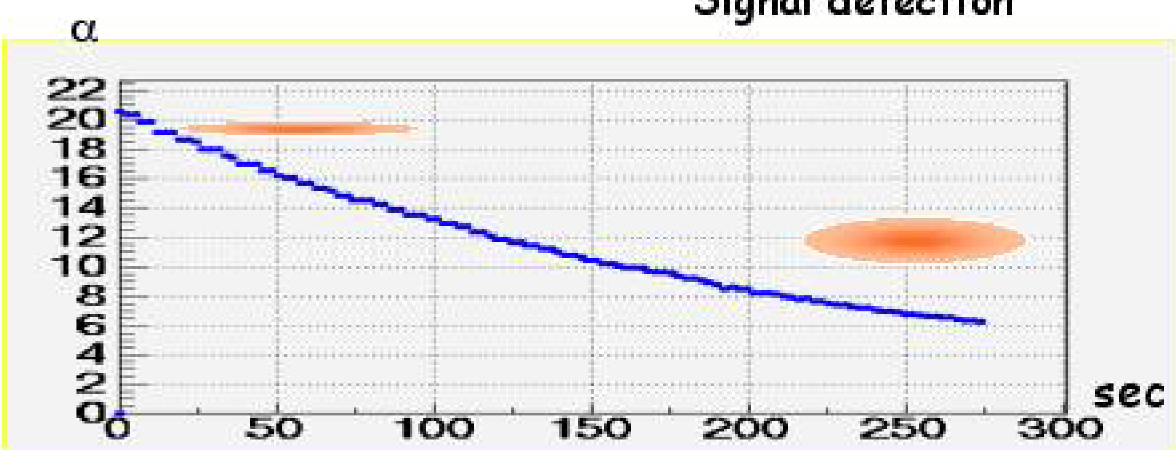
The plasma rotates as a rigid body with a frequency proportional to the density (tenths- hundreds ok KHz)

In the Penning trap the shape is an ellipsoid



$\alpha = Z_{plasma}/R_{plasma}$





Plasma mode detection:

Zero temperature model

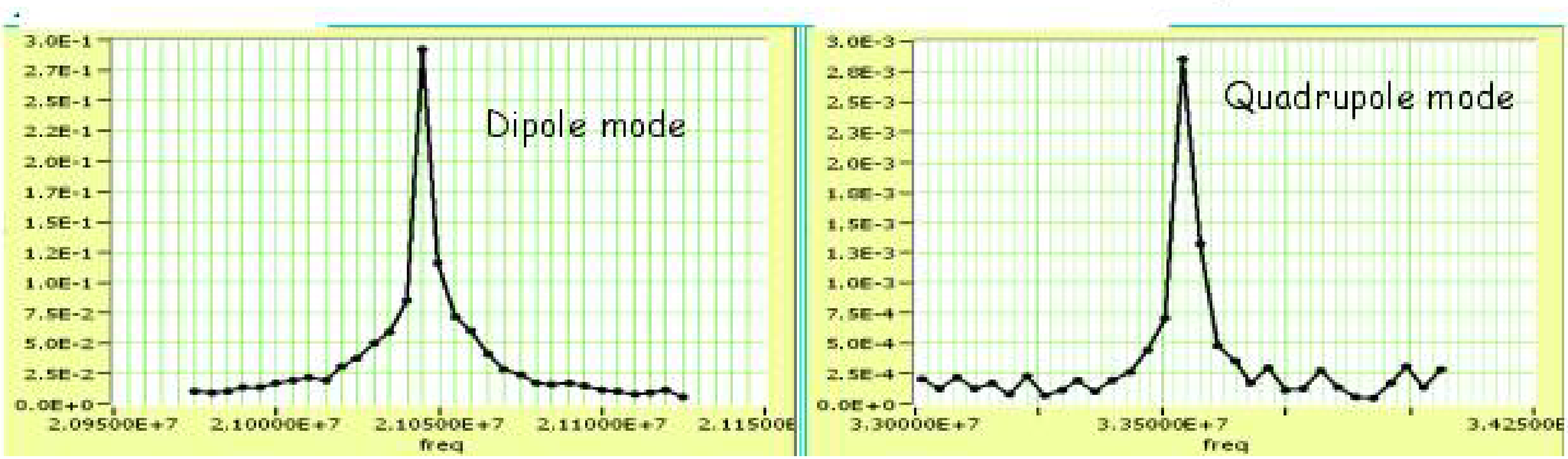
Frequencies: α, density

Line shape fit: Number of particles

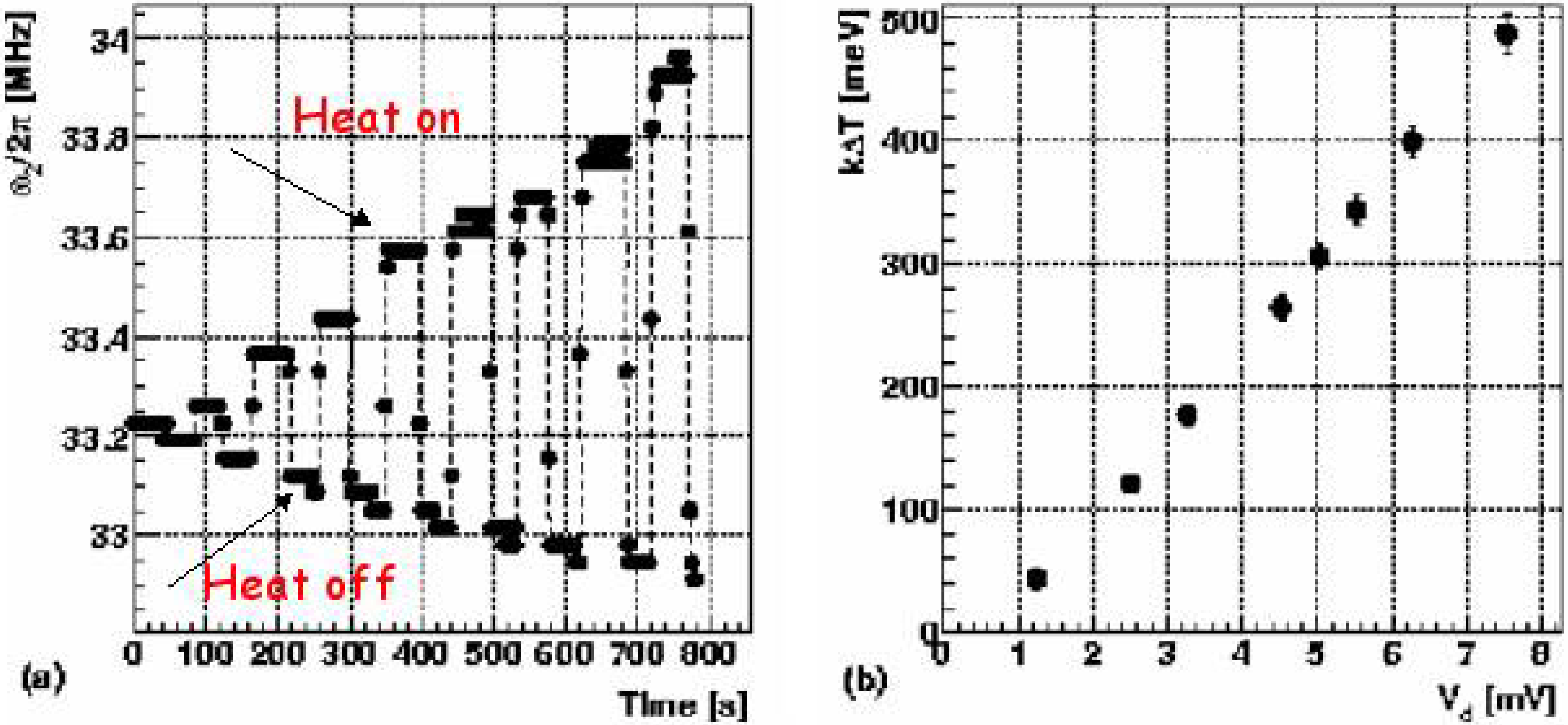
Temperature effect:

shift of the quadrupole mode

ncy



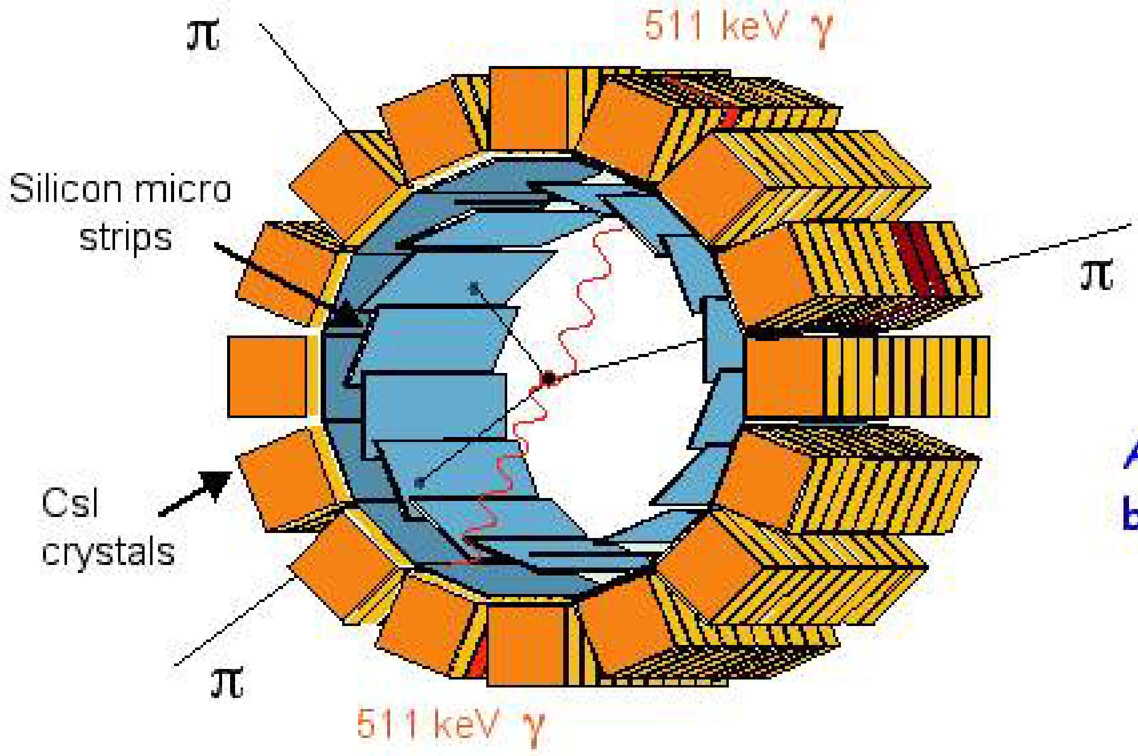
Positron plasma heating and temperature monitor



N, n, Plasma radius, Plasma length, ΔT

T_0?

The Antihydrogen detector



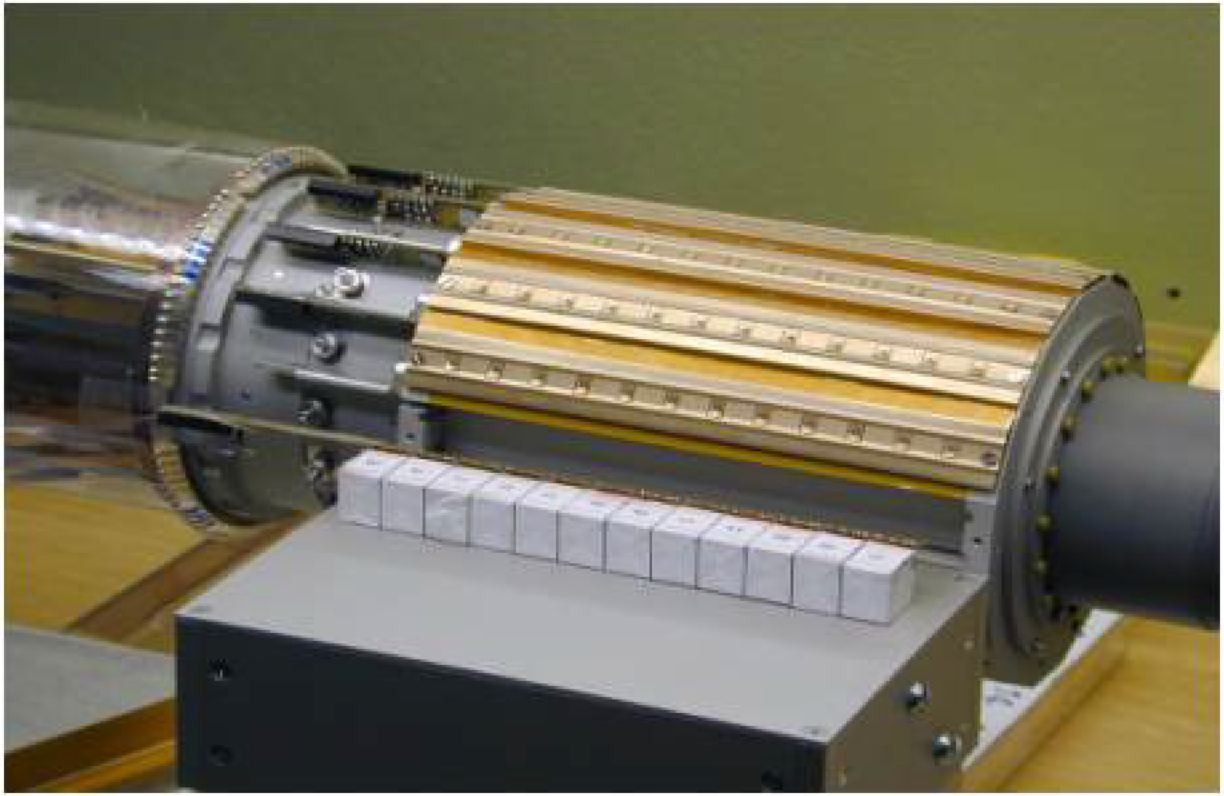
Silicon strips to identify the charged particles from pbars annihilation

CsI scintillators to identify the 511 KeV γ from e+e- annihilation

Antihydrogen signal identified by space and time coincidence

192 CsI crystals with avalanche photodiodes
8096 silicon strips with double side read out z-phi reconstruction

- Compact (3 cm thick) L=14 cm
- Solid angle > 70%
- High granularity
- Operation at 140 K, 3 Tesla
- Space resolution 3-4 mm



Full detector installed: August 2001

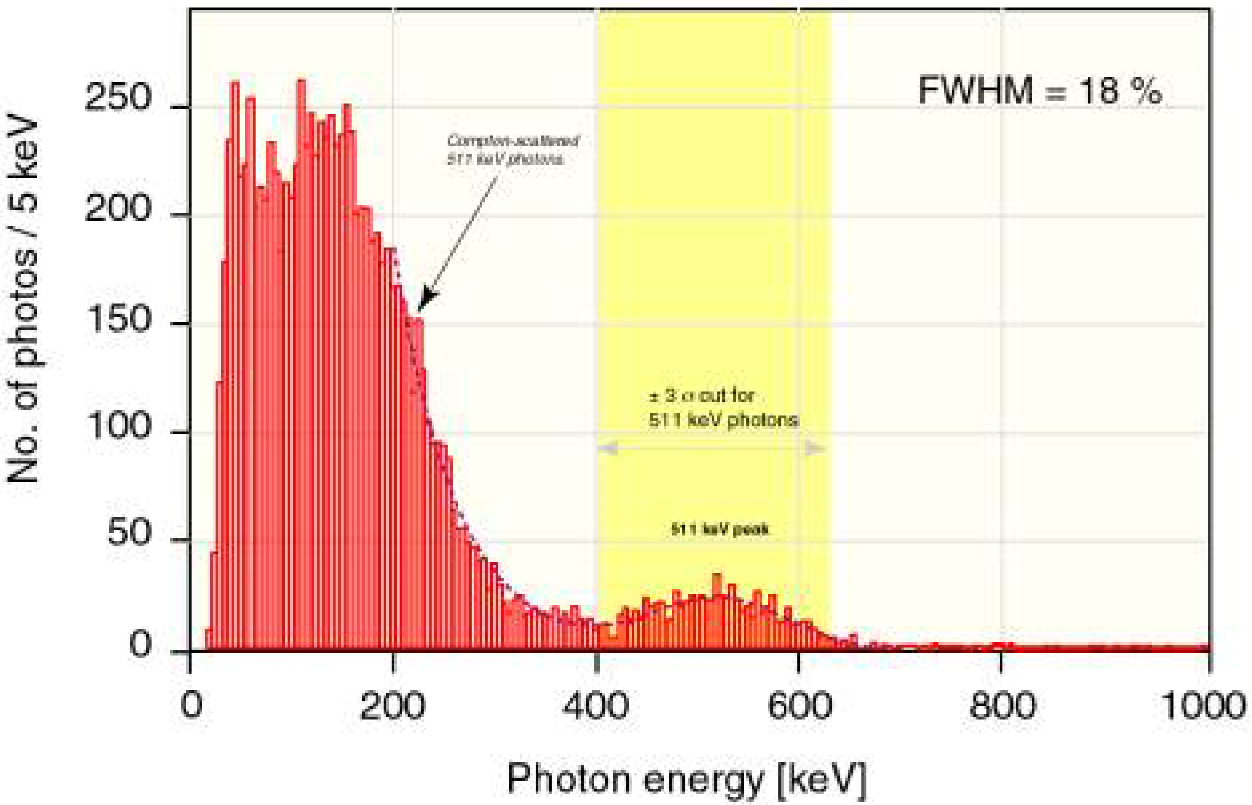
All photodiodes replaced with APDs: Spring 2002

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)

CsI crystals



$17 \times 17 \times 13$ mm^2

16 rows with 12 crystals:
tot 192

N_γ(77 -100 Kelvin) = 50.000 γ/MeV
N_γ(295 Kelvin) = 3200 γ/MeV
Light decay time (77 -100 Kelvin) : about 1 μs

Silicon detector

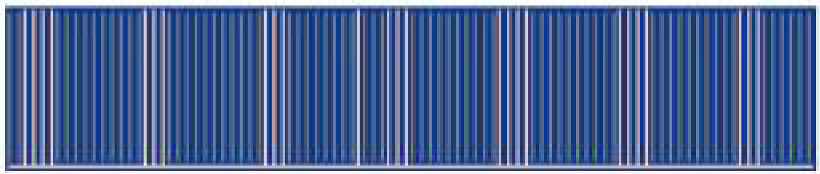
FRONT

Pitch: 139 μm

128 readout strips
18.2 mm active width
85 mm length

BACK

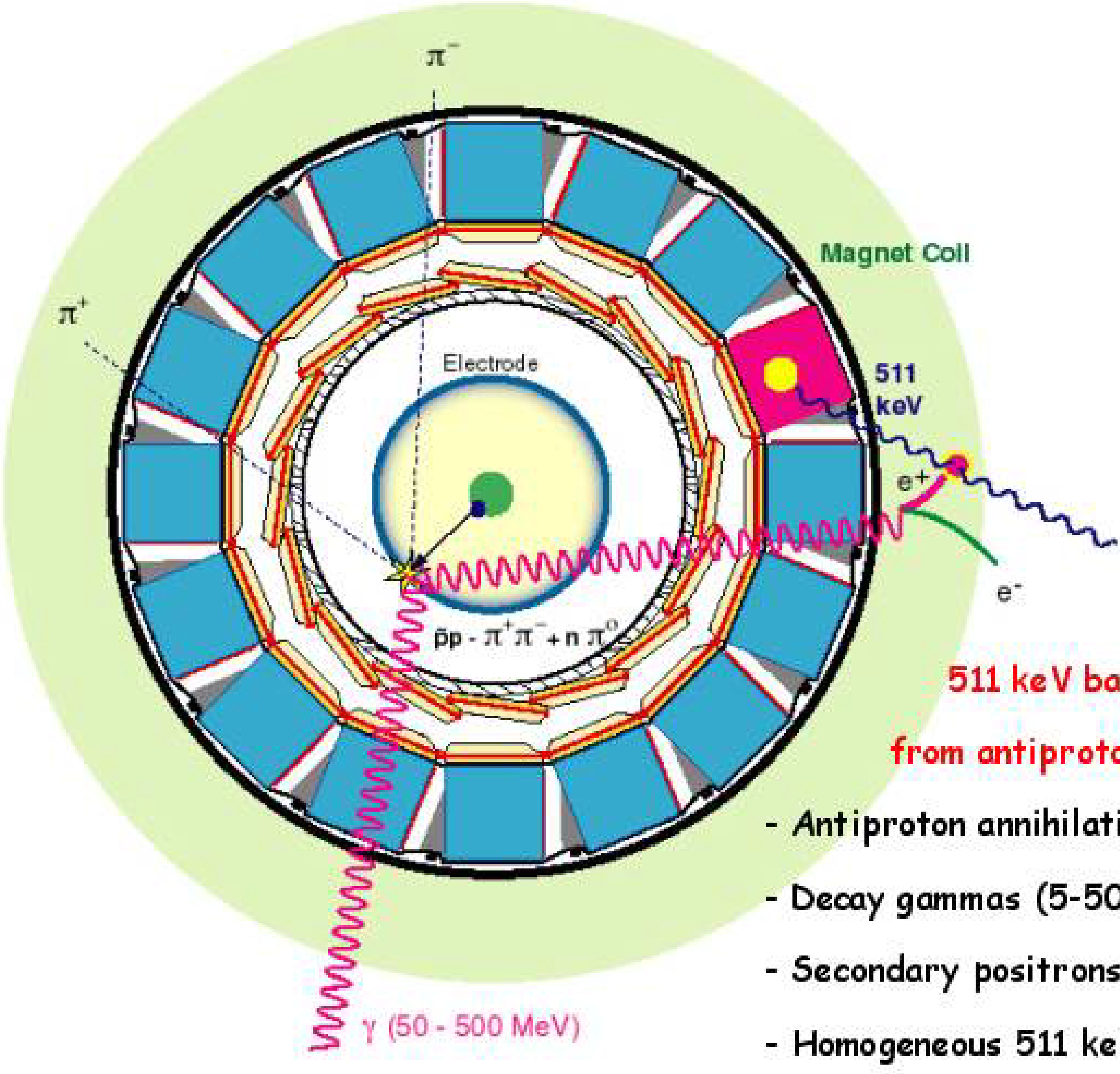
Pitch: 1.1 mm



64 pads
19.0 mm active width
85 mm length

Thickness: 380 μm

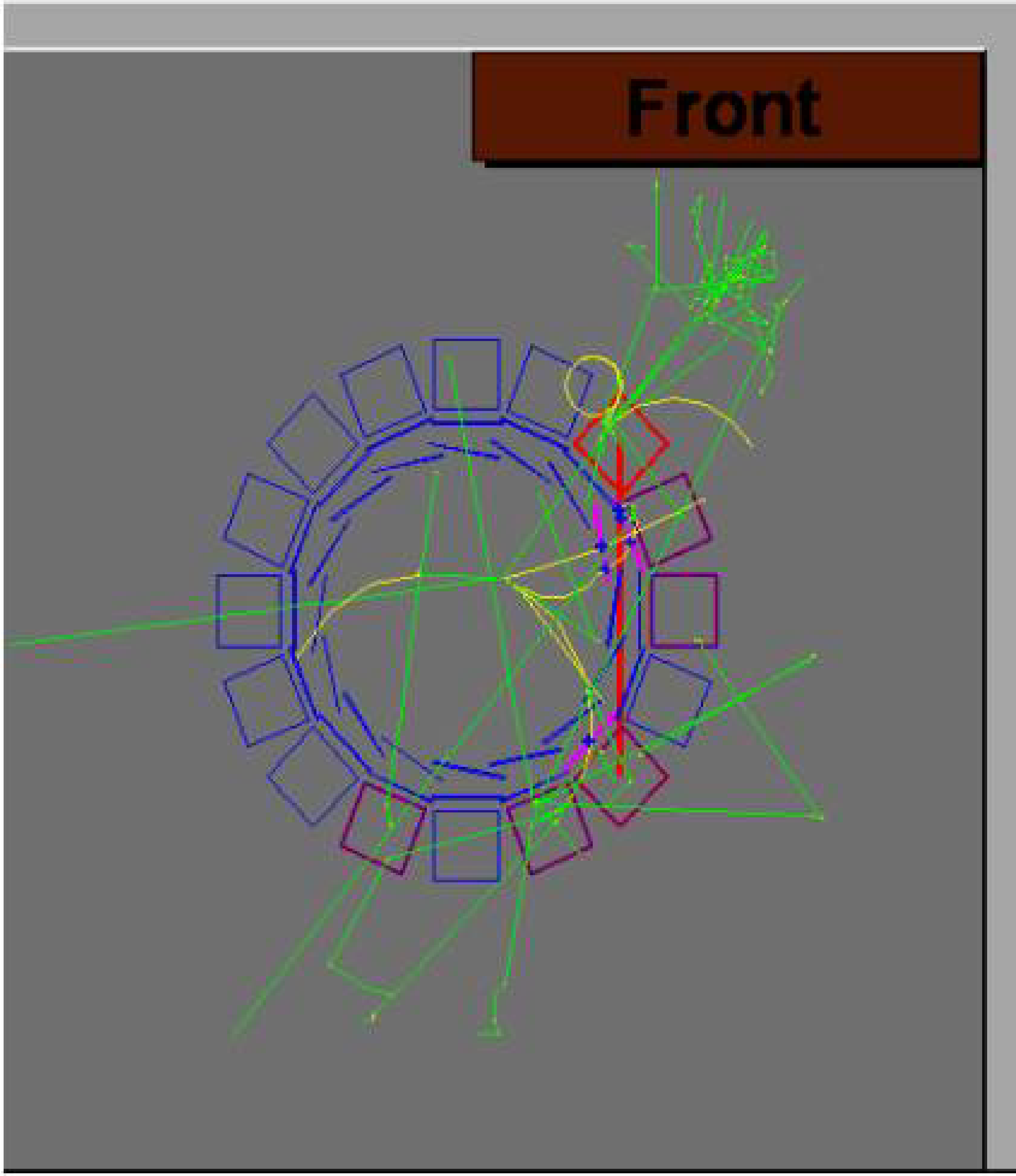
DETECTOR MODULE



511 keV background

from antiproton annihilation

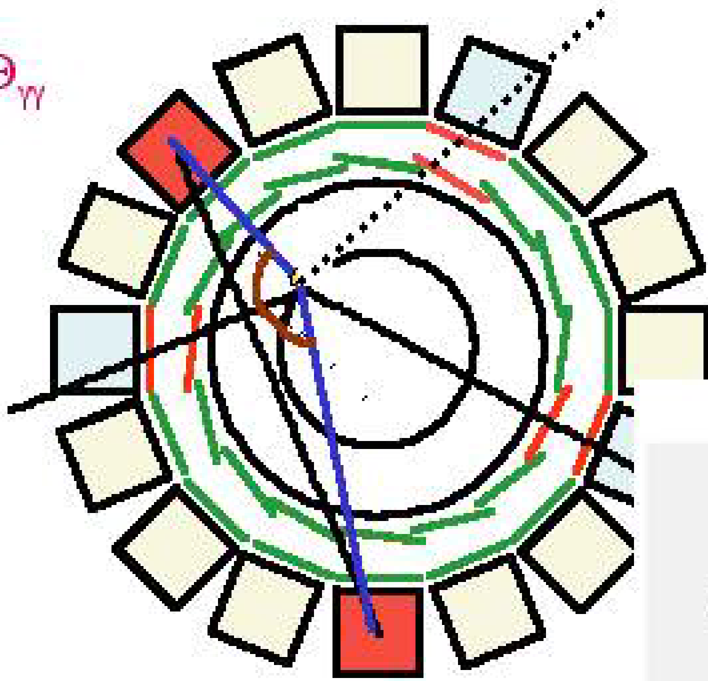
- Antiproton annihilation produces neutral pions
- Decay gammas (5-500 MeV) convert in magnet
- Secondary positrons stop and annihilate
- Homogeneous 511 keV photon background
- Can produce (fake) 2 x 511 keV photon events



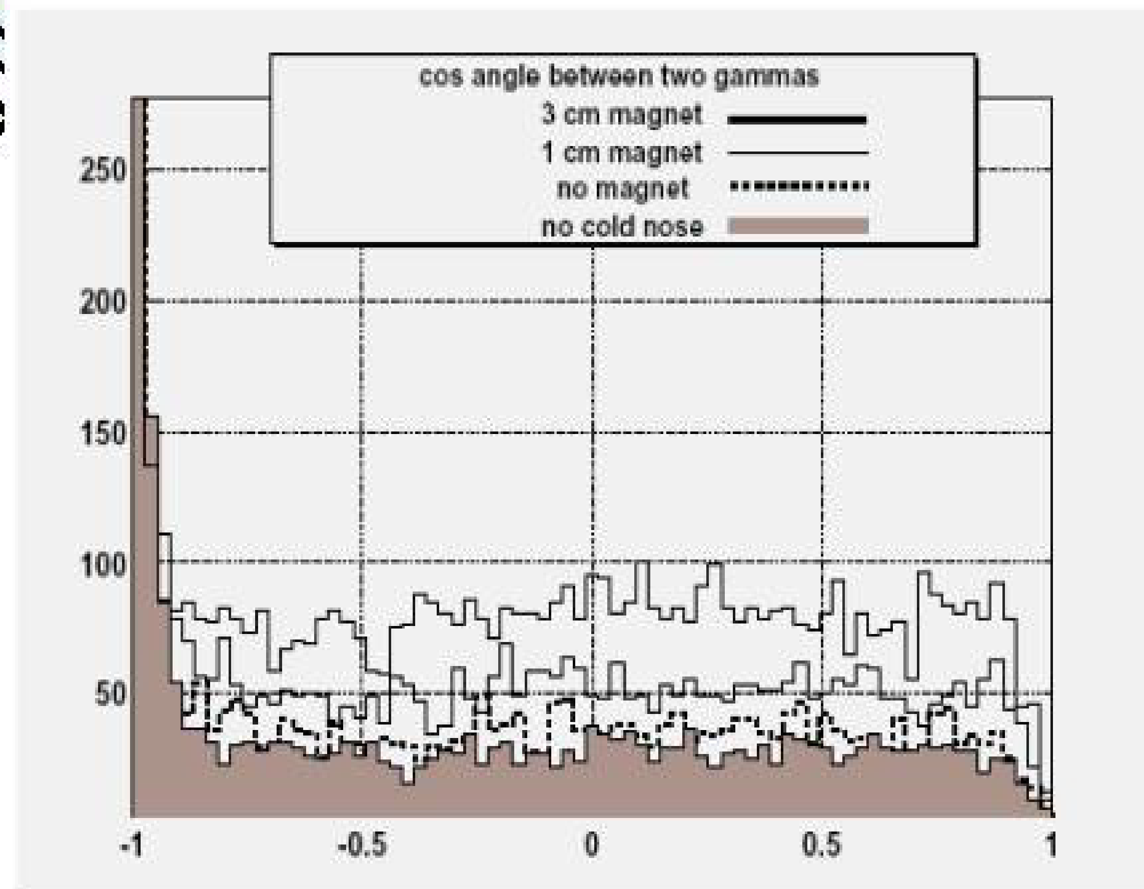
MonteCarlo
Simulation

Green: gamma
Yellow:charged particles

$\Theta_{\gamma\gamma}$



- Time coincidence (μs)
- vertex position
- identify two 511 keV crystal hits
- opening angle $\Theta_{\gamma\gamma}$
- $\cos(\Theta_{\gamma\gamma})$ distribution



Event selection procedure

1) Use the silicon data to find the tracks
2) Vertex reconstruction
3) Extrapolation of the tracks up to the crystals and removal of that crystals from the following analysis
4) Removal of the 8 crystals adjacent to that of 3)
5) Remove any crystal that lies radially outward from an hit silicon on the outer detector
6) Remove the 8 crystals adjacent to that of 5)
7) Examine the energy deposit in the remaining crystals and flag that having signals in the 511 Kev photopeak
8) Eliminate the flagged crystals having a near crystal with a signal
9) Selects events having only two isolated crystals with signals in the 511 Kev photopeak

Hbar production procedure

Positron accumulation: 300 sec, 10^8

Catching and cooling of 3 AD shots
About 2.7 10^4 pbars

Positron transfer in the reco trap: 4-7 10^7

Transferring cold pbars with electrons in the reco trap
About 10^4 pbars

Dumping all the electrons

Injection of the pbars into the positron plasma and wait 190 sec

Understanding the background and the signal

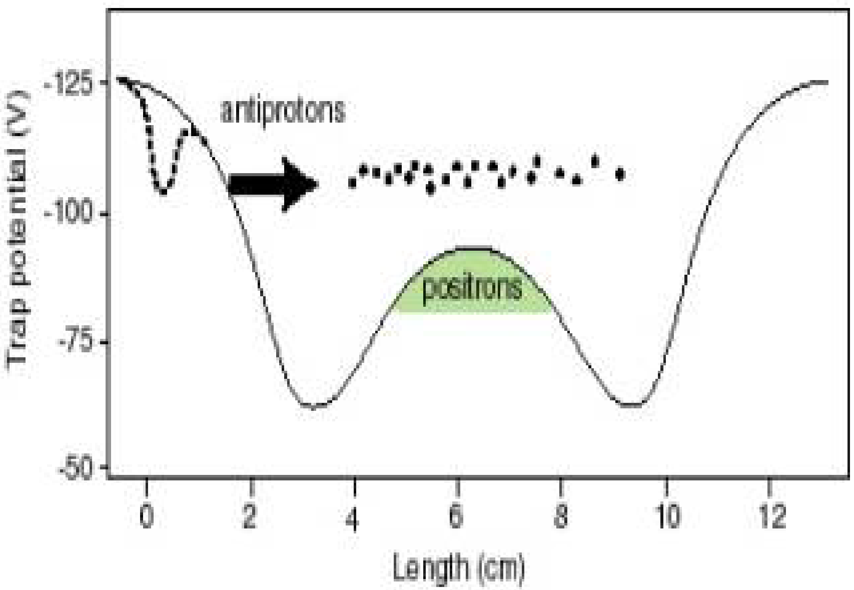
Normal mixing in the nested trap

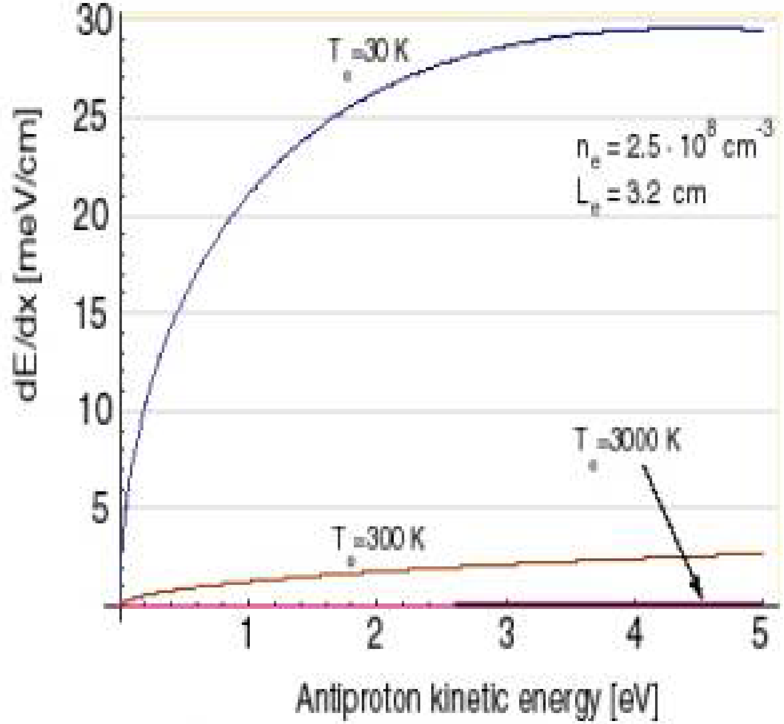
Mixing with positron heating in the nested trap

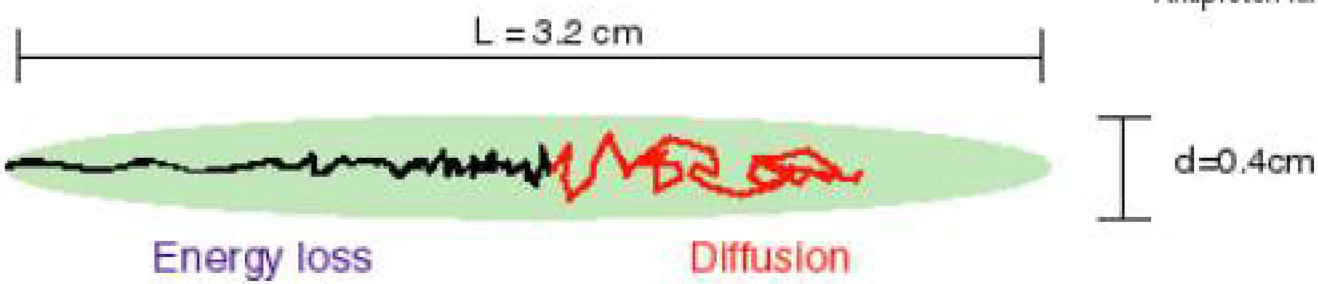
Pbars only in the nested trap or in a Malmerg trap

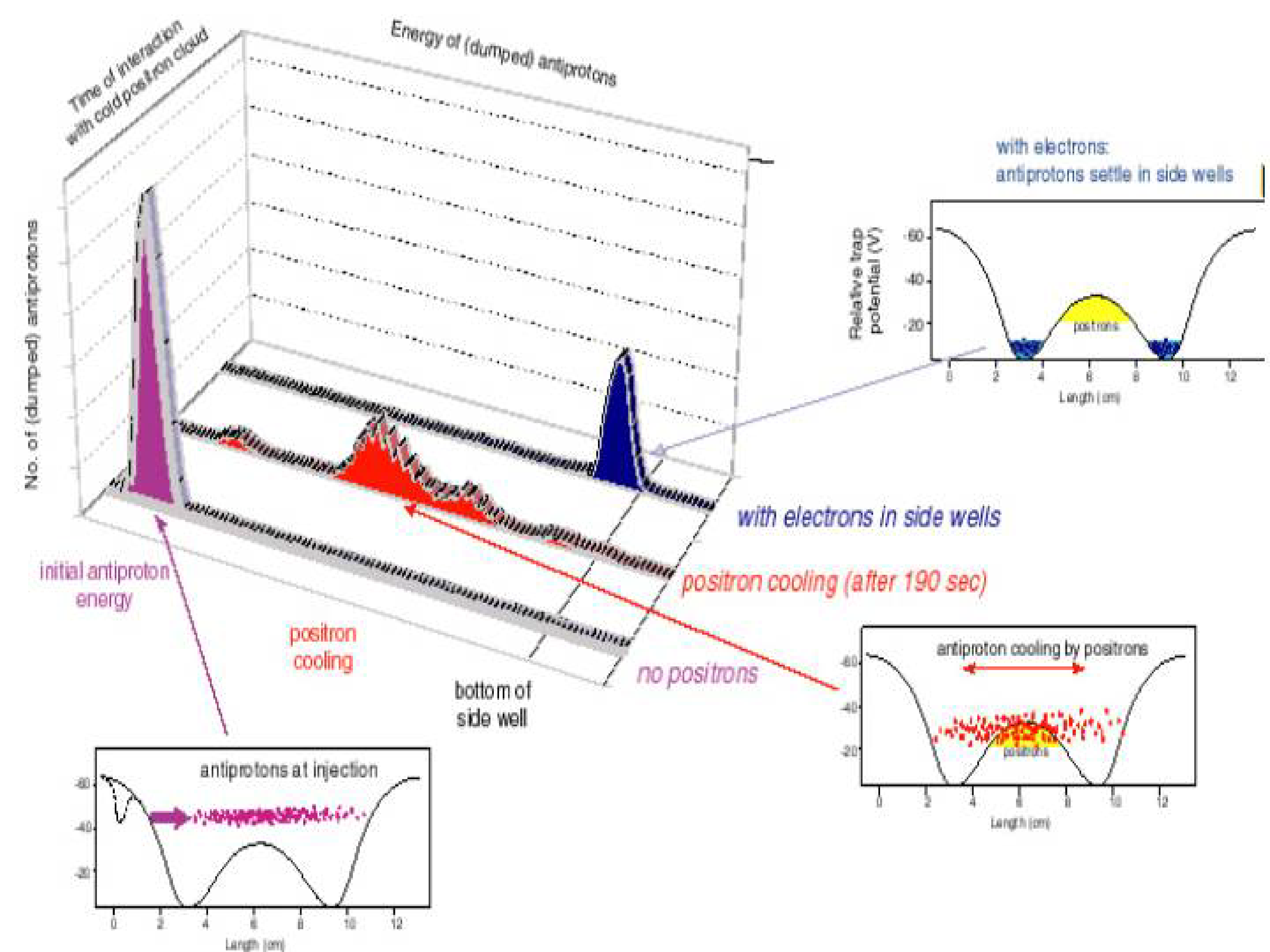
Antiprotons Positrons Interaction: dE/dx

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



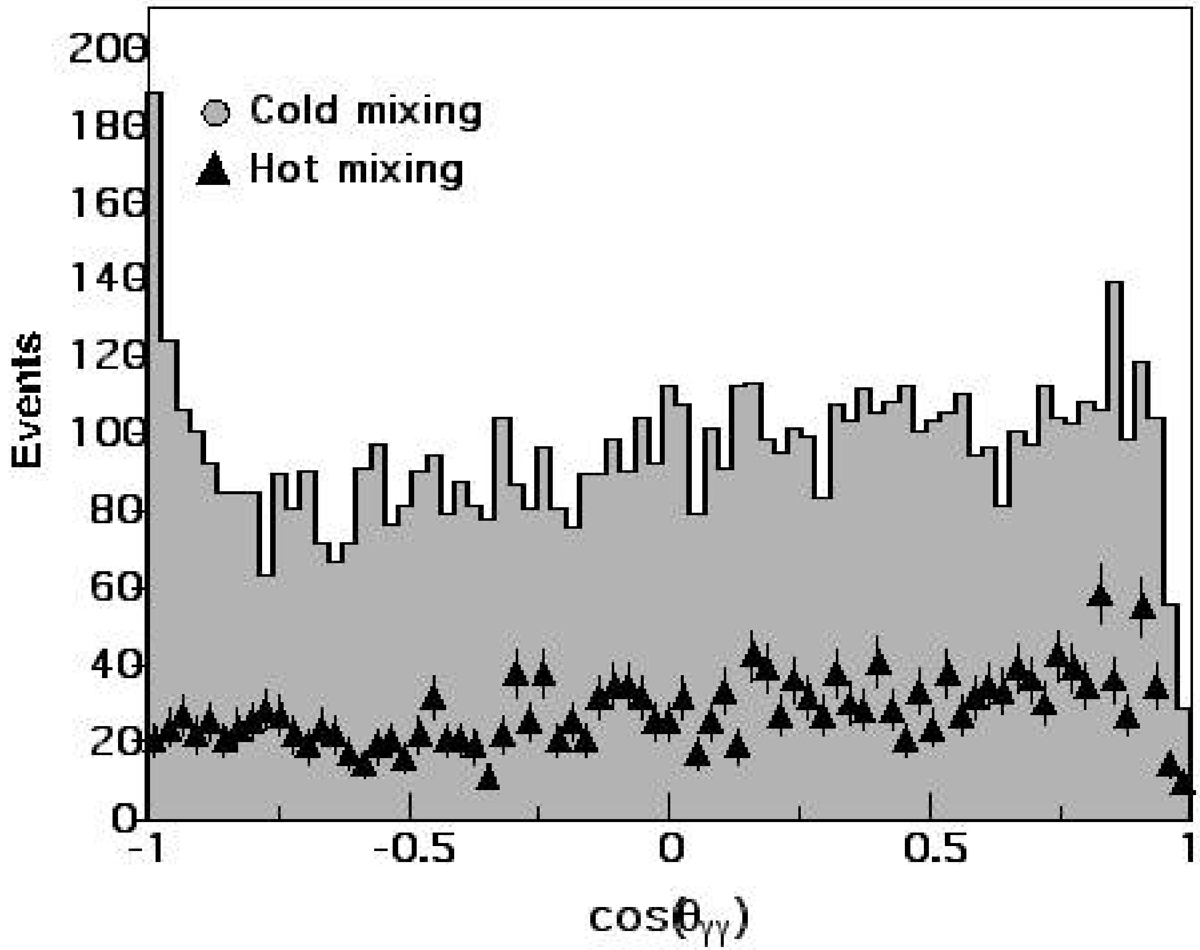






Time of interaction with cold positron cloud
Energy of (dumped) antiprotons
No. of (dumped) antiprotons
with electrons: antiprotons settle in side wells
Relative trap potential (V)
positrons
Length (cm)
with electrons in side wells
positron cooling (after 190 sec)
no positrons
initial antiproton energy
positron cooling
bottom of side well
antiproton cooling by positrons
positrons
Length (cm)
antiprotons at injection
Length (cm)

The antihydrogen signal



Cold Mixing :

103270 vertices,

7125 2x511keV events

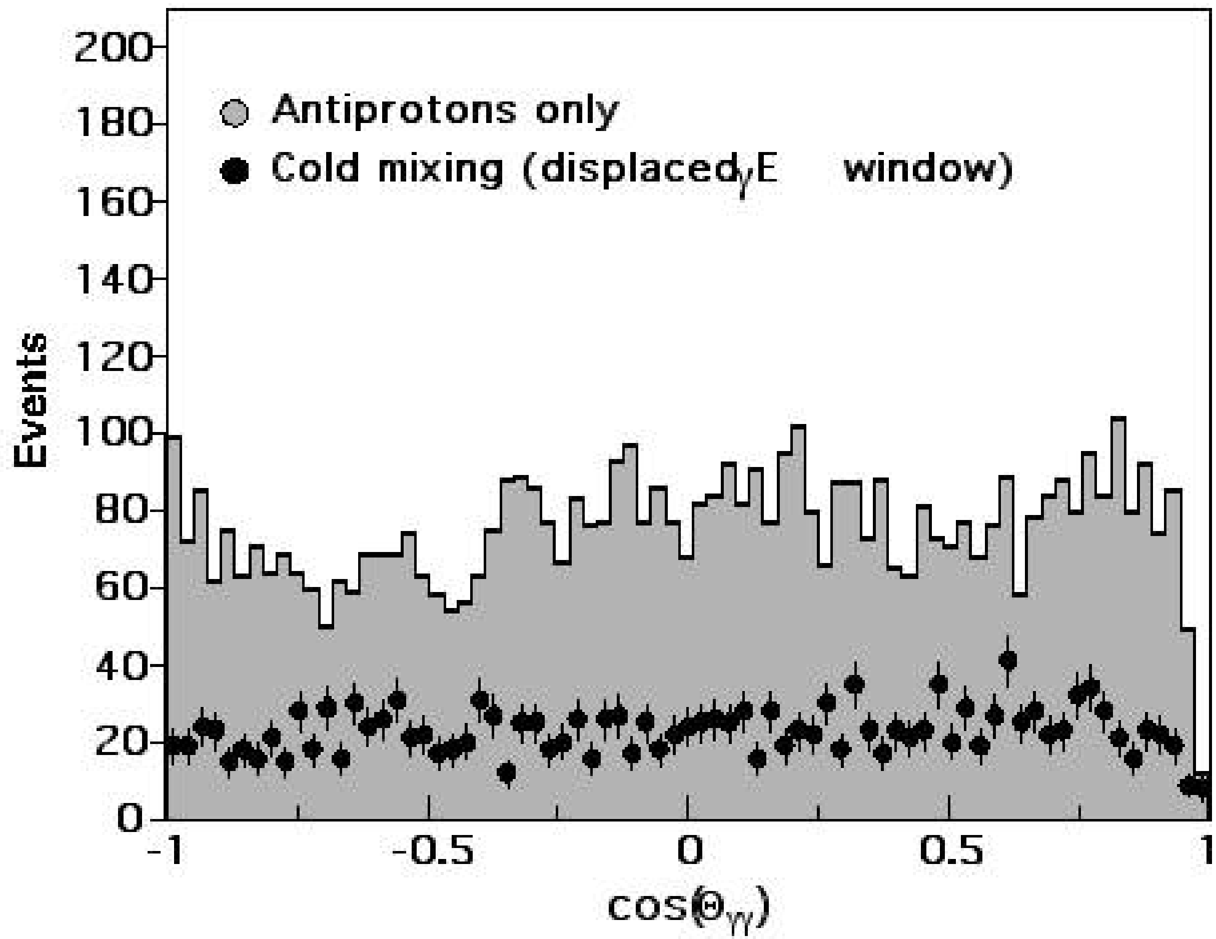
165 mixing cycles

131+-22 golden events

more than 50.000 Hbars

Hot Mixing :

Scaled (x1.6) to 165 mixing cycles.

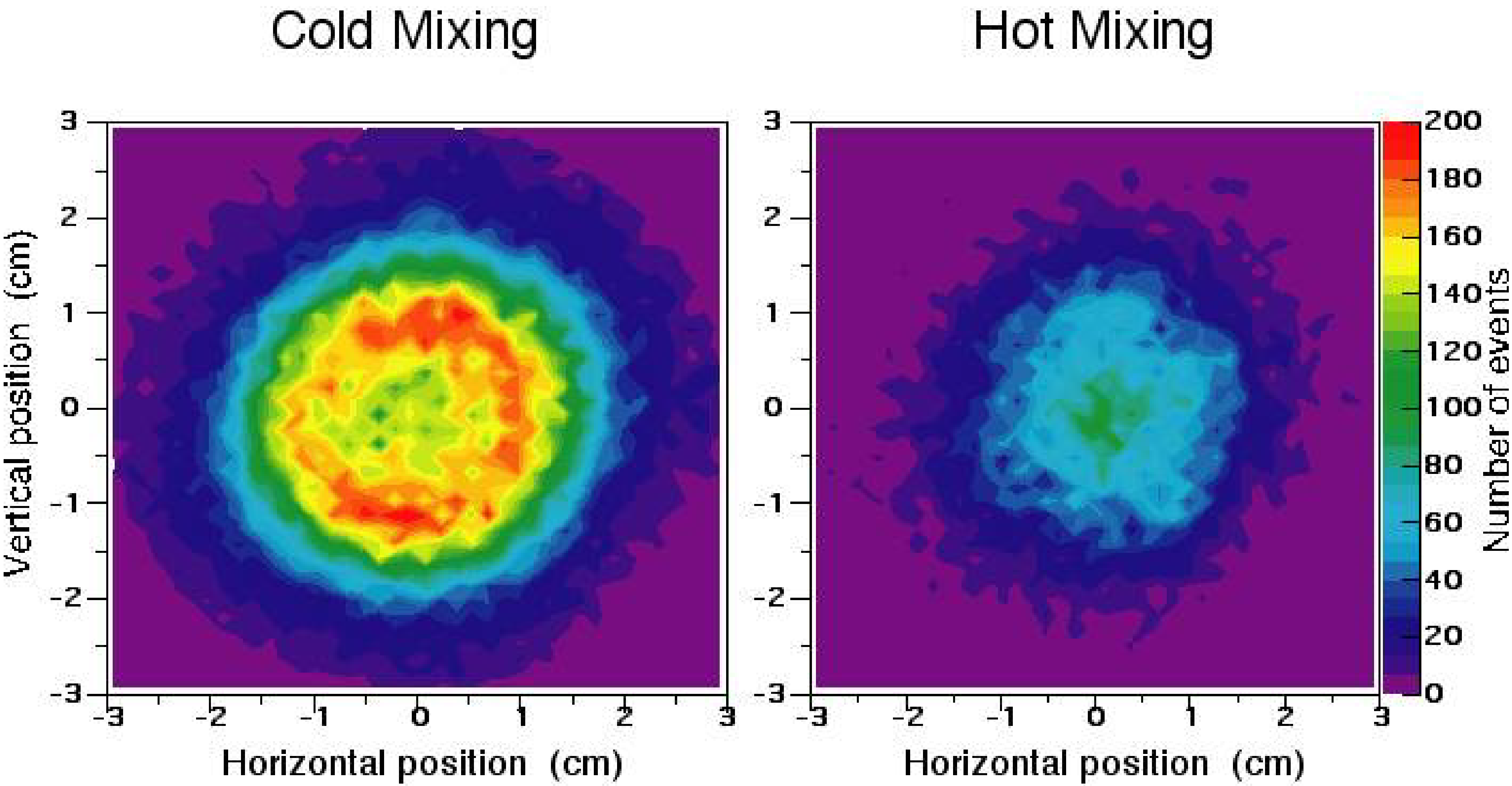


Antiprotons only :

[in harmonic well]

99,610 vertices,

5,658 2x511keV events



Cold Mixing
Hot Mixing
Vertical position (cm)
Horizontal position (cm)
Horizontal position (cm)
Number of events
3
2
1
0
-1
-2
-3
200
180
160
140
120
100
80
60
40
20
0

Summary

- (10^4 antiprotons mixed with $7 \cdot 10^7$ cold positrons)/cycle
- 131± 22 "golden" antihydrogen annihilation events
- 50.000 produced antihydrogen atoms (in 165 cycles ~ few hours mixing)
- ... all the efficiencies evaluated in conservative way
- Back-to-back signal not present when

  positrons are hot

  only antiprotons are present in the mixing trap

Future

2003 -2004	Upgrading of the present apparatus Laser installation
2005	AD stops
2006	New generation experiments (Hbar cooling, trapping, Hbar beam...) new collaborations