The ATHENA experiment

Antihydrogen at Rest
for precision Tests of CPT and WEP

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(for the ATHENA Collaboration)

1. **Physics Goals**
2. **Antiproton Decelerator**
   Providing 100 MeV/c antiprotons
3. **Antiproton capture and cooling**
   Antiprotons "at rest"
4. **Positron Accumulation**
5. **Recombination Physics Issues**
6. **Antihydrogen Detector**
7. **Summary and Outlook**

ATHENA Collaboration

Antiproton Capture
External detectors
Recombination

CERN

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Genoa

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Positron Accumulator

Swansea

Charlton M. Collier M. Jorgensen L.

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Annihilation Detector

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DAQ / Slow Control

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Laser Spectroscopy

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Current Status of CPT Tests

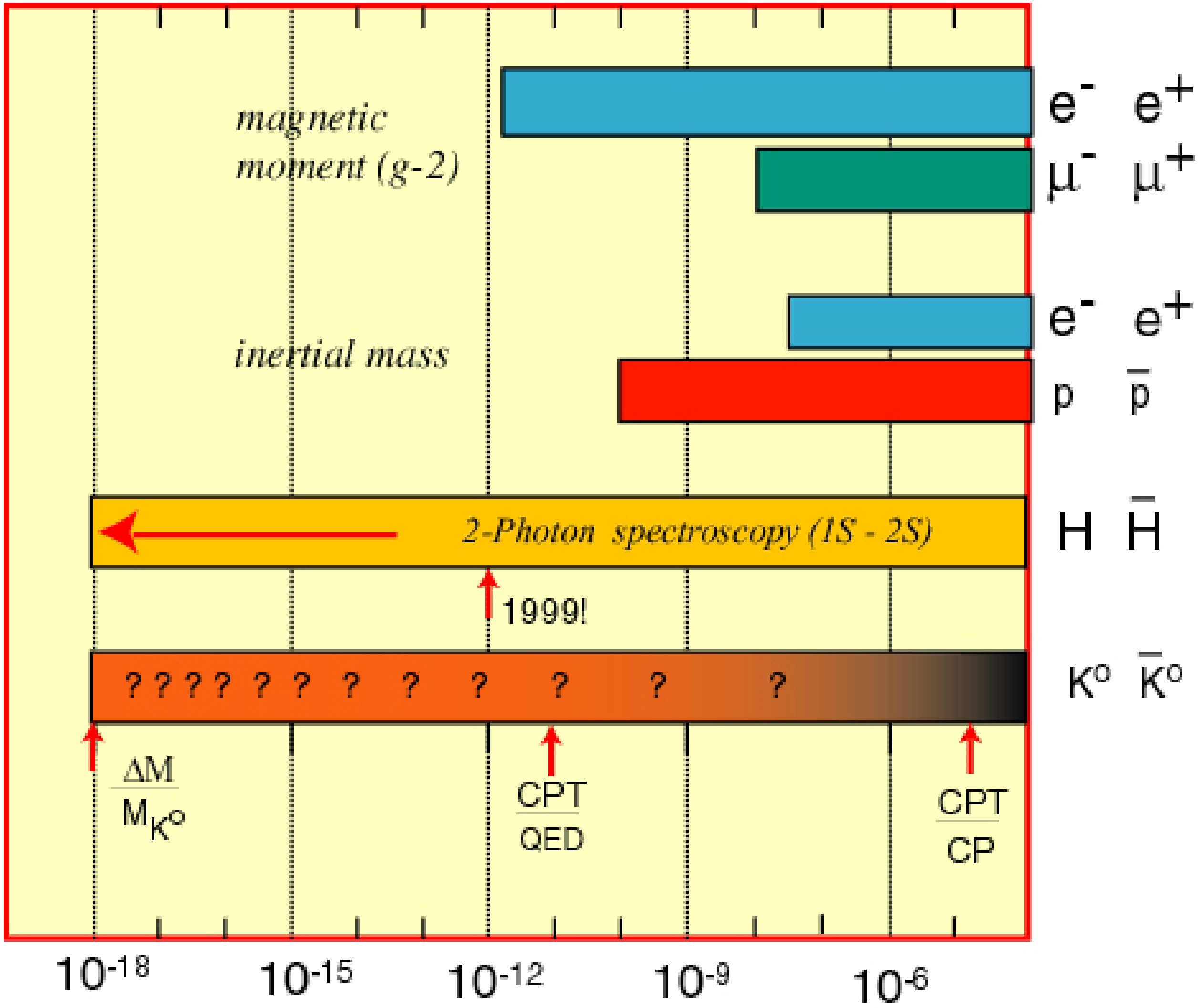
Any local quantum field theory in flat space-time obeying Lorentz invariance and unitarity

requires CPT to be conserved

G. Lüders, Ann. Phys. 2 (1957) 1-15

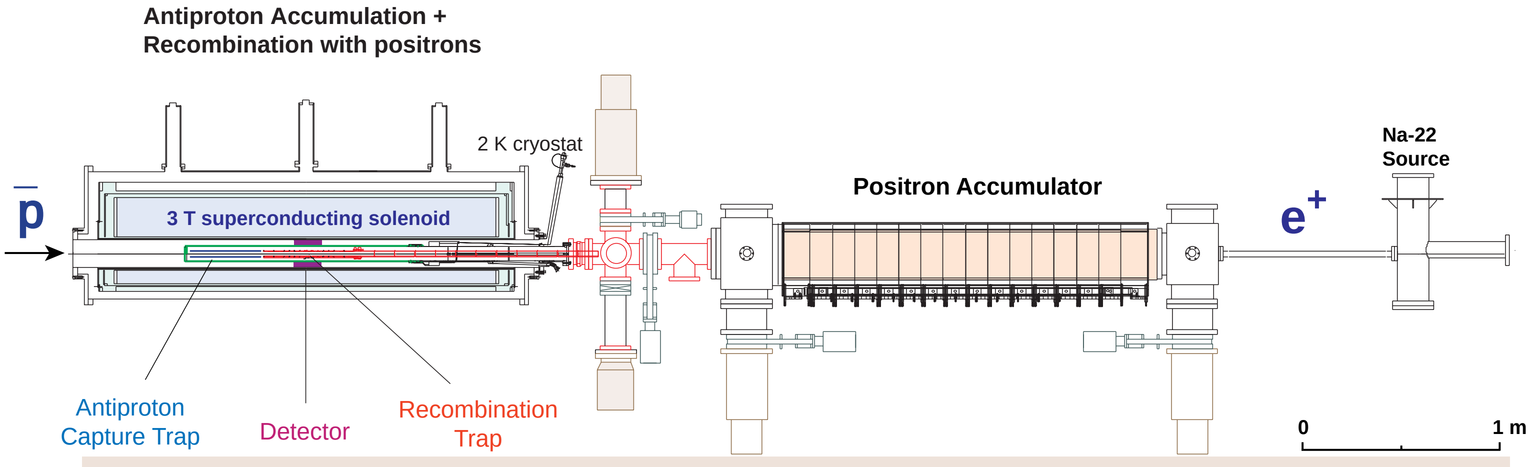
Antihydrogen promises the most precise, direct, and unambiguous test of this principle

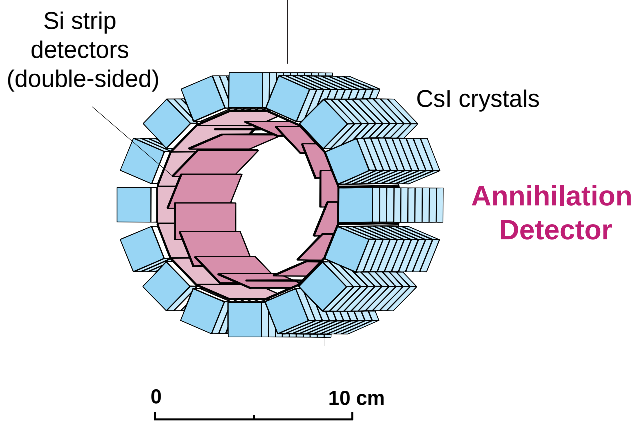
provided that the methods so highly developed for hydrogen spectroscopy can be applied with equal precision



ATHENA General Overview

ATHENA / AD-1 : Antihydrogen Production and Spectroscopy

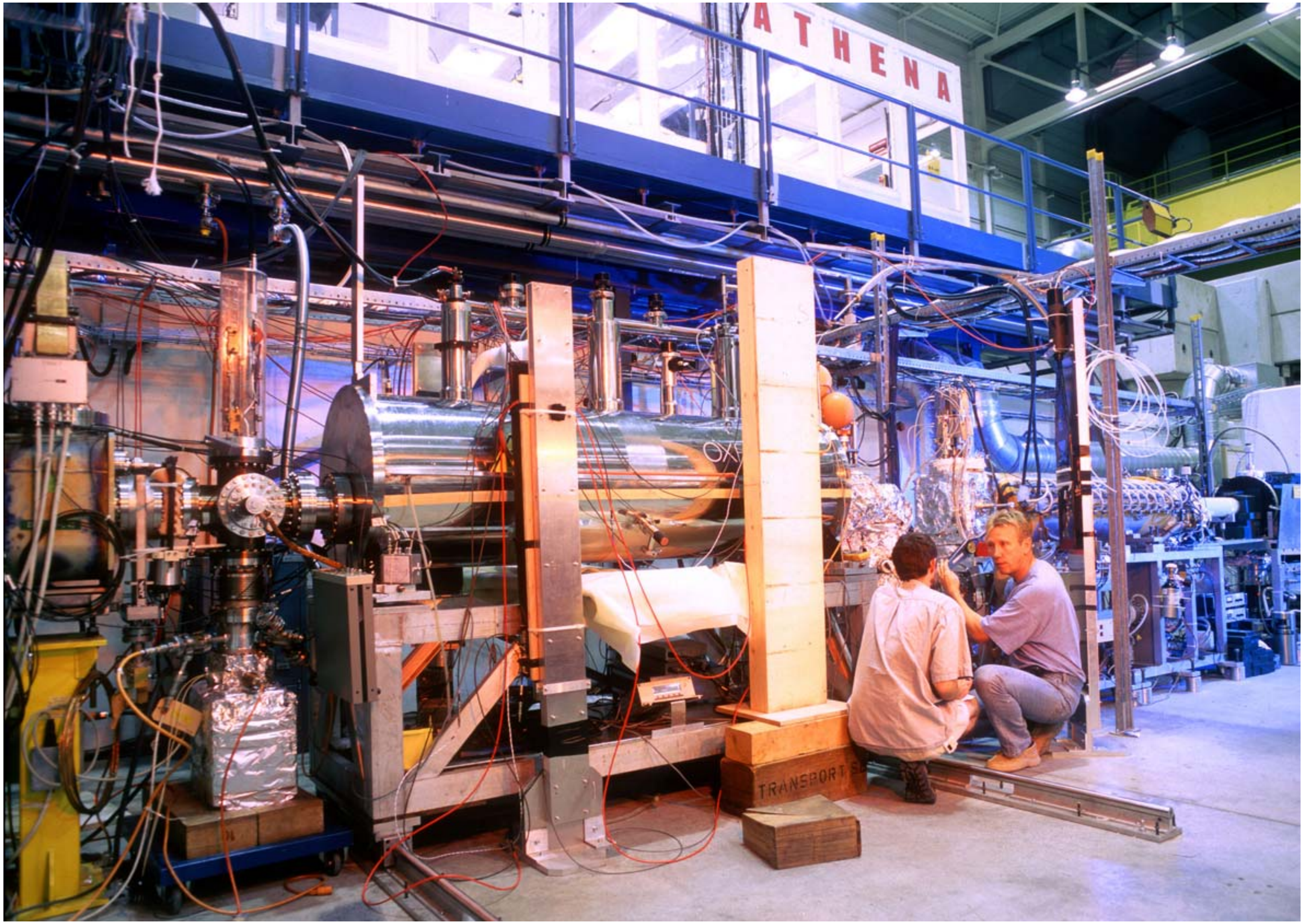




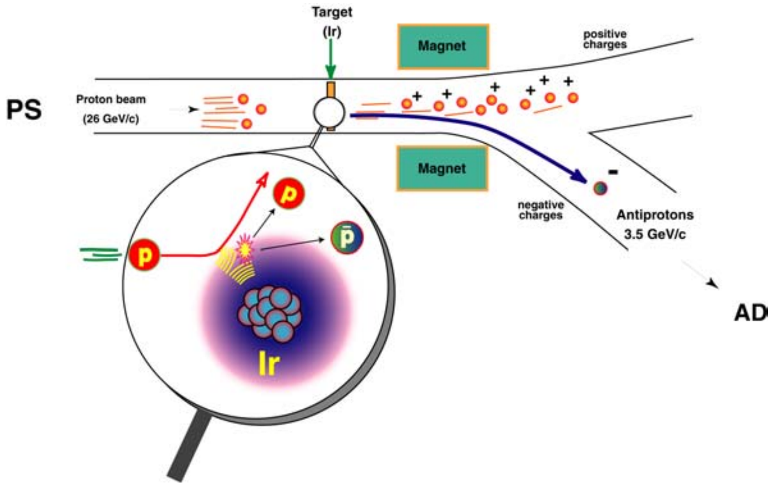
Main Goals:

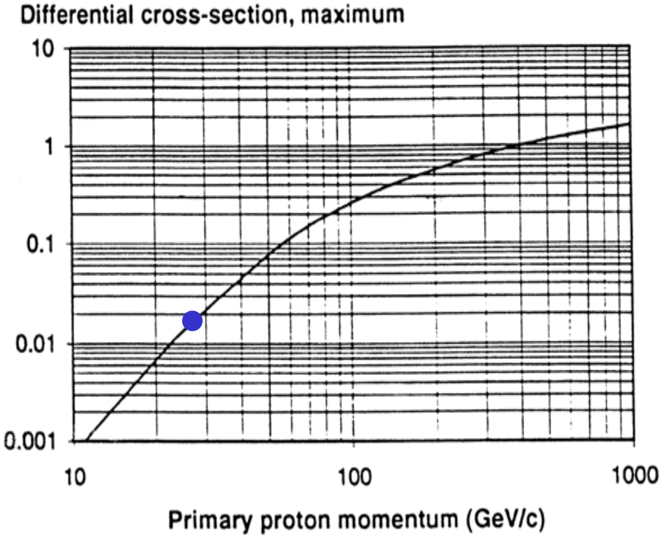
- Modular design
- Maximize total numbers of particles
- Unambiguous detection of events

ATHENA Apparatus is complete

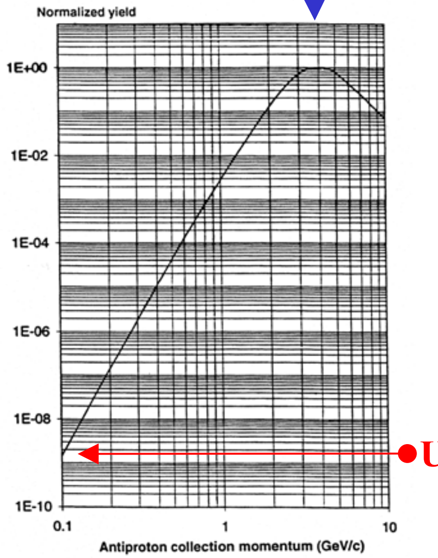


Antiproton Production at CERN

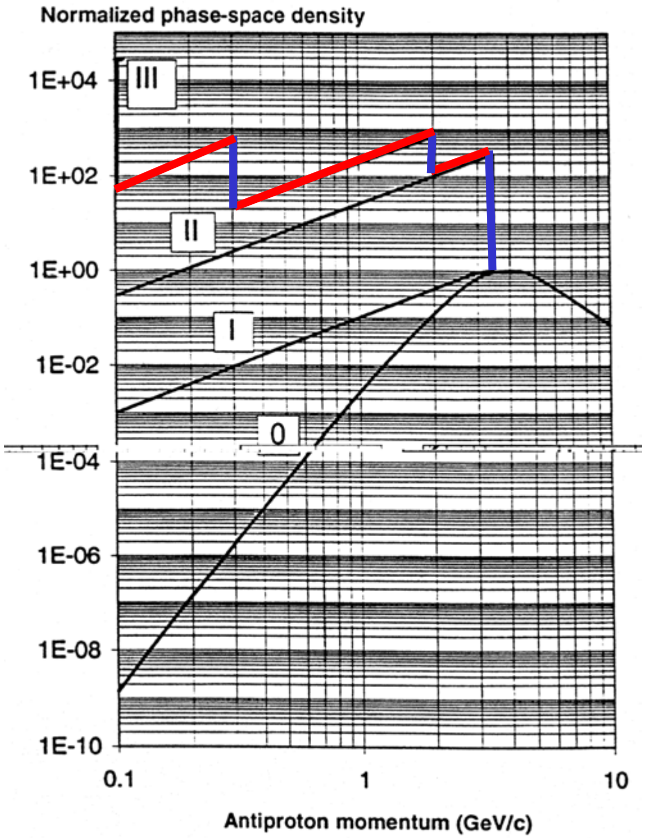




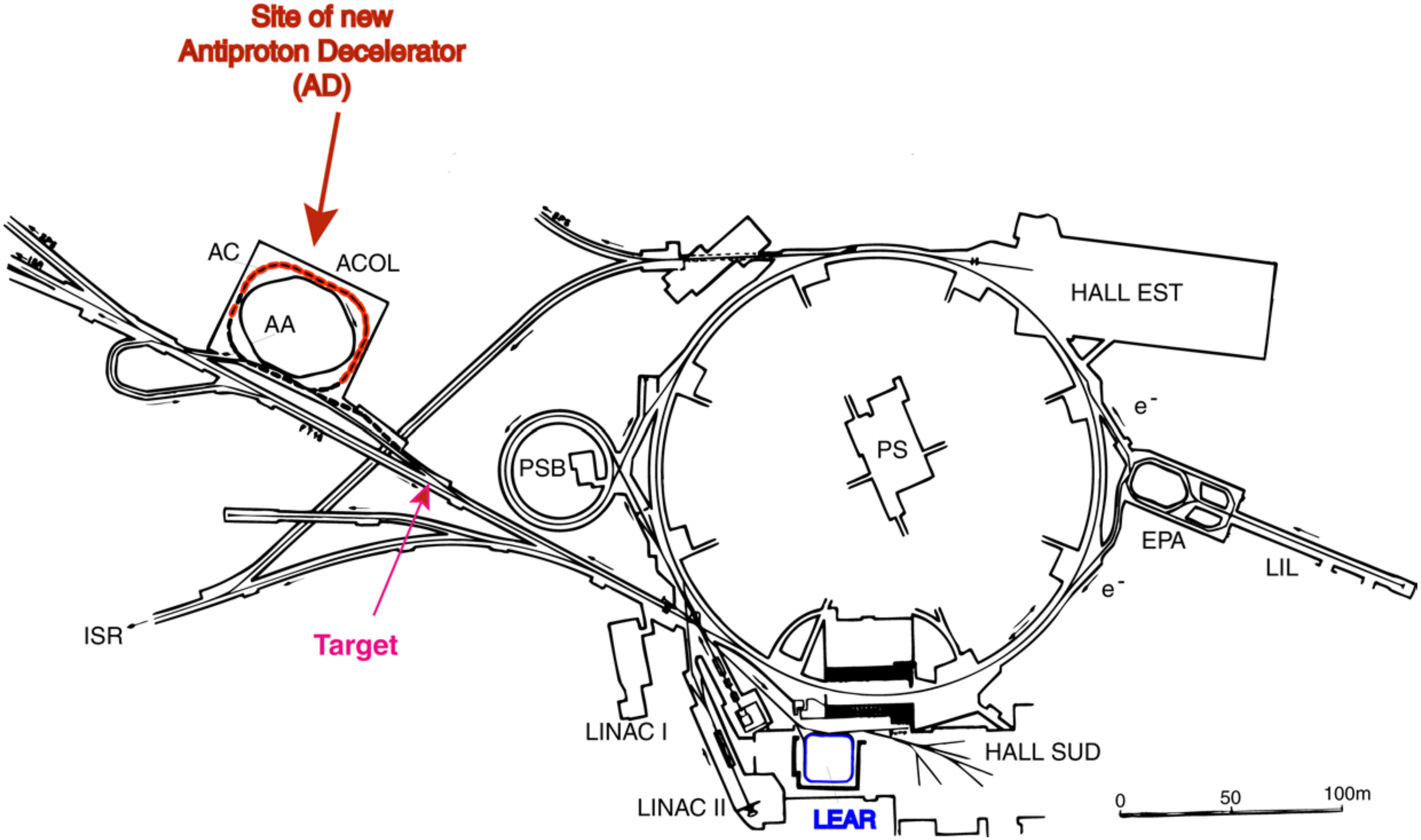
Collect



Use



Old Antiproton Source (LEAR)

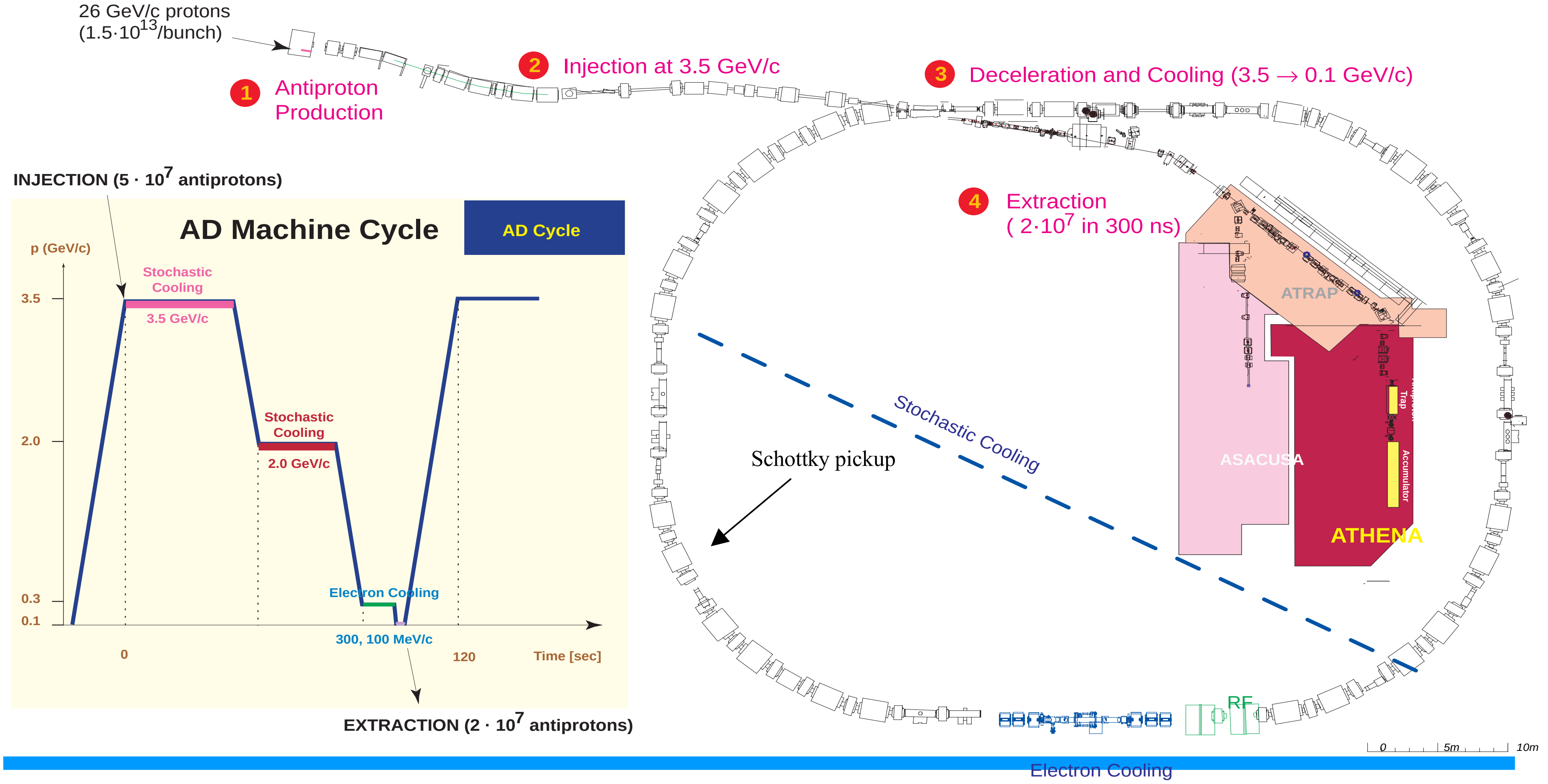


New Antiproton Source (AD)

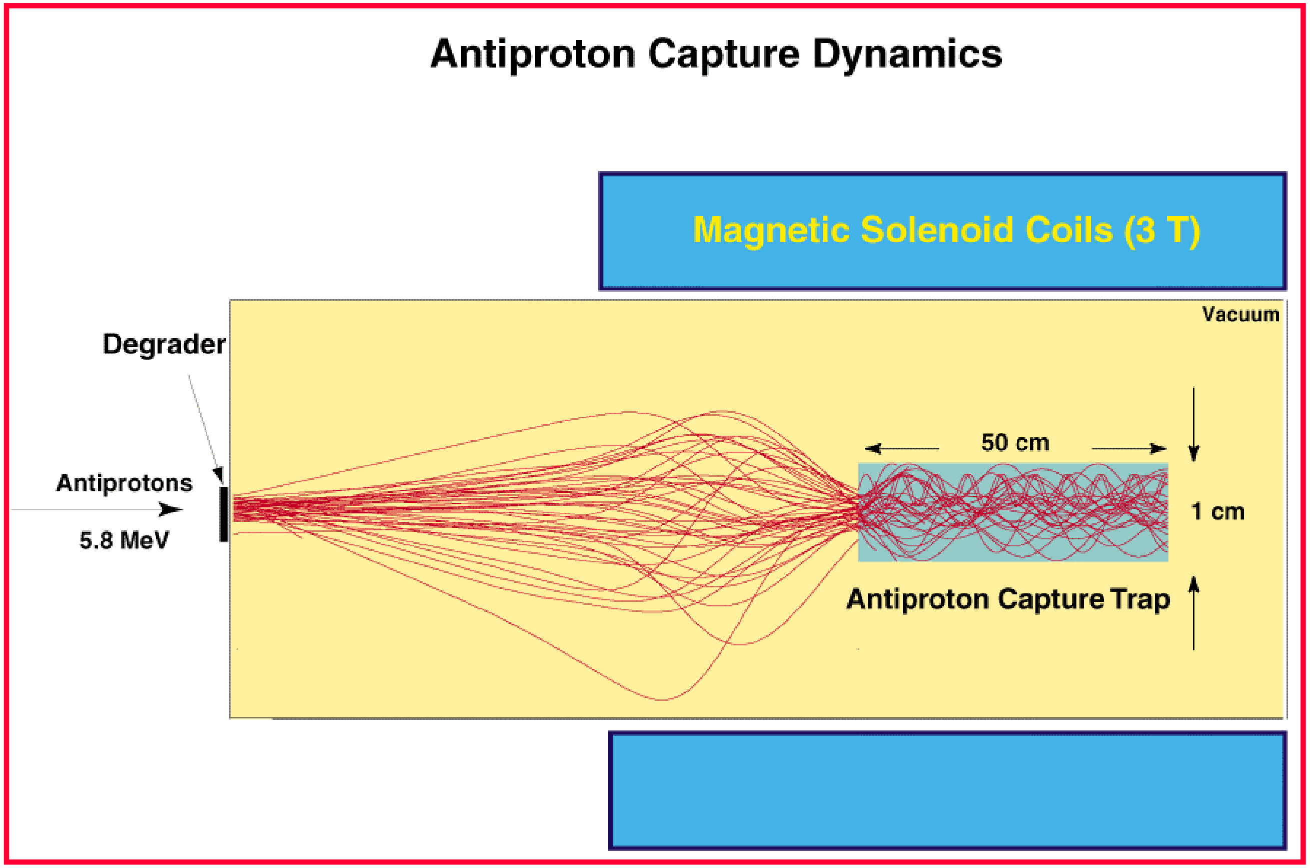
Antiproton Decelerator

AD replaces (AC + AA + PS + LEAR)

Capture Accumulation Deceleration Cooling + Extraction



Slowing Antiprotons from MeV to keV



PS200:

External detector and windows partially degrade incoming beam.

ï Angular divergence of beam
Use magnetic field to refocus beam onto the final degrader

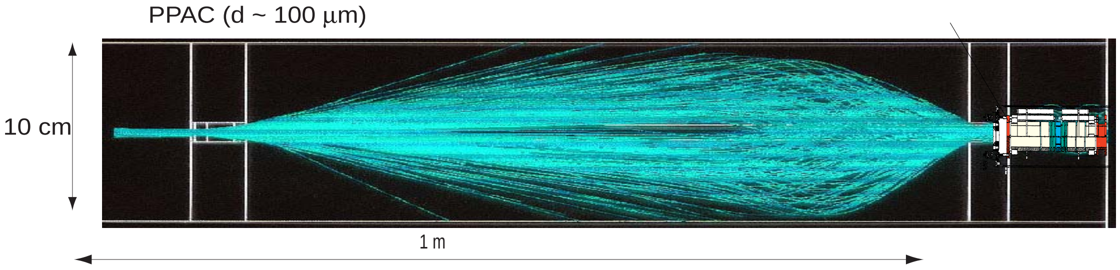
ATHENA:

- Eliminate windows
- Move detector into high B field

ï Capture efficiency independent of magnetic field tune

Beam degrading (Simulation)

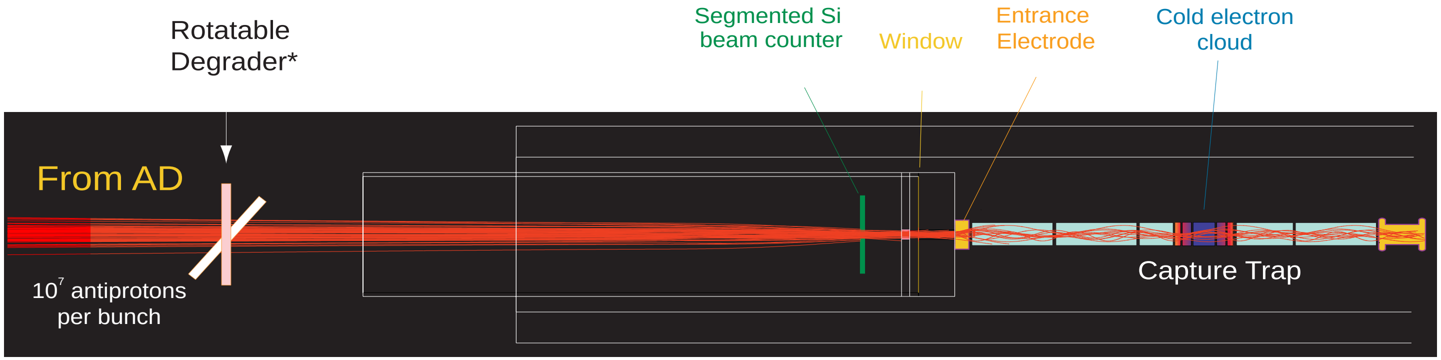
1999:



(Simulation)

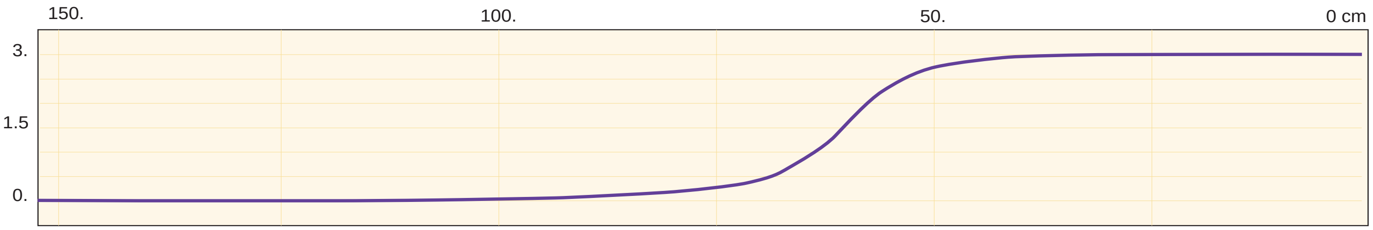
Avoid material far away from trap entrance !

2000:



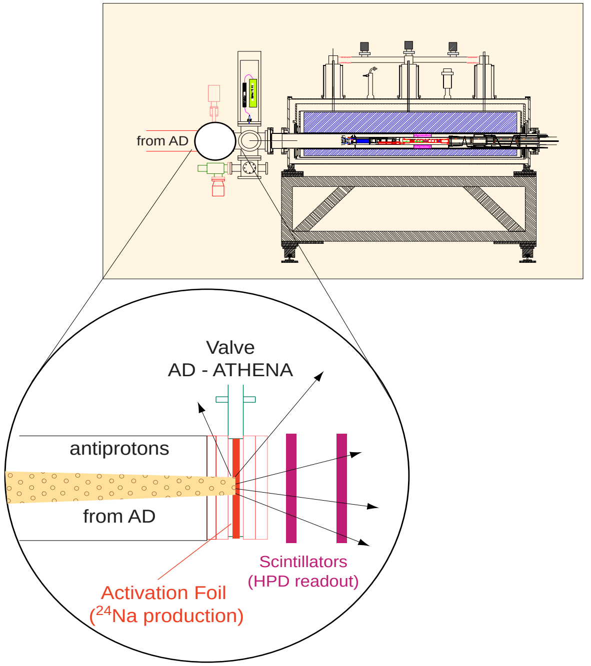
* Period 1: 27 or 54 µ Alu
* Period 2: 9 µ Al (+ 32 µ Al at entrance electrode)

(Simulation without rotatable degrader)

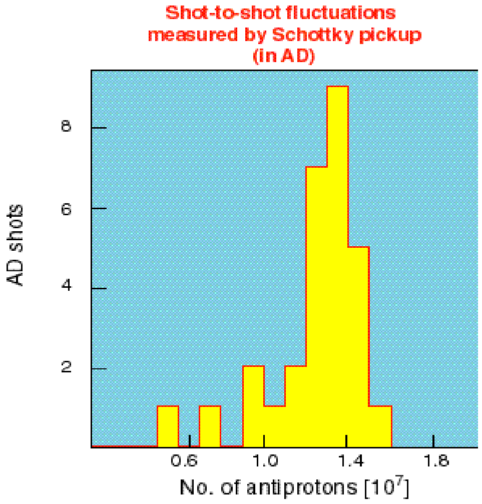


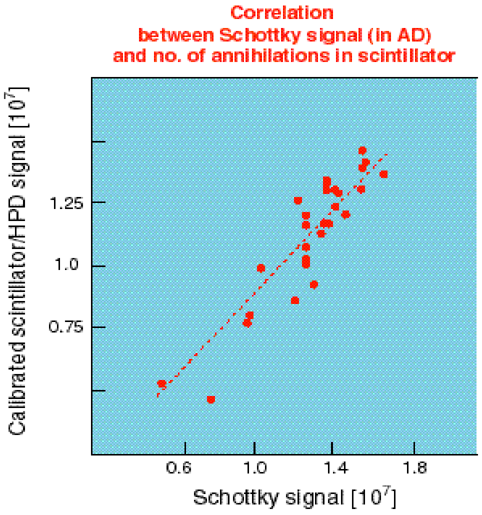
Total magnetic field [T] vs Position [z]

Beam intensity measurement



- Absolute calibration by activation method (Nov 2000)
- Induced activity (^{24}Na) in 0.44 mm Al absorber foil
- Compare integrated beam (29 shots) with internal (Schottky) measurements and external (scintillator/HPD) detector





RESULTS

Average number of antiprotons per shot

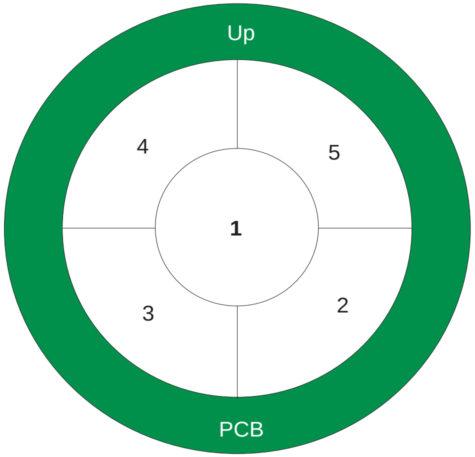
$1.14 \pm 0.2 \cdot 10^7$

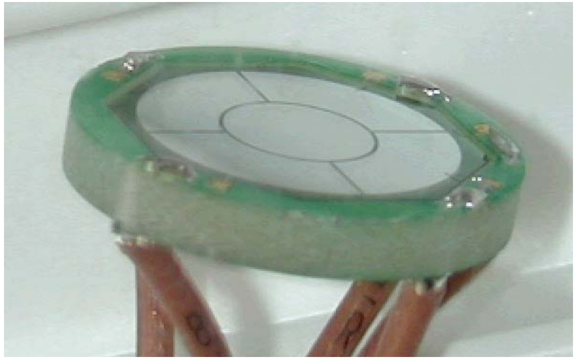
Extraction efficiency ~ 90 % ± 5 %

Good shot-to-shot stability (±10%)

Beam Steering

- Beam steering
- Intensity
- Capture trigger

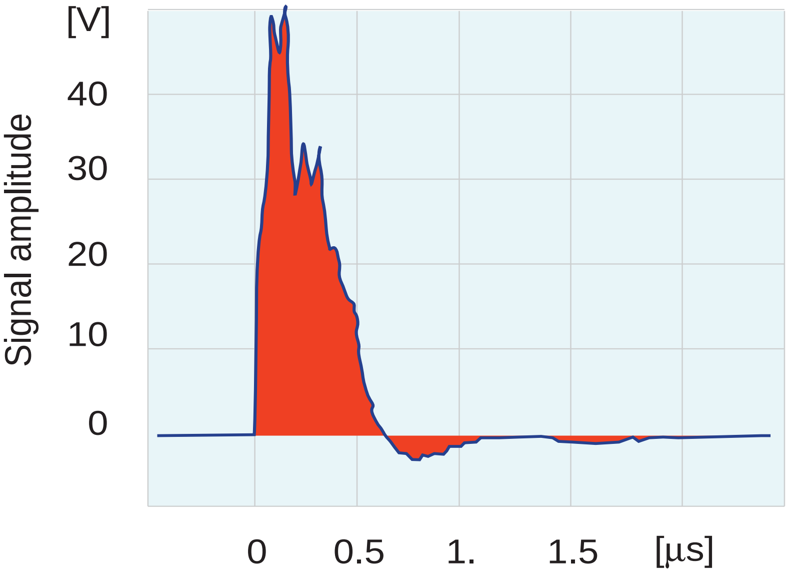




Si diode, 67 µm thickness; 5 segments

Diameter: inner = 7 mm, outer = 15 mm

Depletion: 3.5 V; operation @ 40-70 V



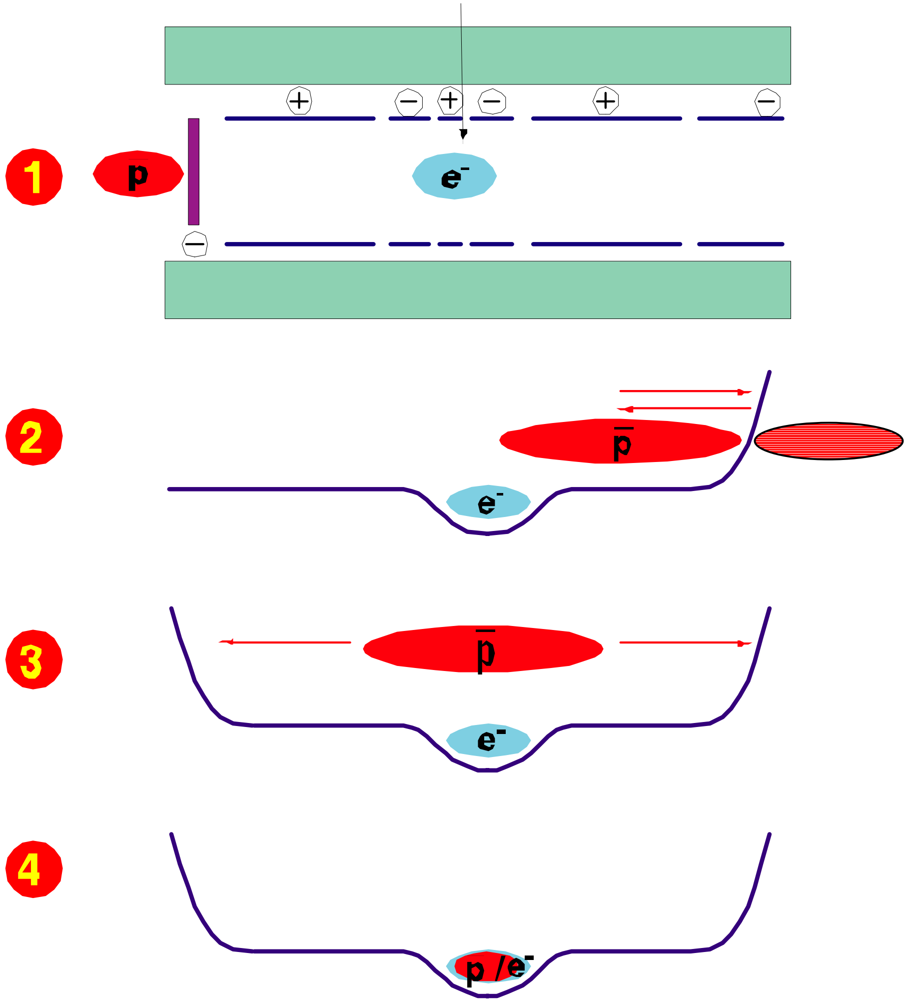
Signal from
Si beam counter (67 µm)

Complementary beam monitors:

- Scintillators (four with HPD readout)

- Intensity ~ 70 % of extracted AD pulse (~ $3 \cdot 10^7$ antiprotons)

Antiproton Capture (Scheme)



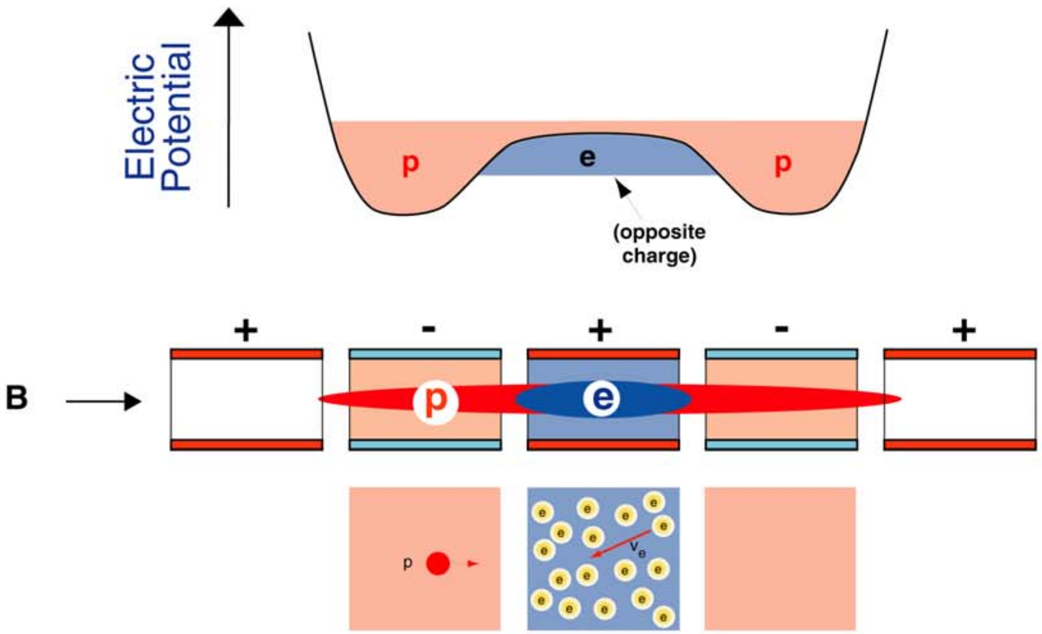
1. **Pre-load trap with electrons.**
   (cool by synchrotron radiation
   τ ª 300 msec in 6 Tesla, T ª 10 K)

2. **Inject antiprotons through degrader**
   î low energy component is reflected
   at exit electrode of trap.

3. **Close entrance electrode after last particle enters but before first particles leave.**
   (Determines minimum length of trap)

4. **Electrons (sympathetically) cool antiprotons.**
   (excess energy is released into cryogenic bath)

Recombination Overview



Particle "p" spends ε_τ of its time inside plasma cloud "e" with density n_e

$$\boxed{d\Gamma_p = \varepsilon_\tau \; n_e \; \sigma(v_r) \, v_r}$$

Spatial Overlap of p and e clouds **Velocity dependence**

$$\Gamma_{SRR} = \int_{Vol} d^3r \; n_e(\vec{r}) \; n_p(\vec{r}) \int_{v} d^3 v \; \sigma(v) \, v \, f(\vec{v})$$

$$= \int_{Vol} d^3r \; n_e(\vec{r}) \; n_p(\vec{r}) \qquad \alpha(v_r)$$

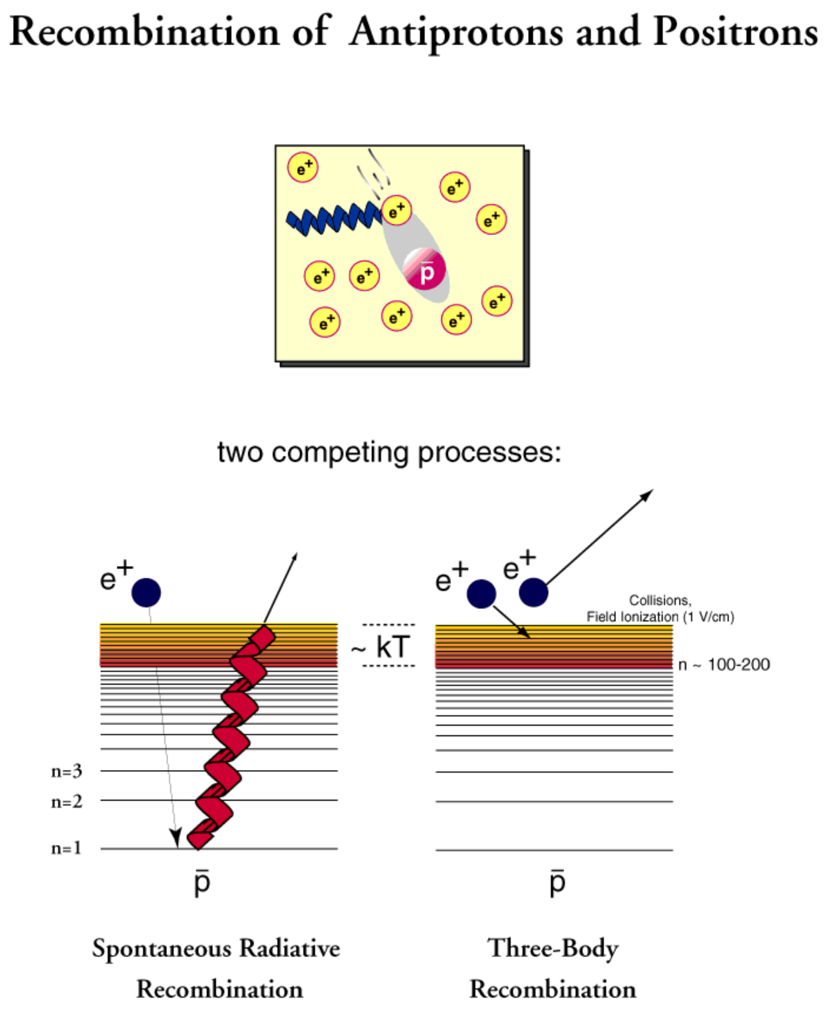
Definition:

$$\boxed{\alpha(v_r) \equiv \int_{v} d^3 v \; \sigma(v) \, v \, f(\vec{v})}$$

'Recombination Coefficient" *

* This recombination coefficient has been measured in electron-cooled proton storage rings, since e-p recombination contributes to losses of stored protons

Routes to Recombination



Spontaneous Radiative Recombination:

- **Yields predominantly low n-states:**
  (20% to n = 1, 60% to n <10)
- Moderate recombination rate, **but:**
  CO_2-Laser stimulation can be used to enhance recombination rate

Three Body Recombination:

- **Very fast rate at low temperature:**
  $\mathbf{R_{(TBR)}} \propto 2.7\ 10^{-27}\ \mathbf{cm^6 s^{-1}\ n_{e^+}\ (1/kT)^{9/2}}$
- **Results in (very) high Rydberg States**
  $\mathbf{R_{(TBR)} \propto n_{e^+}(1/kT)\ n^6}$
- De-excitation by transitions to lower n (n = 11) may (must?) be induced by CO_2-Laser

(Stimulated) Spontaneous Recombination

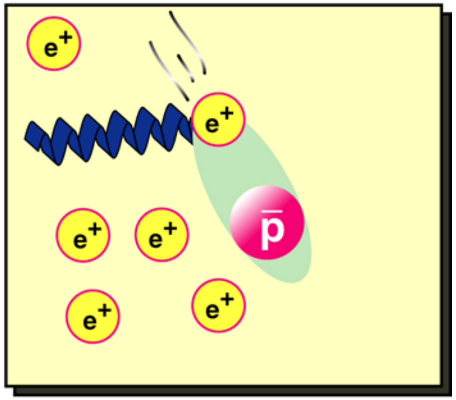
$$\sigma_{\bullet\to n} = 1.96\pi^2 \frac{he^2}{m^2c^3}\frac{\nu_1^2}{\nu(\nu-\nu_n)n^3}$$

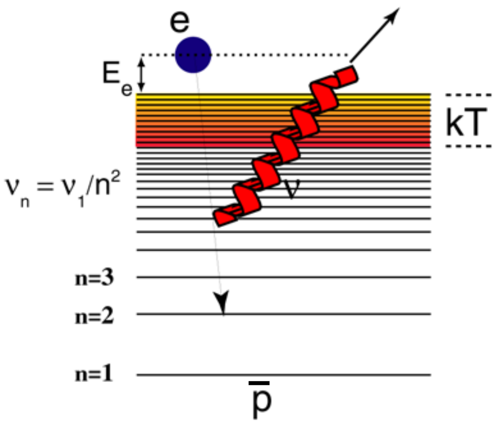
$$= 2.1\cdot10^{-22}\,cm^2\,\frac{1}{nx(1+n^2x)}$$

$$\sigma_{\bullet\to 1-10} \sim 1.0\cdot10^{-16}\ \mathrm{cm}^2 \ \cdot\ T^{-1}\ [K]$$

$$(x \equiv \frac{E_e}{13.6eV})$$

$$\alpha_{SRR} \sim 3.8\cdot10^{-11}\ \mathrm{cm}^3\ \mathrm{s}^{-1}\ T^{-0.5}\ [K]$$





❖**Recombination preferentially to low levels (σ ~ 1/n)**

20 % to n = 1

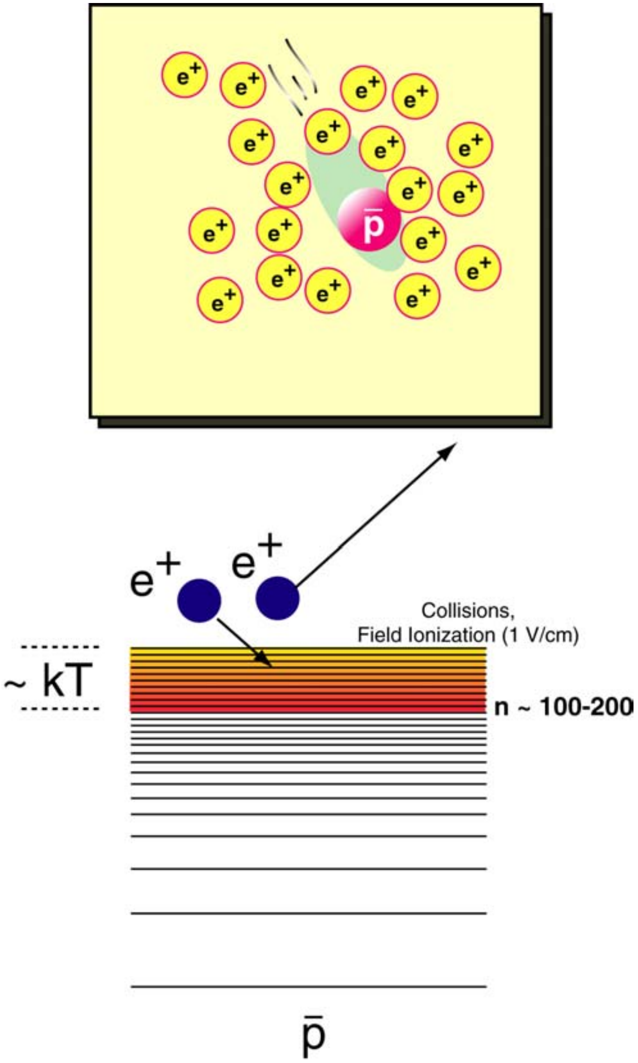
60 % to n = 1 – 10

❖**Lower cross-section**

Needs large number of particles

❖**Atoms are produced in stable levels**

Three-Body Recombination



Γ_{TBR} ~ Γ (e-p collision) x Probability to find 2nd coll.

- e^+-p Coulomb interaction radius: $R_T = e^2/kT$
- $\Gamma(e^+\text{-p collision}) \sim n_e\, Ω\, v_e\, Ω\, R_T^2\ (\, Ø v_e\, n_e^{1/3})$
- Probability (e^+ in vicinity) ~ $n_e\, R_T^3$

$$\Gamma_{TBR} = \kappa\, n_e^2\, R_T^5\, v_e \sim T^{-4.5}$$

(K = 0.76(4) for B=0, k = 0.07(1) for B = 6 Tesla)

❖**High rate at low**

❖**Preferentially populates very high levels ($\sigma \sim n^6$, E ~ kT):**

$$\sigma_{\bullet Æ100} = 10^6\ Ω\ \sigma_{\bullet Æ10} = 10^{12}\ Ω\ \sigma_{\bullet Æ1}$$

❖**Radiative de-excitation is slow:**

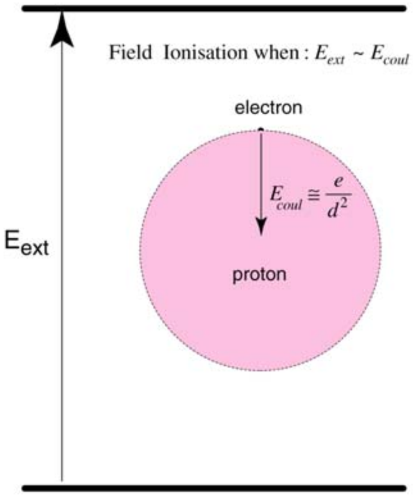
n = 100 : <τ> ~ ¼ second

❖**Needs stimulated de-excitation to n ª 10**

(CO_2 Laser)

Three-Body Recombination (Physics Issues)

Field Ionisation - electric fields:



Field Ionisation when : $E_{ext} \sim E_{coul}$

$$E_{ext} \cong \frac{e}{d^2} \approx \frac{e}{a_B^2\, n_{\max}^4}$$

$$\Rightarrow n_{\max} \leq \left(\frac{e}{a_B^2\ E_{ext}}\right)^{\frac{1}{4}} \cong \left(5 \cdot 10^9\ \text{V/cm} \cdot \frac{1}{E_{ext}}\right)^{\frac{1}{4}}$$

For typical electric fields :

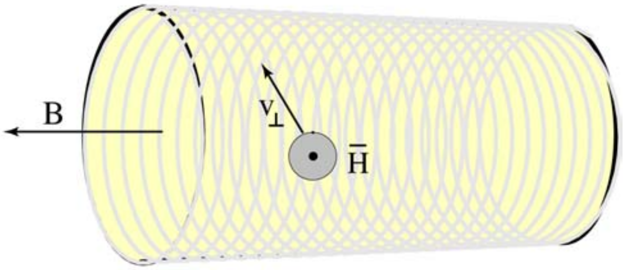
1 V/cm : $n_{max} = 158$

10 V/cm : $n_{max} = 90$

100 V/cm : $n_{max} = 50$

1000 V/cm : $n_{max} = 28$

Field Ionisation - magnetic fields:



$T = 4\text{ K} \rightarrow \beta = 0.9 \cdot 10^{-6}$

Motional electric fields ~ v xB :

(seen by a particle moving with velocity v = β c in mag. field B)

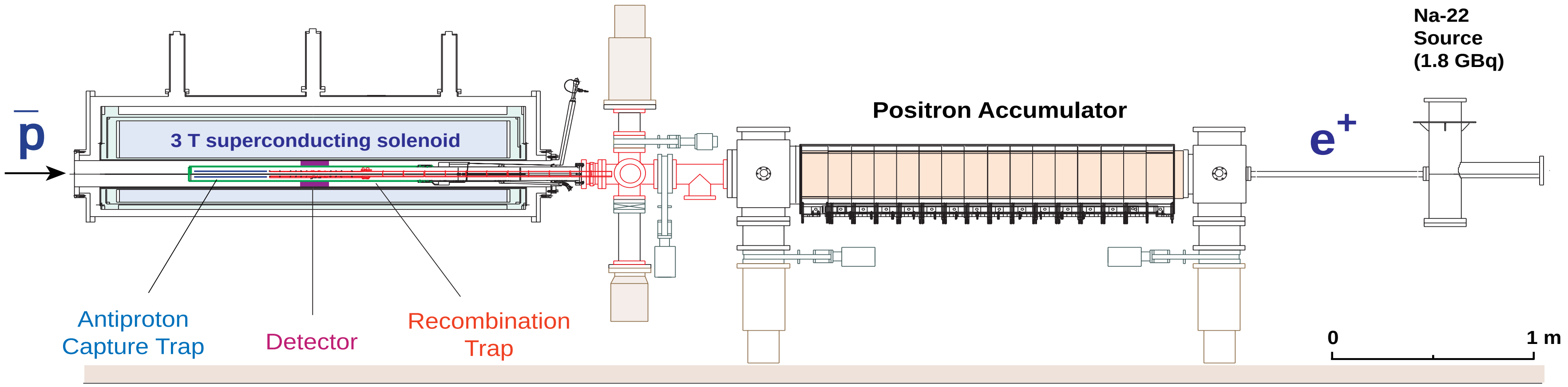
$$v\,B = 3 \cdot 10^6\ \text{V/cm}\ \ \beta\ \ B[T]$$

$$\boxed{n_{\max} \cong 3.8 \left(\frac{1}{\beta\, B[T]}\right)^{\frac{1}{4}}}$$

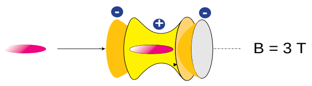
For antihydrogen at 4 K, B = 6 T:

$$n_{\max} \cong 80\ \ (!)$$

Main achievements 2001



① Antiproton capture and electron cooling

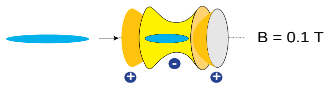


~20,000 $\bar{p}$ / shot

Beam steering (segmented Si diode)
Optimisation of trap efficiency
- degrader
- capture parameters

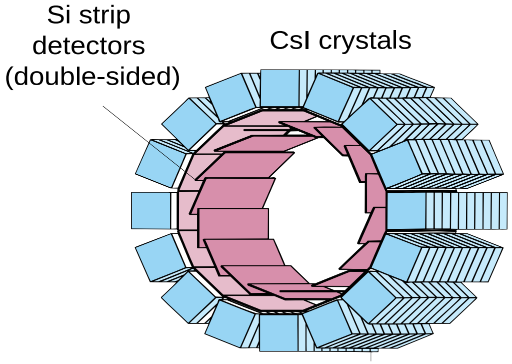
Electron cooling

② Positron accumulation from Na-22 source



10^6 e^+ / sec

Optimization of trapping parameters
Plasma compression



③ Detection of antiproton and positron annihilation

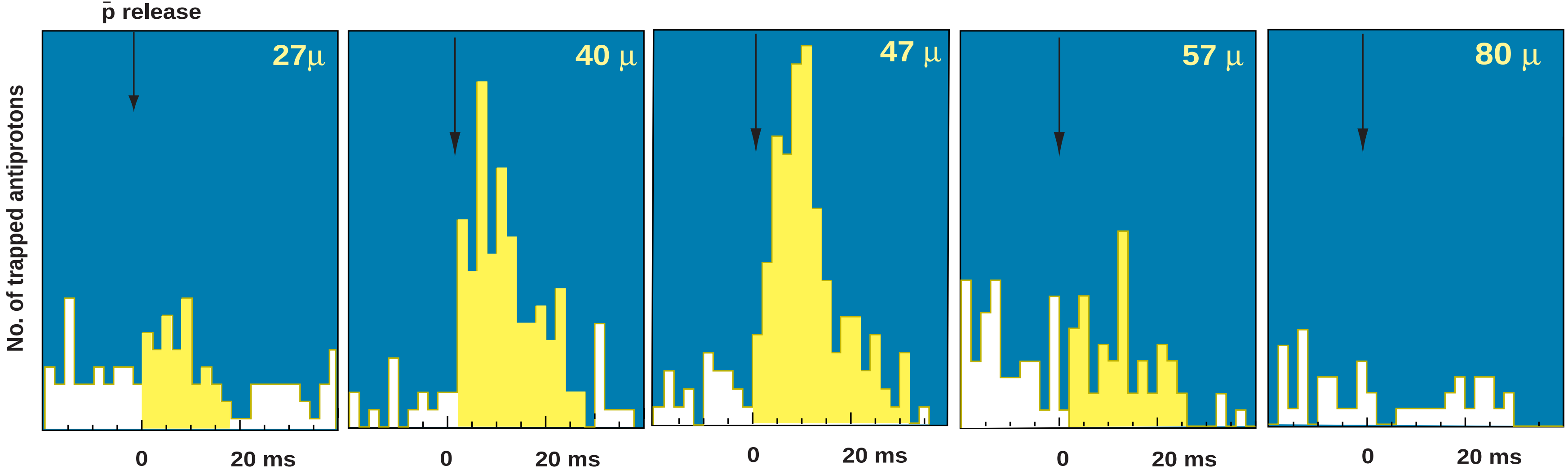
- 16x2 double-sided Si strip detectors (8,192 ch.)
- 16x12 CsI crystals + photodiodes

Construction and Assembly complete
Performance measured
- Position resolution
- Signal amplitudes / noise
- 511 keV energy resolution

Antiproton and Recombination Traps

Degrader Optimization

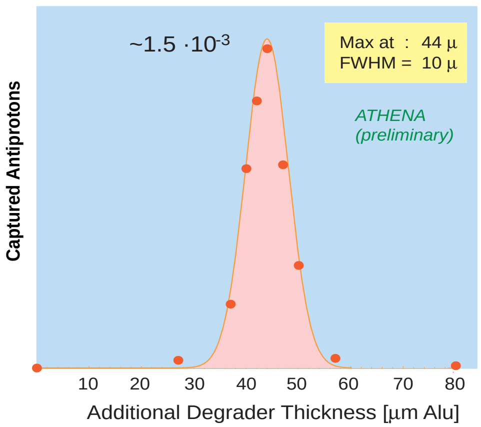
Trap and dump antiprotons for optimization of degrader thickness



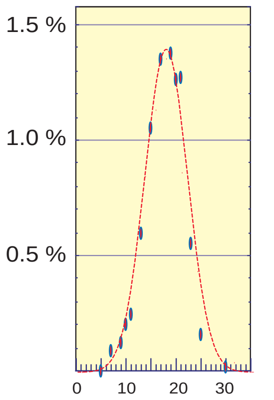
Final geometry:

- Beam Counter directly in front of capture trap
- Entire degrading foil on entrance electrode

Measured capture efficiency (5 kV)



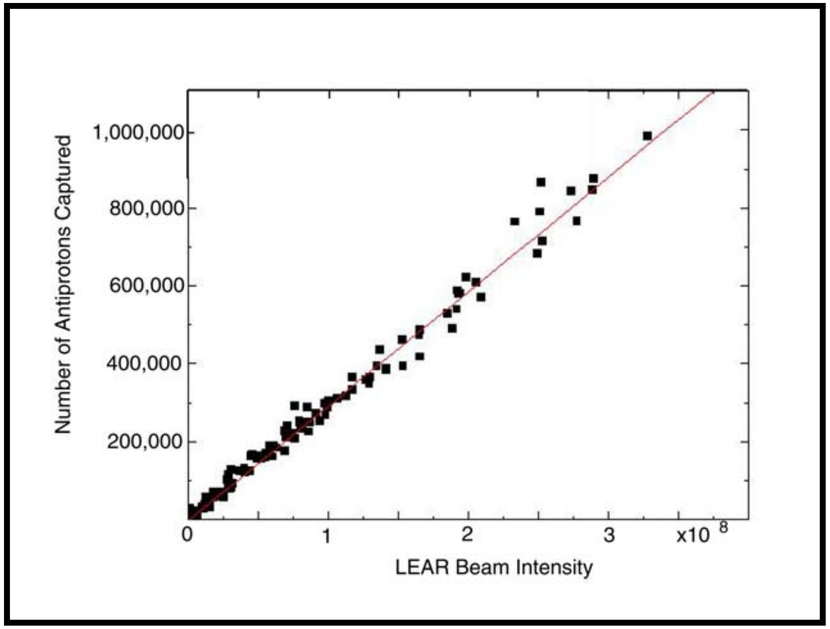
Simulation (50 kV)



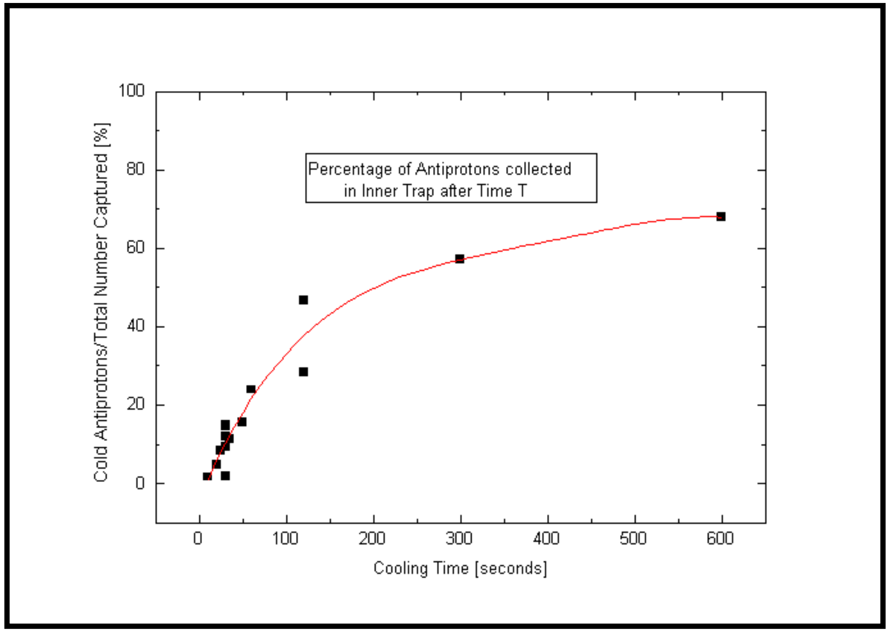
Antiproton Capture

Results from PS200 at LEAR:

- **1 million** antiprotons captured per 3.2 x 10^8 particles from LEAR
- **60+ %** of captured antiprotons **cooled to low energy** in 5 minutes



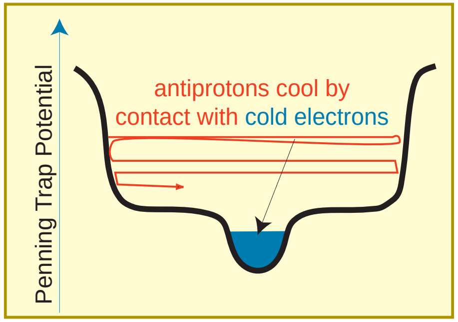
Capture of antiprotons from LEAR



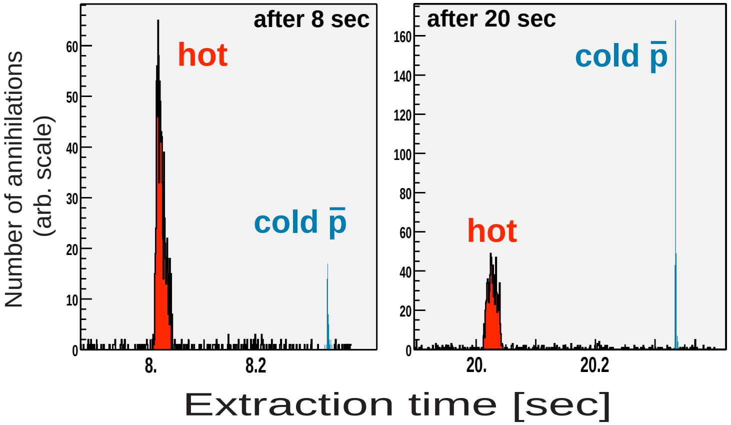
Electron cooling of antiprotons in PS200

Antiproton Cooling and Stacking

First electron cooling of antiprotons at AD (t º 15 sec)



Antiproton Capture + Cooling

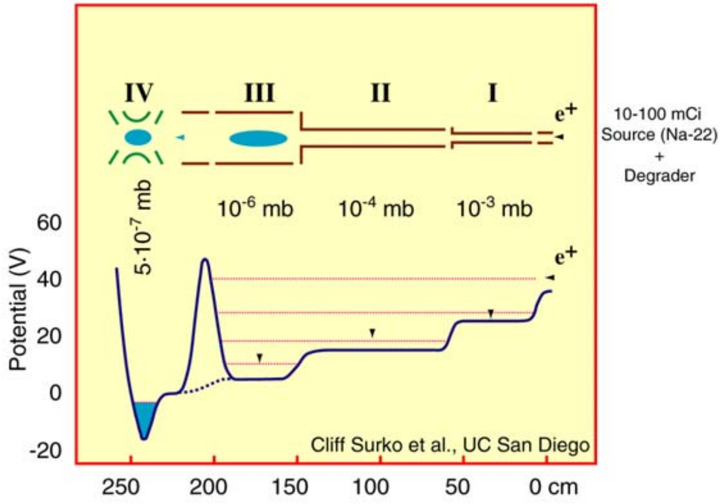


- ➤Capture 10^4 pbars/AD shot
  î ε ª 10^{-3}
- ➤Life time in trap is several hours
  î p ª 10^{-13} mbar
- ➤Cooling time << Life time
  î Stacking multiple shots from AD without losses

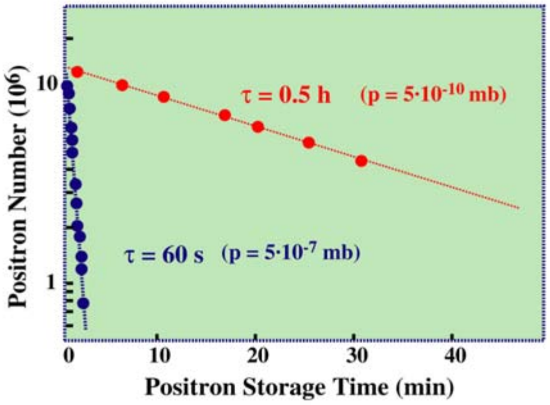
Positron Accumulation (Scheme)

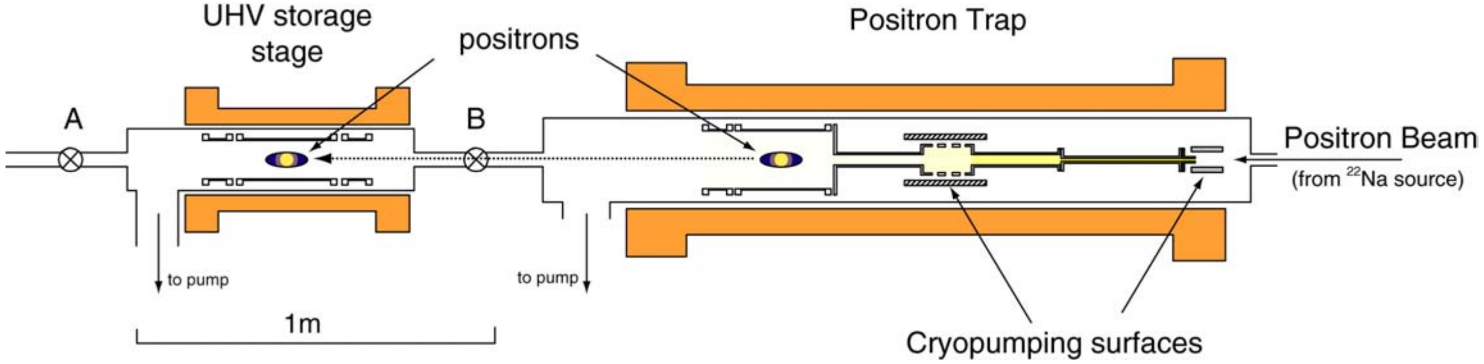
Accumulation Scheme:

- Inelastic collisions with N_2 gas
- Increasing electric trapping potential
- Transfer to UHV trap before annihilation



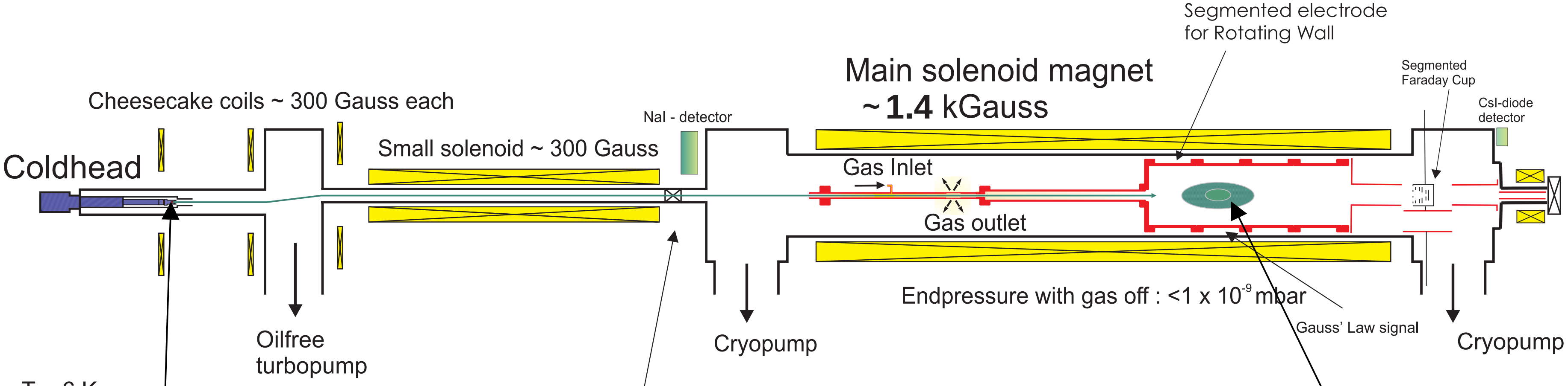
Cliff Surko et al., UC San Diego





Positron Accumulation (Overview)

Schematic of the experimental setup
Positron Accumulator



T = 6 K
1.8 GBq ^{22}Na
e$^+$ radioactive source
Solid neon moderator

Source (0.545 MeV)
= $1.95 \cdot 10^9$ Bq

Beam strength:
7 million e+ per second

$7 \cdot 10^6$ s^{-1}

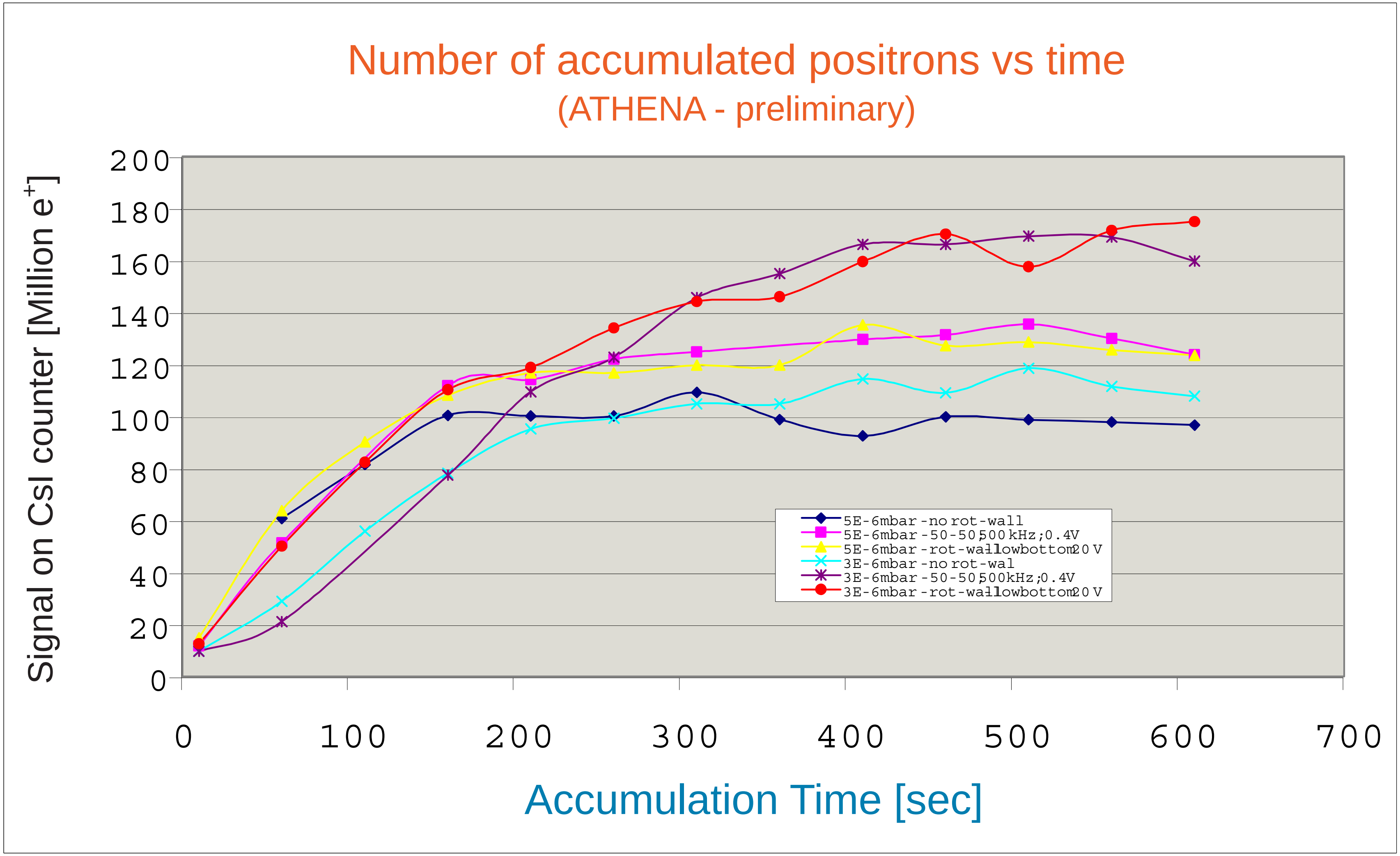
Diagnostics:
Incoming beam: a) NaI detector
b) CsI-diode detector

Trapping: a) CsI-diode detector
b) Segmented Faraday Cup
c) Gauss' Law signal from electrode

Plasma manipulation:
Rotating wall
Buffer gas pressure profile
Electric potentials

$2.0 \cdot 10^8$ /5 min

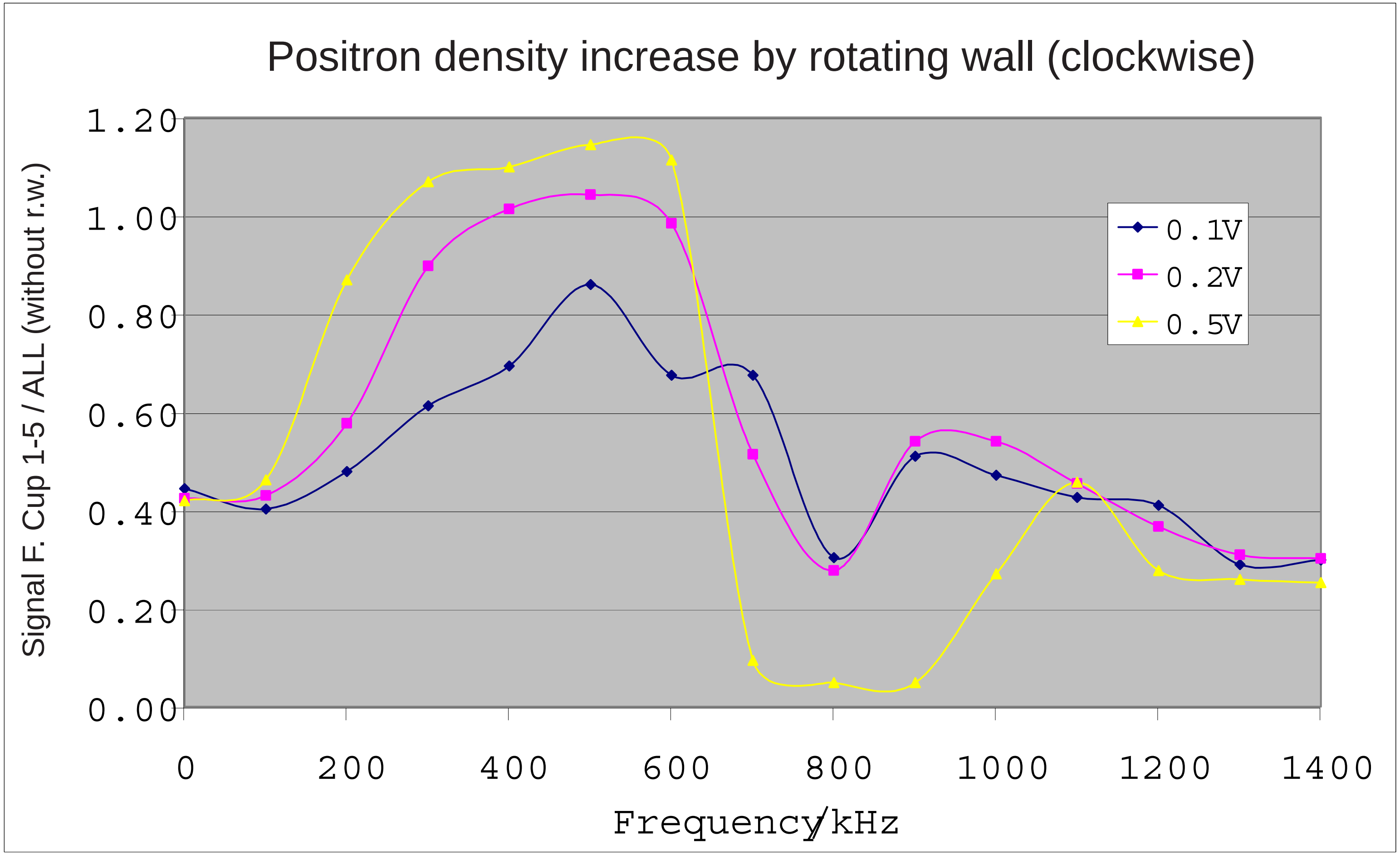
Positron accumulation with new source



Number of accumulated positrons vs time

(ATHENA - preliminary)

Positron cloud compression (rotating wall)

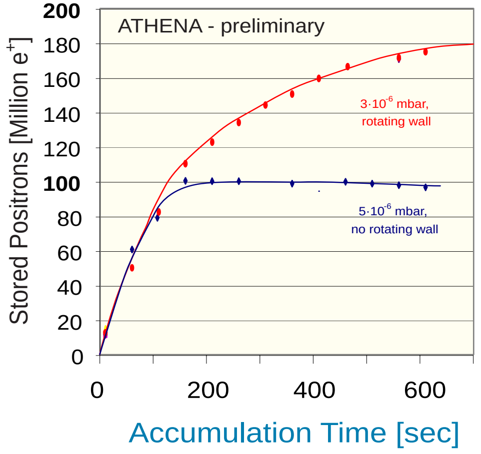


Plasma size before r.w. ~ 15 mm (FWHM)

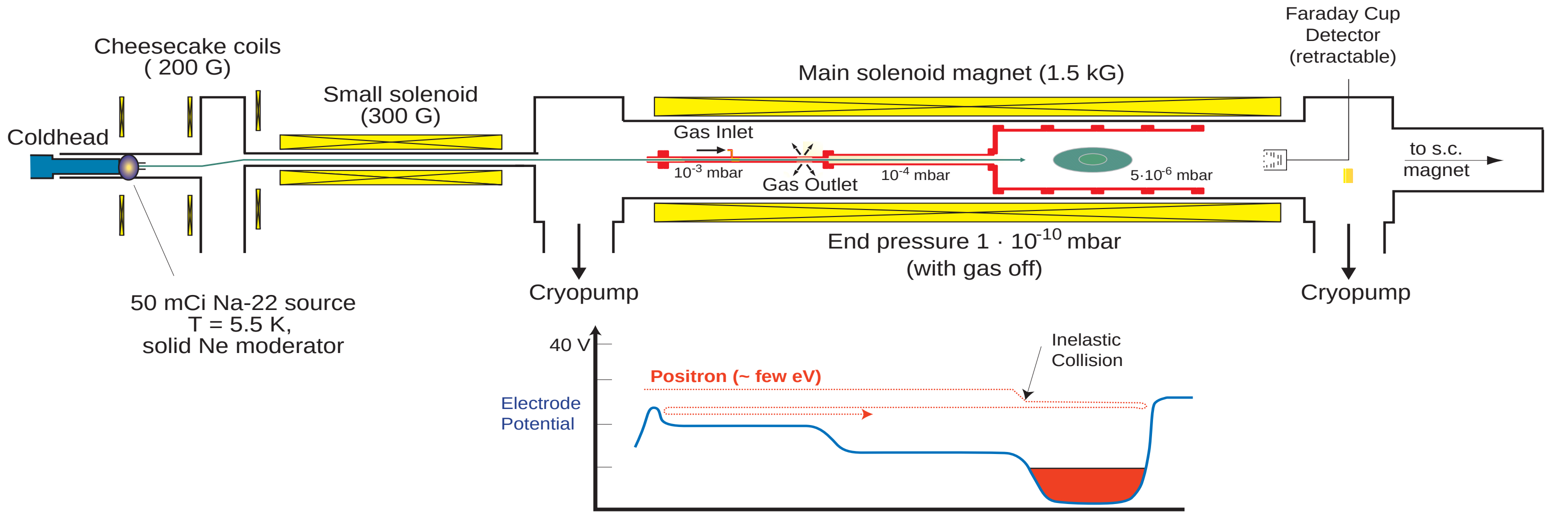
after r.w. ~ 3-4 mm (FWHM)

Positron Accumulation

Accumulated positrons vs time

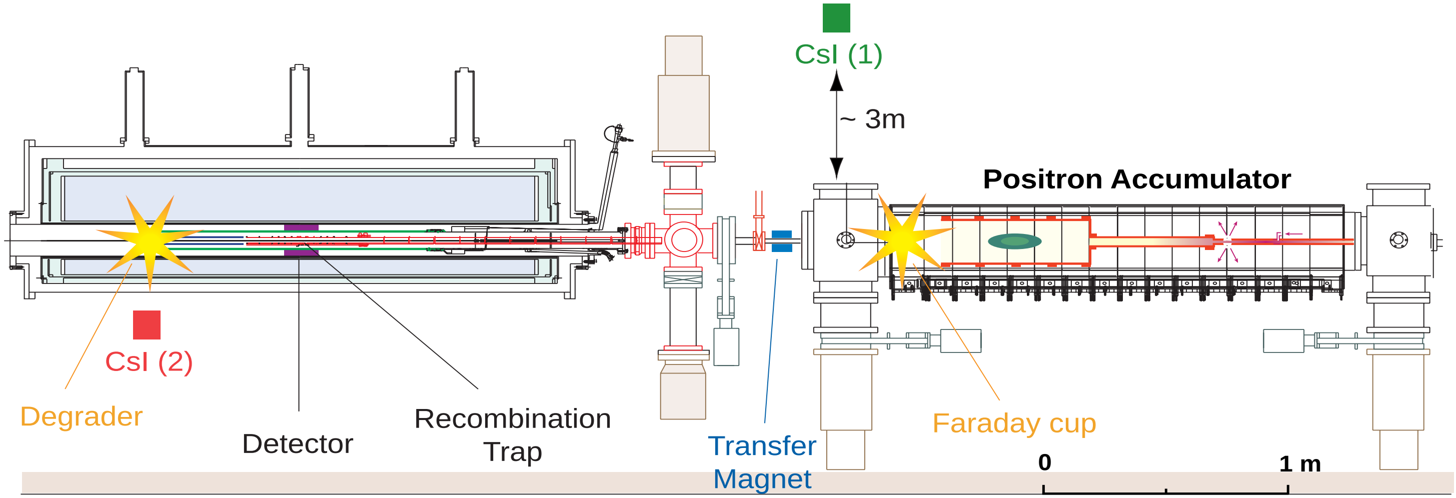


- **High rate**, stand-alone positron accumulator (~ 10^6 e^+/sec)
- **Positron moderation**: solid Ne layer and buffer gas (N_2)
- **1.8 GBq** (50 mCi) Na-22 source
- **Plasma compression** with rotating wall
- **1.7 10^8 positrons** accumulated per 5 minutes
- **Plasma size 3 mm** FWHM (with rotating wall)



Scheme of ATHENA Positron Accumulator

Positron Transfer

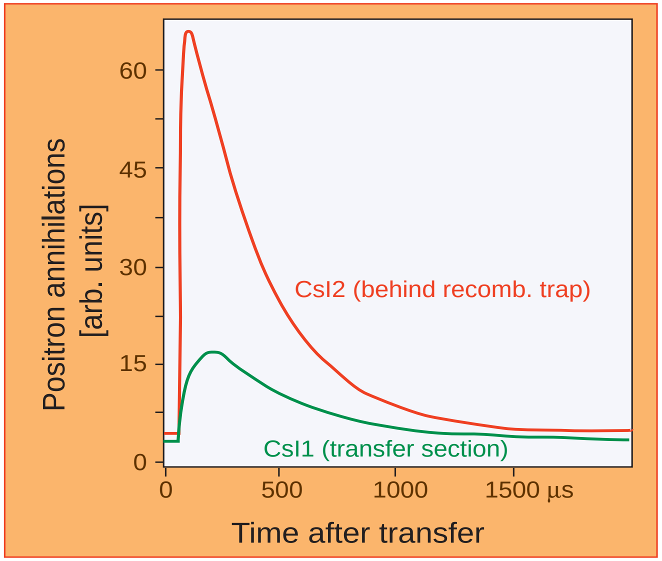


Scheme of positron transfer efficiency measurements

- **Transfer**
  - accelerate positrons ~ 20 V
  - pulse transfer magnet (1.2 T)
  - monitor CsI counters 1, 2

- **Result:**

  > 50 % transfer efficiency



Positrons in recombination trap

- **Capture**

  switch end electrodes ~ 3μs after injection - "squeeze" into centre

- **Positron Lifetime**

  several hours (harmonic potential)

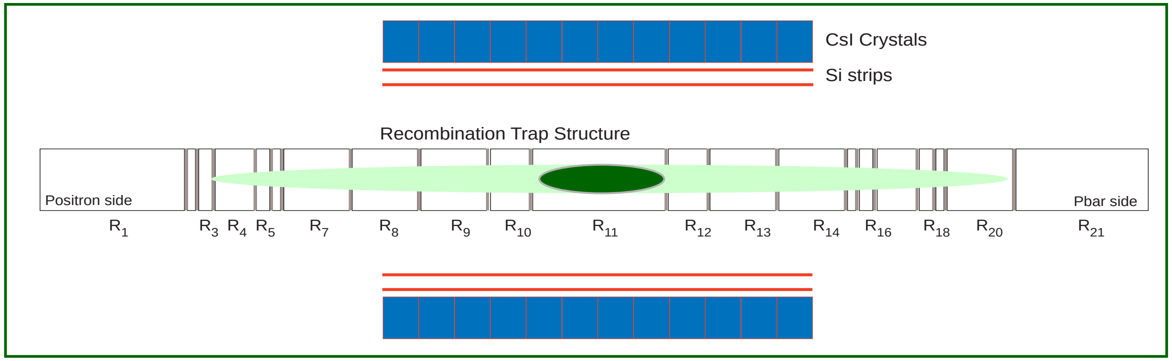
- **Diagnostics**

  Tuned circuit

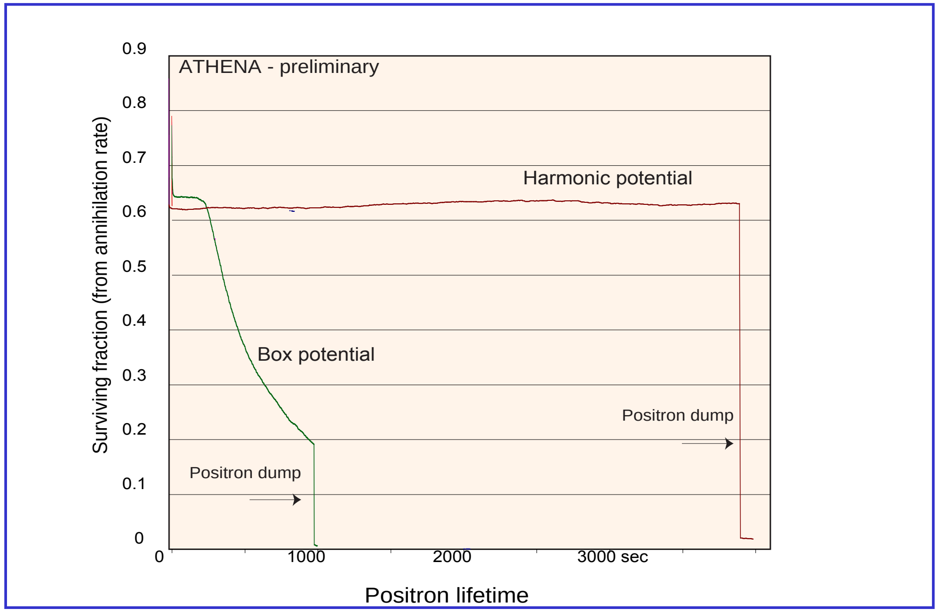
  Collective modes ("drive and read")

  Extraction on Phosphor screen + CCD

  Extraction on Faraday cups



Recombination trap and antihydrogen detector. In green, positron cloud after injection (light) and compression (dark)



Antihydrogen Detector

Identify antihydrogen annihilation at ~ 100 K, B = 3 T

Distinguish from antiproton annihilation by

- charged pion tracking + vertex determination (± few mm)
- detection of two back-to-back 511 keV gammas (seen from vertex)
- within time window of ~ 1 μsec

Beware of background from $\pi^o \rightarrow \gamma \rightarrow e^+e^- \rightarrow$ 511 keV !

Efficiencies

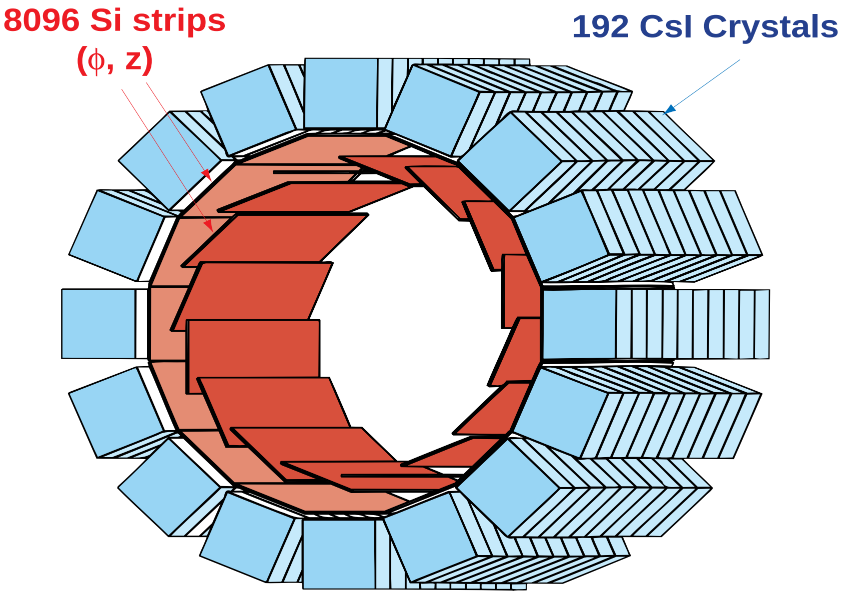
single track $\varepsilon_\Omega = 0.85$

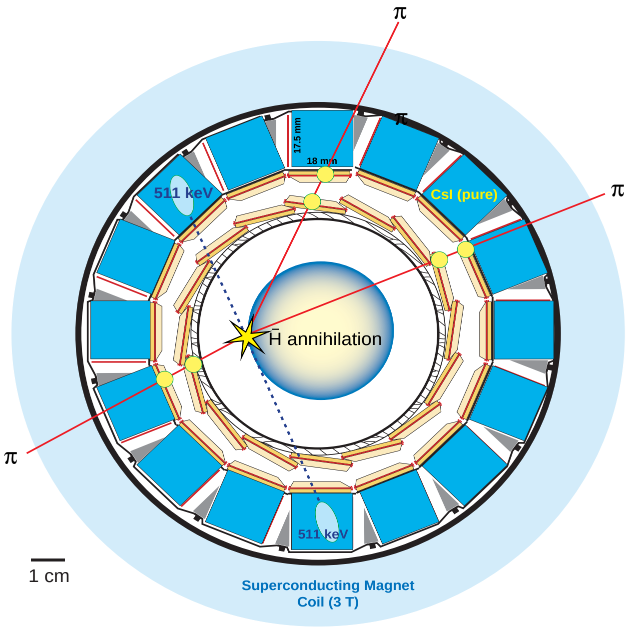
511 keV gamma: $\varepsilon_\Omega \lozenge \varepsilon_{int} = 0.66 \lozenge 0.15 = 0.1$

2 x 511 keV (coll.) $\varepsilon_\Omega \lozenge \varepsilon_{int}^2 = 0.015$

Antihydrogen $\varepsilon_{tot} = 1\%$

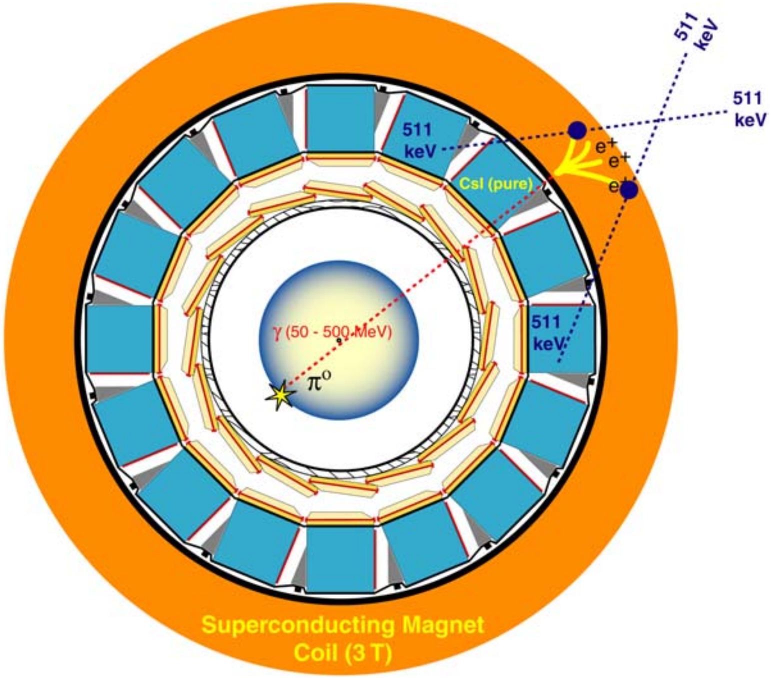
(golden event)





‘False’ Antihydrogen Events

Origin



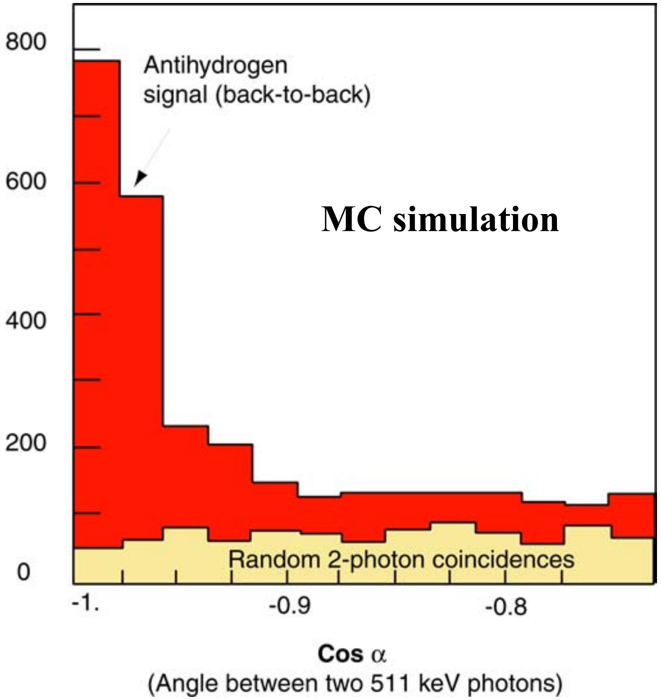
511 keV background from antiproton

- Antiproton annihilation produces neutral pions
- Decay γ’s (50-500 MeV) convert in magnet
- Secondary positrons in shower annihilate
- Homogeneous, coincident 511 keV background
- Fake ‘antihydrogen’ events (together with pion signal)

Prevention

True Antihydrogen Signal

- Measure charged vertex position
- Identify two converted 511 γ’s
- Plot angular correlation as seen from vertex
- Reject above certain threshold angle



Installation of Detector

Main Issues:

Extreme tight tolerances

Self heating from electronics

Thermal changes at cool down

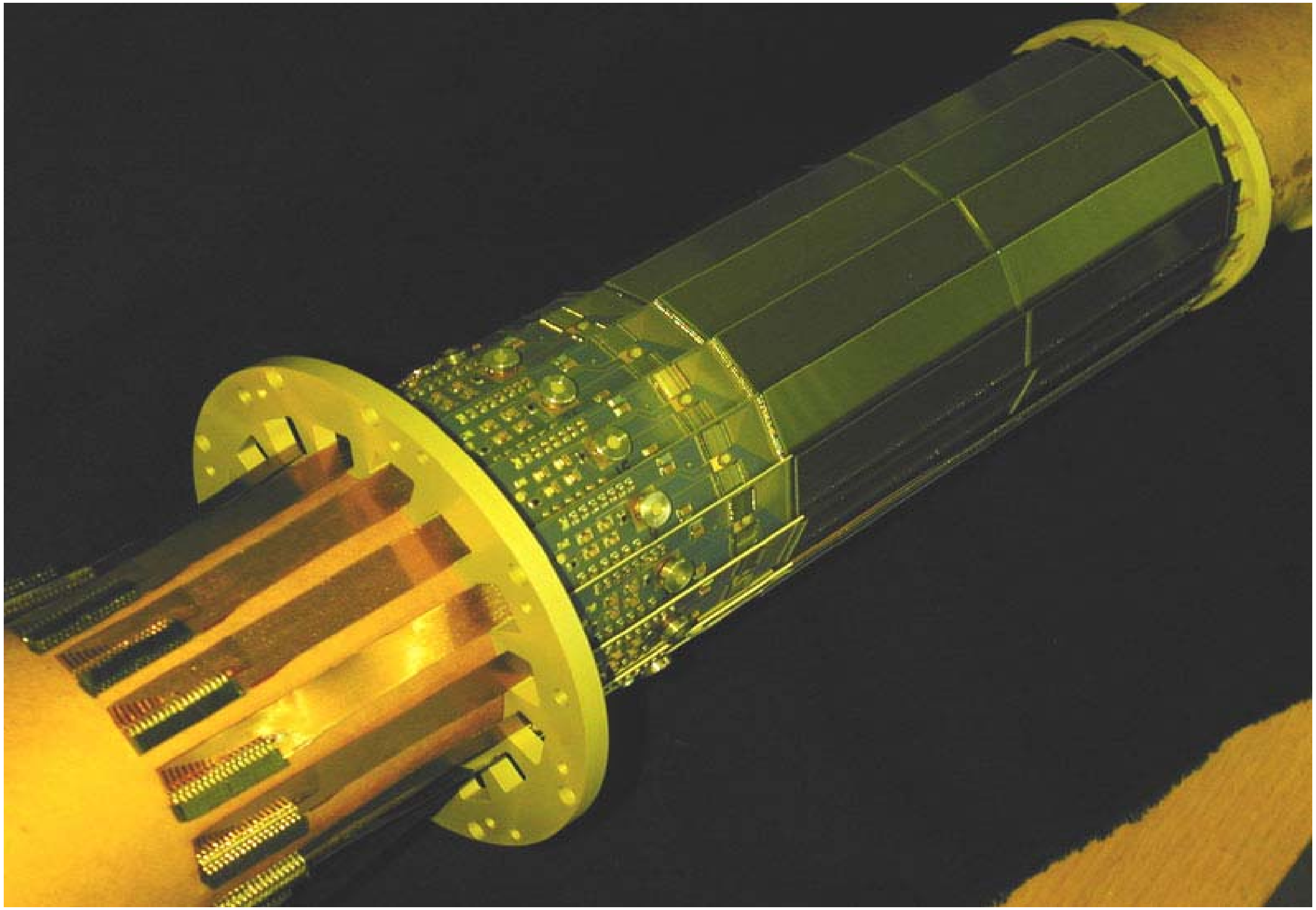
…..

….

…

..

Detector - Inner Layer Si strips



Double sided Si strips
(140 x 19.5 mm^2 x 500μm):

Front
128 strips with 50 μm pitch

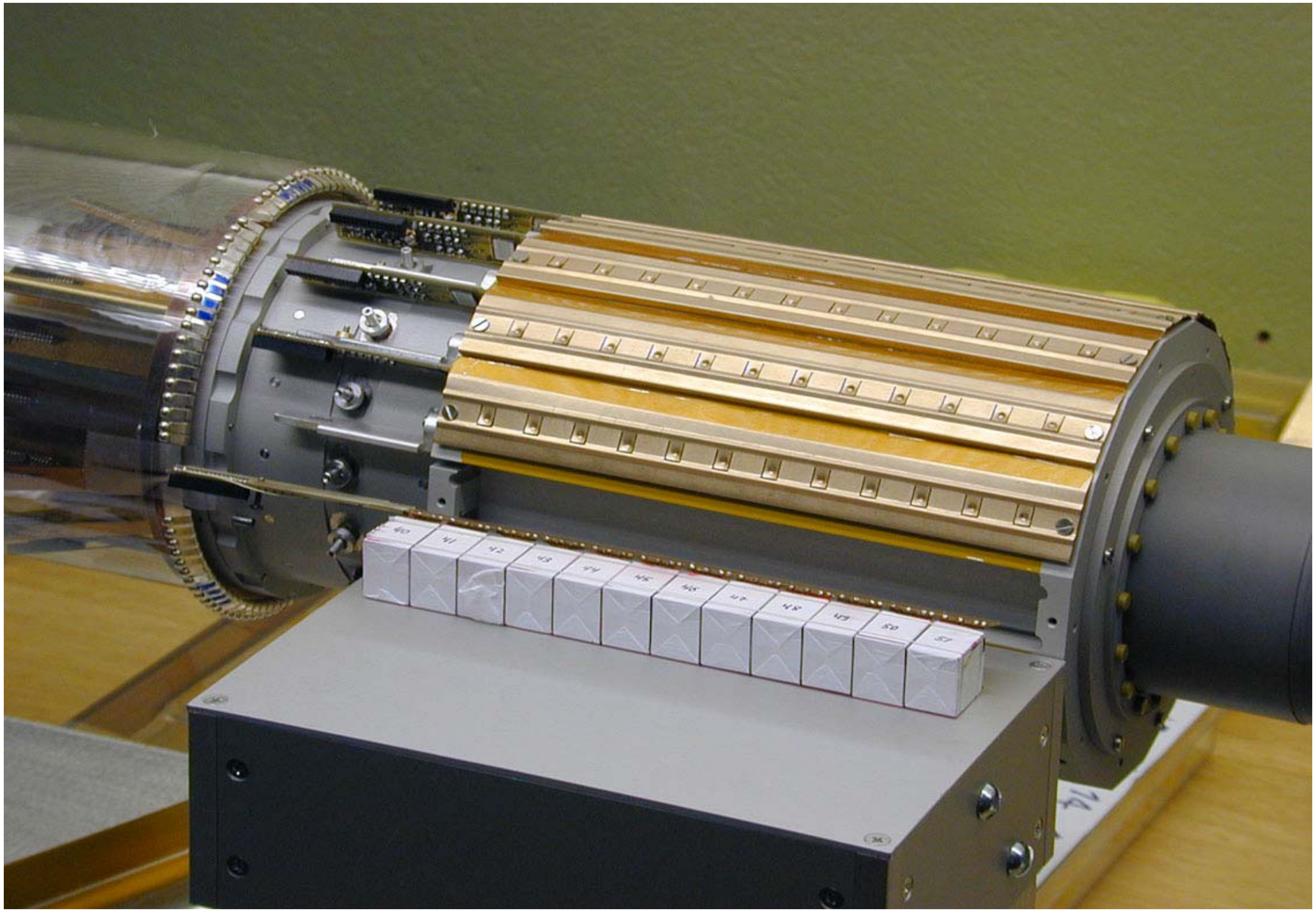
Back
128 pads with 1.1 mm pitch

two strips bonded together
for increased axial length

Significant R & D on

low temperature behavior
of kapton, silicon, ceramics.

Detector - Crystals



Studies done on:

- **light yield of pure CsI**

  (50,000 photons/MeV @ 80 K

  vs. 3,200/MeV @ 300 K)

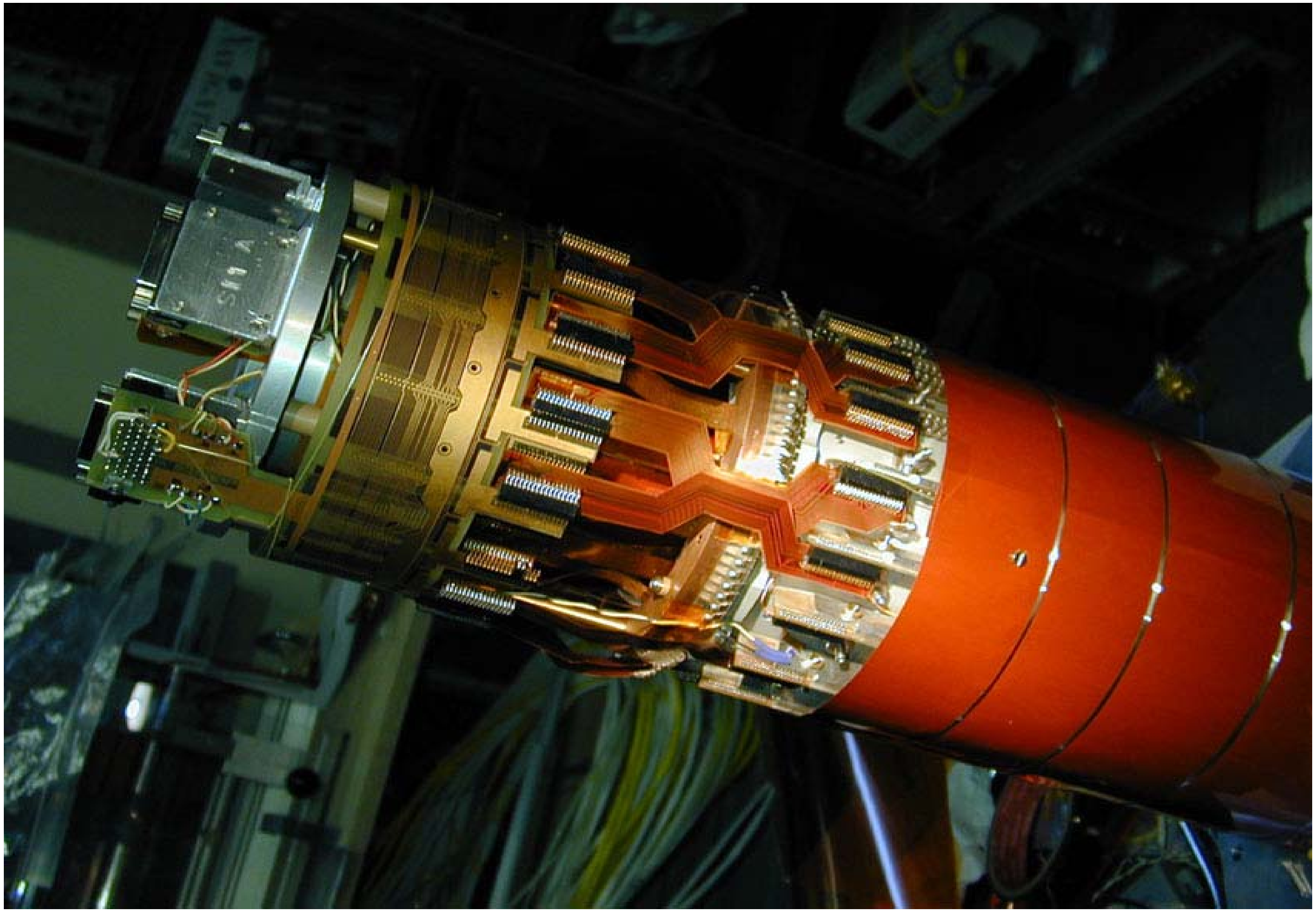
Coupling to read-out diodes

modularity, wrapping

- **Compromise radial dimension**

  Maximize light collection and meet space demands of other components

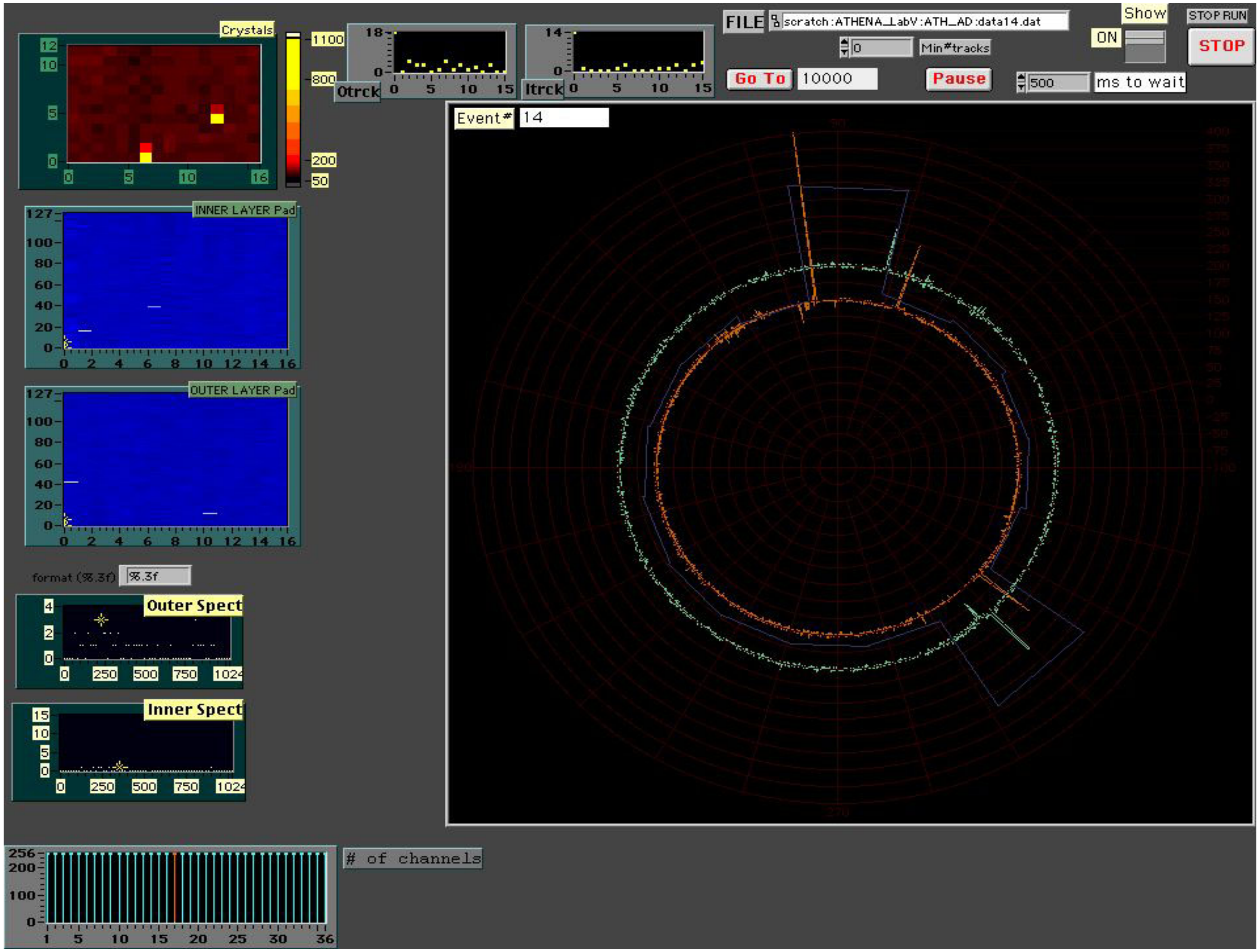
Detector - Readout electronics



- ‘On board’
  of read-out to minimize number of cables from room temperature to cryogenic environment.

- Heat load of electronics elevates detector temperature from 4.2 K to 100 K!

Detector - Cosmic event



FILE scratch:ATHENA_LabV:ATH_AD:data14.dat

Min#tracks 0

Go To 10000

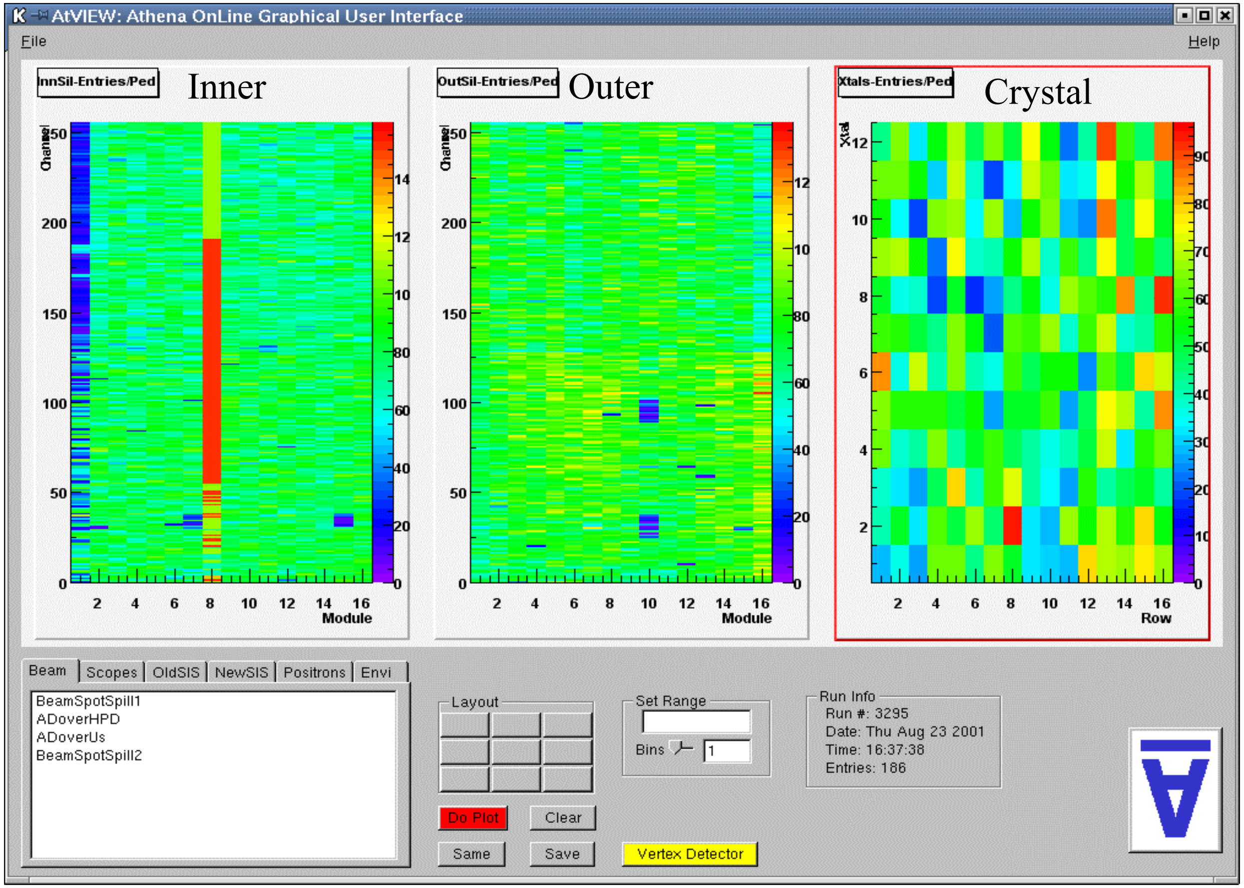
500 ms to wait

Event# 14

format (%.3f) %.3f

Show ON

Detector snapshot with cosmics



Run Info
Run #: 3295
Date: Thu Aug 23 2001
Time: 16:37:38
Entries: 186

Green - working

Red - noisy

Blue - no signal

Strips/Pads

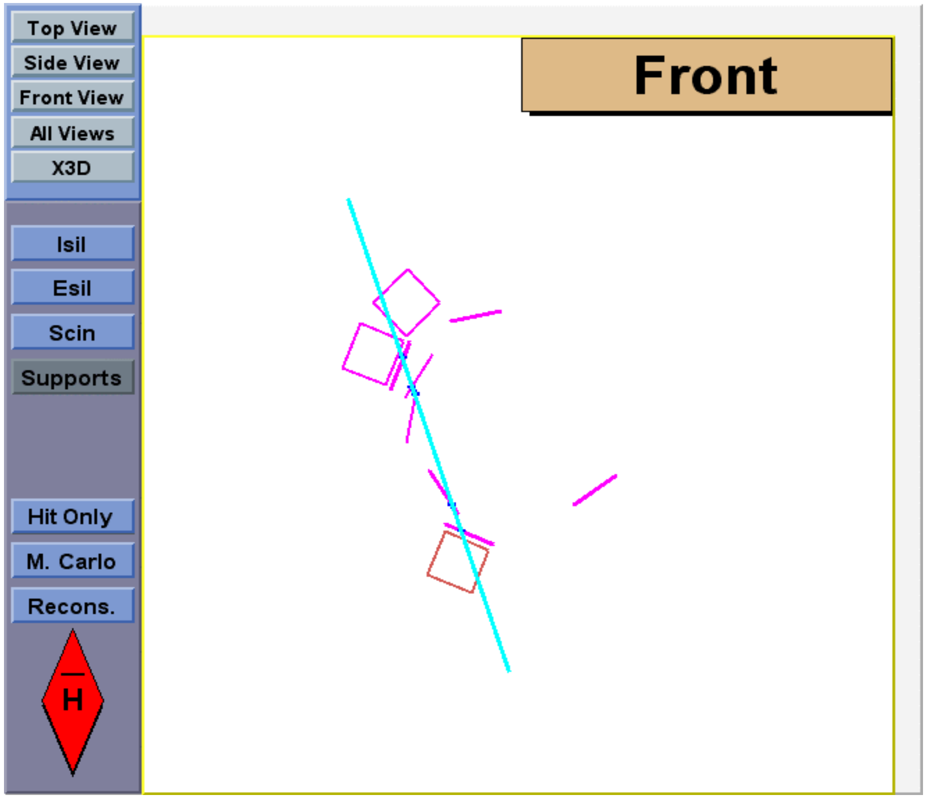
(8192)

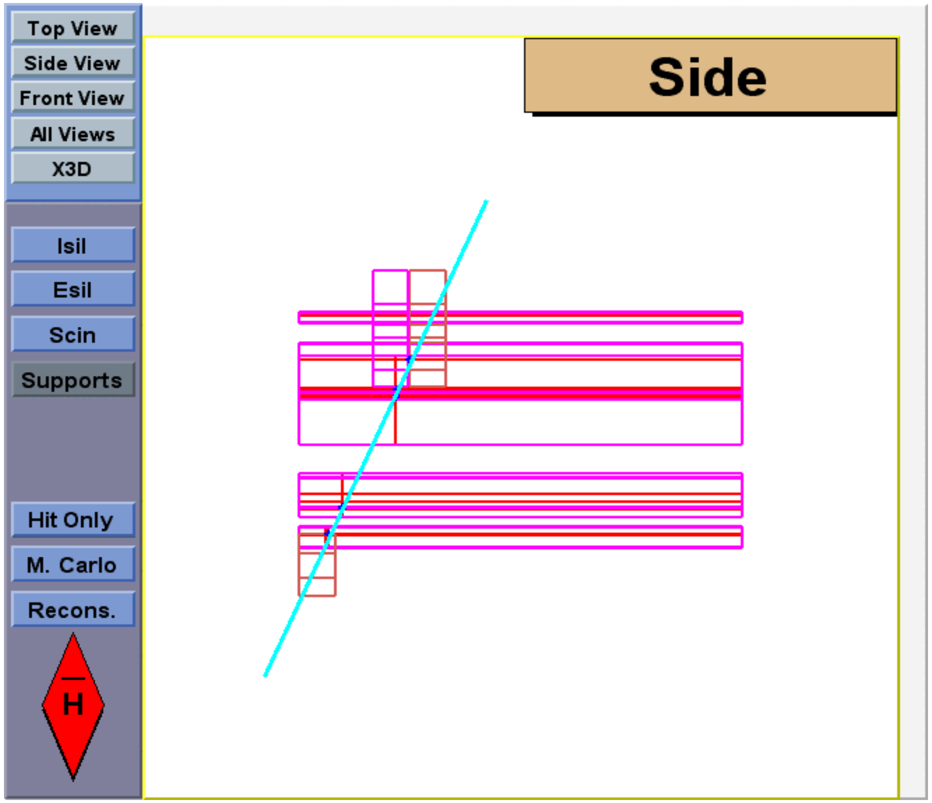
Crystals

(192)

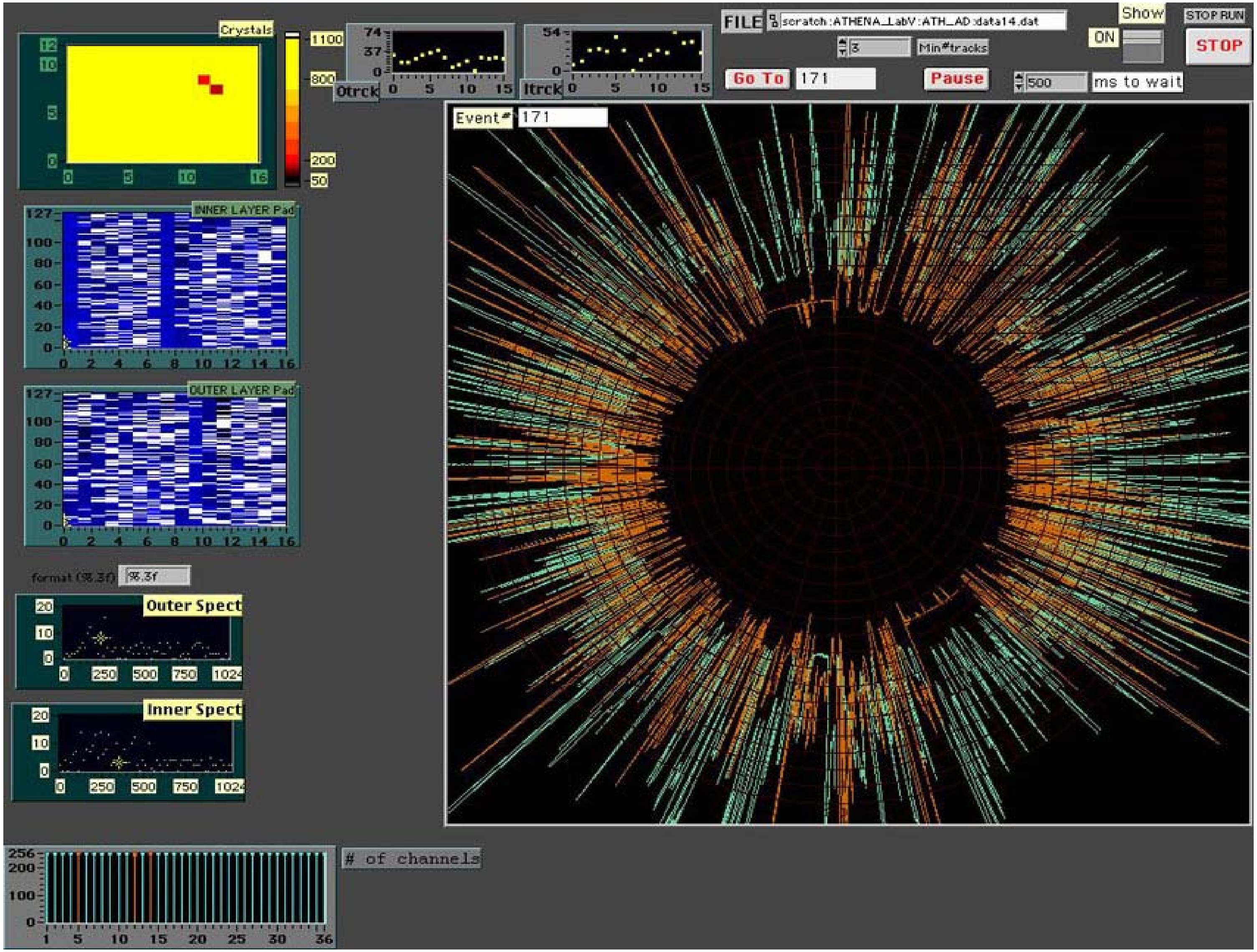
> 95 % of detector working fine !

Reconstruction of cosmic event





Detector - Antiproton injection from AD



FILE scratch:ATHENA_LabV:ATH_AD:data14.dat

3 Min#tracks

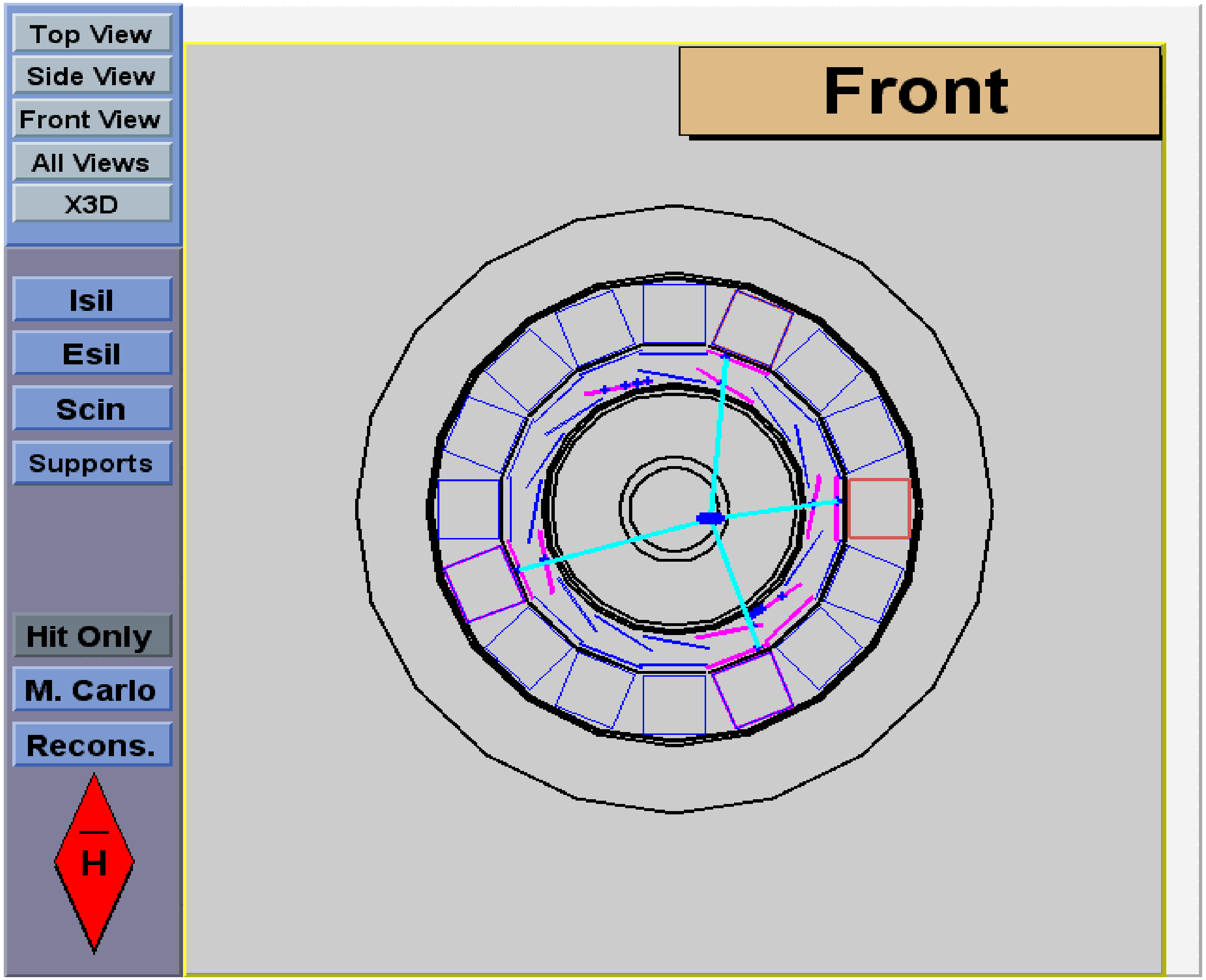
Go To 171

500 ms to wait

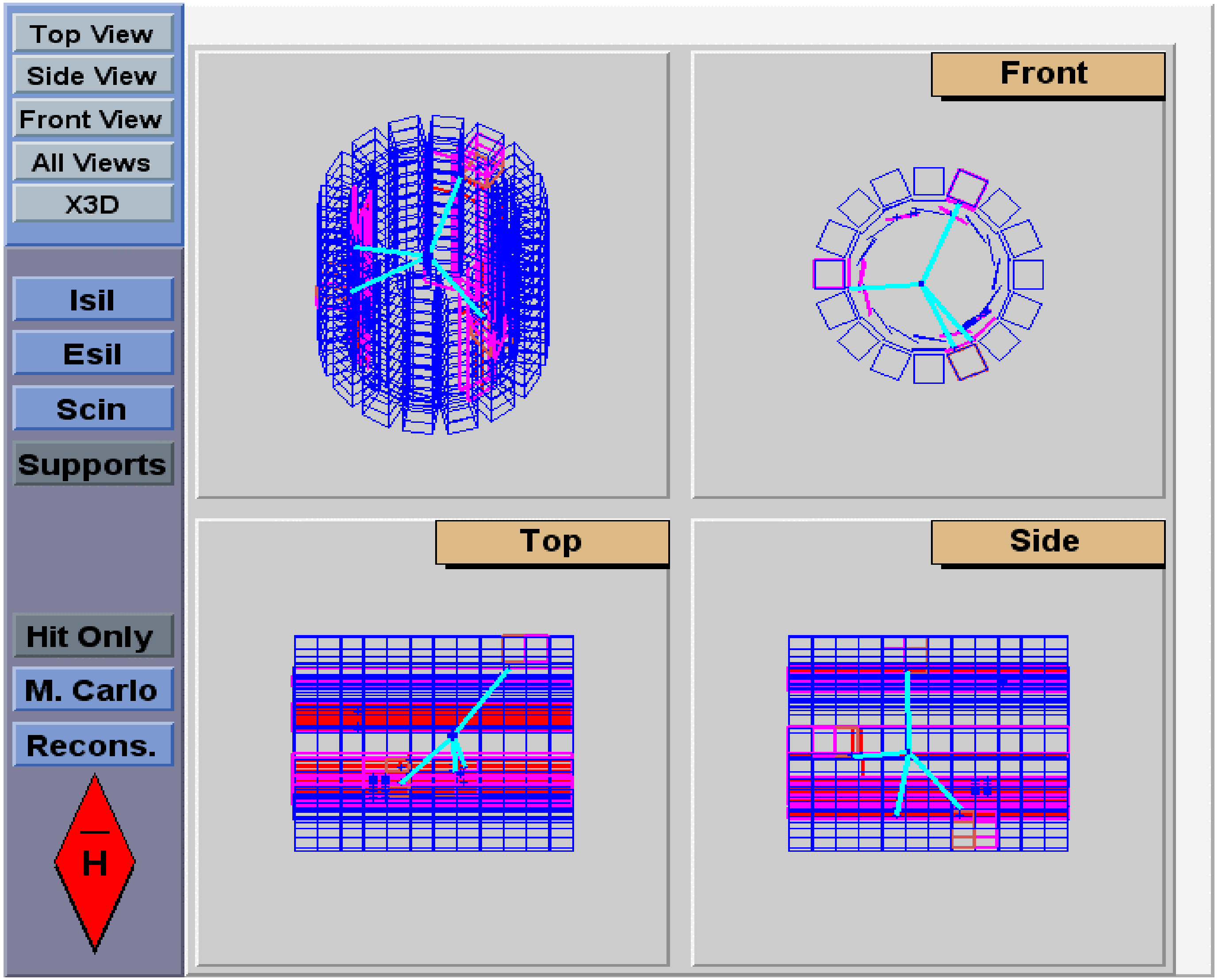
Event# 171

format (%.3f) %.3f

Detector - Single antiproton annihilation

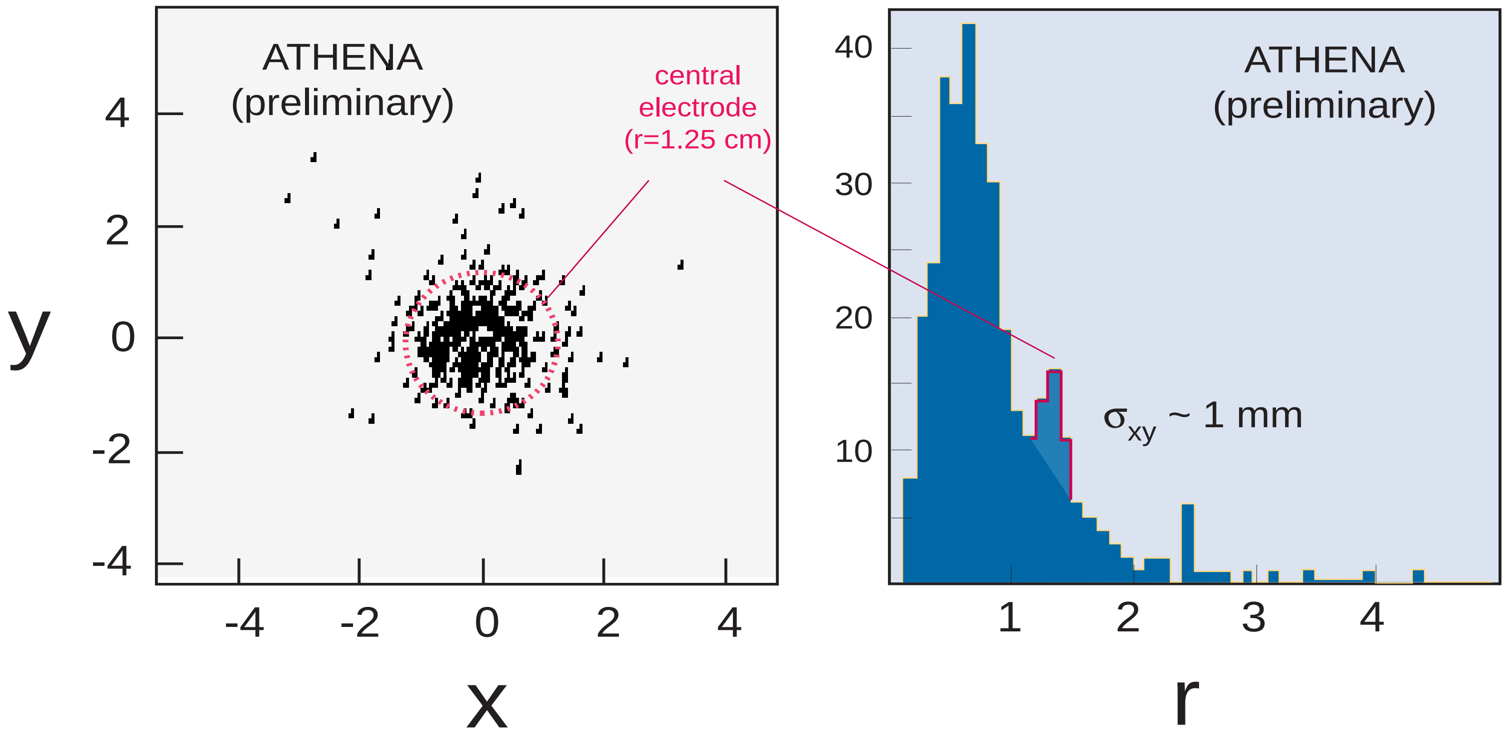


Detector - Full Reconstruction of Annihilation



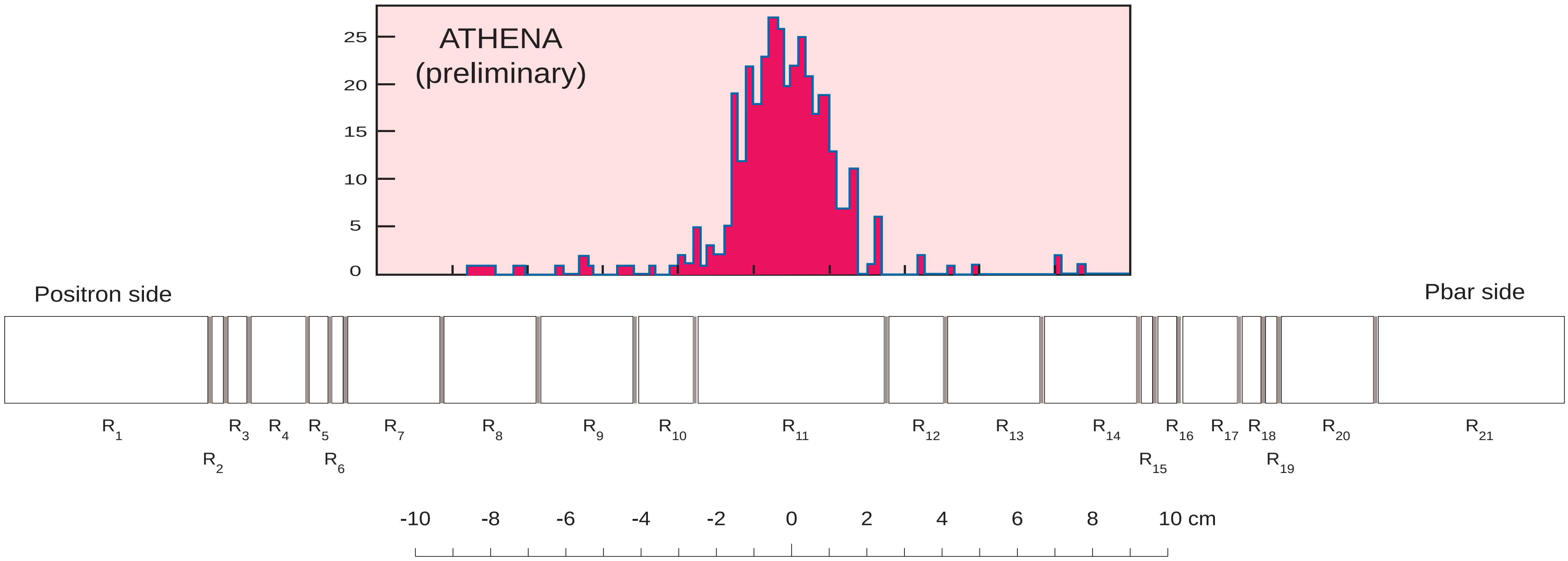
Radial Distribution of Annihilation Vertex

Annihilation vertex distribution in transverse plane
(antiprotons in central trap)



Z Distribution of Annihilation Vertex

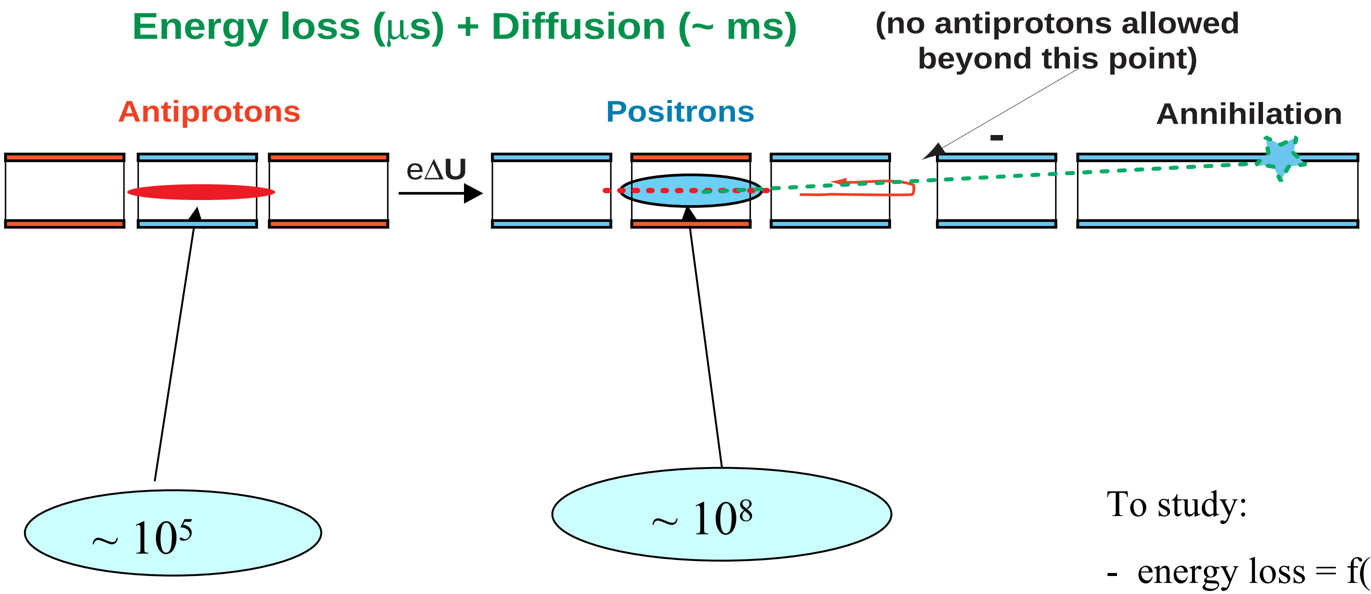
Annihilation vertex distribution along z axis
(antiprotons in central trap)



Next step: Slow Antihydrogen

Pulsed recombination with defined starting point

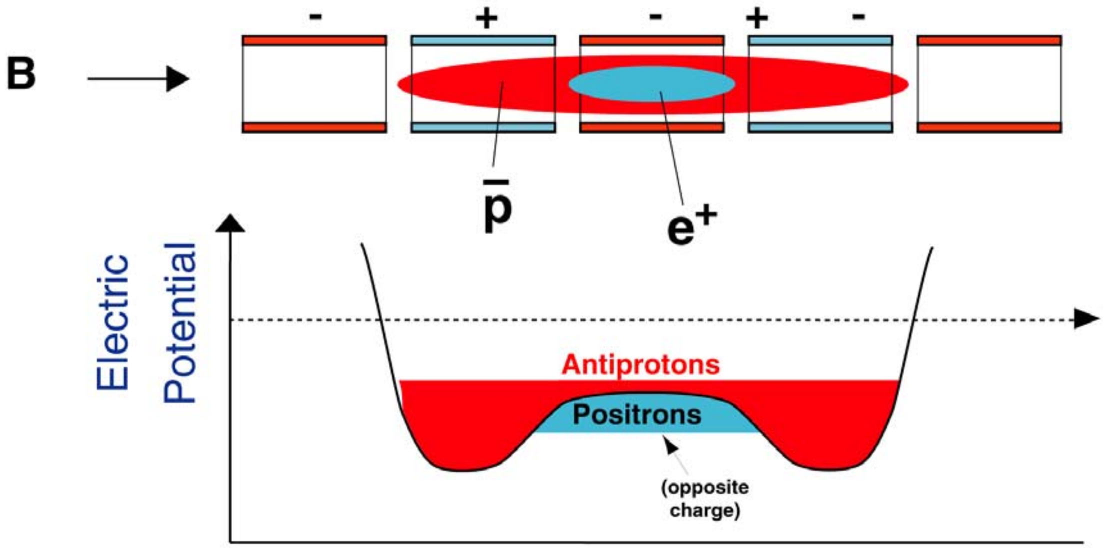
Repetition rate 1 -1000 Hz



To study:

- energy loss = f(n,T,N)
- positron heating by antiprotons
- optimal bounce frequency

Antihydrogen at Rest

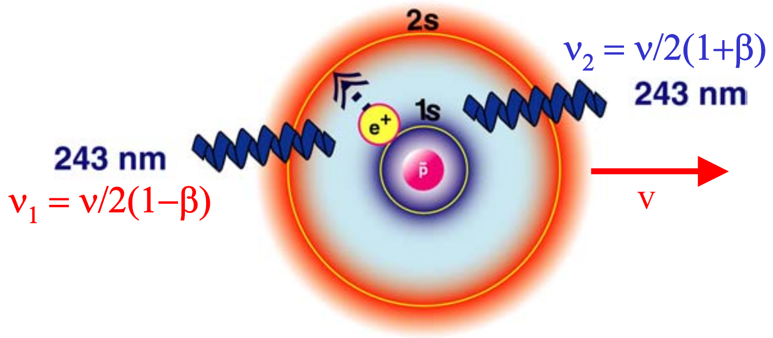


- Theoretical estimate for spontaneous radiative recombination (to low-n levels): 10^7 antiprotons, 10^8 positrons, 10 % overlap of plasma clouds, T = 1 K :

~ 9,000 antihydrogen atoms / second

Main Issue: Maintain overlap (antiprotons are cooled by

2 γ Antihydrogen Spectroscopy



$$\nu_1 + \nu_2 = \nu(1 + O(\beta^2))$$

Doppler free spectroscopy using the 2 photon transition from 1S to 2S in hydrogen has yielded the most amazing precision in atomic physics:

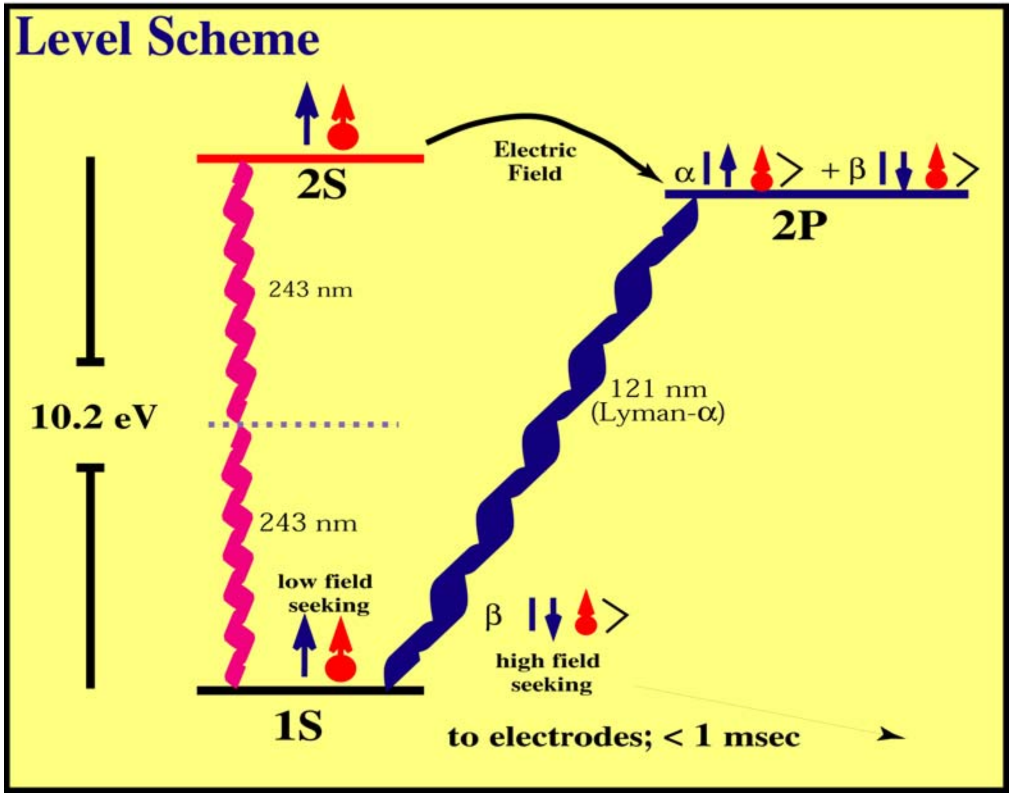
$$\nu_{1S\text{-}2S} = 2\,466\,061\,413\,187\,103(46)\ \mathrm{Hz}$$

$\Delta\nu/\nu$ ª $2 \cdot 10^{-14}$

(note: $\Delta\nu_{nat} = 1.3$ Hz ï $\Delta\nu/\nu$ ª $5 \cdot 10^{-16}$)

Can we do this with Antihydrogen?

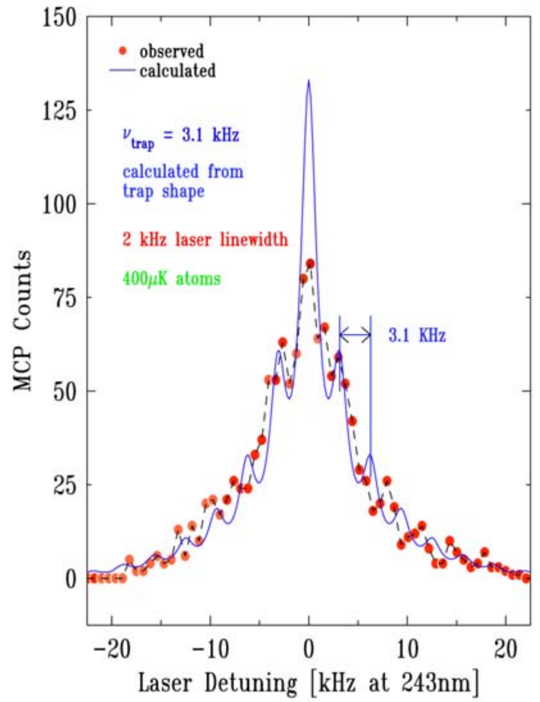
One possibility for a first measurement of 1S-2S in Antihydrogen?



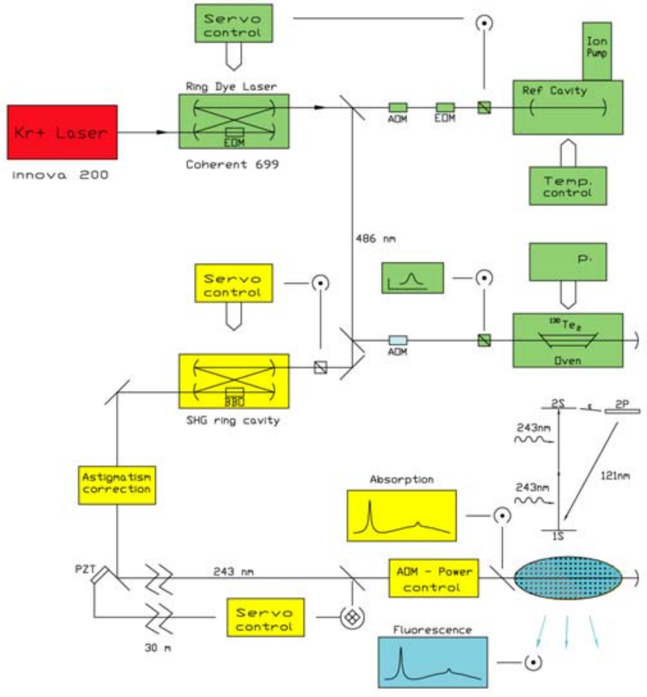
Trapped Hydrogen Spectroscopy

Spectroscopy of Trapped Hydrogen Atoms

C. L. Cesar, et al.; Physical Review Letters 77 (1996) 255



The Hydrogen Spectroscopy Laser System at MIT



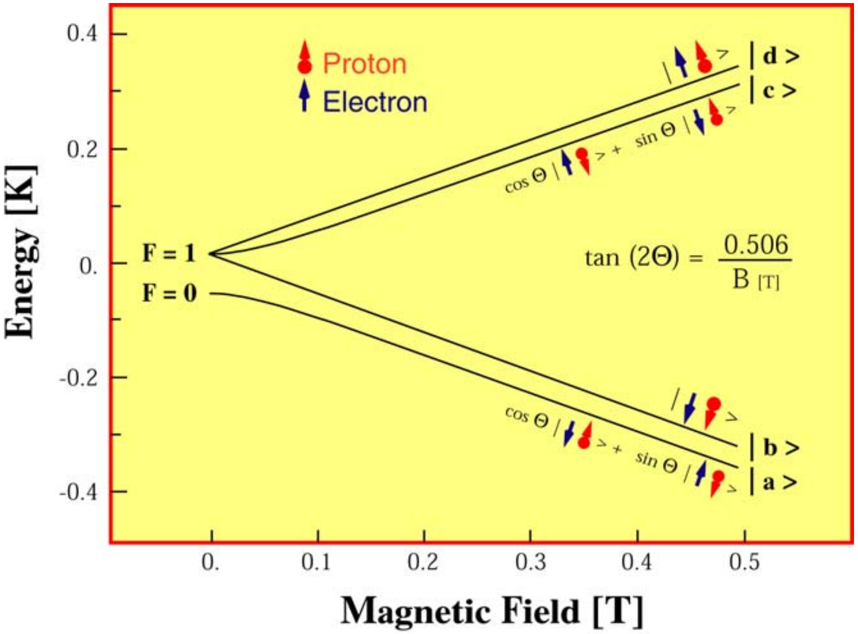
- ➢ **Low number of antihydrogen atoms requires efficient usage î atoms need to be trapped**

Magnetic Trapping of (Anti)Hydrogen

Use force on magnetic moment:

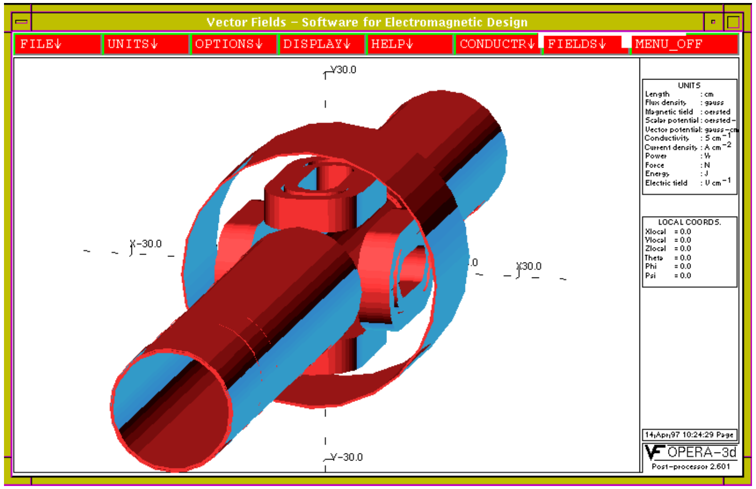
$$F_{mag} = \mu\Sigma\text{—}B$$

to trap 'low field seekers' |d> and



$$\Delta E = \mu_B \Delta B = 0.67\ \Delta B\ [T]\ \text{Kelvin}$$

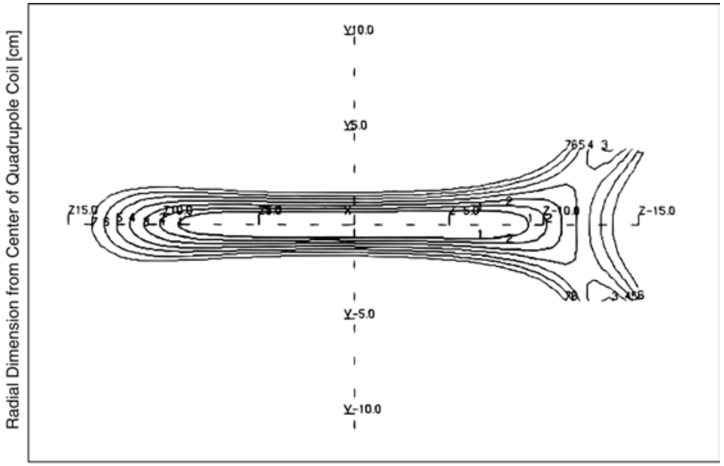
Coil Layout for short quadrupole version



UNITS
Length : cm
Flux density : gauss
Magnetic field : oersted
Scalar potential : oersted–
Vector potential: gauss–cm
Conductivity : S cm^{-1}
Current density : A cm^{-2}
Power : W
Force : N
Energy : J
Electric field : V cm^{-1}

LOCAL COORDS.
Xlocal = 0.0
Ylocal = 0.0
Zlocal = 0.0
Theta = 0.0
Phi = 0.0
Psi = 0.0

14/Apr/97 10:24:29 Page



Axial Dimension from Center of Quadrupole Coil [cm]

CPT Violation beyond Phenomenology?

Simplest Approach: Pure Phenomenology (no microscopic theory)

Example: $|K^0\rangle, |\overline{K^0}\rangle$ oscillations (Lee, Wu 1966)

$$|K_S\rangle \sim (1 + \varepsilon_K + \delta_K)\,|K^0\rangle + (1 - \varepsilon_K - \delta_K)\,|\overline{K^0}\rangle$$

$$|K_L\rangle \sim (1 + \varepsilon_K - \delta_K)\,|K^0\rangle + (1 - \varepsilon_K + \delta_K)\,|\overline{K^0}\rangle$$

ε_K and δ_K parameterize CP violation, with

- **T** violation governed by ε_K
- **CPT** violation governed by δ_K

Note: δ_K is purely phenomenological and can NOT be CALCULATED

To make best progress, we want:

- microscopic theory at the fundamental level
- connection to experiment
  - - quantitative predictions
  - - in framework of standard model

This would allow:

calculation of phenomenological parameters
comparison between different experimental tests
prediction of signals

Example: Spontaneous violation of CPT and Lorentz invariance in Lorenz/CPT covariant fundamental theory
(D. Colladay, V. A. Kostelecky; PRD 55 (1997) 6760 et al.)

Specifically Antihydrogen (QED extension of Theory)
R. Bluhm, V. A. Kostelecky, N. Russell; PRL 82 (1999) 2254

Modified Dirac Equation for a four component electron field Ψ of mass m_e and charge $q = -|e|$ in the proton Coulombfield $A\mu = (|e|/4\pi\mathbf{r},0)$:

$$iD_\mu = i\delta_\mu - qA_\mu \quad \Longrightarrow$$

$$(i\gamma^\mu D_\mu - m_e - \underbrace{a^e_\mu\gamma^\mu - b^e_\mu\gamma_5\gamma^\mu}_{\text{CPT violating}} - \tfrac{1}{2}H^e_{\mu\nu}\sigma^{\mu\nu} + ic^e_{\mu\nu}\gamma^\mu D^\nu + id^e_{\mu\nu}\gamma_5\gamma^\mu D^\nu)\Psi = 0$$

First Observation:

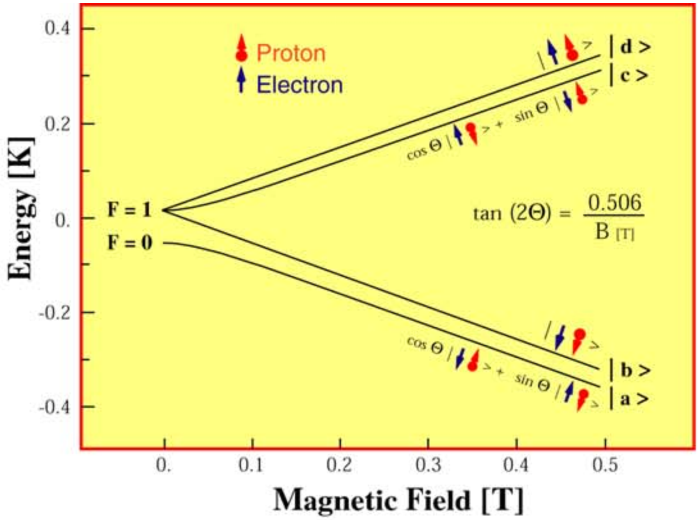
Both 1S and 2S levels in Hydrogen (and Antihydrogen) experience an identical energy shift

⟹ There are no leading order effects in the 1S-2S spectroscopy

This is due to both excited and ground state having the same spin configuration ⟹ Use external field to lift degeneracy (trapped H)

Are there better choices of

Antihydrogen Spectroscopy on HFS



$$\Delta E_a^H \cong \kappa(b_3^e - b_3^p - d_{30}^e m_e + d_{30}^p m_p - H_{12}^e + H_{12}^p)$$

$$\Delta E_b^H \cong b_3^e + b_3^p - d_{30}^e m_e - d_{30}^p m_p - H_{12}^e + H_{12}^p$$

$$\Delta E_c^H = -\Delta E_a^H \qquad \Delta E_d^H = -\Delta E_b^H$$

2. |d> --> |c> at B = 0.65 T (field independent point)

c: $m_J = 1/2$, $m_I = -1/2$; d: $m_J = 1/2$, $m_I = +1/2$

Transition is essentially a proton spin flip:

$$\Delta\nu_{c\text{->}d} = \nu^{H}_{c\text{->}d} - \nu^{\bar{H}}_{c\text{->}d} \sim -2b_3/\pi$$

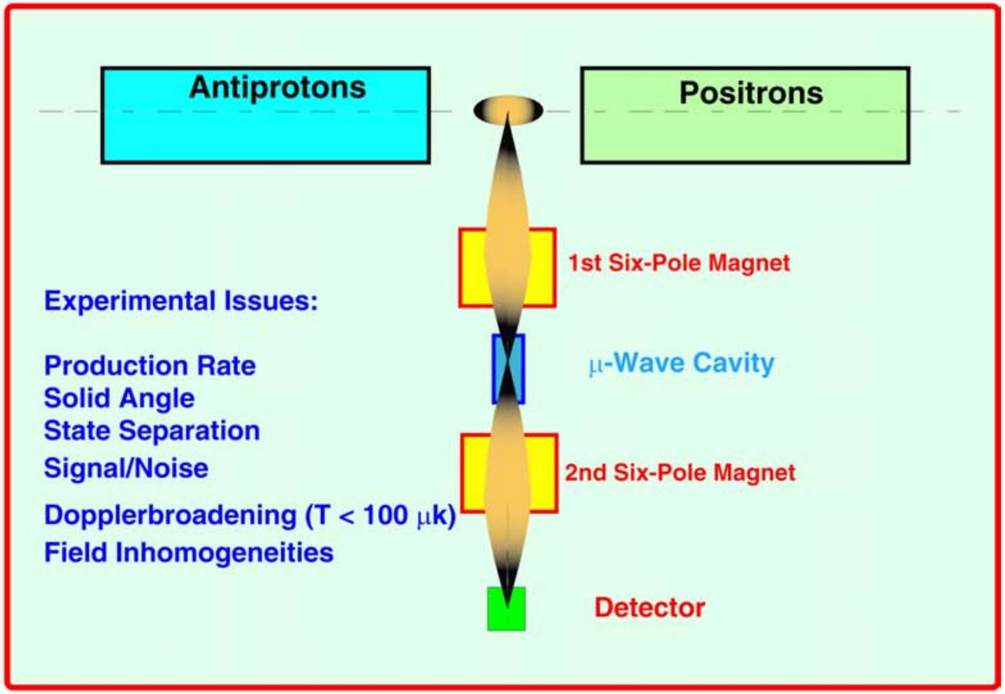
Direct, **clean**, and **accurate** test of CPT violating coupling b_3 for the proton

V. A. Kostelecky, et al.: Minimal extension of standard model

Spontaneous violation of CPT and Lorentz invariance in Lorentz/CPT covariant fundamental theory

- **Allows parametrization of possible violations of CPT/Lorentz invariance**
- **Places different tests on equal footings (figure of merit)**
- **Highlights best tests in given system**
- **1S and 2S in hydrogen (and antihydrogen) experience identical shift**
  - **better to test HFS transition!**

ref.: D. Colladay, V. A. Kostelecky; PRD 55 (1997) 6760;
R. Bluhm, V. A. Kostelecky, N. Russell; PRL 82 (1999) 2254



Experimental Issues:

Production Rate
Solid Angle
State Separation
Signal/Noise
Dopplerbroadening (T < 100 μk)
Field Inhomogeneities

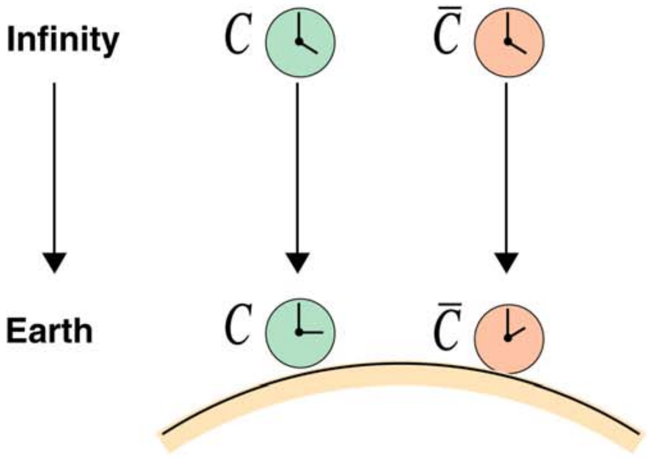
Gravity?

Indirect observation through precision frequency measurements:

Clocks slow down in earth gravitational field

(photon frequency redshift, Pound & Rebka 1962):

$$\Delta\nu/\nu \;=\; \frac{M_{earth} \cdot G}{R \cdot c^{2}} \qquad \sim O\,(10^{-9})$$



Matter (H) and Antimatter ($\bar{H}$) clocks from infinity to the solar system (earth surface) ...

☛ ***ANTIMATTER CLOCK MAY SLOW DOWN DIFFERENTLY FROM MATTER CLOCK***

☛ **Check synchronicity of H - $\bar{H}$ clocks with $\Delta\nu/\nu \sim 10^{-15}$ →**
as earth moves along its eccentric path around the sun ($\Delta U/U \sim 10^{-9}$) →
test equality of gravitational masses to 10^{-6}

References: R. J. Hughes, M. H. Holzscheiter; Phys. Rev. Lett. 66, p. 854 (1991; J. of Modern Optics, 39, 263-278 (1992)

Gravity - Direct Observation

To say the least – this will be VERY difficult!

1. **GRAVITATIONAL SAG IN MAGNETIC BOTTLE?**

   $m \bullet g \bullet h = 1 \bullet 10^{-7}$ eV (for $h = 1$ m) ï

   3 mK Antihydrogen @ 2.6 • 10^{-7} eV @ $\Delta z = 2.6$ m

2. **FREE FALL OF COLD ANTIHYDROGEN ATOMS?**

   $\Delta E = 3$ mK ï Δv ª 7 m/sec

3. **ATOM INTERFEROMETER?**

   $v = 10^4$ m/sec, 4000 atoms, measure phase shift to 0.1 radian

   ï $\Delta g/g$ ª 1 %

   T.J. Phillips, LEAP94; eds. G. Kernel et al.; World Scientific (1995) 589

   D. W. Keith, C. R. Ekstrom, Q. A. Turchette, D. Pritchard; Phys. Rev. Lett. 66 (1991) 2693

4. **ATOMIC FOUNTAIN RAMAN SPECTROSCOPY?**

   Use atomic fountain – split and recombine beam by Raman transitions –
   - final state depends on phase difference between the two paths:

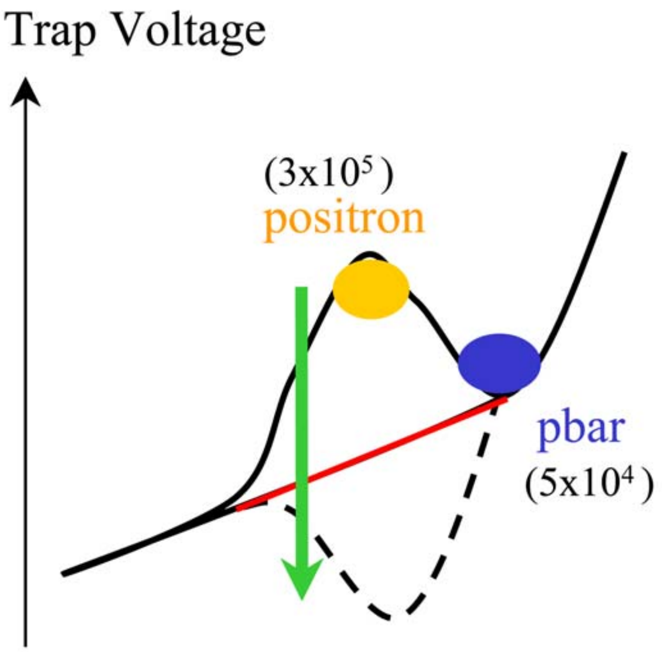
   $\Delta\Phi = k \bullet g \bullet (\Delta t^2)$ ï Measurement on ^{22}Na yields $\Delta g/g$ ª 10^{-9}

   BUT WHAT ABOUT Hydrogen/Antihydrogen?

   hotter (Doppler limit 3 mK) lighter (more recoil, faster atoms, less precision on phase shift)

   M. Kasevich, S. Chu; Appl. Phys. Rev. B54 (1992) 321

ATRAP Results



1. Start from nested trap
2. Ramp potential in 10 ms
3. All free charged particles are swept away by E field
4. Antihydrogen might form in high n states
5. E field ionizes the formed antihydrogen atoms
6. Pbars from ionized antihydrogen are captured in (new) trap

Possible problems:

- Rate too high?
- Patch effects, micro traps not
- N distribution not reproduced ($N(n) \sim n^6$)

Summary and Outlook

:-)) AD performance now better than design values

:-)) **ATHENA construction completed!**

Antiprotons

$2 \cdot 10^4$ captured / AD shot

Stacking: multiple shots, no losses

Cooling below 1 eV

Storage time >> 1 h

Positrons

$2.0 \cdot 10^8$ positrons accumulated in 5 minutes

~ 15 % transferred to recombination trap

Hbar detector

installed + working fine at T ~ 110 K, B = 3 T

tracking: excellent performance in (r-ϕ) and z

511 keV: clear separation from Compton edge

SHORT-TERM GOAL:

- observe + optimize antihydrogen production

MEDIUM-TERM GOALS:

- modify apparatus for laser spectroscopy

- 1S-2S measurement

- further studies of antihydrogen atom

LONG-TERM GOALS:

- add magnetic trap to apparatus to confine antihydrogen atoms

- ultra-precise spectroscopy on 1S-2S or HFS

- study of gravitational interaction of in Earth's gravitational field

Hbar Detector - 511 keV line (source test)

Energy resolution of
assembled CsI crystals
(T = 77 K)