# Physics with ultra-low Energy (trapped) Antiprotons

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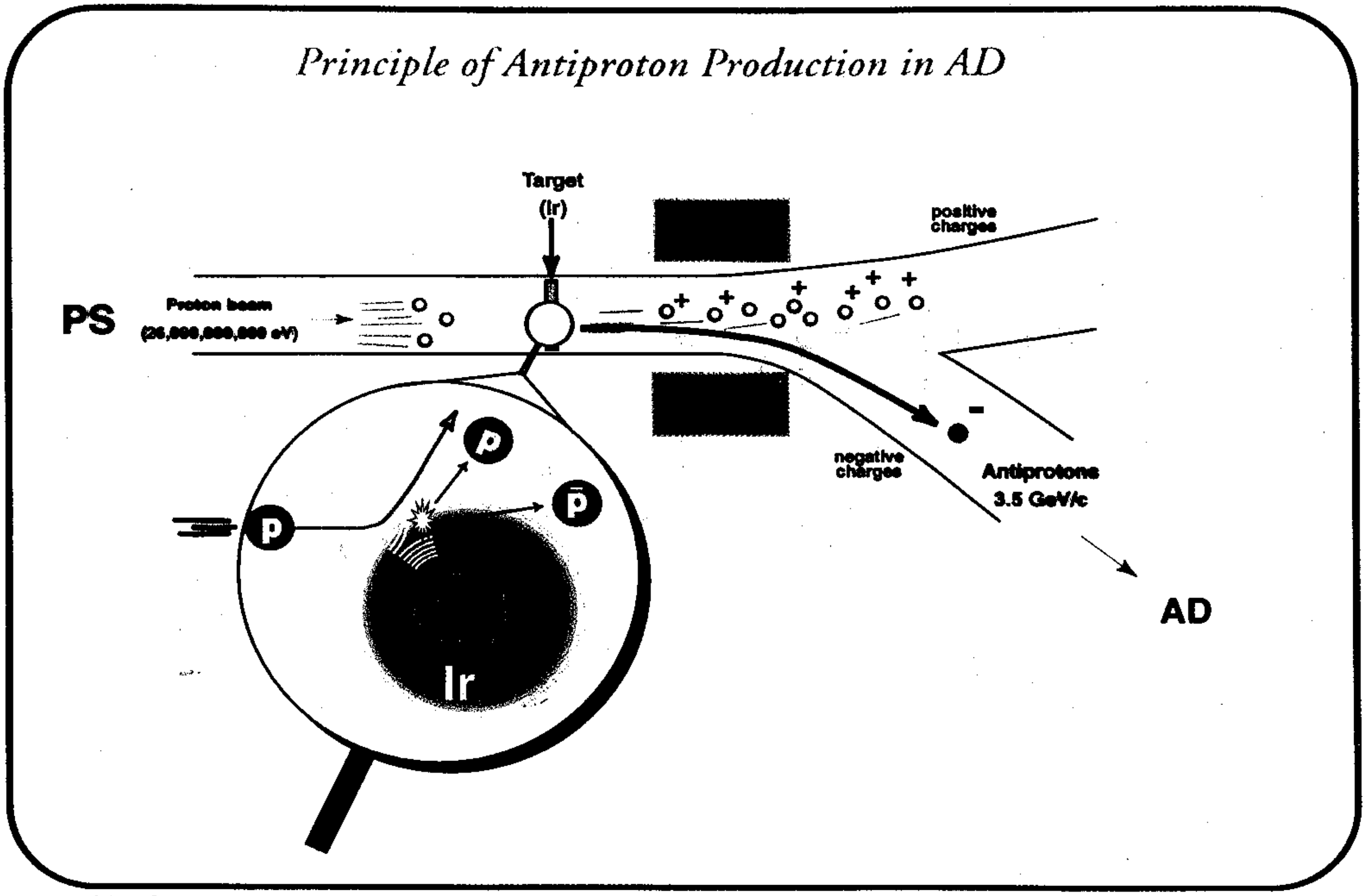
I. **Why Am I Here? - Antiproton Options / Yesterday/Today/Tomorrow**

II. **Antiproton Capture at CERN (LEAR and AD)**

III. **Physics Program**
  (a) **Antihydrogen (ATHENA/ATRAP)**
  (b) **Antiproton Magnetic Moment**
  (c) **Antiproton/Antihydrogen Gravity**
  (d) **Ultra-Low Energy Source of Antiprotons**

IV. **Trapping Possibilities at Fermilab**

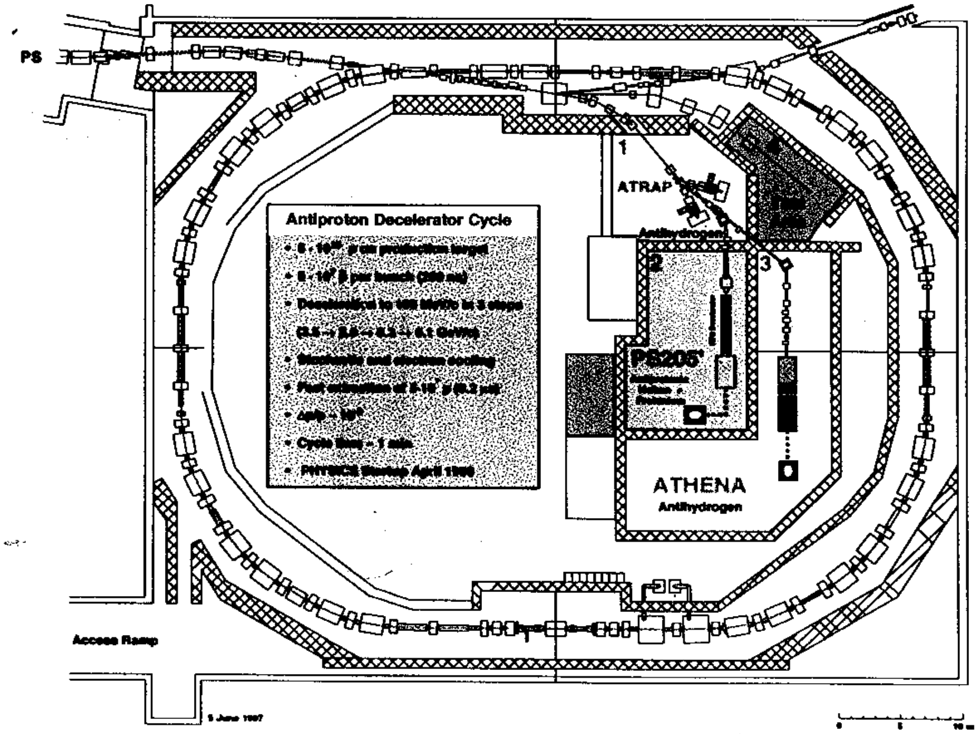
V. **Conclusions**




Antiproton_Production.ai

## *AD Project at CERN*

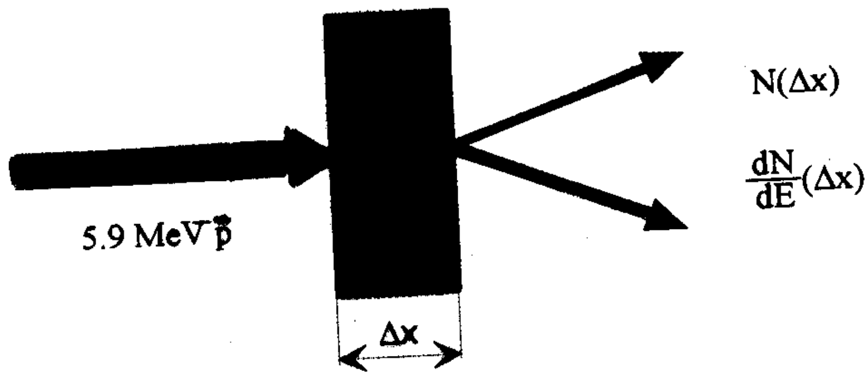
# Antiproton Decelerator (AD)

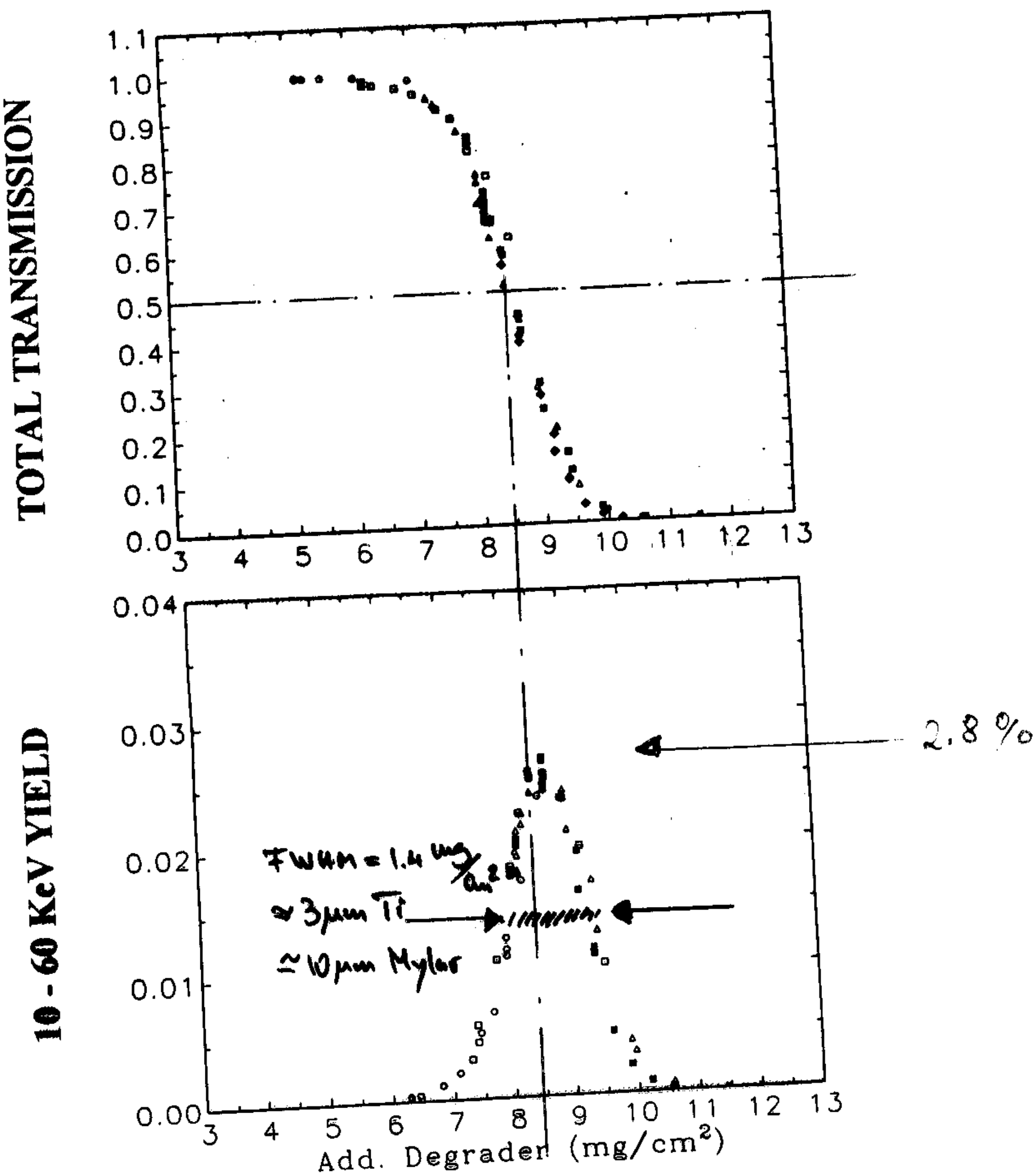


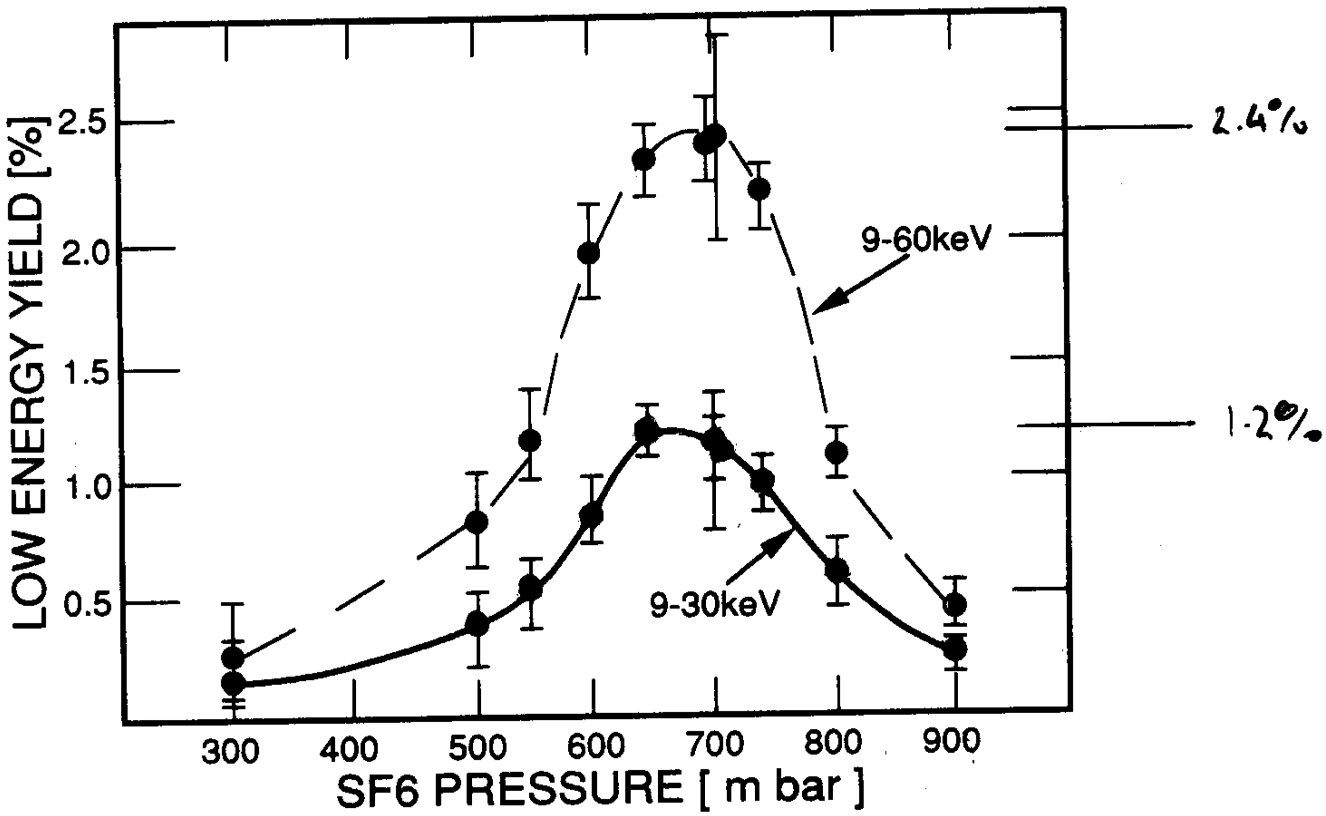

AD_Project.ai

| MACHINE | CERN AC/LEAR | | CERN AD |
|---|---|---|---|
| **Production Beam Momentum (GeV/c)** | **26** | 120 | **26** |
| **Collection Momentum (GeV/c)** | **3.5** | 9 | **3.5** |
| **Production Cross Section [(srxGeV/c)$^{-1}$]** | **0.013** | [illegible] | **0.013** |
| **Acceptance $(A_h x A_v)^{1/2}$ Δp/p (π mm mrad)** | **12 x $10^3$** | [illegible] x 10 | **12 x $10^3$** |
| **Yield (p̄/p)** | **3.5 x $10^{-6}$** | 1.4 x [illegible] | **3.5 x $10^{-6}$** |
| **Protons per pulse** | **1.5 x $10^{13}$** | 0.5 x [illegible] | **1.5 x $10^{13}$** |
| **Antiprotons per pulse** | **5 x $10^7$** | [illegible] x 10 | **1 x $10^7$** |
| Repetition Rate (pulses/minute) | 3.2 | 1 / 30 | 1 |
| <u>Antiprotons per hour</u> | 9 x $10^9$ | | 6 x $10^8$ |
| Output Momentum | 105 MeV/c | | 100 MeV/c |
| Output Energy (kinetic) | 5.9 MeV | | 5.3 MeV |
| Mode of usage | slow/fast extraction | | fast extraction |

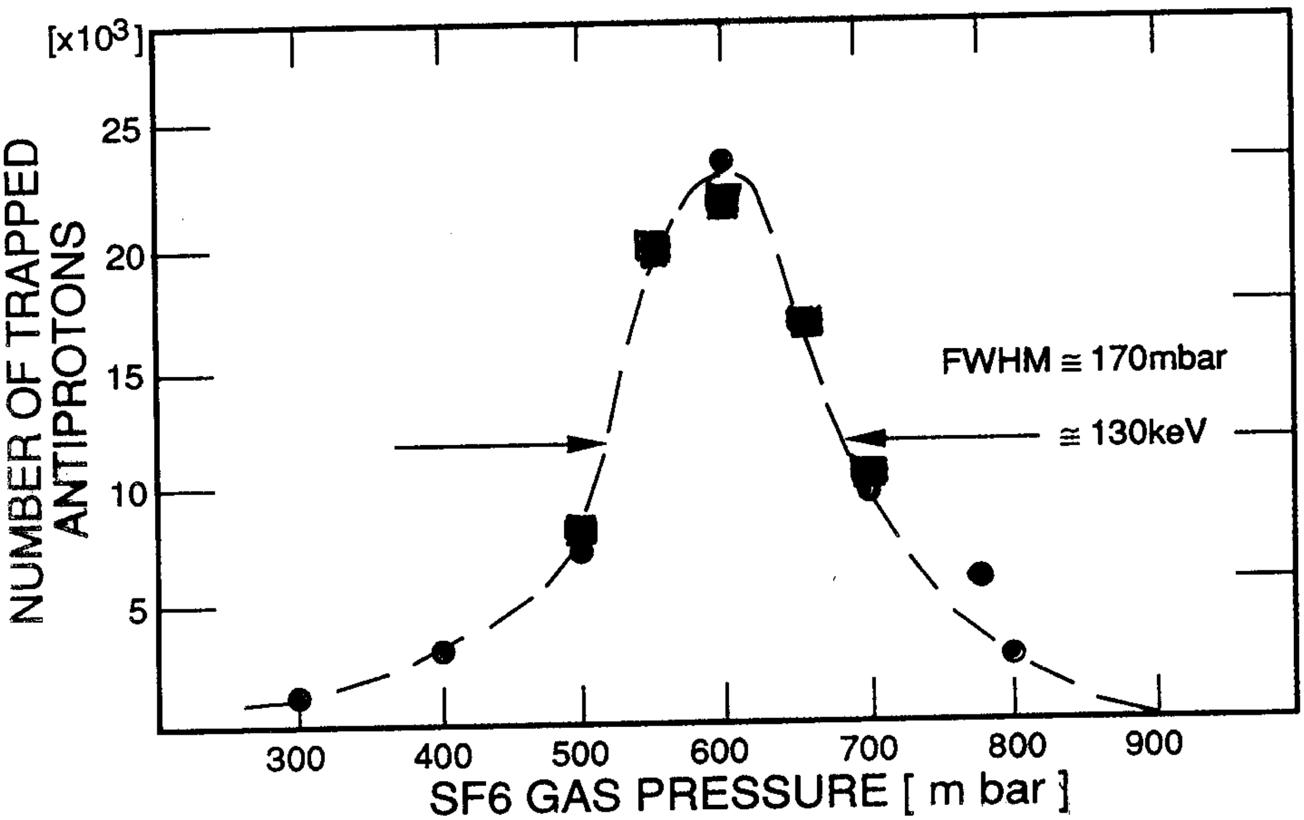
## THE FOIL DEGRADING TECHNIQUE

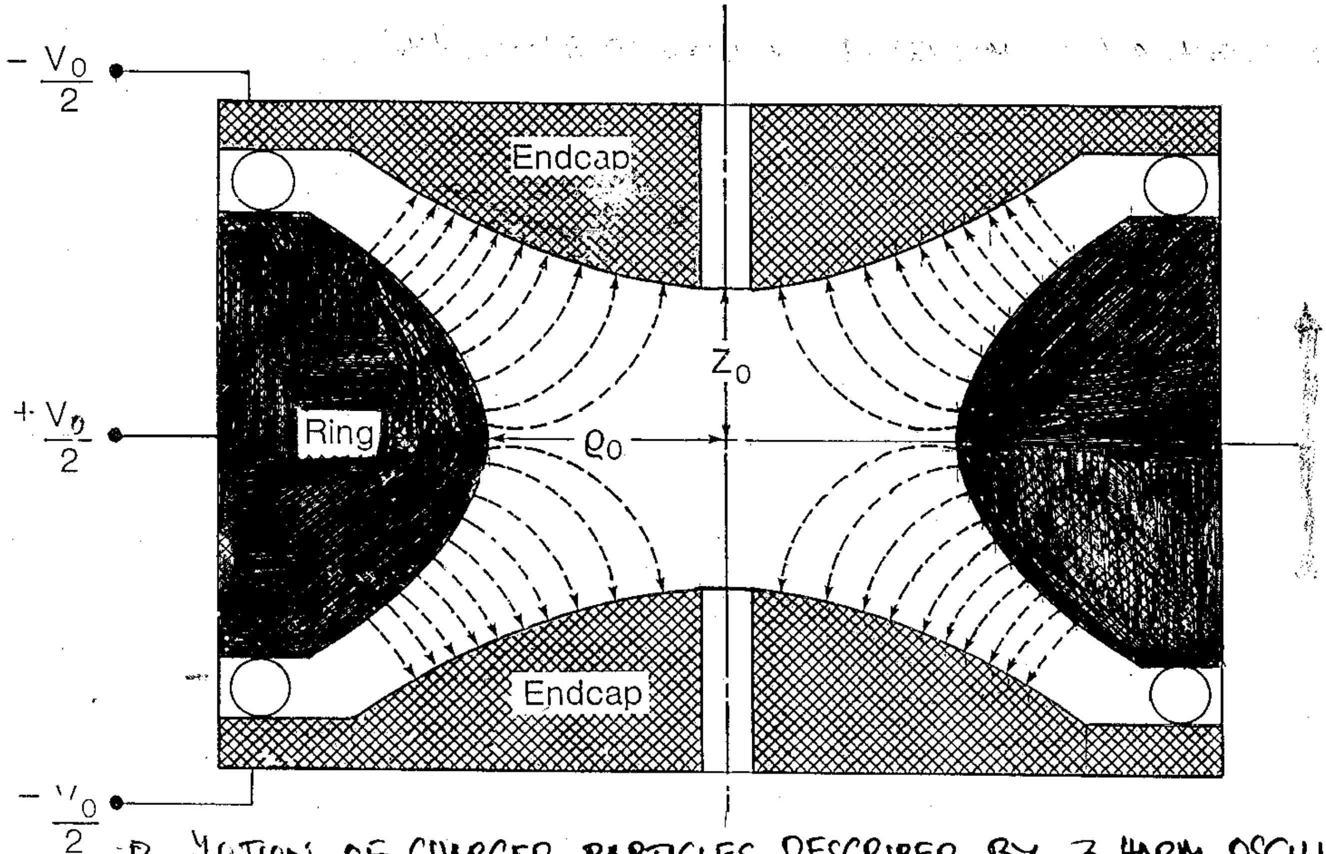




LOW ENERGY YIELD [%]
2.5
2.0
1.5
1.0
0.5
9-60keV
9-30keV
300
400
500
600
700
800
900
SF6 PRESSURE [ m bar ]
2.4%
1.2%


[x10³]
25
20
15
10
5
NUMBER OF TRAPPED ANTIPROTONS
FWHM ≅ 170mbar
≅ 130keV
300
400
500
600
700
800
900
SF6 GAS PRESSURE [ m bar ]



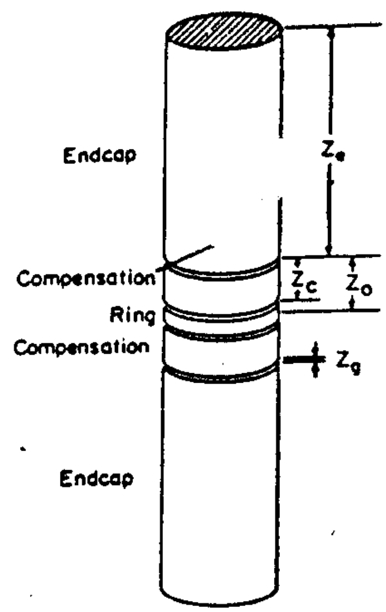

⇒ MOTION OF CHARGED PARTICLES DESCRIBED BY 3 HARM. OSCILLATORS

$\omega_z = \left(\frac{2eV}{m\rho_0^2}\right)^{1/2}$ ; $\omega_+ = \frac{\omega_c}{2} + \sqrt{\frac{\omega_c^2}{4} - \frac{\omega_z^2}{2}}$, $\omega_- = \frac{\omega_c}{2} - \sqrt{\cdots}$ ; $\omega_c = \frac{e}{m}B$

*"Everything's a trap if you're not careful."*

# OPEN END-CAP TRAPS

G. Gabrielse, L. Haarsma, S. L. Rolston
Int. Journal of Mass Spec. Ion Proc. **88**, 319 (1988)




· Fig. 2. Open-endcap Penning trap.

$$V = \tfrac{1}{2} V_0 \sum_{\substack{k=0 \\ \text{even}}}^{\infty} C_k \left(\frac{r}{d}\right)^k P_k(\cos\theta)$$

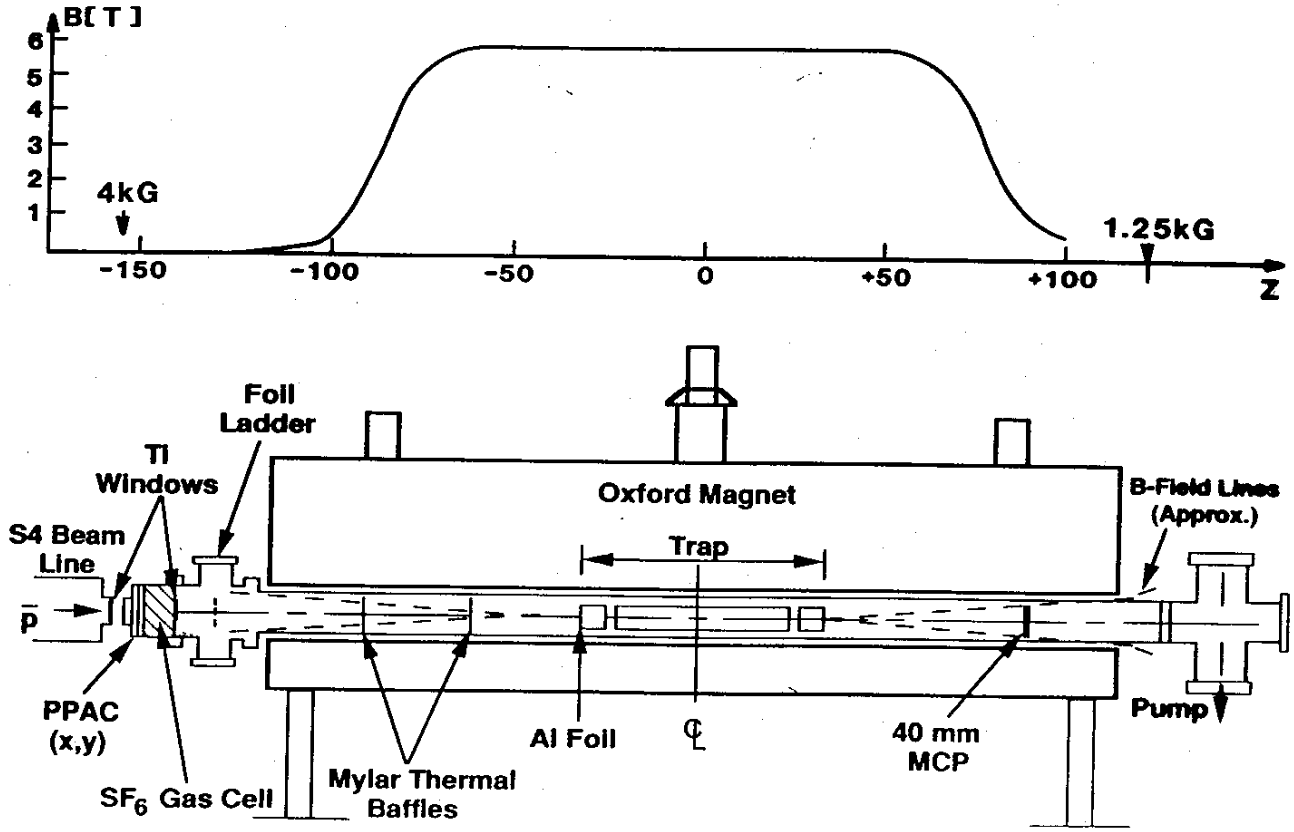
## KEY ISSUES:

**TRAP CAN BE MEADE HIGHLY HARMONIC AT CENTER**
**<u>AND</u> RATHER LONG OVERALL**

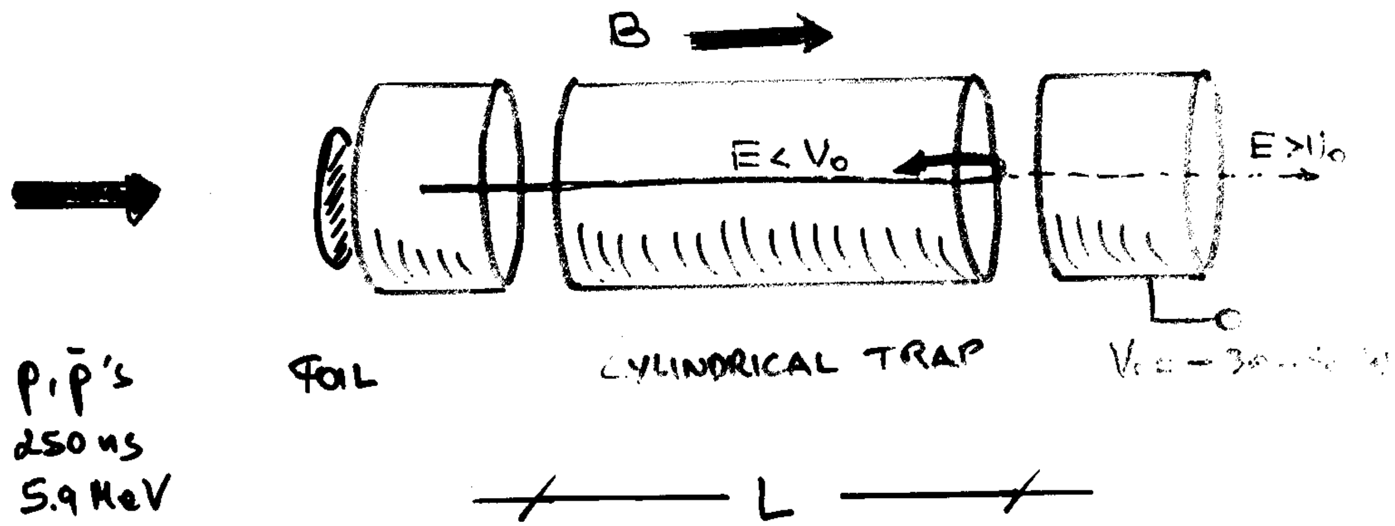
**TRAP CAN BE "ORTHOGONALIZED"**
**($C_4$ Can be tuned to 0 without affecting $C_2$ ($\omega_z$))**

$$\left(\frac{V_c}{V_0}\right)_{c_4=0} = \frac{-C_4^{(0)}}{D_4}\,;\; C_k = C_k^{(0)} + D_k \frac{V_c}{V_0}$$

# LEAR CATCHING TRAP SET - UP



# MATCH TRAP TO LEAR OUTPUT




$$v = 4.5 \times 10^5 \sqrt{E_{kin}[\text{keV}]}$$

$$\Rightarrow v_{50} = 3.2 \times 10^6 \ \text{m/s}$$

$\Rightarrow$ IN 250 ns a 50 keV $\bar{p}$ will travel

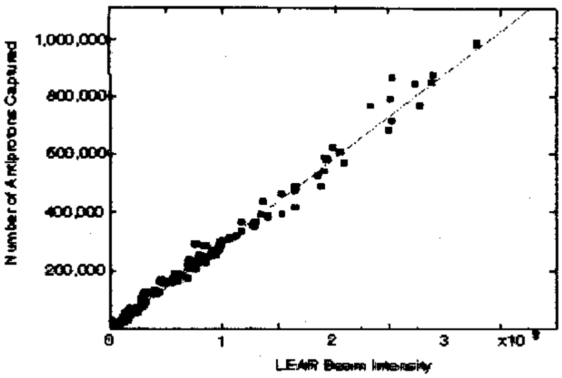
$$S = 80 \ \text{cm} < 2L$$

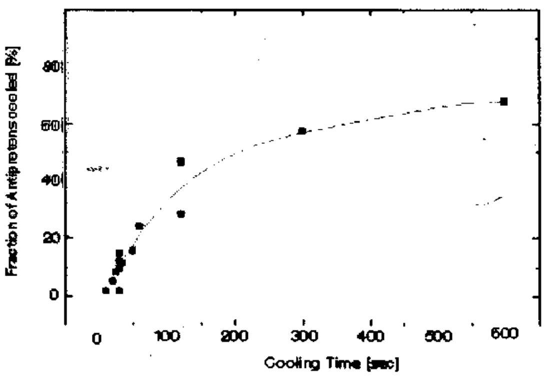
$\Rightarrow$ THIS DEFINES A "LARGE TRAP" AS

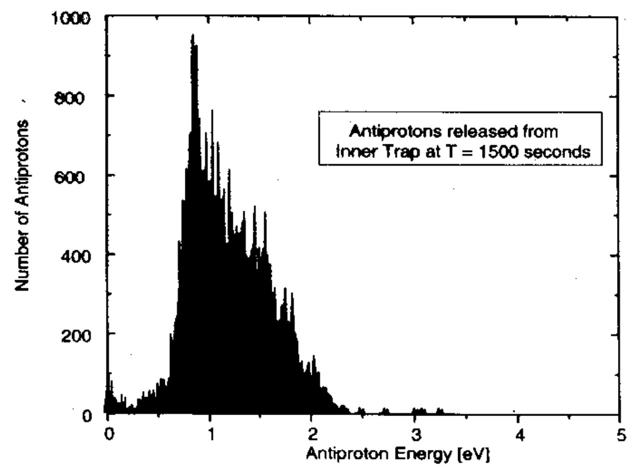
$L = 50$ cm

which leaves ~ 50 ns for dt's

# Summary of Results from P200 Capture and Cooling



# HOW MANY PARTICLES CAN WE PACK INTO A PENNING TRAP?

## BASIC APPROACH:

(a) TRANSVERSE DIRECTION:

MAGNETIC FORCE qv x B HAS TO OVERCOME ELECTRIC FORCE qE

(b) AXIAL DIRECTION

ELECTRIC FORCE HAS TO OVERCOME COULOMB REPULSION (SPACE CHARGE)

single particle: $\omega_c > \sqrt{2}\,\omega_z$

$$\Rightarrow V_{max} = 1200\, B^2(r_o^2 + 2z_o^2)/M$$

many particles: $V_{max} = V_{ext} + V_{space\ charge}$

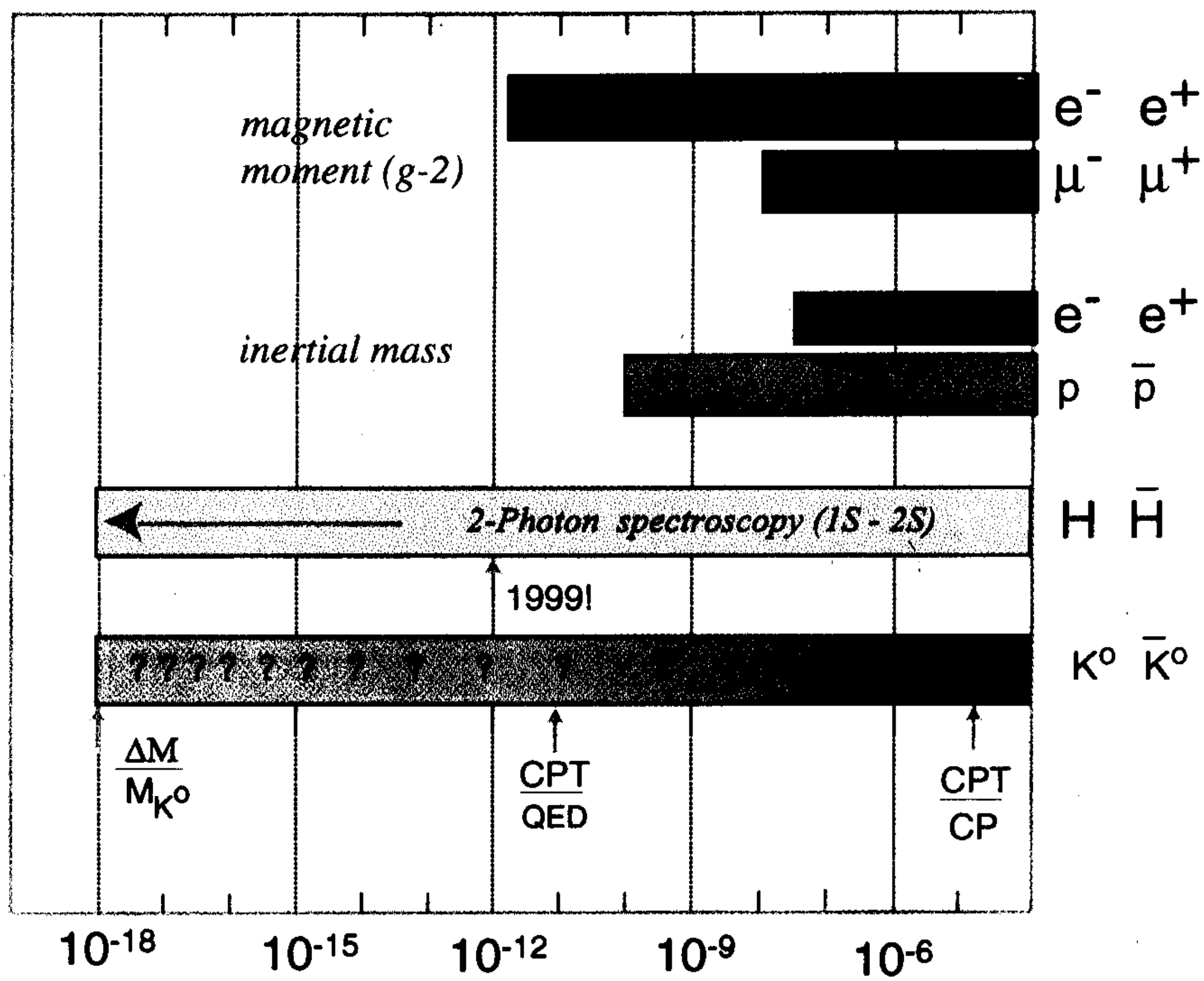
$$\Phi_{SC} = -2/3\, \pi\, \rho\, (a_r^2 + b_z^2)$$

$$\Rightarrow \omega_c' = \omega_c/2 + [(\omega_c/2)^2 - \omega_z^2/2 - 4\pi q \rho a/3m]^{1/2}$$

single particle — space charge shift

$$\Rightarrow \rho_{max} \leq 2.7 \times 10^9\, B^2 \cong 10^{11}\ \mathrm{cm}^{-3}$$

# Current Status of CPT Tests

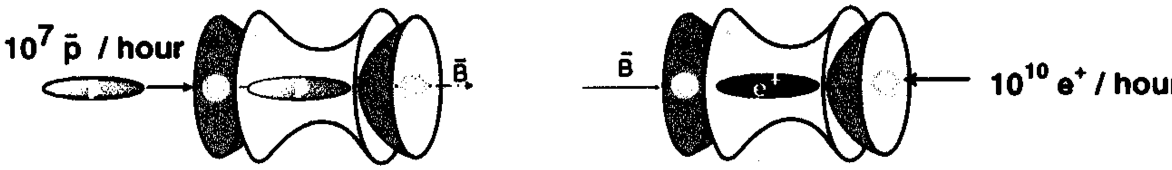



mhh 1998

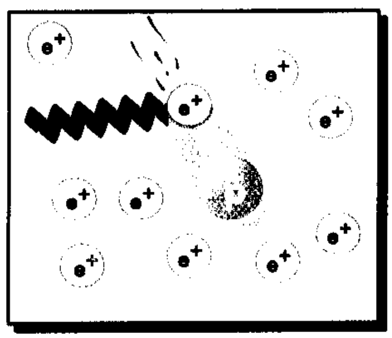
CPT_tests.eps

# ATHENA - Principal Steps

- Antiproton Capture in Penning Trap
- Positron Accumulation from Na-22 source (Buffer Gas Method)




- Positron-Antiproton Recombination at 4.2 - 0.1 K



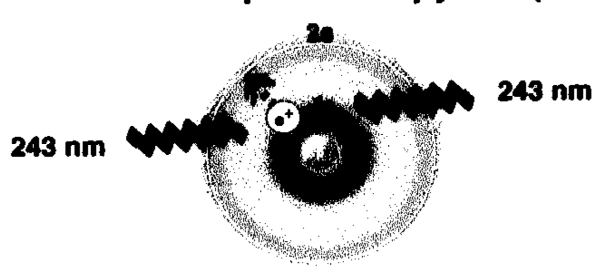

- Antihydrogen Storage and Cooling in Magnetic Bottle

  **Magnetic well depth ~ 0.35 K (35 μeV)**

- Antihydrogen Detection
  - **Annihilation products: Si Pad Detectors**
  - **511 keV Gammas: CsI crystals + Photodiodes**

- Lamb Shift - type experiments

  **2-Photon Laser Spectroscopy: ΔE (1s-2s): T = 125 msec**




Long Term Goal: Comparison H : $\bar{H}$ with precision $10^{-11}$ ... $10^{-15}$

Antihydrogen_Production.ai

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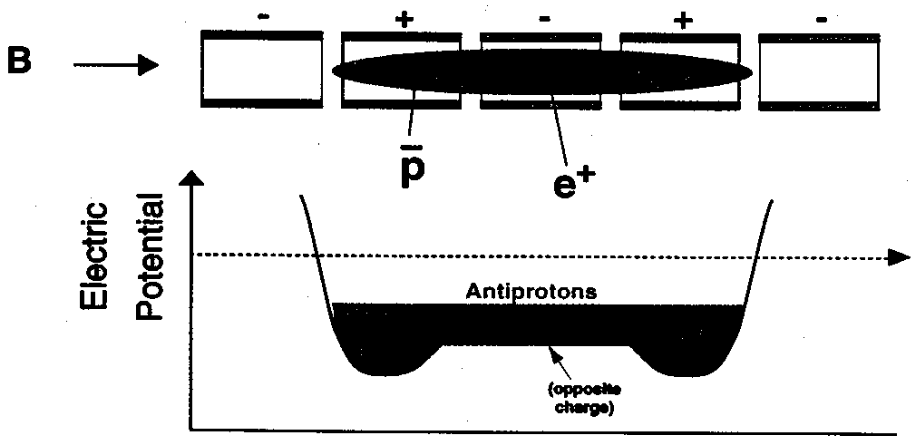
# Recombination in Combined Penning Traps




- 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**

Nested_Trap.eps

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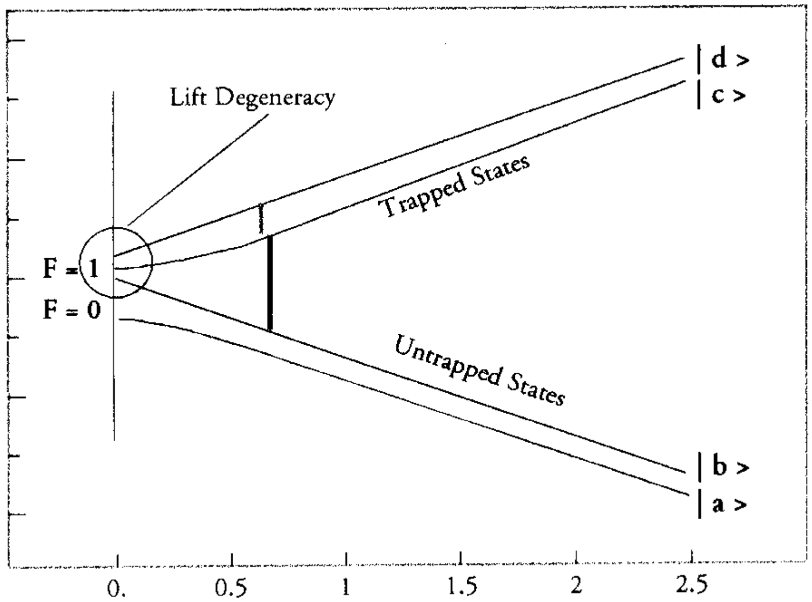
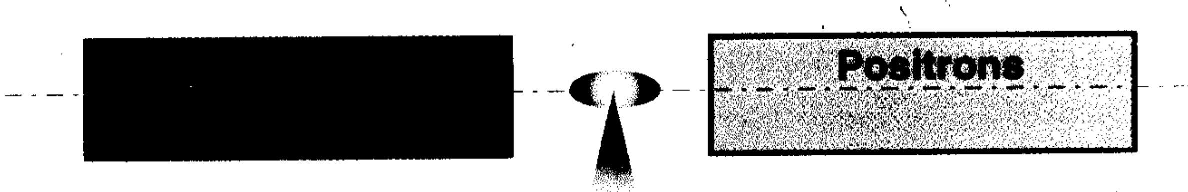
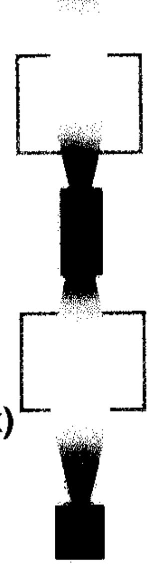
# HFS-Type Measurements



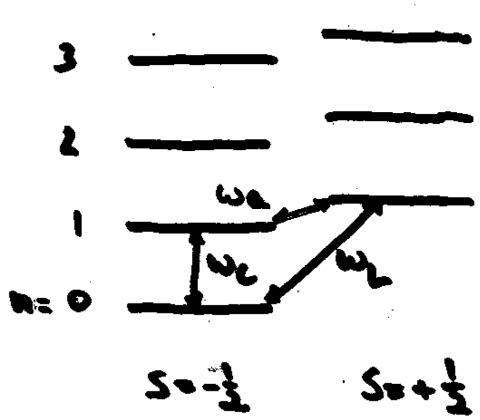

**Experimental Issues:**

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

# Magnetic Moment of the Antiproton

Kostelecky et al: $\mu_p \stackrel{?}{=} \mu_{\bar{p}}$ can test CPT at $1:10^{13}$ +
W. Quint (1993): realistic proposal for experiment

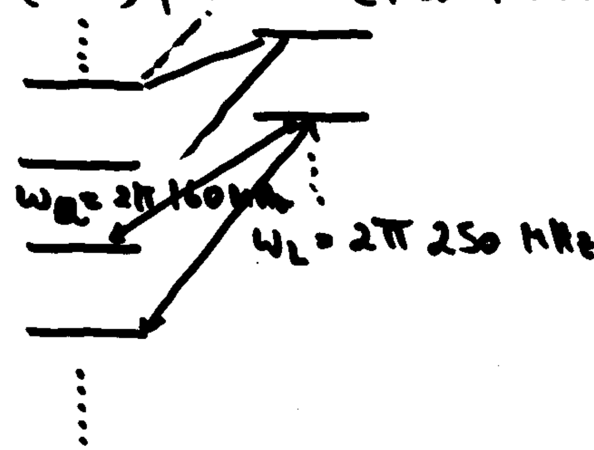
Electron: ($T = 4K$, $\bar{n}_c = 0$)




$\omega_a = \omega_L - \omega_c = \frac{g-2}{2}\omega_c$

$g_e \simeq 2 \Rightarrow \omega_a$ sensitive to CPT

(anti) proton: ($T \gg 4mK$ !)




Scan $\nu_a$ and $\nu_L$ with $\nu_L - \nu_a = \nu_c$

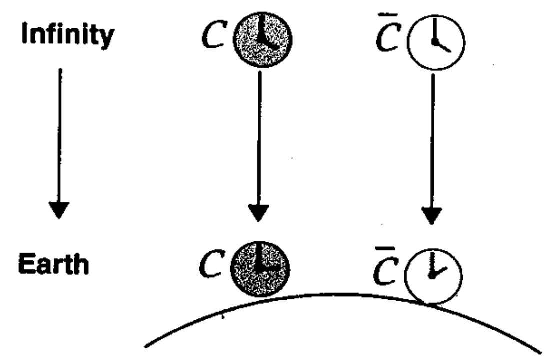
⇒ INCREASE OF $r_c$ : 90 nm/min

⇒ Detectable Signal in 10 min

# Gravitational Mass of Antimatter

Clocks slow down in earth gravitational field
(photon frequency redshift, Pound & Rebka 1962):

$$\Delta v/v = \frac{M_{earth} \cdot G}{R \cdot c^2} \quad o(10^{-9})$$




**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 $\Delta v/v \sim 10^{-15}$ →**
  **as earth moves along its eccentric path around the sun ($\Delta U/U \sim 10^{-9}$) →**
  **test equality of gravitational masses to $10^{-6}$**

Gravity_Redshift.eps

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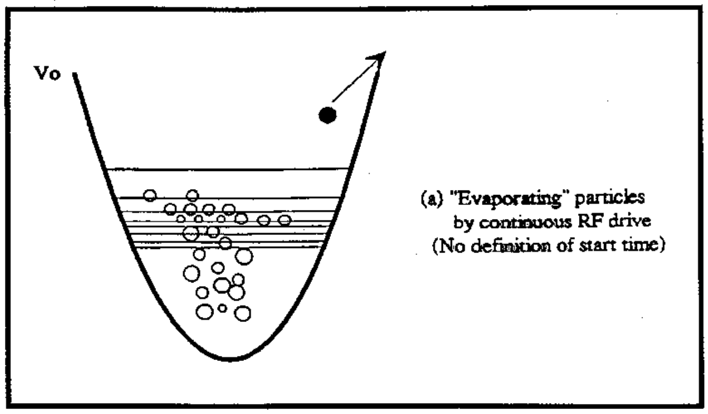
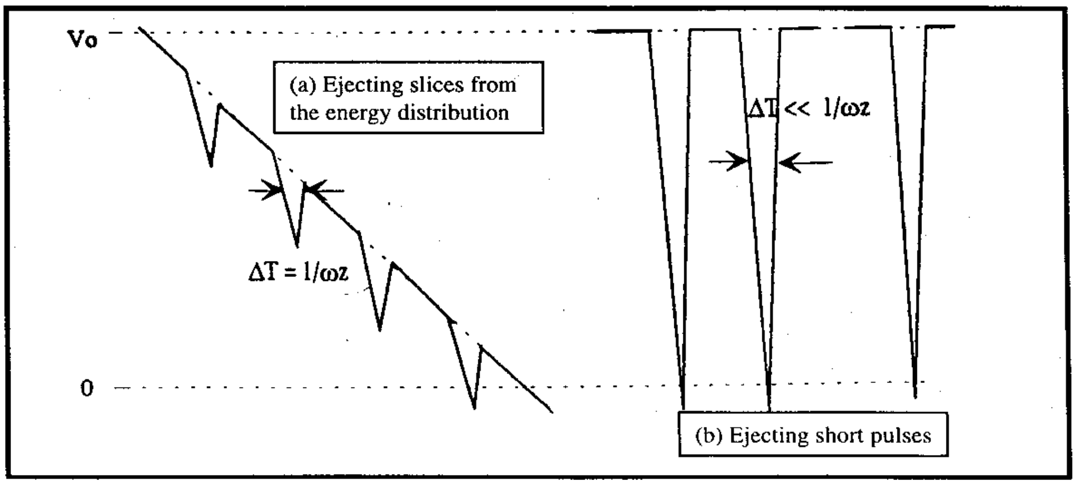
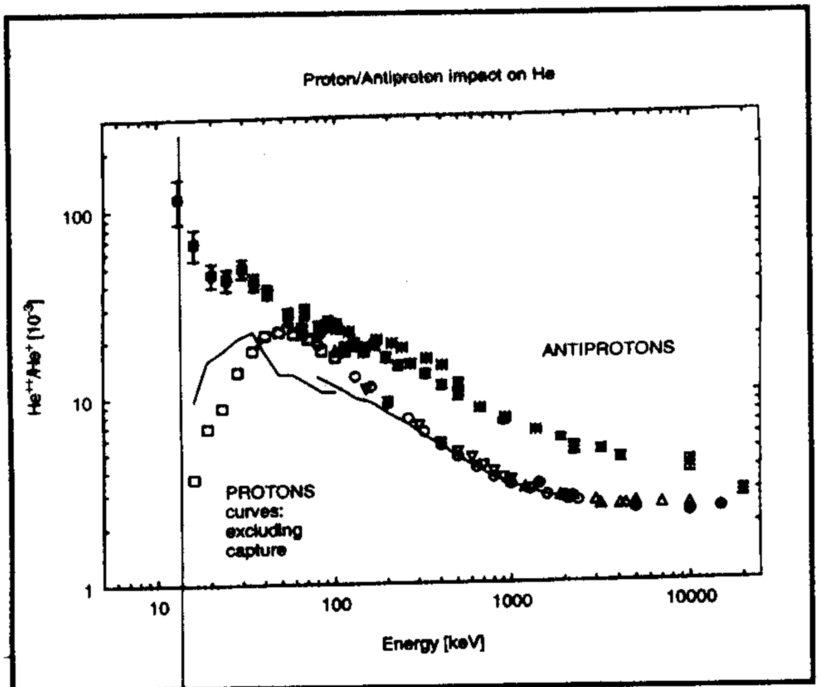
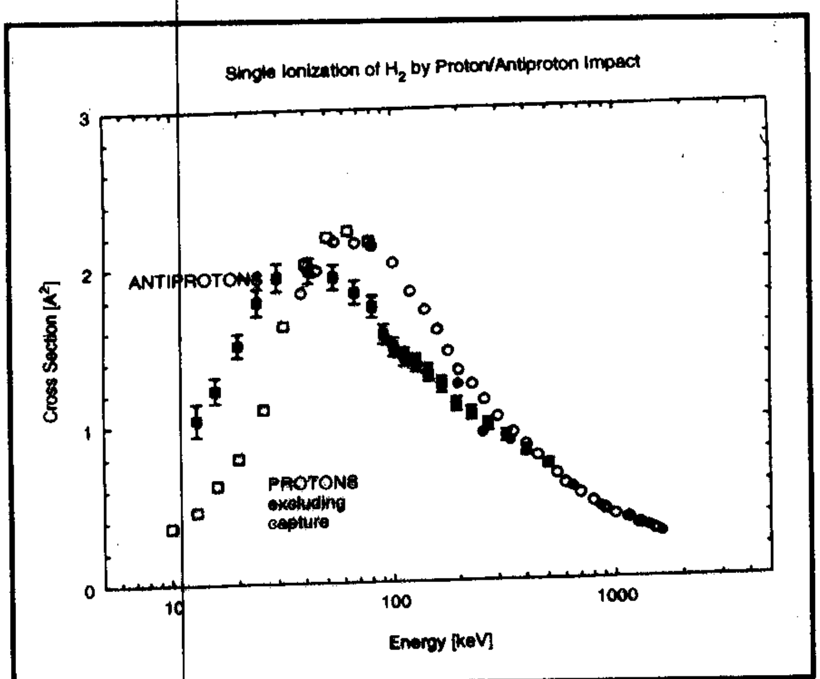
# Using the Trap as <u>source of ultra-low energy</u> particles



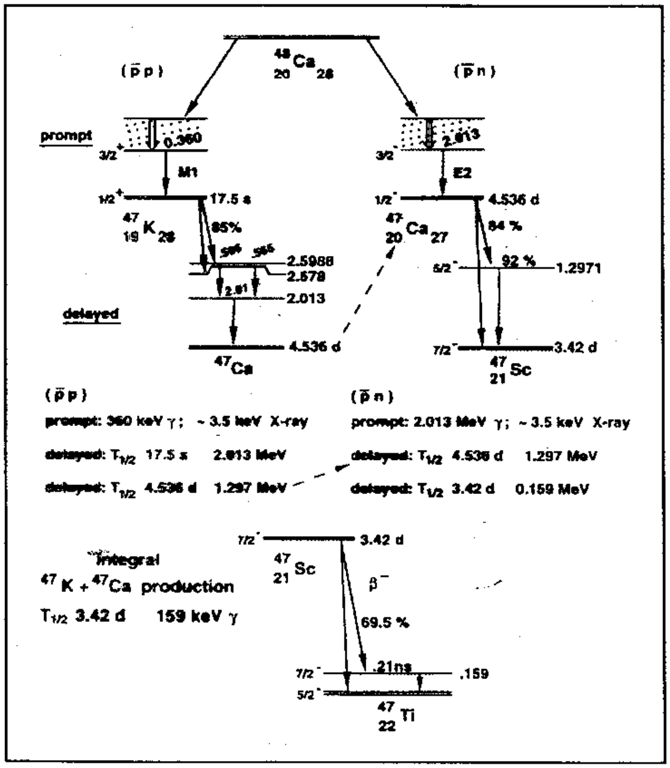
# Collisions of Simple Atomic Systems with Protons and Antiprotons




→ It is just getting interesting !

# Using Antiprotons to probe the nuclear Peripherie




Implant low energy antiprotons in target

Measure X-ray spectrum on line or off line

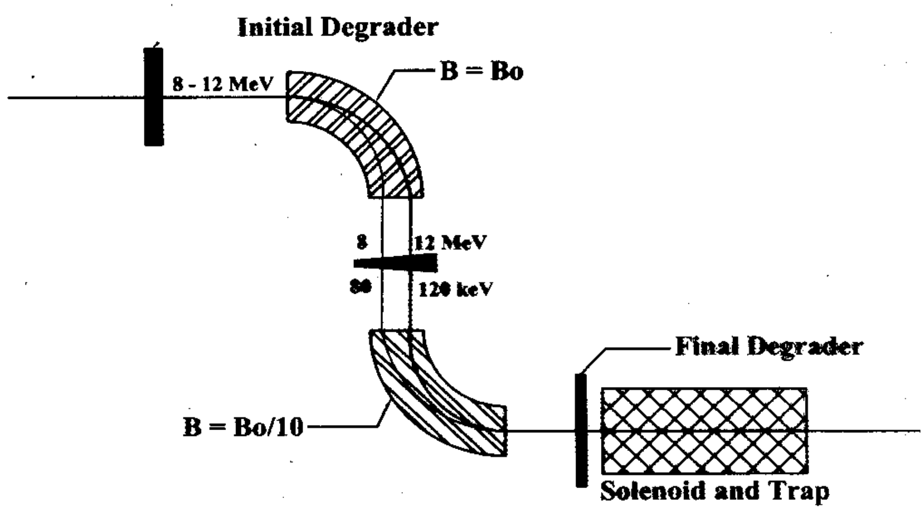
Adaptable to specific (interesting) systems after W. P. Kells, Nucl. Instr. Methods A276 (1989) 117-121

| Momentum GeV/c | Target | Density [g/cm$^3$] | Range [cm] | Int. Length [cm] | Exit Spot Ø [cm] | Yield 0-10 keV x $10^{-5}$ |
|---|---|---|---|---|---|---|
| 0.1 | Al | 2.7 | 0.02 | | 0.2 | 800 |
| 0.7 | Be | 1.8 | 27.1 | 40.9 | 6 | 0.7 |
| 1 | Be | 1.8 | 86 | 40.9 | 18.6 | 0.81 |
| 1 | Pb | 11.4 | 22 | 17.1 | 5.4 | 0.86 |
| 2 | Be | 1.8 | 587 | 40.9 | 110 | 0.37 |

| | | |
|---|---|---|
| **Problems at higher energies** | Increased range straggling | Fewer particles in trappable [illegible] |
| | **Increased Coulomb scattering** | **Increase spot size at end of degrader** |
| | **Nuclear Absorption increases** | **Range > Interaction length** |

# Enhancing the Capture efficiency

(Harald Enge, priv. Comm.)



## SUMMARY:

K(R)ING LEAR IS DEAD
LONG LIVE THE (P)RIN(CE)G AD !

AD IS ONLY HIGH INTENSITY SOURCE
- DEDICATED $\bar{H}$ FACILITY
- LOW (INTEGRATED) INTENSITY

LARGE ARRAY OF ULTRA LOW ENERGY ANTIPROTON PHYSICS UNCOVERED
- CPT ($\mu_p \neq \mu_{\bar{p}}$, $\bar{H} \neq H$, ...)
- GRAVITY ($p \neq \bar{p}$, $H \neq \bar{H}$ ?)
- ATOMIC & NUCLEAR PHYSICS
- ULEAP SOURCE

  (PORTABLE : OPPORTUNITY FOR UNIVERSITY LABORATORIES TO HAVE $\pi, \mu$ SOURCE ON SITE!)

THIS GAPING VOID MUST BE FILLED : FNAL CAN AND MUST SERVE COMMUNITY !!!