Sept.25-26, Villars Meeting

Production of Ultra Slow Antiproton Beam and A Cusp Trap for $\overline{H}$ Synthesis

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On behalf of MUSASHI Group,

ASACUSA Collaboration

Why intense ultra-slow/trapped $\bar{p}$s?

1. Atomic physics of "Heavy Electron"

   Ionization by $\bar{p}$ vs p

   $\bar{p}A^+$ Formation : exchange between $\bar{p}$ & e^-

   $\bar{p}A^+$: A new probe of nuclear structure

2. Atomic physics of Antimatter

   $\bar{H}$ Formation

   CPT symmetry with H vs $\bar{H}$ (1S-2S, HFI, gravity)

3. Non-neutral plasma physics

4. Antimatter chemistry: $\bar{H}_2$, $\bar{H}^+$, $\bar{H}_2^+$,etc.

Double ionization of He

$P(\bar{p}) + He \to$

$p(\bar{p}) + He^{++} + e^- + e^-$

a few body system

just Coulomb force

small "Z"

weak perturbation

however・・・

→ After 20years
$\sigma^+(\bar{p})+\sigma^{++}(\bar{p})=\sigma^+(p)+\sigma^{++}(p)$
by T.Morishita & S.Watanabe

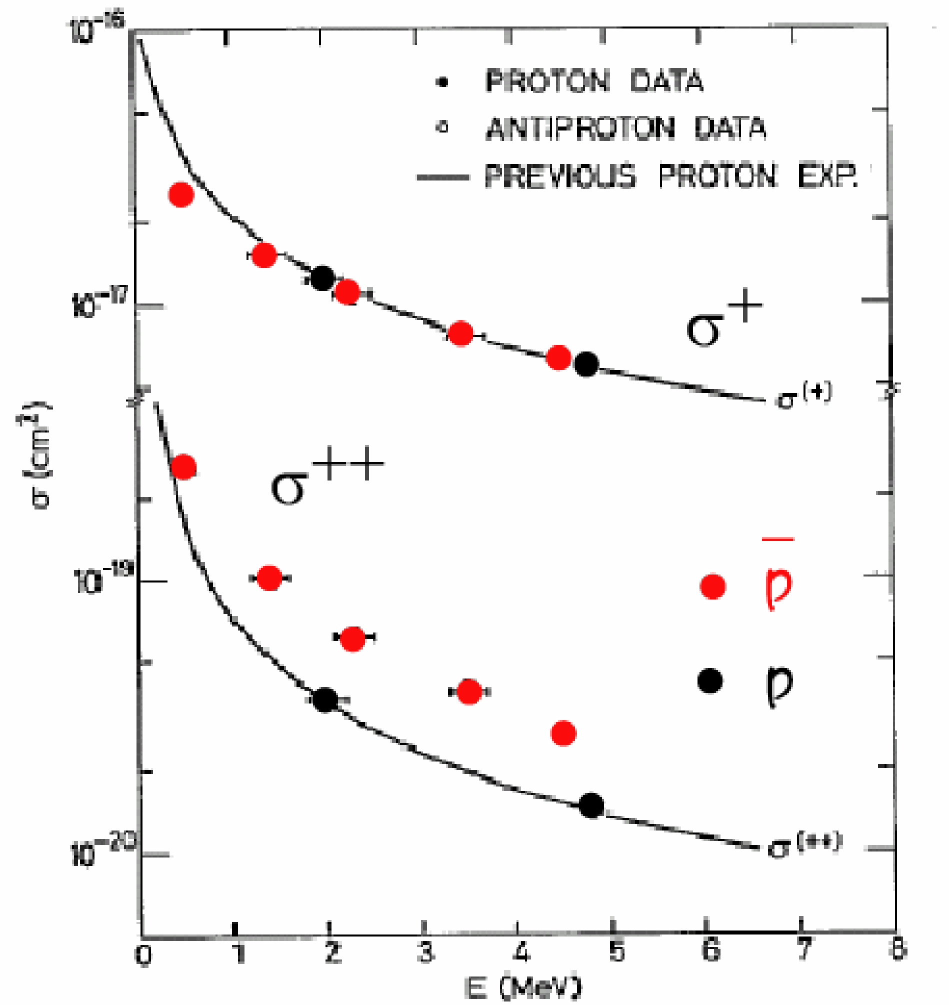


FIG. 3. The cross sections measured in this work.

L.H.Andersen et al., PRL57 (1986)2147, PRA38(1988)395

$\bar{p}$A Formation

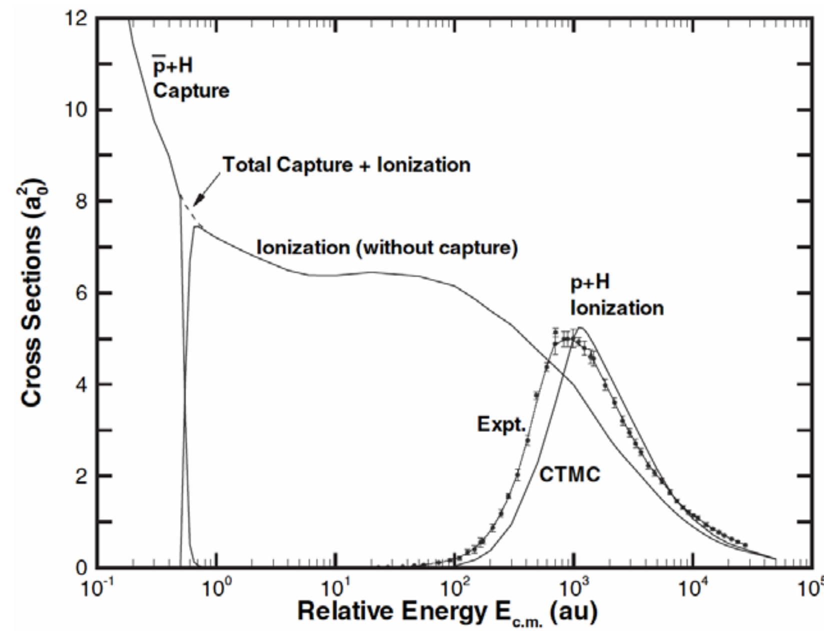
$$\bar{p} + A \rightarrow \bar{p}A^+ + e^-$$

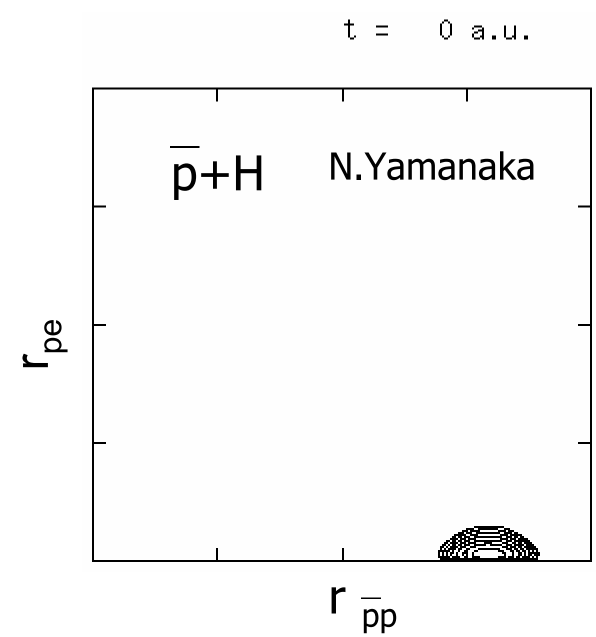
$$K_{\bar{p}A} - \varepsilon_{eA^+} = K_{e(\bar{p}A^+)} - \varepsilon_{\bar{p}A^+}$$

$$\varepsilon_{\bar{p}A^+} \sim \frac{\mu_{\bar{p}A^+}}{m_e}\frac{\varepsilon_R}{n^2} \sim \varepsilon_{eA^+} - K_{\bar{p}A}$$

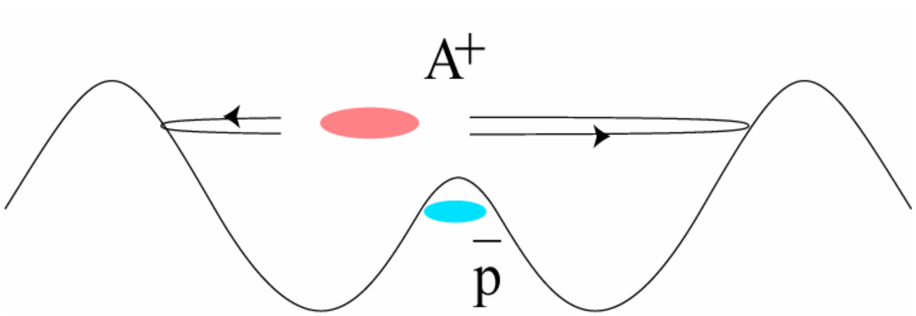
→ "n" controllable!!

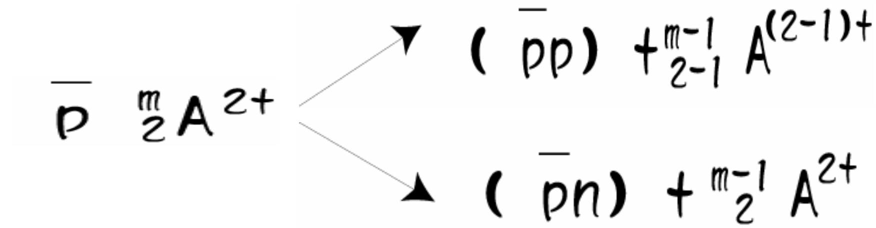
J.Cohen, Rep.Prog. Phys.67(04)1769





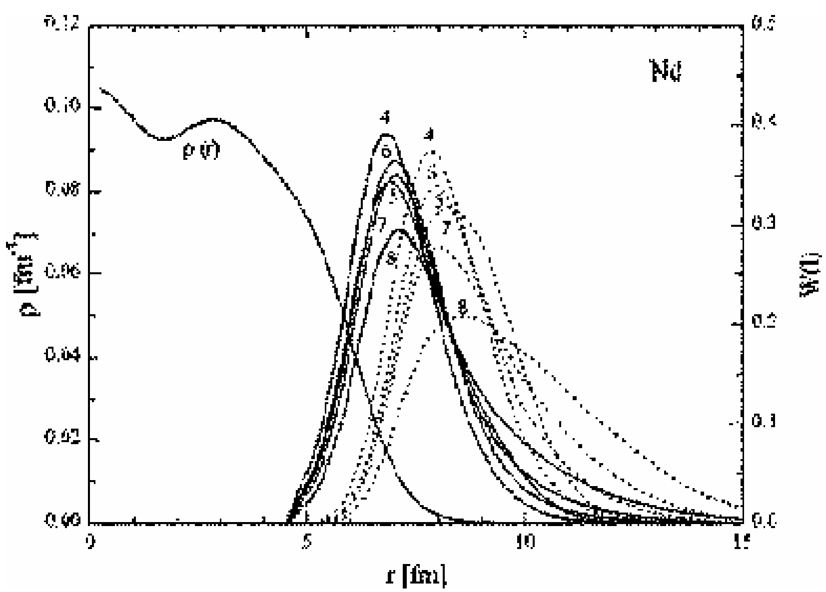
Annihilation of $\bar{p}$ in $\bar{p}A$

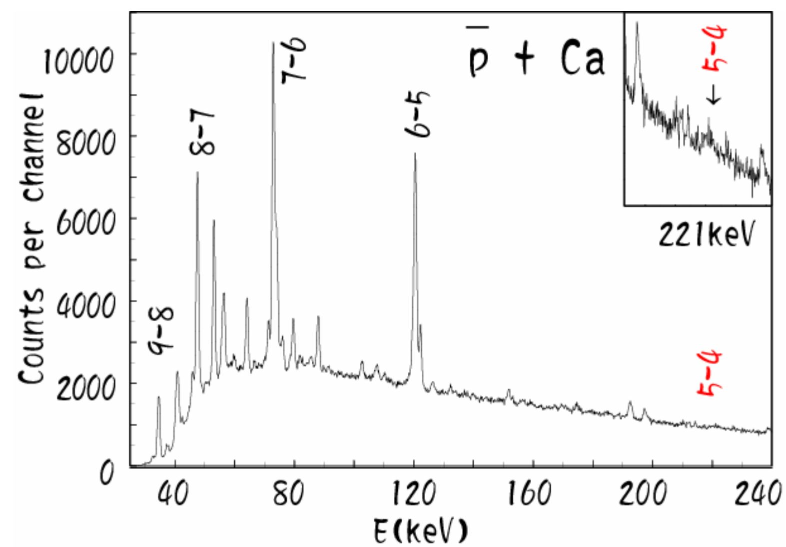




Branching ratio : nucleon distr.

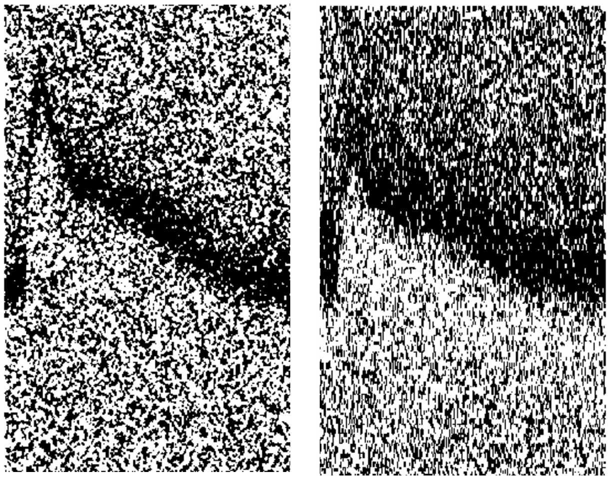
Recoil momentum: Fermi motion





F.J.Hartmann et al.. Phys.Rev.C (to be published)

Dynamics of Non-neutral plasma with $\bar{p}$s



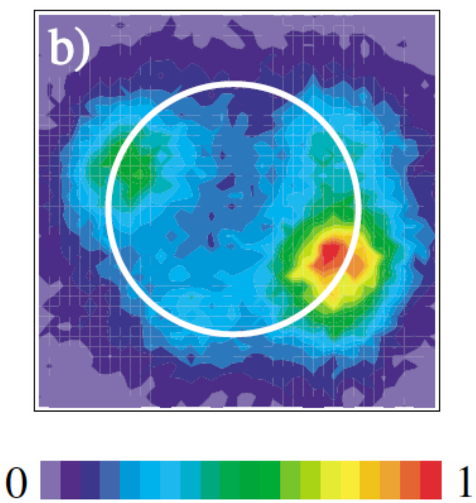
(2,0) (3,0)

Plasma heating & cooling feature

$\bar{p}$:1x10^6, e^-:3x10^8,

ΔT~0.6eV, Δt_{rise}~5sec, Δt_{cool}~30sec

N.Kuroda et al.



Non-neutral plasma dynamics

M.Fujiwara et al., PRL92(2004)065005

Separation of two component plasmas

Antiproton plasma

$\bar{H}$ Production

(1) $\bar{p} + e^+ \rightarrow \bar{H} + h\nu$

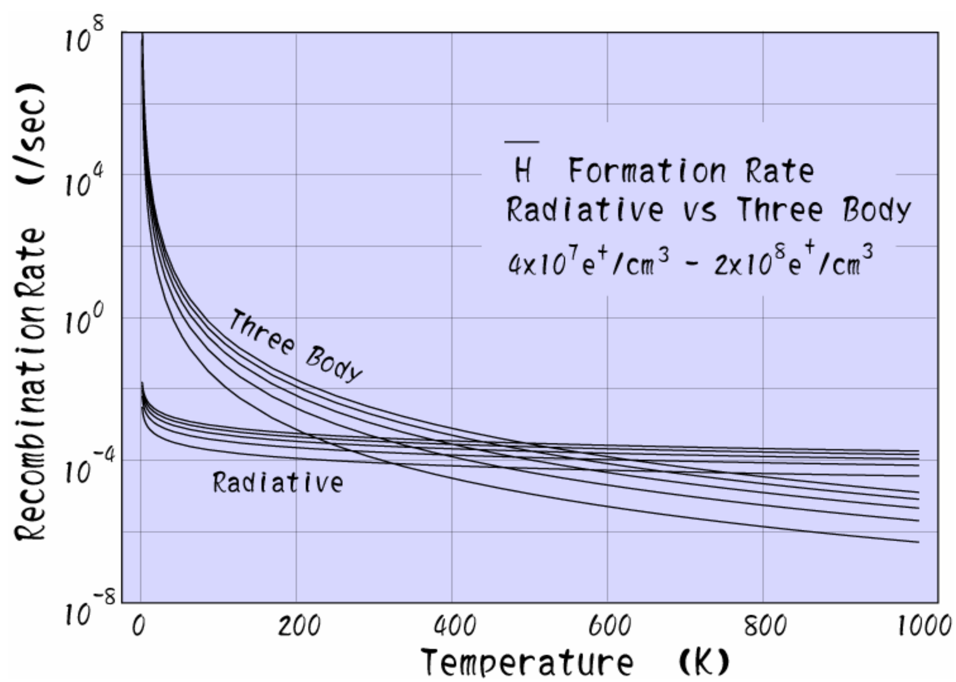
(2) $\bar{p} + e^+ + nh\nu \rightarrow \bar{H} + (n+1)h\nu$

(3) $\bar{p} + e^+ + e^+ \rightarrow \bar{H} + e^+$

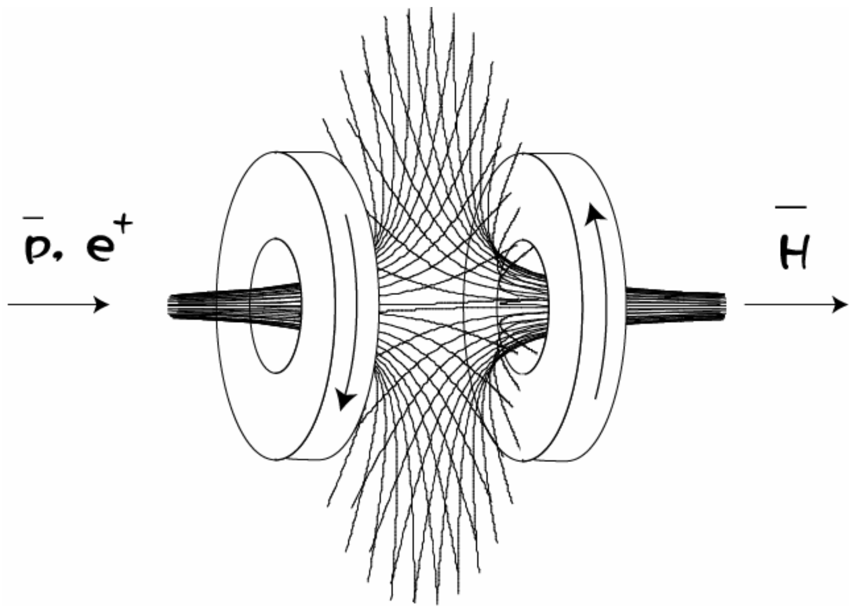
(4) $\bar{p} + (e^+e^-) \rightarrow \bar{H} + e^-$

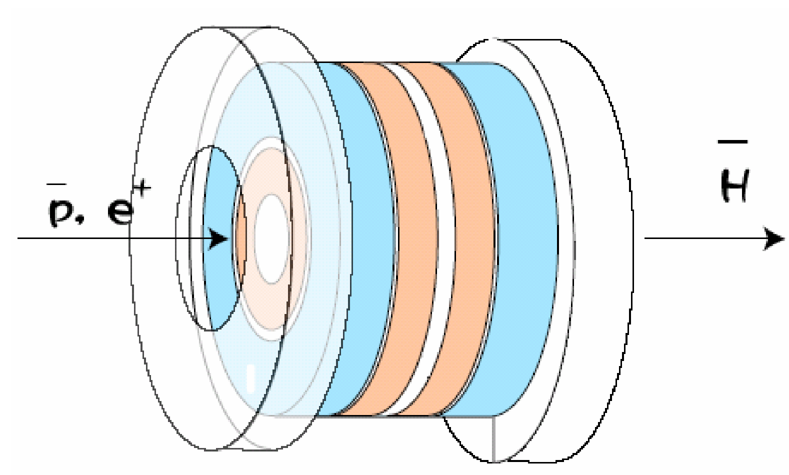
(5) $\bar{p} + A \rightarrow \bar{H} + e^- + A$

Realized by ATHENA & ATRAP



A new scheme to synthesize & trap $\bar{H}$: cusp B-field + octupole E-field





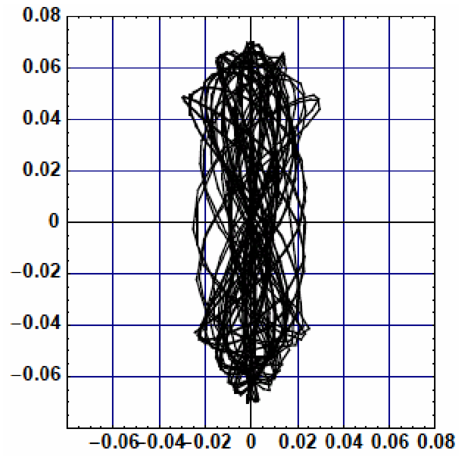
No instability in the cusp field

Magnetic bottle for neutral particles

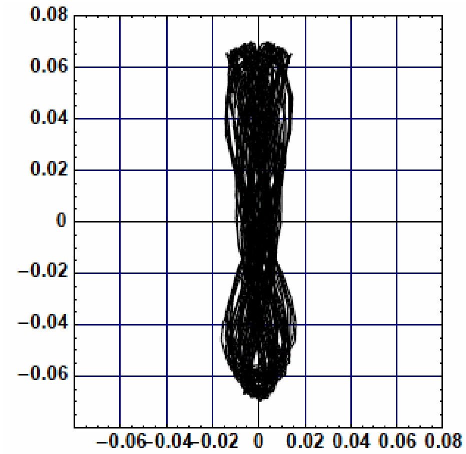
Relaxation time to 1S state of $\bar{H}$

Trajectories of 0.086meV $\overline{H}$(1S)

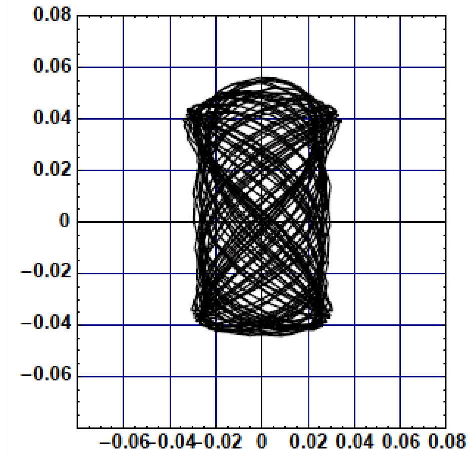
θ=80°



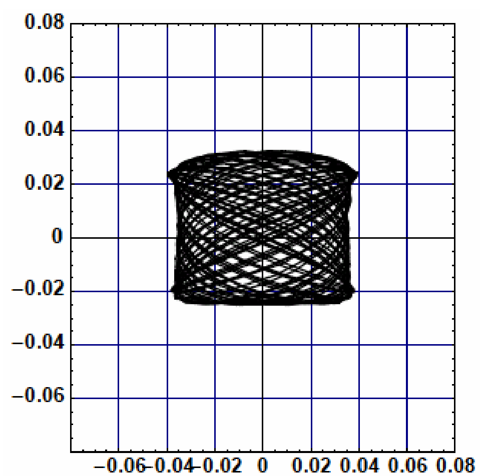
θ=60°



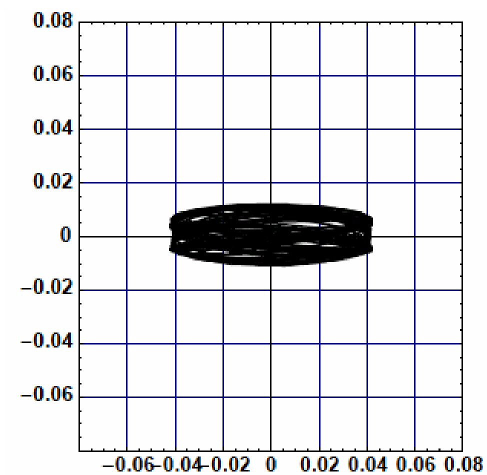
θ=40°



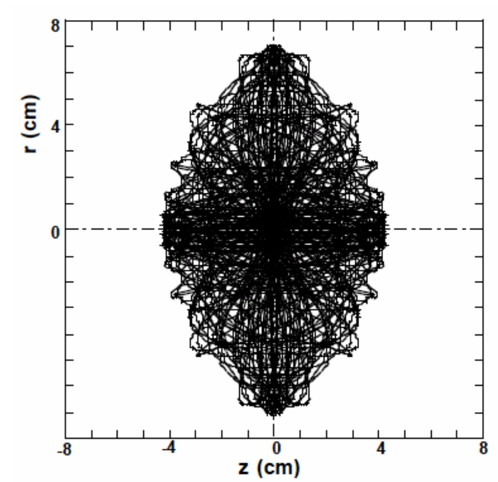
θ=20°



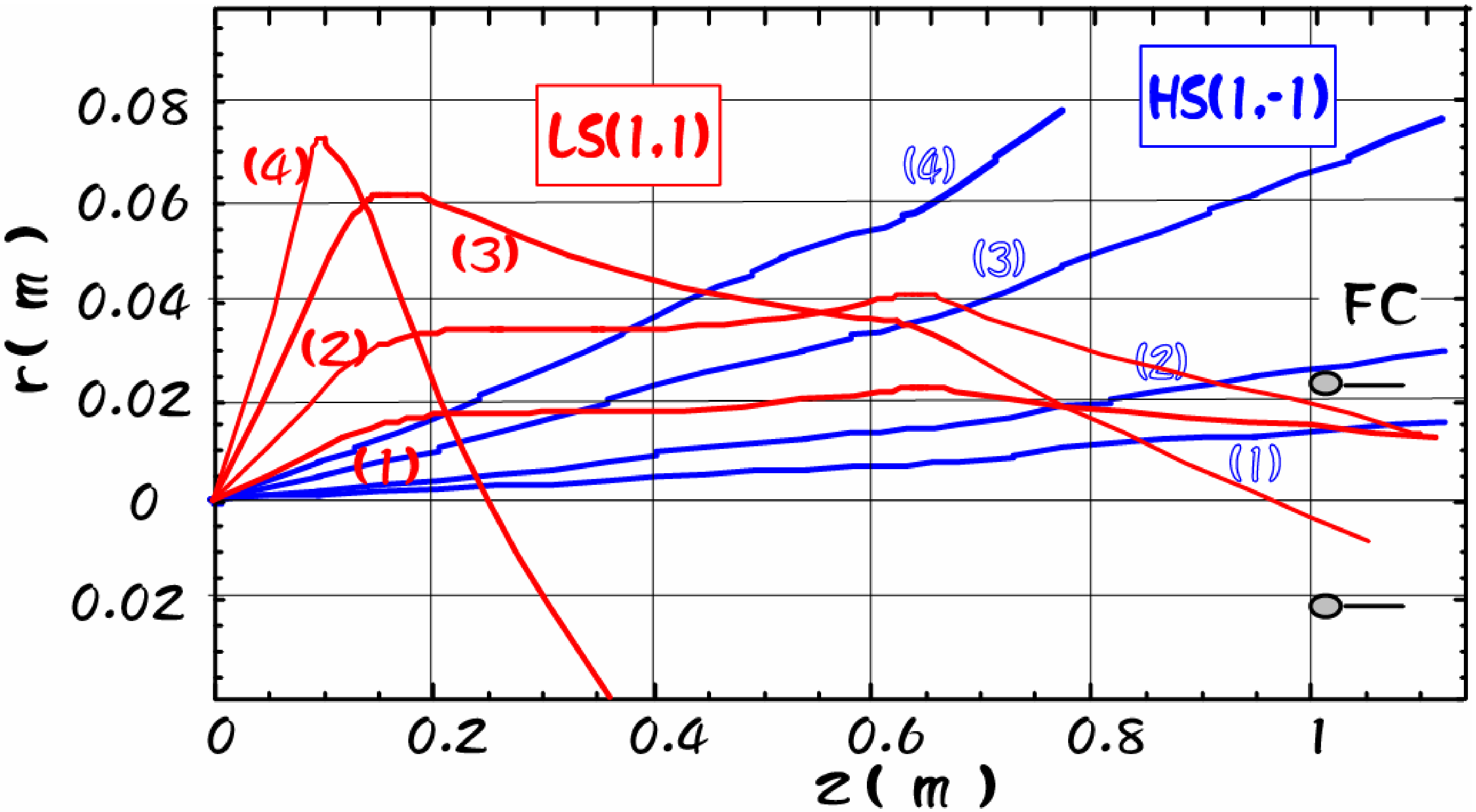
θ= 5°



sum



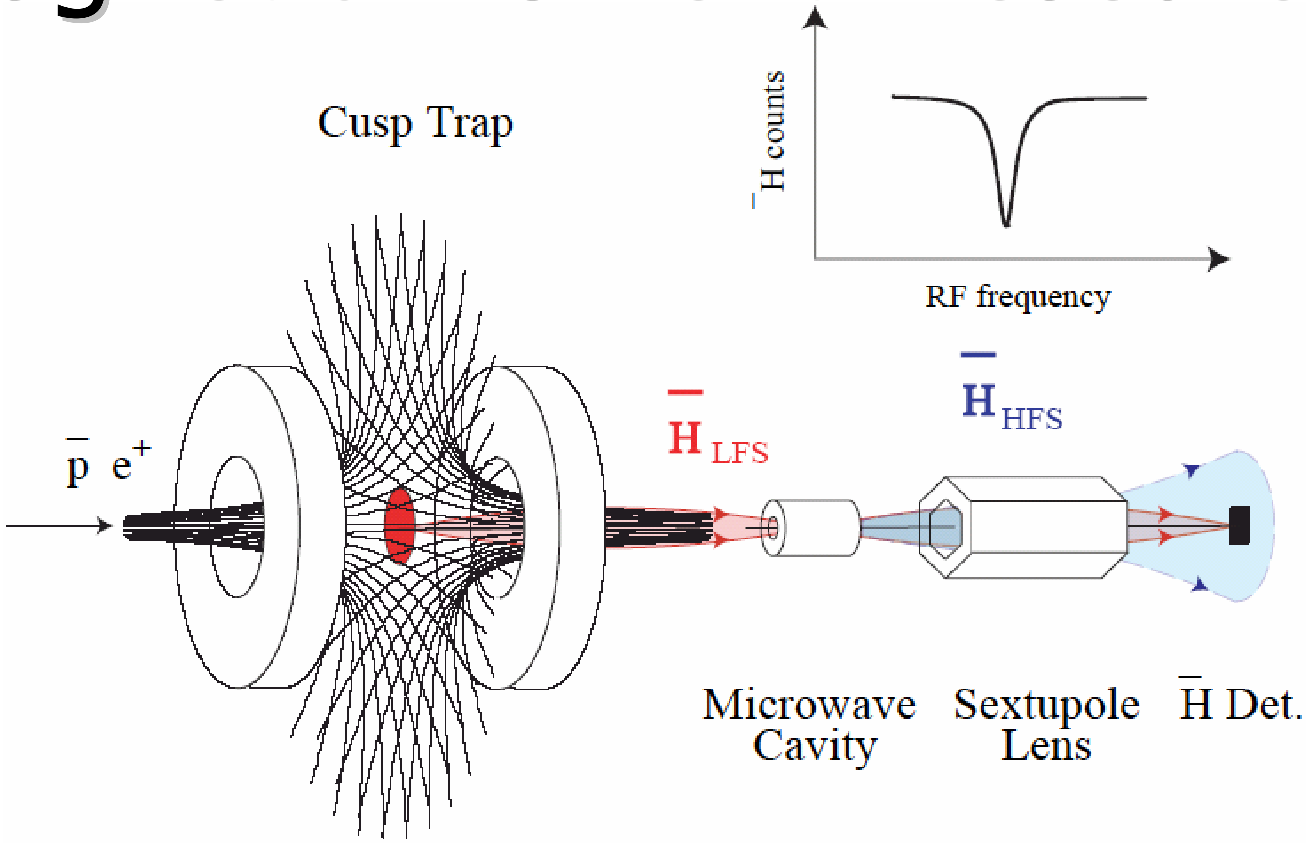
Trajectories of 0.268meV $\bar{H}(1S)$



$\bar{H}$ beam focused, intensified by 400 times

More than 99% spin polarized

$\bar{p}$ magnetic moment measurement



Simultaneous confinements of $\bar{p}$, e^+, AND $\bar{H}$

Automatic cooling

Intensity-enhanced Spin-polarized $\bar{H}$ beam

$\mu_{\bar{p}}$ determination ppm or better

Antiproton Decelerator (AD)

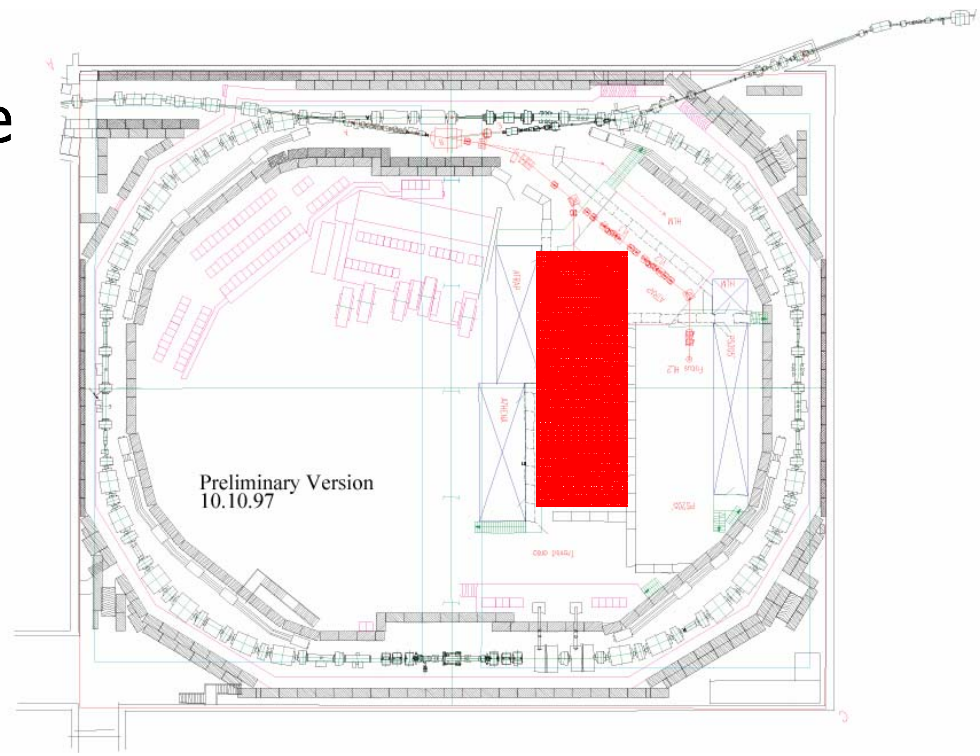
3.5GeV/c→100MeV/c(～5.3MeV) →100keV→10keV →Kelvin

3digits 2digits 1digit 6digits

AD: 26GeV/c 1.5×10^{13} p/pulse

→ 3.5GeV/c 4×10^{7} $\bar{p}$/pulse

→ 0.1GeV/c 3×10^{7} $\bar{p}$/pulse



Further Deceleration

Traditionally : 5.3MeV → 10keV → sub eV

Foil degrader

Trap

Efficiency: ~0.1%

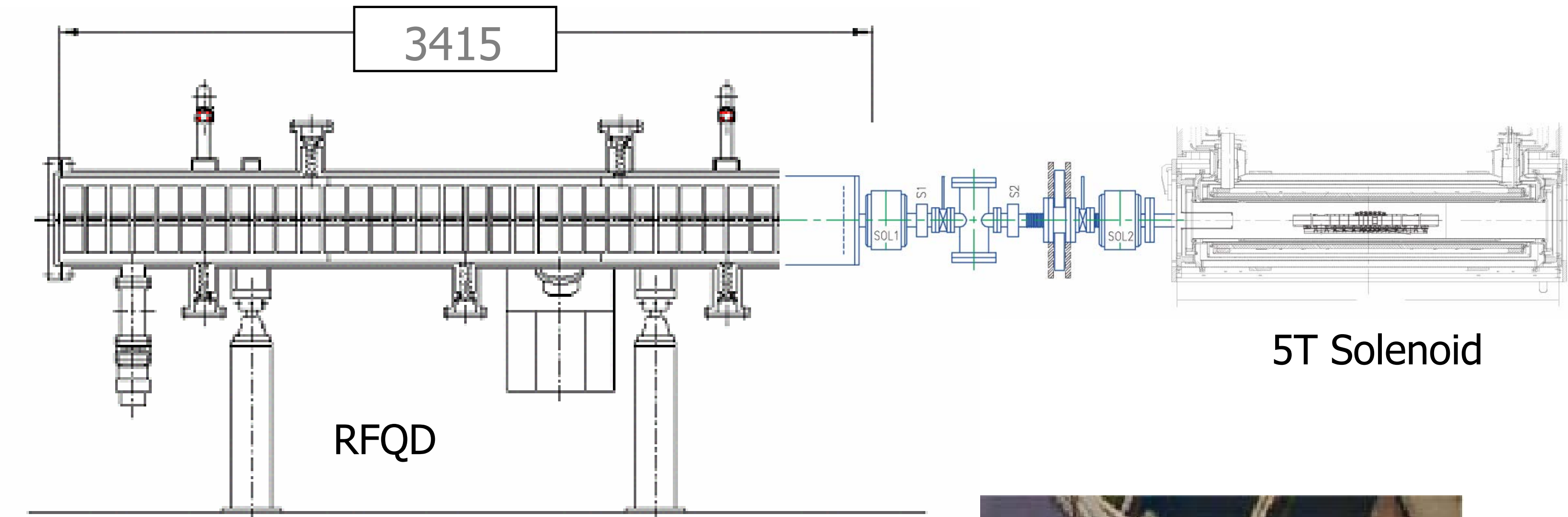
Now : 5.3MeV → 100keV → 10keV →sub eV

RFQD

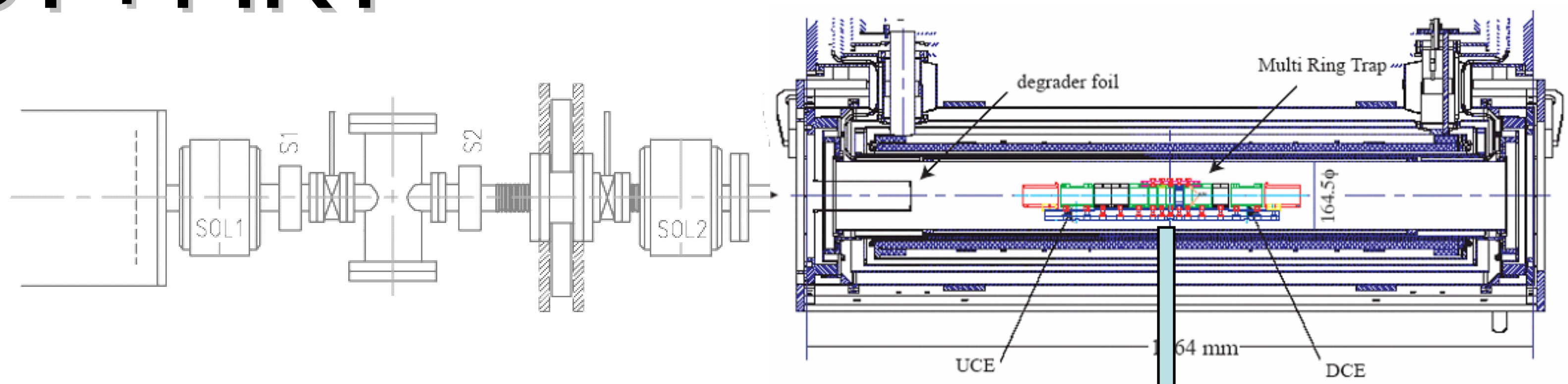
Vacuum Isolator

Trap

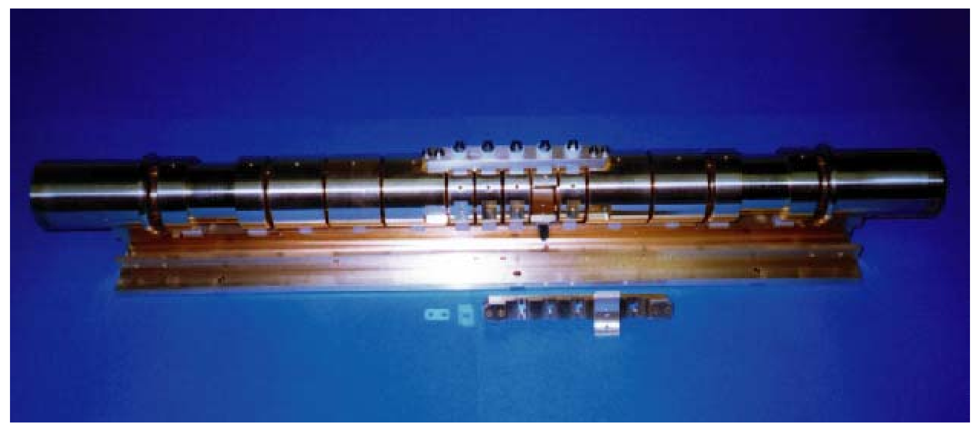
RFQD + LEBT



LEBT+MRT



Multi-Ring Trap

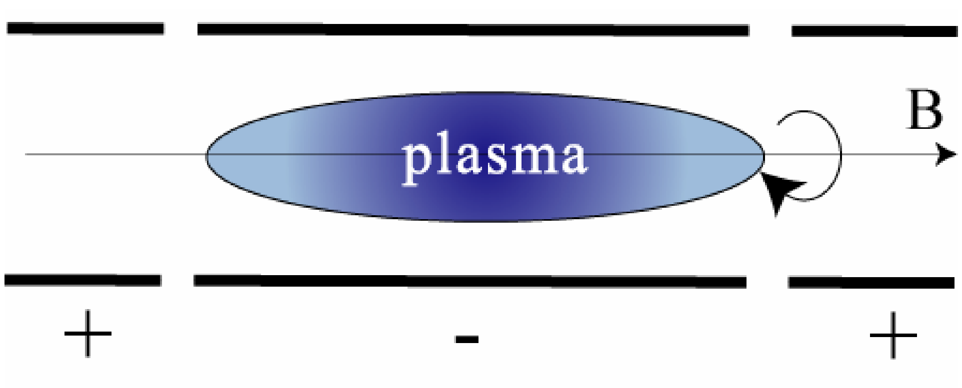


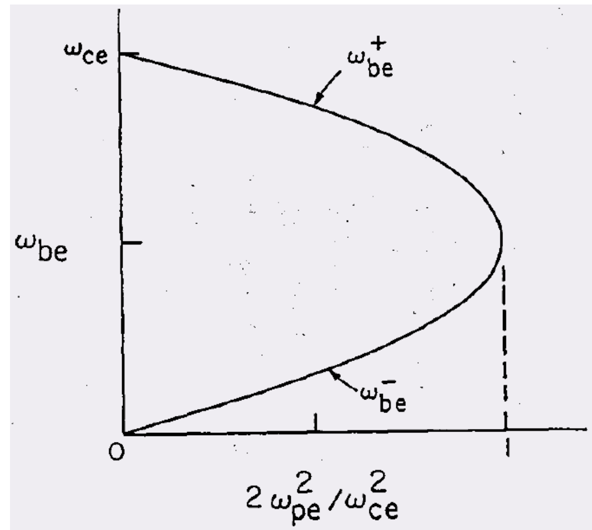
Harmonic potential

Spheroidal plasma

Rigid rotation

Multi-Ring-Trap and Non-neutral Plasma



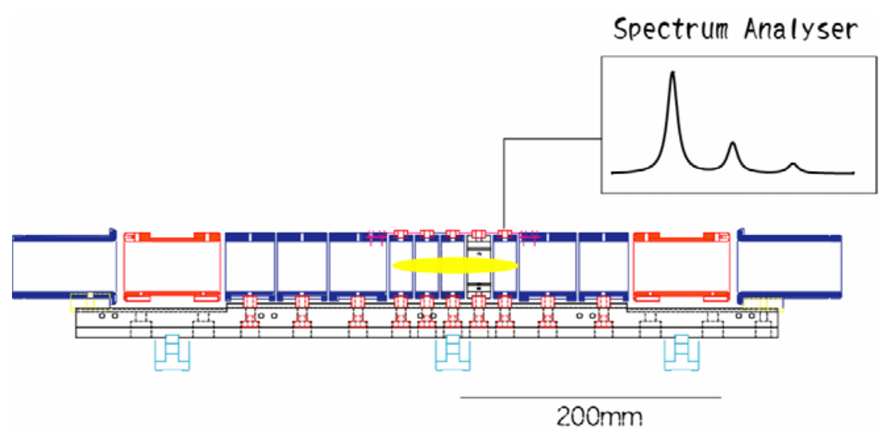


Non-neutral plasma

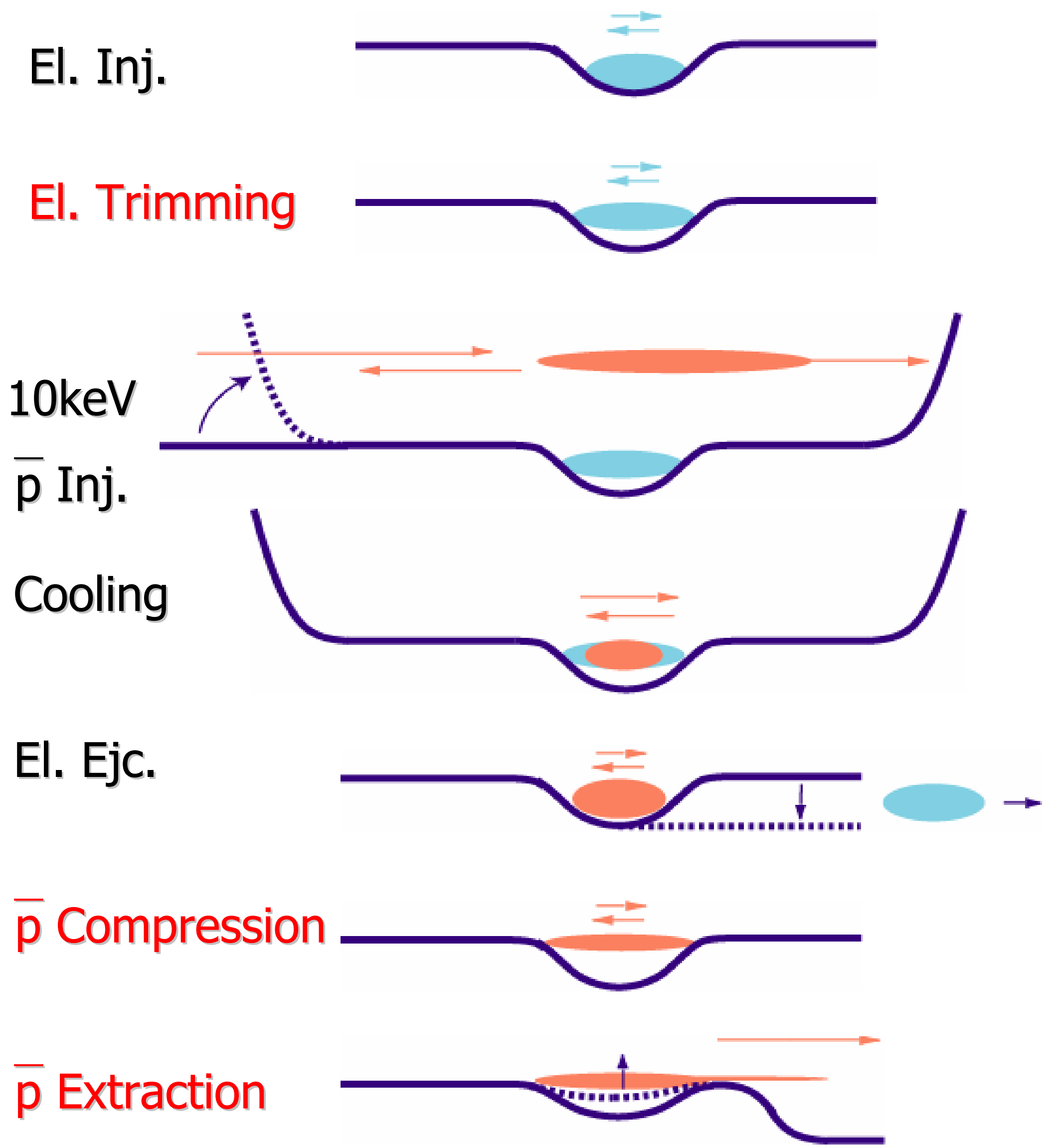
Rigid Rotation of Spheroid

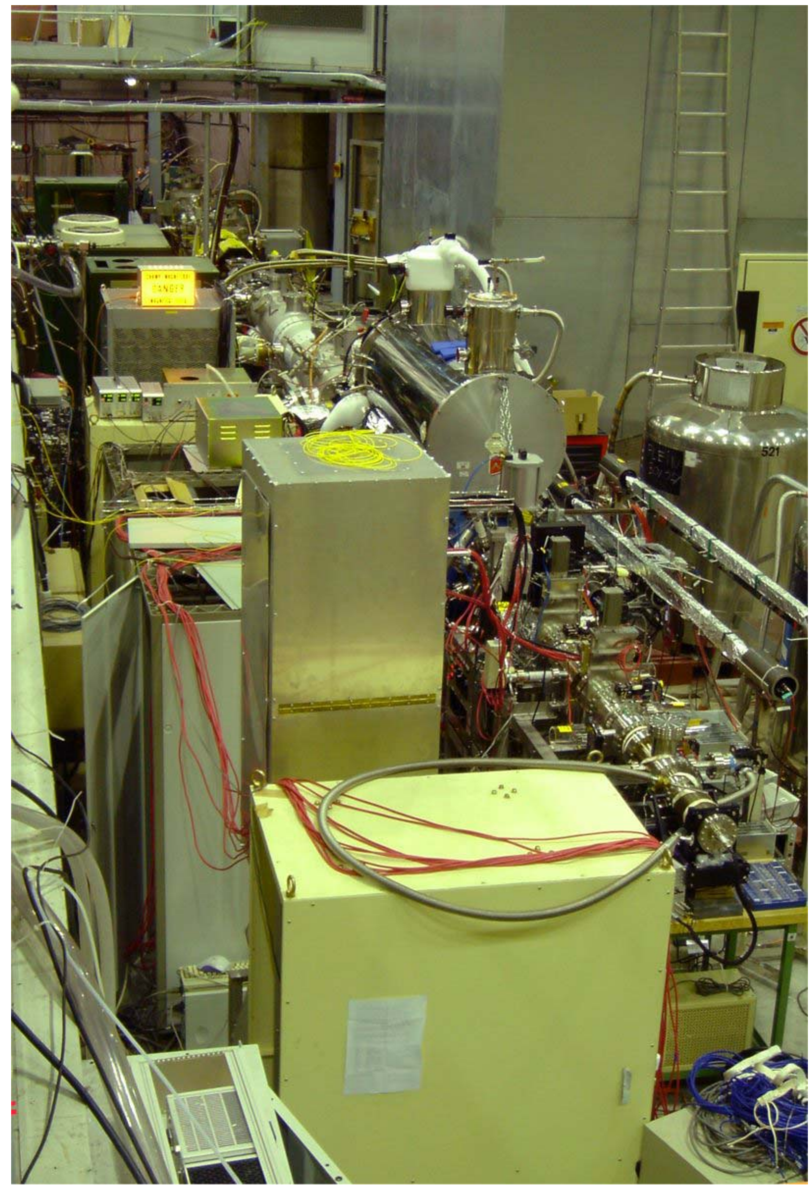
Compression

T-dependent plasma mode

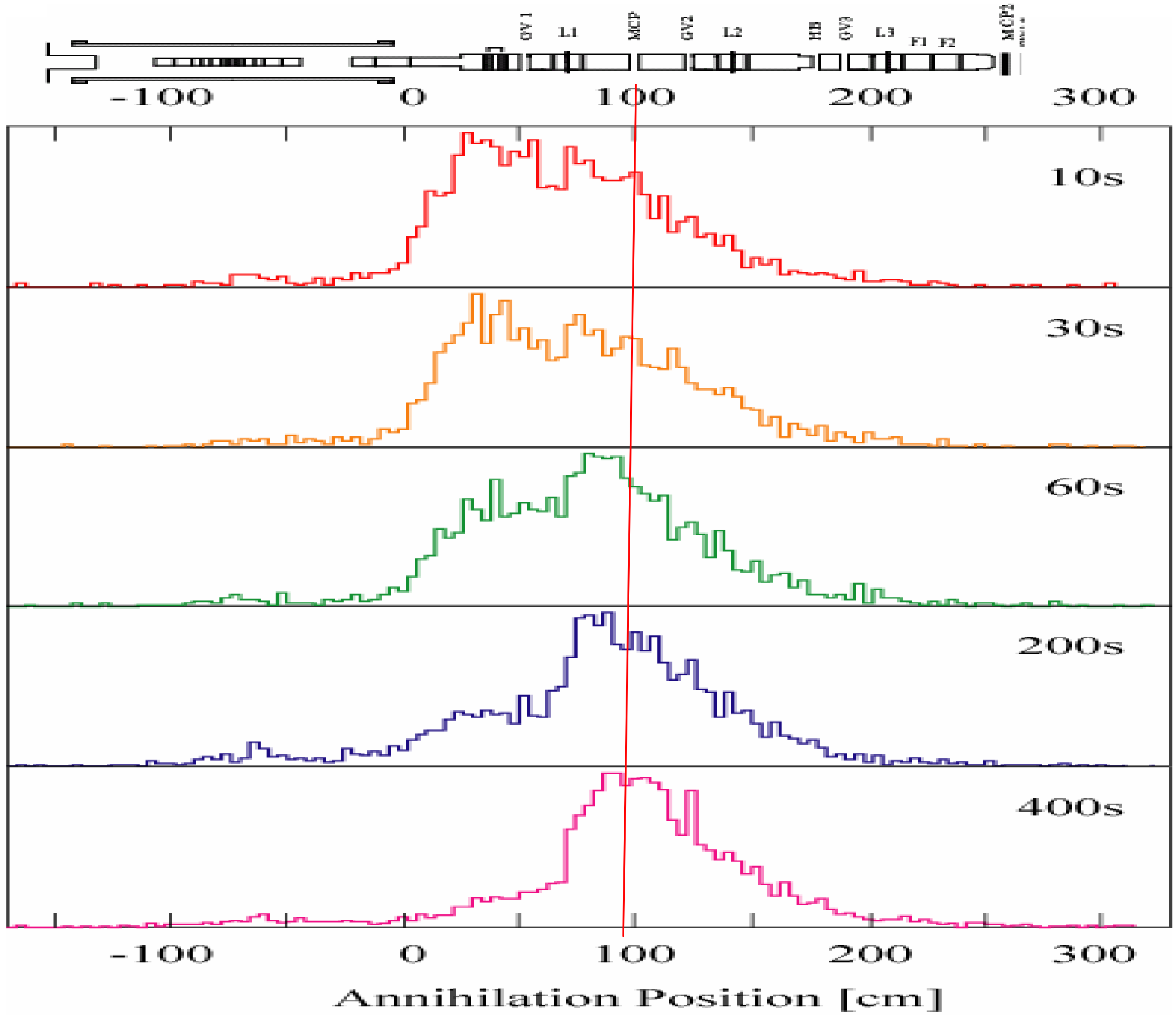


Trapping, Cooling, Trimming, and Extraction





Rotating Wall Compression of $\bar{p}$ under UHV



Ultra Slow $\bar{p}$ Extraction

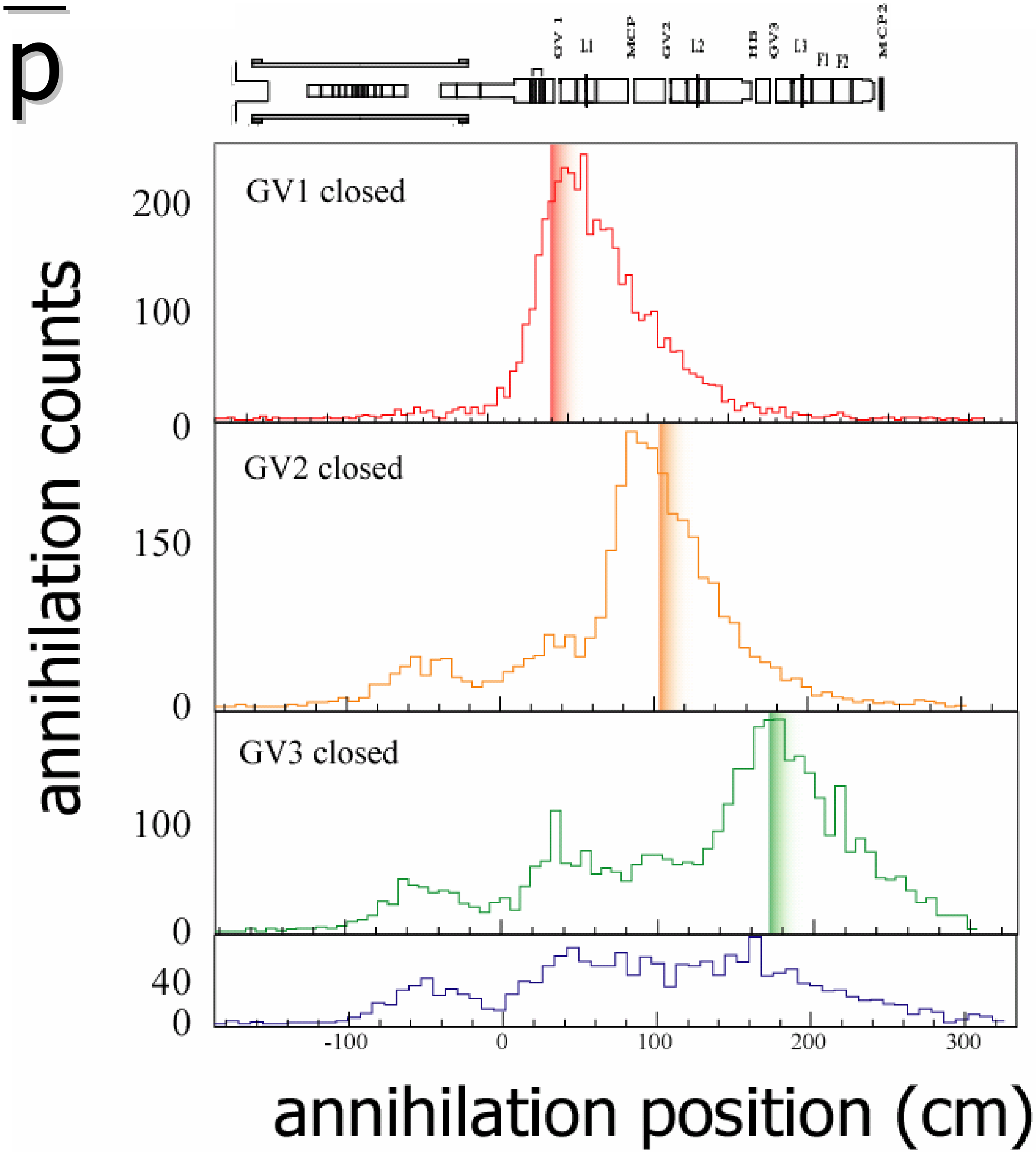
Transported

3.5m downstream

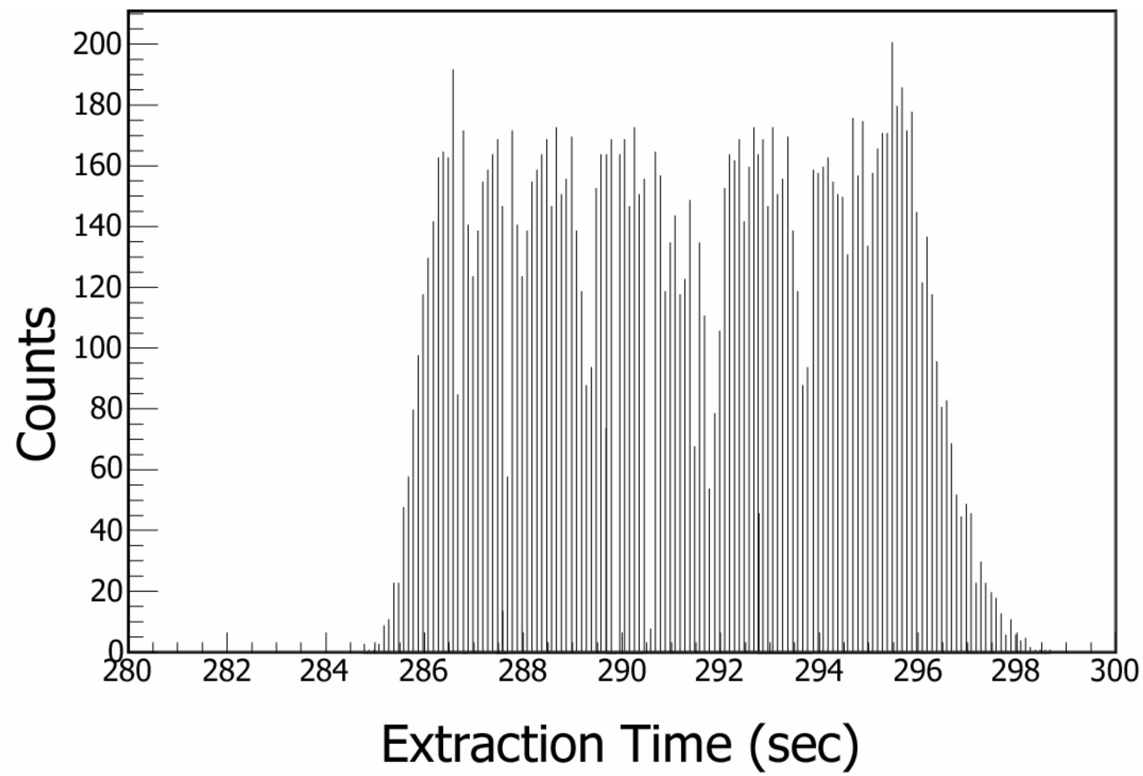
3 small apertures*

>30% efficiency

* Differential pumping of
6 orders of magnitude



Slow Extraction of Ultra -Slow $\bar{p}$ Beam



$\bar{p}$ accumulation and extraction

AD	3×10^{7} $\bar{p}$/shot (5MeV)	
RFQD	9×10^{6} $\bar{p}$/shot(0.12MeV)	30% (30%)
Isolation foil	6×10^{6} $\bar{p}$/shot(10keV)	70% (20%)
MRT captured	1.5×10^{6} $\bar{p}$/shot	25% (5%)
MRT cooled	1.2×10^{6} $\bar{p}$/shot	80% (4%)
Extracted	0.5×10^{6} $\bar{p}$/shot	50% (50%)

Ultra-slow $\bar{p}$ beam in 2004

Stable trapping: More than 1 Million $\bar{p}$s per AD shot

Extraction #: ~0.5 Million $\bar{p}$s per AD shot

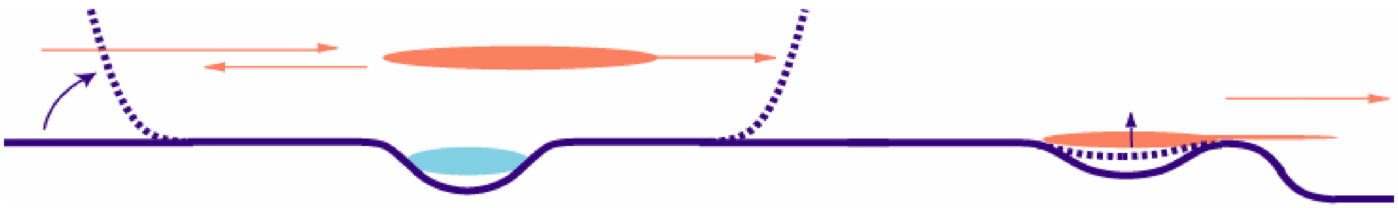
Extraction energy: 10-500eV

Extraction duration: ~10sec

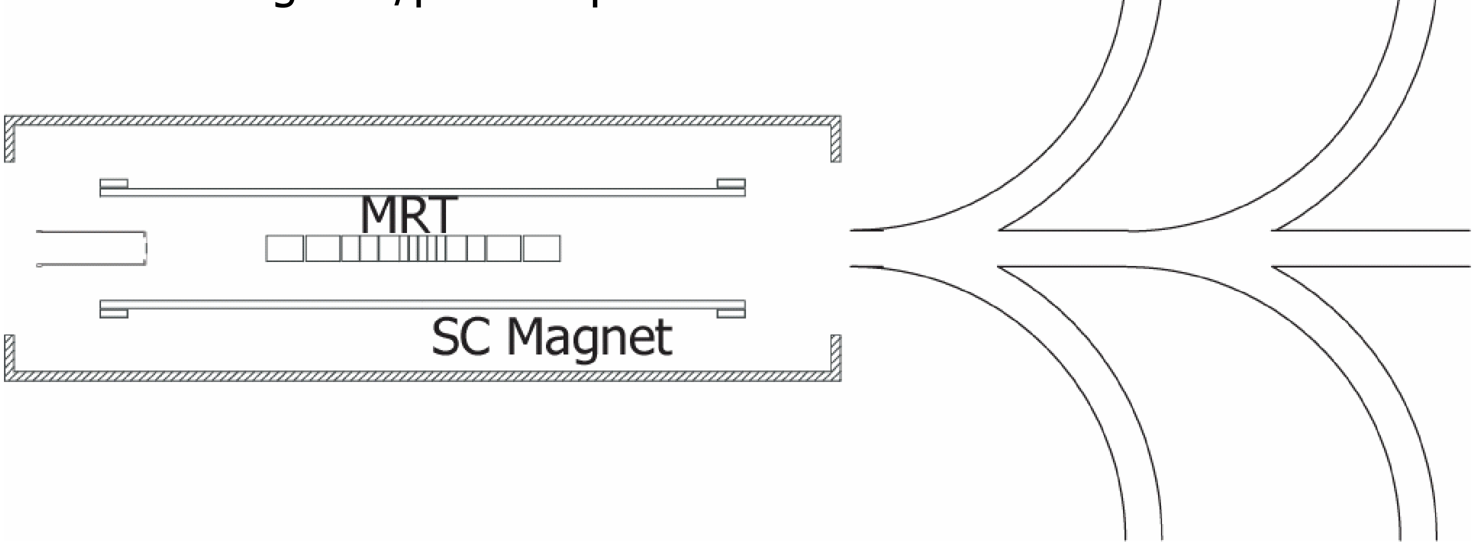
Differential pumping of 6 orders of magnitude

Ultra-Slow $\bar{p}$ Beam from 2006

DC & Pulsed Ultra Slow $\bar{p}$ Beam



Time sharing dc/pulsed $\bar{p}$ beam distributor



Summary

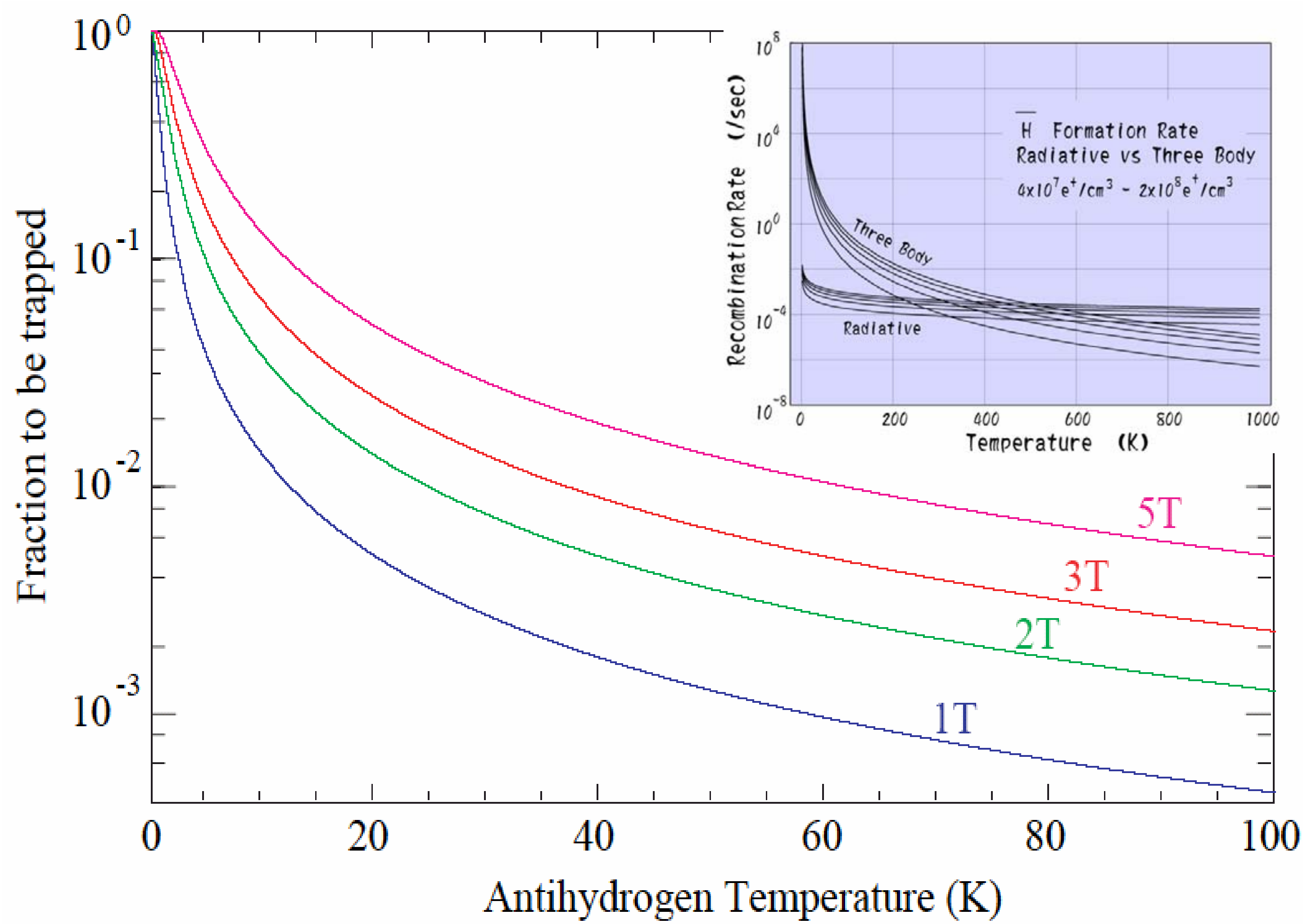
1. Intense ultra slow $\bar{p}$ beam is ready from 2006

2. New cross-disciplinary field will start

3. The cusp trap could be a potential candidate for the future $\bar{H}$ study

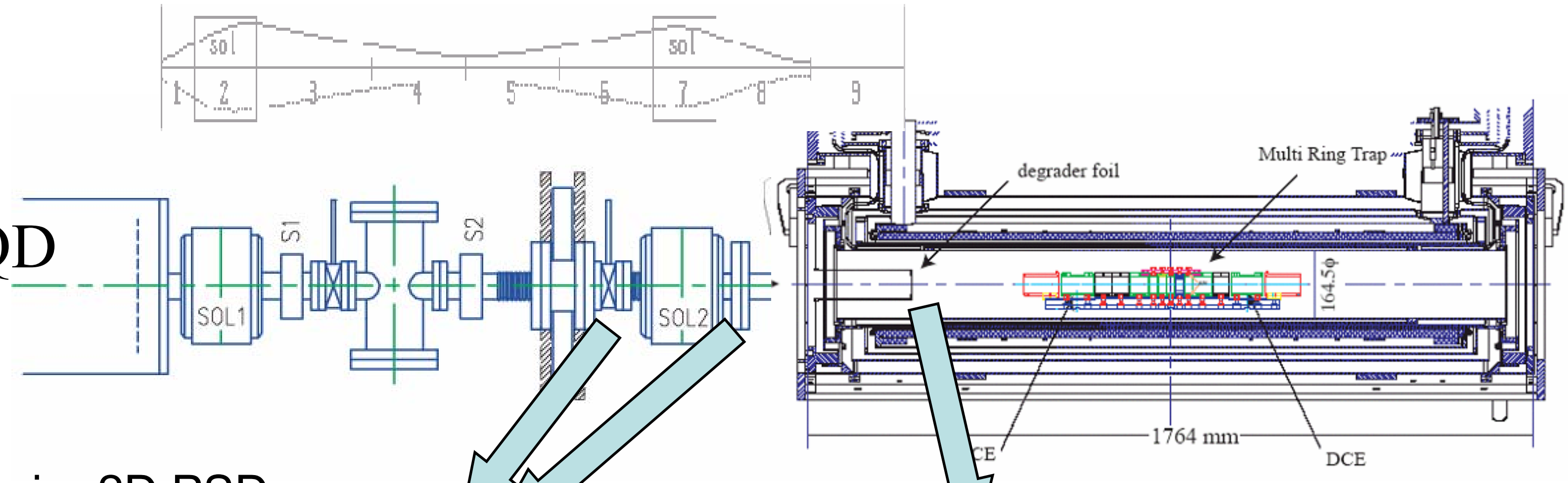
$\overline{H}$ fraction to be trapped

Assumption : $\overline{H}$s in 1S state, MB-distribution



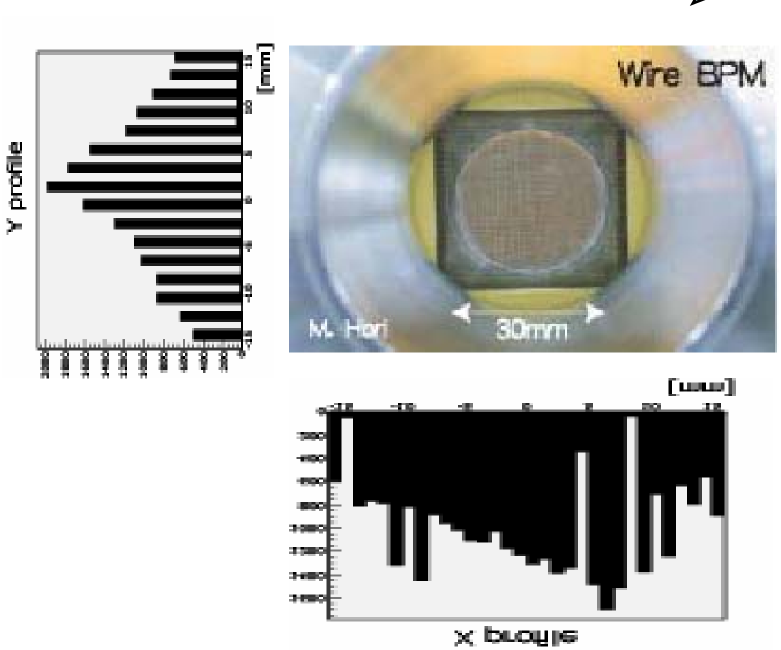
LEBT+ Multi-Ring Trap

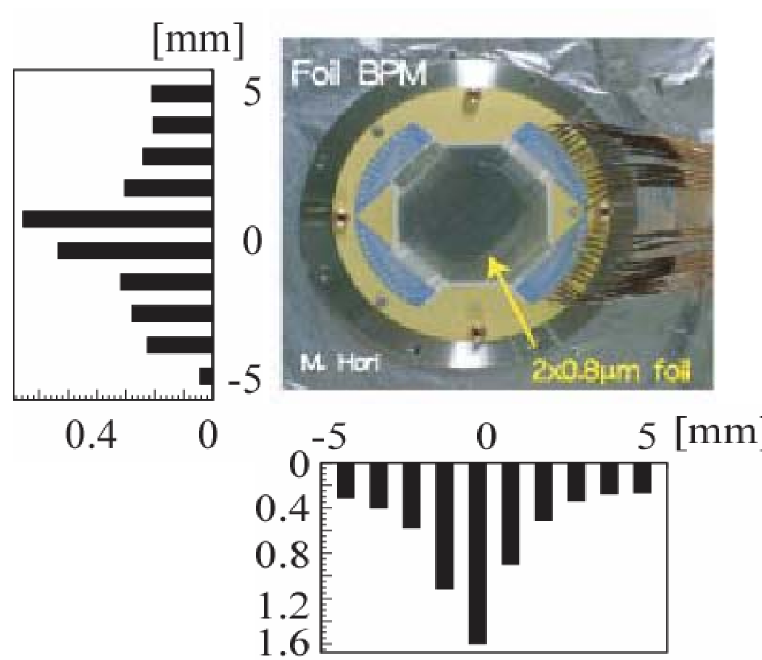
RFQD



Multi-wire 2D PSD

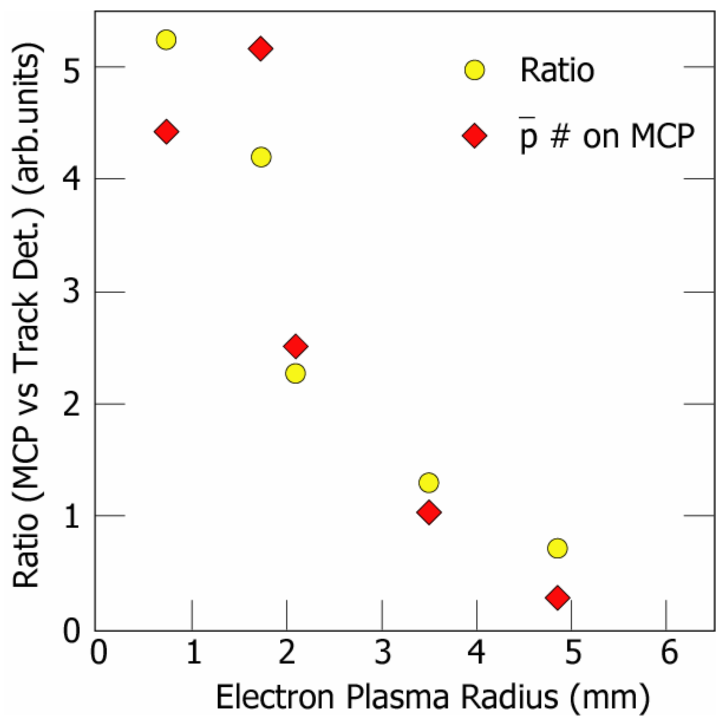
Vacuum Isolation + 2D PSD

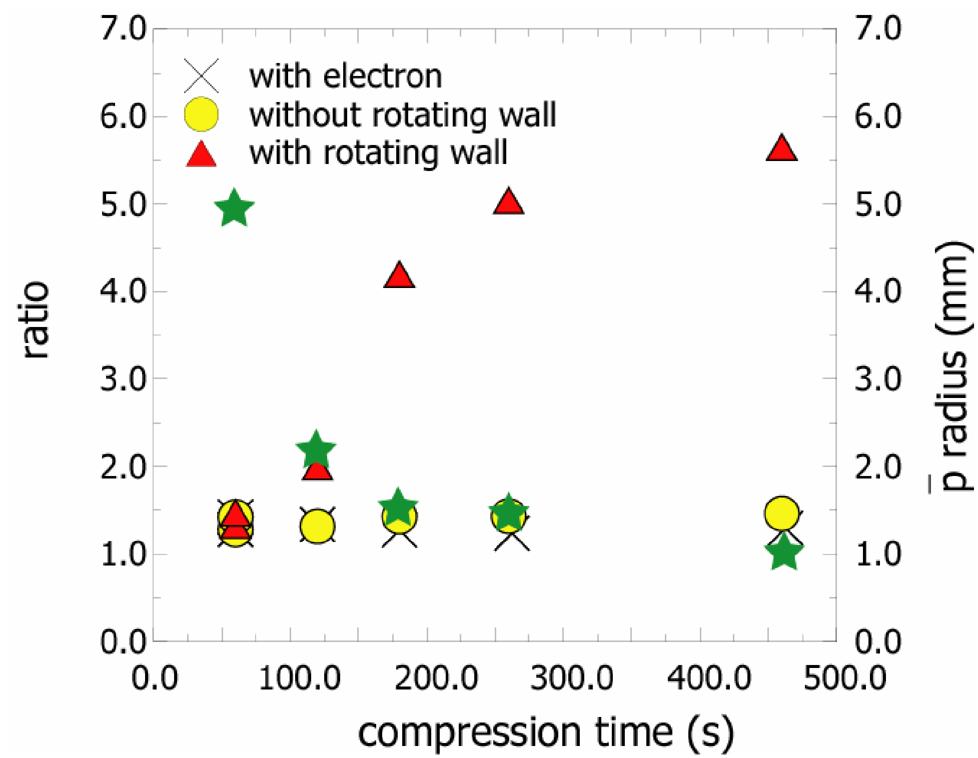




Cooling Feature vs Electron Plasma Radius

Cooled $\bar{p}$s locate only where cooling electron plasma exist





Particles vs Antiparticles

	$(m_m - m_a)/m$	$(q_m + q_a)/q$	$(g_m - g_a)/g$
e^- vs e^+	$<8 \times 10^{-9}$	$<4 \times 10^{-8}$	$(-0.5 \pm 2.1) \times 10^{-12}$
p vs $\bar{p}$	$(-2.5 \pm 2.3) \times 10^{-8}$	$(-2.5 \pm 2.3) \times 10^{-8}$	$(-2.6 \pm 2.9) \times 10^{-3}$
n vs $\bar{n}$	$(9 \pm 5) \times 10^{-5}$	----	----

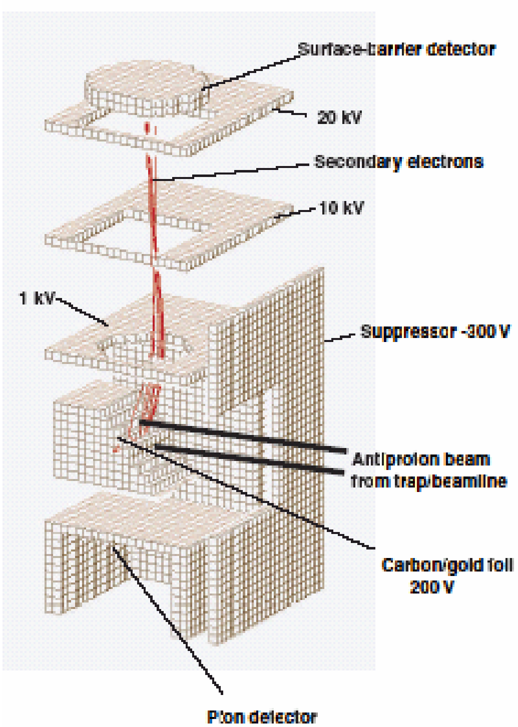
(e^- vs e^+) :cyclotron motion + Ps 1^3S_1-2^3S_1 cyclotron motion

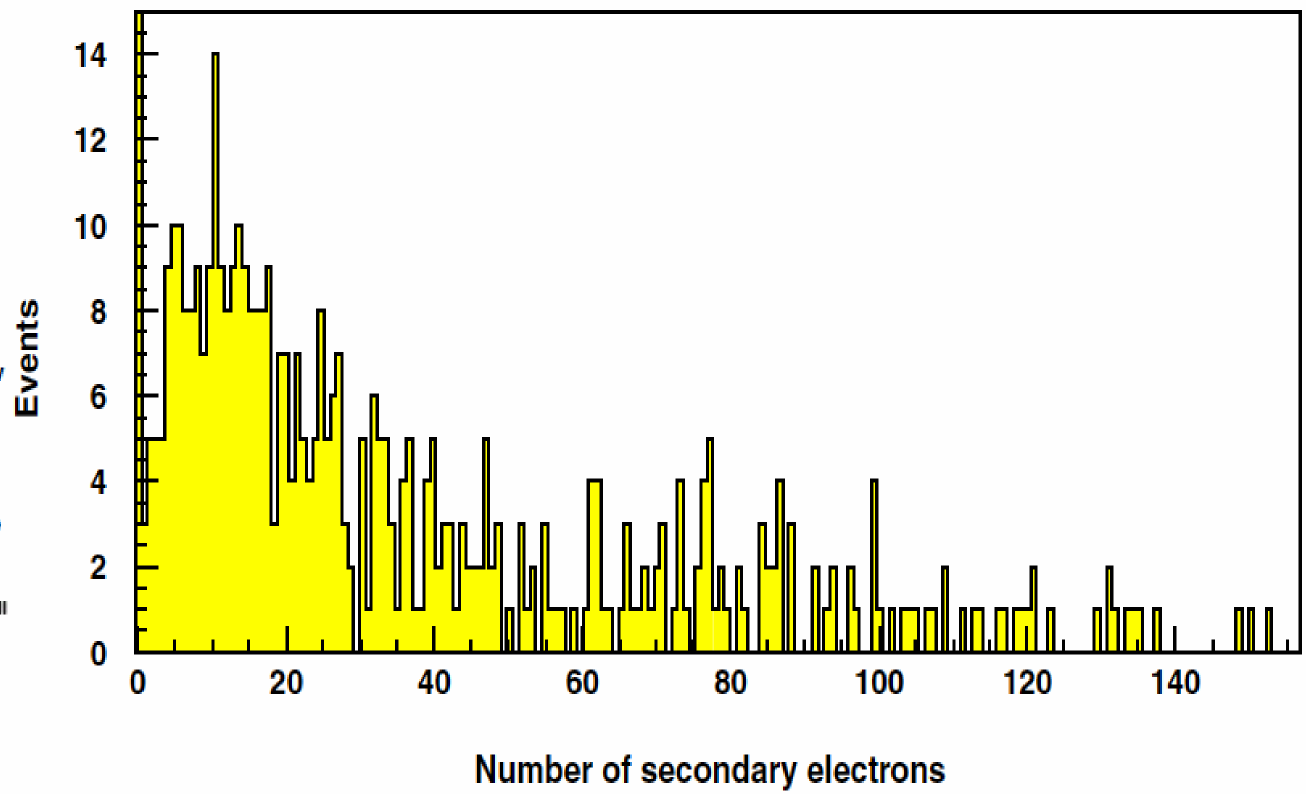
(p vs $\bar{p}$) :cyclotron motion + $\bar{p}He^+(nl,n'l')$ $\bar{p}A$ x-ray

n vs $\bar{n}$: $\bar{p}+p \rightarrow \bar{n}+n$

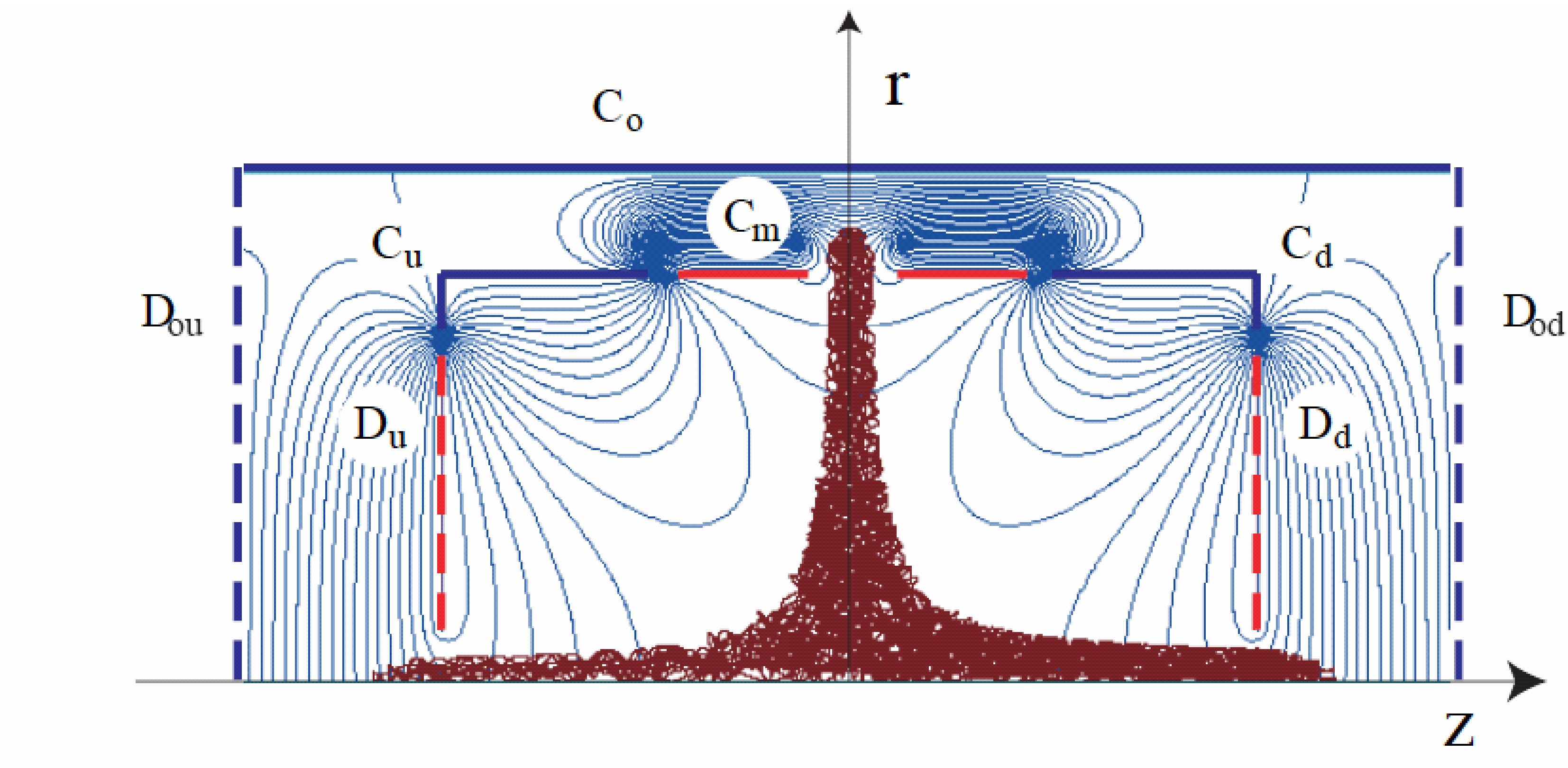
Octupole trap + $\bar{p}$ plug

Secondary Electron Emission with Ultra Slow $\bar{p}$ Beam





Plugging of (anti)proton



Sympathetically cooled with e^+

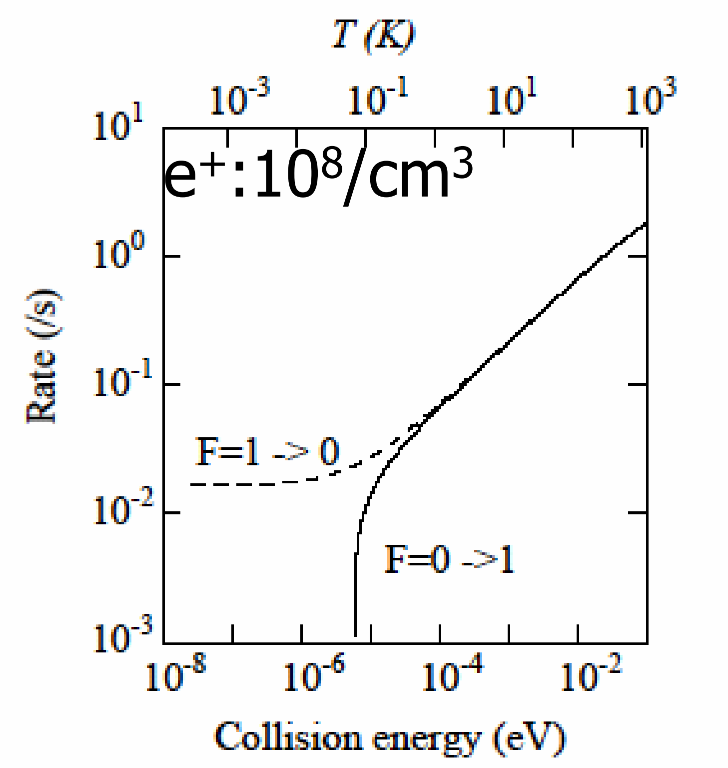
$\overline{\mathrm{H}}$ loss mechanism

Majorana spin-flip

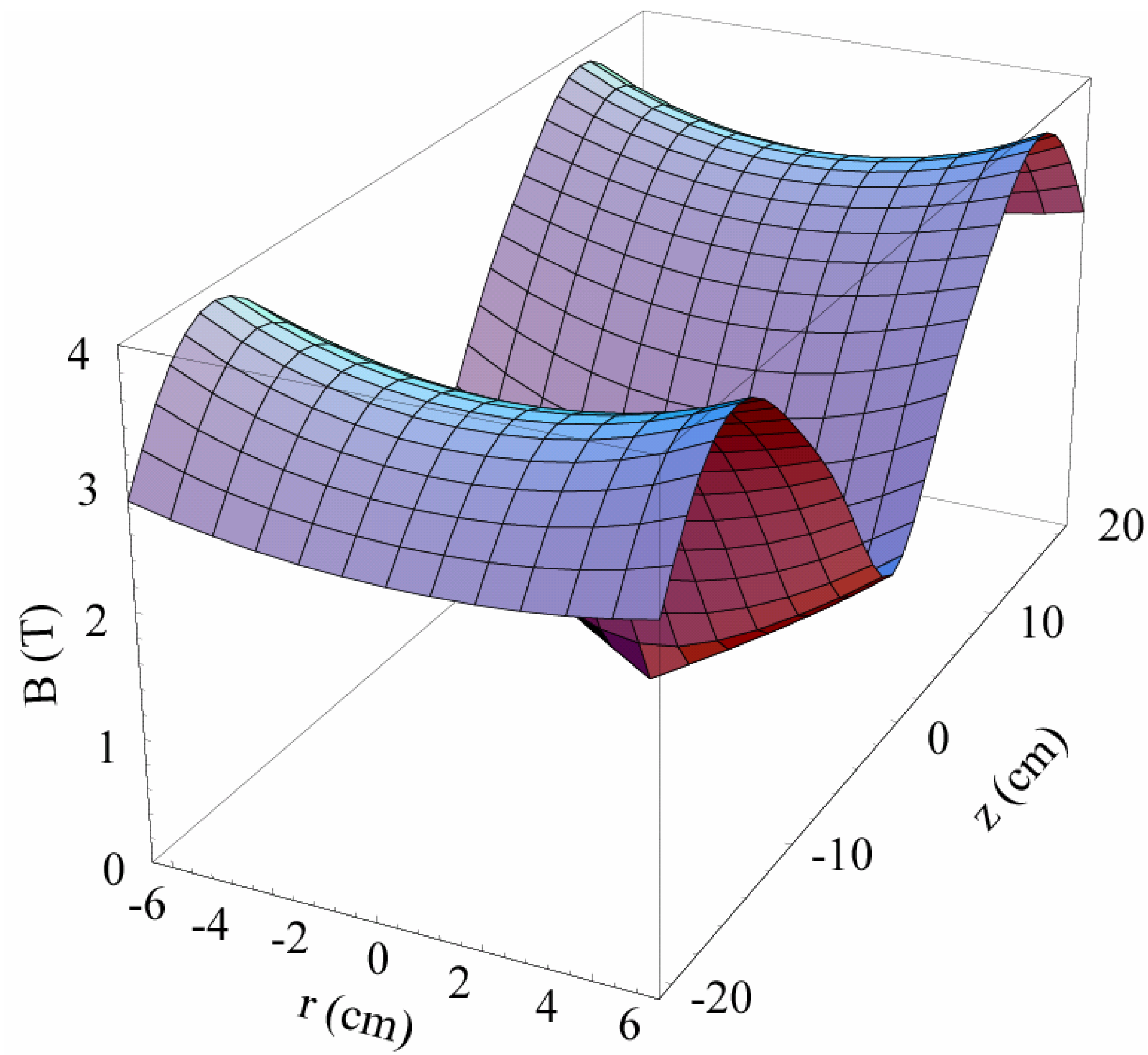
$$\frac{\hbar v}{\mu B}\frac{\partial B/\partial r}{B} \ll 1 \Rightarrow x \gg 3\times10^{-3}T^{1/4}\ (cm)$$

e.g., ~10mK Na trapping ~1sec
@ 10^{-8} Torr & 0.025T

Spin-flip induced by $e^+ + \overline{\mathrm{H}}$ collisions

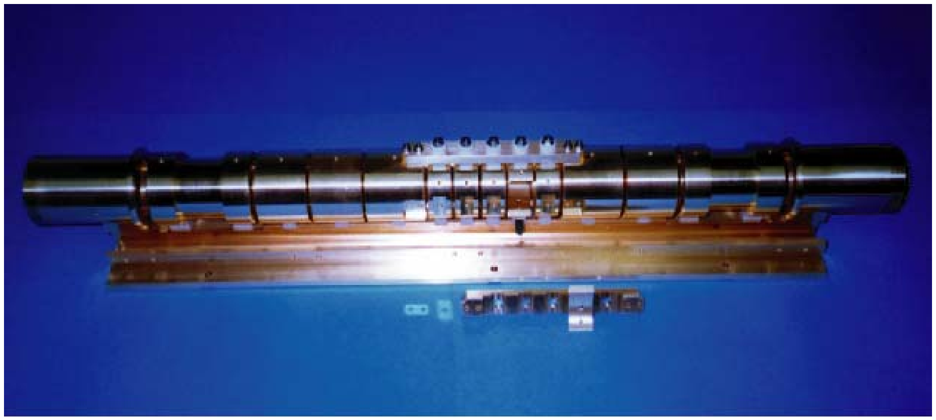


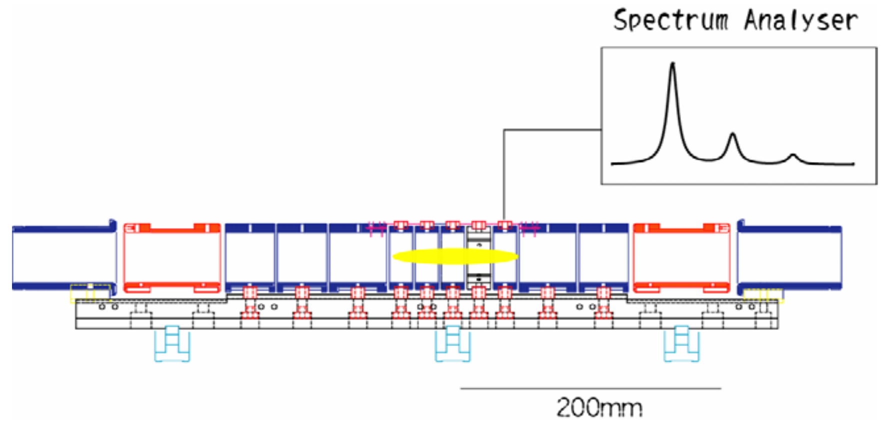
Octupole trap + $\bar{p}$ plug

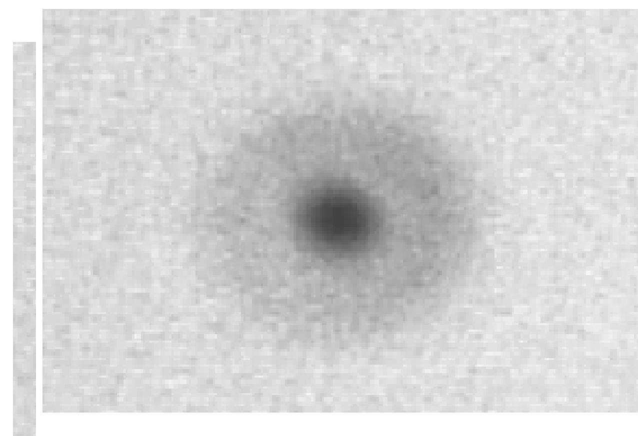


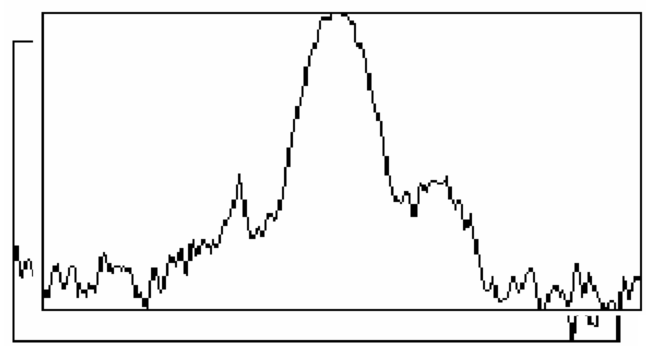
B (T)
4
3
2
1
0
-6
-4
-2
0
2
4
6
r (cm)
-20
-10
0
10
20
z (cm)

Multi-Ring Trap









Non-neutral plasma

Rigid Rotation

Compression

T-dependent plasma mode

Hydrogen & Antihydrogen

$f_{1S\text{-}2S}(H)$ = 2 466 061 413 **1**87.2937 kHz

(Phys.Rev.Lett.84(2000)3232)

Proton charge radius : 0.862(12)fm vs 0.877(24)fm

$$\nu_{HF} = \frac{16}{3}\left(\frac{M_p}{M_p + m_e}\right)^3 \frac{m_e}{M_p} \frac{\mu_p}{\mu_N} \alpha^2 c \quad Ry$$

ν_{HF}(H)= 1 420 405 751,766 7 $\pm$ 0,000 9 Hz

μ(H) = (2,792 847 337 $\pm$ 0,000 000 029) μ_N

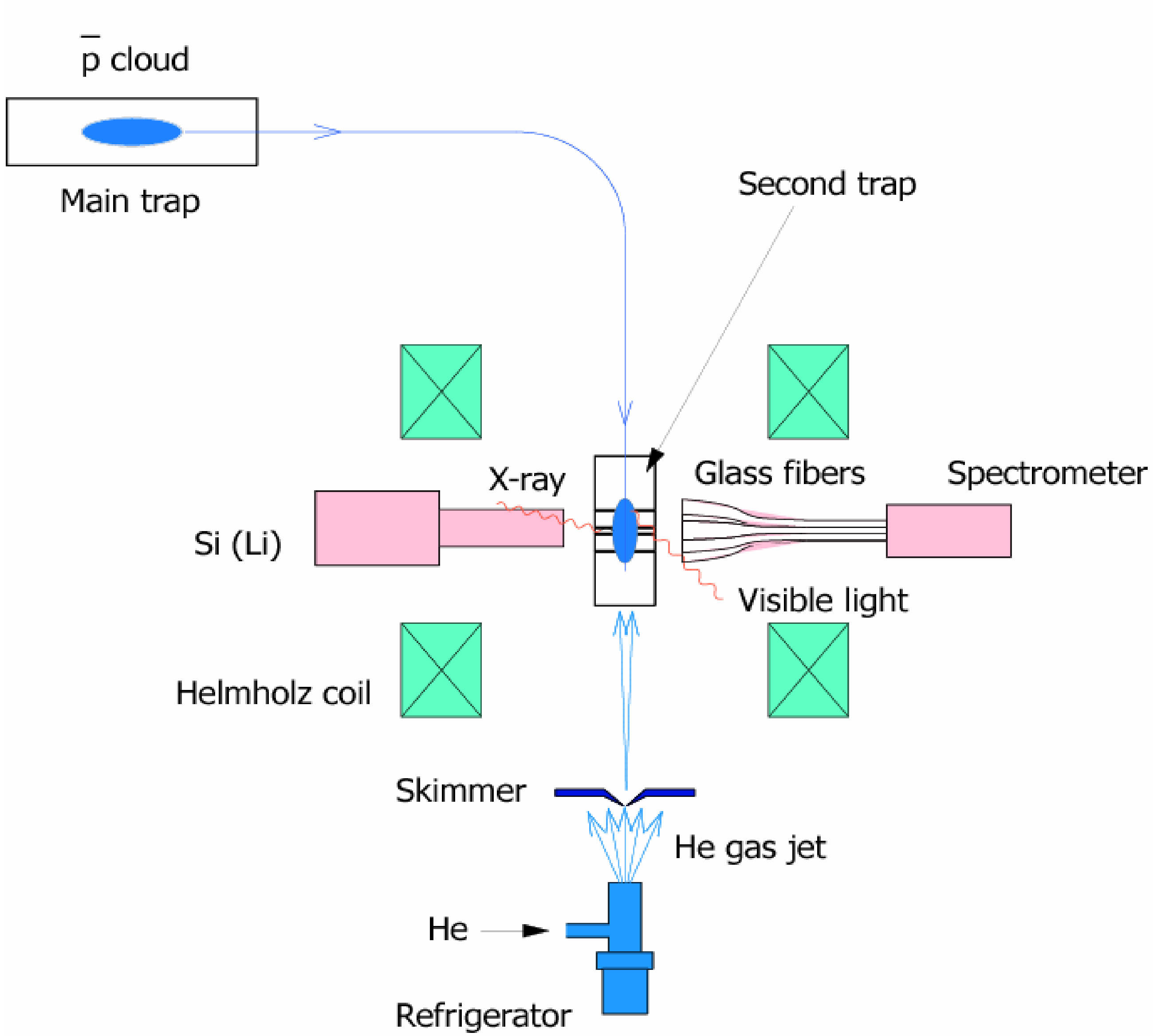
$\mu(\bar{H})$ = (-2,800 $\pm$ 0,008) μ_N

Production Scheme

Trapping/Cooling of Antiprotons

AD → degrader foil → Penning Trap : ~0.1%

AD → RFQD → Multi-ring Trap: 4%



$\bar{p}$ cloud
Main trap
Second trap
X-ray
Glass fibers
Spectrometer
Si (Li)
Visible light
Helmholz coil
Skimmer
He gas jet
He
Refrigerator