2005/09/23, Galena, IL, USA, COOL05

Cooling techniques for trapped particles and new trends in physics with trapped particles

What to do with slow $\bar{p}$

Red:ASACUSA+FLAIR

Blue:FLAIR

1. Atomic physics of Antimatter

   $\bar{H}$ Formation (also $\bar{p}\mu^+$ formation)

   CPT symmetry test via $\bar{H}$ vs H ($\bar{p}\mu^+$ vs $p\mu^-$), gravity

2. Atomic physics of "heavy electron"

   Ionization by heavy electron

   exchange collision between $\bar{p}$ and e^-: $\bar{p}A^+$ formation

   (nuclear surface structure: $\bar{p}A^+$ Annihilation)

3. Non-neutral plasma physics

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

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3. Non-neutral plasma physics

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

What to do with slow e^+

1. Atomic collisions with e^+

   $\overline{H}$ Formation

   Ionization and Ps formation in e^+-atom collisions

   Ps-surface interaction

   Cooling of highly-charged ions

2. e^+-e^- plasma

3. "Half-" matter chemistry: Ps (e^+e^-), Ps^+, Ps^-, Ps_2

CPT symmetry test

☆One possible measure: Planck mass

$$M_{pl} = \sqrt{\hbar c / G} \approx 10^{19} GeV/c^2$$ → Force the Nature to say

☆Listen to a whisper of the Nature

$$(m_p / M_{pl}) m_p \sim 10^{-19} GeV/c^2$$

☆High precision measurements at low energy

	Experimental value (Hz)	$\delta\nu_{exp}/\nu$	$\lvert\nu_{th}-\nu_{exp}\rvert/\nu$
$\nu_{1S\text{-}2S}$	2,466,061,413,187,103 (46)	1.7×10^{-14}	1×10^{-11}
ν_{HFS}	1,420,405,751.768 (1)	7.0×10^{-13}	$(3.5 \pm 0.9) \times 10^{-6}$

2. Trapping, cooling, and manipulation of $\bar{p}$s

	AD		RFQD		MRT		
$\bar{p}$:	2.6GeV	→ 5.3MeV	→ 100keV	→ 10keV	→ 0.1eV	(→ 10^{-4}eV)	
$\bar{p}$ #:	5×10^7	3×10^7	9×10^6	1.5×10^6	1.2×10^6		

Kinetic energy decrease : ~10(13) orders of magnitude

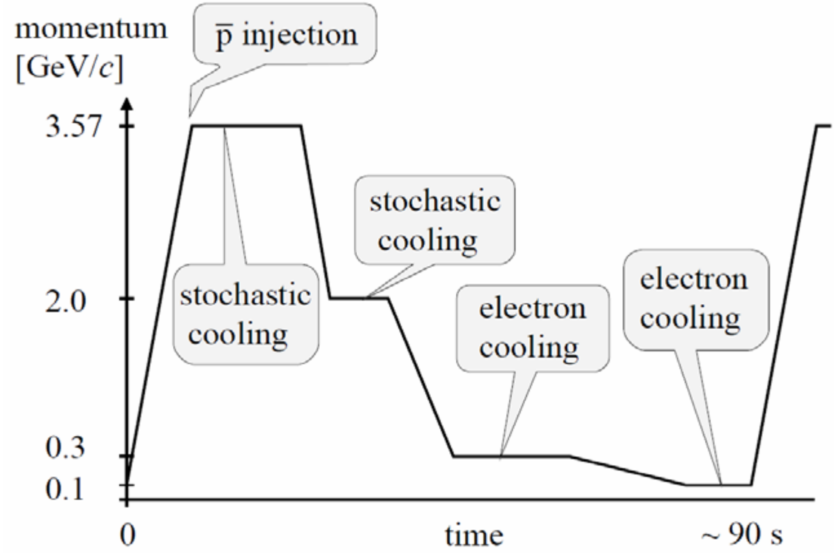
Accumulation efficiency: ~4%

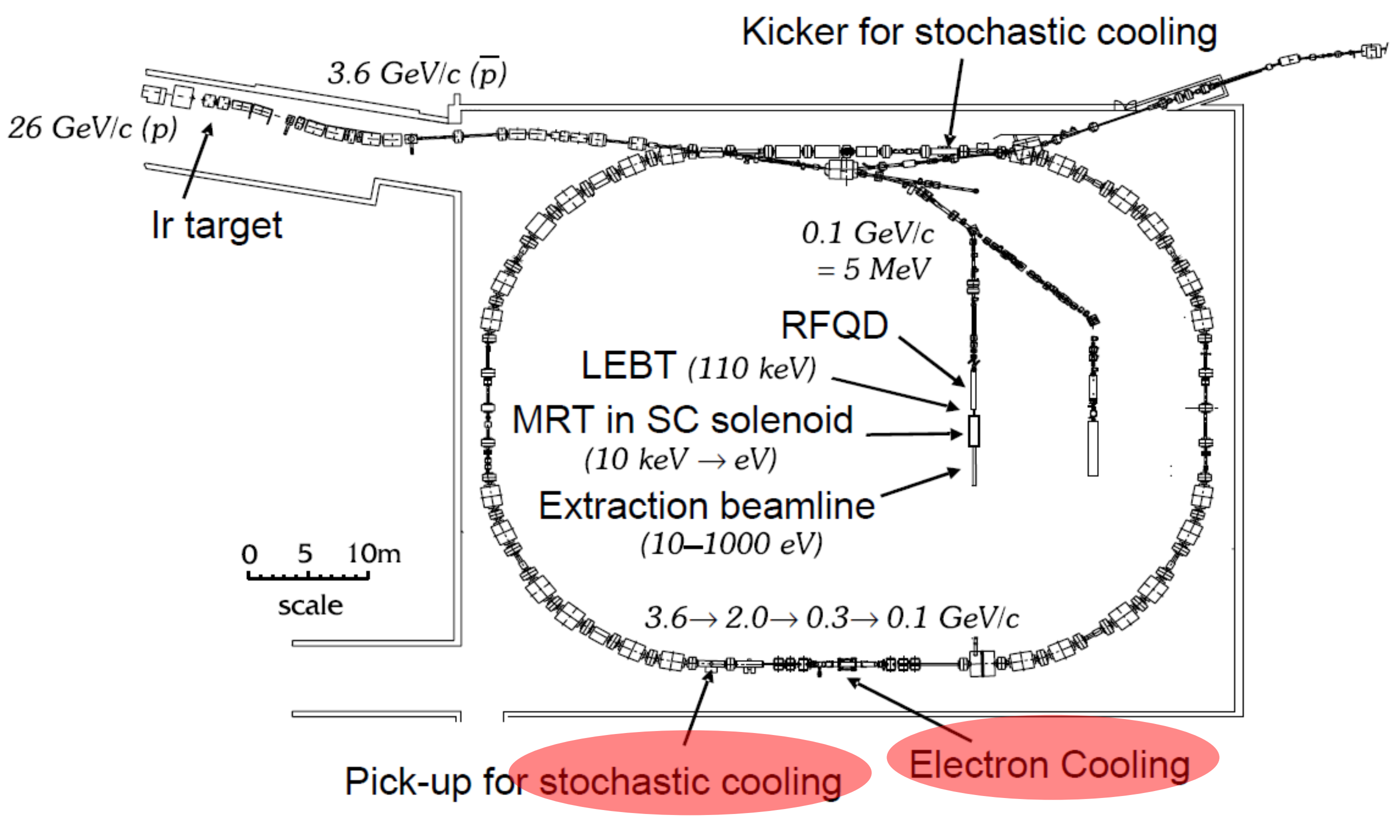
cf: traditional degrader foil scheme :

5.3MeV → 10keV → sub eV

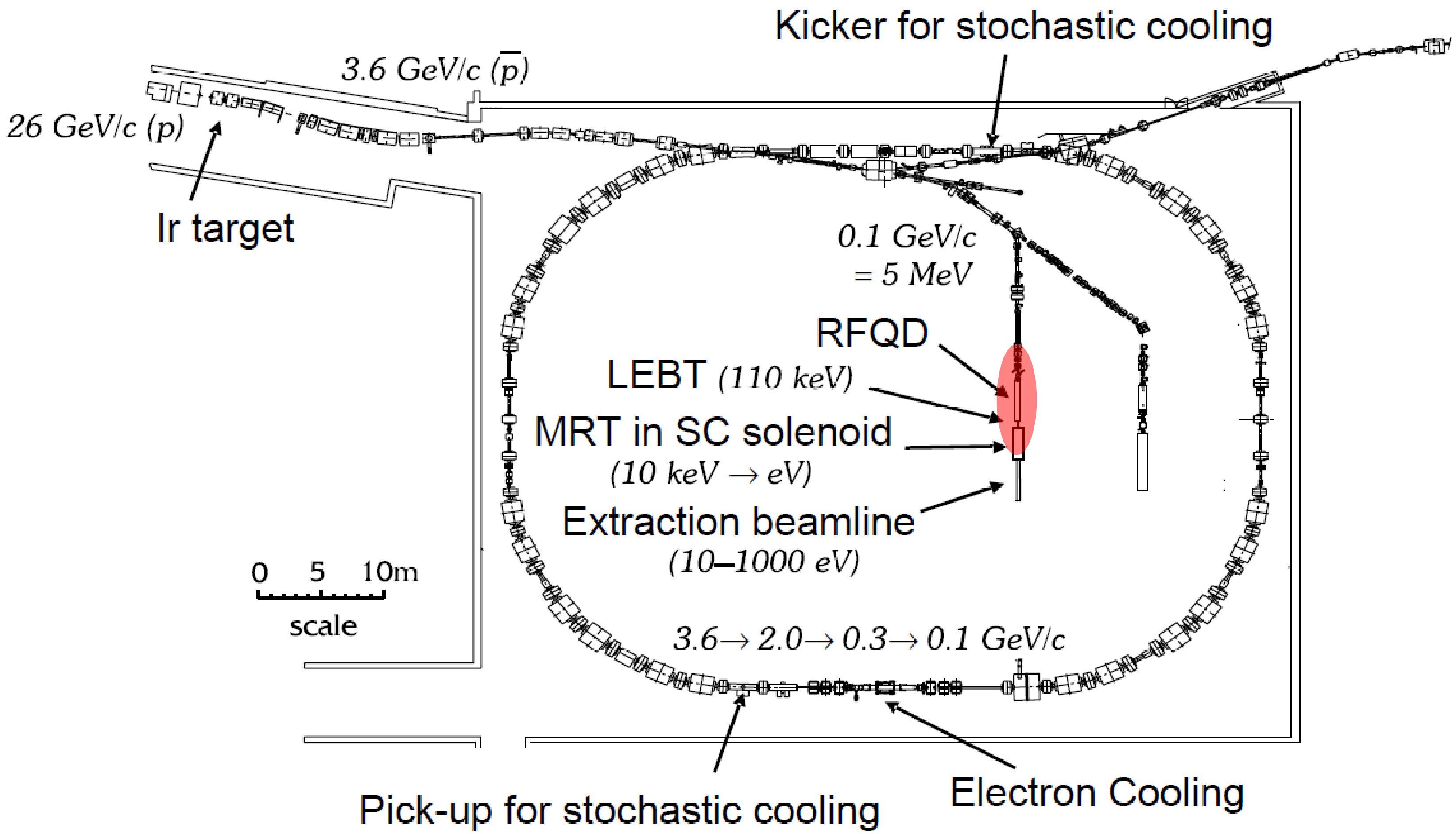
Accumulation efficiency: <0.1%

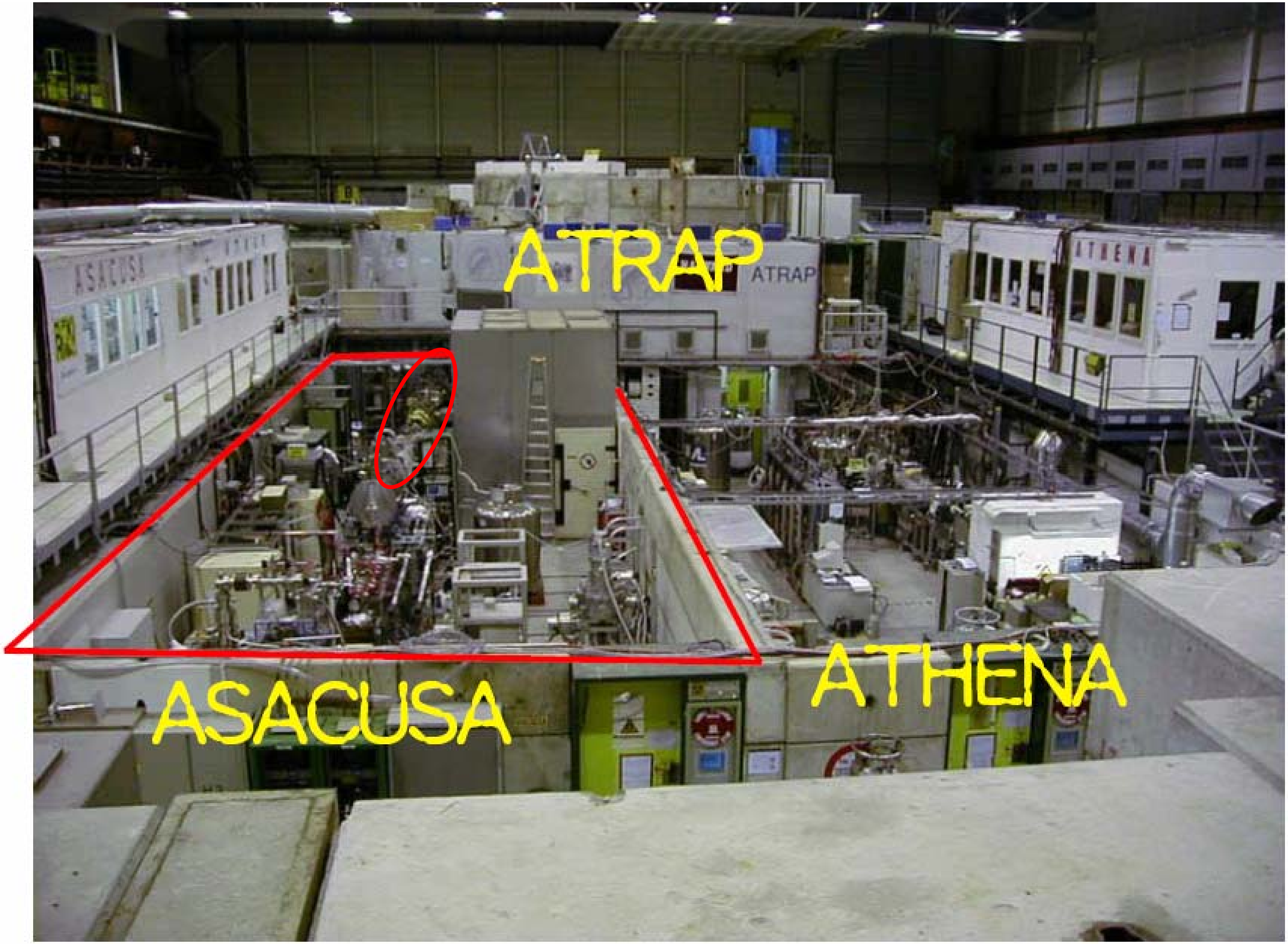
AD: 2.6GeV→5.3MeV



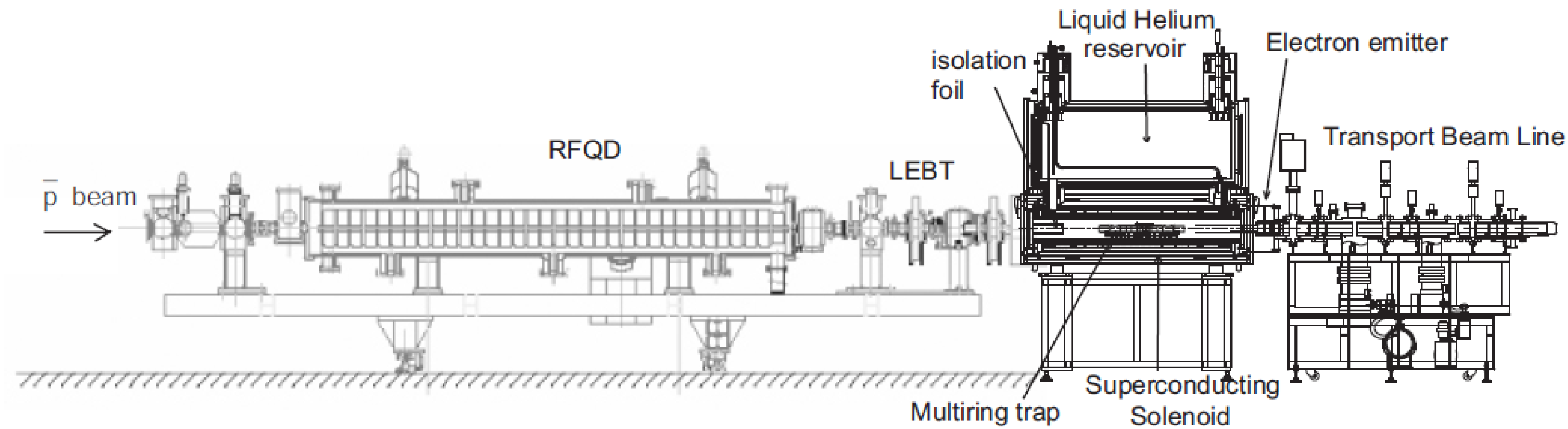


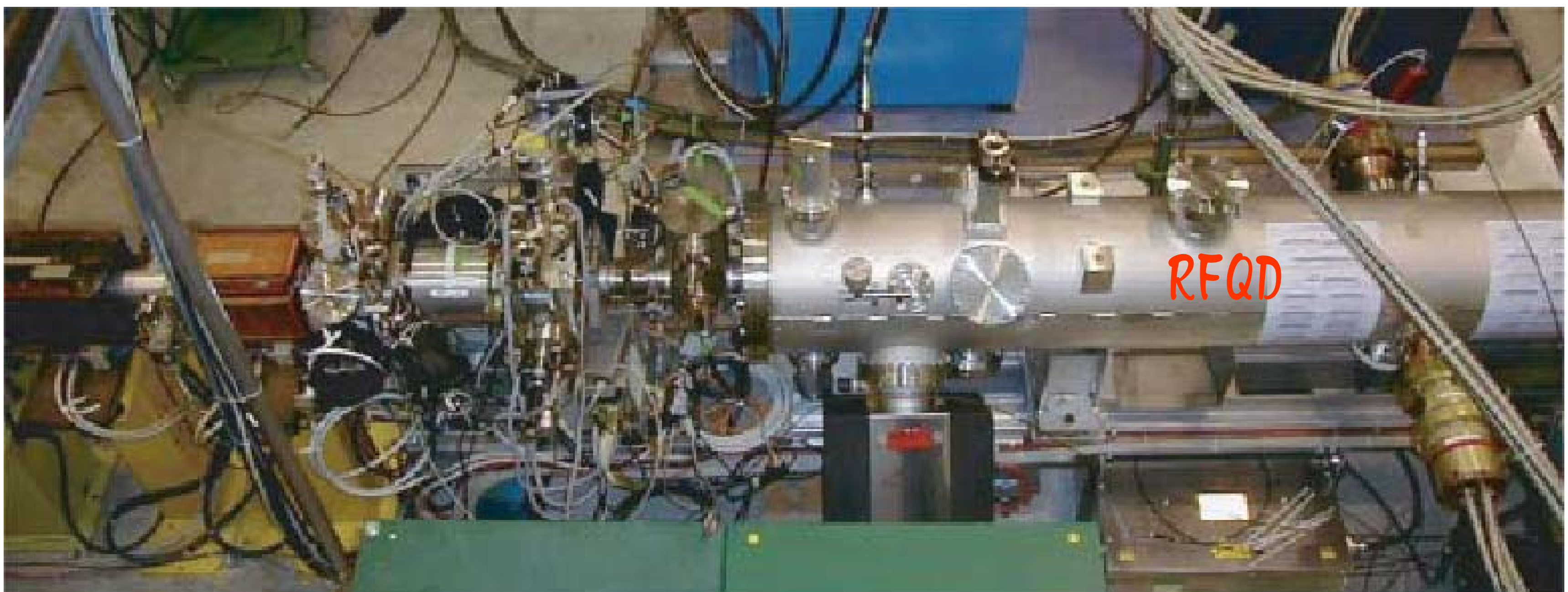
RFQD:5.3MeV→0.1MeV



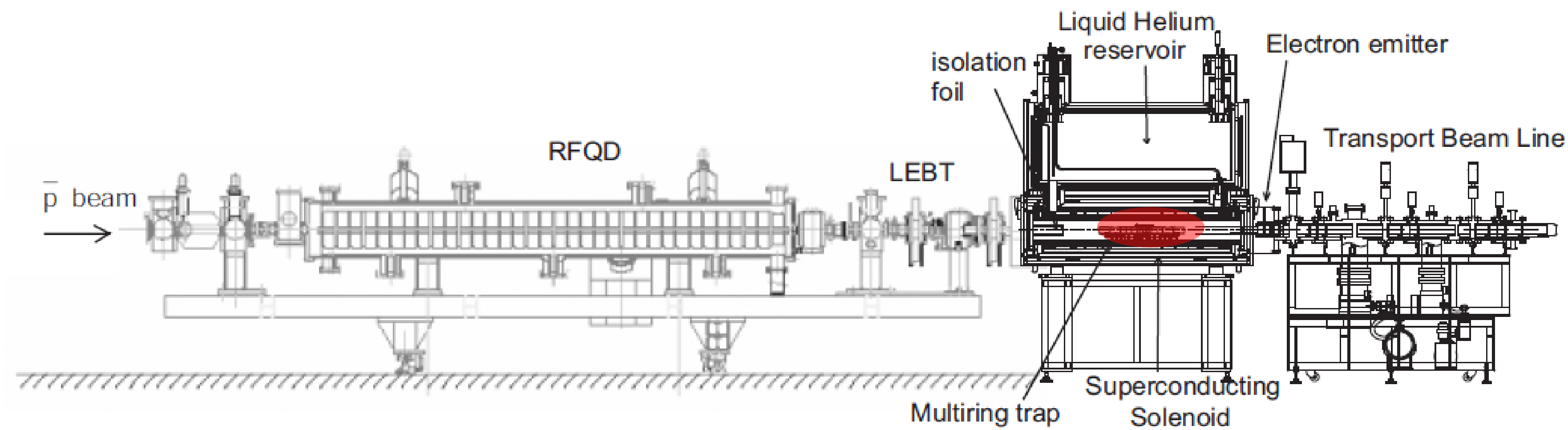

ATRAP
ASACUSA
ATHENA
ASACUSA
ATRAP
ATHENA

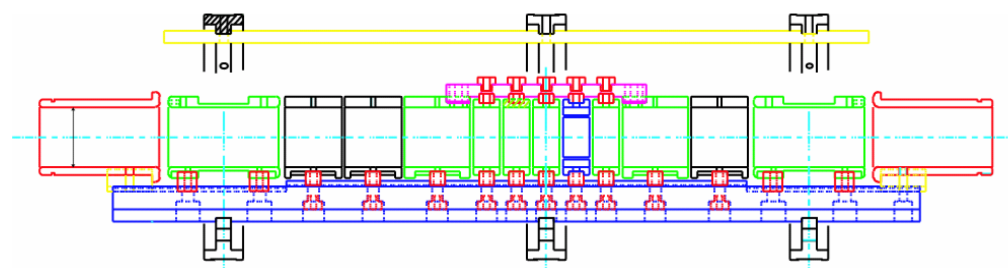
RFQD-MRT-Extraction beamline





MRT (Multi-Ring-Trap)

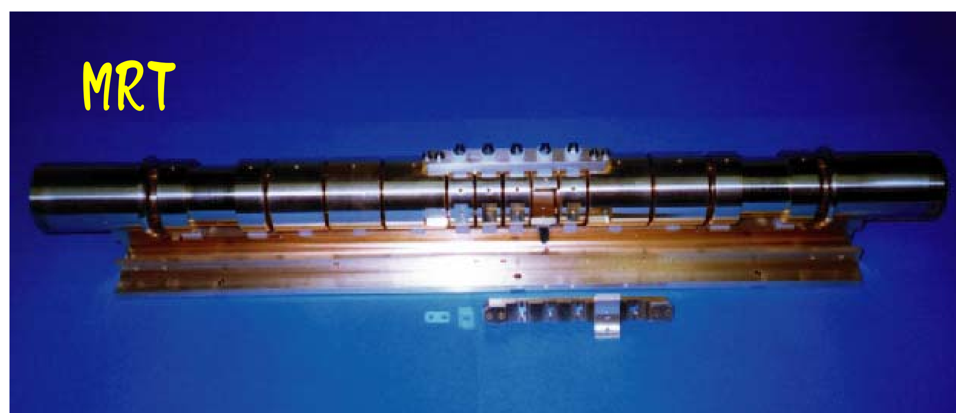




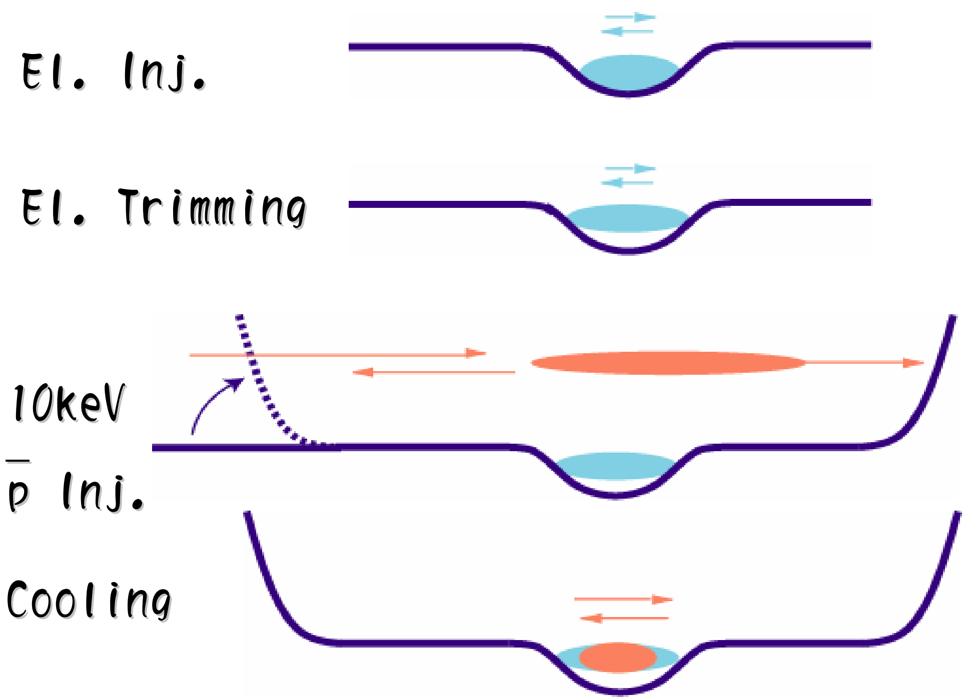
Harmonic potential

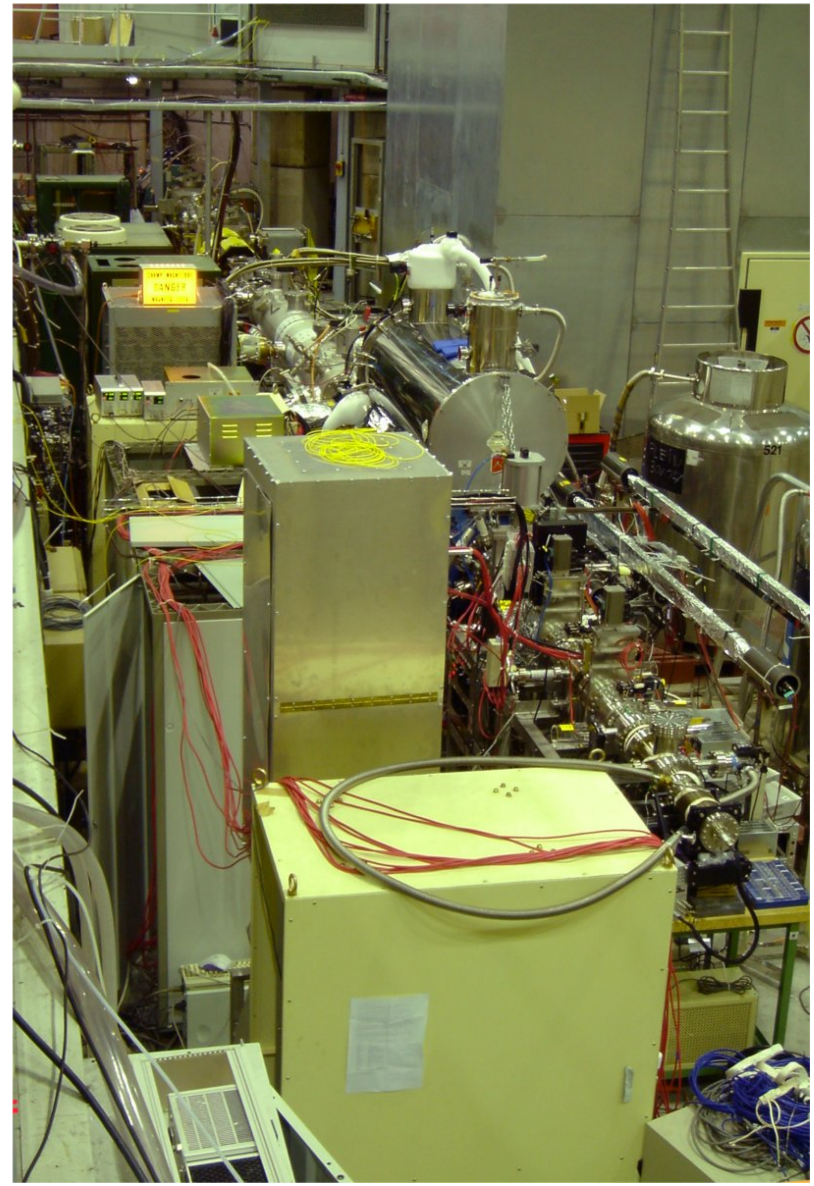
Spheroidal plasma

Rigid rotation



MRT: cooling below 10keV





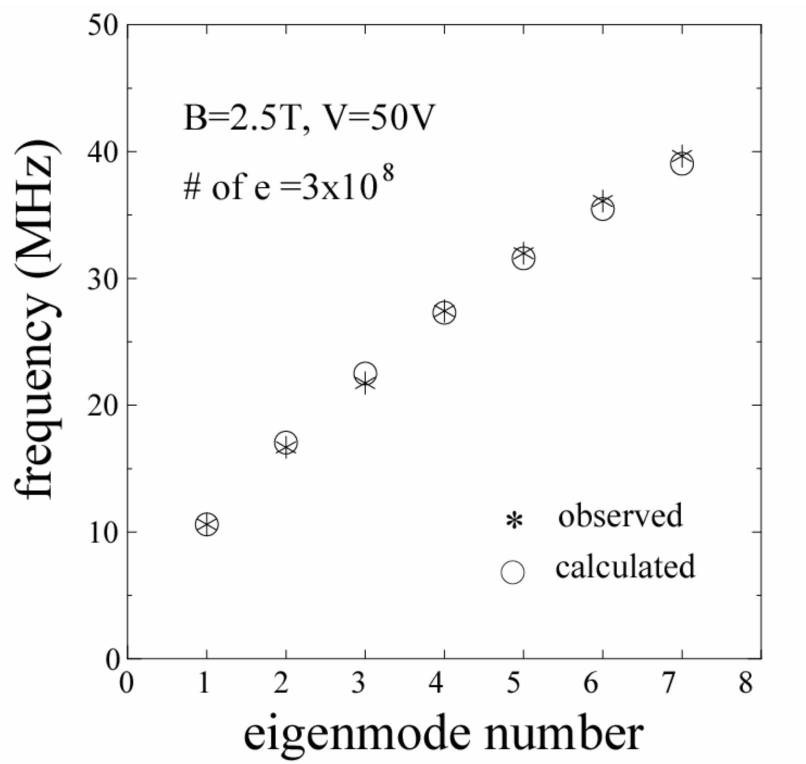
Synchrotron cooling of e^-

Sympathetic cooling of $\bar{p}$

5 shots stacking: 5million $\bar{p}$

Cooling of $\bar{p}$s : realtime meas.

$$\frac{\epsilon_3}{\epsilon_0} = 1 - \frac{\omega_p^2}{\omega_l^2} = \left(\frac{\alpha - \epsilon_3/\epsilon_0}{\alpha^2 - 1}\right)^{1/2} \frac{P_l(\xi_1)Q_l'(\xi_2)}{P_l'(\xi_1)Q_l(\xi_2)}$$



$$\xi_1 = \alpha/\sqrt{\alpha^2 - \epsilon_3/\epsilon_0}$$

$$\xi_2 = \alpha/\sqrt{\alpha^2 - 1}$$

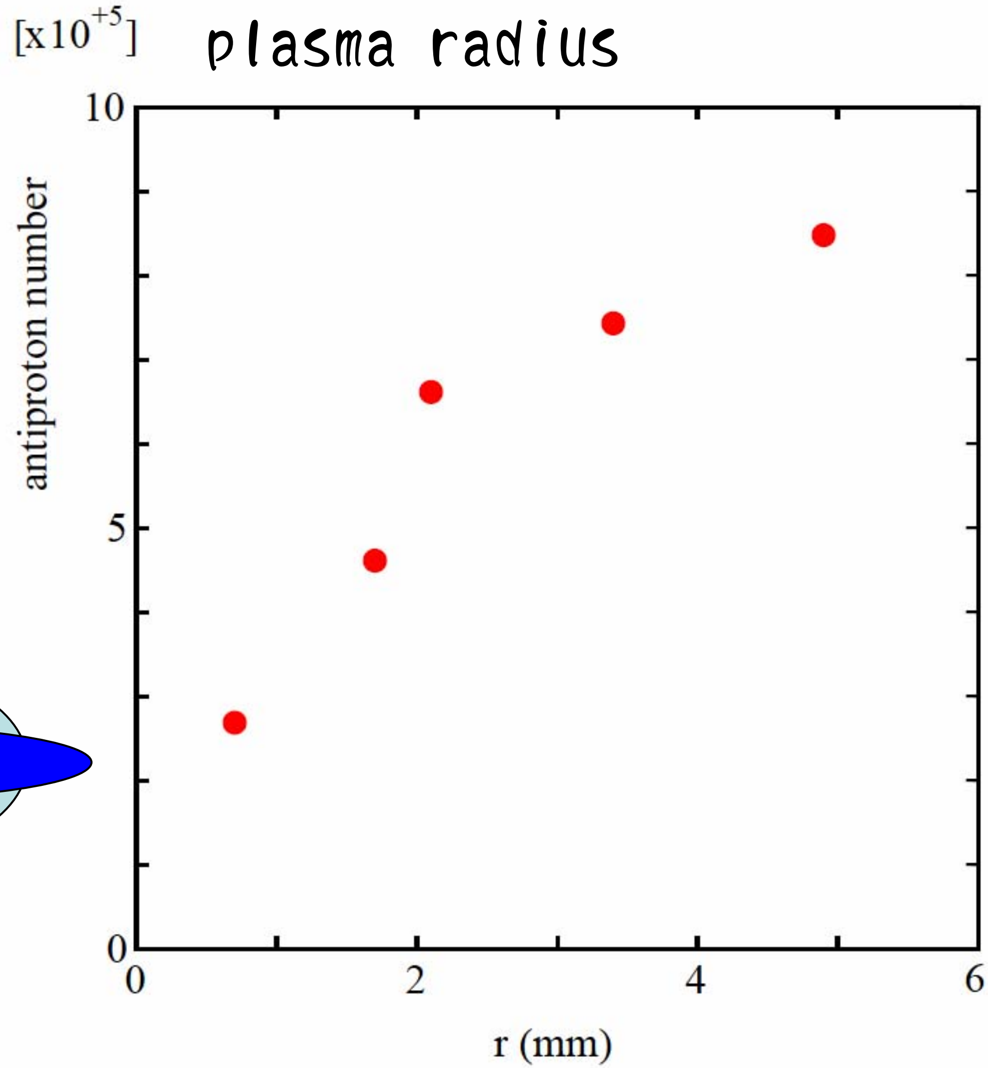
$$\frac{\epsilon_3}{\epsilon_0} = 1 - \frac{\omega_p^2}{\omega_l(T)^2}\left(1 + \frac{3k_B T}{m}\frac{k_l^2}{\omega_l(T)^2}\right)$$

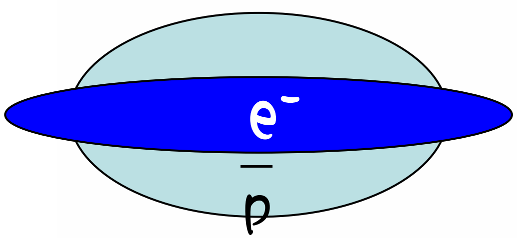
→ΔT~0.6eV, τ_{cool}~20-30s

Kuroda et al., PRL94(05)023401

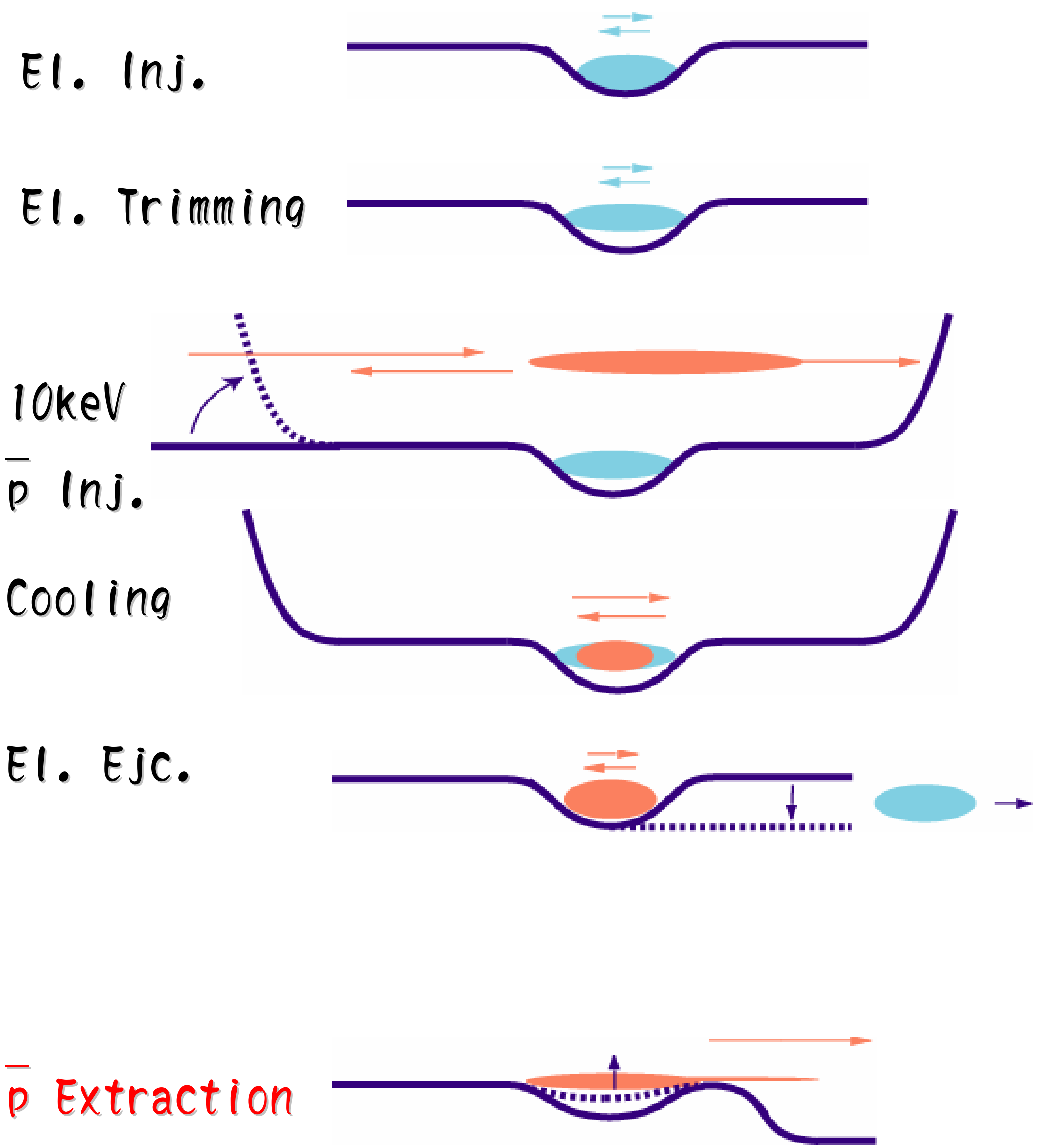
Behavior of $\bar{p}$ cloud

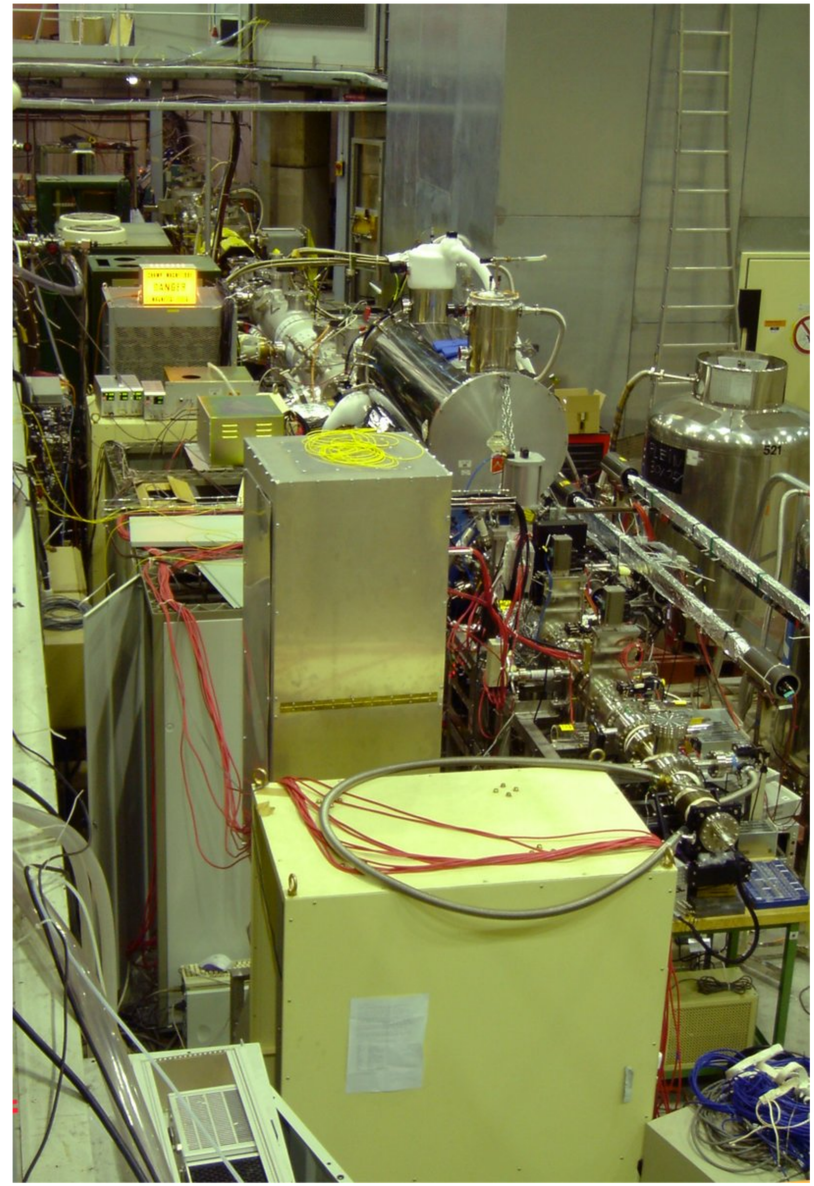
Trapped $\bar{p}$s vs electron plasma radius





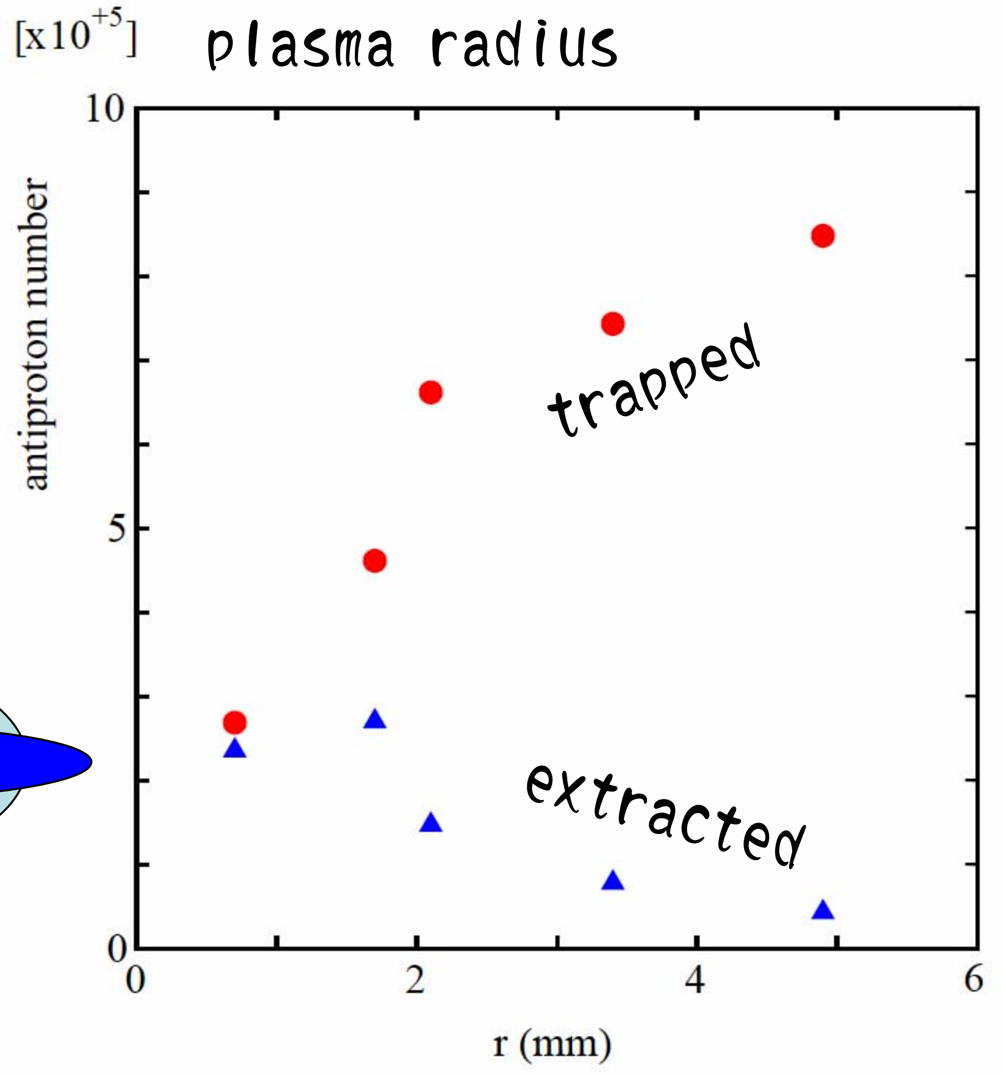
Trapping, cooling, & extraction

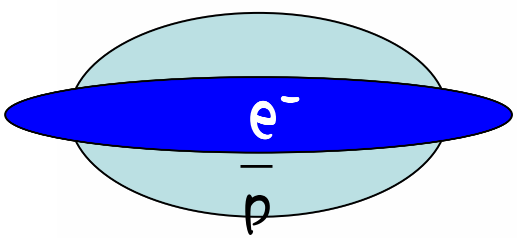




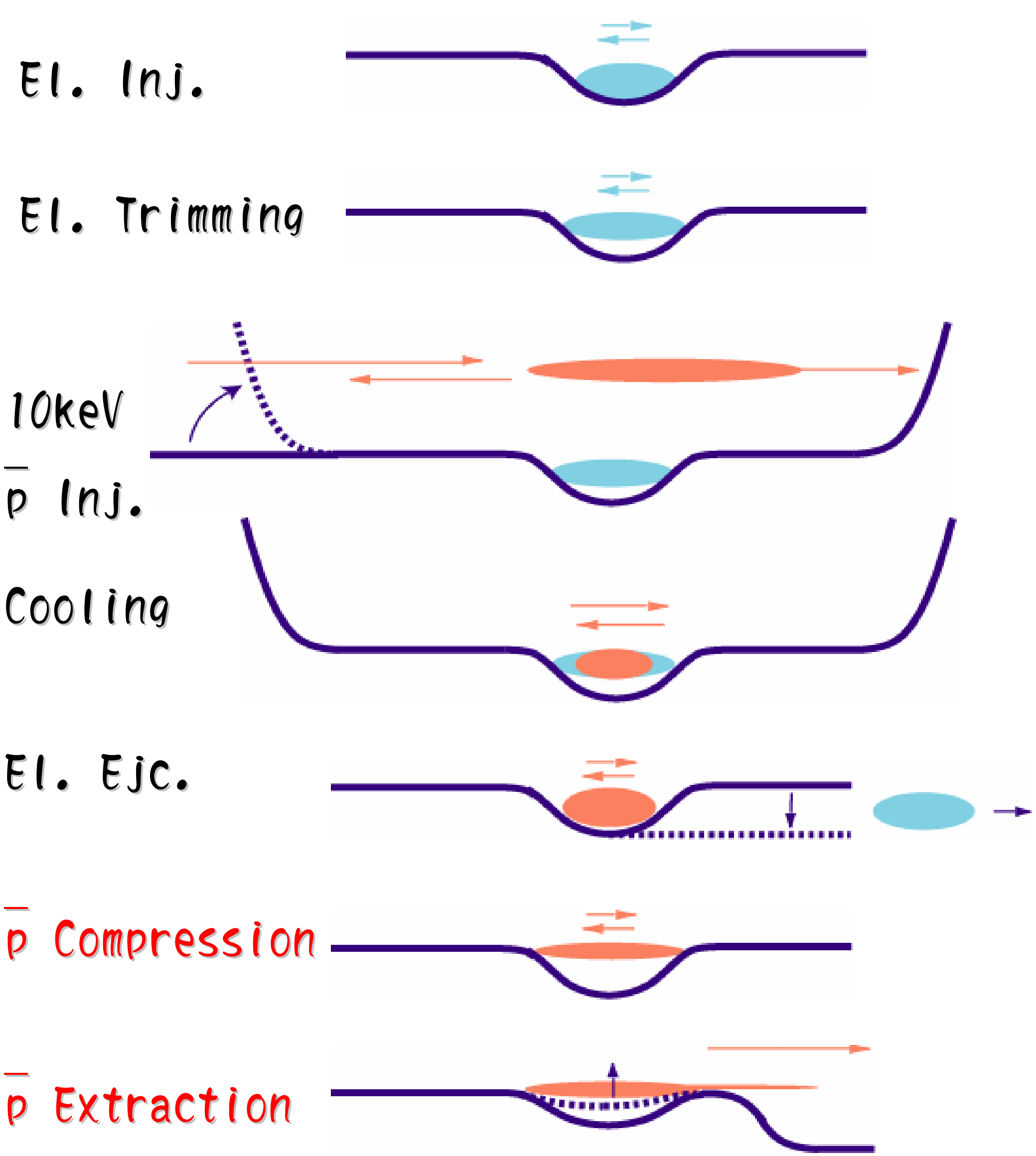
Behavior of $\bar{p}$ cloud

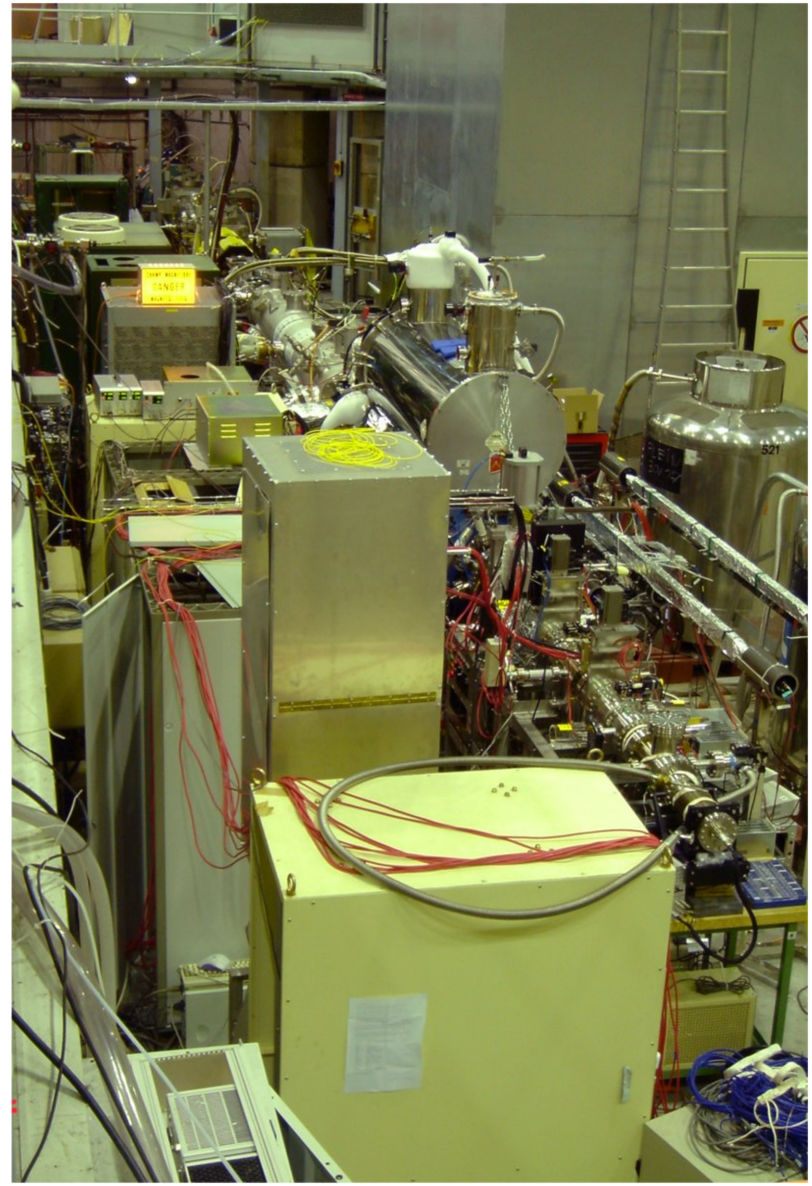
Extracted $\bar{p}$s vs electron plasma radius



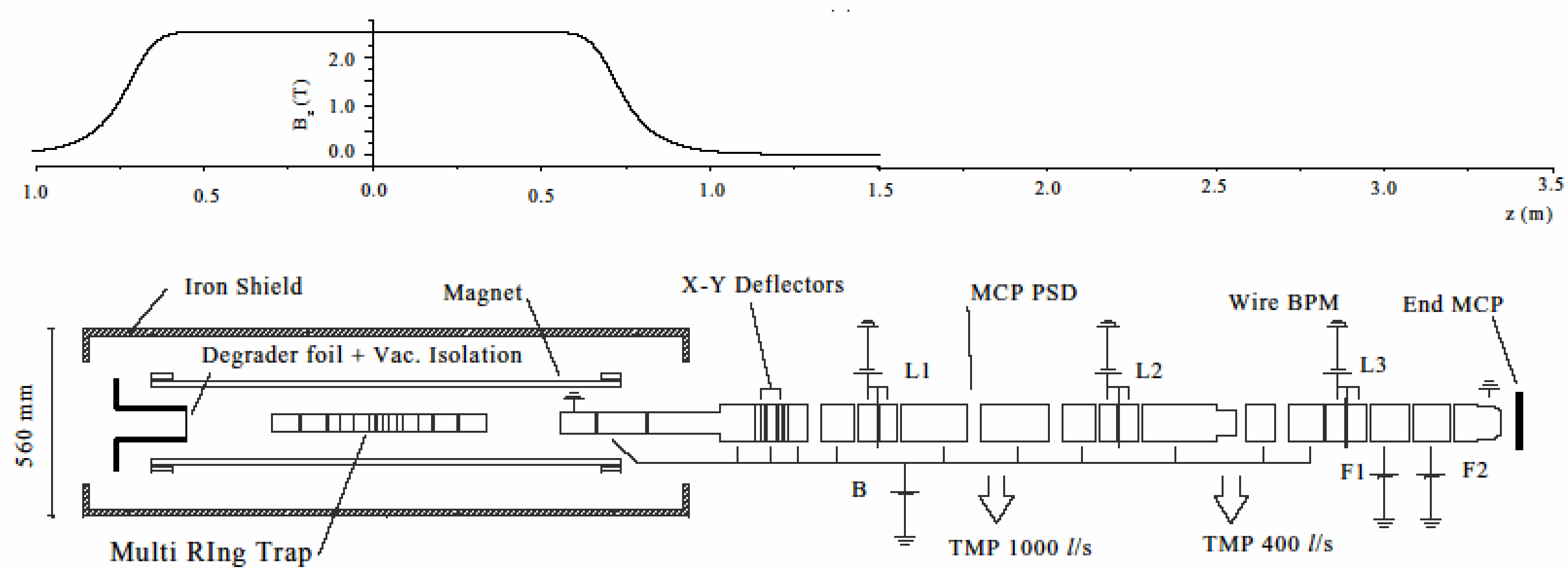


Trapping, cooling, & extraction





Extraction beamline for gas collision

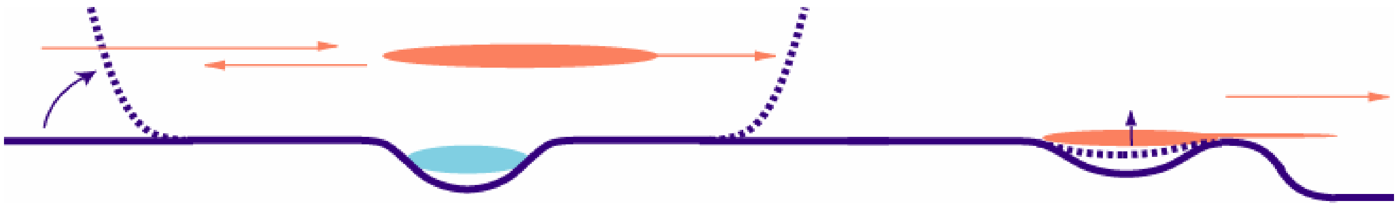


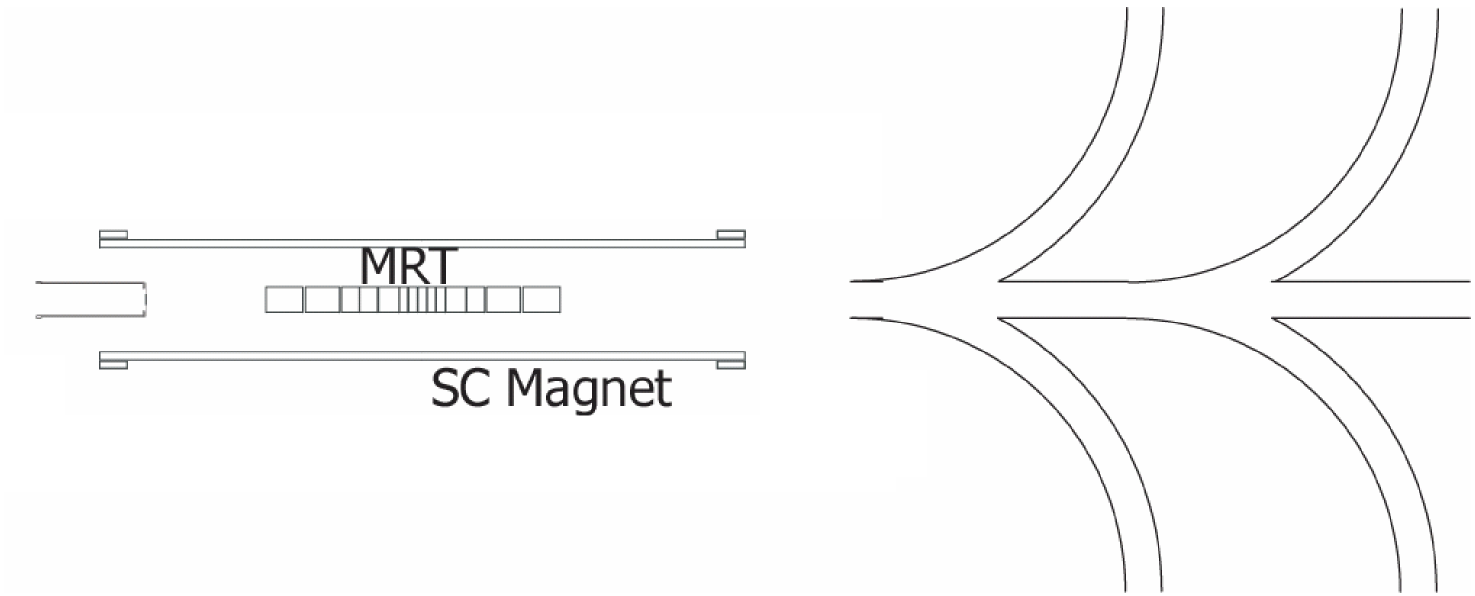
Differential pumping：6 orders of magnitude

Transport efficinecy：>50%

Distribution beamline of $\bar{p}$ beam

DC & Pulsed Ultraslow $\bar{p}$ Beam





→new age of ultraslow $\bar{p}$ science

Comparison among different schemes

Degrader Foil: 10^3-10^4/AD shot

MUSASHI(present): 1.2×10^6/AD shot (3-4 shots for $\bar{p}$ comp.)

ELENA(expected): 1.3×10^7/AD shot (cooling, transport?)

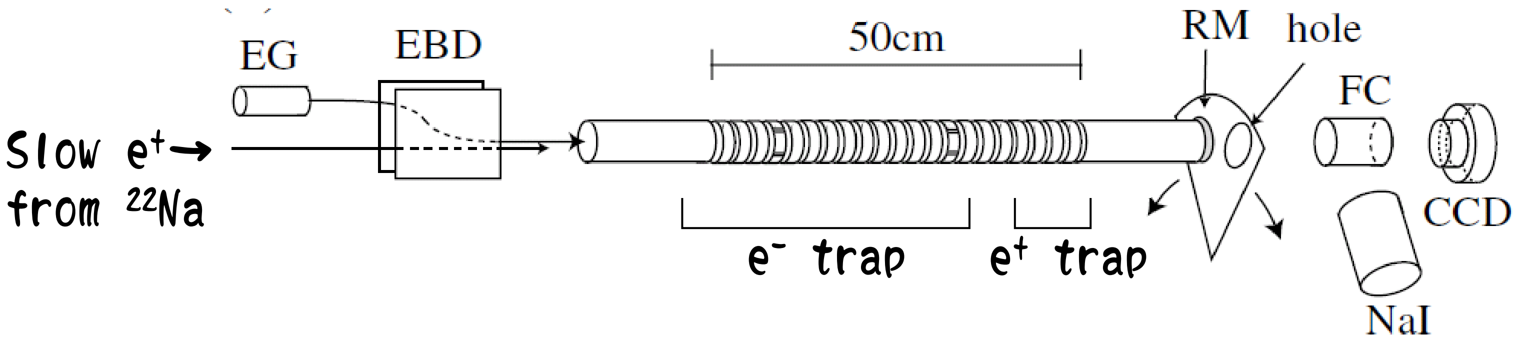
*If $\Delta p/p$ is reduced to 10^{-4} at AD and 10^{-2} at RFQD

↓

30M from AD → 7.5M/AD shot from MUSASHI

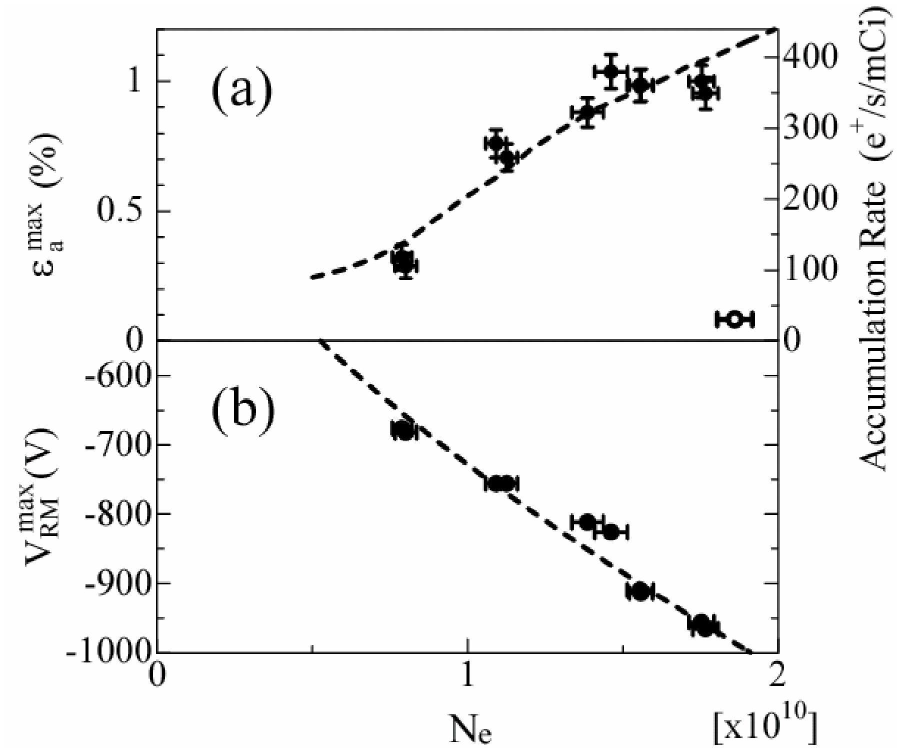
cf. 13M/AD shot from ELENA

3.Trapping of e^+ under UHV cond.



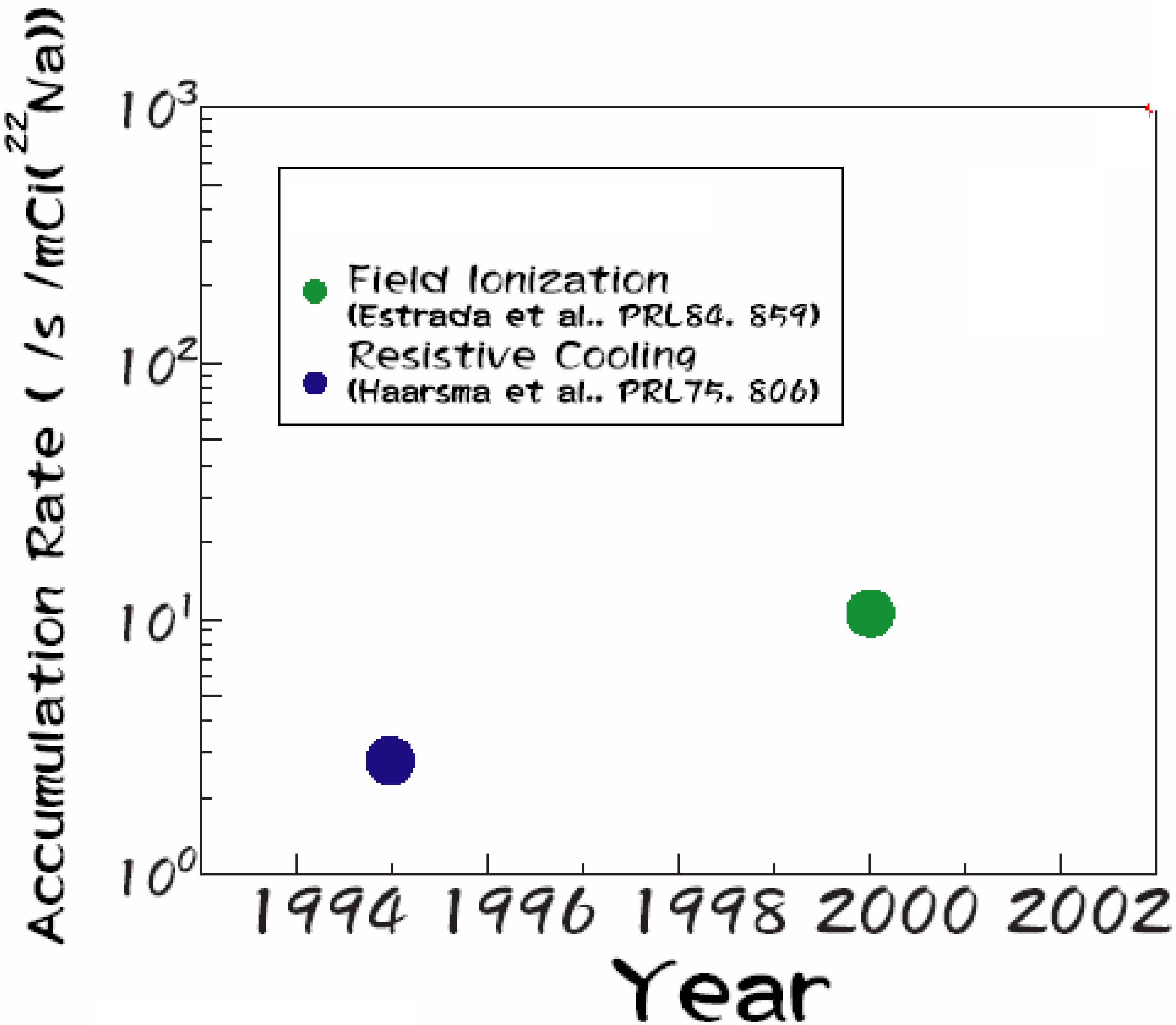
The same principle as $\overline{p}$s

e^+s from ^{22}Na are continuous
→ High density electron plasma (10^{11}/cm^3)



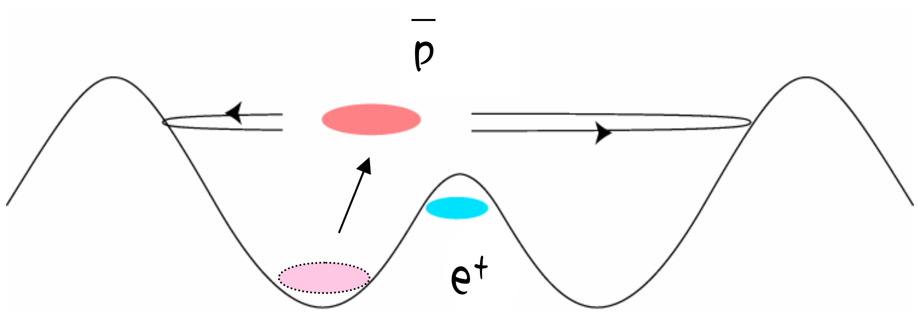
Oshima et al., PRL93(04)195001

Trapping efficiencies in UHV



4. Synthesis of cold $\bar{H}$ atoms & manipulation

4.1 Nested trap scheme



ATHENA: Amoretti et al., Nature 419(2002)456

ATRAP: Gabrielse, et al., PRL89(2002) 213401

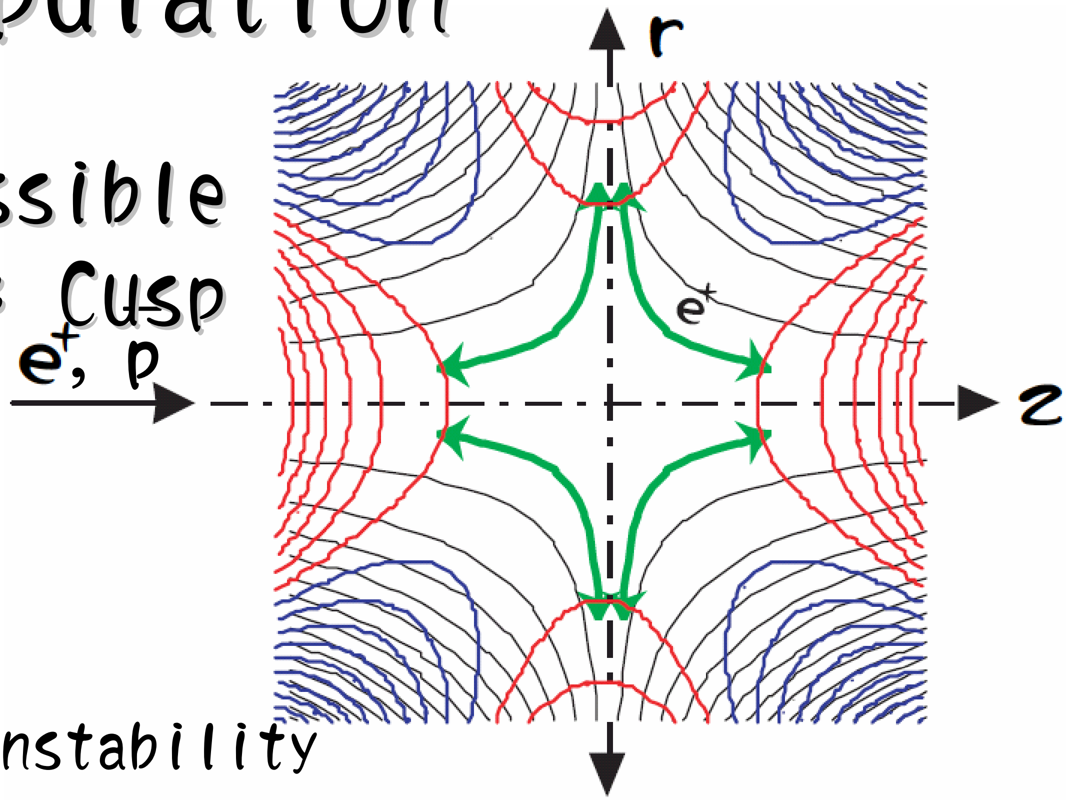
Very hot ! (several thousands K)

In Rydberg states (n>>1) →New scheme

Cannot trap

4. Synthesis of cold $\bar{H}$ atoms & manipulation

4.2 A possible solution: Cusp trap



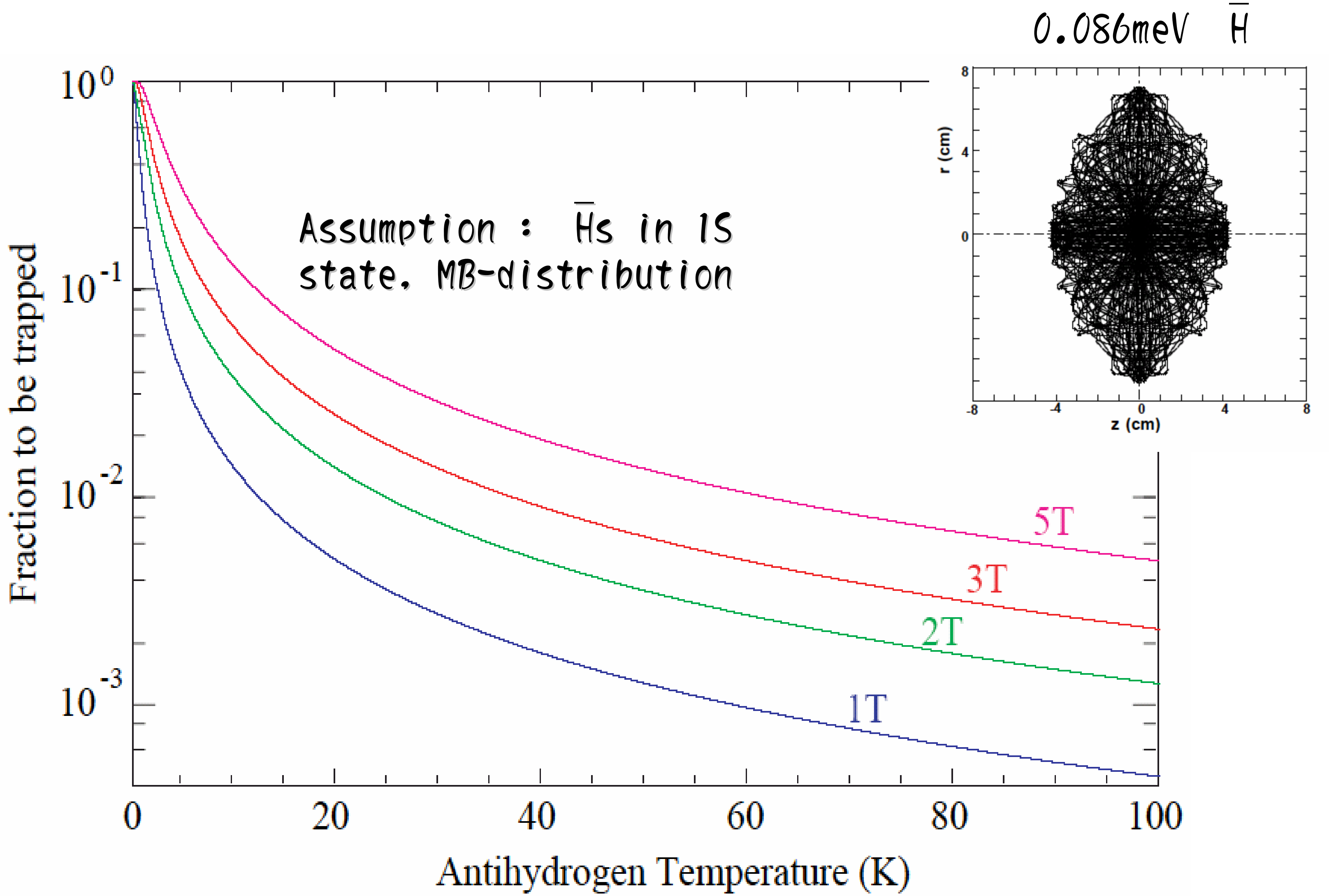
No instability

Automatic cooling of e^+

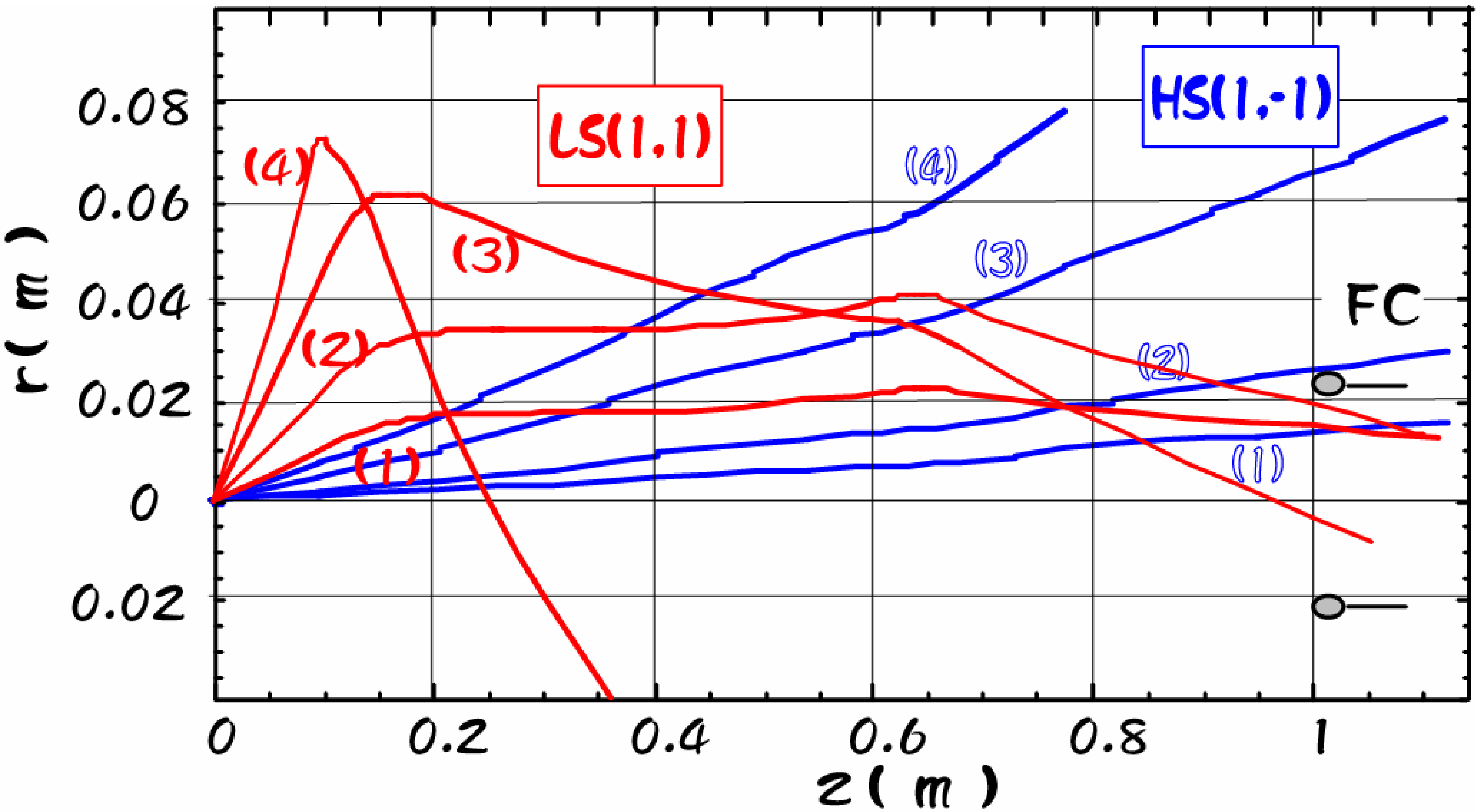
Cold $\bar{p}$ and e^+ in the same region

Magnetic bottle for neutral particles

$\bar{H}$ fraction to be trapped

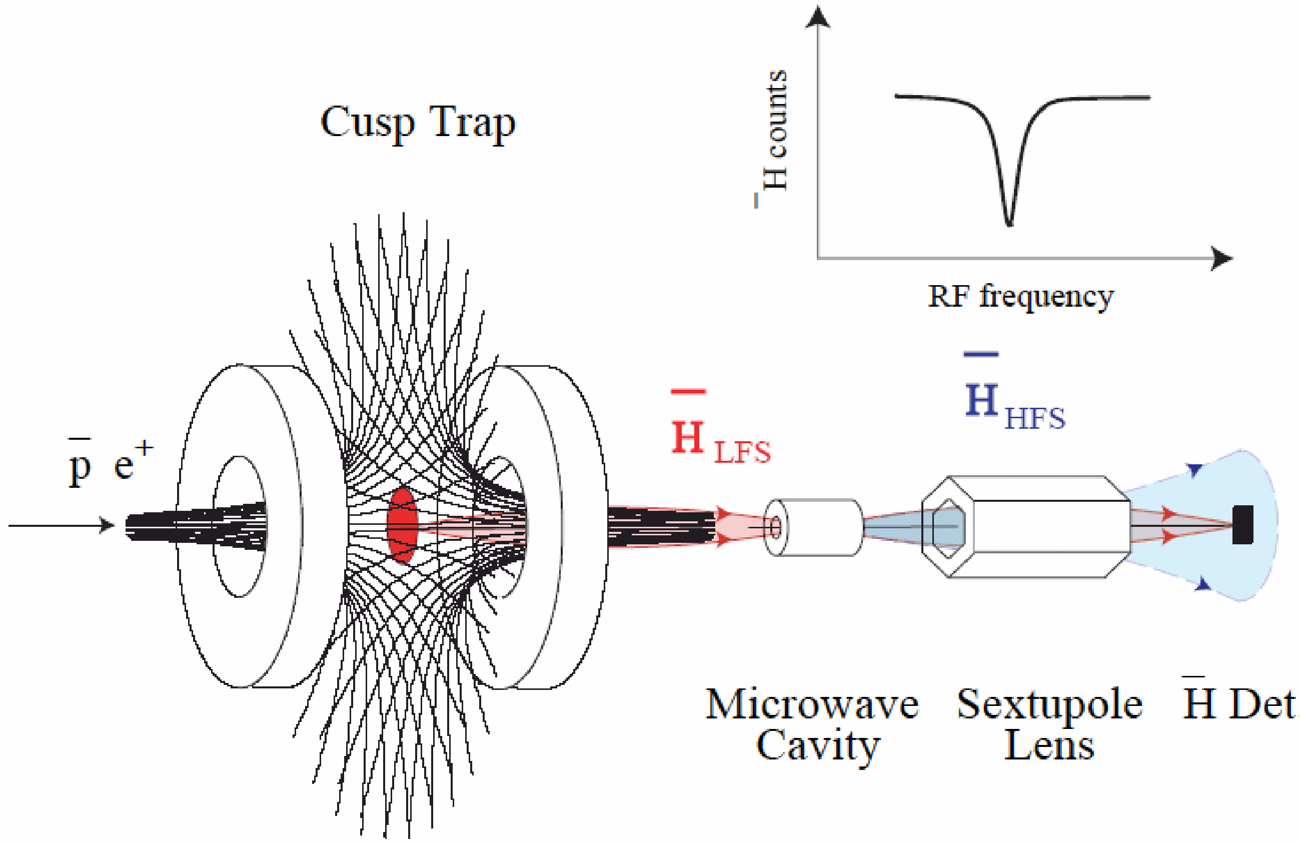


Trajectories of 0.268meV $\bar{H}$(1S)



Spin polarized $\bar{H}$ beam focused and intensified

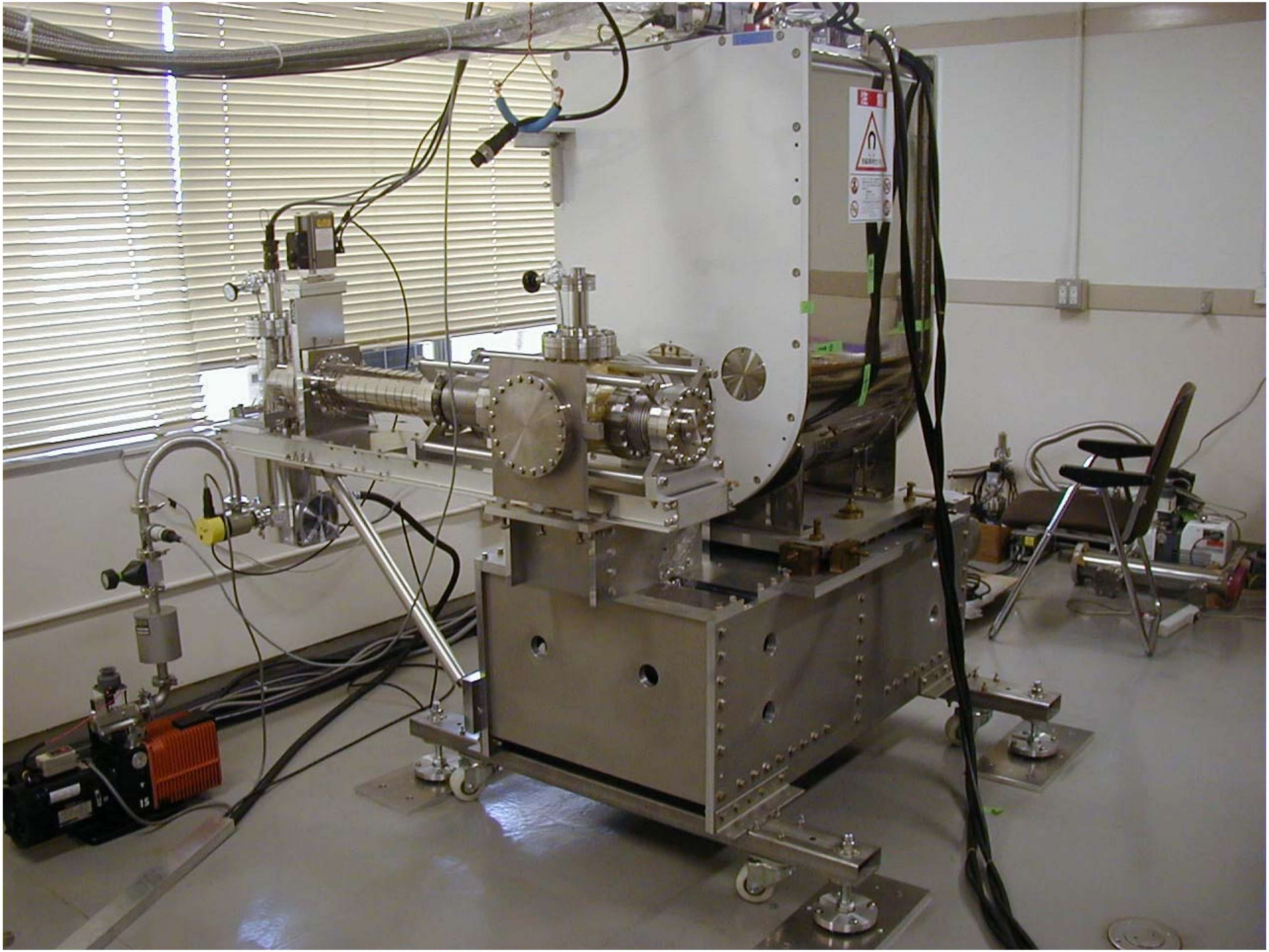
$\bar{p}$ magnetic moment measurement



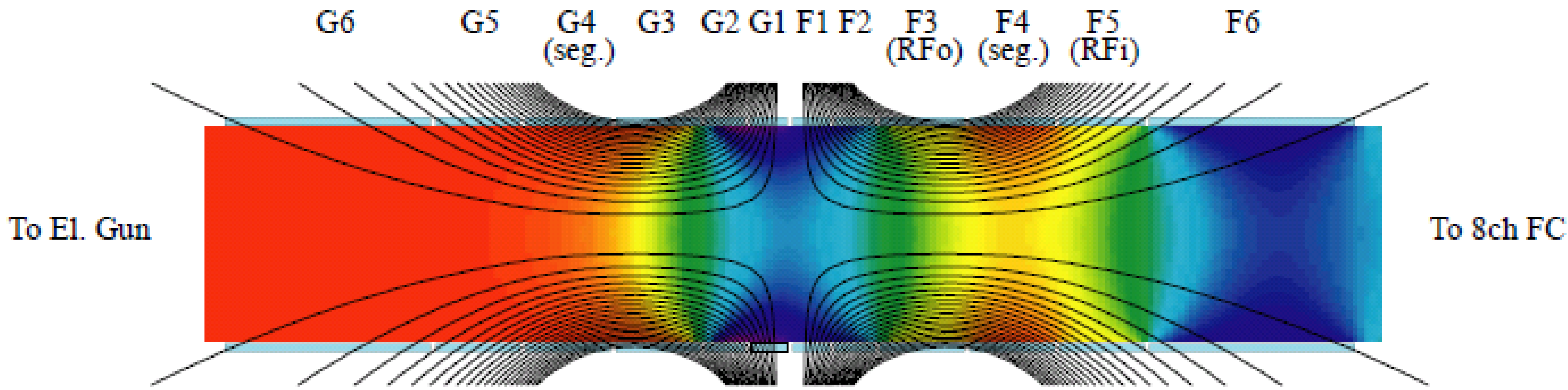
Production of ground state $\bar{H}\downarrow$

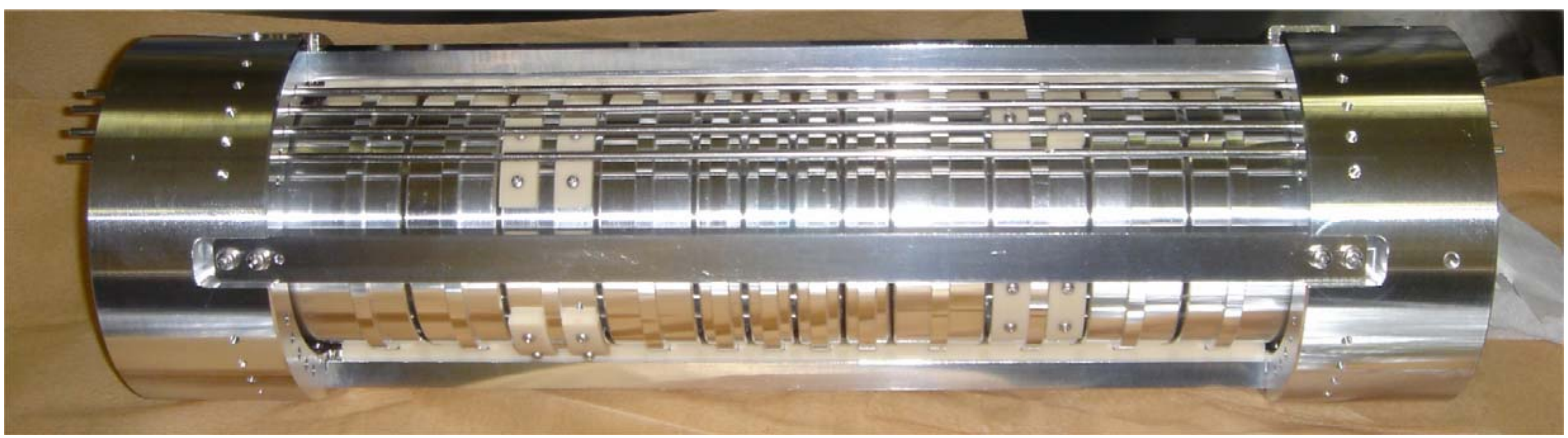
Intensity-enhanced Spin-polarized $\bar{H}$ beam

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



Magnetic & electric fields configurations in the MRT





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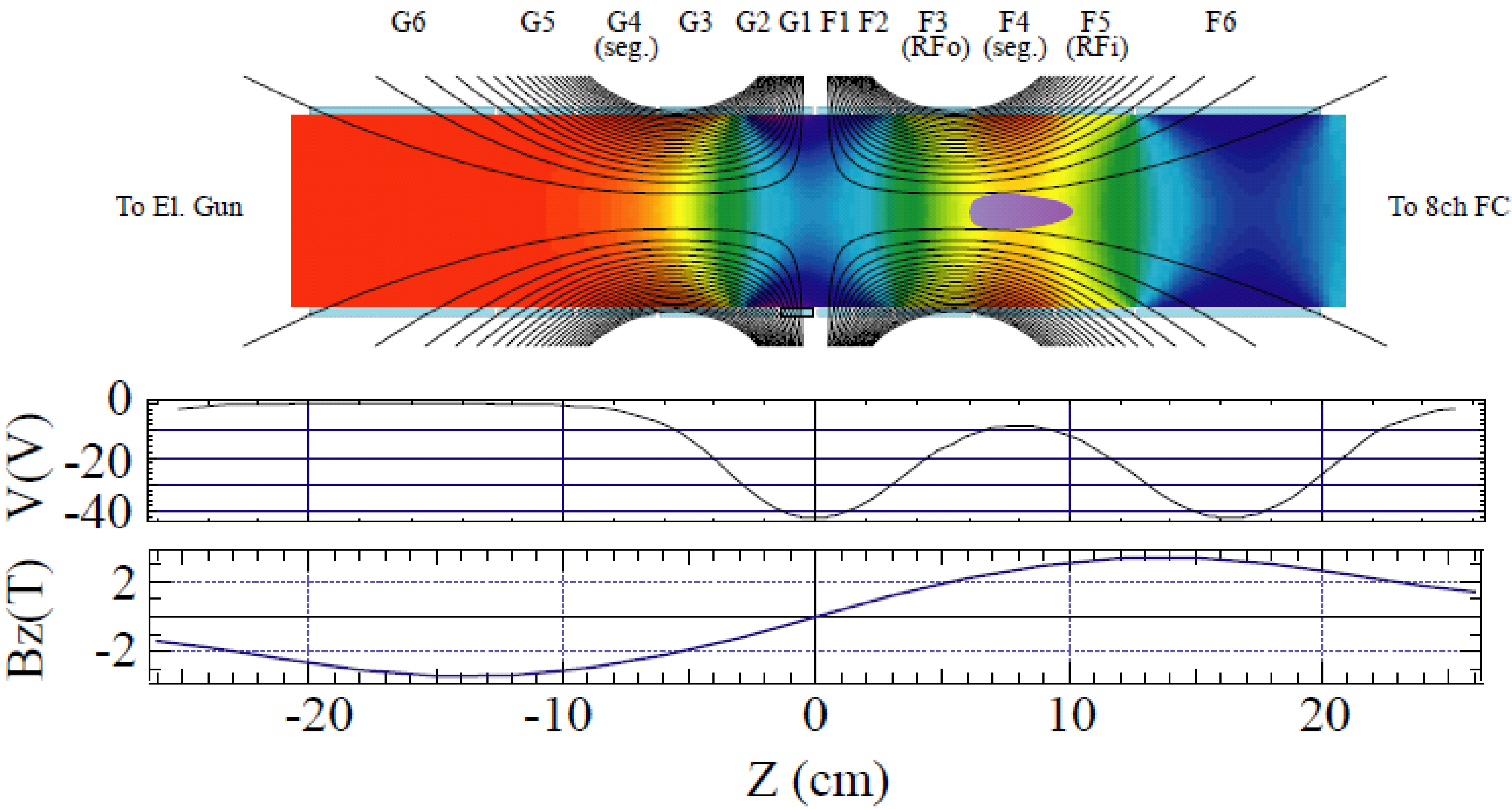
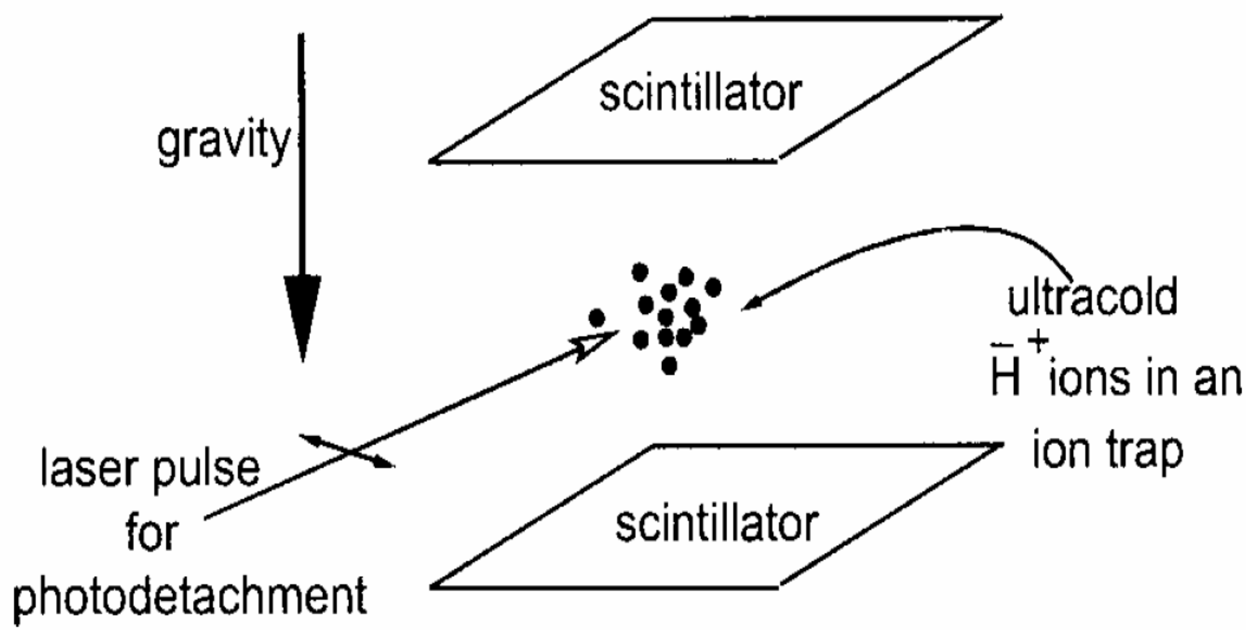


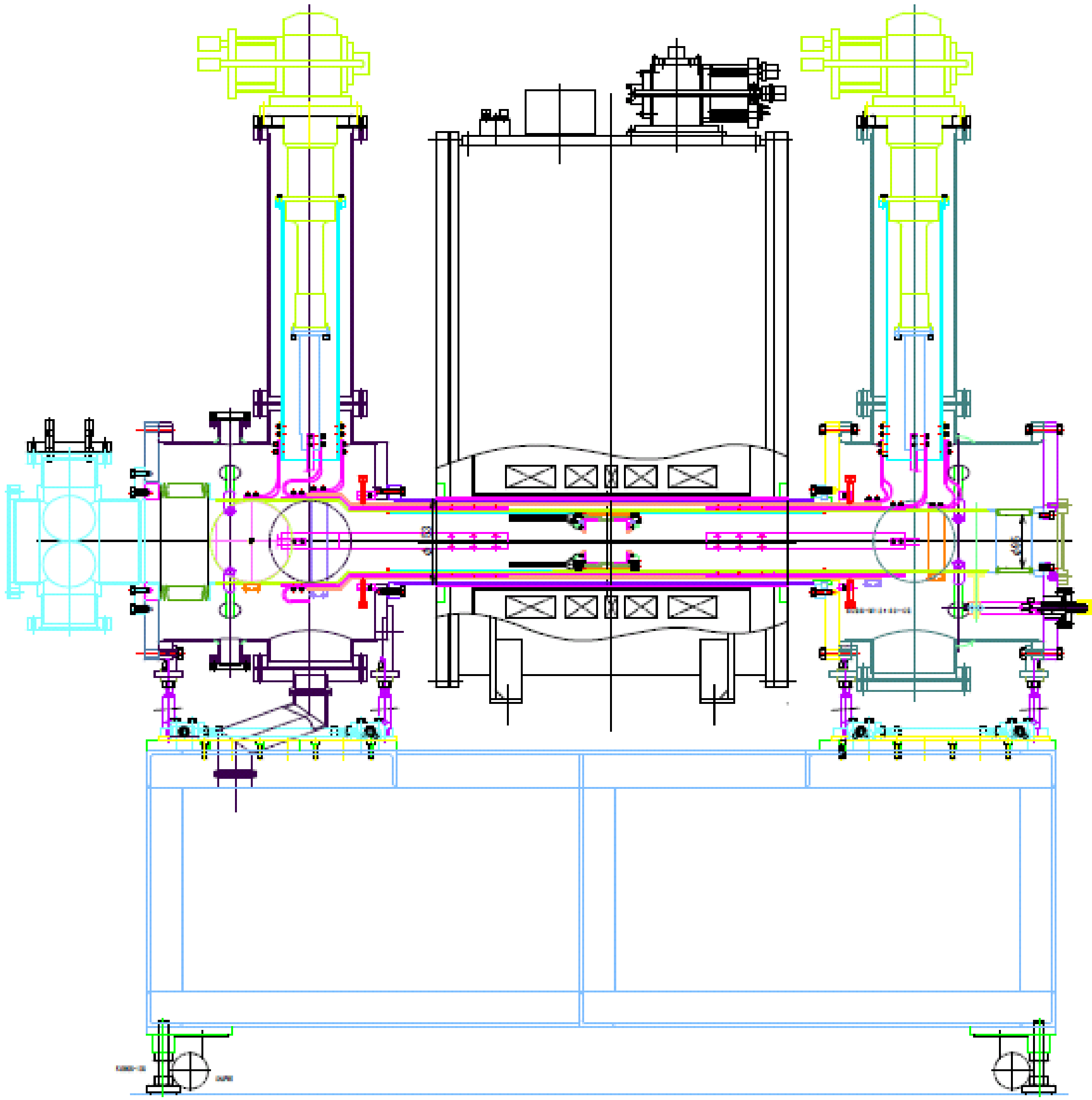
$\bar{H}^+$ synthesis in the cusp trap?

$\bar{H} + e^+ + e^+ \rightarrow \bar{H}^+ + e^+$? (Interaction time of ~10sec)

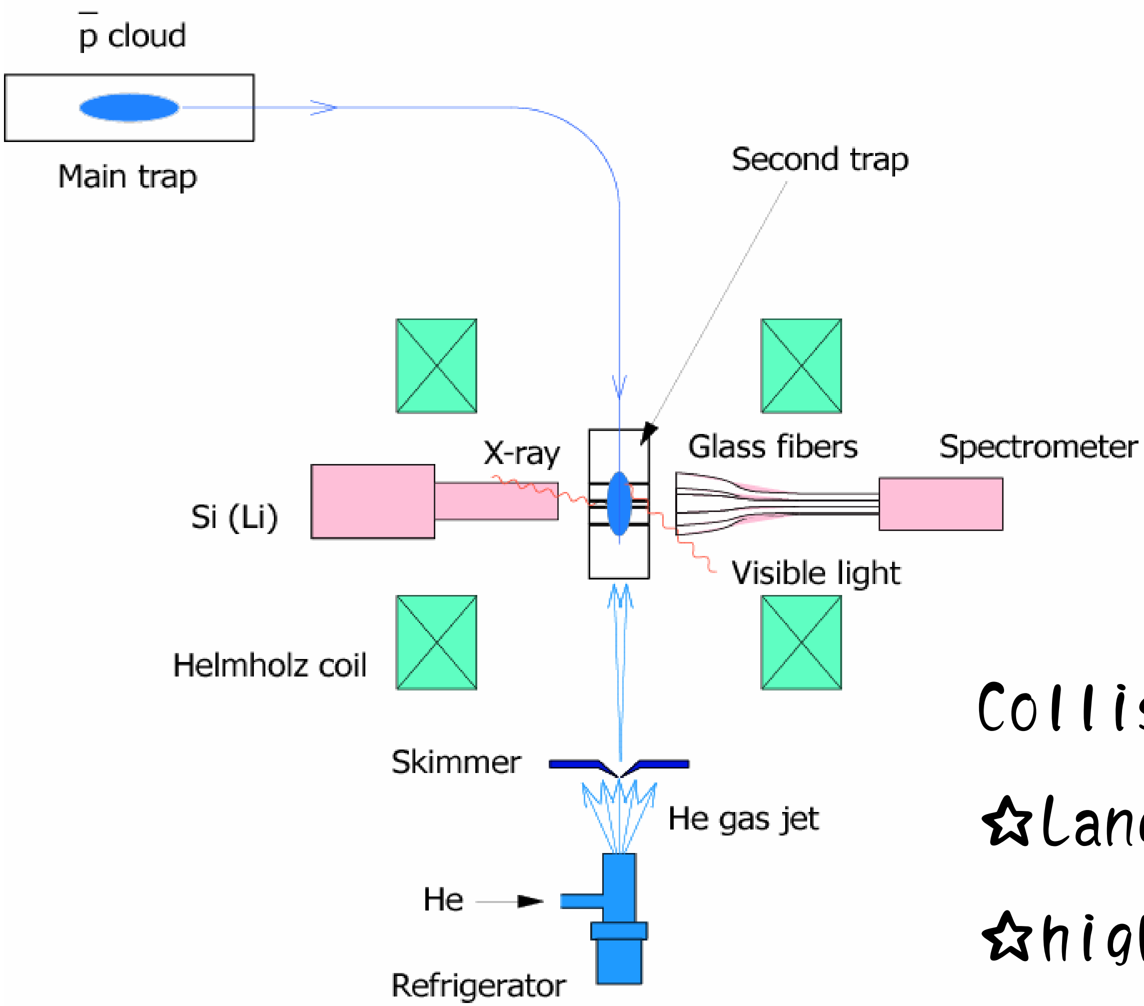


J.Walz, et al., General relativity and gravitation 36(2004)561

Cusp Magnet + Cold Bore



Collision of neutral molecular beams with trapped $\bar{p}$

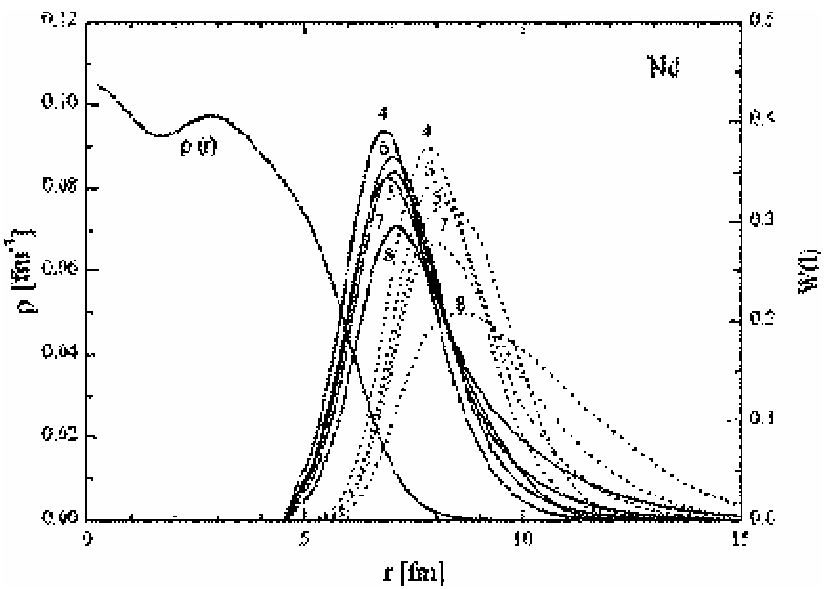


Collision in meV range:

☆Langevin cross section

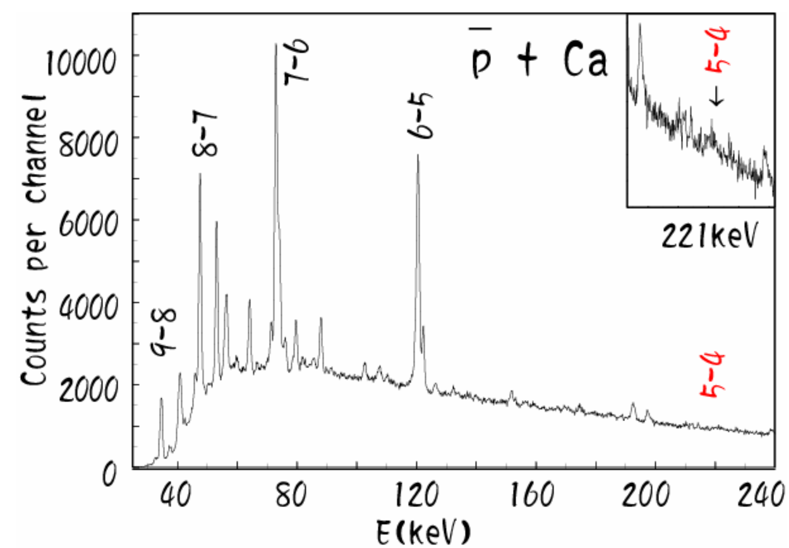
☆high res. X-ray spec.

Study of nuclear surface structure of unstable nuclei

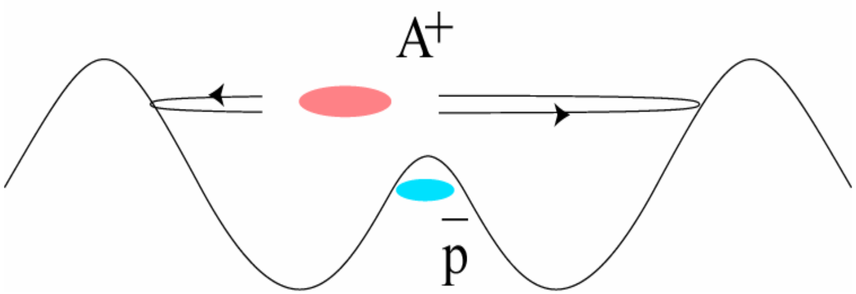


$$\bar{p}\ {}^{m}_{2}A^{2+} \rightarrow (\bar{p}p) + {}^{m-1}_{2-1}A^{(2-1)+}$$

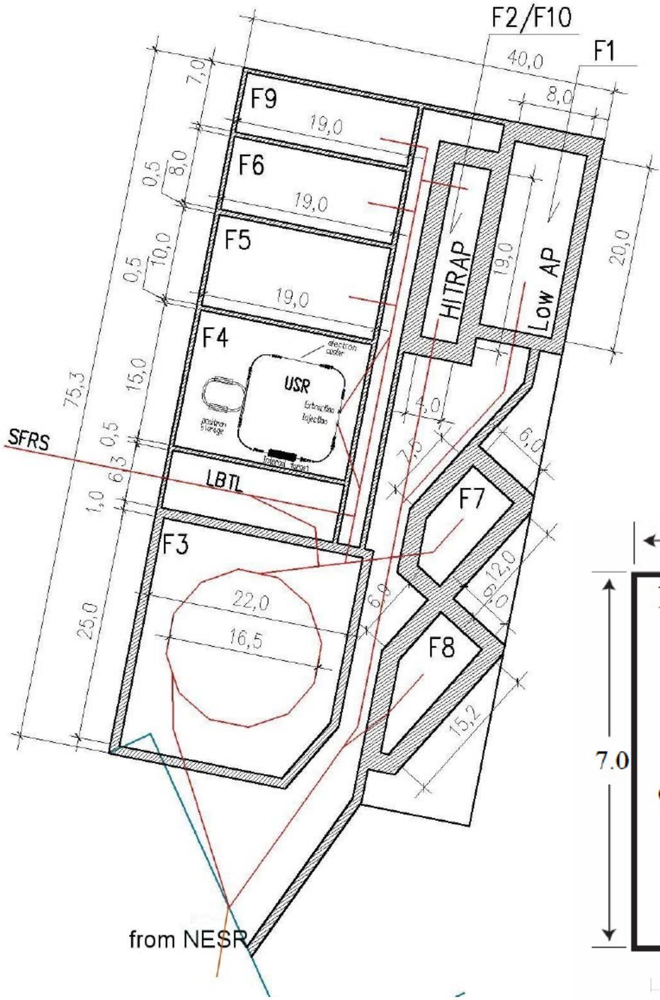
$$\bar{p}\ {}^{m}_{2}A^{2+} \rightarrow (\bar{p}n) + {}^{m-1}_{2}A^{2+}$$



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



Our plan at FLAIR



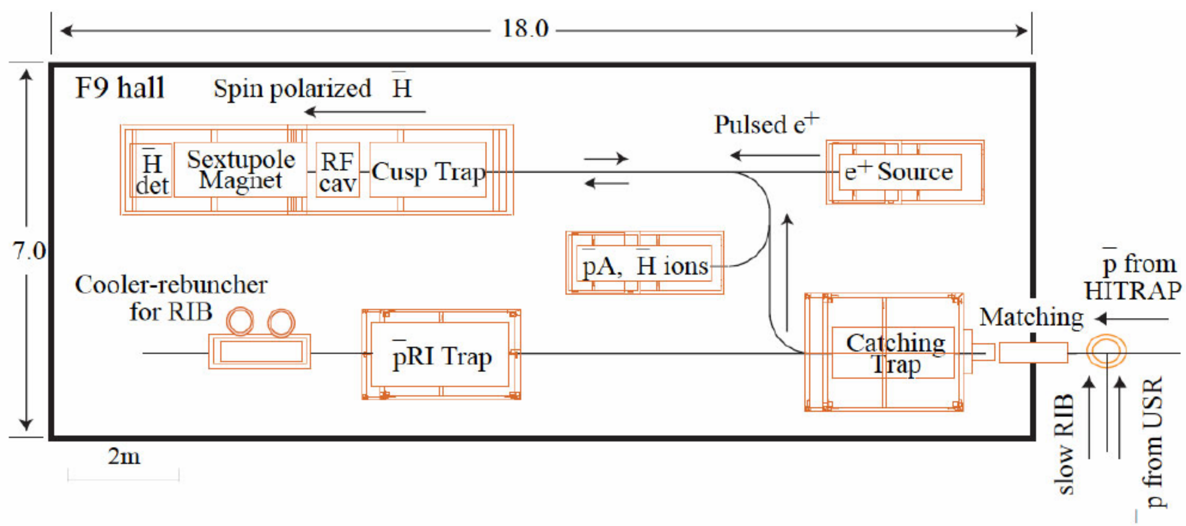


Fig. 57: A schematic layout of F9 hall for spin-polarized antihydrogen experiment.

5.Summary

Trapping and manipulation of e^+, $\bar{p}$, unstable nuclei, highly charged ions

$\bar{p}$: 10^6/AD shot

monoenergetic ultraslow $\bar{p}$ beam of 10-500eV

efficient accumulation of e+ in UHV condition

collision dynamics with "heavy" electron

spin-polarized `H beam and CPT symmetry test

$\bar{p}$RI production and surface structure of unstable nuclei

Collaborators

$\bar{p}$:

Present members: N.Kuroda, H.A.Torii, M.Shibata, Y.Nagata, M.Hori, A.Mohri, D.Horvath, J.Eades, K.Komaki

New Members: H.Saitoh, Y.Enomoto, K.Ogata

Previous Members: D.Barna, H.Higaki, Z.Wang, K.Yoshiki Franzen, S.Yoneda, M.Inoue, B.Juhasz

e^+:

Present Members: N.Oshima, M.Tarek, A.Mohri, K.Komaki, J.Babaud

Previous Members: M.Niigaki, T.M.Kojima

Slow RI:

Present Members: M.Wada, Y.Ishida, T.Nakamura, A.Takamine