COOL15

Anti-particle Accumulation for Low Energy Exotic Beams

Hiroyuki Higaki (ASACUSA - MUSASHI collaboration)

Atomic Spectroscopy And Collisions Using Slow Antiprotons (**ASACUSA**)
Mono-energetic Ultra Slow Antiproton Source for High-precision Investigation (**MUSASHI**)

Graduate School of Advanced Sciences of Matter, Hiroshima University, Kagamiyama, Higashi-Hiroshima, Hiroshima 739-8530, Japan
[1] *RIKEN Atomic Physics Special Research Unit, 2-1 Hirosawa, Wako, Saitama 351-0198, Japan*
[2] *Graduate School of Arts and Sciences, The University of Tokyo, Komaba, Meguro, Tokyo 153-8902, Japan*
[3] *Department of Physics, Tokyo University of Science, Kagurazaka, Shinjuku, Tokyo 162-8601, Japan*
[4] *Dipartimento di Ingegneria dell'Informazione, Universitá di Brescia & Istituto Nazionale di Fisica Nucleare, Gruppo Collegato di Brescia, 25133 Brescia, Italy*
[5] *Stefan Meyer Institute for Subatomic Physics, Austrian Academy of Sciences, 1090 Wien, Austria*

Outline

1) **Low energy anti-hydrogen atoms ($\overline{H}$)**

   Why matter dominates antimatter in the universe ?

   ground state hyperfine splitting in the field free region

   high Rydberg atoms

2) **Low energy antiproton beams , positron beams**

   charged particle confinement, trap based beams

   rotating electric field, nondestructive measurement

   (for atomic physics, beam physics and plasma physics)

3) **Experimental scheme to produce $\overline{H}$ beam**

   low energy $\bar{p}$ beam and e+ plasma

   mixing antiprotons and positrons in the cusp trap

   for the production of $\overline{H}$ beam

4) **For the hyperfine spectroscopy of $\overline{H}$**

Brief history

1996 : Very high energy antihydrogen atoms at Low Energy Antiproton Ring (LEAR)
Phys. Lett. B 368 (1996) 251

1998 : Atomic Spectroscopy And Collisions Using Slow Antiprotons (ASACUSA)

1999 : Antiproton Decelerator (**AD**) in operation

2002 : Low energy antihydrogen atoms synthesized in nested Penning traps
Nature 419 (2002) 456 (ATHENA), Phys. Rev. Lett. 89 (2002) 213401 (ATRAP)

2005 : Low energy (100~1000eV) antiproton beams from MUSASHI
Phys. Rev. Lett. 94 (2005) 023401 (ASACUSA_MUSASHI)

2010 : Trapped antihydrogen in Ioffe-Pritchard trap
Nature 468 (2010) 673 (ALPHA)

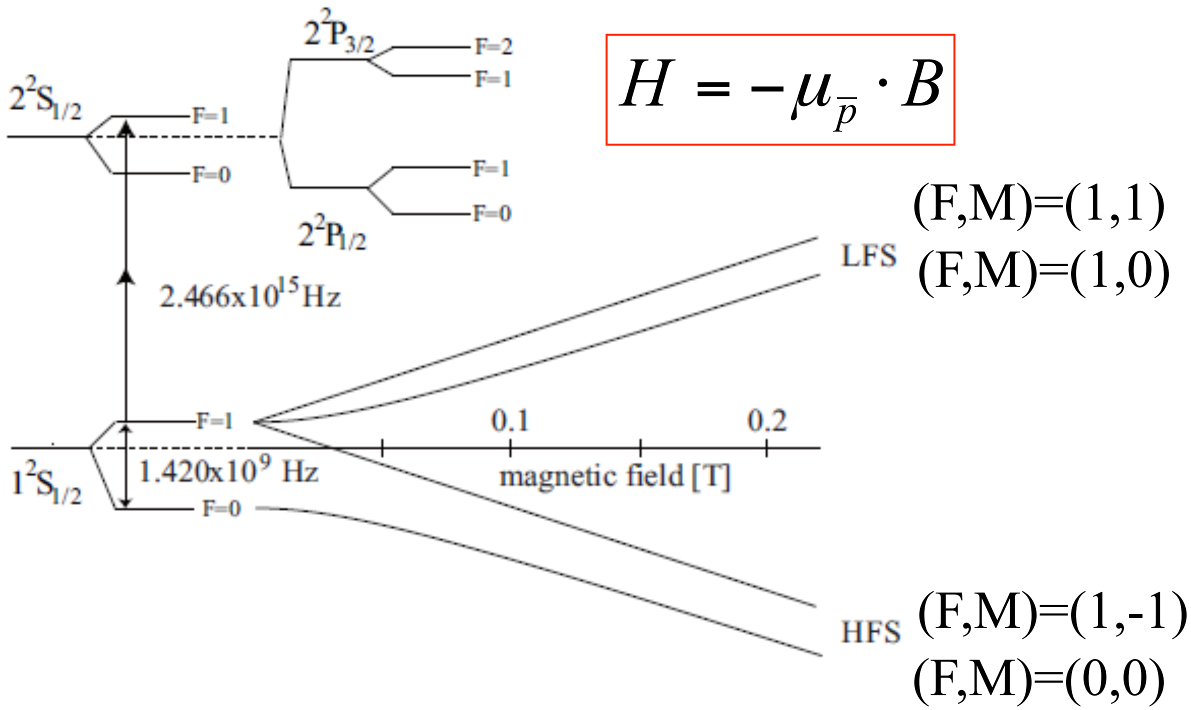
Low energy antihydrogen atoms synthesized in a Cusp trap
Phys. Rev. Lett. 105 (2010) 243401 (ASACUSA_MUSASHI)

2012 : Hyperfine transitions in trapped antihydrogen atoms in 1T ($\Delta\nu/\nu \sim 4\text{x}10^{-3}$)
Nature 483 (2012) 439 (ALPHA)

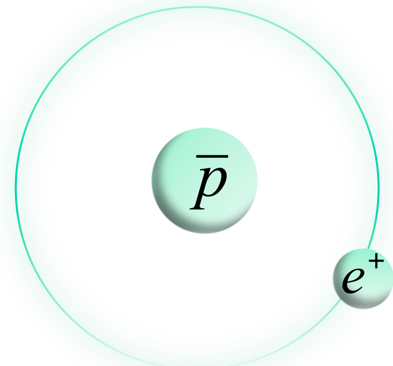
2014 : Low energy antihydrogen atoms detected at field free region
Nature Communications 5 (2014) 3089 (ASACUSA_MUSASHI)

Our purpose is to measure the hyperfine transition in a field free region

Low energy (anti-)hydrogen atoms (level diagrum)



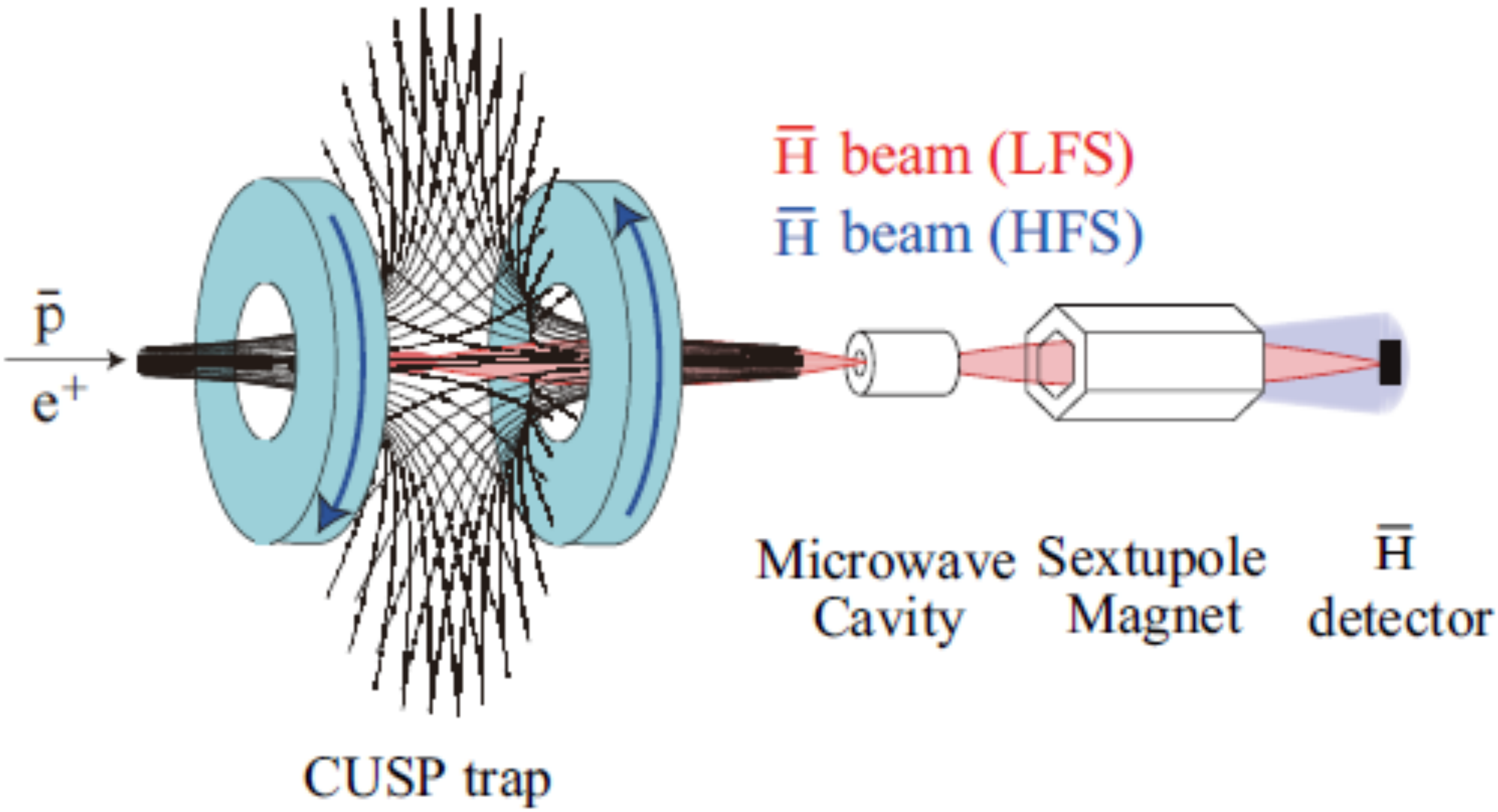
$$\boxed{H = -\mu_{\bar{p}} \cdot B}$$



	experiments (Hz)	$\Delta\nu_{exp}/\nu$	$\lvert\nu_{theory}-\nu_{exp}\rvert/\nu$
$\nu_{1S\text{-}2S}$	2,466,061,413,187,103(46)	1.7×10^{-14}	1×10^{-11}
ν_{HFS}	1,420,405,751.768(1)	6.3×10^{-13}	$(3.5+0.9) \times 10^{-6}$

Schematic of the experimental setup

Rabi-type atomic beam spectroscopy with magnetic field gradient



Low energy anti-hydrogen atoms (How?)

radiative recombination : $\overline{p} + e^{+} \rightarrow \overline{H} + h\nu, \quad \sigma \propto n_{e^{+}} T^{-1/2}$

When the positron density is low, this process is important

three body recombination : $\overline{p} + e^{+} + e^{+} \rightarrow \overline{H} + e^{+}, \sigma \propto n_{e^{+}}^{2} T^{-9/2}$

Due to the strong dependence on the density and temperature of e^{+},
three body recombination is the dominant process at $\sim 10^{8}\mathrm{cm}^{-3}$, $\sim$10K

collisions with Ps : $\overline{p} + Ps \rightarrow \overline{H} + e^{-}$

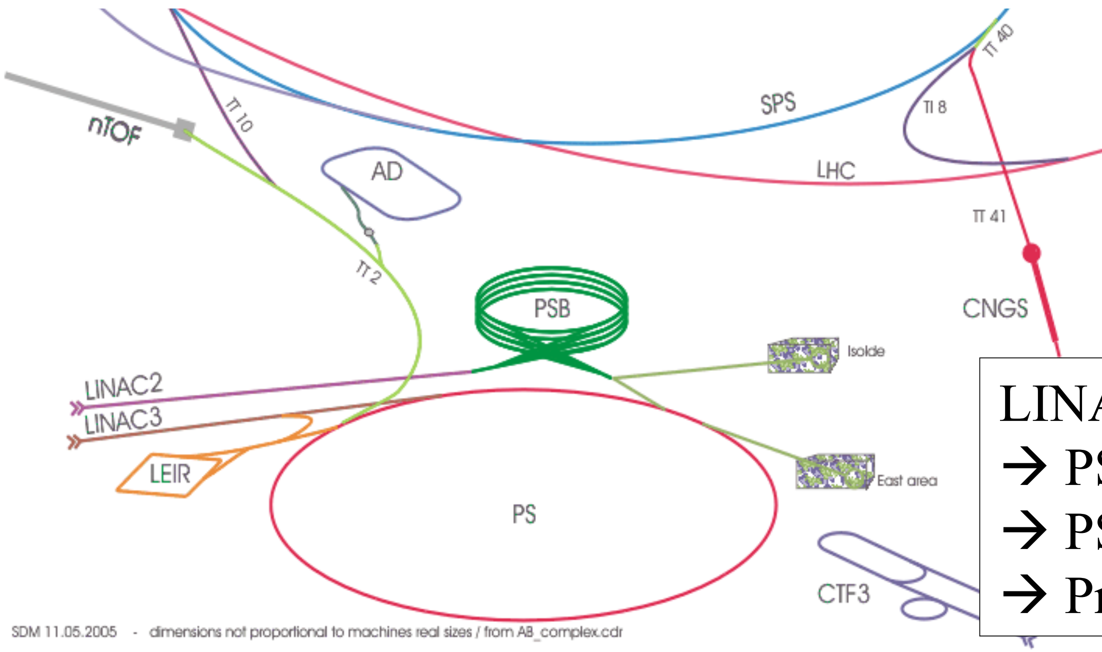
Although the cross section is large, positronium life time is too short.

A low temperature, high density positron plasma is favorable for the effective production of anti-hydrogen atoms

[4] M. E. Glinsky and T. M. O'Neil, Phys. Fluids B 3 (1991) 1279.

How to produce $\overline{H}$ (Low energy antiproton beam)

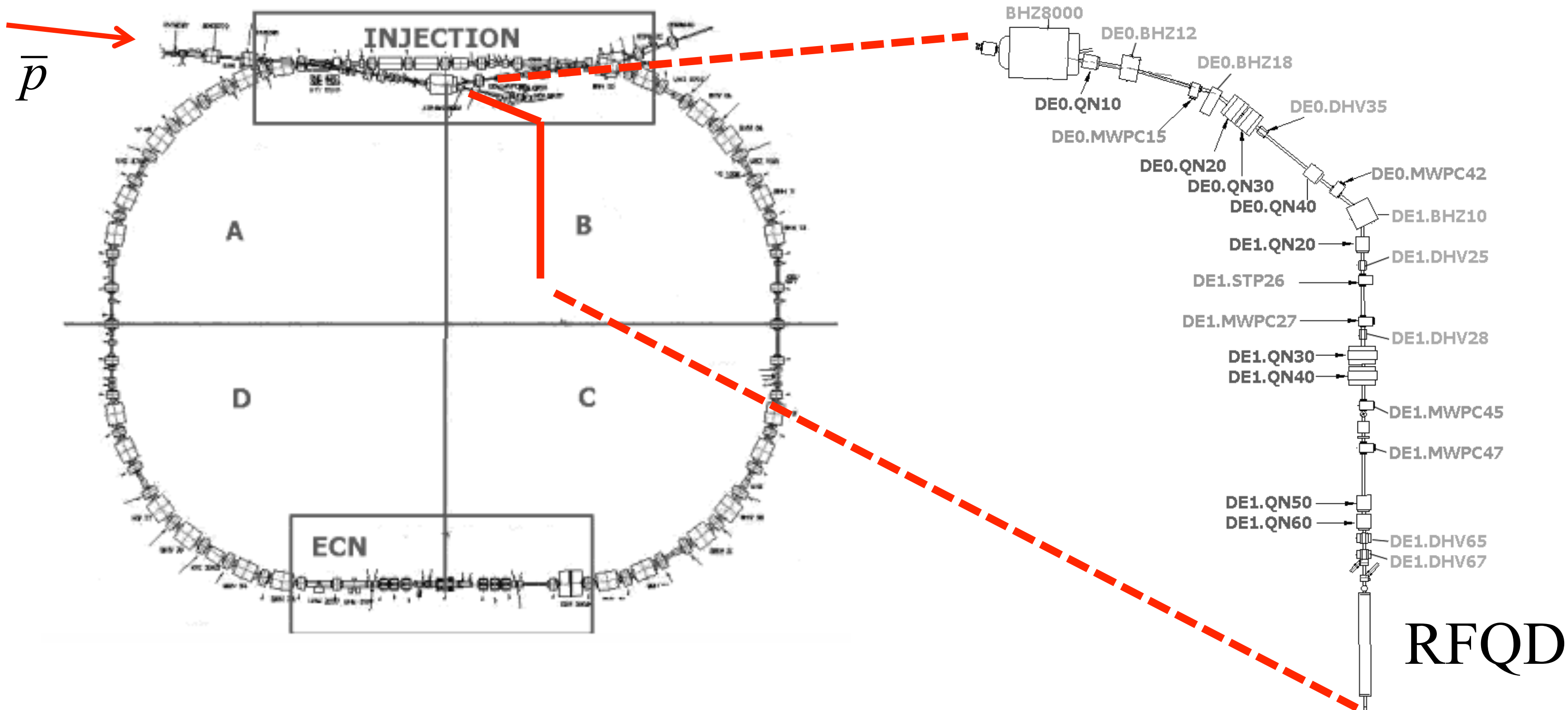
In **Antiproton Decelerator** (**AD**) at CERN, unique low energy antiproton ($\overline{p}$) beams of 5.6 MeV have been delivered for physics experiments. Furthermore, the RFQ decelerator (RFQD) dedicated for **Atomic Spectroscopy And Collisions Using Slow Antiprotons** (**ASACUSA**) collaboration enables the use of 100 keV pulsed $\overline{p}$ beams for experiments. What is more, **Mono-energetic Ultra Slow Antiproton Source for High-precision Investigations** (**MUSASHI**) in ASACUSA can produce **pbar beams with the energy of 100 to 1000 eV**. Since the successful extraction of 250 eV $\overline{p}$ beams reported in 2005, continuous improvements on beam quality and equipments have been conducted.



LINAC2 50MeV proton
→ PSB 1GeV proton
→ PS 26 GeV/c 10^{13} proton
→ Production target for AD

[10] N. Kuroda, H. A. Torii, K. Y. Franzen, *et al.*, Phys. Rev. Lett. 94, 023401 (2005).

How to produce $\overline{H}$ (Low energy antiproton beam)
AD to RFQD



Production target

→3.5GeV/c ~5x 10^7 pbar stochastic cooling

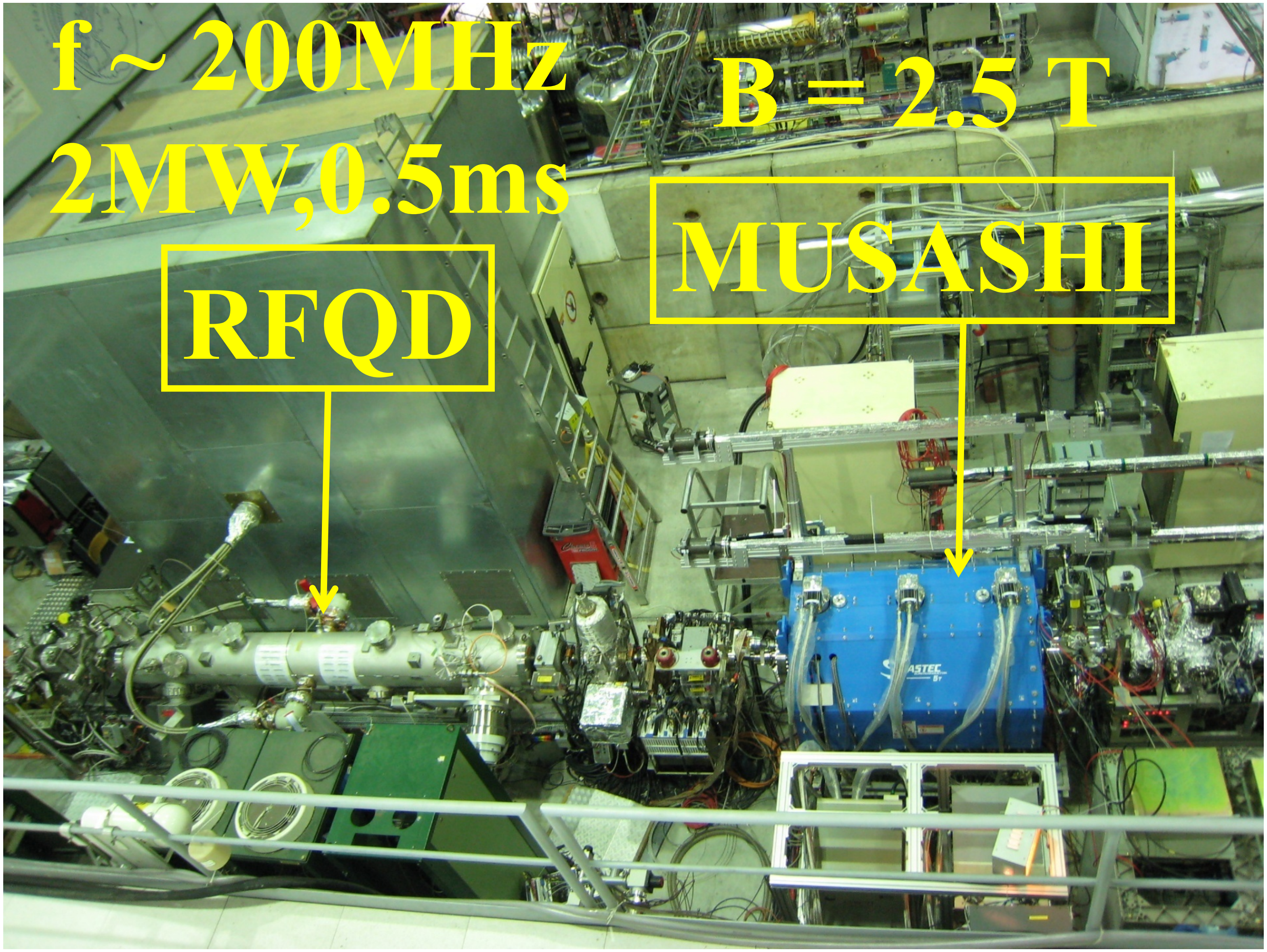
→2 GeV/c stochastic cooling

→300MeV/c stochastic cooling & electron coolling

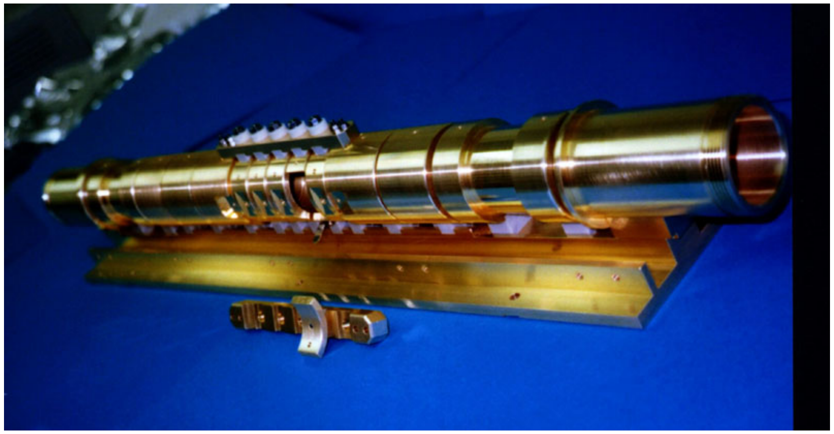
→100MeV/c(~5MeV) ~ 3x10^7 pbar pulse from AD (~100s cycle)

→100keV < 1x 10^7 pbar with RFQD

RFQD + MUSASHI



How to produce $\overline{H}$ (Low energy antiproton beam) MUSASHI trap



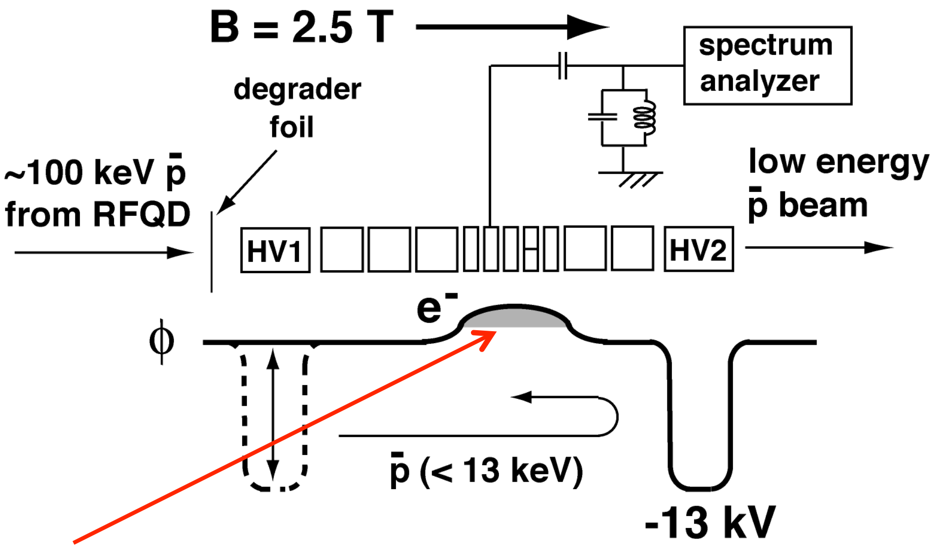
100keV $< 1 \times 10^7$ pbar with RFQD
→degrader foil
→< 13 keV pbar confined in the trap
→< 0.1 eV ~10^6 pbar electron cooling

Multi-ring trap

$$\phi = \frac{U}{2z_0^2 + r_0^2}(2z^2 - x^2 - y^2)$$

A harmonic potential can be produced in an axially long volume, which is necessary for the feasible e-cooling time of ~ 10^6 pbar

$$2r_0 = 4\,cm,\ 2z_0 = 12.3\,cm$$



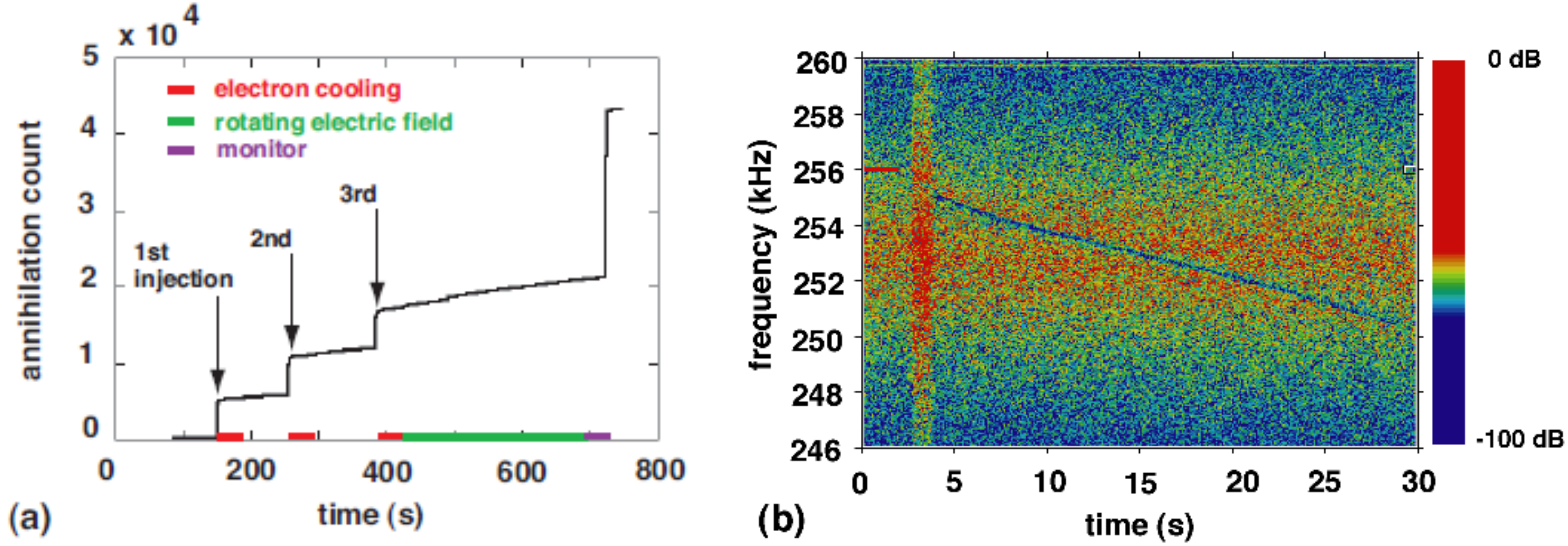
4 x 10^8 electrons for electron cooling in 40s

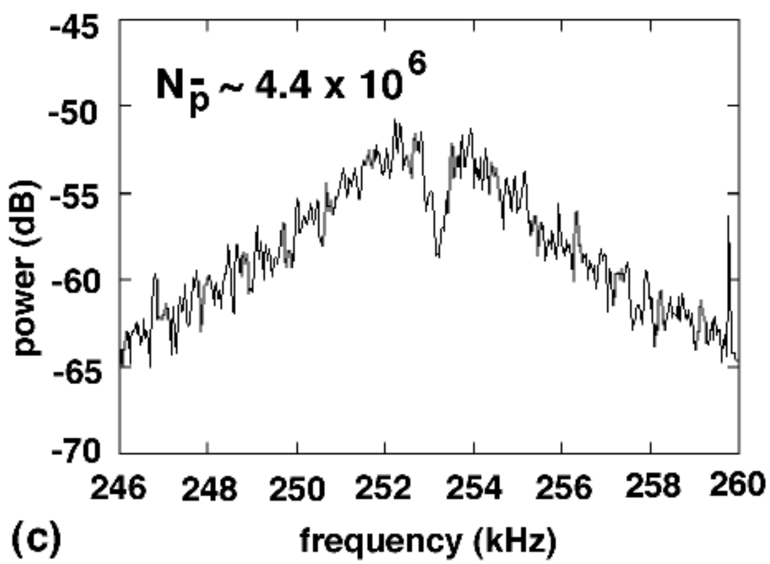
The axial resonance frequency for antiproton

$$\boxed{f_z = 2\pi\sqrt{\frac{4eU}{m(2z_0^2 + r_0^2)}} \sim 250\,kHz}$$

[10] N. Kuroda, H. A. Torii, K. Y. Franzen, *et al.*, Phys. Rev. Lett. 94, 023401 (2005).

How to produce $\overline{H}$ (Low energy antiproton beam)
Tank circuit signal with 3AD shot accumulated in MUSASHI





If necessary, the axial harmonic oscillation of trapped antiprotons can be monitored.

After electron kick out, rotating electric field is applied to increase the antiproton beam intensity.

Rotating electric field to control the beam intensity

“ Steady-State Confinement of Non-neutral Plasmas by Rotating Electric Fields “
X.-P. Huang, F. Anderegg, E. M. Hollmann, et al., Phys. Rev. Lett. **78** (1997) 875.

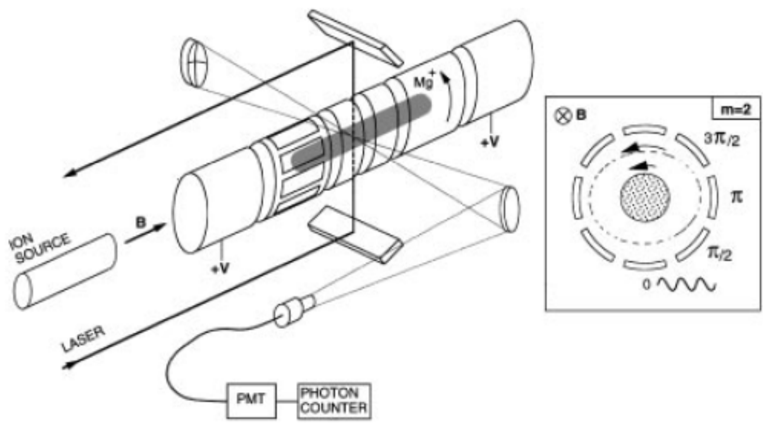
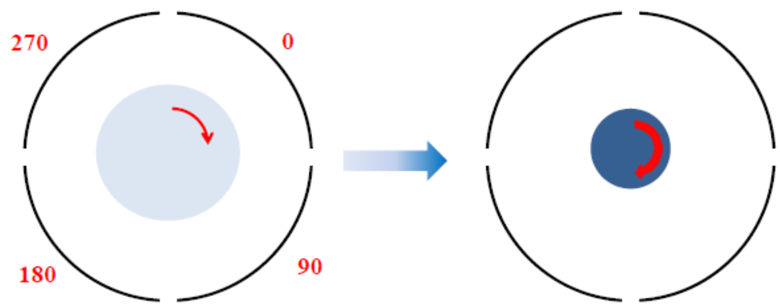


FIG. 1. Ion trap with perpendicular LIF diagnostics, and schematic of $m = 2$ rotating field wall

Mg^+, $r_p \sim 1$cm, $L_p \sim 10$ cm, B = 4T
resonance with rigid rotation



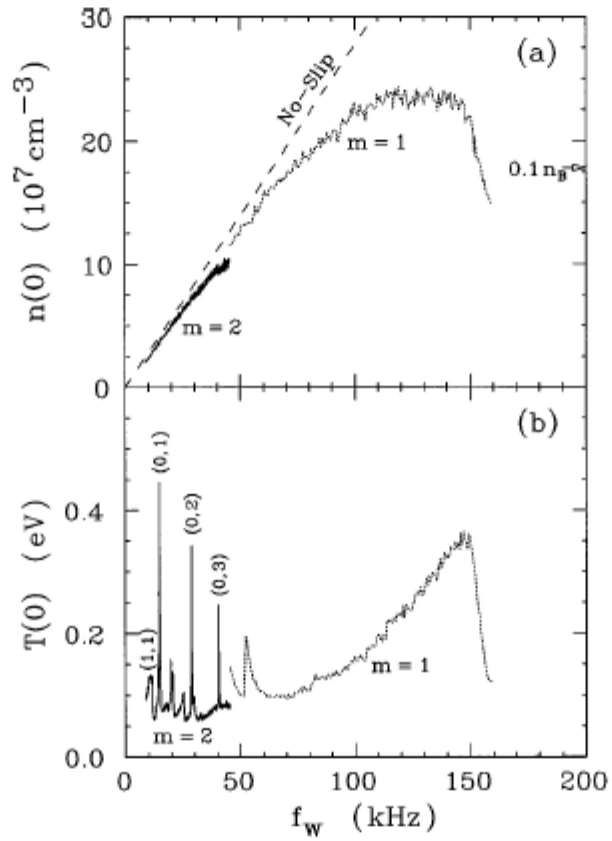
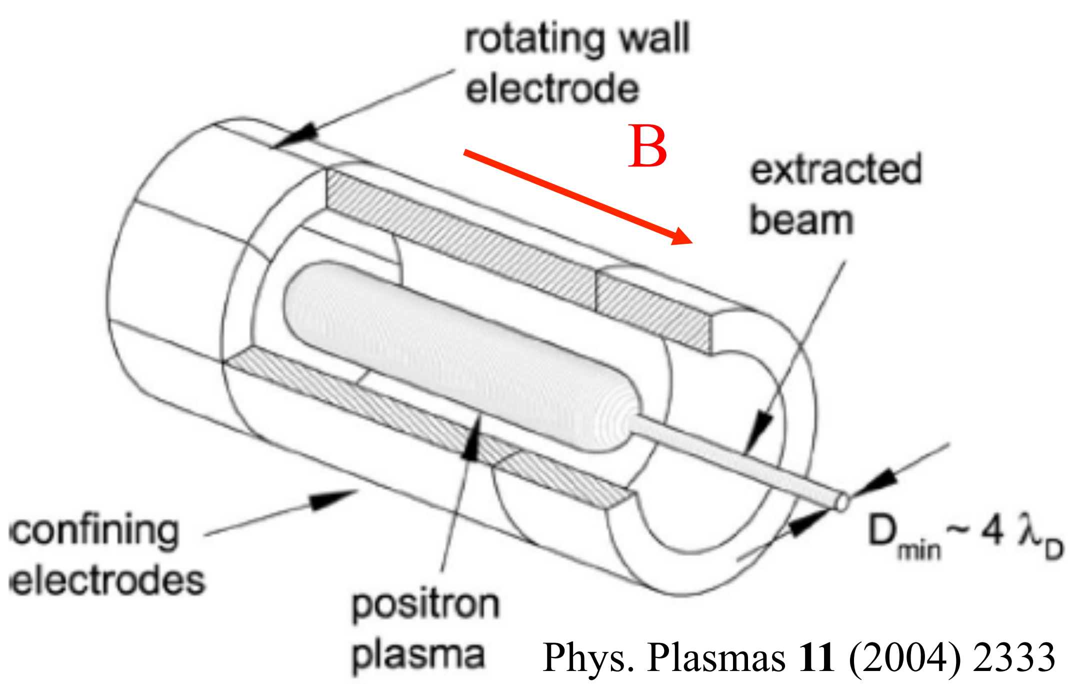


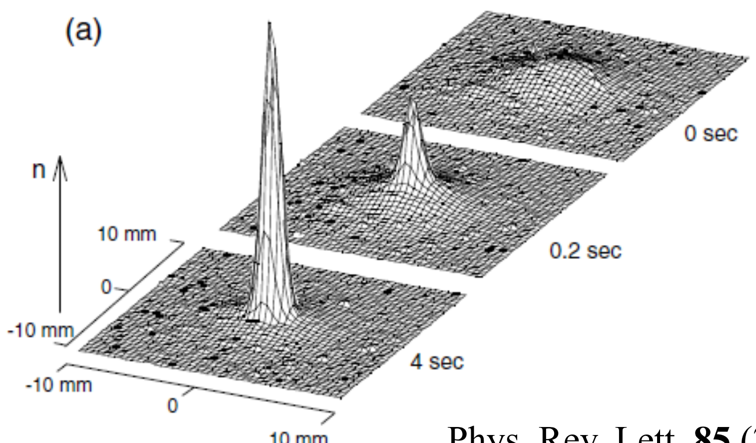
FIG. 5. Evolution of central ion density (a) and temperature (b) during gradual ramp of rotating field frequency. Density compression by an order of magnitude up to 13% Brillouin density limit n_B is shown in (a), and heating resonances due to excitation of $k \neq 0$ plasma modes are observed in (b).

Rotating electric field for trap based beams (examples)

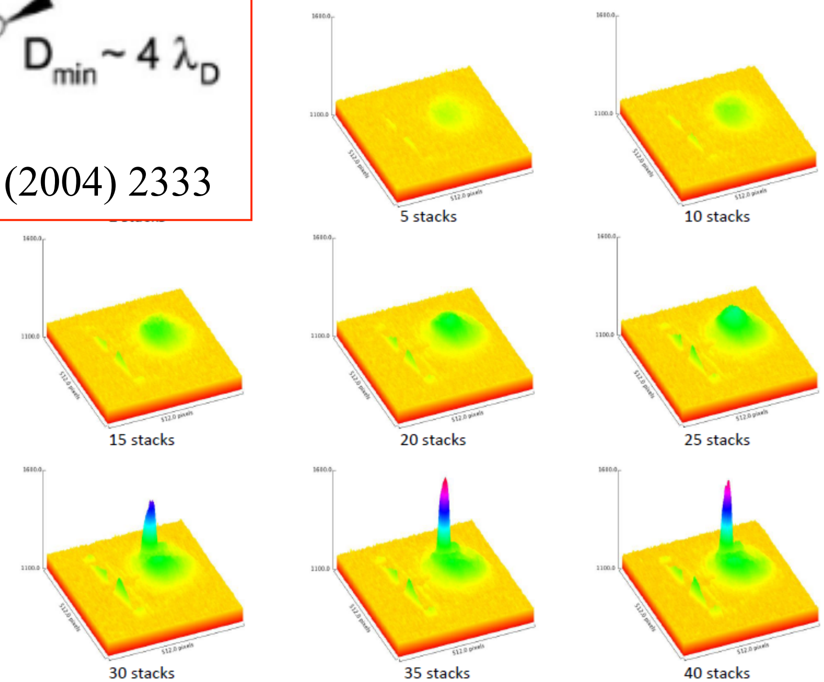


Phys. Plasmas **11** (2004) 2333

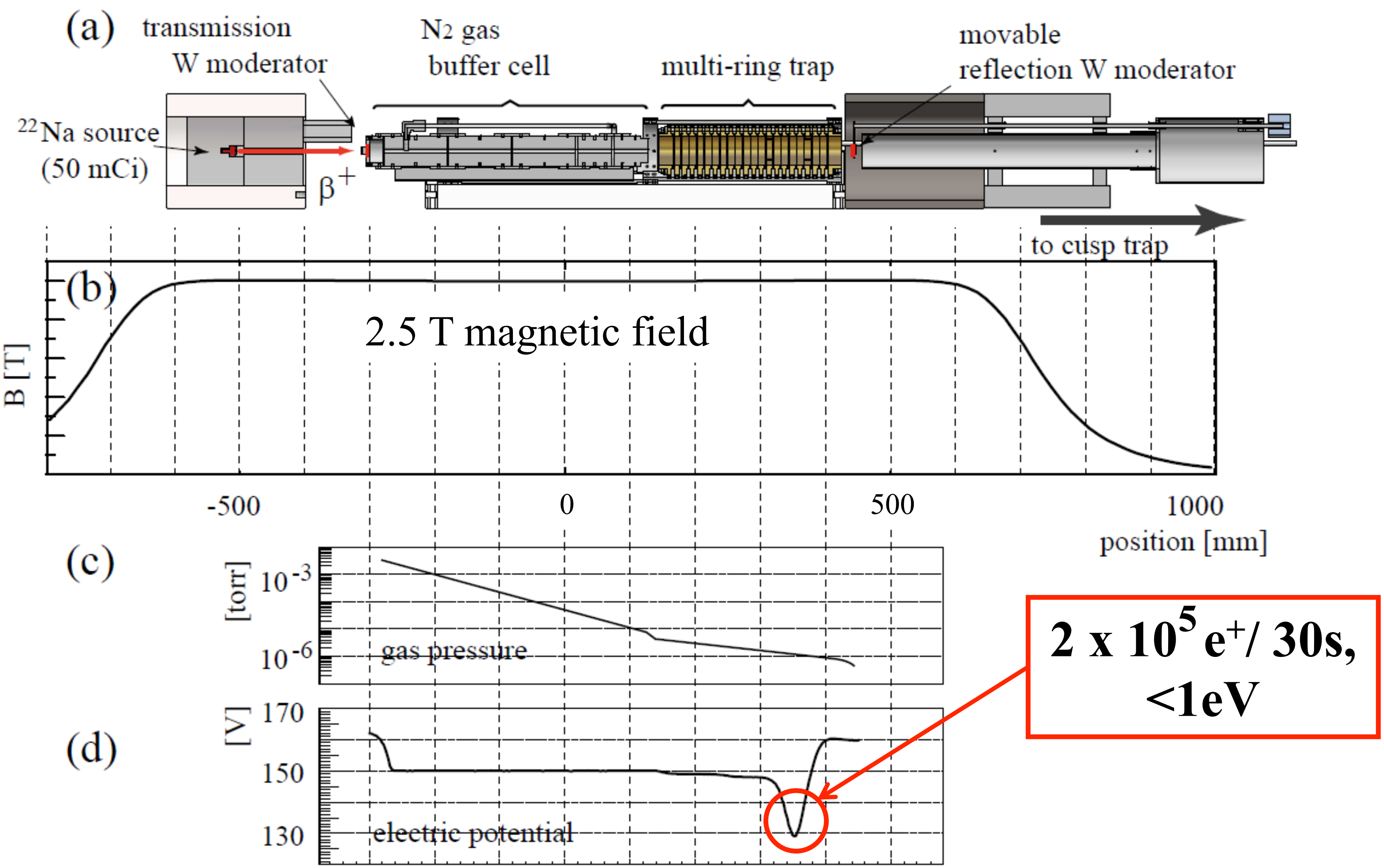
trap based beams



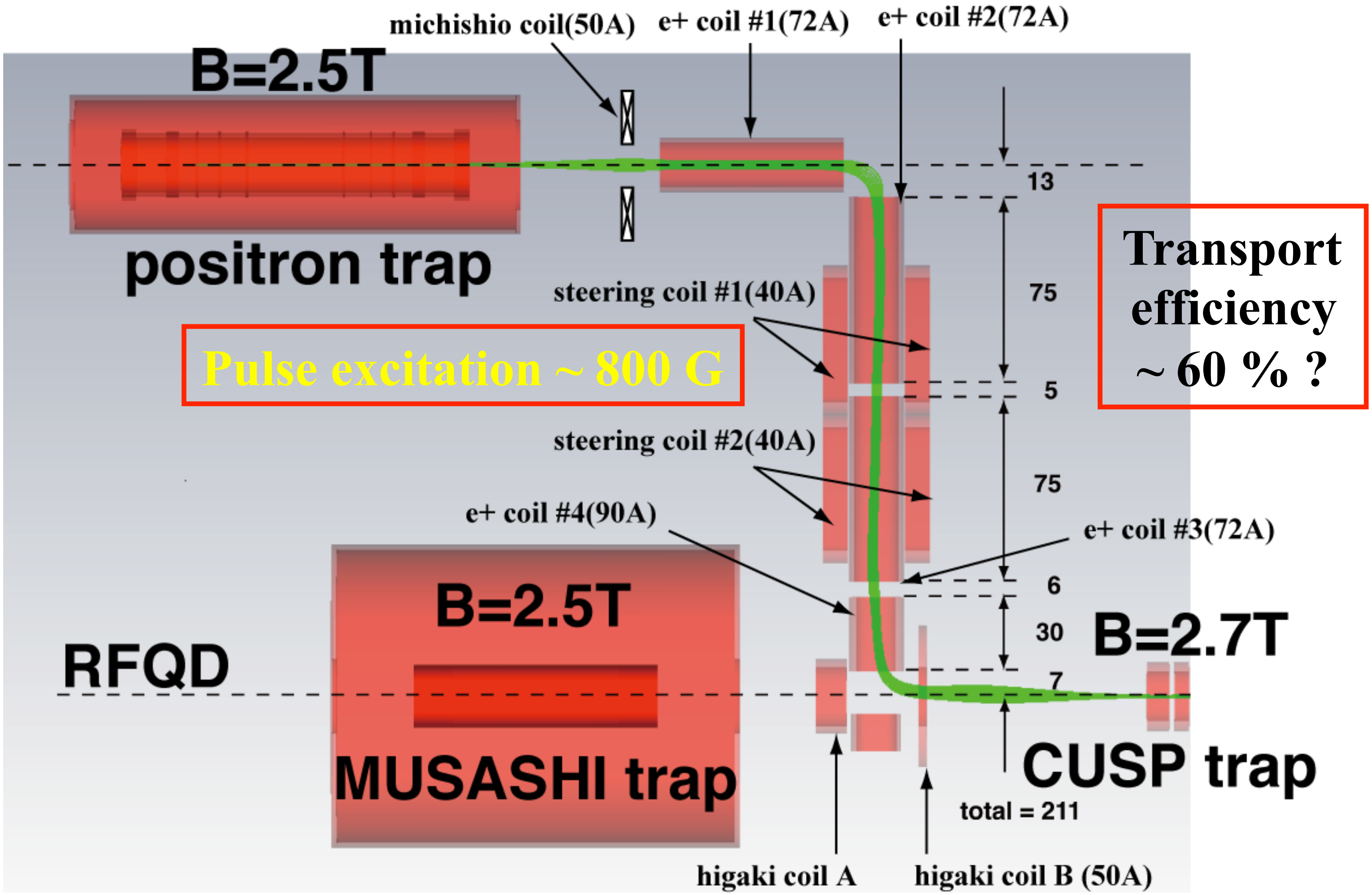
Phys. Rev. Lett. **85** (2000) 1883



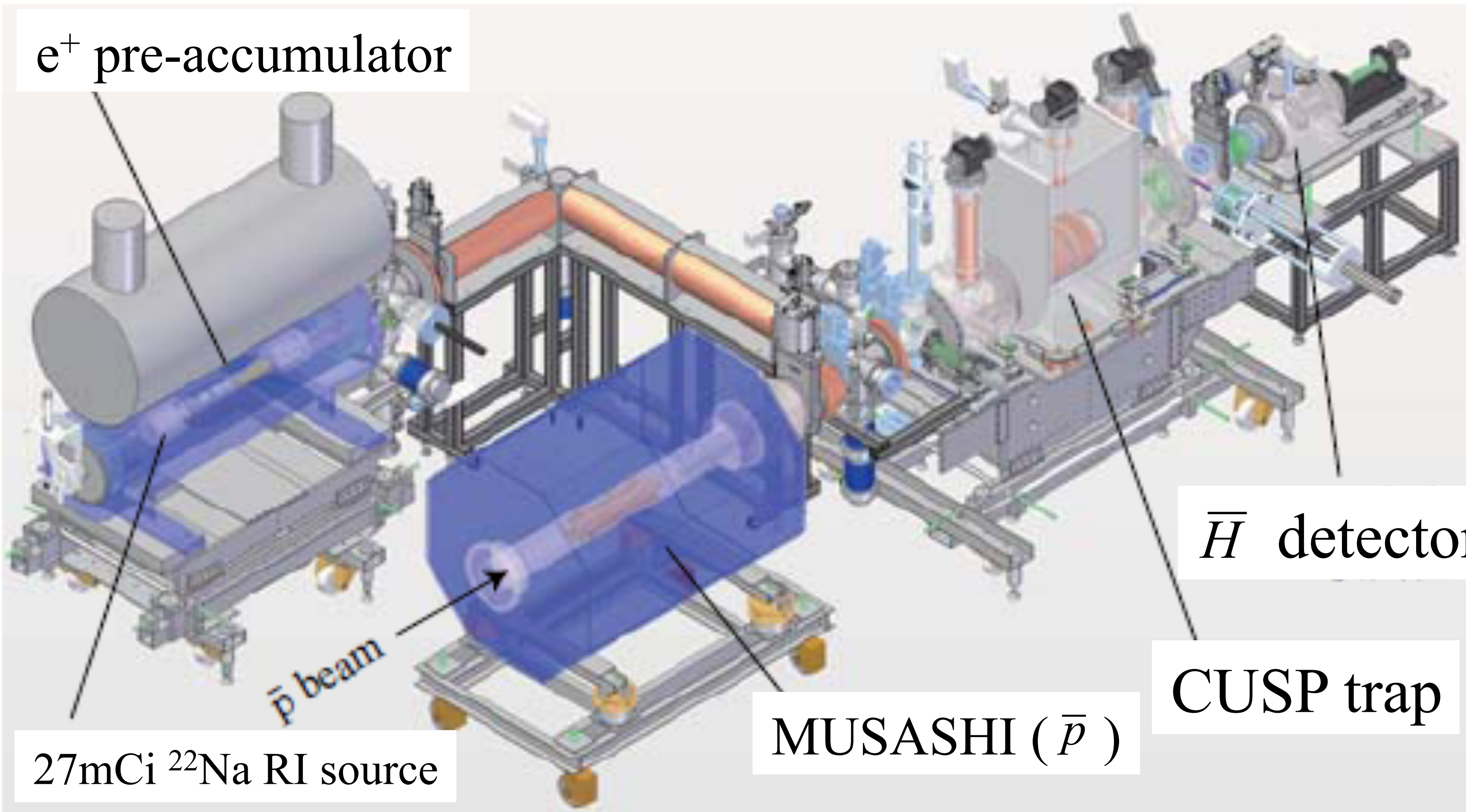
How to produce $\overline{H}$ (Low energy positron)
Positron pre-accumulator



How to produce $\overline{H}$ (Low energy positron)
Trajectory calculation for e^+ transport section



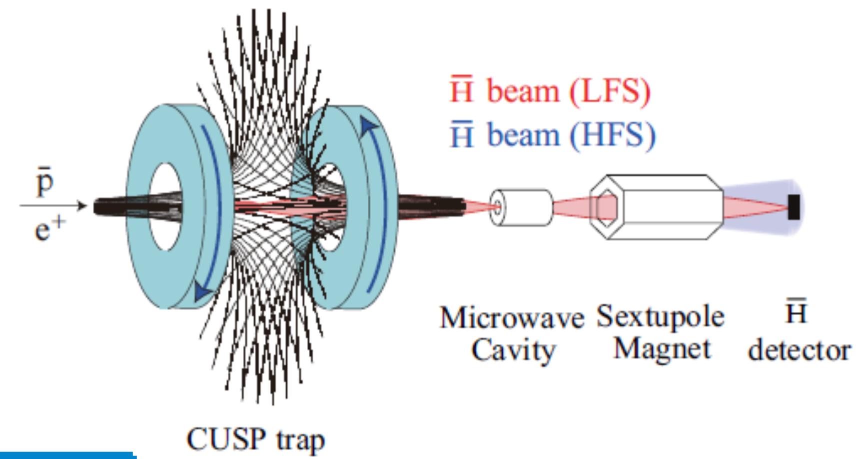
How to produce $\overline{H}$
ASACUSA-MUSASHI experimental setup in 2010



How to produce $\overline{H}$
Specifications

positron

27mCi ^{22}Na
(<100keV, ~10^9 /s)
W moderator, N_2buffer gas
(<3 eV, ~10^6 /s)
Pre-accumulator
(100eV, 2 x 10^5 /30s)



antiproton (pbar)

CERN PS (3.5GeV/c, 5 x 10^7)
AD (5MeV, 10^7)
RFQD (100keV, 5 x 10^6)
MUSASHI
(150eV, 5 x 10^5)

CUSP trap

6 x 10^6 positron
(<0.1eV, n_{e+}~10^8cm^{-3})

3 x 10^5 pbar
(< 20 eV)

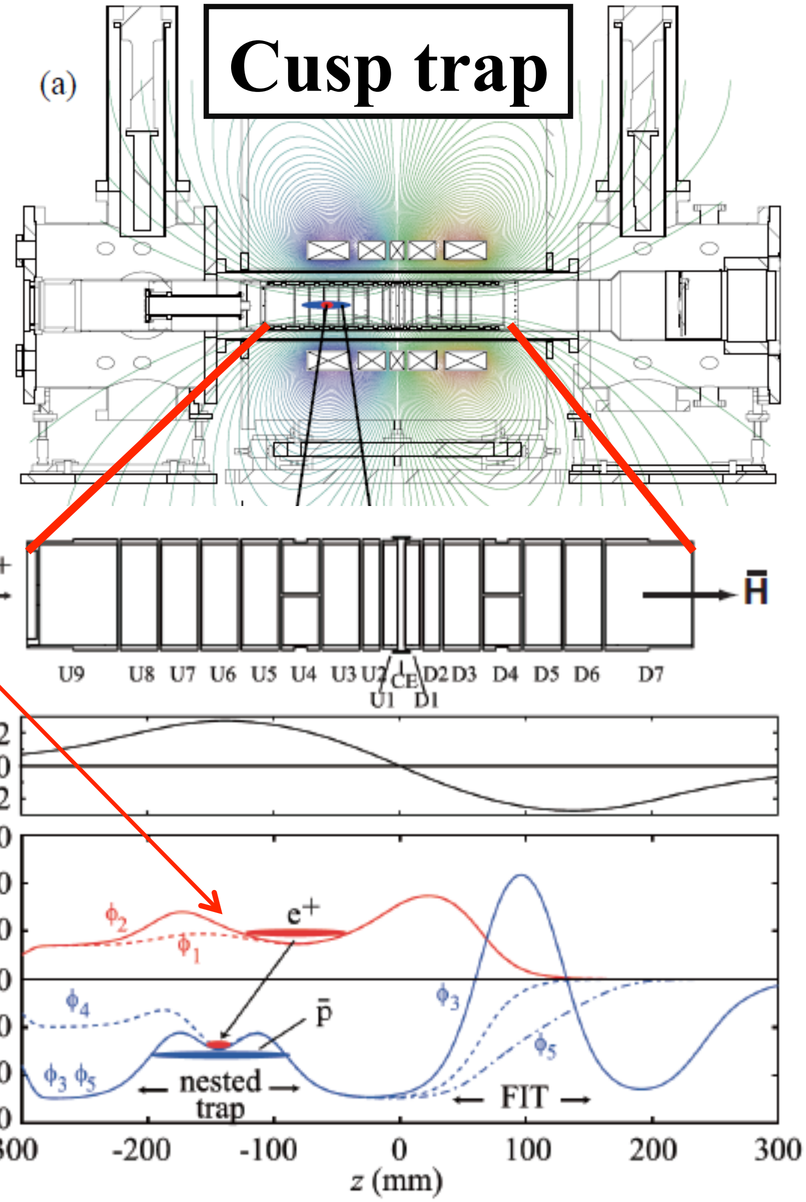
How to produce $\overline{H}$
Mixing in the Cusp trap in 2010

$\overline{H}$ with $n > 25$

~ 100eV e^+ pulse

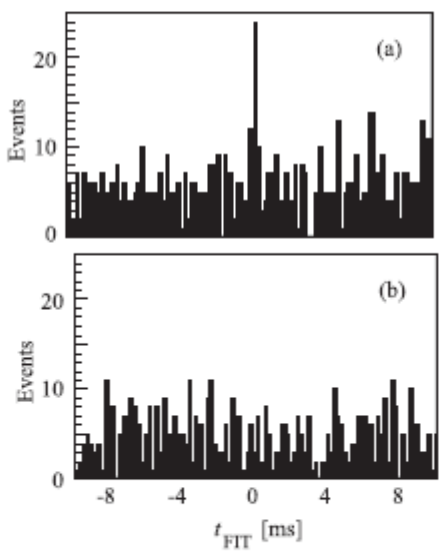
~ 150eV $\bar{p}$ pulse

6 x 10^6 e^+/ 60 shot,
< 0.1eV



w/ e^+

w/o e^+



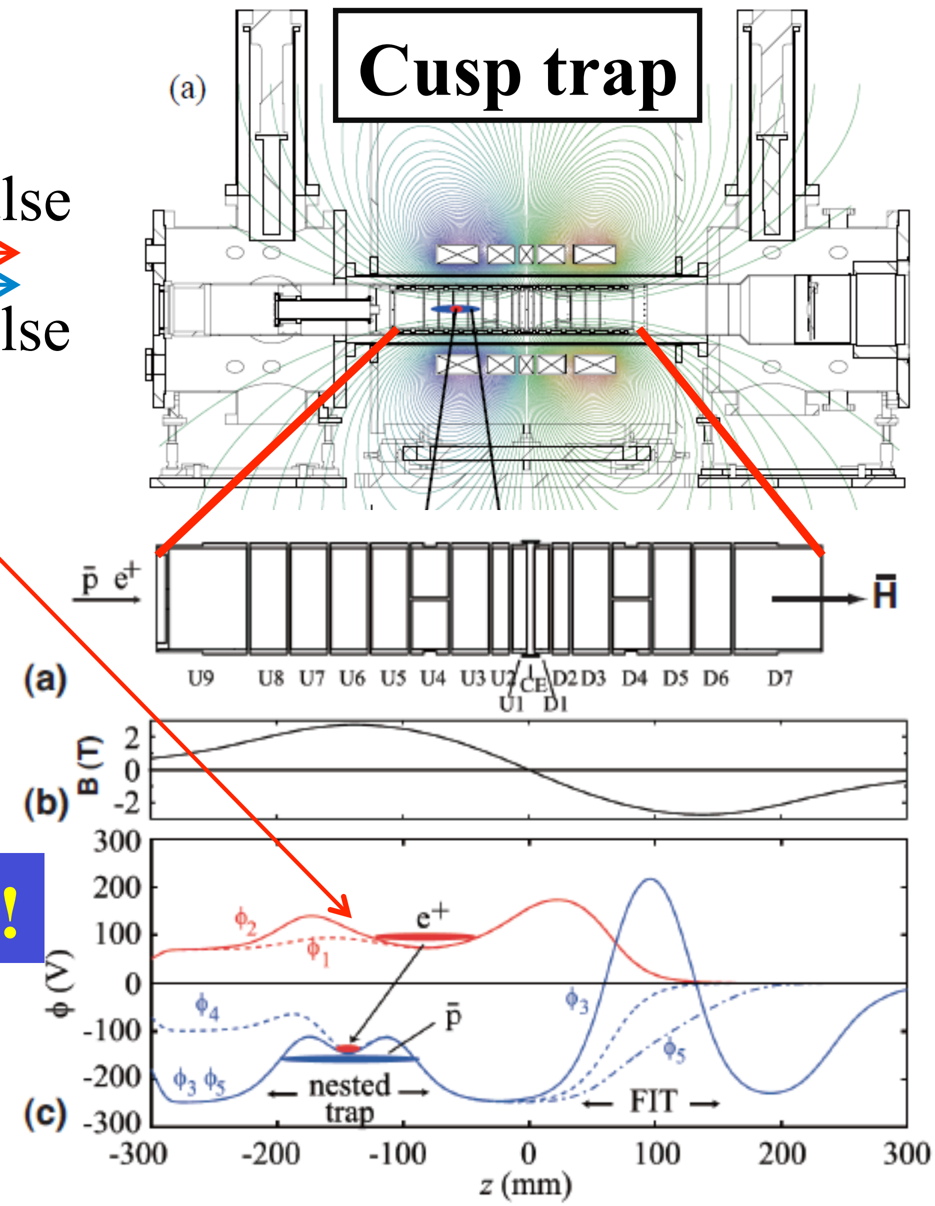
How to produce $\overline{H}$
Mixing in the Cusp trap in 2010

$\overline{H}$ with $n > 25$

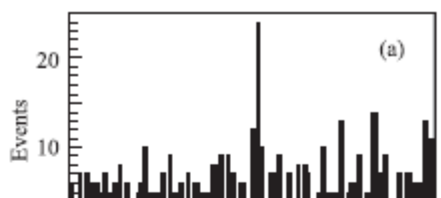
$\sim$ 100eV e^+ pulse

$\sim$ 150eV $\bar{p}$ pulse

6 x 10^6 e^+/ 60 shot,
< 0.1eV

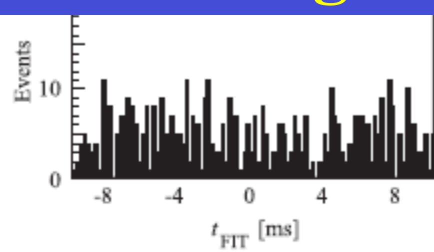


w/ e^+



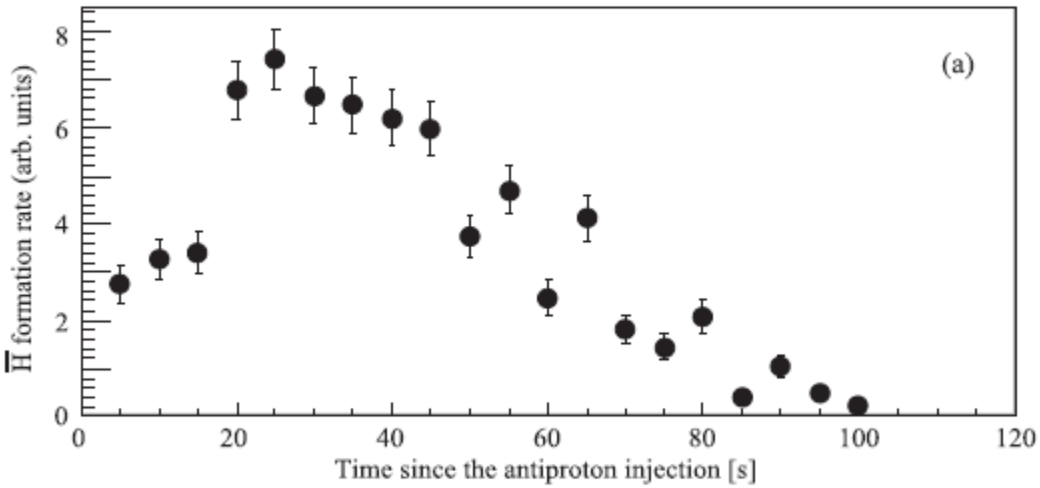
$\overline{H}$ produced in a grad B !

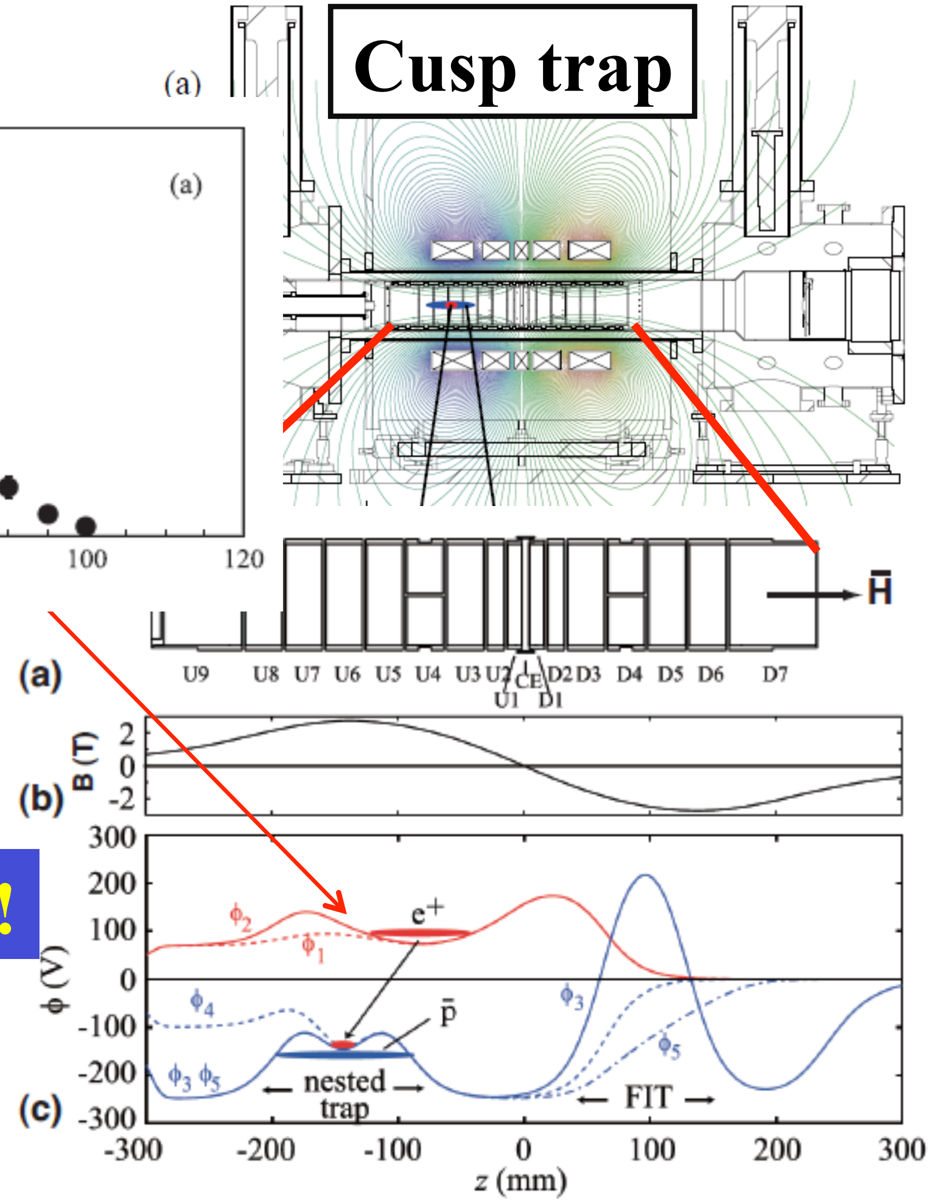
w/o e^+



How to produce $\overline{H}$
Mixing in the Cusp trap in 2010

$\overline{H}$ with $n > 25$

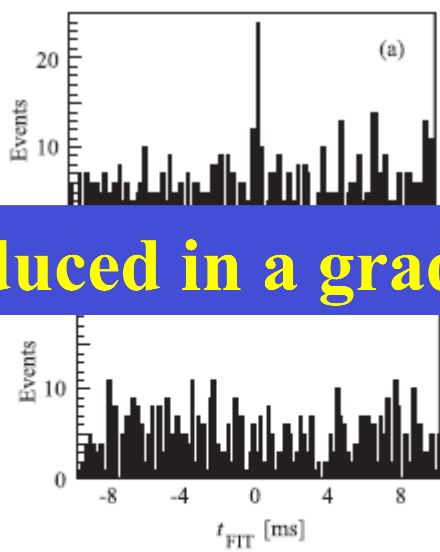




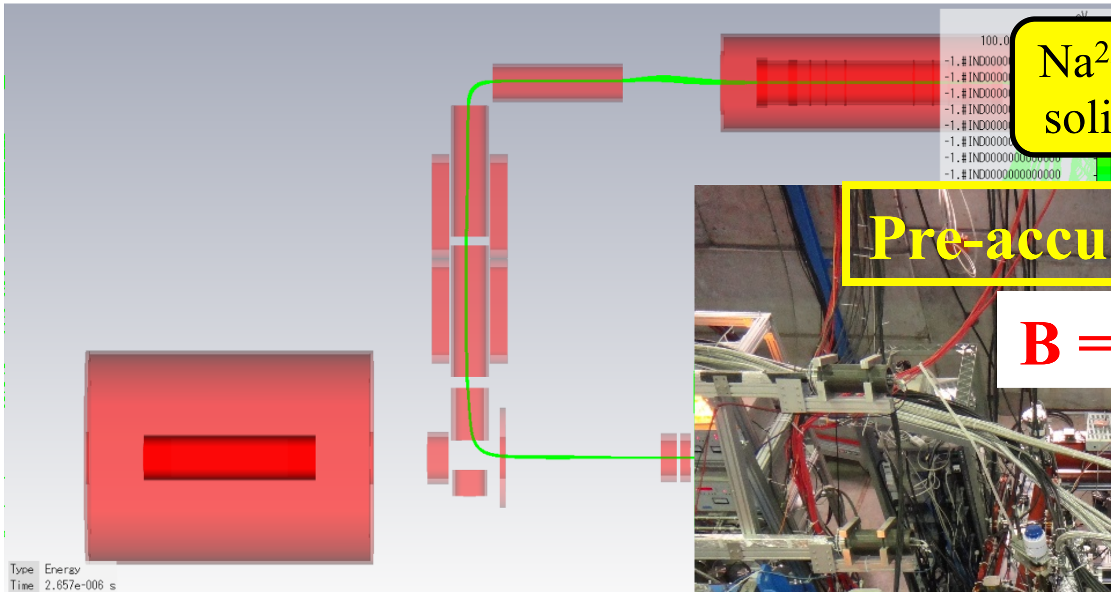
w/ e^+

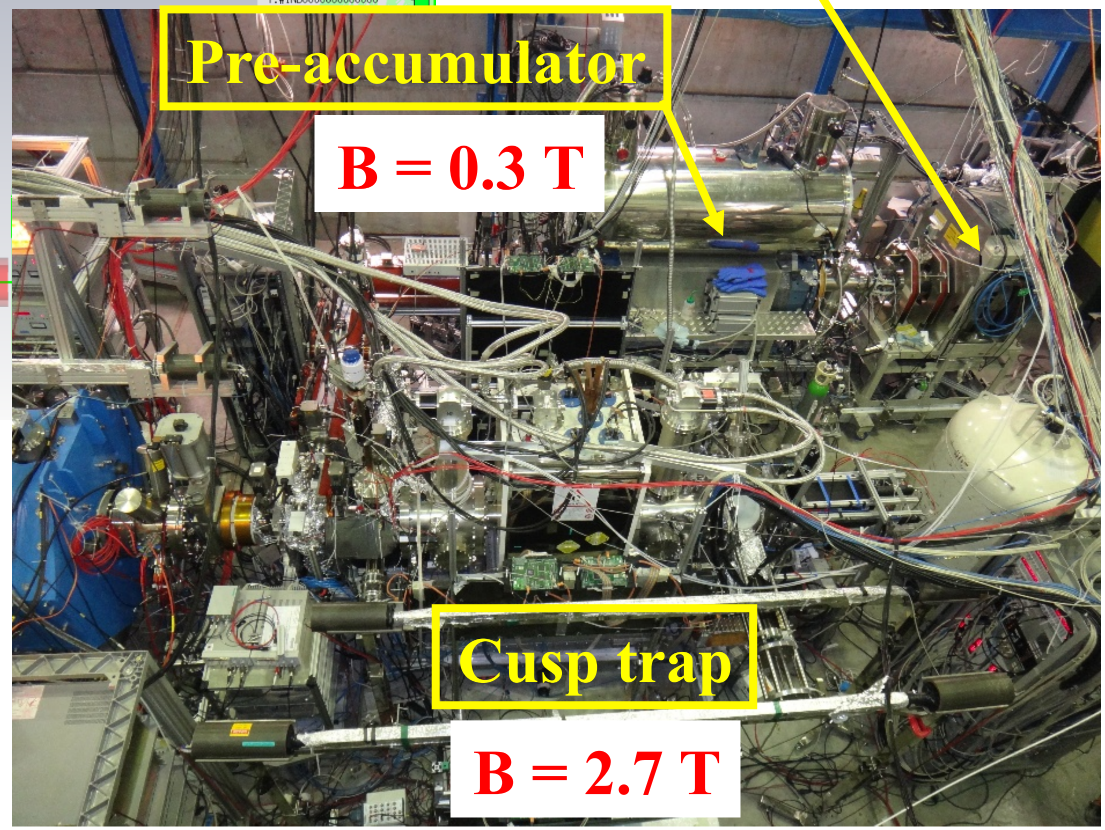
$\overline{H}$ produced in a grad B !

w/o e^+



Setup with a new e+ source in 2011

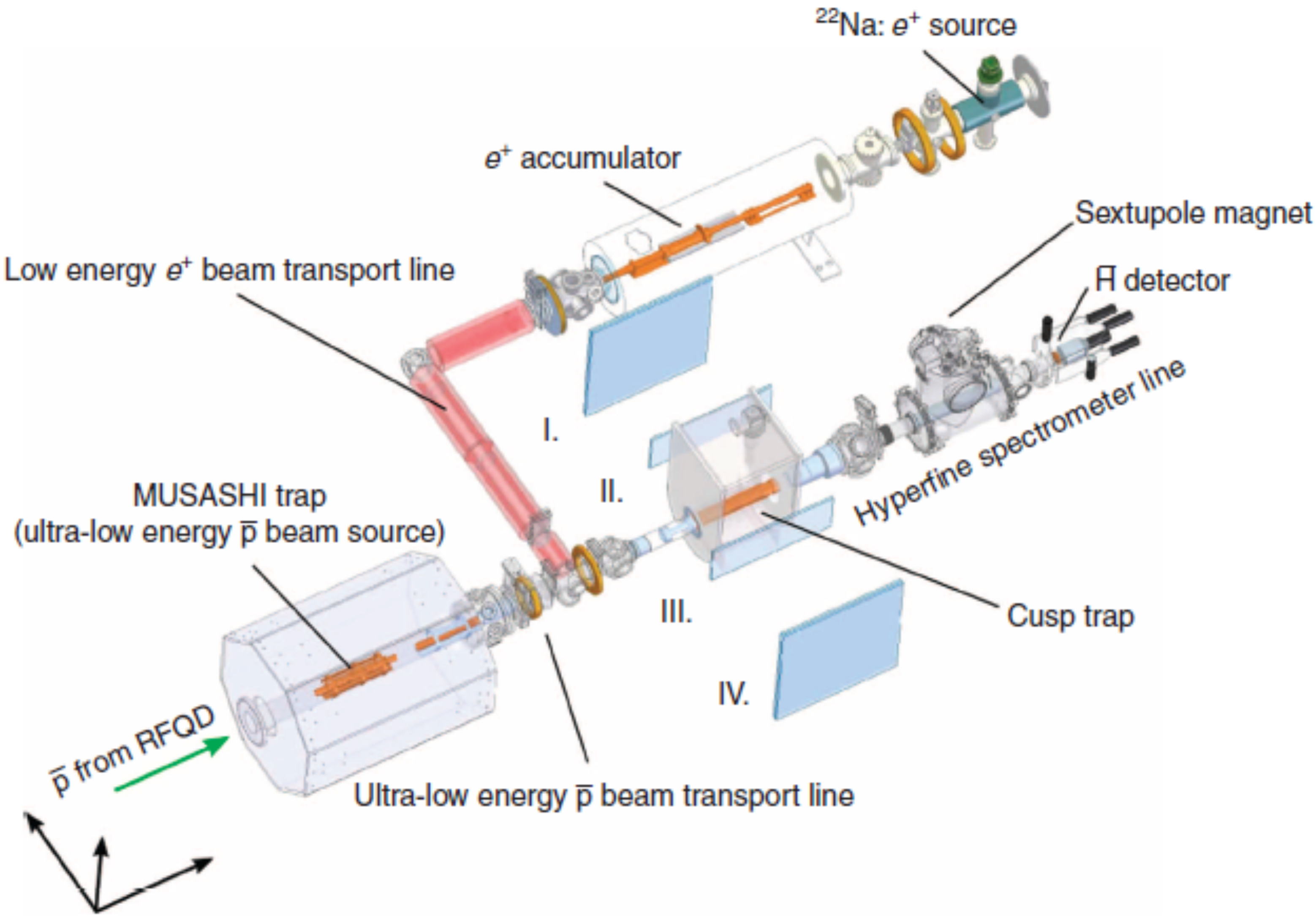




> 6 x 10^7 positrons in the CUSP trap

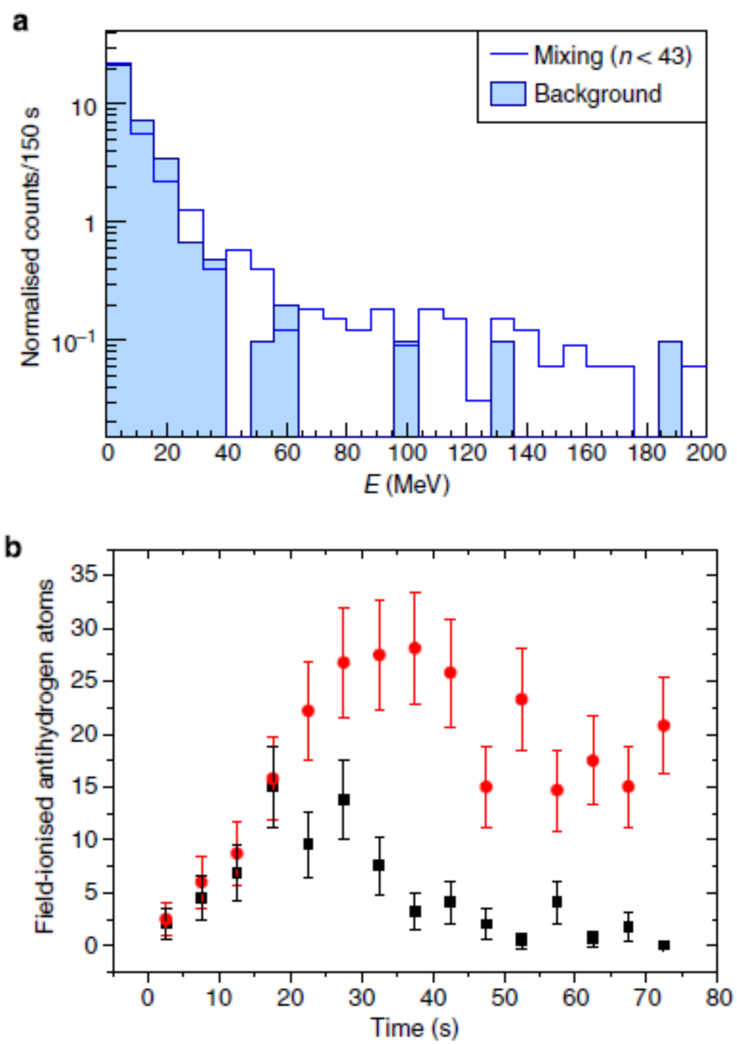
MUSASHI(pbar) + positron source + Cusp trap in 2012

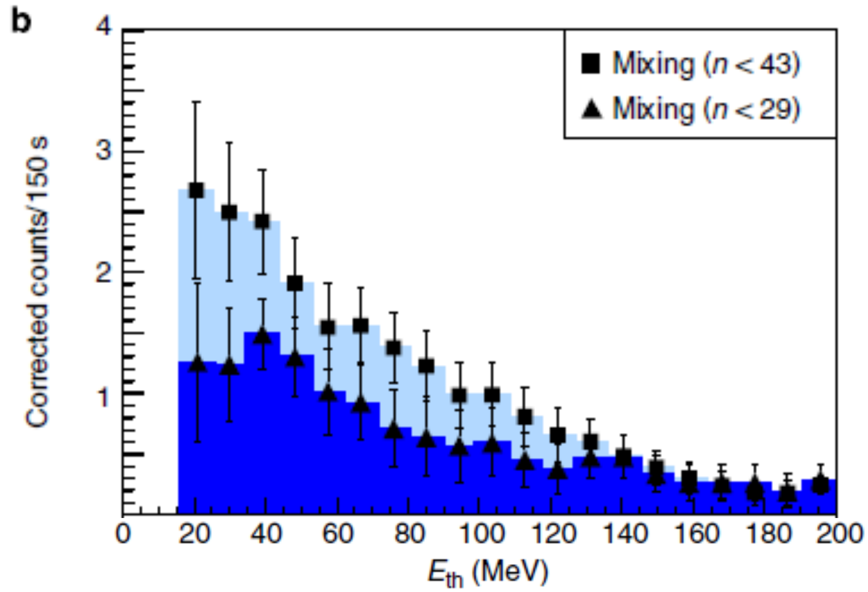
Nature Communications **5** (2014) 3089



Antihydrogen signals at FI trap in CUSP and the end detector

Nature Communications **5** (2014) 3089





Antihydrogen atoms (n<29) are detected at the end of the spectrometer line

Production rate was improved with the use of RF drive

"Driven Production of Cold Antihydrogen …", Phys. Rev. Lett. **89** (2002) 233401

Summary

1) Low energy anti-hydrogen atoms are currently investigated by "ALPHA", "ASACUSA" and "ATRAP" at AD, CERN to obtain new physics results. (AEGIS, BASE, GBAR, …)

2) Non-neutral positron plasmas play crucial roles for the production of $\overline{H}$ and their control is important for the higher production rate

3) $\overline{H}$ atoms in quantum states below $n < 29$ are detected at 2.7 m downstream from the production point.

4) Although $\overline{H}$ from the Cusp trap were detected in a field free region, the improvements of beam quality is necessary for experiments.

We thank AD members at CERN
for providing antiproton beams