Towards the production of an anti-hydrogen beam

S. Van Gorp[1], N. Kuroda[2], S. Ulmer[1], D.J. Murtagh[1], M. Corradini[4], M. Diermaier[6], M. Leali[4], C. Malbrunot[6], V. Mascagna[4], O. Massiczek[6], K. Michishio[3], A. Mohri[1], H. Nagahama[2], Y. Nagashima[3], Y. Nagata[1], M. Otsuka[2], C. Sauerzopf[6], K. Suzuki[6], M. Tajima[2], H. A. Torii[2], L. Venturelli[4], B. Wünschek[6], N. Zurlo[4], H. Higaki[1], Y. Kanai[1], E. Lodi-Rizzini[4], Y. Matsuda[2], E. Widmann[6], and Y. Yamazaki[1,2]

(ASACUSA-CUSP collaboration)

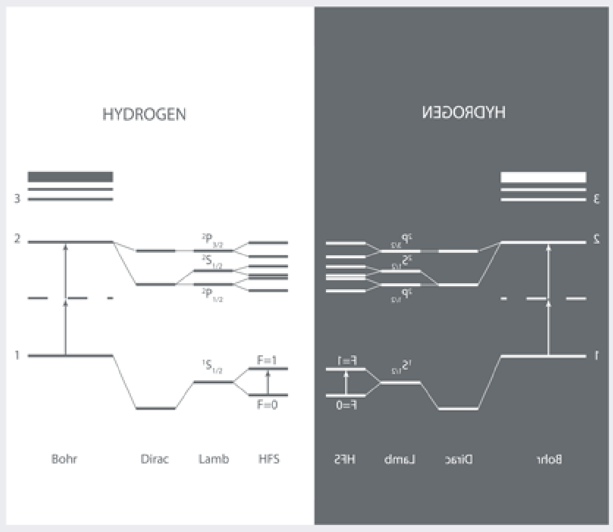
1 RIKEN Advanced Science Institute, Hirosawa, Wako, Saitama 351-0198, Japan
2 Graduate School of Arts and Sciences, The University of Tokyo, Komaba, Meguro, Tokyo 153-8902, Japan
3 Department of Physics, Tokyo University of Science, Kagurazaka, Shinjuku, Tokyo 162-8601, Japan
4 Dipartimento di Chimica e Fisica per l'Ingegneria e per i Materiali, Universitá di Brescia & Istituto Nazionale di Fisica Nucleare, Gruppo Collegato di Brescia, 25133 Brescia, Italy
5 RIKEN Nishina Center for Accelerator Based Science, Hirosawa, Wako, Saitama 351-0198, Japan
6 Graduate School of Advanced Sciences of Matter, Hiroshima University, Kagamiyama, Higashi-Hiroshima, Hiroshima 739-8530, Japan
7 Stefan Meyer Institute for Subatomic Physics, Austrian Academy of Sciences, 1090 Wien, Austria

Why Antihydrogen ?

*Antihydrogen is the simplest atom consisting entirely of antimatter.

*Hydrogen counterpart is one of the best understood and most precisely measured atoms in physics.

*A comparison of antihydrogen and hydrogen offers one of the most sensitive tests of CPT symmetry.



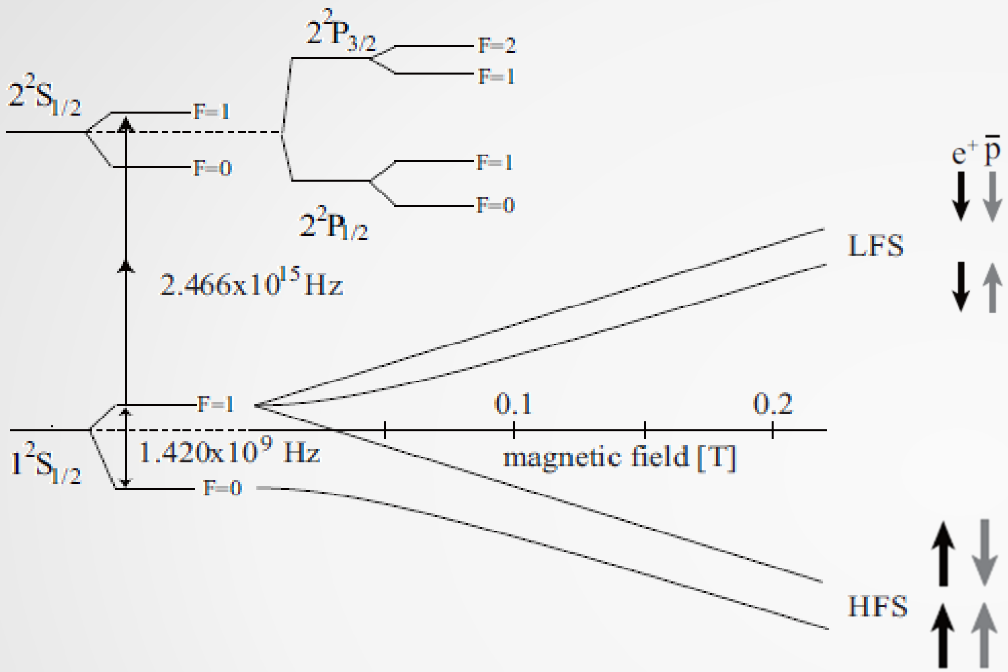
What ?

High precision spectroscopy of the ground state hyperfine splitting of antihydrogen.

How ?

Creation of a spin-polarized anti-hydrogen beam

Low energy anti-hydrogen atoms (Level diagram)



Low Field Seekers (LFS)

$$\nu_{HFS} = \frac{16}{3}\left(\frac{m_p}{m_p+m_e}\right)^3 \frac{m_e}{m_p}\frac{\mu_p}{\mu_N}\alpha^2 c Ry + \Delta$$

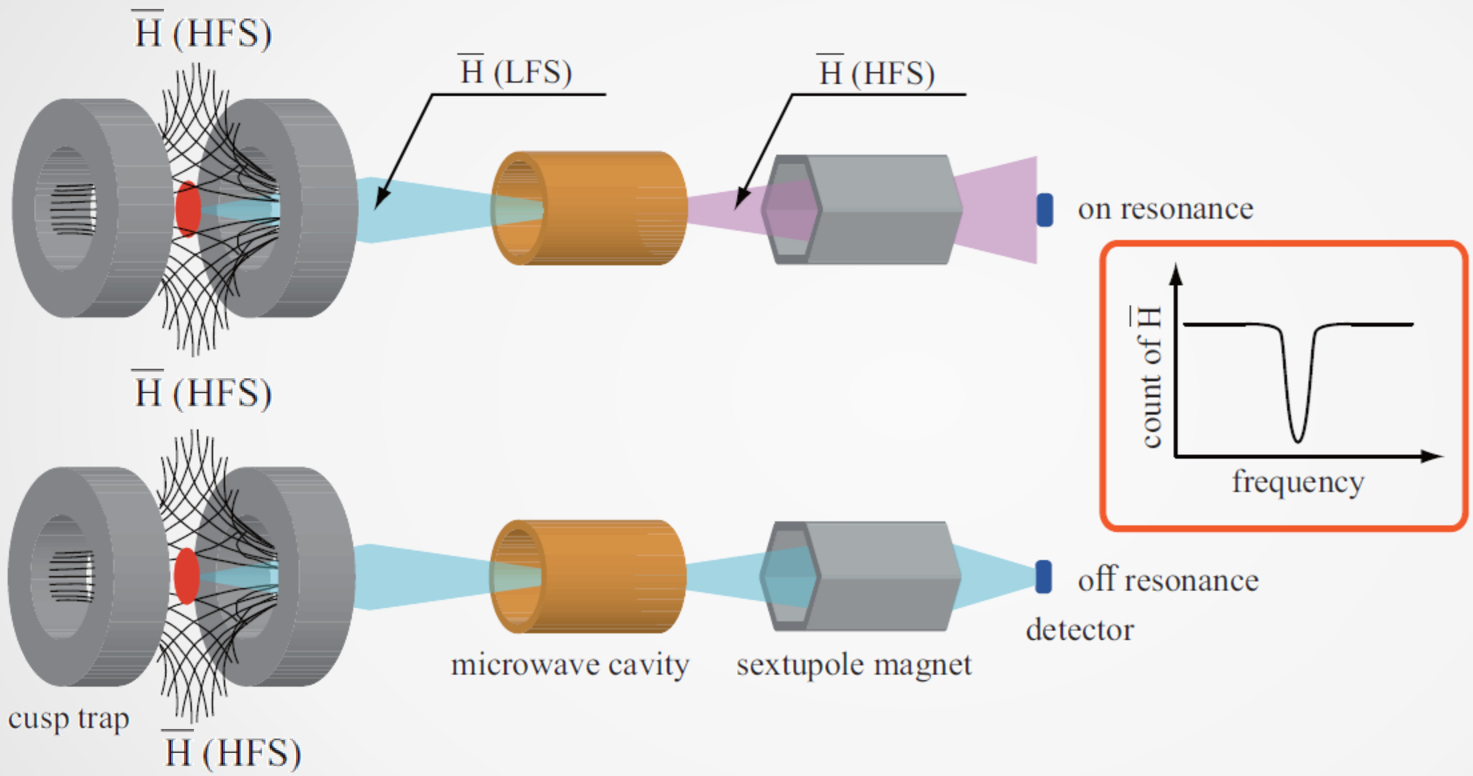
High Field Seekers (HFS)

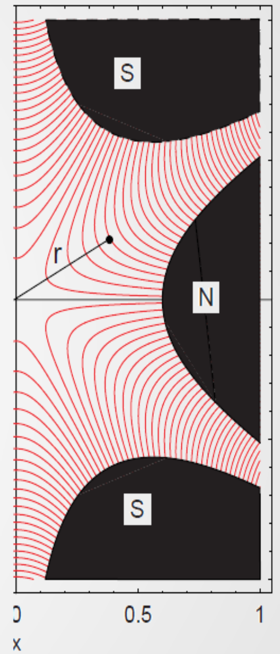
	experiments (Hz)	Δνexp /ν	|νtheory-νexp |/ν
ν_{1S-2S}	2,466,061,413,187,103(46)	1.7×10^{-14}	1×10^{-11}
ν_{HFS}	1,420,405,751.768(1)	6.3×10^{-13}	$(3.5+0.9) \times 10^{-6}$

Aim to measure ν_{HFS} with a precision of 1.8×10^{-6}

Measure antihydrogen under field-free conditions!

Measuring the hyperfine structure





Anti Helmholtz configuration:

- HFS-states: de-focused
- LFS-states: focused
- We require an antihydrogen beam!

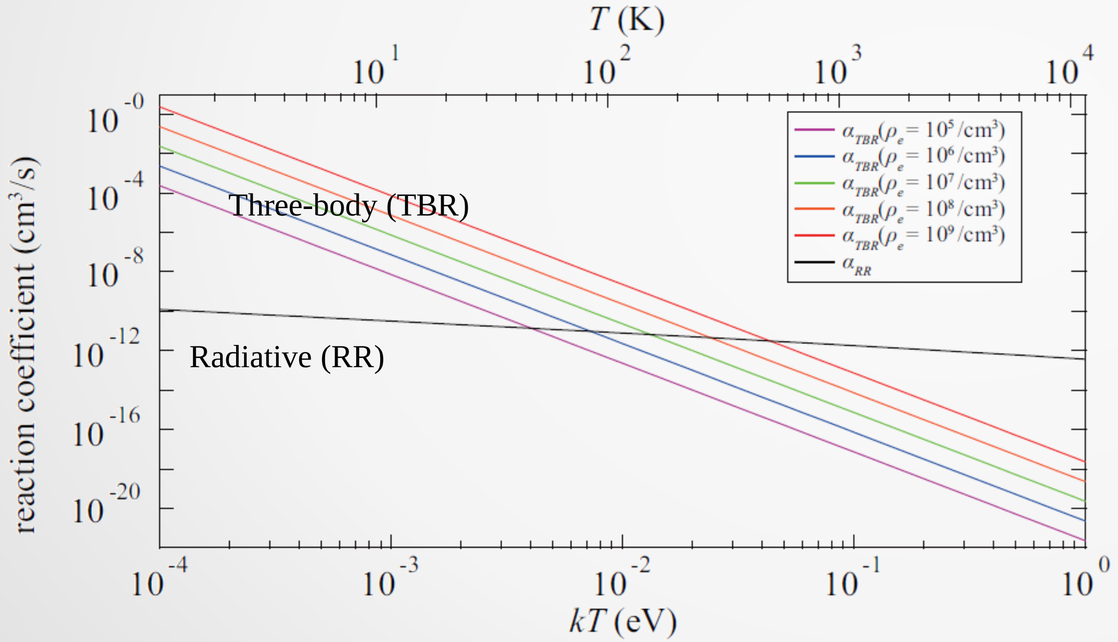
[1] A. Mohri and Y. Yamazaki, Europhys. Lett. **63** (2003) 207. [2] Y. Enomoto et al., Phys.Rev.Lett.**105** (2010) 243401

Cold = ☺ (1)

(a) $\bar{\mathrm{H}}$ formation rate

$$\bar{\mathrm{p}} + \mathrm{e}^+ \rightarrow \bar{\mathrm{H}} + \mathrm{h}\nu \qquad \alpha_{RR} = 1.92 \times 10^{-13} \frac{1}{\sqrt{kT}} \left\{ \ln\left(\frac{5.66}{\sqrt{kT}}\right) + 0.196 (kT)^{\frac{1}{3}} \right\} \ \mathrm{cm}^3/\mathrm{s} \qquad \sigma \propto n_{e^+} T^{-1/2}$$

$$\bar{\mathrm{p}} + \mathrm{e}^+ + \mathrm{e}^+ \rightarrow \bar{\mathrm{H}} + \mathrm{e}^+ \qquad \alpha_{TBR}(n, E_{cm}, \rho_e) = 1.96 \times 10^{-29} \rho_e \frac{1}{kT} n^6 \ \mathrm{cm}^3/\mathrm{s} \qquad \sigma \propto n_{e^+}^2 T^{-9/2}$$



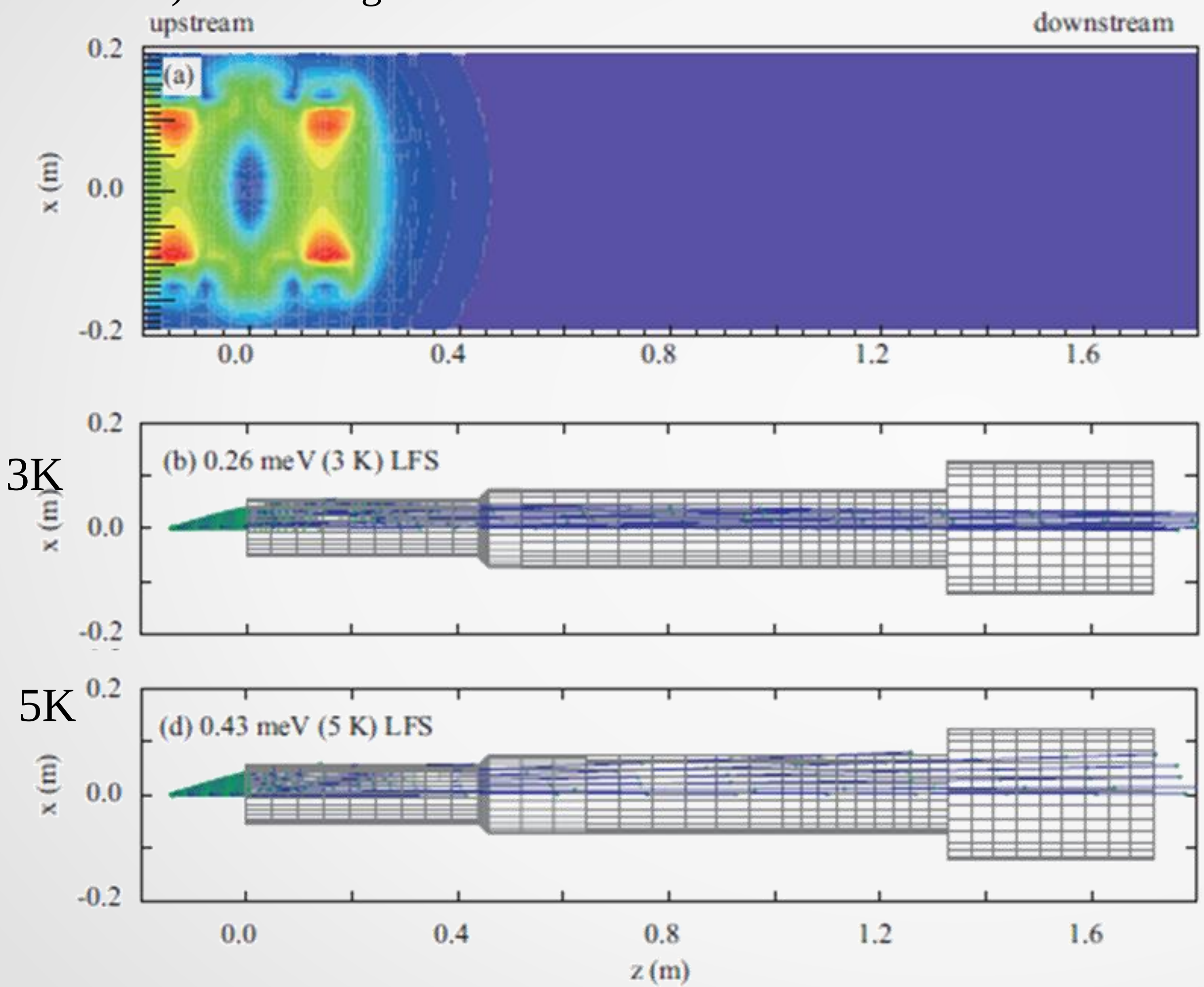
Due to the strong dependence on the density and temperature of e^+, three body recombination is the dominant process at ~10^8cm^{-3}, ~10K

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

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

Cold = ☺ (2)

2) $\bar{H}$ focusing

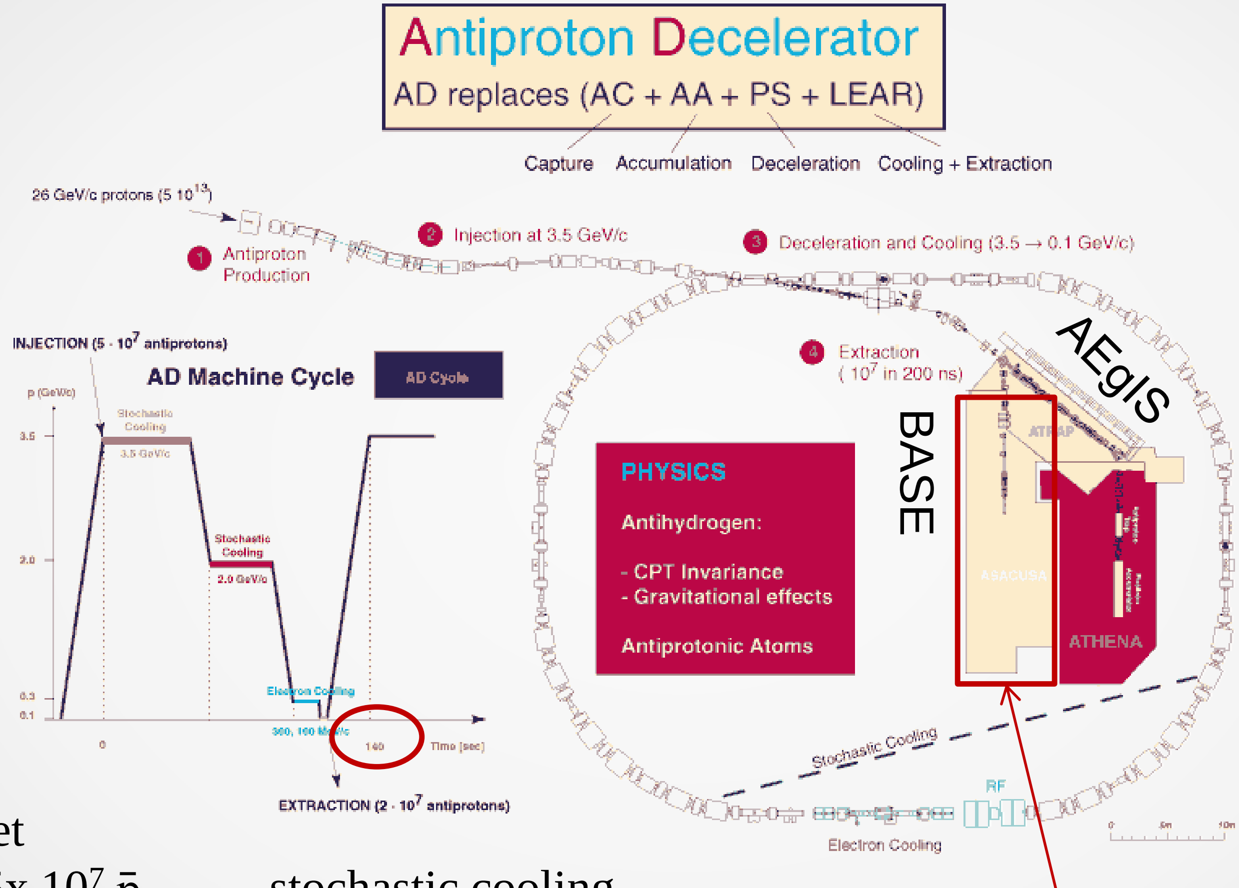


The intensity of LFS $\bar{H}$ from CUSP to detector is much enhanced when the temperature is reduced

For 3K compared to the solid angle, the intensity changes:
→LFS x 50 !!
→HFS suppressed to 1/100

3) Interaction time with u-wave radiation in the cavity
4) Longer TOF -> lower n-state

Antiproton creation (AD)



ASACUSA area

Production target

1) 3.5GeV/c ~5x 10^7 $\bar{p}$ stochastic cooling

2) 2 GeV/c stochastic cooling

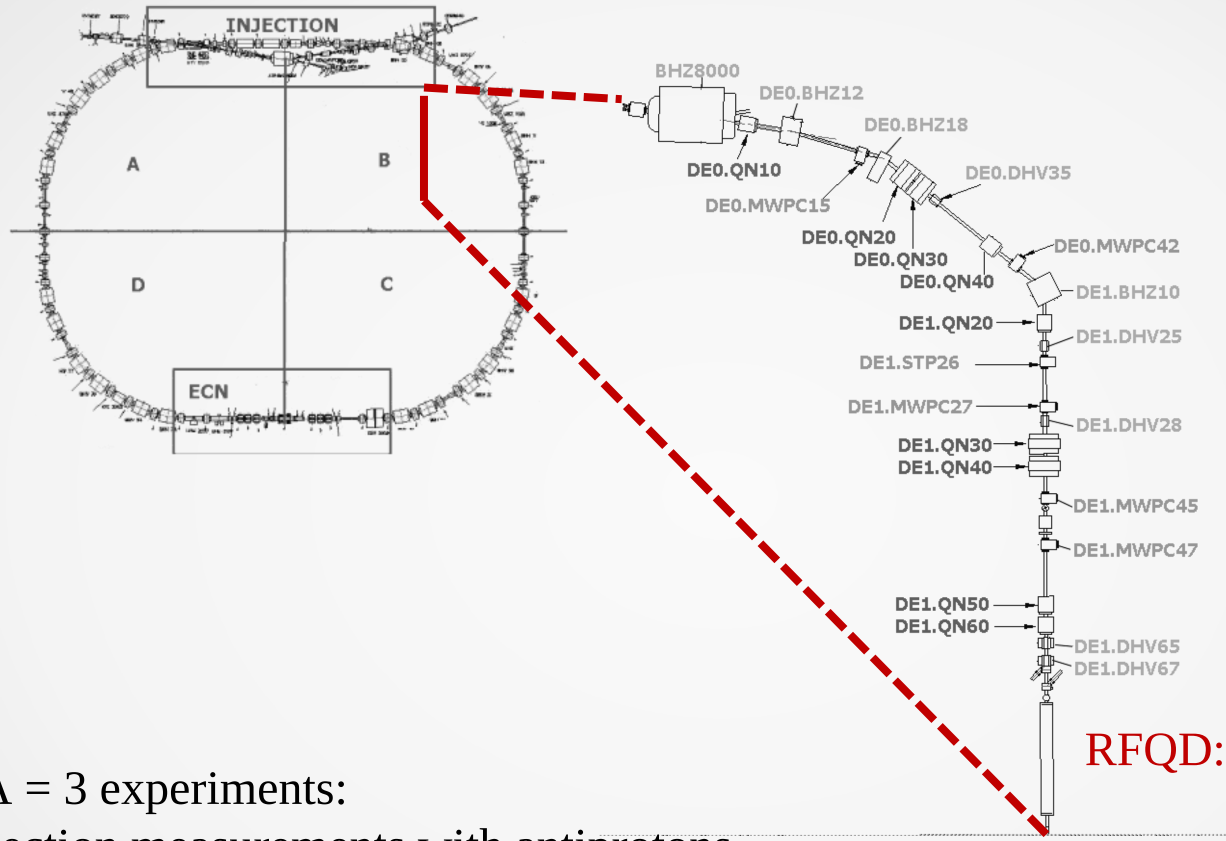
3) 300MeV/c e^- cooling

4) 5.3 MeV (100 MeV/c) e^- cooling

~ 10^7 $\bar{p}$ pulse from AD (~100s cycle)

a) 110keV <5 x 10^6 pbar with RFQD

ASACUSA collaboration:



RFQD: 200 MHz / 1.1 MW

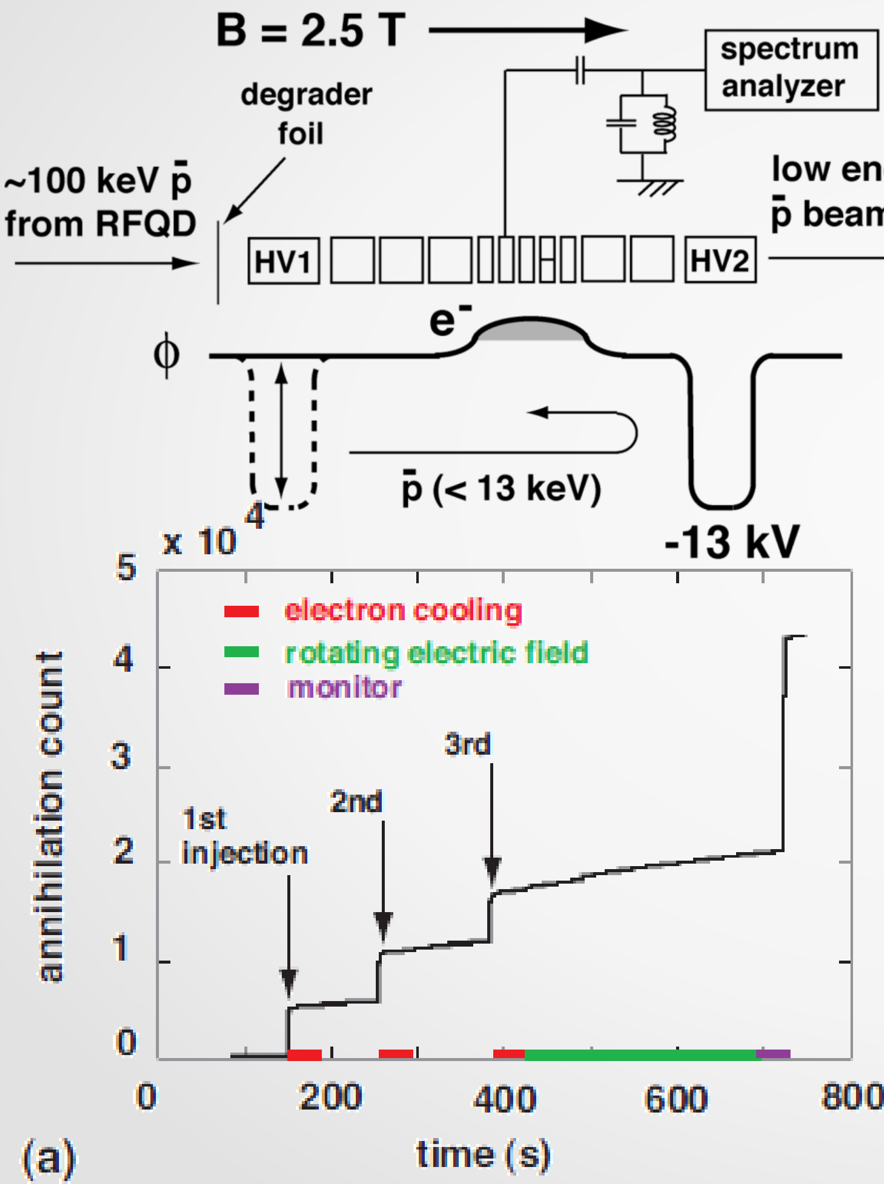
ASACUSA = 3 experiments:

1) Cross section measurements with antiprotons
2) $\bar{p}$-Helium
3) Antihydrogen: ASACUSA-CUSP experiment

-> 3 months/experiment

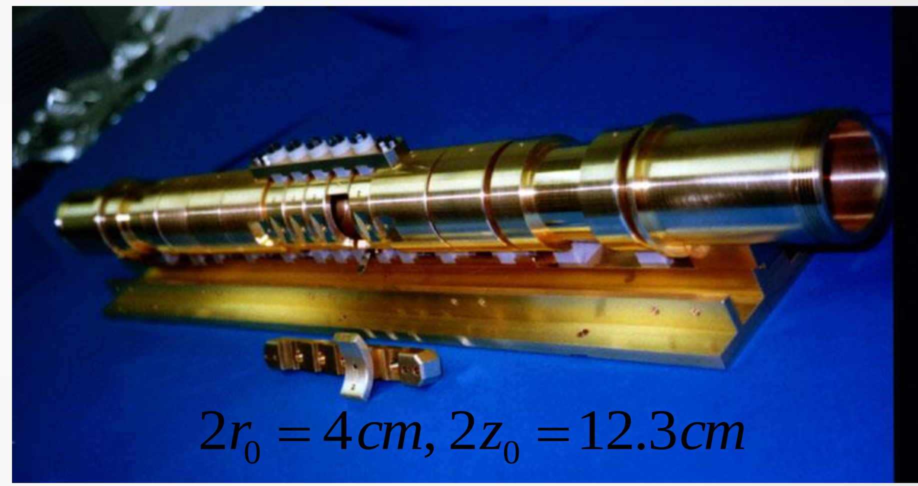
5-50 times more $\bar{p}$/AD cycle compared to other AD experiments

Antiproton accumulator + buncher (MUSASHI trap)



< 13 keV pbar confined in the trap

10^6 p̄ / AD shot

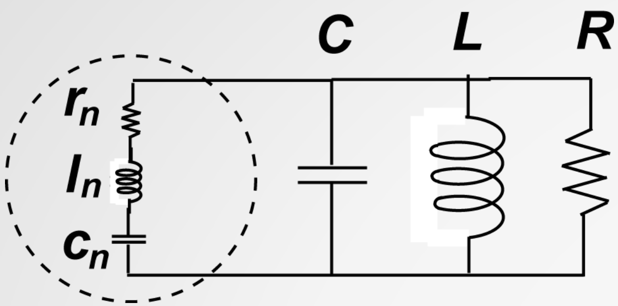


Sympathetically cooled with 3×10^8 e^-s

A rotating wall electric field is superimposed on the trap ring electrodes to control the p̄ density

[4] N. Kuroda, H. A. Torii, K. Y. Franzen, *et al.*, Phys. Rev. Lett. 94, 023401 (2005).
[5] X.-P.Huang, et al.,Phys.Rev.Lett.**78**(1997)875
[6] H. Saitoh, et al.,Phys.Rev. A**77**(2008)051403(R)

Resonant detection of antiproton number ~ Schottky pickup



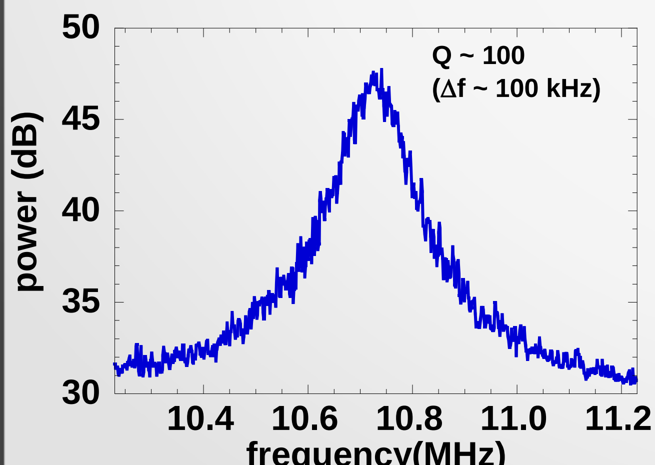
Particle moves axially in a harmonic well. Connect a resonant LC circuit to it to monitor the number density.
Particles effectively short the noise to ground.

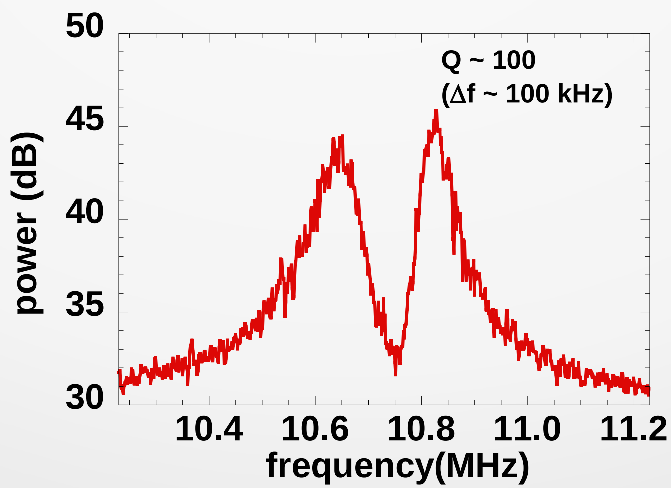
$$V = l_s \frac{di}{dt} + \frac{1}{c_s}\int i\,dt + r_s i$$

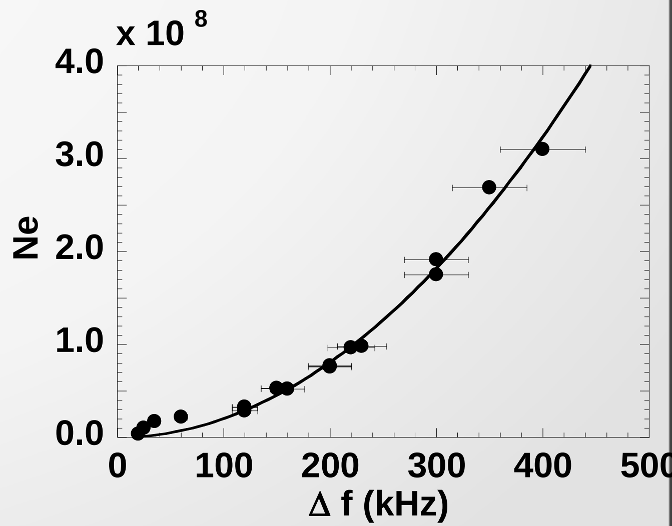
$$I = ni,\ l_n = l_s / n,\ c_n = c_s n,\ r_n = r_s / n$$

$$l_s = \frac{4mz_0^2}{e^2 d_1^2},\ c_s = \frac{e^2 d_1^2}{4m\omega_z^2 z_0^2},\ r_s = \frac{4\gamma m z_0^2}{e^2 d_1^2}$$

$$n \propto \left|(\Delta f)^2\right|$$

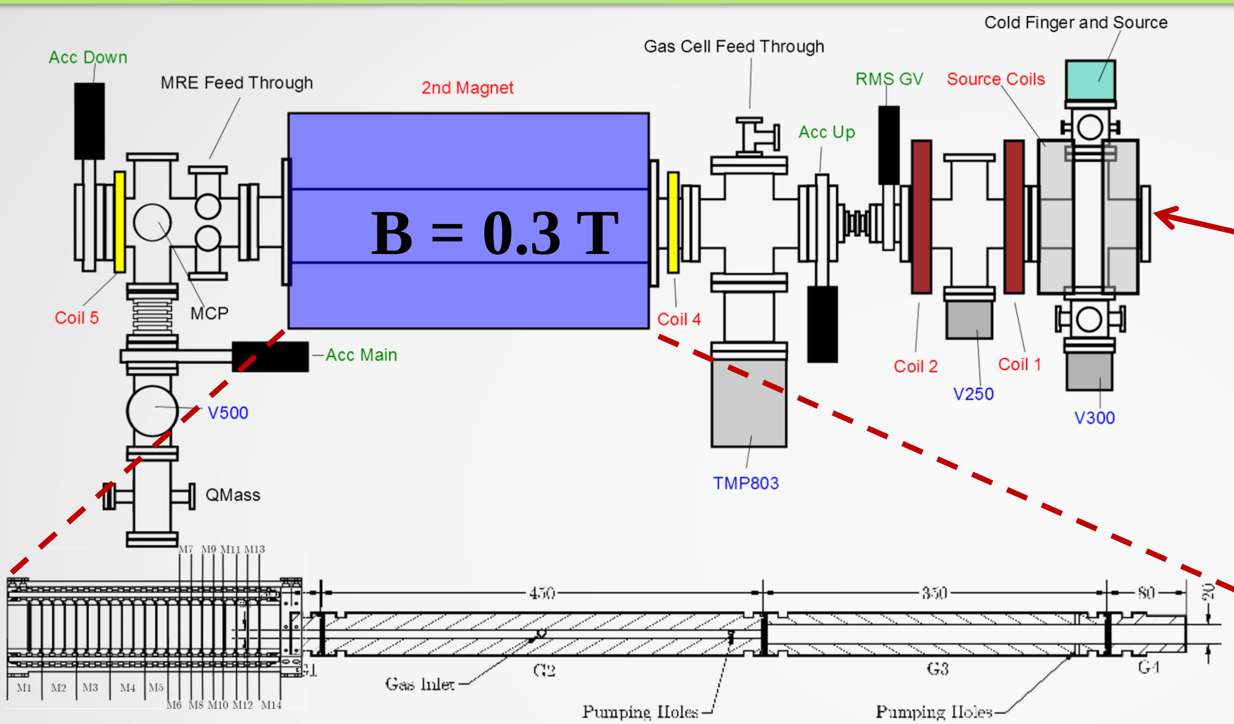






[7] D. J. Wineland and H. G. Dehmelt, *J. Appl. Phys.* **46**, 919 (1975) [8]: X.Feng, M.Charlton, M.Holtzscheiter, *et al*., J. Appl. Phys.79, 8 (1996)

Positron trap



^{22}Na β^+ source (1.7 GBq) + RGS (Rare gas moderator) = 2.3e^6 e+/s

N_2 pressure section

MRE trap + RW electrode

Gas cell: Positrons interact with N_2 and CF_4 and excite discrete, rotational and vibrational states of CF_4 and N_2 losing energy in this process.

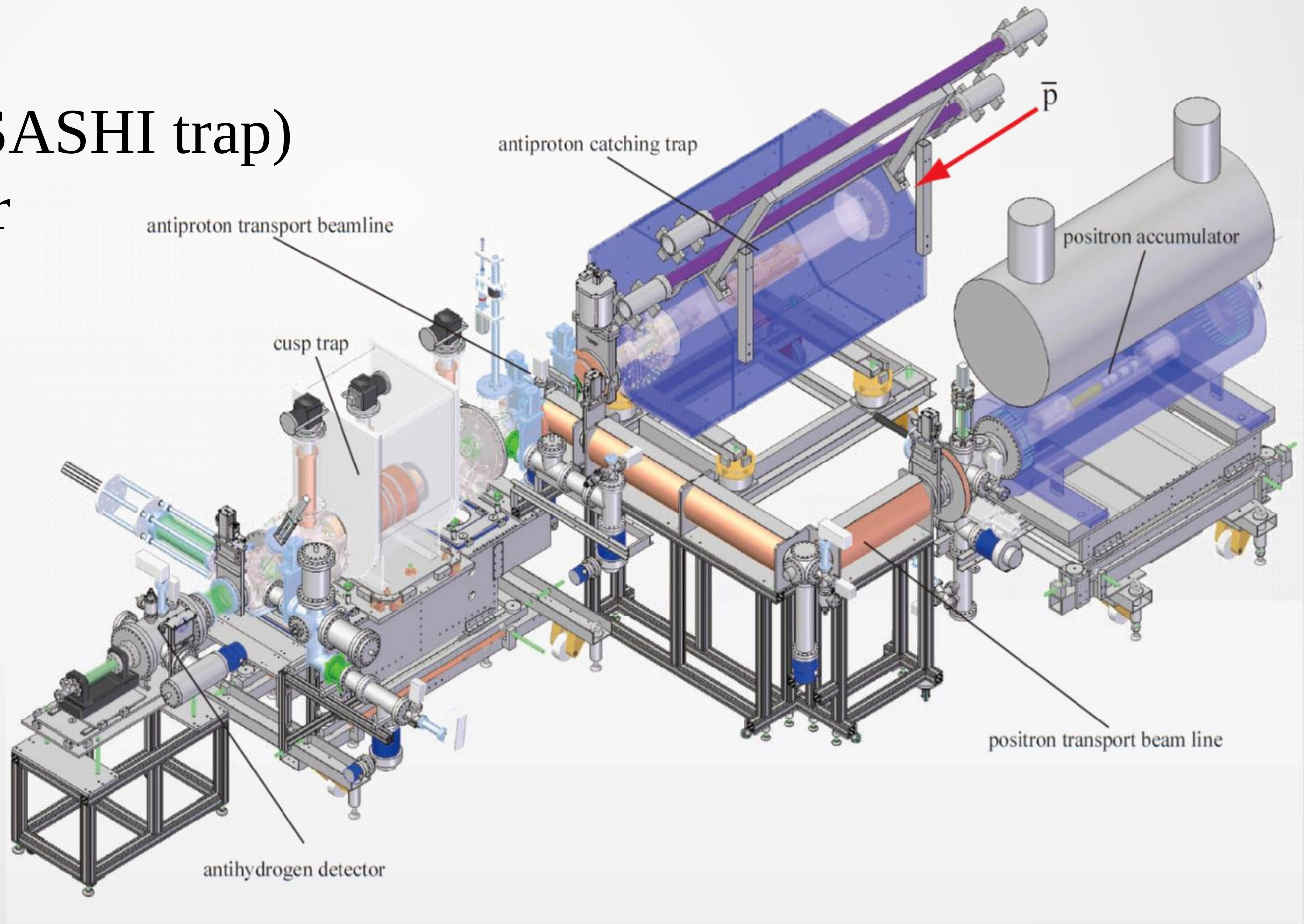
Tuning of gas cell (1V range) potentials according to competition with the positronium formation cross-section (=loss mechanism)

10^6 e^+/15s

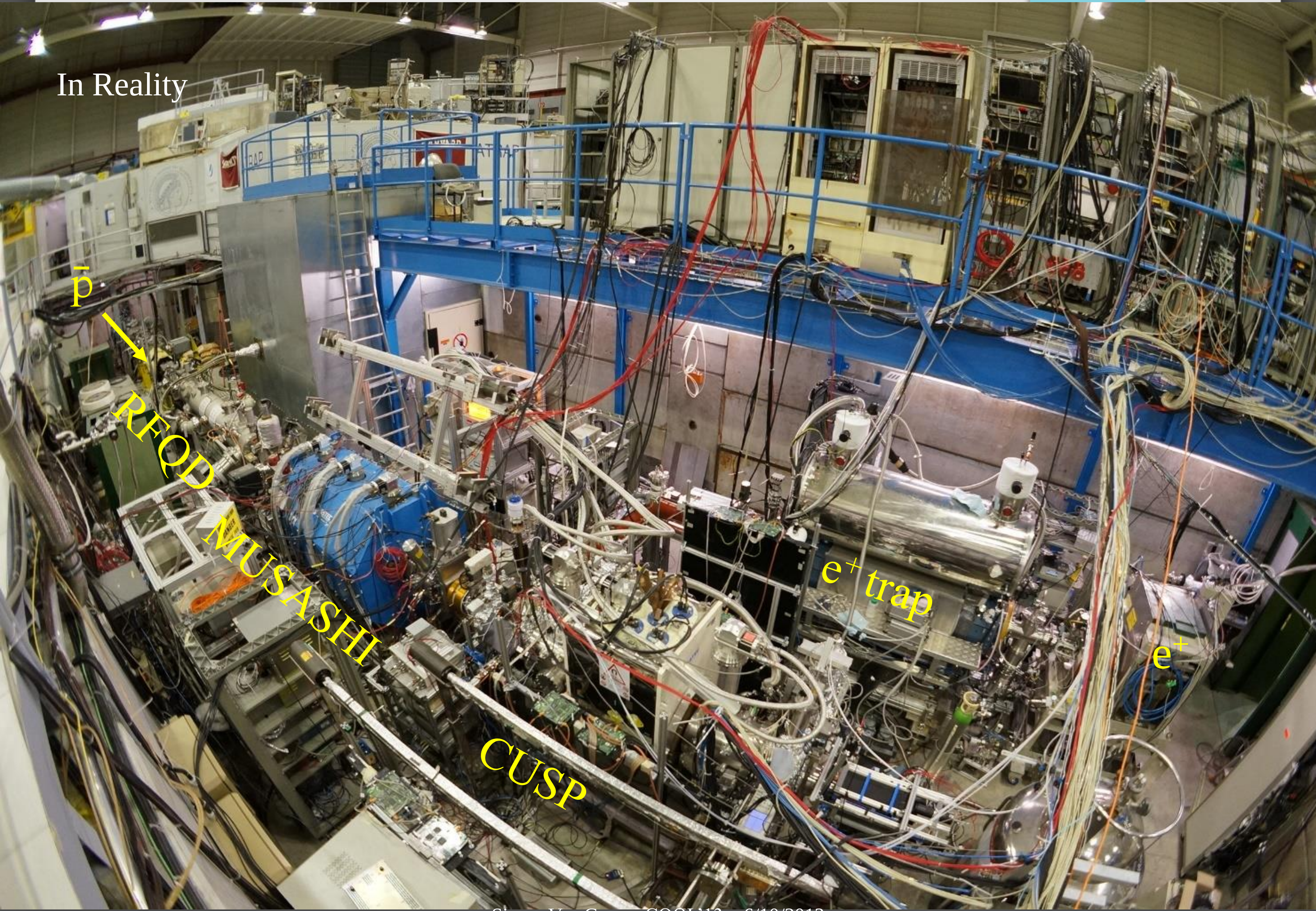
From 5.3 MeV $\bar{p}$ to sub eV $\bar{H}$: the ingredients!

We need antihydrogen → has to be synthesized first

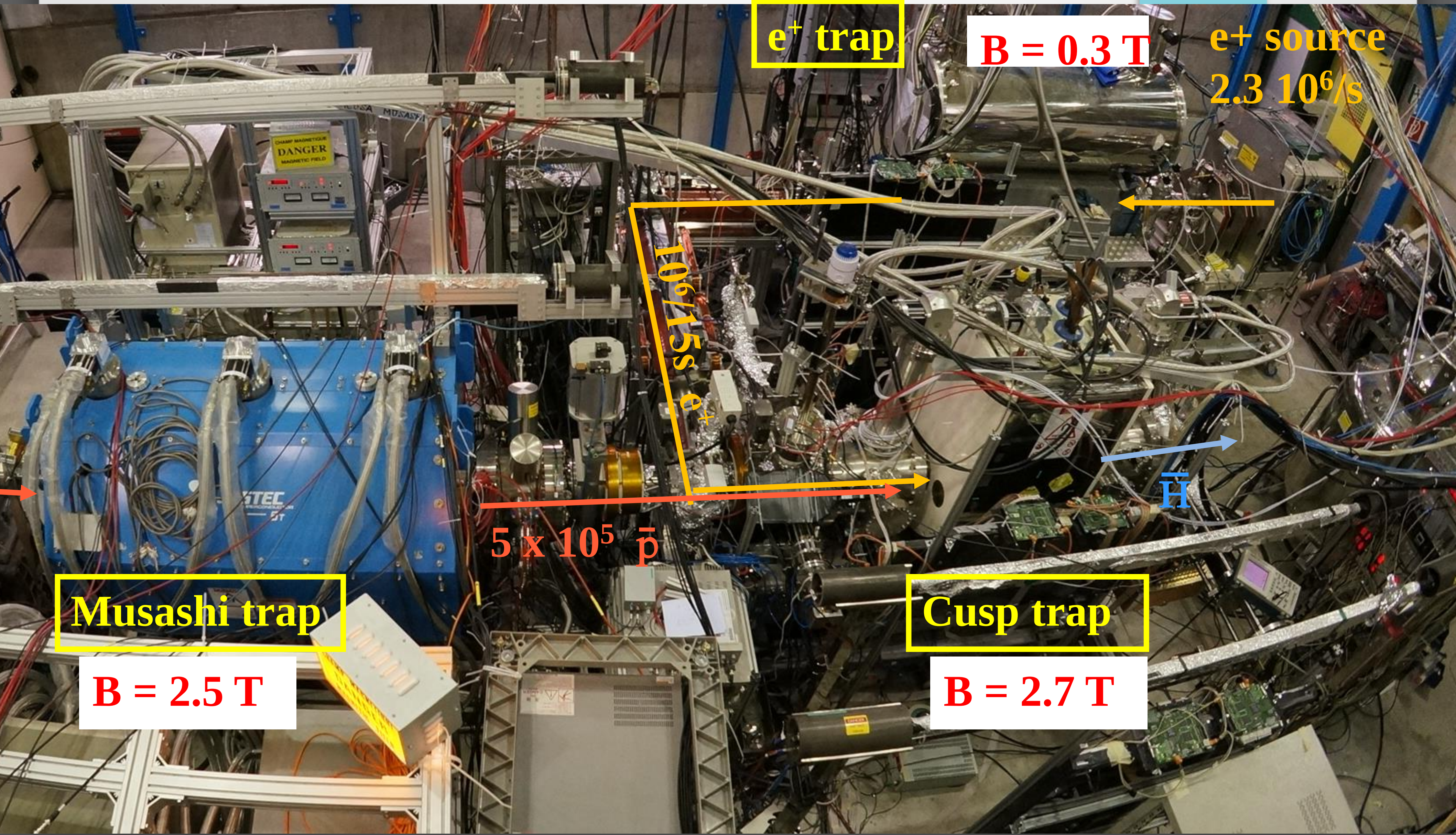
1) $\bar{P}$ accumulator (MUSASHI trap)
2) Positron accumulator
3) CUSP trap
4) Spin flip cavity
5) Sextupole Magnet
6) Detectors



In Reality



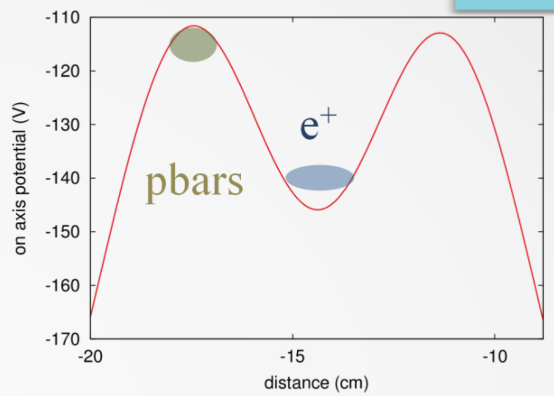
Experiment layout

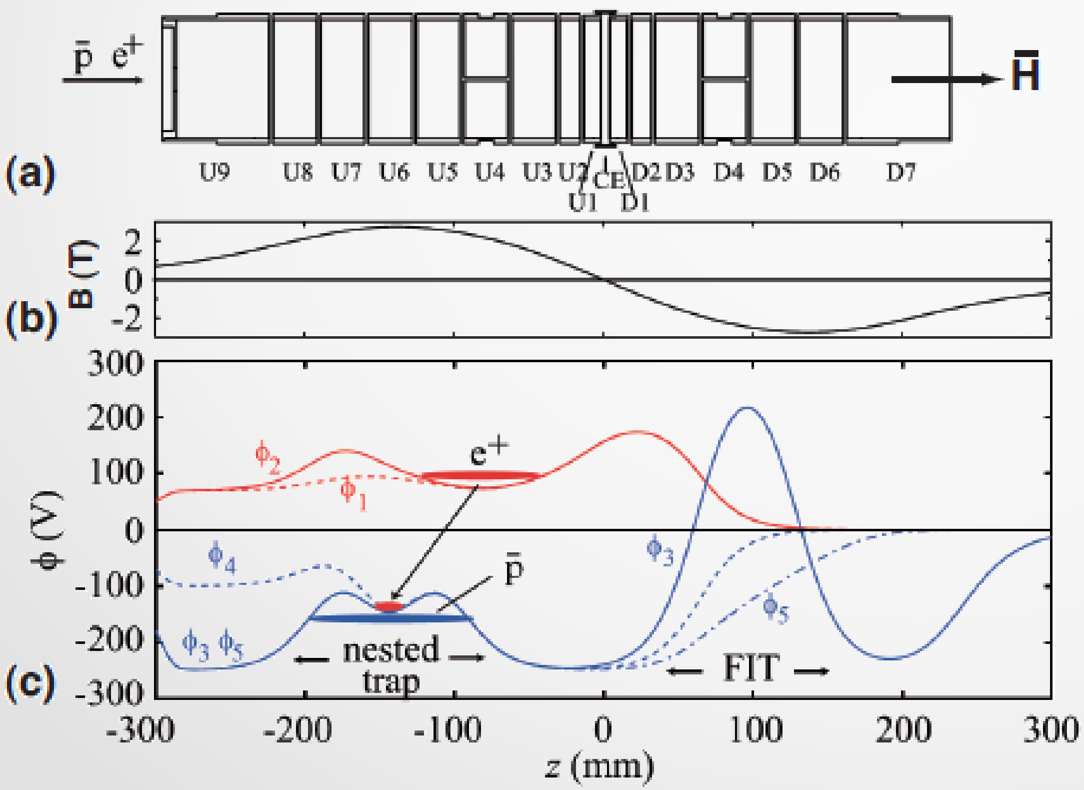


How to create antihydrogen ?

Recipe

1) Load positrons ($6x10^6$ e^+/30 shots)
2) Bring positrons in a nested potential
3) Inject antiprotons ($5x10^5$)





Antihydrogen production rate

Stops after ~10 s since:

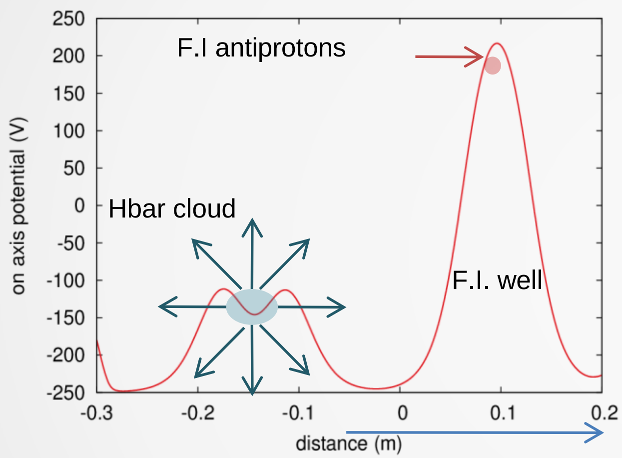
1) P̄ cools down with secondary e^-s from p̄ annihilations

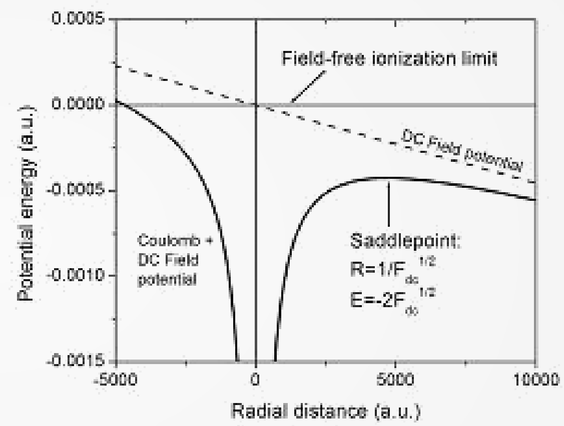
2) P̄ looses energy from scattering in e^+ cloud

⟶ p̄ cloud axially separated from e^+ cloud ⟶ no H̄ formation

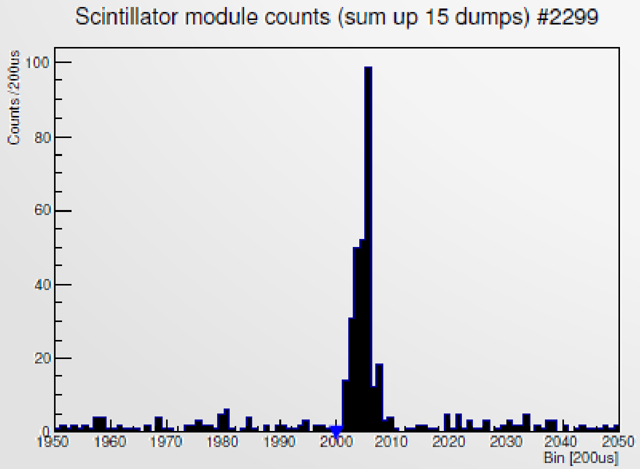
Detection of Antihydrogen

1) Neutral $\bar{H}$ escapes from trap
2) Apply field ionization well $\rightarrow$ strip positron, catch $\bar{p}$
3) Release field ionization well





$$F = \frac{3.2 \cdot 10^8}{n^4} V/cm$$

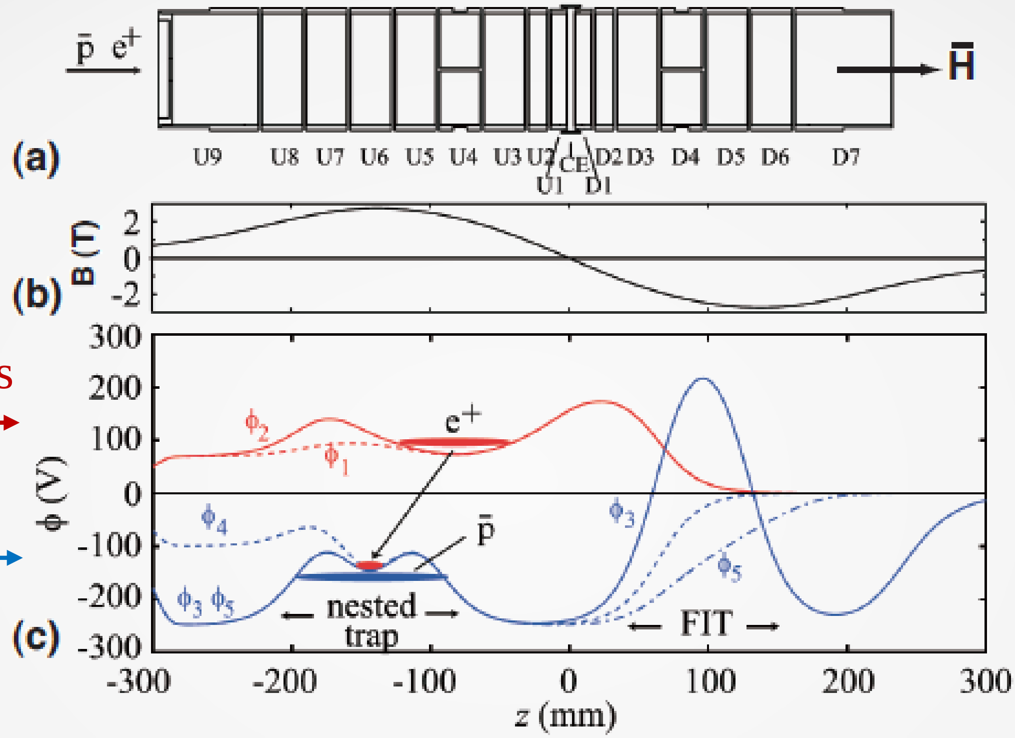


<u>Result after release</u>
No peak without positrons
Clear indication for production of $\bar{H}$

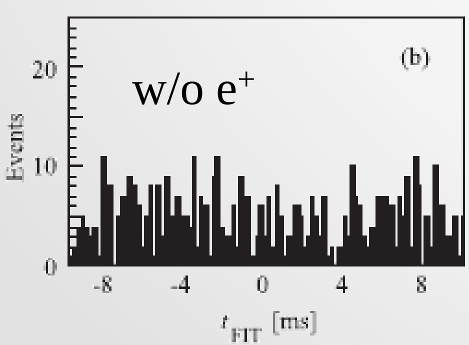
Antihydrogen production in 2010

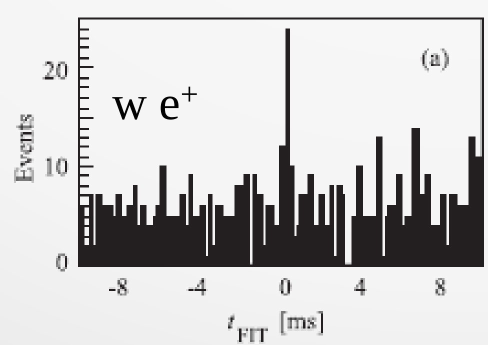
6×10^6 e+ /30 shots

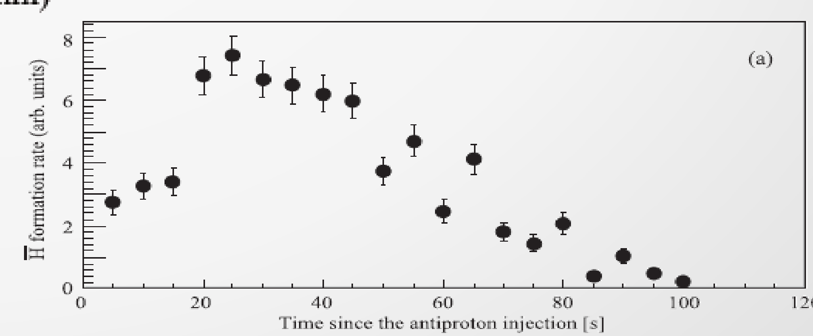
5×10^5 $\bar{p}$ -5 AD shots



Direct injection of Antiprotons to mix With positrons





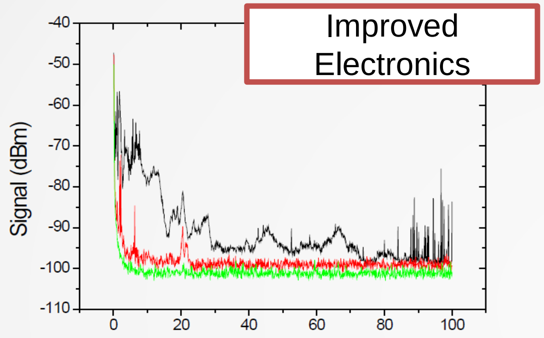


First $\bar{H}$ results! Proof of principle of the CUSP field

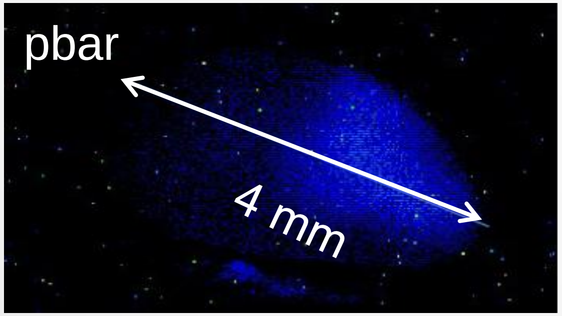
[2] Y. Enomoto et al., Phys.Rev.Lett.**105** (2010) 243401

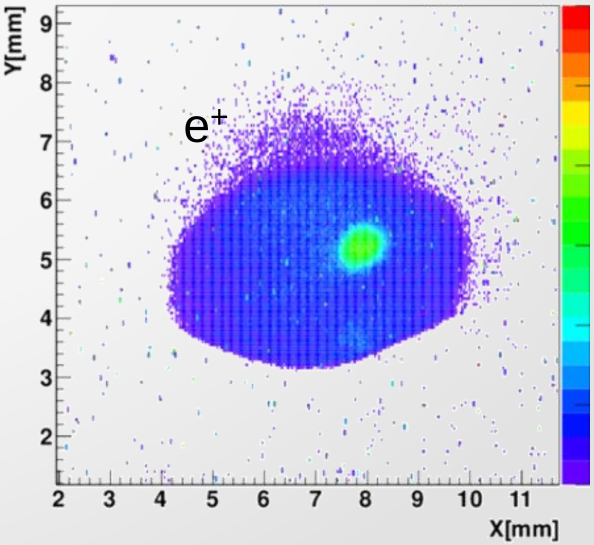
Improvements since 2010

1) Better thermal contact (MRE: 18.5 K -> 12 K)
2) Extra aperture (Ø = 50 mm) to reduce thermal radiation
3) Electronic noise filters for the CUSP



4) Second RW segmented electrode allowed direct $\bar{p}$ compression (100 kHz -> 200 kHz in 200 s)



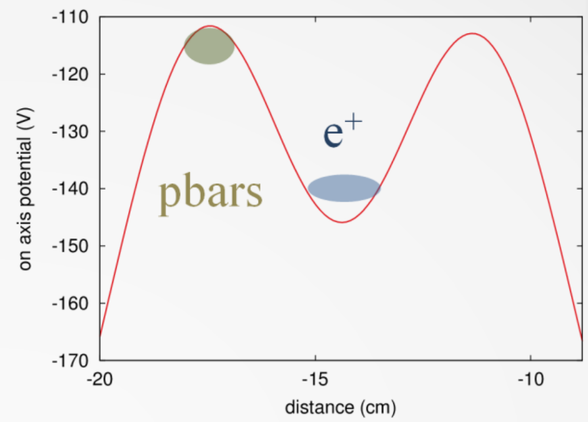


5) Rare Gas moderator for positrons 60 million e^+ in 45 minutes (factor 15-20 improvement)
6) New $\bar{H}$ detector
7) …

How to improve on the $\overline{\mathrm{H}}$ yield? → Autoresonant (AR) Excitation

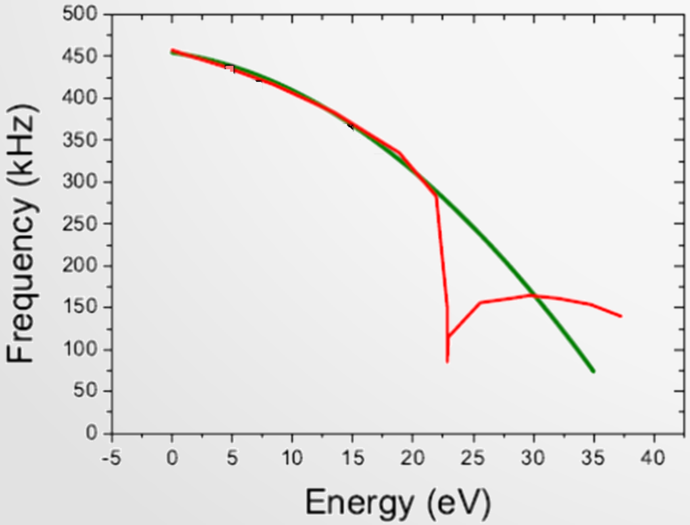
Sweep the axial frequency to catch pbars and "park" them into e^+ cloud

Note: E_{kin} is unaffected



Potential $$\phi(z) = V_0 \sum_{k=0} C_k z^k$$

Axial Frequency Scaling $$\frac{3}{4}\left(\frac{C_4}{C_2^2} + \frac{5}{4}\frac{C_6}{C_2^3}\frac{E_z}{qV_0}\right)\frac{\omega_p}{qV_0}$$

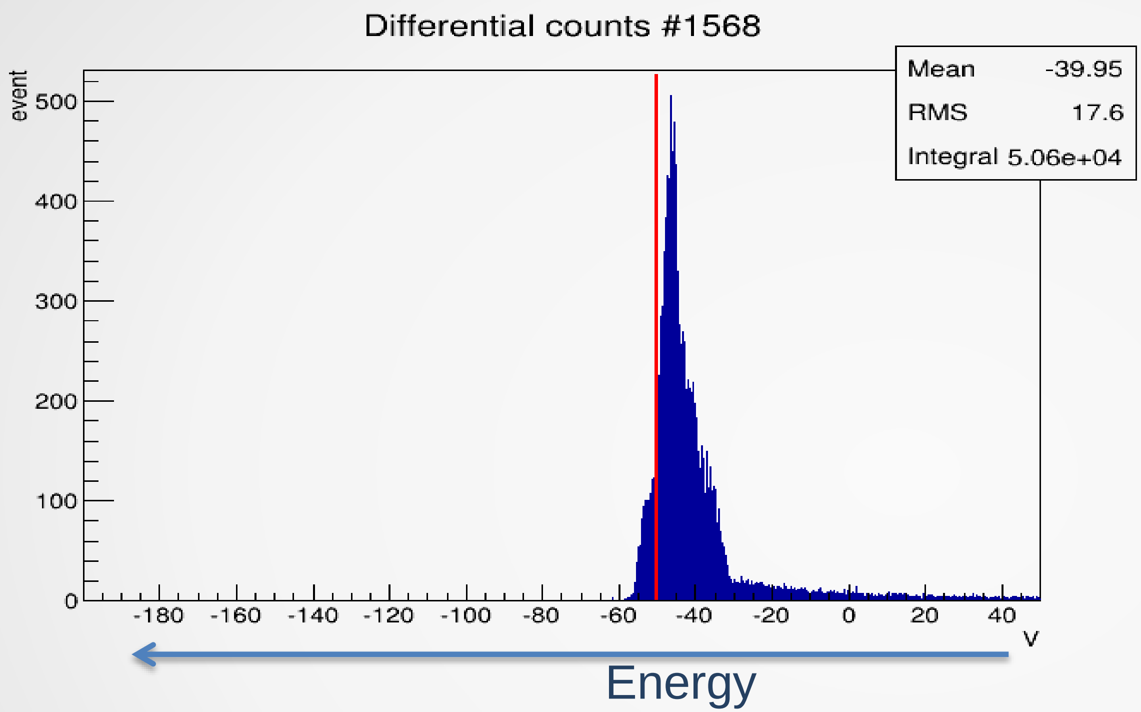


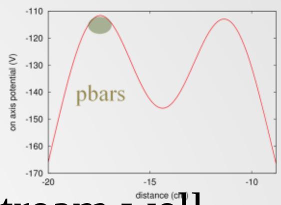
Exciting the particles as by a swept rf with a certain stop frequency:

Definition of interaction energy

[7] J. Fajans, E. Gilson and L. Friedland. Autoresonant excitation of a collective nonlinear mode, *Phys. Plasmas*, **6** 4497, 1999.
[8] Andresen *et al*., Phys. Rev. Lett. 106, 025002 (2011)

Autoresonance excitation (II)

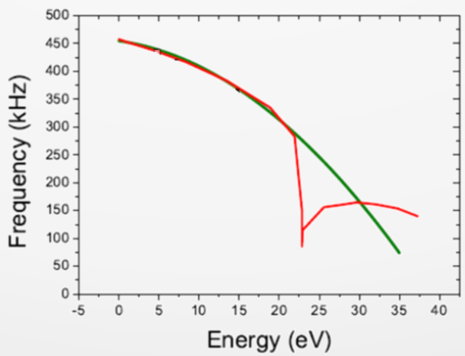


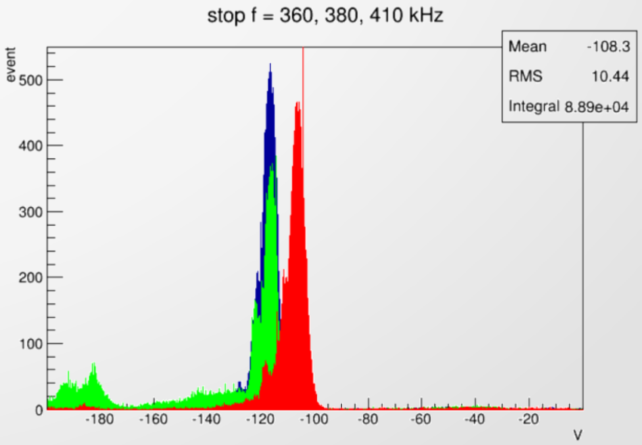


1) p̄ stored in the upstream well
2) Energy distribution is measured by lower the upstream electrode and counting #annihilations
3) The red line coincides with an empty trap (for r=0)

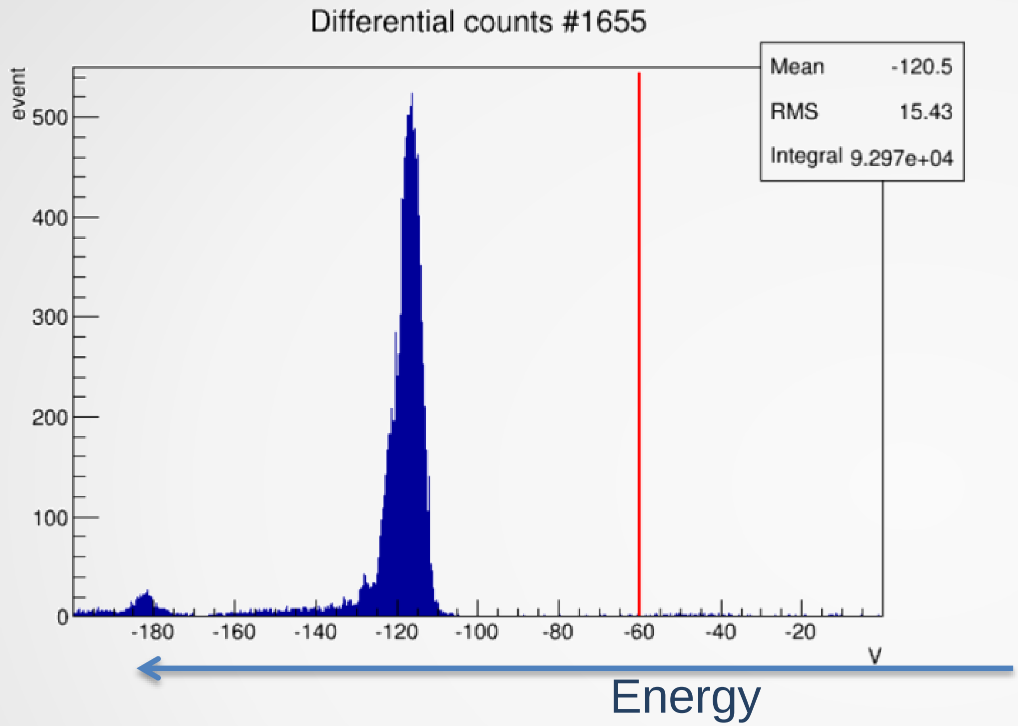
AR recipe

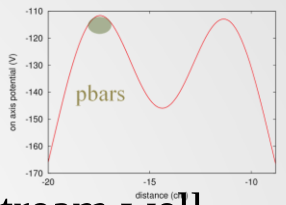
1) e⁻ cooling (30s)
2) e⁻ kickout
3) p̄ compression
(100 -> 250 kHz, 200s , 10 V
+ 220 kHz, 200 s, 10 V)
4) AR: 600 -> 380 kHz, 22 ms, 4 V targeted slightly lower than the level of **e⁺** well





Autoresonance excitation (II)

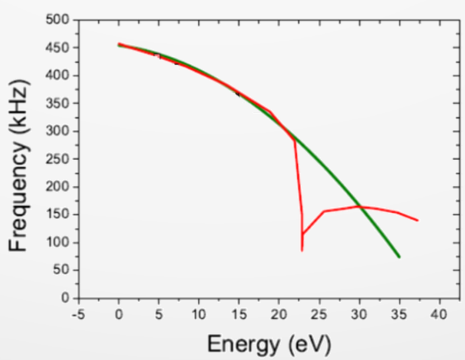


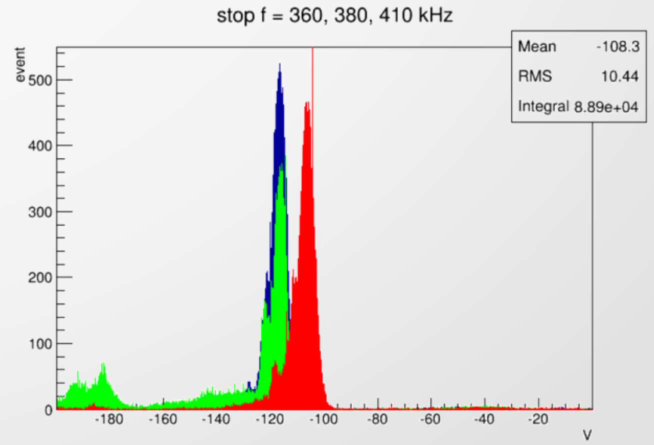


1) $\bar{p}$ stored in the upstream well
2) Energy distribution is measured by lower the upstream electrode and counting #annihilations
3) The red line coincides with an empty trap (for r=0)

AR recipe

1) e^- cooling (30s)
2) e^- kickout
3) $\bar{p}$ compression
   (100 -> 250 kHz, 200s , 10 V
   + 220 kHz, 200 s, 10 V)
4) AR: 600 -> 380 kHz, 22 ms, 4 V targeted slightly lower than the level of **e**$^+$ well





Summary

Production of antihydrogen demonstrated.
Several major improvements resulted in a higher antihydrogen yield …

Analysis of the 2012 data is being finalized and results will be presented soon !

Stay tuned!

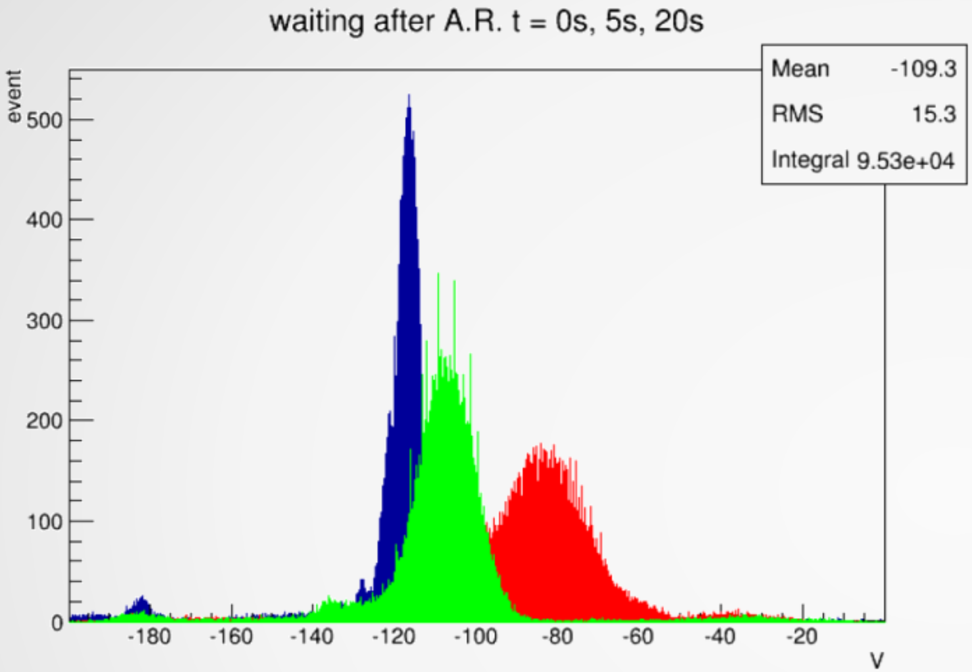
Thank you + Special thanks to the AD operators/… for their support and $\bar{p}$

Antiproton trap
Positron trap
CUSP trap
$\bar{H}$ detector
CUSP detectors
SMI cavity
+sextupole
+ hodoscope

The boss

Backup slides

A.R. : wait time after A.R.

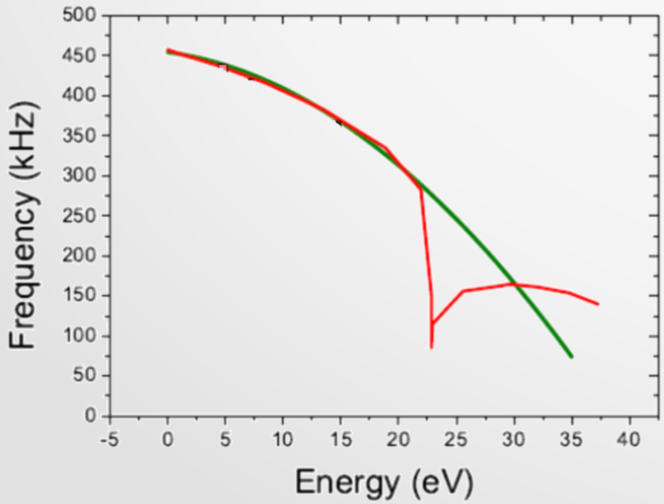


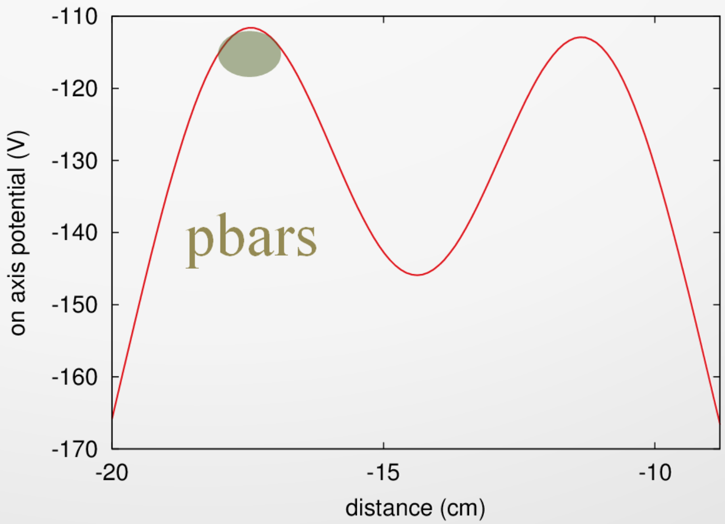
AR recipe

1) e^- cooling (30s)
2) e^- kickout
3) Pbar compression
   (100 -> 250 kHz, 200s , 10 V
   + 220 kHz, 200 s, 10 V)

4) AR: 600 -> 380 kHz, 22 ms, 4 V targeted slightly lower than the level of **e+** Well. wait: 0 s, 5 s, 20 s after AR

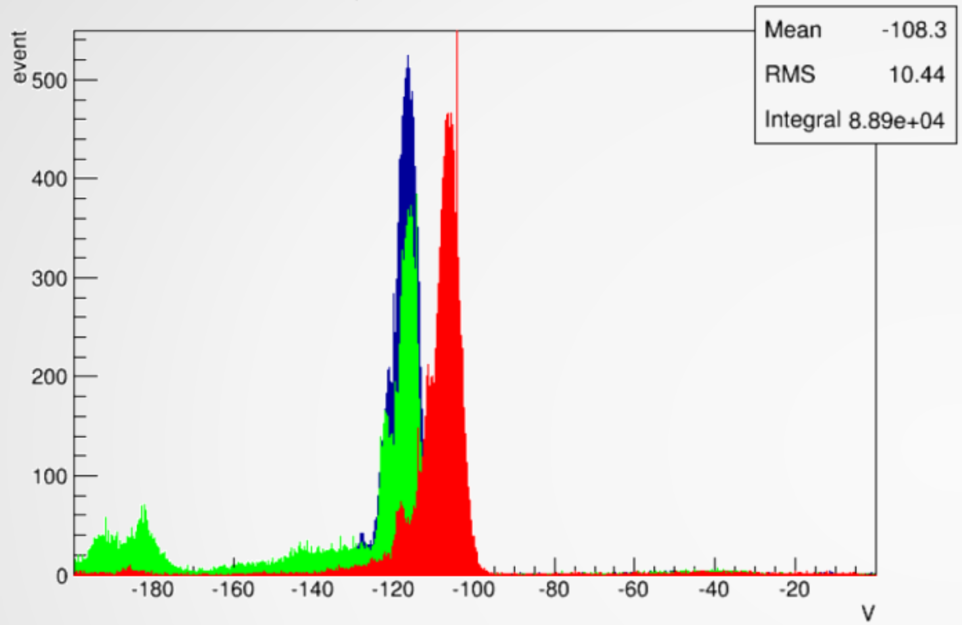
→Pbars cool again and fall again in the well





A.R.

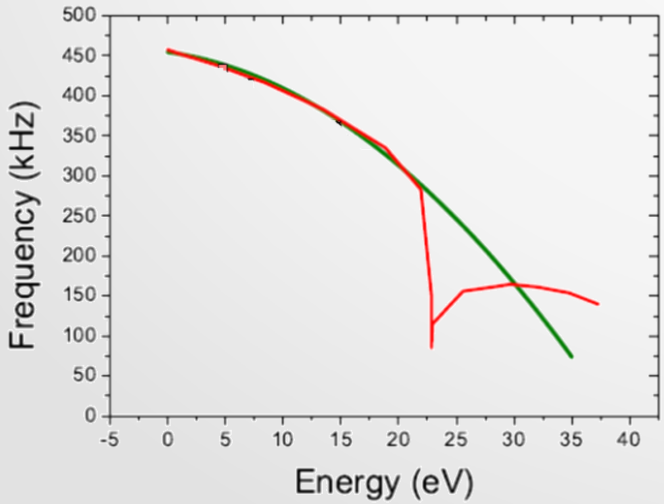
stop f = 360, 380, 410 kHz

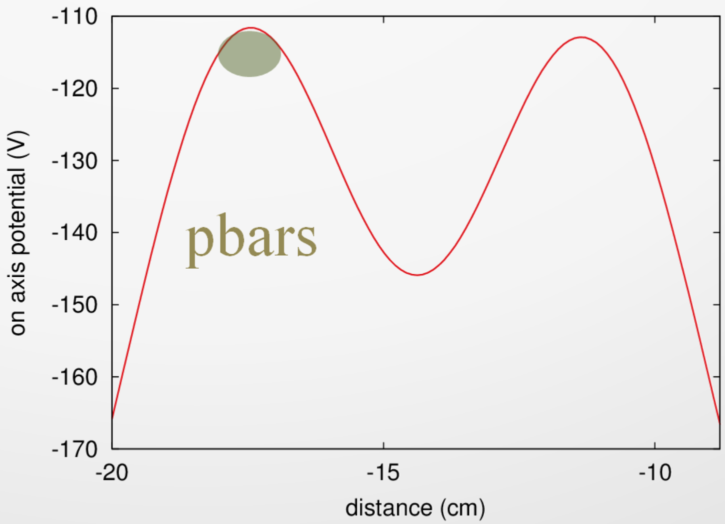


AR recipe

1) e^- cooling (30s)
2) e^- kickout
3) Pbar compression
   (100 -> 250 kHz, 200s , 10 V
   + 220 kHz, 200 s, 10 V)

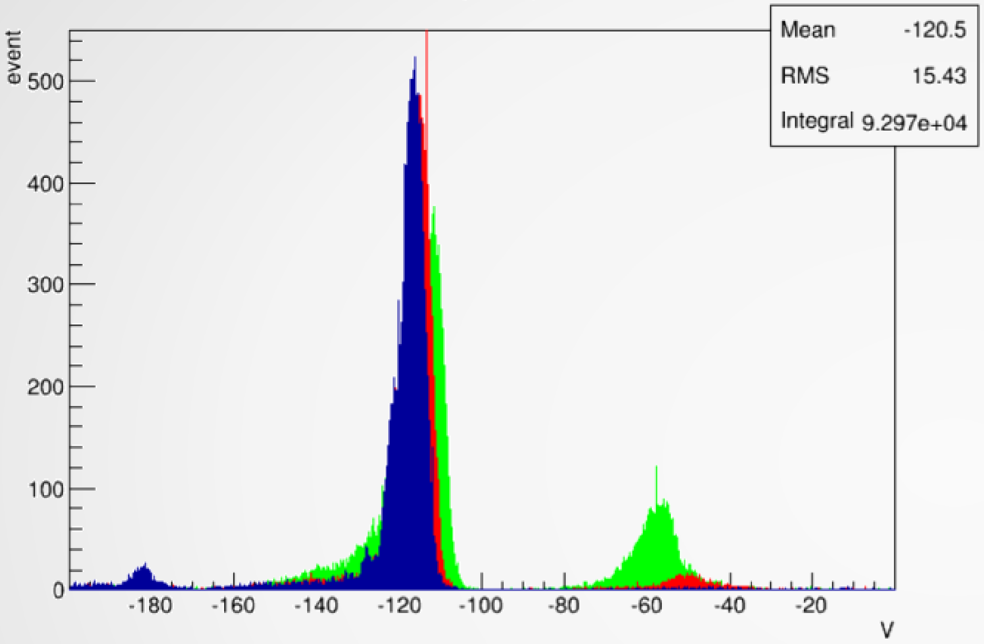
4) AR: 600 -> *f kHz, 22 ms, 4 V*
scanned stop frequency *f = 360, 380,* 410 kHz





A.R. : change start frequency

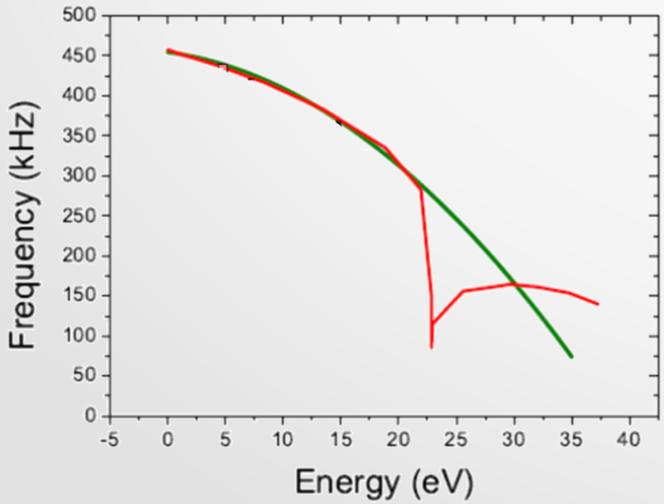
Start f = 490, 530, 600 kHz

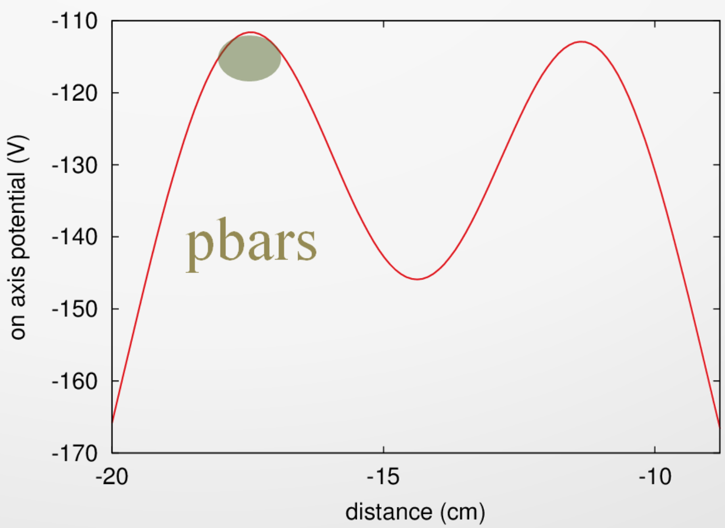


AR recipe

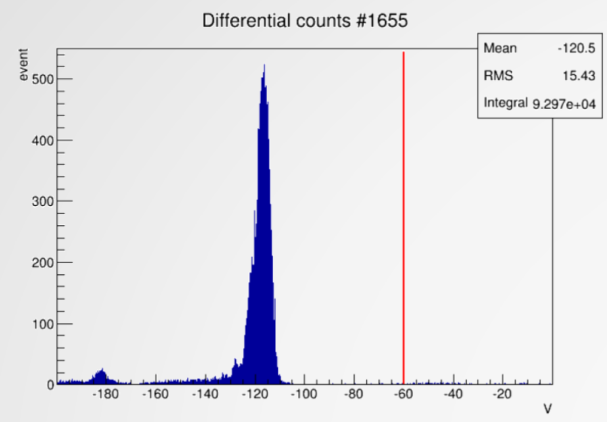
1) e^- cooling (30s)
2) e^- kickout
3) Pbar compression
   (100 -> 250 kHz, 200s , 10 V
   + 220 kHz, 200 s, 10 V)

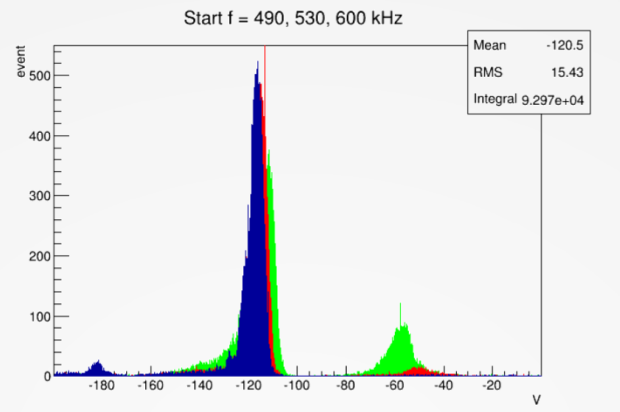
4) AR: *f -> 380 kHz, 22 ms, 4 V*
scanned start frequency *f = 490, 530,* 600 kHz

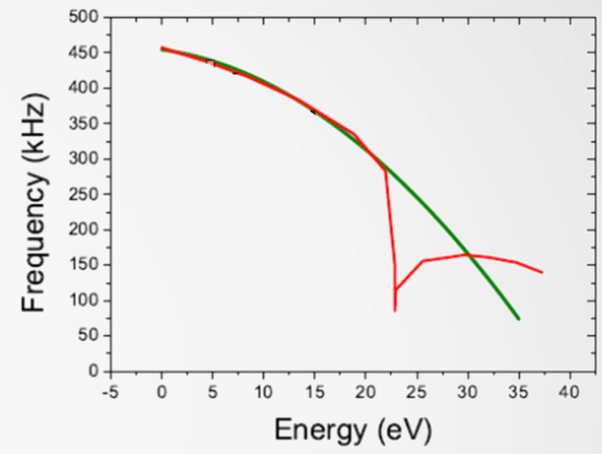


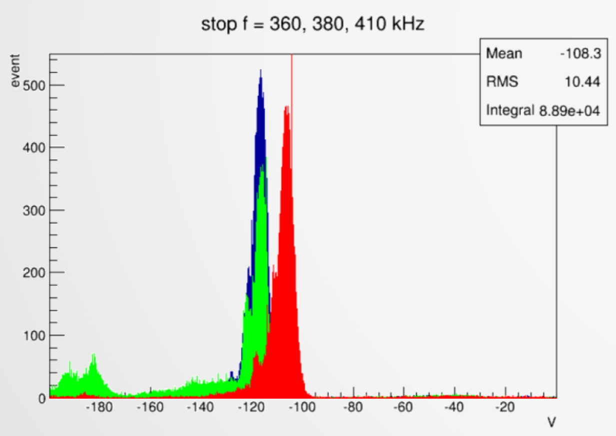


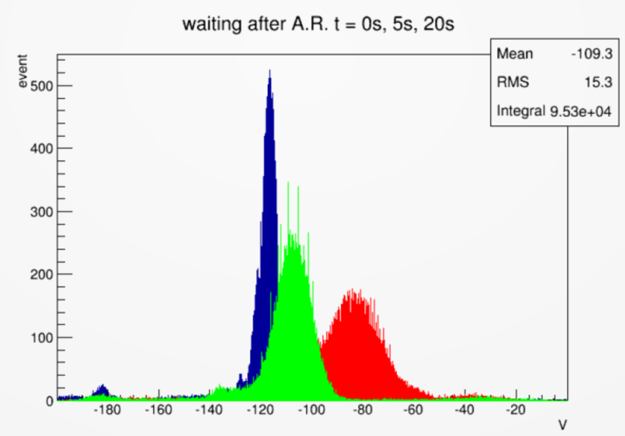
A.R is understood.

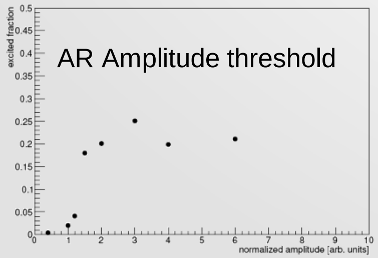






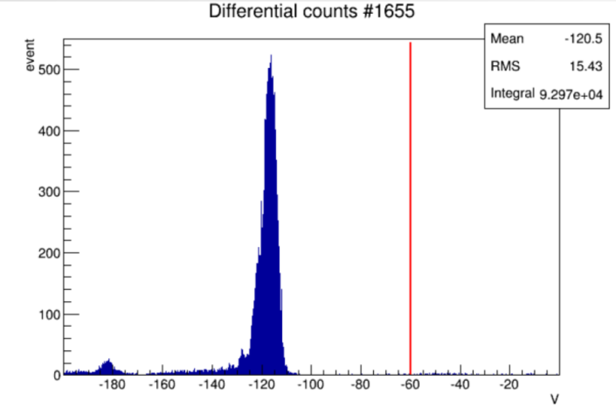


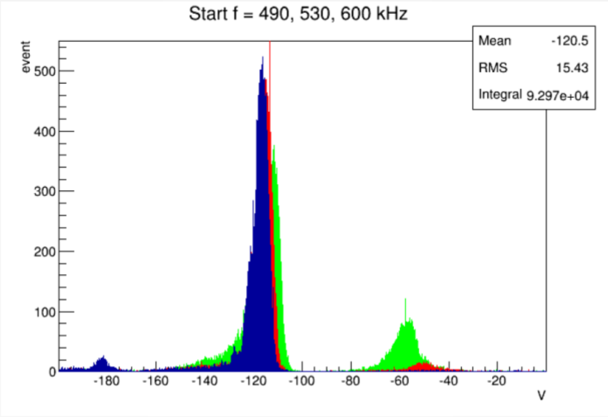


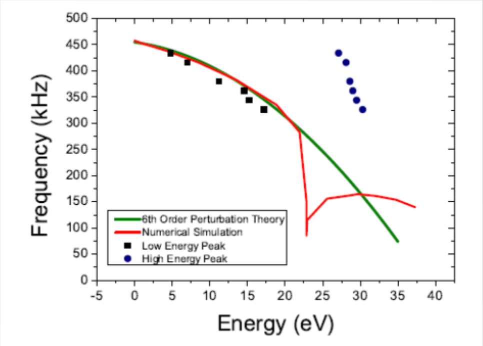


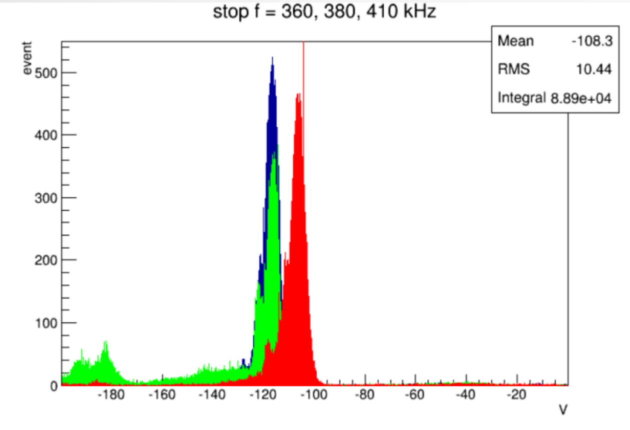
AR works as expected theoretically and is a tool that can be used to produce $\overline{\mathrm{H}}$

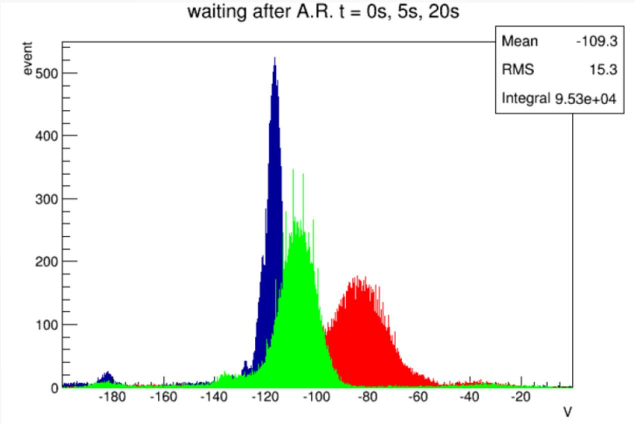
A.R.







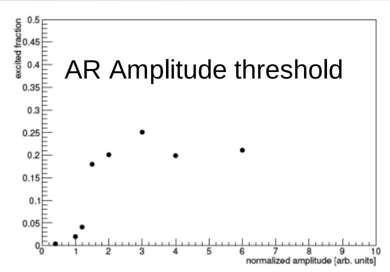




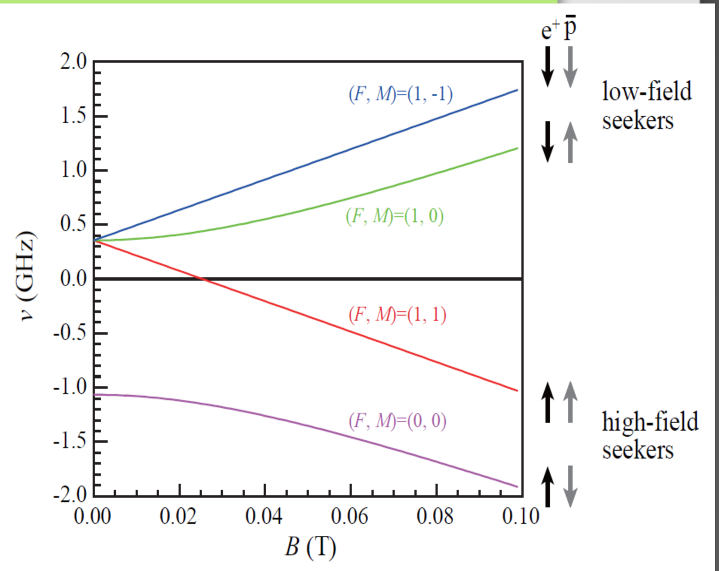
AR recipe

1) e^- cooling (30s)
2) e^- kickout
3) Pbar compression
   (100 -> 250 kHz, 200s , 10 V
   + 220 kHz, 200 s, 10 V)
4) AR

Observations: as expected!



Spectroscopy



1.420 405 751 766 7(9) GHz

Correction: QED and proton/antiproton structure – level 10-6.

n high precision proton g-factor measurement: constraints on antiproto

We aim at 10-6 or better.

Limitations

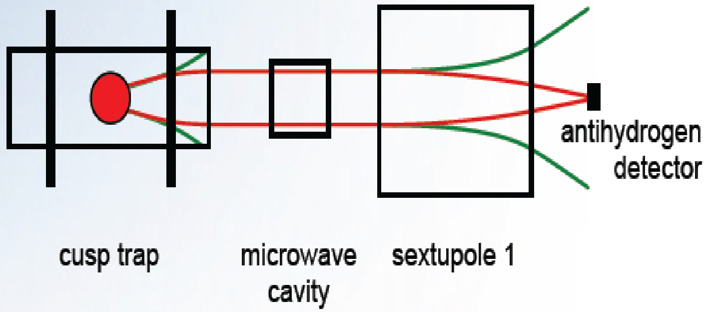
What limits the resolution of a Rabi type experiment?

1.) TOF
2.) Magnetic field homogeneity
3.) …thus beam profile

xperiment: Just limited by TOF (averaging over inhomogeneity) which can be arbitrarily long (

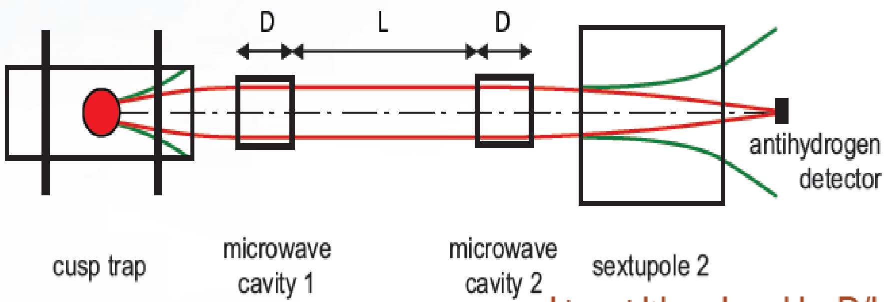
Proposals to measure more precisely

- Phase 1 (ongoing): Rabi method



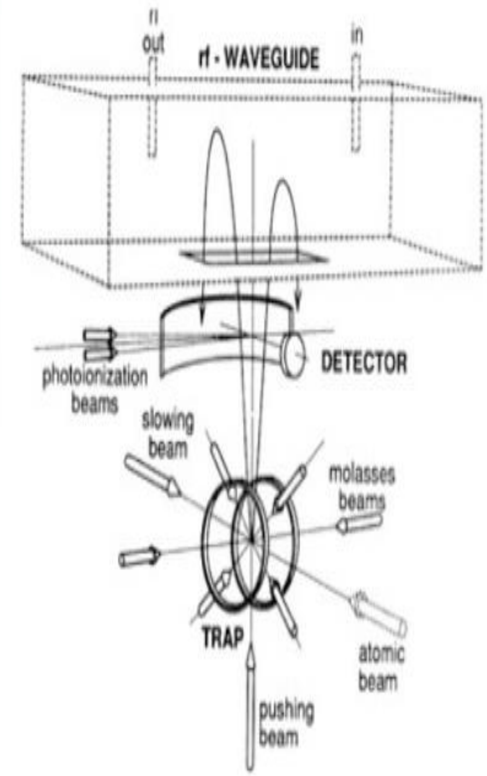
$\Delta\nu/\nu \sim 10^{-7}$

- Phase 2: Ramsey separated oscillatory fields



Linewidth reduced by D/L

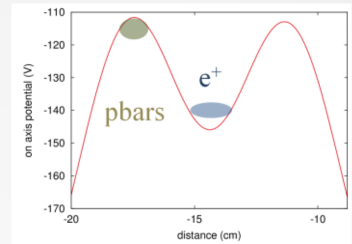
- Phase 3: trapped H^{bar}
  - Hyperfine spectroscopy in an atomic fountain of antihydrogen
  - needs trapping and laser cooling outside of formation magnet
  - slow beam & capture in measurement trap
  - Ramsey method with d=1m
    - $\Delta f \sim 3$ Hz, $\Delta f/f \sim 2\times10^{-9}$



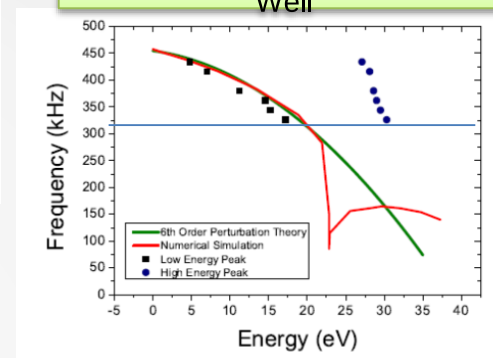
Far Future !

RF Assisted Direct Injection

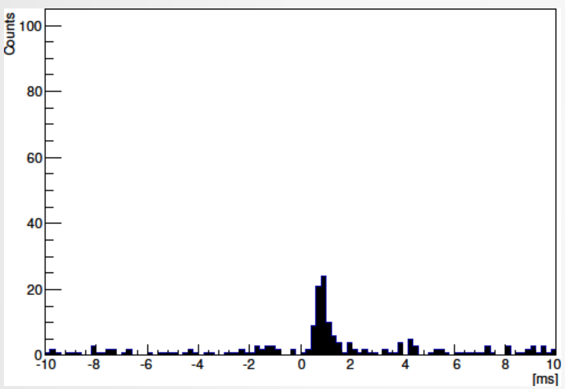
1) 40x10^6 e$^+$ / 5x10^5 pbars
2) Inject directly from MUSASHI trap
3) Apply RF during interaction



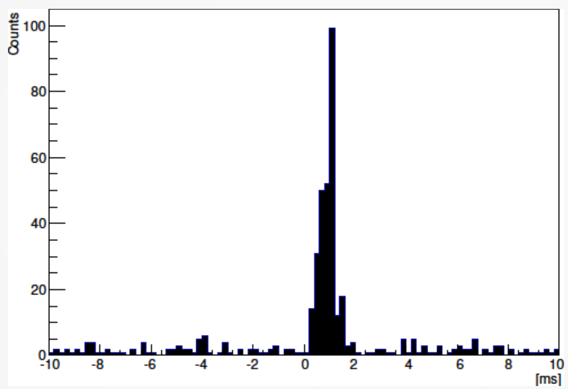
Frequency Scaling in Nested Well

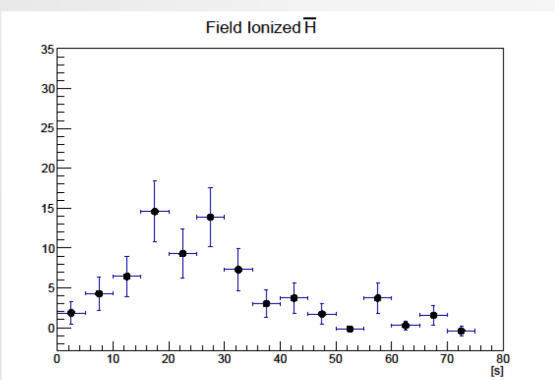


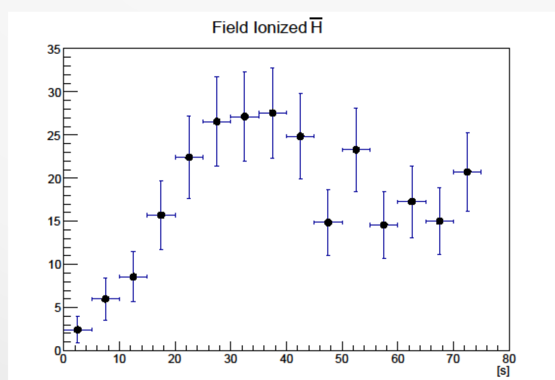
No RF



+ RF







4 fold improvement in Hbar counts

Hbar production continues after 30 seconds

Produced encouraging results – further evaluation in progress

How to produce
Specifications

positron

27mCi ^{22}Na

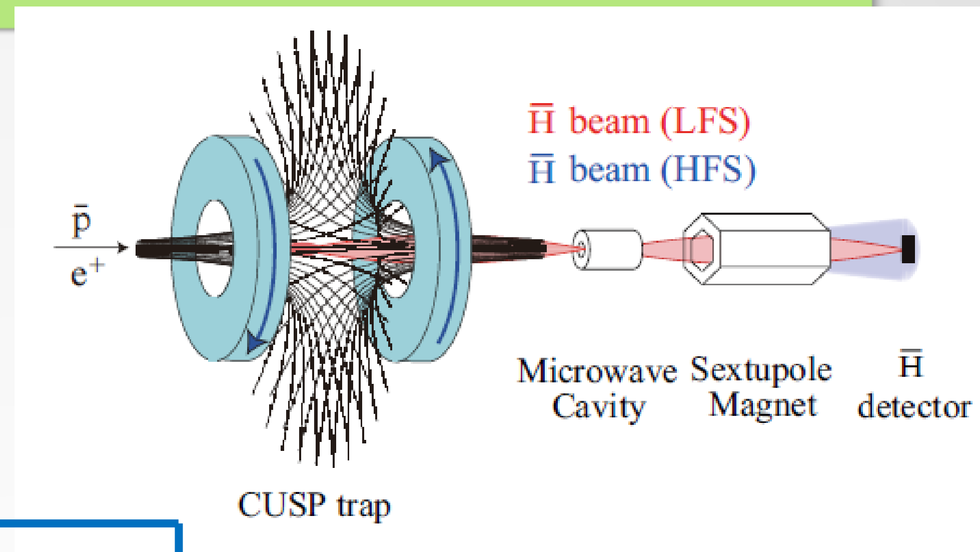
(<100keV, ~109 /s)

W moderator, N2buffer gas

(<3 eV, ~106 /s)

Pre-accumulator

(130eV, 2 x 105 /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

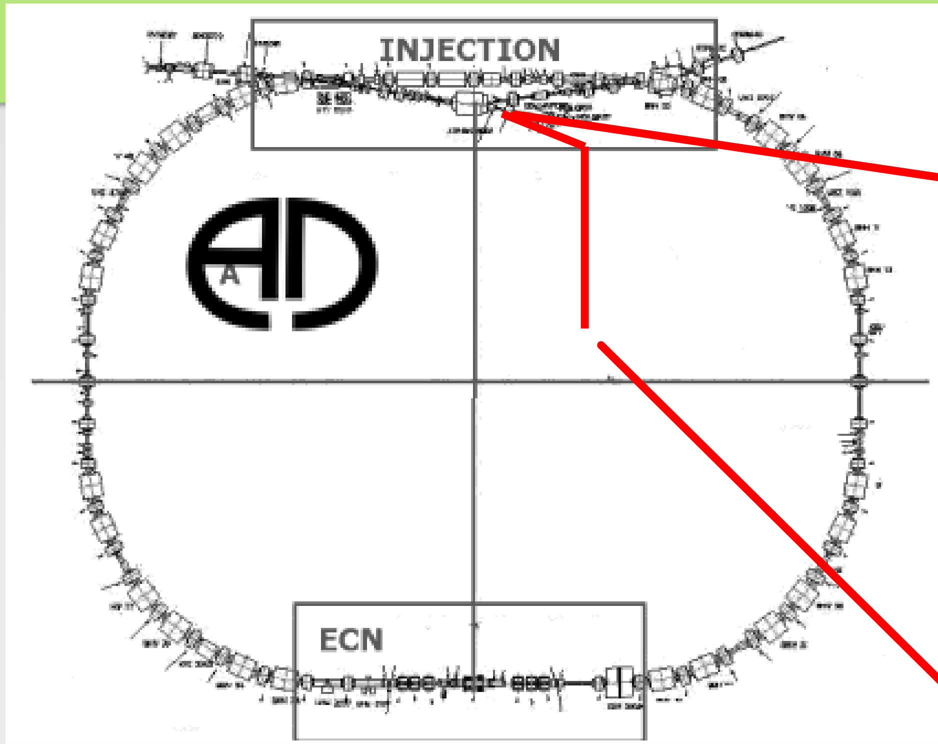
(<0.1eV, ne+~108cm-3)

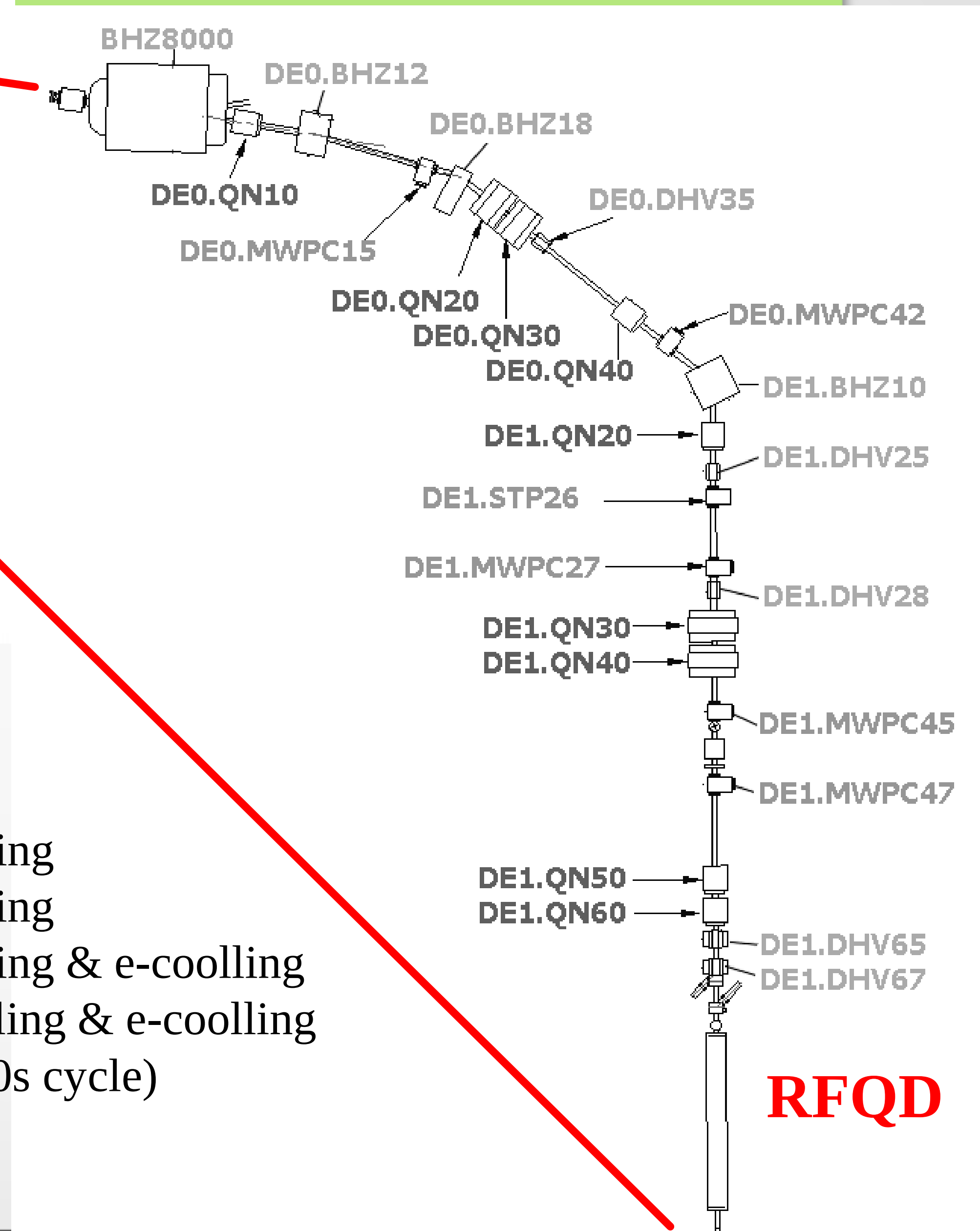
3 x 10^{5} pbar

(< 20 eV)

Low energy anti-proton beams (AD to RFQD)

ASACUSA extraction line





Production target

→3.5GeV/c ~5x 107 pbar stochastic cooling

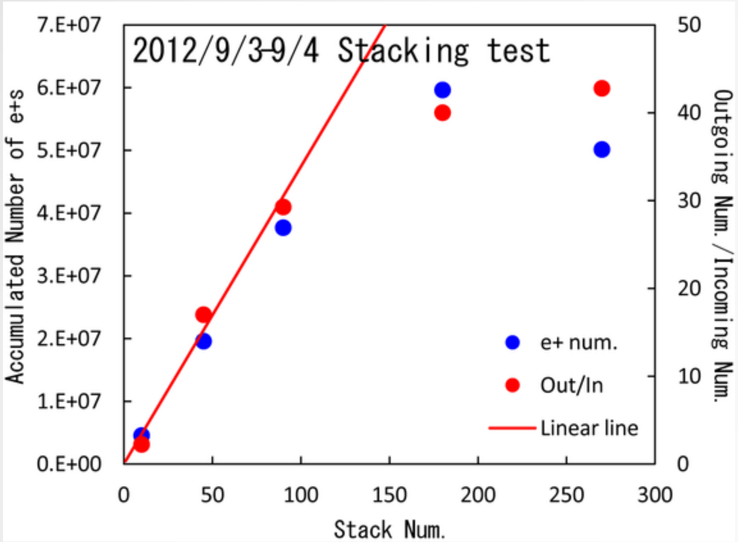
→2 GeV/c stochastic cooling

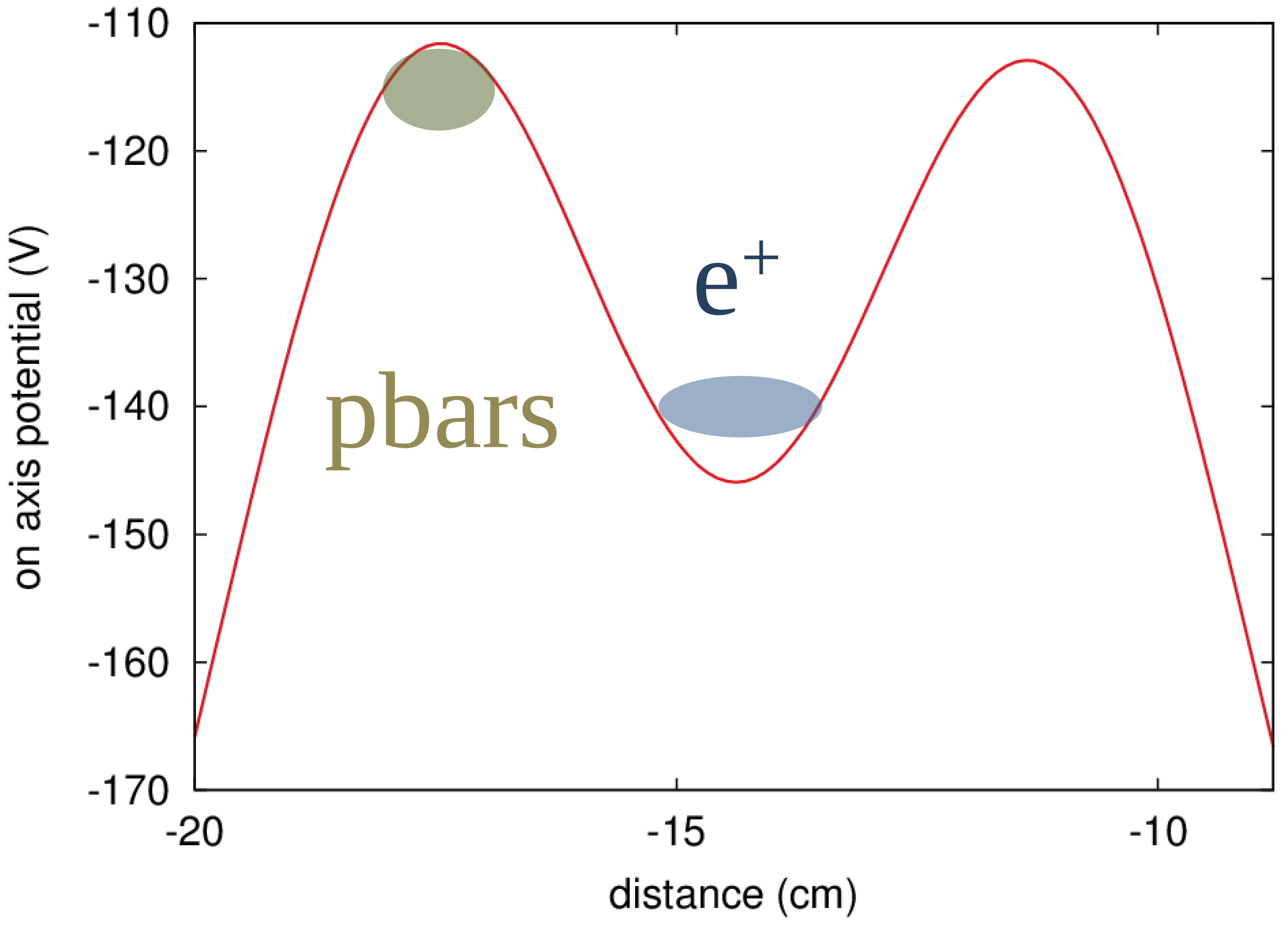
→300MeV/c stochastic cooling & e-coolling

→100MeV/c(~5MeV) stochastic cooling & e-coolling

~ 107 pbar pulse from AD (~100s cycle)

→**100keV <5 x 106 pbar with RFQD**


2012/9/3-9/4 Stacking test
Accumulated Number of e+s
Outgoing Num./Incoming Num.
Stack Num.
e+ num.
Out/In
Linear line
0.E+00
1.E+07
2.E+07
3.E+07
4.E+07
5.E+07
6.E+07
7.E+07
0
10
20
30
40
50
0
50
100
150
200
250
300



-110
-120
-130
-140
-150
-160
-170
on axis potential (V)
-20
-15
-10
distance (cm)
pbars
e^+

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