G. Gabrielse sends regrets

Boston gets record blizzard

airport closed, flights cancelled

no possible way to get from Boston to Geneva to give the ATRAP progress report

cold antihydrogen
for testing fundamental symmetries
some ATRAP - progress

25 January 2005

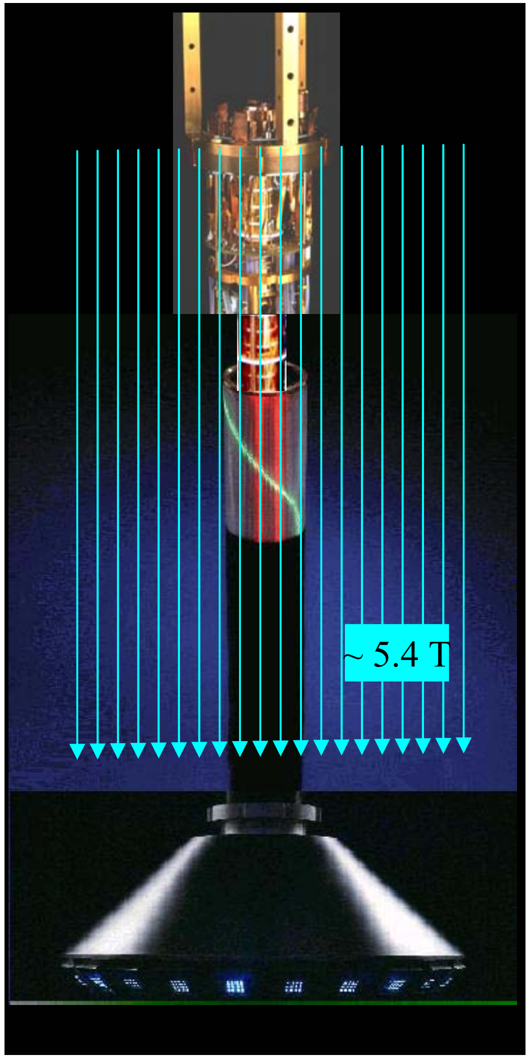
Extensive ATRAP progress report was given at Villars in fall of 2004

Gerald Gabrielse, ATRAP-spokesperson, Harvard University
Walter Oelert, Research Centre Jülich - IKP

1. ***good publication year for ATRAP***
2. ***2004 run***
3. ***basic ATRAP apparatus commissioned***

summary
next steps

a complete picture is not possible in 15 minutes, of course



Cold Antihydrogen

for testing fundamental symmetries

Harvard University	G. Gabrielse, A. Speck, C. Storry, D. Le Sage, N. Guise,	Penning trap for $\bar{p}$ and e^+ Ioffe trap for antihydrogen
York University	E. Hessels, D. Comeau	PPAC, Cs charge exchange
IKP FZ-Jülich	W. Oelert, D. Grzonka, F. Goldenbaum, T. Sefzick, Z. Zhang	charge particle detection, γ detection, *Ioffe trap*
MPI for Quantenoptik	T. W. Hänsch, H. Pittner, J. Walz	laser spectroscopy

2004 ATRAP Papers and Preprints

"Strongly Magnetized Antihydrogen and Its Field Ionization“, 1.
D. Vrinceanu, B.E. Granger, R. Parrott, H. R. Sadeghpour, L. Cederbaum, A. Mody, J. N. Tan and G. Gabrielse
Phys. Rev. Lett. **92**, 133402 (2004).

"G. Gabrielse, et al. reply“, (A reply to a Comment discusses comparing our measured field ionization spectra to theory) 2.
G. Gabrielse, *et al.*
Phys. Rev. Lett. **92**, 149304 (2004).

"Aperture Method to Determine the Density and Geometry of Anti-Particle Plasmas", 3.
P. Oxley, N. S.Bowden, R. Parrott, A. Speck, C. Storry, J.N. Tan, M. Wessels, G. Gabrielse, D. Grzonka, W. Oelert,
G. Schepers, T. Sefzick, J. Walz, H. Pittner, T.W. Haensch and E. A. Hessels
Phys. Lett. B **595**, 60 (2004).

"First Measurement of the Velocity of Slow Antihydrogen Atoms", 4.
G. Gabrielse, A. Speck and C.H. Storry, D. Le Sage, N. Guise, D. Grzonka, W. Oelert, G. Schepers, T. Sefzick,
H. Pittner, J. Walz, T.W. Haensch, D. Comeau, E.A. Hessels
Phys. Rev. Lett. **93**, 073401 (2004).

"First Evidence for Atoms of Antihydrogen Too Deeply Bound to be Guiding Center Atoms", 5.
G. Gabrielse, A. Speck, C.H. Storry, D. Le Sage, N. Guise, D. Grzonka, W. Oelert, G. Schepers, T. Sefzick, H. Pittner,
J. Walz, T.W. Haensch, D. Comeau, E.A. Hessels
To be published.

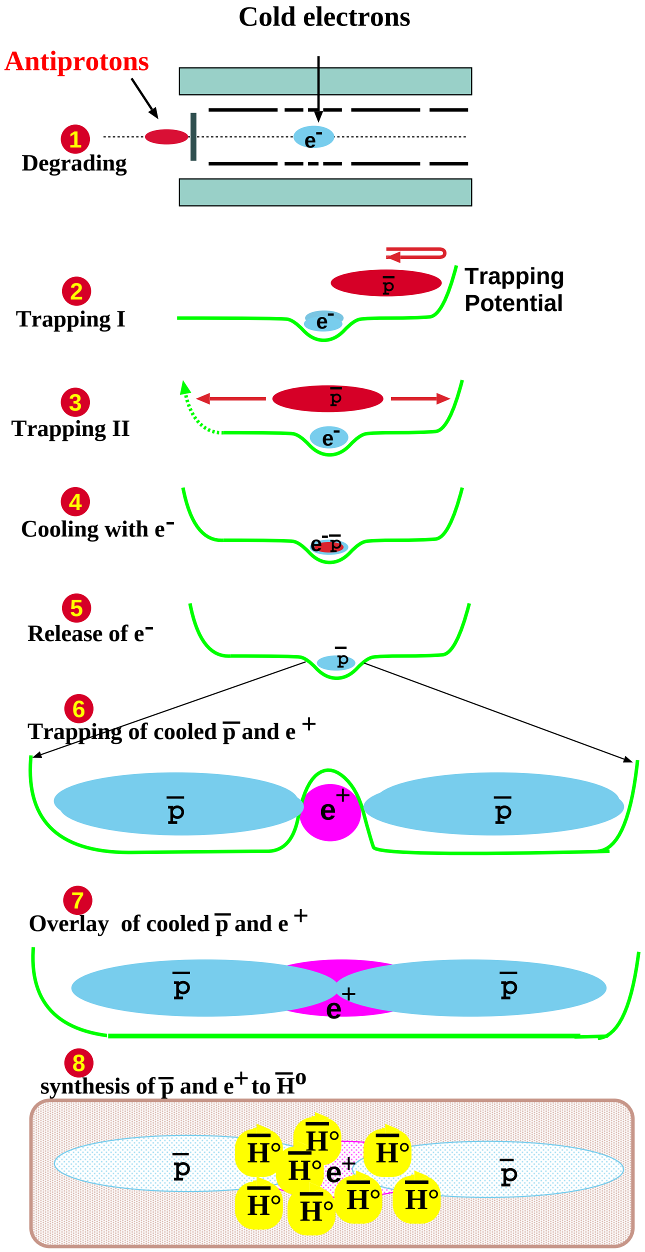
"Laser-Controlled Production of Rydberg Positronium“, 6.
A. Speck, C.H. Storry, E. Hessels and G. Gabrielse
Phys. Lett. B. **597**, 257 (2004).

" Single-Particle Self-excited Oscillator ", (includes proposed application to measuring antiproton spin flips) 7.
B. D'Urso, R. Van Handel, B. Odom and G. Gabrielse
Phys. Rev. Lett. (in press).

"First Laser-Controlled Antihdyrogen Production“ 8.
C.H. Storry, A. Speck, D. Le Sage, N. Guise, G. Gabrielse, D. Grzonka, W. Oelert, G. Scheppers, T. Sefzick, J. Walz,
H. Pittner, M. Herrmann, T.W. Haensch, E.A. Hessels and D. Comeau
Phys. Rev. Lett. **93**, 263401 (2004).

“Atoms made entirely of Antimatter: two methods produce slow antihydrogen“ 9.
G. Gabrielse
Advances in Atomic, Molucular, and Optical Physics, Vol. **50**

trapping - and cooling



Cold electrons

Antiprotons

① **Degrading**

② **Trapping I**

Trapping Potential

③ **Trapping II**

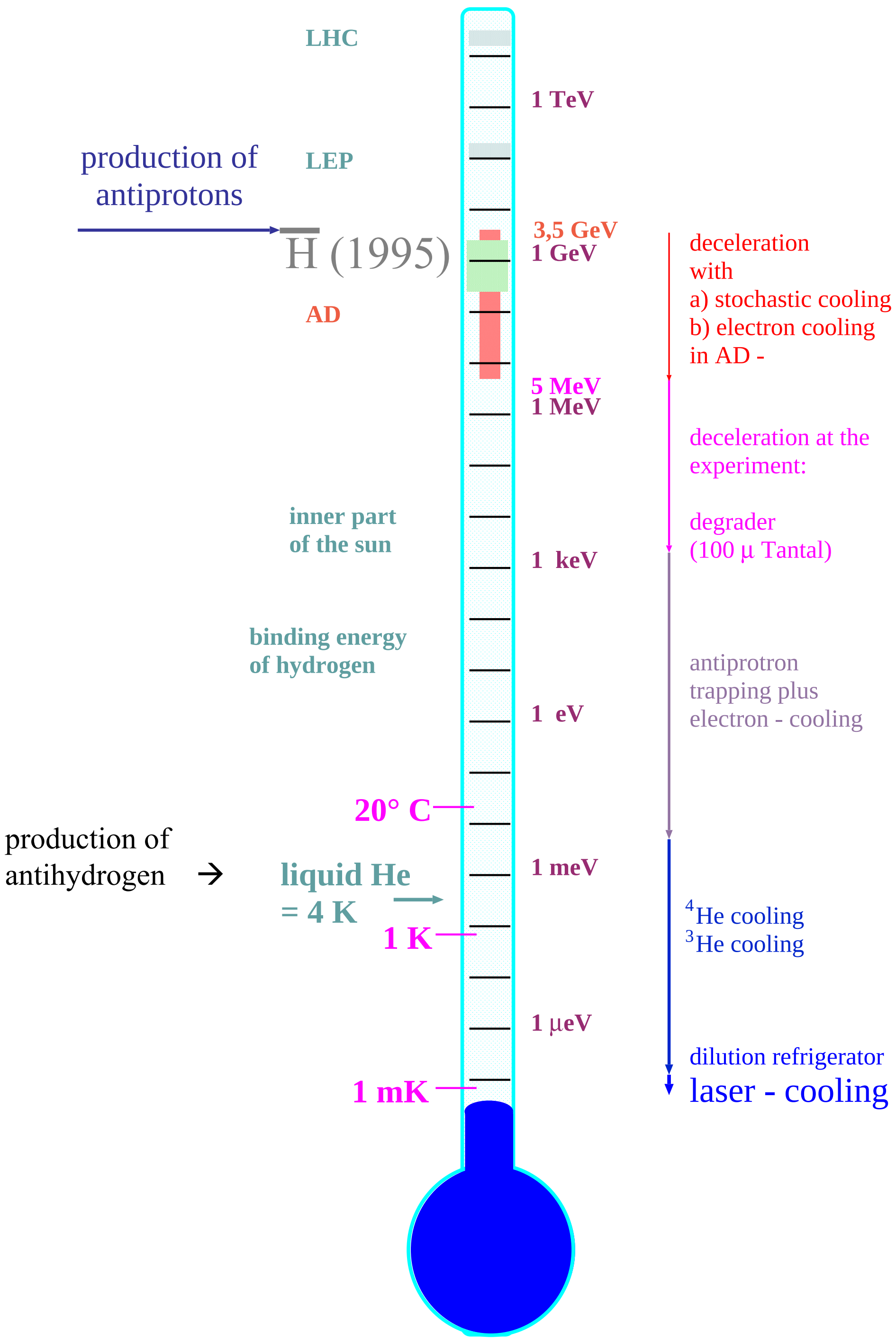
④ **Cooling with e^-**

⑤ **Release of e^-**

⑥ **Trapping of cooled $\bar{p}$ and e^+**

⑦ **Overlay of cooled $\bar{p}$ and e^+**

⑧ **synthesis of $\bar{p}$ and e^+ to $\bar{H}^0$**



production of antiprotons → $\bar{H}$ (1995)

production of antihydrogen →

deceleration with
a) stochastic cooling
b) electron cooling
in AD -

deceleration at the experiment:

degrader
(100 μ Tantal)

antiprotron trapping plus electron - cooling

^{4}He cooling
^{3}He cooling

dilution refrigerator

laser - cooling

Why Cold Antihydrogen?

Goal: highly accurate comparison – antihydrogen and hydrogen

no hope with hot antihydrogen

- **too fast v ~ c**
- **little measurement time**
- **too few atoms**

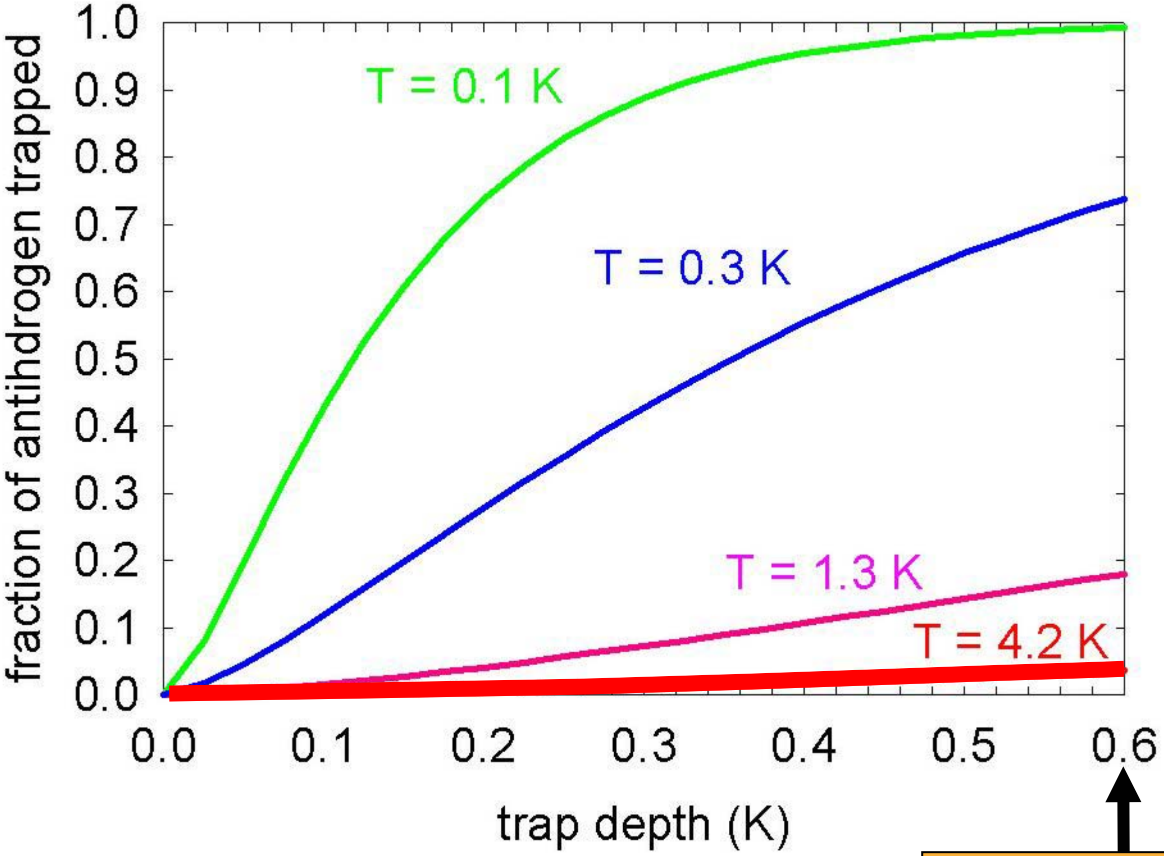
1995 – CERN
1997 -- Fermilab

more hope with much
slow antihydrogen atoms?

2002 – 2004
CERN/AD

$\overline{H}$ trapping efficiency

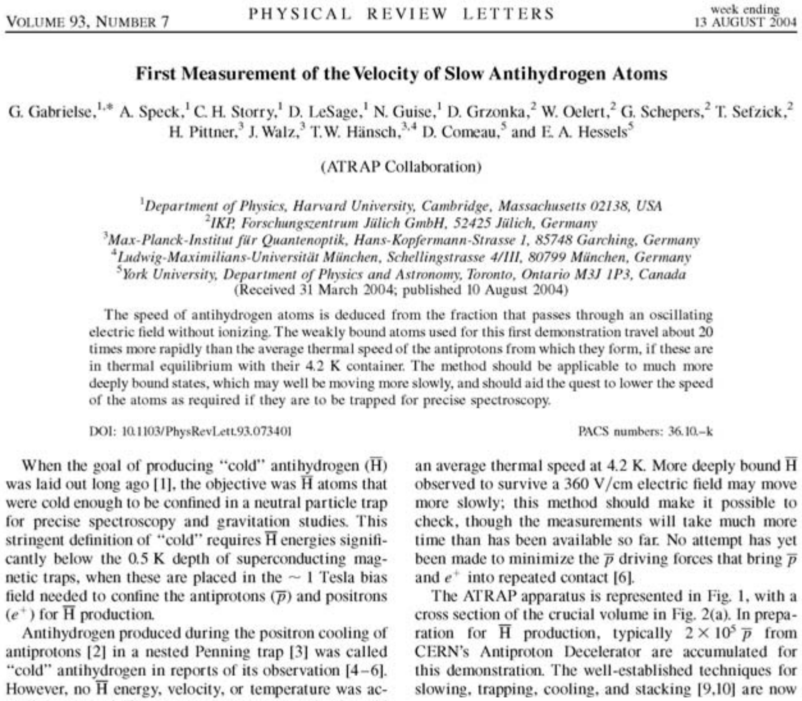
< 5 % (4.2 K , ΔB=1T)



$\Delta B \sim$ 1T

magnetic quadrupol trap (Ioffe trap)

First measurement of antihydrogen velocity



VOLUME 93, NUMBER 7 PHYSICAL REVIEW LETTERS week ending 13 AUGUST 2004

First Measurement of the Velocity of Slow Antihydrogen Atoms

G. Gabrielse,[1,*] A. Speck,[1] C. H. Storry,[1] D. LeSage,[1] N. Guise,[1] D. Grzonka,[2] W. Oelert,[2] G. Schepers,[2] T. Sefzick,[2]
H. Pittner,[3] J. Walz,[3] T.W. Hänsch,[3,4] D. Comeau,[5] and E. A. Hessels[5]

(ATRAP Collaboration)

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[2]*IKP, Forschungszentrum Jülich GmbH, 52425 Jülich, Germany*
[3]*Max-Planck-Institut für Quantenoptik, Hans-Kopfermann-Strasse 1, 85748 Garching, Germany*
[4]*Ludwig-Maximilians-Universität München, Schellingstrasse 4/III, 80799 München, Germany*
[5]*York University, Department of Physics and Astronomy, Toronto, Ontario M3J 1P3, Canada*
(Received 31 March 2004; published 10 August 2004)

The speed of antihydrogen atoms is deduced from the fraction that passes through an oscillating electric field without ionizing. The weakly bound atoms used for this first demonstration travel about 20 times more rapidly than the average thermal speed of the antiprotons from which they form, if these are in thermal equilibrium with their 4.2 K container. The method should be applicable to much more deeply bound states, which may well be moving more slowly, and should aid the quest to lower the speed of the atoms as required if they are to be trapped for precise spectroscopy.

DOI: 10.1103/PhysRevLett.93.073401 PACS numbers: 36.10.–k

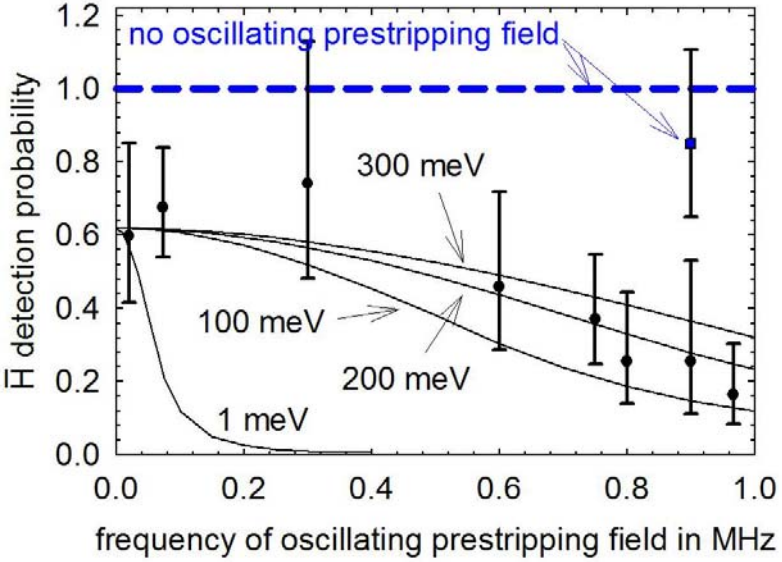
When the goal of producing "cold" antihydrogen ($\overline{\mathrm{H}}$) was laid out long ago [1], the objective was $\overline{\mathrm{H}}$ atoms that were cold enough to be confined in a neutral particle trap for precise spectroscopy and gravitation studies. This stringent definition of "cold" requires $\overline{\mathrm{H}}$ energies significantly below the 0.5 K depth of superconducting magnetic traps, when these are placed in the ~ 1 Tesla bias field needed to confine the antiprotons ($\overline{p}$) and positrons (e^+) for $\overline{\mathrm{H}}$ production.

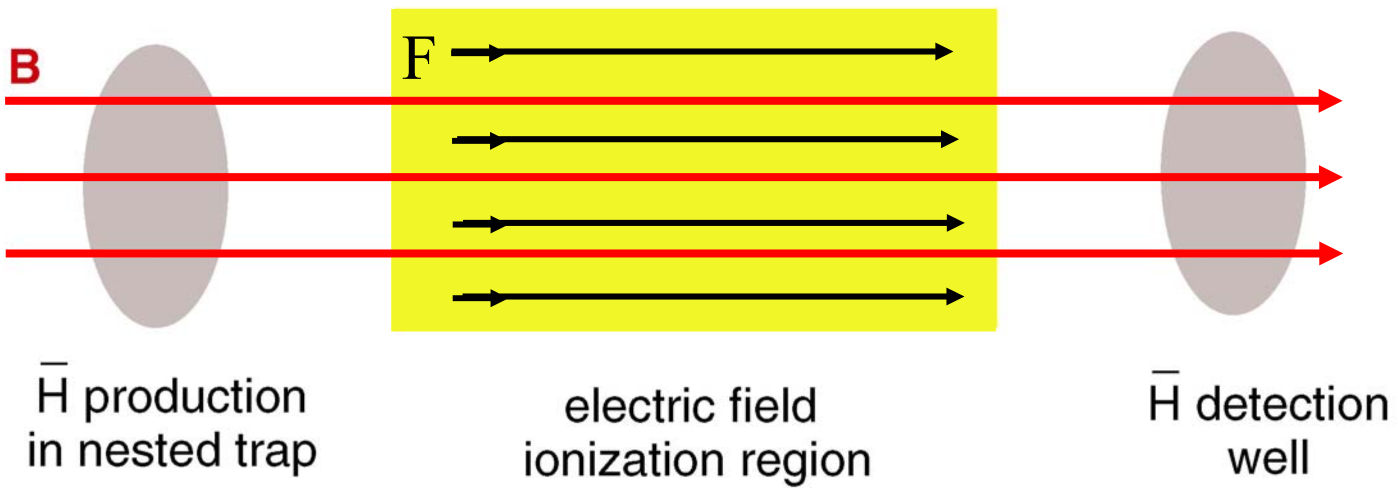
Antihydrogen produced during the positron cooling of antiprotons [2] in a nested Penning trap [3] was called "cold" antihydrogen in reports of its observation [4–6]. However, no $\overline{\mathrm{H}}$ energy, velocity, or temperature was actually measured. The observed atoms were clearly cold compared to $\overline{\mathrm{H}}$ moving at nearly the speed of light [7,8]. Almost certainly the $\overline{\mathrm{H}}$ energy was less than the tens of eV well depths of the potential wells used to confine the $\overline{p}$ and e^+ from which the $\overline{\mathrm{H}}$ were formed. It was naturally hoped that the $\overline{\mathrm{H}}$ were in thermal equilibrium with the 4.2 K [5,6] or 15 K [4] temperature of the electrodes confining the $\overline{p}$ and e^+.

In this Letter we report the first measurement of the velocity of $\overline{\mathrm{H}}$ atoms. The change in $\overline{\mathrm{H}}$ transmission efficiency through an oscillating electric field is measured as a function of the field's oscillation frequency. ATRAP's background-free field ionization detection method [5] registers only $\overline{\mathrm{H}}$ that reach the detection well intact. Atoms moving slowly enough will never make it through the electric field without being ionized. Faster atoms are sometimes able to pass while the oscillating field is too weak to ionize them, depending upon the phase of the field. In this first demonstration we deduce that the most weakly bound $\overline{\mathrm{H}}$ that we detect have an energy that is about 200 meV, a speed that is about 20 times higher than an average thermal speed at 4.2 K. More deeply bound $\overline{\mathrm{H}}$ observed to survive a 360 V/cm electric field may move more slowly; this method should make it possible to check, though the measurements will take much more time than has been available so far. No attempt has yet been made to minimize the $\overline{p}$ driving forces that bring $\overline{p}$ and e^+ into repeated contact [6].

The ATRAP apparatus is represented in Fig. 1, with a cross section of the crucial volume in Fig. 2(a). In preparation for $\overline{\mathrm{H}}$ production, typically 2×10^5 $\overline{p}$ from CERN's Antiproton Decelerator are accumulated for this demonstration. The well-established techniques for slowing, trapping, cooling, and stacking [9,10] are now

073401-1 0031-9007/04/93(7)/073401(4)$22.50





~ cos(ωt)

F

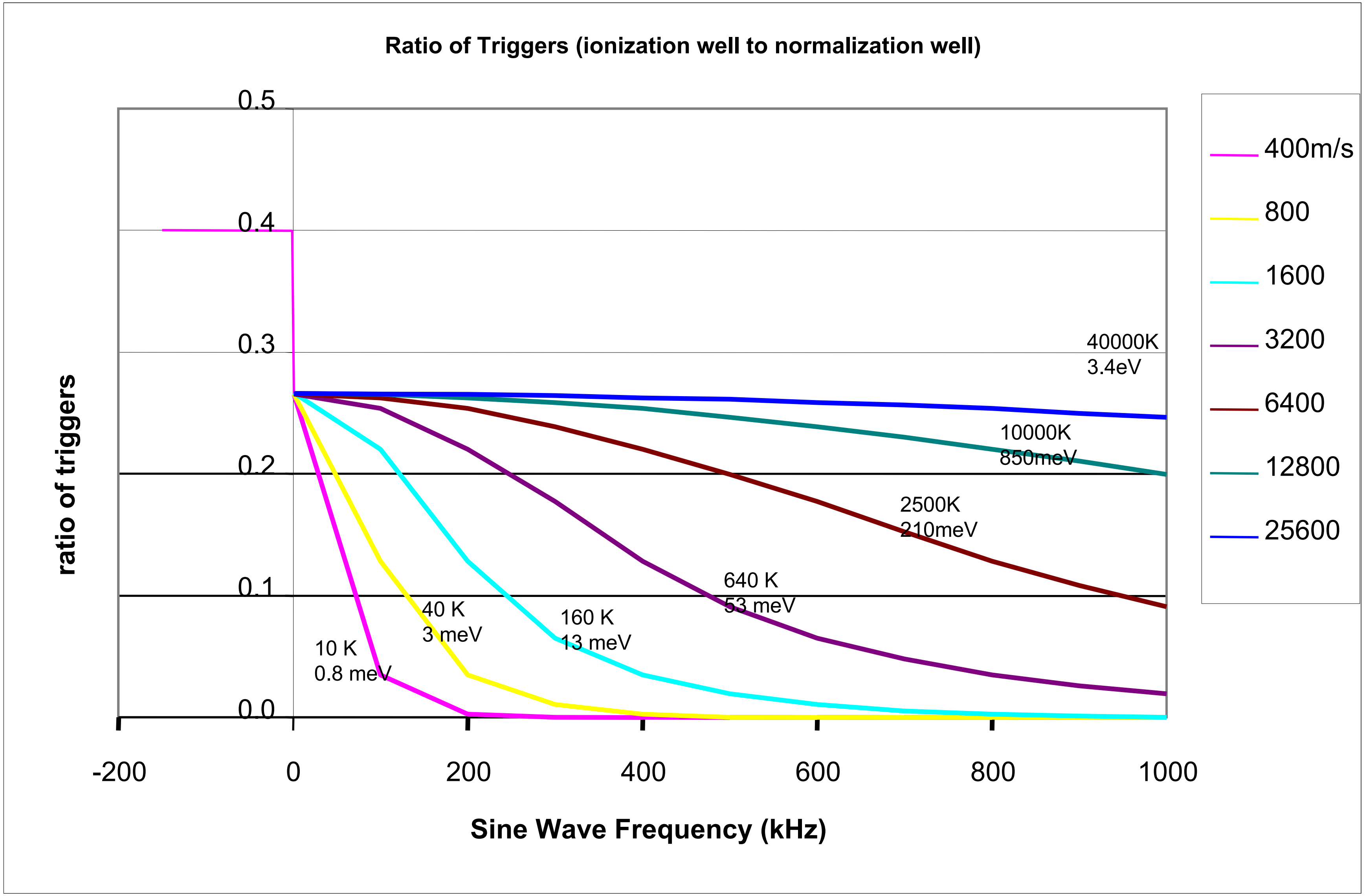
B

$\overline{\mathrm{H}}$ production in nested trap

electric field ionization region

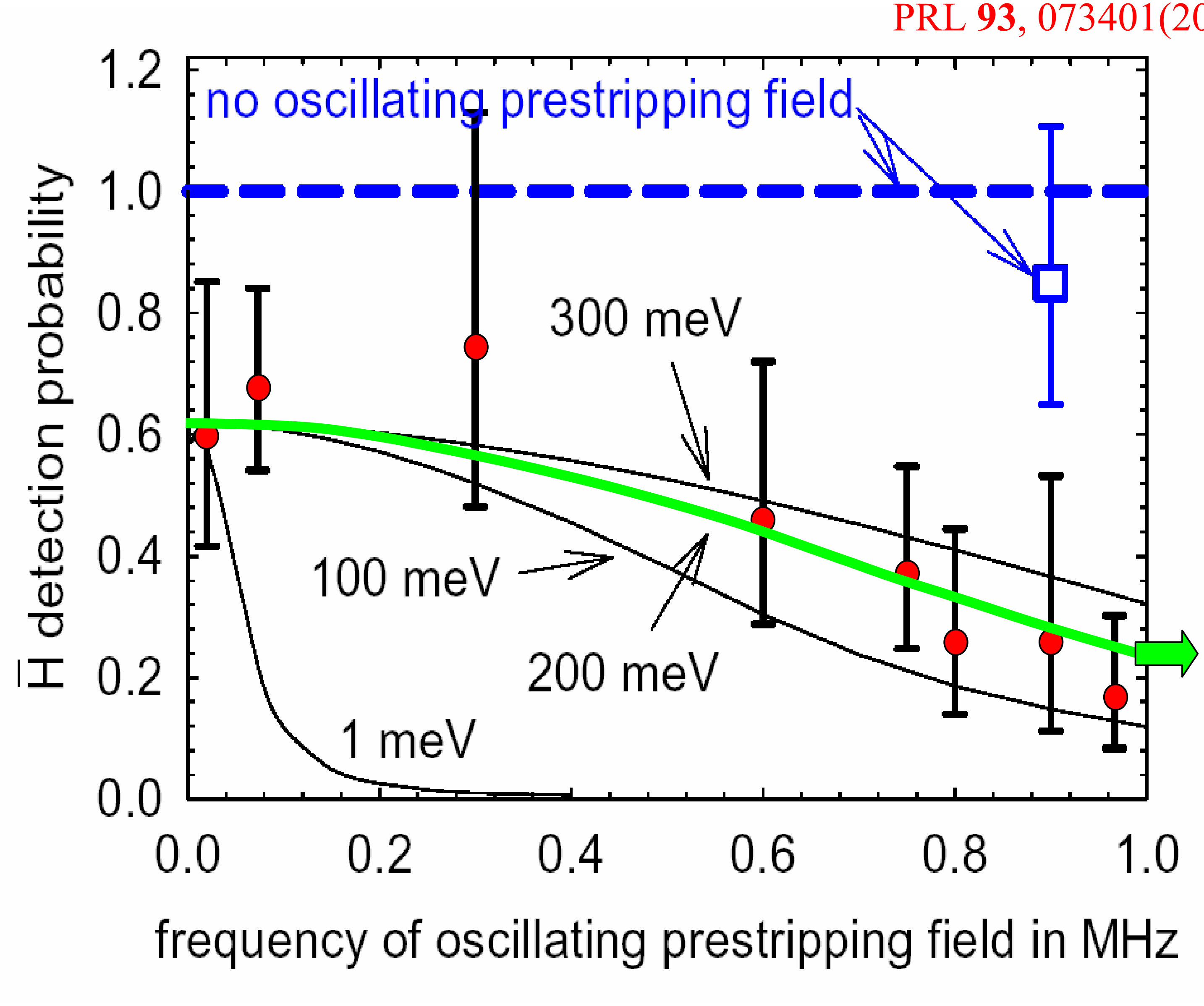
$\overline{\mathrm{H}}$ detection well

velocity measurement



velocity measurement of slow antihydrogen atoms

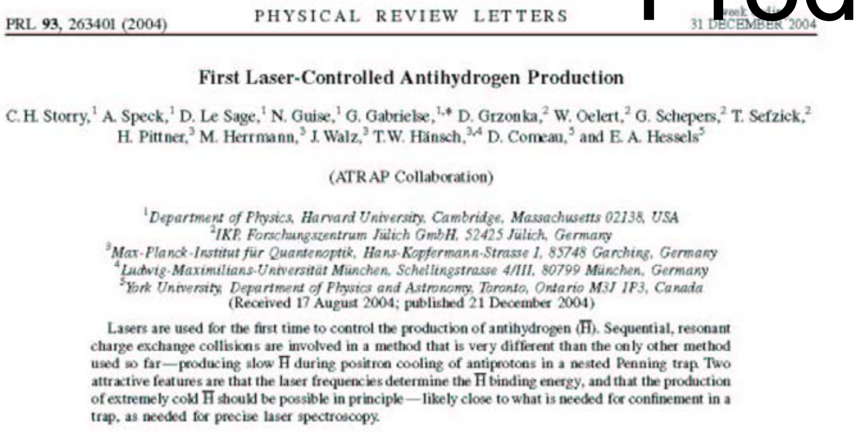
PRL **93**, 073401(2004)



$\bar{H}$ are hotter than expected

also reported by AIP physics update

Laser-Controlled Antihydrogen Production



PRL **93**, 263401 (2004) PHYSICAL REVIEW LETTERS 31 DECEMBER 2004

First Laser-Controlled Antihydrogen Production

C. H. Storry,[1] A. Speck,[1] D. Le Sage,[1] N. Guise,[1] G. Gabrielse,[1,*] D. Grzonka,[2] W. Oelert,[2] G. Schepers,[2] T. Sefzick,[2]
H. Pittner,[3] M. Herrmann,[3] J. Walz,[3] T.W. Hänsch,[3,4] D. Comeau,[5] and E. A. Hessels[5]

(ATRAP Collaboration)

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[4]*Ludwig-Maximilians-Universität München, Schellingstrasse 4/III, 80799 München, Germany*
[5]*York University, Department of Physics and Astronomy, Toronto, Ontario M3J 1P3, Canada*

(Received 17 August 2004; published 21 December 2004)

Lasers are used for the first time to control the production of antihydrogen ($\overline{\mathrm{H}}$). Sequential, resonant charge exchange collisions are involved in a method that is very different than the only other method used so far—producing slow $\overline{\mathrm{H}}$ during positron cooling of antiprotons in a nested Penning trap. Two attractive features are that the laser frequencies determine the $\overline{\mathrm{H}}$ binding energy, and that the production of extremely cold $\overline{\mathrm{H}}$ should be possible in principle—likely close to what is needed for confinement in a trap, as needed for precise laser spectroscopy.

DOI: 10.1103/PhysRevLett.93.263401

All slow antihydrogen ($\overline{\mathrm{H}}$) atoms to date have been produced in the same way—during positron cooling of antiprotons [1] in a nested Penning trap [2], with the $\overline{\mathrm{H}}$ detected using two techniques [3–5]. The high production rate and the observation of highly excited states suggests that the $\overline{\mathrm{H}}$ is produced by a three body mechanism involving two e^+ and one $\overline{p}$—the expected high-rate formation process at low temperature [2,6,7]. The coldest possible $\overline{\mathrm{H}}$ are required for the intriguing goal of achieving $\overline{\mathrm{H}}$ that is cold enough to be trapped for precise spectroscopic comparisons with hydrogen [8], building upon highly accurate hydrogen spectroscopy [9,10]. Hopes for three-body formation of $\overline{\mathrm{H}}$ that is colder than the 200_meV observed in the only $\overline{\mathrm{H}}$ velocity measurement so far [11] remain to be realized.

This Letter reports a very different way to produce $\overline{\mathrm{H}}$. Lasers determine the binding energy of $\overline{\mathrm{H}}$ atoms that are most likely as cold as the $\overline{p}$ from which they form. The lasers directly excite Cs atoms to high Rydberg states, Cs*. Two resonant charge exchange collisions [12],

$$\mathrm{Cs}^* + e^+ \rightarrow \mathrm{Ps}^* + \mathrm{Cs}^+, \qquad (1)$$

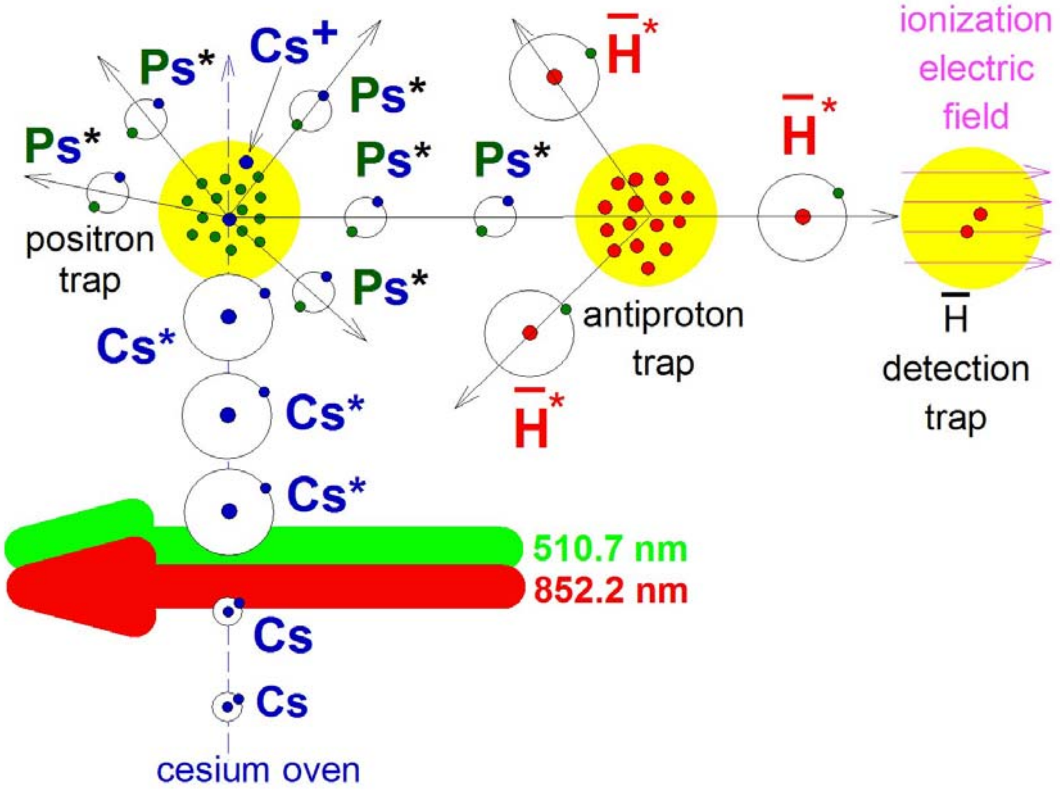
$$\mathrm{Ps}^* + \overline{p} \rightarrow \overline{H}^* + e^-, \qquad (2)$$

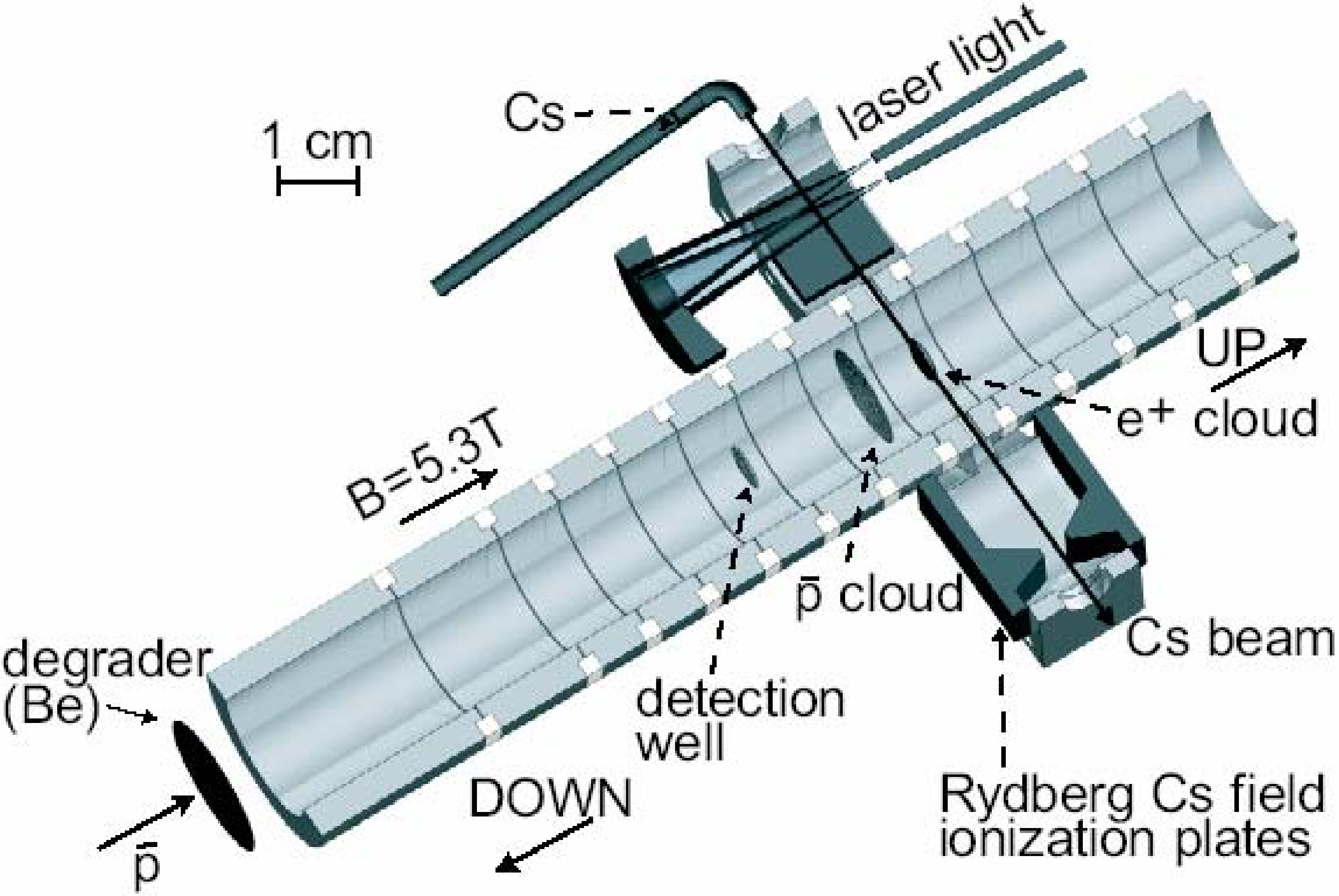
transfer the laser-selected Cs* binding energy to an excited positronium atom (Ps*) [13] and then to an excited $\overline{\mathrm{H}}^*$. Both processes have large cross sections because of the large size of the Cs* and Ps* [14], whereas $\overline{\mathrm{H}}$ formation using ground state Ps [15] has a rate too small to be observed. Very slow $\overline{\mathrm{H}}$ are expected because a Ps* transfers little kinetic energy to a $\overline{p}$ as $\overline{\mathrm{H}}$ forms. The $\overline{p}$ can be no colder than 4 K here, but the $\overline{p}$ could be made much

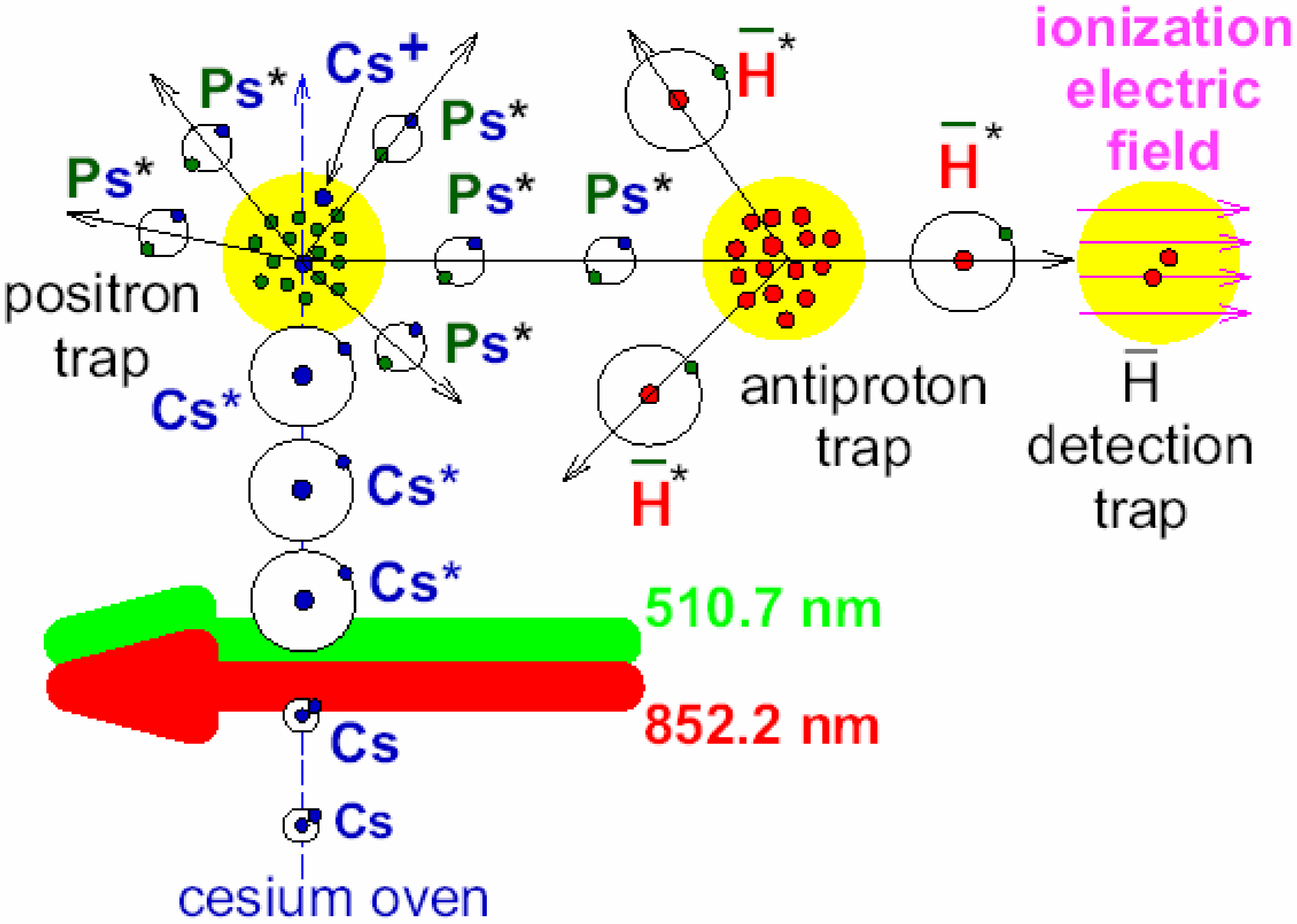
0031-9007/04/93(26)/263401(4)$22.50

- Likely the first truly cold antihydrogen formation

4.2 K



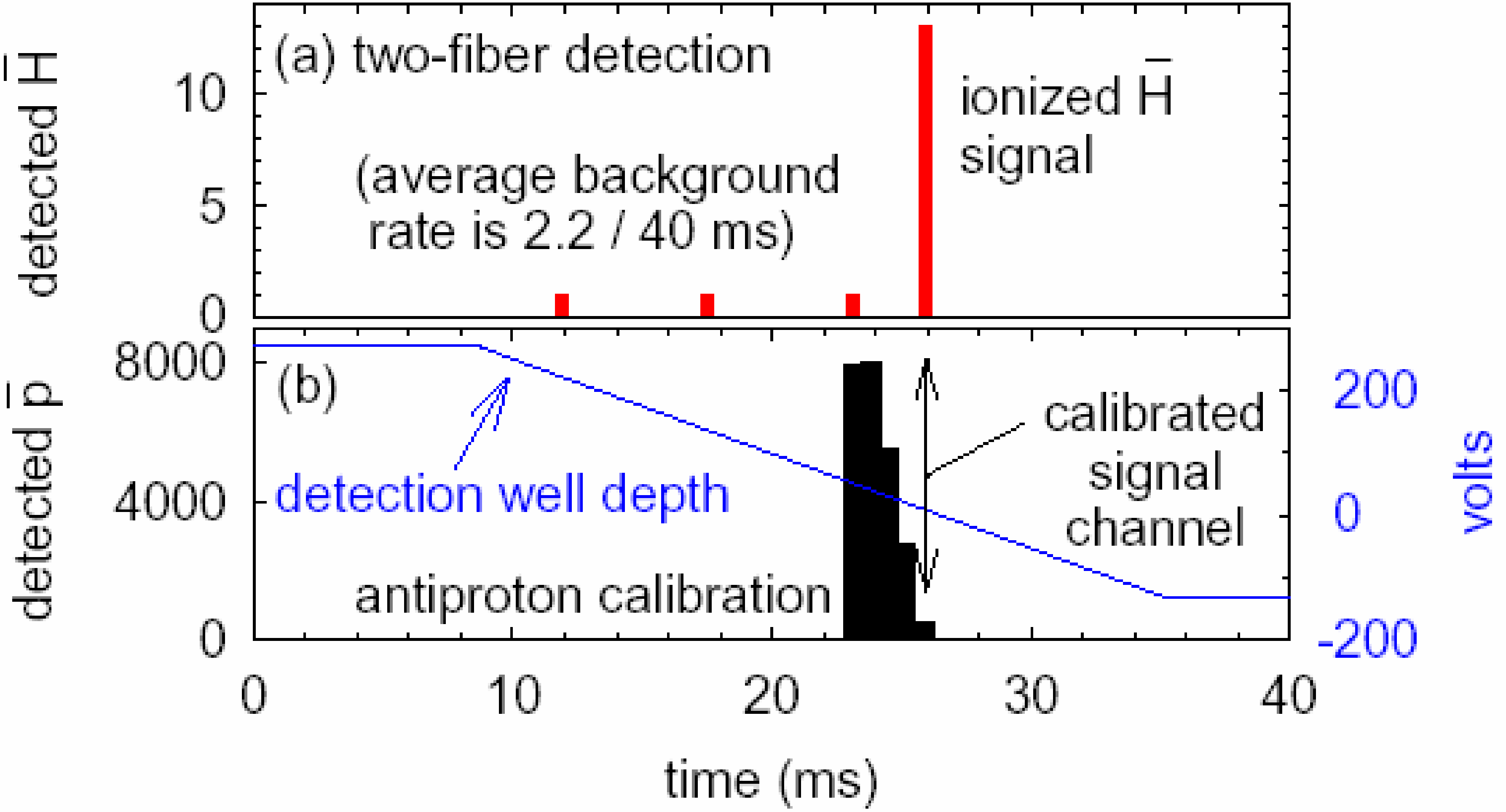

laser light
Cs
1 cm
UP
e⁺ cloud
B=5.3T
p̄ cloud
Cs beam
degrader
(Be)
detection
well
DOWN
Rydberg Cs field
ionization plates
p̄



Schematic of laser-controlled $\overline{\mathrm{H}}$ production.

First laser-controlled antihydrogen production

Phys. Rev. Lett. **93**, 263401 (2004)



also reported by AIP, science, Nature etc …

two methods produce slow antihydrogen

1. in a nested Penning trap,
   during positron cooling of antiprotons

   device and technique – ATRAP
   used to produce slow antihydrogen – ATHENA and ATRAP

   almost all antihydrogen atoms
   have been made this way

2. laser-controlled resonant charge exchange

   ATRAP

   proof of principle experiment

is there a better method 3, 4 or … ?

3. field assisted antihydrogen formation – we could not make work.

4. using a CO_2 laser to stimulate n = 10

tried by ATHENA in 2004

G. Gabrielse, S. L. Rolston, L. Haarsma and W. Kells,
"Antihydrogren production using trapped plasmas",
Phys. Lett. A **129**, 38 (1988).

A. Wolf,
"Laser-Stimulated Formation and Stabilization of Antihydrogen Atoms"
Hyper. Interact. 76, 189 (1993).

Antihydrogen formation

- **Radiative recombination**

$\bar{p} + e^+ \longrightarrow \bar{H} + h\nu$

$\Gamma = 3 \cdot 10^{-11}\,(4.2/T)^{9/2}\, n_e\, n_p\ \ s^{-1}$

$(\sim 3 \cdot 10^{-4}\ \bar{H}/s/\bar{p}$ at $T = 4.2K$, $10^7\ e^+)$

- **Laser-stimul. recombination**

$\bar{p} + e^+ + h\nu \longrightarrow \bar{H} + h\nu$

- **Three body recombination**

$\bar{p} + e^+ + e^+ \longrightarrow \bar{H} + e^+$

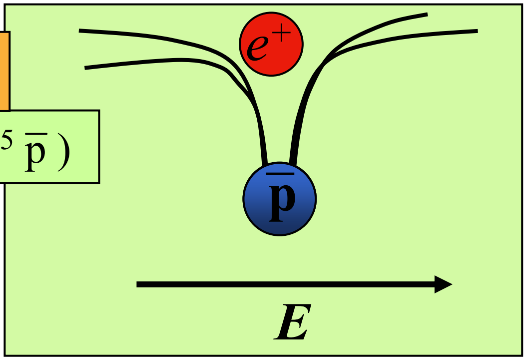
$\Gamma = 6 \cdot 10^{-13}\,(4.2/T)^{9/2}\, n_e^2\, n_p\ \ s^{-1}$

$(\sim 50\ \bar{H}/s/\bar{p}$ at $T = 4.2K$, $10^7\ e^+)$

- **Field assisted recombination**

E-field deforms $\bar{p}$ potential

$10^2\ \bar{H}$/exp. $(10^7\ e^+,\ 10^5\ \bar{p})$



- **Using positronium**

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

- **Using Rydberg positronium**

$\bar{p} + (e^+e^-)^* \longrightarrow \bar{H}^* + e^-$

$Cs + h\nu + h\nu \longrightarrow Cs^*$

$Cs^* + e^+ \longrightarrow (e^+e^-)^* + Cs^+$

Motivations and Goals – still the same

clear, stable, long term

Highly accurate spectroscopic comparisons of antihydrogen atoms and hydrogen atoms.

- clear before the AD was built
- clear now
- clear when the AD rests for one year
- clear in the future

experimental milestones → many have been achieved

* **Need antiprotons and positrons**

  * **AD, antiproton accumulation, positron accumulation**

* **Need to produce antihydrogen:** **method I** *
method II *
other methods?

! **Need useful antihydrogen:** **cold and in its ground state**

  * **inventing a method to measure the antihydrogen velocity**
  * **inventing a method to measure the antihydrogen state**
  ground state antihydrogen
  antihydrogen cold enough to be trapped

! **Need to trap antihydrogen**

  *? **first stability test for trapped particles in Ioffe field**

! **Need antihydrogen spectroscopy**

  * **first continuous Lyman-alpha source**

next milestones:
achieving useful antihydrogen

- cold enough to trap
- ground state

much of ATRAP’s 2004 time was spent pursuing these goals

these next milestones have not been met with production method `1`

however, ATRAP has demonstrated

- a method to measure antihydrogen speed
- a method to measure the binding energy of antihydrogen atoms

likely production method `2` gives antihydrogen with
the low energy distribution of the antiprotons
from which they form.

2004 Run

Goals:

- producing and observing colder antihydrogen atoms
- producing and observing less excited antihydrogen atoms
- obtaining larger numbers of positrons and antiprotons
- investigating Ioffe trap induced instabilities

2004 Run

Difficulties:

- PS and AD bad luck → not so efficient, sometimes, beam time extension
  → antiproton pulses vary in intensity:
  normalization problems

still we appreciate the hard work of people from CERN

- ATRAP difficulties
  → success in getting much larger numbers of positrons
  led to instabilities in our small trap (ATRAP II is larger)
  → we found it very challenging to fit even more apparatus
  in our tiny experimental volume (ATRAP II is larger)

we are still analyzing our Ioffe stability measurements

Progress has been made, but no big punch lines so far

ATRAP II – solenoid, dewar, and outer detectors commissioned

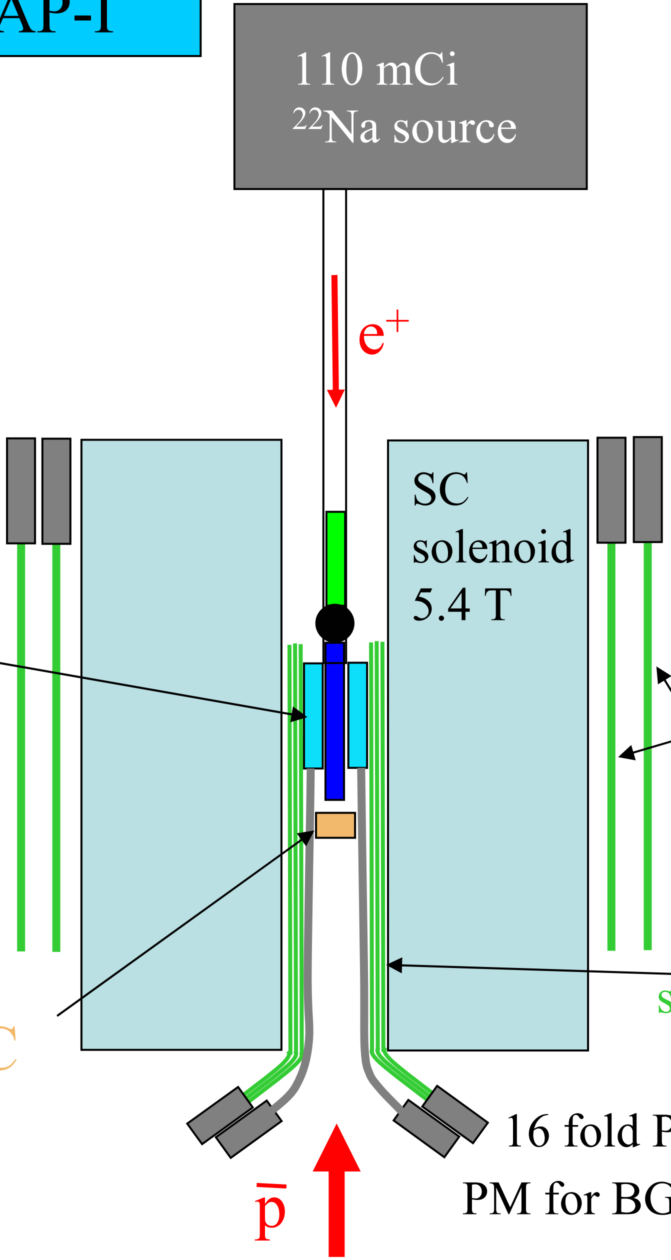
much larger apparatus with volume available for
Particle trapping, detection systems, and laser excess.

The company building the large superconducting solenoid and dewar for ATRAP II experienced many delays

Good news: the solenoid, dewar, and first detectors are now
installed and are operational.

ATRAP intends to shift mostly to ATRAP II when antiprotons are again available at the AD

ATRAP-I



110 mCi

^{22}Na source

e^+

SC

solenoid

5.4 T

BGO

outer

scintillator

2 layer

(6+12)

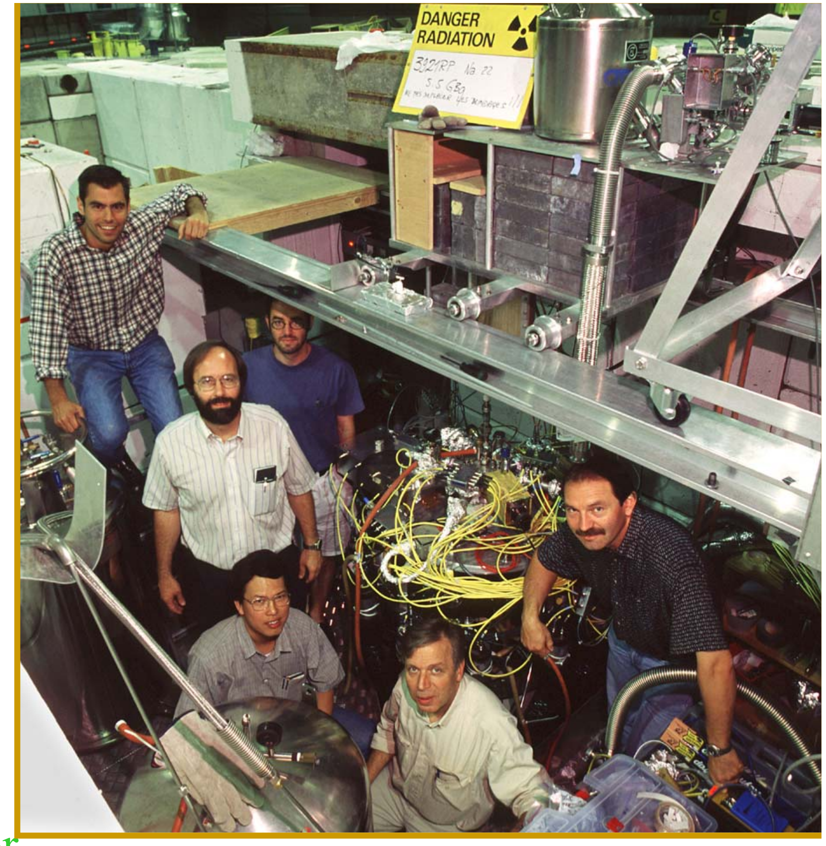
scintillating fibres (3 layer)

PPAC

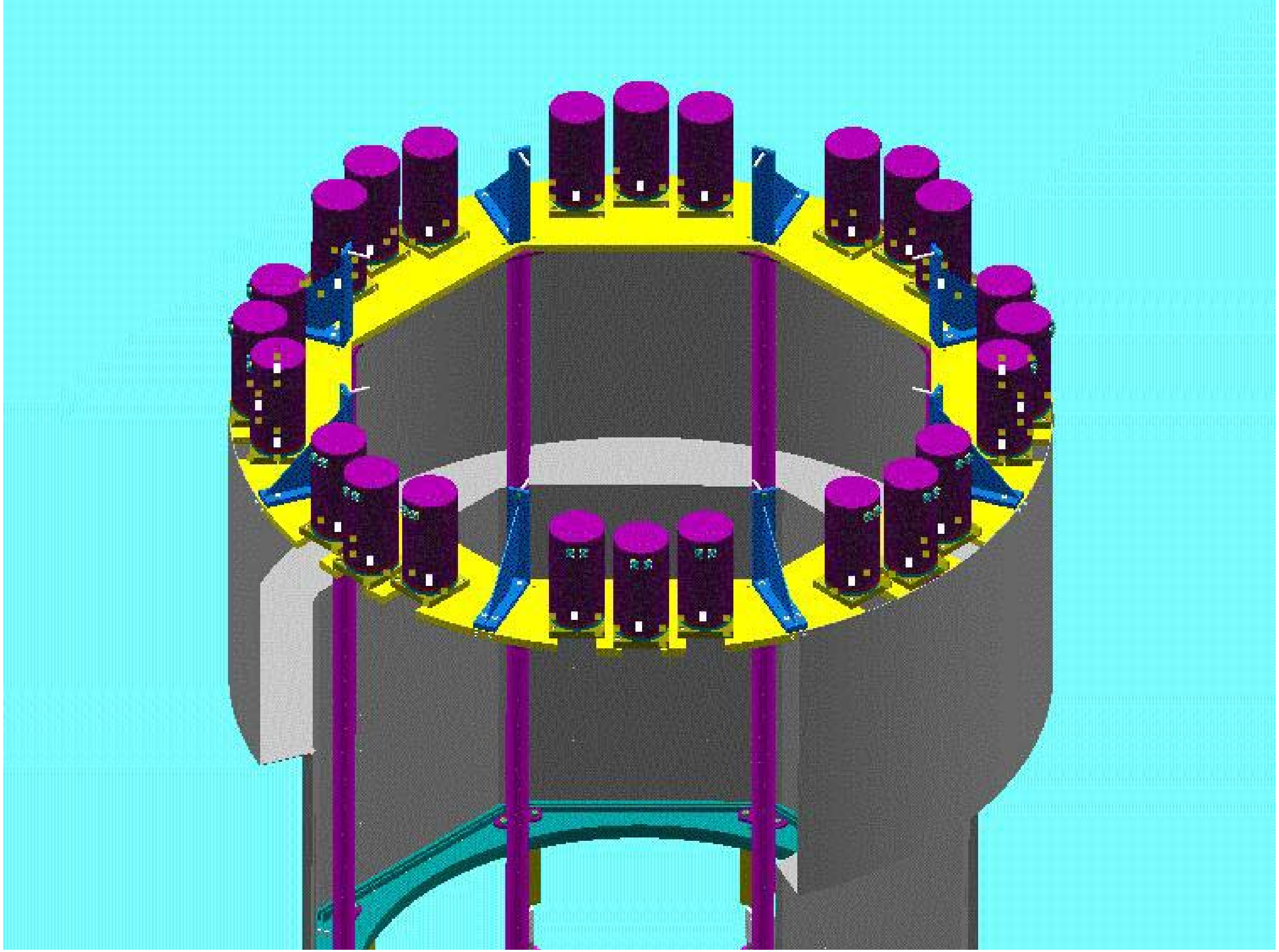
16 fold PM for fibres

PM for BGO

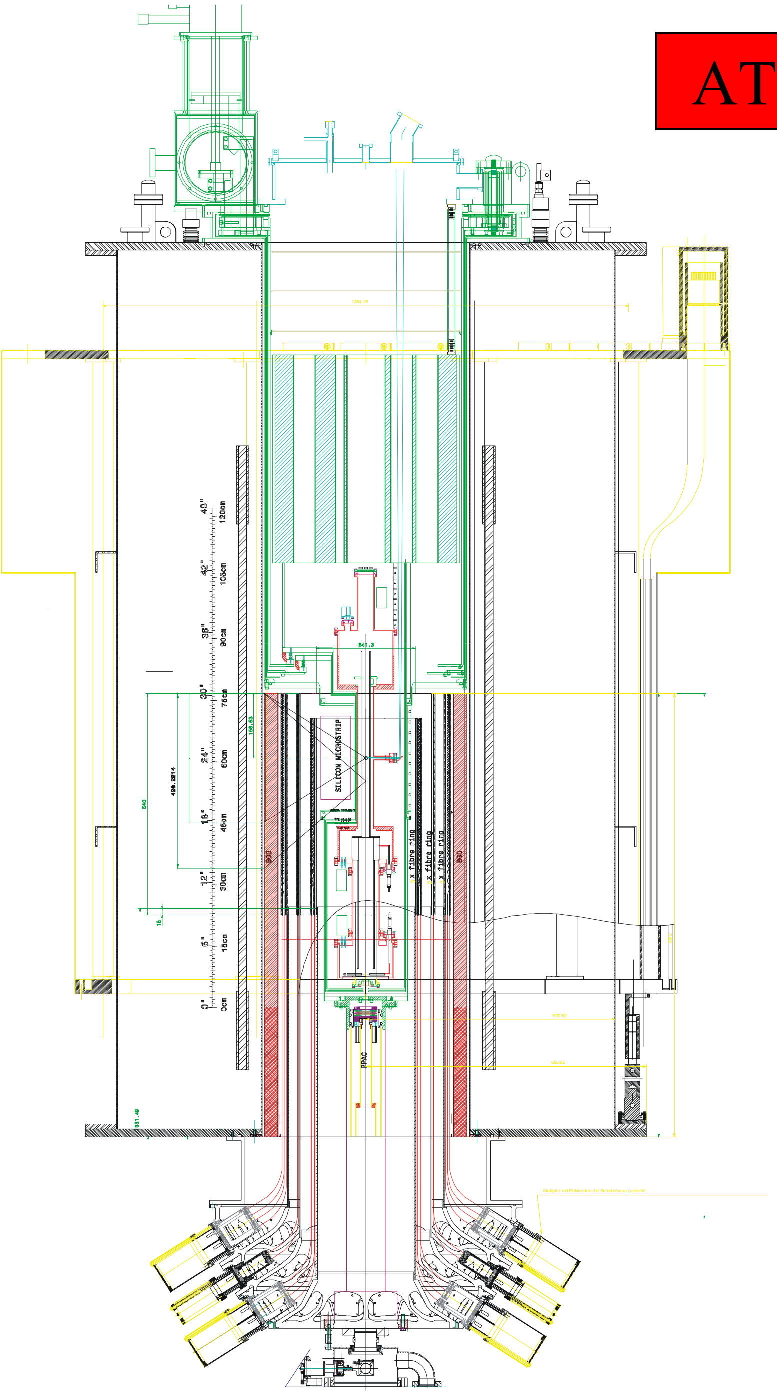
$\bar{p}$

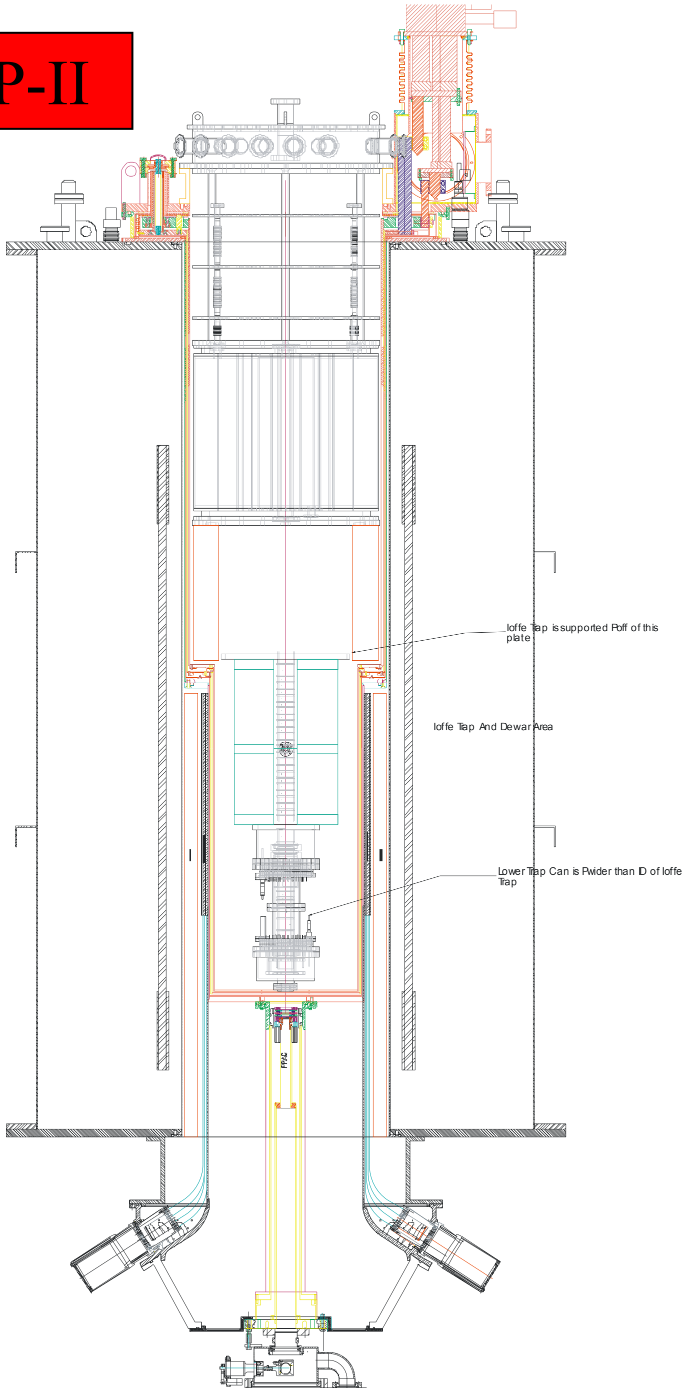


ATRAP-II



ATRAP-II


48"
42"
36"
30"
24"
18"
12"
6"
0"
120cm
105cm
90cm
75cm
60cm
45cm
30cm
15cm
0cm
241.3
158.53
426.2814
540
16
SILICON MICROSTRIP
3 x fibre ring
2 x fibre ring
3 x fibre ring
BGO
BGO
PPAC


Ioffe Trap is supported Poff of this plate
Ioffe Trap And Dewar Area
Lower Trap Can is Pwider than ID of Ioffe Trap
PPAC

Antiprotons – needed improvements

Status: 4.2 K antiprotons are routinely accumulated

Improvements?

- needed: much lower temperatures   when ……
- desired: more antiprotons to speed data accumulation
- desired: more antiprotons to improve spectroscopy signal-to-noise

Decelerator (ELENA)?

- would give the much larger antiproton rate desired
- small ring would fit in AD hall
- new beam lines would be needed
- magnetic fields from experimental apparatus
- substantial cost

positron accumulation

Status: two methods routinely accumulate positrons
enough positrons are available, all independent of CERN

Ionizing Rydberg positronium – compact, in high field,
high vacuum, lower accumulation rate

Gas slowing – larger, outside of high field,
lower vacuum, higher accumulation rate

another possibility: **Electron plasma slowing ??**

Improvements? Likely need much lower temperatures

crucial experimental milestones have been achieved

* **Need antiprotons and positrons**

    * **AD, antiproton accumulation, positron accumulation**

* **Need to produce antihydrogen:** **method I** *

method II *

other Methods?

! **Need useful antihydrogen:** **cold and in the ground state**

    * **inventing a method to measure the antihydrogen velocity**

    * **inventing a method to measure the antihydrogen state**

    ground state antihydrogen

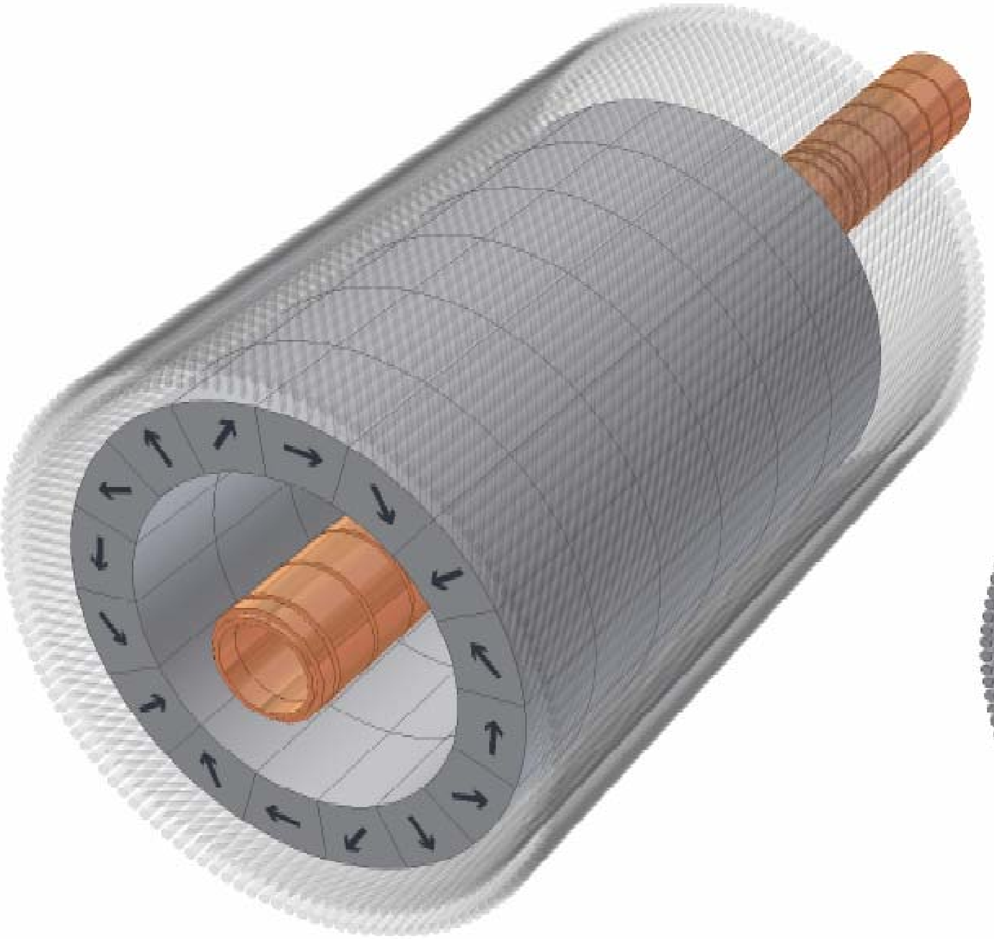
    antihydrogen cold enough to trap

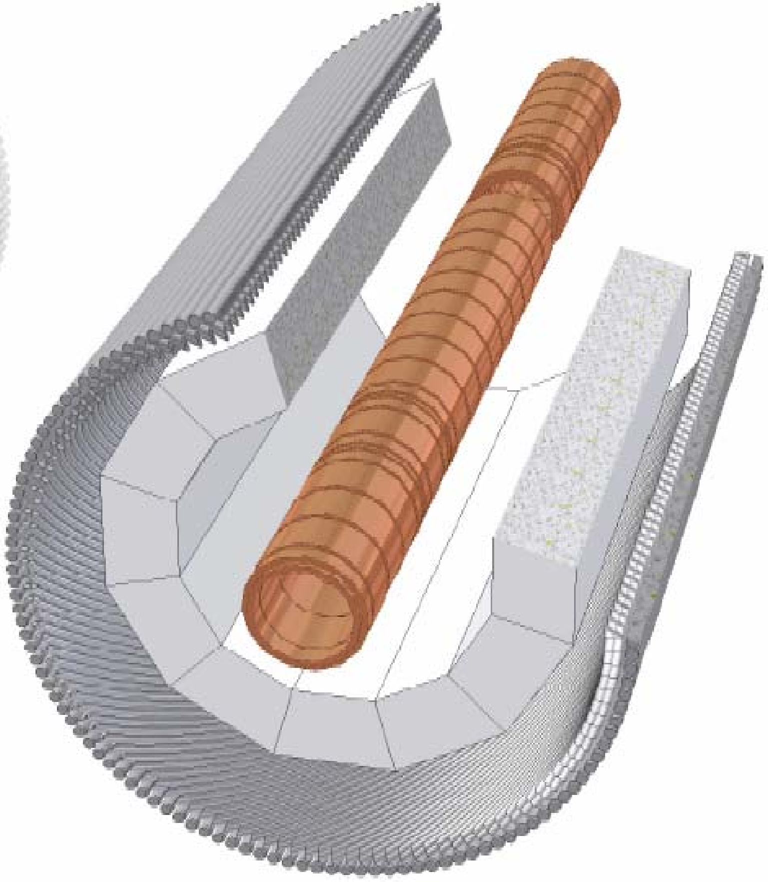
! **Need to trap antihydrogen**

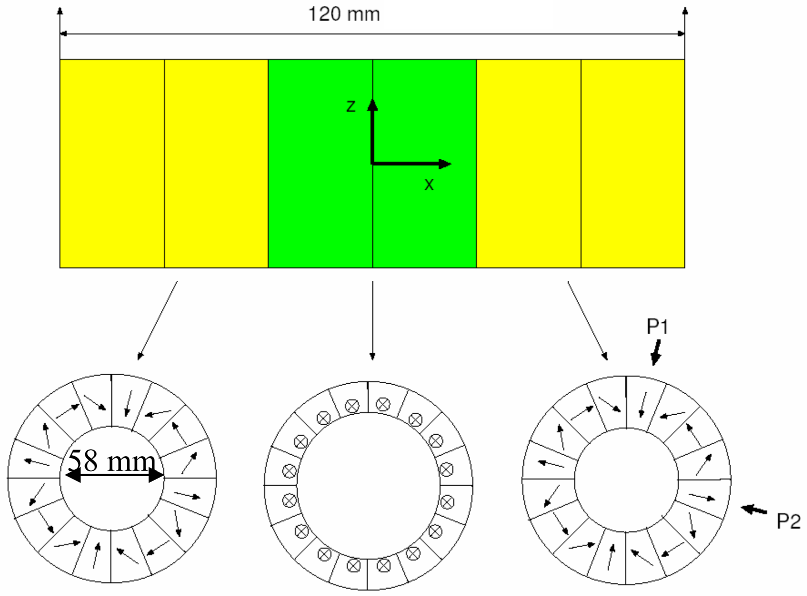
    *? **stability test for trapped particles in Ioffe field**

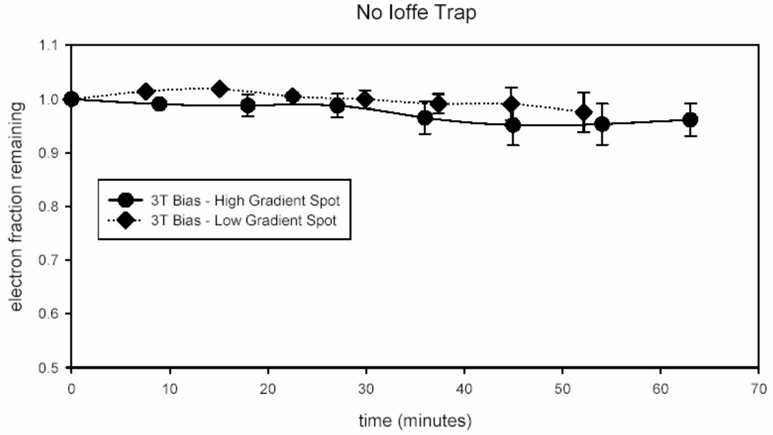
! **Need antihydrogen spectroscopy**

    * **first continuous Lyman-alpha source**

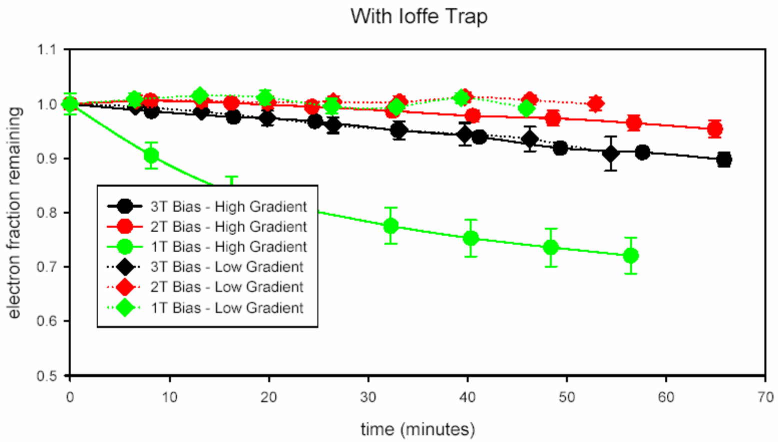




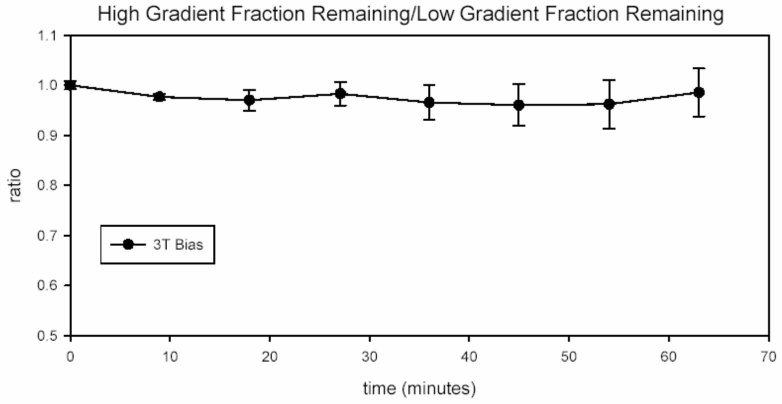

120 mm
z
x
58 mm
P1
P2



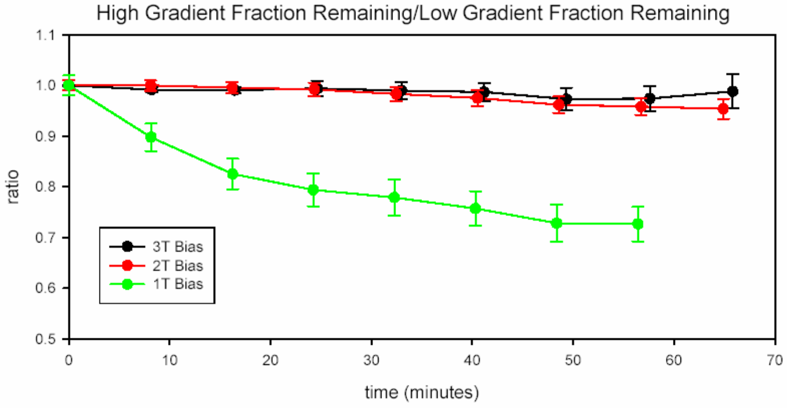
No Ioffe Trap



With Ioffe Trap



High Gradient Fraction Remaining/Low Gradient Fraction Remaining



High Gradient Fraction Remaining/Low Gradient Fraction Remaining

Summary

- cold antihydrogen studies: unique → CERN
- determination of density and spatial distribution of e^+ and $\overline{p}$
  → optimize $\overline{H}$ production
- measurement of n-state distribution
  → de-excitation to the ground state
- velocity measurement of $\overline{H}$
  → trapping of $\overline{H}$
- $\overline{H}$ production via double charge exchange production
  → promising in view of de-excitation and trapping

we hope that you are persuaded that …

1. Cold antihydrogen studies provide a unique opportunity for studies of high scientific importance – studies that are only possible at CERN.

2. These studies are proving to be just as challenging as was anticipated when the long-term AD program was established, given the need to develop and demonstrated many new techniques.

3. Important recent milestones signal great progress
   → Slow antihydrogen atoms can now be produced using two entirely different methods.
   → A method has been devised to measure the speed of antihydrogen atoms
   → A method has been devised to measure the antihydrogen excitation state
   We hope the SPSC is encouraged by the rapid progress and commends it.

4. For highly accurate spectroscopy experiments, ground state atoms that can be trapped are needed. The atoms whose internal states have been probed are still highly excited, and the atoms whose velocity has been measured are moving too rapidly to trap. We hope that the SPSC strongly encourages a proper current emphasis upon
   → speed of antihydrogen atoms (measuring and slowing)
   → state of antihydrogen atoms (measuring and deexciting)

we hope that you are persuaded that …

5. as long as steady progress is reported, we hope that the SPSC will strongly support the ongoing antihydrogen research program.

6. we hope that the committee will note with great interest the studies suggesting that the number of antiprotons that could be made available for antihydrogen experiments (and other users) could be dramatically increased by approximately a factor of 100 if a small decelerator ring could be added at the AD facility. ELENA, see Villars presentation by Pavel Beloshitskii et al,

Thank You!