ATRAP: Context and Status

G. Gabrielse,[1,*] W. S. Kolthammer,[1] R. McConnell,[1] P. Richerme,[1] R. Kalra,[1] E. Novitski,[1] D. Grzonka,[2]
W. Oelert,[1] T. Sefzick,[2] M. Zielinski,[2] D. Fitzakerley,[3] M. C. George,[3] E. A. Hessels,[3] C. H. Storry,[3] M. Weel,[3]
A. Müllers,[4] and J. Walz[4]

(ATRAP Collaboration)

[1]*Department of Physics, Harvard University, Cambridge, Massachusetts 02138, USA*
[2]*IKP, Forschungszentrum Jülich GmbH, 52425 Jülich, Germany*
[3]*Department of Physics and Astronomy, York University, Toronto, Ontario M3J 1P3, Canada*
[4]*Institut für Physik, Johannes Gutenberg Universität and Helmholtz Institut Mainz, D-55099 Mainz, Germany*

Antihydrogen and the Antiproton Magnetic Moment

Gerald Gabrielse
Spokesperson for TRAP and ATRAP at CERN
Leverett Professor of Physics, Harvard University

Context

CERN Pursues Fundamental Particle Physics at Whatever Energy Scale is Interesting

A Long and Noble CERN Tradition

1981 – traveled to Fermilab "TEV or bust"

1985 – different response at CERN when I went there to try to get access to LEAR antiprotons for q/m measurements and cold antihydrogen

It is exciting that there is now

- a dedicated storage ring for antihydrogen experiments
- four international collaborations
- too few antiprotons for the demand

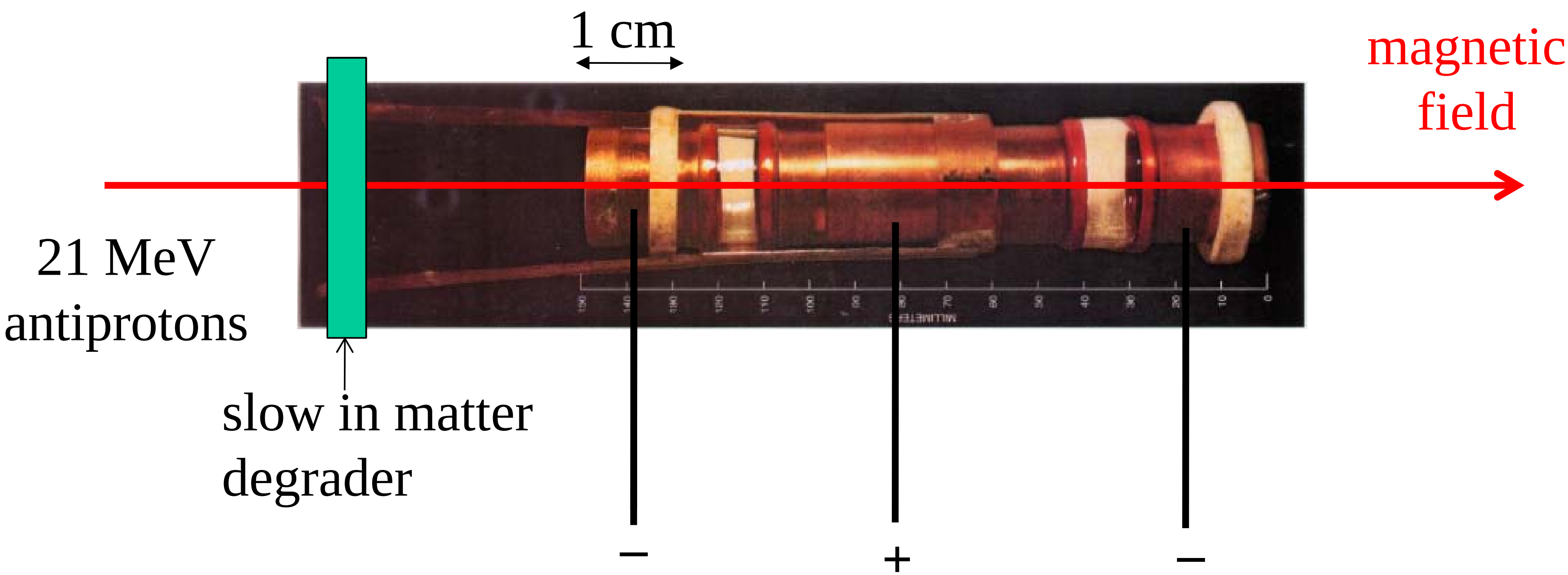
Gabrielse

Pursuing Fundamental Particle Physics at Whatever Energy Scale is Interesting

A Long and Noble CERN Tradition

1986 – First trapped antiprotons (TRAP)

1989 – First **electron-cooling** of trapped antiprotons (TRAP)



CERN's AD, plus these cold methods → make antihydrogen possible

Pursuing Fundamental Particle Physics at Whatever Energy Scale is Interesting

A Long and Noble CERN Tradition

1981 – traveled to Fermilab "TEV or bust"

1985 – different response at CERN when I went there
to try to get access to LEAR antiprotons
for q/m measurements and cold antihydrogen

LHC:	7 TeV + 7 TeV
AD:	5 MeV
ELENA upgrade:	0.1 MeV
ATRAP:	0.3 milli-eV

5×10^{16}

100 times More trapped antiprotons

Physics With Low Energy Antiprotons

First Physics: Compare q/m for antiproton and proton to 9 parts in 10^{11} (could now be improved)

Current Physics: Compare antihydrogen and hydrogen (goal is a higher precision than q/m measur.)

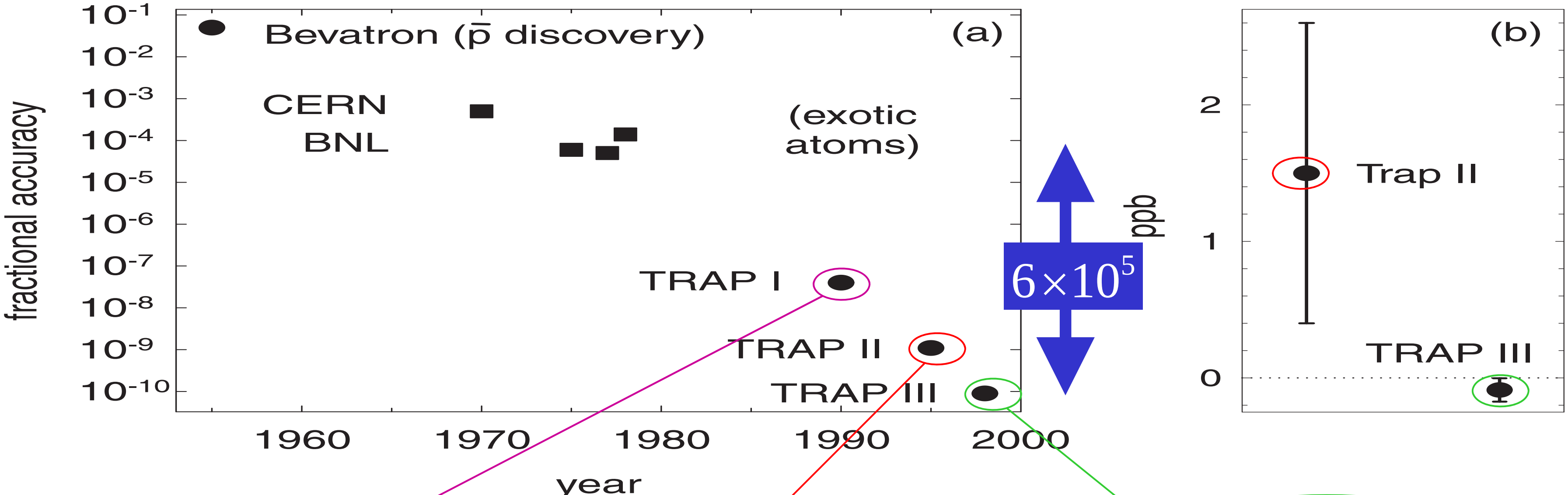
Future Physics: Compare antiproton and proton magnetic moment

First Physics: Comparing Antiproton and Proton

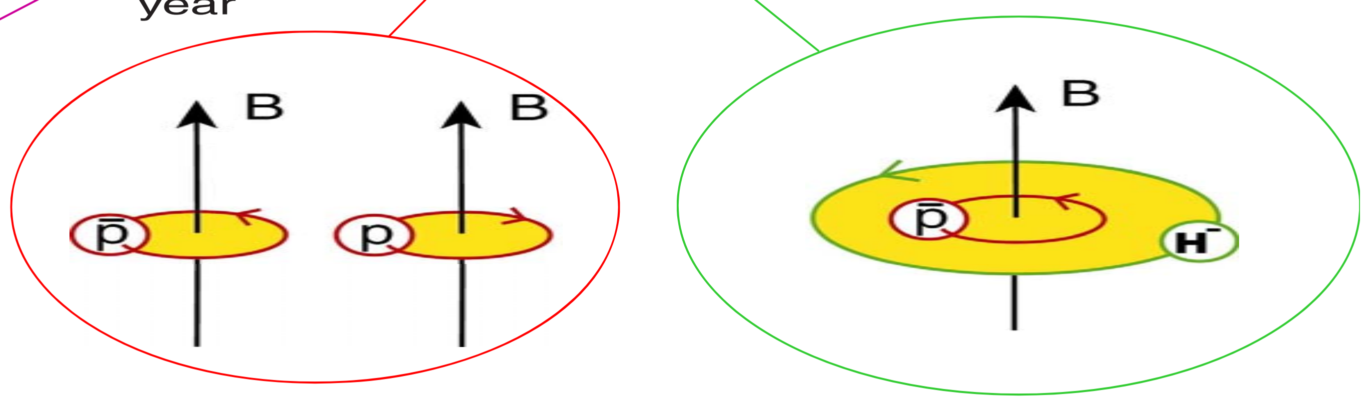
Best CPT test with baryons

$$\frac{q/m \ \text{(antiproton)}}{q/m \ \text{(proton)}} = -0.99999999991(9)$$

$$9\times10^{-11} = 90\,\text{ppt}$$

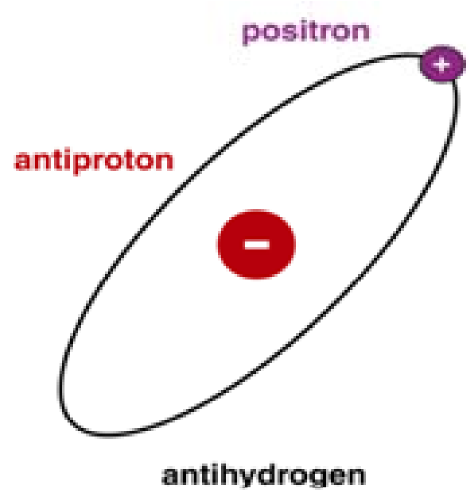


100 antiprotons and protons



Gabrielse, Khabbaz, Hall, Heimann, Kalinowsky, Jhe; Phys. Rev. Lett. **82**, 3198 (1999).

Current Physics: Antihydrogen



Quarter century

Antihydrogen ideas (1986-1988) → realized in 2002-2010

1986 Idea: Use Cold Antiprotons to Make Cold Antihydrogen Atoms

"When antihydrogen is formed in an ion trap, the neutral atoms will no longer be confined and will thus quickly strike the trap electrodes. Resulting annihilations of the positron and antiproton could be monitored. ..."

Gerald Gabrielse, 1986 Erice Lecture (shortly after first pbar trapping)
In **Fundamental Symmetries**, (P.Bloch, P. Paulopoulos, and R. Klapisch, Eds.) p. 59, Plenum, New York (1987).

2002: Antihydrogen observed by ATHENA and by ATRAP

used field ionization detection

Gabrielse

1988 Ideas: Use Nested Penning Trap and 3-Body "Recombination"

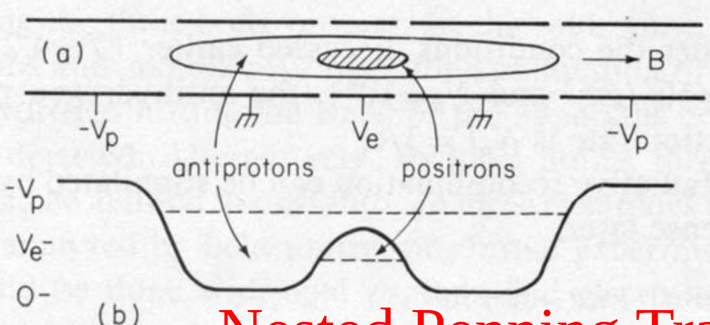
Volume 129, number 1 PHYSICS LETTERS A 2 May 1988

ANTIHYDROGEN PRODUCTION USING TRAPPED PLASMAS

G. GABRIELSE, S.L. ROLSTON, L. HAARSMA
Department of Physics, Harvard University, Cambridge, MA 02138, USA

W. KELLS
Fermi National Accelerator Laboratory, Batavia, IL 60438, USA

To get opposite charges to interact



Nested Penning Trap

Fig. 1. Electrodes (a) and axial potential (b) for a nested pair of Penning traps.

To get fast enough formation rate

We call attention to another three-body recombination

$$p^- + e^+ + e^+ \to \bar{H} + e^+ , \quad (6)$$

which may well be more efficient for antihydrogen production by many orders of magnitude. Its cross

3-Body "Recombination"

Used by ATRAP, ALPHA and ASACUSA

1988 Ideas: Use Nested Penning Trap and 3-Body "Recombination"

1996 – Protons and electrons interact in a nested Penning trap (TRAP)

2001 – Antiprotons and positrons interact in a Nested Penning Trap (TRAP)

2002 – Demonstrate that antihydrogen is produced by this method (ATRAP and ATHENA)

2010 – ASACUSA also uses these methods (with RFQ)

This method produced all slow antihydrogen to date (almost)

1986 Idea: Trap Cold Antihydrogen for Accurate Spectroscopy

"For me, the most attractive way ... would be to capture the antihydrogen in a neutral particle trap ... The objective would be to then study the properties of a small number of [antihydrogen] atoms confined in the neutral trap for a long time."

Gerald Gabrielse, 1986 Erice Lecture (shortly after first pbar trapping)
In **Fundamental Symmetries**, (P.Bloch, P. Paulopoulos, and
R. Klapisch, Eds.) p. 59, Plenum, New York (1987).

Proof-of-principle demo (< 1 trapped atom per trial) – ALPHA, 2011

Need many more atoms

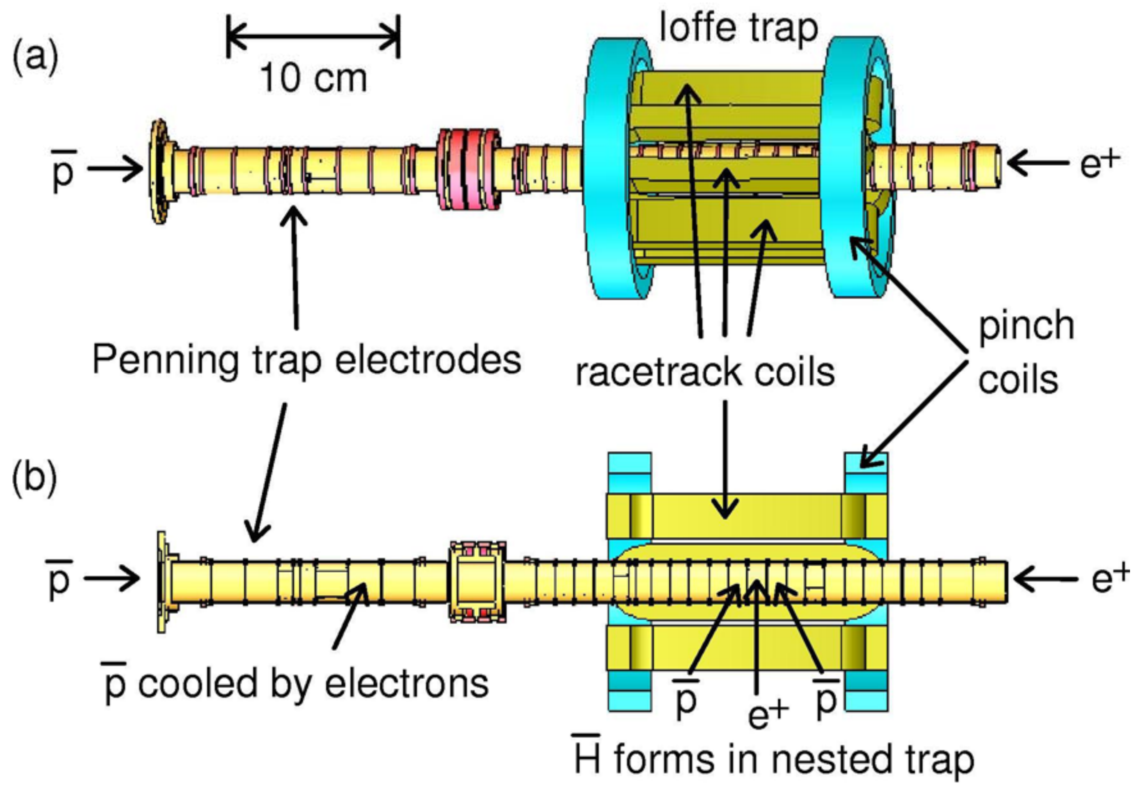
ATRAP PRL 2008

Gabrielse

First Antihydrogen Production within a Penning-Ioffe Trap

G. Gabrielse,[1,*] P. Larochelle,[1] D. Le Sage,[1] B. Levitt,[1] W.S. Kolthammer,[1] R. McConnell,[1] P. Richerme,[1] J. Wrubel,[1] A. Speck,[2] M.C. George,[3,4] D. Grzonka,[3] W. Oelert,[3] T. Sefzick,[3] Z. Zhang,[3] A. Carew,[4] D. Comeau,[4] E.A. Hessels,[4] C.H. Storry,[4] M. Weel,[4] and J. Walz[5]
(ATRAP Collaboration)

[1]*Dept. of Physics, Harvard University, Cambridge, MA 02138*
[2]*Rowland Inst. at Harvard, Harvard University, Cambridge, MA 02142*
[3]*IKP, Forschungszentrum Jülich GmbH, 52425 Jülich, Germany*
[4]*York University, Department of Physics and Astronomy, Toronto, Ontario M3J 1P3, Canada*
[5]*Institut fur Physik, Johannes Gutenberg-Universität, D-55099 Mainz, Germany*



No trapped antihydrogen detected

Detection limit:
< 20 atoms trapped per trial

ATRAP – produced and observed antihydrogen atoms in the fields of a Ioffe trap (PRL 2008)

Limit: less than **20 atoms** were being trapped per trial

ALPHA – did similar production the following year

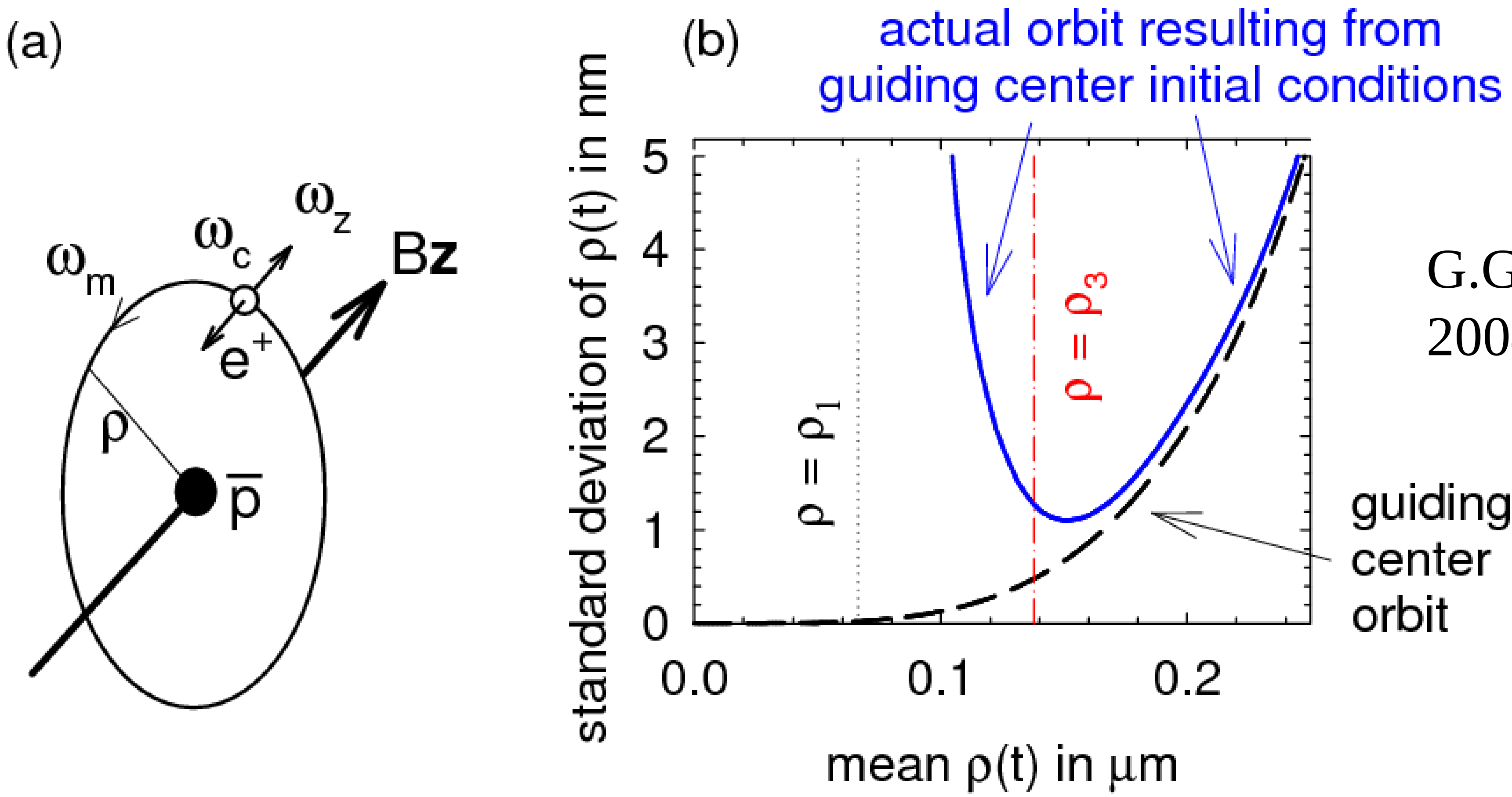
two different approaches

ATRAP
Try to make more atoms

ALPHA
Try to detect fewer atoms
(0.1 per trial in 2010)

Nature's Gift – trapping happens despite deexcitation through chaotic orbital motions

Chaotic Orbits → States that can be trapped



G.G. 2004

$$\rho > \rho_3 = \left[9 r_e c^2 / \omega_c^2\right]^{1/3} = 0.14\ \mu\mathrm{m}$$

ATRAP – observed the first production of antihydrogen atoms within in the fields of a Ioffe trap (PRL 2008)

Set limit: less than **20 atoms** were being trapped per trial

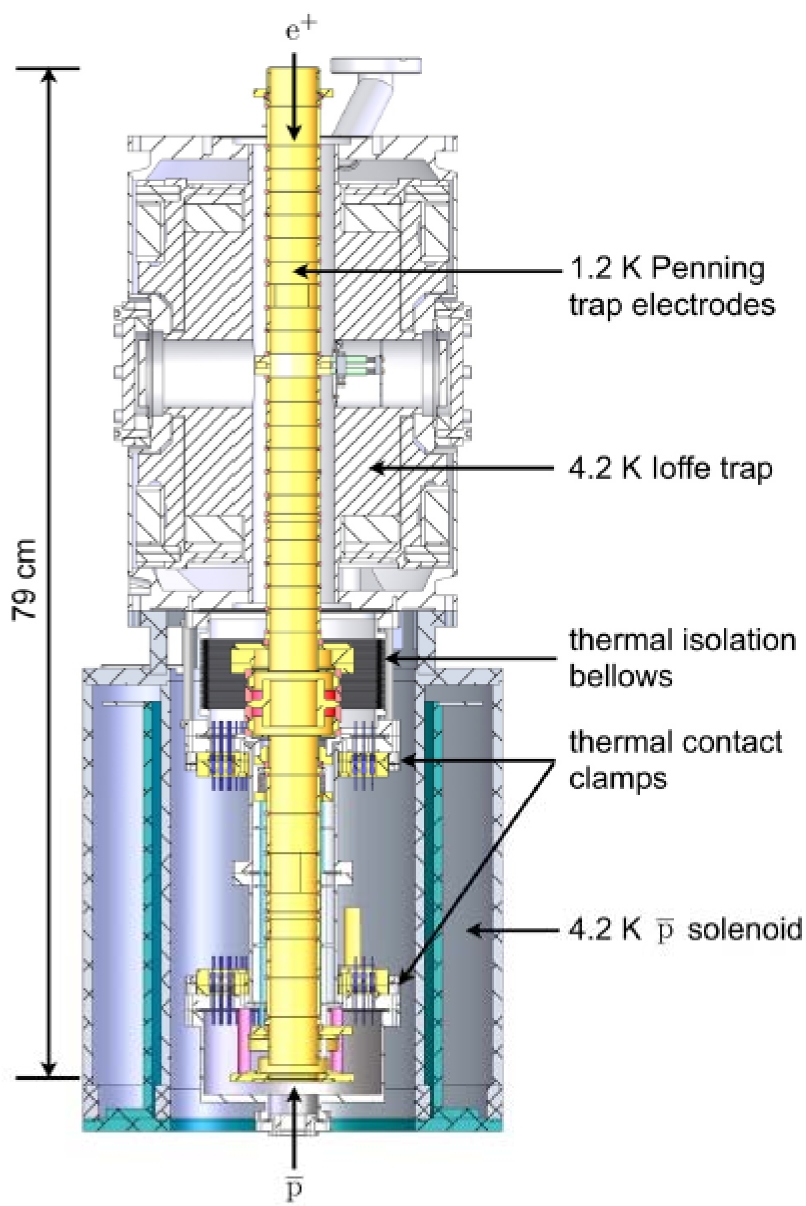
ALPHA – did similar production the following year

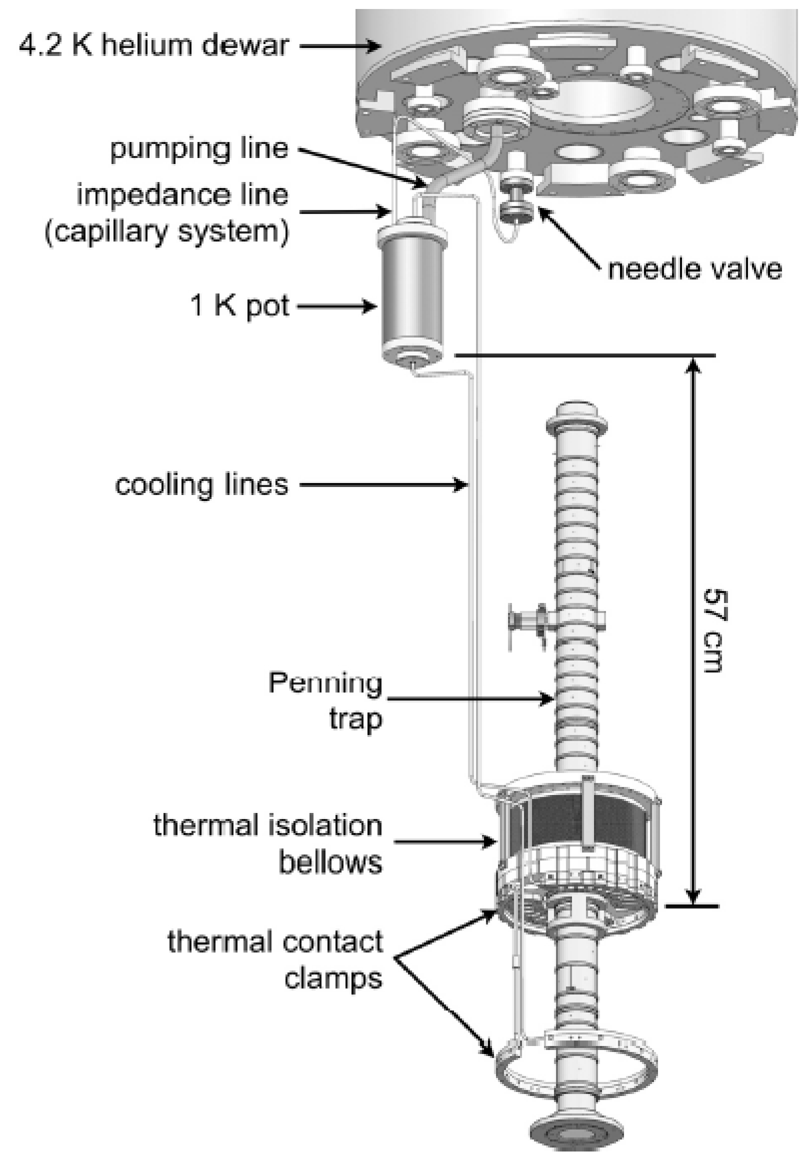
For the next step
two different approaches

ATRAP
Make more cold atoms

ALPHA
Detect fewer atoms
(0.1 per trial in 2010)

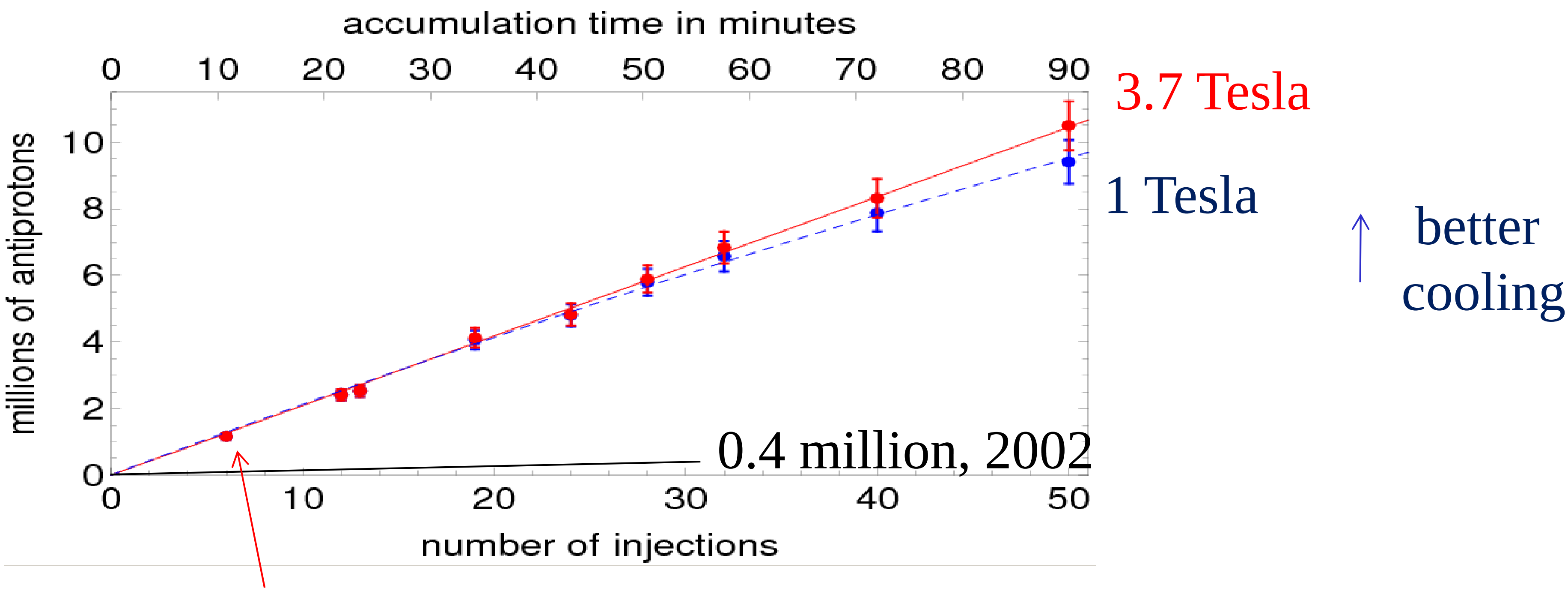
Colder Electrodes: 4.2 K → 1.2 K





10 Million Cold Pbar/Trial at ATRAP

0.4 million → 10 million
(5.4 Tesla) (1 Tesla)



Typical experiment trial uses a few million antiprotons
→ Need ELENA to get 10 million in a reasonable time
→ Need ELENA so that we can use more than 6 hours/day

ATRAP → More Antiprotons, Much Colder

- Lowered electrode temperature to 1.2 K
- Started measuring antiproton temperatures
- Developed new pbar cooling methods

First antiprotons cold enough to centrifugally separate from the electrons that cool them

Phys. Rev. Lett. **105**, 213002 (2010).

Two new cooling methods for antiprotons

-- embedded electron cooling (almost no electrons)

-- adiabatic cooling

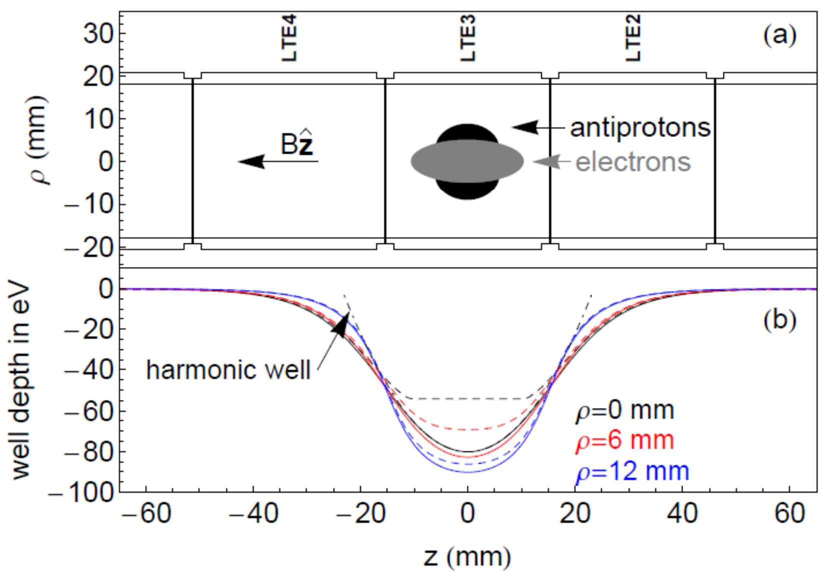
Phys. Rev. Lett. **106**, 073002 (2011).

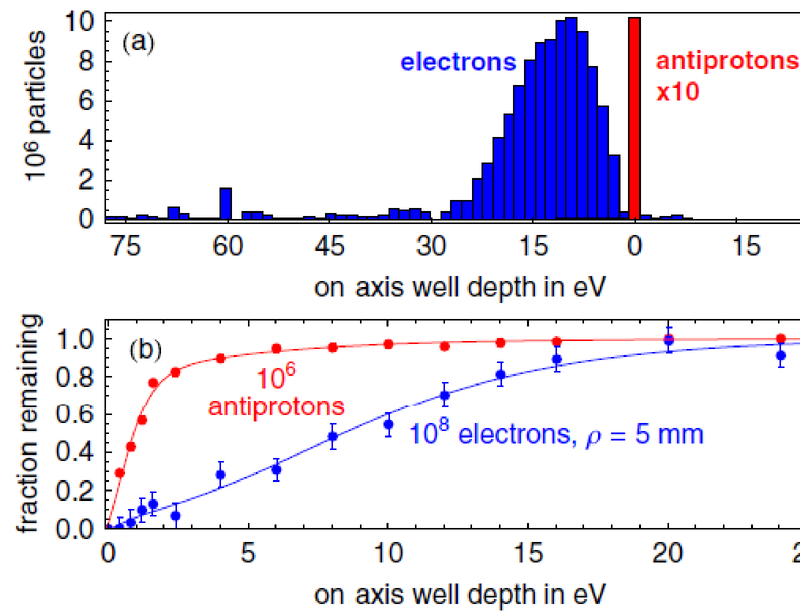
→ 3 million antiprotons at 3.5 K

ATRAP

Centrifugal Separation of Antiprotons and Electrons

G. Gabrielse,[1,*] W. S. Kolthammer,[1] R. McConnell,[1] P. Richerme,[1] J. Wrubel,[1,†] R. Kalra,[1] E. Novitski,[1] D. Grzonka,[2] W. Oelert,[2] T. Sefzick,[3] M. Zielinski,[2] J. S. Borbely,[3] D. Fitzakerley,[3] M. C. George,[3] E. A. Hessels,[3] C. H. Storry,[3] M. Weel,[3] A. Müllers,[4] J. Walz,[4] and A. Speck[5]





- Important for arranging efficient overlap of antiprotons and a positron plasma
- Important for understanding the heating of antiprotons when electrons are ejected

1 million antiprotons,
100 million electrons

PRL 106, 073002 (2011) PHYSICAL REVIEW LETTERS week ending 18 FEBRUARY 2011

ATRAP

Adiabatic Cooling of Antiprotons

G. Gabrielse,[1,*] W. S. Kolthammer,[1] R. McConnell,[1] P. Richerme,[1] R. Kalra,[1] E. Novitski,[1] D. Grzonka,[2] W. Oelert,[1] T. Sefzick,[2] M. Zielinski,[2] D. Fitzakerley,[3] M. C. George,[3] E. A. Hessels,[3] C. H. Storry,[3] M. Weel,[3] A. Müllers,[4] and J. Walz[4]

(ATRAP Collaboration)

[1]*Department of Physics, Harvard University, Cambridge, Massachusetts 02138, USA*
[2]*IKP, Forschungszentrum Jülich GmbH, 52425 Jülich, Germany*
[3]*Department of Physics and Astronomy, York University, Toronto, Ontario M3J 1P3, Canada*
[4]*Institut für Physik, Johannes Gutenberg Universität and Helmholtz Institut Mainz, D-55099 Mainz, Germany*
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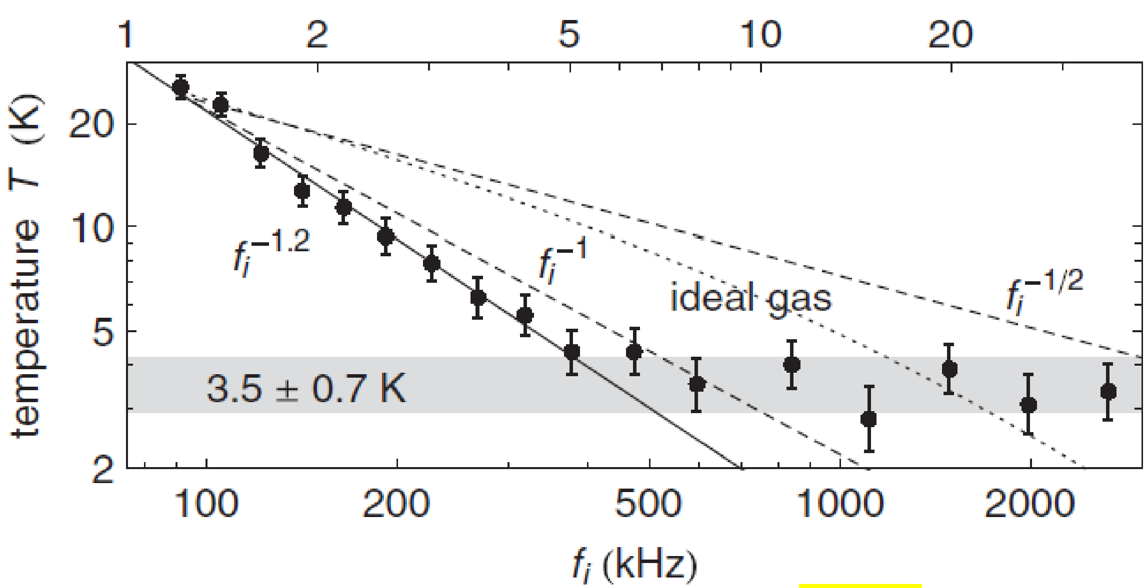


0.4 K

Embedded electron cooling

(to 31 K or 17 K)

Followed by adiabatic cooling

(to 3.5 K or below)

Compare Adiabatic and Evaporative Cooling

Compare to evaporative cooling – ALPHA (PRL 2010) starting 100 K

→ 1000 times more antiprotons per trial

→ 3 times lower temperature

(Need to show that these give better antihydrogen production)

Even Lower Temperatures Should be Possible

Embedded electron cooling

→ Adiabatic cooling

→ Evaporative cooling (if large particle loss is ok)

There is a Second Method to Produce Slow Antihydrogen

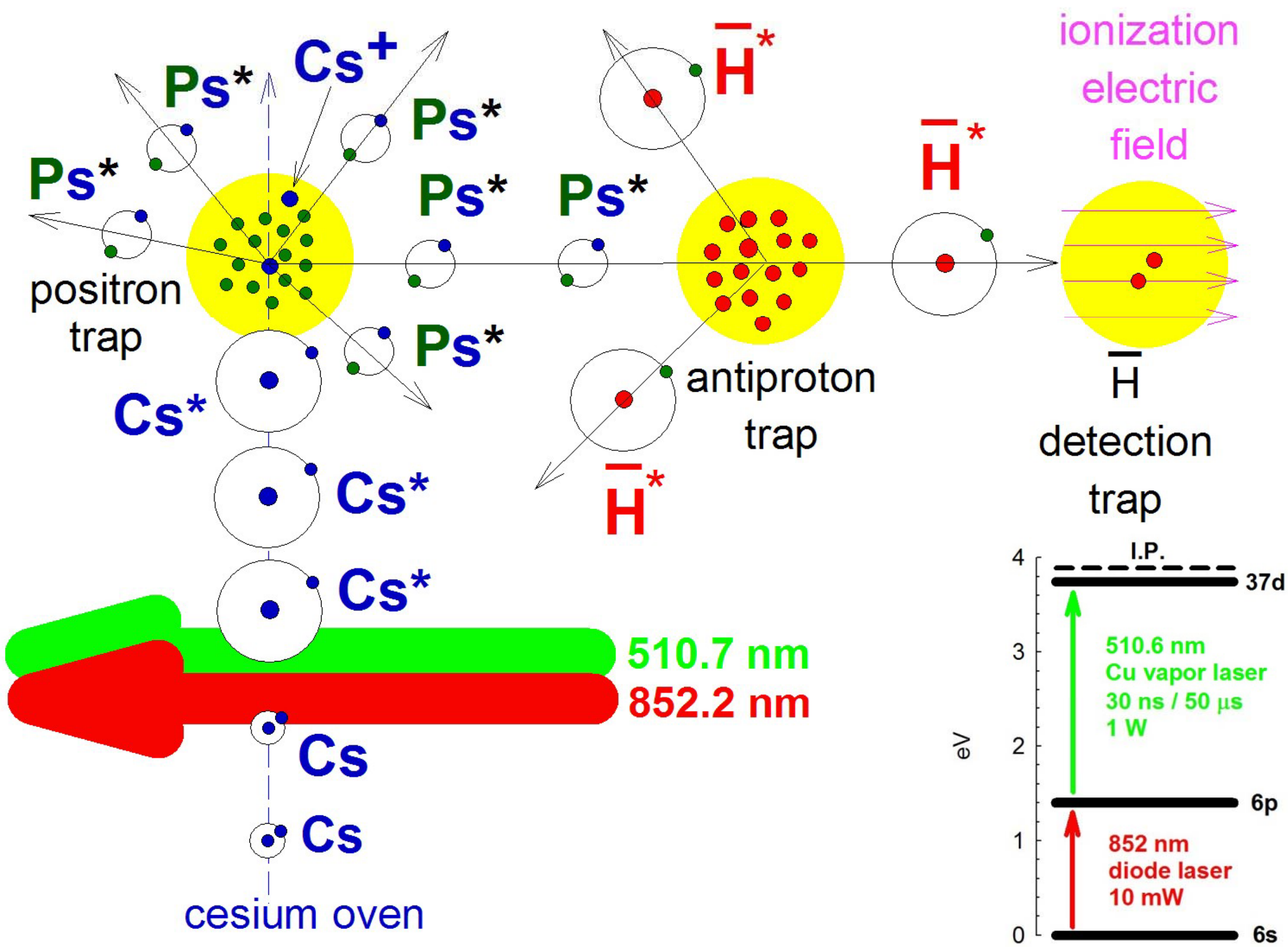
1. In a nested Penning trap, during positron cooling of antiprotons
   ATRAP, ALPHA, ASACUSA

2. Laser-controlled resonant charge exchange

   ATRAP

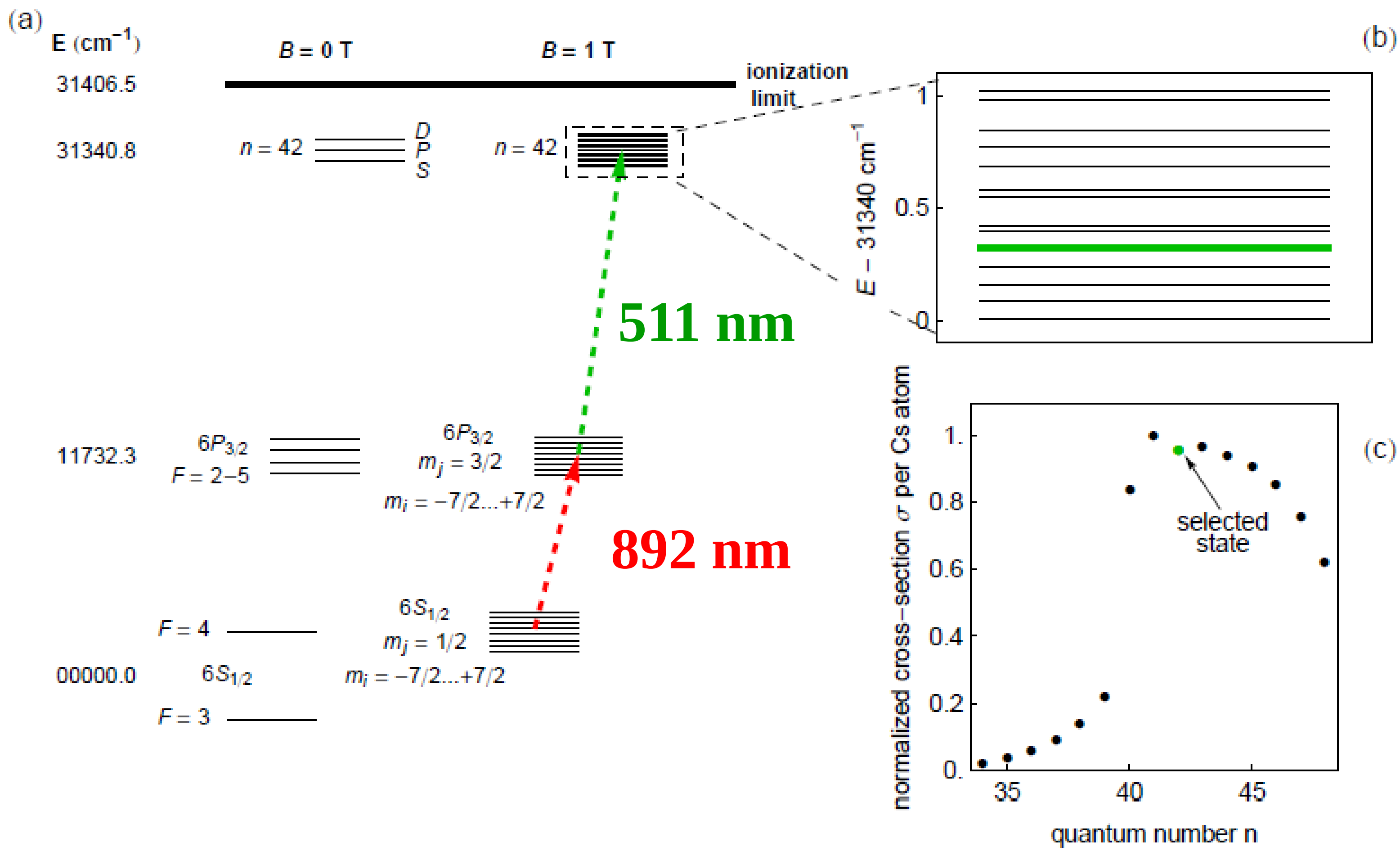
   - Proof-of-principle demo (2004)
   - 200 times more atoms produced (2010-2011)

Method II: Antihydrogen Via Laser-Controlled Resonant Charge Exchange



ATRAP, Phys. Rev. Lett. **93**, 263401 (2004) -- demo with a few atoms

Make Big Cs Atoms



We Returned to this Method in 2010

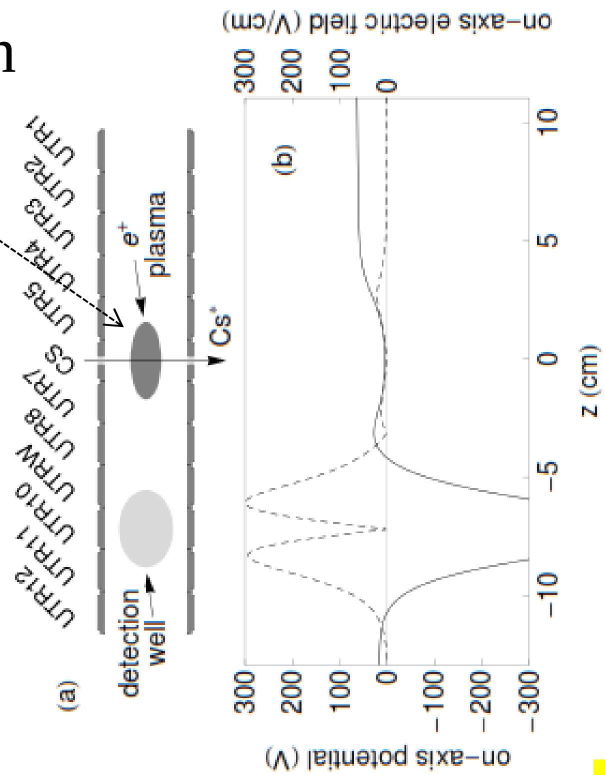
- greatly increased number of positrons and antiprotons
- better control of the positron and antiproton plasmas
- better laser systems
- Cs source lasted the whole beam run
- greatly reduced antiproton losses

→ 500 times more positronium than in 2004 demo
→ Looks like much more antihydrogen (not yet published)

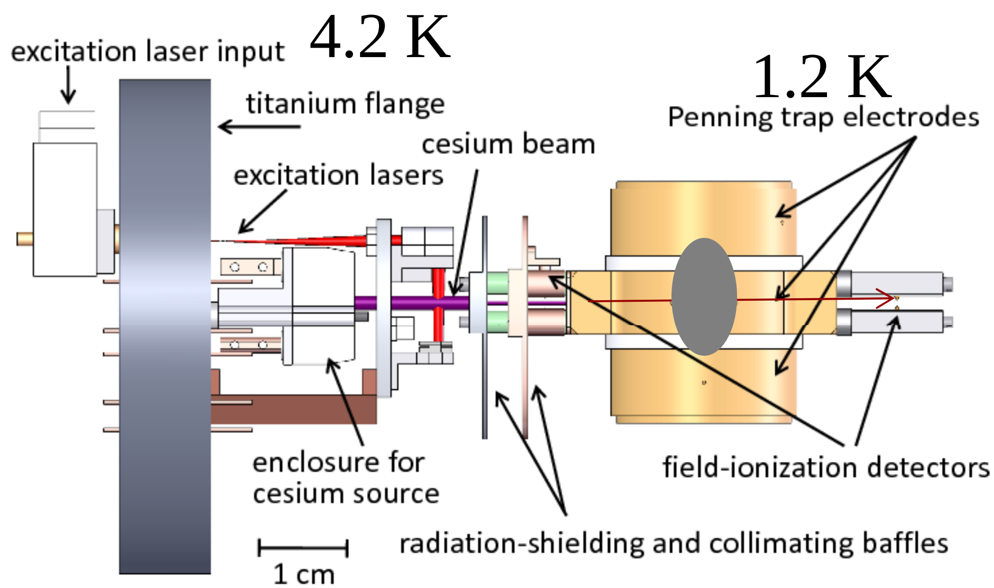
??? Detection well seems to spill the ionized antiprotons before we can count them (due to hot electrons from positronium)

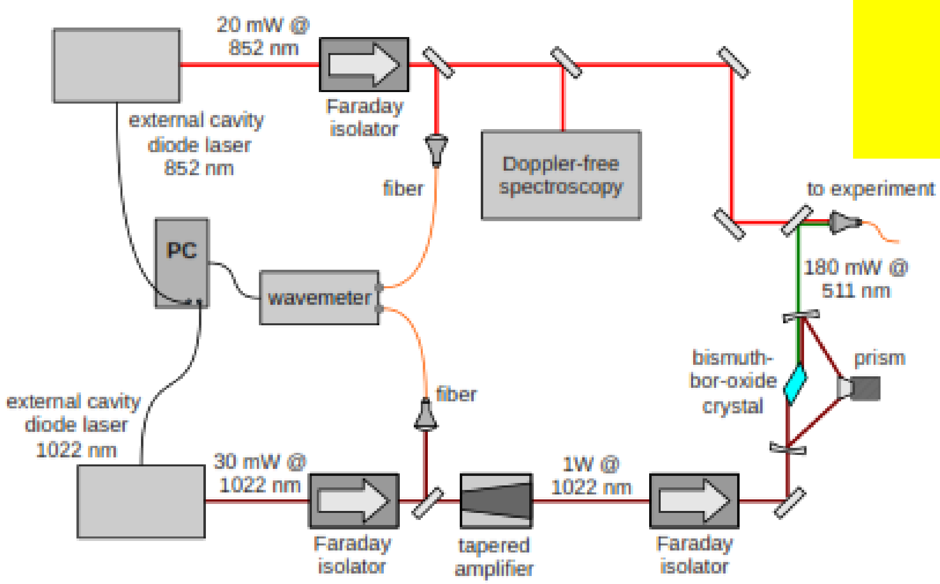
→ do not yet understand
→ must detect without using detection well so far

30 million positrons



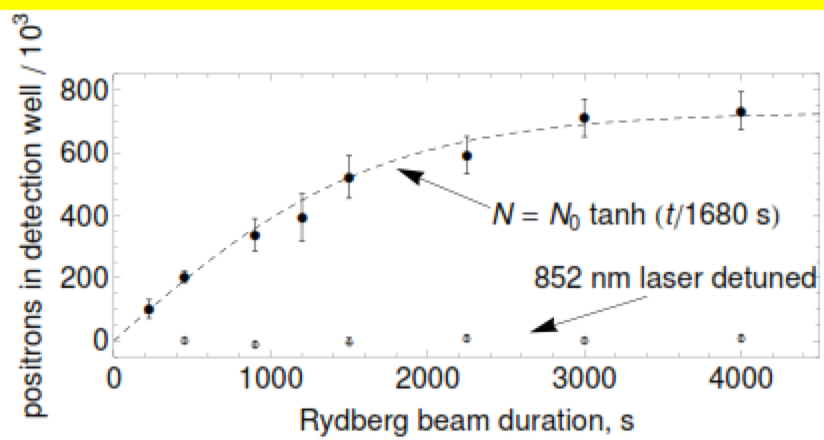
Gabrielse





92 +/- 5 % of trapped positrons form Ps

- 520 time more Ps than in demo
- 3.5 higher efficiency per positron

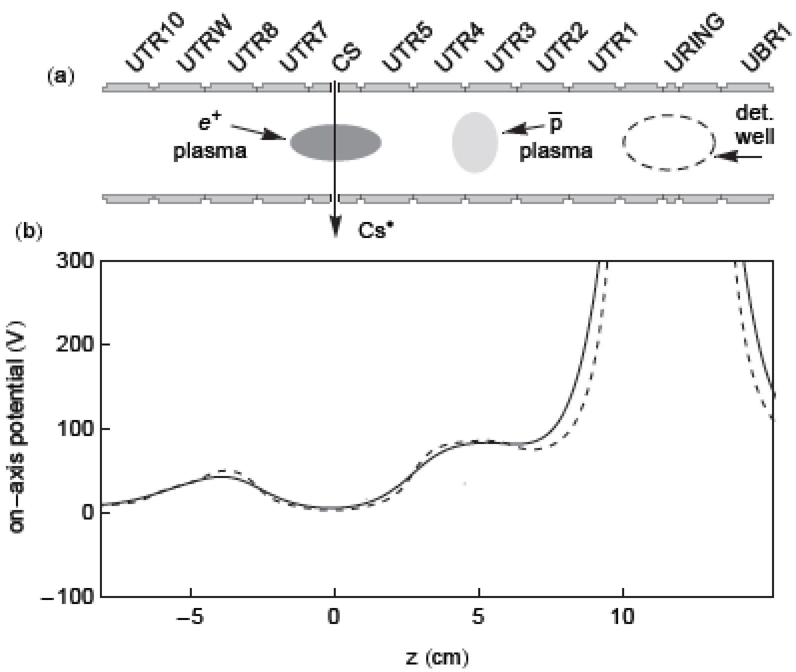


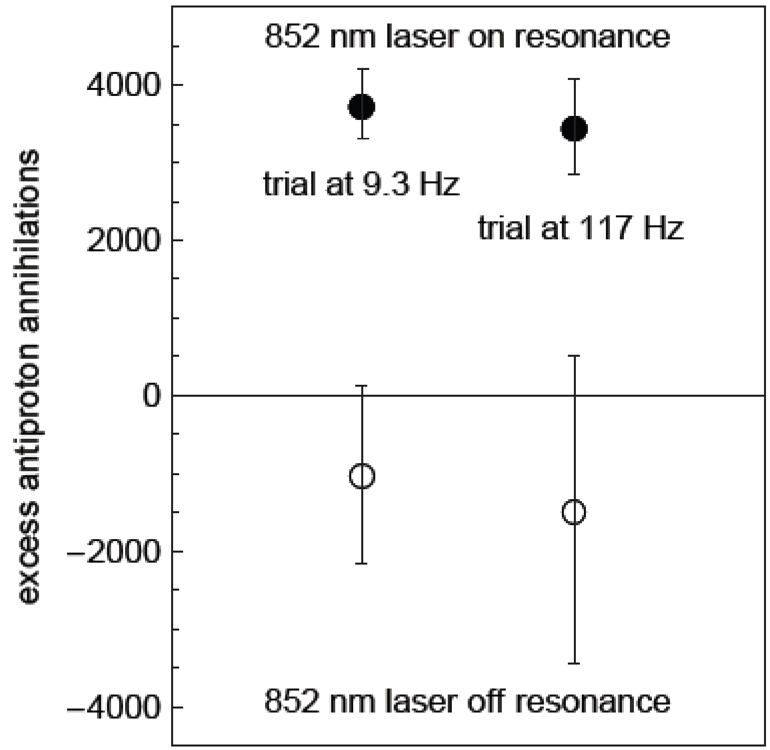
200 Times More Antihydrogen Made Per Trial

(compared to proof-of-principle demonstration)

Antiprotons: 5 million
Positrons: 300 million

$3600 \pm 610\ \overline{\mathrm{H}}$





Remains to be done in a Ioffe field

During 2011

Use much larger and much colder antiprotons for hbar production

Looking for trapped antihydrogen from laser-controlled charge exchange

Second generation Ioffe trap (with laser access)

- Built
- Not yet fully tested

Improving Lyman alpha laser for laser cooling antihydrogen

Comparing the antiproton and proton magnetic moments

- Demonstrated parts in 10^{10} cyclotron frequency measurements long ago
- Should be able to improve pbar/p comparison by $>10^6$
- Using a single trapped proton to develop spin flip methods