ATRAP Progress in 2015

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Spokesperson of the CERN ATRAP Collaboration

Supported by NSF and AFOSR

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29 Years Since We First Trapped and Then Cooled Antiprotons

1981 – went to Fermilab wanting to do trap antiprotons from
the electron cooler ring → found “TEV or Bust”

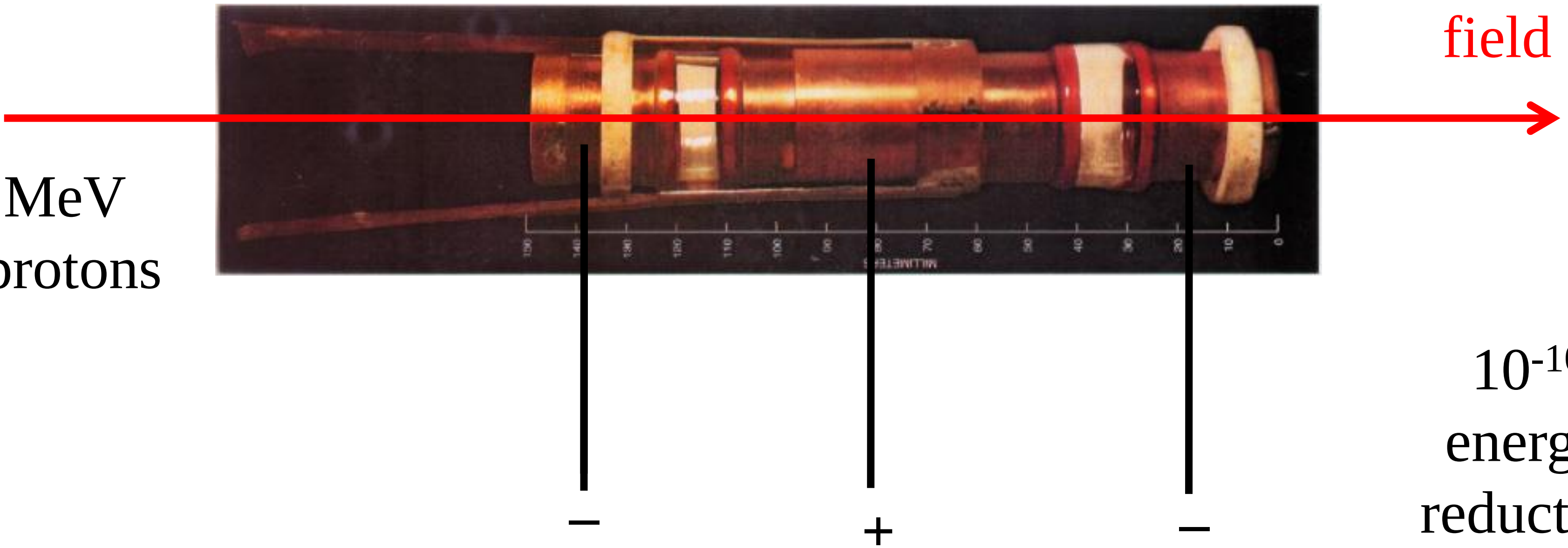
1986 – headed to CERN and trapped the first antiprotons

1986 – proposed making cold antihydrogen from cold
antiprotons and positrons
– proposed trapping cold antihydrogen for study

29 Years Since We First Trapped and Then Cooled Antiprotons

TRAP Collaboration
at CERN's LEAR

1 cm



magnetic field

21 MeV antiprotons

−

+

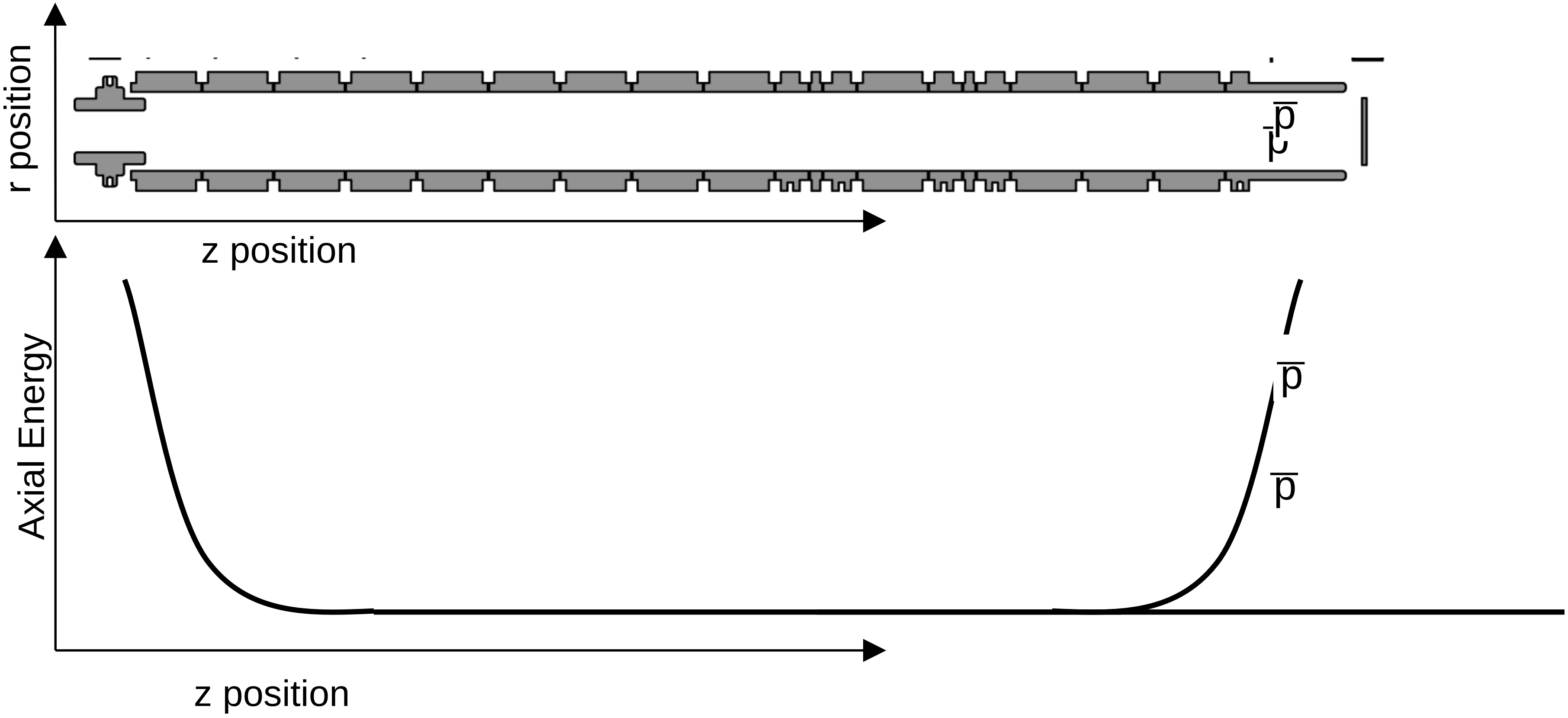
−

10^{-10} energy reduction

- **Slow antiprotons in matter**
- **Capture antiprotons in flight**
- **Electron cooling → 4.2 K**
- **5 x 10^{-17} Torr**

Now used by 5 collaborations
at the CERN AD
ATRAP, ALPHA, ASACUSA,
AEGIS, BASE

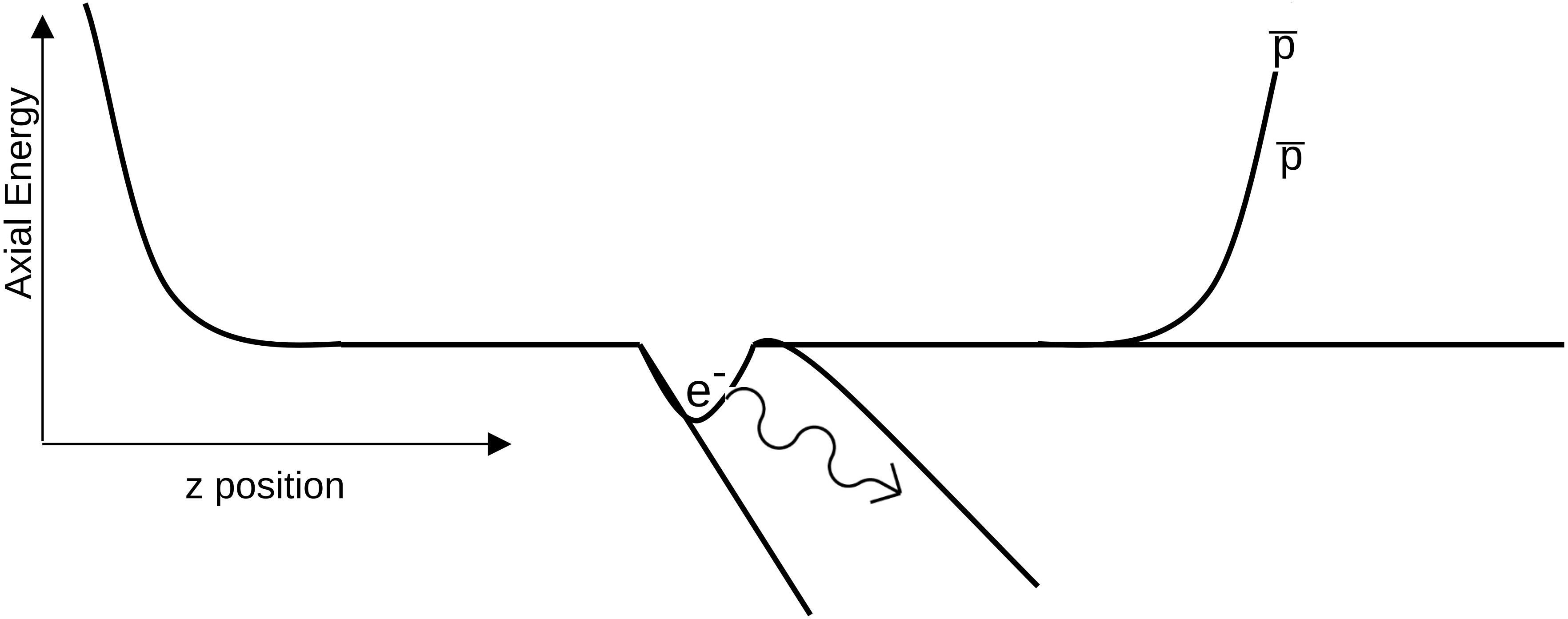
Antiproton Capture – the Movie



"First Capture of Antiprotons in a Penning Trap: A KeV Source",
G. Gabrielse, X. Fei, K. Helmerson, S.L. Rolston, R. Tjoelker, T.A. Trainor, H. Kalinowsky, J. Haas, and W. Kells;
Phys. Rev. Lett. 57, 2504 (1986).

Electron-Cooling of Antiprotons – in a Trap

- Antiprotons cool via collisions with electrons
- Electrons radiate away excess energy



"Cooling and Slowing of Trapped Antiprotons Below 100 meV",
G. Gabrielse, X. Fei, L.A. Orozco, R. Tjoelker, J. Haas, H. Kalinowsky, T.A. Trainor, W. Kells;
Phys. Rev. Lett. 63, 1360 (1989).

Goals: Precisely Compare Matter and Antimatter

Why?

Start general

Embarrassing, Unsolved Mystery: How did our Matter Universe Survive Cooling After the Big Bang?

Big bang → equal amounts of matter and antimatter created during hot time

As universe cools → antimatter and matter annihilate

Big Questions:

- How did any matter survive?
- How is it that we exist?

Our experiments are looking for evidence of any way that antiparticles and particles may differ

Our “Explanations” are Not so Satisfactory

Baryon-Antibaryon Asymmetry in Universe is Not Understood

Standard “Explanation”

- CP violation
- Violation of baryon number
- Thermodynamic non-equilibrium

Alternate

- CPT violation
- Violation of baryon number
- Thermo. equilib.

Bertolami, Colladay, Kostelecky, Potting
Phys. Lett. B 395, 178 (1997)

Why did a universe made of matter survive the big bang?
Makes sense look for answers to such fundamental questions in the few places that we can hope to do so very precisely.

Bigger problem: don’t understand dark energy within 120 orders of magnitude

Why Compare H and $\bar{H}$ (or P and $\bar{P}$)?

Reality is Invariant – symmetry transformations

~~P~~	parity
~~CP~~	charge conjugation, parity
CPT	charge conjugation, parity, and time reversal

CPT Symmetry

→ Particles and antiparticles have
- same mass
- opposite charge
- same magnetic moment
- same mean life

→ Atom and anti-atom have
  → same structure

Looking for Surprises
- simple systems
- extremely high accuracy
- comparisons will be convincing
- reasonable effort
- FUN

Comparing the CPT Tests

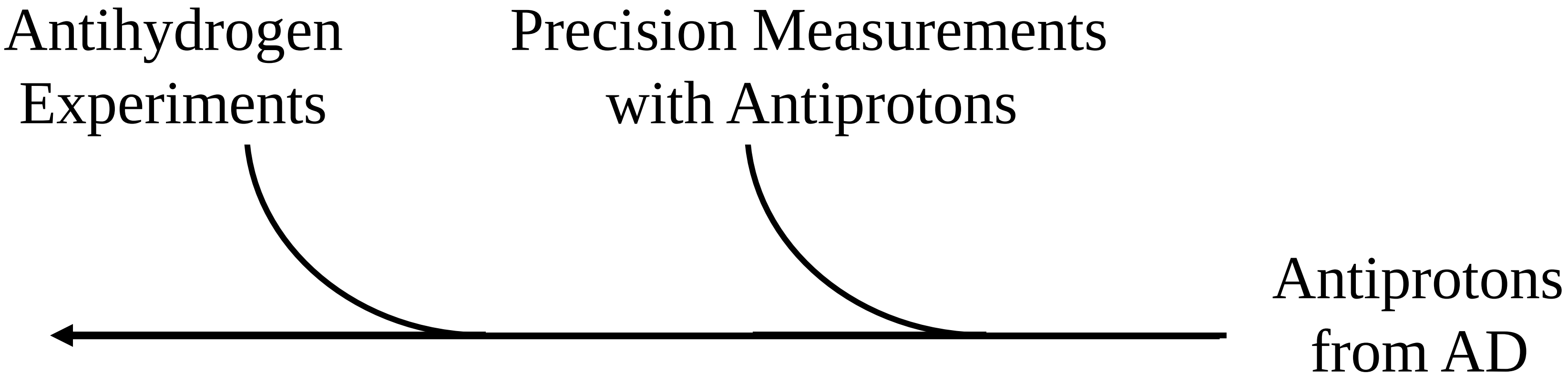
Warning – without CPT violation models it is hard to compare

3 fundamentally different types of particles

	CPT Test Accuracy	Measurement Accuracy	Free Gift
$K_0 \bar{K}_0$ Mesons	2×10^{-18}	2×10^{-3}	10^{15}
$e^+ e^-$ Leptons	2×10^{-12}	2×10^{-9}	10^{3}
$P \bar{P}$ baryons	9×10^{-11}	9×10^{-11}	1

improve with antihydrogen

ATRAP Apparatus Built to do Two Types of Comparisons Simultaneously



Antihydrogen Experiments

Precision Measurements with Antiprotons

Antiprotons from AD

trapped antihydrogen in its ground state

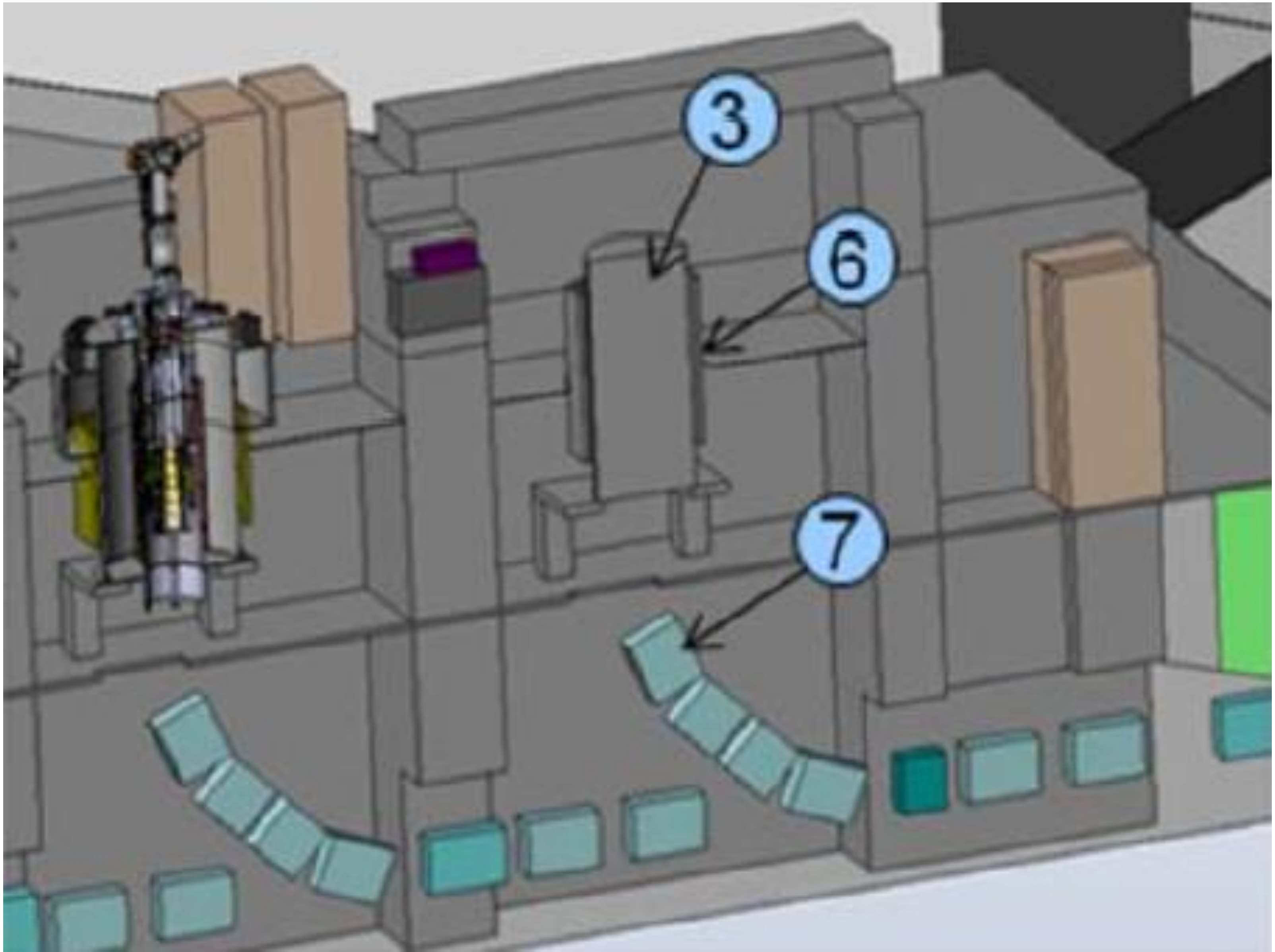
laser cooling

precise laser spectroscopy

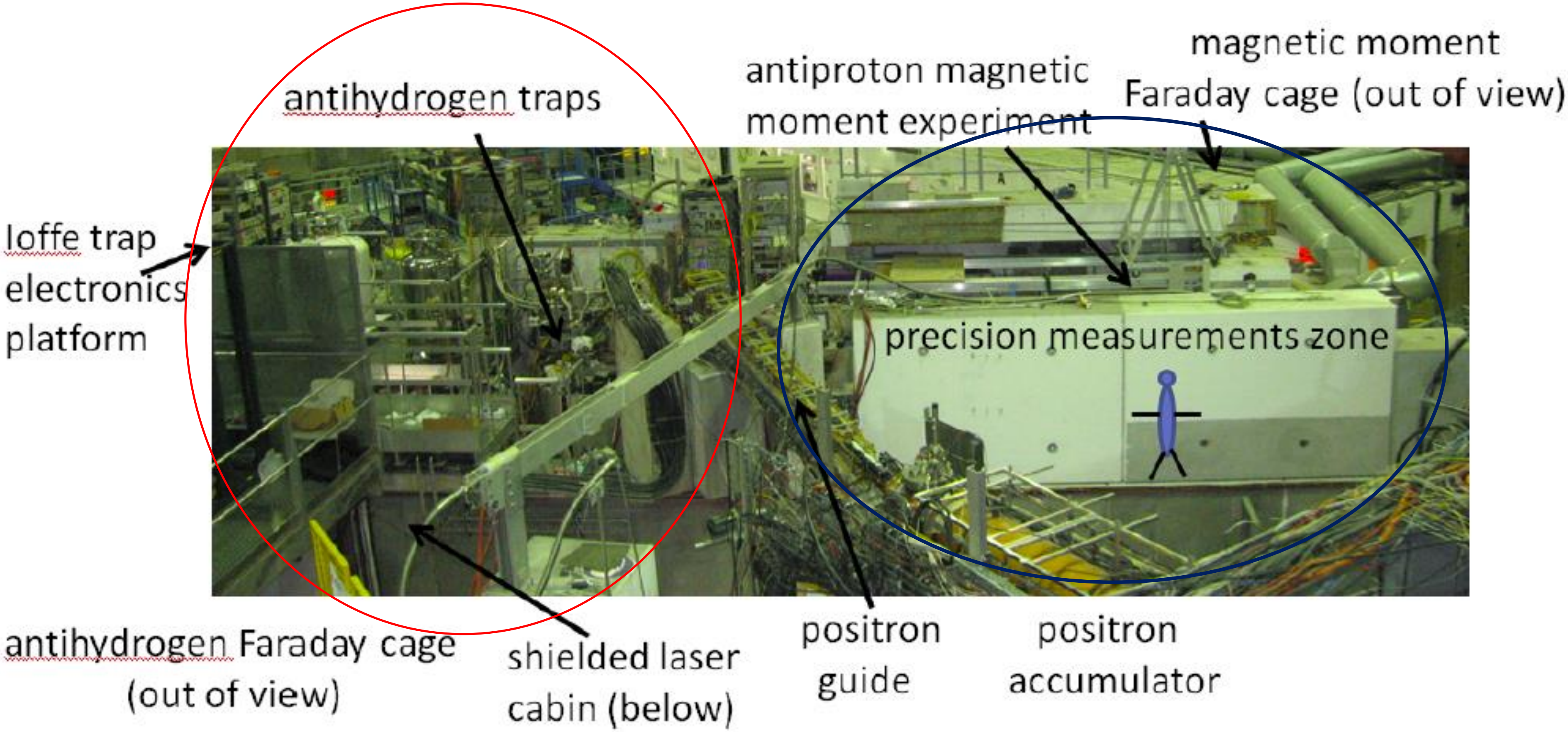
680-fold improved measurement of the antiproton magnetic motion

(parasitic)

More Detailed View

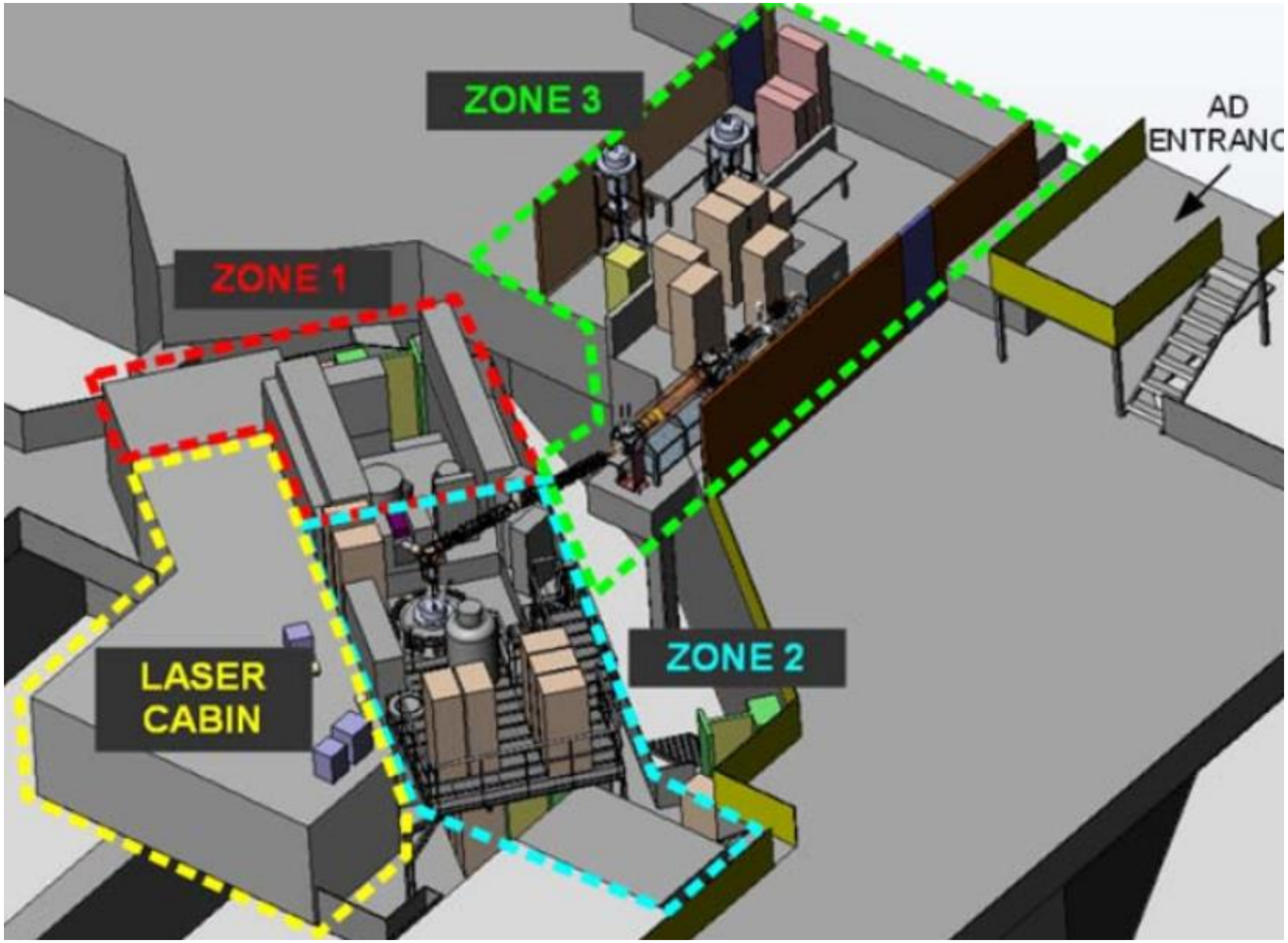


Photos



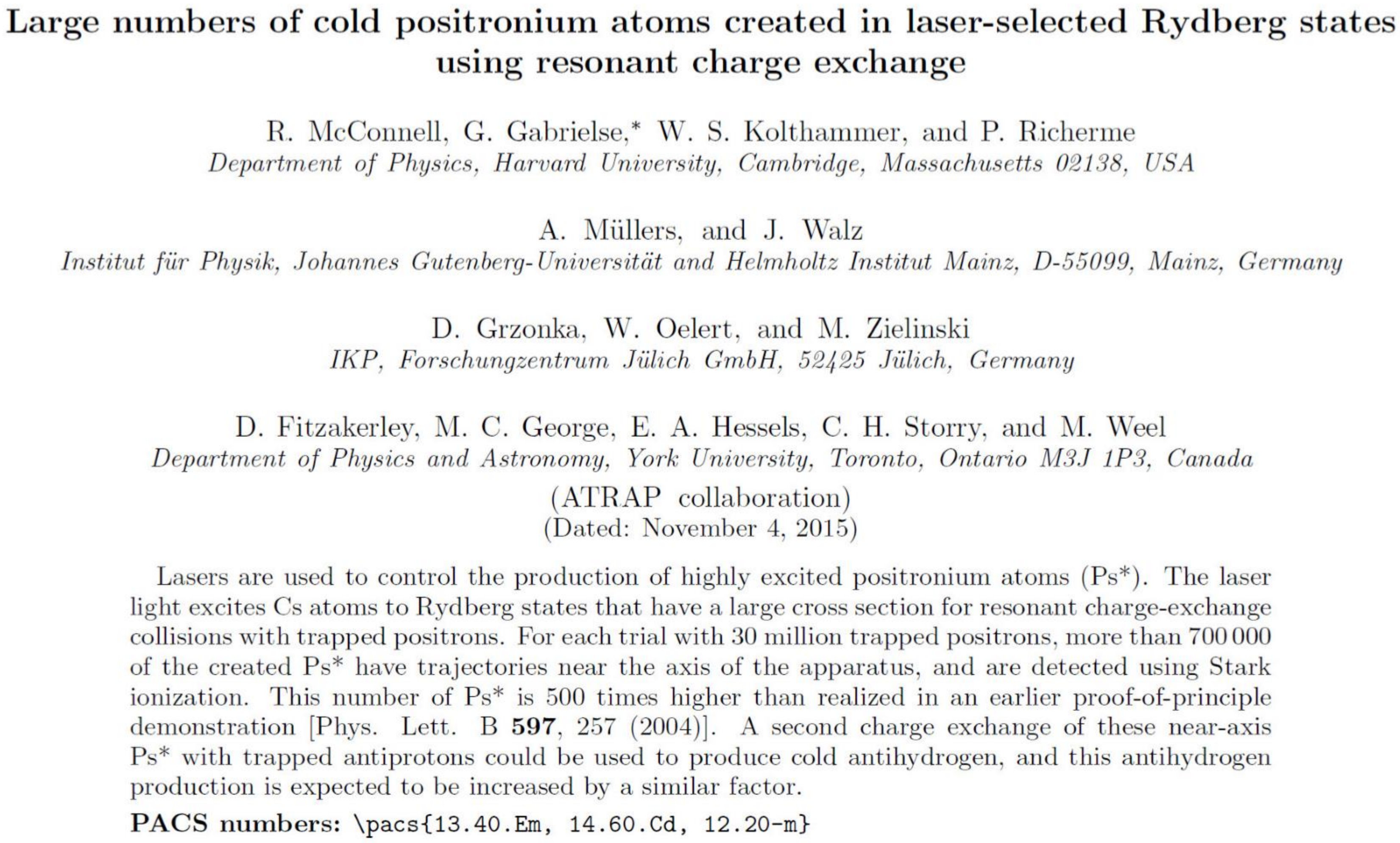
ATRAP Experimental Area

ATRAP Overview



(more detailed roadmap in the written report)

Positronium Formation using Laser-Controlled Charge Exchange



Large numbers of cold positronium atoms created in laser-selected Rydberg states using resonant charge exchange

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D. Fitzakerley, M. C. George, E. A. Hessels, C. H. Storry, and M. Weel
Department of Physics and Astronomy, York University, Toronto, Ontario M3J 1P3, Canada

(ATRAP collaboration)

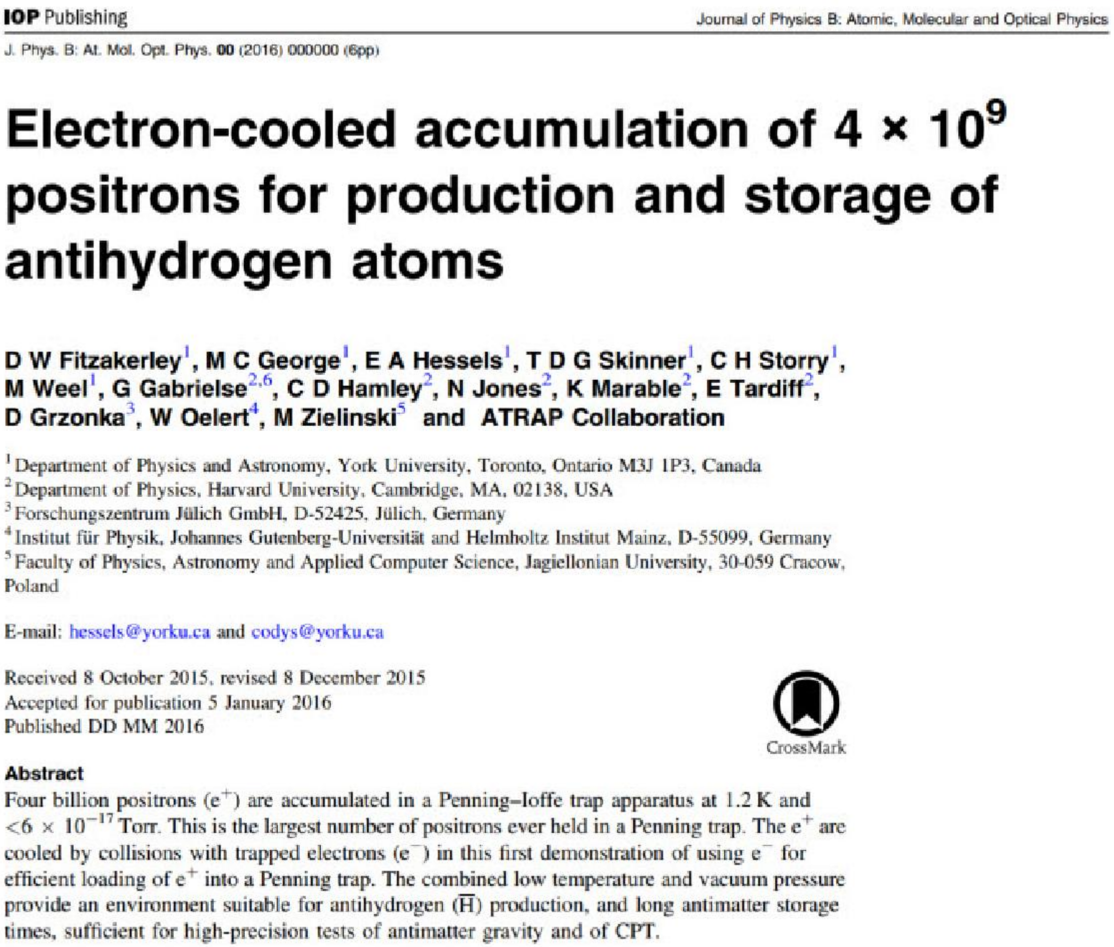
(Dated: November 4, 2015)

Lasers are used to control the production of highly excited positronium atoms (Ps*). The laser light excites Cs atoms to Rydberg states that have a large cross section for resonant charge-exchange collisions with trapped positrons. For each trial with 30 million trapped positrons, more than 700 000 of the created Ps* have trajectories near the axis of the apparatus, and are detected using Stark ionization. This number of Ps* is 500 times higher than realized in an earlier proof-of-principle demonstration [Phys. Lett. B **597**, 257 (2004)]. A second charge exchange of these near-axis Ps* with trapped antiprotons could be used to produce cold antihydrogen, and this antihydrogen production is expected to be increased by a similar factor.

PACS numbers: `\pacs{13.40.Em, 14.60.Cd, 12.20-m}`

500 times higher rate of Rydberg Ps production

Paper on the ATRAP Positron Accumulation



IOP Publishing Journal of Physics B: Atomic, Molecular and Optical Physics

J. Phys. B: At. Mol. Opt. Phys. **00** (2016) 000000 (6pp)

Electron-cooled accumulation of 4×10^9 positrons for production and storage of antihydrogen atoms

D W Fitzakerley[1], M C George[1], E A Hessels[1], T D G Skinner[1], C H Storry[1], M Weel[1], G Gabrielse[2,6], C D Hamley[2], N Jones[2], K Marable[2], E Tardiff[2], D Grzonka[3], W Oelert[4], M Zielinski[5] and ATRAP Collaboration

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CrossMark

Abstract

Four billion positrons (e^+) are accumulated in a Penning–Ioffe trap apparatus at 1.2 K and $<6 \times 10^{-17}$ Torr. This is the largest number of positrons ever held in a Penning trap. The e^+ are cooled by collisions with trapped electrons (e^-) in this first demonstration of using e^- for efficient loading of e^+ into a Penning trap. The combined low temperature and vacuum pressure provide an environment suitable for antihydrogen ($\overline{\mathrm{H}}$) production, and long antimatter storage times, sufficient for high-precision tests of antimatter gravity and of CPT.

Status of Precise Comparisons of Antiprotons and Protons (and Antihydrogen and Hydrogen)

1. Comparison of the charge-to-mass ratios of the antiproton and proton

9×10^{-11} *TRAP* 1999

7×10^{-11} *BASE* 2015

2. Comparison of the gravitational interaction of the antiproton and proton

1×10^{-6} *TRAP* 1999

3. Comparison of the magnetic moment of the antiproton and proton

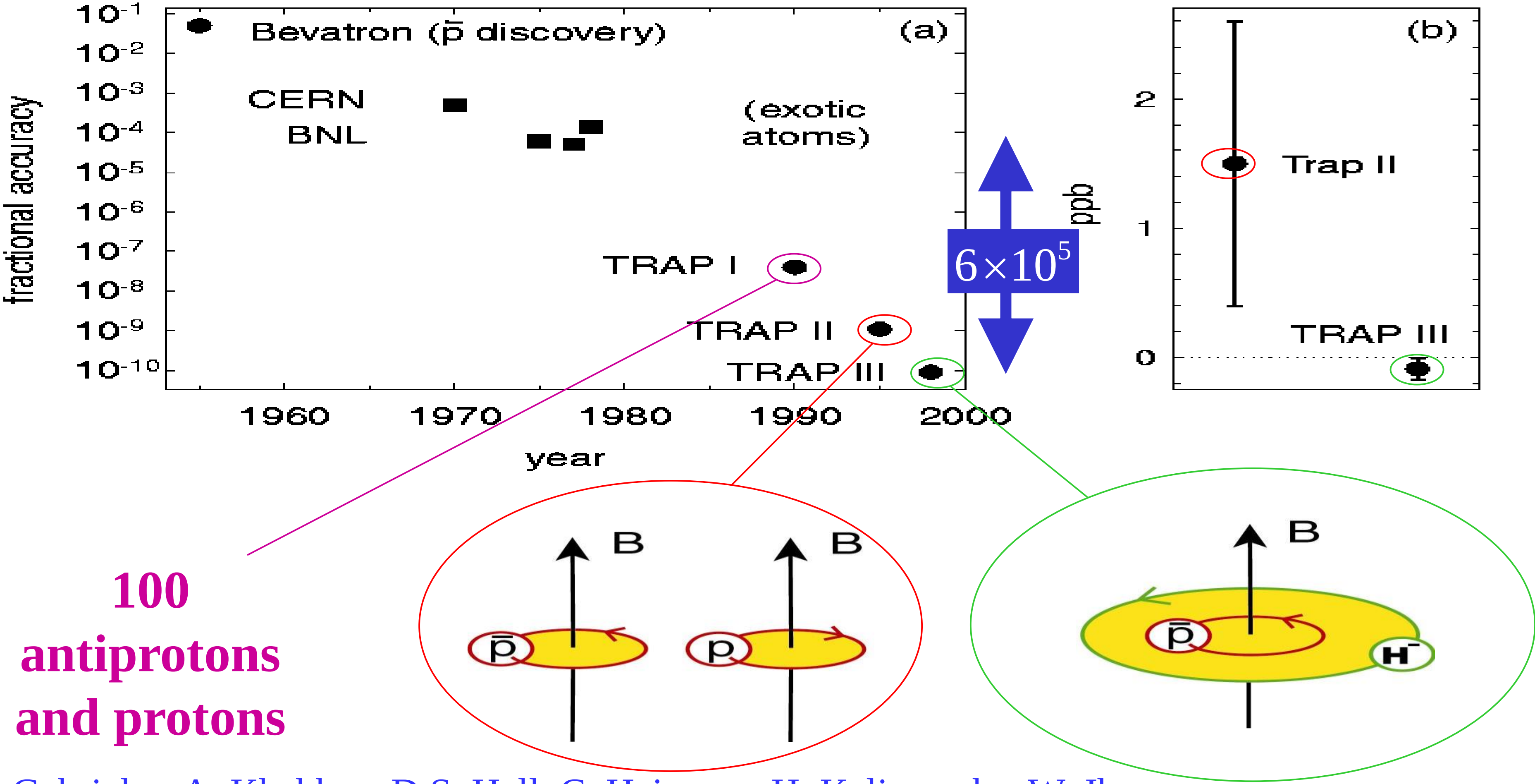
5×10^{-6} *ATRAP* 2013

No precise or scientifically interesting comparisons of antihydrogen and hydrogen yet

Status of the Comparison of the Antiproton and Proton Charge-To-Mass Ratios

At TRAP We Improved the Comparison of Antiproton and Proton by ~10^6

most stringent CPT test with baryons



100 antiprotons and protons

G. Gabrielse, A. Khabbaz, D.S. Hall, C. Heimann, H. Kalinowsky, W. Jhe;
Phys. Rev. Lett. **82**, 3198 (1999).

High Precision Tests of CPT Invariance

The Most Precise CPT Test with Baryons → by TRAP at CERN

G. Gabrielse, A. Khabbaz, D. S. Hall, C. Heimann, H. Kalinowsky, and W. Jhe, Phys. Rev. Lett. **82**, 3198 (1999).

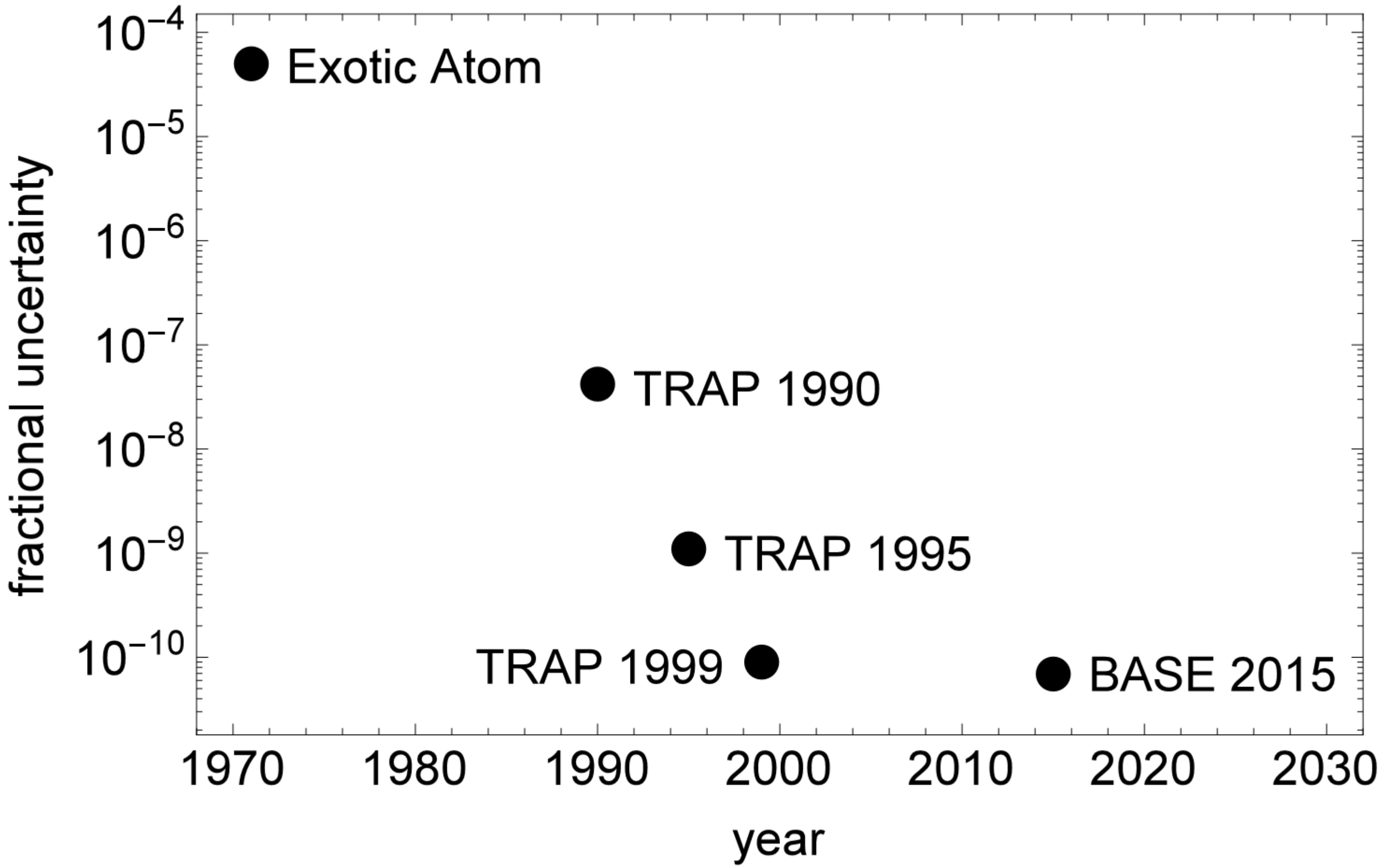
$$\frac{q/m\ \ (\text{antiproton})}{q/m\ \ (\text{proton})} = -0.99999999991(9)$$

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

(most precise result of CERN’s antiproton program before the AD)

Goal at the AD: Make CPT tests that approach
or exceed this precision

BASE 2015
16 Years Later → 20% Reduction in Uncertainty



Could We Do Better?

- The last antiproton (before LEAR closed),
  with a better tuned apparatus,
  gave most of the precision in the last measurement
  (i.e. could have done better with more time)

- Methods and technology have improved in 15 years

→ Probably could measure at least 10 time more precisely

maybe 100

We hope to do such measurements in the same apparatus
that we use for magnetic moment measurements

Not a high priority yet because of lack of time. BASE on the case.

Status of Direct Comparisons of Antimatter and Matter Gravity

Direct Comparison of Antimatter and Matter Gravity

Does antimatter and matter accelerate at the same rate in a gravitational field?

$$g_{antimatter} = \kappa \, g_{matter}$$

acceleration due to gravity
for antimatter

acceleration due to gravity
for matter

The Most Precise Experimental Answer is "Yes" → to at lease a precision of 1 part per million

Gravitational red shift for a clock: $\Delta\omega / \omega = g\, h / c^2$

→ Antimatter and matter clocks run at different rates
if g is different for antimatter and matter

$$\frac{\Delta\omega_c}{\omega_c} = 3(\kappa - 1)\frac{U}{c^2}$$

Hughes and Holzscheiter,
Phys. Rev. Lett. 66, 854 (1991).

for tensor gravity
(would be 1 for scalar gravity)

grav. pot. rnergy difference
between empty flat space time
and inside of hypercluster of galaxies

Experiment: TRAP Collaboration, Phys. Rev. Lett. 82, 3198 (1999).

$$\frac{\Delta\omega_c}{\omega_{\partial c}} < 10^{-10} \quad --> \quad \kappa = 1 \pm\ (< 10^{-6})$$

Comparable limit to that on neutrinos and antineutrinos 1987A

Comparison of an Antimatter and Matter Clock

The Most Precise CPT Test with Baryons → by TRAP at CERN

G. Gabrielse, A. Khabbaz, D. S. Hall, C. Heimann, H. Kalinowsky, and W. Jhe, Phys. Rev. Lett. **82**, 3198 (1999).

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

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

(most precise result of CERN's antiproton program)

Goal at the AD: Make CPT test that approaches and exceed this precision

Hard to Get the Part per Million Precision of the Redshift Limit with Antihydrogen and Hydrogen

$$g_{antimatter} = \kappa \, g_{matter}$$

Our TRAP gravitational redshift: $\frac{\Delta\omega_c}{\omega_{\partial c}} < 10^{-10}$

$$--> \quad 0.999999 < \kappa < 1.000001$$

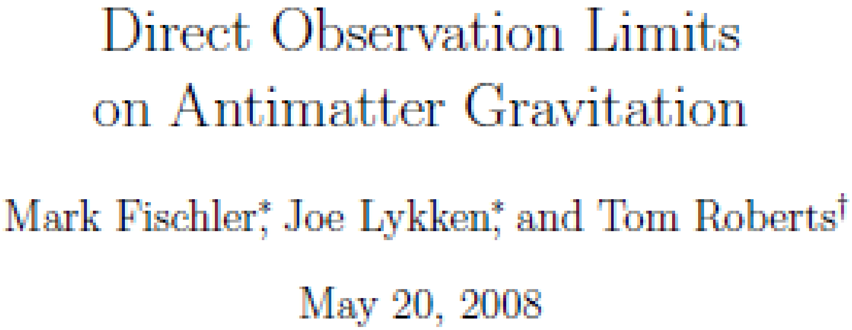
10^8

ALPHA trapped antihydrogen released (2013): $-110 < \kappa < 110$

(no mention direct redshift comparison)

Gravitational Redshift Comparison is Ignored citing an unpublished rational for a Fermilab gravity measurement proposal (not approved)

arXiv 0808.3929



Direct Observation Limits
on Antimatter Gravitation

Mark Fischler*, Joe Lykken*, and Tom Roberts†

May 20, 2008

- Perhaps CPT violations in the electromagnetic clocks cancel the CPT violation for gravity ← not likely
- If gravity would have a finite range then using the local supercluster of galaxies would not be appropriate ← adds violations
- Use of gravitational potential energy isn't sound ← not needed
  - → can use metric perturbation to flat space that must vanish at infinity to ensure that matter and antimatter look the same away from gravitational sources

How Much Better Could the Gravitational Comparison Be?

If we improve the charge-to-mass ratio measurement by a factor of 100
→ gravitation comparison will be 100 times more stringent

BASE is working on this.

We still hope to contribute but do not have enough time and people yet.

Current Status of the Comparison of the Antiproton and Proton Magnetic Moments

quick study

Can we do as well as the electron magnetic moment?

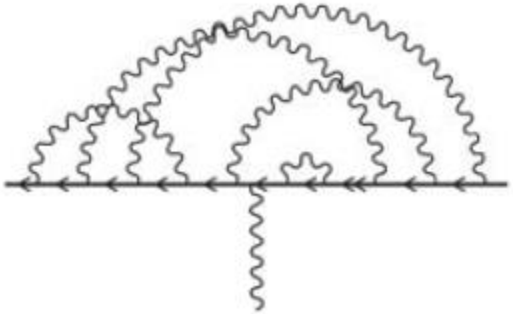
→ hard to get this precise

The standard model's greatest triumph

Gerald Gabrielse

The standard model predicts the electron magnetic moment to an astonishing accuracy of one part in a trillion.

Gerald Gabrielse is the George Vasmer Leverett Professor of Physics at Harvard University in Cambridge, Massachusetts.

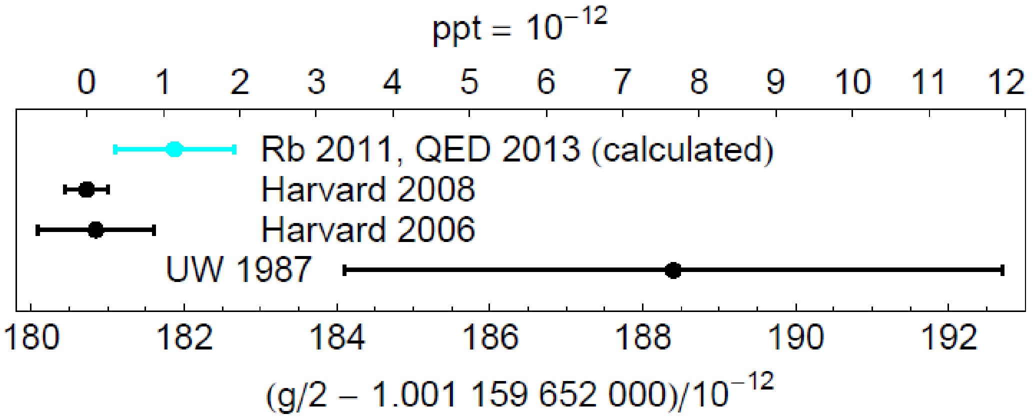


3×10^{-13}

from measured fine structure constant

Predicted: $\mu/\mu_B = -1.001\,159\,652\,181\,78\,(77)$

Measured: $\mu/\mu_B = -1.001\,159\,652\,180\,73\,(28)$

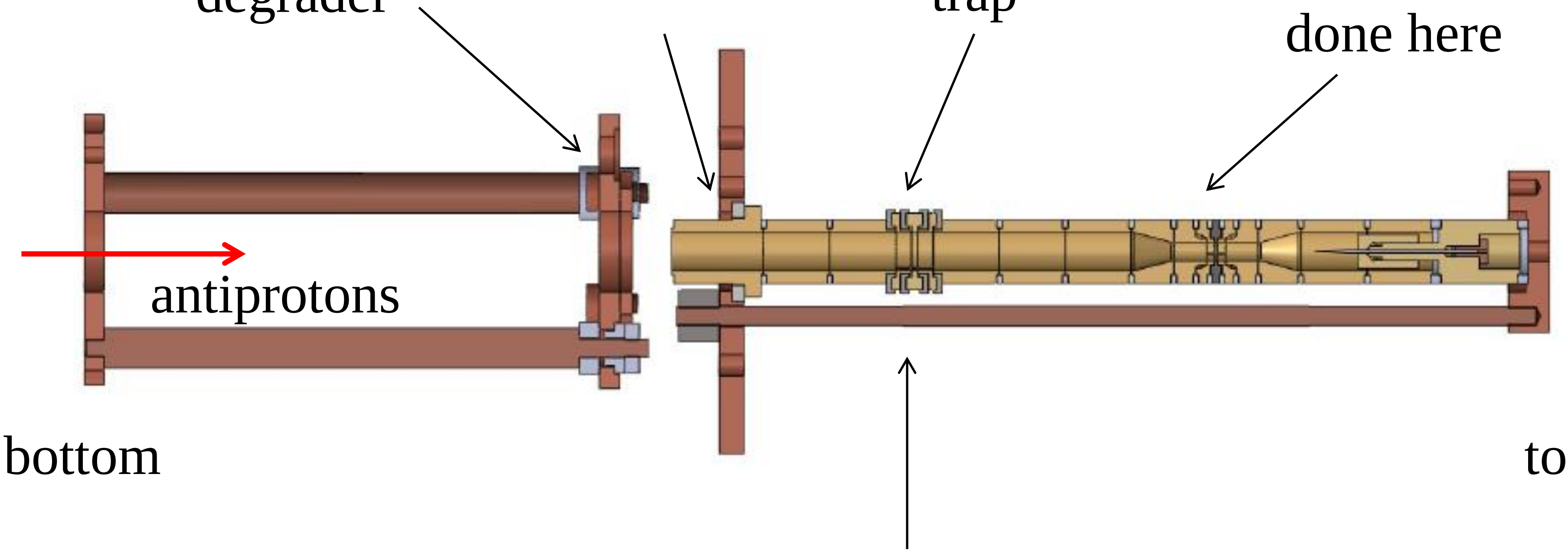


Proton and Antiproton Magnetic Moments are Much Smaller

Harder: nuclear magneton rather than Bohr magneton

$$\mu_N/\mu_B = m_e/m_p \sim 1/2000$$

For Magnetic Moments: Three Antiproton Traps



degrader

catch and cool antiprotons

cyclotron cooling trap

proton and antiproton measurements done here

antiprotons

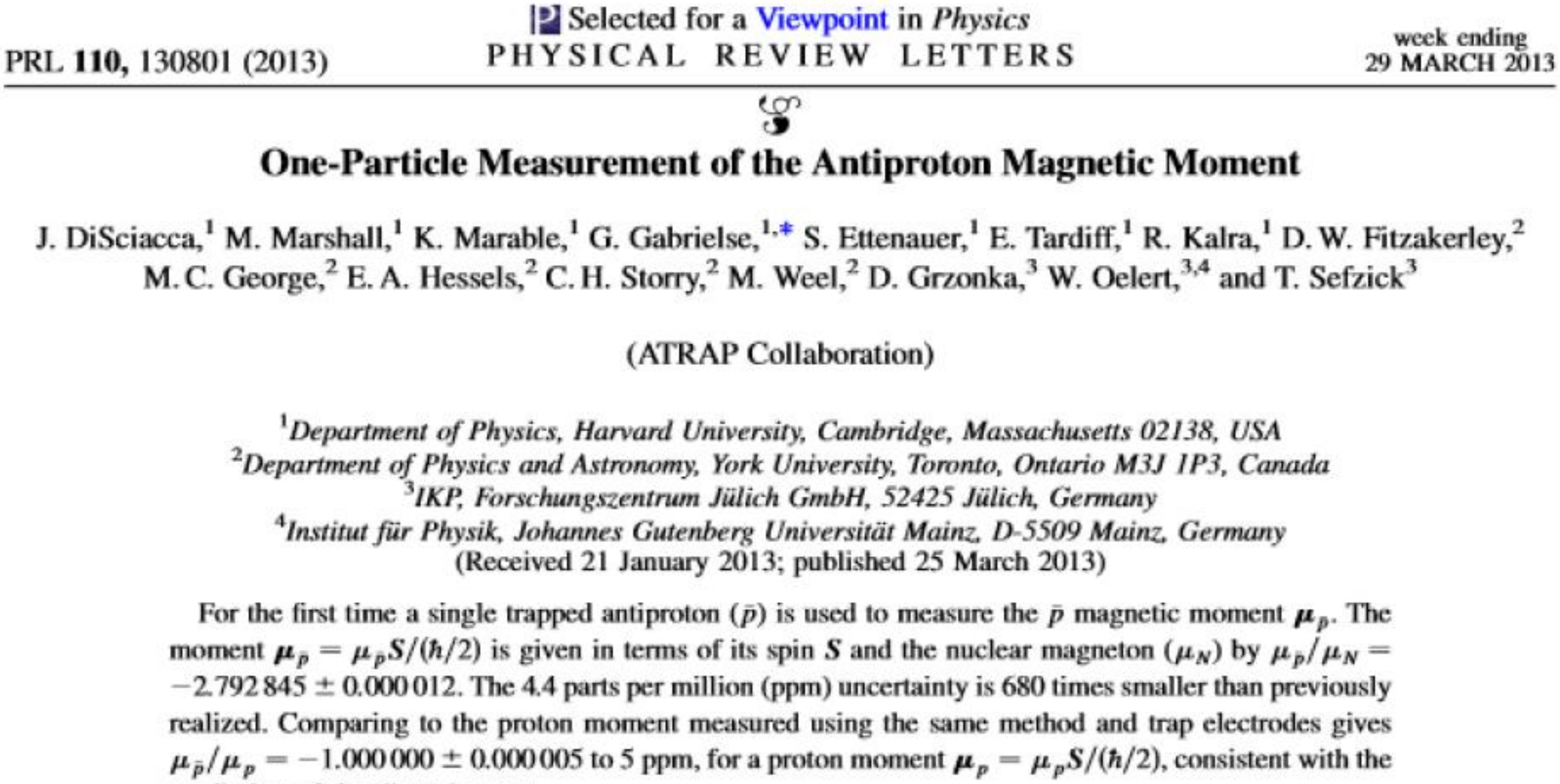
bottom

top

more precise measurements will take place here

Located within a self-shielding superconducting solenoid
→ we invented in part to deal with magnetic noise at CERN

680 Times Improved Pbar to P Comparison



Selected for a Viewpoint in *Physics*

PRL **110,** 130801 (2013) PHYSICAL REVIEW LETTERS week ending 29 MARCH 2013

One-Particle Measurement of the Antiproton Magnetic Moment

J. DiSciacca,[1] M. Marshall,[1] K. Marable,[1] G. Gabrielse,[1,*] S. Ettenauer,[1] E. Tardiff,[1] R. Kalra,[1] D. W. Fitzakerley,[2] M. C. George,[2] E. A. Hessels,[2] C. H. Storry,[2] M. Weel,[2] D. Grzonka,[3] W. Oelert,[3,4] and T. Sefzick[3]

(ATRAP Collaboration)

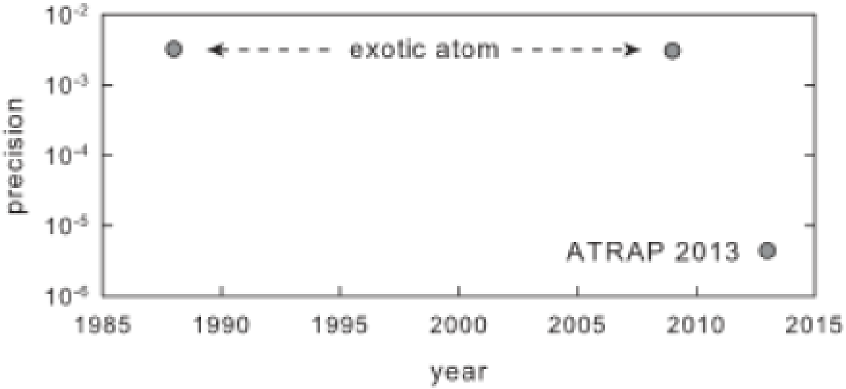
[1]*Department of Physics, Harvard University, Cambridge, Massachusetts 02138, USA*
[2]*Department of Physics and Astronomy, York University, Toronto, Ontario M3J 1P3, Canada*
[3]*IKP, Forschungszentrum Jülich GmbH, 52425 Jülich, Germany*
[4]*Institut für Physik, Johannes Gutenberg Universität Mainz, D-5509 Mainz, Germany*

(Received 21 January 2013; published 25 March 2013)

For the first time a single trapped antiproton ($\bar{p}$) is used to measure the $\bar{p}$ magnetic moment $\boldsymbol{\mu}_{\bar{p}}$. The moment $\boldsymbol{\mu}_{\bar{p}} = \mu_{\bar{p}}\boldsymbol{S}/(\hbar/2)$ is given in terms of its spin $\boldsymbol{S}$ and the nuclear magneton (μ_N) by $\mu_{\bar{p}}/\mu_N = -2.792\,845 \pm 0.000\,012$. The 4.4 parts per million (ppm) uncertainty is 680 times smaller than previously realized. Comparing to the proton moment measured using the same method and trap electrodes gives $\mu_{\bar{p}}/\mu_p = -1.000\,000 \pm 0.000\,005$ to 5 ppm, for a proton moment $\boldsymbol{\mu}_p = \mu_p\boldsymbol{S}/(\hbar/2)$, consistent with the prediction of the *CPT* theorem.

$$\mu_{\bar{p}}/\mu_p = -1.000\,000 \pm 0.000\,005 \qquad [5.1\ \text{ppm}],$$

$$\mu_{\bar{p}}/\mu_p = -0.9999992 \pm 0.0000044 \quad [4.4\ \text{ppm}].$$



Comparing to Other CPT Tests

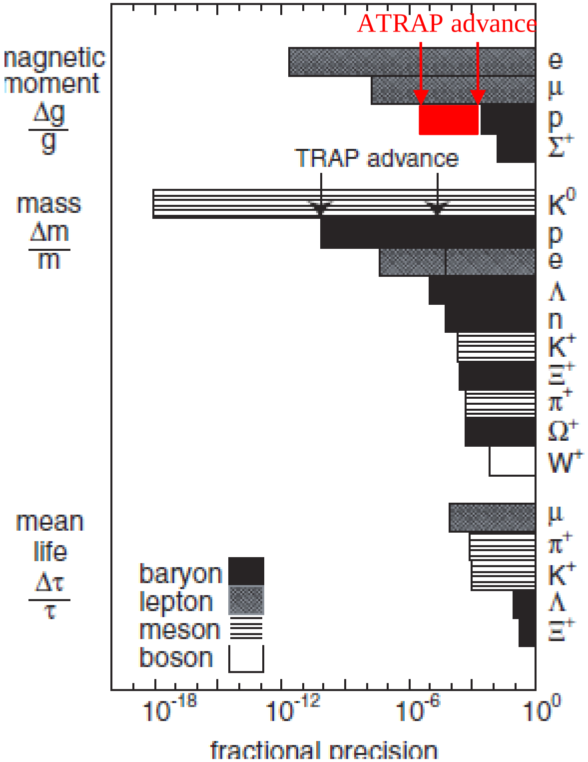
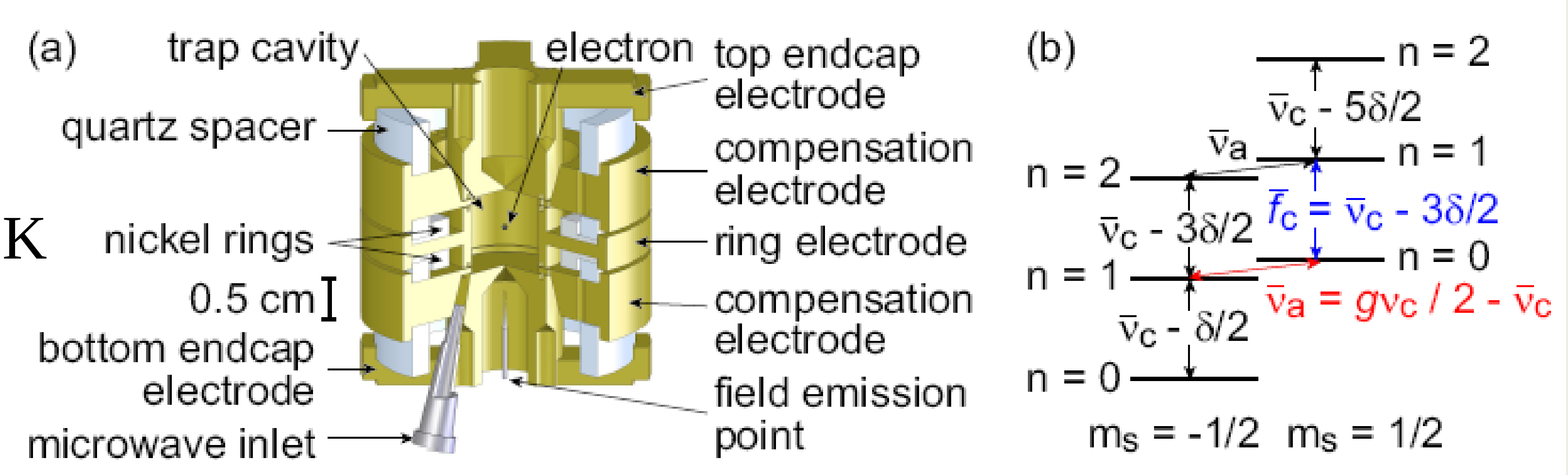


Figure 1: CPT Tests (primarily from the Particle Data Group compilation). Charge-to-mass ratio comparisons are included in "mass" measurements.

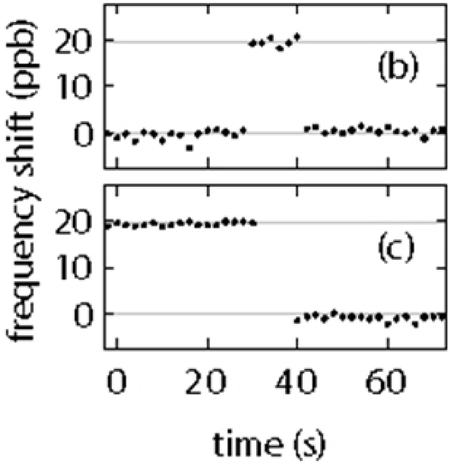
- Already one of the most precise antimatter-matter comparisons
- Will be one of the most precise tests if we improve by an additional 1000 to 10,000

One Electron: Resolve One-Quantum Excitation

0.1 K



QND observations
of one-quantum
transitions

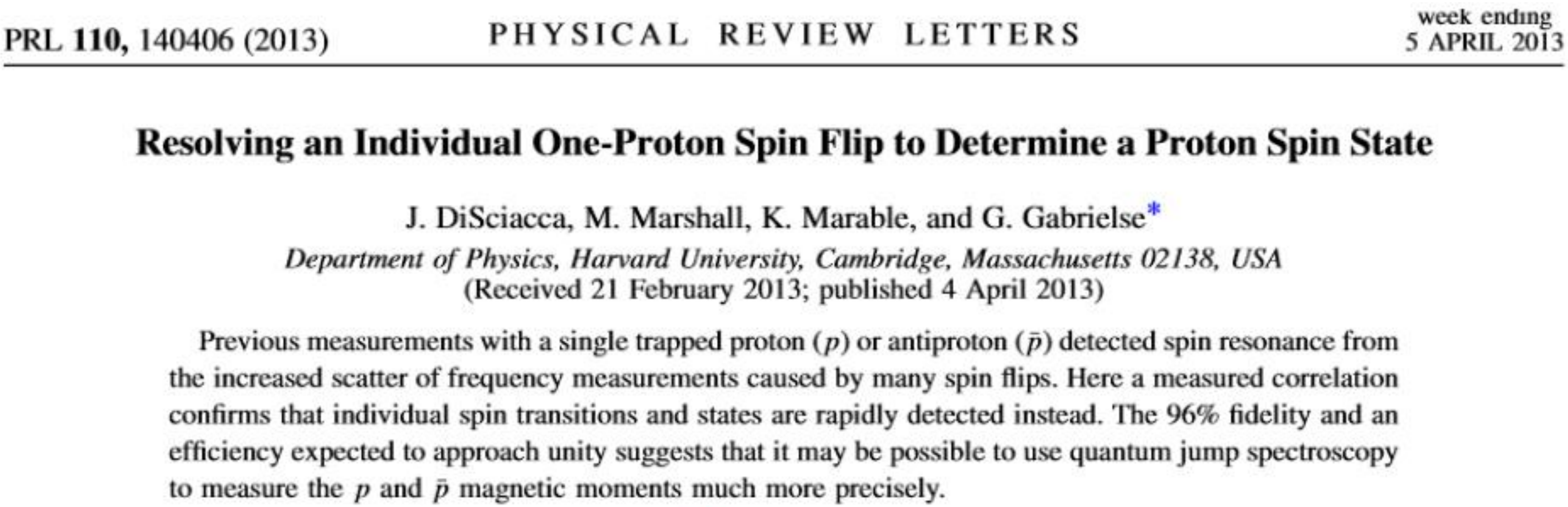


one quantum
cyclotron
excitation

spin flip

"Single-Particle Self-excited Oscillator",
B. D'Urso, R. Van Handel, B. Odom and G. Gabrielse
Phys. Rev. Lett. **94**, 113002 (2005).

Resolving Proton and Antiproton Spin Flips



PRL 110, 140406 (2013) PHYSICAL REVIEW LETTERS week ending 5 APRIL 2013

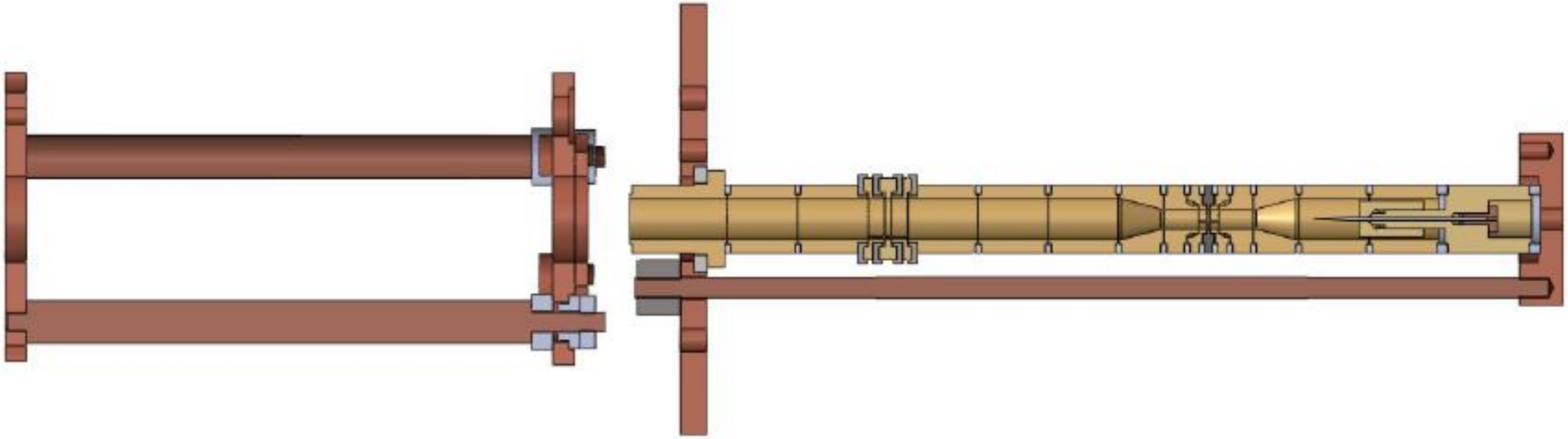
Resolving an Individual One-Proton Spin Flip to Determine a Proton Spin State

J. DiSciacca, M. Marshall, K. Marable, and G. Gabrielse*

Department of Physics, Harvard University, Cambridge, Massachusetts 02138, USA

(Received 21 February 2013; published 4 April 2013)

Previous measurements with a single trapped proton (p) or antiproton ($\bar{p}$) detected spin resonance from the increased scatter of frequency measurements caused by many spin flips. Here a measured correlation confirms that individual spin transitions and states are rapidly detected instead. The 96% fidelity and an efficiency expected to approach unity suggests that it may be possible to use quantum jump spectroscopy to measure the p and $\bar{p}$ magnetic moments much more precisely.



Gabrielse

PRL **110,** 140406 (2013) PHYSICAL REVIEW LETTERS week ending 5 APRIL 2013

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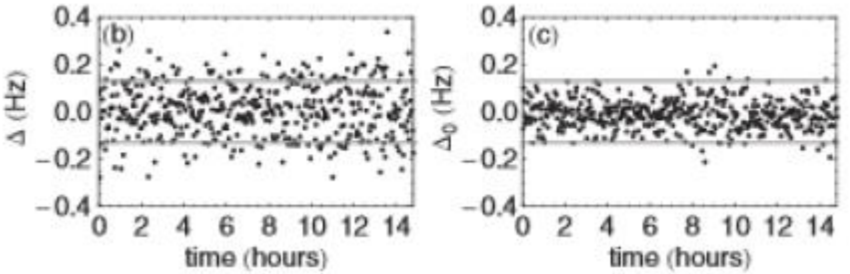
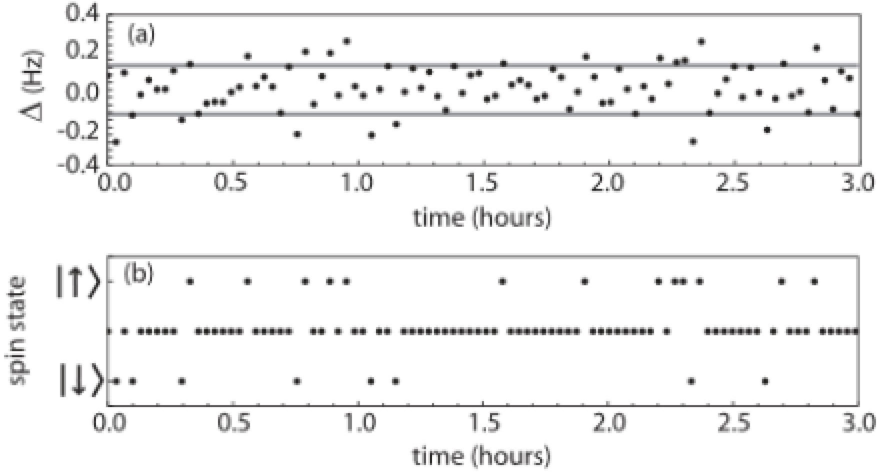
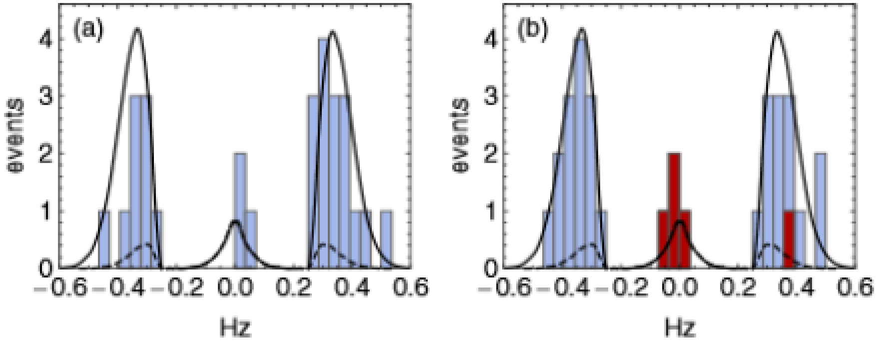


$\sigma = 109$ mHz

$\sigma_0 = 63$ mHz





Pbar Magnetic Moment During 2015 and 2016

We thought that we were ready to make a new measurement in 2015

But aspirations for higher precision → more apparatus, methods, software, infrastructure, …

examples

- More spatially uniform magnetic field (trap changes, NMR,…)
- More time stability in magnetic field
- Much more decoupled from the He recovery system
- Still improving pbar loading diagnostics
- Removed unneeded Hbar detectors
- Removed a lot of unused electronics
- Started dealing with AD noise

Progress depends in large part on how well we can deal with AD noise, and upon new methods being developed.

Optimistic for 2016 but much more cautious. Hoping to grow team.

Current Status of ATRAP Antihydrogen

Proposal to Trap Cold Antihydrogen – 1986

- **Produce cold antihydrogen from cold antiprotons**

“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. ..."

- **Trap cold antihydrogen**
- **Use accurate laser spectroscopy to compare antihydrogen and hydrogen**

“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).

Use trapped antihydrogen
to measure antimatter gravity

G. Gabrielse, Hyperfine Interact. 44, 349 (1988)

Current ATRAP Apparatus

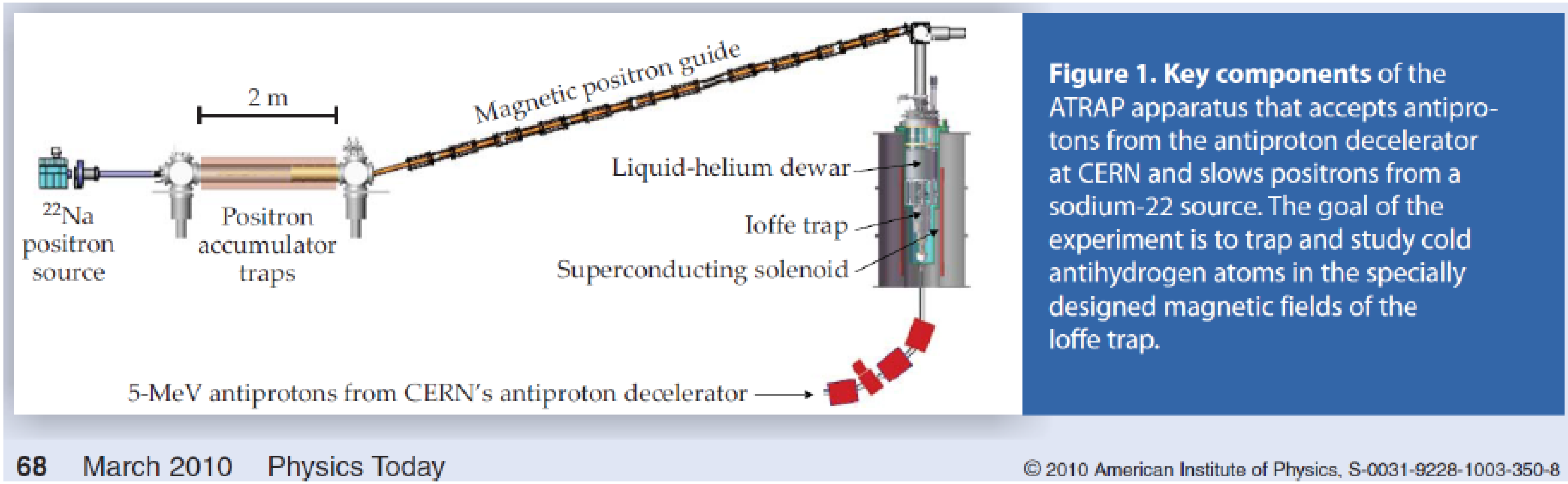


Figure 1. Key components of the ATRAP apparatus that accepts antiprotons from the antiproton decelerator at CERN and slows positrons from a sodium-22 source. The goal of the experiment is to trap and study cold antihydrogen atoms in the specially designed magnetic fields of the Ioffe trap.

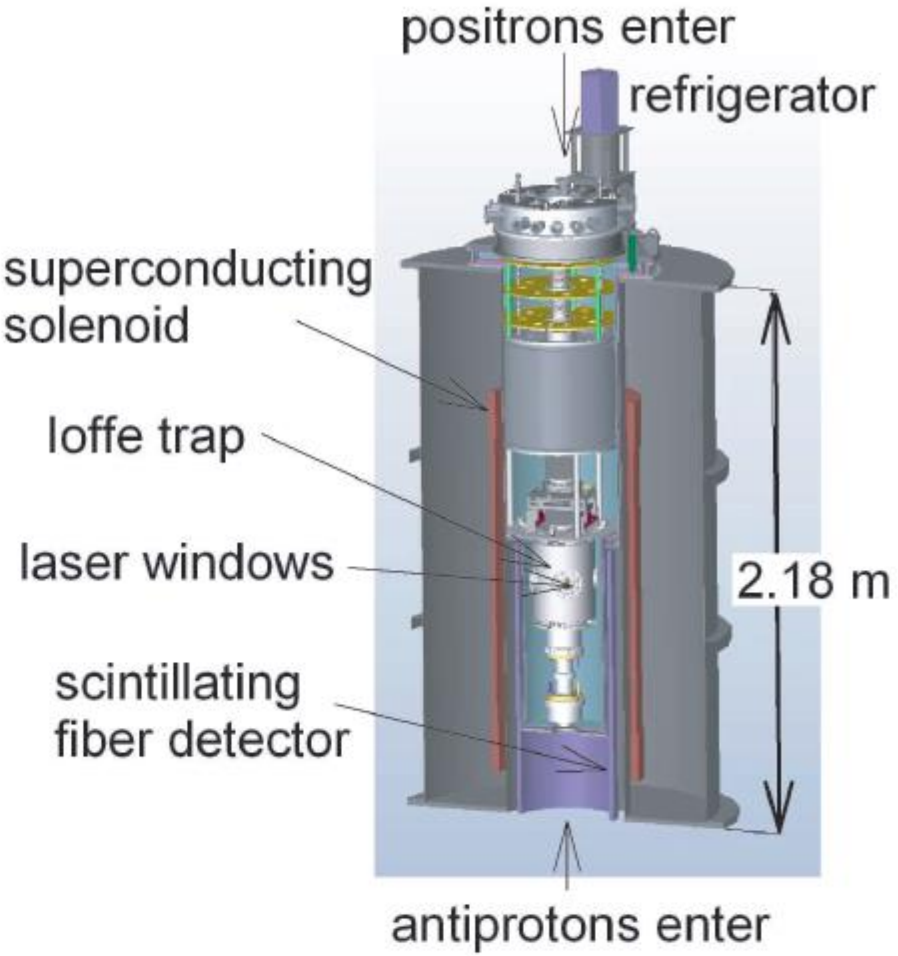
68 March 2010 Physics Today

© 2010 American Institute of Physics, S-0031-9228-1003-350-8

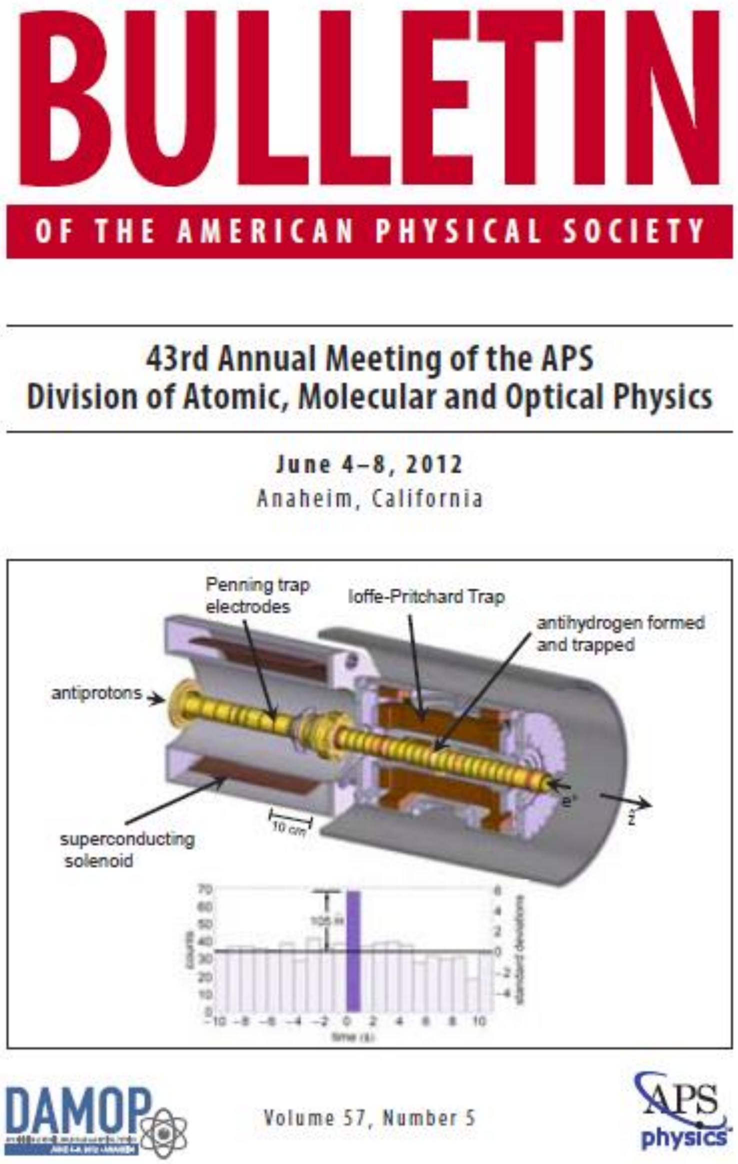
The vacuum system for the Ioffe trap is being changed

- generation 1 → generation 2
- volume is unchanged

Expanded View of the Traps



Gen. I trap: Most Trapped Hbar Per Trial



BULLETIN

OF THE AMERICAN PHYSICAL SOCIETY

43rd Annual Meeting of the APS
Division of Atomic, Molecular and Optical Physics

June 4–8, 2012
Anaheim, California

Volume 57, Number 5

5 +/- 1 ground state atoms
simultaneously trapped

Expect more with 2nd generation Ioffe trap

Enough to demonstrate 3-d Lyman alpha laser cooling (with 2nd generation trap)

Need more atoms/trial

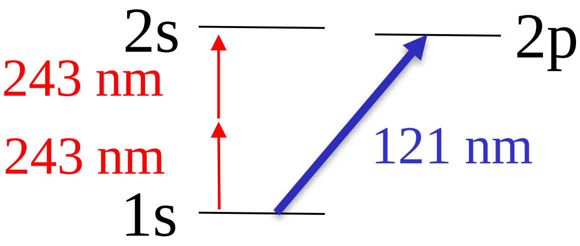
ATRAP, "Trapped Antihydrogen in Its Ground State", Phys. Rev. Lett. **108**, 113002 (2012)

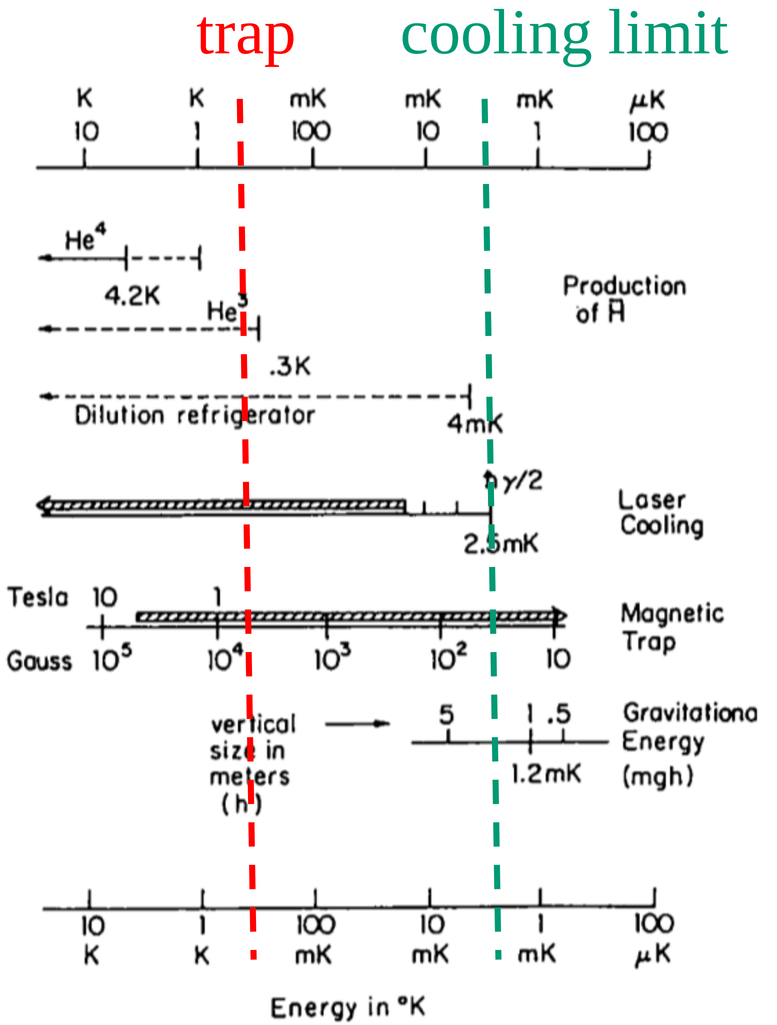
Immediate ATRAP Objectives:
Laser Cooling of Trapped Antihydrogen

Requirements:

1. Need 121 nm radiation
2. Preferably more trapped Hbar ← Second generation Ioffe trap

Need Lyman Alpha Light (121 nm)





- For cooling trapped antihydrogen

  nW ~ minutes

- For “shelving”

  → to measure 1s – 2s transition frequency

121 nm challenges

- difficult to produce
- limited lossy optics choices

Not so easy to laser cool

- light atom
- energetic photon

Big ATRAP Laser Change in 2015

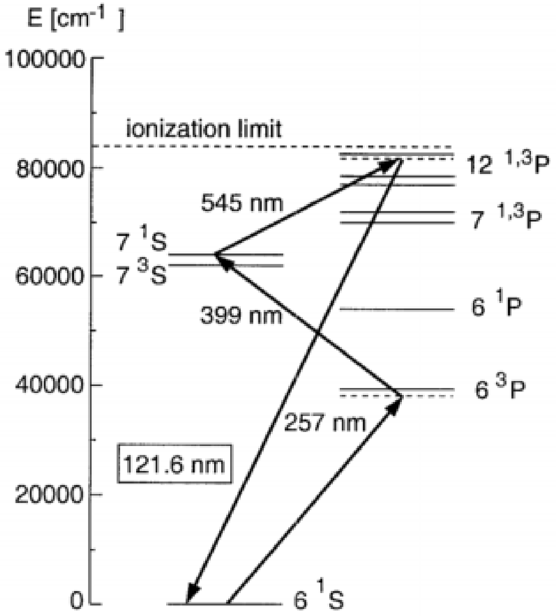
Mainz collaborator decided to withdraw from ATRAP rather than bring a continuous UV source to CERN

↓

Colorado State University collaborators signed up to help with producing pulsed 121 nm light

First Continuous Source of Lyman Alpha

J. Walz, A. Pahl, K.S.E. Eikema, T.W. Haensch, Nuc. Phys. A 692, 163c (2001)



Double Ar+ in BBO → 900 mW at 257 nm

Double TiSaph in LBO → 920 mW at 399 nm

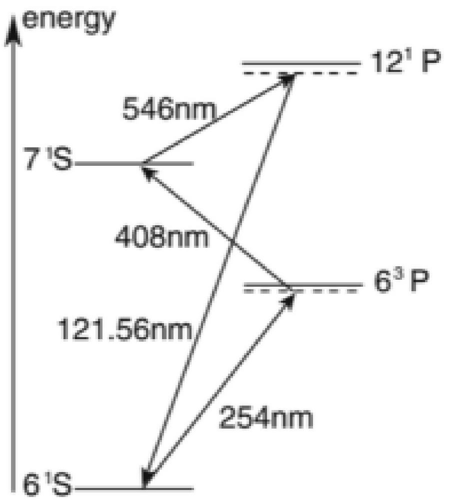
Dye-laser (rhodamine 110) → 1.7 W at 545 nm

121 nm produced: 20 nW

Expected: “increase by several orders of magnitude”

12 years later:

D. Kolbe, M. Scheid, J. Walz, Appl. Phys. B 113, 559 (2013).

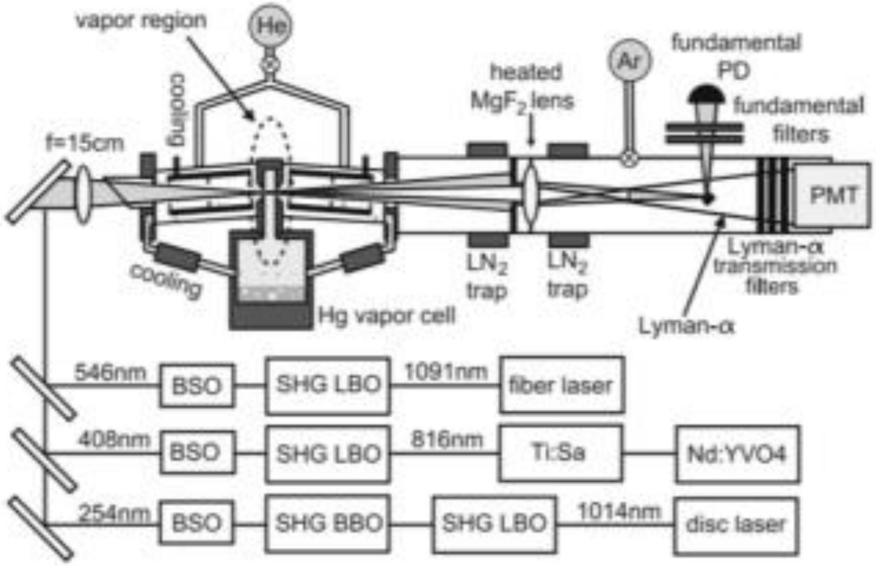


Hg cell

280 mW

300 mW

200 mW



Demonstrated: 0.3 nW of 121 nm

Our estimate

Expected that "at full power" → 140 nW for short time

Toptical: 15 W

4 W (but damages fiber laser output)

We have 2 W

500 mW

Toptica: 120 mW

750 mW (but damages doubling crystal)

At 121 nm expect only
330 nW without damage
550 nW with damage

Our conclusion: Continuous 121 nm not yet ready

Need More Power Quickly
→ Go Pulsed (as in 1993)

Dylan Yost, Siu Au Lee, Nathan Jones, G.G.

W. Phillips, S.L. Rolston, P.D. Lett, T. MeIrath, N. Vansteenk,
C.I Westbrook, Hyper. Int. **76**, 265 (1993)   13 nJ at 10 Hz → 130 nW

I.D. Setija, H.G.C. Werij, O.J. Luiten, M.W. Reynolds, T.W. Jijmans,
J.T.M. Walraven, Phys. Rev. Lett. 70, 2257 (1993).
3 nJ at 50 Hz (0.5 nJ at cold sample) → 150 nW

R. Hilbig, R. Wallenstein, IEEE J. of Quant. Elect. QE-17, 1566 (1981)
- Triple in Kr cell: 10^{-5} to 10^{-6} efficiency
- 367 nm → 121 nm

Thanks to Rolston, T. Udem   for suggestions

Current ATRAP Plan

1. Develop a pulsed 121 nm source quickly (2015-2016). Use for cooling trapped antihydrogen in 2016.

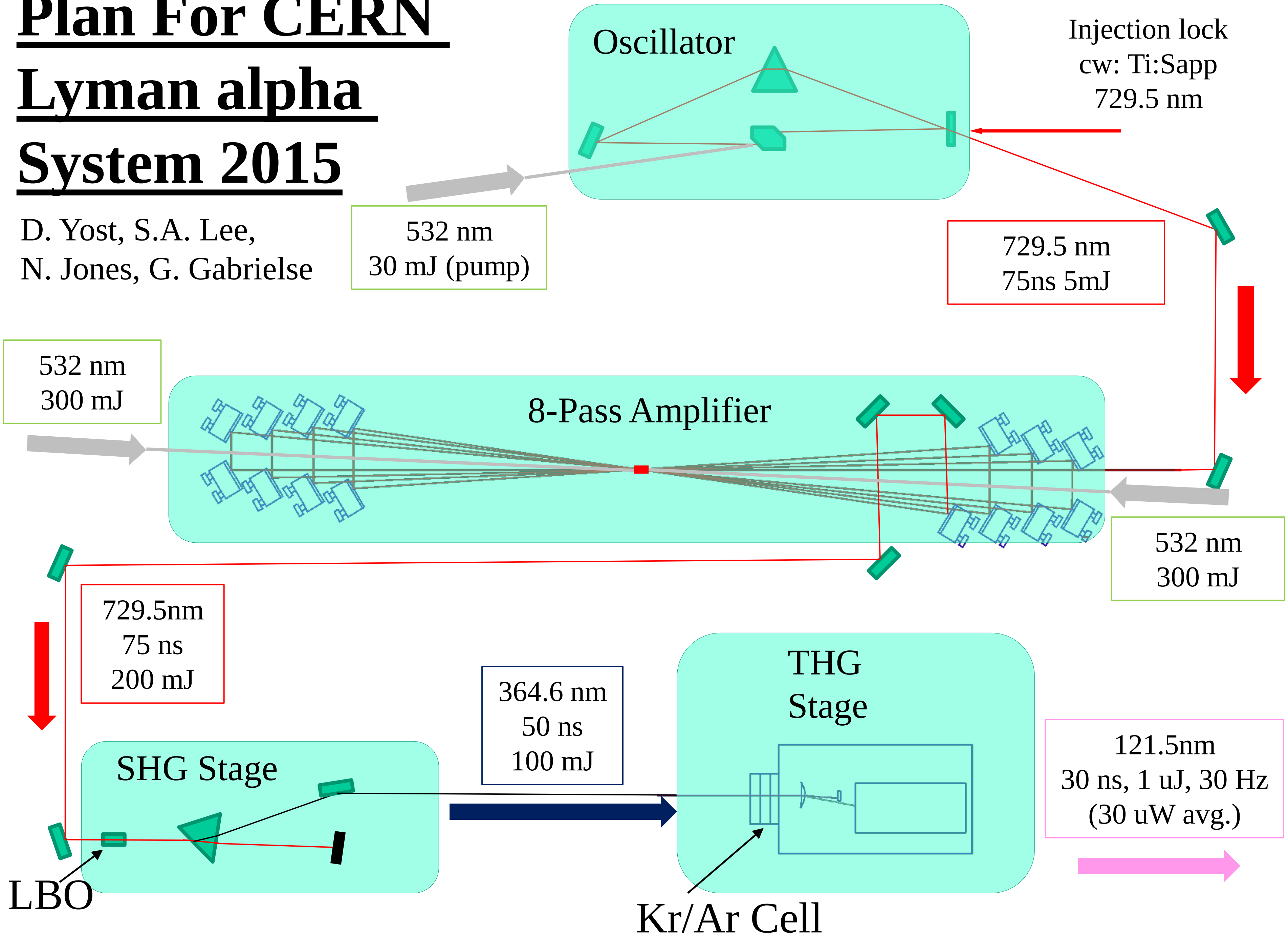
2. Develop a second generation pulsed source for 2017

3. Develop a continuous 121 nm source 2016 – 2018. (Not at CERN before 2018)

Plan For CERN Lyman alpha System 2015

D. Yost, S.A. Lee,
N. Jones, G. Gabrielse

Gabrielse



Oscillator

Injection lock
cw: Ti:Sapp
729.5 nm

532 nm
30 mJ (pump)

729.5 nm
75ns 5mJ

532 nm
300 mJ

8-Pass Amplifier

532 nm
300 mJ

729.5nm
75 ns
200 mJ

364.6 nm
50 ns
100 mJ

THG
Stage

SHG Stage

121.5nm
30 ns, 1 uJ, 30 Hz
(30 uW avg.)

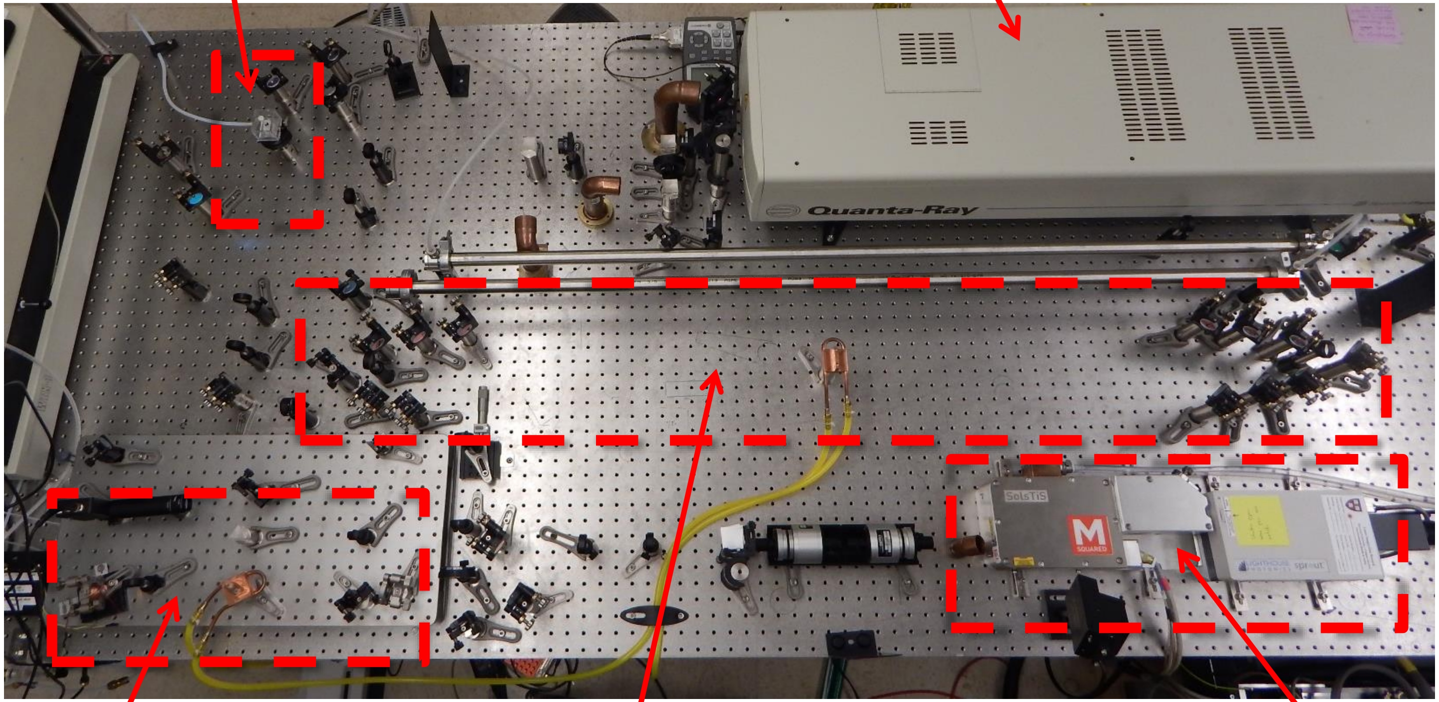
LBO

Kr/Ar Cell

Some Tests Done at CSU, August 2015

THG LBO
365 nm
20 mJ

532 nm 240 mJ PUMP LASER



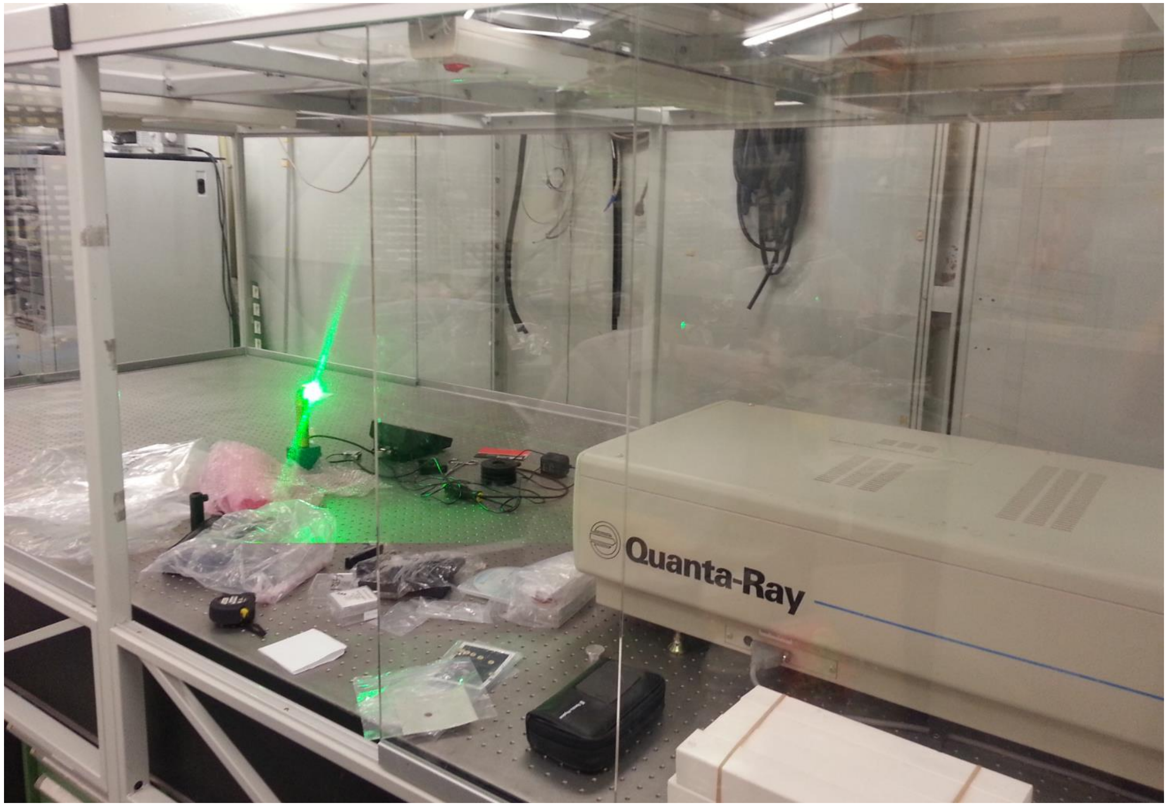
OSCILLATOR
5 mJ 730 nm, 75 ns

6 pass AMPLIFIER 50 mJ

SEED LASER 730 nm
40 mW

D. Yost, S. A. Lee (Colorado State)

Harvard Sends Serious Pump Laser to CERN



532 nm
~850 mJ
30 Hz

Current Status of Lyman-alpha Source

Stage of System	**Energy per Pulse**	**Pulse Width**
532 nm Pump Energy	600 mJ	10 ns
730 nm Oscillator Output	10 mJ	44 ns
730 nm Amplifier Output	80 mJ	44 ns
365 nm Second Harmonic Generation	30 mJ	30 ns
121 nm Third Harmonic Generation	20 nJ	20 ns

600 nW

- Effective linewidth of Lyman-alpha: 20 MHz

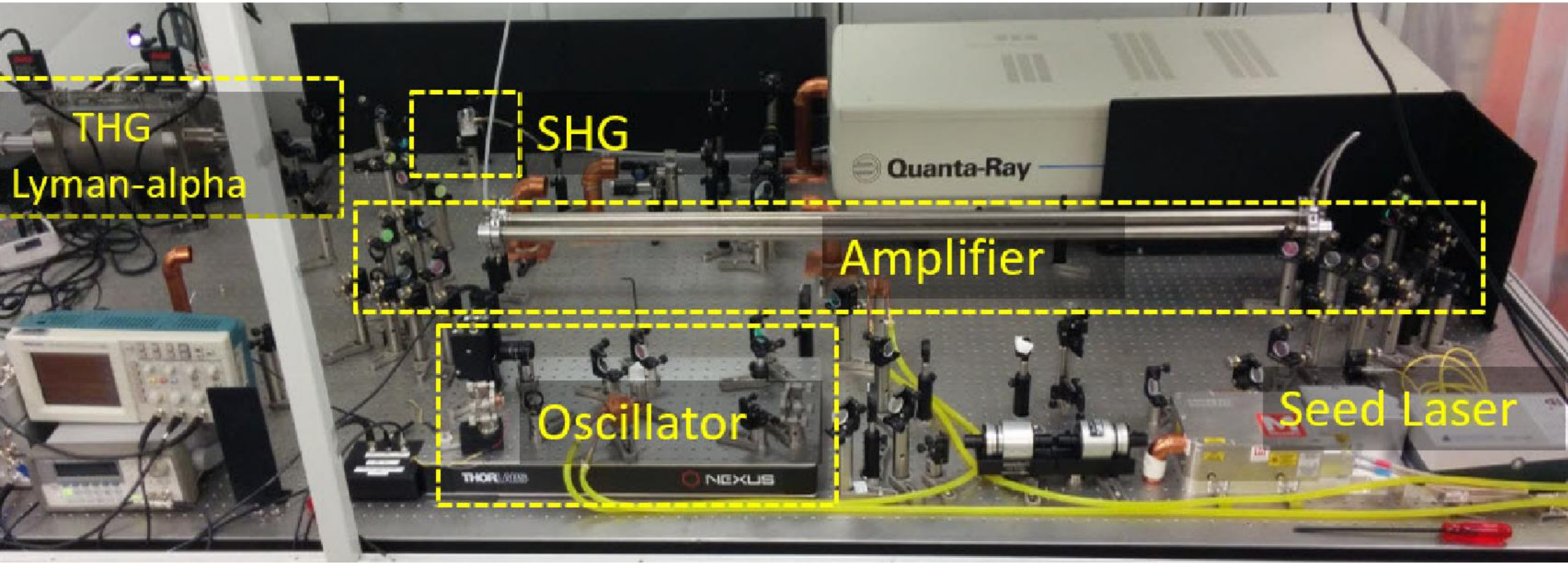
- 20 nJ at 30 Hz gives 600nW average power

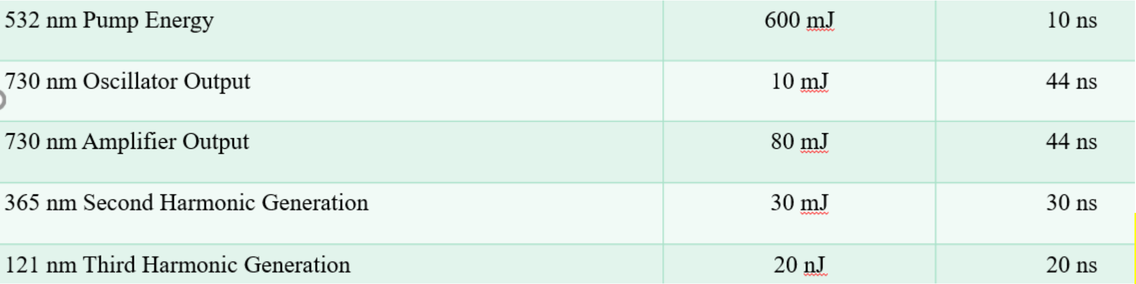
- Lyman-alpha generation in Krypton cell is not phase-matched. Can expect 10 times more in phase matched cell.

- As a comparison, Walraven [PRL **70** 2257 (1993)] generated 150 nW and laser cooled hydrogen in a magnetic trap, but only delivered 2.3 nW to the experiment.

Observe 600 nW of 121 nm Light at CERN

CSU: D. Yost, S.A. Lee, S. Ronald, C. Rasor
Harvard: N. Jones, C. Hamley, G.G.





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Effective linewidth: 20 MHz

600 nW at 30 Hz

no phase matching yet → 10x

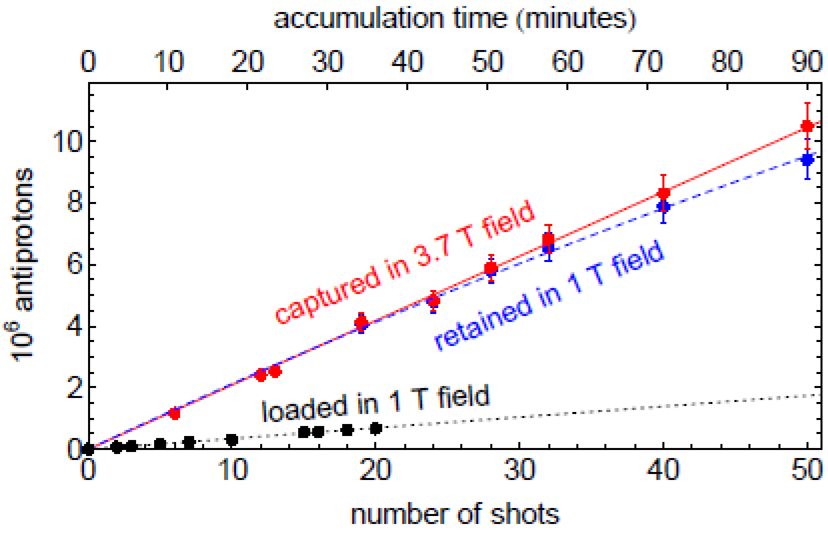
Compare pulsed: NIST and Amsterdam (1993): 120 nW, 150 nW
continuous: 20 nW, 0.3 nW

Immediate ATRAP Objectives: Laser Cooling of Trapped Antihydrogen

Requirements:

1. Need 121 nm radiation
2. Preferably more trapped Hbar ← Second generation Ioffe trap

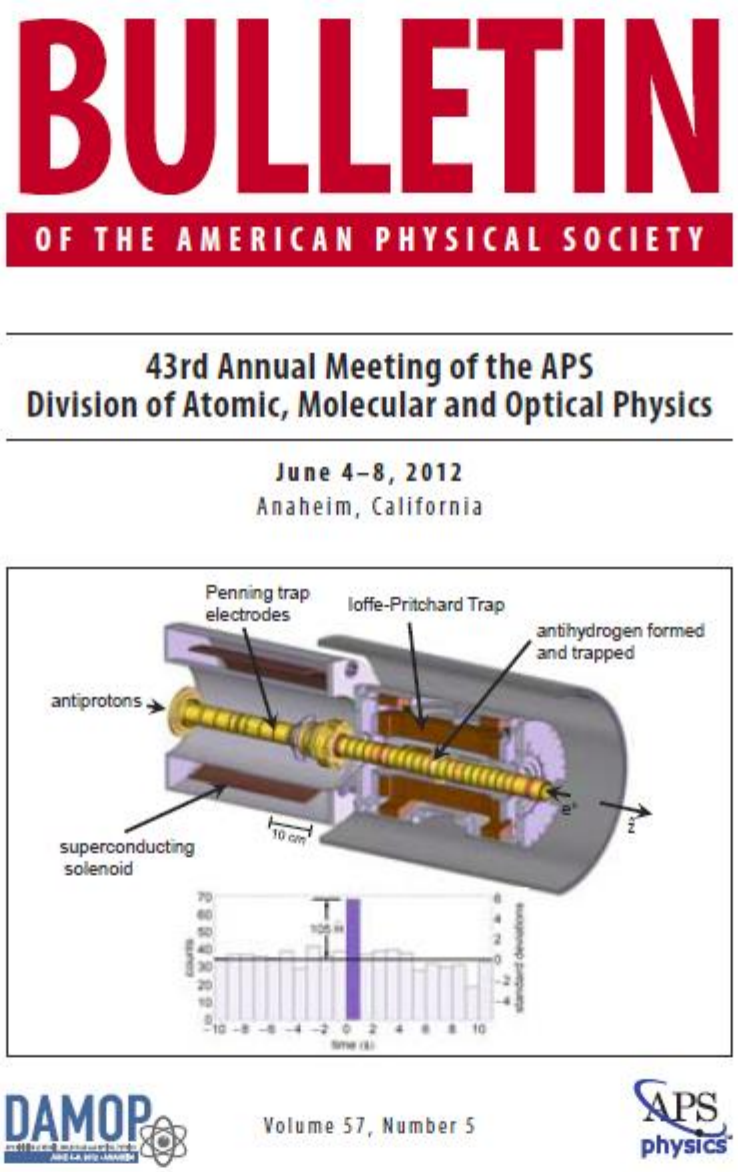
Focus on Using Large Numbers of Antiprotons



Hope to trap more antihydrogen per trial with generaion 2 Ioffe trap

- control of magnetic gradients
- much more rapid turn on of the Ioffe trap
- better detection signal to noise with more rapid turn off
- can do multiple trials per shift

Trapped Hbar Per Trial Does Not Scale



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Need more atoms/trial

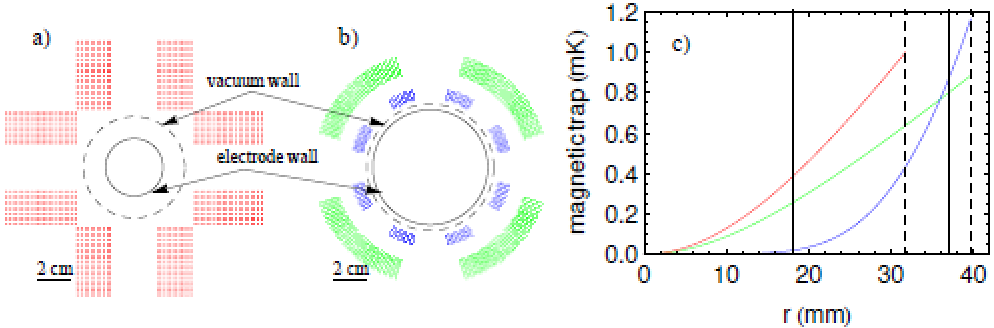
ATRAP, “Trapped Antihydrogen in Its Ground State”, Phys. Rev. Lett. **108**, 113002 (2012)

Generation II: Low Inductance Ioffe Trap with Laser Windows

- Energize more than once in an 8 hour shift
- Faster turn on → more trapped hbar per trial
- Faster turn off → better detection
- Octupole as well as quadrupole traps
- Side windows for efficient laser cooling

the cause of all our difficulties

Top view and field of Ioffe traps

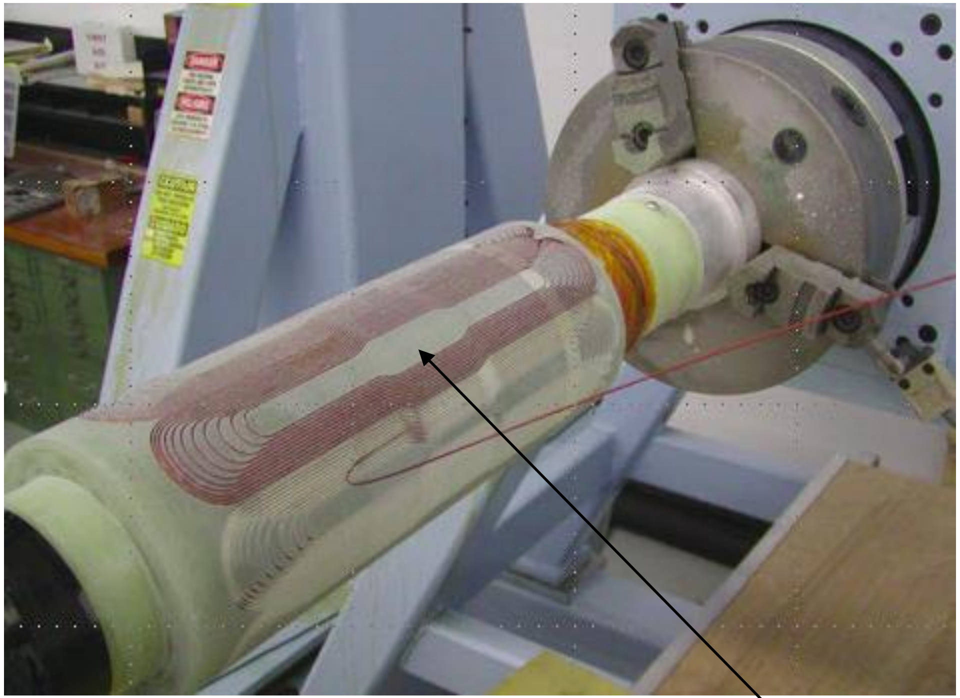


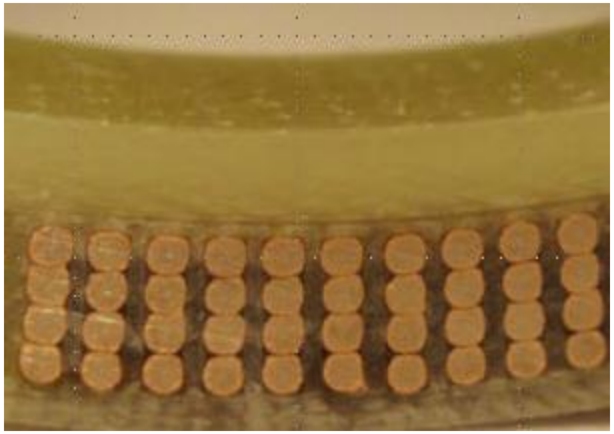
old

new

Generation II Technology

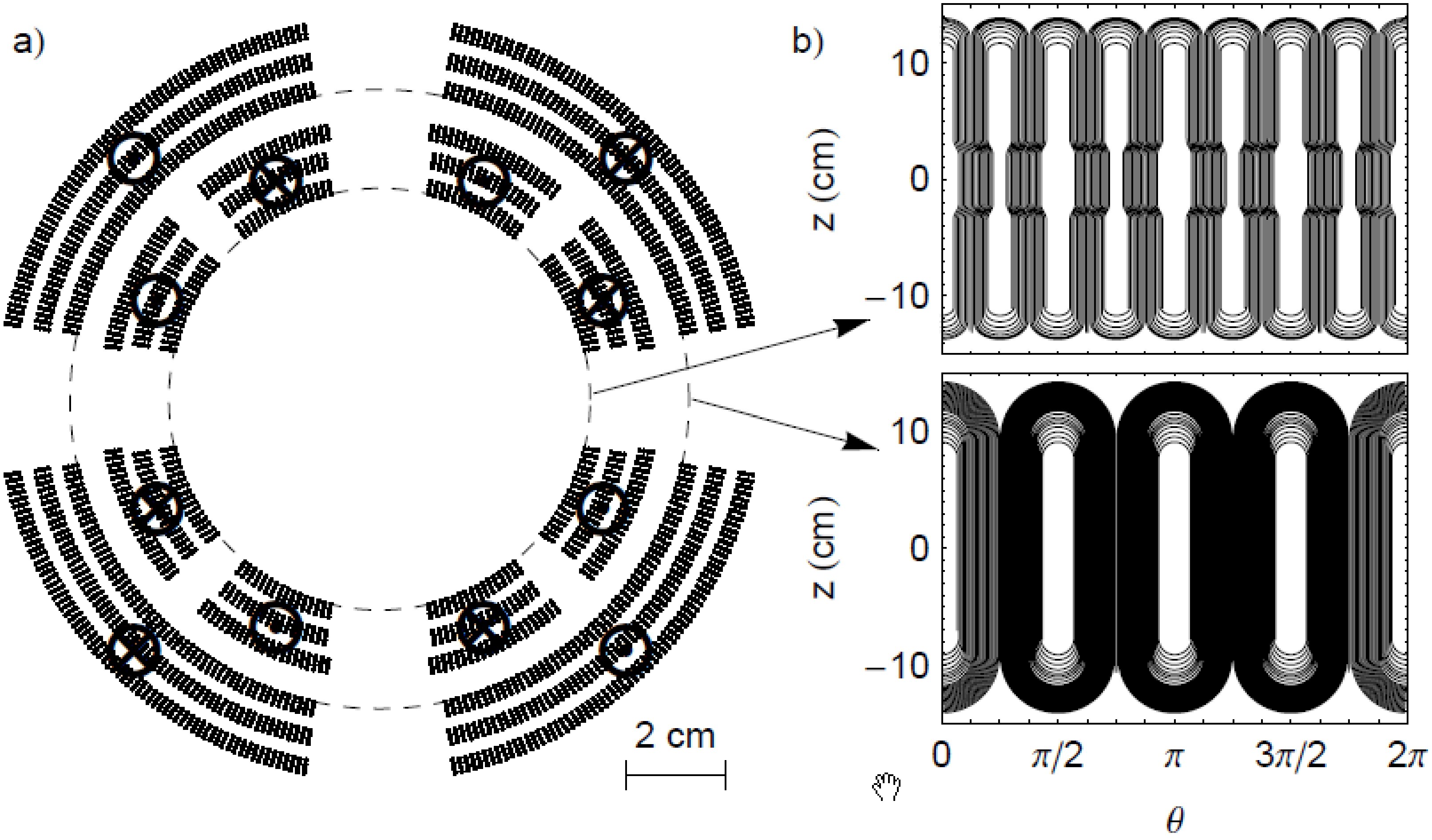
Superconducting wires embedded in epoxy-fiberglass



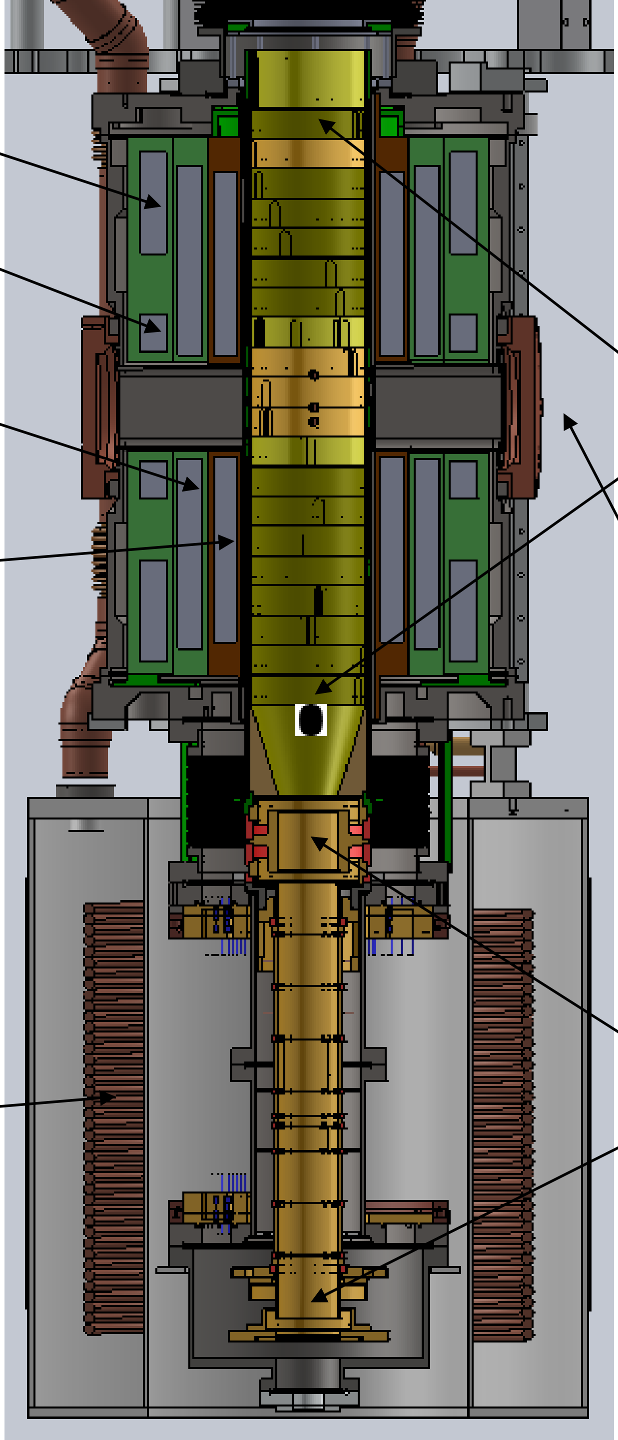


distortion for side window insertion

Side Windows for Laser Cooling and Spectroscopy



Gabrielse



pinch coils

bucking coils

quadrupole racetracks

octupole racetracks

positron catching and Hbar formation trap electrodes

SIDE WINDOWS

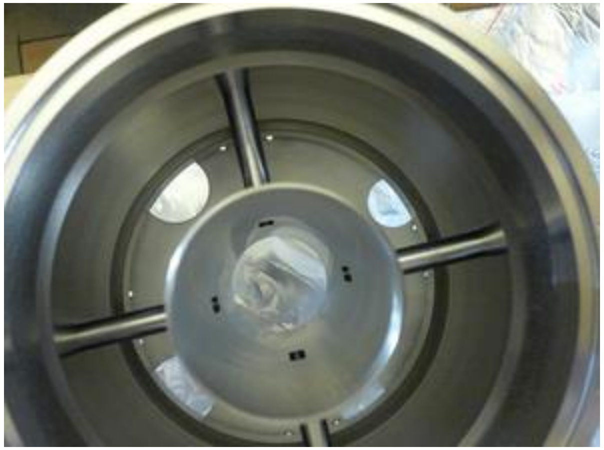
extra catching magnetic field solenoid

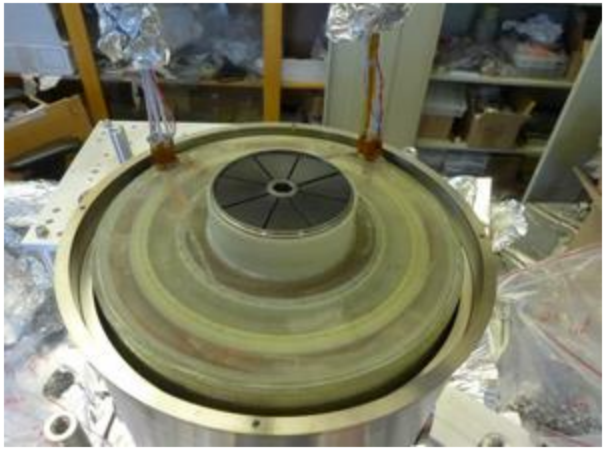
antiproton catching trap electrodes (2 K)

Upper Electrodes

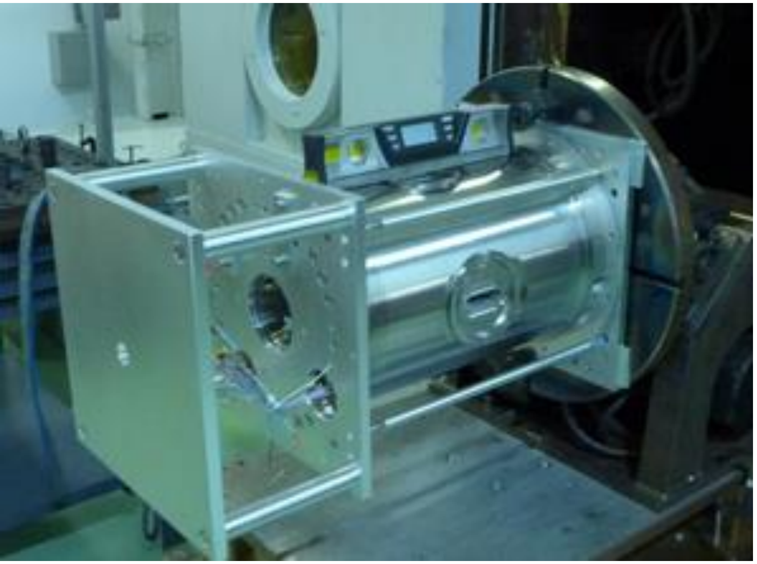
Assembled in new building.
→ Sheds are a big improvement on lines on the floor

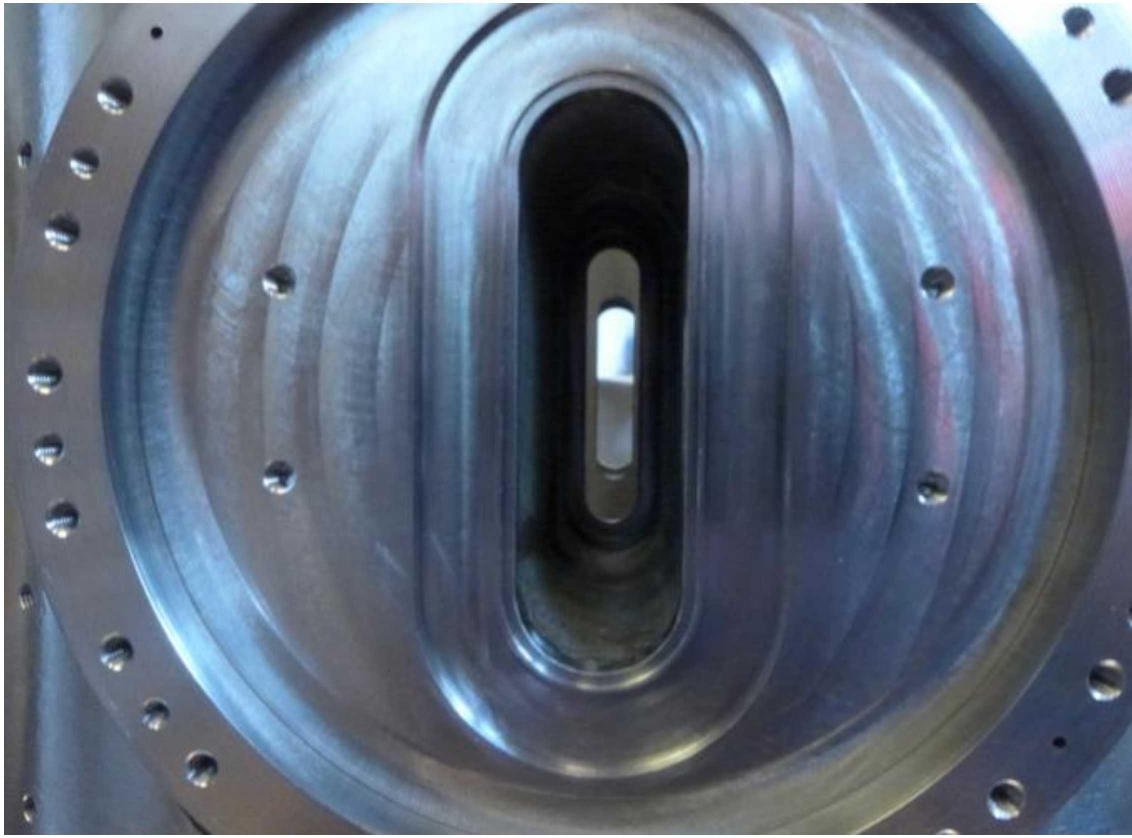
Titanium Vacuum Enclosure

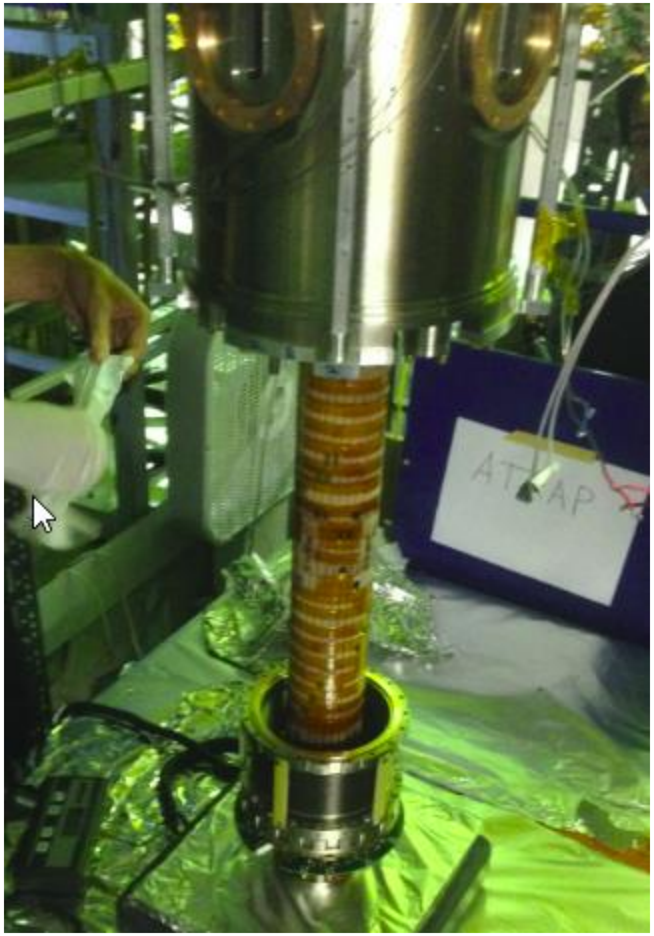




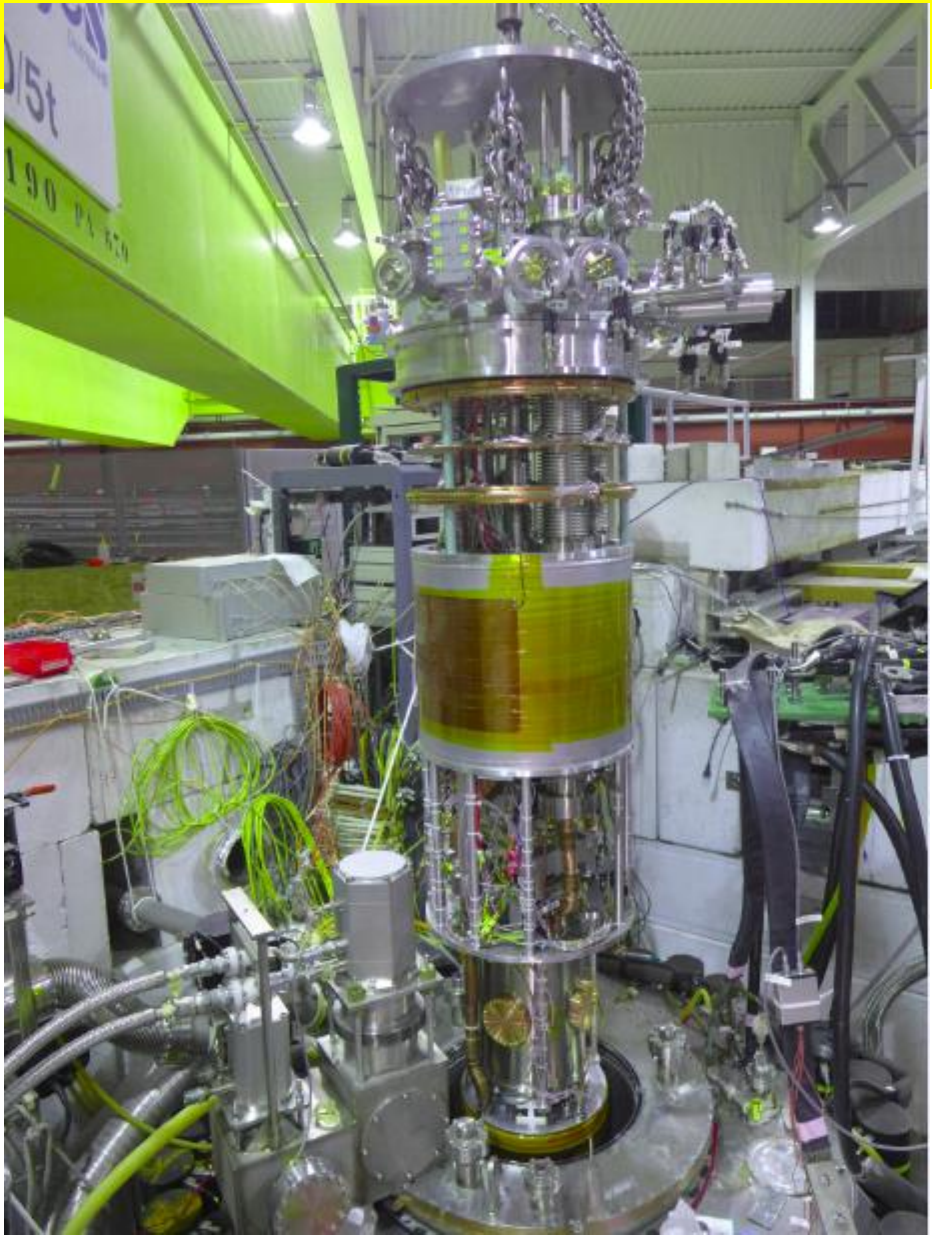
Titanium Vacuum Enclosure







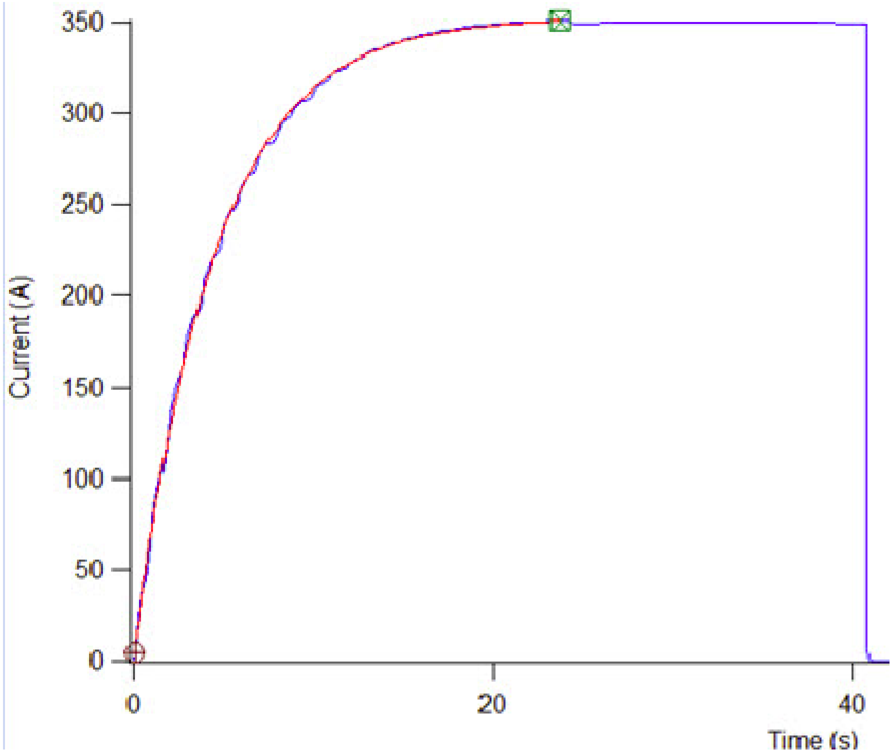
Electrodes into Ioffe trap



Penning-Ioffe Apparatus into Solenoid

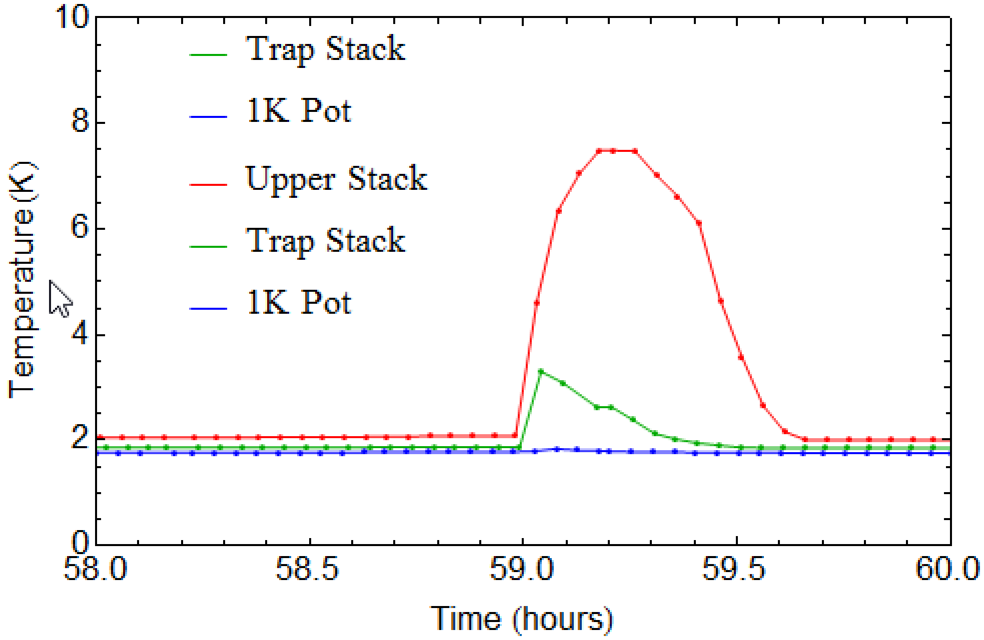
All the Coils Work to Design Current

One example



Turn on time ~ 10 s
Turn off time ~ 15 ms

Penning Trap Electrodes Heated by Eddy Currents When Ioffe Trap Current is Quickly Removed



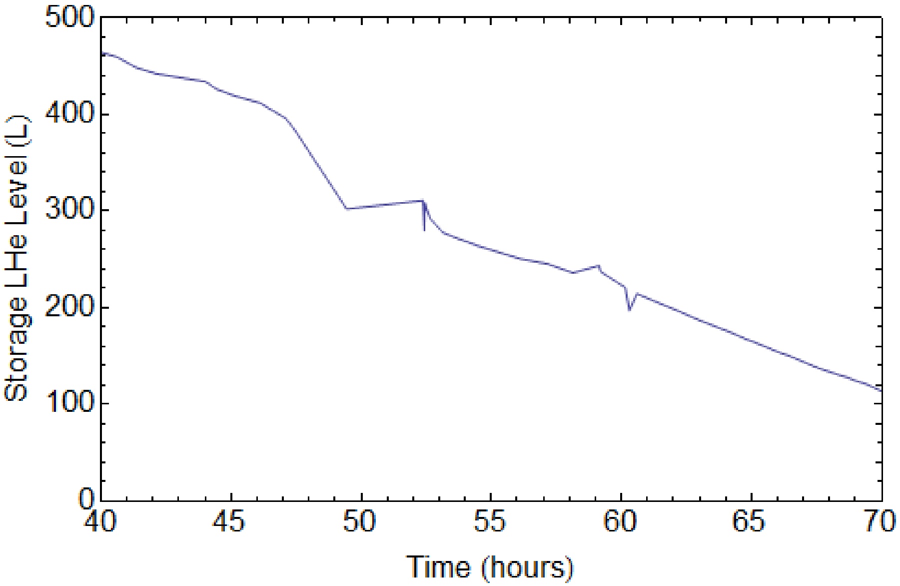
Quadrupole coil initially at 490 ampere

Vacuum in the trap can may not be so good
for a half hour after the current is quickly removed.

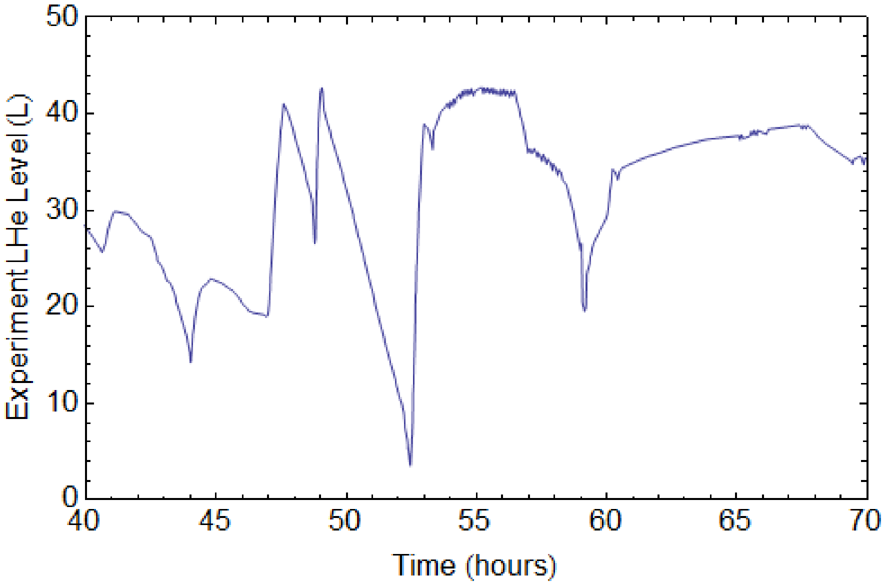
Many Hundreds of Amps
Heat the Current Leads

Hybrid leads include high temperature superconductor

Storage dewar



Experiment dewar
with crude manual autotransfer



Helium loss: ~11 liters / hour
~ 500 liters / 2 days

Much better autotransfer
as run progressed

Aspirations for 2015

Before beam: cool entire apparatus

- → can cycle many times during a shift
- → rapid turn on
- → rapid turn off
- → both quadrupole and octupole traps working

When antiprotons became available

- ~~→ show that we can trap many more atoms per trial~~
- ~~→ trap atoms from laser-controlled charge exchange~~
- ~~→ first attempts at Lyman alpha cooling~~

very disappointing

Instead → unanticipated trap modifications

→ decided to finish and add all the cryogenic laser optics

→ ran into the always dreaded "cold vacuum leak"
(takes 2 weeks just to cycle, leak never opened up,
now dismantling and testing every piece)

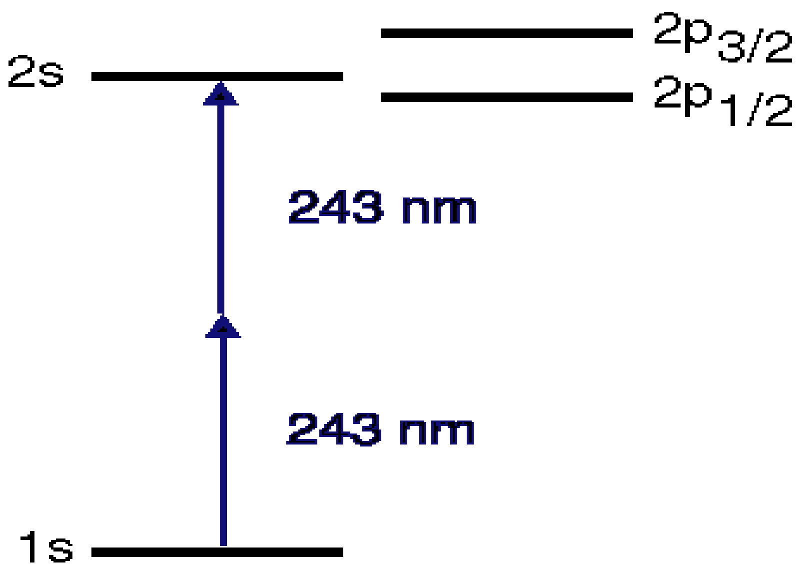
ATRAP Aspirations for 2016

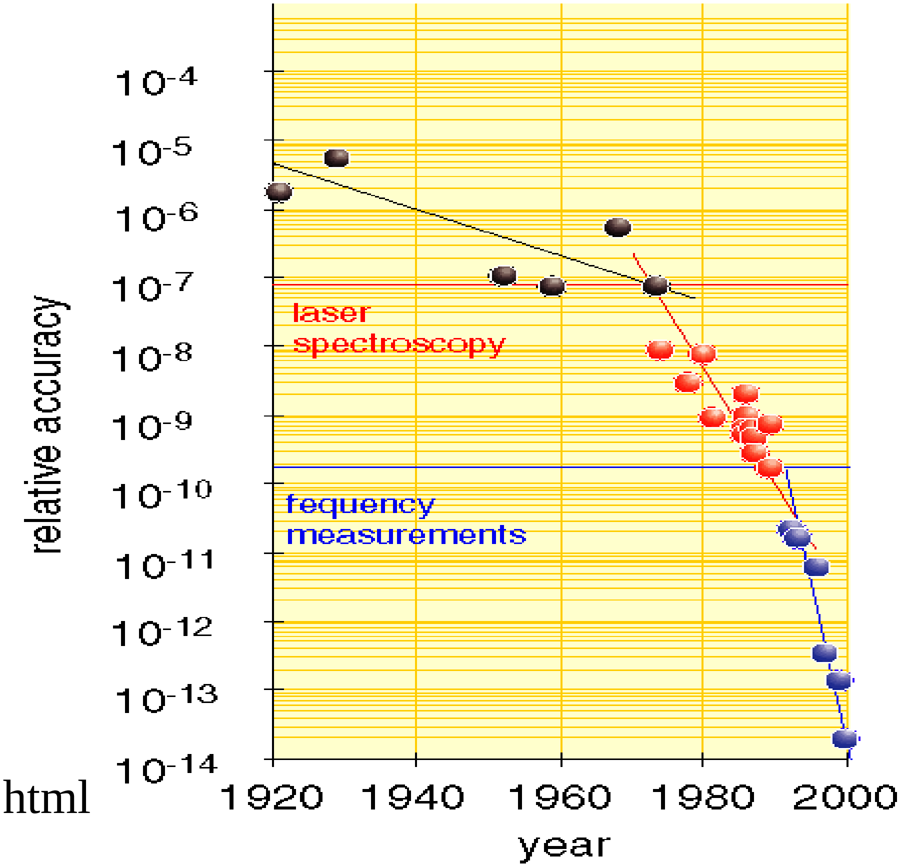
Antihydrogen

- Fully working pulsed Lyman alpha sent to trapped Hbar
- Fully working Penning and Ioffe traps → more trapped Hbar
- 3-d laser cooling of trapped Hbar

Hopeful but cautious for 2016

Ultimate Goal: Hydrogen 1s – 2s Spectroscopy





(Haensch, et al., Max Planck Soc., Garching)
http://www.mpq.mpg.de/~haensch/hydrogen/h.html

Many fewer antihydrogen atoms will be available

→ We now have an operating 1s-2s laser system at Harvard
→ Will likely be installed at CERN in 2015

Spectroscopy Laser for 1s – 2s (243 nm)

Commercial copy of MPQ lasers

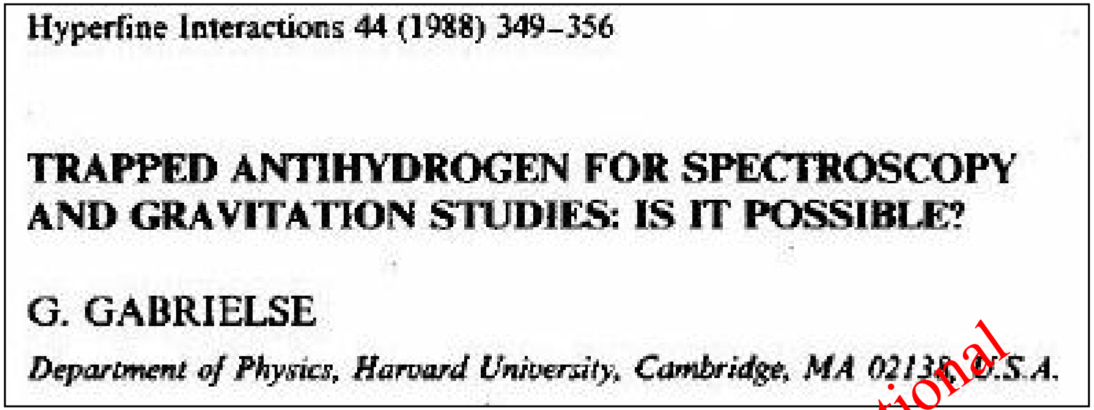
972 nm diode doubled twice → >35 mW @ 243 nm

Still to be locked to ULE cavity

Still to be referenced to the fiber comb that is waiting for it

Have extended cavity diodes ready (thanks to T. Udem and D. Yost for testing) -- awaiting enough people to complete the system

Gravity and Antihydrogen

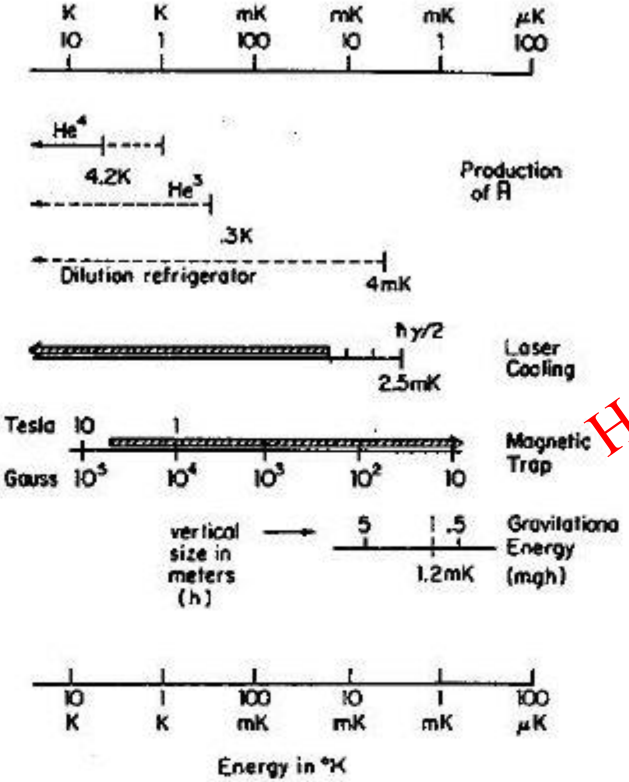


Hyperfine Interactions 44 (1988) 349–356

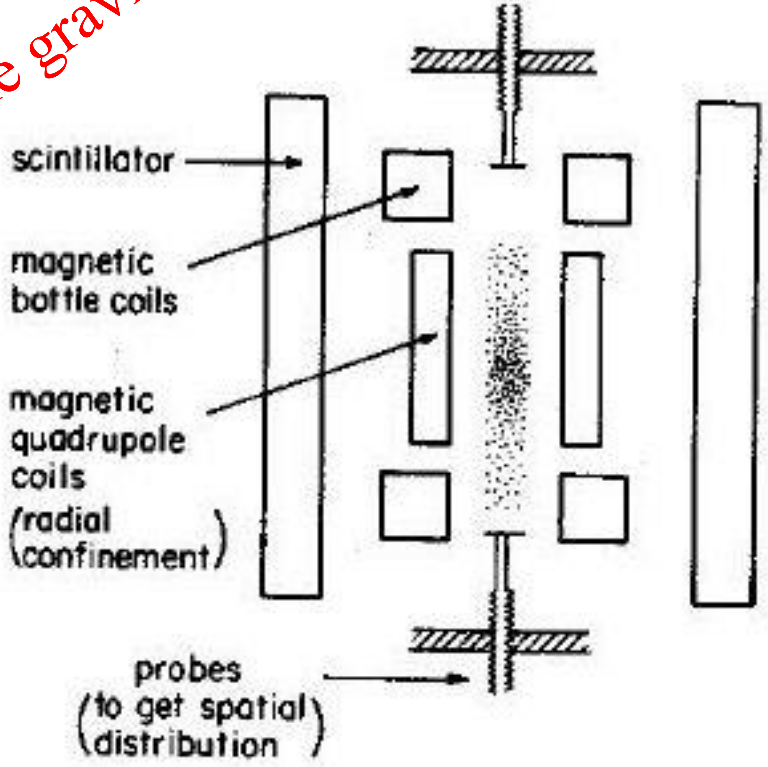
TRAPPED ANTIHYDROGEN FOR SPECTROSCOPY AND GRAVITATION STUDIES: IS IT POSSIBLE?

G. GABRIELSE

Department of Physics, Harvard University, Cambridge, MA 02138, U.S.A.

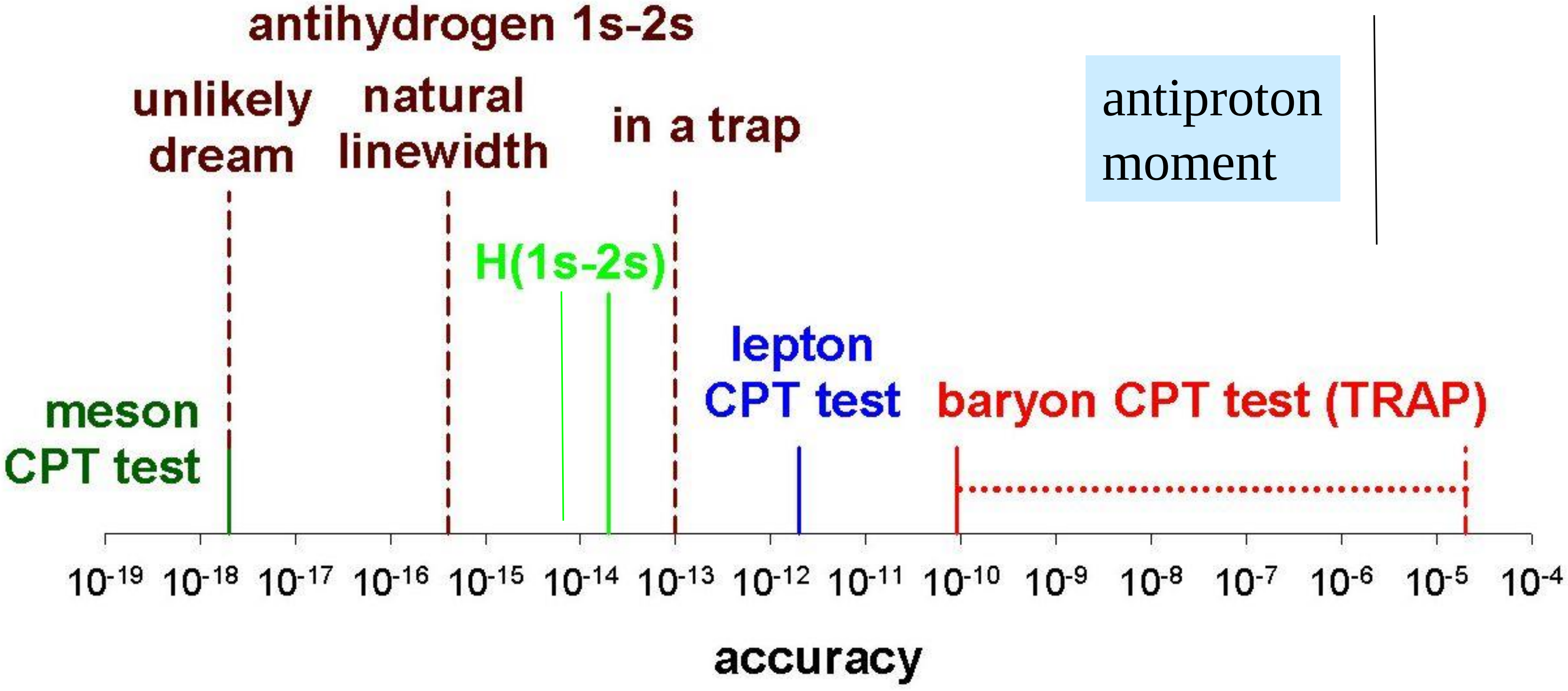


Hard to compete with the gravitational redshift measurement



Summary

Seek to Improve Lepton and Baryon CPT Tests



$$\frac{R_\infty[\overline{\mathrm{H}}]}{R_\infty[\mathrm{H}]} = \frac{m[e^+]}{m[e^-]}\left(\frac{q[e^+]}{q[e^-]}\right)^2\left(\frac{q[\bar{p}]}{q[p]}\right)^2\frac{1+m[e^-]/M[p]}{1+m[e^+]/M[\bar{p}]}$$

Precision Measurements with Antimatter and Matter

what may be possible

Antiproton-Proton Comparisons

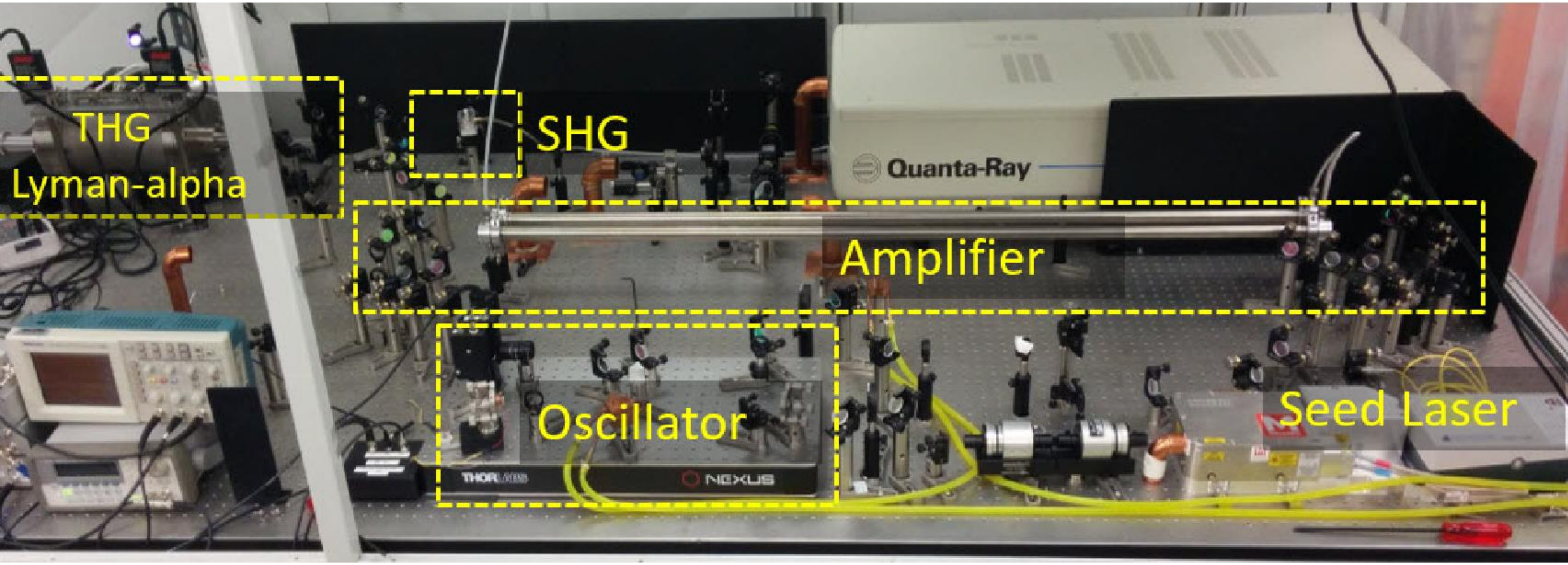
- q/m TRAP (and also now BASE) x 100
- gravity x 100
- q and m TRAP and ASACUSA (indirect)
- magnetic moment ATRAP x 10000

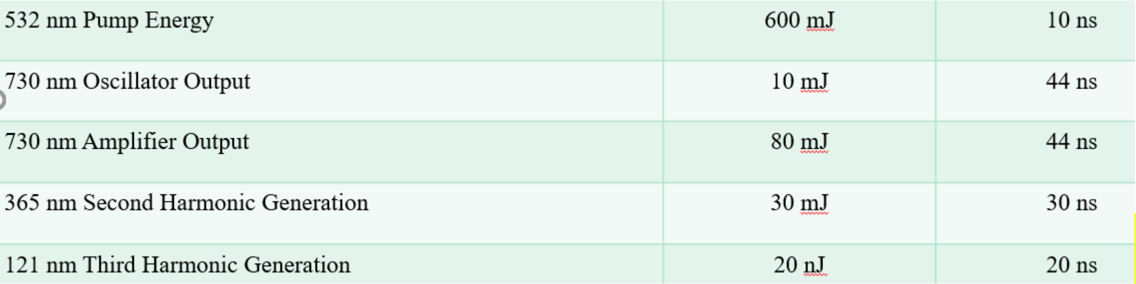
Antihydrogen-Hydrogen Comparisons – no interesting comparisons

but encouraging progress continues

Observe 600 nW of 121 nm Light at CERN

CSU: D. Yost, S.A. Lee, S. Ronald, C. Rasor
Harvard: N. Jones, C. Hamley, G.G.





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600 nW at 30 Hz

no phase matching yet → 10x

Compare pulsed: NIST and Amsterdam (1993): 120 nW, 150 nW
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- Fully working pulsed Lyman alpha source to trapped Hbar
- Fully working Penning and Ioffe traps → more trapped Hbar
- 3-d laser cooling of trapped Hbar

Hopeful but cautious for 2016

Antiproton magnetic moment

- Working on new measurement

Hopeful but cautious for 2016

Antiproton charge-to-mass ratio

- Much more precise since 1999 so less urgent
- We do not have time or people to work in this now

Leave this to BASE till we have time after 2016

ATRAP and the ELENA Schedule

ELENA will be a wonderful step forward

- Ten times more trapped antiprotons per AD pulse
- Pbars available every day (without the rotating shifts)

ATRAP beamlines are more challenging than others because of the bends and the crane-limited length

- We are concerned about whether our beam lines will work as quickly as the others in 2017

ATRAP has started planning needed apparatus modifications

- We could be ready in 2017
- Substantial apparatus modifications are required

A Personal Note from G.G.

You will likely hear that I am moving from Harvard to Northwestern (starts in 2017)

Founding director of a Center for Fundamental Physics at Low Energy (have 2 faculty openings along with postdoc openings)

One motivation: hoping to contribute more to ATRAP

Please send me good faculty, students and postdocs