JAGIELLONIAN UNIVERSITY
IN KRAKOW

Investigations of CPT symmetry using antihydrogen atoms at CERN

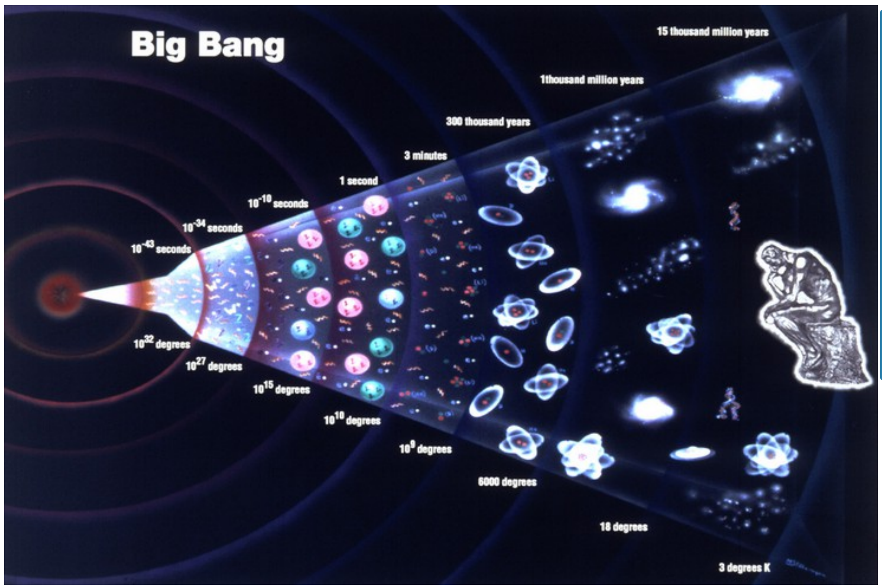
Marcin Zielinski

II Symposium on Applied Nuclear Physics and Innovative Technologies in Kraków

> Scientific motivation for research

Motivation arises from general unanswered question:

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

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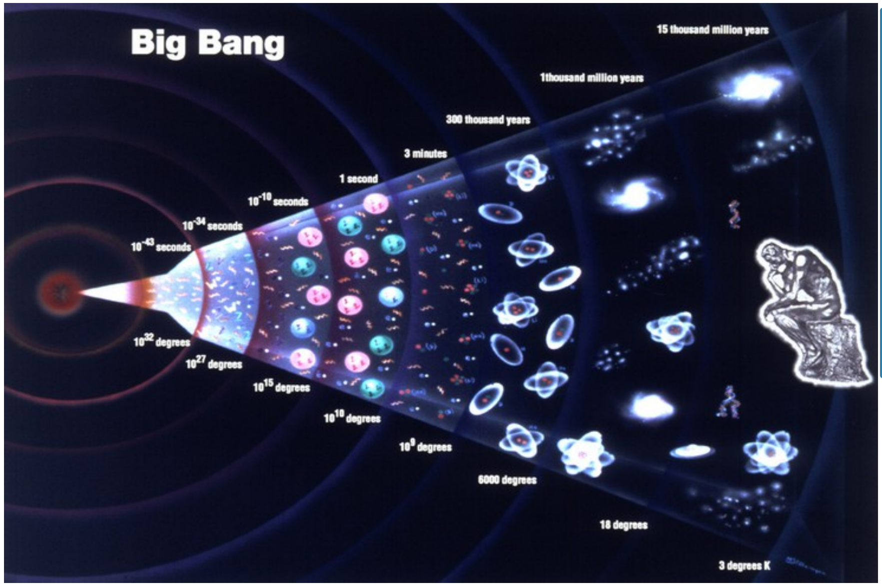

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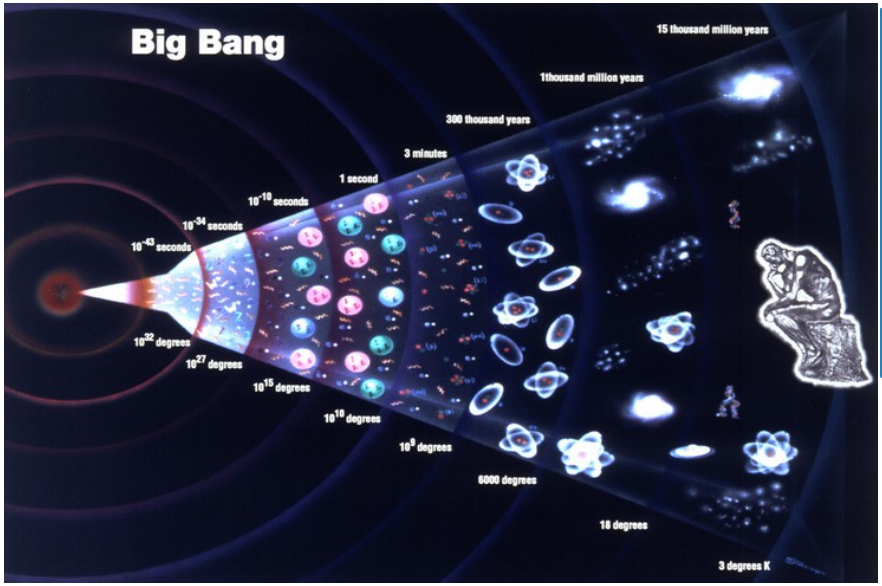

Big bang:

equal amounts of matter and antimatter created during „hot time”

As universe cools:

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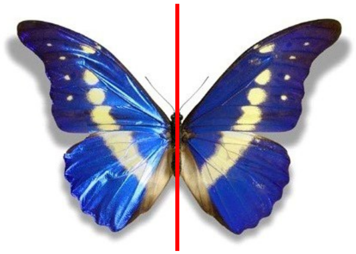
Our experimental way to search for the answer:

looking for evidence that antiparticles and particles may differ!!

> Scientific motivation for research

Is reality invariant under symmetry transformations ?

SYMMETRY



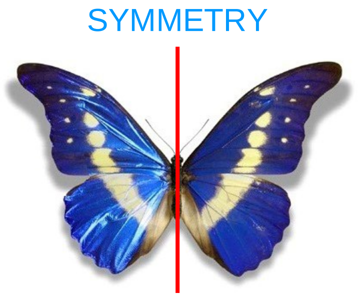
> Scientific motivation for research

Is reality invariant under symmetry transformations ?

P – parity, C – charge conjugation , T – time reversal ✗

CP - charge conjugation, and parity ✗

CPT - charge conjugation, parity, and time reversal ✓



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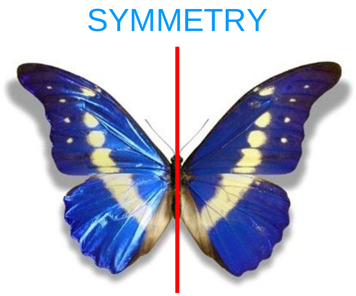

According to CPT Symmetry particles and antiparticles have:

- same mass,
- opposite charge,
- same magnetic moment
- same mean life time
- atom and anti-atom have: **same structure**

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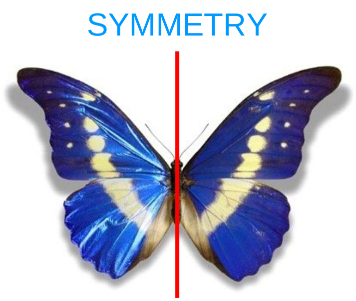

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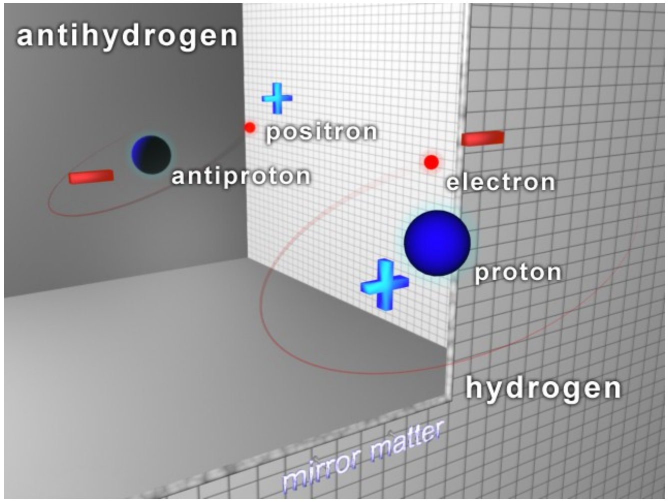


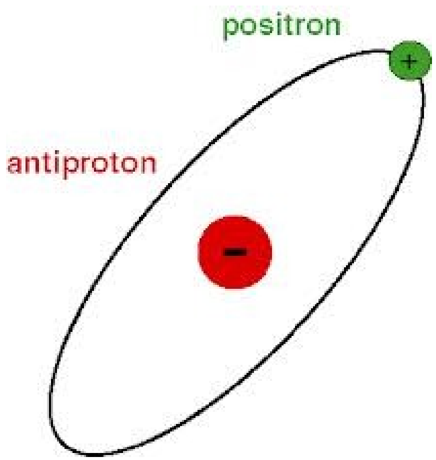
Maybe we can compare H and $\overline{\mathrm{H}}$?

> Scientific motivation for research

Original idea was formulated back in 1986 by Gerald Gabrielse*:

(* Spokesperson of the ATRAP Collaboration)

"For me, the most attractive way . . . would be to capture the antihydrogen in a neutral particle trap such as has been used for neutrons and neutral atoms. The objective would be to then study the properties of a small number of [antihydrogen] atoms conf ned in the neutral trap for a long time."



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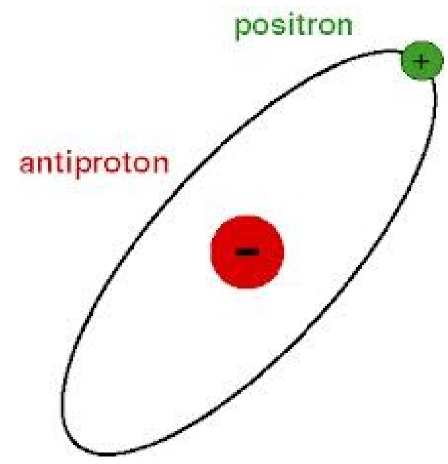

Therefore, $\bar{H}$ may hold the key to answering some of the most important questions in physics today:

1) Is CPT an exact symmetry of nature?

2) Why is there vastly more matter than antimatter in the universe?

3) Does antimatter fall under the influence of gravity in the same way as matter, or does it violate the weak equivalence principle?

> The first antihydrogen atoms

-antiprotons were shot at Xenon clusters.

-when an antiproton gets close to a Xenon nucleus, an electron-positron pair can be produced, and with some probability the positron will be captured by the antiproton to form antihydrogen.

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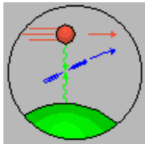
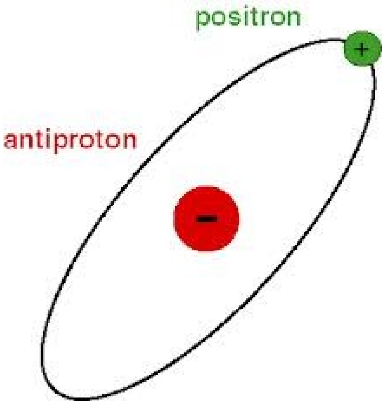
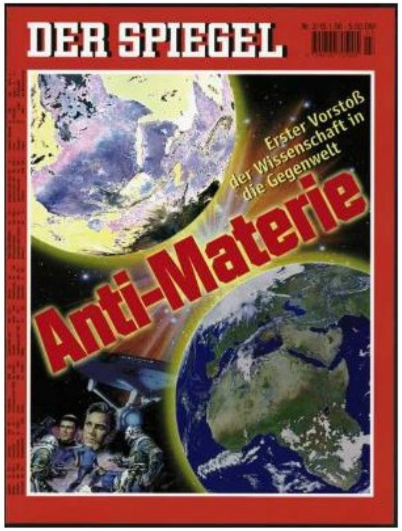
Prof. Walter Oelert


PS210

-the f rst antihydrogen was produced by a team of researchers under the lead of Prof. Walter Oelert at the CERN in experiment PS210 at LEAR facility in 1995.



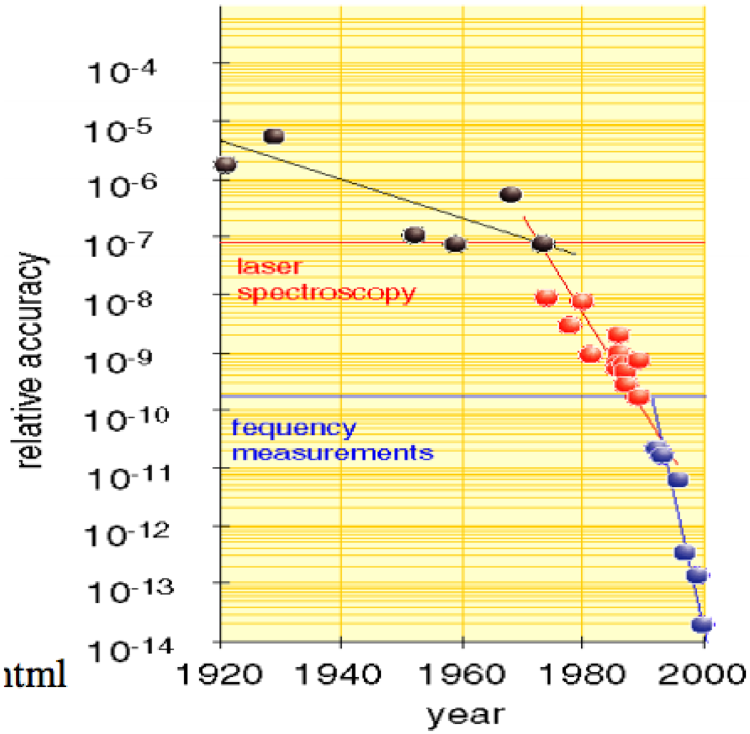


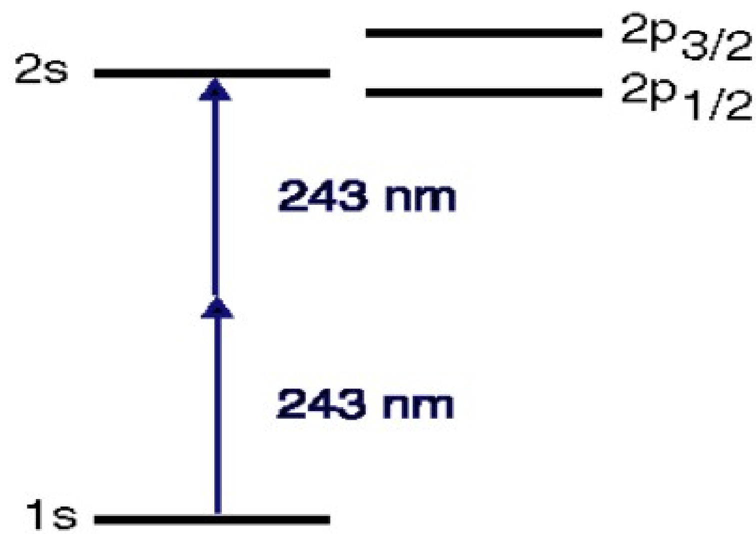
-at that time f rst 9 atoms of antihydrogen were produced, but all with relativistic velocities, making them much to „hot" to be investigated.

> 1s – 2s spectroscopy of $\overline{\mathrm{H}}$ - H (the long term goal)

- Since we do not know where violations of CPT may occur, it is important to look for them in systems that differ in significant ways.

- Comparisons of the energy level structures of H and $\overline{\mathrm{H}}$ could significantly improve upon existing tests of CPT symmetry with leptons and baryons.

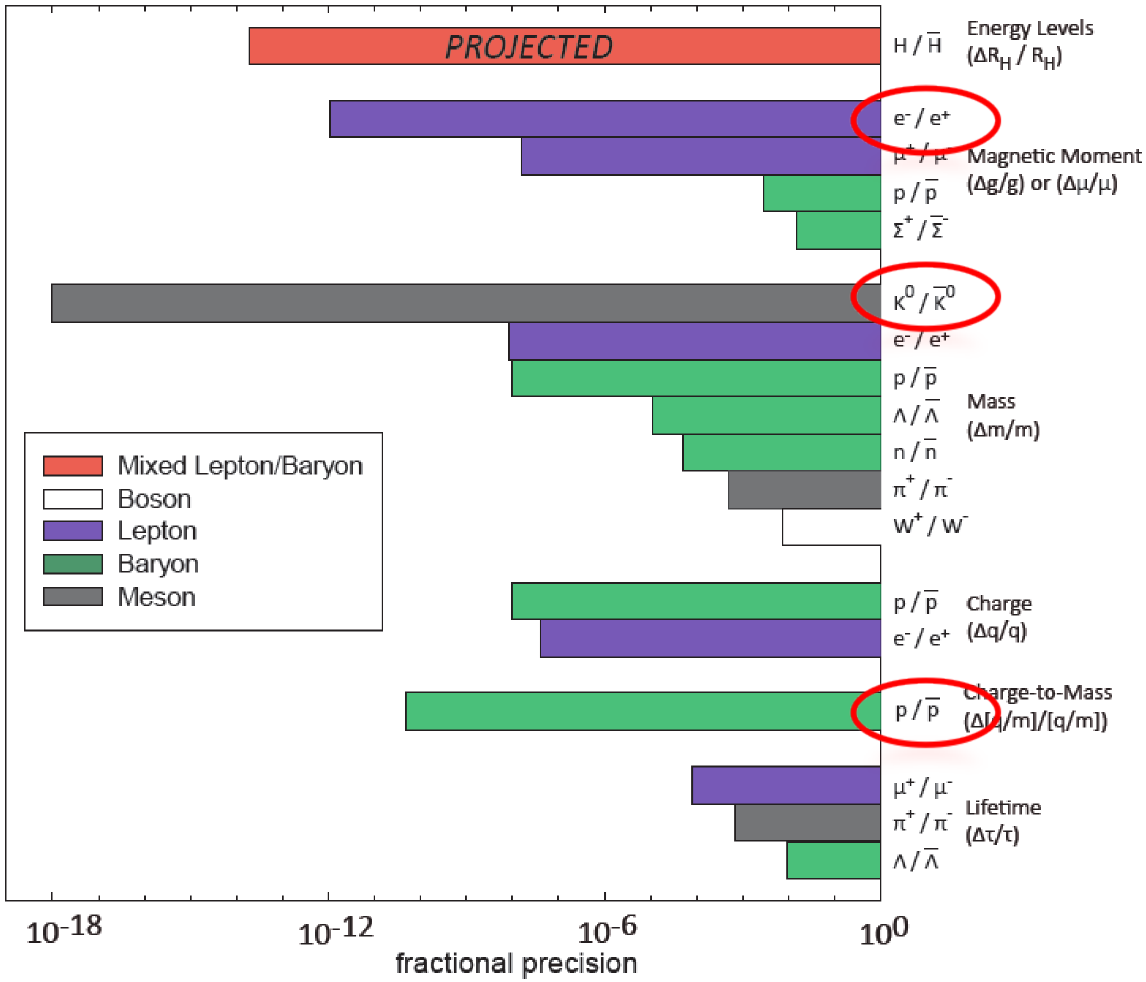




Relative accuracy of 1s – 2s in Hydrogen is 4.2×10^{-15}

C. Parthey et. al, Phys. Rev. Lett. 107, 203001 (2011)

> 1s – 2s spectroscopy of $\overline{\mathrm{H}}$ (the long term goal)

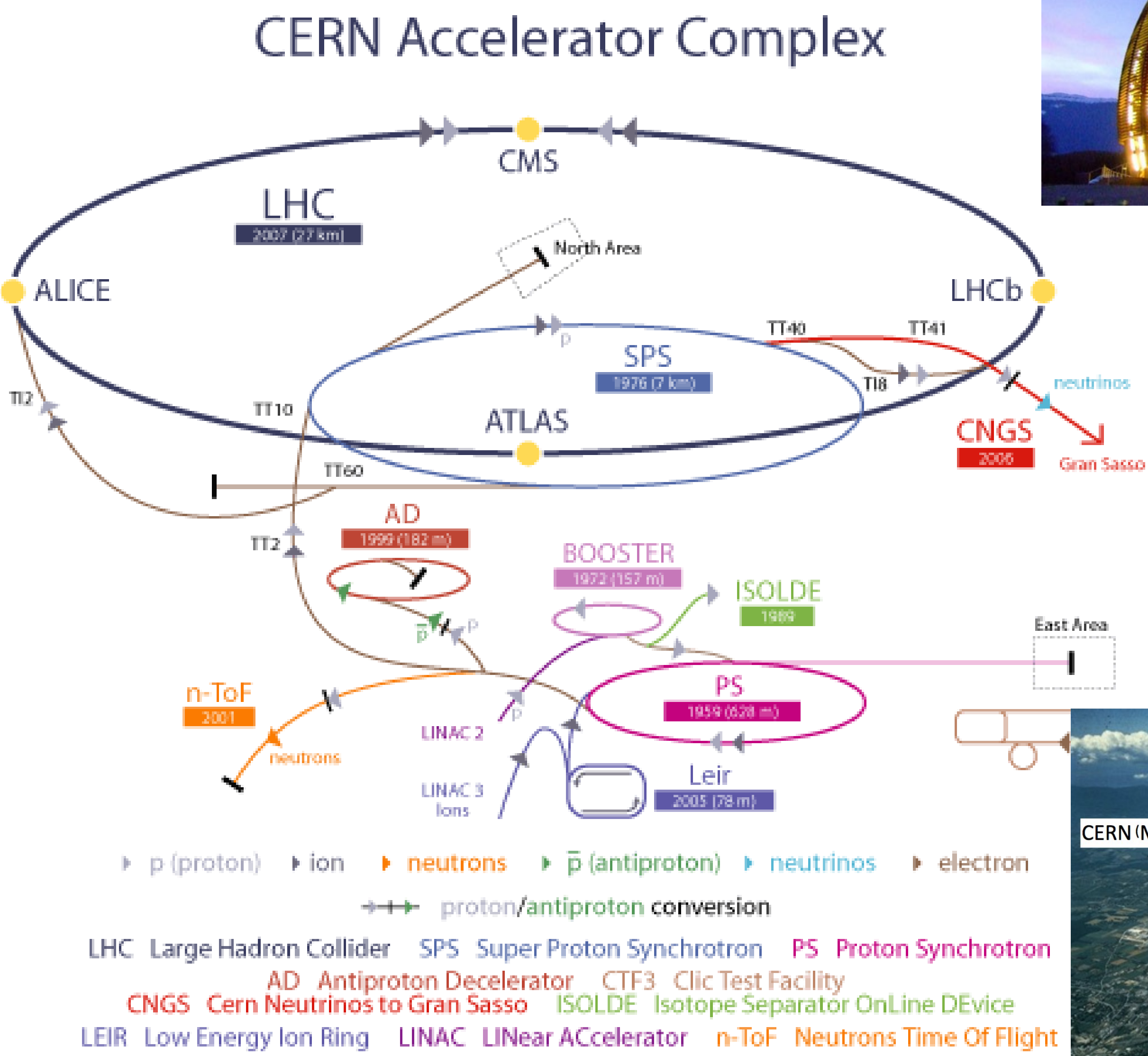


- Comparison of the projected fractional precision achievable with a 1S-2S measurement in $\overline{\mathrm{H}}$ to existing tests of CPT. Values taken from the best measurement of the 1s-2s line in H and tables compiled by the PDG.

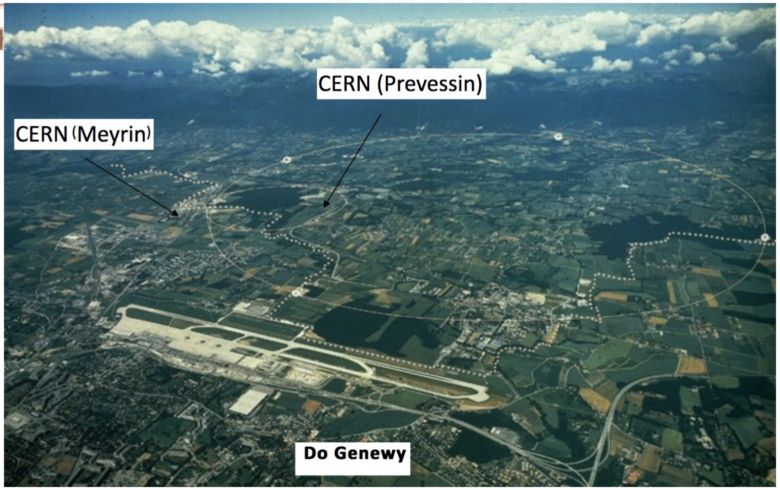
- In addition 1s - 2s spectroscopy in $\overline{\mathrm{H}}$ could also improve lepton and baryon measurements. Comparison of the 1s - 2s line in H and $\overline{\mathrm{H}}$ directly compares the Rydberg constants for both systems.

$$\frac{R_{\overline{\mathrm{H}}}}{R_{\mathrm{H}}} = \left(\frac{m_{e^+}}{m_{e^-}}\right)\left(\frac{q_{e^+}}{q_{e^-}}\right)^2\left(\frac{q_{\overline{p}}}{q_p}\right)^2\left(\frac{1+m_{e^-}/m_p}{1+m_{e^+}/m_{\overline{p}}}\right)$$

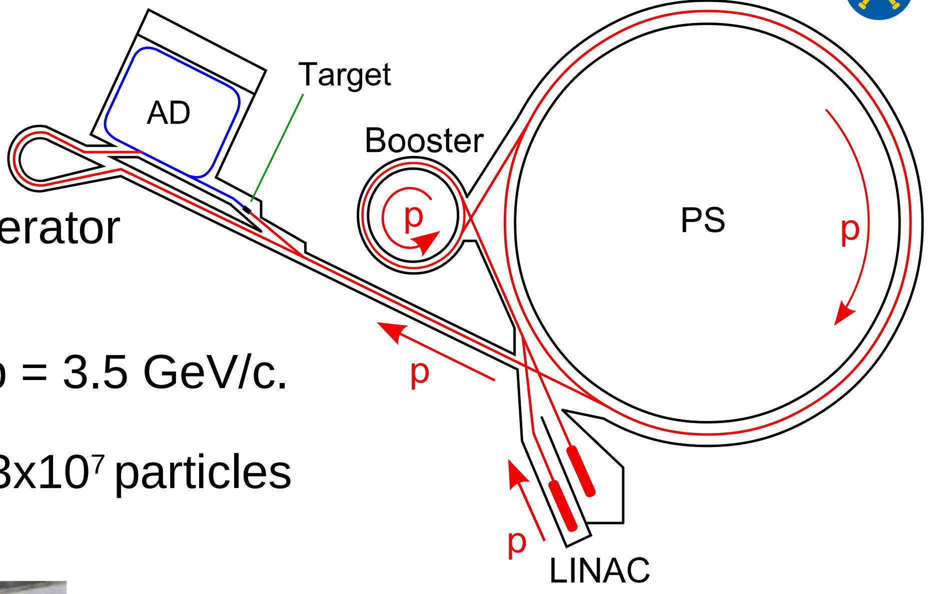
> CERN Complex



European Organization for Nuclear Research



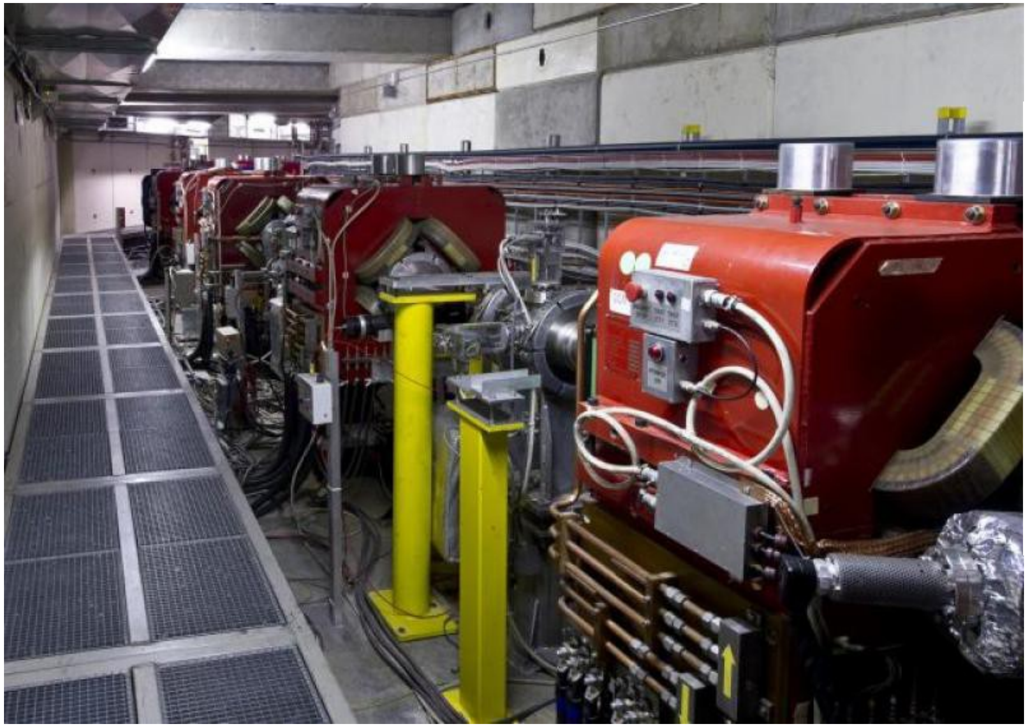
> AD – Antiproton Decelerator



- Antiprotons are made by colliding proton beam of p = 26 GeV/c served by PS accelerator on a iridium target.

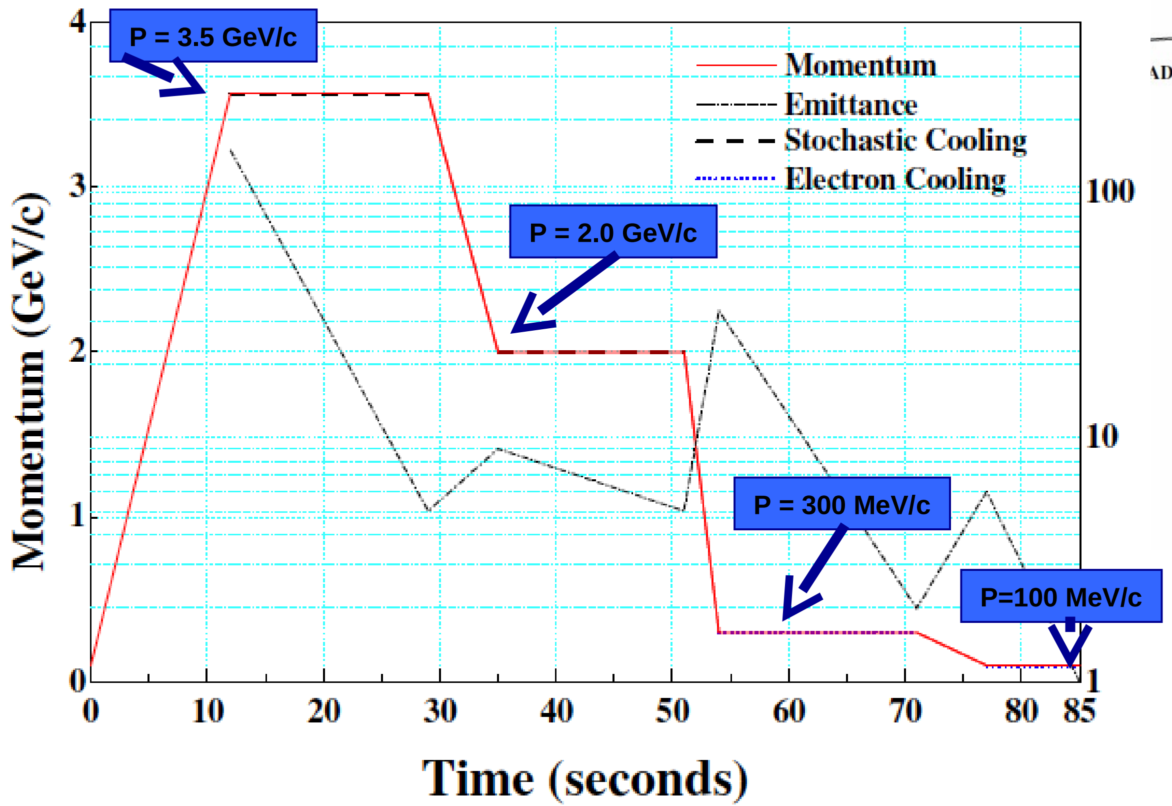
- Initial antiproton beam injected to AD has p = 3.5 GeV/c.

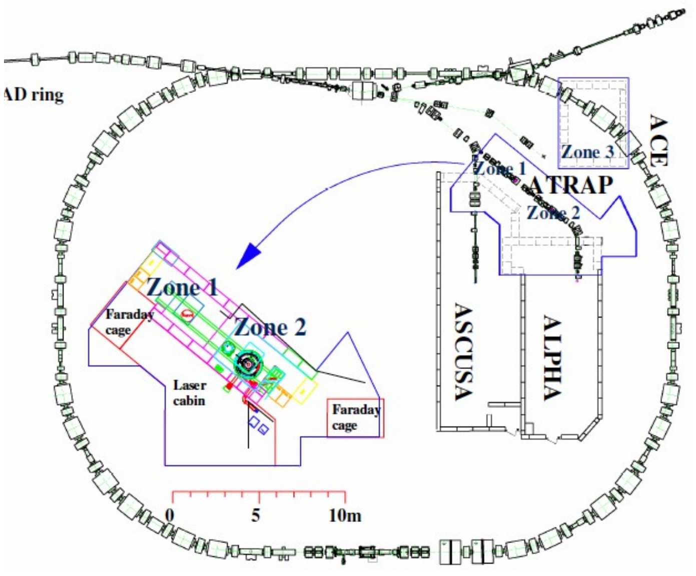
- Deceleration of antiproton bunch of about 3×10^7 particles takes about 90 seconds.



Antimatter FACTORY

> AD cycle of antiproton deceleration



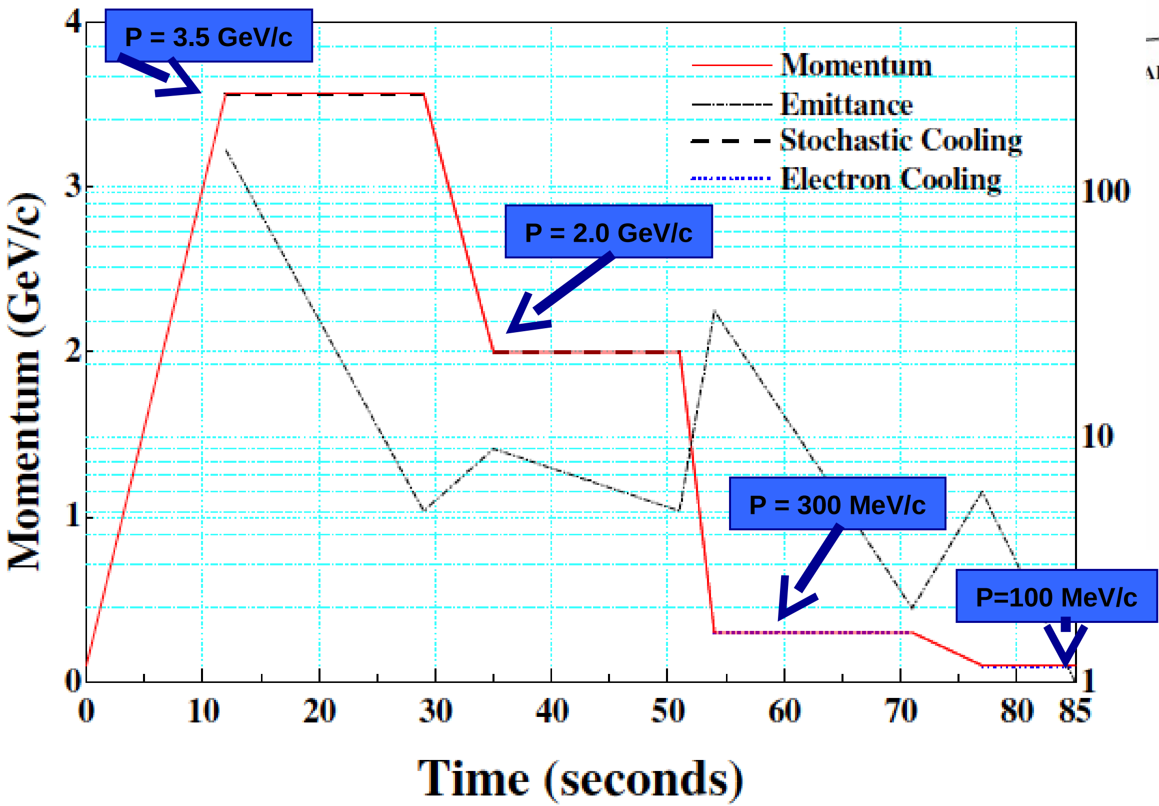


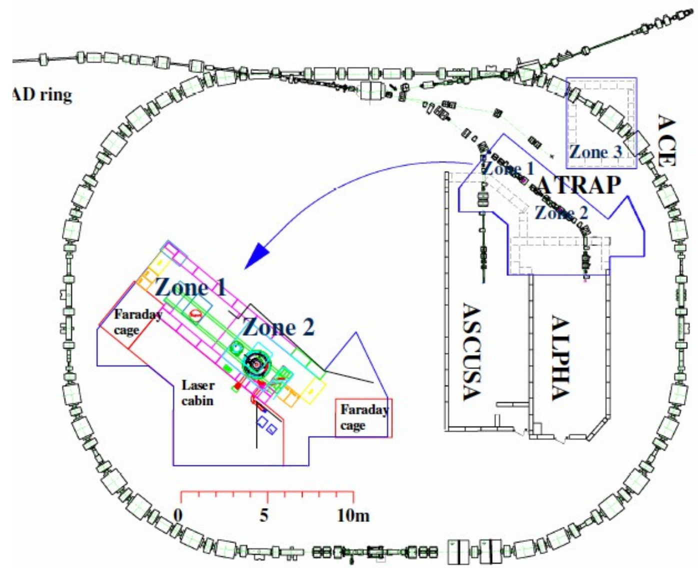
P = 100 MeV/c
E = 5.3 MeV

Cycle : < 3 · 10^7 / 90 s

- First the stochastic cooling is used to reduce spatial emittance and momentum spread.
- Next the beam is decelerated to 2 GeV/c and again stochastic cooling is applied.
- Electron cooling is used after subsequent deceleration to 300 MeV/c and 100 MeV/c.

> AD cycle of antiproton deceleration





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How to improve cooling of antiprotons ?

ELENA Project
Talk by Prof. Walter Oelert at 11:40

ELENA

> AD – Antiproton Decelerator

Presently AD serves beam to 6 experiments:

AD-2 : *(ATRAP)* Cold Antihydrogen for Precise Laser Spectroscopy

AD-3 : *(ASACUSA)* Atomic Spectroscopy and Collisions Using Slow Antiprotons

AD-4 : *(ACE)* Relative Biological Effectiveness and Peripheral Damage of Antiproton Annihilation

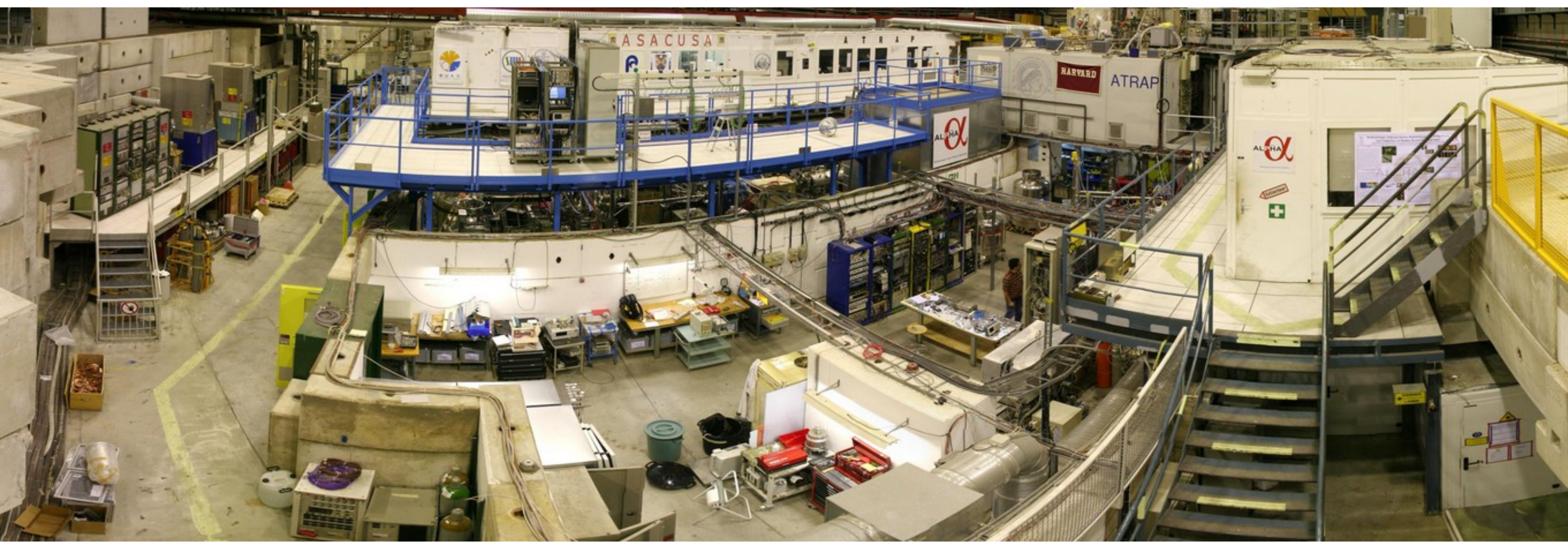
AD-5 : *(ALPHA)* Antihydrogen Laser PHysics Apparatus

AD-6 : *(AEGIS) Antihydrogen Experiment Gravity Interferometry Spectroscopy*

AD-8 : *(BASE)* Baryon Antibaryon Symmetry Experiment

In preparation:

AD-7 : GBAR



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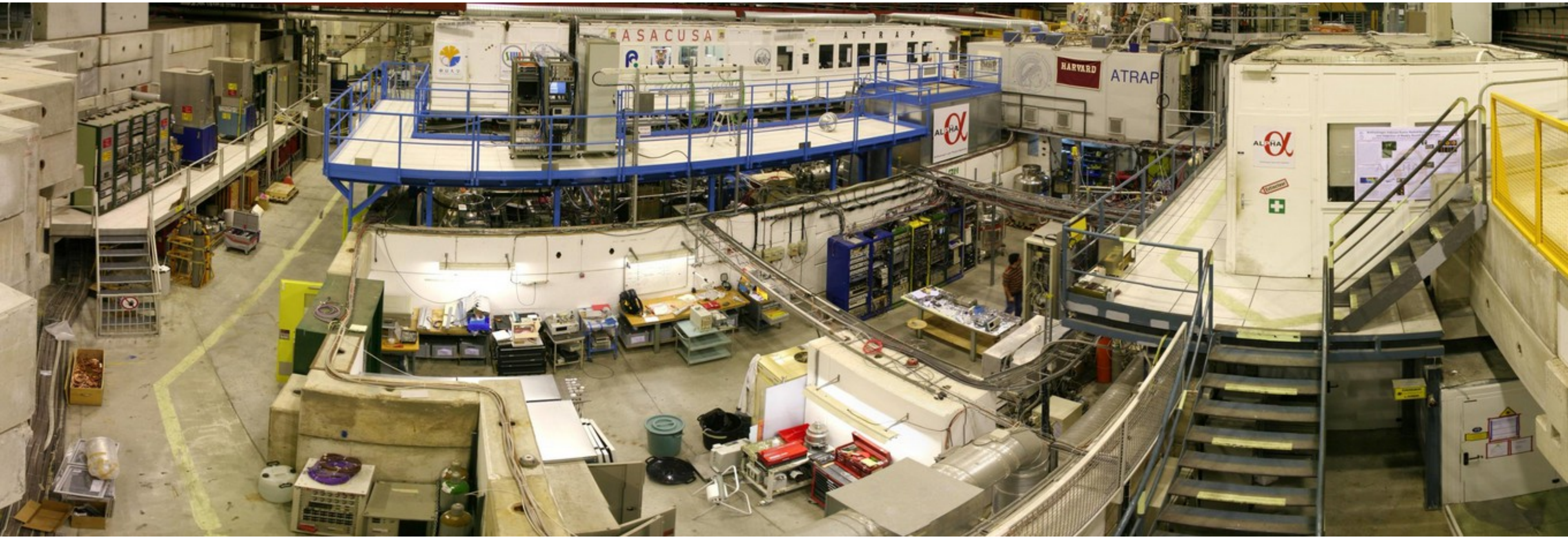
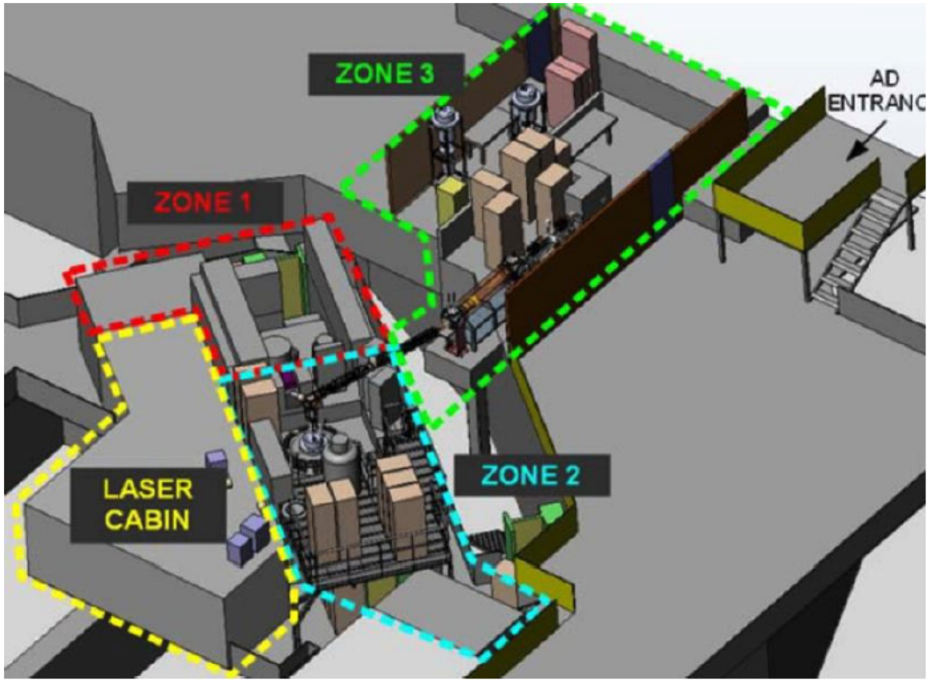
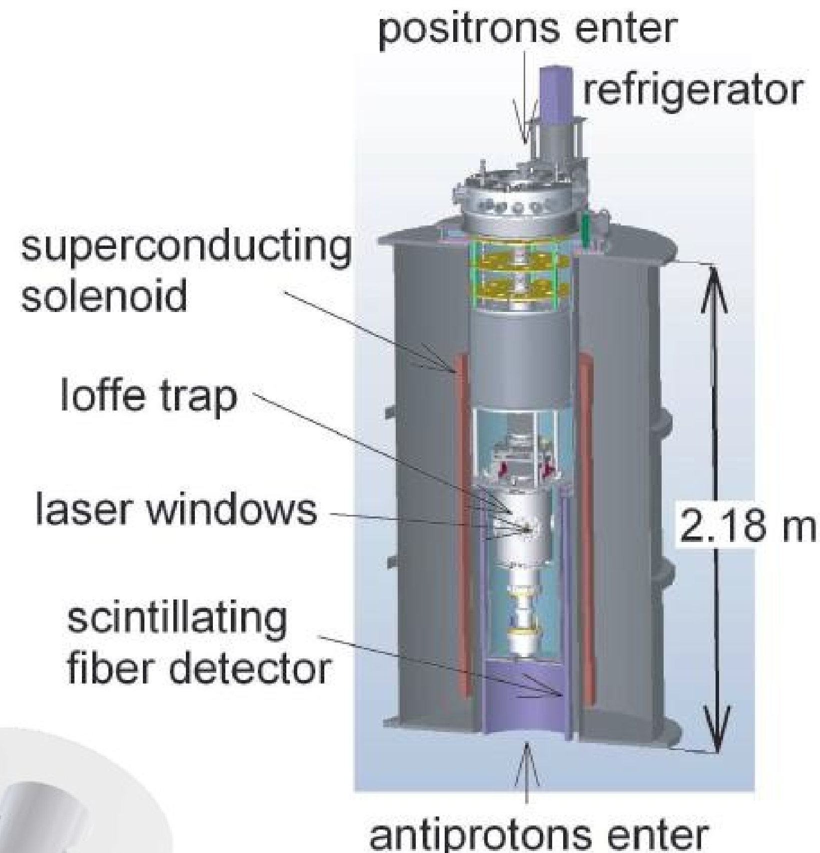


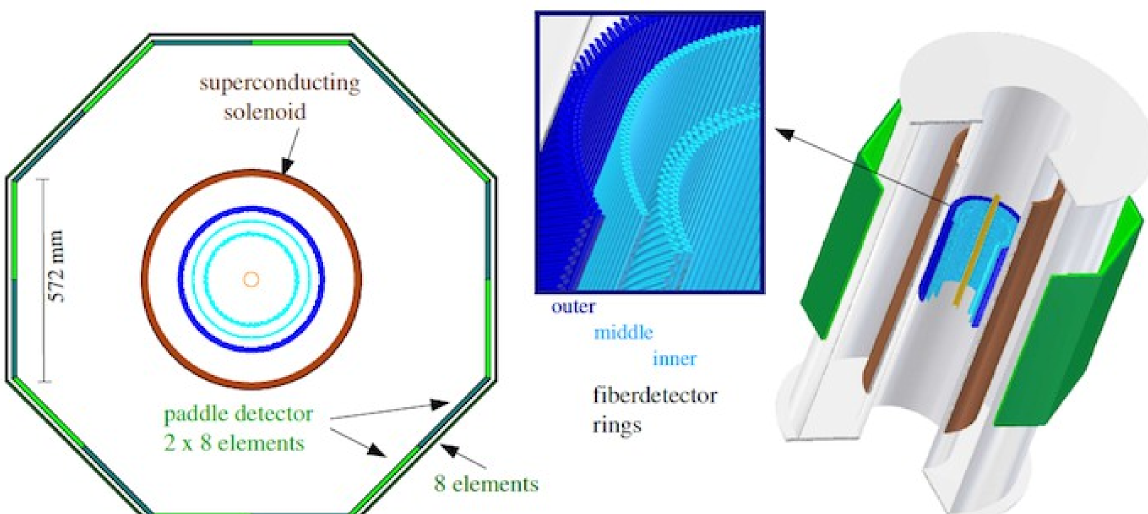
> ATRAP Collaboration

HARVARD UNIVERSITY	G. Gabrielse, K. Marable, M. Marshall, E. Tardiff, R. Kalra, C.D. Hamley, N. Jones	A
YORK UNIVERSITÉ UNIVERSITY	E. Hessels, C. Storry, D. Fitzakerley, M. George, M. Weel, T.D.G. Skinner	T
JÜLICH FORSCHUNGSZENTRUM	D. Grzonka, T. Seftzik	R
JG|U JOHANNES GUTENBERG UNIVERSITÄT MAINZ	W. Oelert , J. Walz,	A
JAGIELLONIAN UNIVERSITY IN KRAKOW	M. Zielinski	P

> ATRAP apparatus







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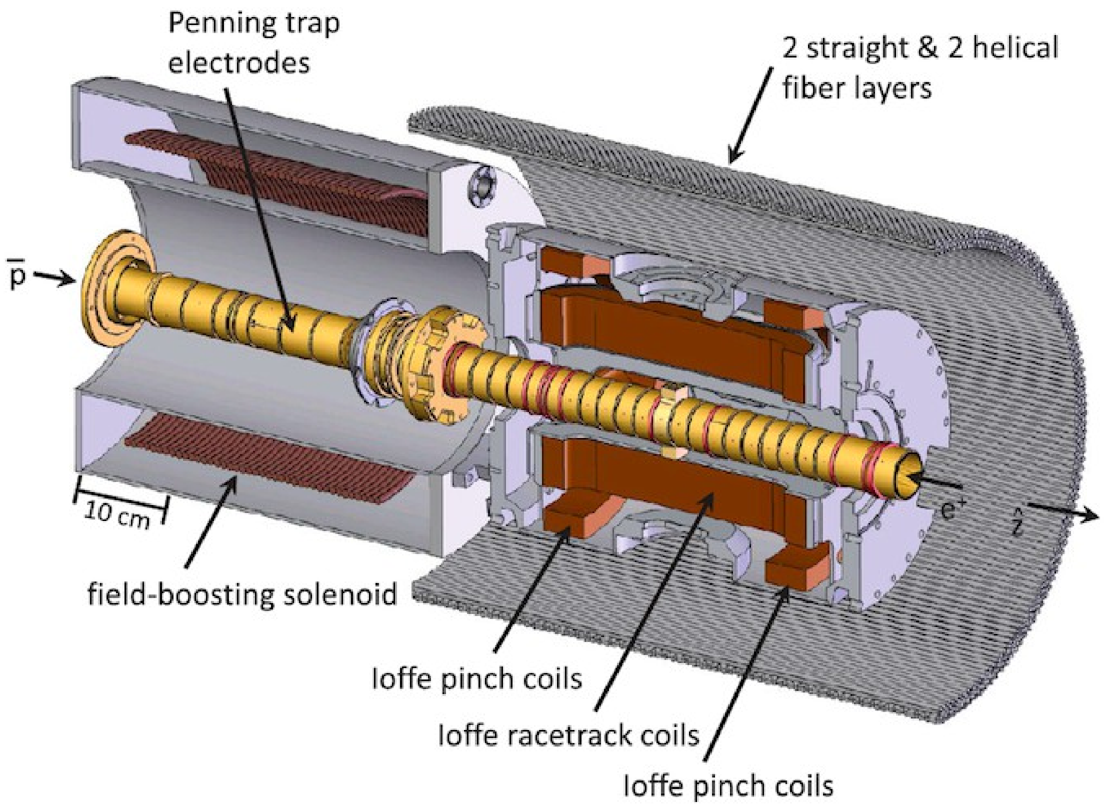
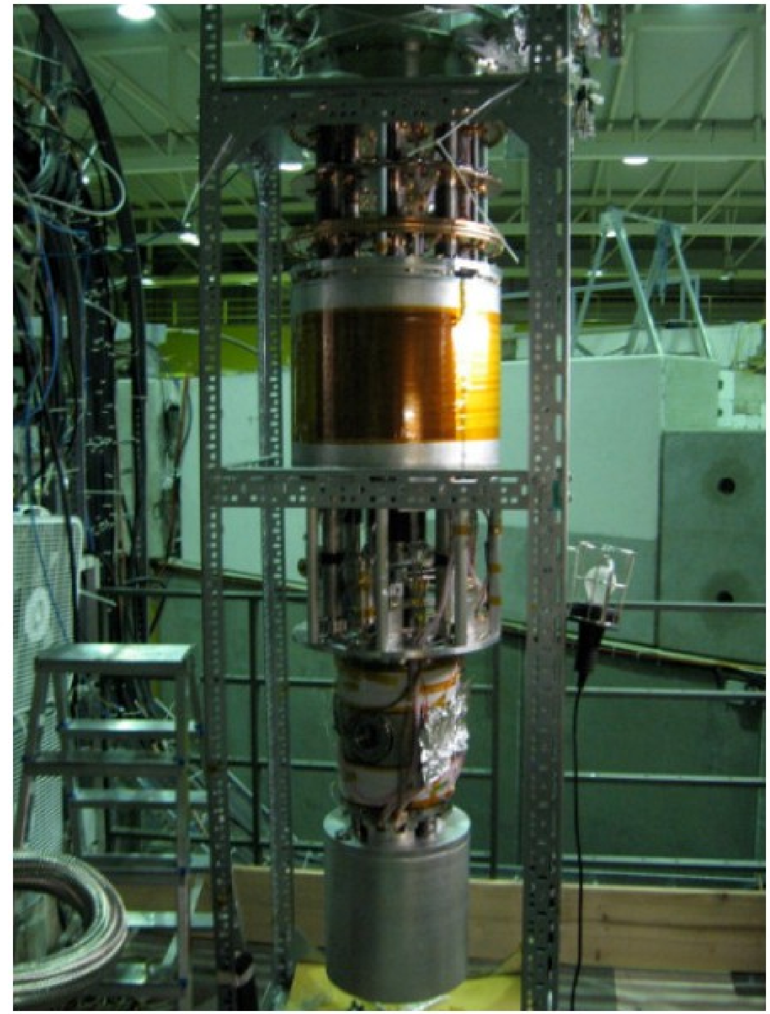
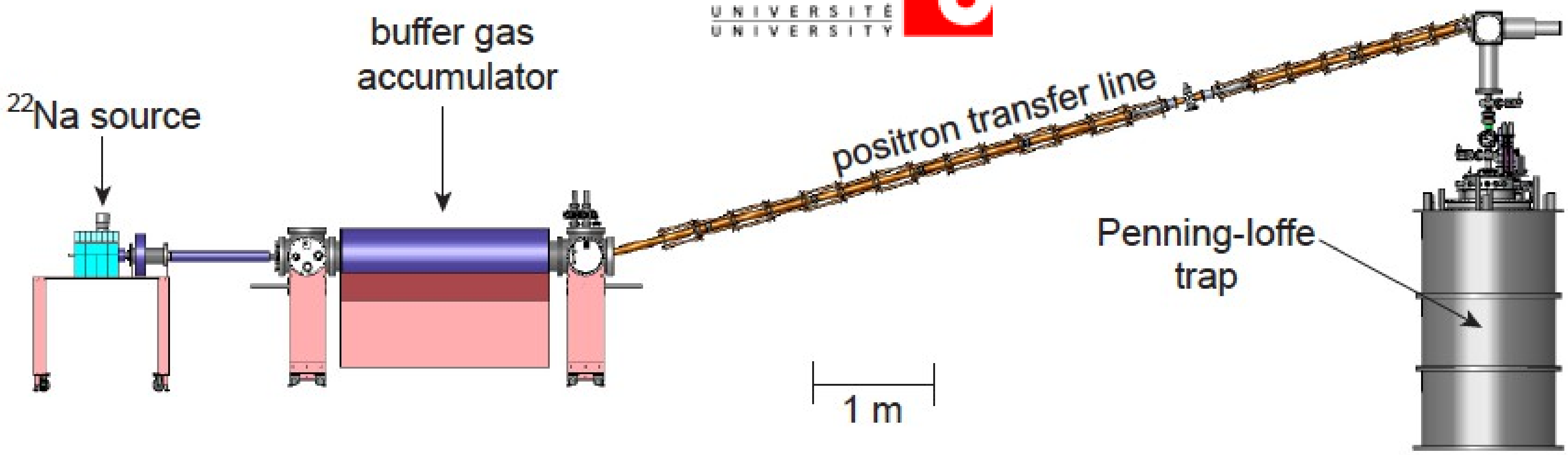




> Positrons production



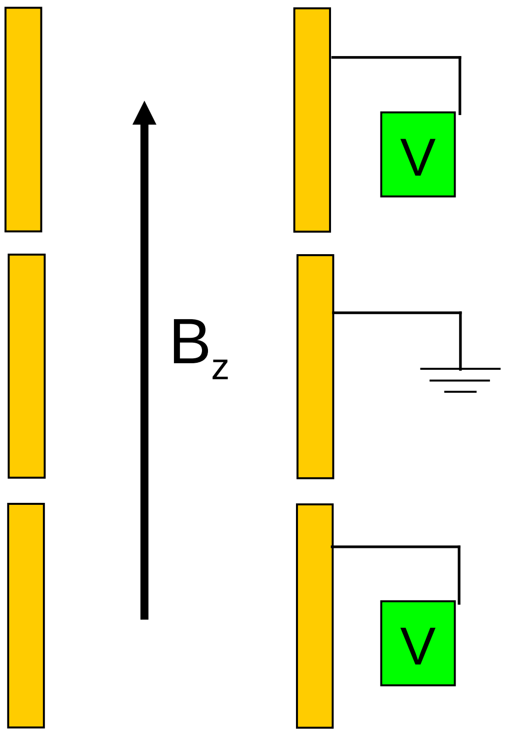
- A radioactive ^{22}Na source supplies the e^+ used for $\overline{H}$ experiments.

- High energy e^+ emitted in a reverse-beta decay process pass through a solid neon moderator reducing their energy to 15 eV.

- Next low energy e^+ are accumulated and transported though a 9.5 m magnetic guide to enter the trap.

-Approximately $3x10^7$ e^+ are transferred to experiment area and placed in the center of the trap.

> How does the Penning trap work?

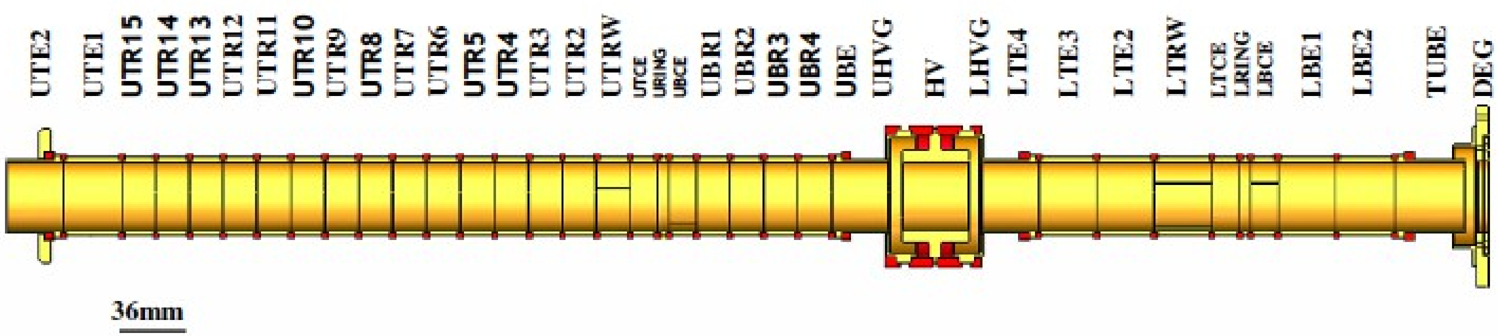


- Penning trap confines charged particles using a combination of static magnetic and electric fields with the motion governed by the Lorentz force law:

$$\vec{F} = q(\vec{E} + \vec{v} \times \vec{B}).$$

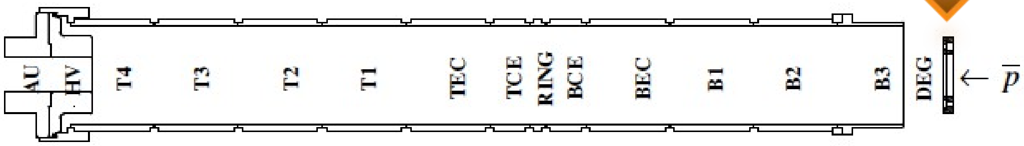
-Classically, a charged particle in a magnetic field executes a cyclotron motion around a field line. This confines the particle radially, though it is free to move along the direction of the magnetic field.

- Trapping along the third dimension may then be accomplished via the addition of a confining electric field.



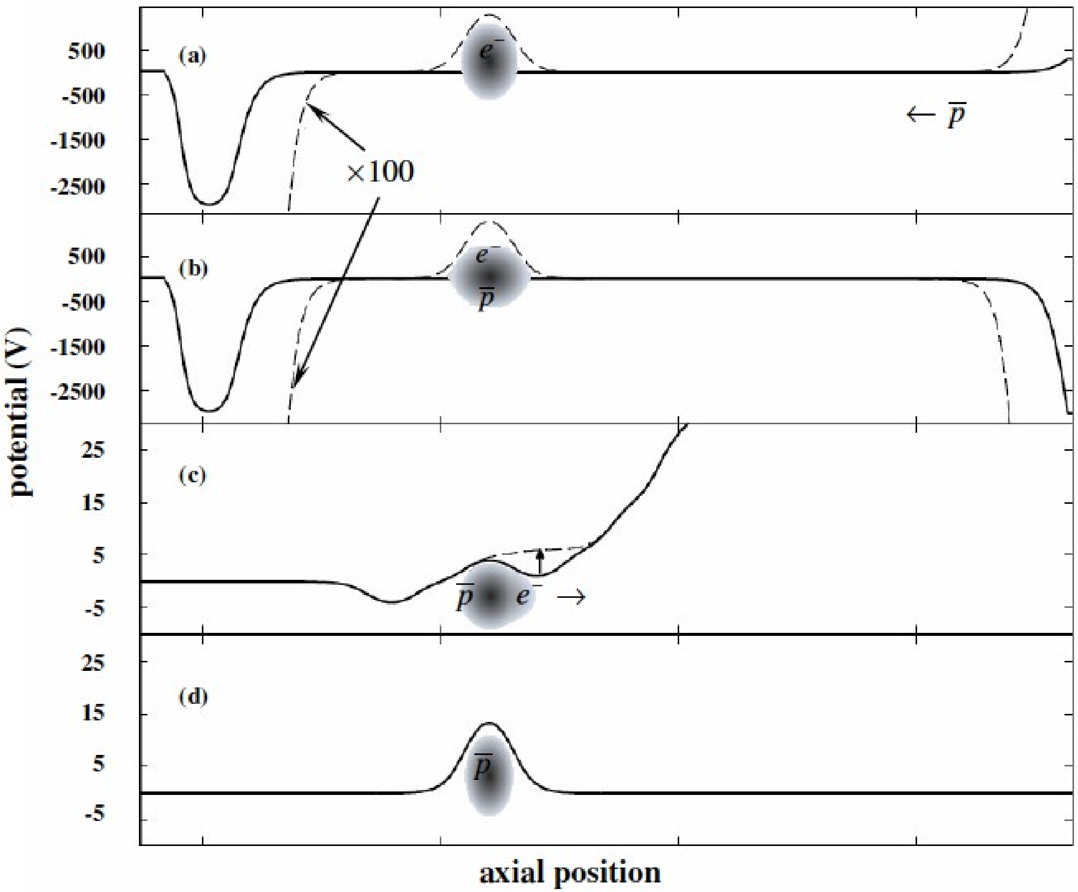
> Loading of antiprotons

T < 5 keV



AD:

P=100 MeV/c
T=5.3 MeV



1) Loading antiprotons (DEG ~ 600V)

2) Closing the well (DEG < -5keV) anitiprotons cooled with electrons.

3) Unloading the electrons.

4) The process is repeated to stack large number of antiprotons.

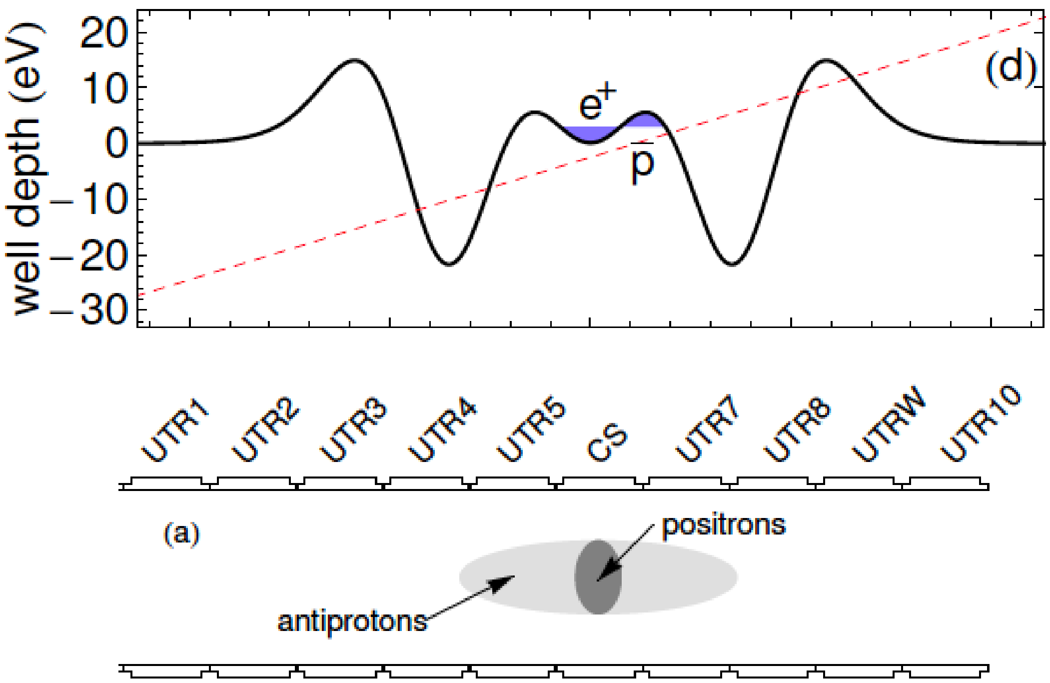
Typically during this procedure (which takes 1 h – 1.5 h) 10^7 antiprotons are accumulated.

> Antihydrogen production and trapping

- To synthesize $\overline{H}$, an initially free $\overline{p}$ and e^+ must bind together, and a third body must carry away the excess energy and momentum.

- In our studies we use antihydrogen production by the three-body recombination process:

$$\overline{p} + e^+ + e^+ \rightarrow \overline{H} + e^+$$



- Antihydrogen production and trapping last from 2 ms to 15 min.

- Antihydrogen storage times ranges from 15 – 1000 s.

- Antihydrogen atoms are conf ned by the Penning-Ioffe trap

Alternative: Laser controlled, two stage charge exchange process which is also now studied by ATRAP

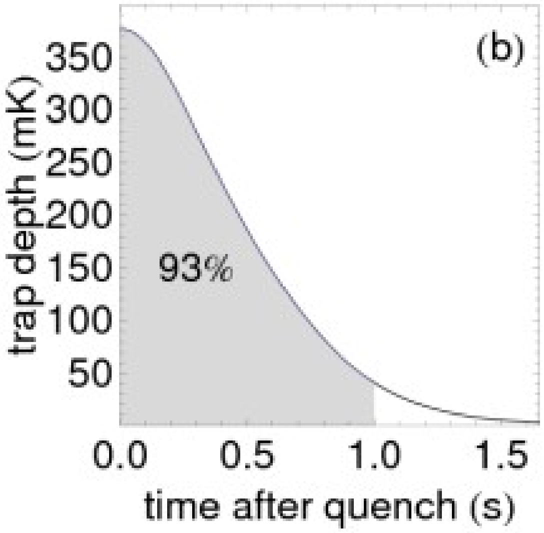
> Antihydrogen production and trapping

-After the time remaining in the Penning-Ioffe trap antihydrogen atoms are released by quenching the Ioffe trap by applying a hit pulse.

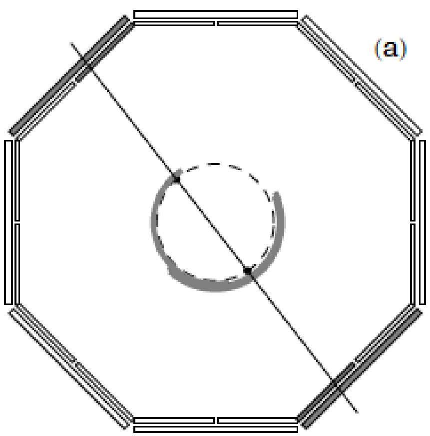
- After the quench in 1 s more then 90% of produced antihydrogen atoms will leave the trap.

- Released antihydrogen goes to the trap walls and annihilates.

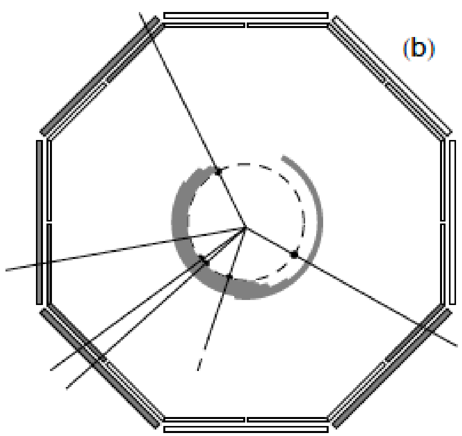
- Annihilations are detected by the 4 layers of scintillating f bers and 2 layers of scintillating paddles.



- Coincidence between paddles and f bers detect annihilations with the 54% eff ciency.

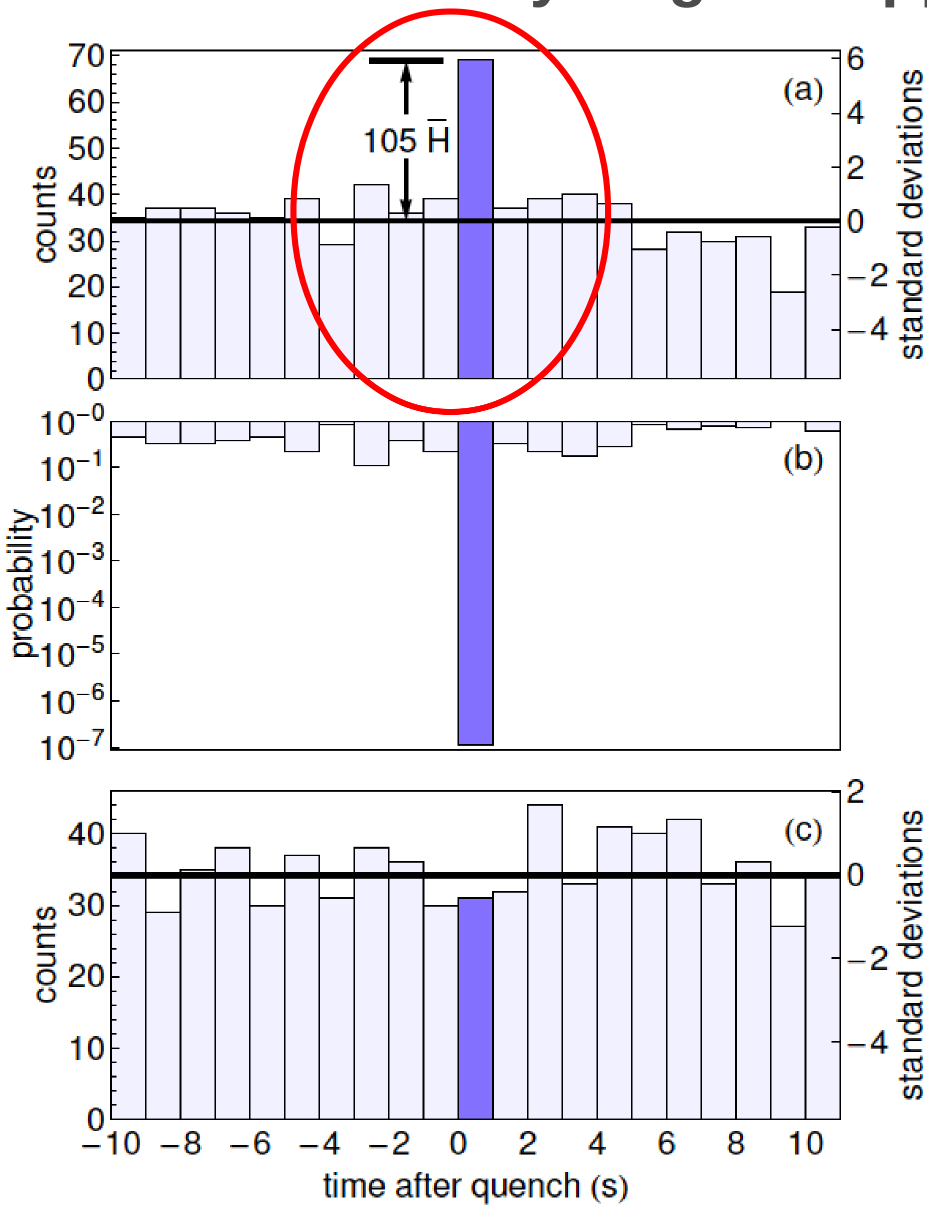


Cosmic event (straight line)



Antiproton annihilation

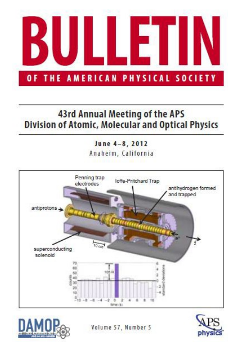
> Results: Antihydrogen trapping



Signal is during the 1 second quench window
(20 trials averaged together)

1 chance in 107 that such a signal comes from the cosmic ray background

Control trial: quench without particles.



ATRAP Collaboration, Phys. Rev. Lett. 108, 113002 (2012)

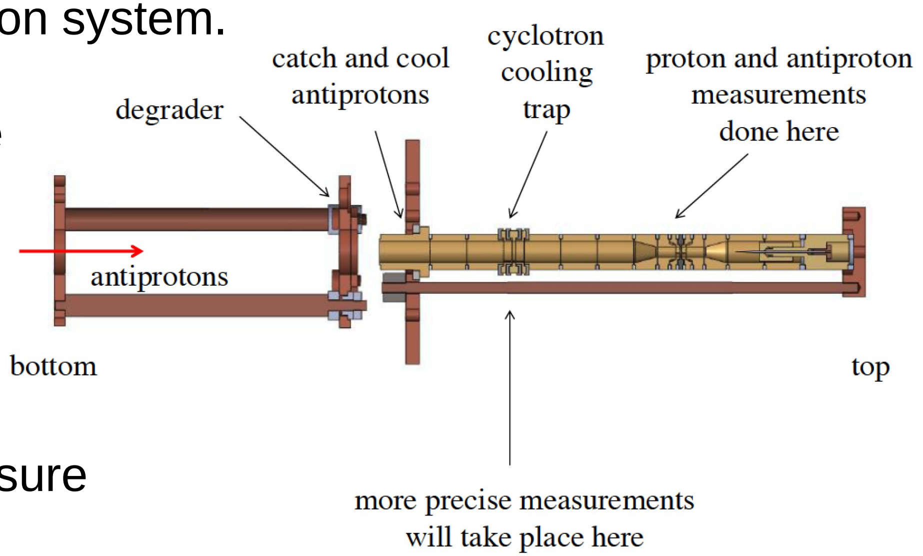
> Results: Antiproton magnetic moment

- Precise test of CPT with baryon – antibaryon system.

- Magnetic moments of p and $\bar{p}$ should have the same magnitude and opposite sign.

$$\boldsymbol{\mu}_{\bar{p}} = \mu_{\bar{p}} \boldsymbol{S}/(\hbar/2)$$

- ATRAP used the single antiproton to measure its magnetic moment.



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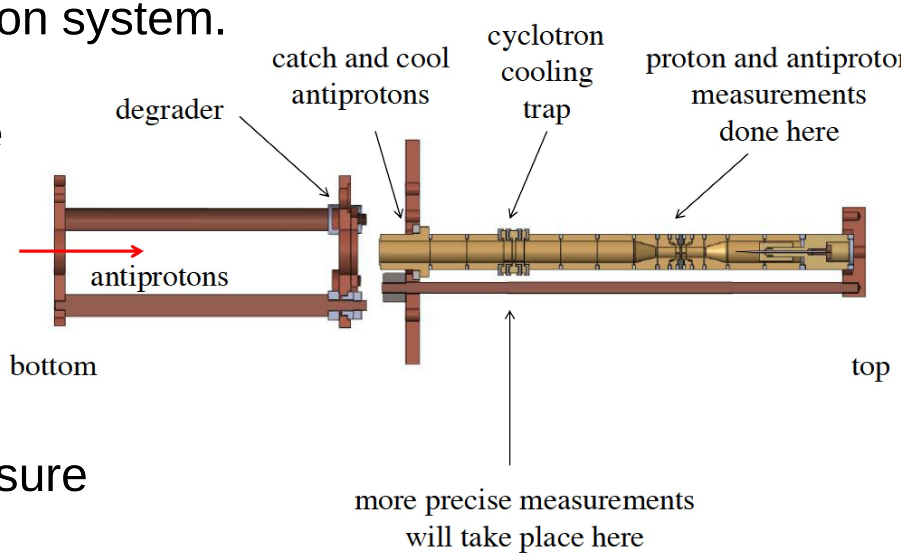
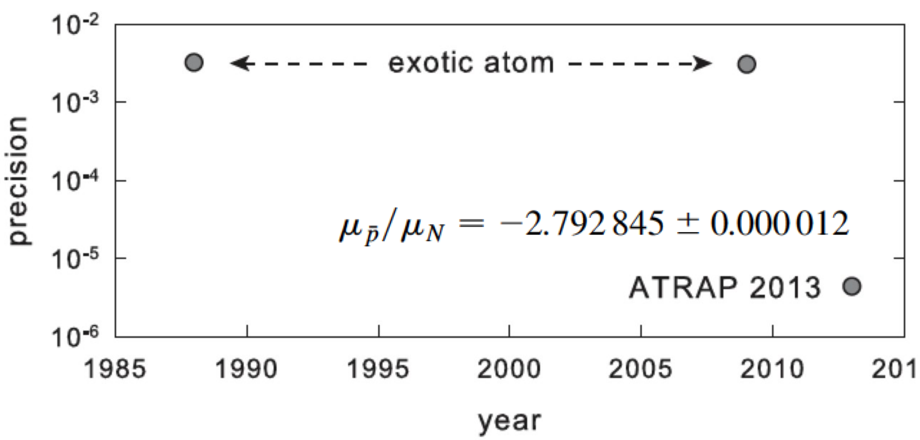


- ATRAP used the single antiproton to measure its magnetic moment.

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

$$\mu_{\bar{p}}/\mu_p = -0.999\,999\,2 \pm 0.000\,004\,4 \quad [4.4 \text{ ppm}],$$



Uncertainties in measurements of the $\bar{p}$ magnetic moment measured in nuclear magnetons.

Already one of the most precise antimatter-matter comparisons which is consistent with the CPT theorem.

ATRAP Collaboration, Phys. Rev. Lett. 110, 130801 (2013)

> Outlook

- New generation of traps and detection systems are installed now in CERN, they should increase the number of trapped antihydrogen atoms.

- More precise method of plasma manipulations are tested and developed.

- Charge exchange methods for more efficient antihydrogen production are being tested.

- More efficient utilisation of antiprotons will be possible with the ELENA project.

Thank you !