JAGIELLONIAN UNIVERSITY
IN KRAKOW

Investigations of antihydrogen atoms with ATRAP experiment at CERN

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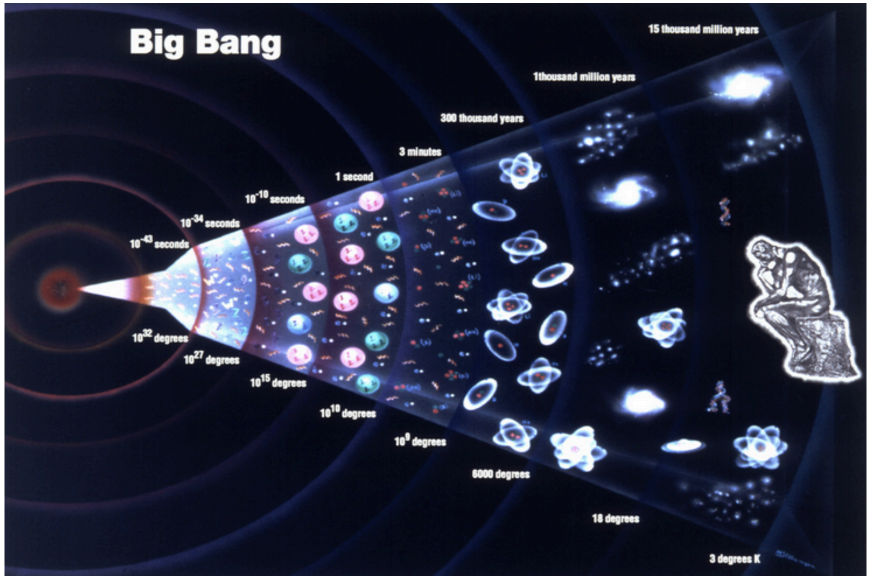
Symposium on applied nuclear physics and innovative technologies

Kraków, 05.06.2013

> 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

Baryon - Antibaryon asymmetry in Universe is not understood!

Our experimental way to search for the answer:

looking for evidence that antiparticles and particles may differ!!

> Scientific motivation for research

Reality is Invariant under symmetry transformations:

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

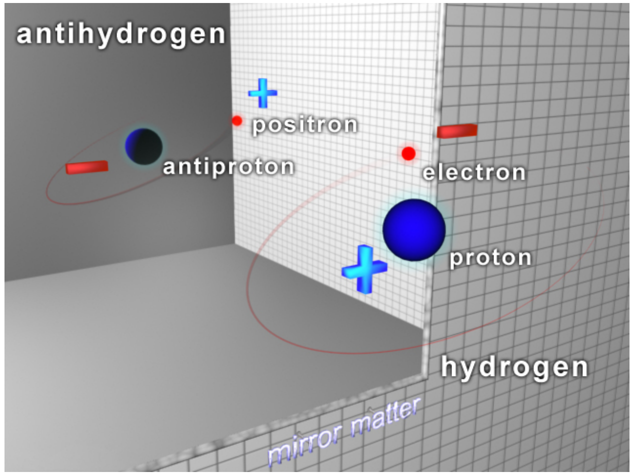
CP - charge conjugation, and parity

CPT - charge conjugation, parity, and time reversal

Accoarding to CPT Symmetry particles and antiparticles have:

- same mass,
- opposite charge,
- same magnetic moment
- same mean life time
- atom and anti-atom have: <u>same structure</u>

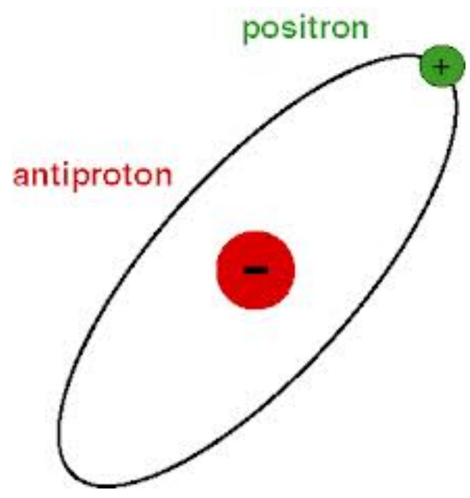
Maybe we can compare H and $\overline{H}$?



> Scientific motivation for research

Original idea was formulated back in 1986 by Gerald Gabrielse:

"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 confined in the neutral trap for a long time."



Therefore, $\overline{\mathrm{H}}$ 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

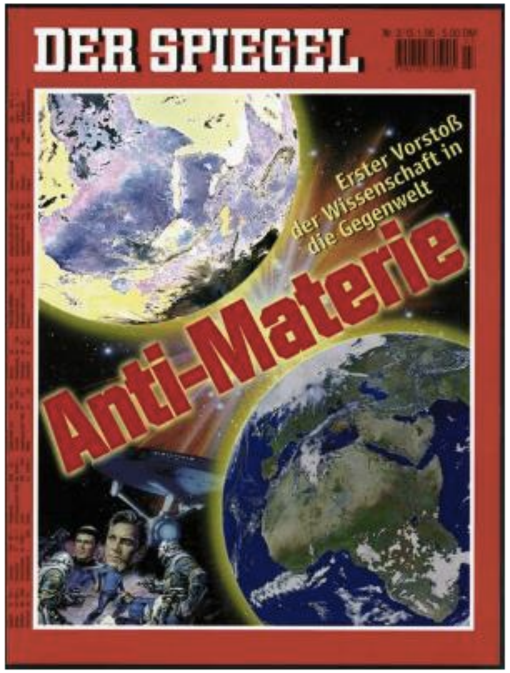
- the first antihydrogen was produced by a team of researchers under the lead of Prof. Walter Oelert at the CERN in experiment PS210 at LEAR facillity in 1995.

- 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.

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

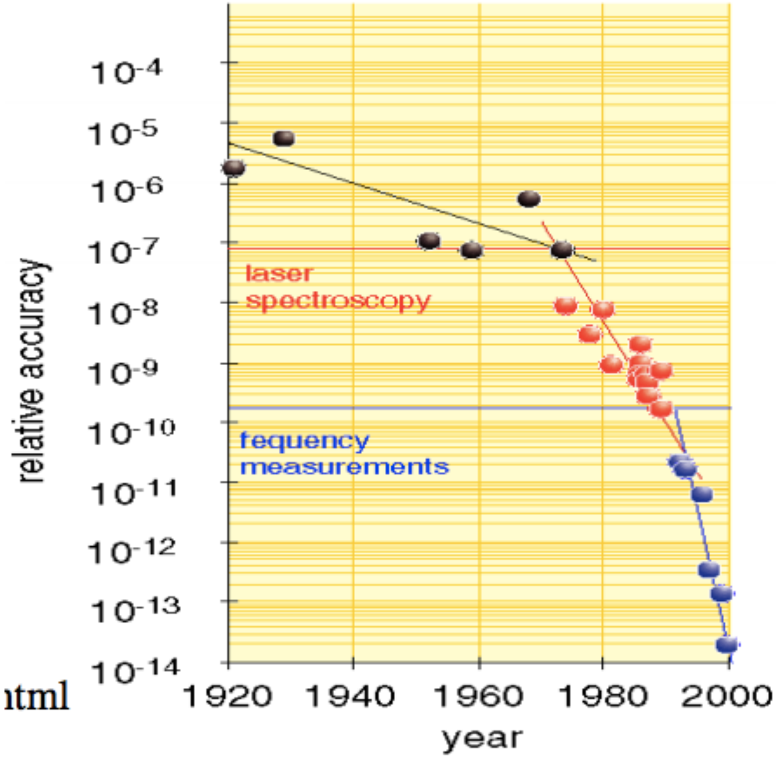
Prof. Walter Oelert

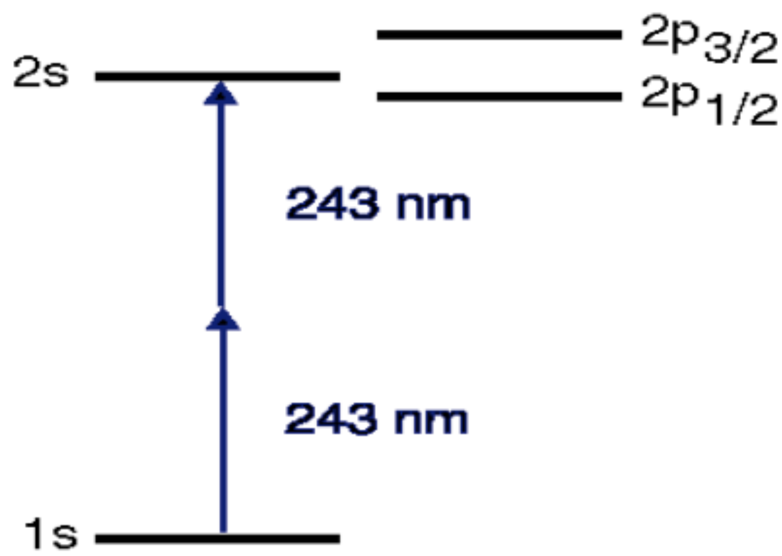


> 1s – 2s spectroscopy of $\overline{H}$ - H (the long term goal)

- Since we do not know where violations in 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 $\overline{H}$ could significantly improve upon existing tests of CPT symmetry with leptons and baryons.

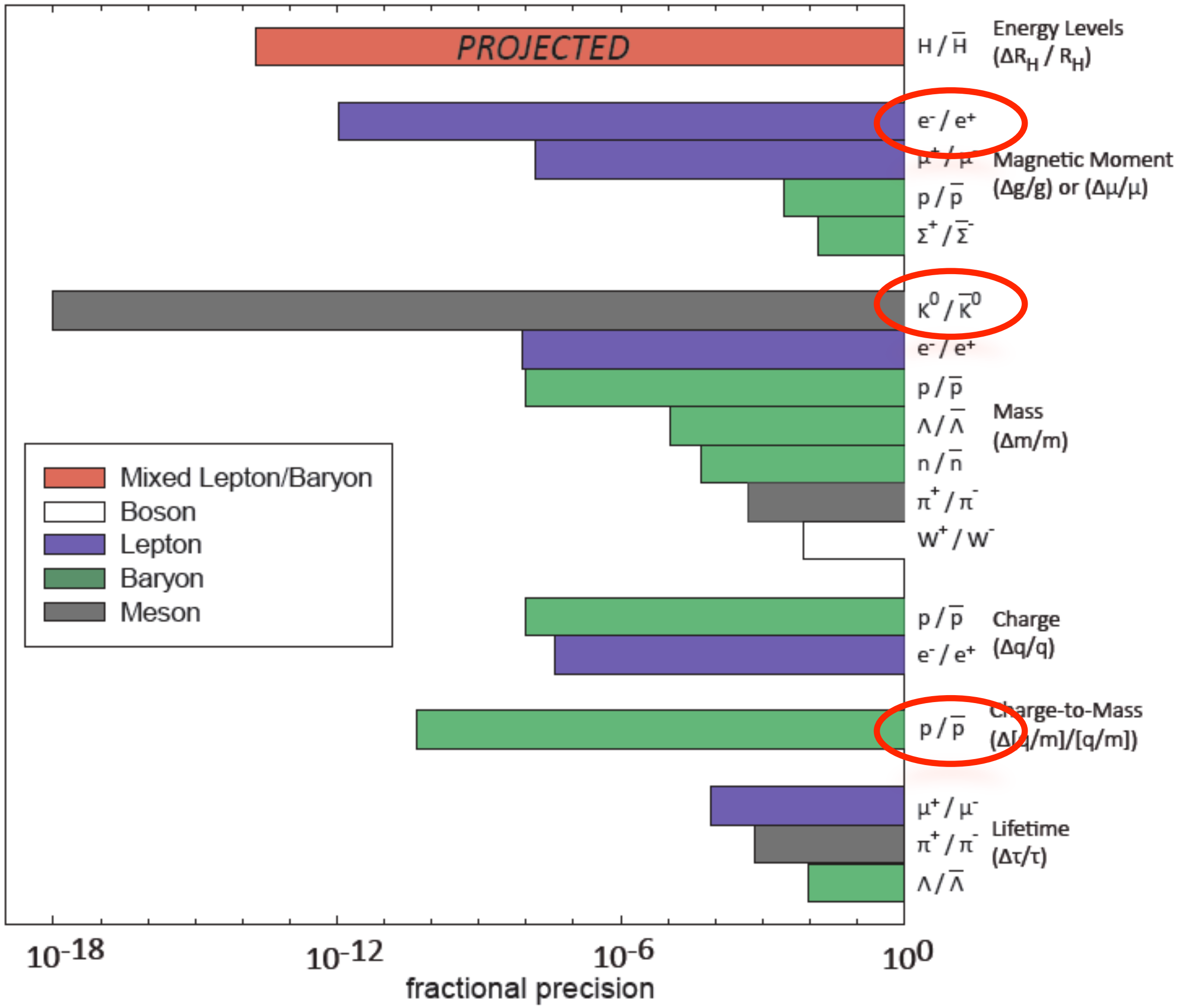




Relative accuracy of 1s – 2s in Hydrogen is 4.2×10^{-15}

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.

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

> ATRAP Collaboration

HARVARD UNIVERSITY	G. Gabrielse, J. DiSciacca, S. Ettenauer, K. Marable, M. Marshall, E. Tardi, R. Kalra	A
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JÜLICH FORSCHUNGSZENTRUM	W. Oelert, D. Grzonka, T. Seftzik	R
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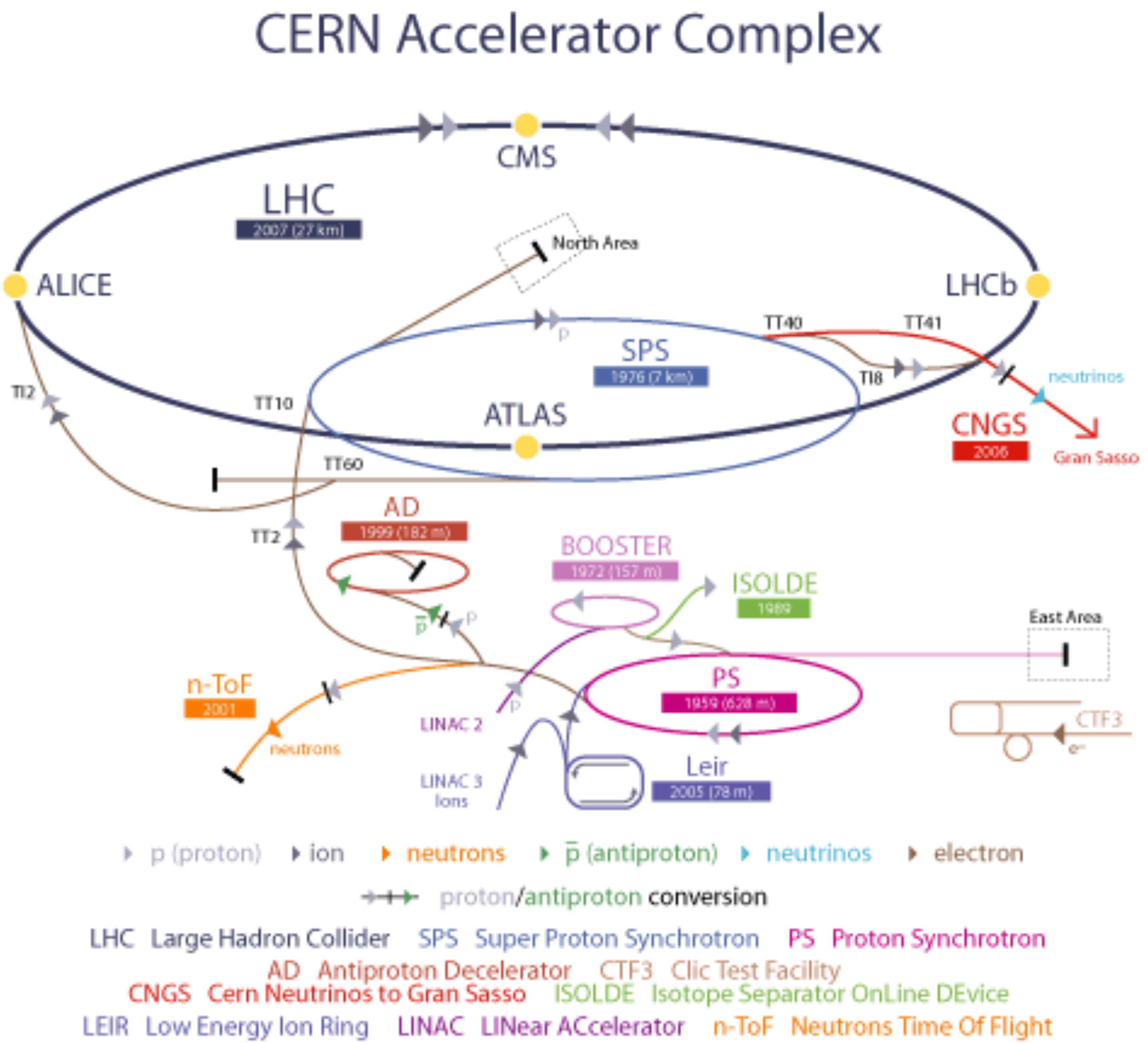
JAGIELLONIAN UNIVERSITY IN KRAKOW	M. Zieliński	P

> CERN Complex



CERN

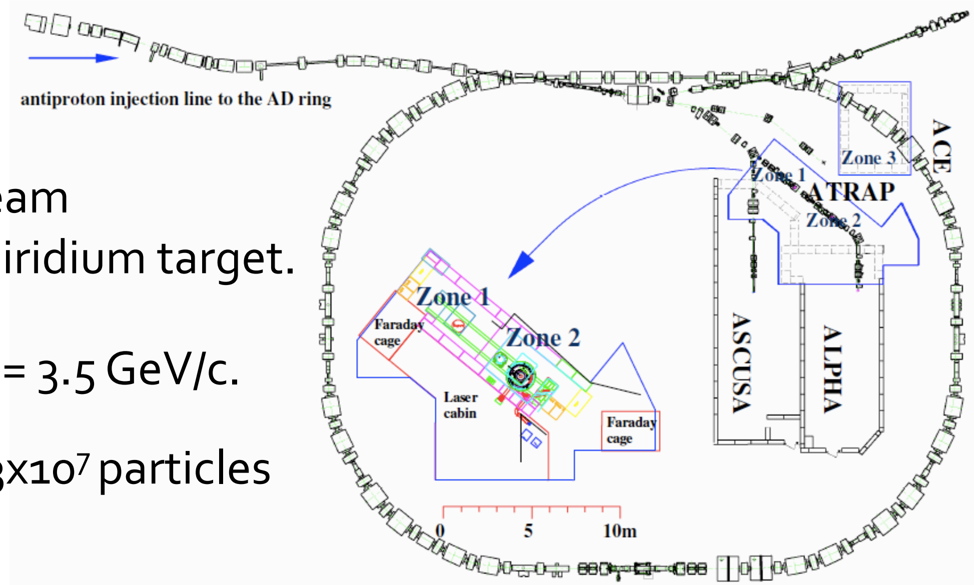
European Organization for Nuclear Research

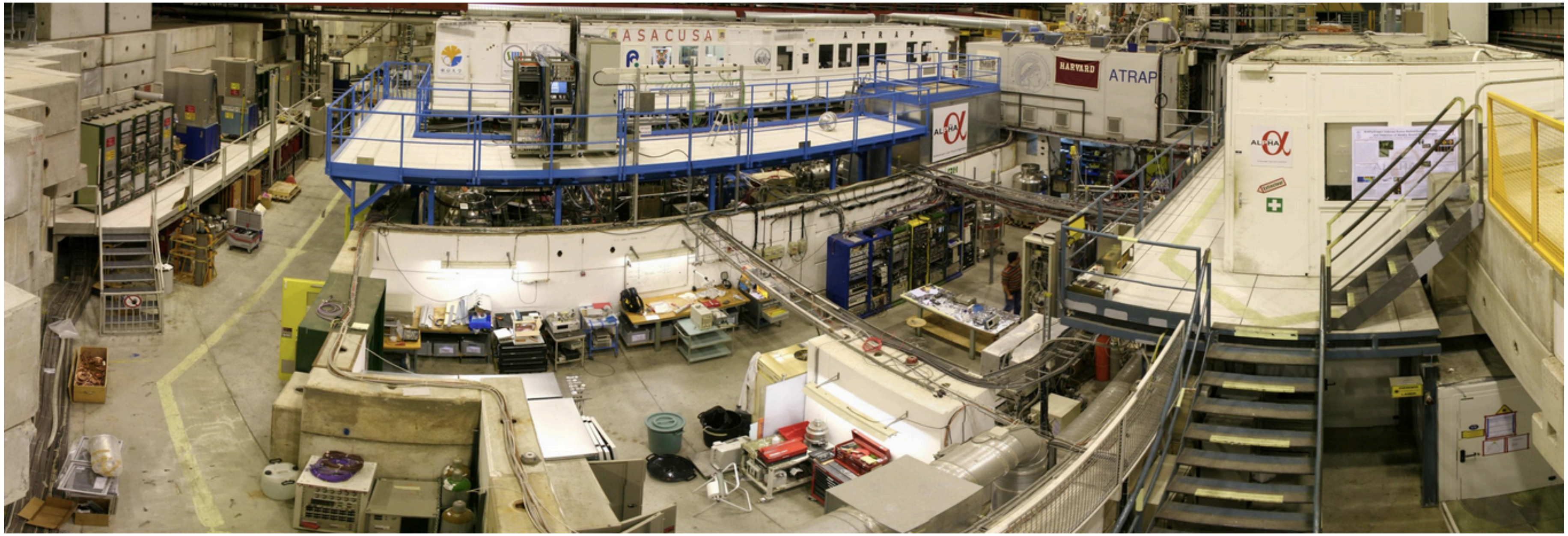
> AD – Antiproton Decelerator

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

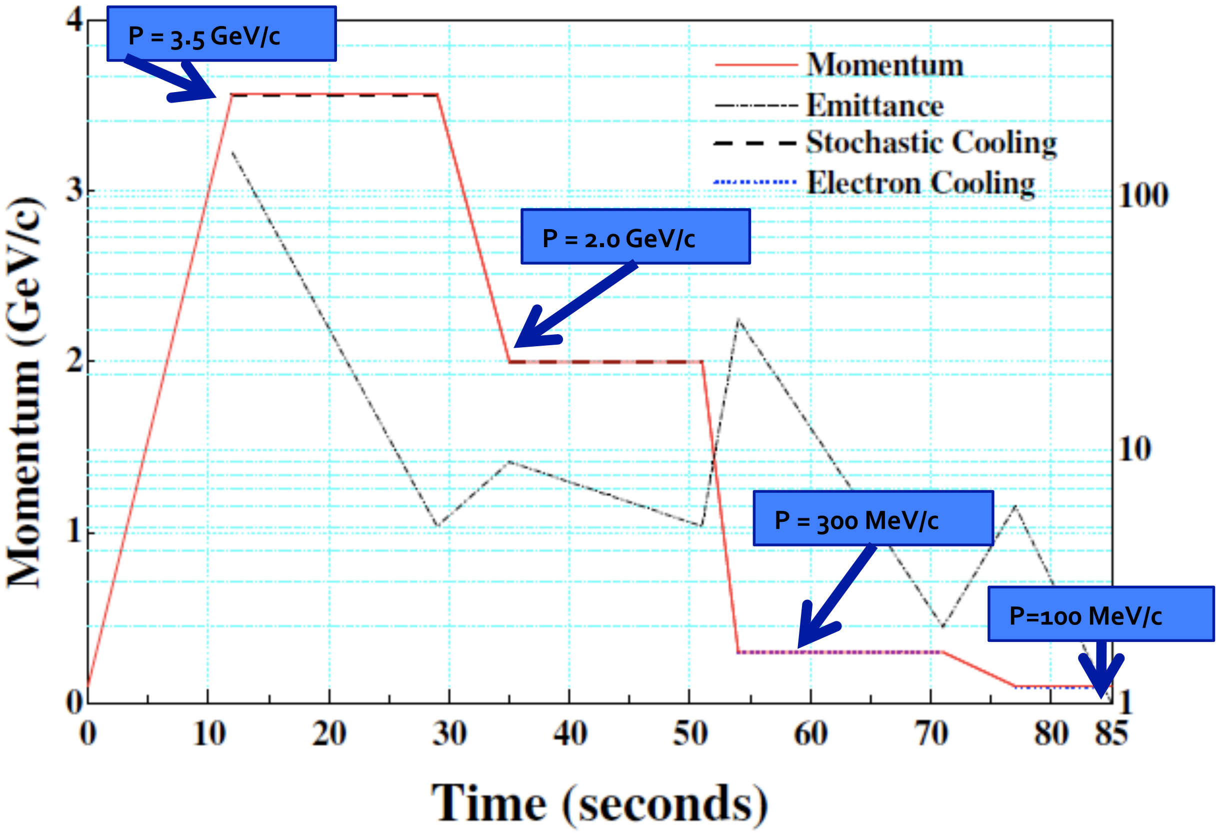
- Initial antiproton beam injected to AD has p = 3.5 GeV/c.

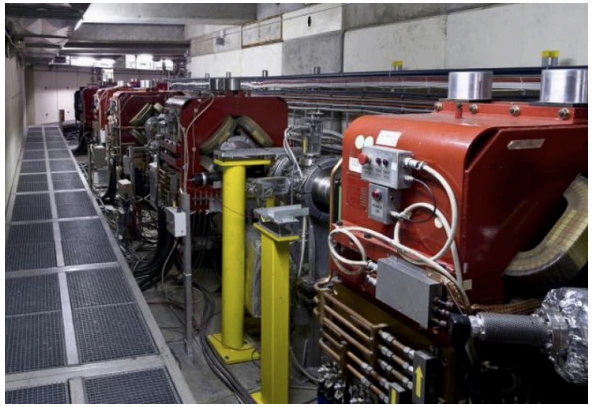
- Deceleration of antiproton bunch of about $3x10^7$ particles takes about 90 seconds.





> AD cycle of antiproton deceleration





P = 100 MeV/c
E = 5.3 MeV

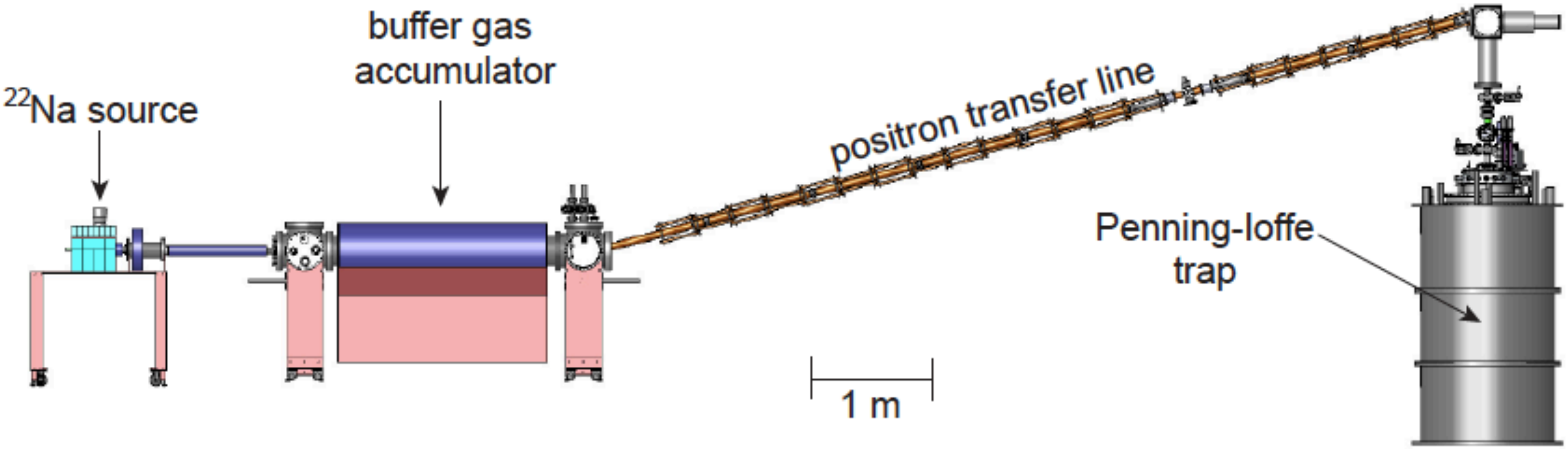
Cycle : < $3 \cdot 10^7$ /90 s

- First the stochastic cooling is used to reduce spatial emittance and momentum spread.

- Next the beam is decelerated to 2GeV/c and again stochastic colling is applied.

- Electron cooling is used after subsequent deceleration to 300MeV/c and 100MeV/c.

> Positrons production



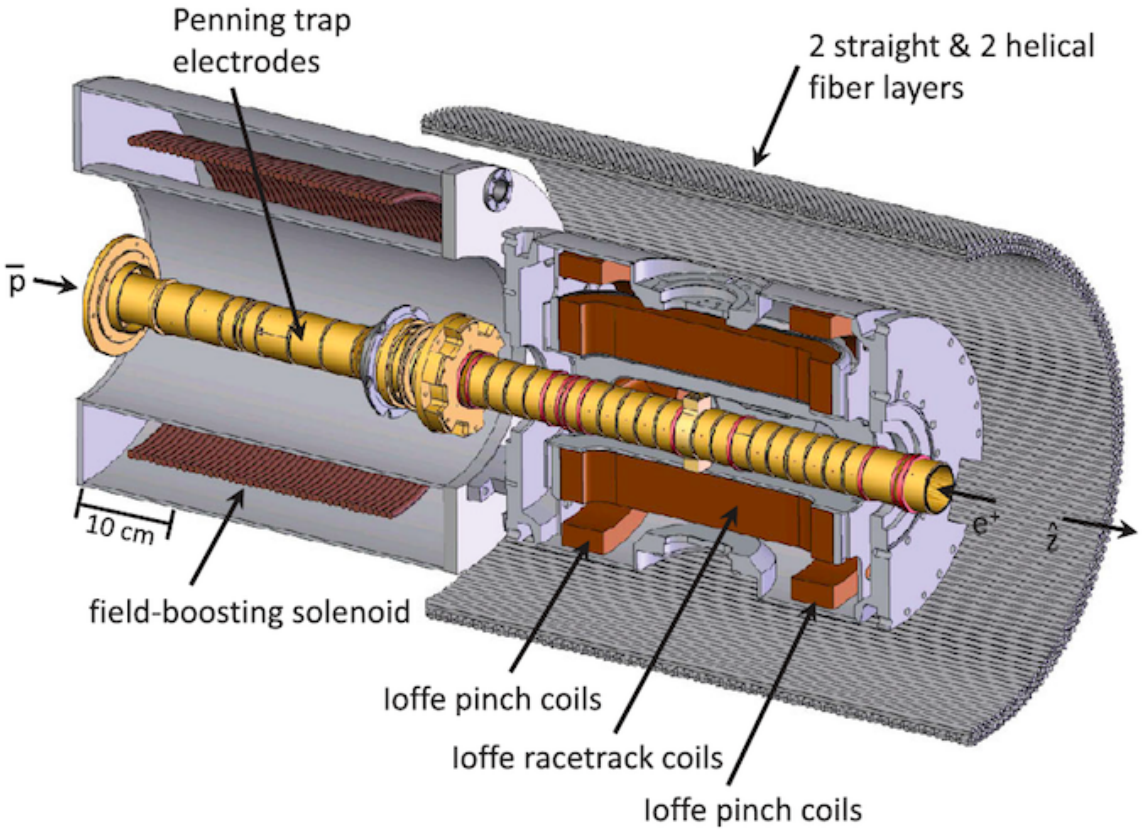
- A radioactive ^{22}Na source supplies the e^+ used for $\overline{H}$ experiments.

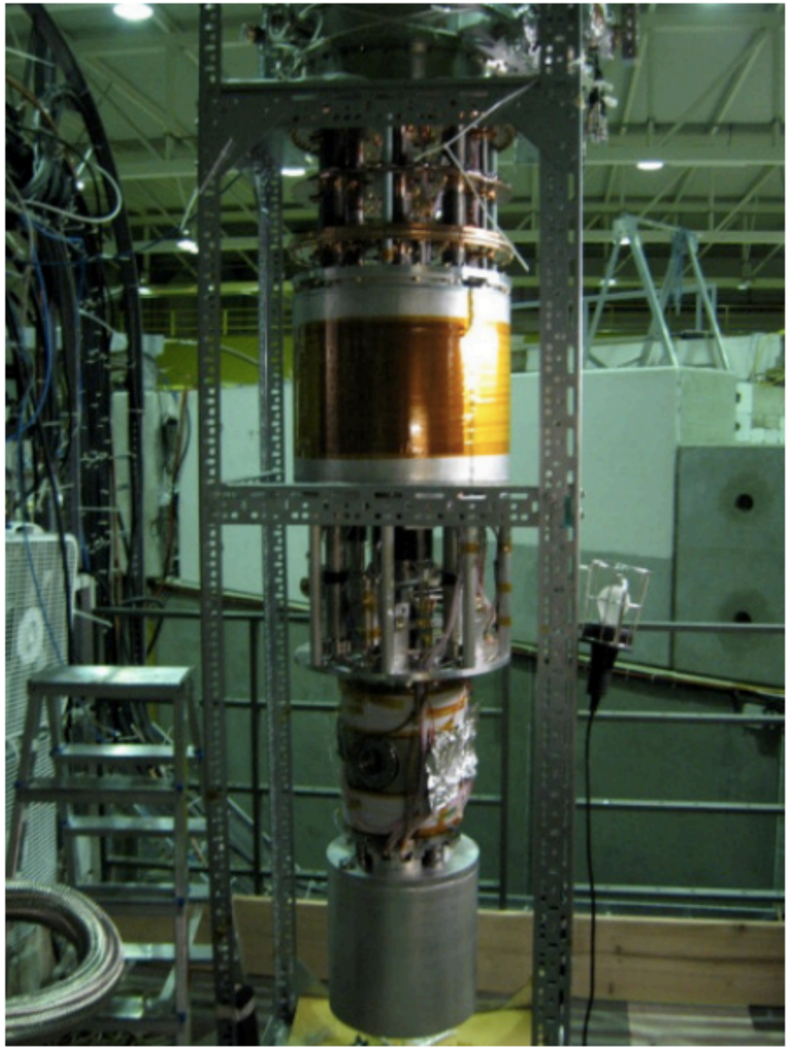
- High energy e^+ emitted in a reverse-beta decay process pass through a solid neon moderator reducing their energy to 15 eV.

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

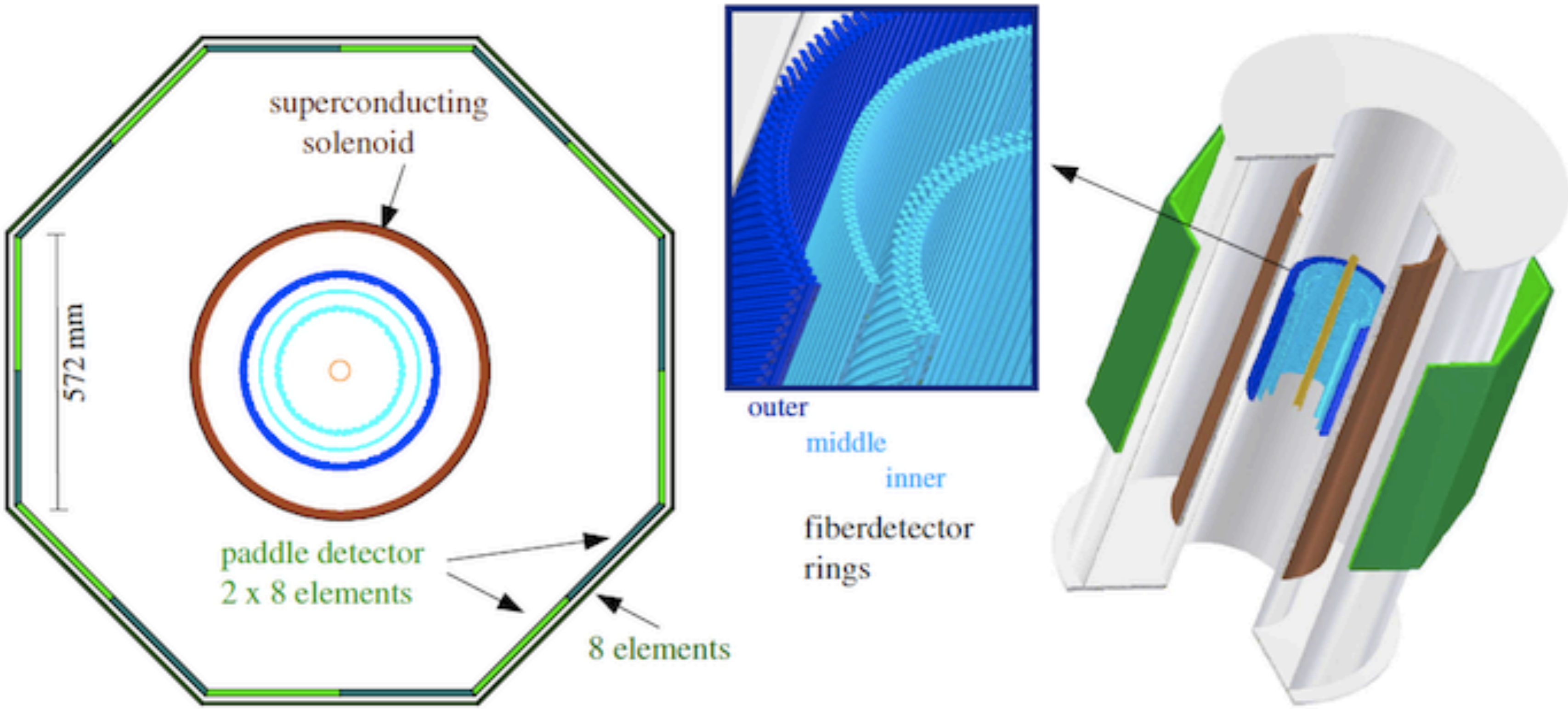
-Approximately 3×10^7 e^+ are transferred to experiment area and placed in the center of the trap.

> ATRAP apparatus

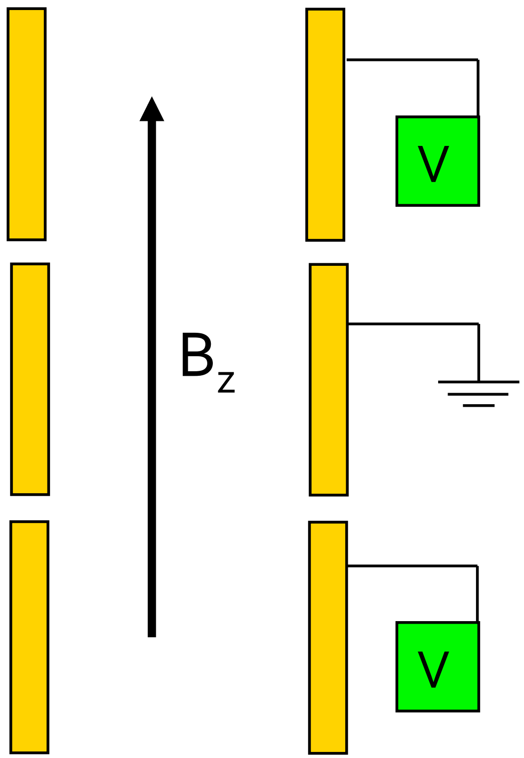




> ATRAP apparatus – detection system



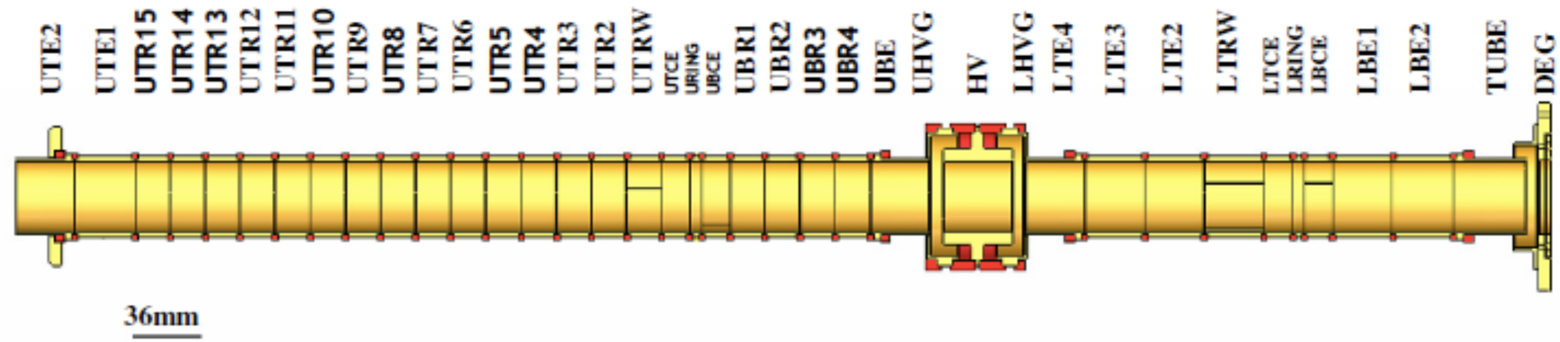
> How does the Penning trap work?



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

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

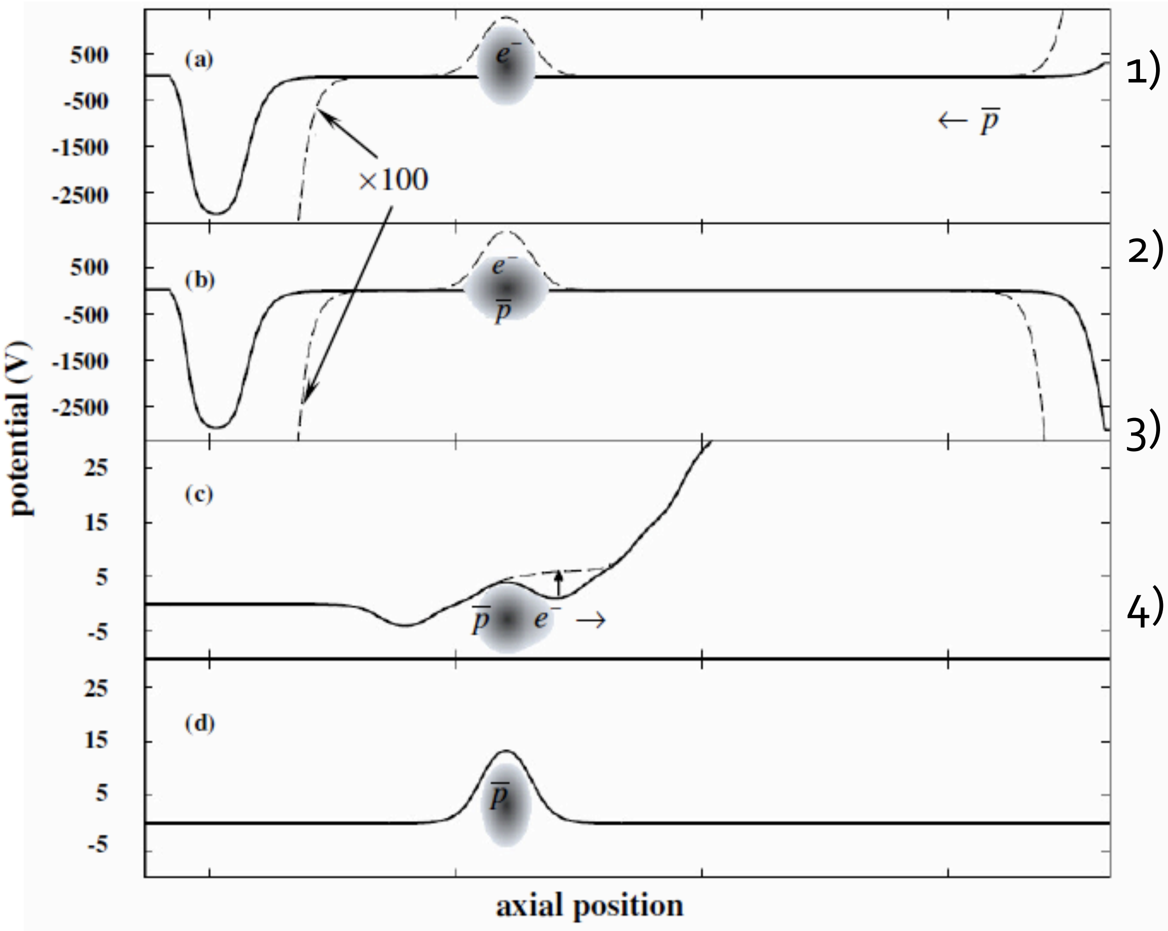
-Classically, a charged particle in a magnetic field executes a cyclotron motion around a field line. This confines the particle radially, though it is free to move along the direction of the magnetic field.
- Trapping along the third dimension may then be accomplished via the addition of a confining electric field.



> Loading of antiprotons

AD:

P=100 MeV/c
T=5.3 MeV



1) Loading antiprotons (DEG ~ 600V)

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

3) Unloading the electrons.

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

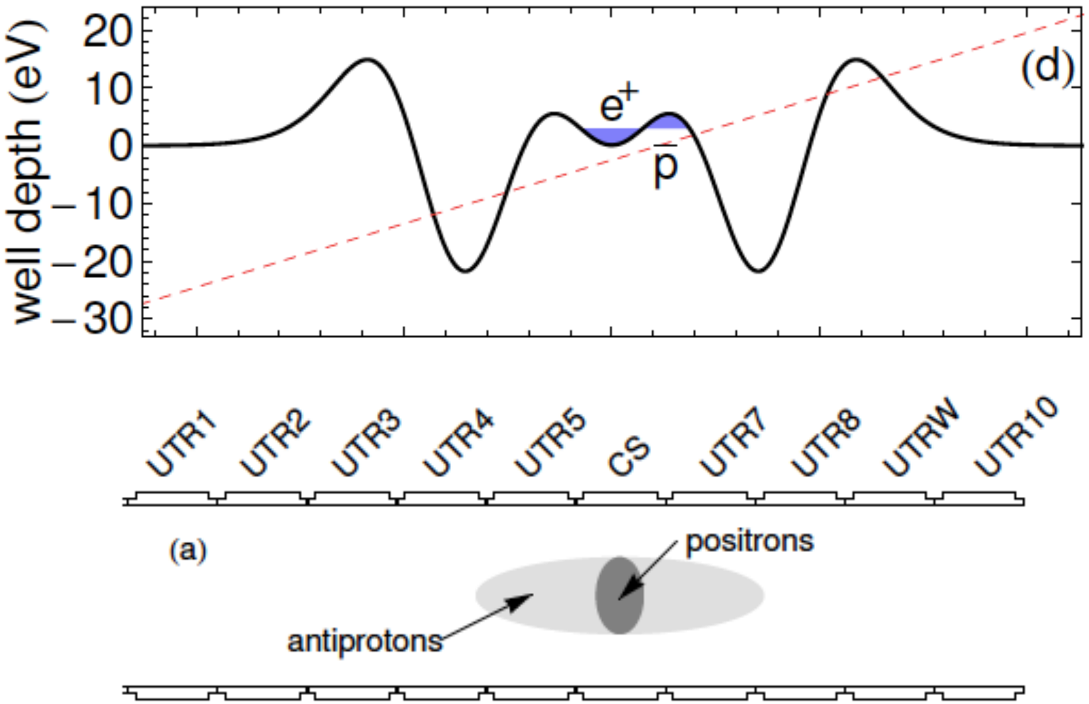
Typically during this procedure (which takes 1 h – 1.5 h) 10^7 antiprotons are accumulated.

> Antihydrogen production and trapping

- To synthesize $\overline{\mathrm{H}}$, an initially free $\overline{\mathrm{p}}$ 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:

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



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

- Antihydrogen storage times ranges from 15 – 1000 s.

- Antihydrogen atoms are confined by the Penning-Ioffe trap

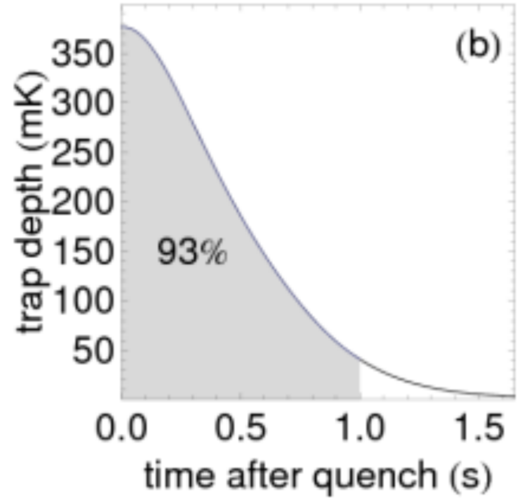
> Antihydrogen production and trapping

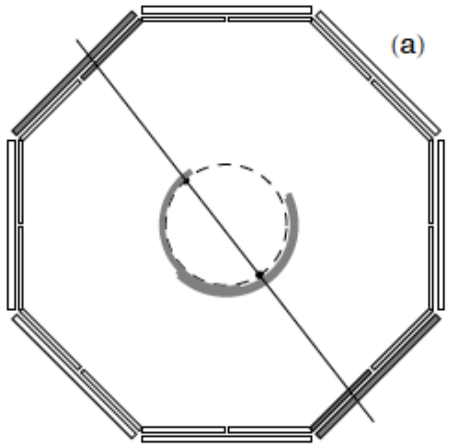
-After the time remaining in the Penning-Ioffe trap antihydrogen atoms are released by quenching the Ioffe trap by applying a hit puls.

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

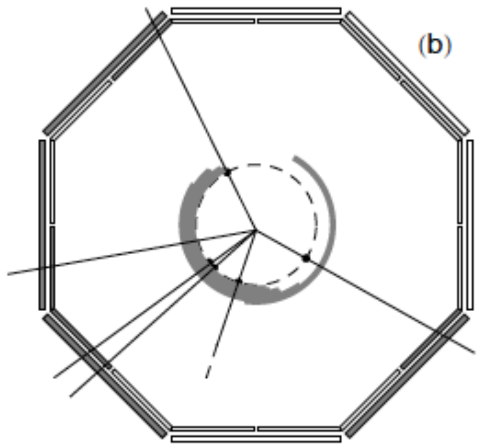
- Released antihydrogen goes to the trap walls and annihilates.

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





Cosmic event
(straight line)



Antiproton annihilation

- Coincidence between paddles and fibers detect annihilations with the 54% efficiency.

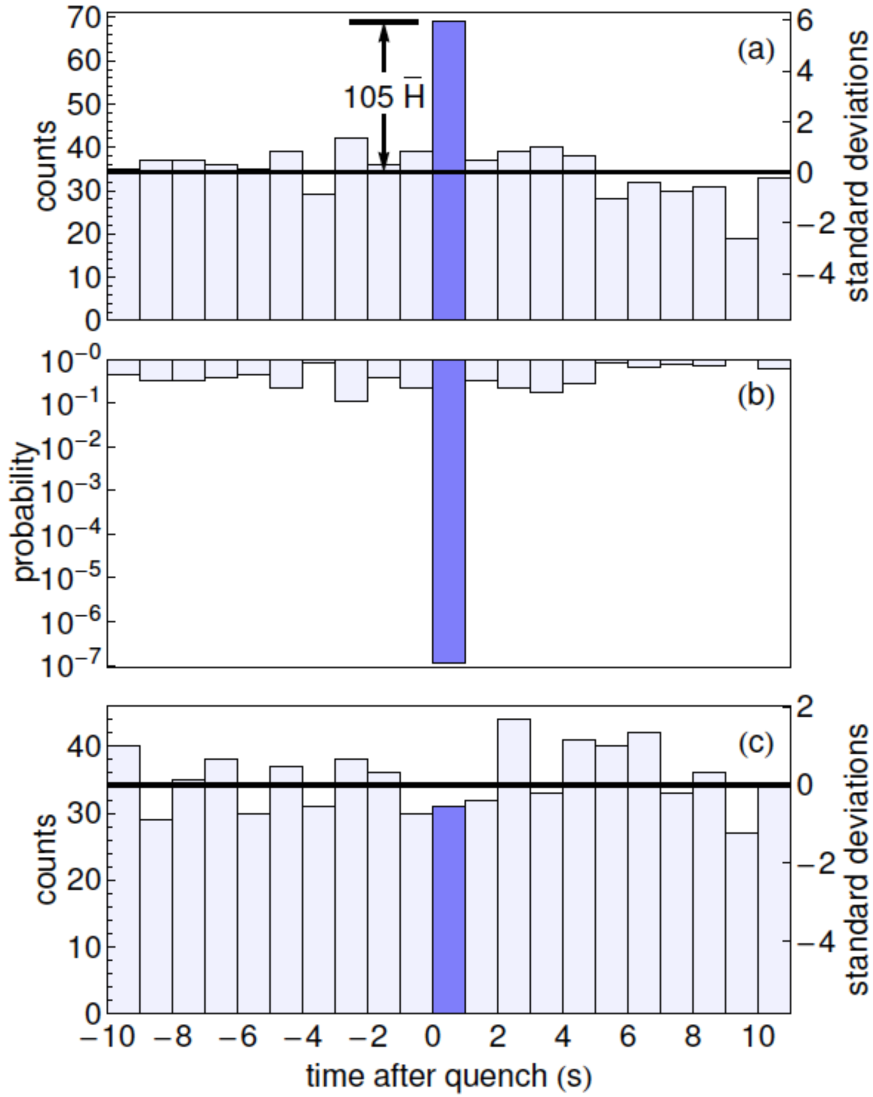
> Results

G. Gabrielse et. al, Phys. Rev. Lett. 108, 113002 (2012)

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.



> Conclusions and future steps

-Approximately 105 antihydrogen atoms were produced in 20 trials which makes it 5 atoms simultaneously trapped per trial.

- Antihydrogen atoms were storage for long times ranging from 15 - 1000 s.

- New generation of traps (Penning – Ioffe) and detection systems are under development, which should increase the number of traped antihydrogen atoms.

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

Thank you !