Advances in antiproton and positron trapping in the AEGIS experiment

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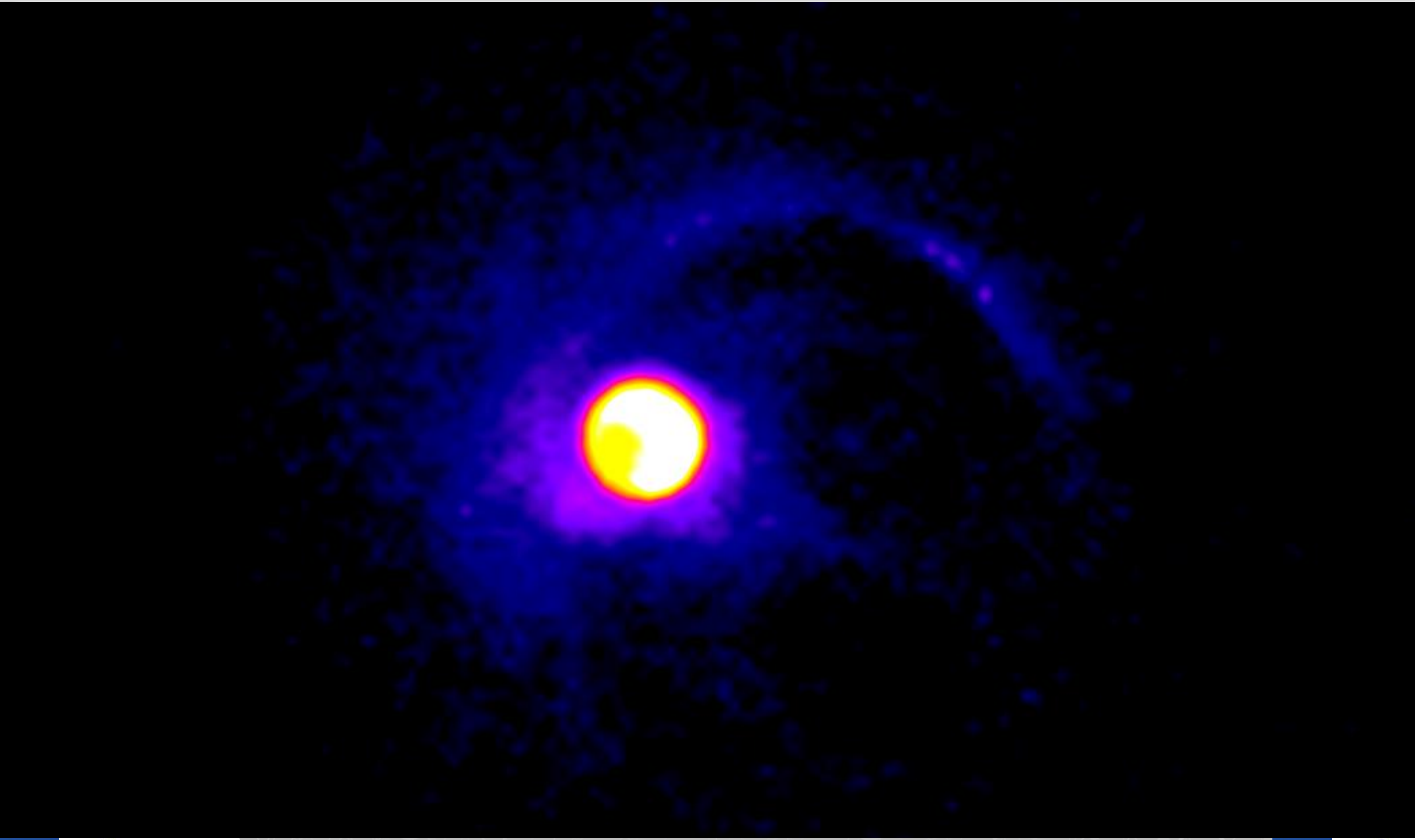
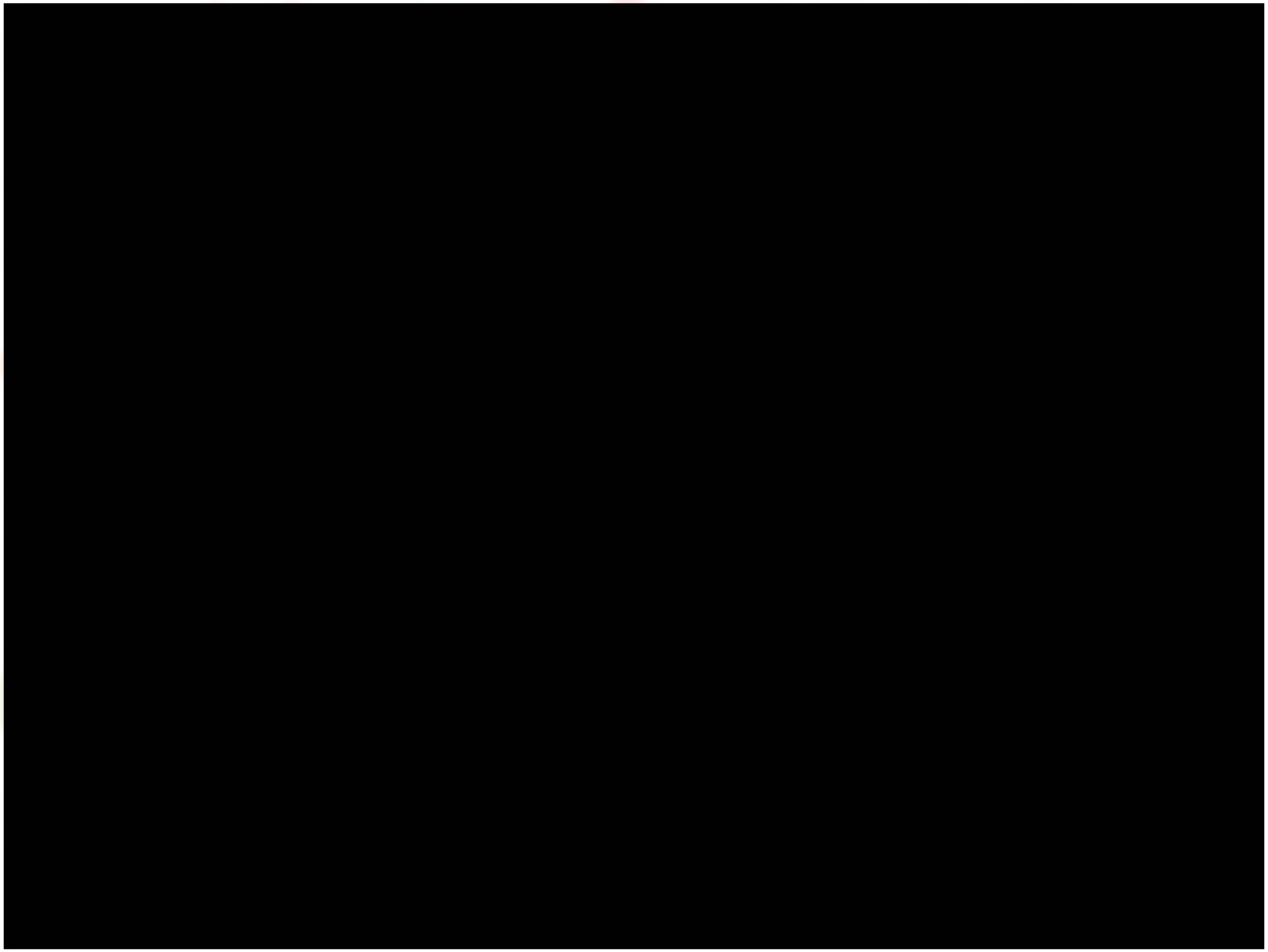
*CERN, Università degli Studi di Genova and INFN



Outline of the talk

- AEgIS physics goals
- Measuring gravity on anti-hydrogen
- Synthesis of cold anti-hydrogen
- The actual experimental apparatus
- Recent results in antiproton and positron catching
- Short and long term perspectives

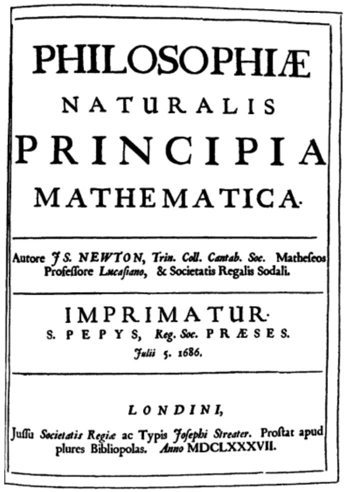
Universality of free-fall



David Scott, mare Imbrium, 1979

Universality of free-fall

- Galileo's observation: free-fall independent of the body mass
- Newton's dynamics and gravitation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S. PEPYS, Reg. Soc. PRÆSES.
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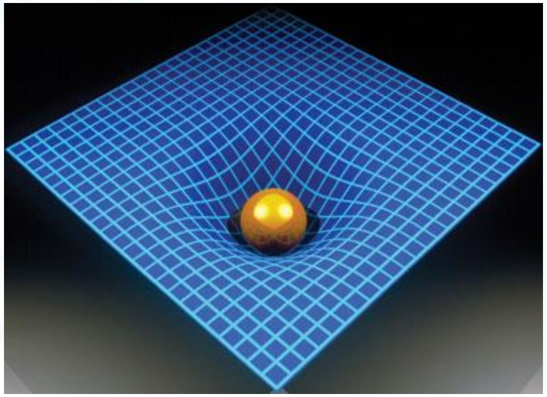
$$\begin{cases} \mathbf{F} = m_i \mathbf{a} \\ \mathbf{F_g} = m_g \mathbf{g} \end{cases} \xrightarrow{UFF} m_i = m_g$$

> conjecture known as the **weak equivalence principle** (WEP)

Einstein's equivalence principle



WEP is valid, and the result of any local non-gravitational experiment is independent from the velocity of an observer in free-fall and his position and time in the universe

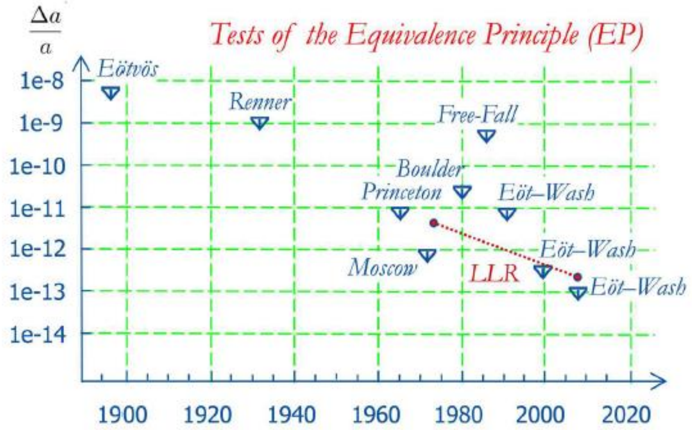
EEP = **WEP** (equivalence of masses)
+ **LLI** (local lorentz invariance)
+ **LPI** (local position invariance)

Clifford M. Will, *Theory and experiment in gravitational physics* (1993)

Tests of the weak equivalence principle

Accurate tests of the WEP were performed only on matter systems

- Lunar laser ranging (LLR)
- Eötvös-like torsion balance experiments



$$m_i^{antiparticle} \stackrel{??}{=} m_g^{antiparticle}$$

Probing gravity and WEP on a pure antimatter system

- Experiments with e+ e- (Witteborn FC, PRL 19 (1967))
- PS200@LEAR with antiprotonsLimits set by Ps 1s-2s spectroscopy
- Limits set by antiproton cyclotron frequency in Penning traps (ATRAP)
- ALPHA (2014), anti-hydrogen, first limit on gravity

any unexpected deviation from the usual value of g would have an enormous impact

Brief history of antimatter research

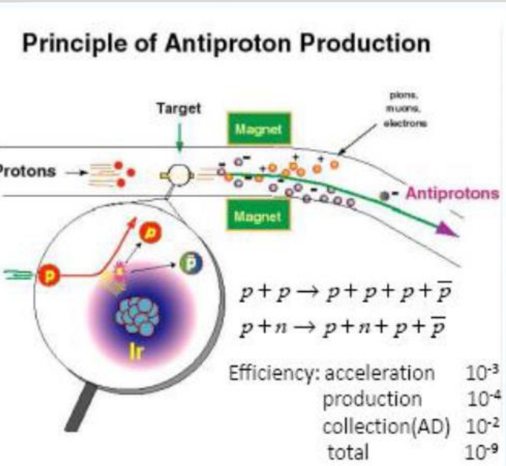
- 1928: relativistic equation of the electron with spin ½ (Dirac)
- 1931: antimatter prediction (Dirac, Oppenheimer, Weyl)
- 1932: discovery of positrons in cosmic rays (Anderson)
- 1933: discovery of pair production e+/e- (Blackett, Occhialini)
- 1937: symmetric theory for electrons and positrons
- 1954: Bevatron construction (Berkeley)
- 1955: discovery of antiproton (Segrè, Chamberlain, Wiegand)
- 1956: discovery of antineutron (Cork, Lambertson, Piccioni, Wenzel)
- 1965: discovery of anti-nuclei (Zichichi, Lederman)
- 1978: first antiproton trapping (CERN)
- 1982: LEAR construction (CERN)
- 1995: anti-hydrogen synthesis at high energy (CERN, Fermilab)
- 2000: construction of Antiproton Decelerator (CERN)
- 2002: synthesis of anti-hydrogen at 10K (Athena, Atrap)
- 2011: magnetic confinement of anti-hydrogen (Alpha)
- 2013: limit on gravity on anti-hydrogen (Alpha)
- 2013: beam of anti-hydrogen (Asacusa)
- 2015-20: ELENA construction (CERN)

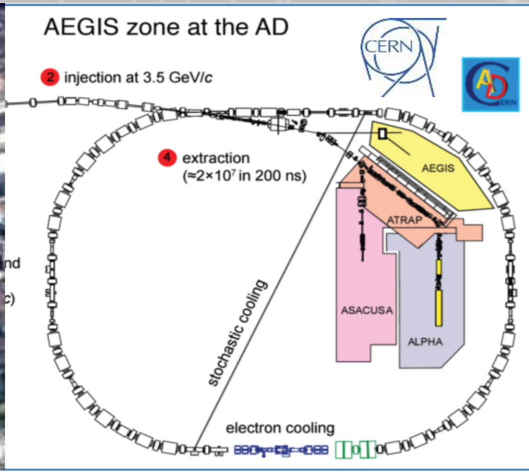
positron era

antiproton era

anti-hydrogen era

Antiproton Decelerator





Antiproton Decelerator (AD) at CERN

- Only source in the world of low energy antiprotons (5.3 MeV)
- Produced by colliding a proton beam from CERN Proton Synchrotron (PS) on a target
- Stored and cooled in AD
- Extracted towards the experiments in bunches of around $3 \cdot 10^7$ every 110 s
- Captured in the experiments with energy degraders and high-voltage/RF cavities

AEgIS collaboration

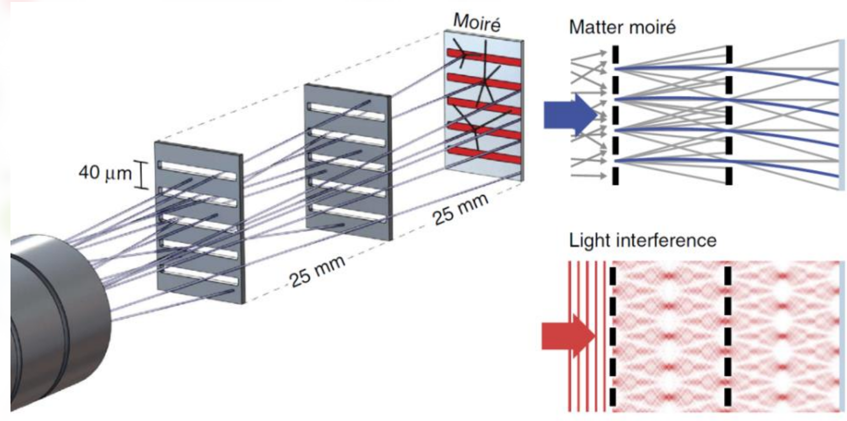
Stefan Meyer Institute	CERN	Czech Technical University	ETH Zurich
University of Genova	University of Milano	University of Padova	University of Pavia
Institute of Nuclear Research of the Russian Academy of Science	Max-Planck Institute Heidelberg	Politecnico di Milano	University College London
University of Bergen	University of Bern	University of Brescia	Heidelberg University
Université de Lyon University of Lyon 1	University of Oslo	University of Paris Sud	University of Trento

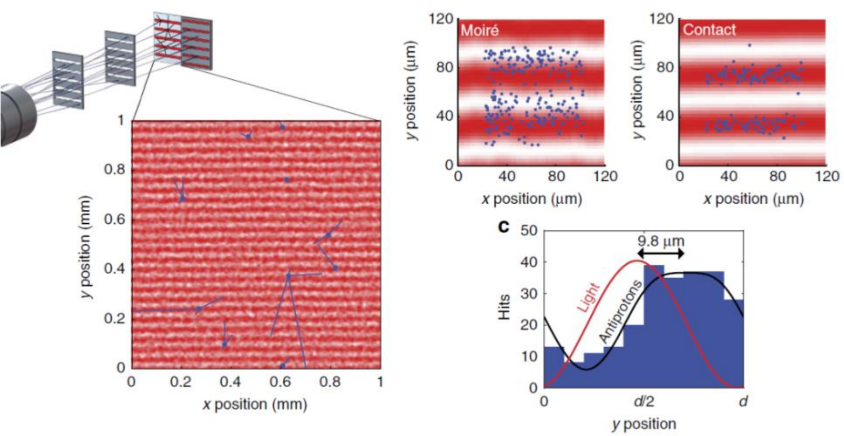
INFN sections of: Genova, Milano, Padova, Pavia, Trento

AEgIS in synthesis

AEgIS physics objectives

- Direct measurement of g on $\bar{H}$
- 1 % sensibility (phase 1)
- Atom interferometry (phase 2)
- Anti-hydrogen beam (v ~ 100 m/s)





Measurement technique

- Measurement of the vertical displacement of the free-falling beam
- Classical moiré deflectometer/Talbot-lau interferometer
- Position-sensitive detector (emulsions)

Aghion S. et al (AEgIS collaboration), *Nature communications (2013)* DOI: 10.1038/ncomms5538
Aghion S. et al (AEgIS collaboration), JINST 8 (2013) P08013

dedicated talk!

Example of annihilation in emulsions

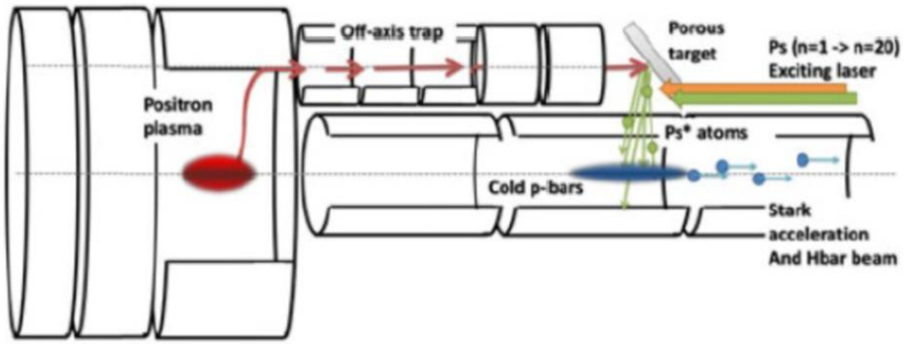
AEgIS in synthesis

Cold anti-hydrogen sinthesys

- Pulsed scheme
- Charge exchange reaction between antiproton and Rydberg-excited Positronium
- Anti-hydrogen temperature fixed to the antiproton initial temperature
- Cross section $\sigma \propto n_{Ps}^4$

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

$$\sigma \simeq 10^{-10}\, cm^2 , \qquad n_{Ps} = 20$$

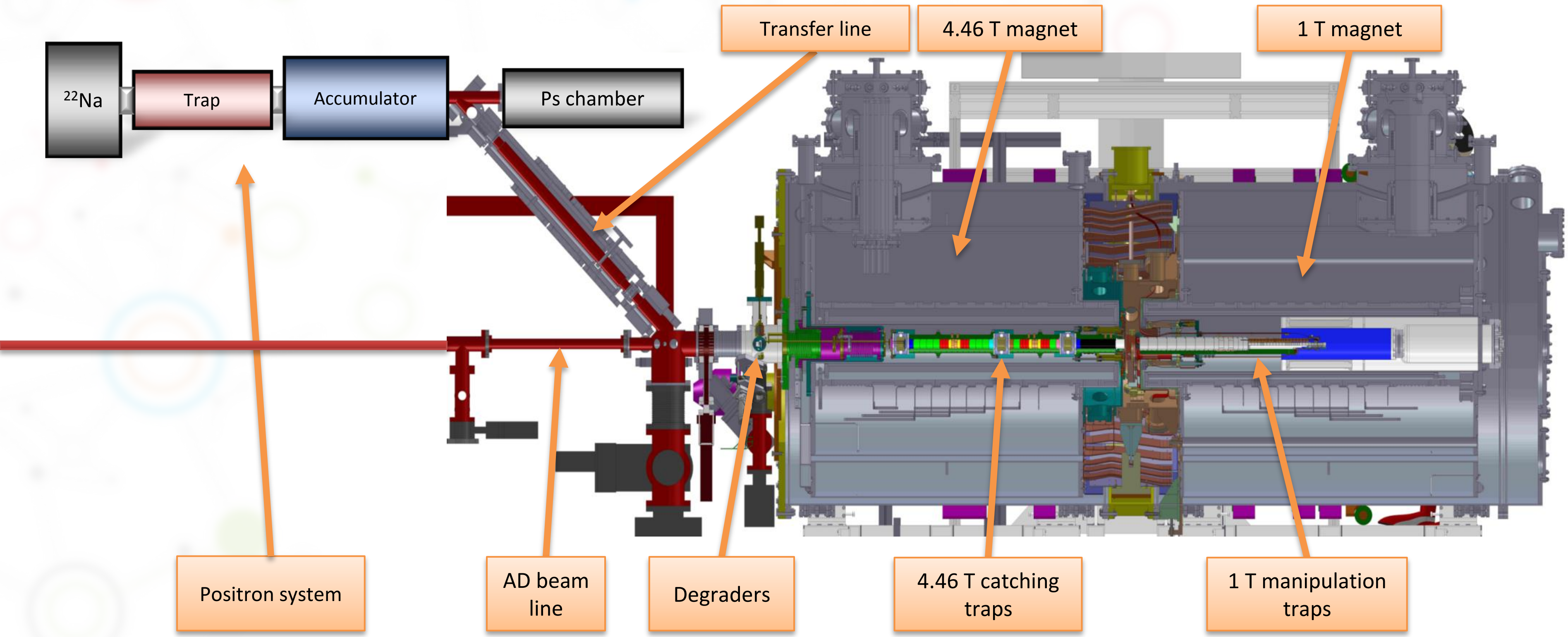


Kellerbauer A. et al., NIM B 266 (2008) 351-356
Canali C. et al., Eur. Phys. J D 65 (2011) 499-504
E. Vliegen and F. Merkt, J. Phys. B: At. Mol. Opt. Phys. 38 (2005) 1623

Experimental scheme

- Preparation of a cold antiproton plasma in trap
- Off-axis displacement of a positron plasma (autoresonant diocotron excitation)
- Implantation at 7 kV in a silica positronium converter
- Laser excitation of positronium
- Anti-hydrogen sinthesys by charge-exchange
- Form a beam of anti-hydrogen

The experimental apparatus



Status of the experiment

Achievements towards the gravity measurement

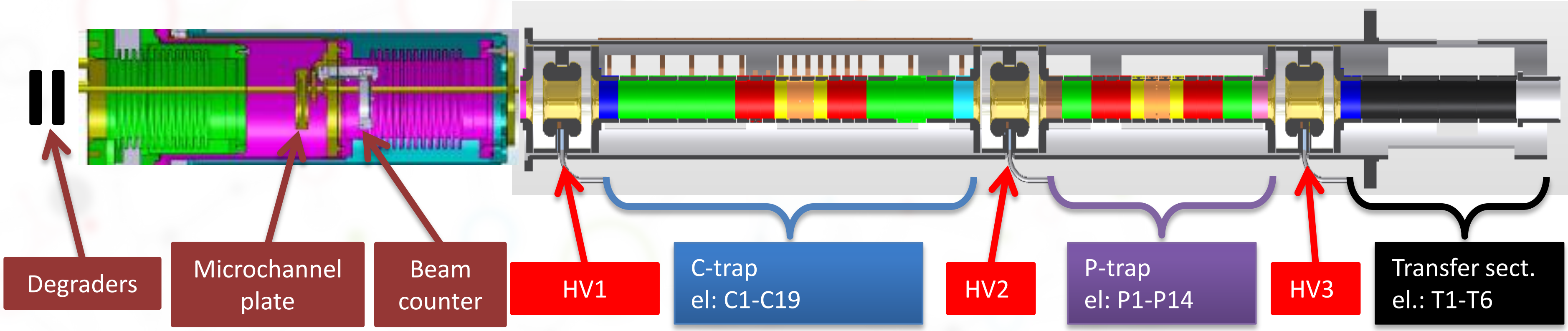
- Catching and cooling of large number of antiprotons
- Transfer of the antiproton plasma in the production region
- Production, transfer and storage of an high number of positrons
- Studies of Ps formation and laser excitation to Rydberg levels[1]

Under development

- Off-axis recapture of the positron plasma
- Antihydrogen formation
- Synthesis of a forward anti-hydrogen beam

[1] dedicated talk

Particle catching hardware

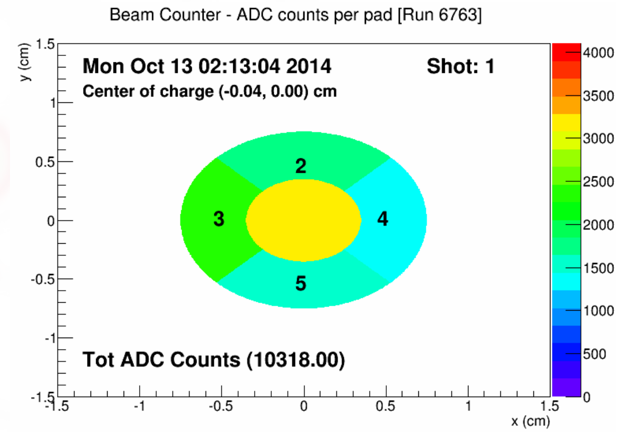


Antiprotons and positrons catching hardware

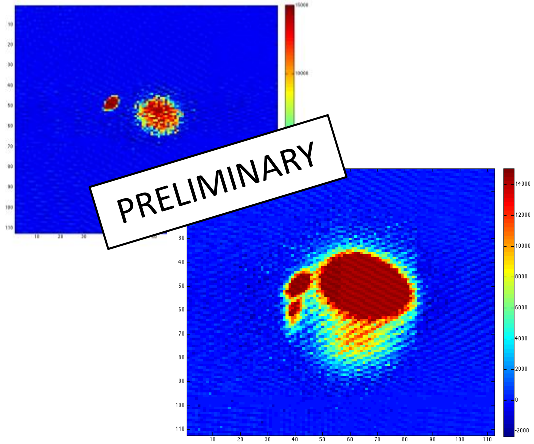
- Two variable-thickness aluminum degrader foils in front
- Movable beam counter + fixed degrader for beam diagnostics
- Catching traps system
  - Two regions of UHV cryogenic Malmberg-Penning traps
  - Magnetic field of 4.46 T for radial confinement
  - Terminated by HV electrodes tested up to 10 kV
- HPD and scintillators outside the cryostat

Antiproton beam monitoring

2014 antiproton run – Sectorized BC
- Silicon beam counter
- Five sensitive silicon pads
- Time-integrated information
- Limited diagnostics on beam size



2015 antiproton run - MiMiTO
- Upgraded beam monitor
- Based on MIMO detector
- High-resolution spatial detector
- Zero dead time



Aghion S. et al (AEGIS collaboration), *JINST 9 (2014) P06020*
Sellner S. et al (ACE collaboration), Hyp. Int. 213:159-174 (2012)
Boll R. et al., Radiation Measurements 46 (2011) 1971-1973

Antiproton catching efficiency

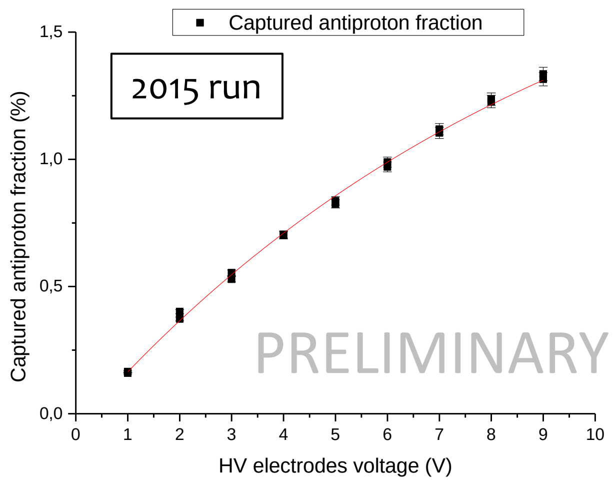
Antiproton catching efficiency

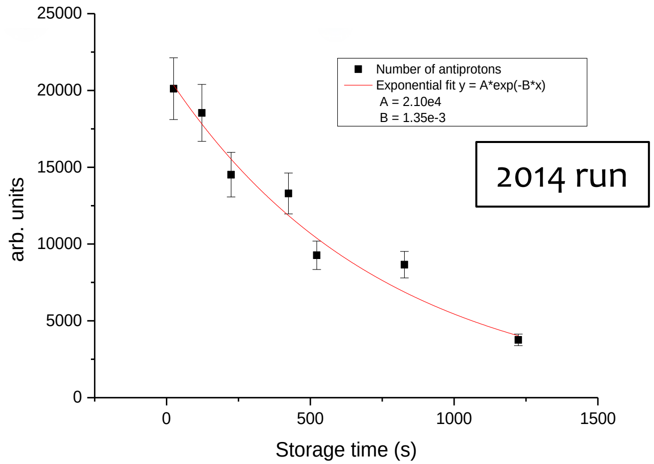
- 1.3% catching efficiency obtained at 9 kV, corresponding to around $4 \cdot 10^5$ pbars
- Average intensity of $3.6 \cdot 10^7$ pbars/shot

Storage time

- Antiprotons are stored in the traps before dumping for some time
- Number of antiprotons measured with external scintillators
- Lifetime is a measurement of vacuum

$$\tau_{2014} = 12.3\ min$$
$$\tau_{2015} = 13.0\ min$$





Krasnicky D. et al (AEgIS collaboration), AIP Conf. Proc. 1521 (2013) 144

Antiproton cooling

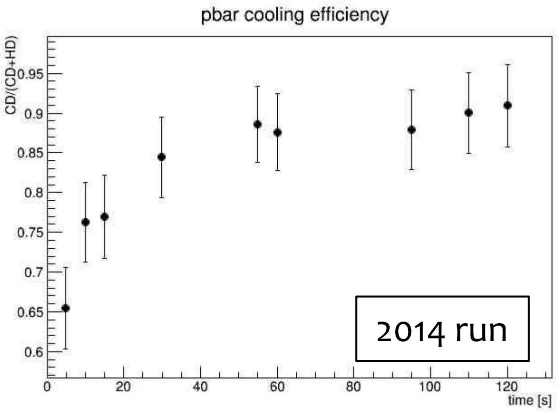
Antiproton cooling efficiency

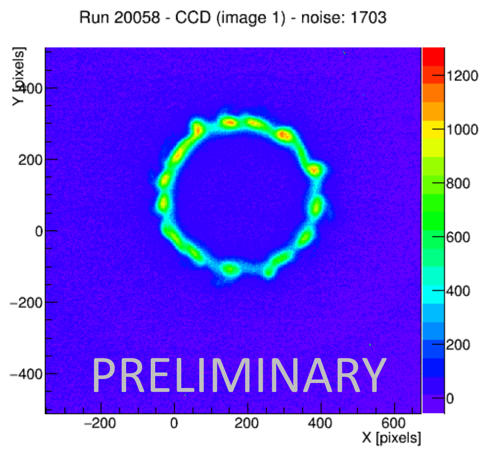
- Large electron cooling plasma
- 90% cooling efficiency in 100-120 s
- Electrons and antiprotons filled the whole trap

Observed the centrifugal separation of plasmas

- Known effect of a two-species plasma in thermal equilibrium
- Electrons removed from the traps with a sequence of pulses
- Antiprotons do not significally move
- Sets a coarse limit on the plasma temperature: $T \sim 10 - 20\ K$

$$KT_{min} = \frac{1}{8\epsilon_0^2} m_p q^2 \left(\frac{nr}{B}\right)^2$$





Dubin D.H.E. and O'Neil T.M., Rev. Mod. Phys. 71 (1999) 1

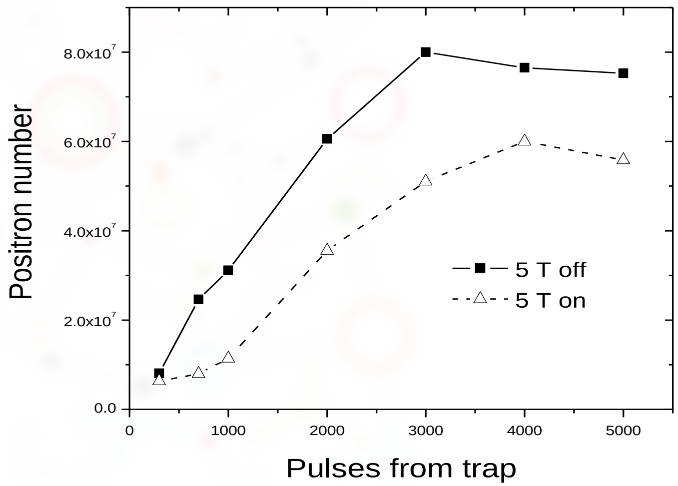
Performance of the positron accumulator

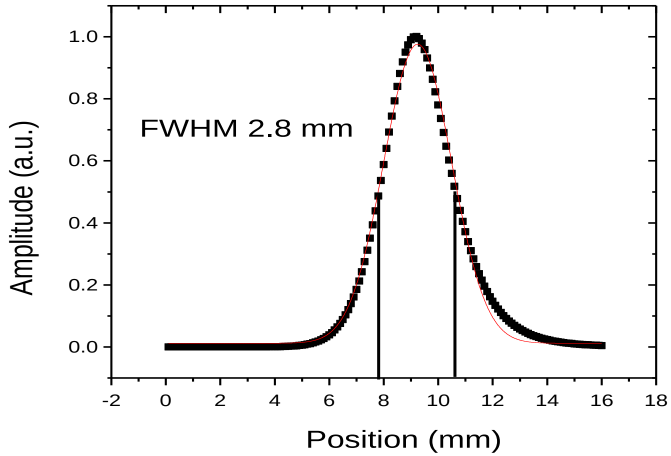
Surko-type positron source:

- 8 mCu source
- Solid neon moderator + buffer-gas cooling in a ladder trap
- Pulses of positrons are constantly stacked in a 0.1 T magnetic accumulator (360 pulses / minute)

Positron accumulator

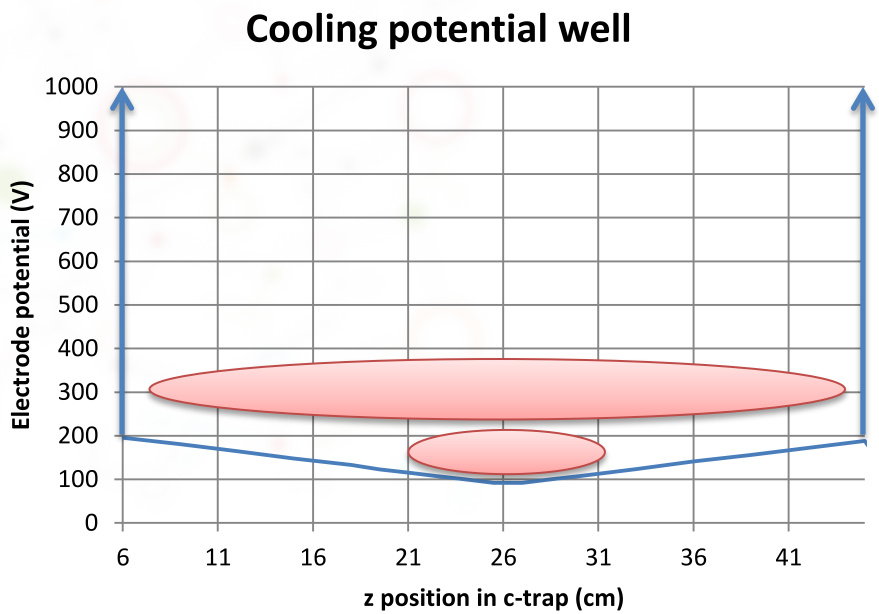
- Low buffer gas pressure for cooling
- Rotating wall to reduce plasma size and increase lifetime
- Sensitive to external fields
- Number of positrons saturates after 3000 pulses from the trap
- Usually transferred to the main traps after 2000 pulses

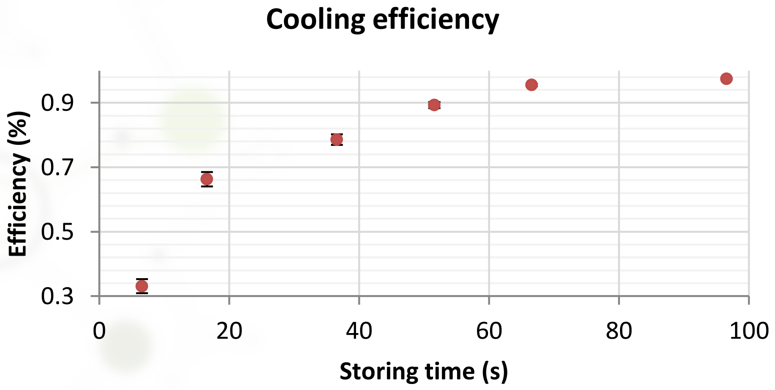




Positron catching procedure

- A cooling potential well is set before injecting particles in the trap
- End-cap electrode is set to 1kV
- Positrons are injected in the trap with an energy distribution of 300 ± 50 V
- After a 100ns delay, corresponding to the 92cm of available trap, entrance electrode is raised to 1kV
- > 95% transfer and cooling efficiency





“M-shaped” double-linear cooling trap:

- Very simple cooling trap, defined only by two parameters, an *offset* and a *slope*
- The slope is the voltage drop per trap electrode (i.e. a constant axial electric field)
- Found empirically to be a very effective trap for cooling

Positron stacking

- The positron accumulator ability to store positrons is limited by the losses on the buffer gas
- Antihydrogen formation by charge exchange is limited by the number of positrons
- UHV traps are more suitable for storing large number of positrons
- Stacking of several shots from the accumulator with RW
- Stacked $2.2 \cdot 10^8$ positrons (AEgIS current record) in about 1 hour with a 8 mCu source

New 50 mCu ^{22}Na source

- In delivery at the end of the year
- ~6 times more positrons per shot
- Reduced sensibility to external spurious fields
- Higher measurement rate

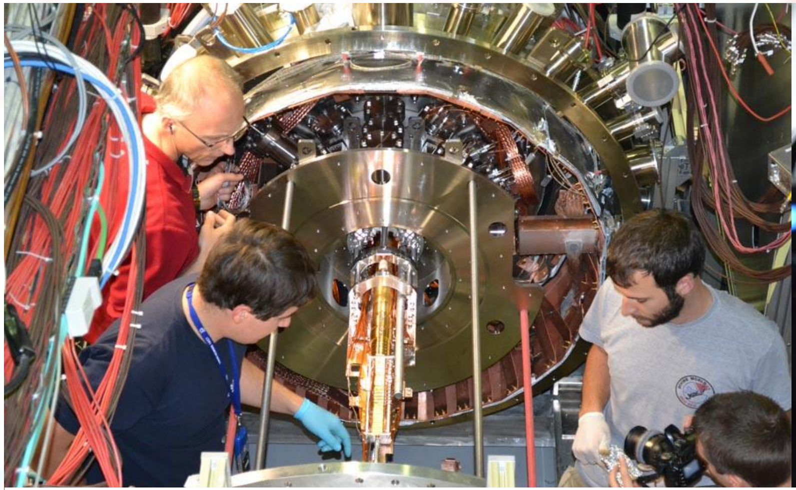
Summary and future prospects

Summary of the talk

- Measuring gravity on anti-hydrogen
- Description of the experimental apparatus
- Recent results with antiprotons and positrons

- AEgIS entered in data taking – extremely stimulating moment
- Goal for the next runs: **demonstrate the formation of anti-hydrogen suitable for a gravity measurement**
  - Necessary milestone: positron implantation at 7 kV and Ps formation
  - Necessary milestone: Ps excitation to Rydberg levels in B = 1T
  - Necessary milestone: cooling of antiprotons to Kelvin temperatures
- Parallel goal: spectroscopic studies of Ps in the dedicated setup

Summary e prospetti futuri




> thank you for your attention <