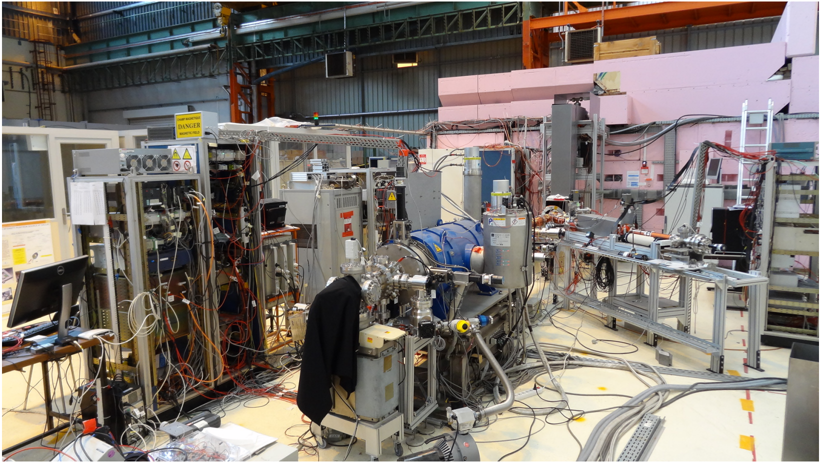
Towards (anti)hydrogen production

Amélia Leite

GBAR, SPP/Irfu



Education

- Bachelor in Physics @ University of Porto, Portugal (2008-2012)
- Master in High Energy Physics @ École Polytechnique (2012-2014)
- M2 internship in GBAR group @ Irfu, CEA → PhD

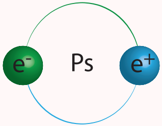
PhD subject

Measurement of charge exchange cross sections between positronium, proton and hydrogen

1. Hydrogen and negative hydrogen ion production

$\mathrm{p} + \mathrm{Ps} \rightarrow \mathrm{H} + \mathrm{e}^{+}$ @Cea

$\mathrm{H} + \mathrm{Ps} \rightarrow \mathrm{H}^{-} + \mathrm{e}^{+}$ @Cern



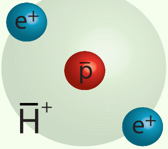
PhD subject

Measurement of charge exchange cross sections between positronium, proton and hydrogen

2. Antihydrogen and antihydrogen ion production

$\bar{p}$ + Ps → $\bar{H}$ + e$^-$ @Cern

$\bar{H}$ + Ps → $\bar{H}^+$ + e$^-$ @Cern



Outline

- Motivation for GBAR
- GBAR in 3 steps
- How do we produce (anti)hydrogen?
- Positron production and accumulation
- Positronium
- Proton source
- Conclusion

Motivation

Weak Equivalence Principle is a cornerstone of relativity

↓

Never been tested with Antimatter

↓

Absence of primordial antimatter in the observable Universe

→ Different behaviour of antimatter under gravity?

⇓

GBAR: **G**ravitational **B**ehaviour of **A**ntihydrogen at **R**est

↓

$\bar{g}$ measurement

GBAR: Gravitational Behaviour of Antihydrogen at Rest

Measure the acceleration of $\bar{H}$ in free fall

$$\Delta z = \frac{1}{2}\frac{m_g}{m_i}g(\Delta t)^2 + v_{0,z}\Delta t$$

- m_g gravitational mass of $\bar{\mathrm{H}}$
- m_i inertial mass of $\bar{\mathrm{H}}$
- Δt free fall time
- Δz free fall height
- g gravitational acceleration
- $v_{0,z}$ initial vertical velocity

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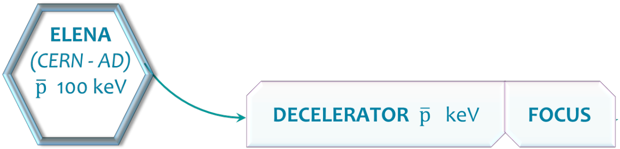
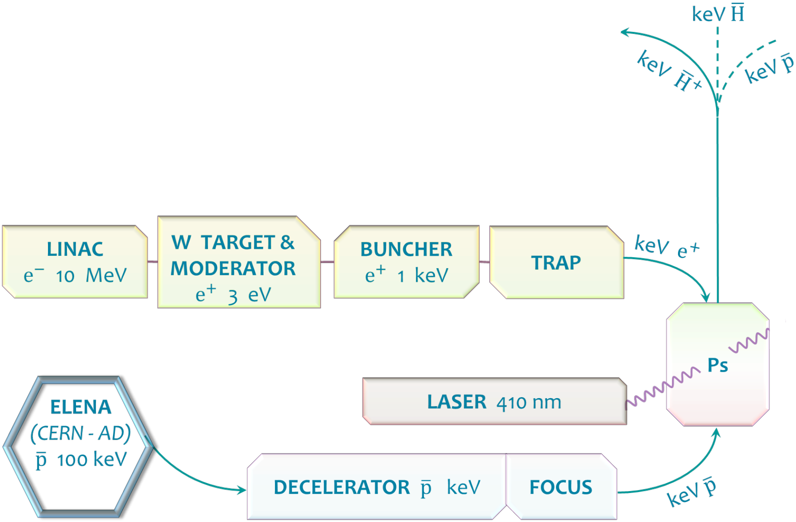
Original idea:

Use $\bar{H}^+$ ions to achieve μK temperature (0.1 m/s) by sympathetic cooling → e^+ photodetachment → $\bar{H}$ free fall

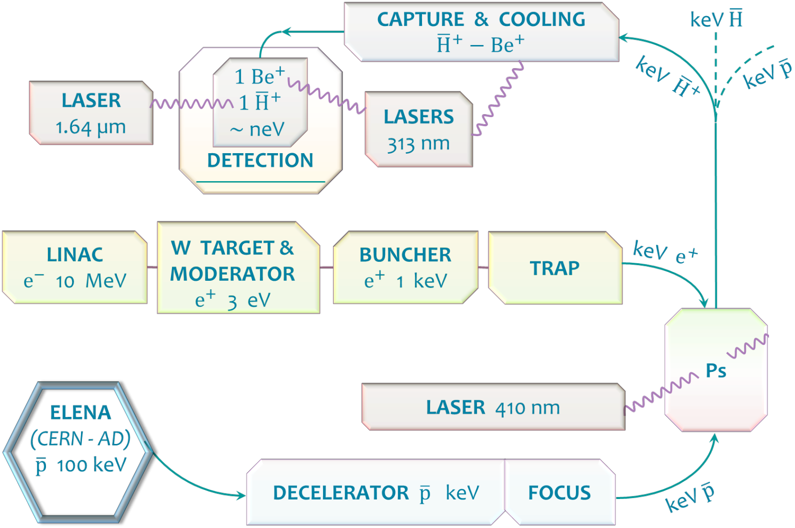
GBAR in 3 steps



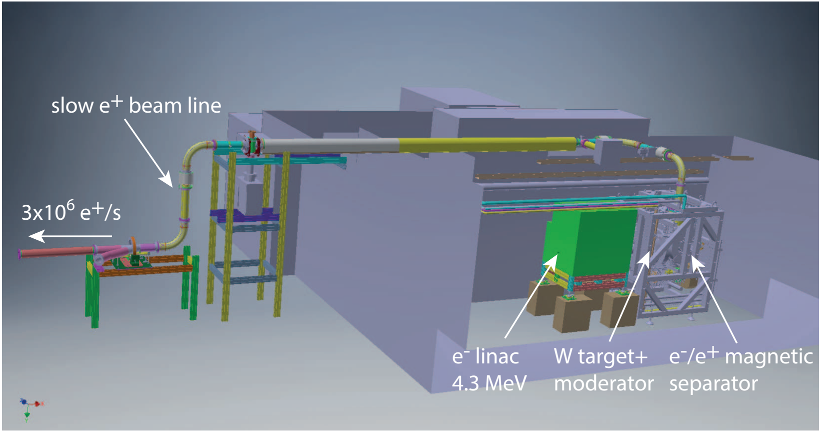
GBAR in 3 steps



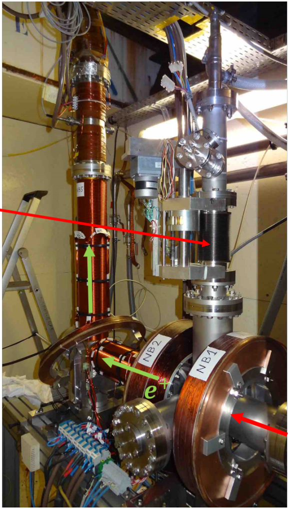
GBAR in 3 steps



GBAR @ Saclay


slow e+ beam line
3x10^6 e+/s
e- linac
4.3 MeV
W target+
moderator
e-/e+ magnetic
separator

GBAR @ Saclay

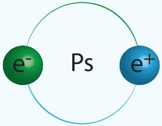


Cross section measurements

1. Hydrogen and negative hydrogen ion production

$$p + Ps \rightarrow H + e^{+}$$ @Cea

$$H + Ps \rightarrow H^{-} + e^{+}$$ @Cern

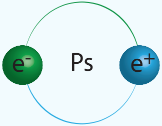


Cross section measurements

1. Hydrogen and negative hydrogen ion production

$p + Ps \rightarrow H + e^+$ @Cea

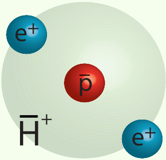
$H + Ps \rightarrow H^- + e^+$ @Cern



2. Antihydrogen and antihydrogen ion production

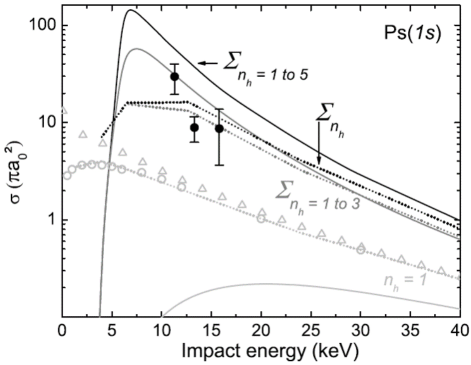
$\bar{p} + Ps \rightarrow \bar{H} + e^-$ @Cern

$\bar{H} + Ps \rightarrow \bar{H}^+ + e^-$ @Cern



Cross section measurements

Only one previous study on p + Ps → H + e^+ for p energies 11.3, 13.3 and 15.8 keV with a total of **211 events**



Merrison et al, Phys. Rev. Letters 78,2728 (1997)

Positron accumulation

Buffer gas trap

Charged particles can be stored in a Penning trap ad eternum (if your trap is good enough!)

Yet the e^+ need to loose enough energy $\rightarrow$ use a buffer gas for inelastic collisions: $e^+_{8-11eV} + N_2 \rightarrow e^+ + N_2^*$

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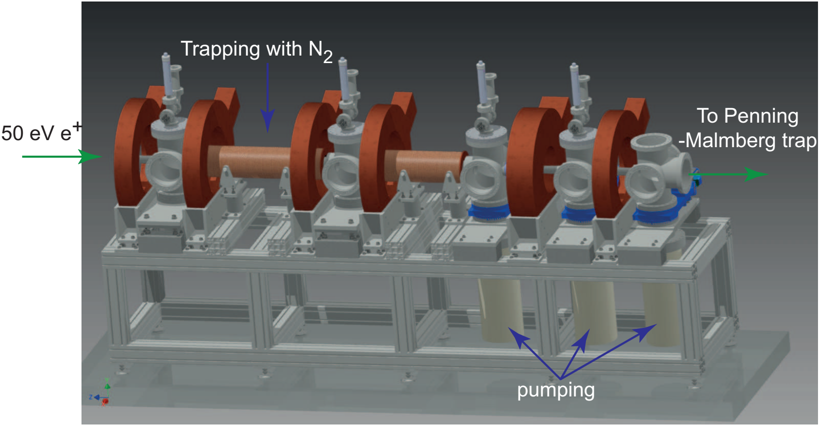
Penning-Malmberg trap

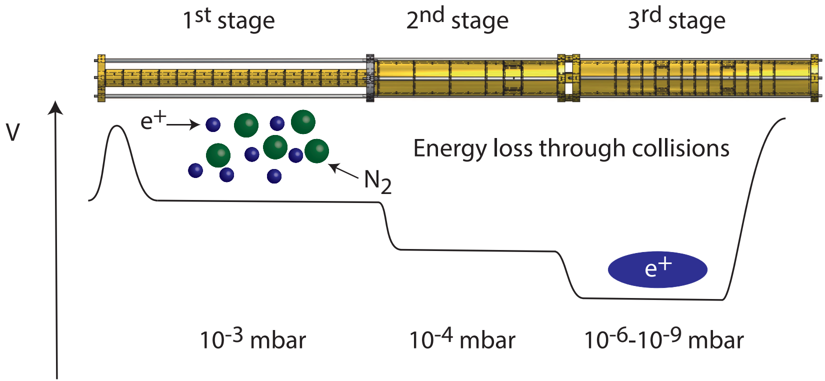
Store e^+ bunches and form a plasma with 10^{10} e^+

Buffer gas trap

Two stage trap with a third stage accumulator
Efficiency ~ 20% to 30%

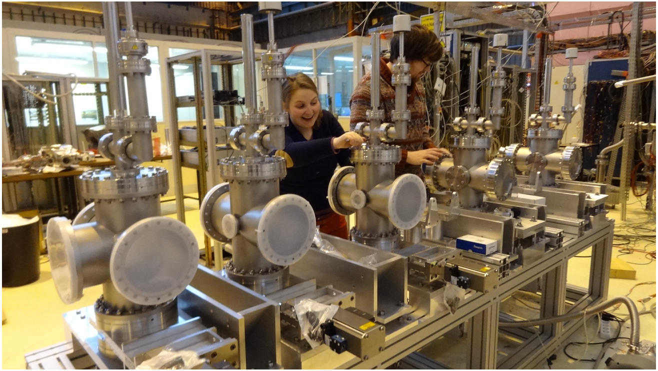


Buffer gas trap



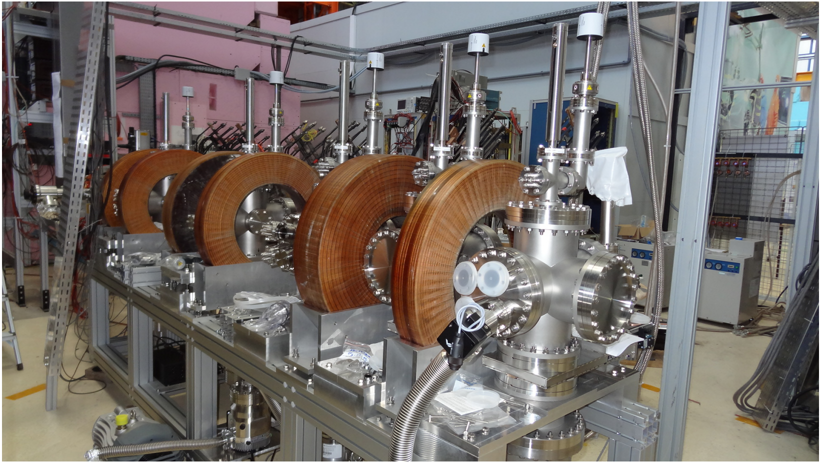
Buffer gas trap

We are slowly building the trap from scratch...



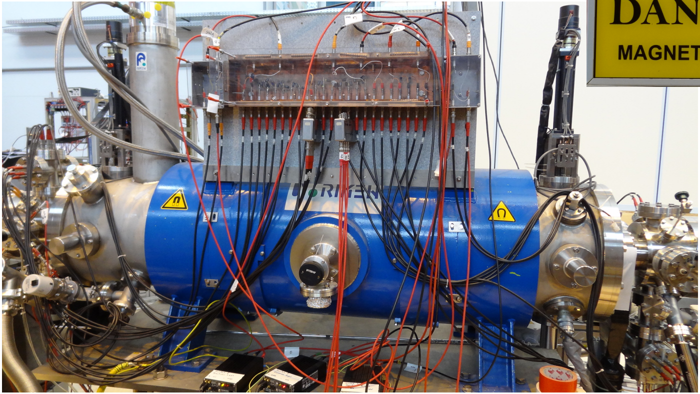
Buffer gas trap

Now it looks better but it's not ready yet!



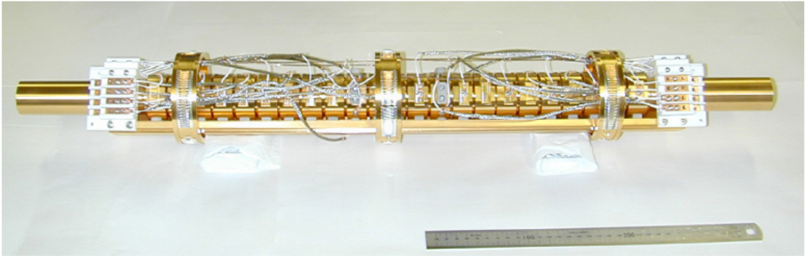
Penning-Malmberg trap

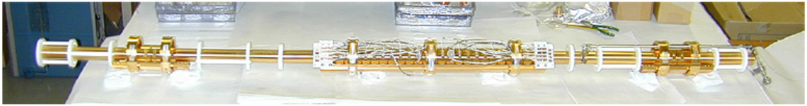
Superconducting magnet: 5T $\rightarrow$ radial confinement



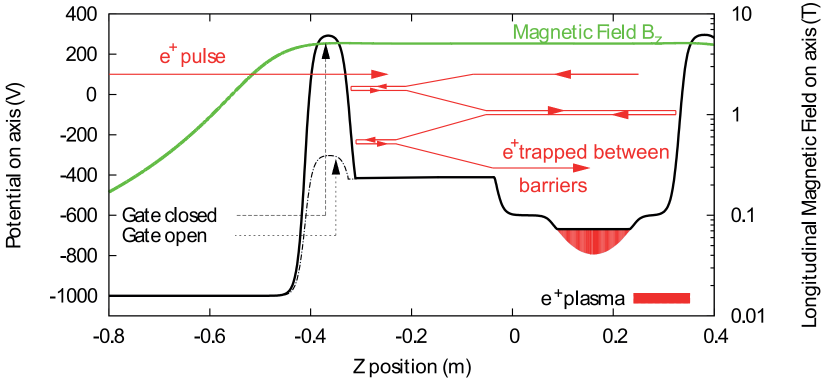
Penning-Malmberg trap

27 annular electrodes: electrostatic field → longitudinal confinement





Accumulation technique

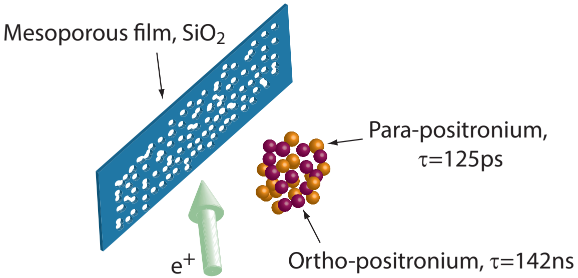


e^+ injection $\rightarrow$ e^+ confinement + stacking $\rightarrow$ e^+ ejection

Positronium production

Mesoporous film

- pure silica (SiO_2) with nanometer size pores
- emits ortho-positronium (~50 meV) upon implantation of e^+ (~keV)
- high (~30%) efficiency



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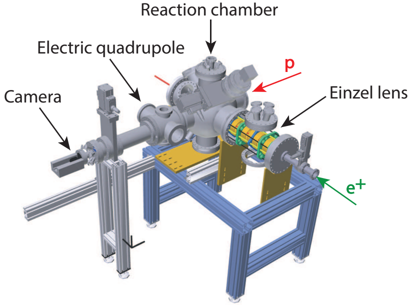
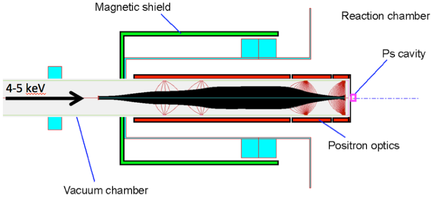
Ps cloud density:

@Cea: 10^{10} Ps/cm^3
@Cern: 10^{12} Ps/cm^3

ANTION setup

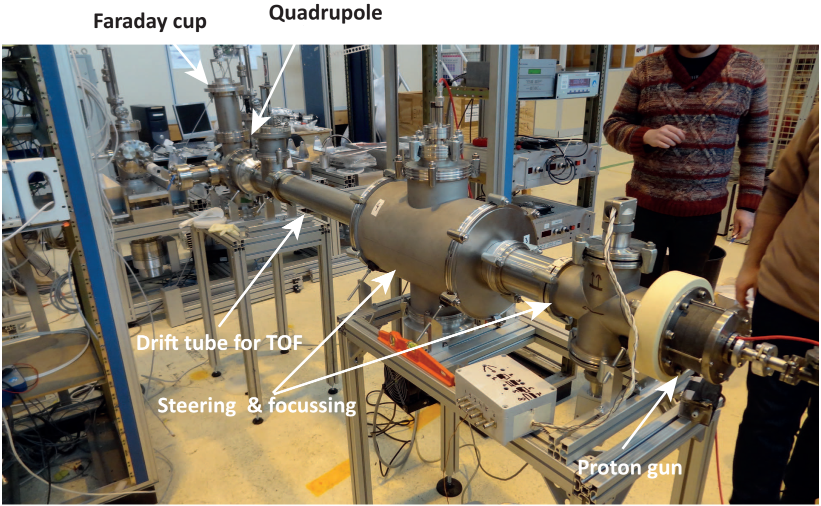




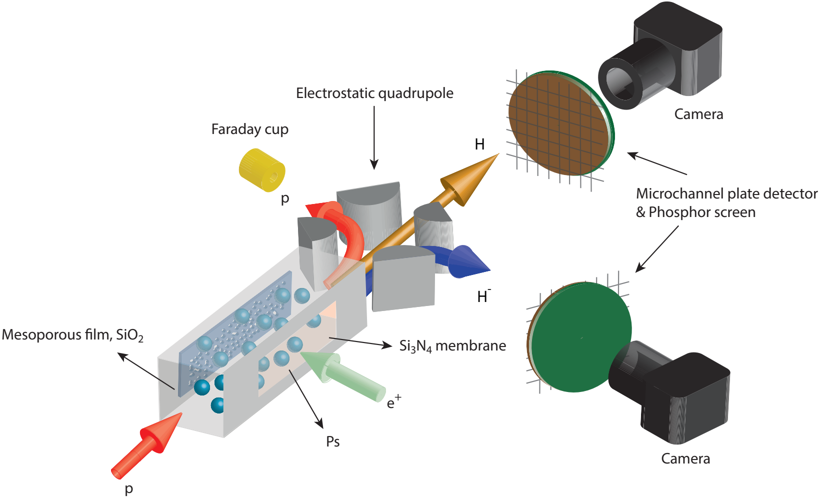
Positron optics after the trap:

- Electrostatic focussing + magnetic shielding
- Exit from magnetic field with 4 keV energy

Proton source



Reaction scheme

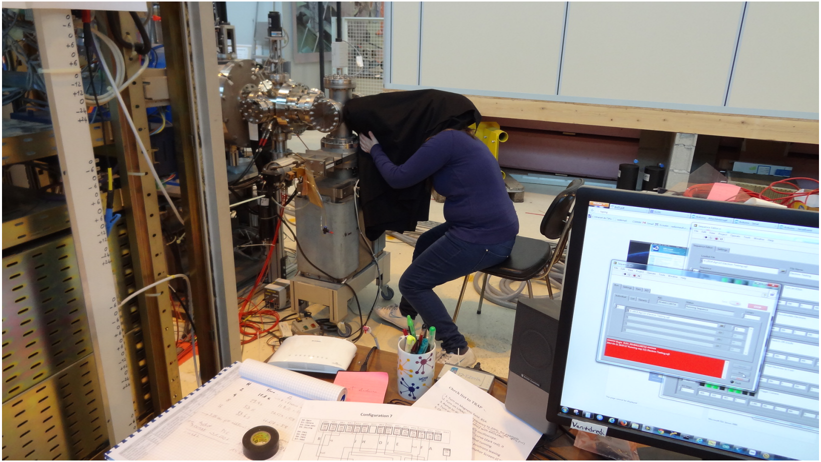


Conclusion

- We are currently assembling the experimental setup
- Commission during summer
- Stay tuned for hydrogen production next fall!

Thank you!

Questions?



Extra Slides

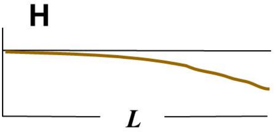
GBAR vs AEGIS

GOAL: $\frac{\Delta \mathbf{g}}{\mathbf{g}} \leq \mathbf{1\%}$

GBAR: cooled $\bar{\mathrm{H}}^{+} \rightarrow$ slow $\bar{H}$
$\mathrm{L} = 0.1\,\mathrm{m}$ and $v_{\bar{H}} = 0.5\,\mathrm{m/s} \Rightarrow 20\,\mathrm{cm}$
$(T_{\bar{H}} \sim 10\,\mu K \sim 7neV)$

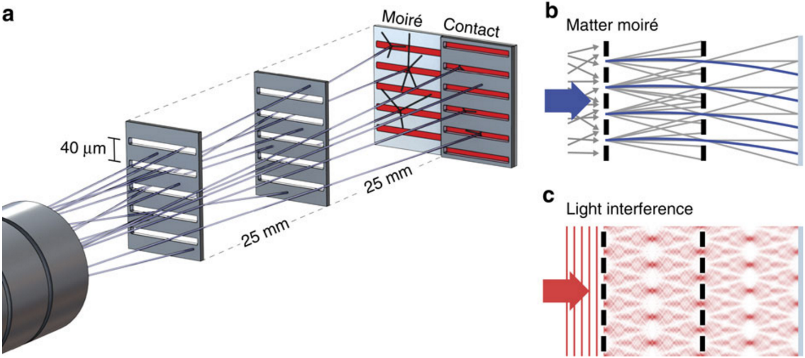
AEGIS: $\bar{H}$ beam
$\mathrm{L} = 1\,\mathrm{m}$ and $v_{\bar{H}} = 500\,\mathrm{m/s} \Rightarrow 20\,\mu\mathrm{m}$
$(T_{\bar{H}} \sim 100\,mK \sim 7\,\mu eV)$

$$m_i \vec{a} = m_g \vec{g}$$



$$h = v_z^0 t + \frac{1}{2}\frac{m_g}{m_i} g t^2 = v_z^0 \left(\frac{L}{v_h}\right) + \frac{1}{2}\frac{m_g}{m_i} g \left(\frac{L}{v_h}\right)^2$$

GBAR vs AEGIS



(a) A divergent antiproton beam impinges on two subsequent gratings that restrict the transmitted particles to well-defined trajectories. This leads to a shadow fringe pattern as indicated in b, which is shifted in the presence of a force (blue trajectories). Finally, the antiprotons are detected with a spatially resolving emulsion detector. To infer the force, the shifted position of the moiré pattern has to be compared with the expected pattern without force. (c) This is achieved using light and near-field interference, the shift of which is negligible. A grating in direct contact with the emulsion is used to reference the antimatter and the light measurements.

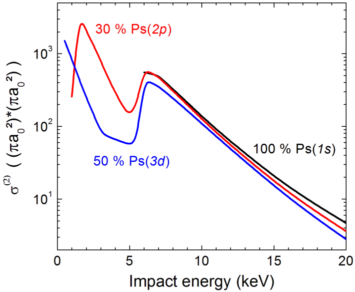
Equivalence principle

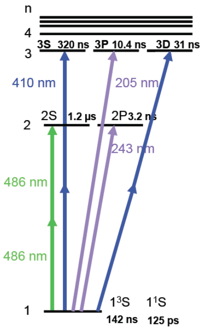
"The trajectory of a point mass in a gravitational field depends only on its initial position and velocity, and is independent of its composition and structure."

Equivalence principle

Researcher	Year	Method	Result
John Philoponus[clarification needed]	6th century	Described correctly the effect of dropping balls of different masses	no detectable difference
Simon Stevin[8]	~1586	Dropped lead balls of different masses off the Delft churchtower	no detectable difference
Galileo Galilei[clarification needed]	~1610	Rolling balls down inclined planes	no detectable difference
Isaac Newton	~1680	Measure the period of pendulums of different mass but identical length	difference is less than 1 part in 10^3
Friedrich Wilhelm Bessel	1832	Measure the period of pendulums of different mass but identical length	no measurable difference
Loránd Eötvös	1908	Measure the torsion on a wire, suspending a balance beam, between two nearly identical masses under the acceleration of gravity and the rotation of the Earth	difference is less than 1 part in 10^9
Roll, Krotkov and Dicke	1964	Torsion balance experiment, dropping aluminum and gold test masses	$\|\eta(\mathrm{Al},\mathrm{Au})\| = (1.3 \pm 1.0) \times 10^{-11}$ [9]
David Scott	1971	Dropped a falcon feather and a hammer at the same time on the Moon	no detectable difference (not a rigorous experiment, but very dramatic being the first lunar one[10])
Braginsky and Panov	1971	Torsion balance, aluminum and platinum test masses, measuring acceleration towards the Sun	difference is less than 1 part in 10^{12}
Eöt-Wash group	1987–	Torsion balance, measuring acceleration of different masses towards the Earth, Sun and galactic center, using several different kinds of masses	$\eta(\mathrm{Earth},\mathrm{Be\text{-}Ti}) = (0.3 \pm 1.8) \times 10^{-13}$ [11]

$\bar{H}^+$ formation cross sections





For a pulse of 3×10^6 $\bar{p}$:

- 1.2 $\bar{H}^+$ for 1 keV + Ps(3d)
- 3 $\bar{H}^+$ for 2 keV + Ps(2p)
- 0.9 $\bar{H}^+$ for 6 keV + Ps(1s)

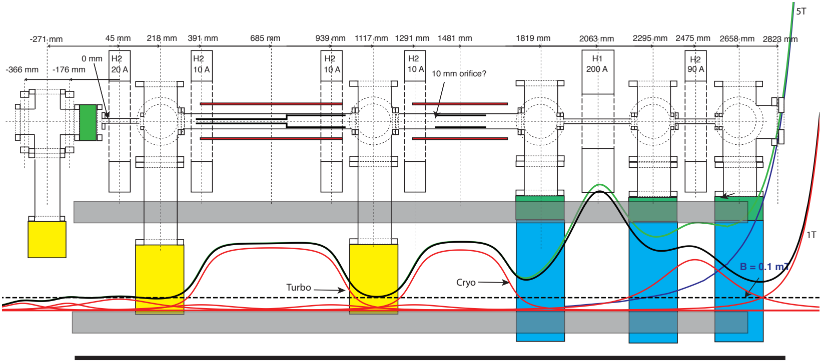
Buffer gas trap - energy loss mechanism

- A continuous beam of positrons can only be trapped in a Penning-type trap if there is a suitable way to loose energy.
- Solution: use a buffer gas for inelastic collision, however, competing process: positronium formation
- Surko and co-workers invented buffer gas trap using nitrogen.
- Positron - Nitrogen interactions:

$$\mathrm{e}^+_{(<8eV)} + \mathrm{N}_2 \rightarrow \mathrm{e}^+ + \mathrm{N}_2^{\mathrm{rot/vib}}$$
$$\mathrm{e}^+_{(>8eV)} + \mathrm{N}_2 \rightarrow \mathrm{Ps} + \mathrm{N}_2^+$$
$$\mathrm{e}^+_{(8-11)eV} + \mathrm{N}_2 \rightarrow \mathrm{e}^+ + \mathrm{N}_2^*$$

- In the last reaction the positrons loose about 9 eV. Around 11 eV the Ps formation rate equals the inelastic collision rate, so there is a $\sim$ 3 eV window with an efficient energy loss.

Buffer gas trap



Positronium production & spectroscopy

Spectroscopy

Detection of the fluorescence light:

3D to 2P transition → infra-red photon at 1312nm

2P to 1S transition → UV photon at 243nm

Detectors:

Annihilation → scintillators Fluorescence → optical fibers + photomultipliers

Hydrogen detection

Background sources

- Gamma radiaton from e^+ and Ps annihilation
- MCP noise
- Charged particles - separated by TOF