Apparatus to Explore the Gravitational Interactions of antiatomS: the R&D programme

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Toward fundamental physics with cold antihydrogen

1997: ATHENA and ATRAP approved

1) Cold antihydrogen production

2002: ATHENA AND ATRAP:

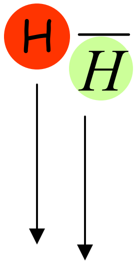
2) Trapping and cooling

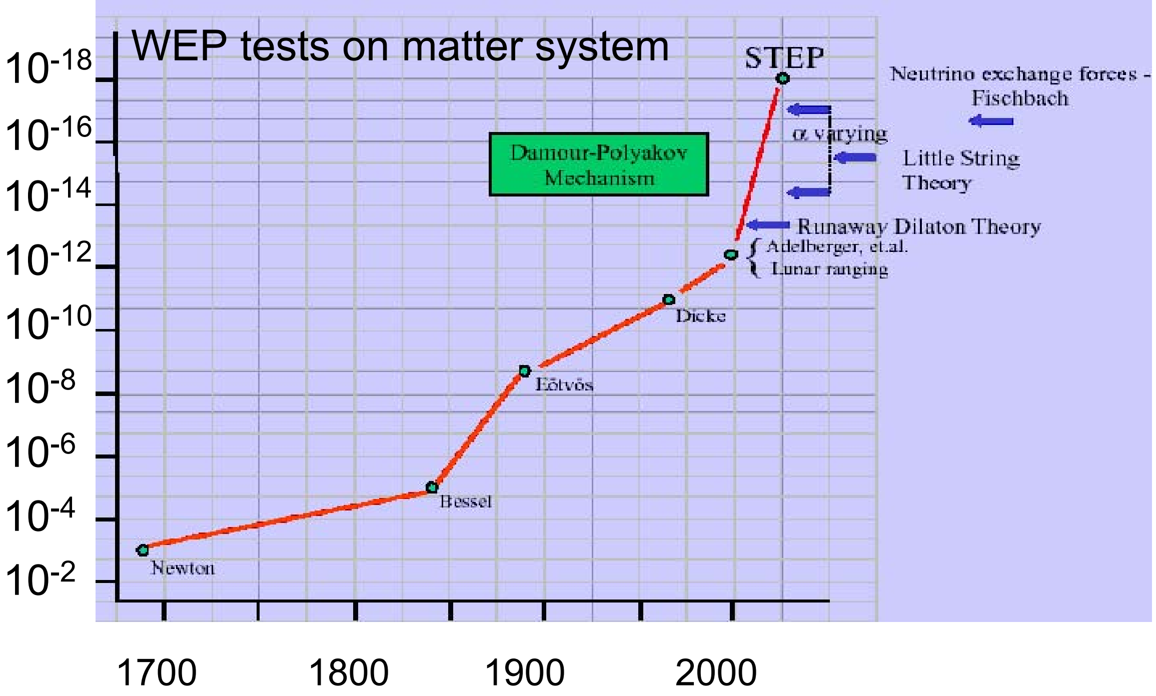
R&D is needed

3) High precision comparison
of H an AntiHydrogen

CPT, gravity

Fundamental physics with cold antihydrogen : Weak Equivalence Principle





- •No direct measurements on gravity effects on antimatter
- •“Low” precision measurement will be the first one
- •Sensitivity of the experiments should aim to reach the values set by the indirect limits

WEP and antimatter: indirect limits

Virtual pairs e+ e- contribute to the mass

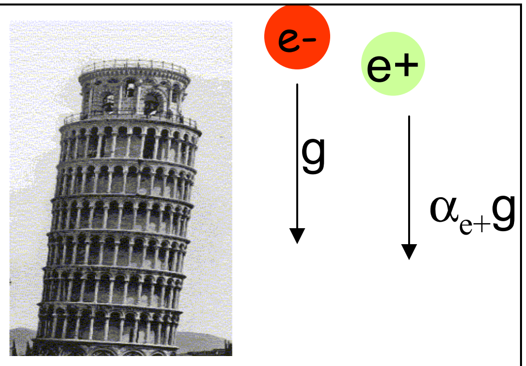
WEP violation for positrons originates a Z dependent effect

$$m_i - m_g = (\alpha_{e+} - 1)\frac{4m_e}{3\pi^2}\left(\frac{Z}{137}\right)^2\left(\log(h/mcR_{nuc}) + 0.338\right)$$

L.I. Schiff PRL 1 254 (1958), Proc. Natl Acad. Sci. 45 (1959) 69

$$\longrightarrow \quad (\alpha_{e+} - 1) < 10^{-6}$$

T.E.O. Ericson and A. Richter, Europhysics Letter 11 (1990) 295



M. Nieto et al Phys Rep. 205 (5) 221 (1991)
M. Charlton et al Phys. Rep 241 65 (1994)
R. Hughes Hyp Int. 76 3 (1996)

WEP: frequency shift
in presence of gravitational field U

$$\omega \to \omega\left(1 + \frac{U}{c^2}\right) \qquad \frac{\omega_{clock} - \omega_{anticlock}}{\omega_{clock}} = 3(\alpha - 1)\frac{U}{c^2}$$

- •CPT validity
- •U/c^2=3 10^{-5} (supercluster)
- •U ⟶ 0 at infinit

$$\frac{m_{K_0} - m_{\overline{K_0}}}{m_{K0}} < 5\,10^{-18} \Rightarrow \left|\alpha_{K_0} - \alpha_{\overline{K_0}}\right| < 2.5\,10^{-18}$$

+ input from quark model ...

R. Hughes et al,J. Mod Opt. 39 263 (1992)

$$\left|\alpha_{\bar{p}} - 1\right| < 2\ \ 10^{-8}$$

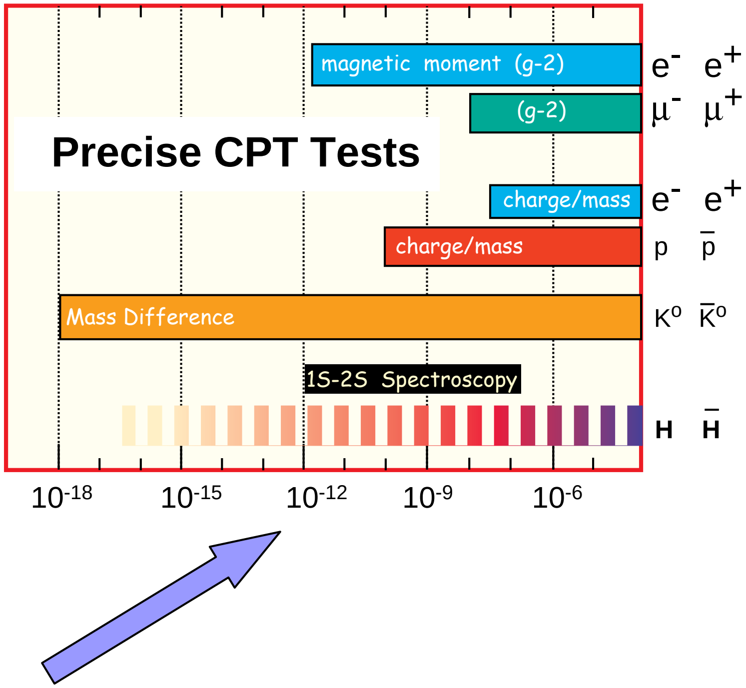
Gravity measurements and spectroscopy

1S-2S ν=2 466 061 413 187 103 (46) Hz

Natural width: 1.3 Hz

.....$\Delta\nu/\nu < 10^{-15}$

CPT symmetry



Achieved results on Hydrogen

$\Delta\nu/\nu$= 1.5 10^{-14} Cold beam $E \approx 100\, mK$

PRL84 5496 (2000) M. Niering et al

$\Delta\nu/\nu$ = 10^{-12} Trapped H $E \approx 100\, \mu K$

PRL 77 255 (1996) C. Cesar et al

WEP and antihydrogen

…accepting all the previous hypothesis
(gravitational shift of clock and anticlock frequency)

$$\frac{\omega_{clock}-\omega_{anticlock}}{\omega_{clock}} = 3(\alpha-1)\frac{U}{c^2}$$

$$\frac{\omega^{H}_{1S-2S}-\omega^{\overline{H}}_{1S-2S}}{\omega^{H}_{1S-2S}} \cong 10^{-15} \Rightarrow (\alpha_{\overline{H}}-1) \cong 10^{-11}$$

Not assumption free….

WEP ⟶ $\Delta\omega = \frac{\Delta U}{c^2}$

Null red shift experiment" : CPT independent

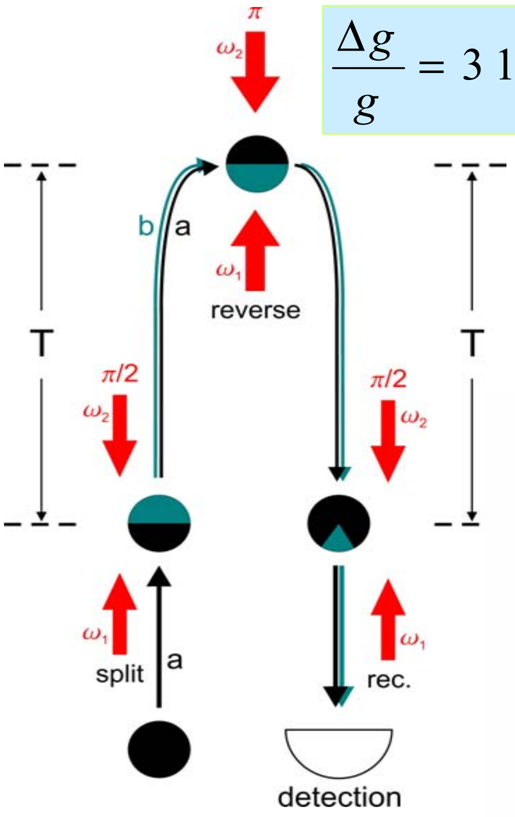
$$\frac{\Delta\omega^{H}_{1S-2S}-\Delta\omega^{\overline{H}}_{1S-2S}}{\Delta\omega^{H}_{1S-2S}} \approx 10^{-15} \Rightarrow (\alpha_{\overline{H}}-1) \approx 10^{-6}$$

Direct measurements : time of flight, beam deflection….
atom interferometry : 10^{-4} …10^{-6} ..10^{-9} ..$10^{-?}$

g measurement using Atom Interferometry

Matter wave interference:

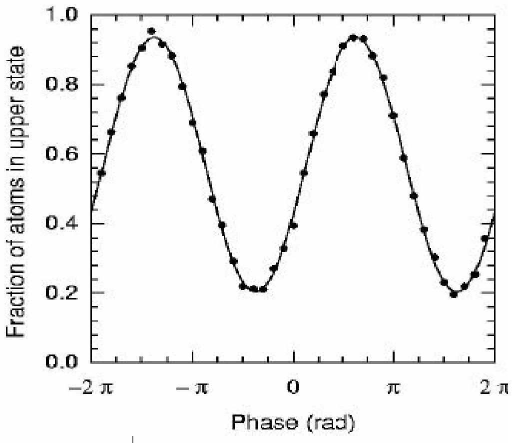
- Material grating
- Light
- Light and change of internal state population



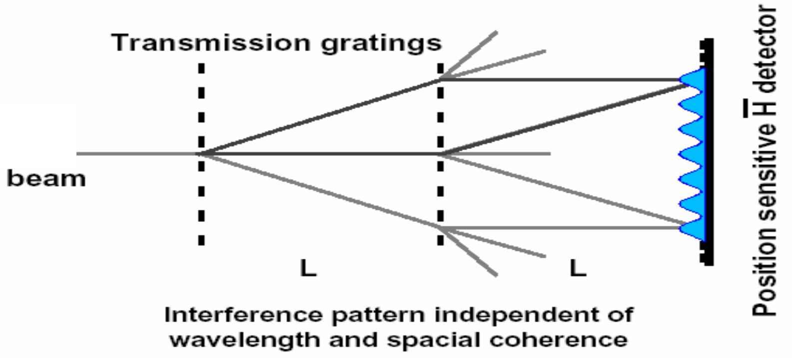
$$\frac{\Delta g}{g} = 3\,10^{-9} \propto T^2$$

Very cold Cs atoms µK!!!!!

A. Peters et al, Nature 400 (1999) 849



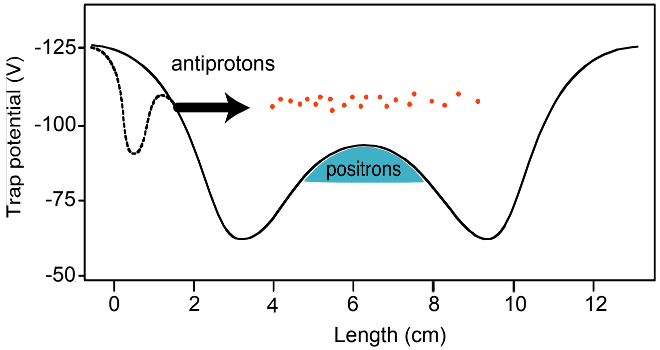
-Split and recombination of cold atomic beams
-Interference pattern (vs time or vs space)
-Phase shift due to gravity



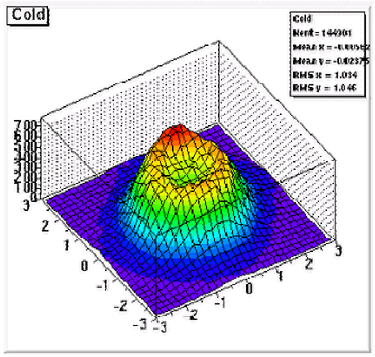
MAGIA experiment

(Florence group)

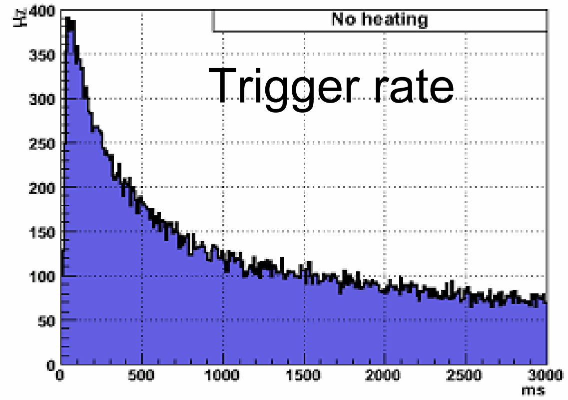
Some antihydrogen results



ATHENA: mixing in the nested trap

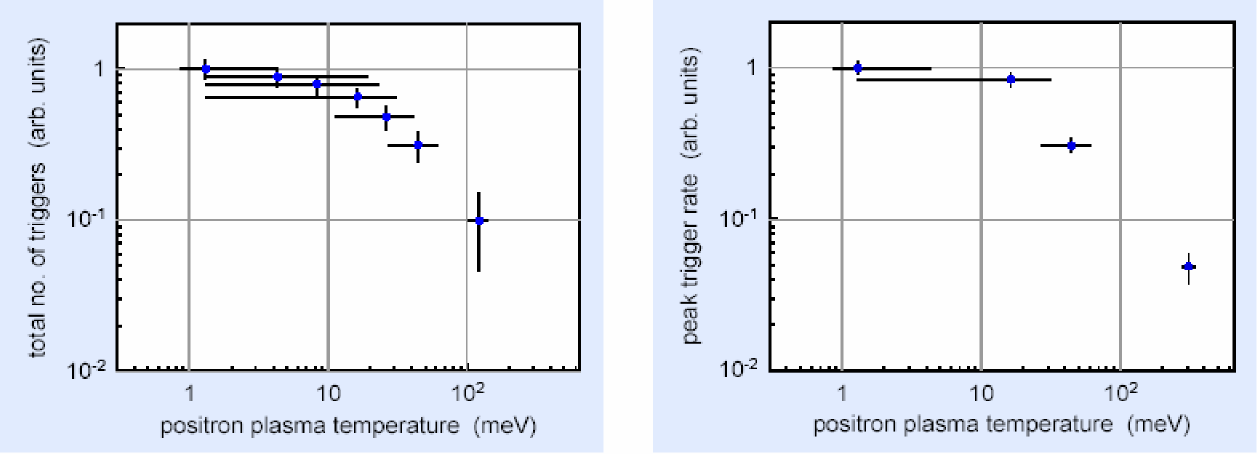


typical vertex distribution



trigger rate vs time

Accumulation and cooling of pbars and positrons:	10^4 cold pbars, 7 10^7 e+
Non destructive plasma parameter measurements:	n, r, L
Mixing in a nested trap for tens of sec:	about 20% of pbars recombine
Background :	plasma heating, controlled increase of T
Reconstruction of Hbar vertex:	radial analysis, opening angle
Several mixing schemes:	optimization of pbars use
Hbar production rate vs mixing time:	initial rate 300-400 Hz
Hbar spatial distribution:	isotropic



Pbar production: positron temperature dependance

Radiative recombination

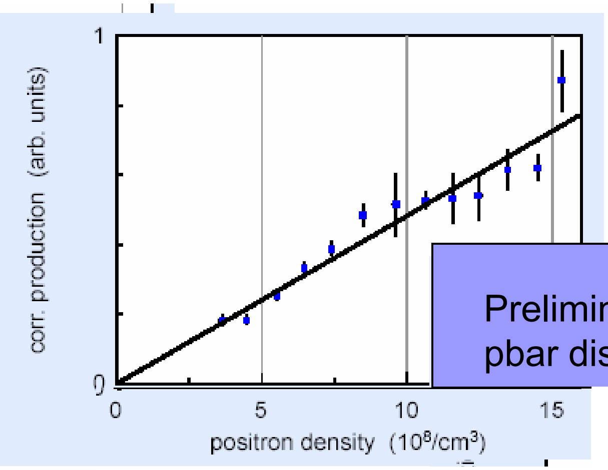
$T^{-1/2}$, n_{e+}

Low n states

3body

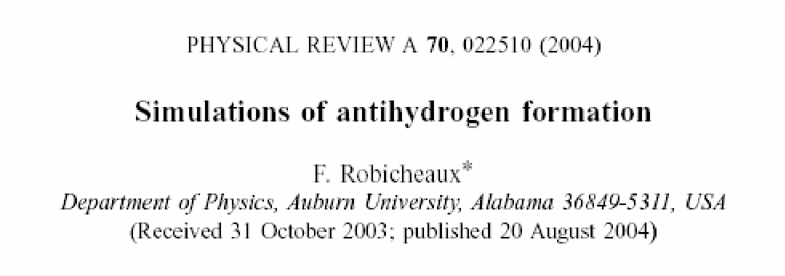
$T^{-9/2}$, $(n_{e+})^2$

High n states



Preliminary, uniform radial pbar distribution …?

Pbar production: positron density dependance r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Simulations of antihydrogen formation

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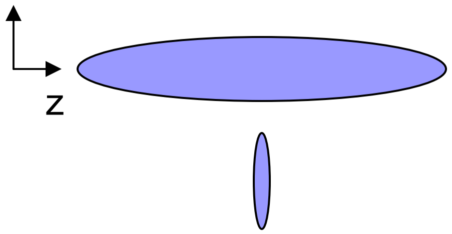
(Received 31 October 2003; published 20 August 2004)



ATHENA plasma shape

ATRAP plasma shape

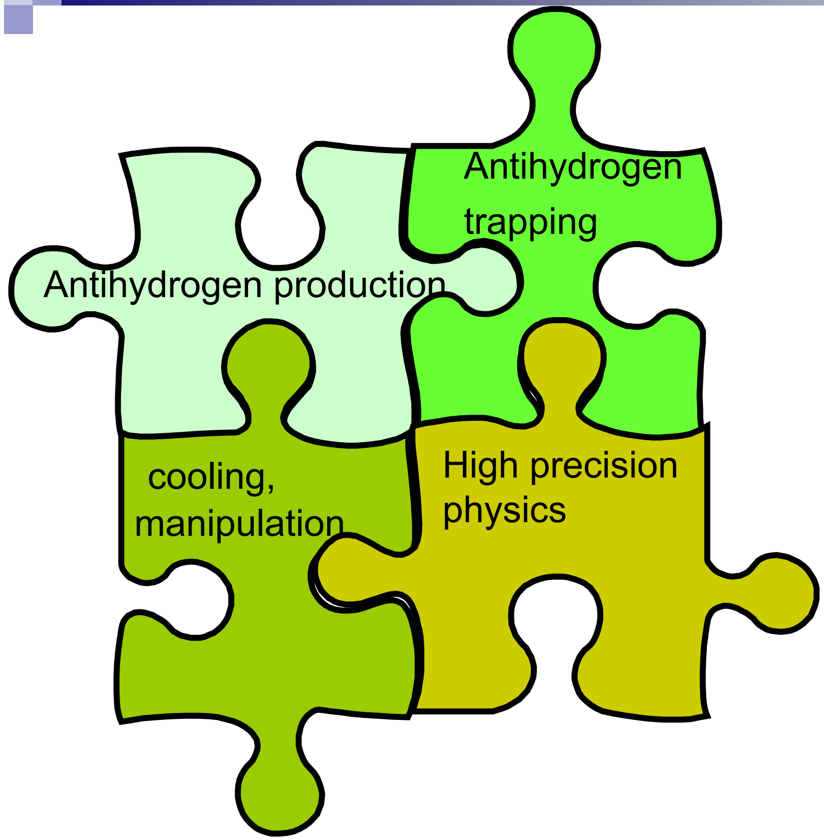
Simulations based on 3body only

Extended, dense e+ plasma → more deeply bound states

A fraction of low energy trappable antiatoms should be produced

Energy of the antihydrogen ?

Cooling – thermalization- recombination- energy due to the plasma rotation…



The AEGIS group is working on an extensive R&D programme using e-,p,(ions)

- Antihydrogen trapping: field configurations able to trap Hbar and charged plasma
- Antihydrogen positive ion production: test experiment with H and e-
- Development of Lyman alpha laser with sufficient power for antihydrogen cooling
- Cold antihydrogen manipulation
- g measurement using an atom interferometer coupled to a silicon detector (see C. Regenfus talk)
- High precision g measurement

Preparation of a proposal for a gravity measurement on antihydrogen at AD

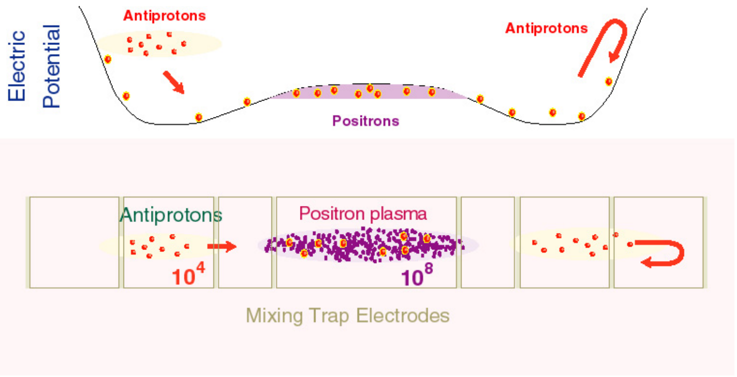
Trapping antihydrogen : production and trapping in the same volume ?

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

Hbar production : several secs mixing time

Charged plasmas and neutral antiatoms have to be confined in the same volume

Trapping charged particles



No rotational symmetry, no plasma stability

Trapping neutral particles

$$U = -\vec{\mu} \cdot \vec{B} = \pm \mu B$$

$$F = \vec{\nabla}(\vec{\mu} \cdot \vec{B}) = \mp \mu \vec{\nabla} B$$

$$\mu = 670\, mK / T$$

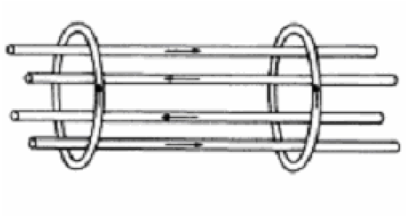
$$\Delta B \approx T \qquad \Delta r \approx cm$$

Magnetic field gradient

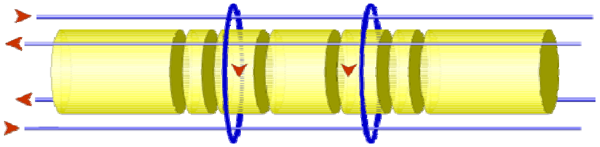
High B values

B minimum, not zero

No rotational symmetry



Trapping charged and neutral particles



?

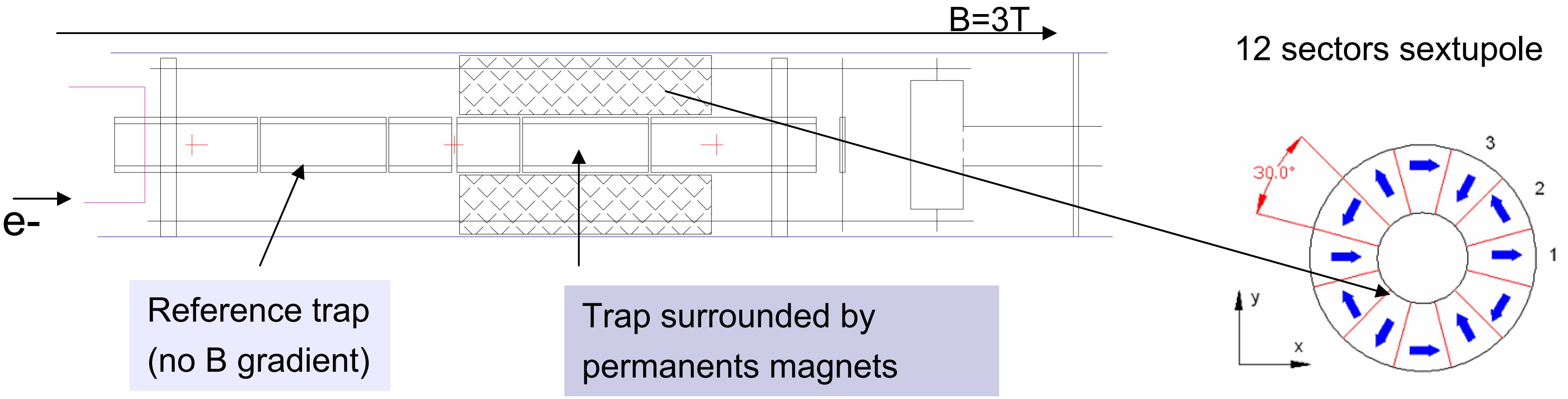
Trapping antihydrogen : production and trapping in the same volume ?
TEST experiment in progress (Genoa, CERN,Trento)

- Test experiment with permanent magnets inserted in 3T axial superconducting magnet
- Several configurations can be compared
- High depth for neutral : several hundreds mK
(NdFeB Renmant field 1-1.4 T)

Radial multipole 2n
”Flat” field near the trap center

$$B \propto \left(\frac{r}{R_1}\right)^{n-1}$$

Permanent magnets to be delivered soon
Apparatus in advanced state of installation in Genoa



Reference trap
(no B gradient)

Trap surrounded by
permanents magnets

1) e- plasma: study of the radial transport

2) Nested trap, p and e- inside the trap for neutral atoms

1) Plasma storage time of some tens of secs

2) Observation of p cooling from e- (proxy signal for recombination)

Trapped antiHydrogen has energy of the order of 1K- 0.5 K

Work on antihydrogen cooling

High precision measurements need not only trapping but also cooling

1S-2S lineshift and broadening for trapped H (T=1K, B=Tesla)

$$\frac{\Delta\upsilon}{\upsilon} \approx some\,10^{-10} \qquad \xrightarrow{\qquad ? \qquad} \qquad 10^{-15}$$

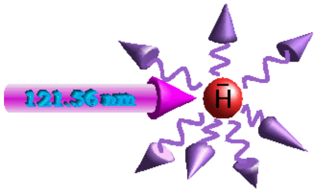
Gravity measurements

$$L \approx m \qquad v_o t \approx \frac{1}{2} g t^2 \qquad v < v_o \approx \text{ m/sec} \longrightarrow \text{mK}$$

Development of a CW powerful, portable Lyman alpha source

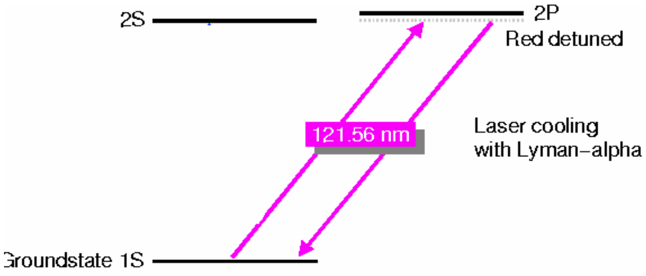
Florence, Bologna

K. S. E. Eikema, et al.PRL 83, 3828 (1999), 86 (2001) 5679



$$\Delta v = \frac{\hbar k}{M}$$

(20 nW@ 121.6 nm)



Antihydrogen cooling

Final energy : mK

Cooling below the mK range

- Simulation in progress (adiabatic reduction of the confining B after Laser cooling, collisionless mechanism)
- Antihydrogen ion production

Antihydrogen ions production $\overline{H}^{+}$ CERN group

J. Walz and T. Hansch, Gen. rel. and gravitation Vol 36, n3 (2004)

$\overline{H}^{+}$

sympathetic cooling with ions

Cooling to sub-mk energies

e+ photodetachment ⟶ very cold antiHydrogen

- Design of a test experiment in progress
- H^- production at low energies by laser induced recombination of H and e- in a 3T magnetic field

$$H + e^- + h\nu \rightarrow H^-$$

- Theoretical work in progress

The next steps

Is magnetic trapping feasible?

Is the production of antihydrogen ions feasible?

Realistic timescale 2007

Proposal to SPSC