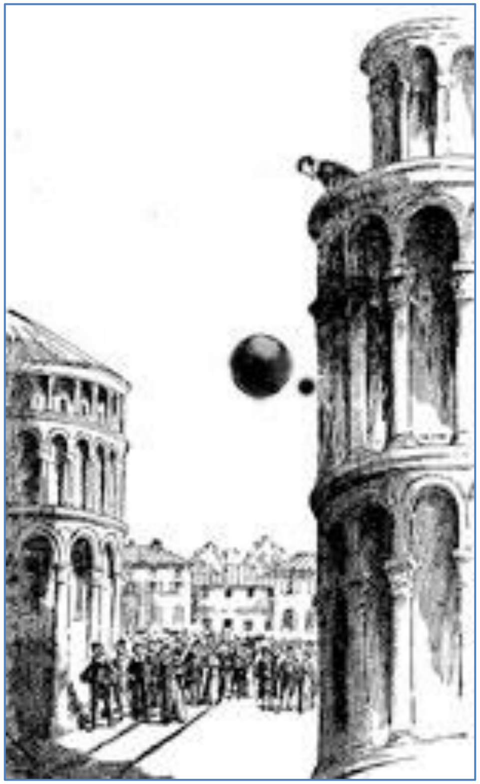
Verification of the Equivalence Principle for antimatter and anti-hydrogen spectroscopy : the AEgIS experiment

Gemma Testera

INFN Genova-ITALY



Ferrara: May. 20th, 201

AEgIS collaboration (about 60-70 people)

- CERN
- INFN (Genova, Milano, Pavia-Brescia,Tranto-Padova, Bologna)
- IPNL Lyon
- MPI-K Heidelberg
- University of Heidelberg
- INR Moscow
- University of Bergen
- UCL College (London)
- Lab. Aime’ Cotton Orsay (France)
- Czech Tech. Univ. (Prague)
- University of Bern
- ETH Zurich

AEgIS at AD@CERN

AEgIS: Antimatter Experiment gravity Interferometry Spectroscopy

AEgIS goals

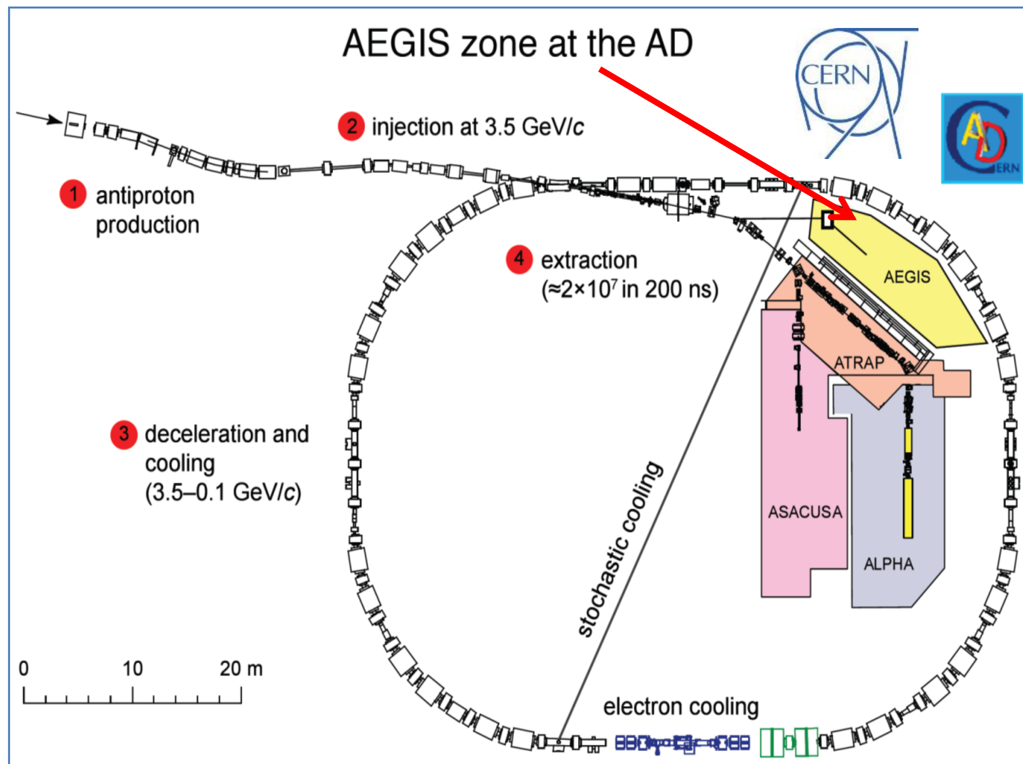
1) Verification of equivalence principle for antimatter: measure the Earth acceleration g on a beam of ultracold (100 mK) Hbar
2) Antihydrogen spectroscopy (HFS, 1S-2S) (CPT and Lorentz Invariance tests)

AD: Antiproton Decelerator : pbar@5MeV

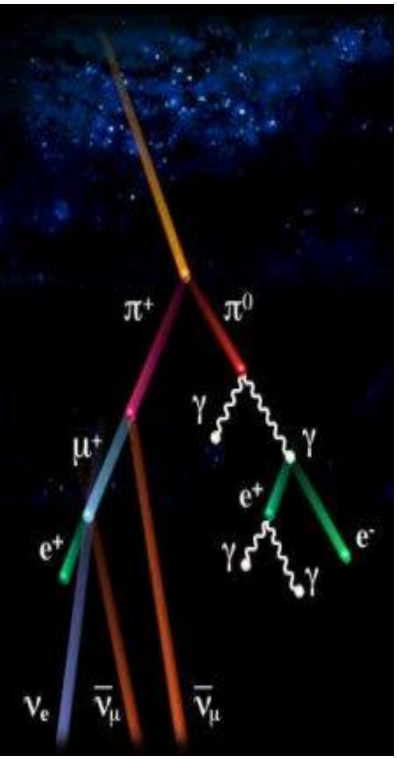
From 1999:
Cold antihydrogen formation &physics

2002: ATHENA (and then ATRAP)
millions of Hbar
temperature few 10K-100K
Athena Collaboration Nature 419, 456-459 (2002)

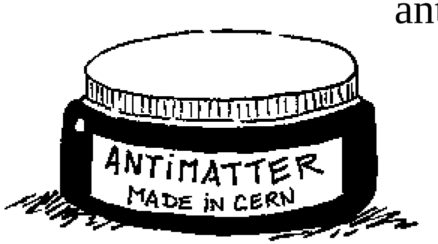
Now running:
ATRAP,ALPHA : trapping Hbar for spectroscopy
ASACUSA : beam for HFS measurement
exotic atoms, nuclear physics
AEgIS : cold Hbar beam for g
measurement (and spectroscopy)
GBAR : approved (it will be installed after 2015)



Antimatter history



- 1928 P. Dirac : antimatter must exist
- 1932 : C. Anderson discovers positrons in cosmic rays
- 1954 : E. Segre' discover s antiprotons (Bevatron)
- 1960 : detection of antineutrons.
- 1965 : Zichichi, Lederman detect : antimatter nuclei
- Antimatter particles are routinely produced at accelerators;
  there are many experiments studying antimatter particles at accelerator or in space
- 1995 : CERN , FERMILAB: few antihydrogen atoms (relativistic velocity)
- 1999 : at CERN the AD machine starts working: devoted to cold antihydrogen
- 2002 : ATHENA al CERN (e ATRAP) : millions of cold (tens, hundreds K) antihydrogen atoms
- From 2006 on: new experiments to produce and study very cold antihydrogen atoms (ALPHA, ATRAP, ASACUSA, AEGIS, (GBAR))



AEgIS experimental challenge

- Formation of "cold" beam of antihydrogen : temperature in the 100mK range and manipulation of antiprotons, positrons and electrons with very low energies
- methods: particle physics + atomic physics

$$1\, eV = 1.16\, 10^4\, K$$

$$8.6 \mu eV = 100 mK$$

Summary of the talk

•Motivation: -WEP and antimatter
-Antihydrogen and CPT (and Lorentz Invariance)

•Description of the AEgIS experiment

WEP and EEP: from Newton to General Relativity

Newton

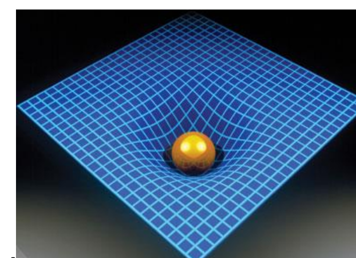
$$\vec{F} = m_i \vec{a} \quad \vec{F_g} = m_g \vec{g}$$

Weak Equivalence Principle (WEP)

$$m_i = m_p$$

Einstein Equivalence Principle = WEP (Weak EquivalencePrinciple) +
LLI (Local Lorentz Invariance) +
LPI (Local Position Invariance)

Einstein General Relativity



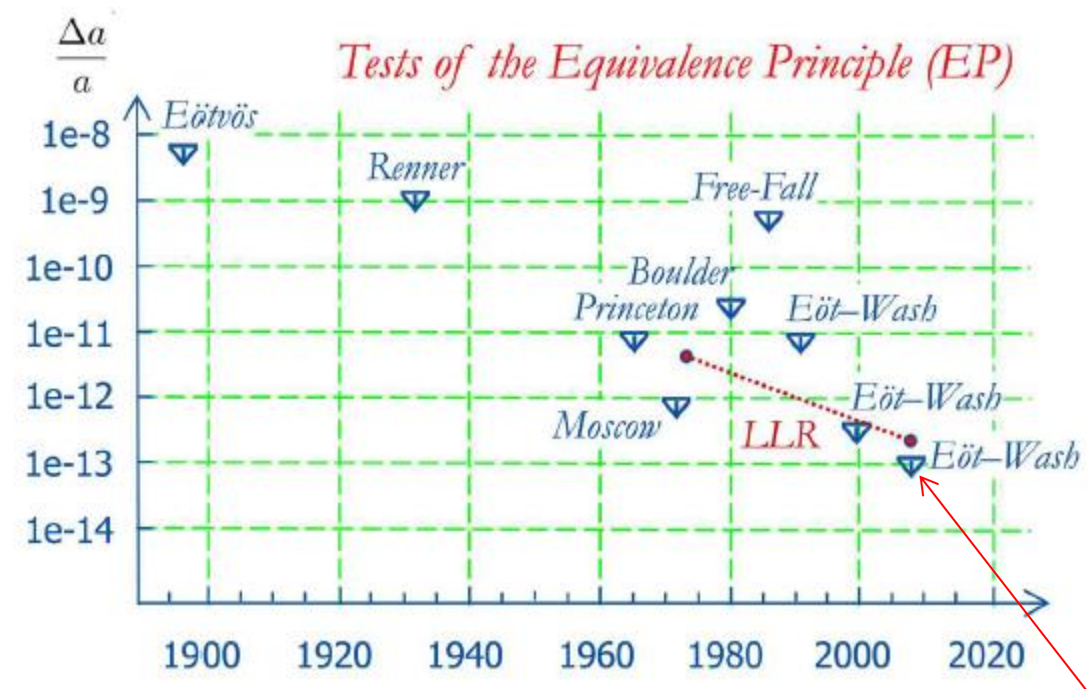
EEP
1) WEP is valid
The outcome of any local non-gravitational experiment is independent
2) of the velocity of the freely-falling reference frame in which it is performed (LLI)
3) of where and when in the universe it is performed (LPI)

C. M. Will "Theory and experiment in gravitational physics"

EEP tests : WEP tests + LLI tests + LPI tests

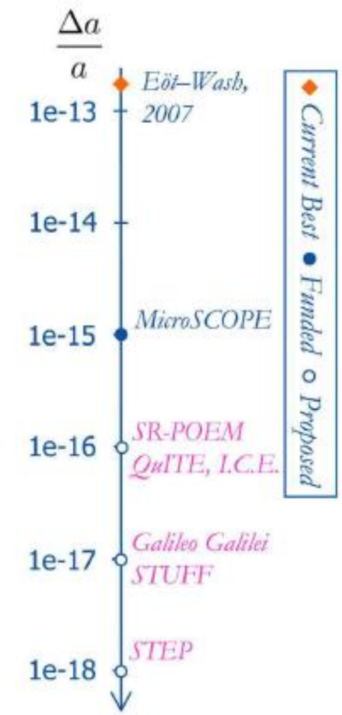
$$\eta = \frac{\Delta a}{a} = \frac{a_1 - a_2}{(a_1 + a_2)/2}$$

WEP tests: Universality of Free Fall (UFF)



C.M. Will Living Rev. Rel. 9(2006) 3
S. G. Turishev Phys.Usp. 52 (2009) 1-27

http://www.npl.washington.edu/eotwash/



Anticipated progresses in the test accuracy

$$m_G(A,Z) = m_I(A,Z) + \eta_e Z m_e + \eta_p Z m_p + \eta_n (A-Z) m_n + \eta_E E(A,Z)$$

$$|\eta_e| < 4 \cdot 10^{-6}$$

$$|\eta_n| = |\delta_p| < 5 \cdot 10^{-9}$$

$$|\eta_E| < 5 \cdot 10^{-9}$$

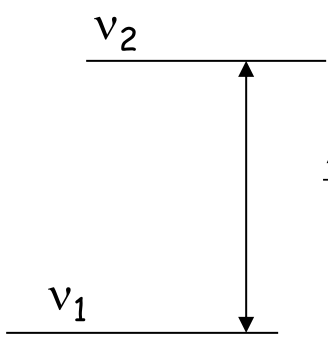
WEP is valid for e,p,n ...

Only for matter

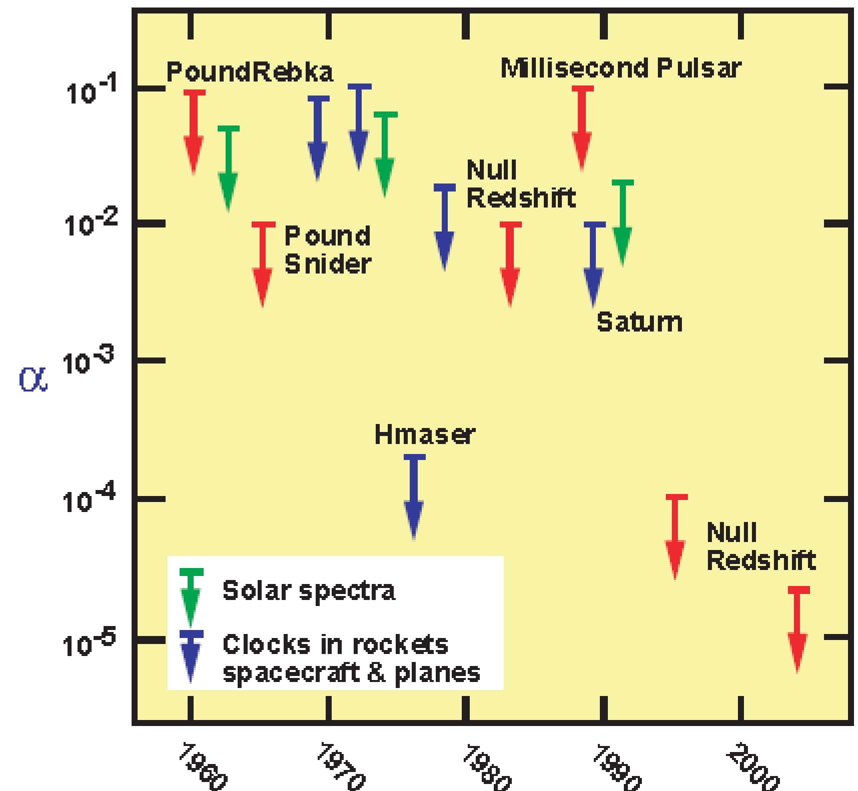
R. J. Hughes, Cont. Phys. 34,177 (1993)

Local Position Invariance Tests

1) Gravitational red shift



$$\frac{\Delta\upsilon}{\upsilon} = \left((1+\alpha)\frac{\Delta U}{c^2} \right)$$



Only for matter

C.M. Will Living Rev. Rel. 9(2006) 3
S. G. Turishev Phys.Usp. 52 (2009) 1-27

There are not direct tests of the equivalence principle for antimatter

$$m_i^{antimatter} \stackrel{?}{=} m_g^{matter}$$

- No direct experimental tests
- Main reason for making the experiment!

▪Attempt with e^+ and e^- : dominated by systematic effects; test with e+ never performed

F. C.Witteborn andW. M. Fairbank, Phys. Rev. Lett. 19, 1049 (1967).

▪Experiment with antiprotons PS200@LEAR (CERN) : never completed
control stray electric field 10^{-7} V/m;
development of many basic technologies later used in the antihydrogen experiments

▪Cold Antihydrogen @ AD : 2002 ATHENA and ATRAP

▪Alpha recent exp. limit: m_g / m_i for antihydrogen cannot be larger than 110

AEgIS @ CERN: Antimatter Experiment gravity Interferometry Spectroscopy

- produce cold (100 mK) antiH beam
- measure the Earth acceleration g: initial accuracy 1% (more precision later)
- + antiH spectroscopy

"Indirect" arguments:

- Controversial
- model dependent
- large differences between matter and antimatter unexpected

Equivalence principle for antimatter (ν – anti ν) and SN1987A

SN1987A

- 11 (Kamiokande II) + 8 (IMB)+ 5 (Baksan) = 24 (anti)neutrino events
- burst duration <13 sec
- $T_{light} - T_{\nu}$ = 6 hours
- Time delay generated by the field in our Galaxy: 4.8 months (Shapiro delay)
- ν and light experience the same time delay within 6 hours/4.8 months→0.5%

⟹ ν satisfy EEP

- If there was at least one neutrino detected then S. Pakvasa et al., Phys. Rev. D 39 ,6, 1989 pag 1761

ν and anti ν satisfy EEP within 13 sec/4.8 months → 1.6 10^{-6}

BUT

1) There is no signature for ν and antiν: unclear if there are ν events
2) Shapiro delay of relativistic particles is not a EEP test:

".. due to the overwhelming contribution of the kinetic energy to the effective passive gravitational mass, Shapiro delay neither tests the equivalence principle nor anomalous long-range couplings related to the intrinsic properties and quantum numbers of the particles… "

G.T. Gillies Class. Quantum Grav. **29** (2012) 232001

Sensitivity to any violation is suppressed by relativistic factors

Equivalence principle for antimatter and frequency measurements

"Red shift type" argument : clock frequency is influenced by the gravitational field

PRL 66,7 (1991) R. J. Hughes et al

Cyclotron frequency of protons and antiprotons in the same magnetic field

$$\left|\frac{\omega_c - \overline{\omega}_c}{\omega_c}\right| < 9\cdot 10^{-11}$$

G. Gabrielse et al PRL 82 (3198) (1999)

Assumptions

1) Protons do not violate the Equivalence Principle
2) EEP violation for antiprotons parametrized by α
3) At "infinity" by CPT summetry $\omega_{c0} = \overline{\omega}_{c0}$

Gravitational potential

$$\frac{\omega_c - \overline{\omega}_c}{\omega_c} = (3\alpha - 1)\frac{U}{c^2}$$

$\alpha < 3\cdot 10^{-6}$ if matter and antimatter are coupled to a same tensor field $\frac{U}{c^2} = 3\cdot 10^{-5}$

$\alpha < 10^{-1}$ for anomalous interaction with limited range $\frac{U}{c^2} = 6\cdot 10^{-10}$

Model dependent, CPT symmetry is assumed, absolute potential ....

Equivalence principle for antimatter and scalar-vector forces

- General relativity is a classical (non quantum) theory;
- Theoretical difficulties in building a unified quantum field theory including gravity;
- New quantum scalar and vector fields (in addition to the tensor gravitational field) are allowed in some models (Kaluza Klein ….)
- These fields may mediate interactions violating the equivalence principle

Scalar: "charge" of particle equal to "charge of antiparticle" : attractive force
Vector: "charge" of particle opposite to "charge of antiparticle" : repulsive/attractive force

Phys. Rev. D 33 (2475) (1986)

$$V = -\frac{G_\infty}{r} m_1 m_2 \left(1 \mp a\, e^{-r/v} + b\, e^{-r/s}\right)$$

M. Nieto and T. Goldman, Phys. Rep. 205, 5 221-281,(1992)
Bellucci & Faraoni, Phys. Lett. B 377 (1996) 55
J. Scherk, Phys. Lett. B 88 (1979) 265.

Limits on vector forces from torsion balance experiments

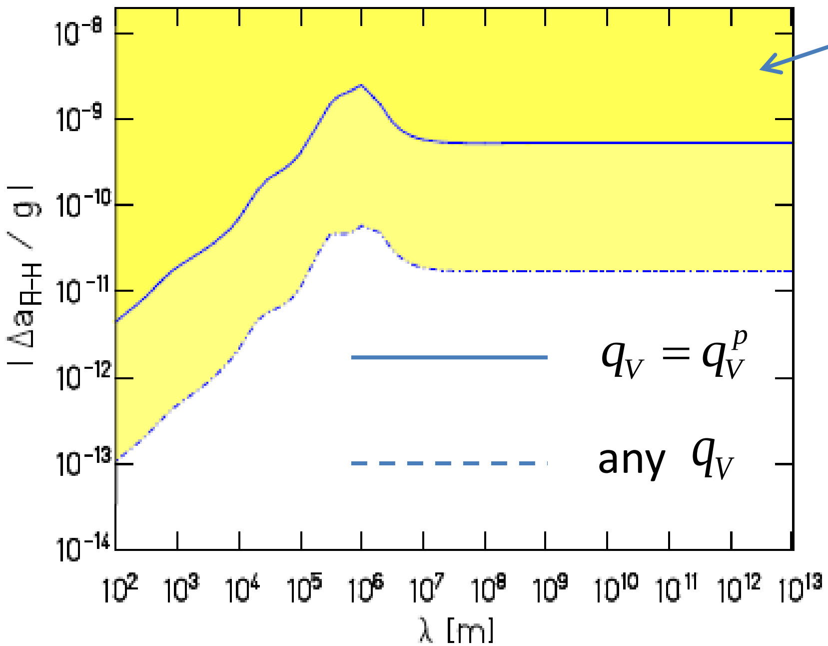
http://www.npl.washington.edu/eotwash/

$$q_V = q_V^p Z + q_V^e Z + q_V^n (A-Z)$$

$$\frac{\Delta a_{1,2}}{a} \propto \left(q_V^p + q_V^e\right)\left(\frac{Z_1}{\mu_1} - \frac{Z_2}{\mu_2}\right) + \left(q_V^n\right)\left(\frac{(A-Z)_1}{\mu_1} - \frac{(A-Z)_2}{\mu_2}\right)$$

Where

$$\mu = \frac{m}{atomic\ mass}$$



T.A. Wagner et al.,Class. Quantum Grav. 29 (2012) 184002

Updated of previous results

E. Adelberger et al, PRL 66,7 (1991) 850

Criticism by

- M. Nieto et al Phys. Rep. 205 (5) 221 (1991)
- T. Goldmann et al, PRL 67,8 (1048) 1991
- M. Charlton et al Phys. Rep 241 65 (1994)
- R. Hughes Hyp. Int.76 3 (1996)

- The analysis is model dependent
- Cancellation between scalar and vect. contributions are possible

See also:

M. Fischler et al.,arXiv:0808.3929 [hep-th] (2008)

D. S. Alves et al., 0907.4110v1 [hep-ph] (2009)

Symmetries and CPT

- Symmetries: operations leaving theory and experiment unchanged
- Symmetries are associated to operators in quantum field theory whose values do not change as result of the interaction
- P (parity- change of sign in coordinates): em and strong interaction are P invariant
- Until 1956 P was considered fundamental like energy conservation
- 1956 : Lee and Yang suggest that there is no evidence that weak interaction respect parity
- 1956: Wu et al.: study of angular distribution of electrons in b decay of spin polarized nuclei : evidence of P violation
- P Violation was a revolution: CP must be conserved
- But also CP is violated!
- We do not detect until now any process where CPT is violated (T:Time reversal)

Equivalence principle for antimatter and CPT

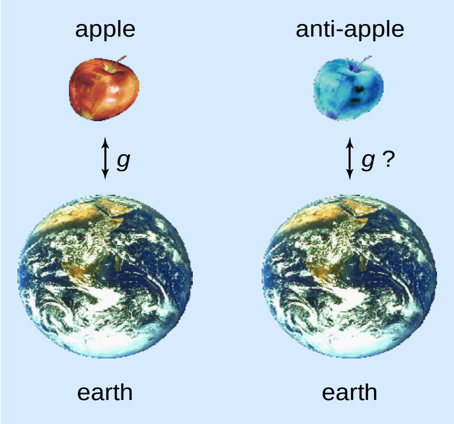
1) CPT : $$m_i^{particle} = m_i^{antiparticle}$$

2) General Relativity is "classic": it does not know CPT

3) Attempt to construct quantum gravity theories: effort in progress……
   no final theory until now….

5) Anyway : CPT will eventually tell us
   that the force between anti Apple and anti Earth
   is equal to that between Apple and Earth ……

What about anti Apple and Earth??



M. Nieto et al Phys. Rep. 205 (5) 221 (1991)

- CPT is related to basic principle of quantum field theory: not to one particular theory
- CPT proof only needs
- Lorentz invariance
- local field concepts
- Consequences :

  - equality of mass of particles and antiparticles
  - equality of energy levels of systems made by matter and antimatter
  - ………..

Standard Model Extension (SME) and Lorentz Invariance Violation

http://people.carleton.edu/~jtasson/
http://www.physics.indiana.edu/~kostelec/
http://physics2.nmu.edu/~nrussell/

SME: (Standard Model Extension) it is an effective field theory which contains

- General Relativity
- Standard Model
- Possibility of Lorentz Invariance Violation
- CPT violation comes with Lorentz violation

Violation of Lorentz invariance in several class of theory appears as effect of spontaneous breaking of the symmetry: SME accounts for this in very general way

It contains parameters allowing to make comparison with experiments

CPT odd

$$L = \underbrace{\tfrac{1}{2}\left(m + \tfrac{5}{3} N^w m^w \bar{c}^w_{TT}\right)}_{m_{\mathrm{i,eff}}} v^2 - gz \underbrace{\left(m + N^w m^w \bar{c}^w_{TT} + 2\alpha N^w (\bar{a}_{\mathrm{eff}})^w_T\right)}_{m_{\mathrm{g,eff}}}$$

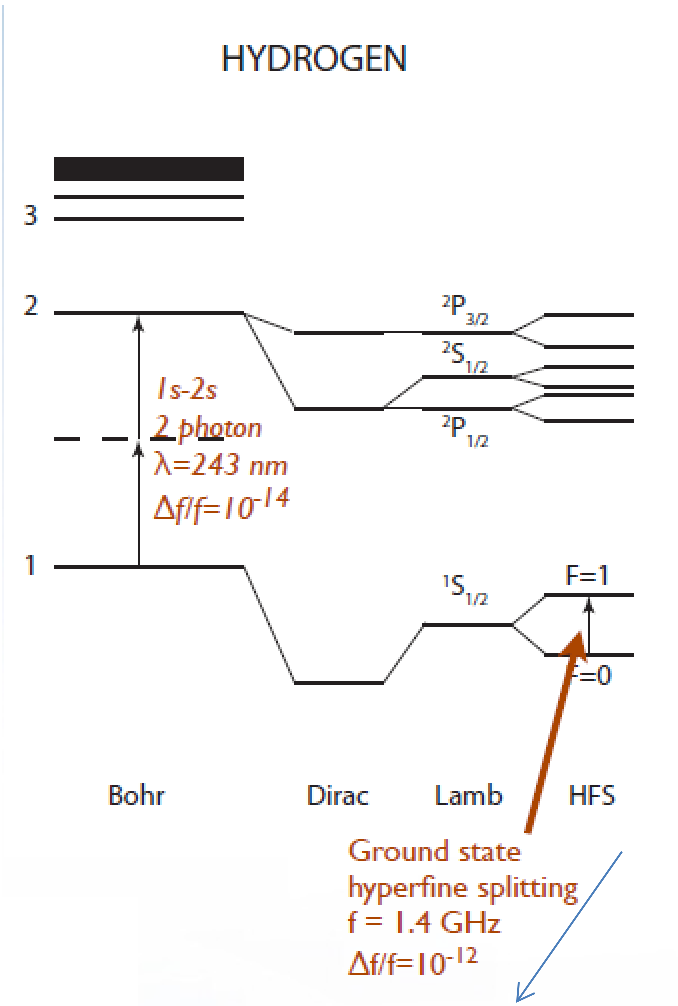
$m_i = m_g$ for matter

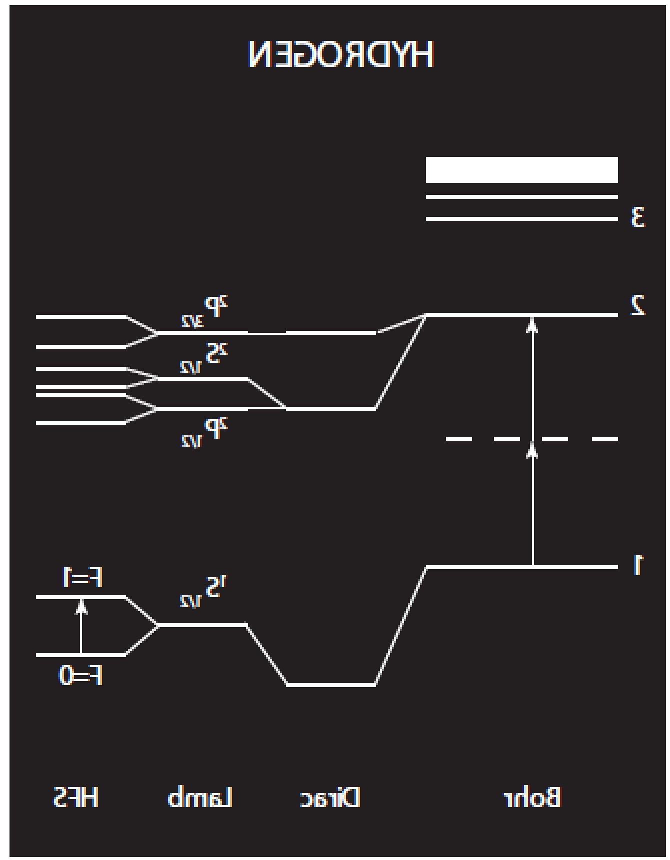
$m_i \neq m_g$ for antimatter

J. Tasson Hyperfine Interactions (2012) 213:137-146

Model allowing a different inertial and gravitational mass for antimatter are “possible”

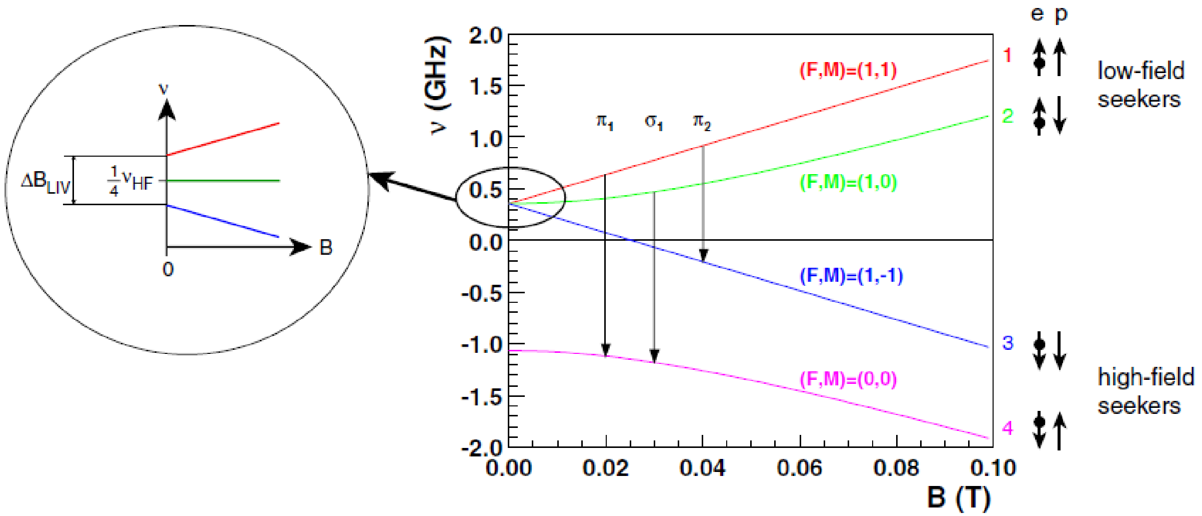
AntiHydrogen HFS: Hyperfine structure of the fundamentale state





$$\nu_{HF} = 1\,420\,405\,751.766\,7 \pm 0.0009 \quad Hz$$

AntiHydrogen HFS: CPT and Lorentz violation



Correction to the energy levels:

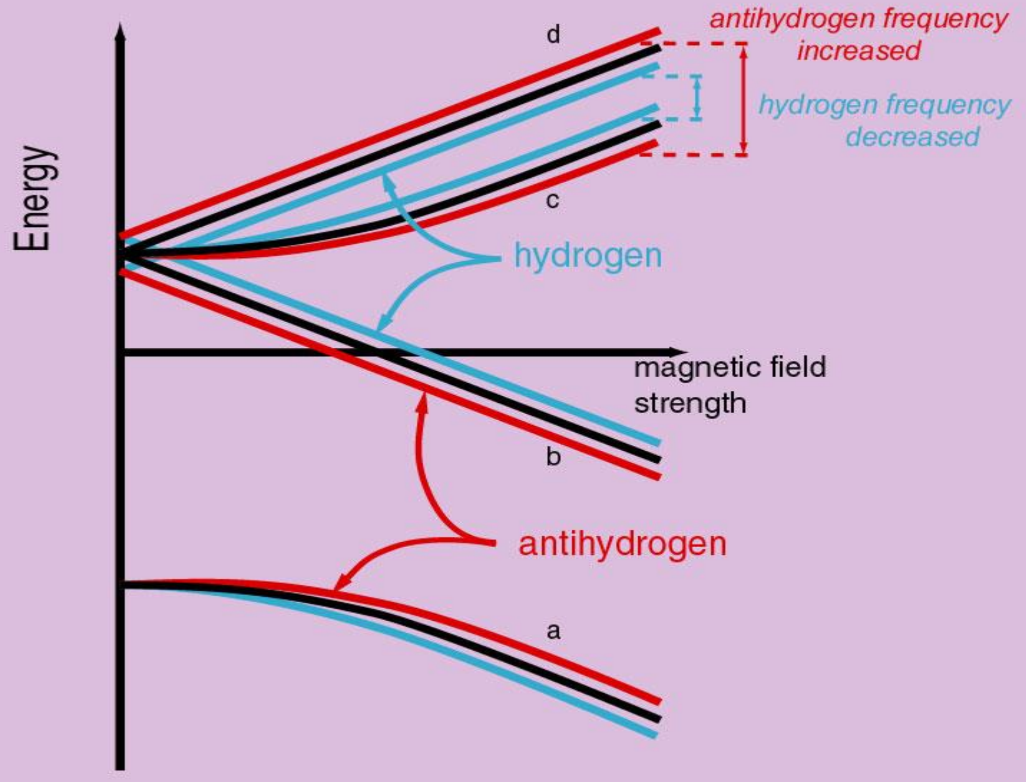
SME:

$$
\begin{array}{llll}
\#1 & (F,M) & =(1,1): & \Delta E_1^H = -b_3^e - b_3^p + d_{30}^e m_e + d_{30}^p m_p + H_{12}^e + H_{12}^p \\
\#2 & (F,M) & =(1,0): & \Delta E_2^H = -\cos 2\theta \, [b_3^e - b_3^p - d_{30}^e m_e + d_{30}^p m_p - H_{12}^e + H_{12}^p] \\
\#3 & (F,M) & =(1,-1): & \Delta E_3^H = -\Delta E_1^H \\
\#4 & (F,M) & =(0,0): & \Delta E_4^H = -\Delta E_2^H ,
\end{array}
$$

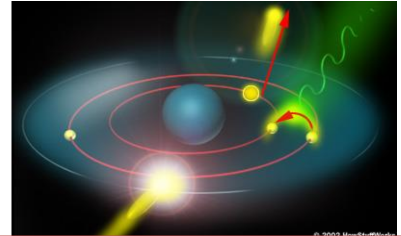
R. Bluhm, V. A. Kosteleck, and N. Russell, Phys. Rev. Lett. 82 (1999) 2254.

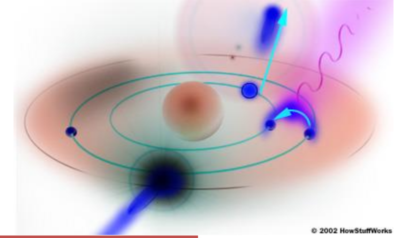
Lorentz invariance violation, CPT violation will show up as anomalous HFS frequency for Hbar: low energy signal of new physics at GUT scale….

Shifts in the hydrogen and antihydrogen ground-state energy levels



CPT and Hbar spectroscopy

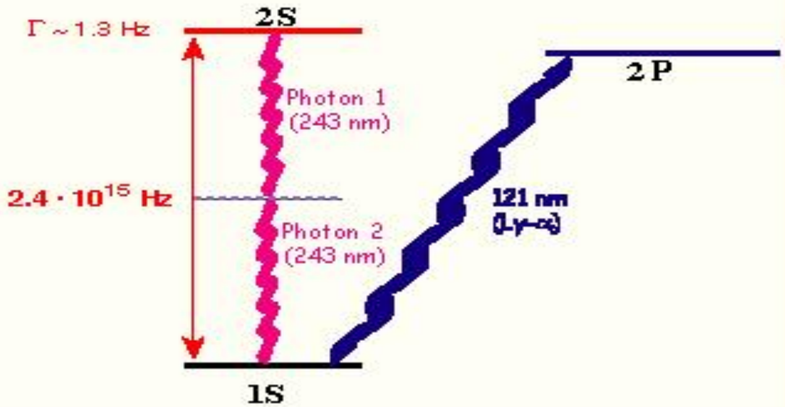




1S-2S in hydrogen

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

Natural width



2 466 061 413 187 103 (46) Hz

$\Delta\nu/\nu = 1.5\ 10^{-14}$

Cold beam $E \approx 100\ mK$

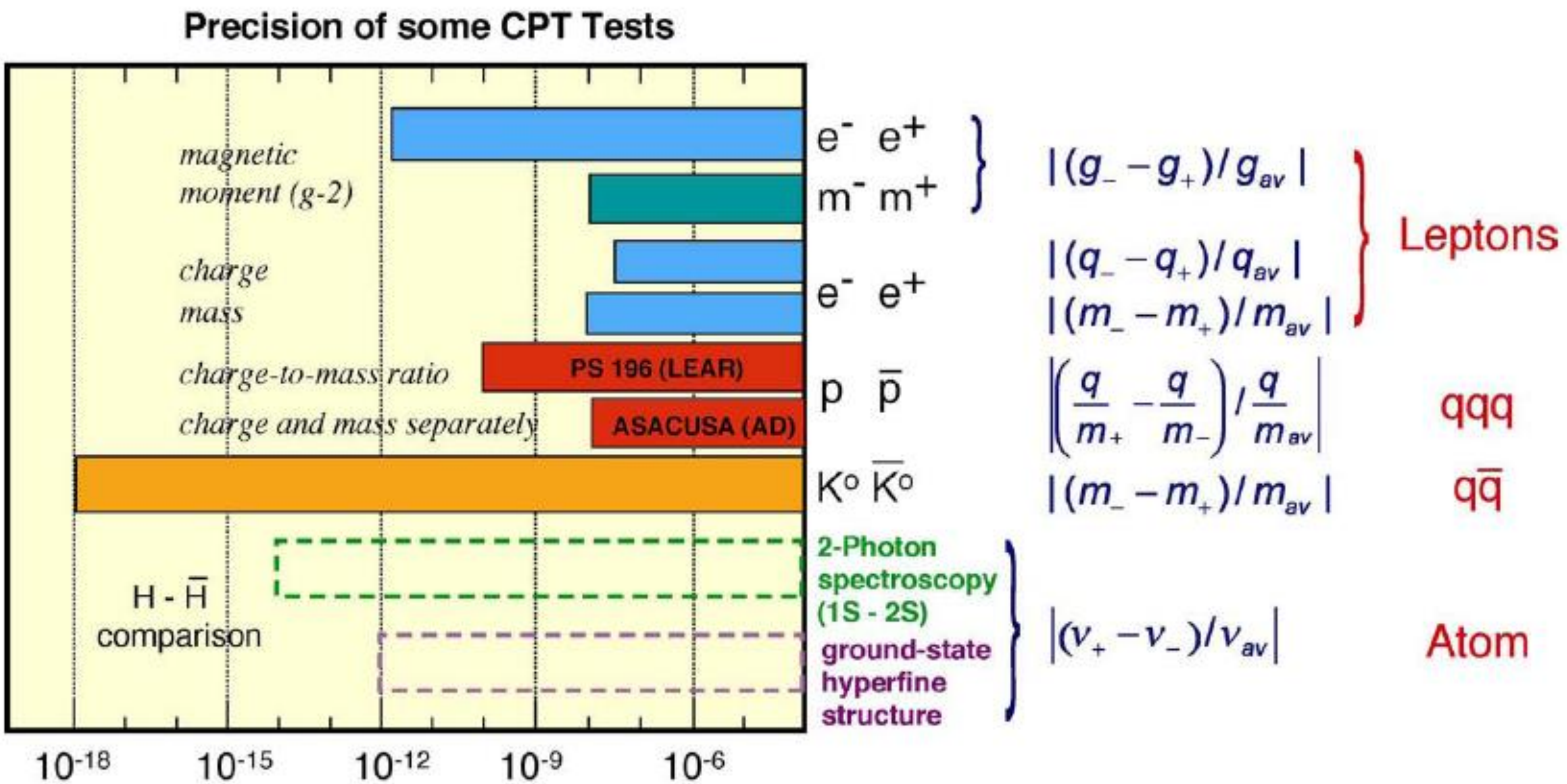
[M. Niering et al., Phys. Rev. Lett. 84 (2000) 5496

Measure 1S-2S of H and antiH in two period of the year: the gravitation field change by ΔU

WEP $\longrightarrow$ $\Delta\omega = \dfrac{\Delta U}{c^2}$ Null red shift experiment" : CPT independent

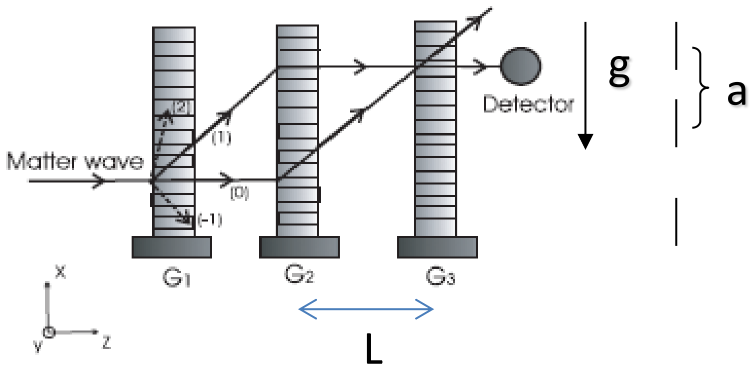
$$\frac{\Delta\omega^{H}_{1S-2S} - \Delta\omega^{\overline{H}}_{1S-2S}}{\Delta\omega^{H}_{1S-2S}} \approx 10^{-15} \Rightarrow (\alpha_{\overline{H}} - 1) \approx 10^{-6}$$

CPT tests



Precision of some CPT Tests
magnetic
moment (g-2)
charge
mass
charge-to-mass ratio
charge and mass separately
PS 196 (LEAR)
ASACUSA (AD)
H - H̄
comparison
10^{-18}
10^{-15}
10^{-12}
10^{-9}
10^{-6}
$e^- \ e^+$
$m^- \ m^+$
$e^- \ e^+$
$p \ \bar{p}$
$K^o \ \bar{K}^o$
2-Photon
spectroscopy
(1S - 2S)
ground-state
hyperfine
structure
$|(g_- - g_+)/g_{av}|$
$|(q_- - q_+)/q_{av}|$
$|(m_- - m_+)/m_{av}|$
$\left|\left(\frac{q}{m_+} - \frac{q}{m_-}\right)/\frac{q}{m_{av}}\right|$
$|(m_- - m_+)/m_{av}|$
$|(\nu_+ - \nu_-)/\nu_{av}|$
Leptons
qqq
$q\bar{q}$
Atom

Atom interferometry and high precision gravity measurements on cold atoms



T: flight time between G_1 and G_2

•Split and recombine the atomic wave function in presence of gravity
•Interference pattern with phase shift sensitive to g

$$\Delta\phi_g = \mathrm{kgT}^2 = \frac{2\pi}{a}\mathrm{gT}^2$$

Quantum interference if $a = \frac{2\pi}{k} << \sqrt{\lambda_{DB} L} = \sqrt{\frac{h}{mv} L}$

Very cold (anti)atoms are needed
We need a beam very collimated

Matter wave interference:

- material grating: period 100-200 nm   for Hbar with T << 100 mK
- Light
- light and change of internal state population

$$\frac{\Delta g}{g} \propto 10^{-10} \propto T^2$$

Very cold Cs atoms: µK nK launched in a atomic fountain

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

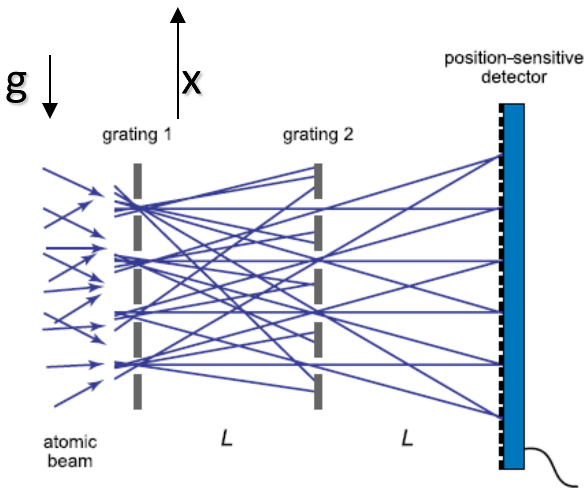
The first goal of AEgIS: gravity measurement with a classical Moire' Deflectometer

- It is very difficult to obtain very cold antihydrogen
- The antihydrogen beam will be poorly collimated
- Difficult to observe quantum effect with material gratings (poor beam collimation)
- Difficult to build a (anti)atomic fountain

First goal:

- use two gratings with classical paths (no quantum interference)
- Moire' deflectometer
- Initial accuracy 1% (even reaching this accuracy is challenging!!)
- It works with non collimated beam
- grating period 40 micron

The AEGIS Moire' deflectometer



- Antihydrogen can pass only through holes in the grating
- Observe the number of particles arriving at a distance L from second grating
- N(x) shows a periodical structure with period a
- Gravity effect: "fall" of the pattern by Δx

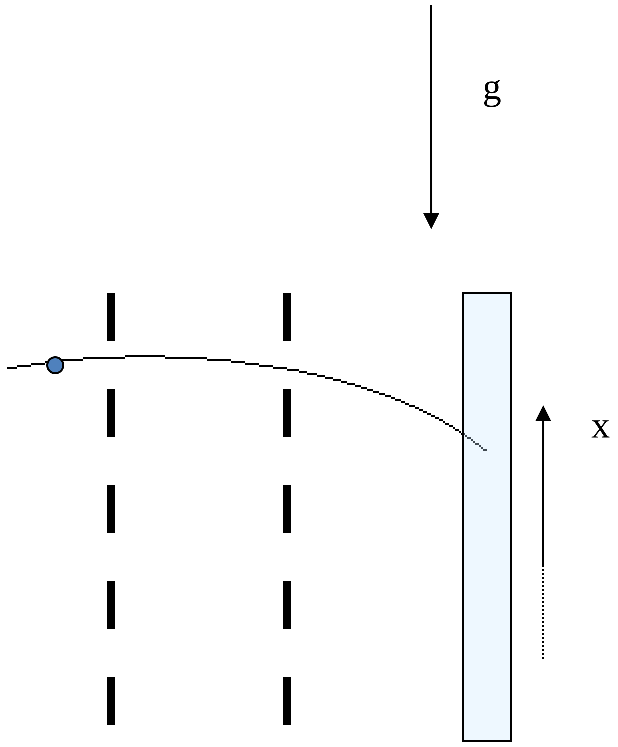
$$\Delta x = gT^2 = g\left(\frac{L}{v_h}\right)^2$$

- No collimated beam
- Classical paths
- Large dimension gratings

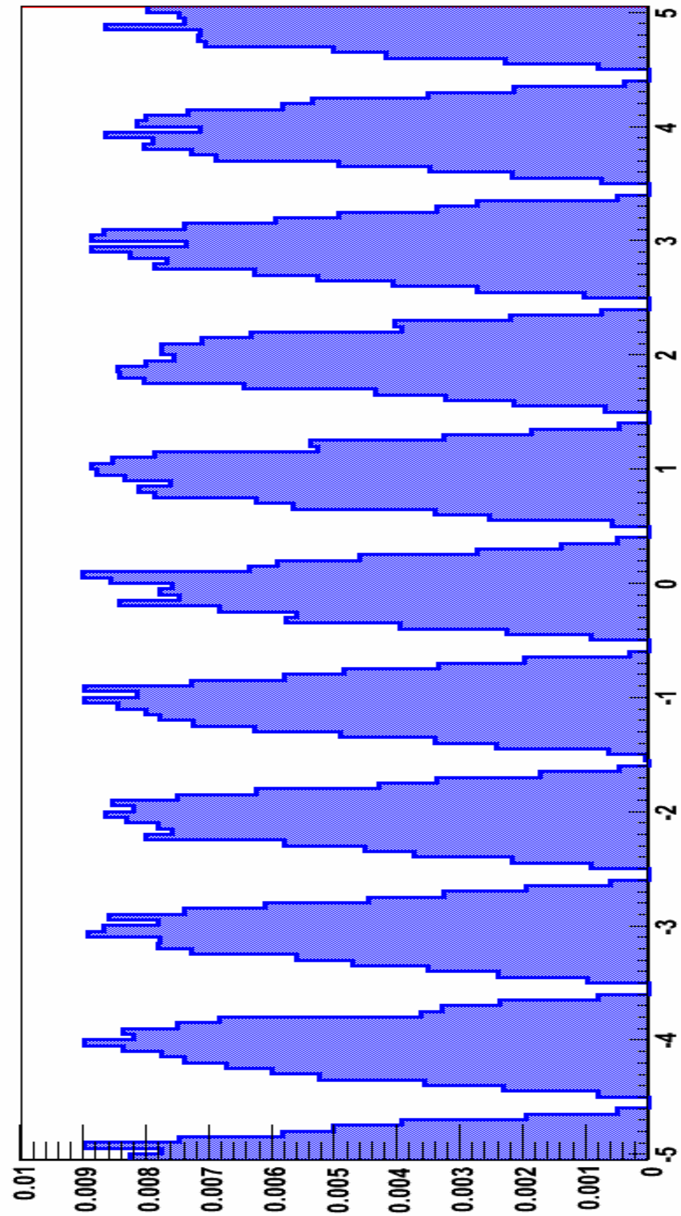
Grating distance L	40 cm
Grating size:	20 x 20 cm^2
Grating period:	a=40 μm
Opening fraction:	30%
Δx:	17.4 μm (v_h=300 m/s)
Pos. resol.	10 μm in the proposal (1 μm seems possible with emulsions.. see later)

3 gratings, g on Argon atoms M. Oberthaler et al., Phys Rev. A 54 4 1996

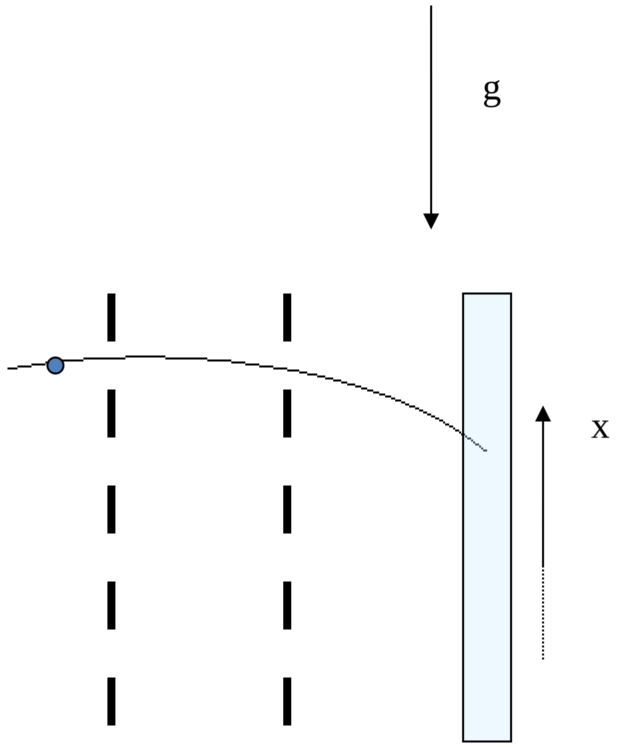
With gravity force



V_h= 600 m/s

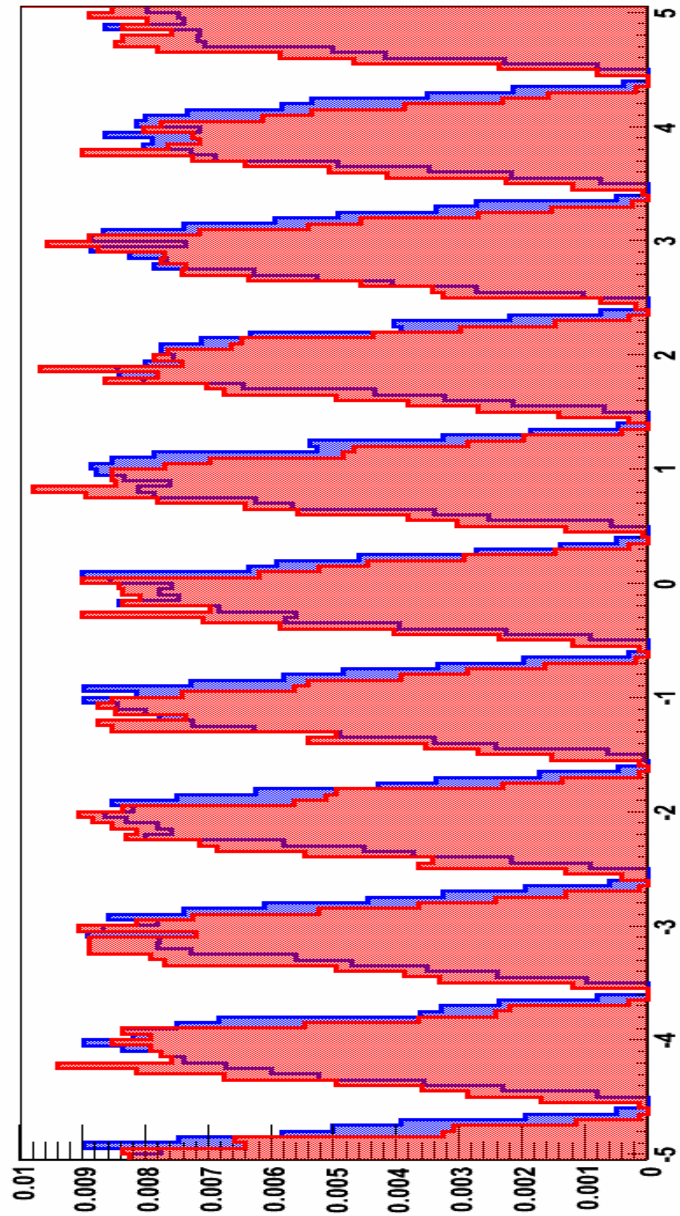


With gravity force

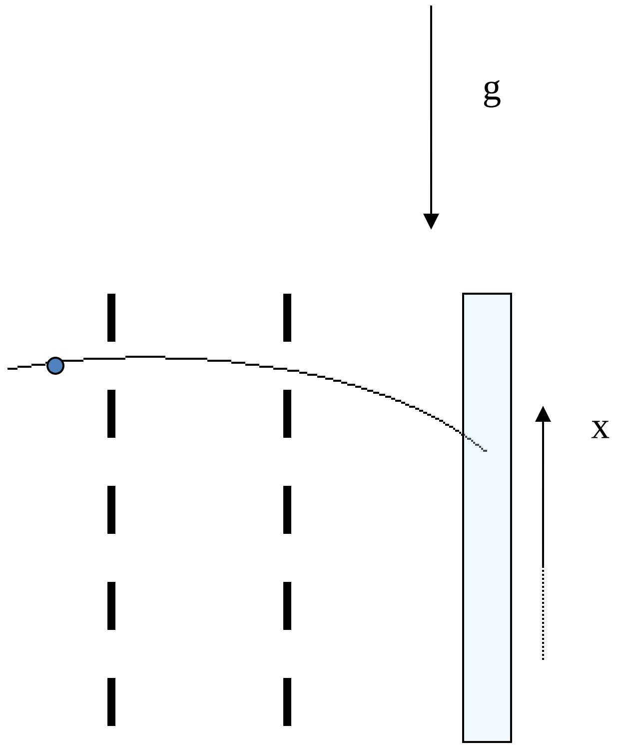


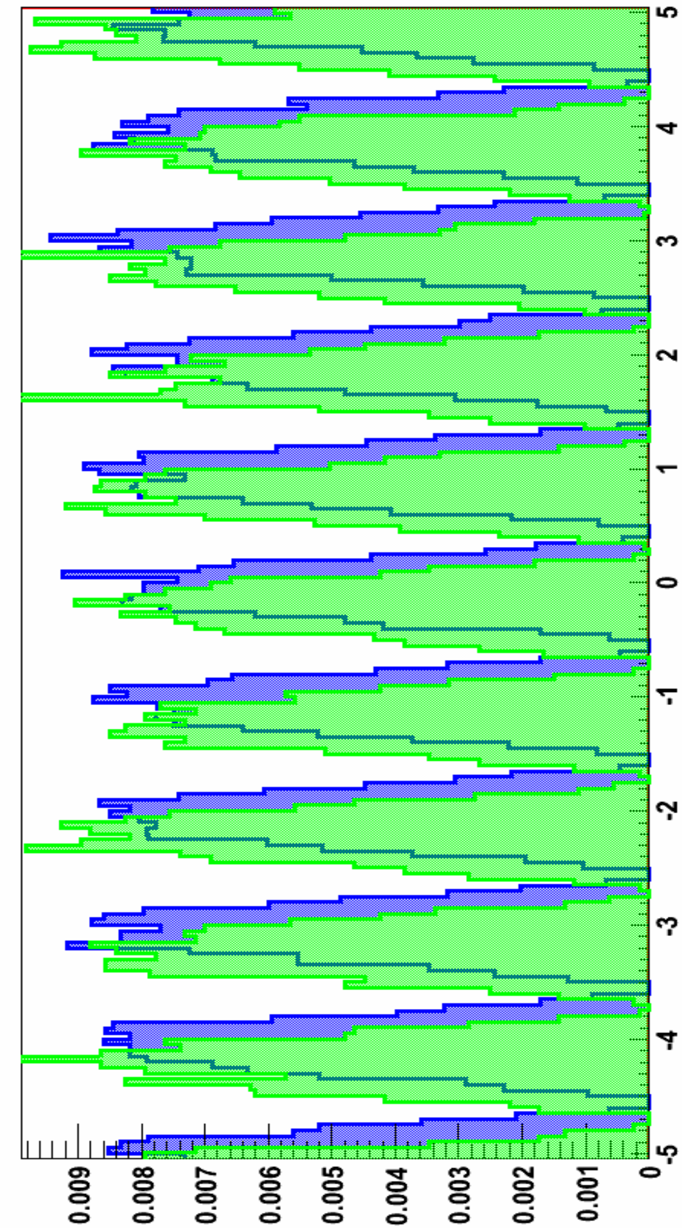
V_h= 600 m/s

V_h= 400 m/s



With gravity force



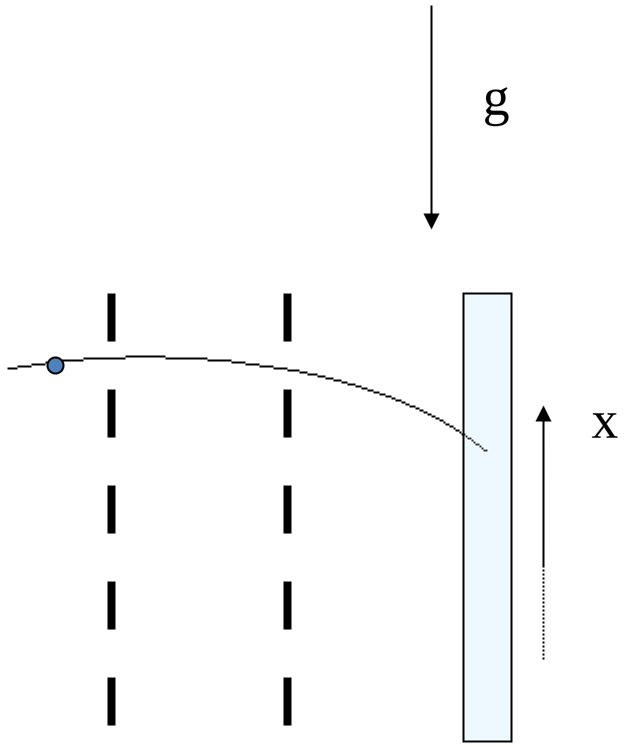


V_h= 600 m/s

V_h= 300 m/s

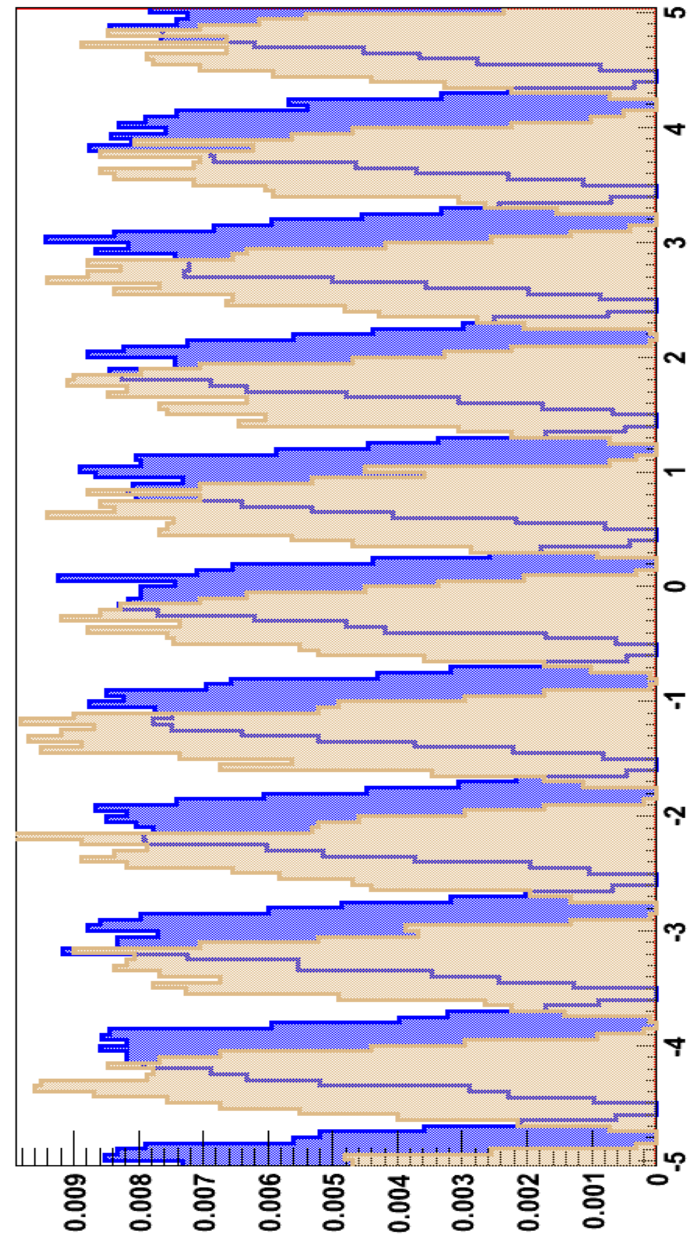
Gratin units

With gravity force

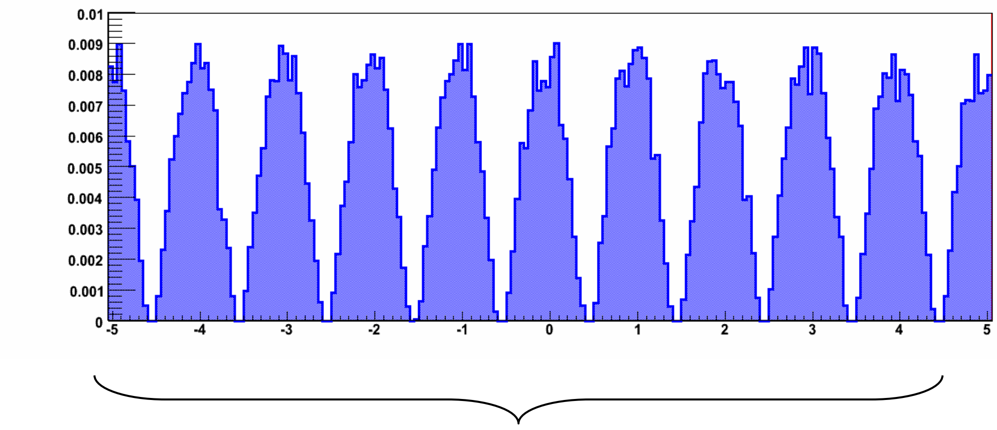


V_h= 600 m/s

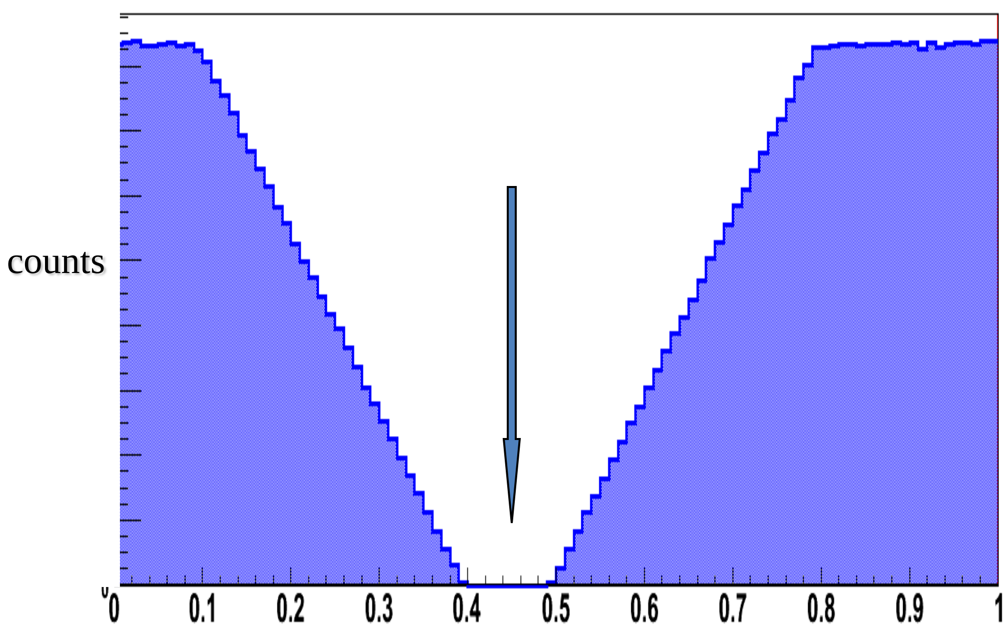
V_h= 250 m/s



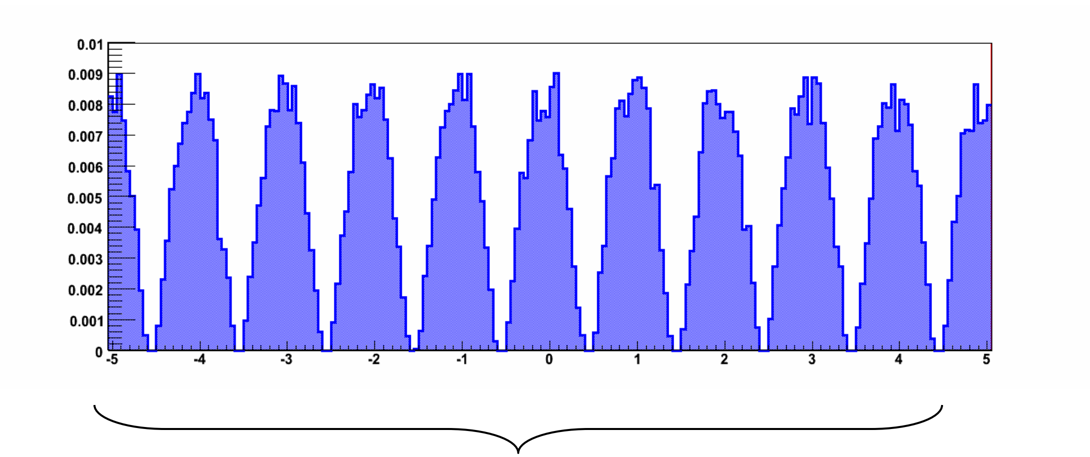
Plot the hit position along the detector modulo the grating period a



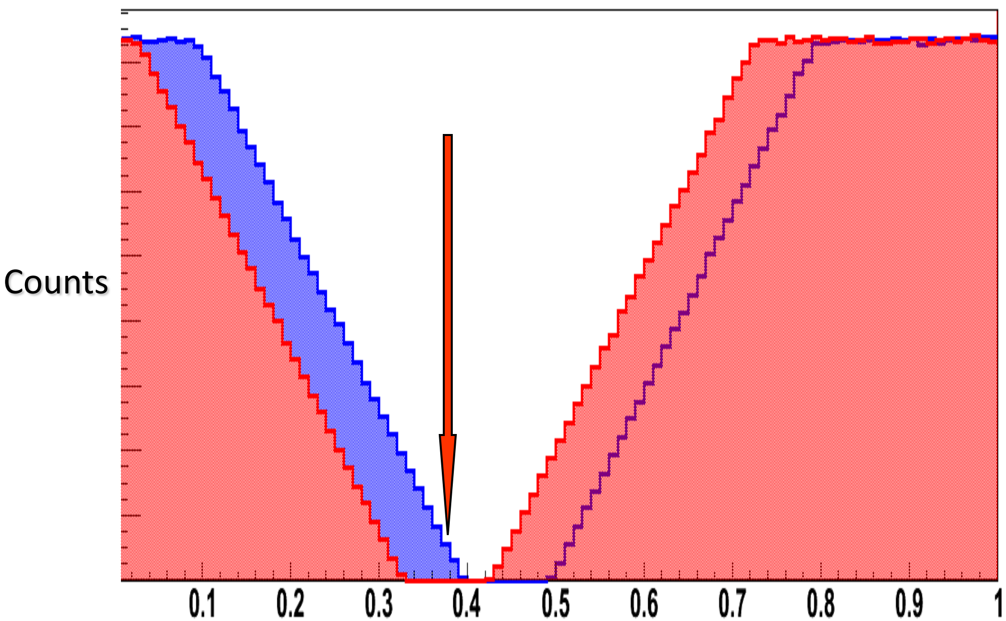
$V_h = 600$ m/s



X (grating units)



Plot the hit position along the detector modulo the grating period a

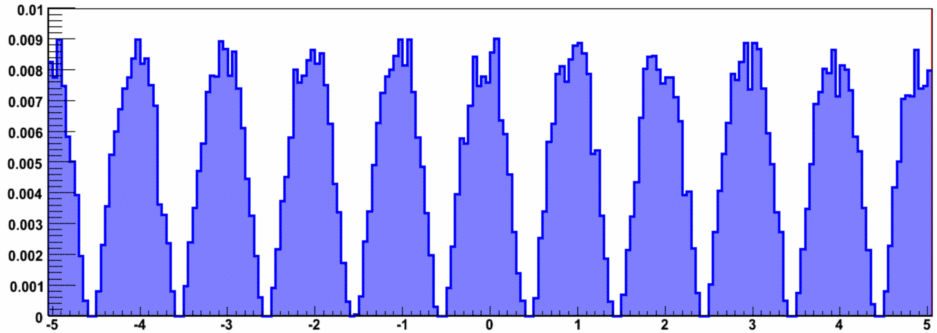


V_h= 600 m/s

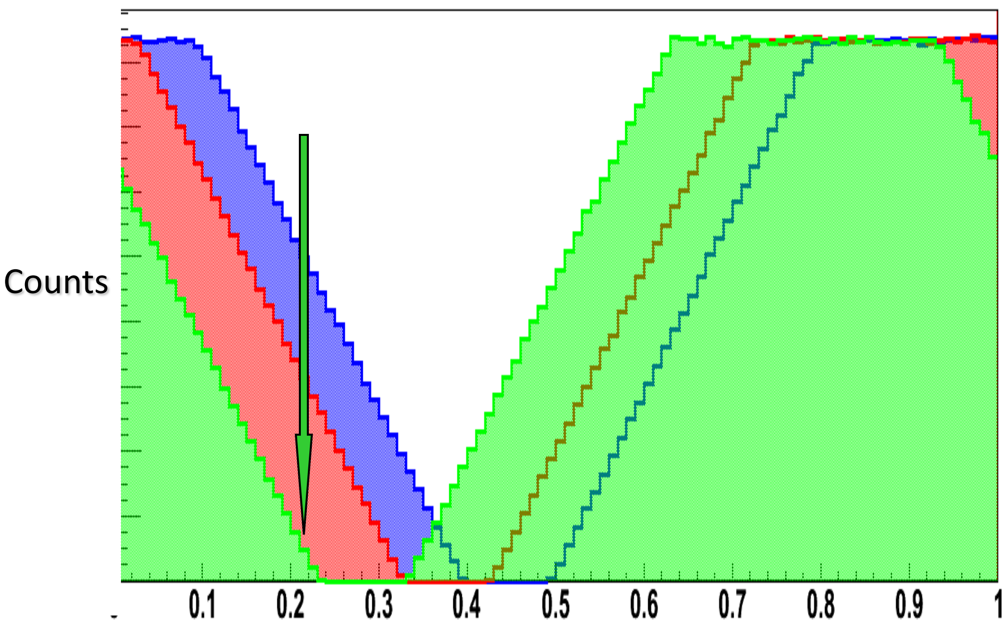
V_h= 400 m/s

X (grating units)

1 grating period: 80 μm



Plot the hit position along the detector modulo the grating period a



V_h= 600 m/s

V_h= 400 m/s

V_h= 300 m/s

X (grating units)

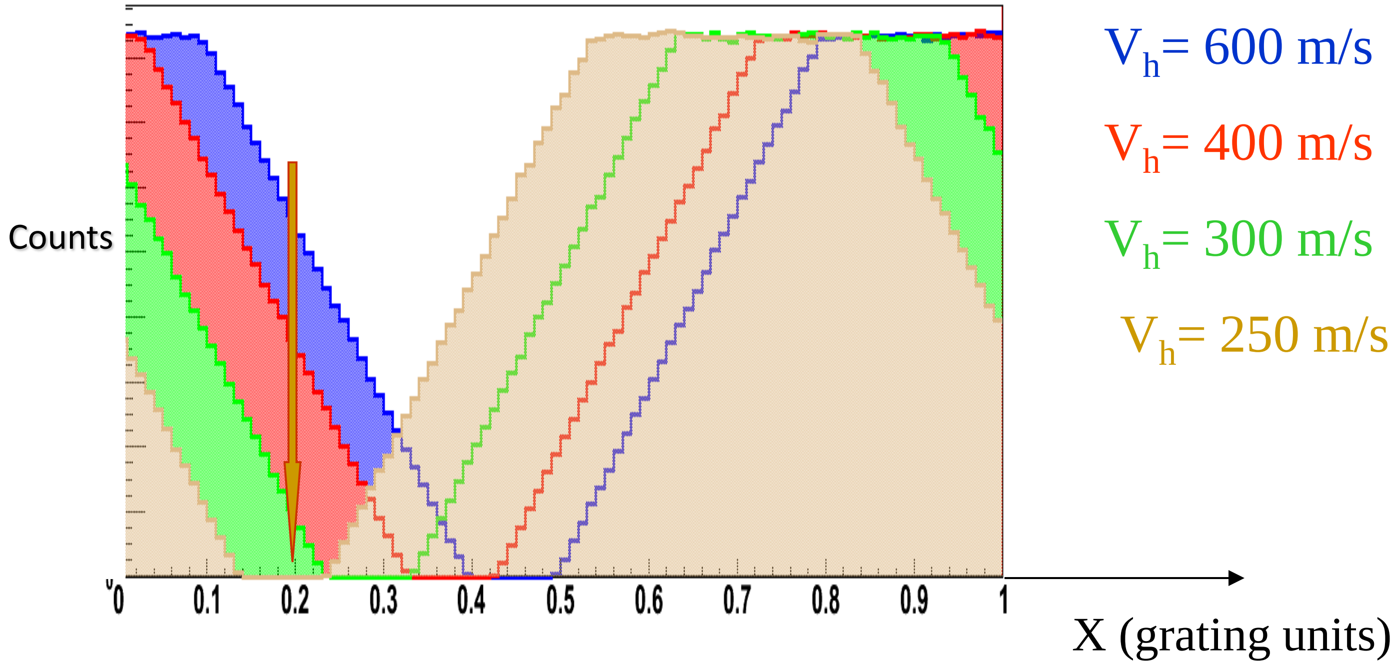
1 grating period: 80 μm

Gravity induced vertical shift of the pattern (grating units)

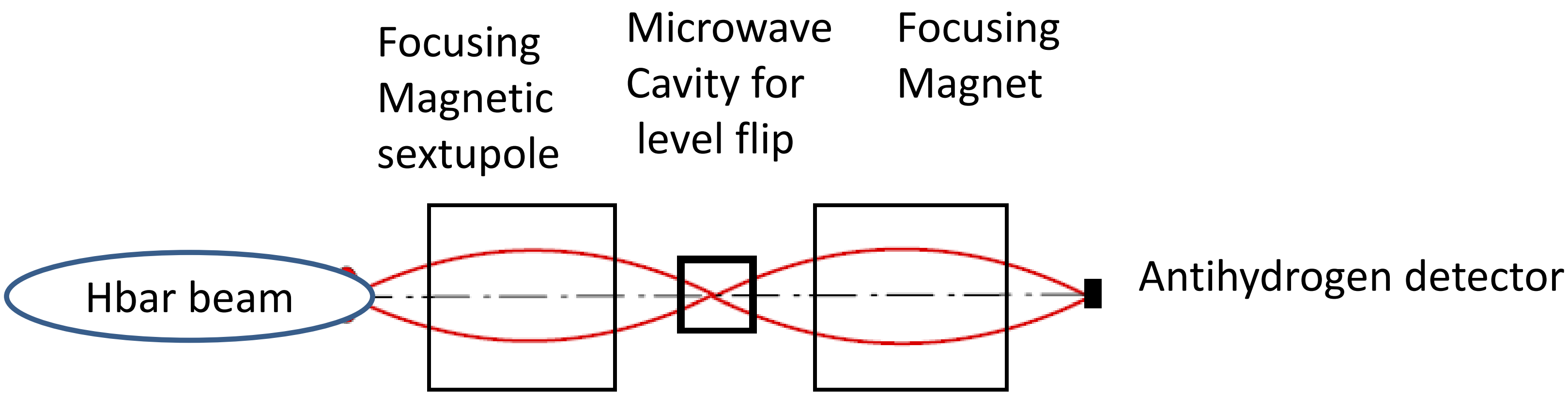
$$\delta = \frac{gT^2}{a}$$

a: grating period

T: time of flight between the two gratings



The HFS measurement with the Hbar beam



Expected sensitivity: 10^{-6}

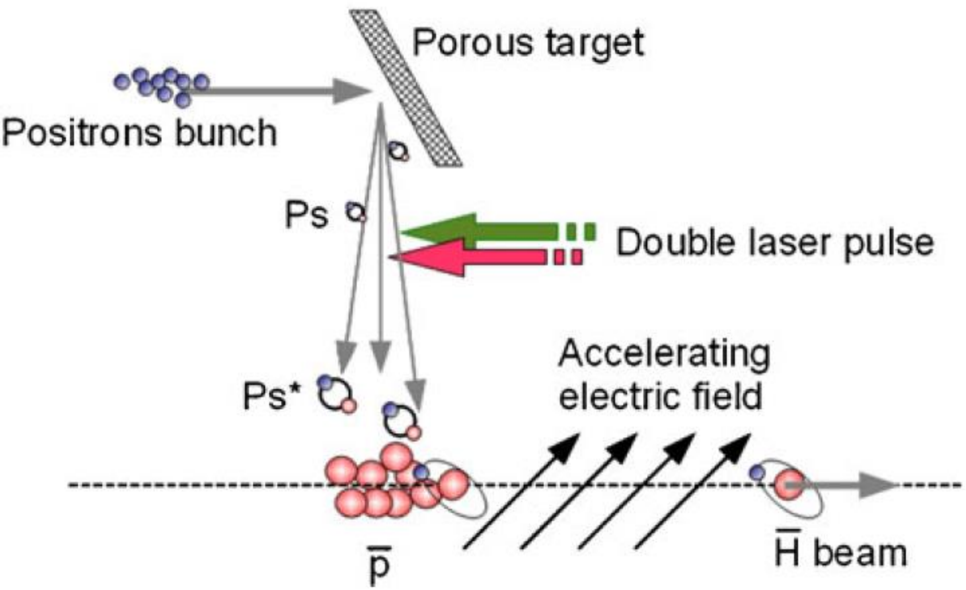
The AEgIS experiment

•How anti-hydrogen is made in AEgIS?
•How the beam is formed?

Many different tecnologies are integrated in AEgIS:

• atomic physics
•non neutral plasma physics
•detectors typical of particle physics
•XHV
•Cryogenics

Pulsed antihydrogen formation in AEgIS



$$\overline{p} + Ps^{*} \rightarrow \overline{H}^{*} + e^{-}$$

- It is very hard to get extremely cold antiprotons
- Beam collimation: related to antiproton temperature
- 100 mK: never reached until now!

- Prepare ultracold antiprotons

$$100\ mK \approx 8 \mu eV$$

Some 10^5, 1 mm radius, 1 cm lenght

- Prepare a bunch of positrons
10^8, 1 mm radius

- Launch e+ toward a nonoporous target
$\Delta t < 10$ ns

- Positronium is formed with 30% eff.

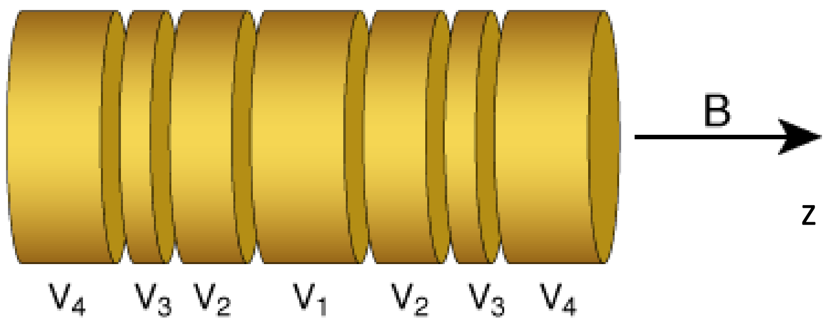
- Excite Ps to selected Rydberg states: n= 18-22 with two laser pulses

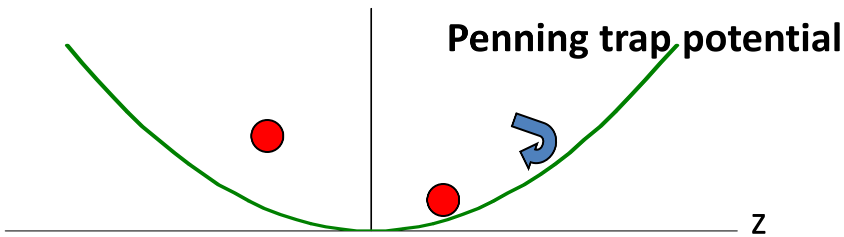
- Form antihydrogen by charge exchange; formation time known within few μs

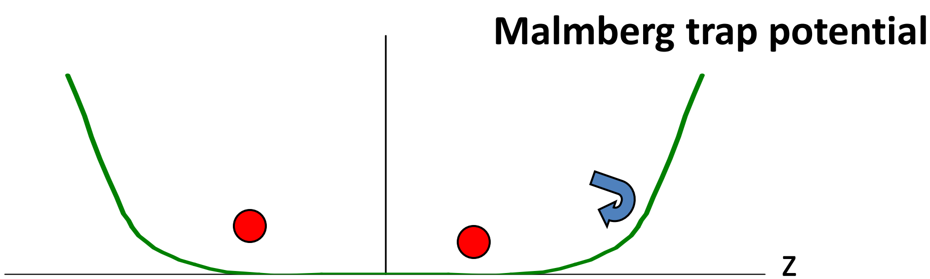
- Accelerate antiH toward the grating using non homogeneous electric fields

- Repeat every few minutes

Trapping, long term storage and cooling charged particles



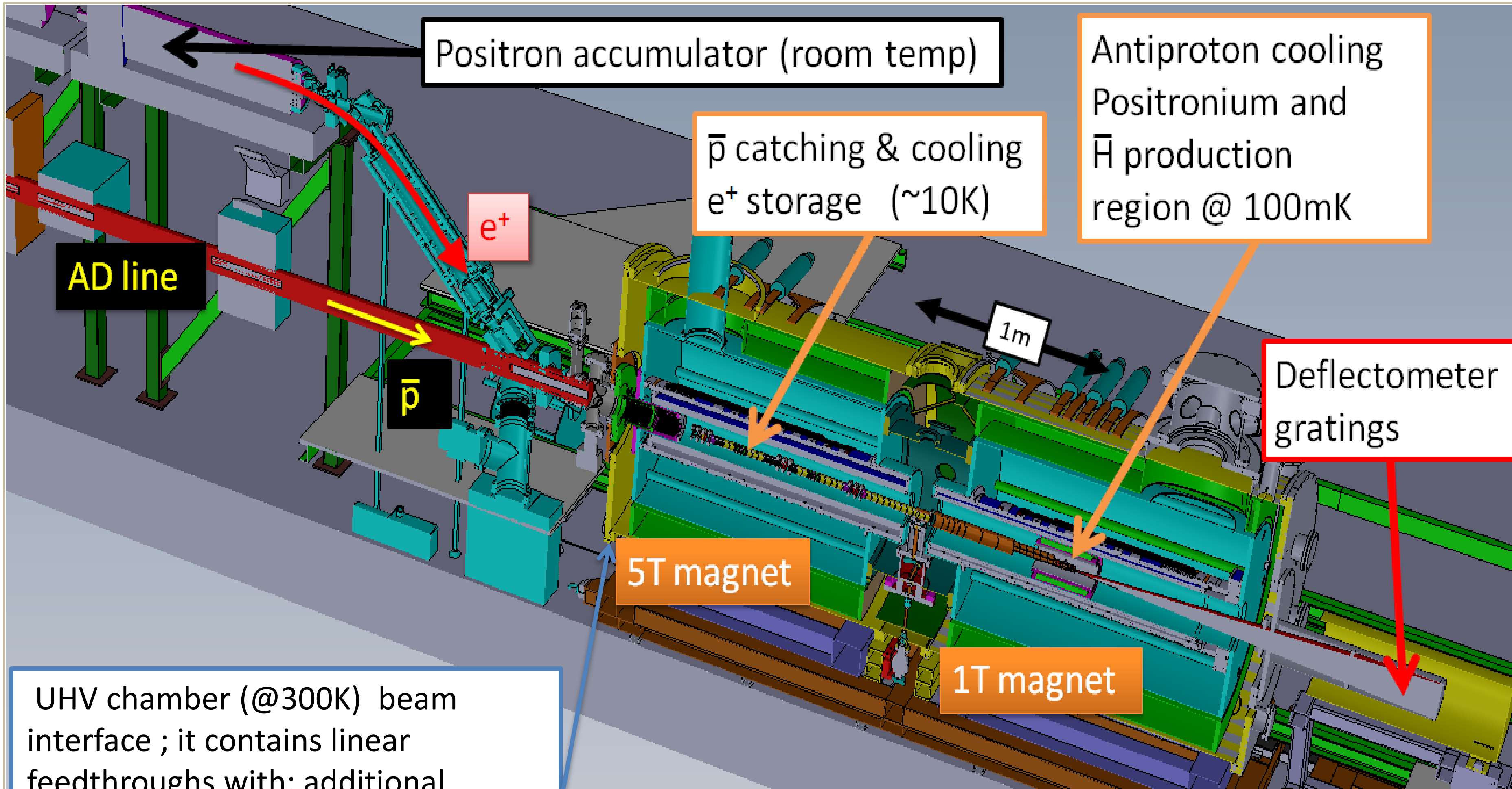




- Radius : 0.5-2 cm
- Lenght : 2 m in AEgIS
- more than 100 electrodes
- B = 5 Tesla , 1 Tesla
- 0.1 T in e+ accumulator
- V = Volts or KV
- Pressure <<10^{-12} mb XHV
  cryogenic environment

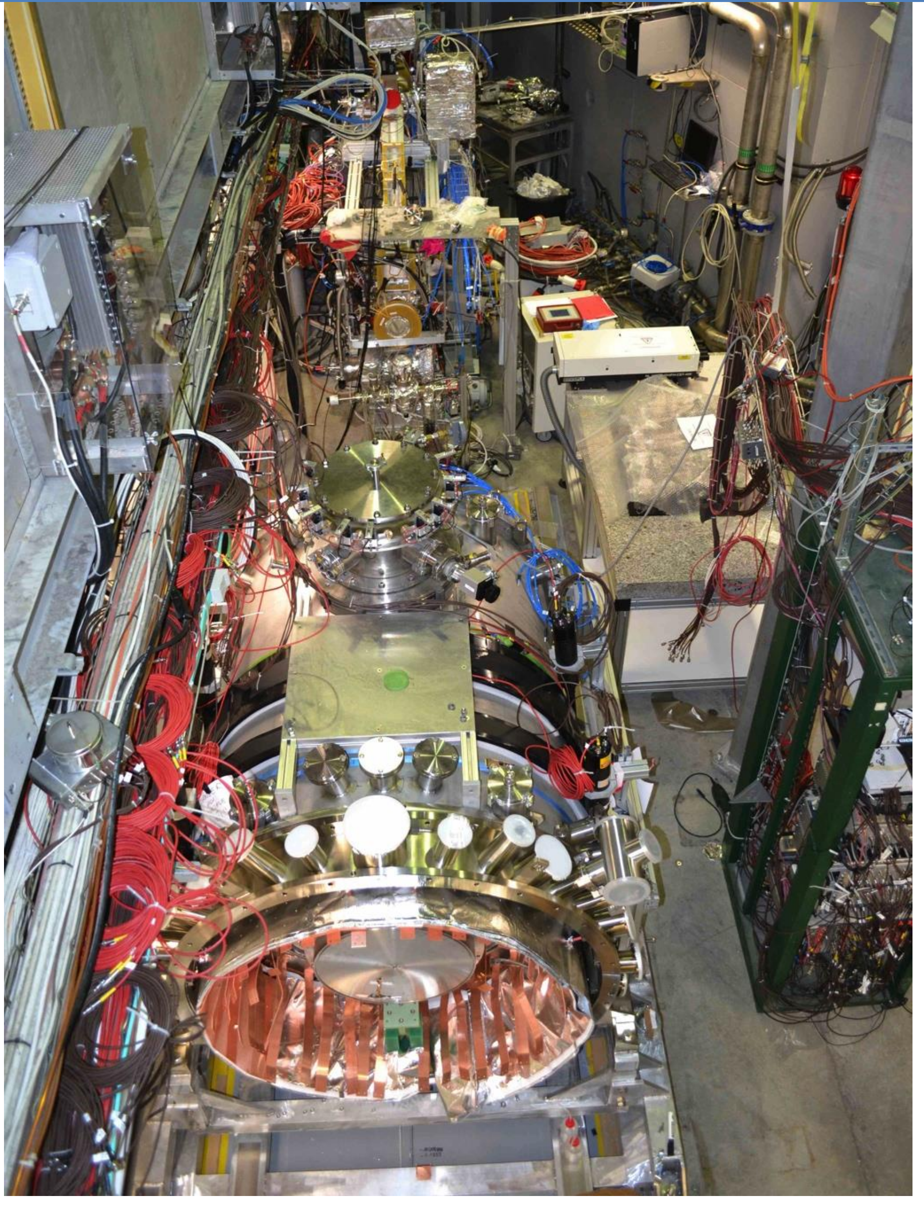
- Cold non neutral plasma
- Collective effect
- Dynamics determined by space charge

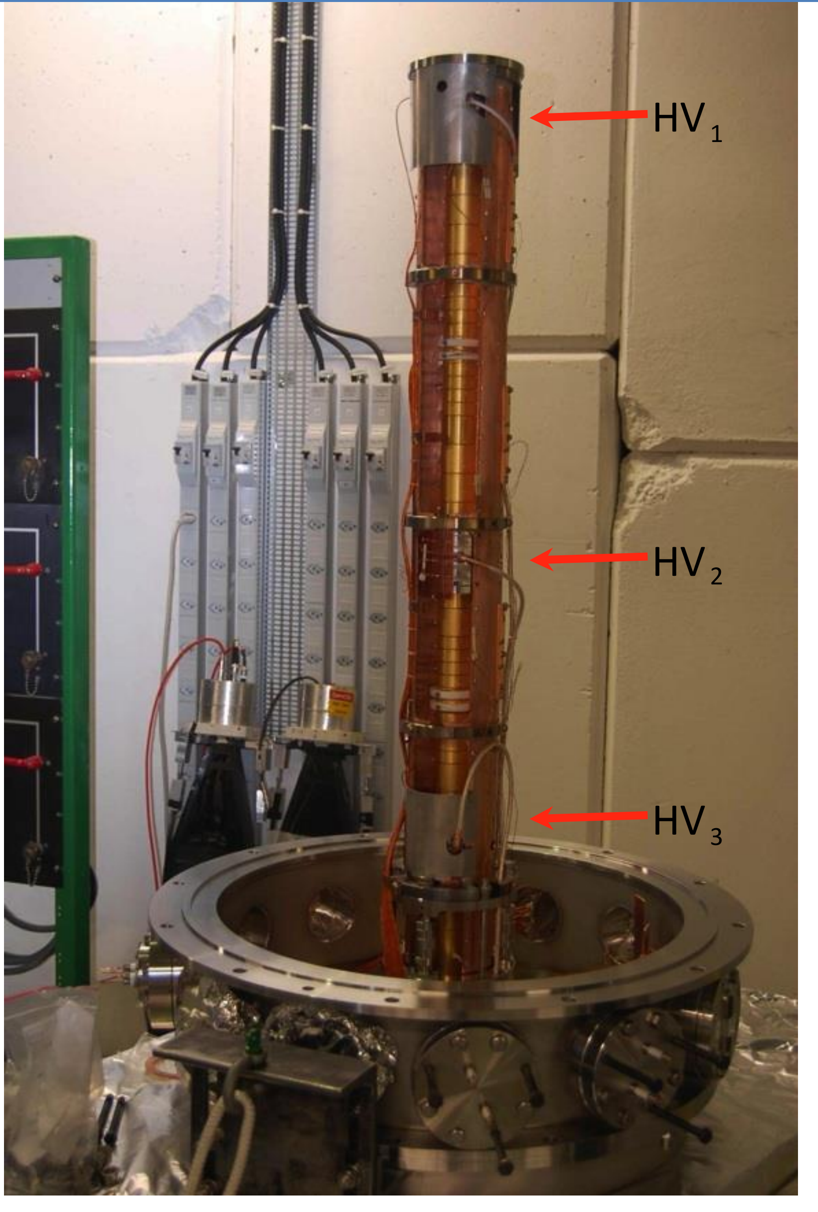
AEgIS experimental apparatus

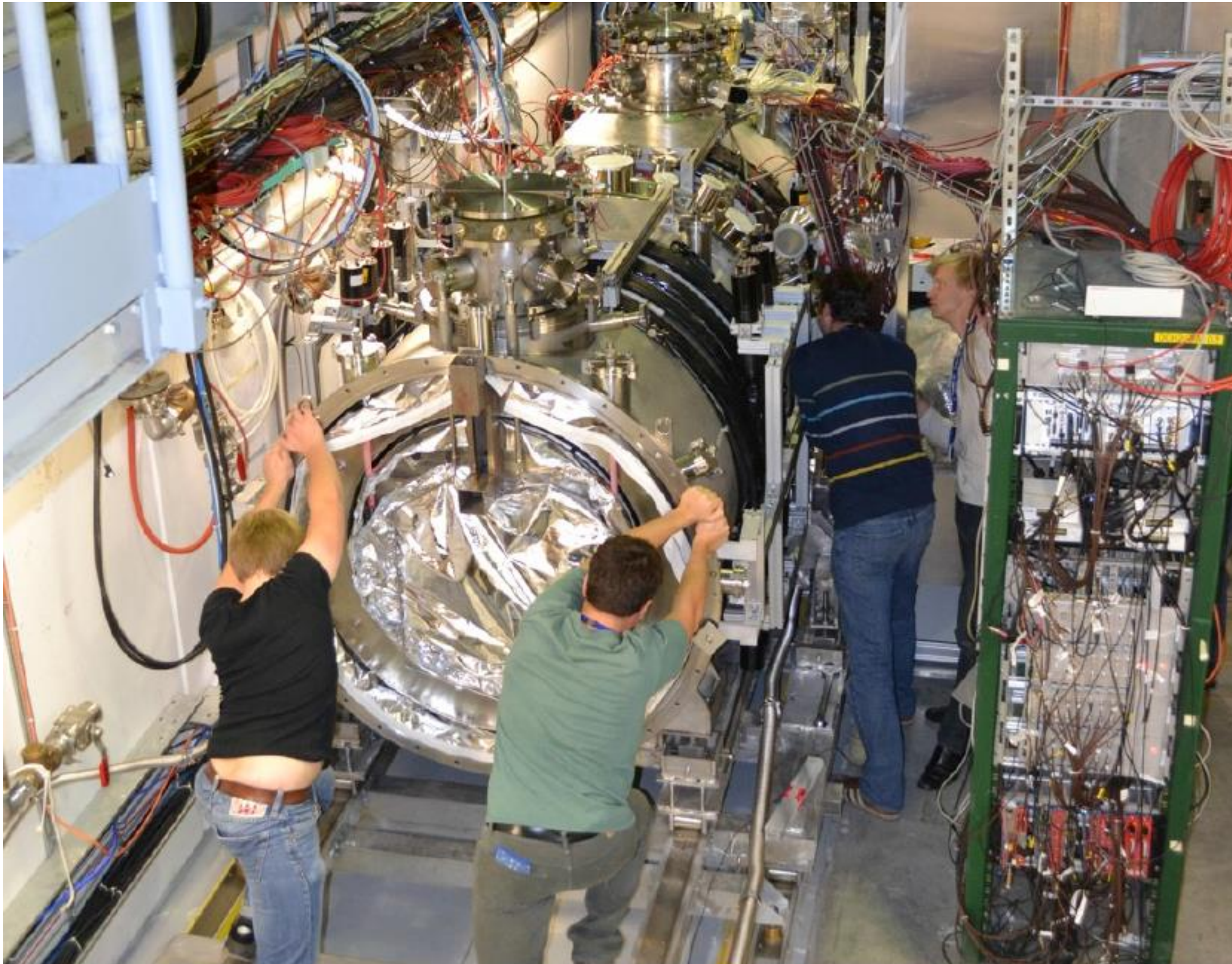


UHV chamber (@300K) beam interface ; it contains linear feedthroughs with: additional degrader foils; e^- gun; mirror for CCD; MCP and final degrader movement

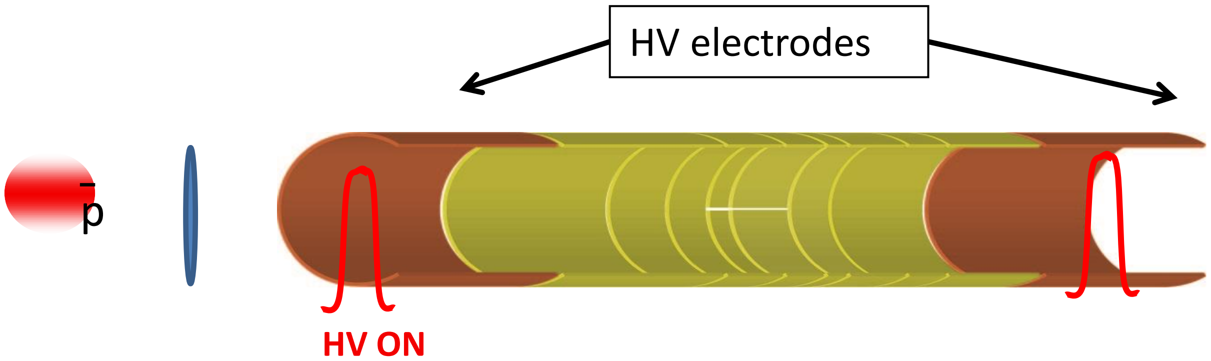
AEgIS has been mounted in 2012: first data with antiprotons in May and Dec. 2012



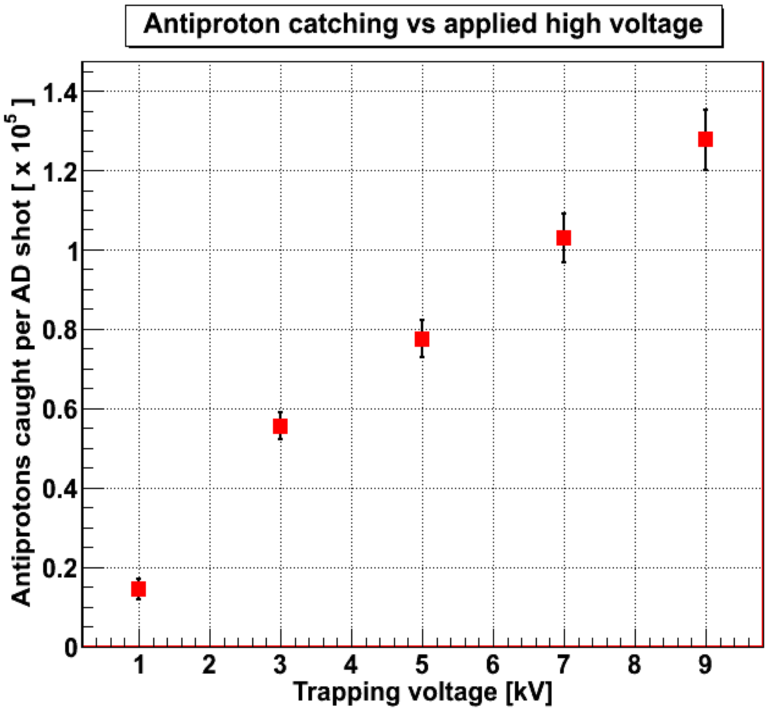




Antiproton catching in AEgIS: from 5 MeV to 9 KeV



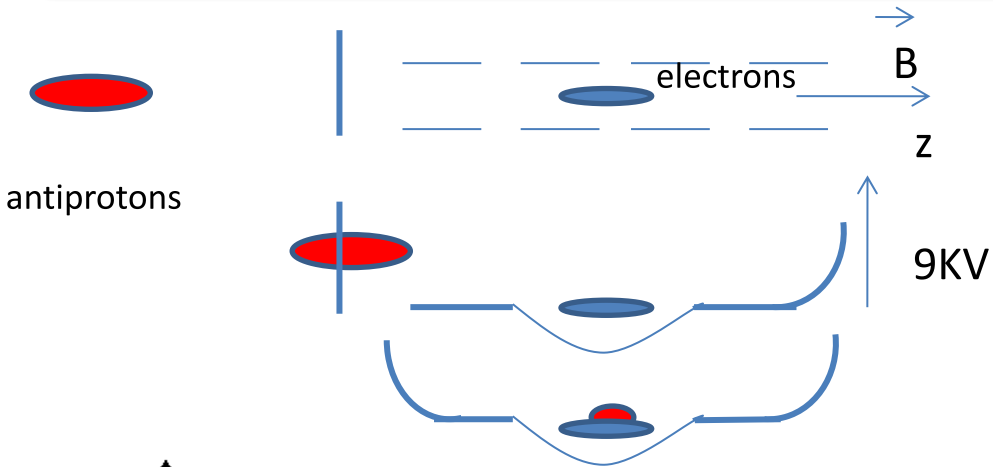
- 3.5 10^7 antiproton/shot
- about 120 ns lenght
- every 100 sec
- 5 MeV kinetic energy
- Dp/p = 10^{-4}
- catch in flight after deceleration through material foils of proper thickness

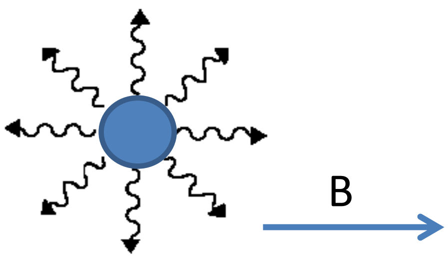


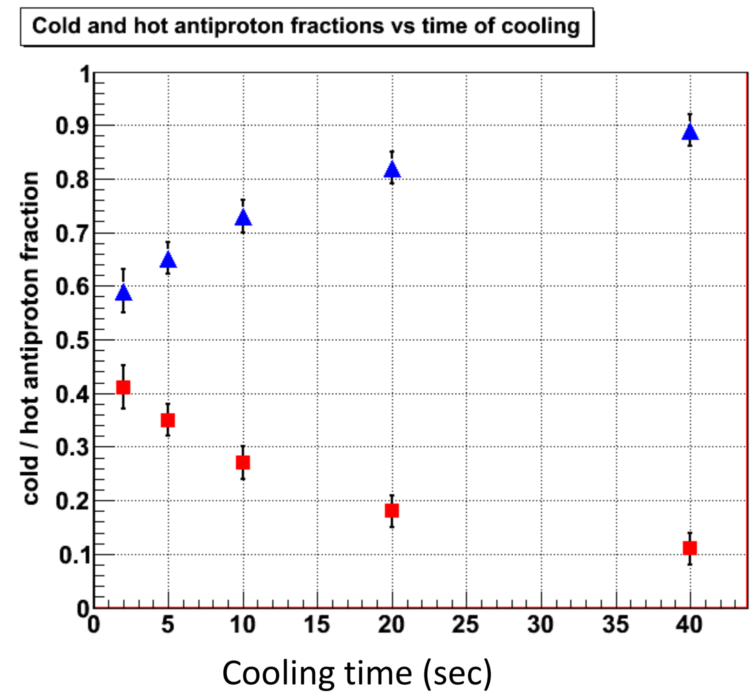
$$1.3 10^5 \; \bar{p}/_{shot}$$

Preliminary AEgIS results
May-Dec2012 antiproton run

Antiproton cooling in AEgIS: from 9 KeV to about 100 meV (about 100K)







e- (and also positrons)
Radiation in high magnetic field (cyclotron cooling)

$$T = T_{iniz} e^{-t/\tau_{rad}} + T_{trap}$$

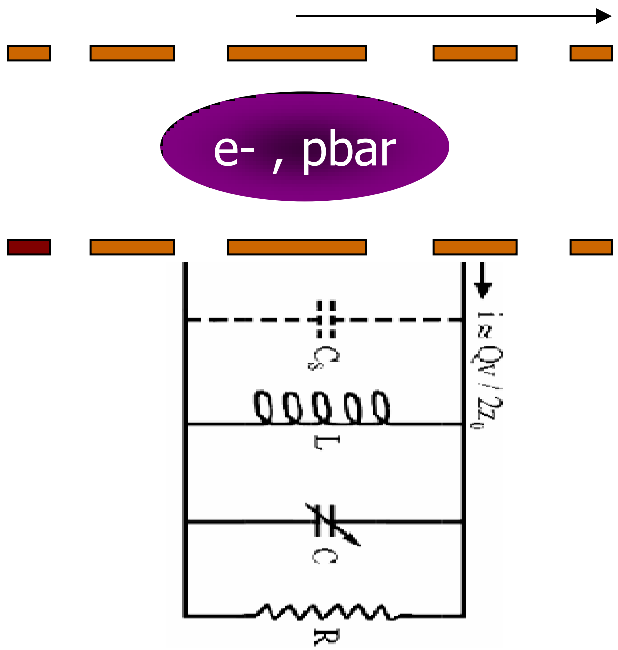
$$\tau_{rad} \propto \frac{m^3}{B^2}$$

e^-, e^+	$\tau_{rad} \cong 0.1 \sec @ 5T$
$\overline{p}$	$\tau_{rad} \cong 10^9 \sec @ 5T$

Cyclotron radiation + Coulomb collisions = thermal equilibrium for e- and pbar

Final energy estimation: about 100 K

Antiproton ultra-cooling in AEgIS: toward 100 mK



$$T = T_{iniz} e^{-t/\tau_{rad}} + T_{trap}$$

Make the trap colder and colder

Traps in 100 mK region (dilution refrigerator)

e- radial energy: quantum limit 800 mK@ 1 T
400 mK@ 0.5 T

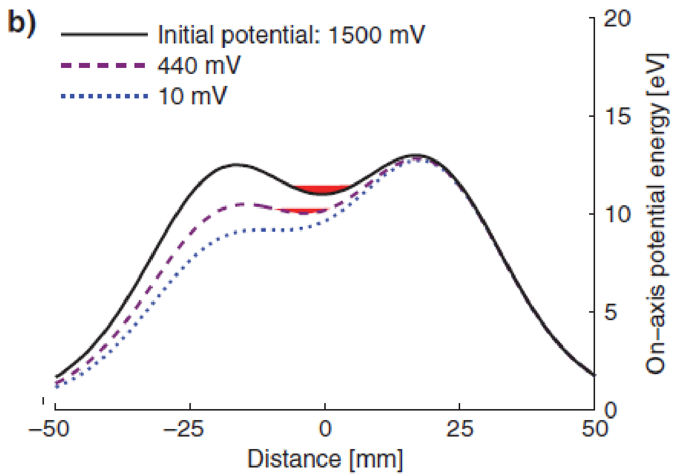
$$n_c + \frac{1}{2}\hbar\omega_c$$

Add an additional cooling mechanism:

- Resonant circuit removing energy form the axial electron motion of the electrons
- The axial temperature of the electron reach 100 mK
- Antiprotons cooled by Coulomb collision
- Tech development: high noise and low power cryo-amplifier
- Plasma physics: energy exchange at low energy in magnetic field
- Plasma equilibrium: radial separation between heavy and light particles

Antiproton ultra-cooling in AEgIS: toward 100 mK

Evaporative cooling of antiprotons: recently (2010) demonstrated by ALPHA
(PRL 105,013003 2010)



Final antiproton temperature: 9 K

Can we get lower temperature?
What about the radial temperature?

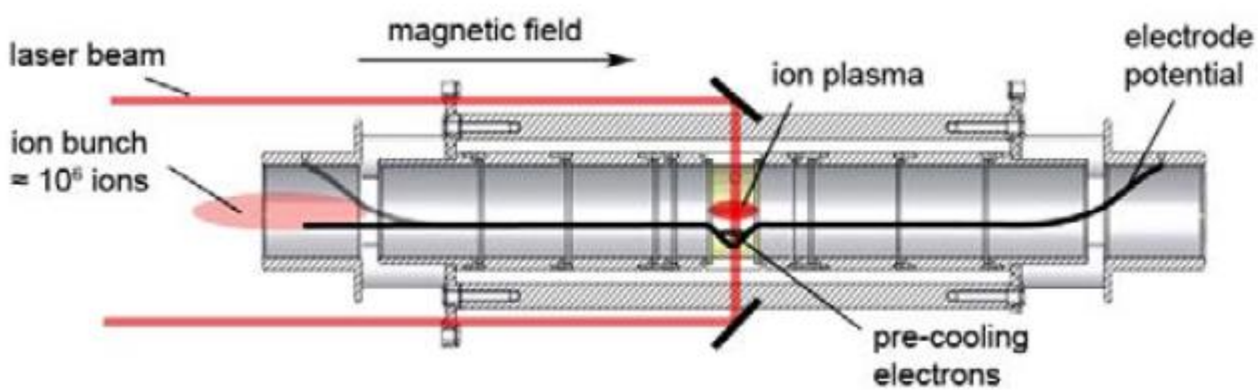
Adiabatic cooling of antiprotons (2011)
With embeeded electrons demonstrated by ATRAP
(PRL 106, 073002 2011)

- Final antiproton temperature: 3.5 K
- No losses of antiprotons
- Can we get lower Tempertaure ?
- What about the radial one

How to measure the charged particles temperature in reliable way at such low temperature?

Antiproton ultra-cooling in AEgIS: below 100 mK ??

- Load negative ions in the trap
- Load antiprotons together with ions
- Laser cooling of negative ions: final T << μeV
- Cooling of antiprotons by collisions with the negative ions



Experiment on laser cooling of La^- in progress by members of AEgIS

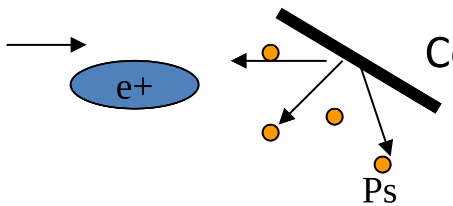
Accumulation of e^+ and formation of positronium

- ^{22}Na β+ source
- Accumulation: a known technology
- Transfer into the main magnet and AEgIS trap system
- 10^8 positrons ready to form Ps

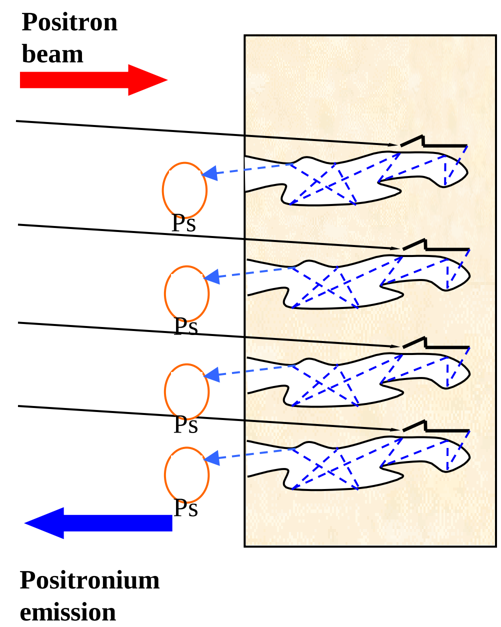
$> 10^8 e^+$

$\Delta r \approx 1\ mm$

$\Delta t \approx 10\ ns$



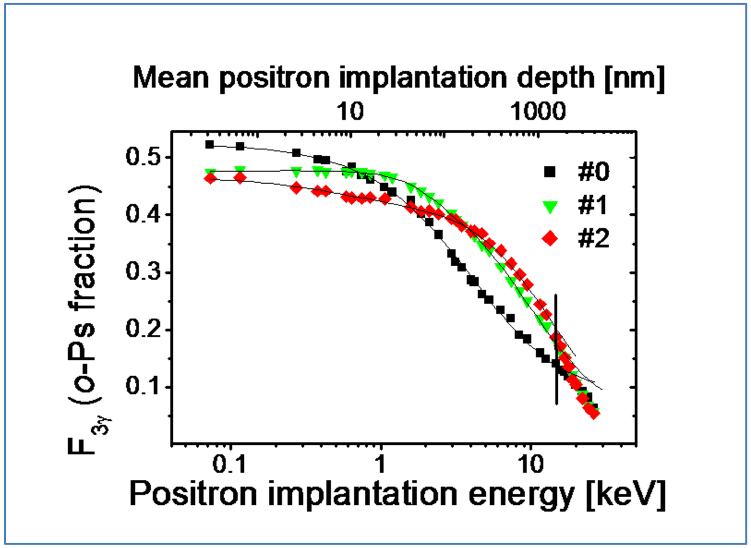
Cold target (100 mK)

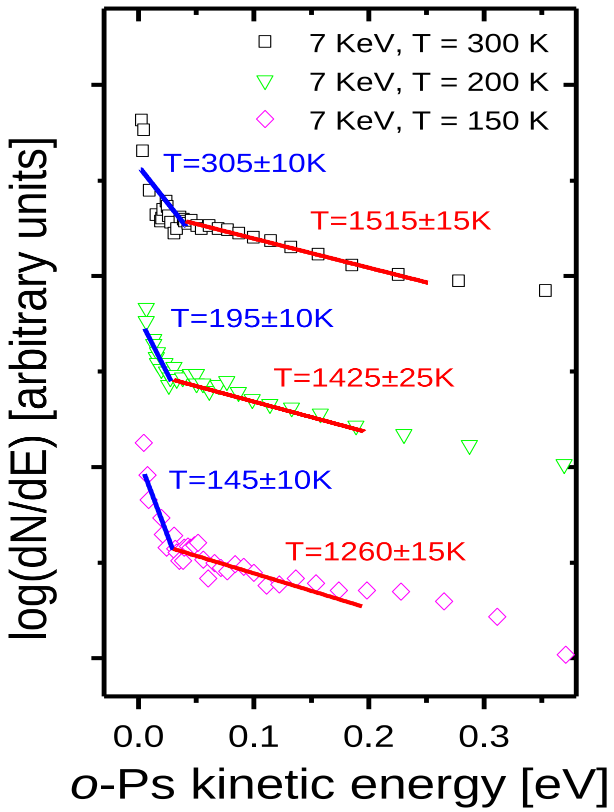


Ps formation

- Ps slowing down by collisions with the pore walls
- "Cold" positronium: we need Ps with about v= 10^4 m/s (0.25 meV)
- Cold positronium: important to maximize the cross section for Hbar production

Formation of positronium and cooling



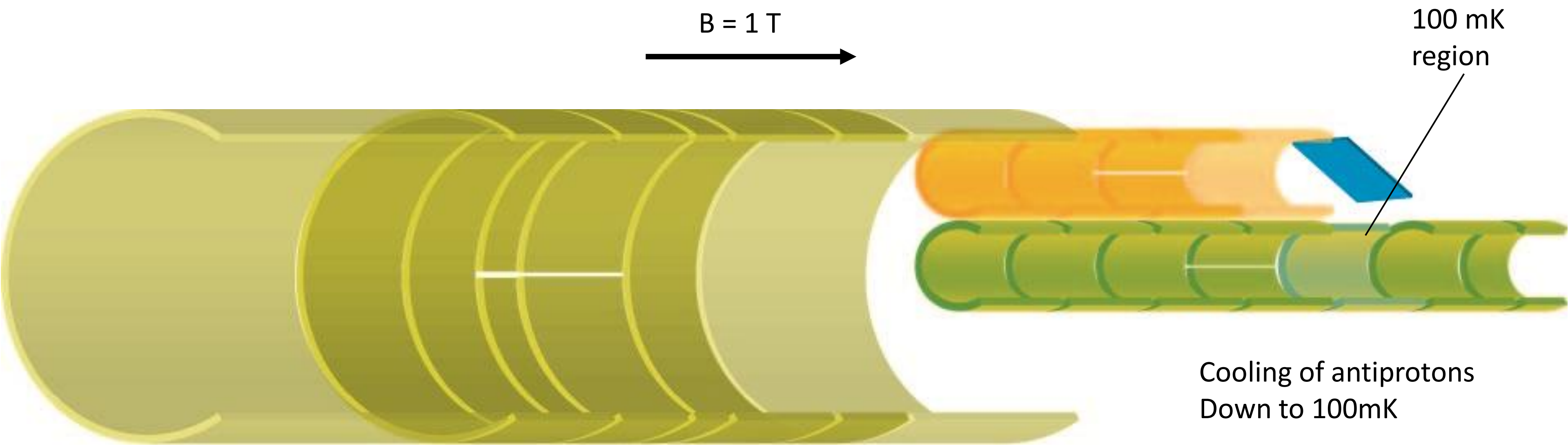


- ORDERED nanochannels SiO_2 on Si substrate
- Nanochannel size 5-8 nm

at 7 keV 27 % of implanted positrons escape into the vacuum as *o*-Ps

S. Mariazzi et al., Appl. Surf. Sci **255** (2008) 191

Positronium production in AEgIS



Positrons transfer
and
diocotron jump on target

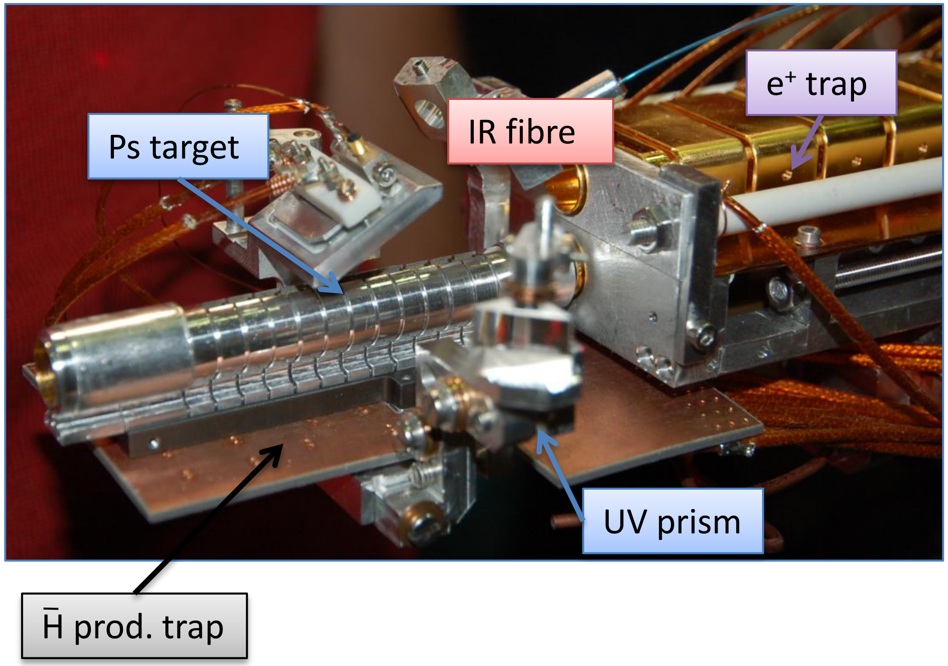
Cooling of antiprotons
Down to 100mK

The temperature of
Pbars here will determine
the temperature of
produced H-bar!

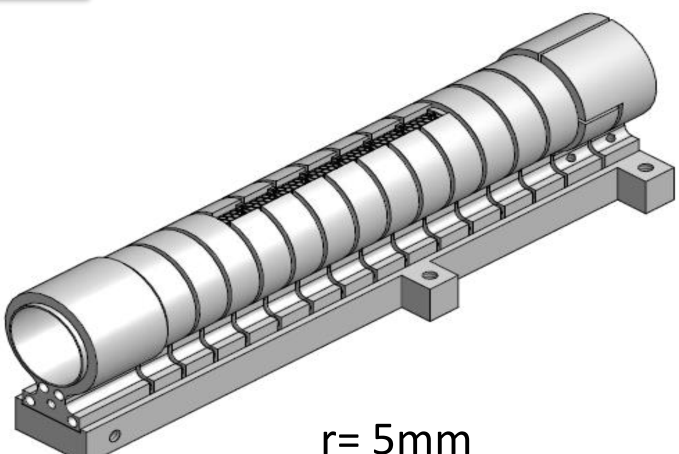
Movement of the e+ cloud off axis across the magnetic field: excitation of a plasma mode

C. Canali et al. Eur. Phys. J. D **65, 499–504 (2011)**

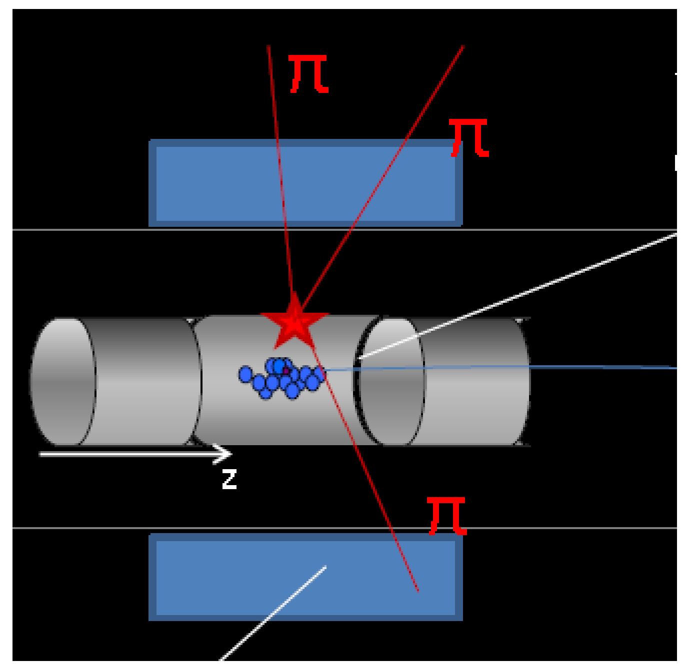
The antihydrogen formation region mounted at CERN   (4 K cryostat)



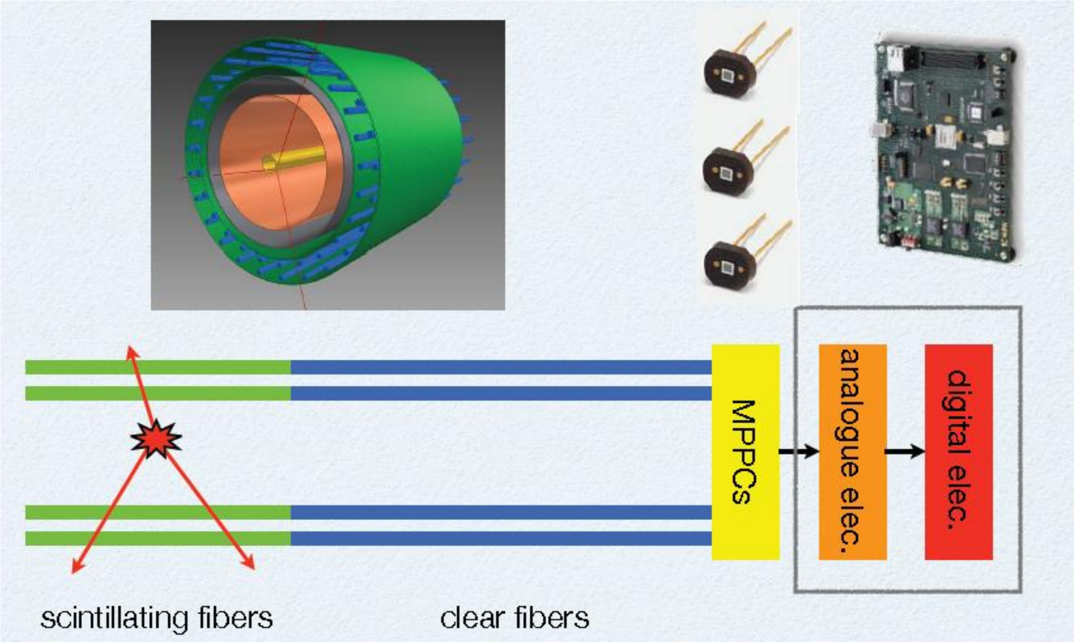
Antihydrogen detector
around the formation region
Scintillating fibers
The best method to measure the
antiproton temperature!! (TOF)



r= 5mm



AntiHydrogen detector



•Detect beam formation   (z resolution 2.5 mm from simulation)
•Measure Hbar energy (time resolution)
•Work @4 K : vacuum vessel separated from the UHV
•Around the Hbar formation trap
•Two double layers of scintillating fibers read by da Hamamatsu MultiPixel Si PMT
•800 fibers,   detector lenght 20 cm
•Read with Fast FPGA

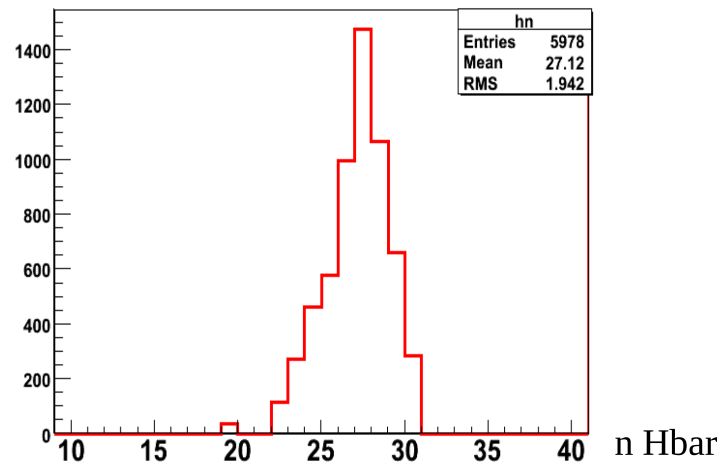
Charge exchange

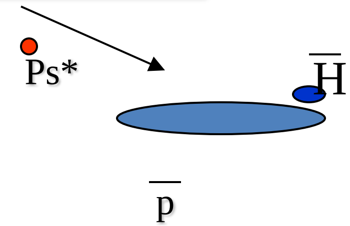
$$\bar{p} + (Ps)^* \rightarrow \bar{H}^* + e^-$$

- cross section $\sigma \propto n_{Ps}^4$

$$\sigma \approx 10^{-8} - 10^{-10}\ cm^2$$

n state of antiH (n (Ps*)=20)





Rydberg (anti)hydrogen is accelerated or decelerated by electric field gradients

Experimentally demonstrated with hydrogen by members of AEgIS

Energy level in presence of electric field F

$$E = -\frac{1}{2n^2} + \frac{3}{2} nkF$$

$$Force = -\frac{3}{2} nk\vec{\nabla} F$$

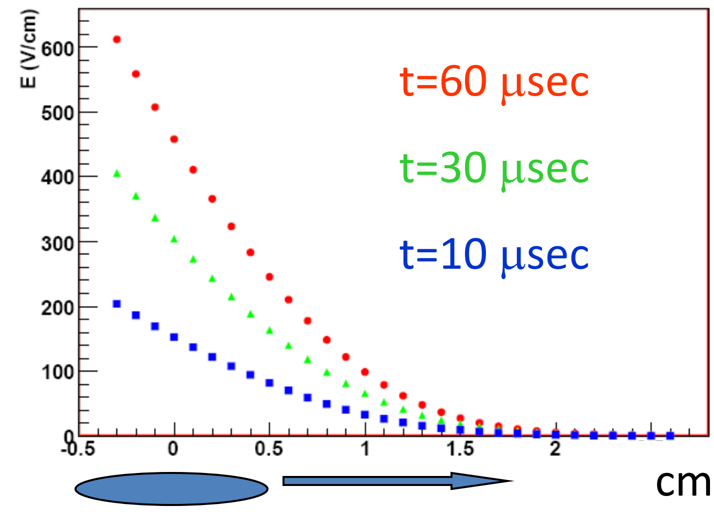
n,k: quantum number

E. Vliegen, F. Merkt J. Phys. B 39 (2006) L241

Making the beam

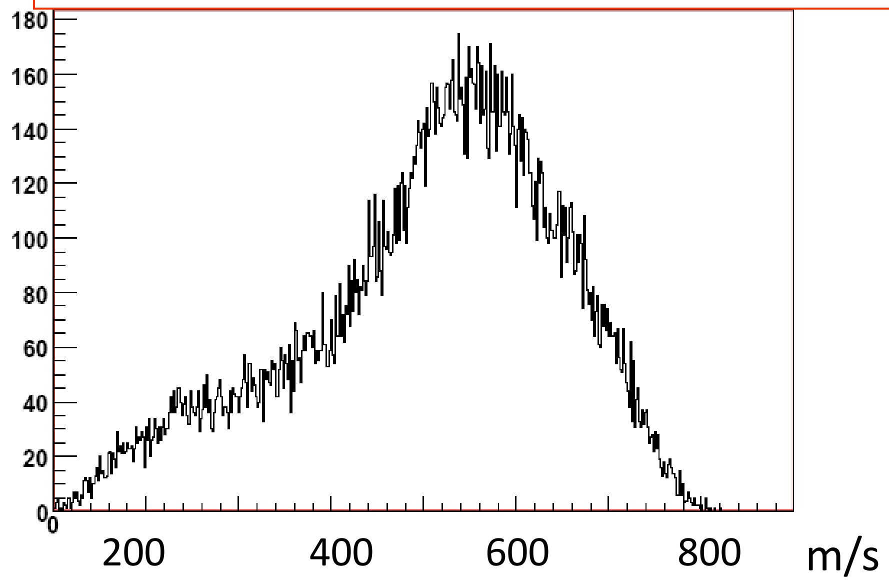
- Trap voltages fast switched from Penning trap to “Rydberg accelerator”
- Voltages of few 100 V applied to trap sectors
- Electric field with space and time gradient
- Duration: 70-80 μsec

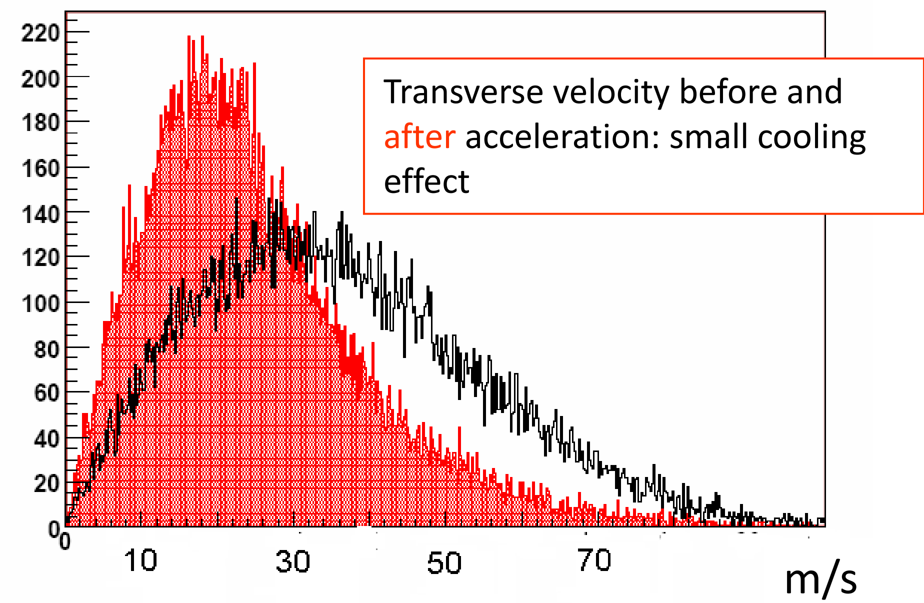
Electric field modulus on trap axis



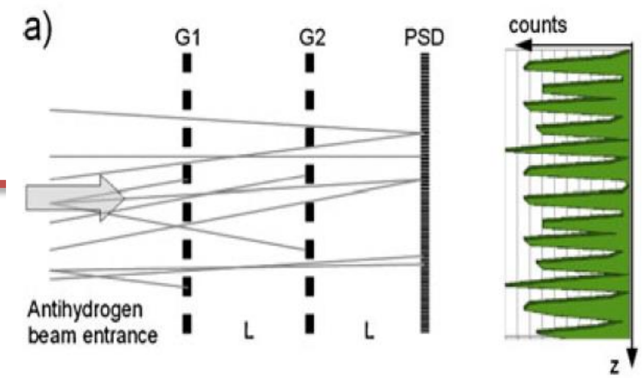
Simulated antihydrogen horizontal velocity

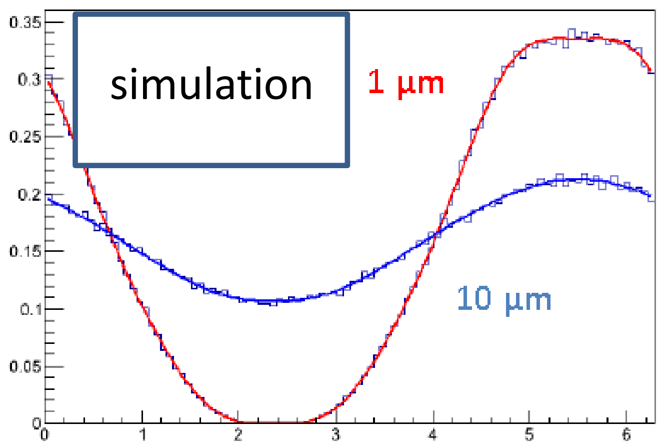
n(Ps*) = 20





Position sensitive detector after the two gratings





Example of simulated distribution of the reconstrucetd pbar annihilation points

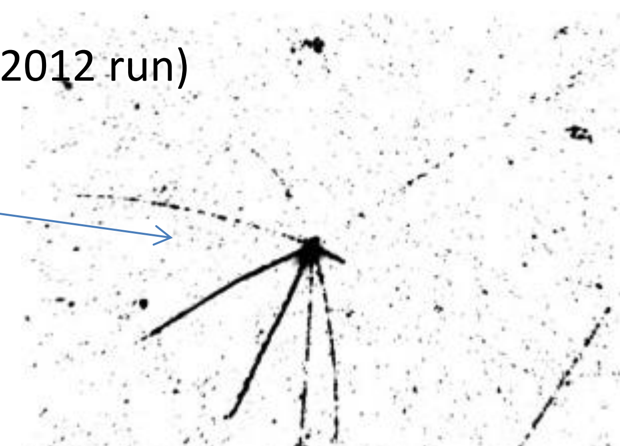
Counts folded in one grating period

Resolution of the detector included

- New developments and tests with antiprotons (May-Derc2012 run)

- Emulsion : 1 µm resolution seems possible
- A factor 4 gain compared with the original proposal

- !!!!!!   1% measurement with 500 Hbar detected !!!!



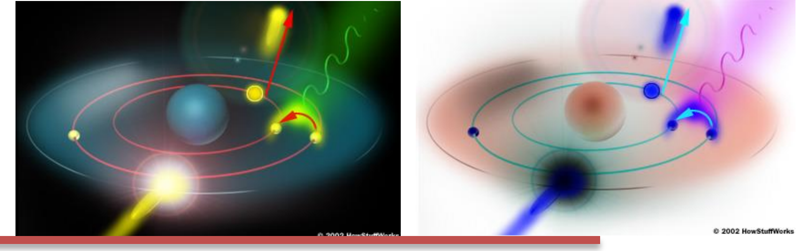
Antiprotons annihilations as detected with the emulsion in AegIS

Summary

- AEgIS is installed at CERN
- First run with antiprotons in 2012
- Large area grating development and tests with Argon by collaborators in Heidelberg
- Many experimental challenges
- Exciting developments in progress
- No antiprotons in 2013 (CERN shutdown)
- Work with e+, e- (and protons)
- First results about gravity expected in few years from now

- A cold antihydrogen beam will allow spectroscopy too!!

CPT and Hbar spectroscopy



1S-2S in hydrogen

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

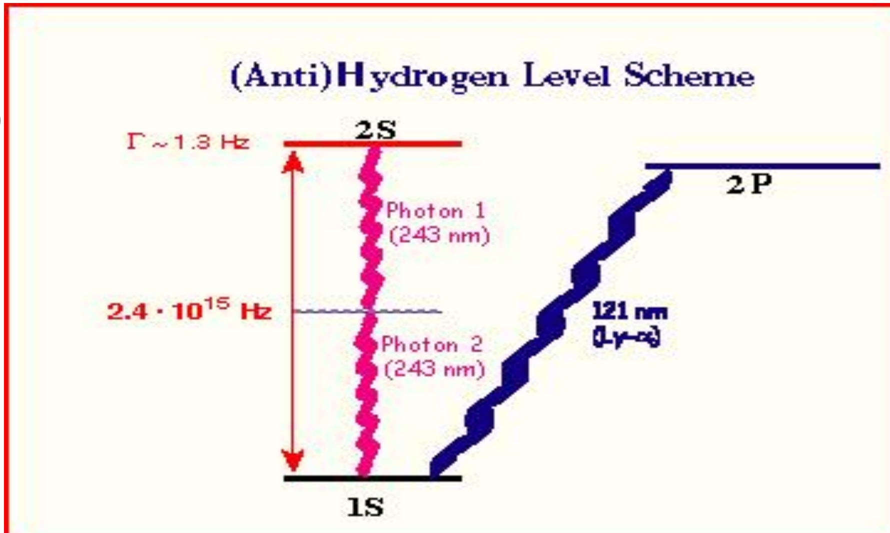
Natural width

2 466 061 413 187 103 (46) Hz

$\Delta\nu/\nu = 1.5\ 10^{-14}$

Cold beam $\quad E \approx 100\ mK$

[M. Niering et al., Phys. Rev. Lett. 84 (2000) 5496

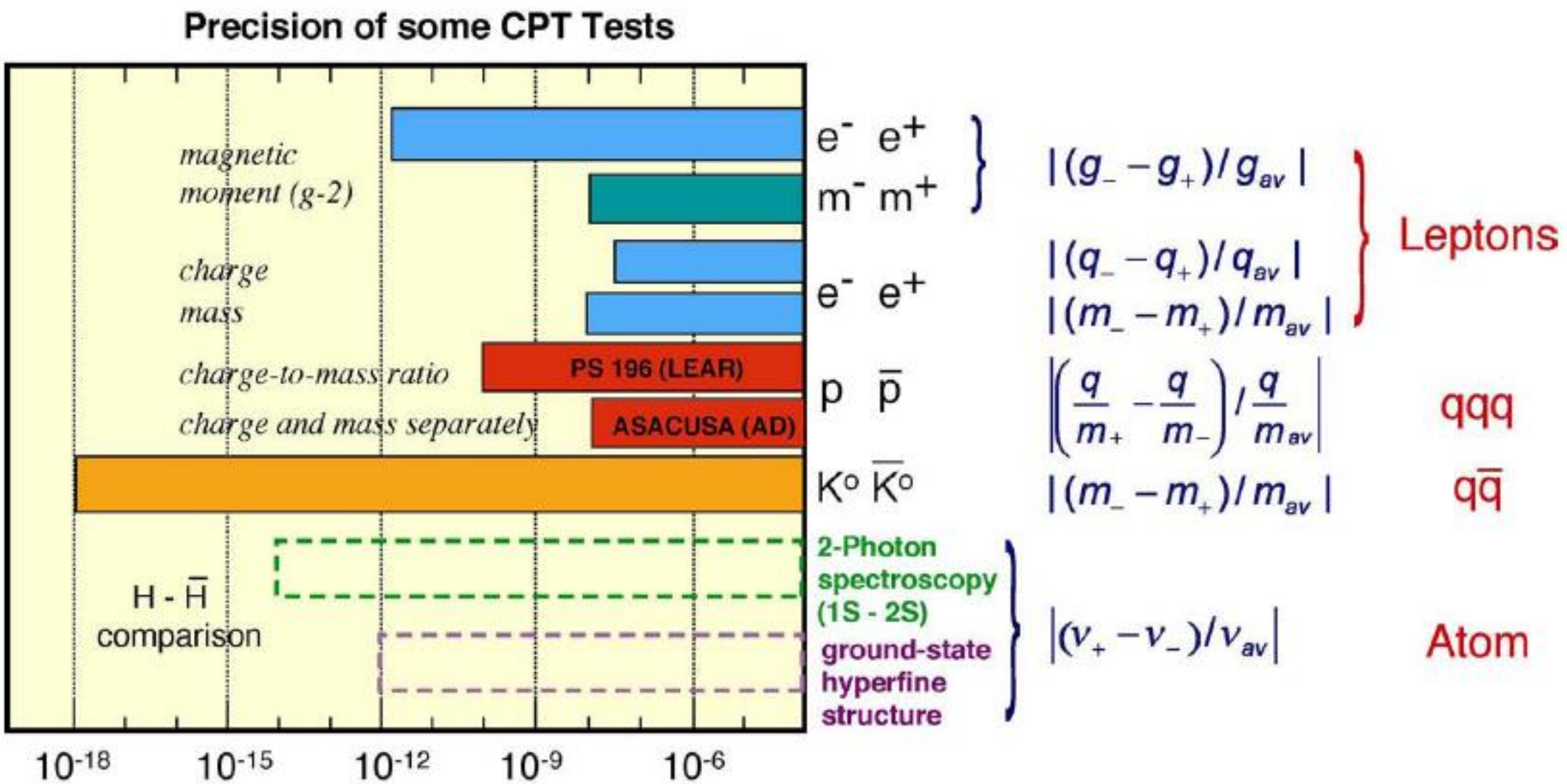


Measure 1S-2S of H and antiH in two period of the year: the gravitation field change by ΔU

WEP $\longrightarrow \Delta\omega = \dfrac{\Delta U}{c^2}$ Null red shift experiment" : CPT independent

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

CPT tests

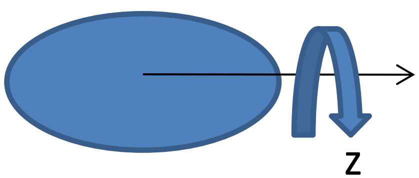


Precision of some CPT Tests
magnetic
moment (g-2)
charge
mass
charge-to-mass ratio
charge and mass separately
PS 196 (LEAR)
ASACUSA (AD)
H - H̄
comparison
e⁻ e⁺
m⁻ m⁺
e⁻ e⁺
p p̄
K° K̄°
2-Photon
spectroscopy
(1S - 2S)
ground-state
hyperfine
structure
$|(g_- - g_+)/g_{av}|$
$|(q_- - q_+)/q_{av}|$
$|(m_- - m_+)/m_{av}|$
$\left|\left(\frac{q}{m_+} - \frac{q}{m_-}\right)/\frac{q}{m_{av}}\right|$
$|(m_- - m_+)/m_{av}|$
$|(\nu_+ - \nu_-)/\nu_{av}|$
Leptons
qqq
qq̄
Atom
10^{-18}
10^{-15}
10^{-12}
10^{-9}
10^{-6}

Cold non neutral plasma at T=0 are not at rest

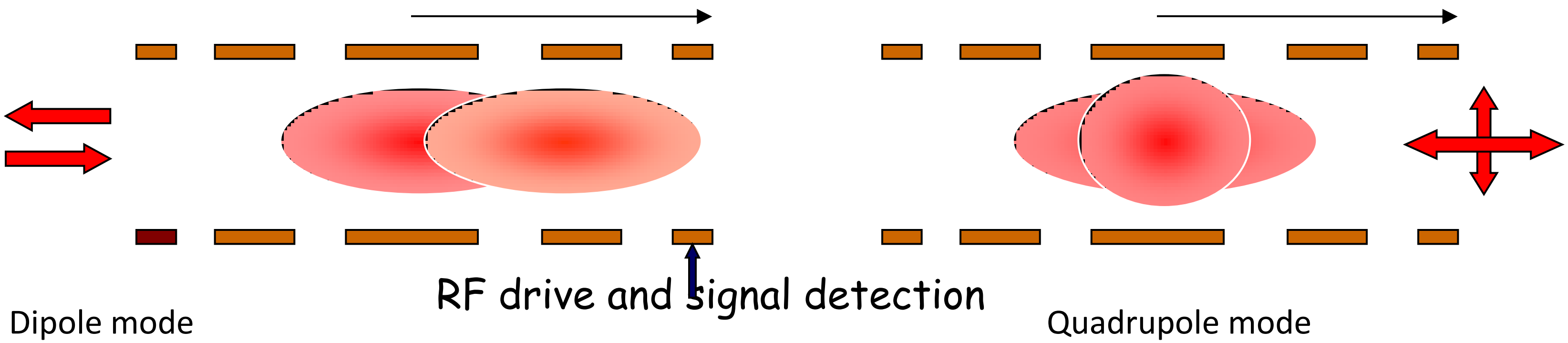
What is limiting the antihydrogen minimal temperature?
•Antiproton temperature before recombination
•Antiproton recoil
•It is difficult to get antihydrogen temperature below some 10 mK

•Future developments: cool the antihydrogen beam (laser cooling….)



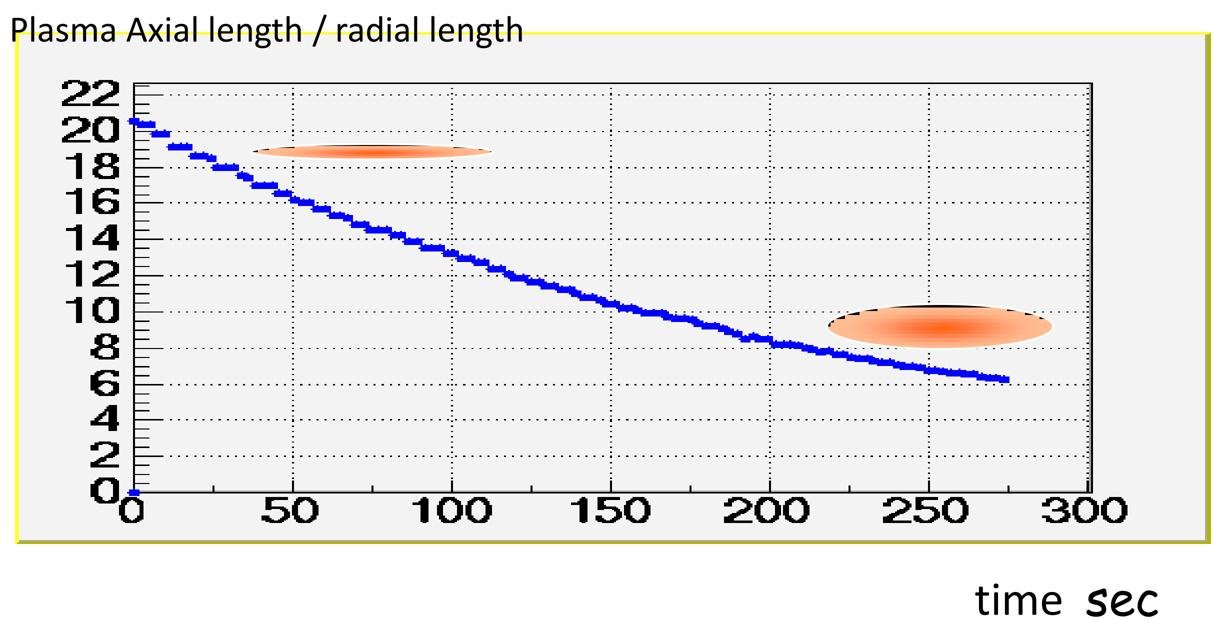
Debye Length << plasma size
Uniform density and sharp boundary
Space charge electric fields compensate trap field in the axial direction (free particles!)
Rigid body rotation : LIMIT THE MINIMUM TEMPERATURE to 100 mK
Radial temperature is defined in this rotating frame

Plasmi freddi completamente carichi confinati



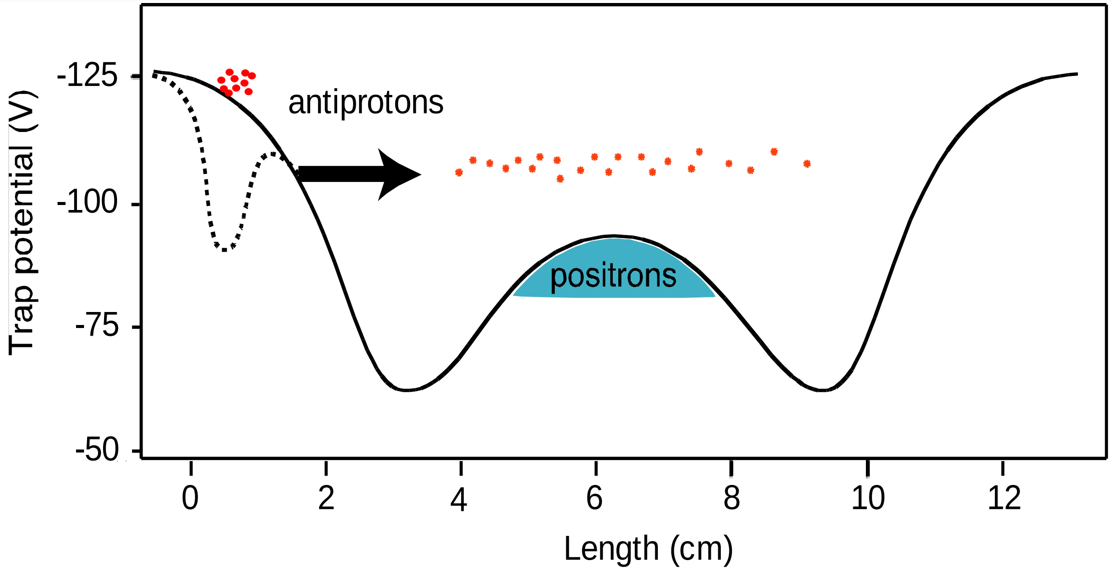
e-, e+

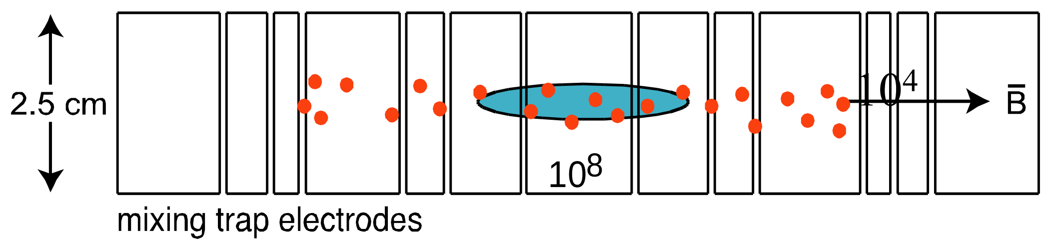
$n=10^8 - 10^9/cm^3$



Misura non distruttiva della forma e della densita' del plasma attraverso la rivelazione dei modi di plasma

Mixing di positroni e antiprotoni in trappole nested





- Competizione tra cooling di antiprotoni su positroni e ricombinazione
- Energia dell'antidrogeno prodotto: dipende da energia antiprotone
- Se la ricombinazione e' dominata dal processo a 3 corpi puo' avvenire prima che gli antiprotoni siano termalizzati

Processi di ricombinazione

Ricombinazione radiativa

Pbar + e^+ = Hbar + hν

Ricombinazione a 3 corpi

Pbar + e^+ + e^+ = Hbar + e^+

$$\frac{dN_{Hbar}}{dt} = N_{pbar}\,\Gamma_{rad/3bodies}$$

$$\Gamma_{rad}(s^{-1}) = 3\,10^{-11}\sqrt{\frac{4.2}{T_{eff}(K)}}\,n_{e_+}(cm^{-3})$$

$$\Gamma_{3bodies}(s^{-1}) = 6\ 10^{-12}\left(\frac{4.2}{T_{eff}(K)}\right)^{9/2}\left(n_{e+}(cm^{-3})\right)^2$$

Antiprotoni e positroni in equilibrio termico T = Teff

Altrimenti $T_{eff} \propto \left(v_{antiprotone} - v_{positrone}\right)^2$

Confinamento di antidrogeno

B disomogeneo
Con un minimo non nullo B_{min}

$$U = \pm\mu(B - B_{\min})$$

$$F = \mp\mu\vec{\nabla}B$$

$$\mu = 670 mK/T$$

$$B - B_{\min} \approx 1T$$

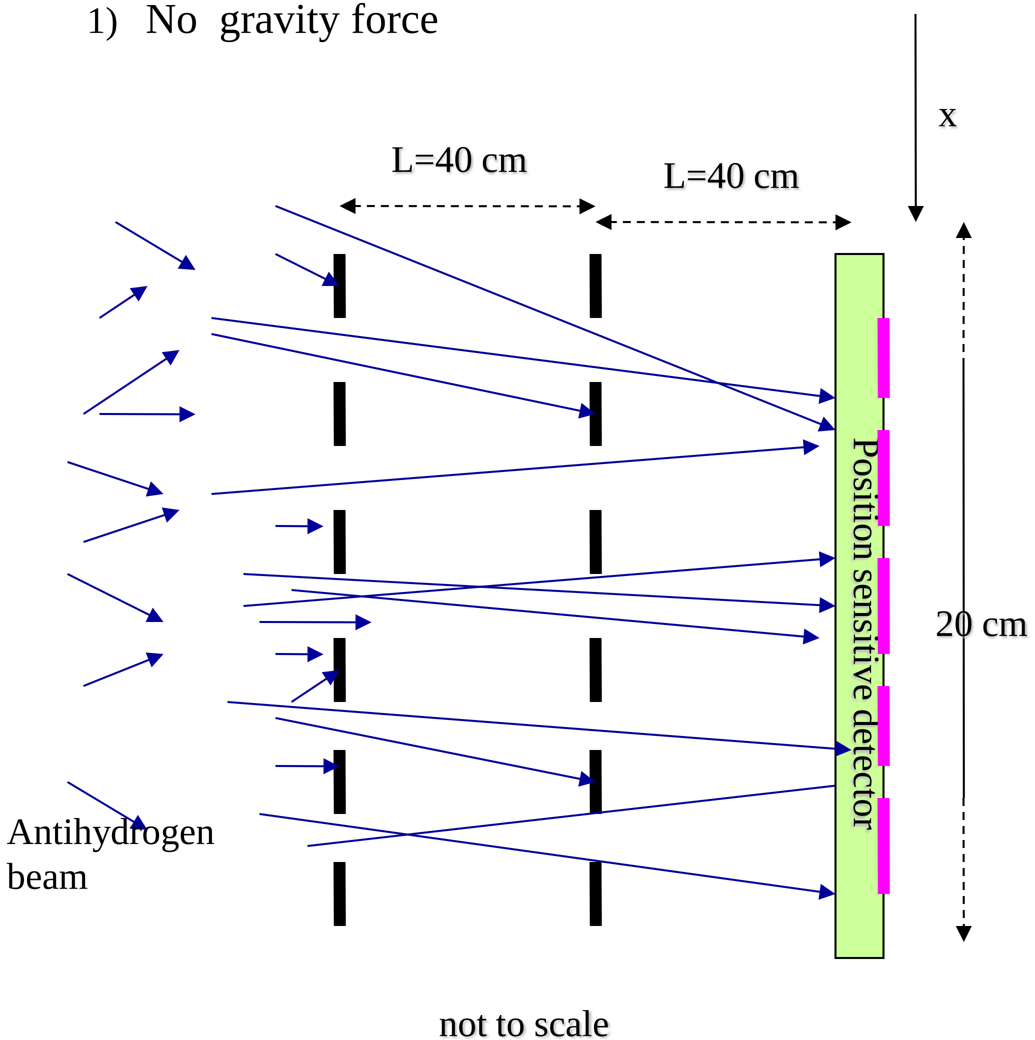
$$\Delta r \approx 1\,cm$$

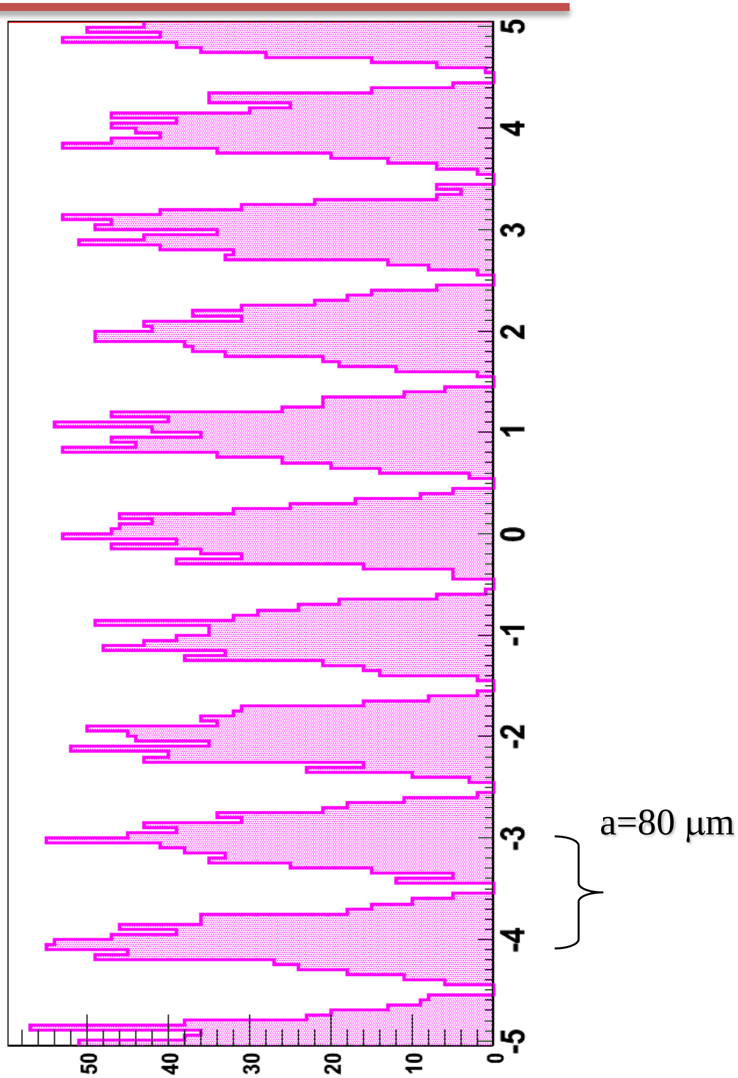
1) Anti-idrogeno viene prodotto nella trappola magnetica in cui sara' confinato
   Deve essere prodotto freddo
1) Regione di produzione e di confinamento sono spazialmente separate
   Formazione di un fascio freddo
   Nessuna evidenza di confinamento di anti-idrogeno

L'opzione 1) e' quella in fase di studio da ATRAP e ALPHA dal 2006
L'opzione 2) e' quella di AEgIS

La misura di gravita’:
deflettometro di Moire’

1) No gravity force





Indirect limits on EEP validity for antimatter systems

"Red shift type" argument

R. J. Hughes et al., PRL 66,7 (1991)

Cyclotron frequency of p and pbar in the same magnetic field

$$\left|\frac{\omega_c - \overline{\omega}_c}{\omega_c}\right| < 9 \cdot 10^{-11}$$

G. Gabrielse et al PRL 82 (3198) (1999)

→ If matter and antimatter are coupled to the same tensor field: $\alpha_{p\bar{p}} < 3 \cdot 10^{-6}$

For anomalous interaction coupling to antimatter with R_{Earth} < range < Distance Earth-Sun: $\alpha_{p\bar{p}} < 10^{-1}$

- The limit is model dependent
- Exact CPT is assumed

SN1987A

$\alpha_{\nu\bar{\nu}} < 10^{-5} - 10^{-6}$

Neutrino-antineutrino arrival time difference

- Only one ν_e detected, several caveats
- Model dependent

S. Pakvasa et al., Phys. Rev. D 39 (1989) 176

The "Schiff argument"

S.I. Schiff PRL 1 254 (1958)

Virtual e+ e- pairs in the atoms

WEP violation for e+ → m_I-m_G should depend on Z

$\alpha_{e+e-} < 10^{-6}$

- Several criticisms
- Uncorrected remormalization procedure…

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)

K_0 $\overline{K_0}$

CPLEAR coll. Phys. Lett. B 452 (1999) 425

Very stringent limits

$\alpha_{K_0\overline{K_0}} < 10^{-9} - 10^{-14}$

Depending on the range of the anomalous interaction

WEP and antihydrogen

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

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

WEP $\longrightarrow$ $\Delta\omega = \dfrac{\Delta U}{c^2}$ Null red shift experiment" : CPT independent

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

Direct measurements : time of flight

atom interferometry 10^{-6} ,10^{-9} $10^{-?}$

$K_0 - \overline{K_0}$ and the equivalence principle

•Anomalous (Yukawa) vector, scalar or tensorial interactions produced by astronomical sources can couple to K_0 and K_0bar with different strength

•They produce an apparent mass variation and not zero gK0-gK0bar.

•The source distance change with time $K_0 - \overline{K_0}$

•Limits on the range of the anomalous force from time variation of the measured parameters

CPLEAR coll. Phys. Lett. B 452 (1999) 425