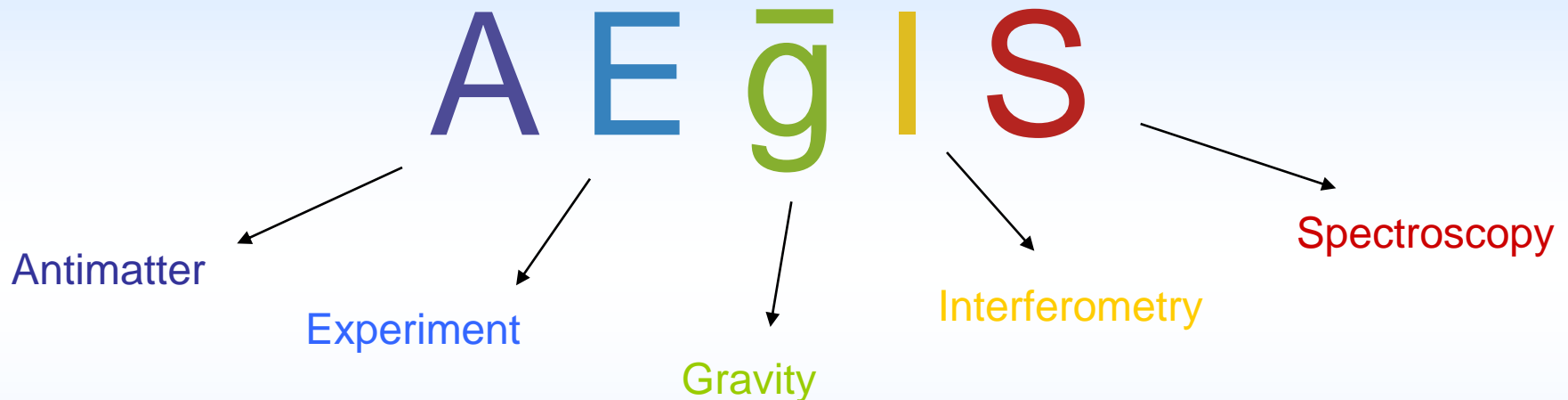


AEGIS at CERN: measuring Antihydrogen fall



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Istituto Nazionale Fisica Nucleare - Milano



Outline of talk:

- Theoretical motivation
- General experimental strategy
- Antimatter beam preparation
- Gravity measurement

AEGIS: AD-6 Experiment

<http://aegis.web.cern.ch/aegis/>

Antimatter history in a slide

- 1928: relativistic equation of the $\frac{1}{2}$ spin electron (Dirac)
- 1929: electron sea and hole theory (Dirac)
- 1931: prediction of antimatter (Dirac, Oppenheimer, Weyl)
- 1932: discovery of positron in cosmic rays (Anderson)
- 1933: discovery of e^-/e^+ creation and annihilation (Blackett, Occhialini)
- 1937: symmetric theory of electrons and positrons
- 1955: antiproton discovery (Segre', Chamberlain, Wiegand)
- 1956: antineutron discovery (Cork, Lambertson, Piccioni, Wenzel)
- 1995: creation of high-energy antihydrogen (CERN, Fermilab)
- 2002: creation of 10 K antihydrogen (Athena, Atrap)
- 2011: antihydrogen confinement (Alpha)



Future: study of Antimatter properties !!

AEGIS Collaboration



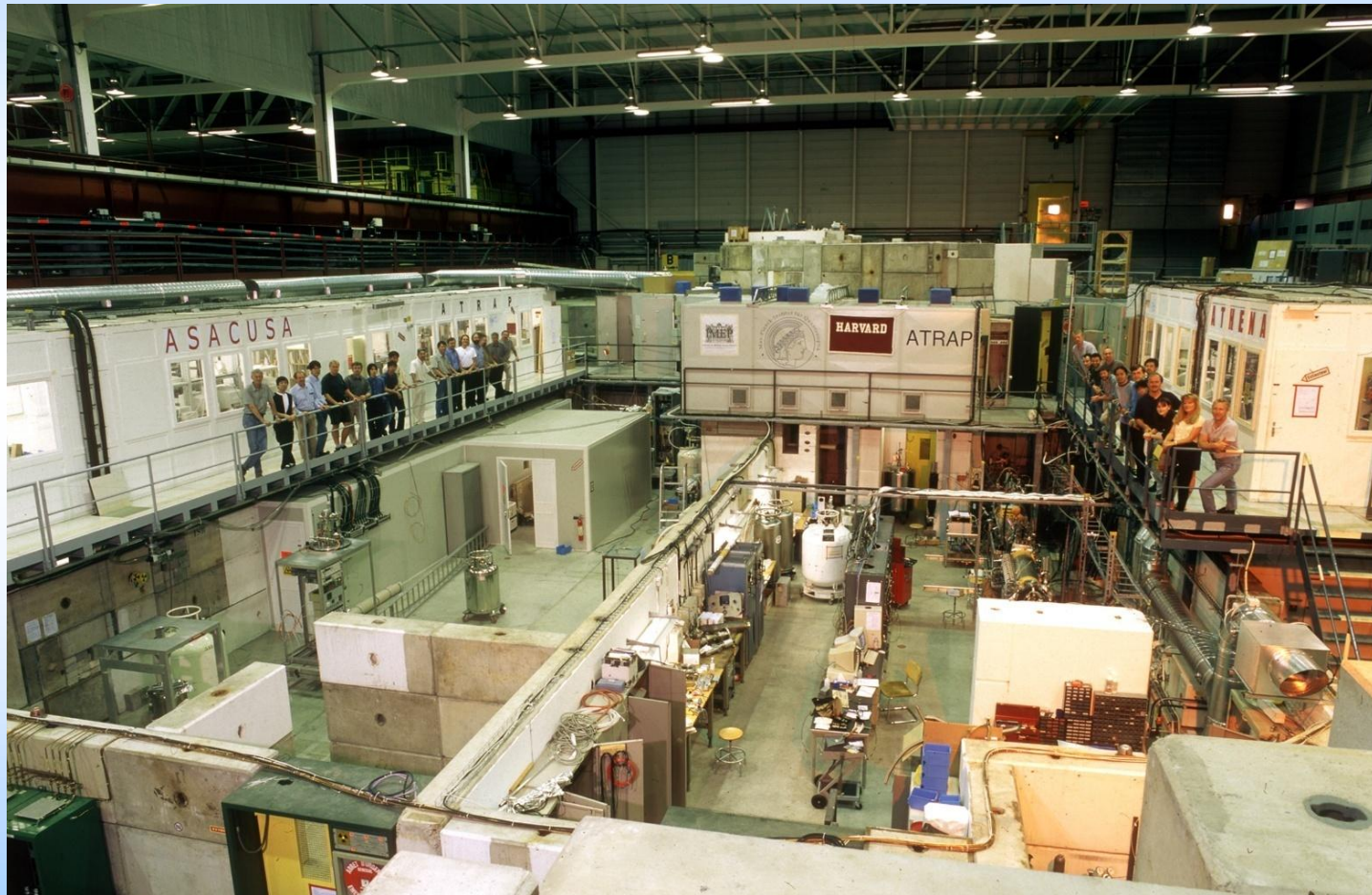
CERN, Geneva, Switzerland M. Doser, D. Perini, T. Niinikoski, A. Dudarev, T. W. Eisel, R. Van Weelderen, F. Haug, L.. Dufay-Chanat, J. L.. Servai
LAPP, Annecy, France. P. Nédélec, D. Sillou
Queen's U Belfast, UK G. Gribakin, H. R. J. Walters
INFN Firenze, Italy G. Ferrari, M. Prevedelli, G. M. Tino
INFN Genova, University of Genova, Italy C. Carraro, V. Lagomarsino, G. Manuzio, G. Testera, S. Zavatarelli
INFN Milano, University of Milano, Italy I. Boscolo, F. Castelli, S. Cialdi, M. G. Giammarchi, D. Trezzi, A. Vairo, F. Villa
INFN Padova/Trento, Univ. Padova, Univ. Trento, Italy R. S. Brusa, D. Fabris, M. Lunardon, S. Mariazzi, S. Moretto, G. Nebbia, S. Pesente, G. Viesti
INFN Pavia – Italy University of Brescia, University of Pavia G. Bonomi, A. Fontana, A. Rotondi, A. Zenoni
MPI- K, Heidelberg, Germany C. Canali, R. Heyne, A. Kellerbauer, C. Morhard, U. Warring
Kirchhoff Institute of Physics U of Heidelberg, Germany M. K. Oberthaler
INFN Milano, Politecnico di Milano, Italy G. Consolati, A. Dupasquier, R. Ferragut, F. Quasso
INR, Moscow, Russia A. S. Belov, S. N. Gninenko, V. A. Matveev, A. V. Turbabin
ITHEP, Moscow, Russia V. M. Byakov, S. V. Stepanov, D. S. Zvezhinskij
New York University, USA H. H. Stroke
Laboratoire Aimé Cotton, Orsay, France L. Cabaret, D. Comparat
University of Oslo, Norway O. Rohne, S. Stapnes
CEA Saclay, France M. Chappellier, M. de Combarieu, P. Forget, P. Pari
INRNE, Sofia, Bulgaria N. Djourelou
Czech Technical University, Prague, Czech Republic V. Petráček, D. Krasnický
ETH Zurich, Switzerland S. D. Hogan, F. Merkt
Institute for Nuclear Problems of the Belarus State University, Belarus G. Drobychev
Qatar University, Qatar I. Y. Al-Qaradawi

AD (Antiproton Decelerator) at CERN

3×10^7 antiprotons / 100 sec

6 MeV

$10^4 \bar{p}$ / 100 sec



6/29/2012

POSMOL 2011

Physics with Antimatter is at the very foundation of Modern Physics:

CPT Physics

WEP (Weak Equivalence Principle)

CPT Theorem

Charge conjugation (C) : reversing electric charge and all internal quantum numbers

Parity (P): space inversion; reversal of space coordinates

Time reversal (T): replacing t by $-t$. Reverses time derivatives

Any local, Lorentz invariant Lagrangian is CPT symmetric (Lüders, Pauli 1959). CPT is proven in axiomatic Quantum Field Theory.

Consequences:

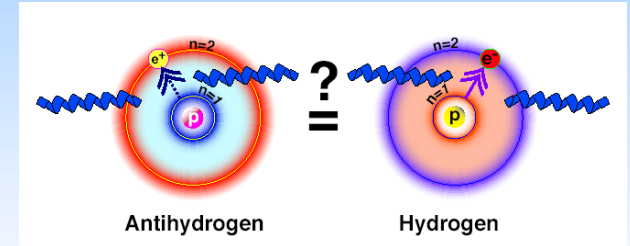
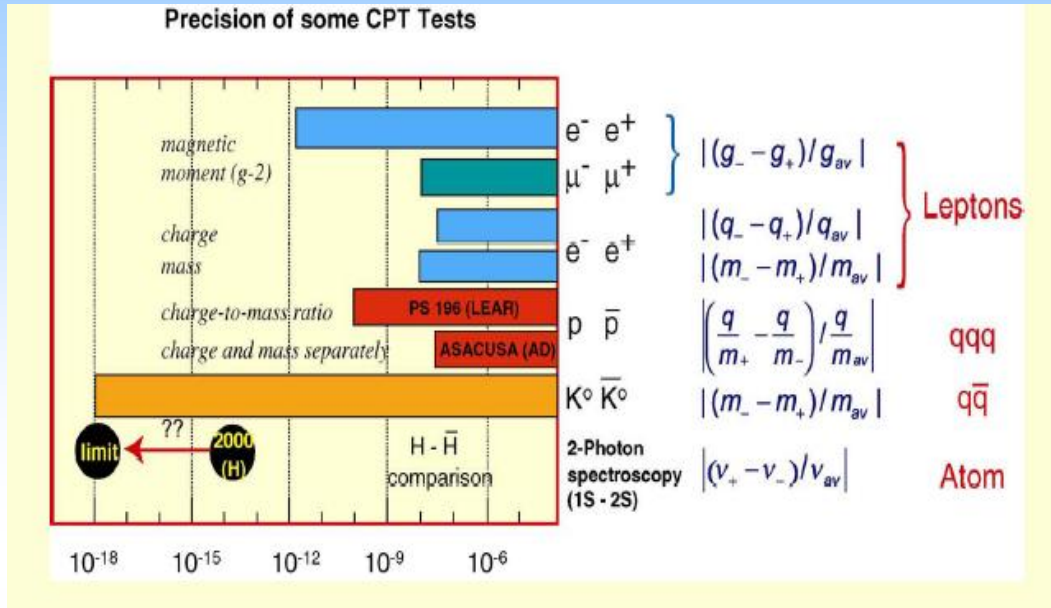
Particles and antiparticles have identical masses and lifetimes

All internal quantum numbers of antiparticles are opposite to those of particles

CPT conserved to the best of our knowledge. So why look for violations?

- 1) A test of CPT is not only a test of a discrete symmetry. It is a test of the validity of Quantum Field Theory
- 2) CPT could break down in a Quantum Theory of Gravity

Current status and possible improvements



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

Results achieved on Hydrogen

1S-2S $\nu=2\ 466\ 061\ 413\ 187\ 103\ (46)$ Hz

Natural width: 1.3 Hz

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

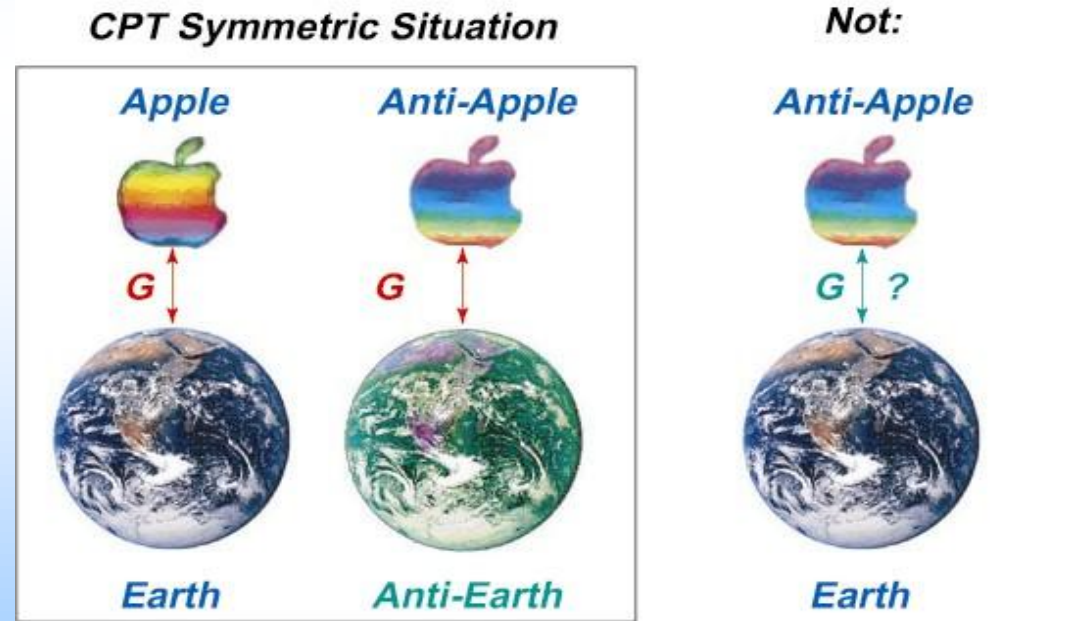
Requires antihydrogen at
mK temperature

WEP: Weak Equivalence Principle

The trajectory of a falling test body depends only on its initial position and velocity and is independent of its composition (a form of WEP)

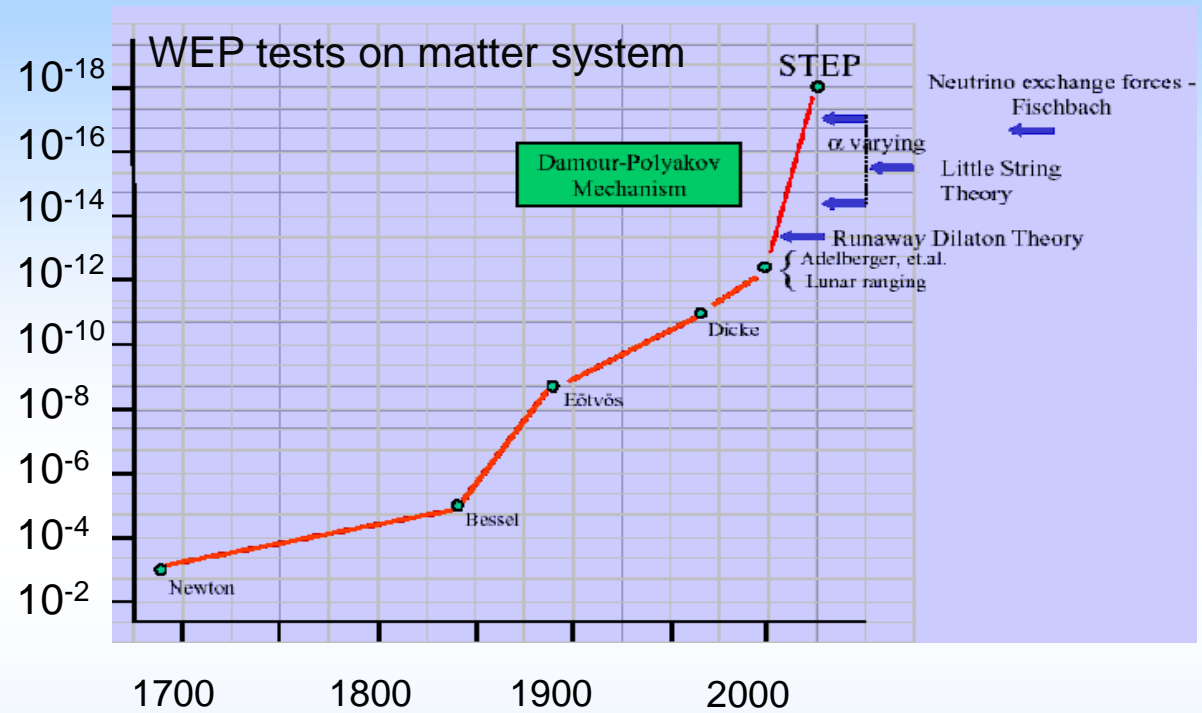
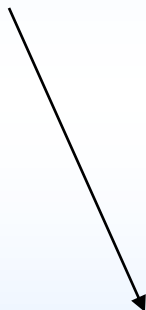
All bodies at the same spacetime point in a given gravitational field will undergo the same acceleration (another form of WEP)

1. Direct Methods:
measurement of
gravitational acceleration of
H and Hbar in the Earth
gravitational field
2. High-precision spectroscopy:
H and Hbar are test clocks
(this is also CPT test)

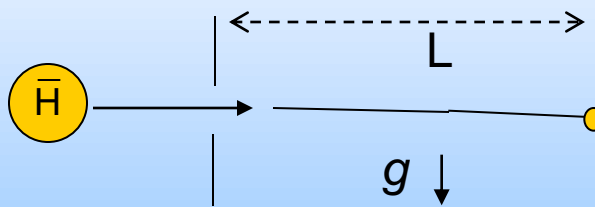


Gravitational Physics: Weak Equivalence Principle

- No direct measurements on gravity effects on antimatter
- “Low” precision measurement (1%) will be the first one



Can be done with a beam of Antiatoms flying to a detector!



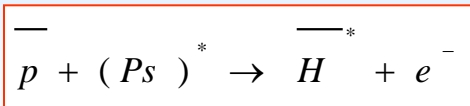
$$h = \frac{1}{2}gT^2 = \frac{g}{2} \left(\frac{L}{v_z} \right)^2$$

AEGIS
first phase

AEGIS strategy to produce Antihydrogen:

1. COLD ANTIHYDROGEN PRODUCTION

- ~~Nested Penning Trap (warm antihydrogen / highly excited antiatoms)~~
- Charge Exchange with Rydberg Positronium



- Slow antiprotons (cold antihydrogen)
- Rydberg Positronium

Positronium formation

Positronium excitation

Avoid the problem of a particle trap able to simultaneously confine charged particles (Penning trap) and Antihydrogen (by radial B gradients).

- Have a charged particle trap only
- Form a neutral (antihydrogen) beam → **g measurement**
- Confine only neutrals (future) → **(CPT physics)**

A \bar{g} | S in short

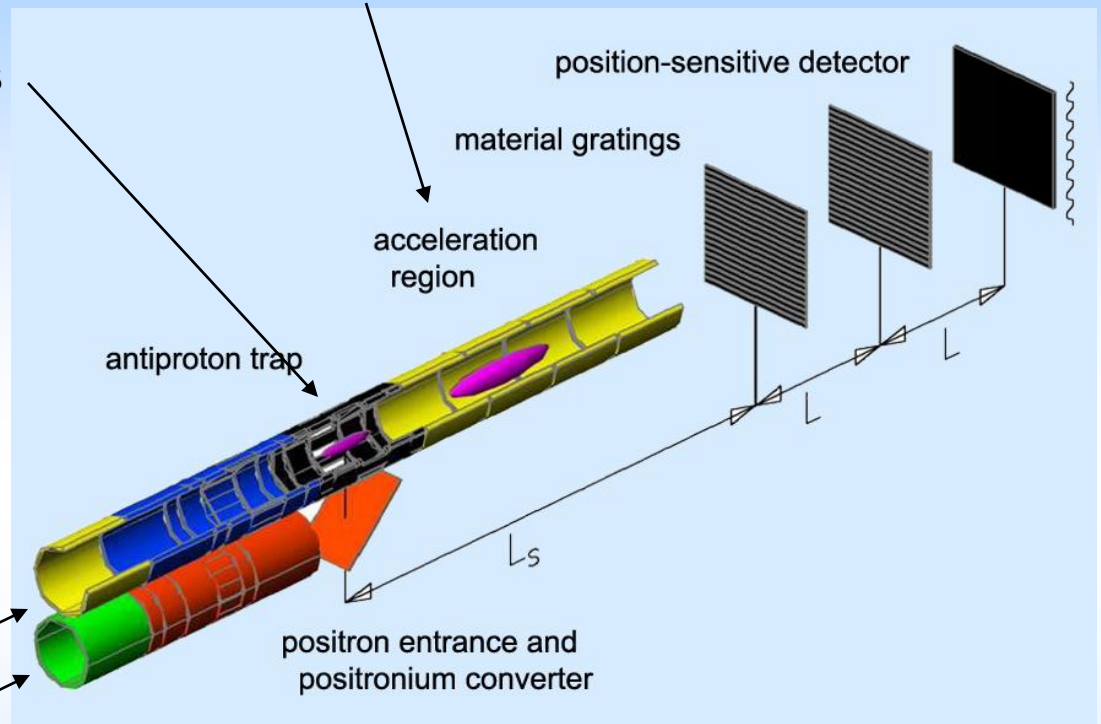
Acceleration of antihydrogen.

Formation of antihydrogen atoms

The antihydrogen beams will fly (with $v \sim 400$ m/sec) through a Moire' deflectometer, the classical counterpart of a matter wave interferometer

Antiprotons

Positrons

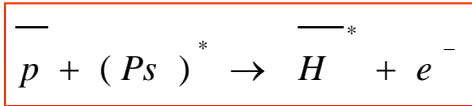


The vertical displacement (gravity fall) will be measured on the last (sensitive) plane of the deflectometer

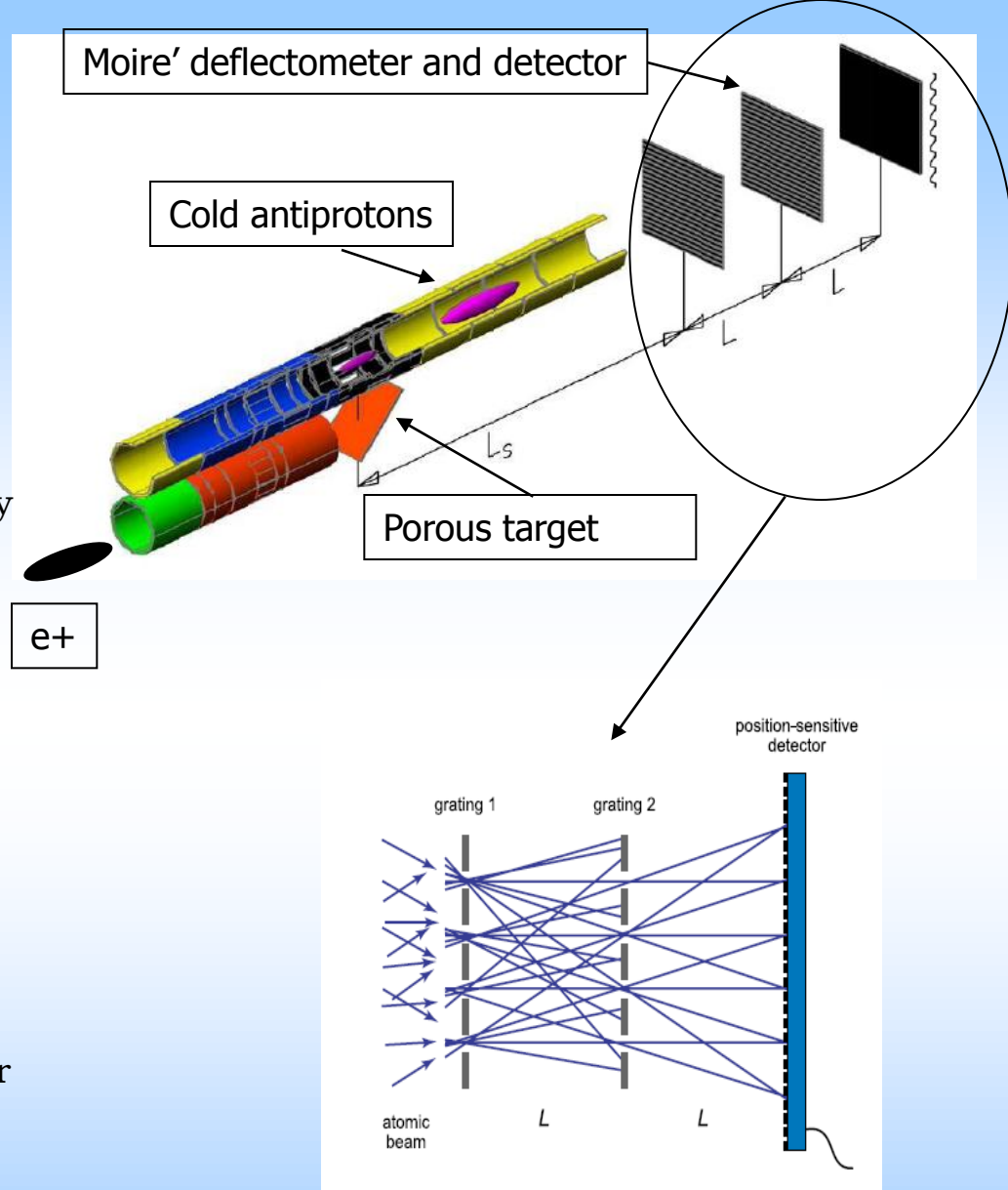
Such measurement would represent the first direct determination of the gravitational effect on antimatter

AEGIS experimental strategy

- 1) Produce ultracold antiprotons (100 mK)
- 2) Accumulate e^+
- 3) Form Ps by interaction of e^+ with porous target
- 4) Laser excite Ps to get Rydberg Ps
- 5) Form Rydberg cold (100 mK) antihydrogen by



- 6) Form a beam using an inhomogeneous electric field to accelerate the Rydberg antihydrogen
- 7) The beam flies toward the deflectometer which introduces a spatial modulation in the distribution of the \overline{H} arriving on the detector
- 8) Extract g from this modulated distribution



Ultracold Antiprotons

- The CERN AD (Antiproton Decelerator) delivers 3×10^7 antiprotons / 80 sec
- Antiprotons catching in cylindrical Penning traps after energy degrader
- Catching of antiprotons within a 3 Tesla magnetic field, UHV, 4 Kelvin, e^- cooling
- Stacking several AD shots ($10^4/10^5$ subeV antiprotons)
- Transfer in the Antihydrogen formation region (1 Tesla, 100 mK)
- Cooling antiprotons down to 100 mK
- 10^5 antiprotons ready for Antihydrogen production

Antiprotons	
Production	GeV
Deceleration	MeV
Trapping	keV
Cooling	eV

- Resistive cooling based on high-Q resonant circuits
- Sympathetic cooling with laser cooled Os^- ions

U. Warring et al., PRL 102 (2009) 043001

A few comments on AEGIS strategy (and timing) to produce Antihydrogen:

Use of 10^8 positrons in a bunch

Bunch of 20 ns and 1 mm beam spot

500 sec accumulation time

Catch \bar{p} from AD, degrade the energy

Cool down the \bar{p} with e^-

500 sec accumulation time (a few AD shots, $10^5 \bar{p}$)

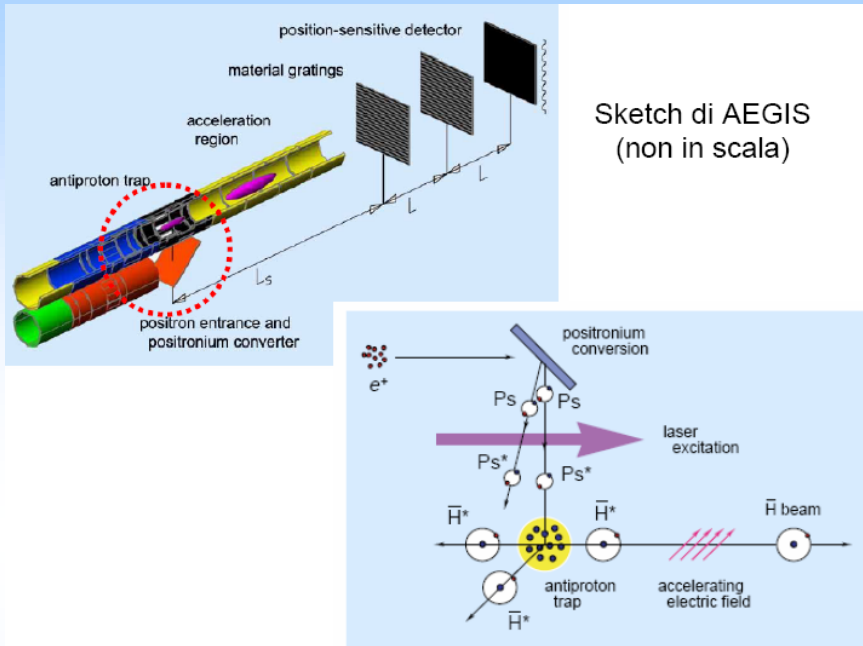
- Source and moderator
- Trap
- Accumulator (Surko-type)

An antihydrogen production shot every 500 sec

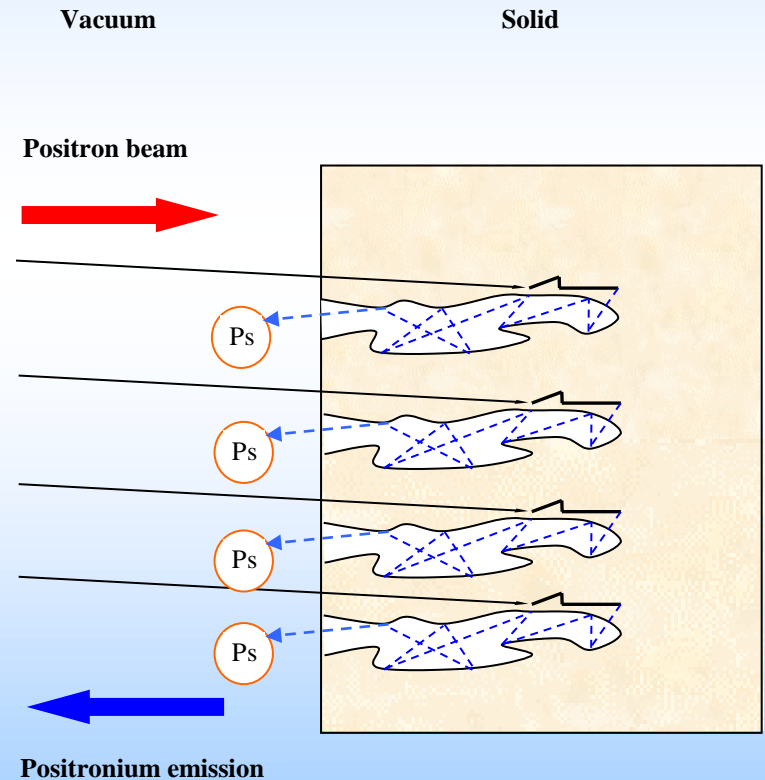
Avoid the problem of a particle trap able to simultaneously confine charged particles (Penning trap) and Antihydrogen (by radial B gradients).

- Have a charged particle trap only
- Form a neutral (antihydrogen) beam \longrightarrow **g measurement**
- Confine only neutrals (future) \longrightarrow **(CPT physics)**

Positrons and Positronium (Ps) production

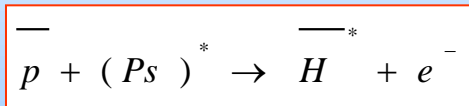


Technique: have a bunch of $10^8 e^+$ in 20 ns
 Have them impinge at $\sim keV$ energy on a (likely porous Silica) target

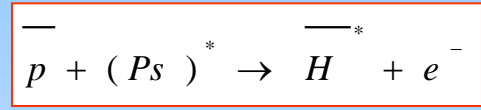


Orto-Ps produced in the bulk and “thermalized” by collision on pore walls

Ps used for the reaction:



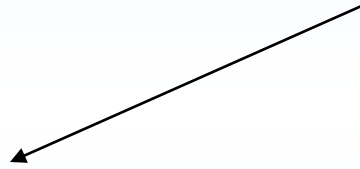
The charge-exchange reaction:



Conceptually similar to a charge exchange technique based on Rydberg cesium performed by ATRAP - C. Storry et al., Phys. Rev. Lett. 93 (2004) 263401

The cross-section is strongly dependent on the principal quantum number:

$$\sigma \approx 58 n_{ps}^4 \pi a_o^2$$



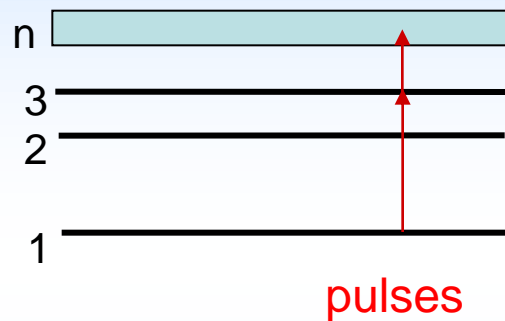
Laser excitation to Rydberg states of the Positronium atom is needed

The travel distance in 20 ns (pulse duration) is only 2 mm.
With a production of 10^7 oPs atoms per pulse (20 ns -10^8 e+)
a density of 10^{15} Ps/m³ is expected

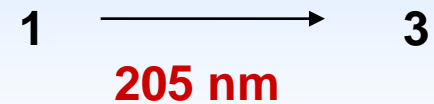
Ps excitation and Antihydrogen production

Laser Ps-excitation will be used to pump the Ps atoms up to the $n \sim 25$ level

Laser excitation will take place in the 1 T magnetic field



11 ns lifetime for the intermediate $n=3$ level



Linewidth Doppler-dominated



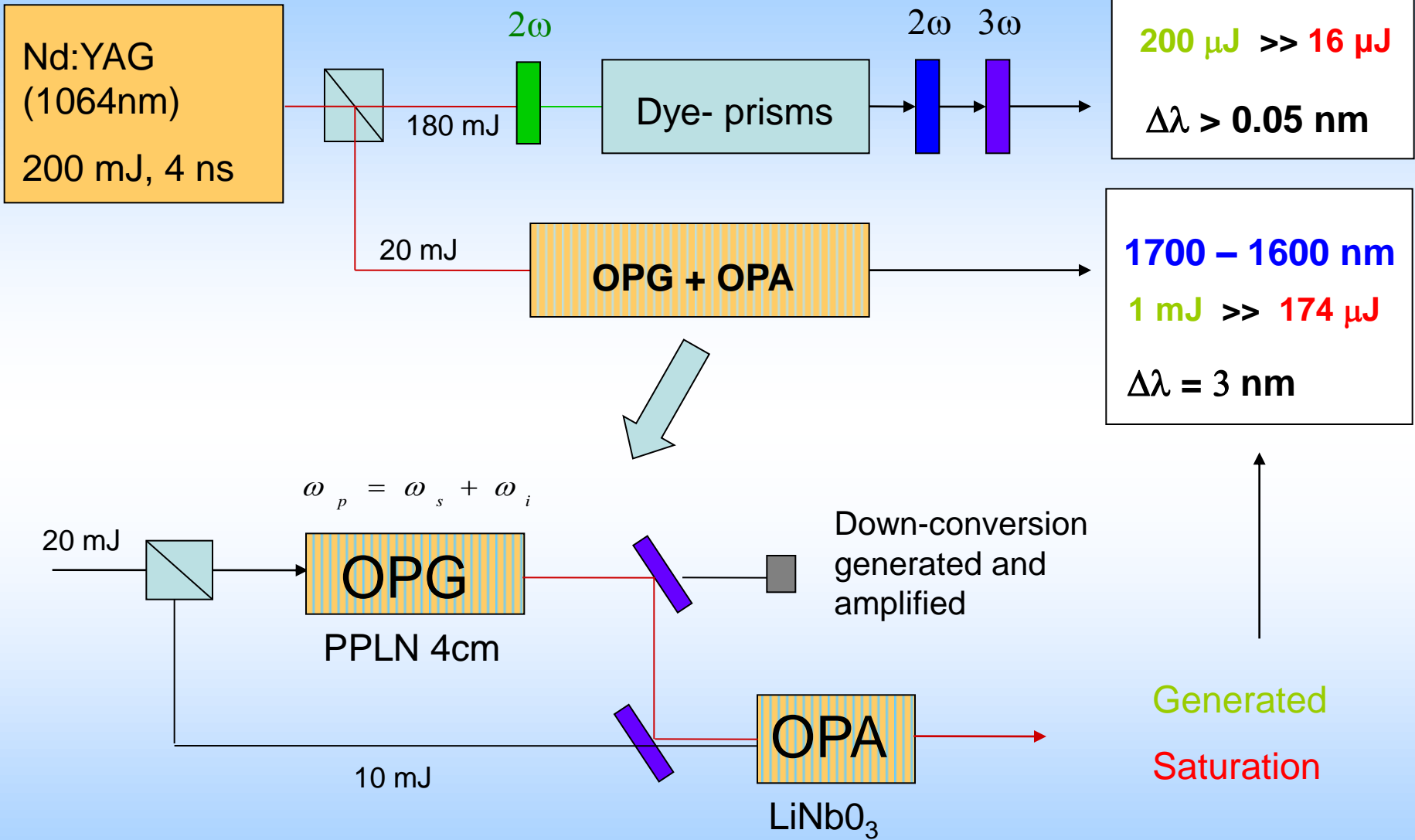
Linewidth motional Stark-dominated

Duration of pulses will be ~ 5 ns and since

$$\Delta t_{coh} = \lambda^2 / c \Delta \lambda \ll 5 \text{ ns}$$

The excitations will be incoherent

Laser system for Ps excitation to Rydberg states



Antihydrogen (Stark) acceleration

Rydberg antihydrogen is accelerated or decelerated by electric field

Stark acceleration *Stark acceleration of hydrogen atoms”, E. Vliegen and F. Merkt, Journ. Phys. B 39 (2006) L241*

The energy levels of an H (anti)atom in an electric field F are given to first order, in atomic units, by

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

E = excitation energy

n = principal quantum number

k = quantum number which runs from $-(n-1-|m|)$ to $(n-1-|m|)$

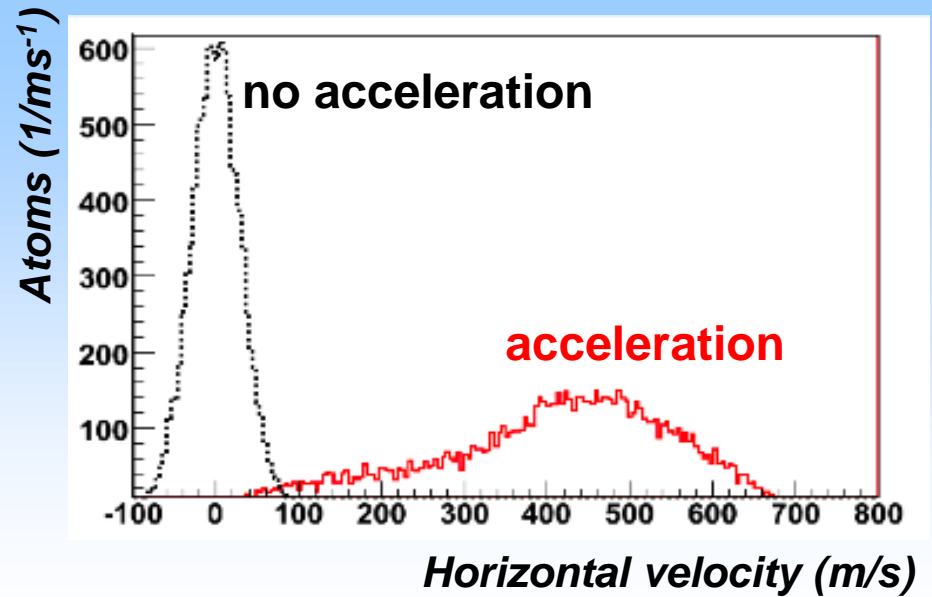
m = azimuthal quantum number

If the excited atoms are moving in a region where the amplitude of the electric field is changing then their internal energy changes accordingly (to conserve total energy), they are accelerated or decelerated

$$\Delta E_{kin} = \frac{3}{2}nk\Delta F$$

- electric fields of few 100 V/cm are used (limited by field ionization)

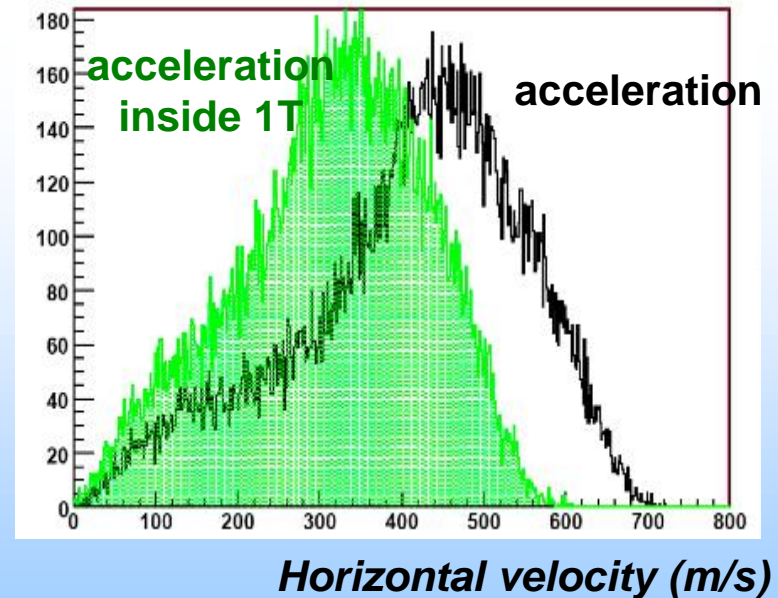
- Δv of few 100 m/s within about 1 cm can be achieved



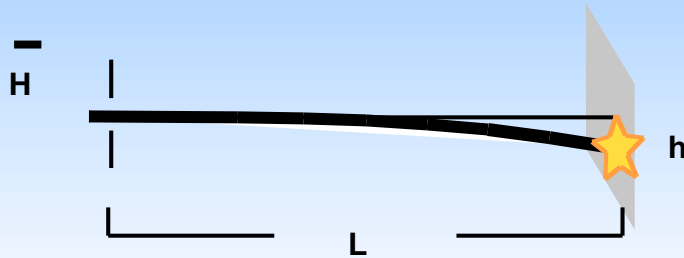
Effect of the magnetic field (e.g. 1 T)

$$E = -\frac{1}{2n^2} + n' \sqrt{\gamma^2 + 9n^2 F^2}$$

n' = quantum number which runs from $-(n-1)/2$, $-(n-3)/2$ to $(n-3)/2$, $(n-1)/2$
 γ = magnetic field in atomic units



Antihydrogen fall and detection



$$h = \frac{1}{2}gT^2 = \frac{g}{2} \left(\frac{L}{v_z} \right)^2$$

AEgIS realistic numbers:

- horizontal flight path $L \sim 1$ m
- horizontal velocity $v_z \sim 500$ m/s

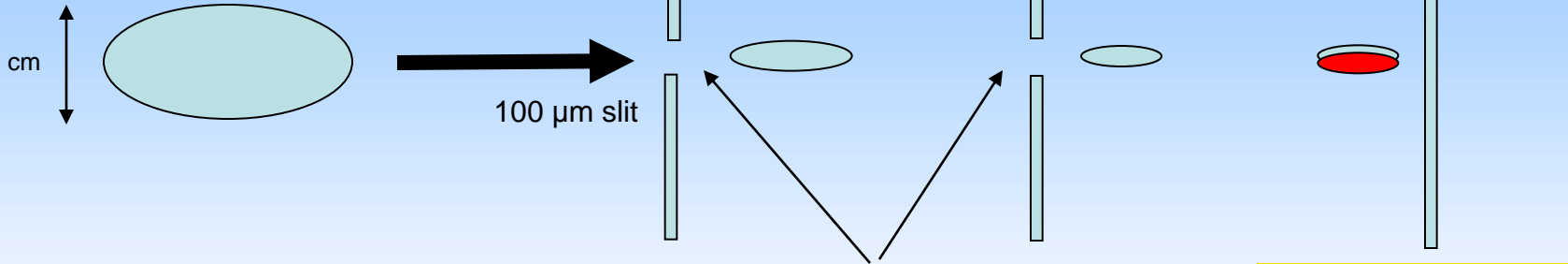


vertical deflection ~ 20 μm

- BUT:
- antihydrogen has a radial velocity (related to the temperature)
 - any anti-atom falls by $20 \mu\text{m}$, but, in addition it can go up or down by few cm
 - beam radial size after 1 m flight \sim several cm (poor beam collimation)

DISPLACEMENT DUE TO GRAVITY IS IMPOSSIBLE TO DETECT IN THIS WAY

Let us collimate!

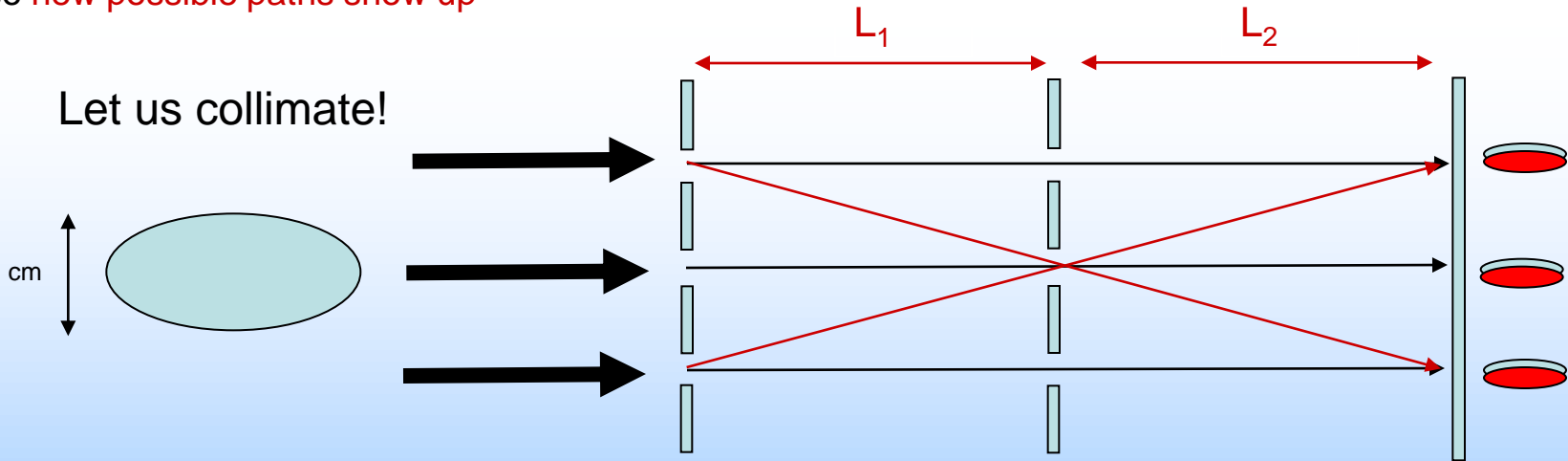


$$\frac{\Delta h}{h} \cong \frac{30 \mu m}{100 \mu m} = 0.3$$

Now displacement easily detectable. At the price of a huge loss in acceptance

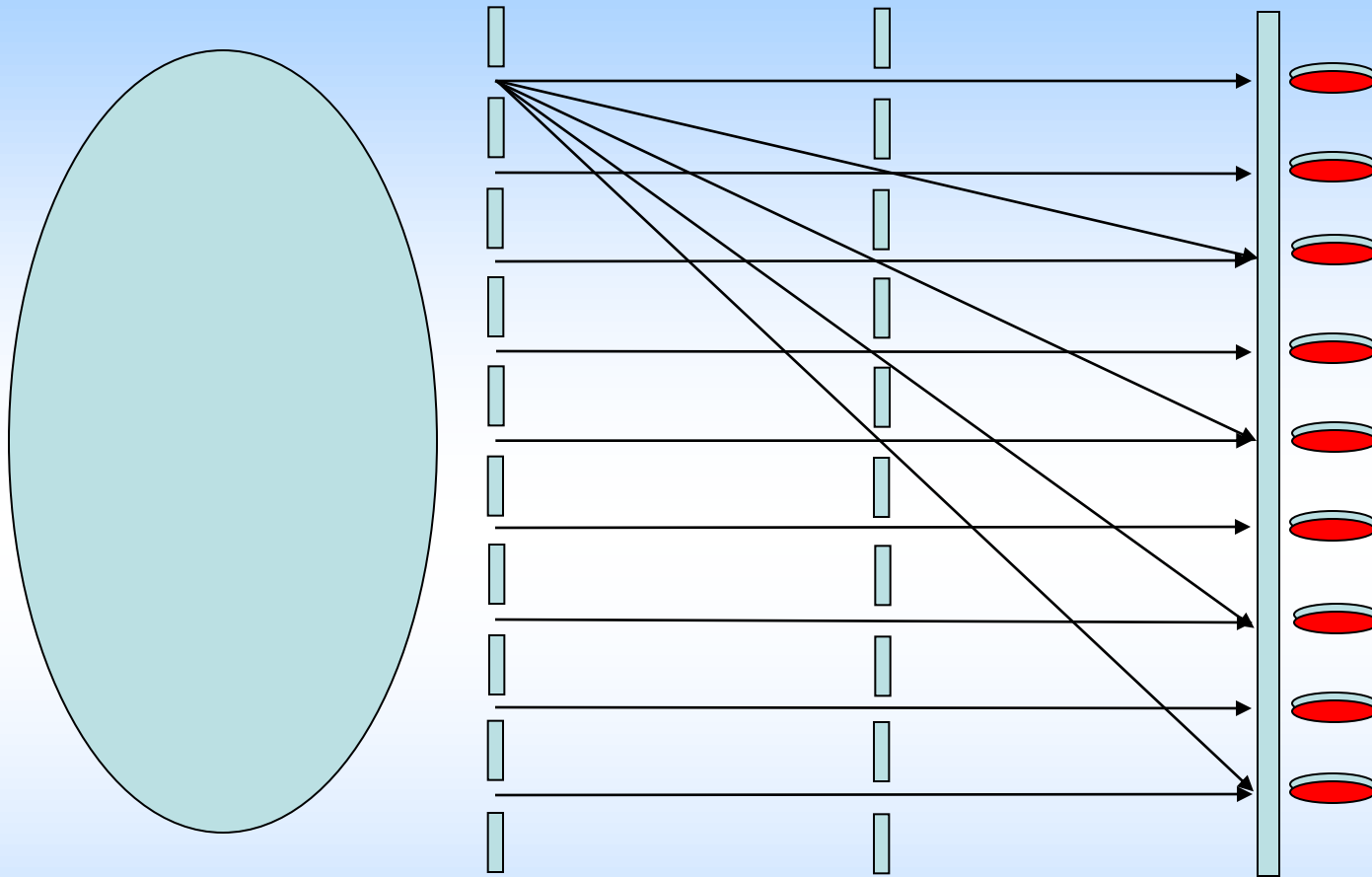
Acceptance can be increased by having several holes. In doing so **new possible paths show up**

Let us collimate!



If $L_1 = L_2$ the new paths add up to the previous information on the 3rd plane

Based on a totally geometric principle, the device is insensitive to a bad collimation of the incoming beam (which however will affect its acceptance)



Moiré Deflectometry is an [interferometry](#) technique, in which the object to be tested (either phase object or secular surface) is mounted in the course of a [collimated](#) beam followed by a pair of transmission gratings placed at a distance from each other. The resulting [fringe](#) pattern, i.e., the moiré deflectogram, is a map of ray deflections corresponding to the optical properties of the inspected object.

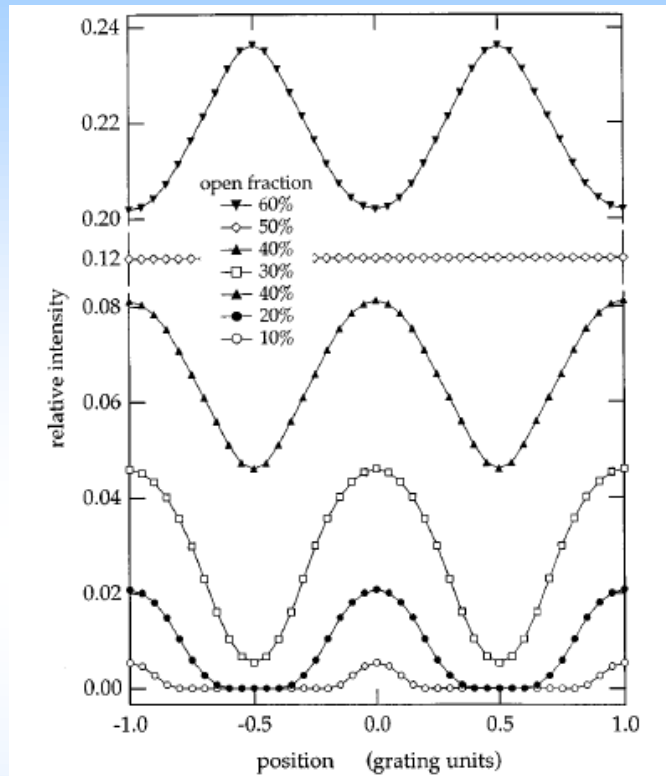


FIG. 2. Fringe patterns, as obtained by translating the third grating, calculated for various open fractions f_{open} of the gratings. For $f_{\text{open}} < 25\%$ the fringe pattern shows distinct peaks at the position of the shadow image. For $25\% < f_{\text{open}} < 50\%$ the fringes show an increasing constant background, and at $f_{\text{open}} = 50\%$ they vanish completely. For $f_{\text{open}} > 50\%$ the fringes reappear but are shifted by half a grating period (π fringe shift).

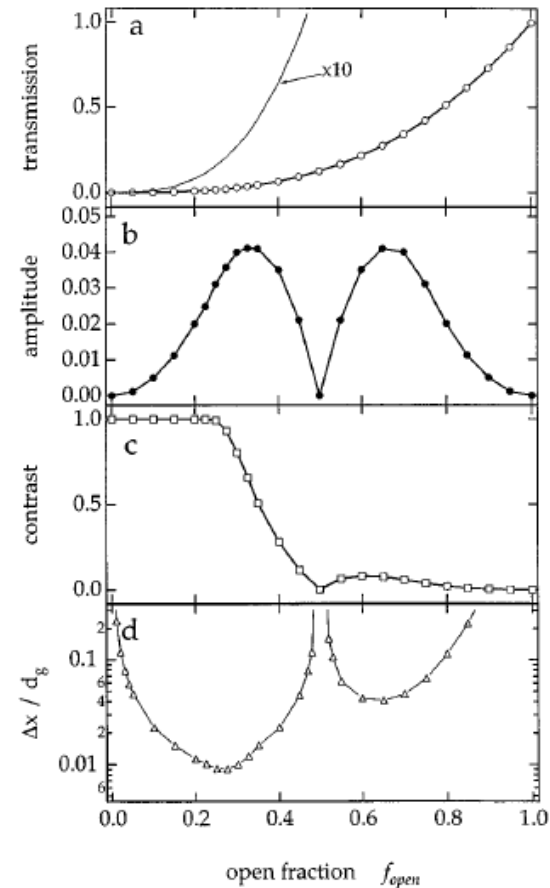
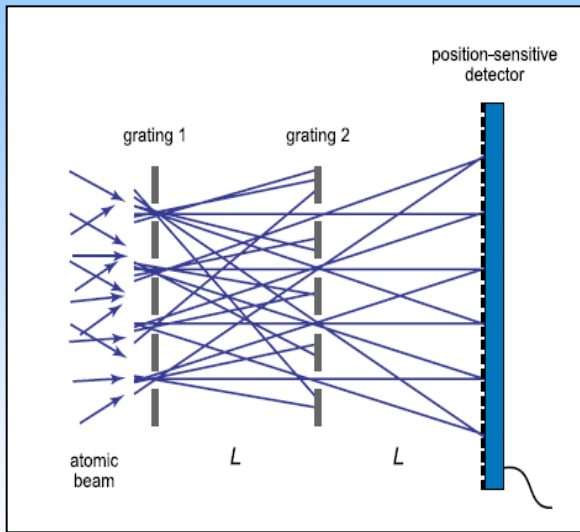


FIG. 3. Characteristic parameters of the Moiré deflectometer and their dependence on the open fraction f_{open} of the gratings. The top graph (a) shows the total transmission through the three-grating setup, (b) shows the amplitude of the obtained fringe pattern, and (c) the resulting contrast. The lowest graph (d) displays the minimal deflection in units of the grating period d_g that can be detected if 10 000 atoms impinge on the Moiré deflectometer.



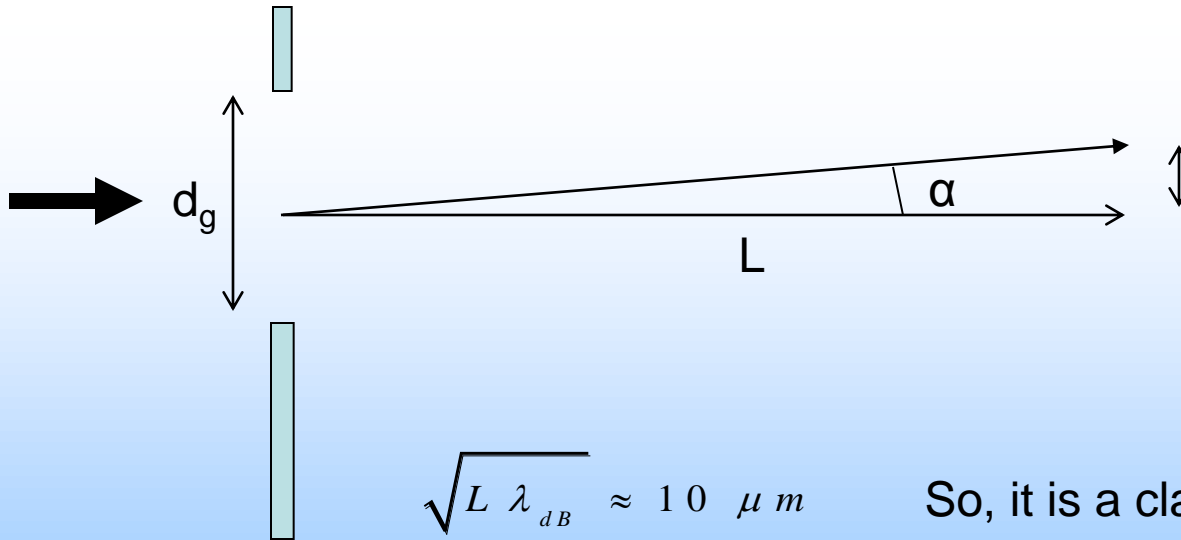
The final plane will be made of Silicon Strip detectors with a spatial resolution of about 10-15 μm

De Broglie wavelength of a 500 m/s H atom:

$$\lambda_{dB} = \frac{h}{mv} = \frac{2\pi}{c} 197 \text{ (MeV)} (10^{-15} \text{ m}) \frac{1}{940 \frac{\text{MeV}}{c^2} 500 \frac{\text{m}}{\text{s}}} = 8 \times 10^{-10} \text{ m}$$

$$L \lambda_{dB} = 0.3 \times 8 \times 10^{-10} \text{ m}^2 = 2.4 \times 10^{-10} \text{ m}^2$$

Now, this is NOT a quantum deflectometer, because:



$$p_y \cong \frac{h}{d_g} \quad \text{tg } \alpha \approx \frac{h}{d_g p}$$

$$L \frac{h}{d_g p} \ll d_g \quad L \frac{h}{p} \ll d_g^2$$

$$L \lambda_{dB} \ll d_g^2$$

$$\sqrt{L \lambda_{dB}} \approx 10 \mu\text{m}$$

So, it is a classical device if $d_g \gg 10 \mu\text{m}$

Collimation of the beam with a classical **Moiré** deflectometer

PHYSICAL REVIEW A

VOLUME 54, NUMBER 4

OCTOBER 1996

Inertial sensing with classical atomic beams

Markus K. Oberthaler, Stefan Bernet, Ernst M. Rasel, Jörg Schmiedmayer, and Anton Zeilinger
Institut für Experimentalphysik, Universität Innsbruck, Technikerstrasse 25 A-6020 Innsbruck, Austria

new position-sensitive detector
(to detect antihydrogen
annihilation)

upgraded version

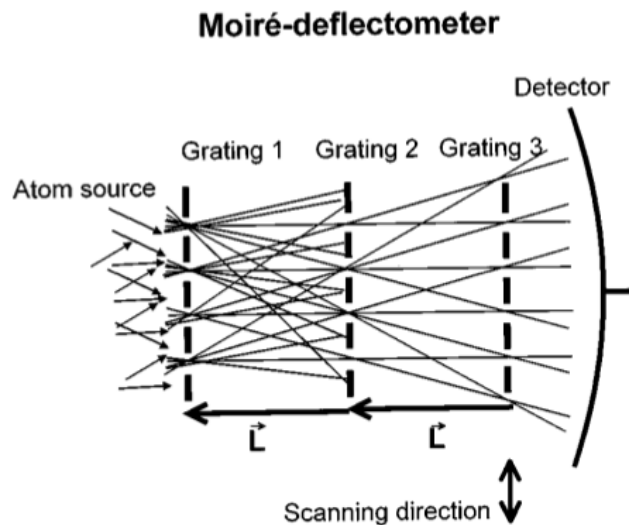
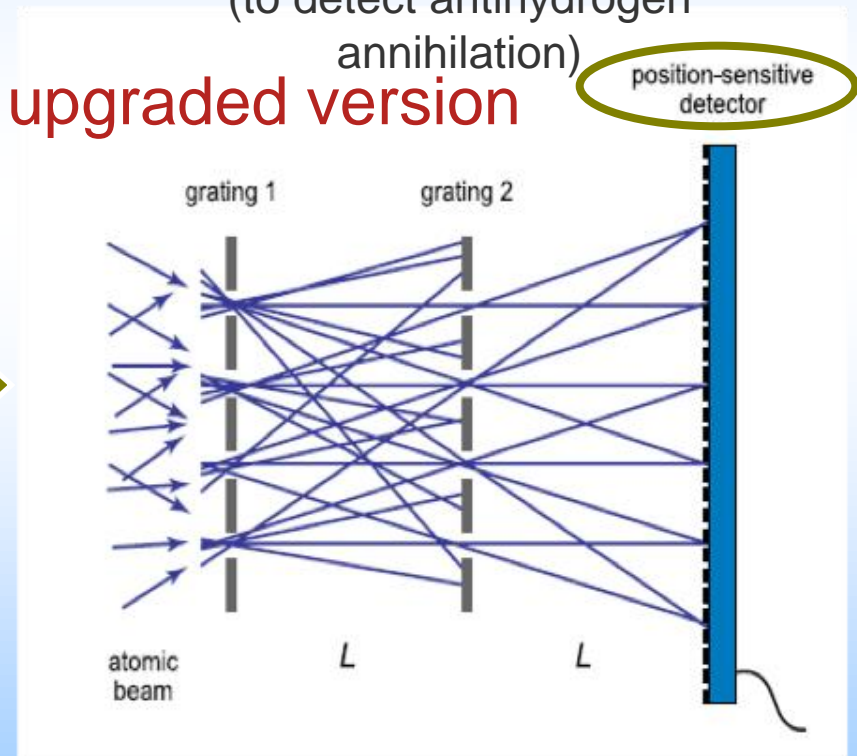
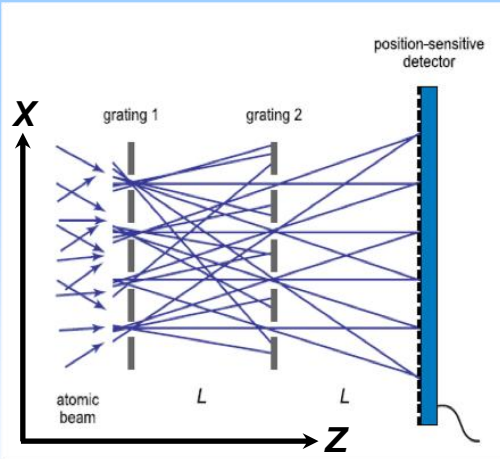


FIG. 1. Principle of a Moiré deflectometer. The first two identical gratings collimate the originally undirected atoms into various directions. After a distance L corresponding to the distance between the first two gratings, an image of the collimation gratings is formed. At this position, a third identical probe grating is placed. Its translation along the indicated direction leads to a periodic modulation of the transmitted intensity.



moiré
deflectometer



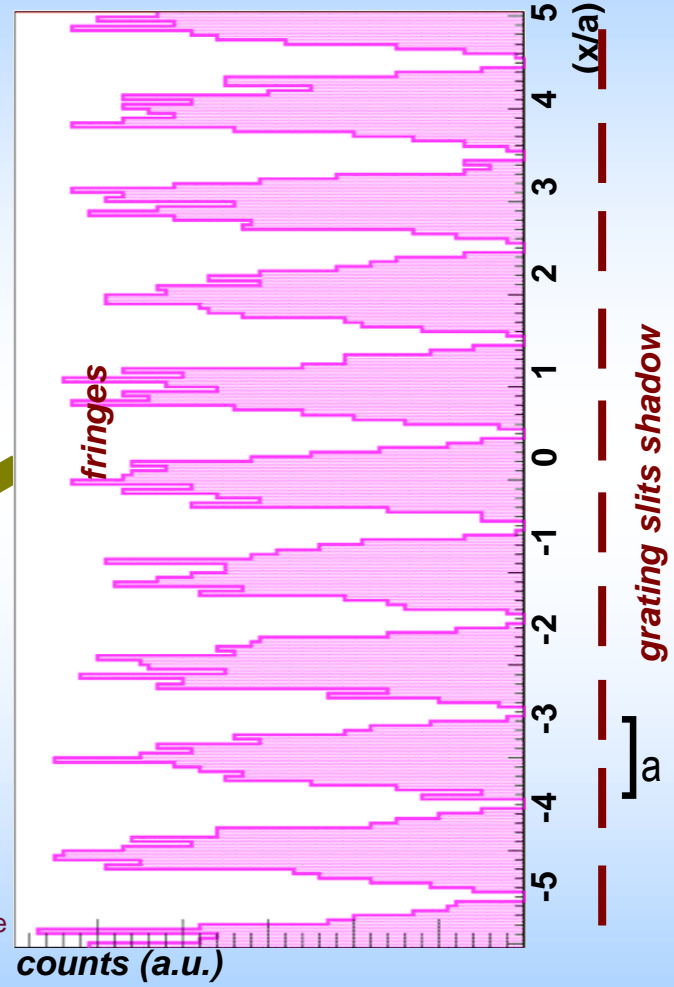
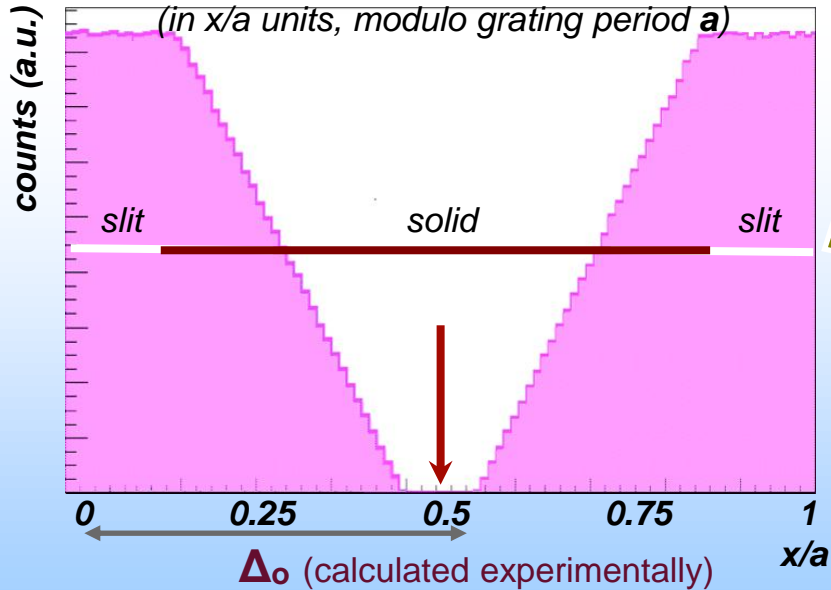
- Suppose:
- $L = 40$ cm
 - grating period $a = 80$ μm
 - grating size = 20 cm (2500 slits)
 - no gravity

Grating transparency = 30%
(total transmission 9%)

annihilation hit position on the final detector

Moiré deflectometer

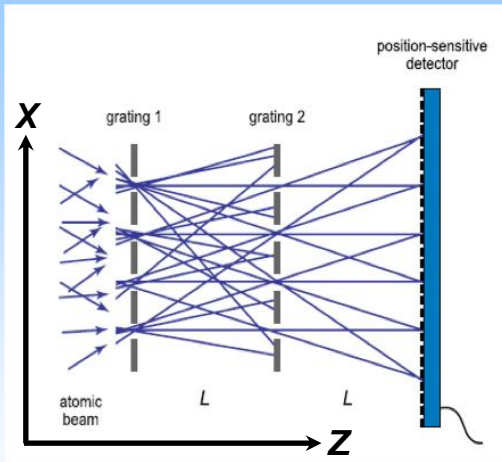
annihilation hit position on the final detector
(in x/a units)



depends on the alignment between the gratings, and on the alignment between them and the center of the antihydrogen cloud. It is independent to the radial antihydrogen velocity and profile

moiré
deflectometer

Moiré deflectometer



Suppose:

- $L = 40$ cm
- grating period $a = 80$ μm
- grating size = 20 cm (2500 slits)
- gravity

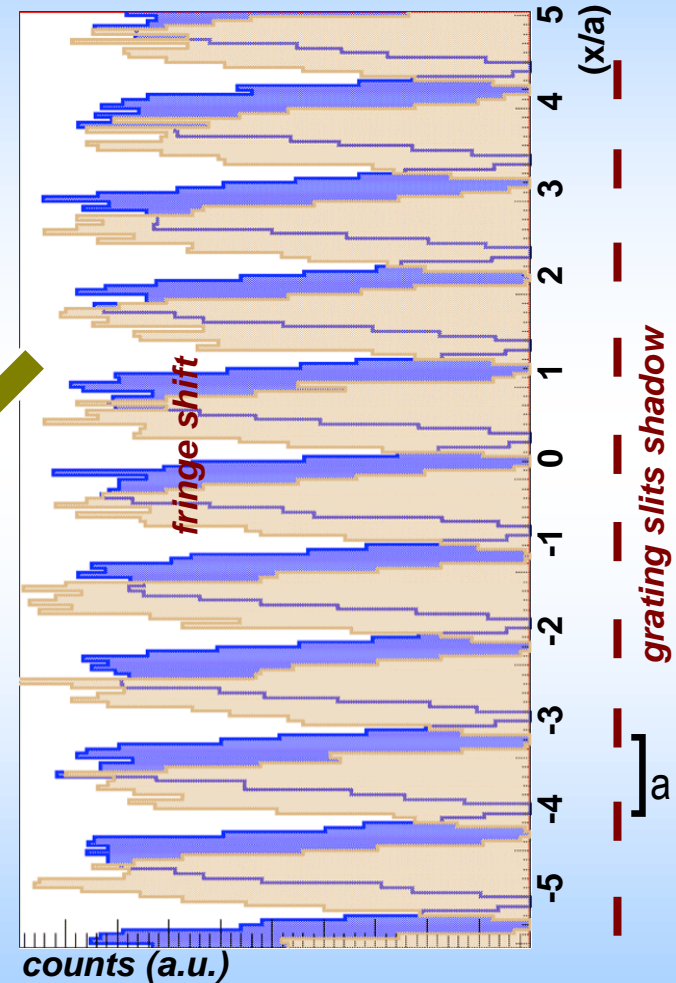
beam horizontal velocity

$v_z = 600$ m/s

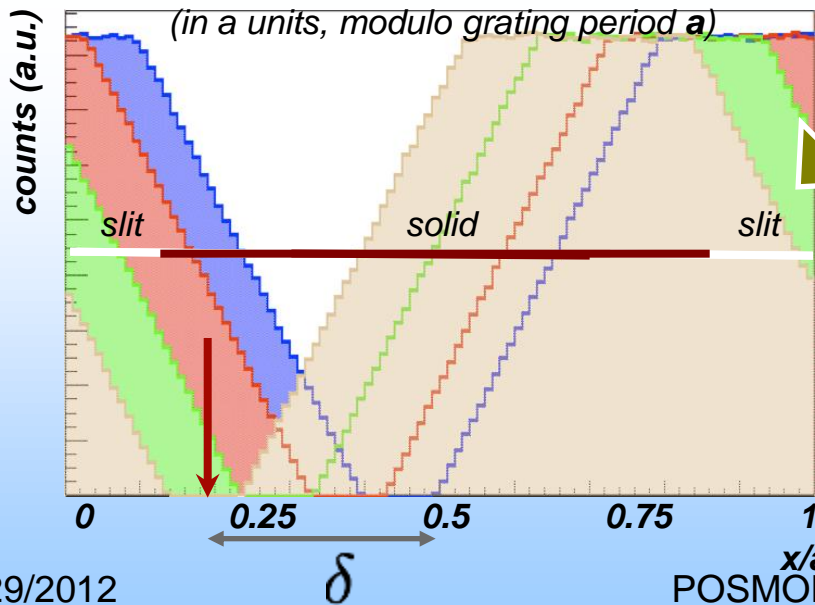
$v_z = 250$ m/s

Grating transparency = 30%
(total transmission 9%)

annihilation hit position on the final detector
(in a units)



annihilation hit position on the final detector
(in a units, modulo grating period a)



Fringe shift !

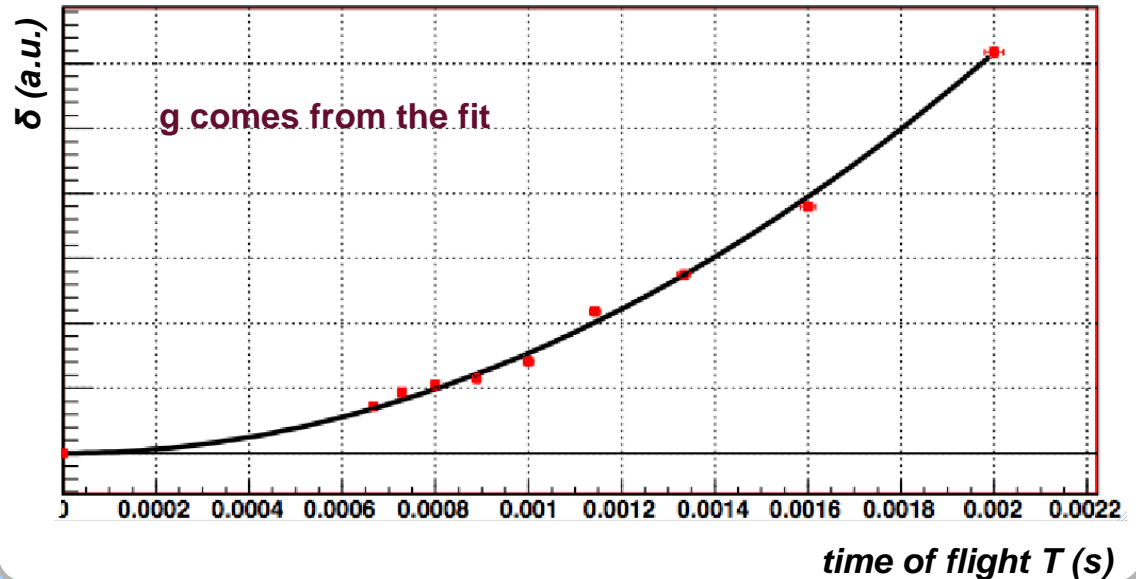
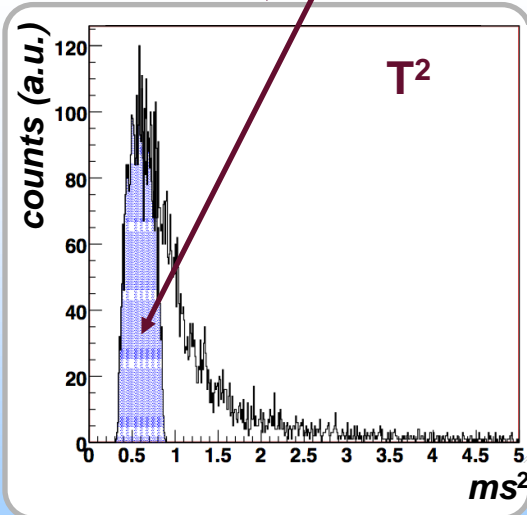
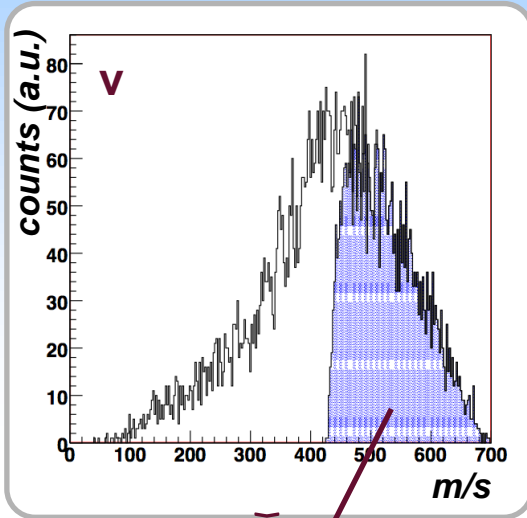
Moiré deflectometer

Out beam is not monochromatic
(T varies quite a lot)

$$\delta = \frac{gT^2}{a} \quad \text{fringe shift of the shadow image}$$

$$T = \text{time of flight} = [t_{\text{STARK}} - t_{\text{DET}}] \quad (L \sim 1 \text{ m}, v \sim 500 \text{ m/s} \Rightarrow T \sim 2 \text{ ms})$$

Binning antihydrogens with mean velocity of 600-550-500-450-400-350-300-250-200 m/s,
and plotting δ as a function of $\sqrt{\langle T^2 \rangle}$



Conclusions

AEGIS to develop a new “staged approach” to antimatter studies

Produce a beam of cold Antihydrogen starting from ultracold protons

Stark-effect accelerate Antihydrogen atoms

Let the beam fall in a Moire’ deflectometer

Measure the fringe shift and the arrival times on the final detector

Goal: 1% precision in the measurement of g for Antihydrogen

Experiment approved at CERN

...and by various funding agencies

Installation in experimental Hall began in 2010

Physics to begin in 2011/2012