The AEgIS experiment at CERN

Germano Bonomi [University of Brescia & INFN Pavia] on behalf of the AEgIS Collaboration

- Physics motivations
- The AEgIS experiment @ CERN
  - The measurement strategy
  - The experimental apparatus
- First results
- Conclusions

Physics motivations

Scientific goal

- The primary scientific goal of AEgIS is the direct measurement of the gravitational acceleration (g) on antihydrogen in the earth field [test of the WEP]

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

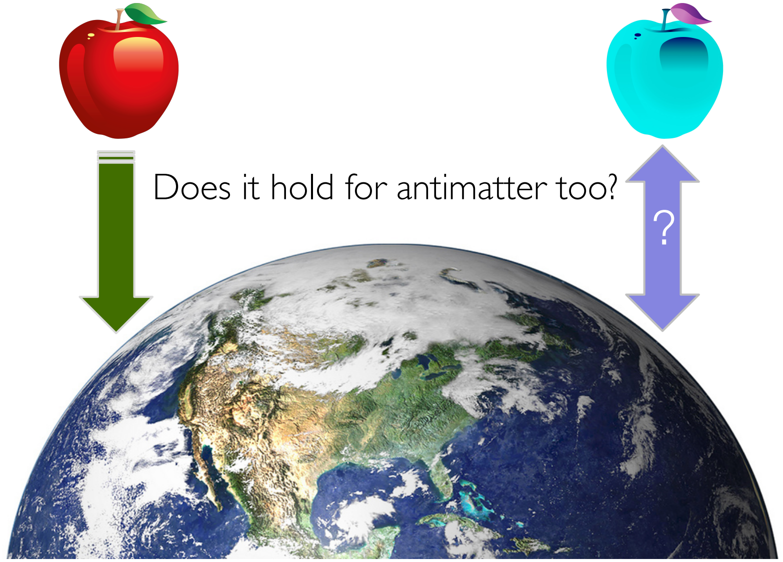
Weak equivalence principle (WEP) - Cornerstone of Einstein Theory of Relativity

$$m_i = m_g$$

Universality of free fall established by Galileo and Newton

- Unique behavior:

electric field:	gravitational field:
$\mathbf{F} = q \cdot \mathbf{E}$	$\mathbf{F} = m \cdot \mathbf{G}$
$\lvert\mathbf{E}\rvert \sim \frac{Q}{r^2}$	$\lvert\mathbf{G}\rvert \sim \frac{M}{r^2}$
$\lvert\mathbf{a}\rvert \sim q$	$\lvert\mathbf{a}\rvert \neq \mathcal{F}(m)\,,\; a = const.$



[Antimatter was discovered **after** Theory of Relativity]

- Long term goal (phase 2): test of CPT (anti-hydrogen spectroscopy)

WEP for antimatter: why to test it

- Our attempts for a quantum theory of gravity typically result into new interactions which may violate the WEP (ex. **Kaluza-Klein theory**)
  Int. J. Mod. Phys. D18, 251–273 (2009)
- Some open questions (like **dark matter** and **baryogenesis**) could benefit from a direct measurement
  Astrophys. Space Sci. 334, 219–223 (2011)
  JHEP 1502, 076 (2015)
- Some studies explicitly talk about "anti-gravity"
  G. Chardin - **Phys.Lett. B282 (1992) 256-262**
- Even if WEP is widely expected to hold for antimatter, a violation *is not a-priori excluded* and more importantly … no direct measurement is available …

- Previous attempts:
  - **1967**: **Fairbank** and **Witteborn** tried to use positrons
    Phys. Rev. Lett. 19, 1049 (1967)
  - **1989**: PS-200 experiment at CERN tried to use (4 K) antiprotons
    Nucl. Instr. and Meth. B, 485 (1989)
  - Both **unsuccessful** because of stray E and B fields

    Higher precision **is reachable** with neutral antimatter
  - **2013**: ALPHA experiment at CERN set limit on m_g/m_i for $\overline{\text{H}}$
    Nature Communications 4, 1785 (2013)

    $m_g/m_i > 110$ excluded at 95% CL

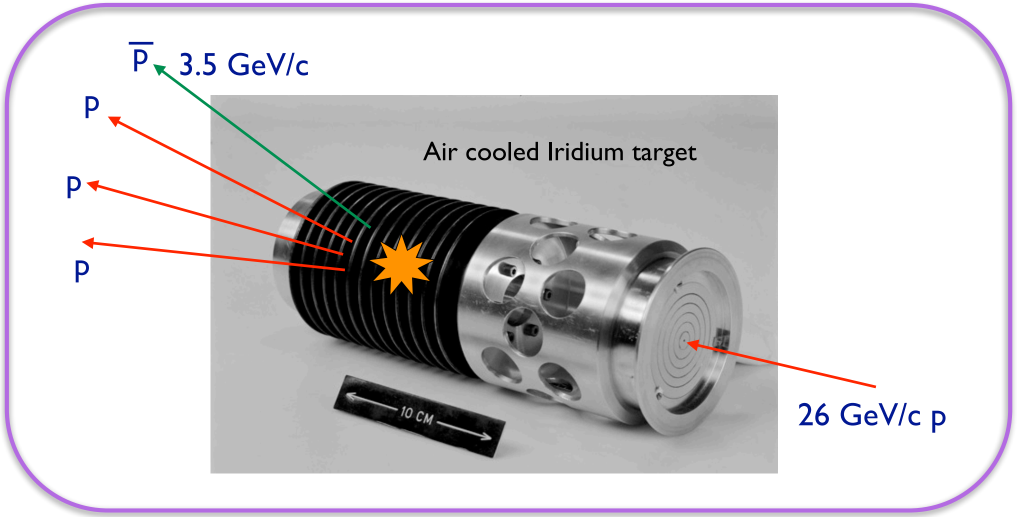
The AEgIS experiment @ CERN

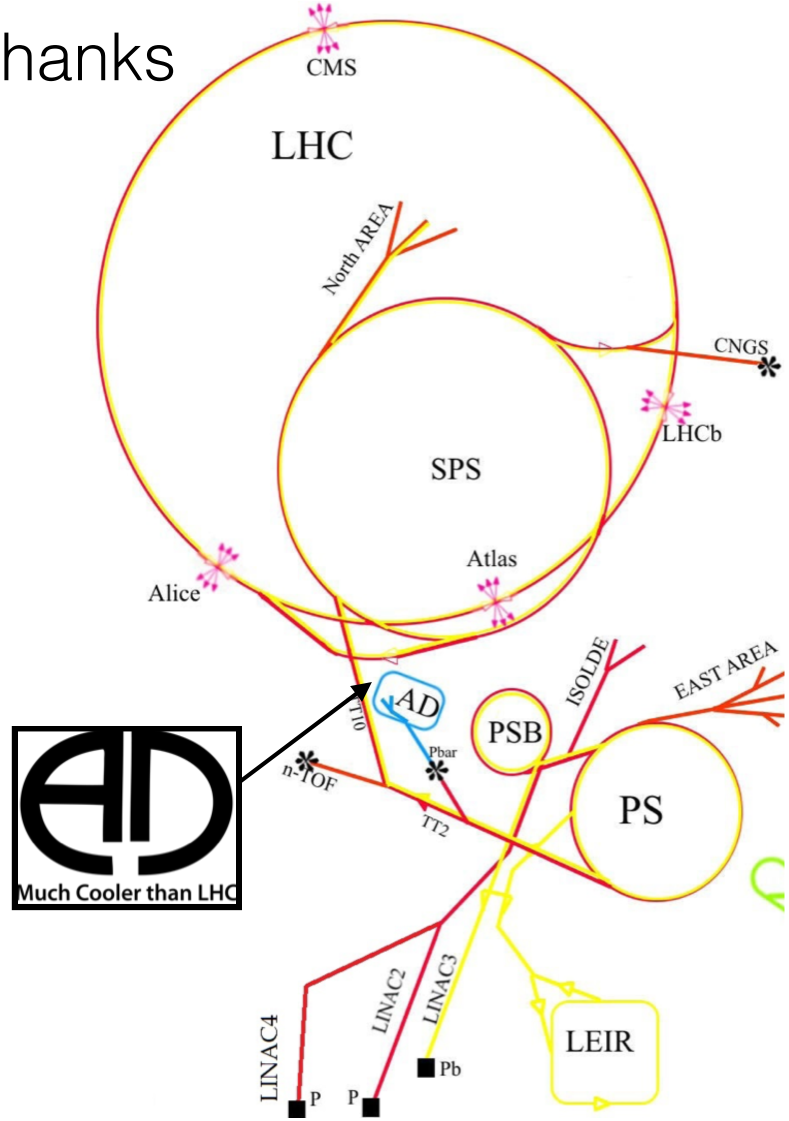
The Antiproton Decelerator (AD - Antimatter factory @ CERN)

- At CERN antimatter studies are possible thanks to the **Antiproton Decelerator (AD)**

- 26 GeV/c p from PS used to produced $\bar{p}$

  (~10^{13} p per bunch -> ~ 10^{7} $\bar{p}$ per bunch)

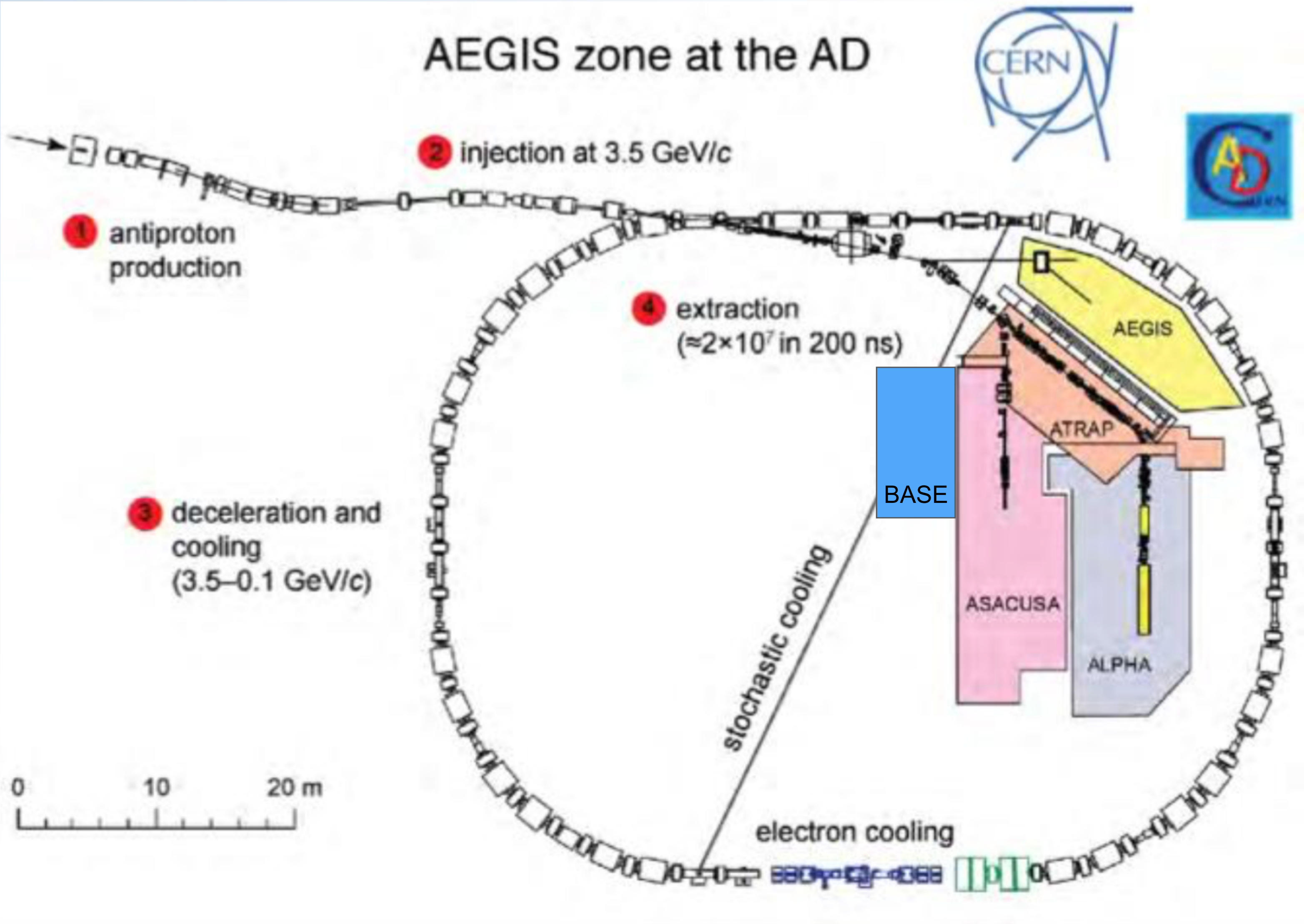


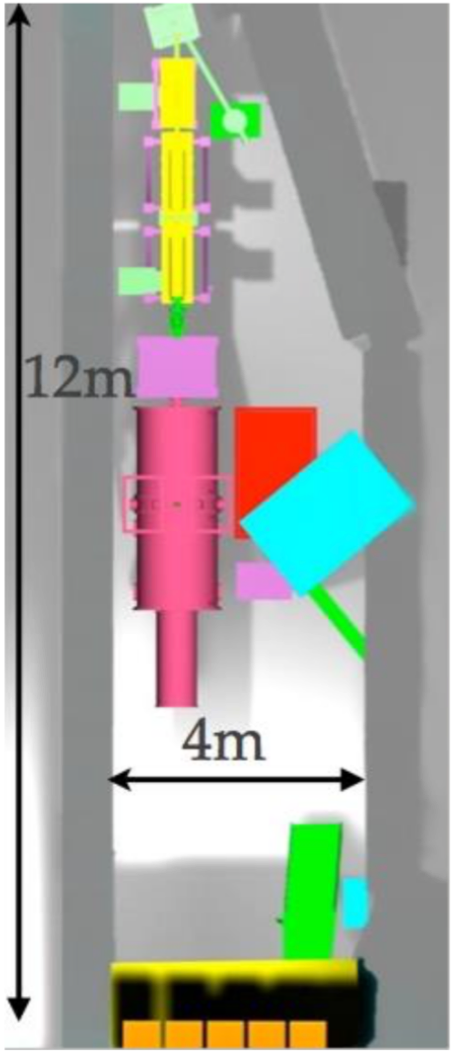


- AD slows down $\bar{p}$ to ~100 MeV/c in a 100 s cycle

- Approximately 3 x 10^{7} $\bar{p}$ delivered each cycle to the experiments

The Antiproton Decelerator (AD - Antimatter factory @ CERN)

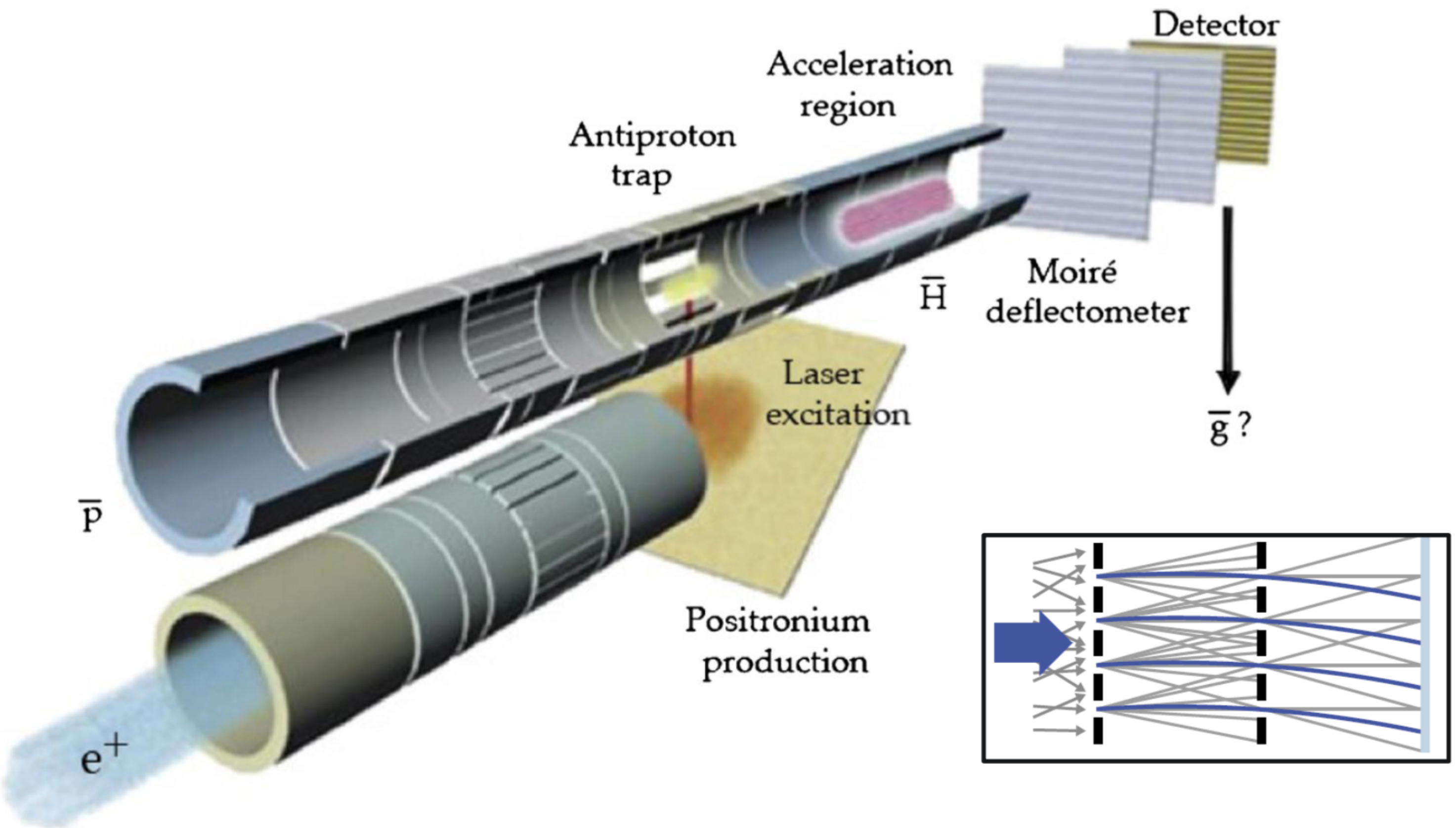




AEgIS measurement procedure

- AEgIS measurement overview

- Produce a beam of antihydrogen, let it fly and measure its "fall" [see details below]



- It would be the first precise (few %) direct measurement for antimatter -> with no theoretical assumptions

AEgIS measurement procedure

Capture of antiprotons from the CERN-AD

Cooling of the trapped antiprotons

Positronium (e^+e^-) production by e^+ on SiO_2

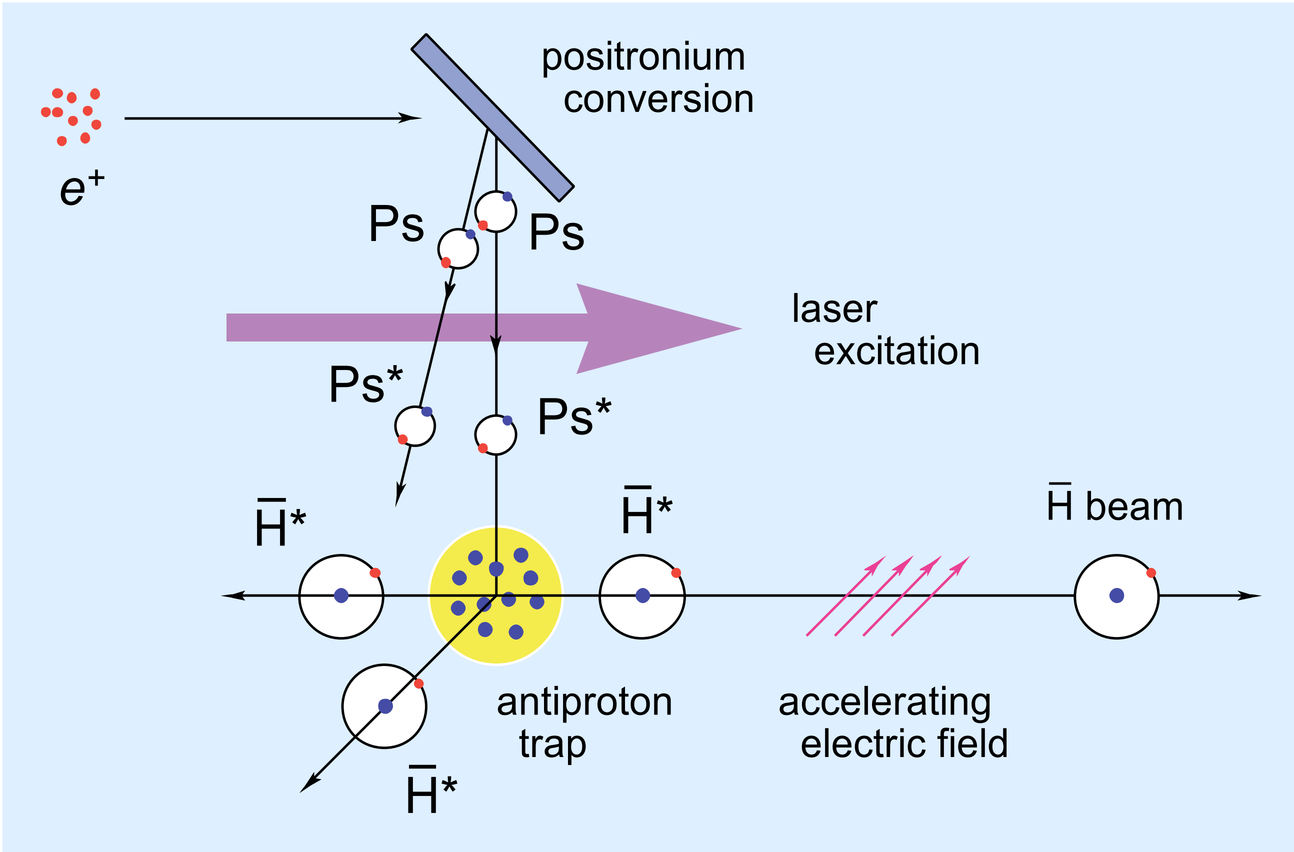
Ps laser excitation to Rydberg state

Interaction of Ps* with the antiproton cloud

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

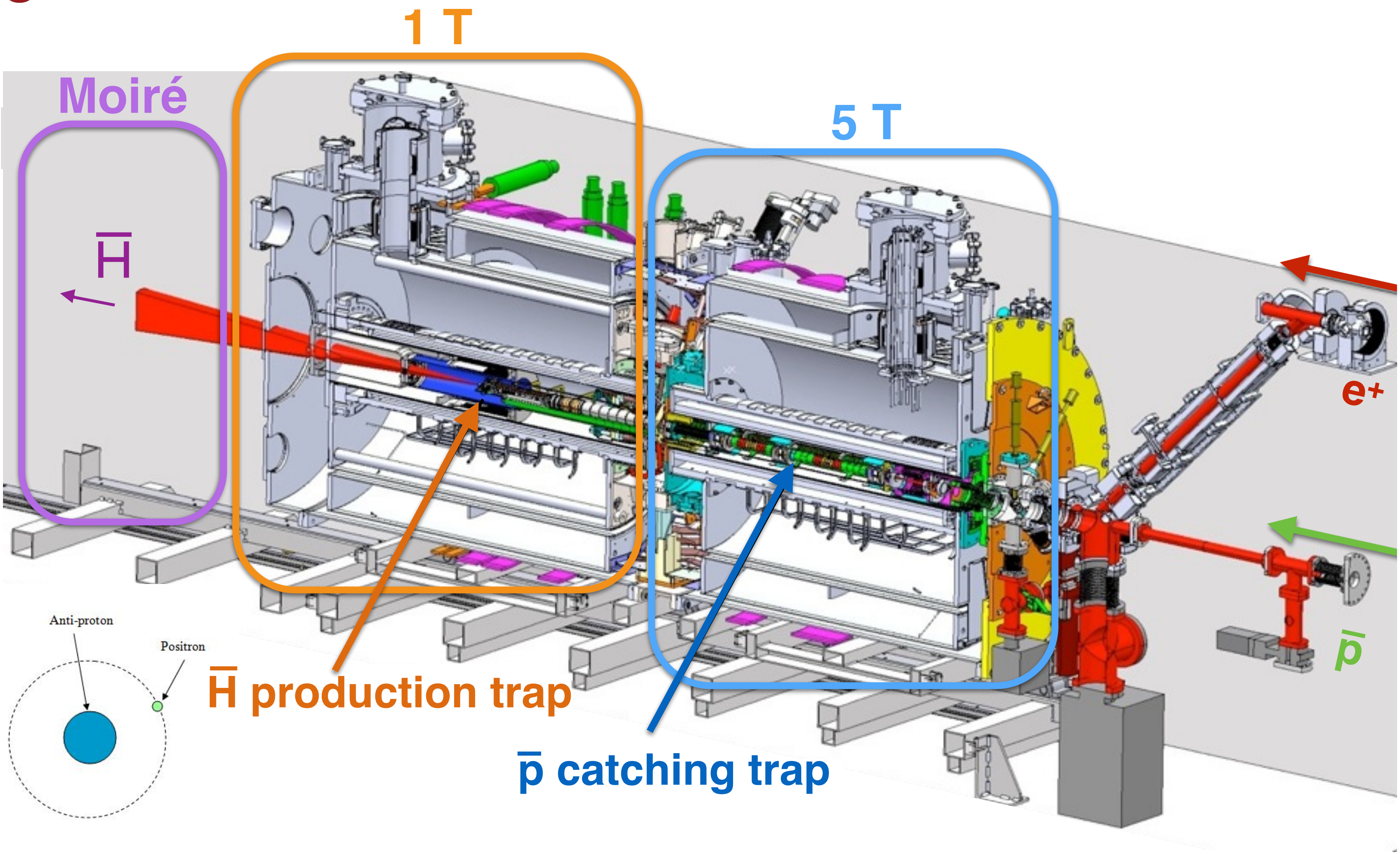
Positronium charge exchange reaction
[*same charge exchange reaction with a similar technique based on Rydberg cesium performed by ATRAP C. Storry et al., Phys. Rev. Lett. 93 (2004) 263401*]

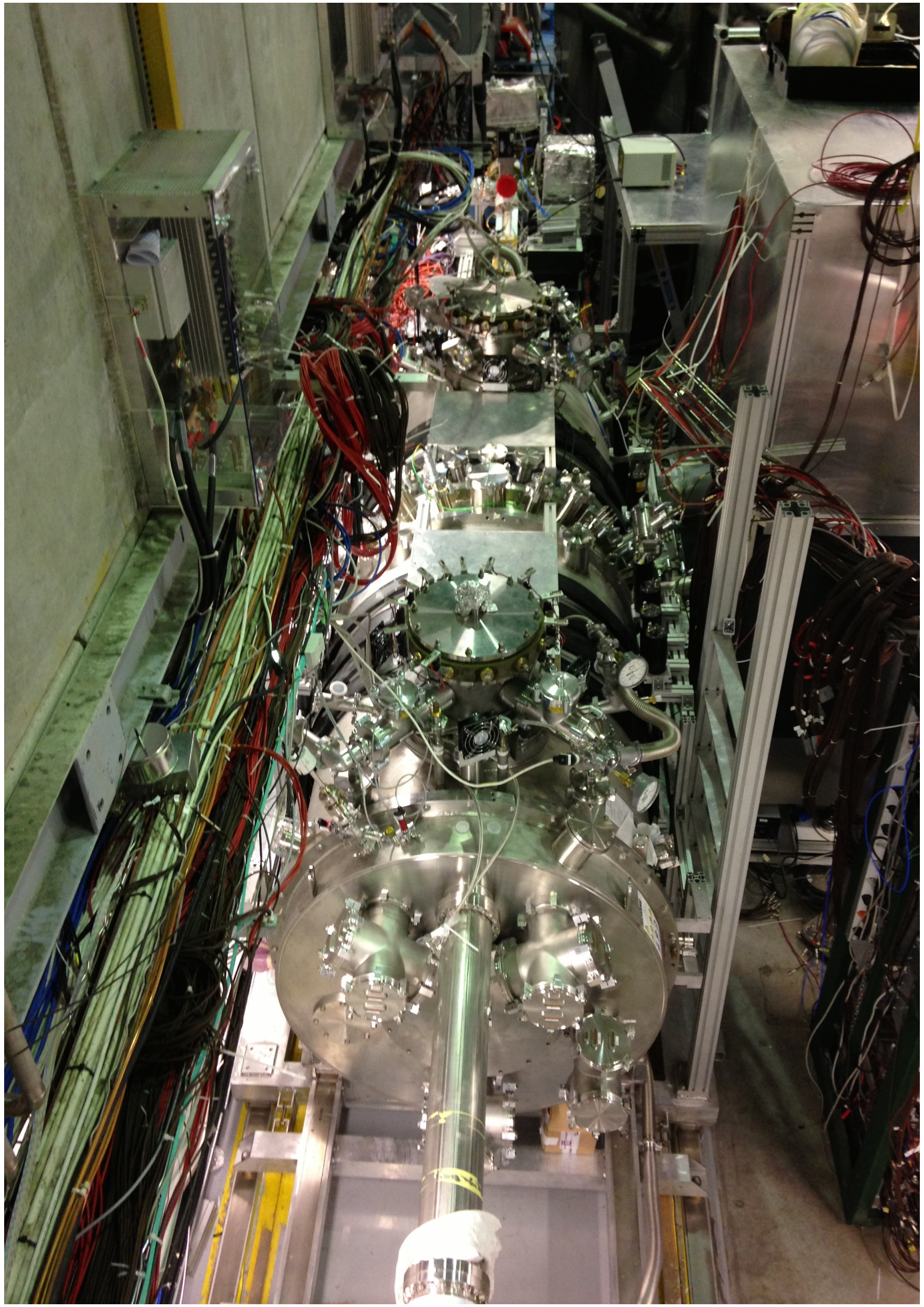
ADVANTAGES
- Large cross section $\sigma \propto (n_{Ps})^4$
- Narrow and well defined band of final states ($n_H \approx \sqrt{2}n_{Ps}$, with a rms of few units)

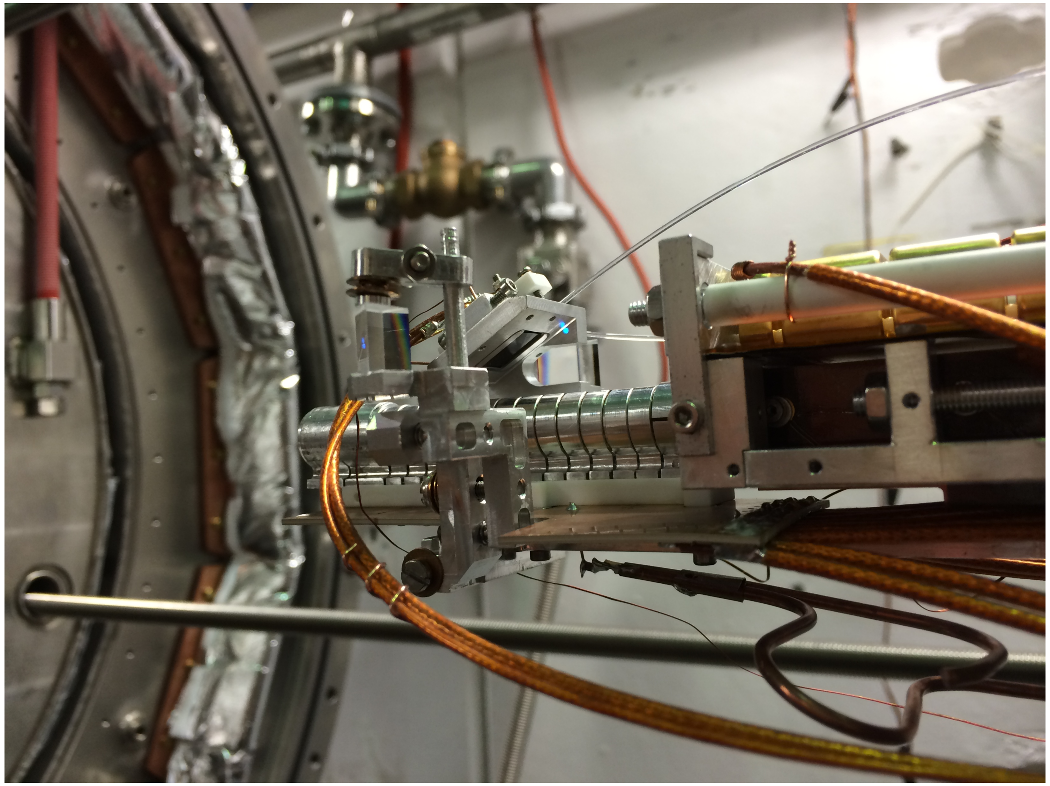


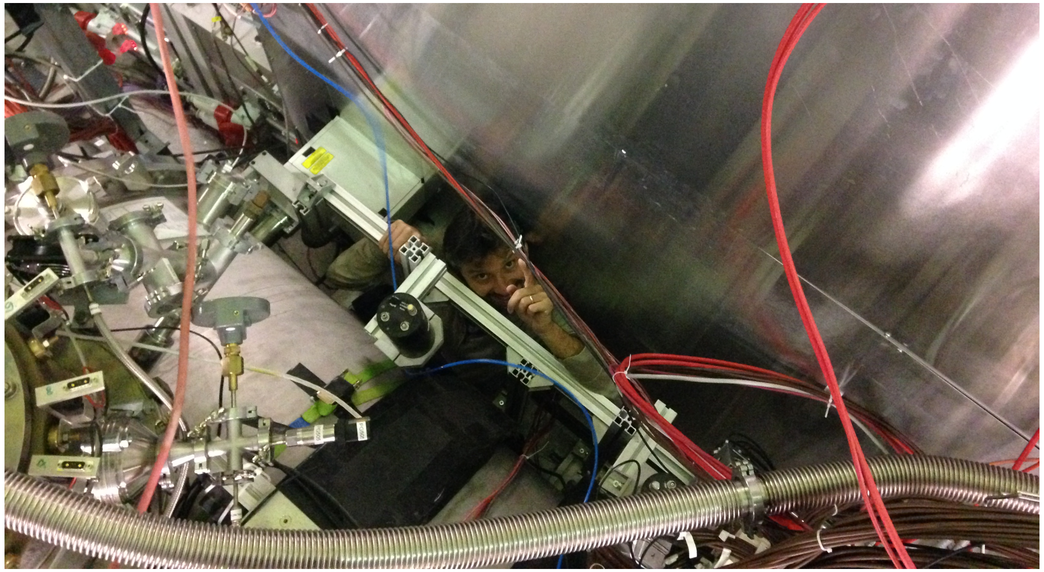
Antihydrogen is then accelerated and fly toward a "moiré deflectometer"

the AEgIS apparatus









First (preparatory) results

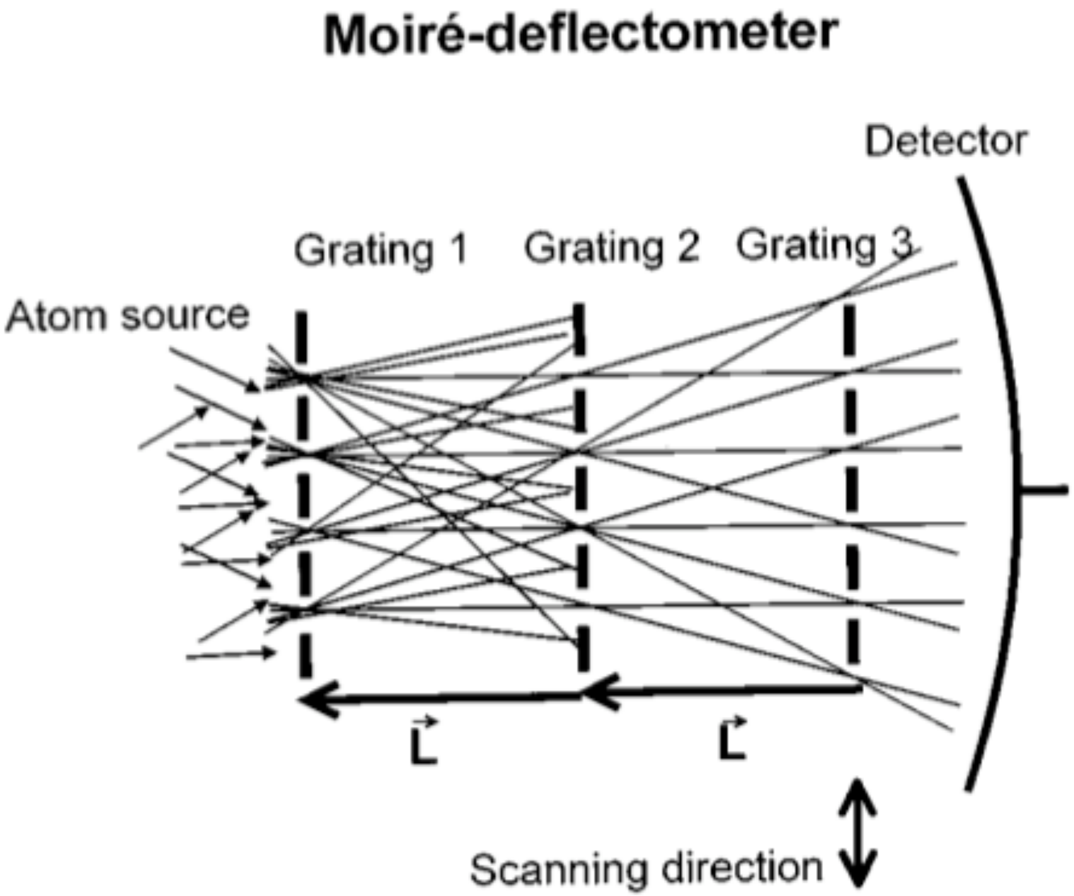
- Fall measurement proof of principle
- Ps production & excitation
- Antiprotons manipulation

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



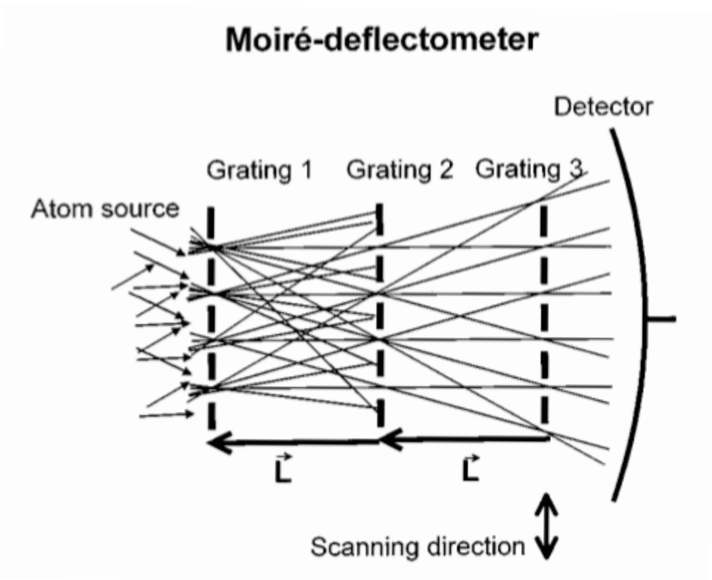
Moiré deflectometer

HOW DOES IT WORK?

Text from Oberthaler work: *Phys. Rev. A 54 (1996), 3165*

Our Moiré deflectometer is based on geometric propagation of an atomic (or molecular) beam through a set of three identical gratings. Accelerated movements of the gratings with respect to the atomic beam result in a change of the total transmitted intensity. The device is nondispersive, i.e., atoms with a broad energy distribution and without collimation can be used.

purely "classical"



Behind the first two gratings the atoms are distributed in a shadow image forming sets of fringes, very similar to an atom interferometer, at various distances from the second grating.

If such a device is in accelerated motion a fringe shift of the shadow image results.

II. THE MOIRÉ DEFLECTOMETER

A schematic sketch of our Moiré-imaging setup is shown in Fig. 1. It consists of three material gratings which are equally spaced and aligned parallel to each other. An atomic beam passes the three gratings successively. The first two gratings select propagation directions of an originally diverging atomic beam in such a way, that an atomic density modulation is created at the position of the third grating. This modulation corresponds to an image of the collimation gratings. Such an imaging is a characteristic self-focusing feature of any two-grating setup. It can be explained by drawing the geometric paths of an undirected beam through the grating slits, as shown in Fig. 1. The illustration shows, that in the plane of the third grating all atomic trajectories which are selected by the slits of the first two gratings are intersecting and forming a periodic atomic density modulation with the gratings periodicity. Due to geometric ray optics such an imaging appears periodically at those distances from the second grating which correspond to integer multiples of the distance between the first two gratings.

Moiré deflectometer

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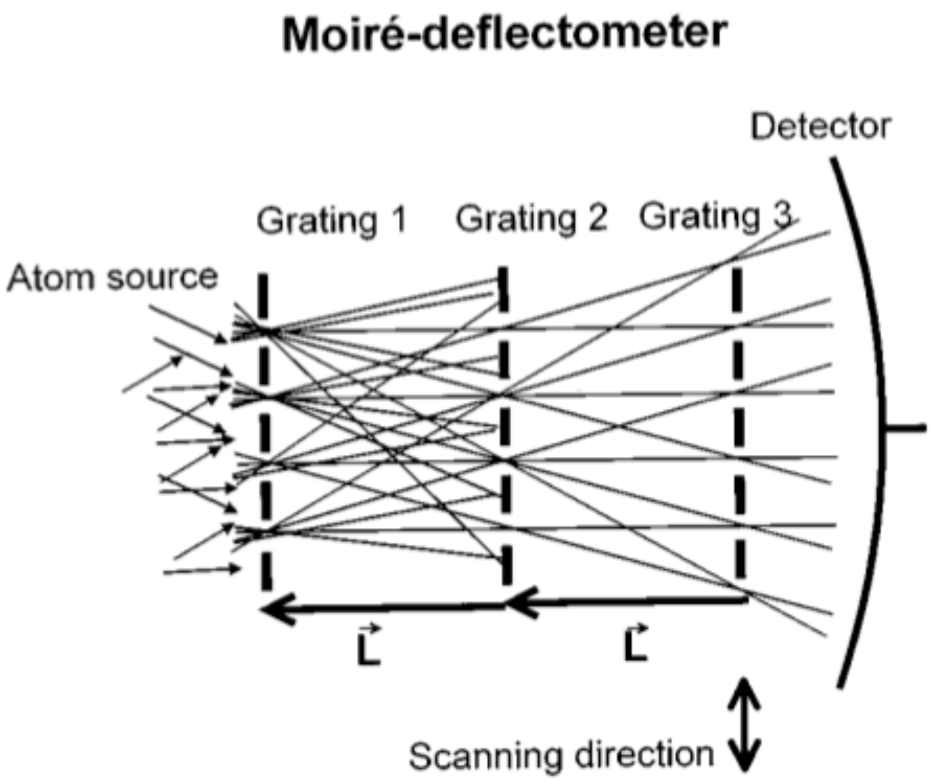
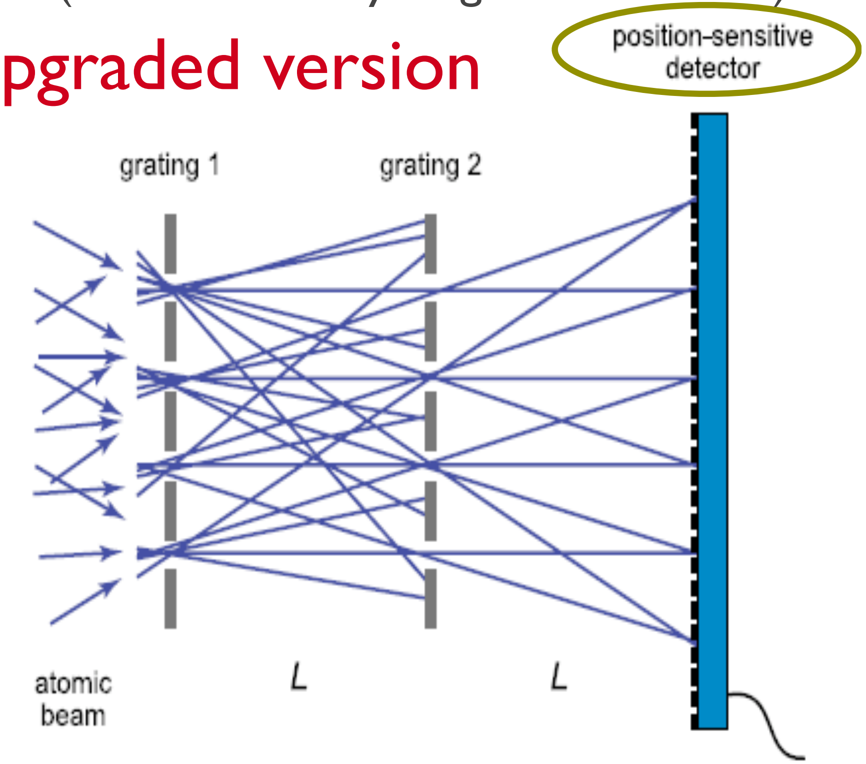
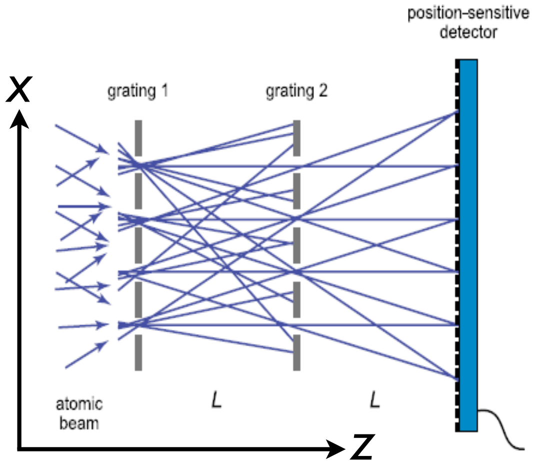


new position-sensitive detector
(to detect antihydrogen annihilation)

upgraded version



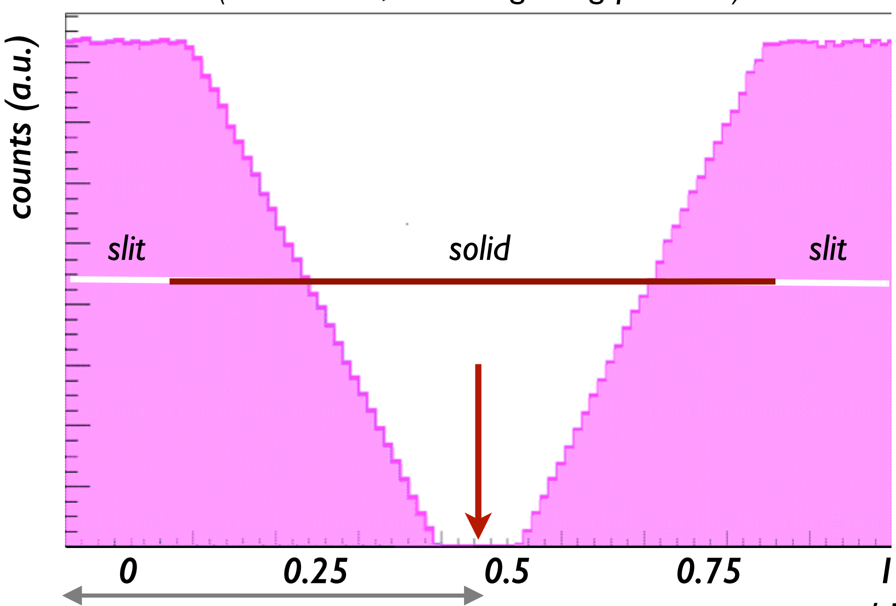
Moiré deflectometer



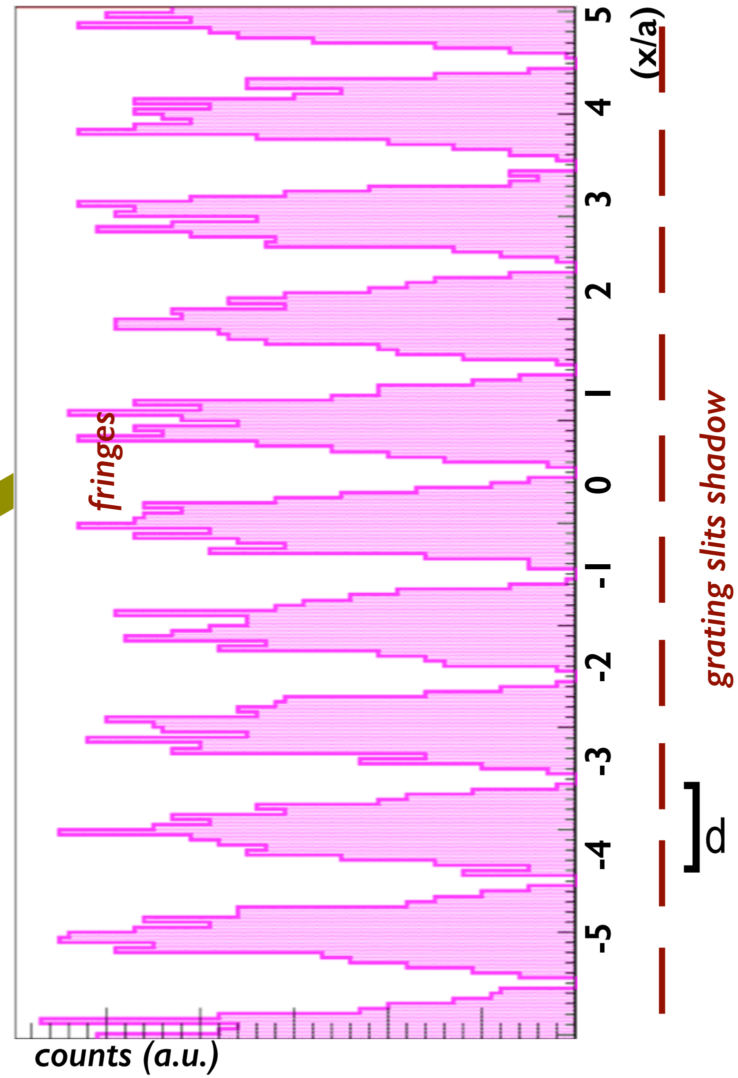
Suppose:
- L = 40 cm
- grating period d = 80 μm
- grating size = 20 cm (2500 slits)
- no gravity

Grating transparency = 30%
(total transmission 9%)

annihilation hit position on the final detector
*(in x/d units, modulo grating period **d**)*

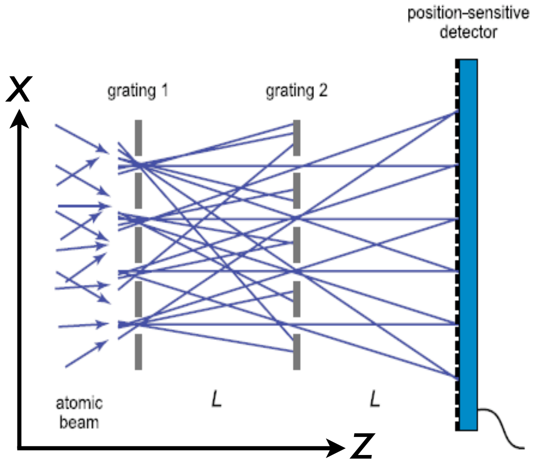


annihilation hit position on the final detector
(in x/d units)



Δ_0 (calculated experimentally) 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

M o i r é deflectometer

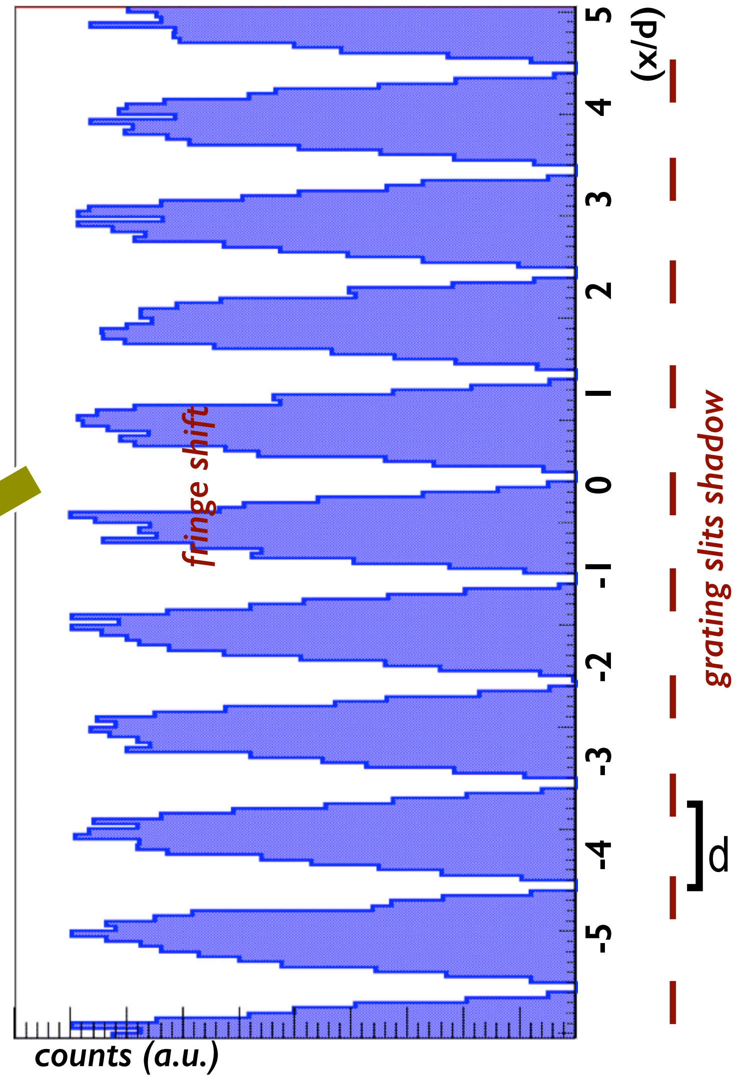


Suppose:
- L = 40 cm
- grating period d = 80 μm
- grating size = 20 cm (2500 slits)
- gravity (g)

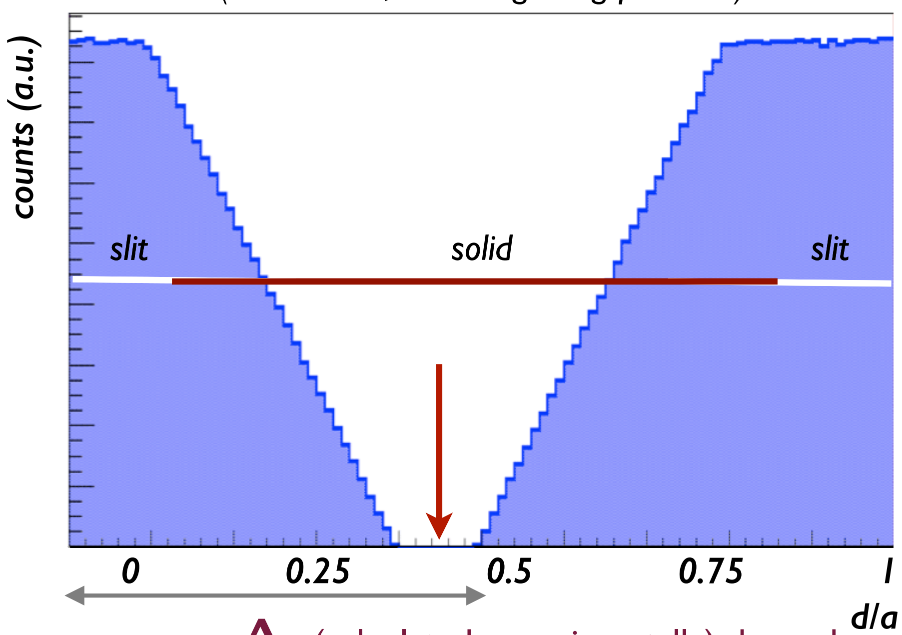
beam horizontal velocity
v_z = 600 m/s

Grating transparency = 30%
(total transmission 9%)

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



annihilation hit position on the final detector
*(in x/d units, modulo grating period **d**)*



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First (preparatory) results

- Fall measurement proof of principle
- Ps production & excitation
- Antiprotons manipulation

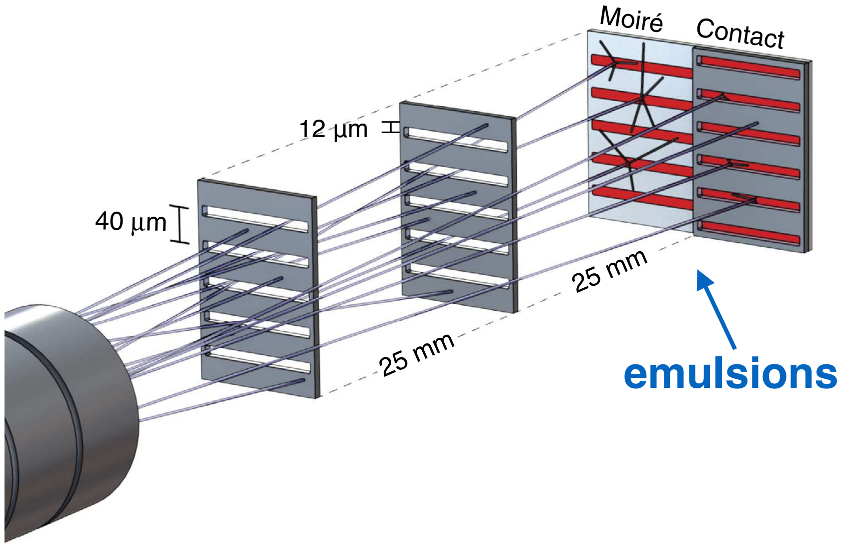
gravity measurement proof of principle

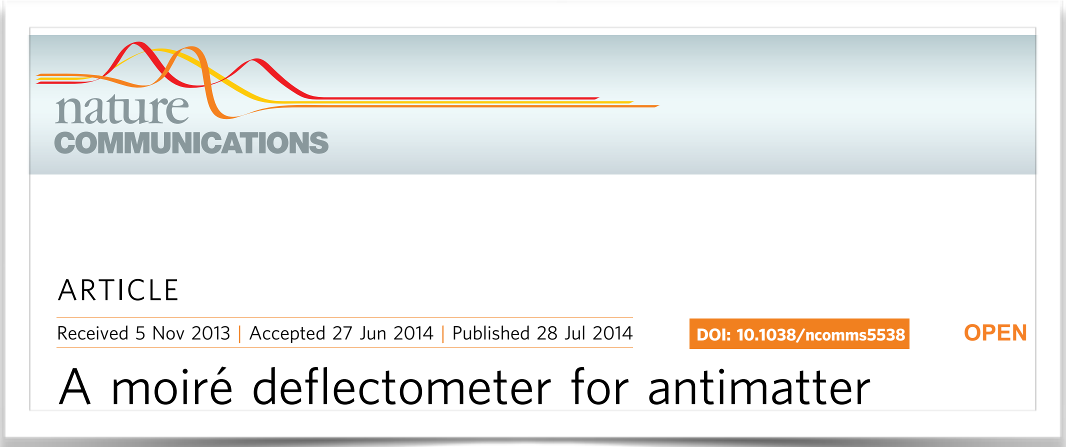
AEgIS experiment is taking data ($\overline{H}$ production expected in 2017)

Small-scale test of the moiré deflectometer with $\overline{p}$ was performed

Mini-moiré deflectometer

- distance 25 mm
- slit 12 μm, pitch 40 μm, 100 μm thick
- pbar beam E~(100±150) keV
- light reference: Talbot-Lau
- emulsion detector

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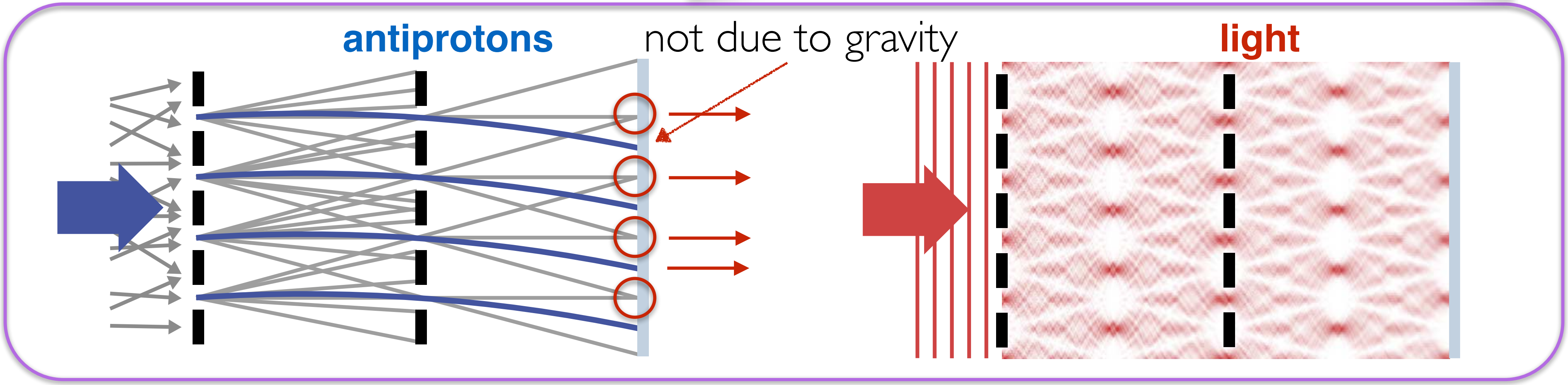
ARTICLE

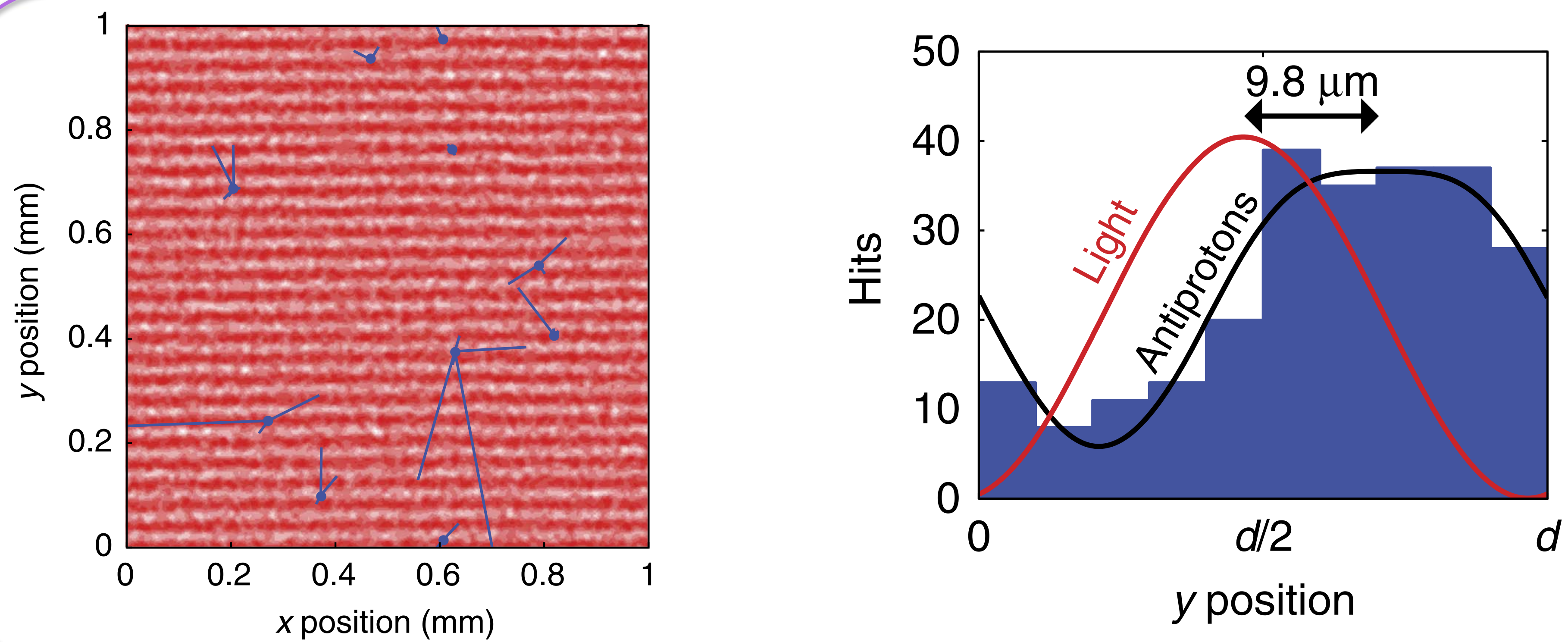
Received 5 Nov 2013 | Accepted 27 Jun 2014 | Published 28 Jul 2014
DOI: 10.1038/ncomms5538
OPEN

A moiré deflectometer for antimatter



gravity measurement proof of principle

- 146 antiprotons recorded (emulsion detector with 1-2 um resolution!)



$$\Delta y = 9.8 \pm 0.9(\text{stat}) \pm 6.4(\text{syst})\ \mu m$$

- $F = 530 \pm 50\,\text{aN}\ (\text{stat.}) \pm 350\,\text{aN}\ (\text{syst.})$
- consistent with a B ~ 7.4 G

B ~ 10 G measured at the moiré position

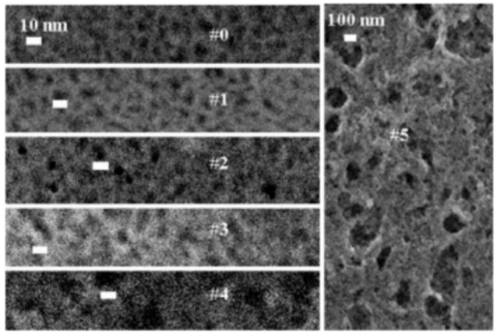
First (preparatory) results

- Fall measurement proof of principle
- **Ps production & excitation**
- Antiprotons manipulation

positronium production

Positronium (Ps) production by implanting e+ in a nanochanneled Si target

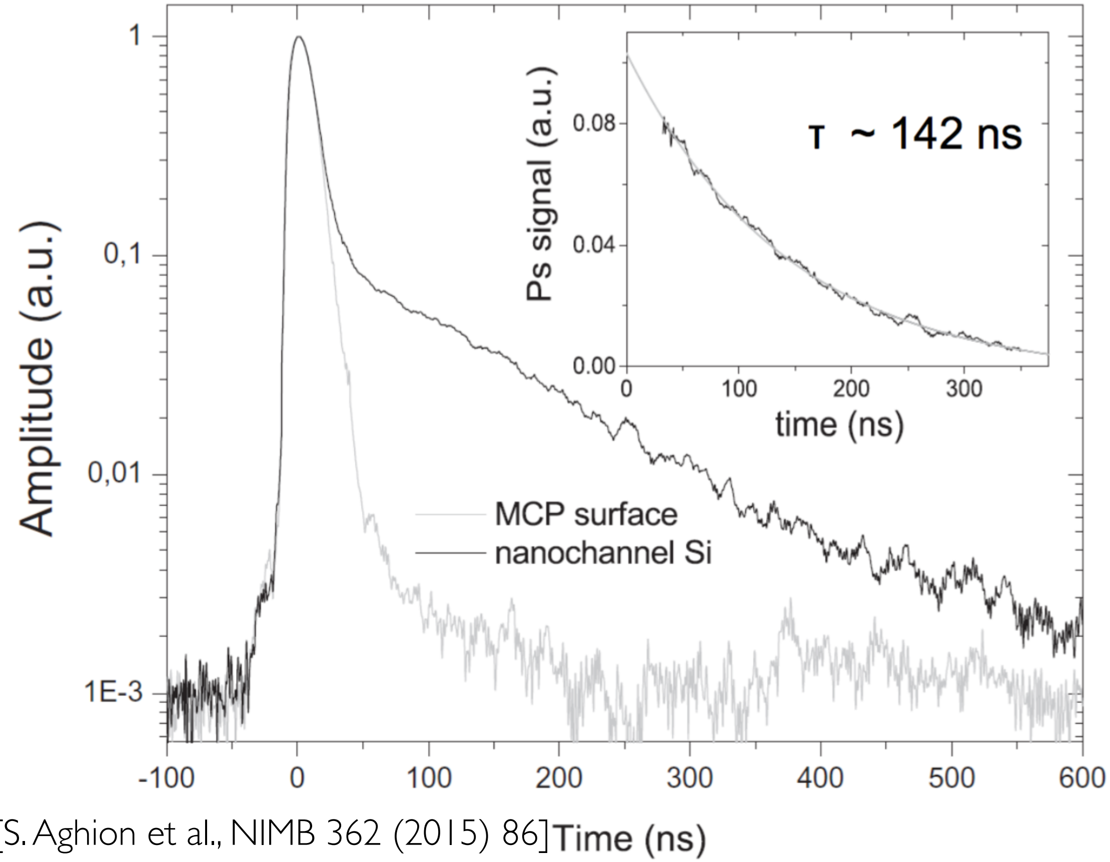
e^+/Ps converter



nanochanneled Si
(5-100 nm range, depth 2 um)

[S. Mariazzi et al., Phys. Rev. B 81 (2010) 235481]

4×10^6 Ps atoms in vacuum



[S. Aghion et al., NIMB 362 (2015) 86]

Single Shot Positron Annihilation Lifetime Spectroscopy (SSPALS) measurement
[D. B. Cassidy et al. NIMB 508 (2007) 1338]

Positrons impinging:
(a) passive surface (MCP)
(b) nanochanneled Si

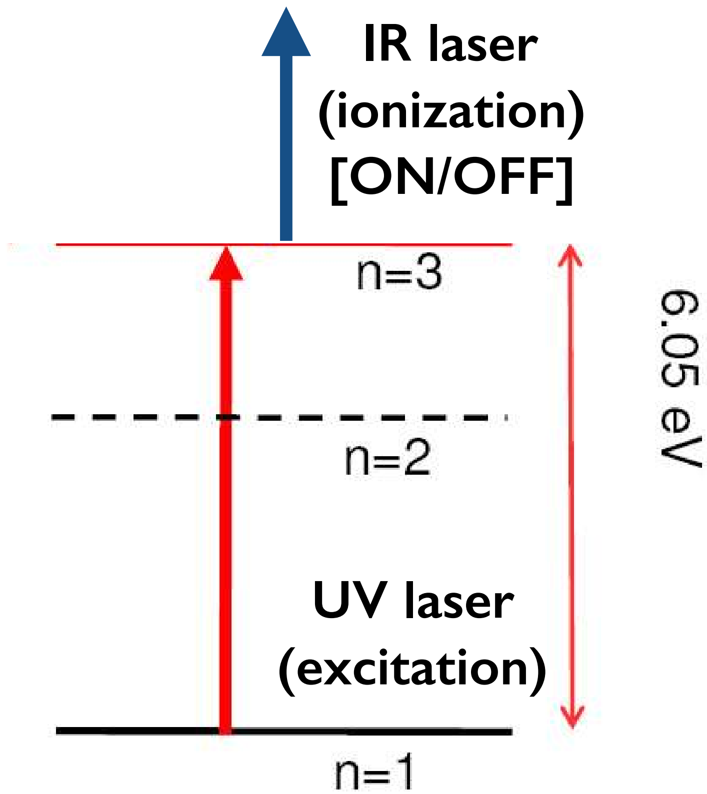
Comparing the two spectra and measuring the decay time of the signal showed that Ps was formed

demonstration of Ps n=3 laser excitation

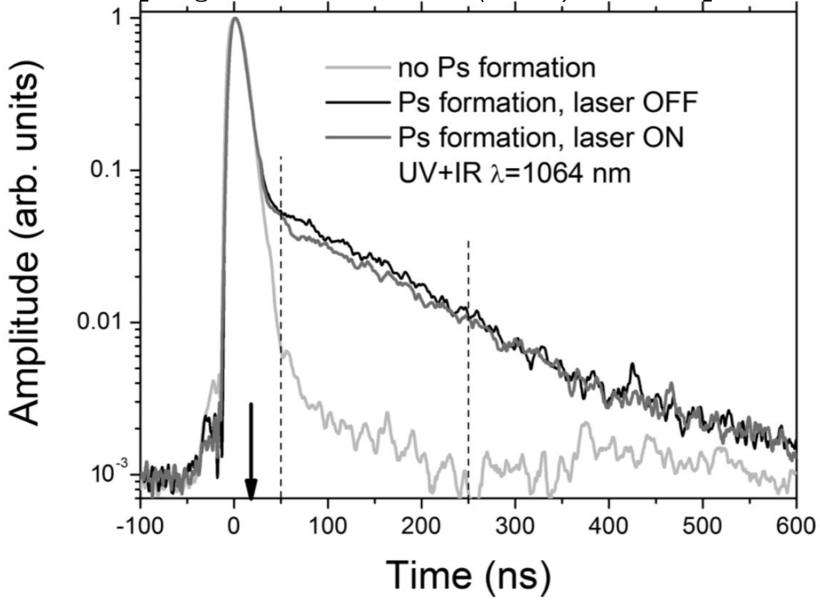
Positronium (Ps) excitation with laser pulse

- 3P excitation (UV laser) found at 205.5 +/- 0.02 nm
- excitation-ionisation efficiency ~ 15%

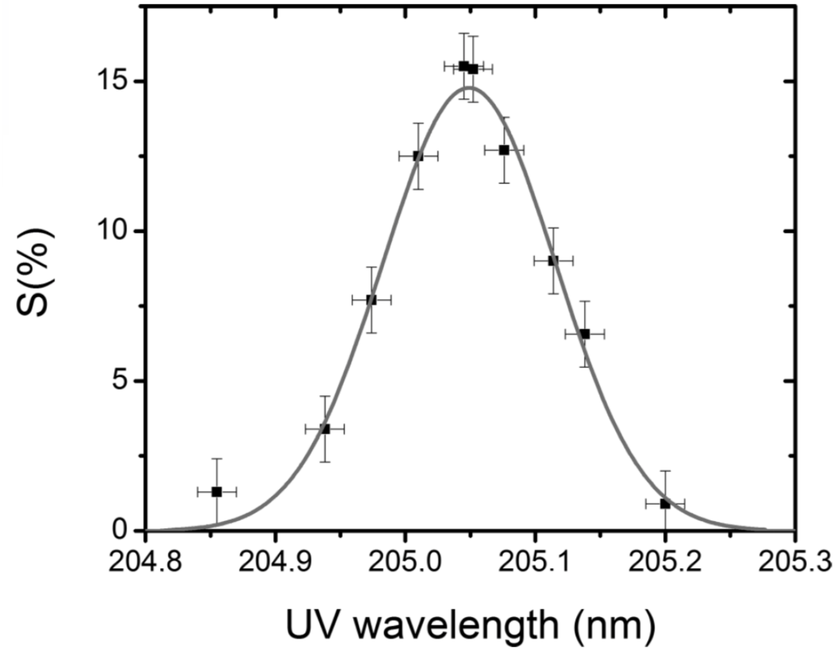
  (determined by ionisation by IR pulse)



[S. Aghion et al., PRA 94 (2016) 012507]



S(%) = (Area laser OFF-Area laser ON)/Area laser OFF

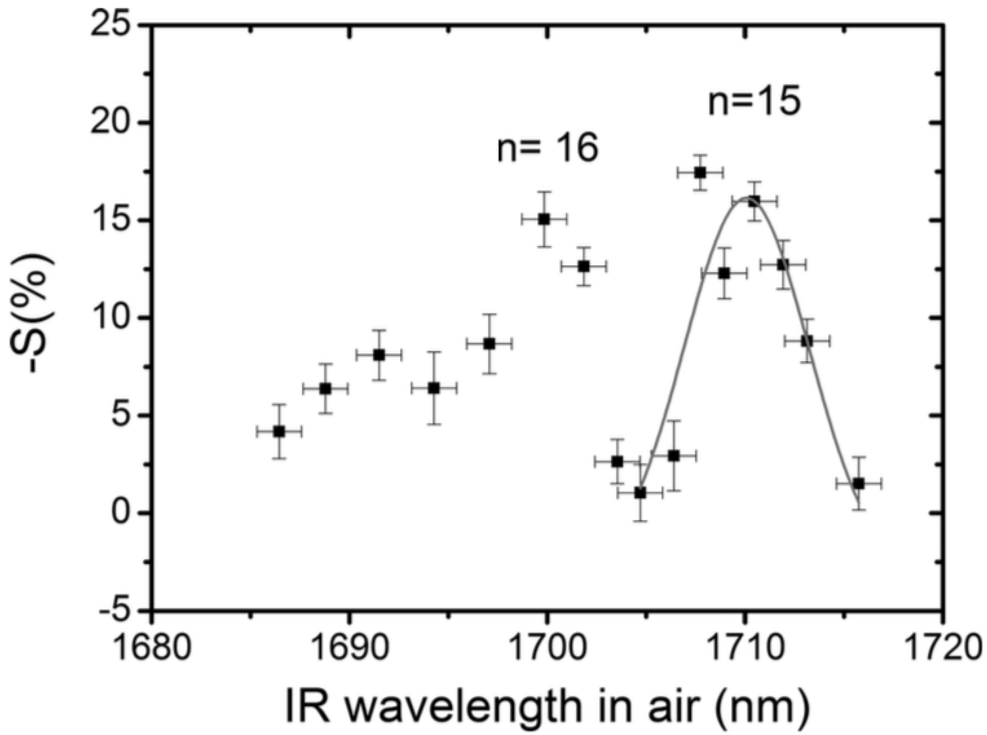


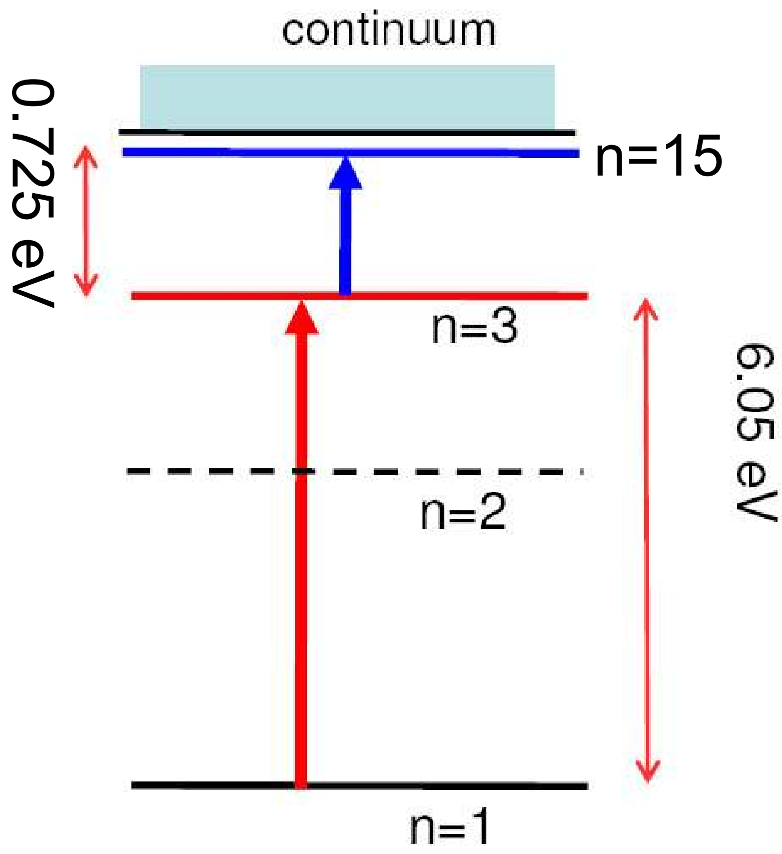
demonstration of Ps n=3 laser excitation

[S. Aghion et al., PRA 94 (2016) 012507]

Positronium (Ps) excitation with laser pulse

- 3P excitation (UV laser)
- n = 15 second step excitation (IR laser)





Evidence for n=15-18 Rydberg excitation by 2-step laser excitation

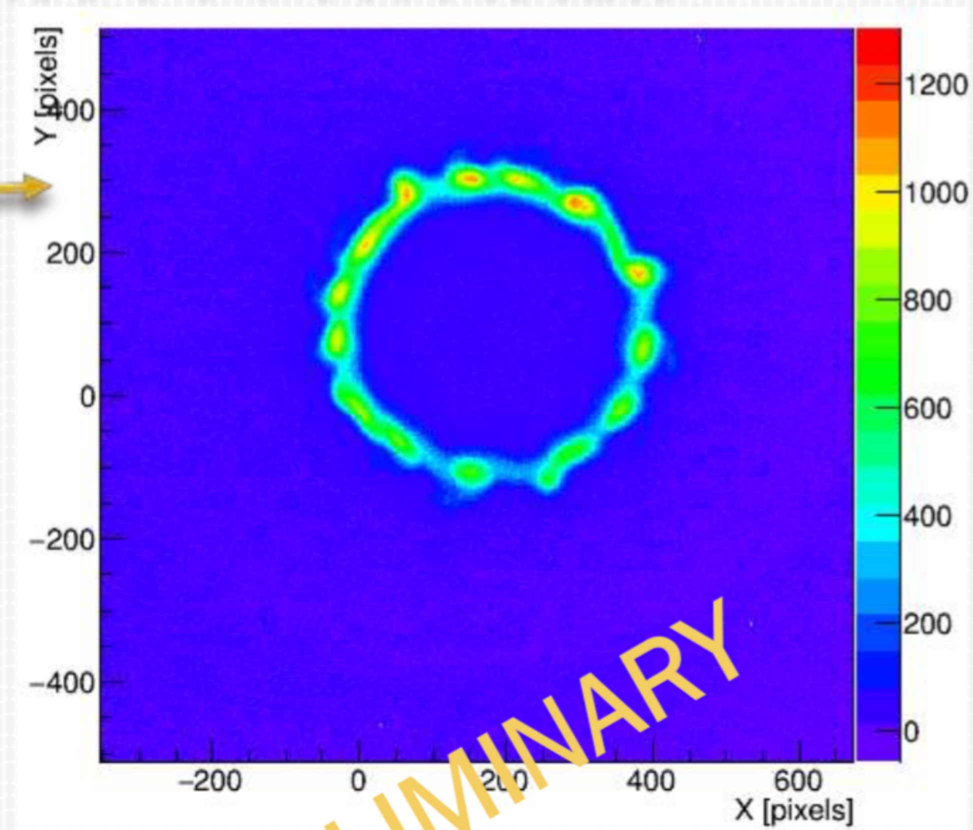
First (preparatory) results

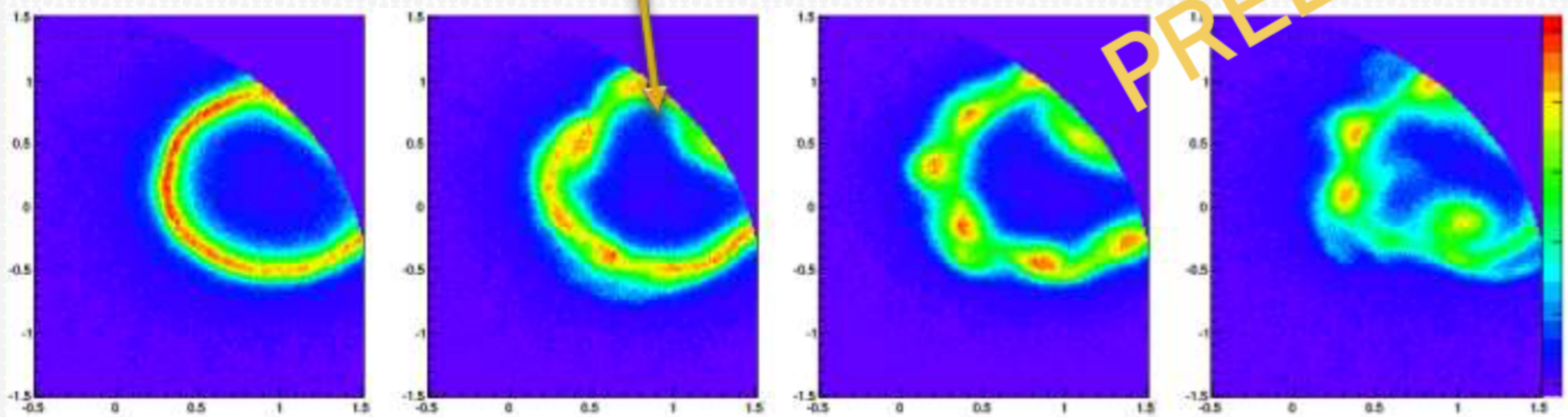
- Fall measurement proof of principle
- Ps production & excitation
- **Antiprotons manipulation**

antiprotons manipulation

- Observation of electron & antiproton centrifugal separation
  -> expected effect in our experimental conditions

- Observation of antiproton ring decay through vortices





Compression of mixed antiproton and electron non-neutral plasma to high densities

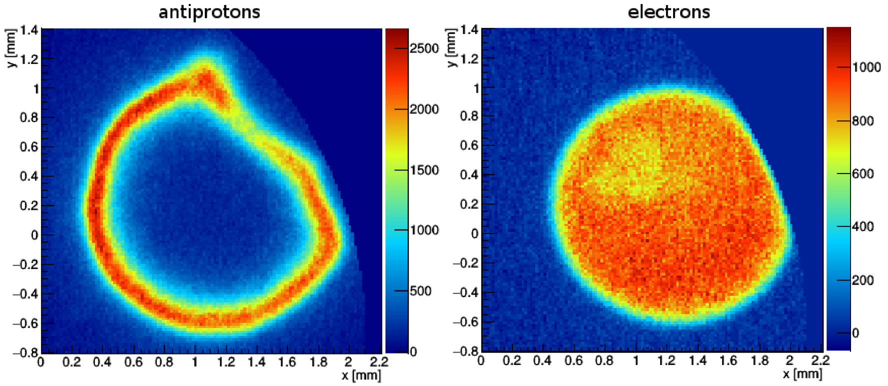


Fig. 2. Example of raw images from the MCP detector for identical particle operations with antiproton detection (left) or electron detection (right). Centrifugal separation effect between electrons and antiprotons is clearly visible. The zero point of axes is arbitrary while the distances are rescaled to in-trap (4.46 T) dimensions. The origin of the distortion in the upper right quadrants is described in the text.

After a multi-step Rotating Wall and electrons removal cycles (the antiprotons are compressed with electrons) and avoiding centrifugal separation a radius of 170 um and a density of the order of 2×10^{13} m^{-3} have been achieved (**lowest antiproton cloud radius and highest density ever**)

- Article in preparation

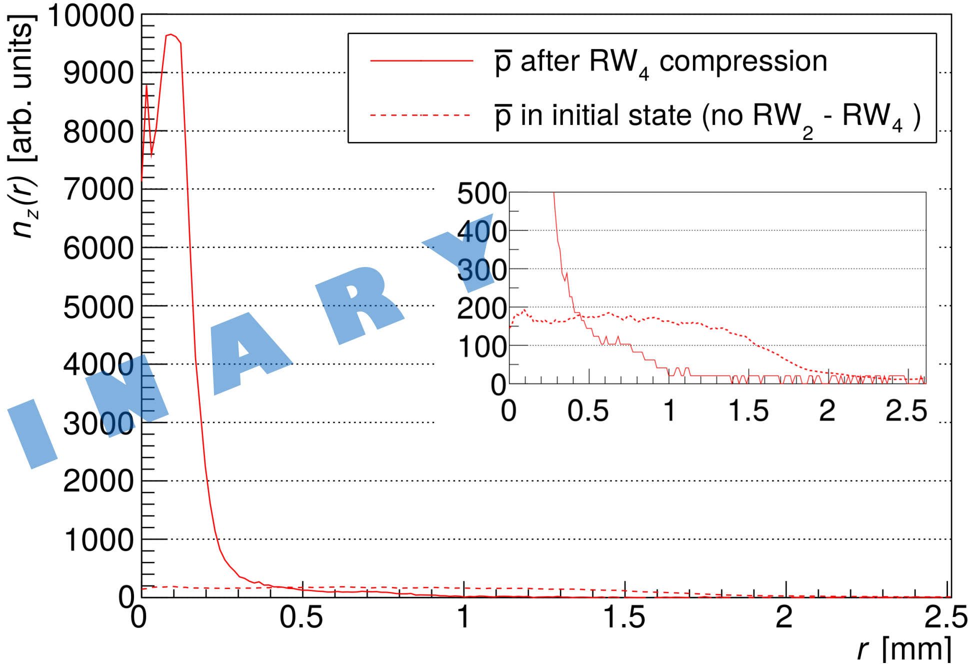


Fig. 10. Antiproton radial profile before (dotted line) and after (full line) multi-step RW compression with $f_{RW_4} = 2\,\mathrm{MHz}$ and $A_{RW_4} = 0.5\,\mathrm{V}$. The inset shows the same figure zoomed to see the original $\bar{p}$ distribution before compression. During this procedure two e^- reduction steps were applied and in total three $\bar{p}$ RW compression steps were used. $\bar{p}$ HWHM was 1.63 mm before and 0.17 mm after the compression.

Conclusions and future plans

Goal

- AEgIS aims at probing the WEP on antimatter
- No precise direct measurement so far

Results

AEgIS is taking data (until the LHC Long Shutdown 2)

- Antiprotons are routinely trapped and "manipulated" in the traps
- Positronium have been formed and excited to Rydberg states
- The working principle tested using antiprotons

Future plans

- $\bar{H}$ production expected to be achieved this/next year
- First gravity measurements planned for the next years
- Longer term plans also include H-$\bar{H}$ spectroscopy (in particular HFS)

the AEgIS collaboration

University of Bergen	University of Brescia	CERN, Geneva	University of Genova
Heidelberg University	Max Planck Institute for Nuclear Physics, Heidelberg	University College London	University of Lyon 1
University of Milano	Politecnico di Milano	Institute of Nuclear Research of the Russian Academy of Science, Moscow	University of Oslo
University Paris-Saclay and CNRS	University of Pavia	Czech Technical University, Prague	University of Trento
Stefan Meyer Institute, Vienna	ETH Zurich	INFN Sections of Genova, Milano, Padova, Pavia, Trento	谢 谢 您 的 关 注