Projet AEGIS

Un projet de (mesure de) poids …

… devenant réalité !

Patrick Nedelec - IPNL

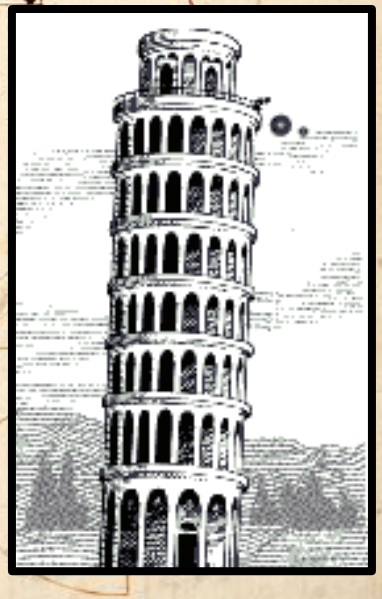
Plan

- Problématique scientifique abordée
- Le projet AEGIS
- Préparation de l' expérience
- Mise en route

Un problème de poids !

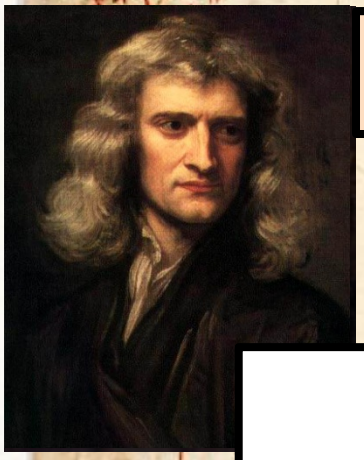
Galileo Galilei - 1564 – 1642

1ere mesure expérimentale de la chute gravitationnelle de la matière

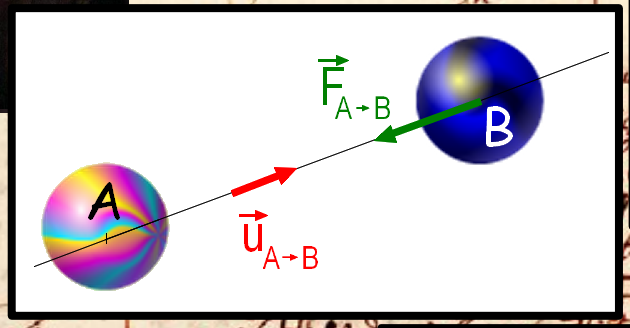


Tous les corps graves chutent de façons identique dans le vide.
Ils sont accélérés

De l'expérience à la théorie



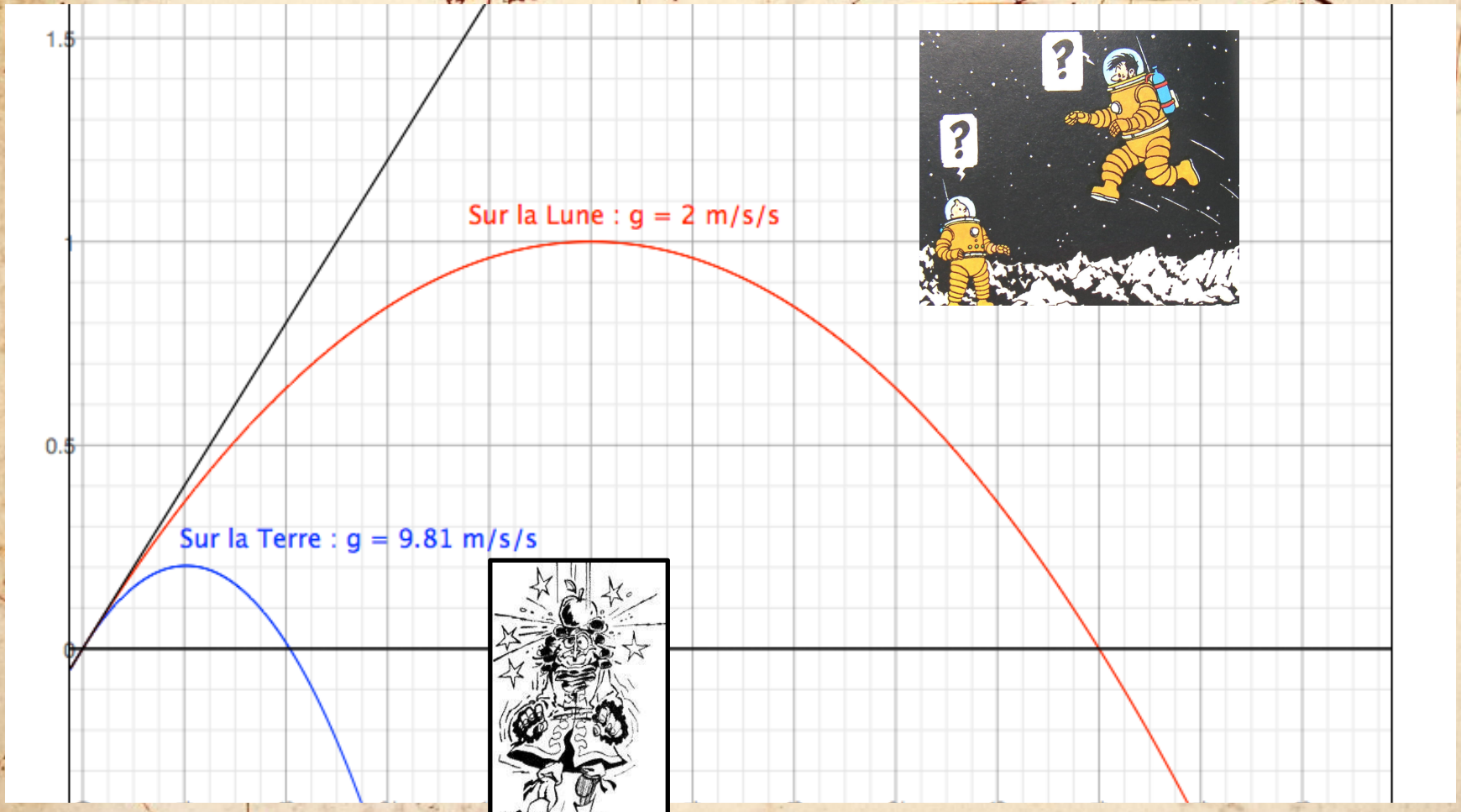
Isaac Newton – 1643 - 1727



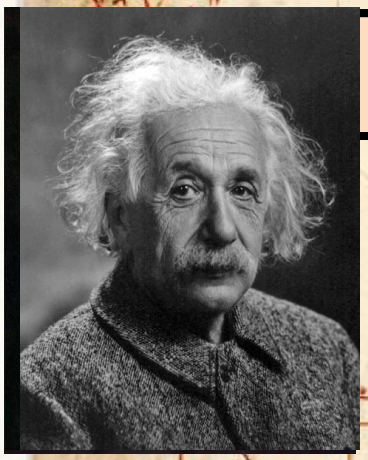
Théorie de la gravitation universelle

$$\vec{F}_{A/B} = -G\frac{m_A m_B}{\left\|\overrightarrow{r_{AB}}\right\|^2}\vec{u}_r$$

Chute libre : la parabole



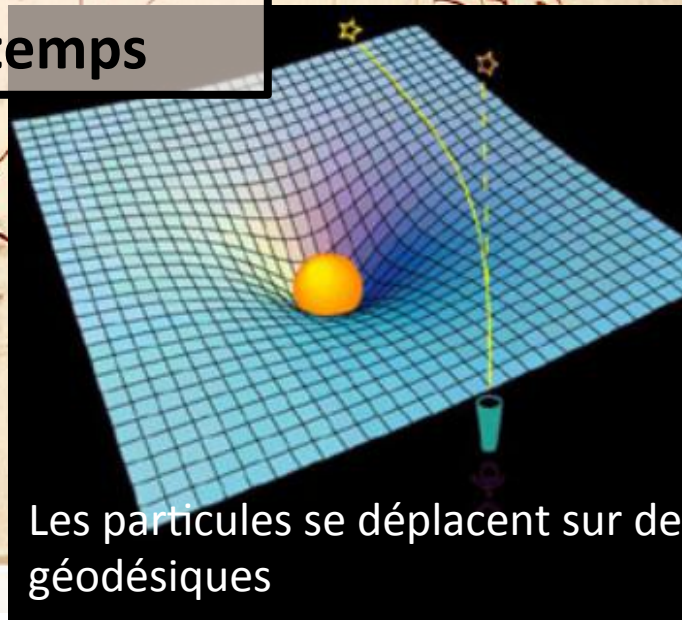
La théorie relativiste



Albert Einstein – 1879 - 1955

Théorie de la relativité générale :
Matière-Energie créent
la géométrie de l'espace-temps

$$\mathrm{G} = \frac{8\pi G}{c^4}\mathrm{T}. \quad G_{\mu\nu} = R_{\mu\nu} - \frac{1}{2}Rg_{\mu\nu}$$

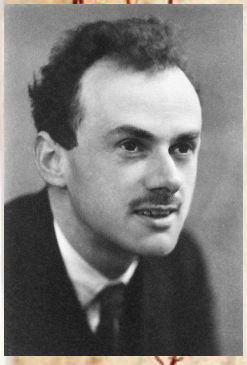


Les particules se déplacent sur des géodésiques

Modèle standard de physique des particules

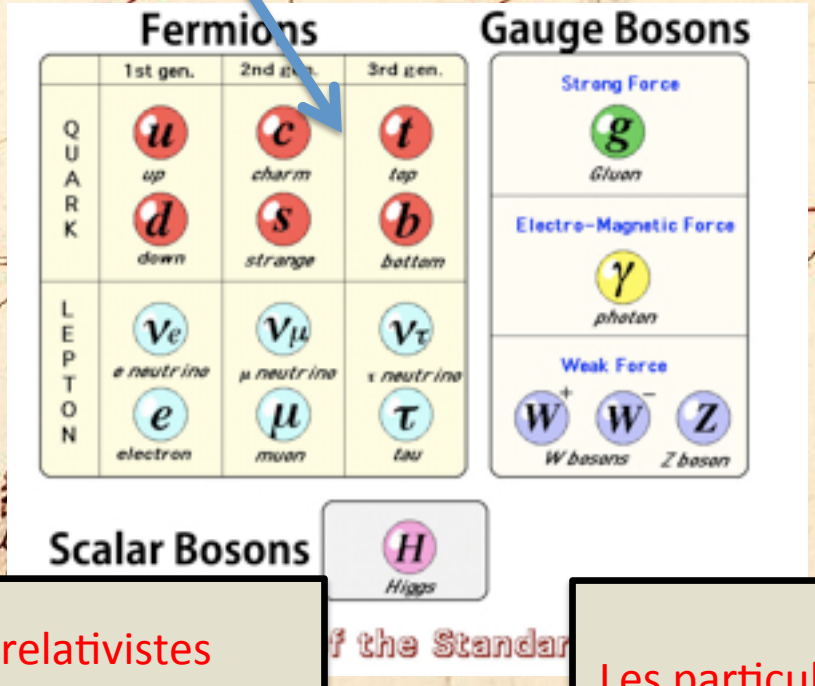
Théorie quantique des champs + relativité restreinte

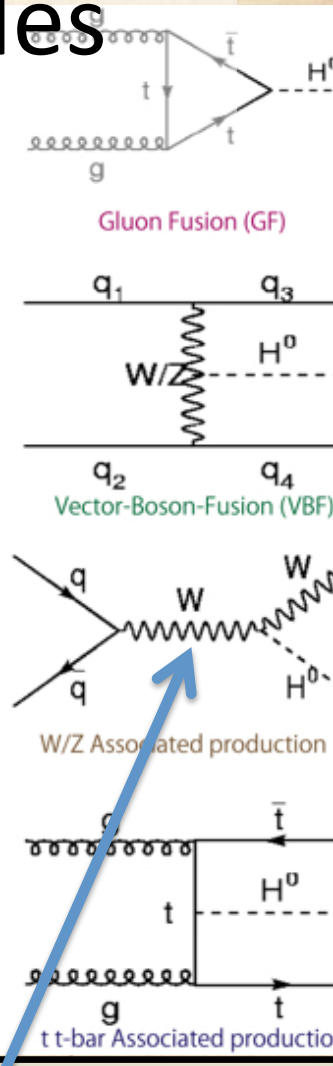
P. Dirac et al. – 1930 – 2014…



$$(i\gamma^\mu \partial_\mu - m)\psi = 0$$

Décrit les particules relativistes
et
les **antiparticules** (prédites)



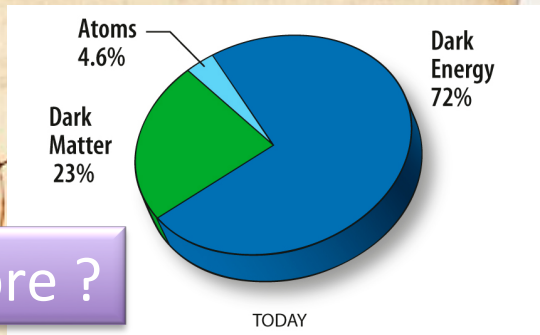


Les particules interagissent par **échange** d'autres particules (bosons)

Asymétrie Matière - antimatière

symétries ~~C~~, ~~P~~, ~~CP~~, CPT ?

Matière sombre ?



2014 : Situation expérimentale/théorique

$$(i\gamma^\mu\partial_\mu - m)\psi = 0$$

Energie noire ?

Peu de mesures
Des interrogations

Quelles expériences
Pour demain ?

Au-delà du Modèle standard ?

Modèle standard + gravitation = ?

Idées claires ?

Antimatière & (anti) gravité

$$V = -G\frac{MM'}{r}\left(1 \mp ae^{-\frac{r}{v}} + be^{-\frac{r}{s}}\right)$$

Newton

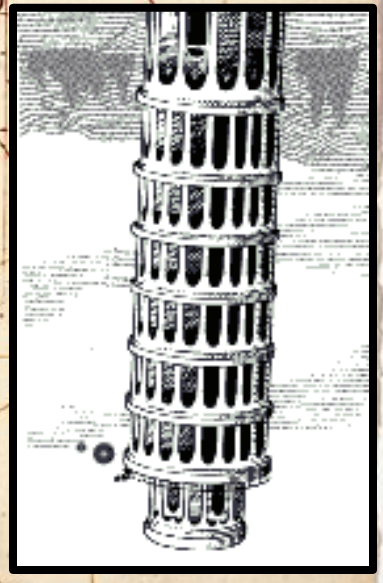
Supergravité N=2,..,8 : anti-graviton
-> gravité répulsive !

- Contraintes exp. : M. Nieto & al. Phys. Rep. 205 (1991)
- Motivation pour l' antigravité : G. Chardin, Hyp. Int. 109, 83 (1997)
- Violations de ~~Lorentz~~ & ~~CPT~~ : V.A. Kostelecky et al., Phys. Rev. D83 (2011)
- Workshop on Antimatter & Gravitation, Paris (2011)
- DM & DE : gravitation. pol. & dipole of vaccuum : D.S.Hajdukovic, Astro Space Sciences 338, (March 2012)

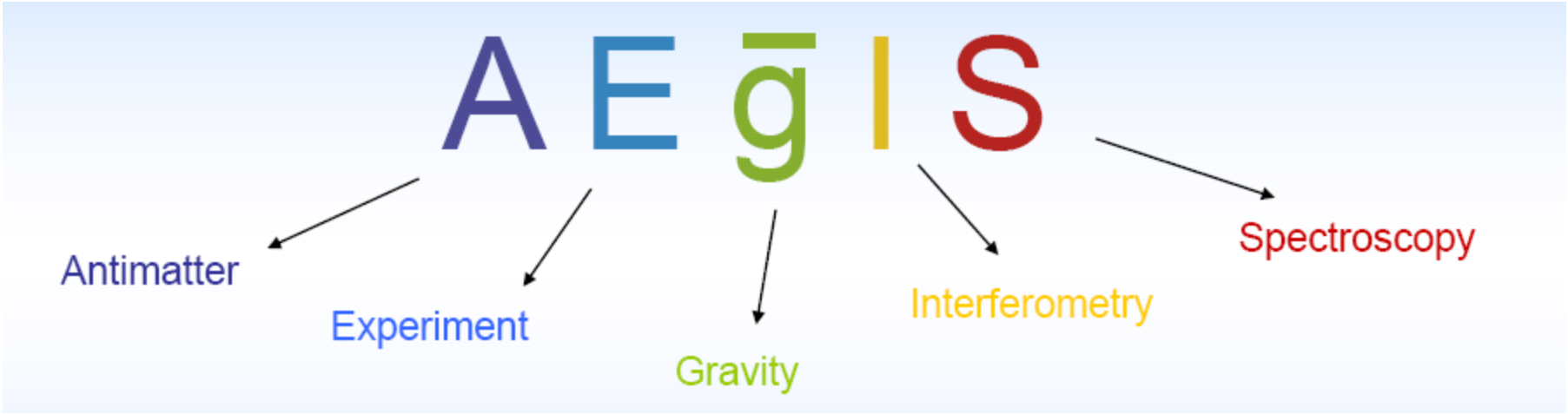
- Nouvelles expériences :
  - Gbar (CERN-AD 2016)
  - AEGIS (CERN-AD6 -2012)

AEGIS - 2010 – 202x

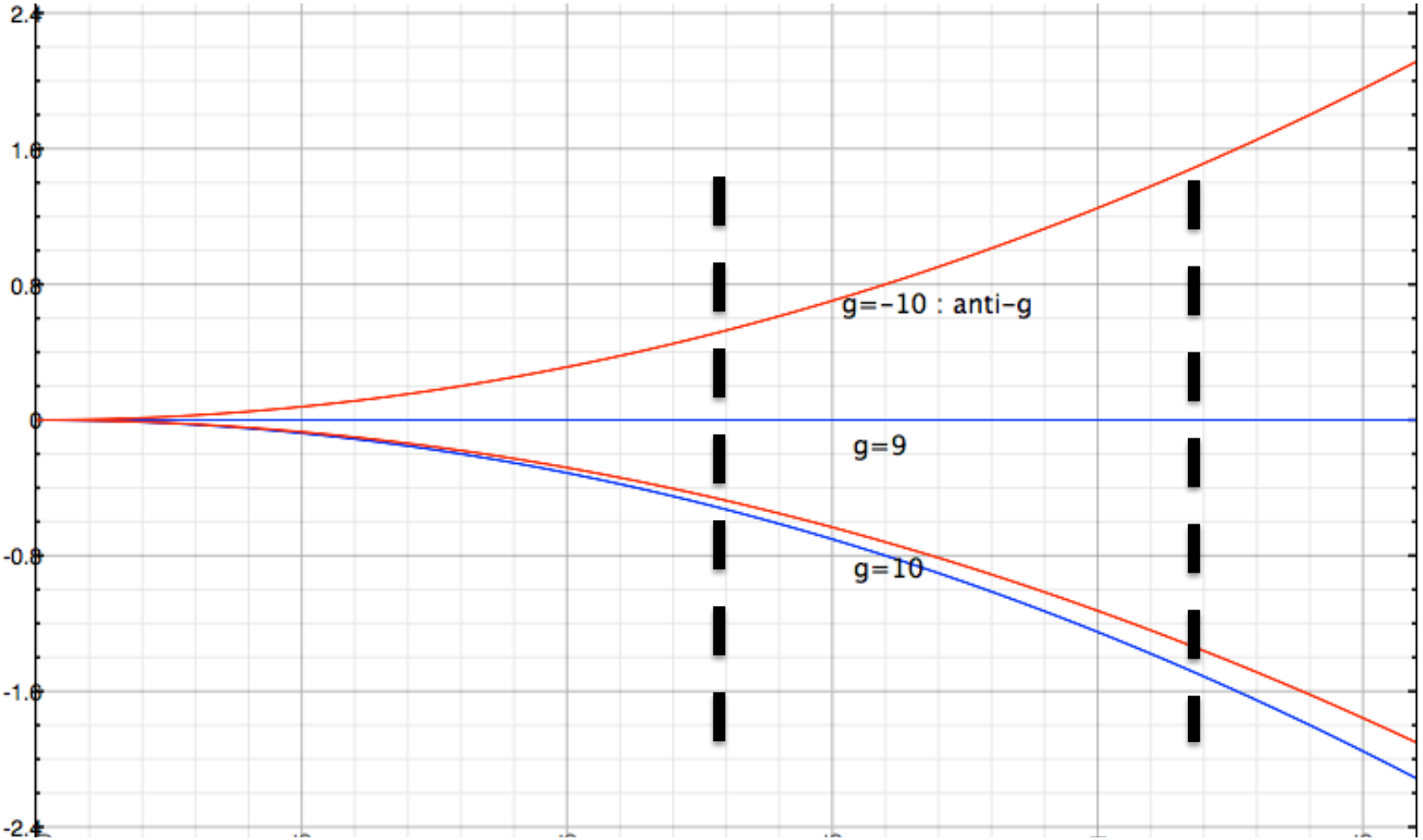
1ere mesure expérimentale de la chute gravitationnelle de l'ANTIMATIÈRE



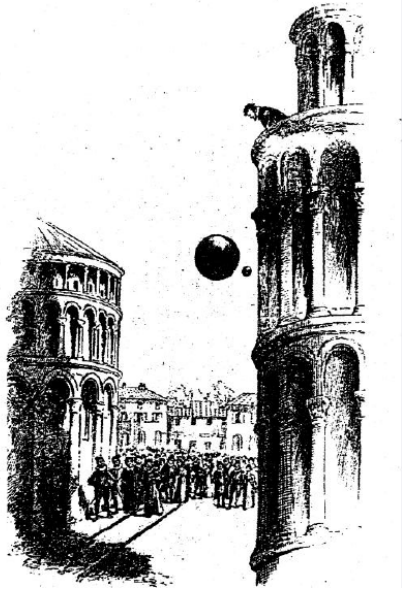
L’expérience AEGIS/CERN-AD-6



Principe : la parabole filtrée



Les buts scientifiques d' *AE* $\overline{g}$ *IS*



Primary goal: mesure de l'accélération gravitationnelle terrestre $\overline{g}$ sur l'anti hydrogène

Test Weak Equivalence Principle

- The trajectory of a falling test body depends ONLY on its INITIAL POSITION and VELOCITY and is independent of its composition
- All bodies at the same spacetime point in a given gravitational field will undergo the SAME acceleration

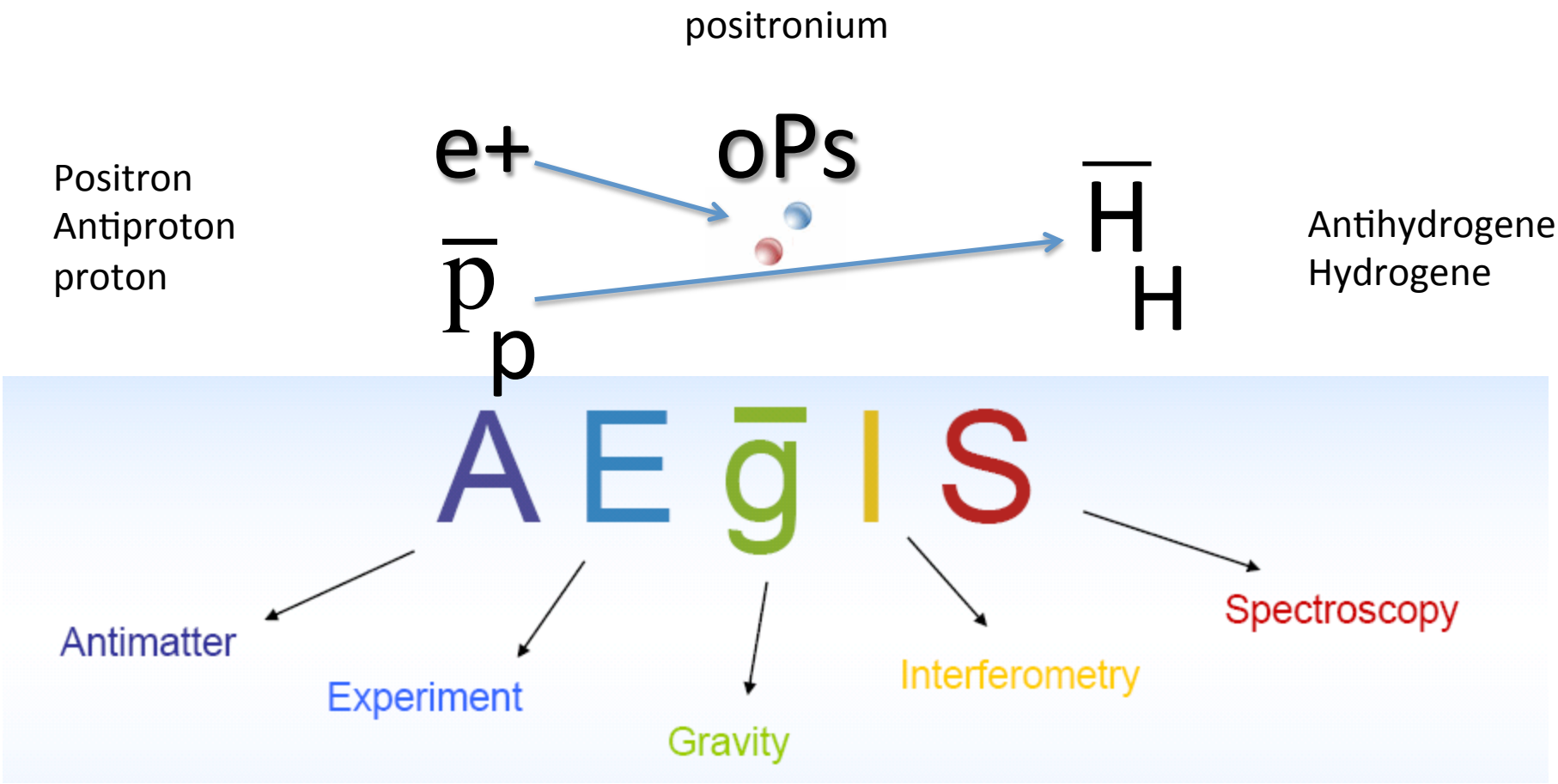
- First direct measure of WEP validity for antimatter
- WEP violations for antimatter possible in some quantum gravity model

Precision : first goal 1% with 10^5 antihydrogen atoms
higher accuracy in the future

Additional physics interests:

- High precision antihydrogen spectroscopy (CPT tests)
- Positronium physics

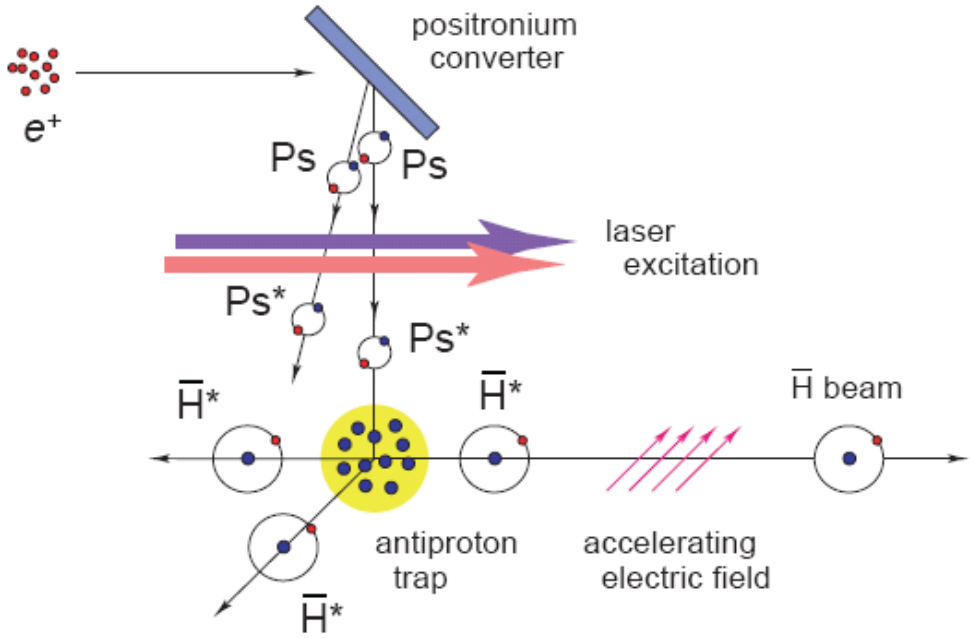
Les ingrédients de AEGIS/AD-6

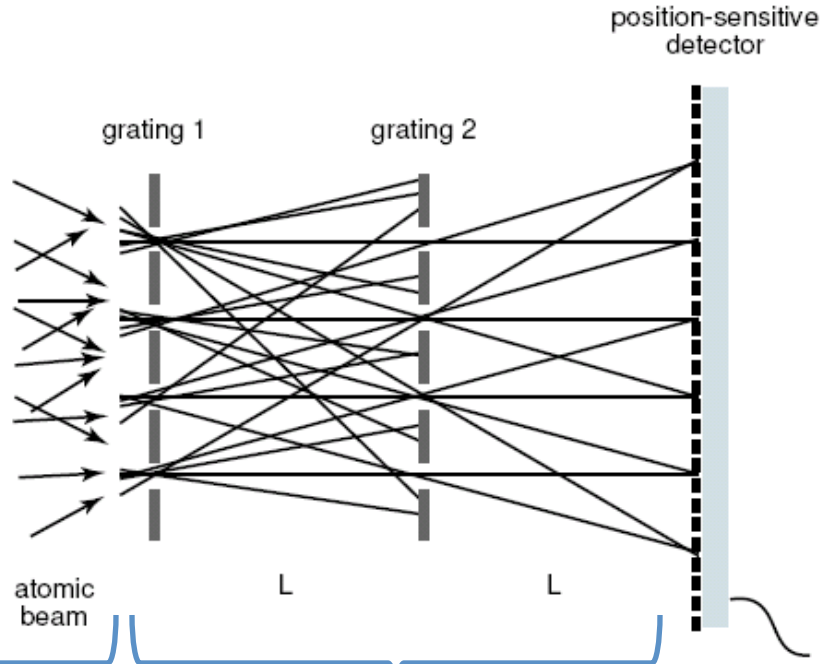


Principe :

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

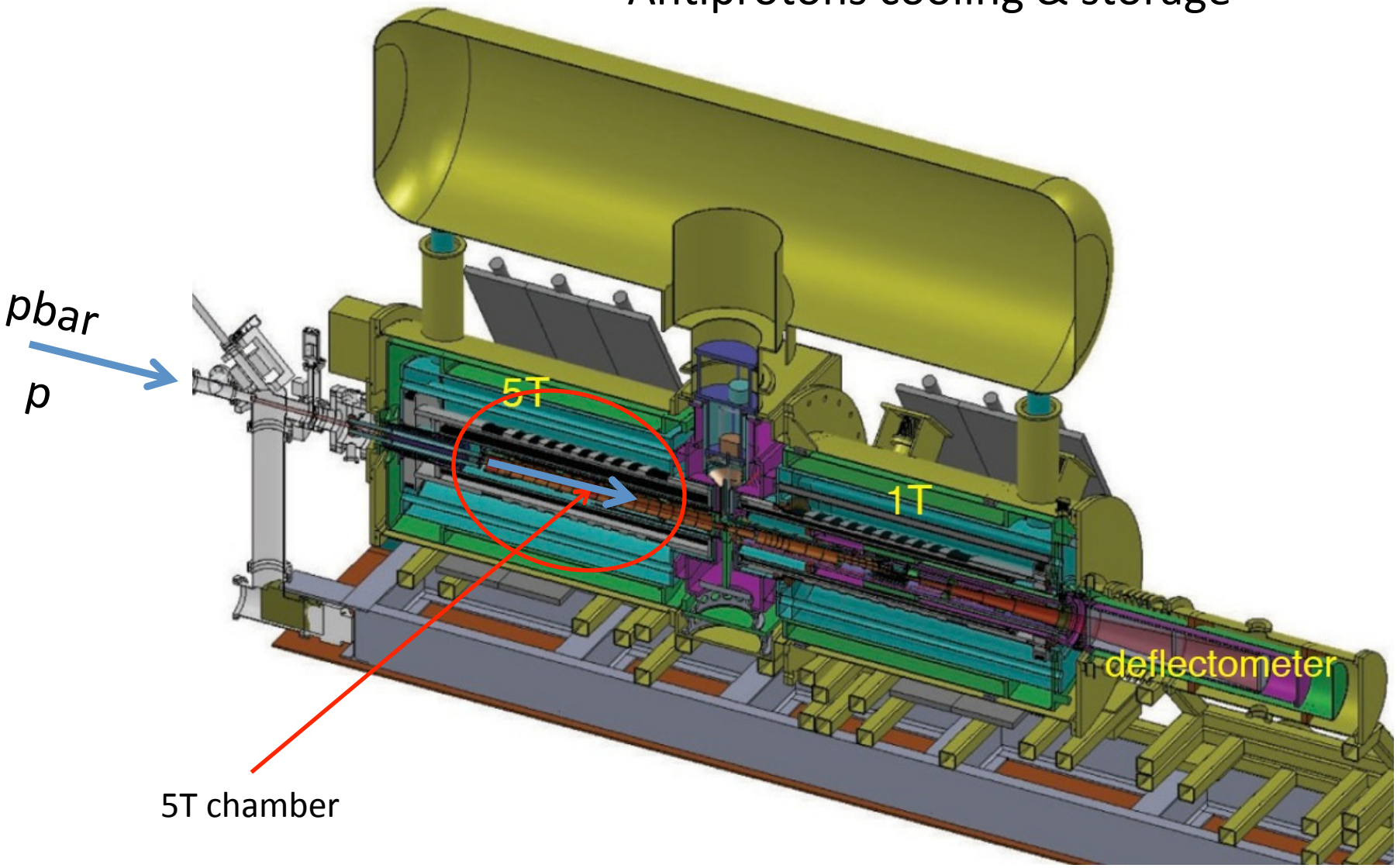
$e^+ e^-$



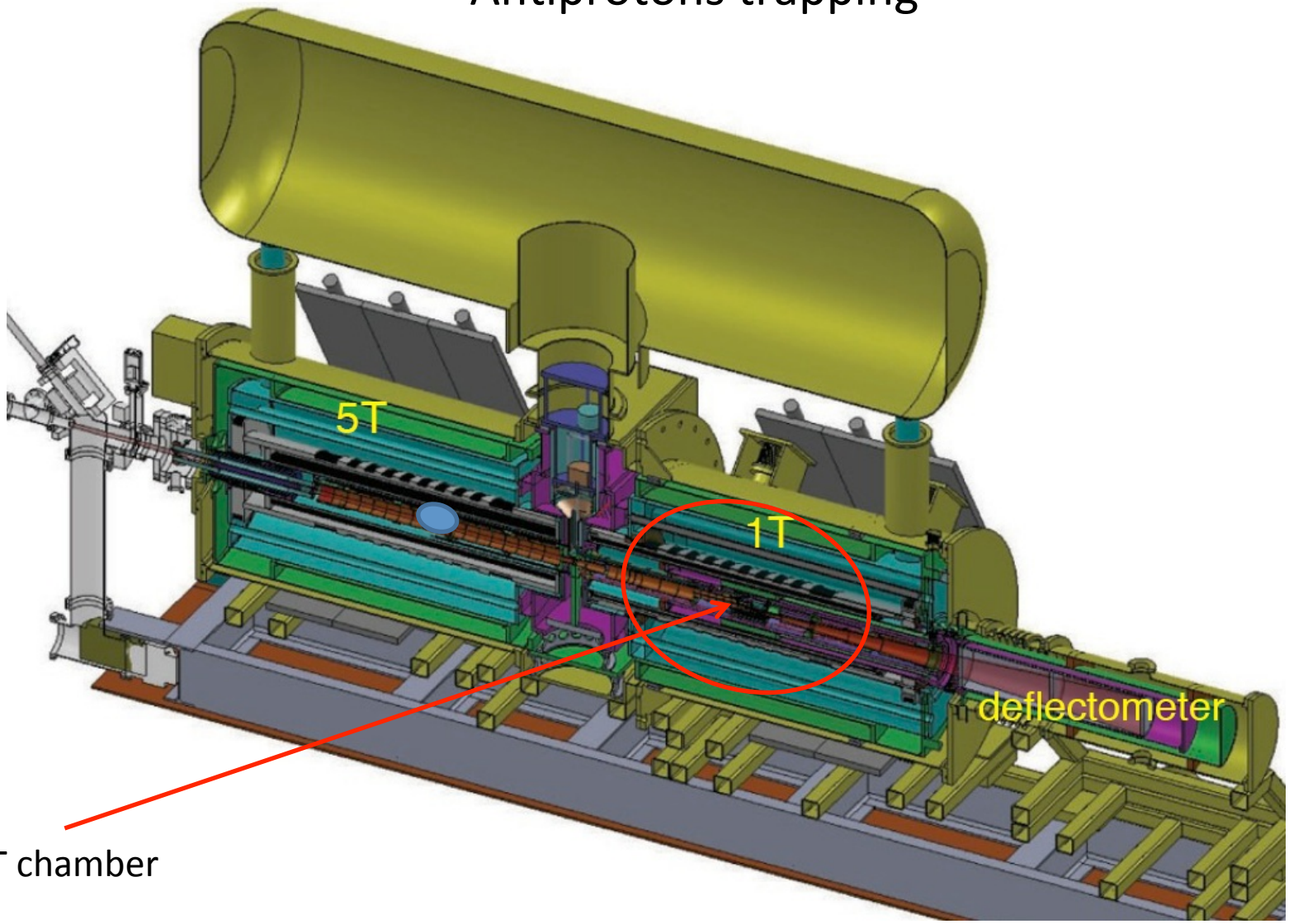


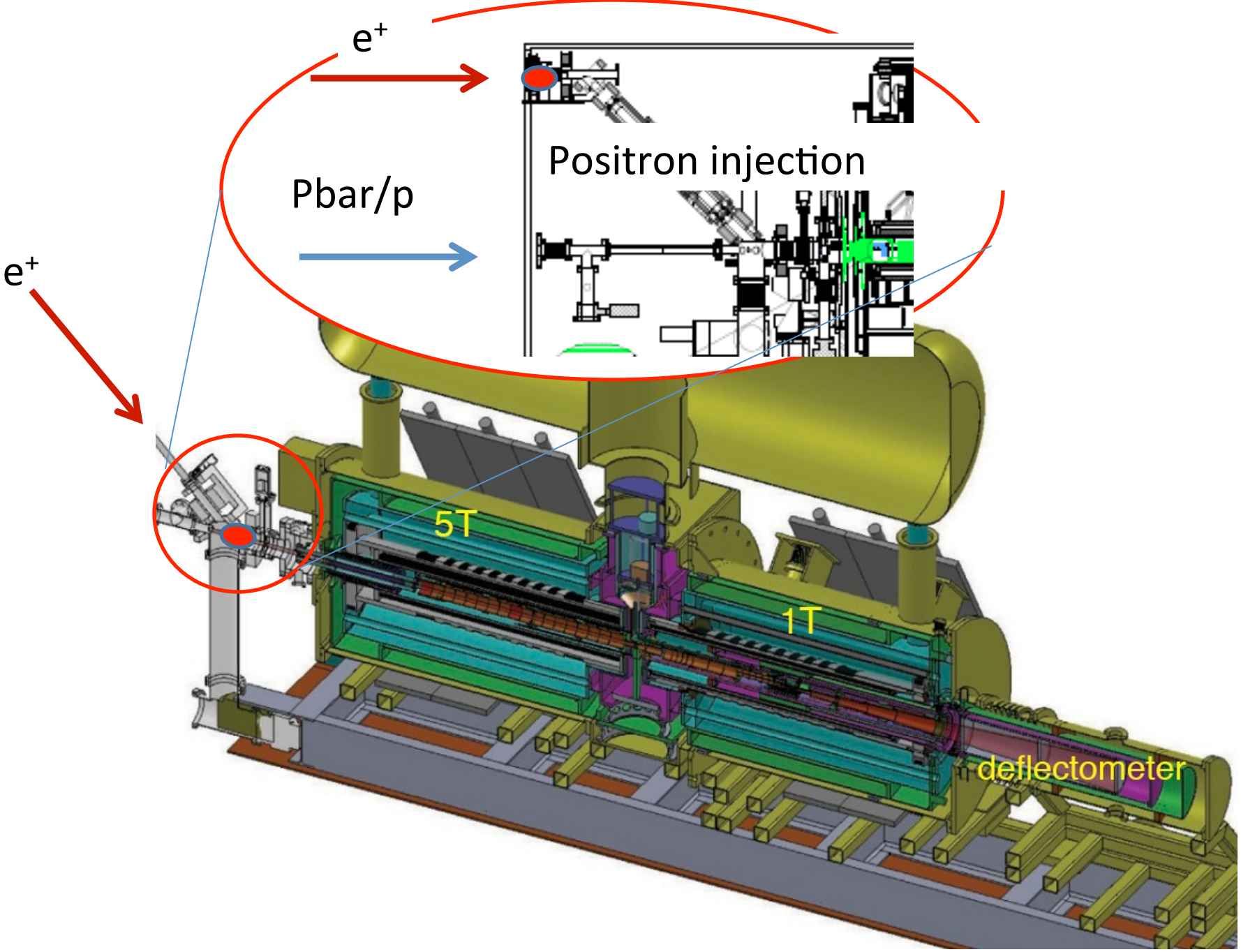
1)Hbar formation 2)beam formation 3) Trajectory measurement

Antiprotons cooling & storage



Antiprotons trapping



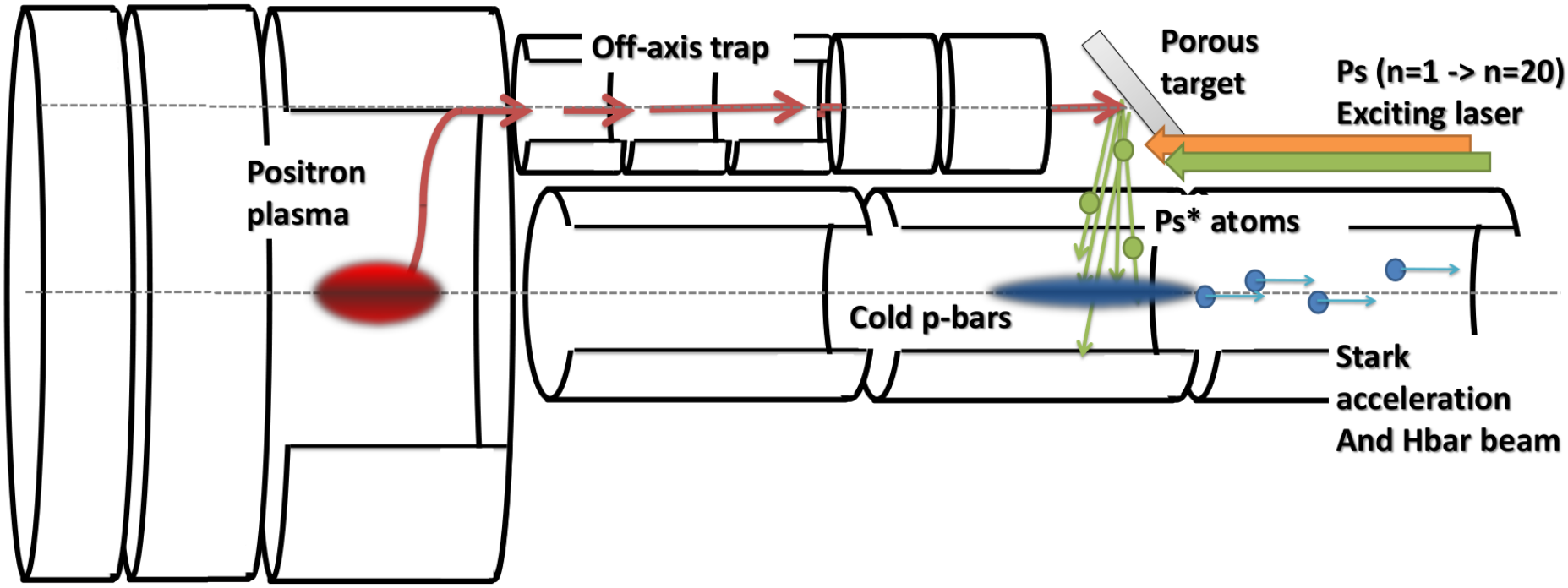

e+
Positron injection
Pbar/p
e+
5T
1T
deflectometer

AEgIS : antihydrogen production

- $\overline{H}$: form cold (100 mK) antihydrogen atoms by the charge exchange process

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

- Accelerate the antihydrogen atoms to ~ few 100 m/s using electric fields



The *AEgIS*: pbar beam

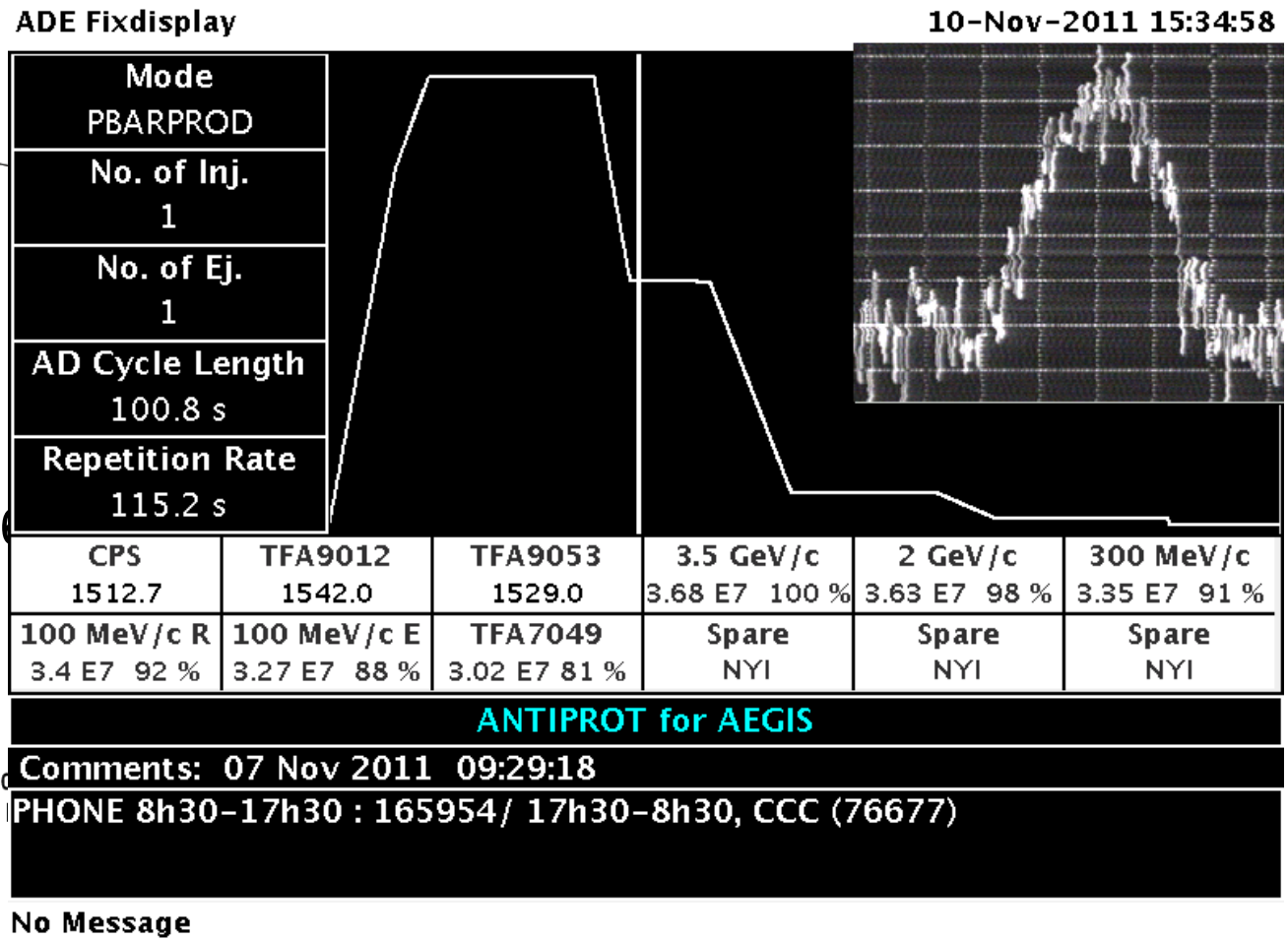
Antiproton beam

- pbar from CERN-AD
  - E = 3.5 GeV/c production
  - electron cooling

- AD-6 pbar beam
  - E = 5 MeV
  - 2 10^7 / 200 ns

(futur → ELENA (201
  - E=100 keV

First AEGIS pbar signal



AEgIS : Production of positronium

- Ps : Produce ground state positronium sending the e+ into a nanoporous target :
  - Al_2O_3 (INP, IPNL) :
    - t_0 = 142 ns
    - Pores ~30-50 nm
    - 22% produced oPs / e^+
  - Si/SiO2 (INFN) :
    - Pores ~ 10-20 nm
    - 35-40% produced oPs / e^+

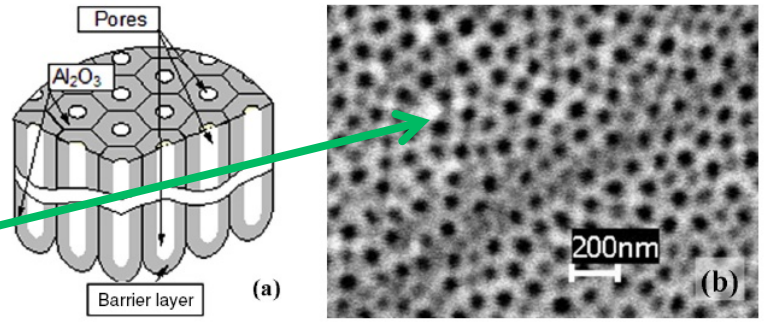
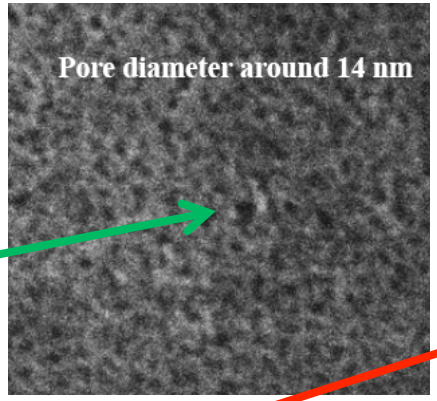
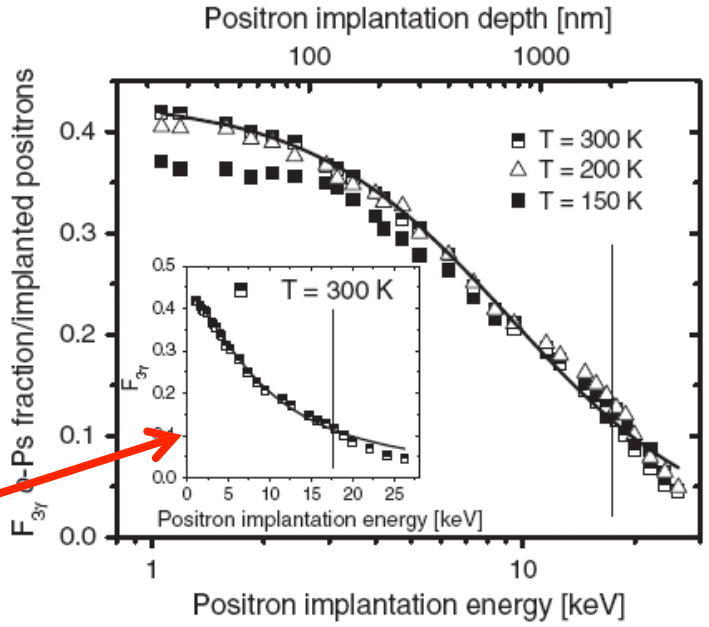


Figure 1. (a) Schematic representation of anodic alumina structure and (b) electron microscopy image of the surface of anodic Al_2O_3.

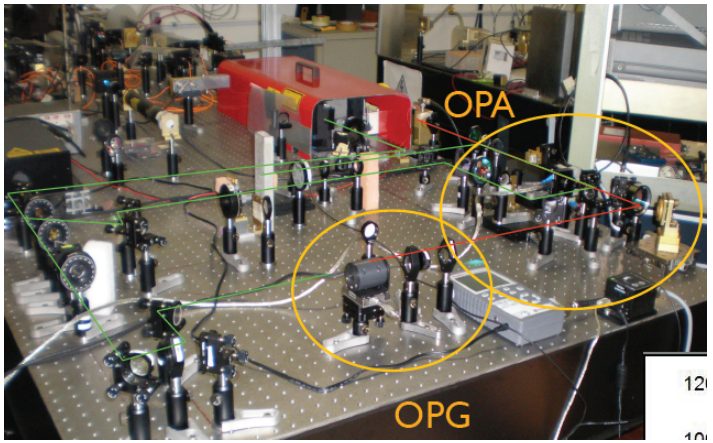


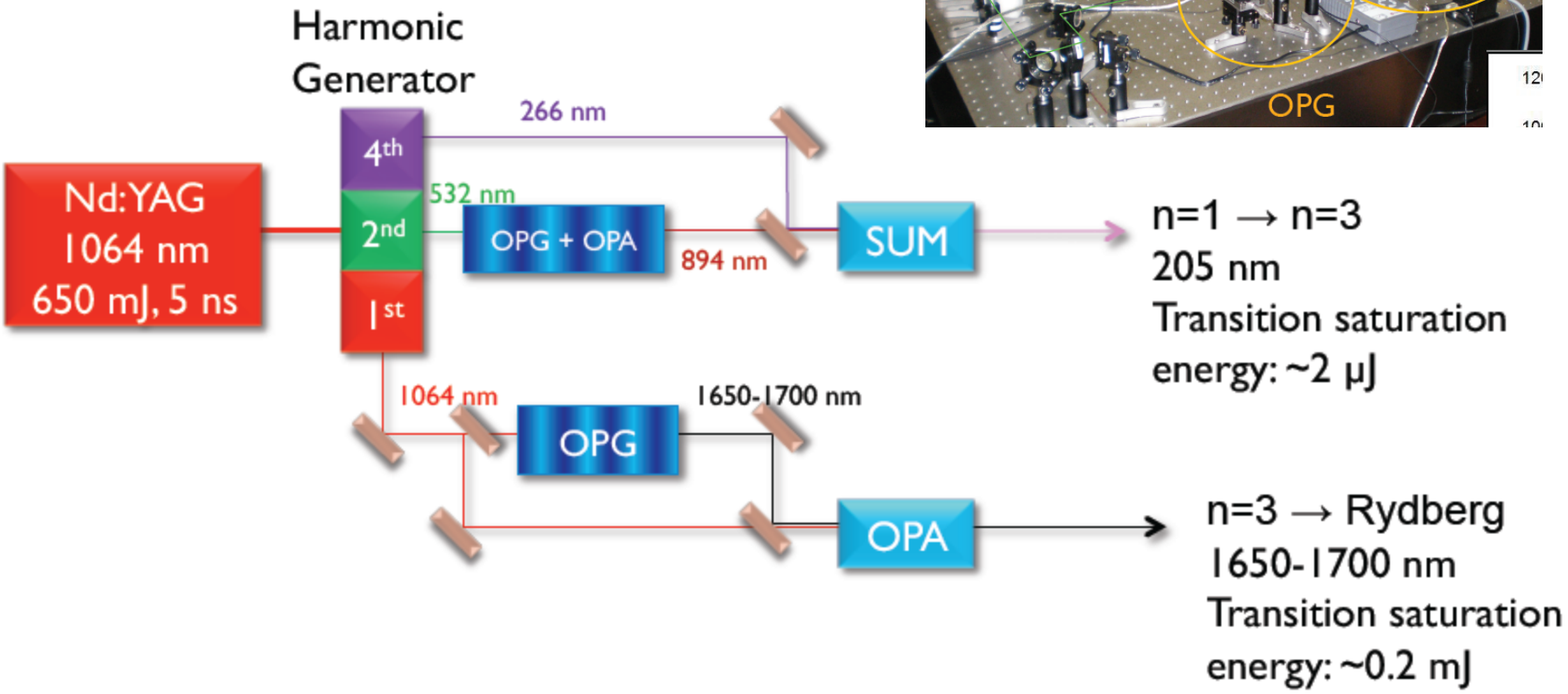


AEgIS : oPs excitation

- oPs* : produce Rydberg positronium via laser excitation: n=1→n=3 ; 3→30-35
  - G [illegible] $1/n^3$
  - $t = 1/G = t_0 \times n^3$, $t_0 = 142$ ns
  - n = 30-35 → t = 4-8 ms

- Contributions/studies: CNRS-LAC & INFN



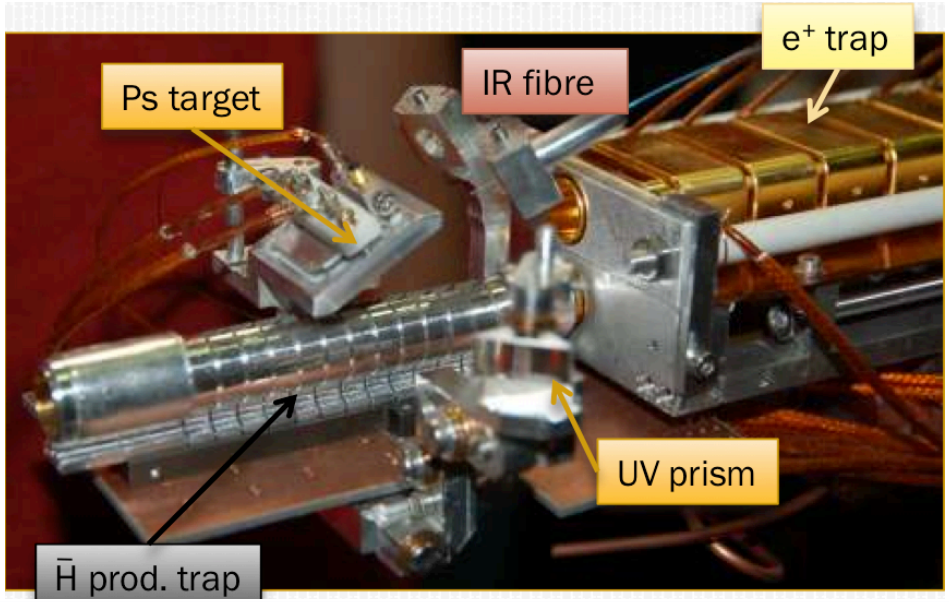


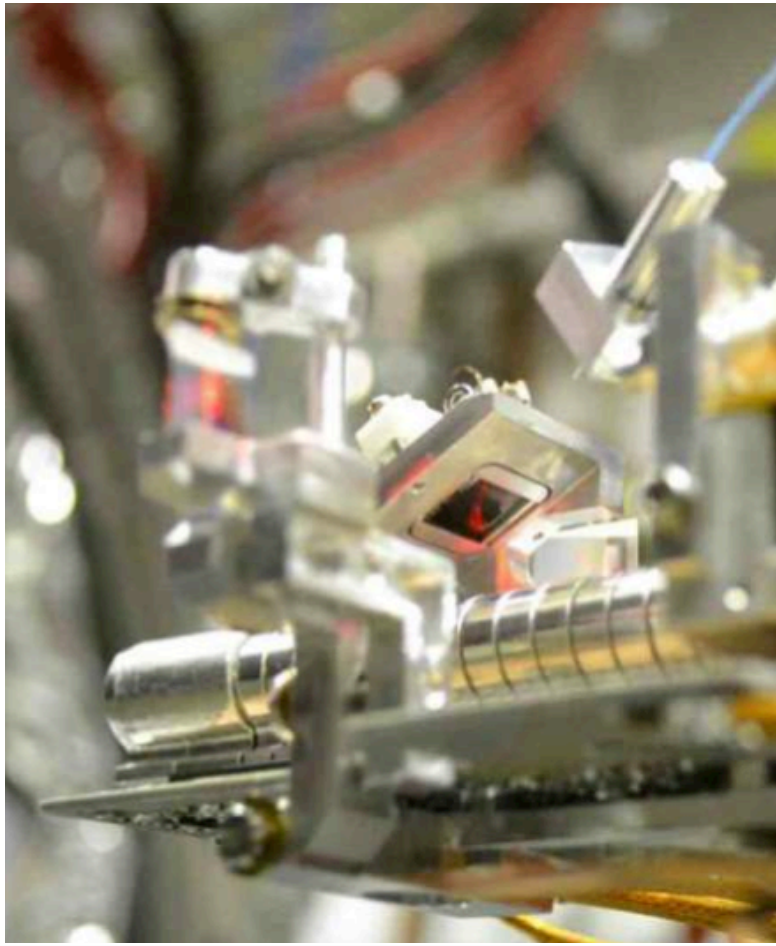
AEgIS : antihydrogen production trap

- $\bar{H}$: form cold (100 mK) antihydrogen atoms by the charge exchange process

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

- Principle demonstrated by ATRAP
- C.H. Storry et al. Phys. Rev. lett 93 (2004) 263401





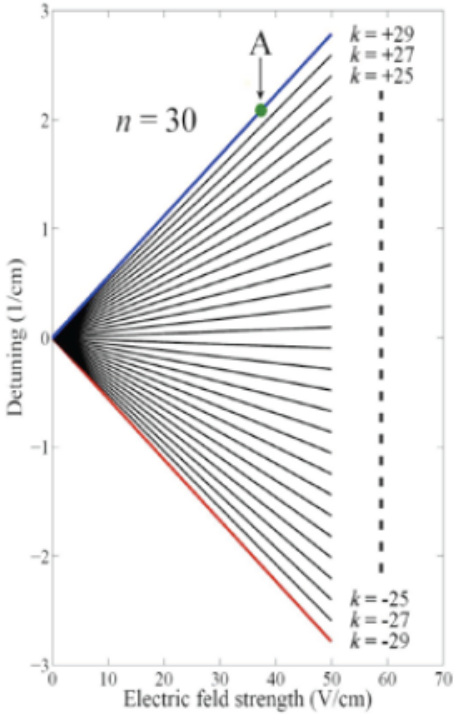
AEgIS : antihydrogen beam formation

- Electric field gradients exert force on electric dipole moments of neutral atoms:

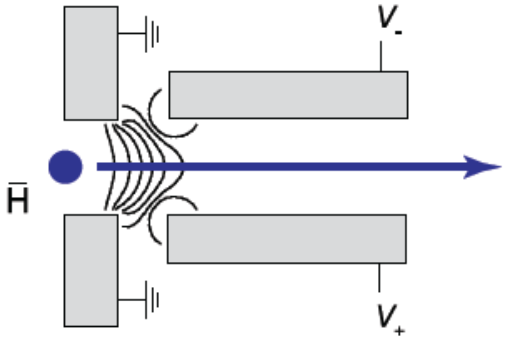
$$U = \frac{2}{3} e a_0 \boxed{n(n-1)} F$$

$$\boldsymbol{F} = -\frac{2}{3} e a_0 \boxed{n(n-1)} \nabla F$$

⇒ Rydberg atoms are very sensitive to inhomogeneous electric fields



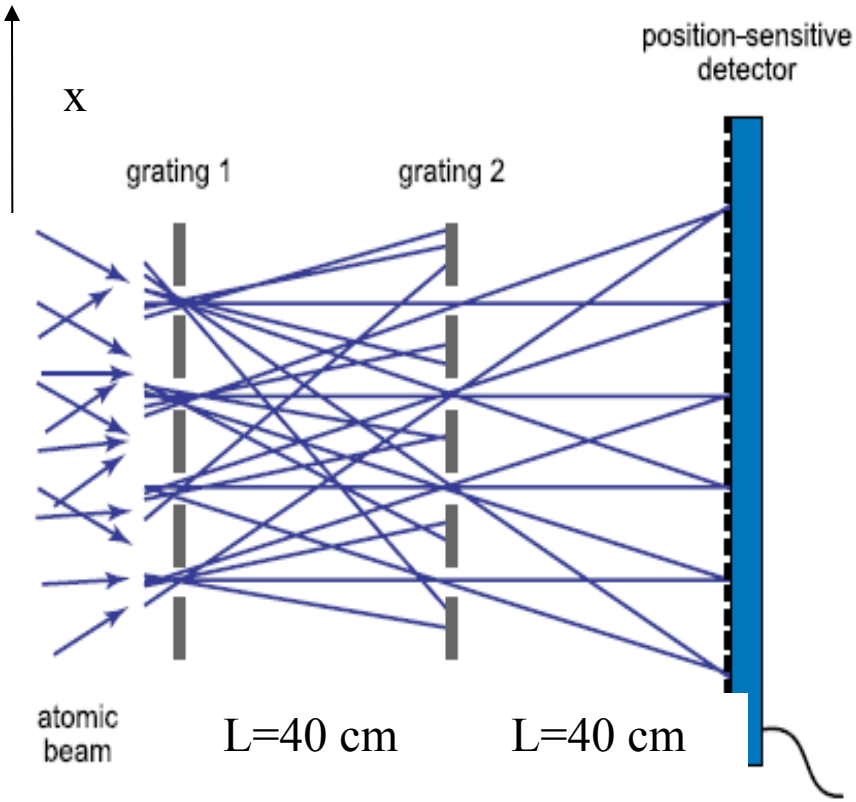
- Stark deceleration of hydrogen demonstrated (ETH group)
  [E. Vliegen & F. Merkt, J. Phys. B **39** (2006) L241]



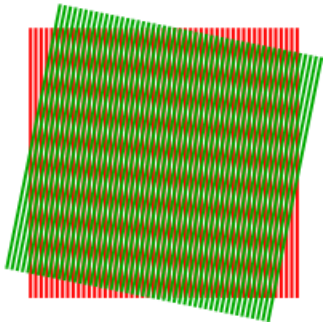
- n = 22,23,24
- Accelerations of up to 2×10^8 m/s^2 achieved
- Hydrogen beam at 700 m/s can be stopped in 5 µs over only 1.8 mm

AEgIS : free fall measurement

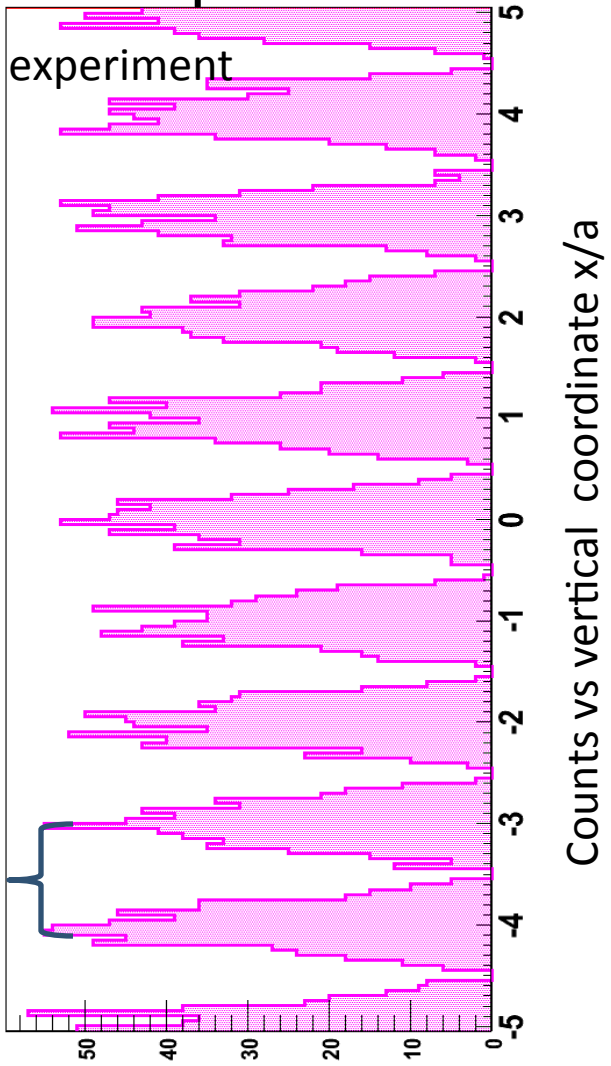
The Moiré deflectometer : principle of operation



Simulations of the experiment



a=80 mr



Grating period = 80 µm

Grating size = 20 cm (2500 slits)

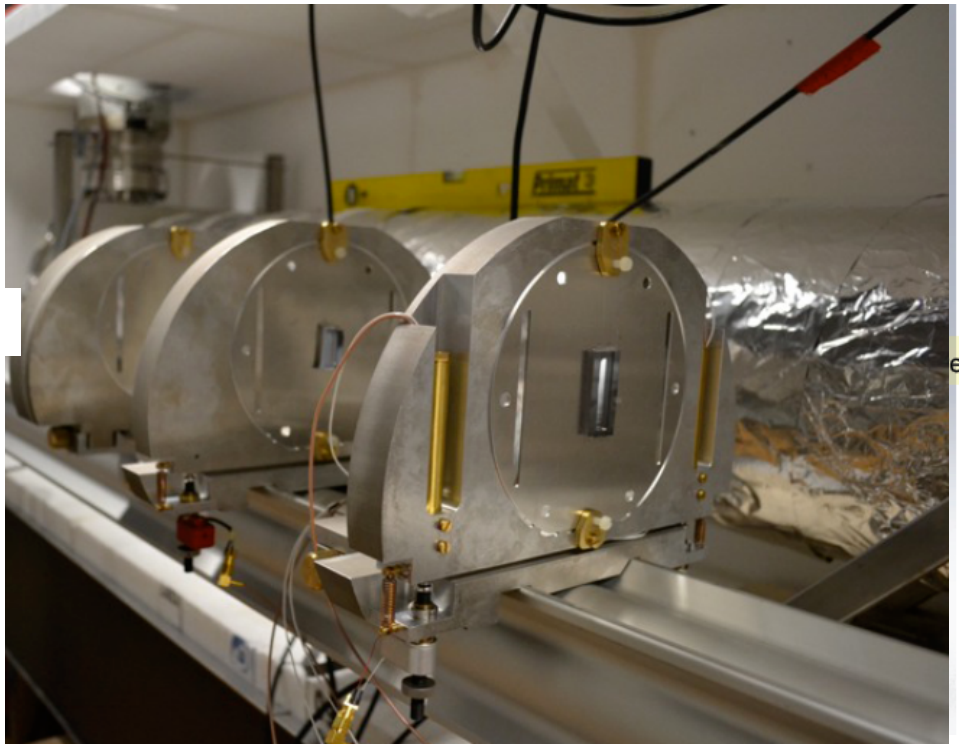
Moire' deflectometer: measurements/estimations

- Ordinary matter [M. K. Oberthaler *et al.*, Phys. Rev. A **54** (1996) 3165]
  - Measurement performed for Ar
  - $s(g)/g = 2 \times 10^{-4}$

- Anti-matter

[A. Kellerbauer *et al.*, Phys. Rev. A **54** (1996) 3165]

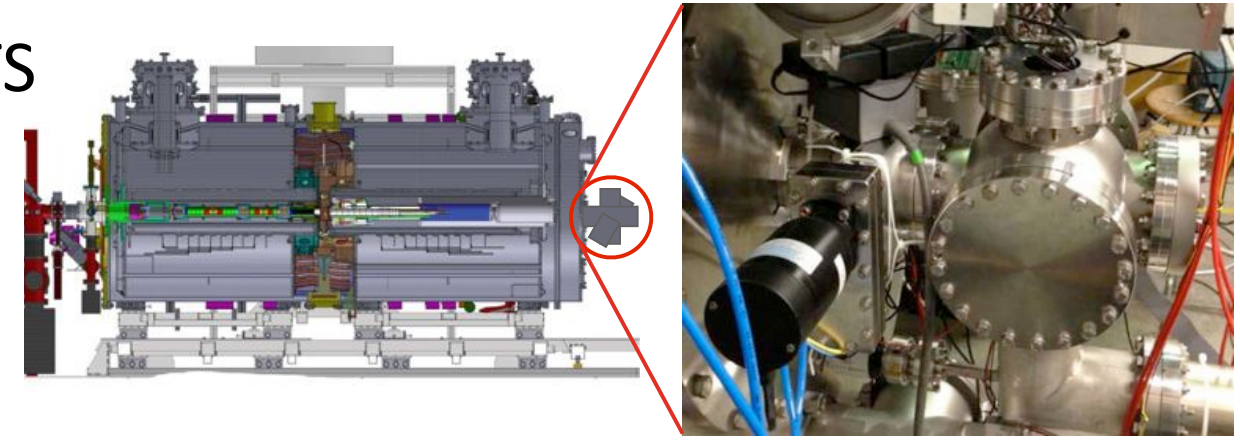
  - AEGIS:
    - With 10^5 $\bar{H}$
    - @100mK
  - $s(g)/g = 1\%$

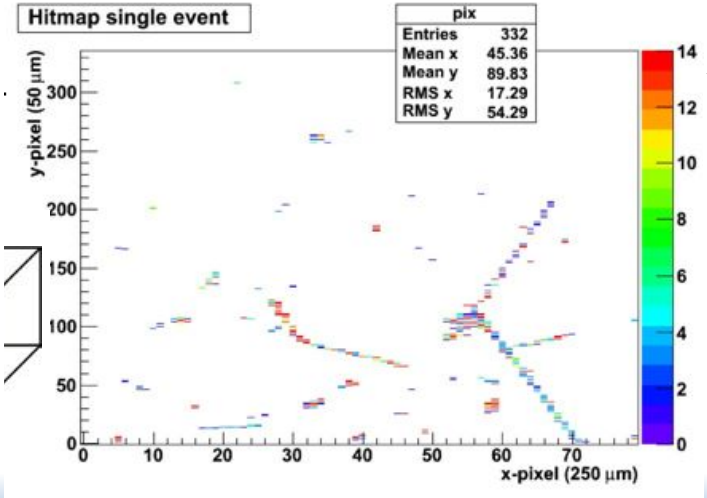


Final Hbar detector

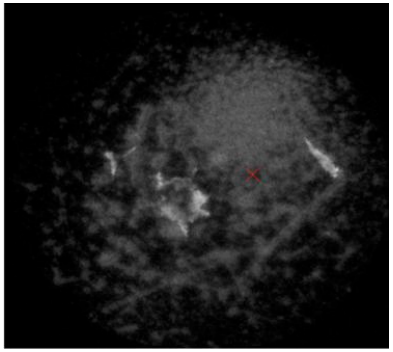
– Pbar TESTS

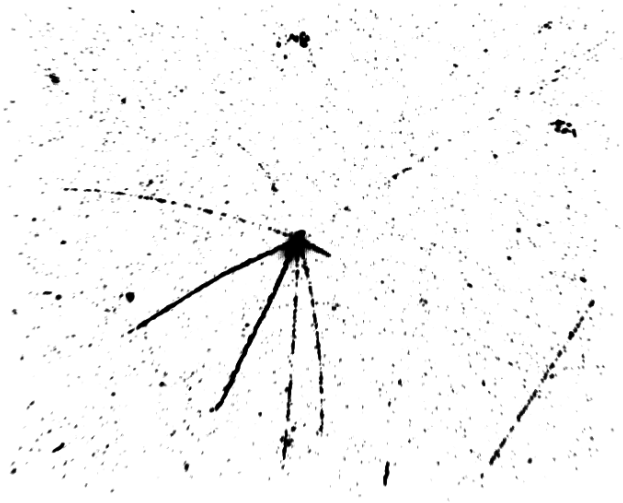
In AEGIS





/Multi Channel





The *AEgIS* collaboration (~50 f)

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R.Ferragut, G.Consolati,
F.Moia, F.Castelli, F.Prelz

Pavie

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A. Fontana, L. Dassa,
A. Rotondi, C. Riccardi

Trento

R. Brusa, S. Mariazzi, G. Nebbia, G. Ferrari

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S. Gninenko, A. Belov, V. Matveev

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P. Lebrun
P. Nedelec

L. Cabaret
D. Comparat

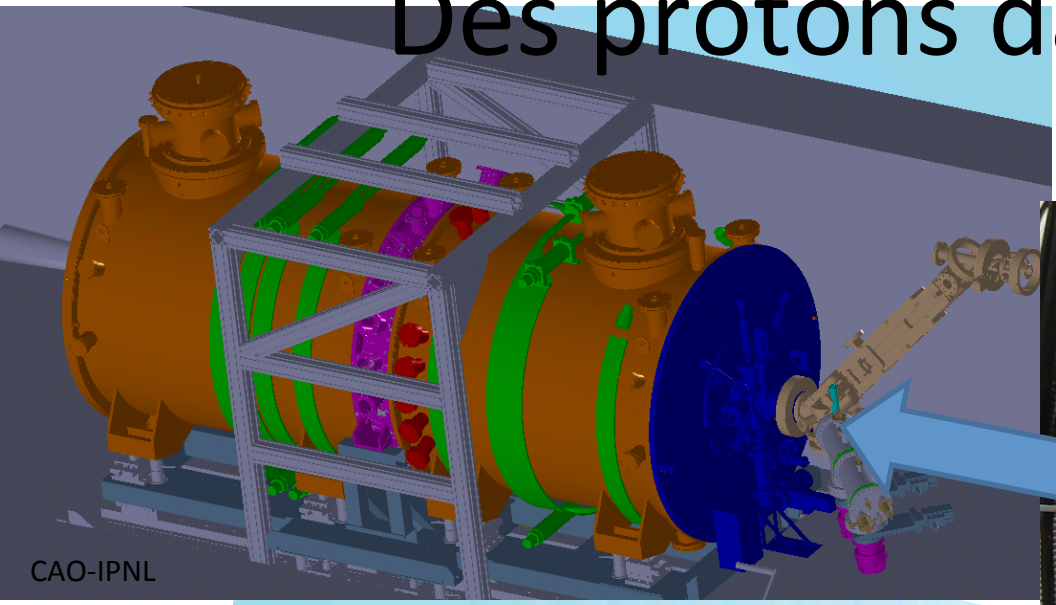
Source de proton: pourquoi faire ?

- Produire :
  - Long & délicat (>2013)
  - *Beam duty cycle* = 50%
  - Systématiques ?
- Préparer la C-exp. :
  - Permet : mise au point/réglage d'AEGIS
    - Source e^+ + source p (*machine independant*)
  - Contrôle des systématiques de l'expérience
    - Cœur de la manip !
- Caractéristiques du faisceau?
  - E < qlq keV
  - F ~ 10^6 – 10^8 p/s

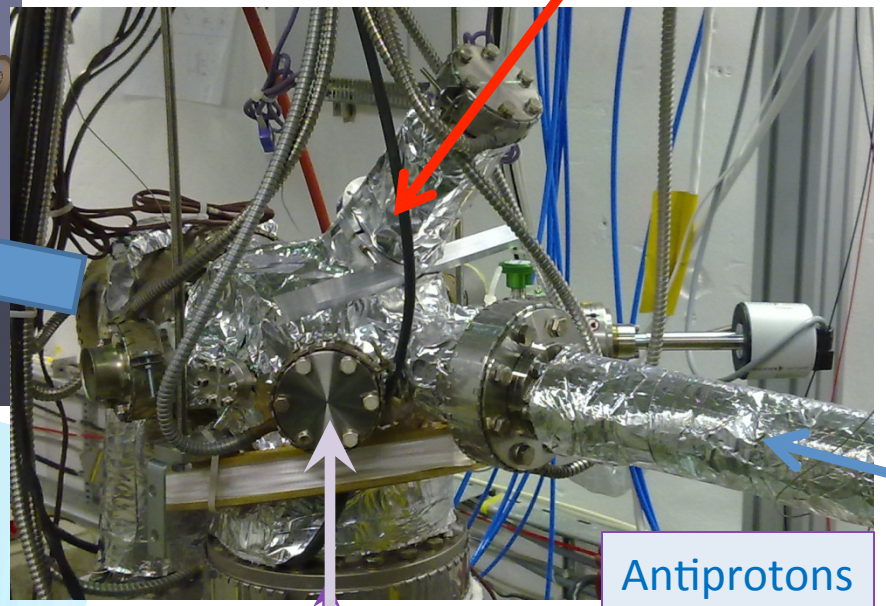
$$\bar{p} + (Ps)^* \rightarrow \bar{H}^* + e^-$$

$$p + (Ps)^* \rightarrow H^* + e^+$$

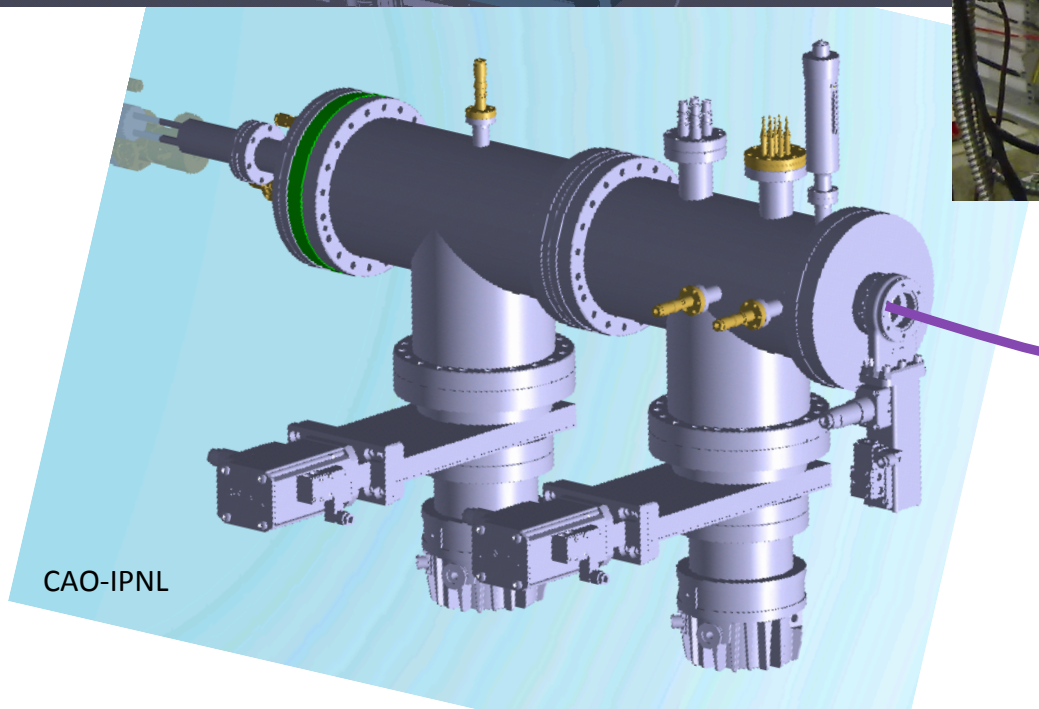
Des protons dans AEgIS



Positrons
To MC



Antiprotons
From AD



Protons
to mixing chamber :

Les protons suivent
le meme chemin dans AEGIS
que les pbar

Conclusion

- **AEGIS : expérience physique fondamentale**
  - **Collaboration internationale (CERN)**
    - **Réunie des physiciens de domaines ⅄ (HEP, laser, atome, cryogenié, …)**
    - **Démarrée en 2012 (e+,oPs,p); 2014 (H-Hbar)**
    - **France: Lab. A. Cotton, IPNL**
  - **Techniques HEP ⇔compétences CNRS/IN2P3/IPNL**
    - **Faisceau p, Mécanique (BE, Atelier), DAQ, Qualité, …, Administration**
  - **« Amusante & Formatrice »**
    - **Il y a plein de physique ! HEP, Ps, atomique, beams, laser, cryo, H, Hbar,…**
    - **Outreach / Grand Public**
- **Des extensions possibles (faisceau e+,ELENA) :**
  - **Etudes oPs (fondamentales + matériaux)**
  - **Violation de CPT, spectroscopie, comparaisons H-Hbar**