

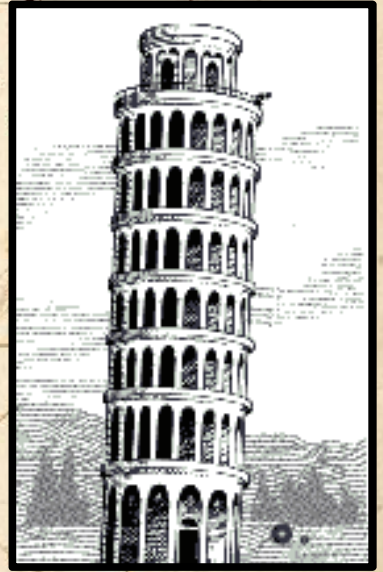
# AEGIS – CS – IN2P3

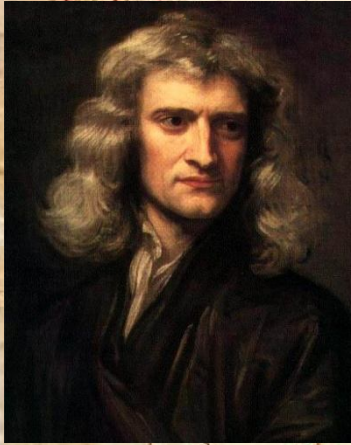
## 2 février 2012



Galileo Galilei - 1564 – 1642

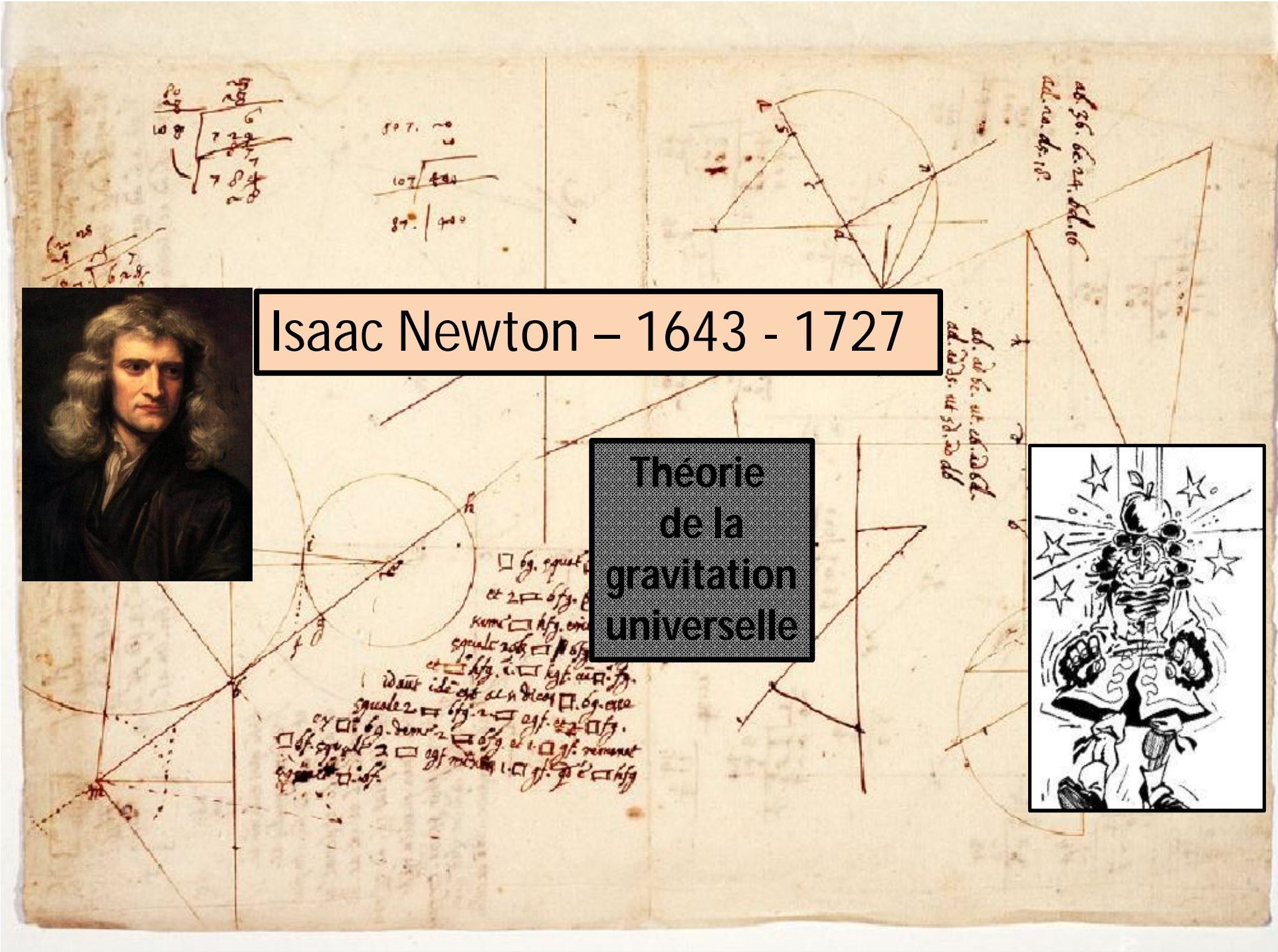
1<sup>ere</sup> mesure expérimentale de la chute gravitationnelle de la matière

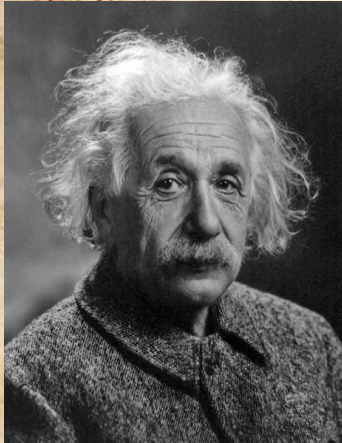




Isaac Newton – 1643 - 1727

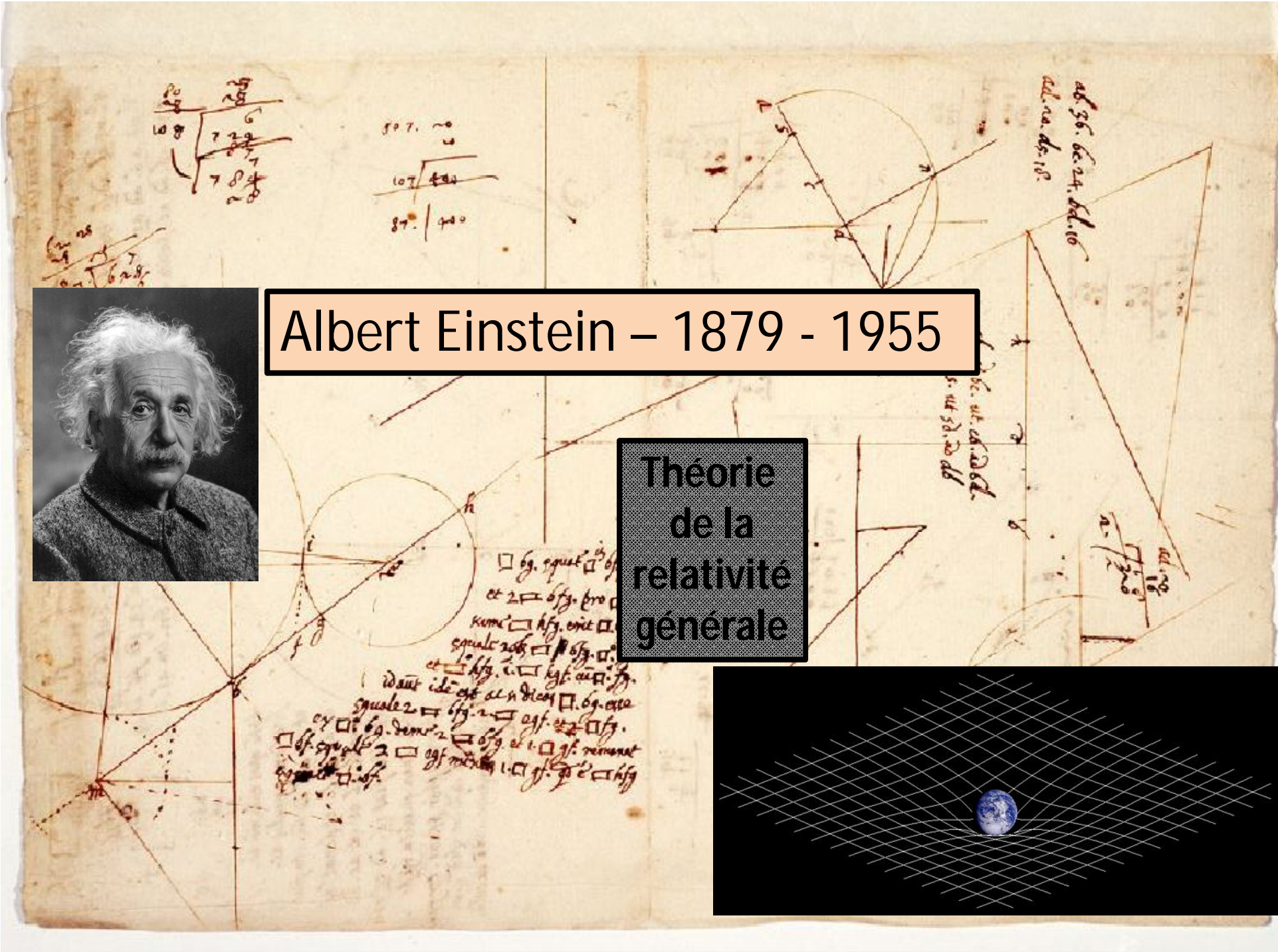
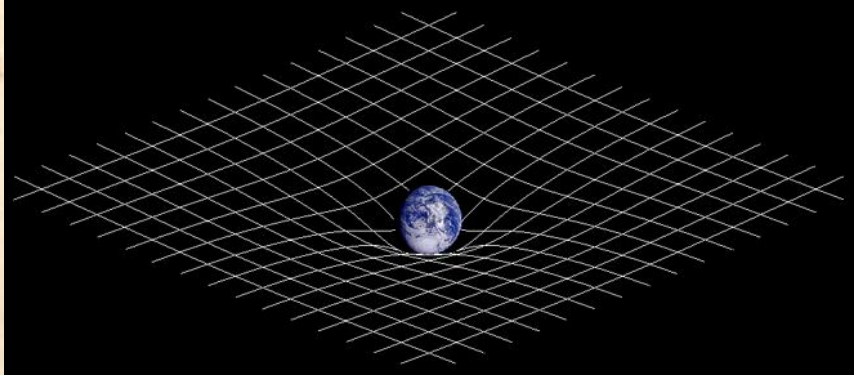
Théorie  
de la  
gravitation  
universelle





Albert Einstein – 1879 - 1955

Théorie  
de la  
relativité  
générale



Asymétrie Matière - antimatière

symétries  $C, P, CP, CPT$  ?

Matière sombre ?

Situation expérimentale/théorique

Energie noire ?

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

Peu de mesures  
Des interrogations

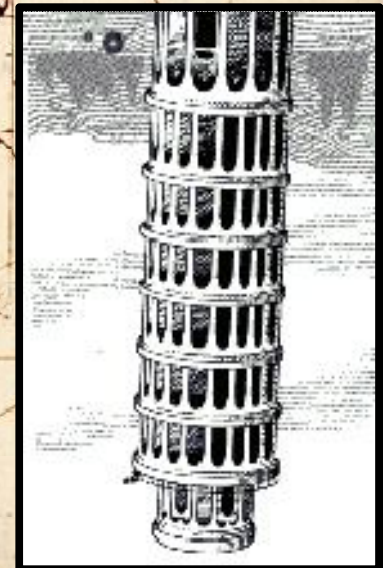
Quelles expériences  
Pour demain ?

Idées claires ?



AEGIS - 2010 – 202x

1<sup>ere</sup> mesure expérimentale de la chute gravitationnelle de l'ANTIMATIÈRE



# 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 vacuum : D.S.Hajdukovic, Astro Space Sciences 338, (March 2012)
- Nouvelles expériences :
  - Gbar (CERN-AD 2016)
  - AEGIS (CERN-AD6 -2012)

Pierre FAYET

Int. Workshop on Antimatter and Gravitation  
Paris, October 10<sup>th</sup>, 2011

## CONCLUSIONS

Comparing the behavior of particles and antiparticles in a gravitational field would allow to further establish the validity of the **Equivalence Principle** and of the basic principles of **Quantum Field Theories**

*One should also be attentive to possible new long-range forces, as mediated by a massless or light **U boson** gauging an **extra-U(1) symmetry***

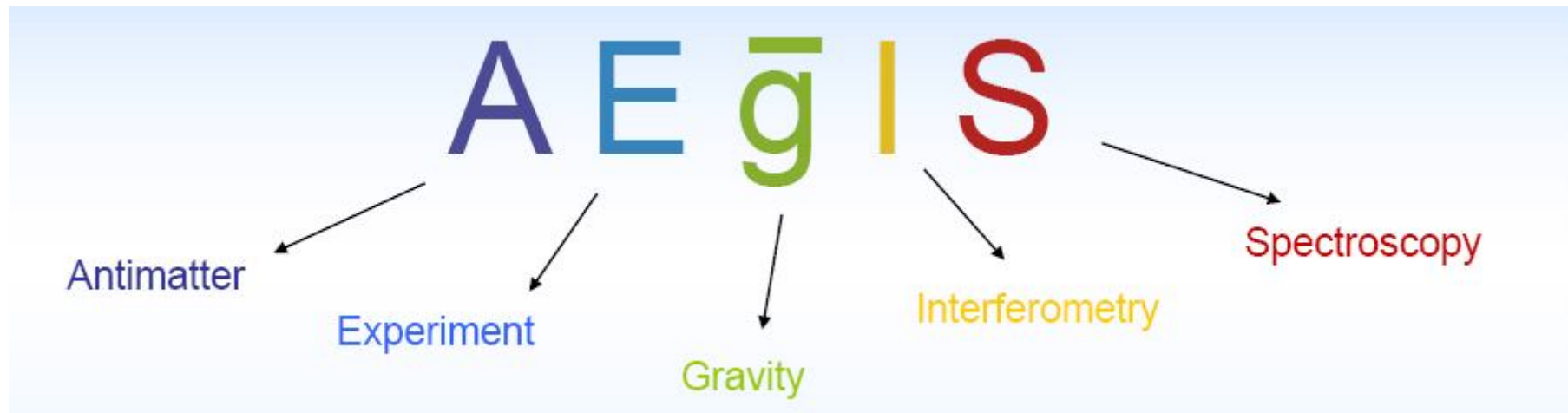
Hard to imagine how  $H$  and  $\bar{H}$  would fall  
or could be measured to effectively fall differently

*(but more room for surprises with charged particles, especially electrons and positrons)*

***The action of gravity on antimatter is worth being tested***

# Proposition pour une participation à l'expérience AEGIS/AD-6

$e^+$       oPs       $\bar{H}$





# The $AE\bar{g}$ IS physics goals

**Primary goal:** measurement of the Earth gravity acceleration  $g$  on antihydrogen

Test Weak Equivalence Principle

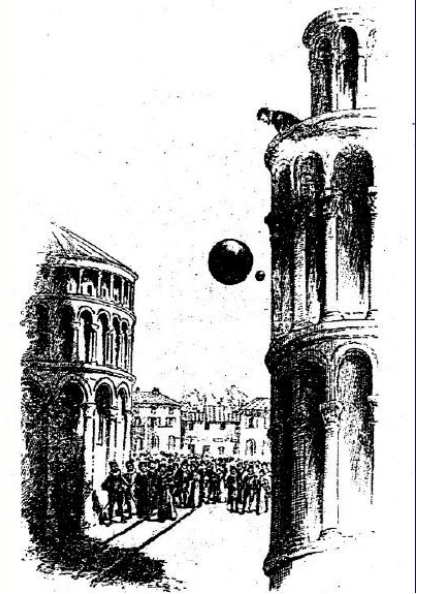
- The trajectory of a falling test body depends ONLY on its INITIAL POSITION and VELOCITY and is independent of its composition
- All bodies at the same spacetime point in a given gravitational field will undergo the SAME acceleration

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

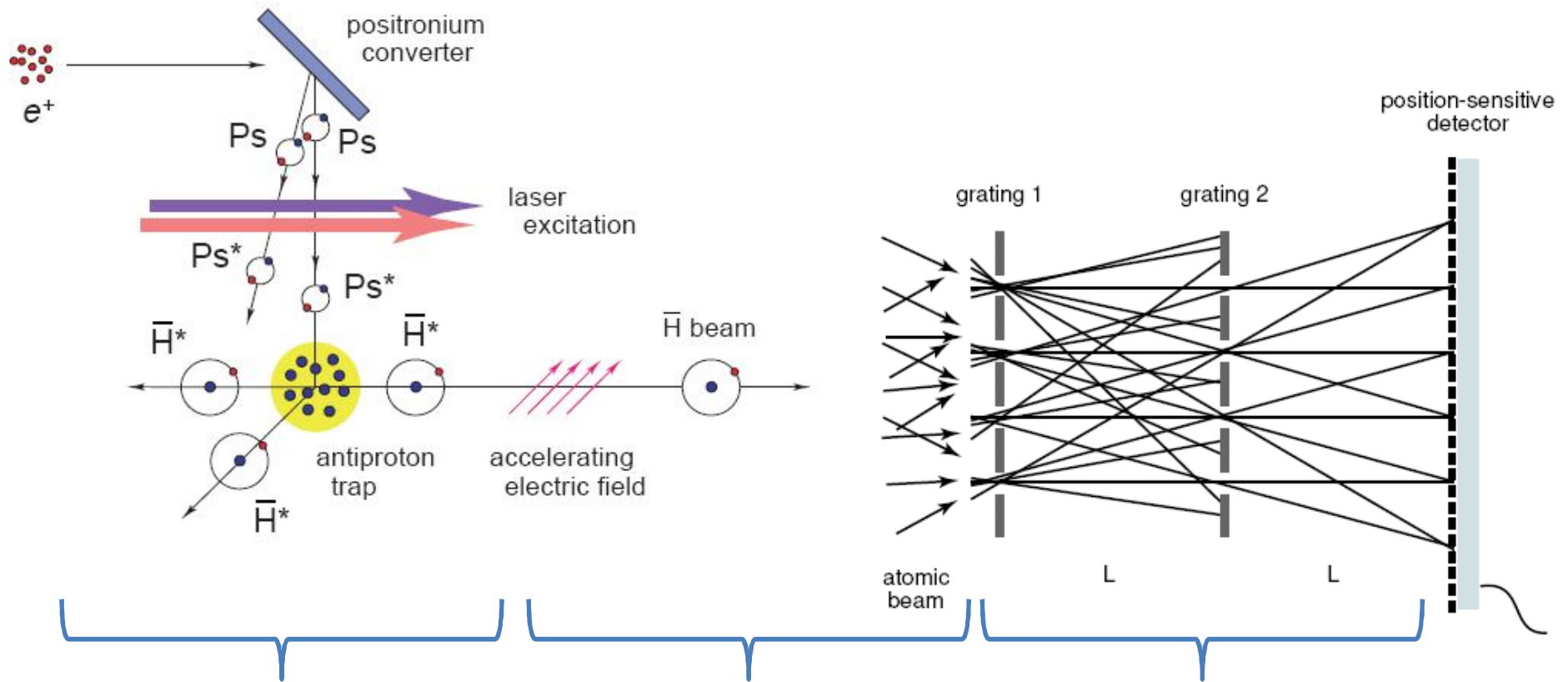
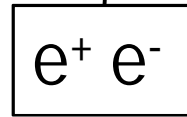
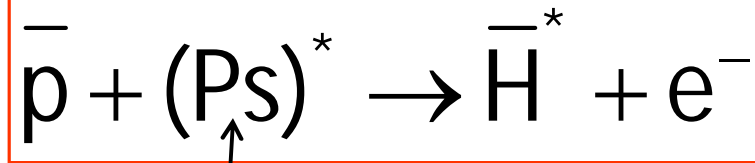
Precision : first goal 1% with  $10^5$  antihydrogen atoms  
higher accuracy in the future

**Additional physics interest:**

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

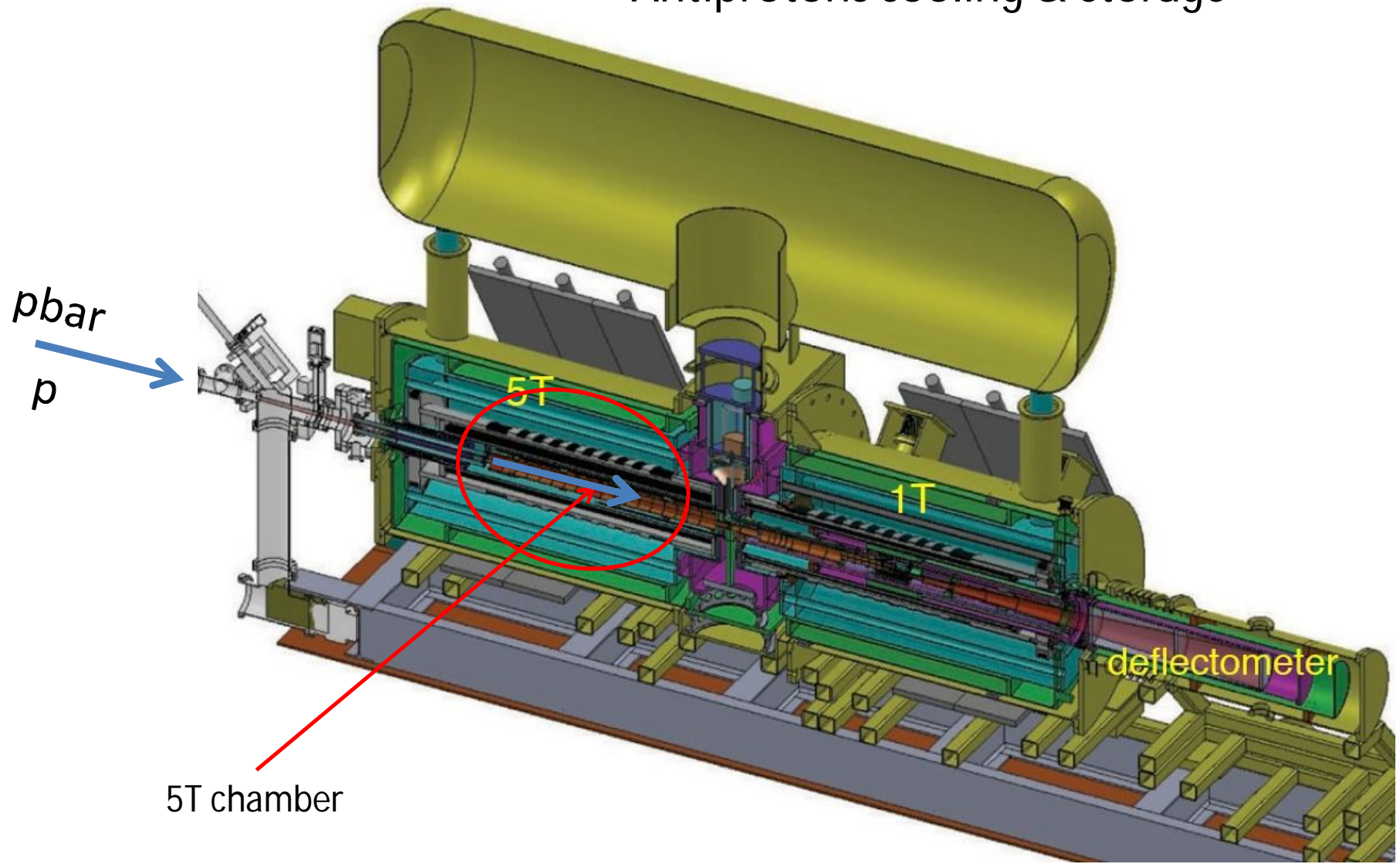


Principe :



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

# Antiprotons cooling & storage



$p\bar{a}r$   
 $p$

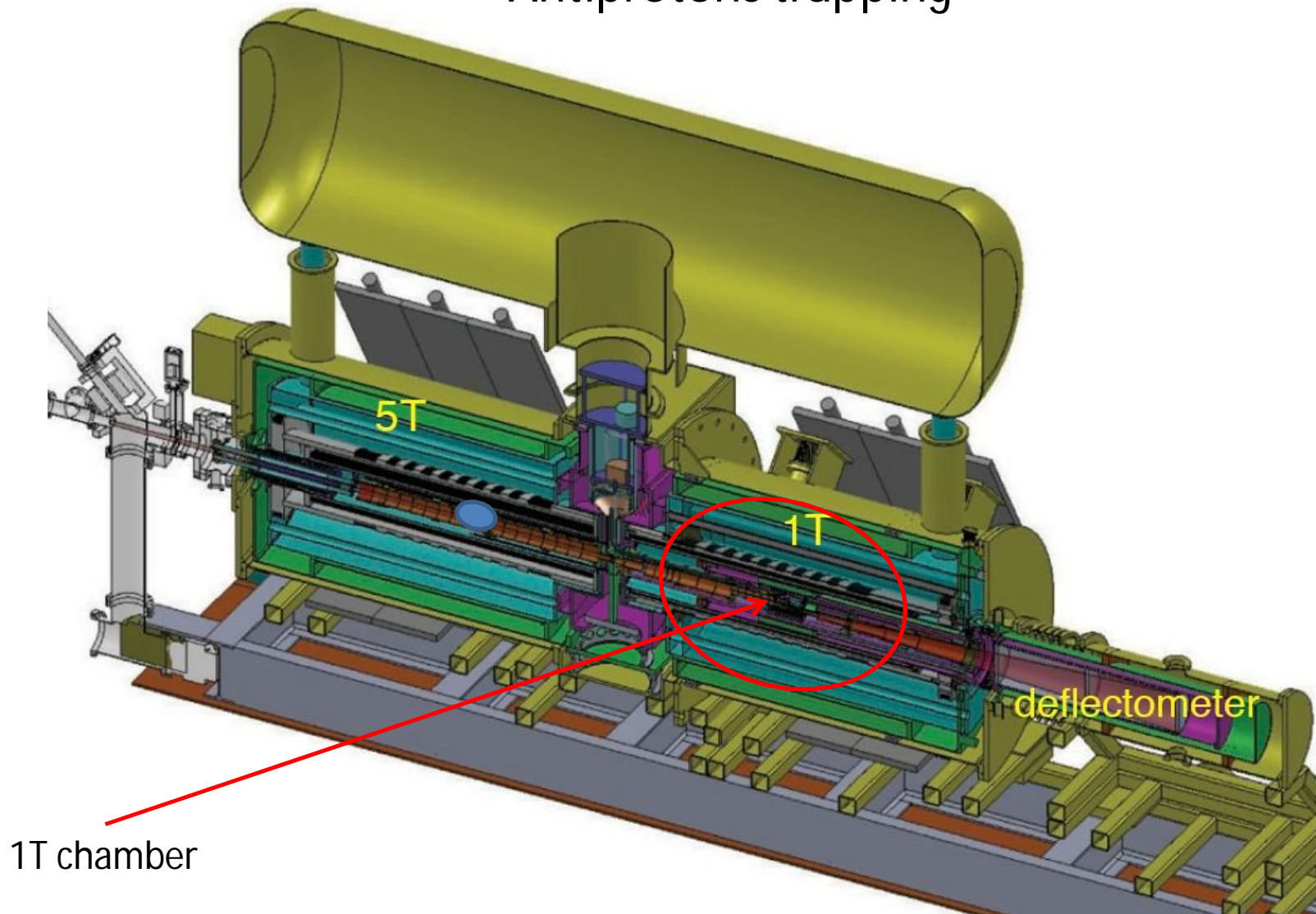
5T

1T

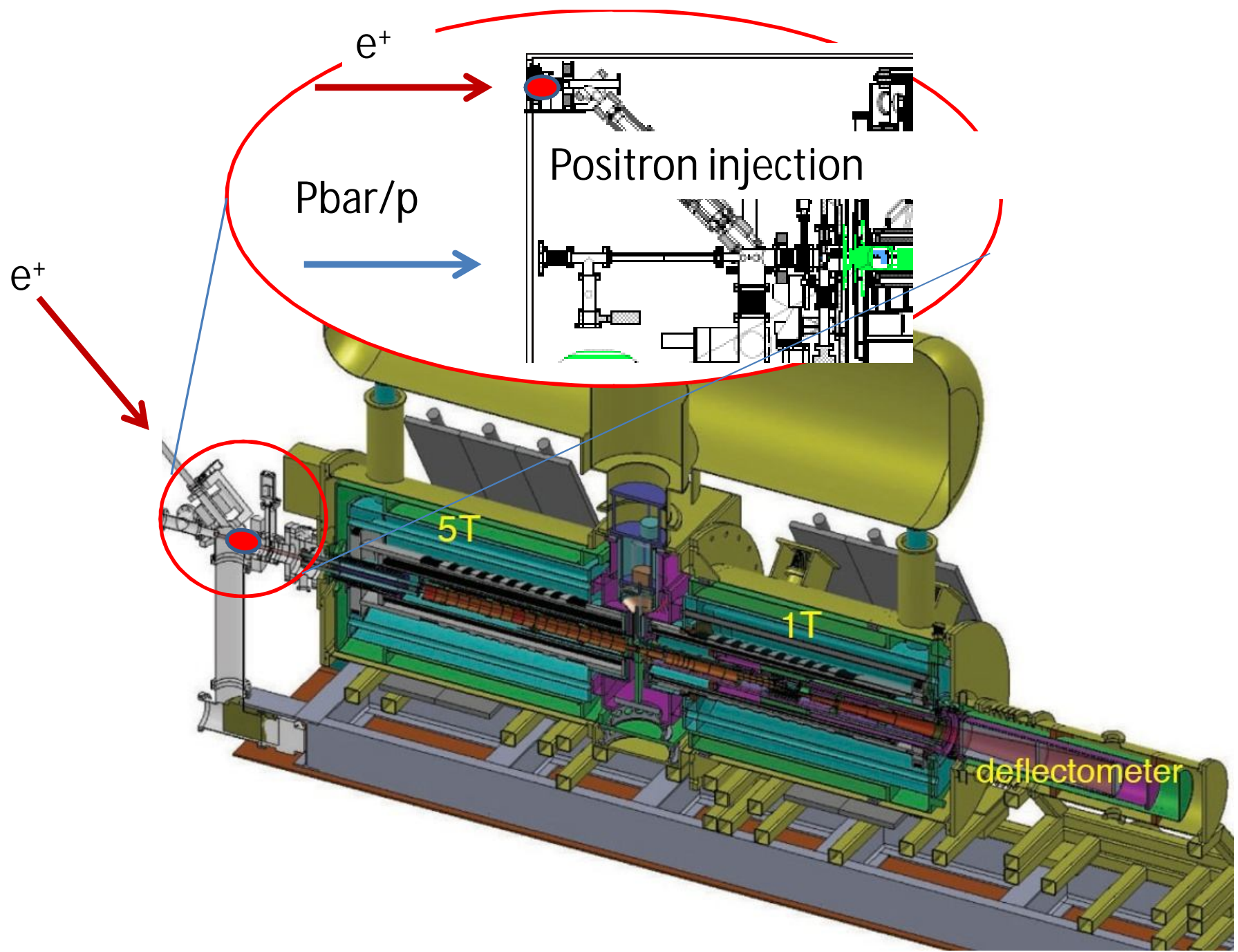
deflectometer

5T chamber

# Antiprotons trapping

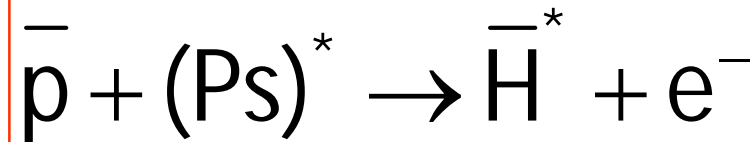


1T chamber

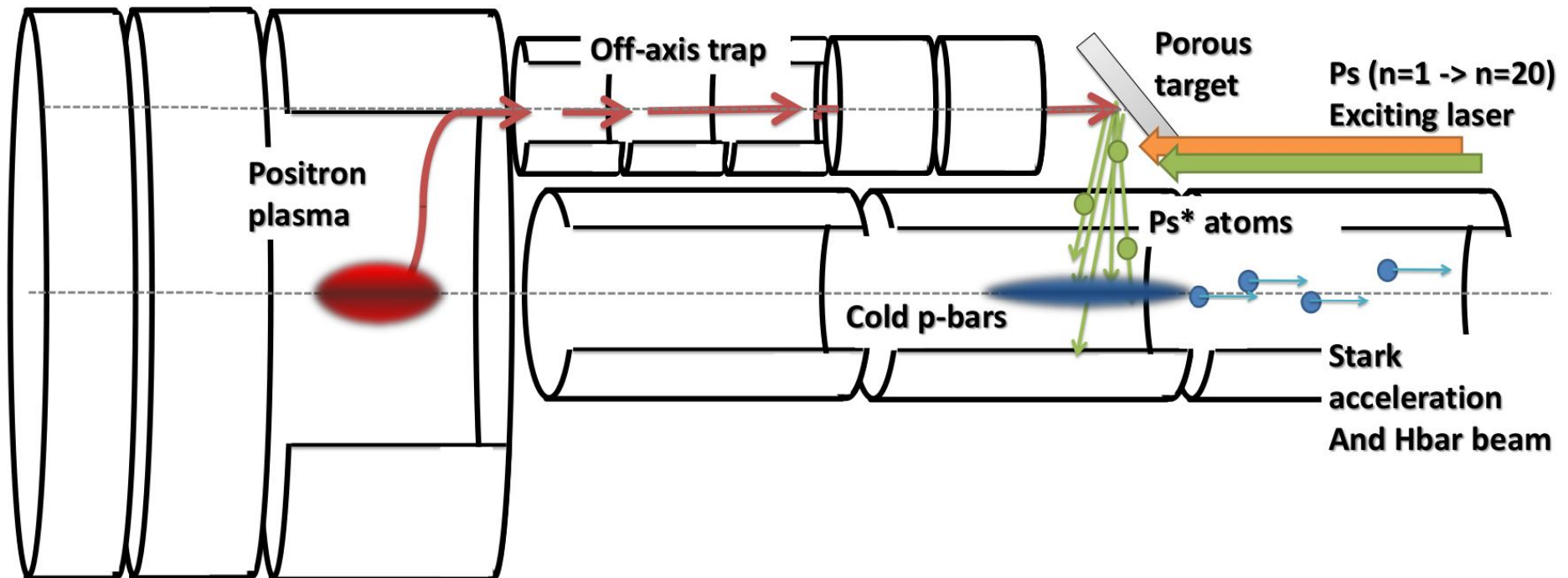


# AEgIS : antihydrogen production

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



- 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
  - $2 \cdot 10^7$  / 200 ns

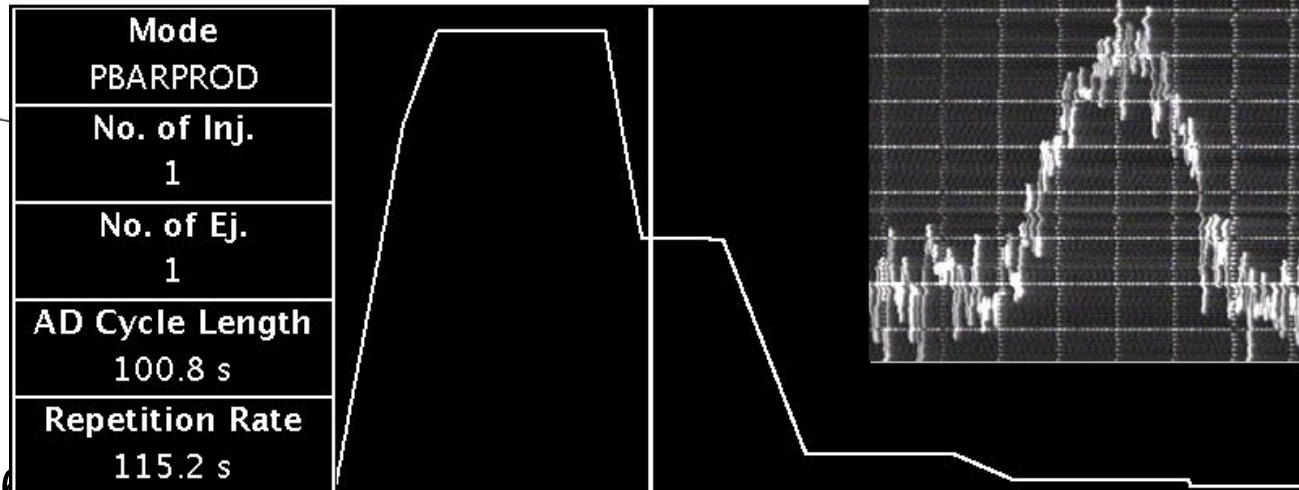
- (futur → ELENA (2016))
- E=100 keV

First AEGIS pbar signal



10-Nov-2011 15:34:58

ADE Fixdisplay



CPS	TFA9012	TFA9053	3.5 GeV/c	2 GeV/c	300 MeV/c
1512.7	1542.0	1529.0	3.68 E7 100 %	3.63 E7 98 %	3.35 E7 91 %
100 MeV/c R	100 MeV/c E	TFA7049	Spare	Spare	Spare
3.4 E7 92 %	3.27 E7 88 %	3.02 E7 81 %	NYI	NYI	NYI

ANTIPROT for AEGIS

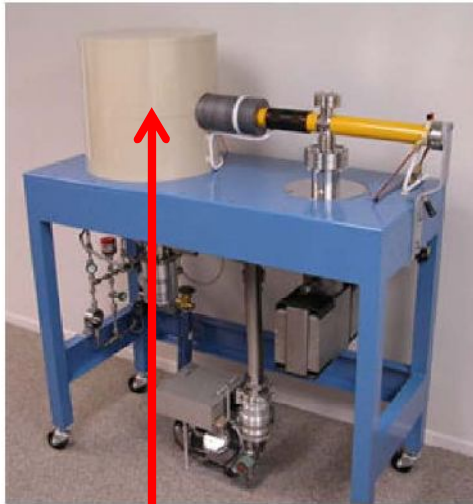
Comments: 07 Nov 2011 09:29:18

PHONE 8h30-17h30 : 165954/ 17h30-8h30, CCC (76677)

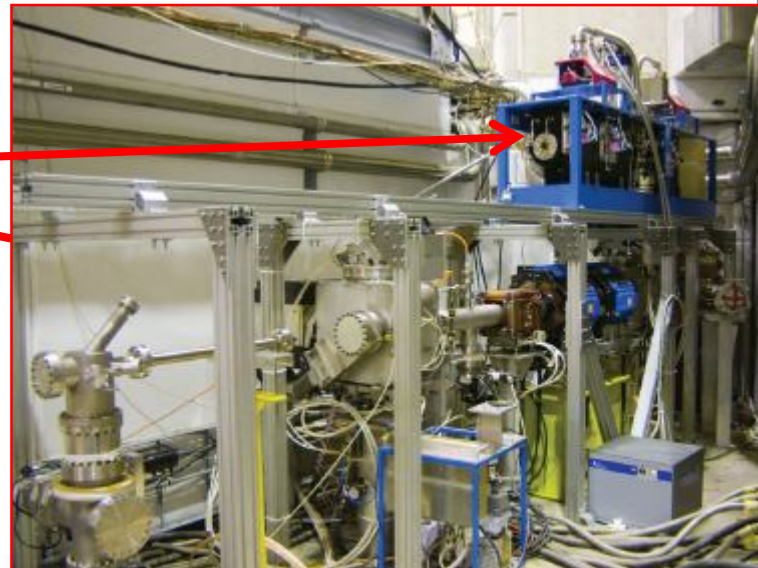
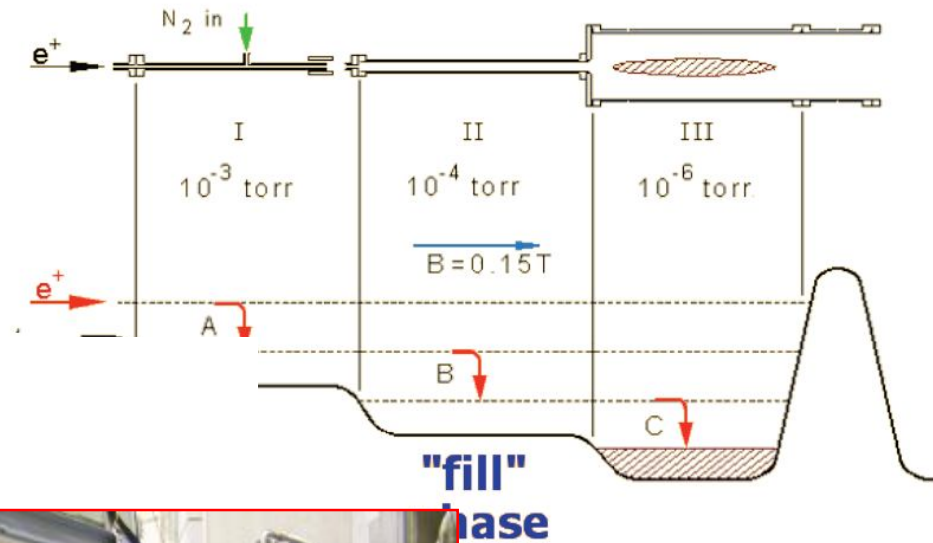
No Message

# The AEGIS : positrons beam

Accumulate a cloud of positrons in a trap:



- <sup>22</sup>Na source
  - 25 mCi – May 2012
  - 75 mCi > 2013
- ABPS
  - Installed @ AD
- Accumulator
  - Feb 2012
  - $3 \times 10^8$  e<sup>+</sup> in few min.
  - B=0.15-0.20 T





# AEGIS : Production of positronium

- Ps : Produce ground state positronium sending the  $e^+$  into a nanoporous target :

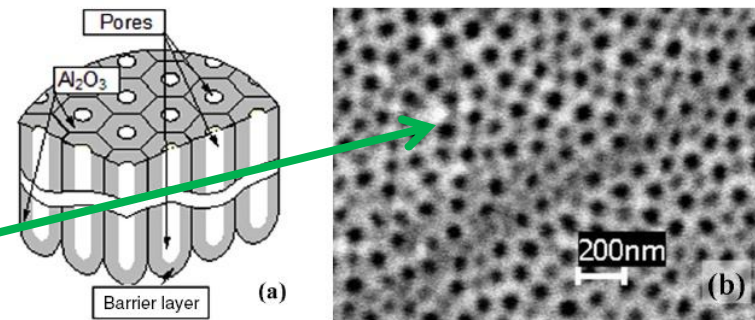
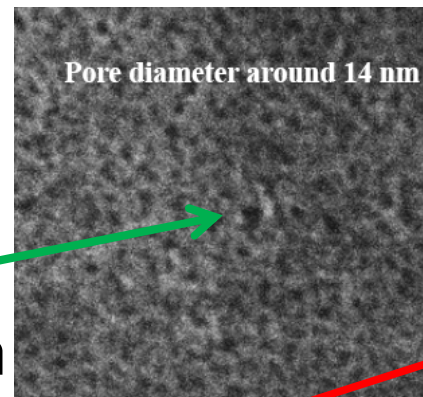
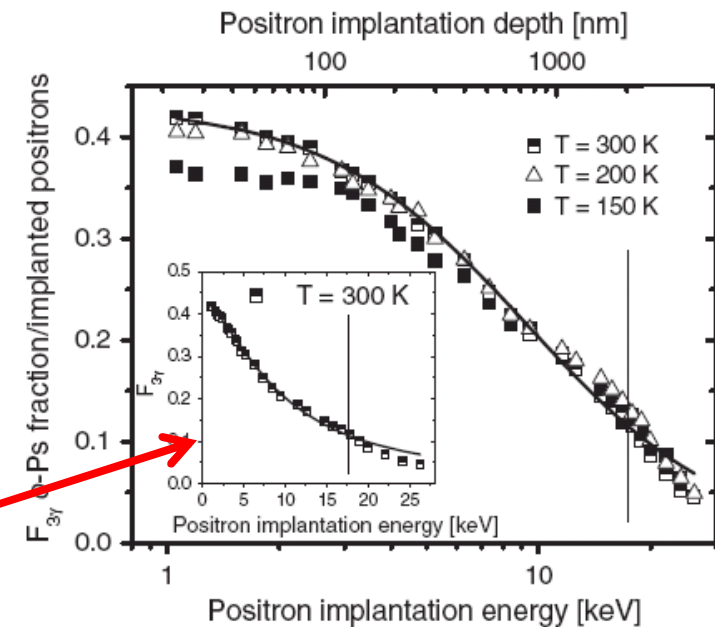


Figure 1. (a) Schematic representation of anodic alumina structure and (b) electron microscopy image of the surface of anodic  $Al_2O_3$ .

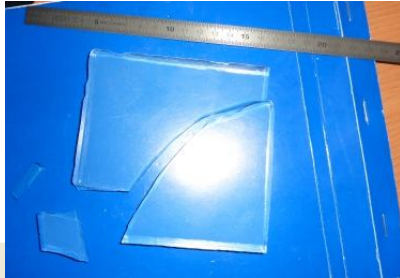
- $Al_2O_3$  (INP, IPNL) :
  - $\tau_0 = 142$  ns
  - Pores  $\sim 30$ -50 nm
  - 22% produced oPs /  $e^+$



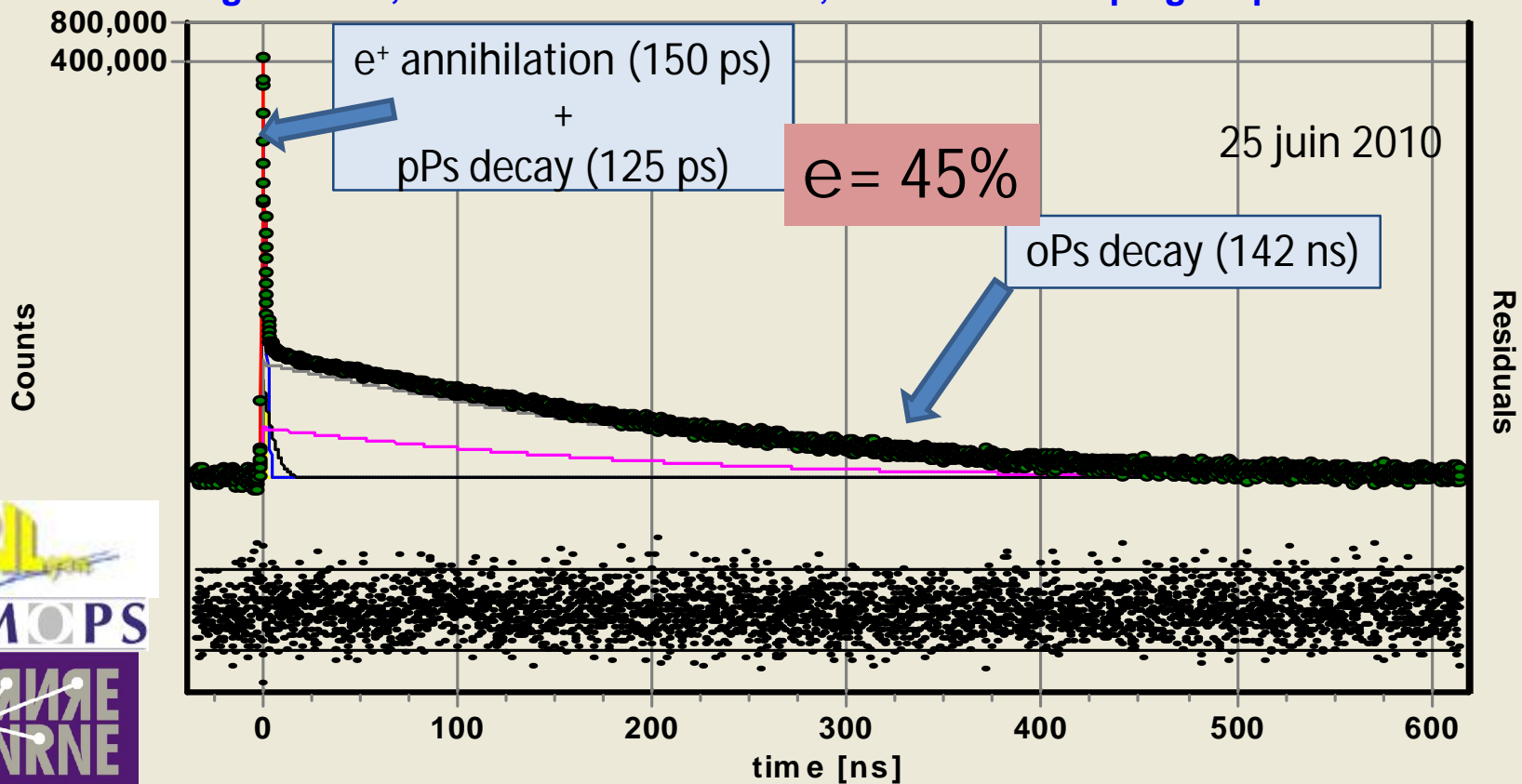
- Si/SiO<sub>2</sub> (INFN) :
  - Pores  $\sim 10$ -20 nm
  - 35-40% produced oPs /  $e^+$



# Production d'oPs dans l'aérogel



Aerogel SP30, in vacuum 10-5 mBar; binwidth = 181ps group2 to 12



# AEgIS : oPs excitation

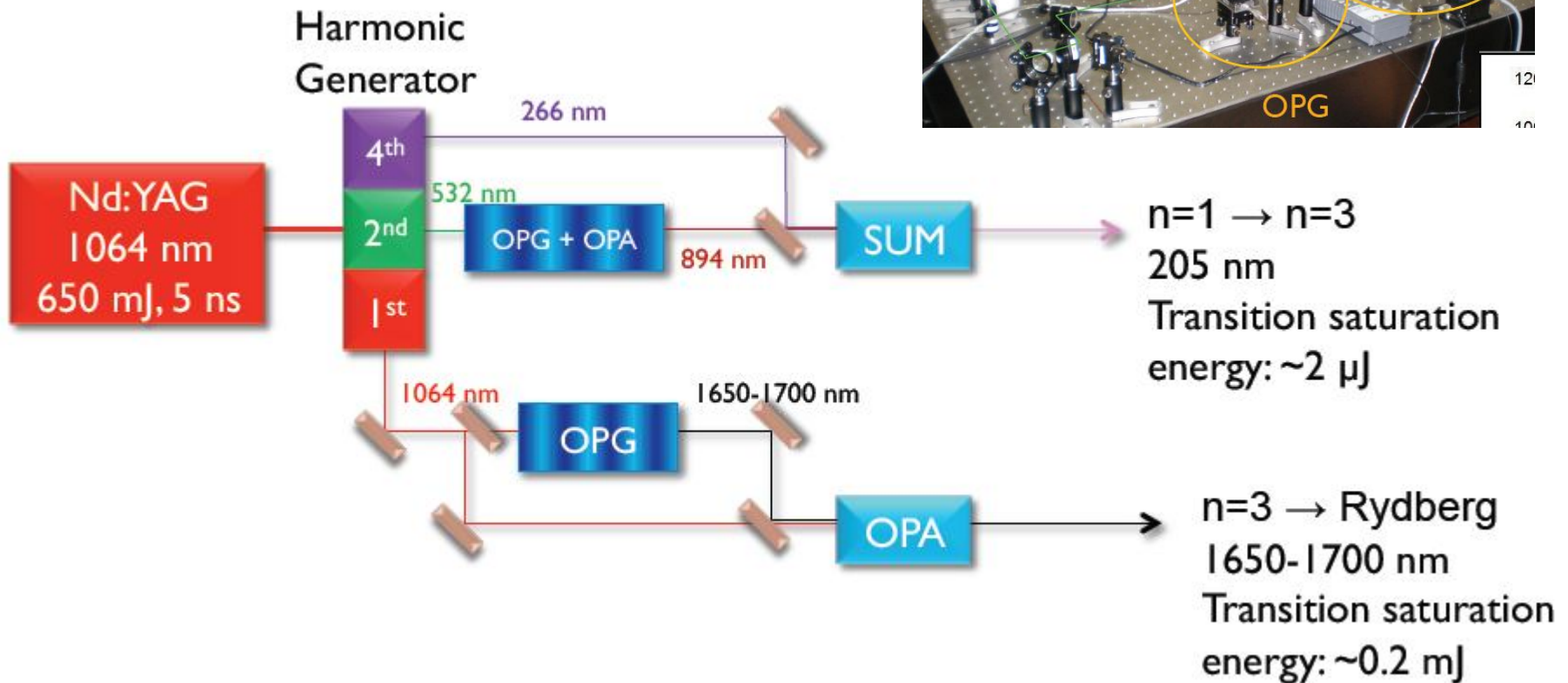
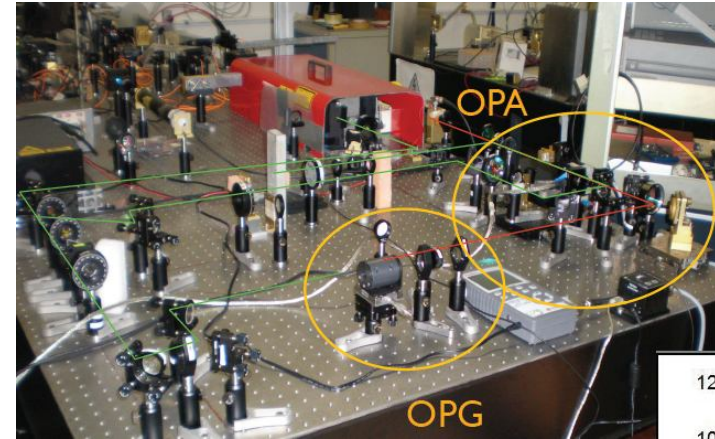
• oPs\* : produce Rydberg positronium via laser excitation:  $n=1 \rightarrow n=3$  ;  $3 \rightarrow 30-35$

•  $G \propto 1/n^3$

•  $t = 1/G \propto n^3$

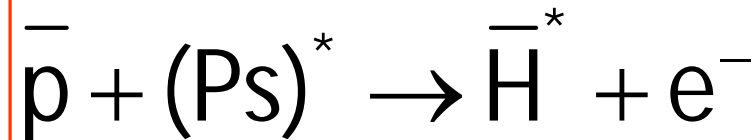
•  $n = 30-35 \rightarrow t = 4-8$  ms

• Contributions/studies: CNRS-LAC & INFN



# AEgIS : antihydrogen production

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

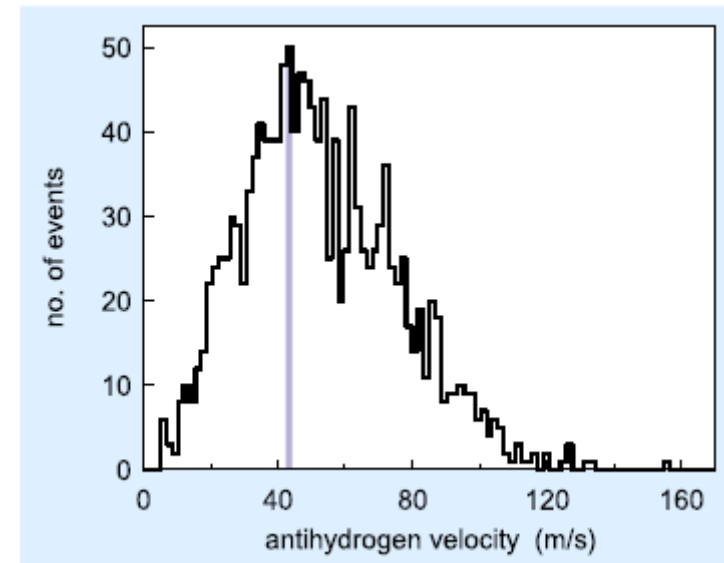


- Principle demonstrated by ATRAP ( $\text{Cs}^* \rightarrow \text{Ps}^* \rightarrow \bar{\text{H}}^*$ )
  - C.H. Storry et al. Phys. Rev. Lett 93 (2004) 263401

- Advantages:

- Large cross-section :  $\sigma \approx a_0 n^4$
- Narrow and well-defined n-state
- $\bar{\text{H}}$  production from ultracold pbar
  - Ultracold  $\bar{\text{H}}$
  - Pulsed production of  $\bar{\text{H}}$

- $T(\text{pbar})=100\text{mK}$ ;  $n(\text{oPs})=35 \rightarrow v(\bar{\text{H}}) \sim 45\text{m/s}$   
 $T(\bar{\text{H}}) \sim 120\text{mK}$



# AEgIS : antihydrogen beam formation

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

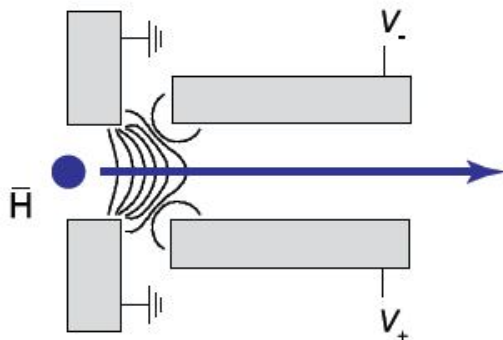
$$U = \frac{2}{3} ea_0 n(n-1) F$$

$$F = -\frac{2}{3} ea_0 n(n-1) \nabla F$$

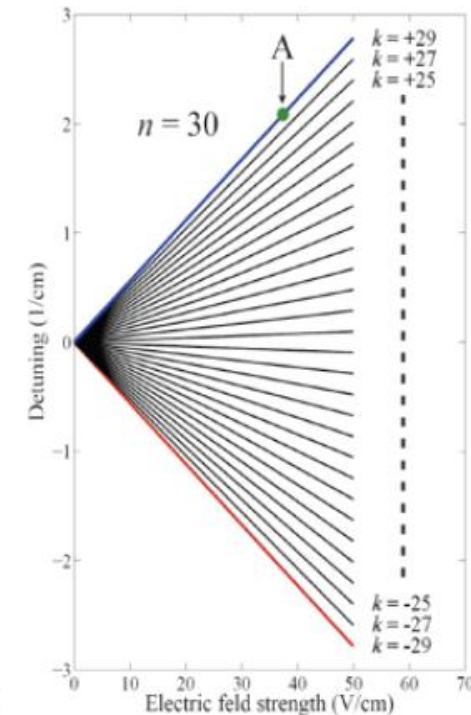
⇒ Rydberg atoms are very sensitive to inhomogeneous electric fields

- Stark deceleration of hydrogen demonstrated (ETH group)

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

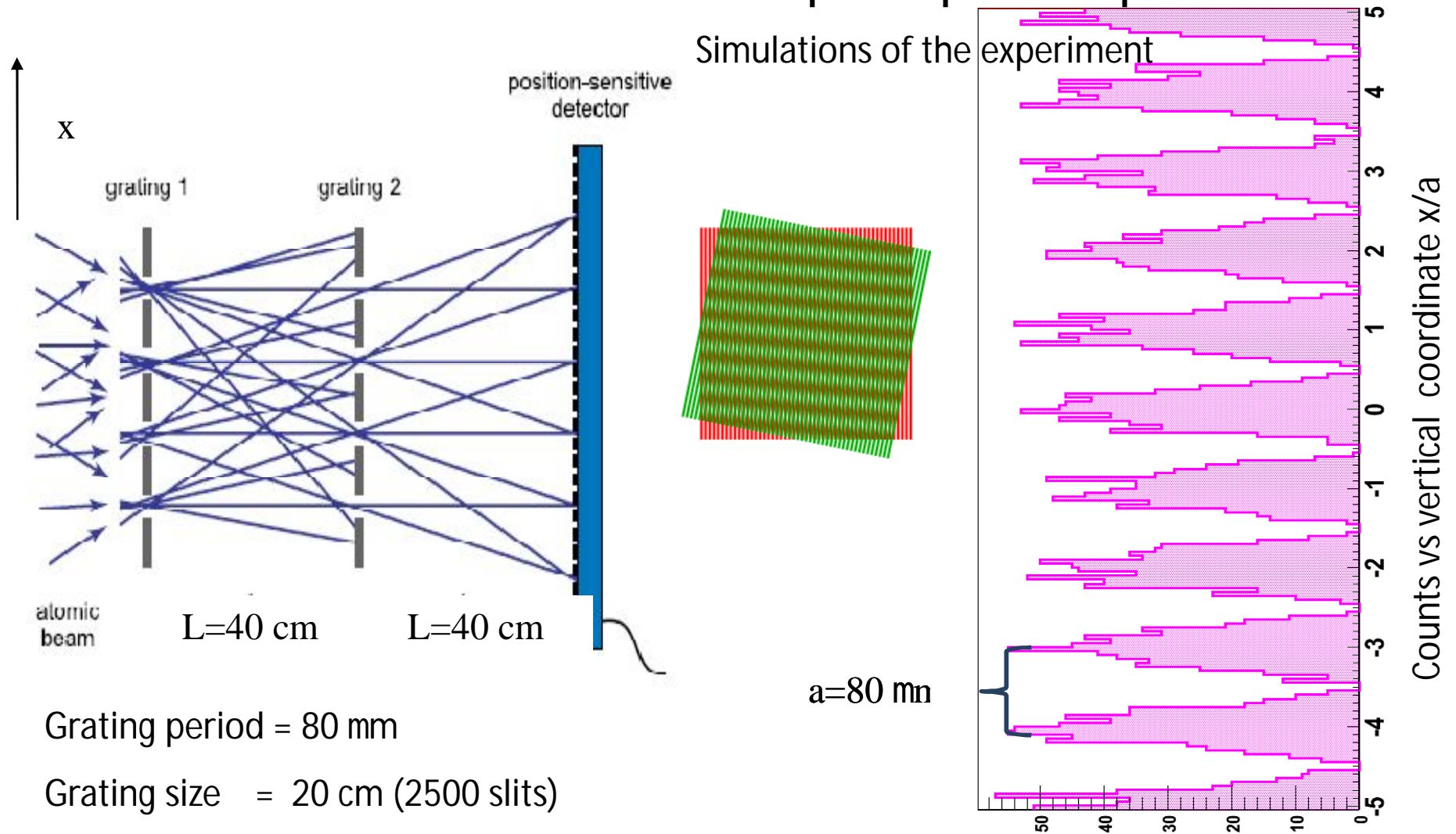


- $n = 22, 23, 24$
- Accelerations of up to  $2 \times 10^8 \text{ m/s}^2$  achieved
- Hydrogen beam at  $700 \text{ m/s}$  can be stopped in  $5 \mu\text{s}$  over only  $1.8 \text{ mm}$



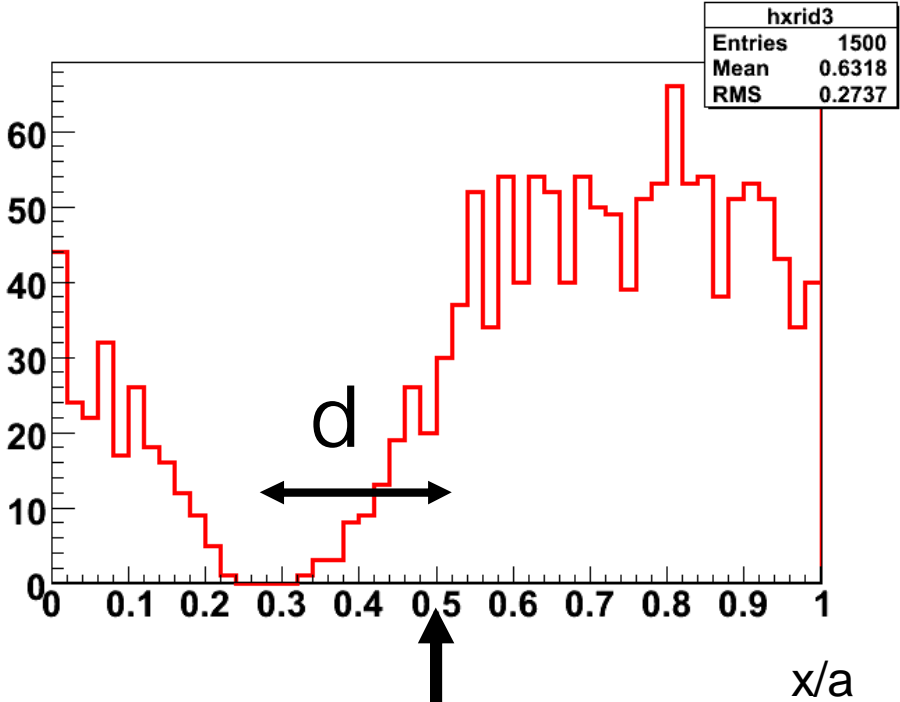
# AEgIS : free fall measurement

## The Moiré deflectometer : principle of operation



# Moire' deflectometer: simulation

Distribution of antihydrogen vertical position  $x$  modulo the grating unit  $a$



1500 detected antihydrogen  
 $V_z = 300$  m/s  
 Ideal detector

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

Time of flight

Grating period

Expected position of the minimum count if  $g=0$



# 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















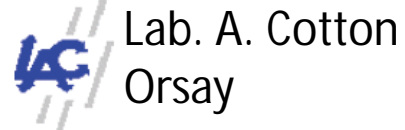
[A. Kellerbauer *et al.*, Phys. Rev. A **54** (1996) 3165]

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



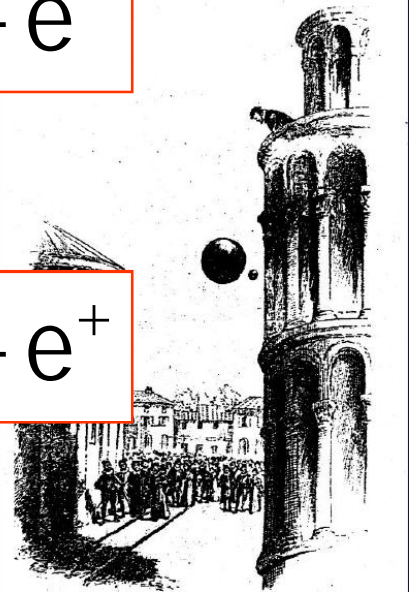
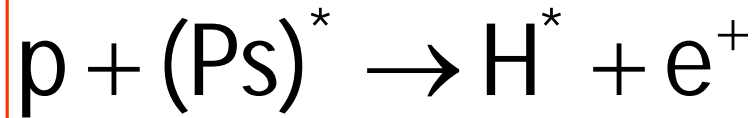
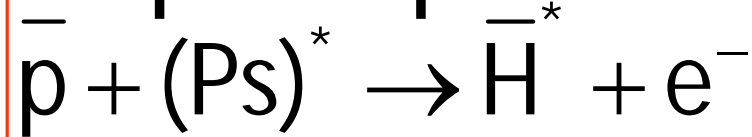


# The AEGIS collaboration (~50 f)

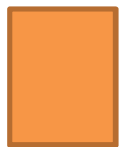
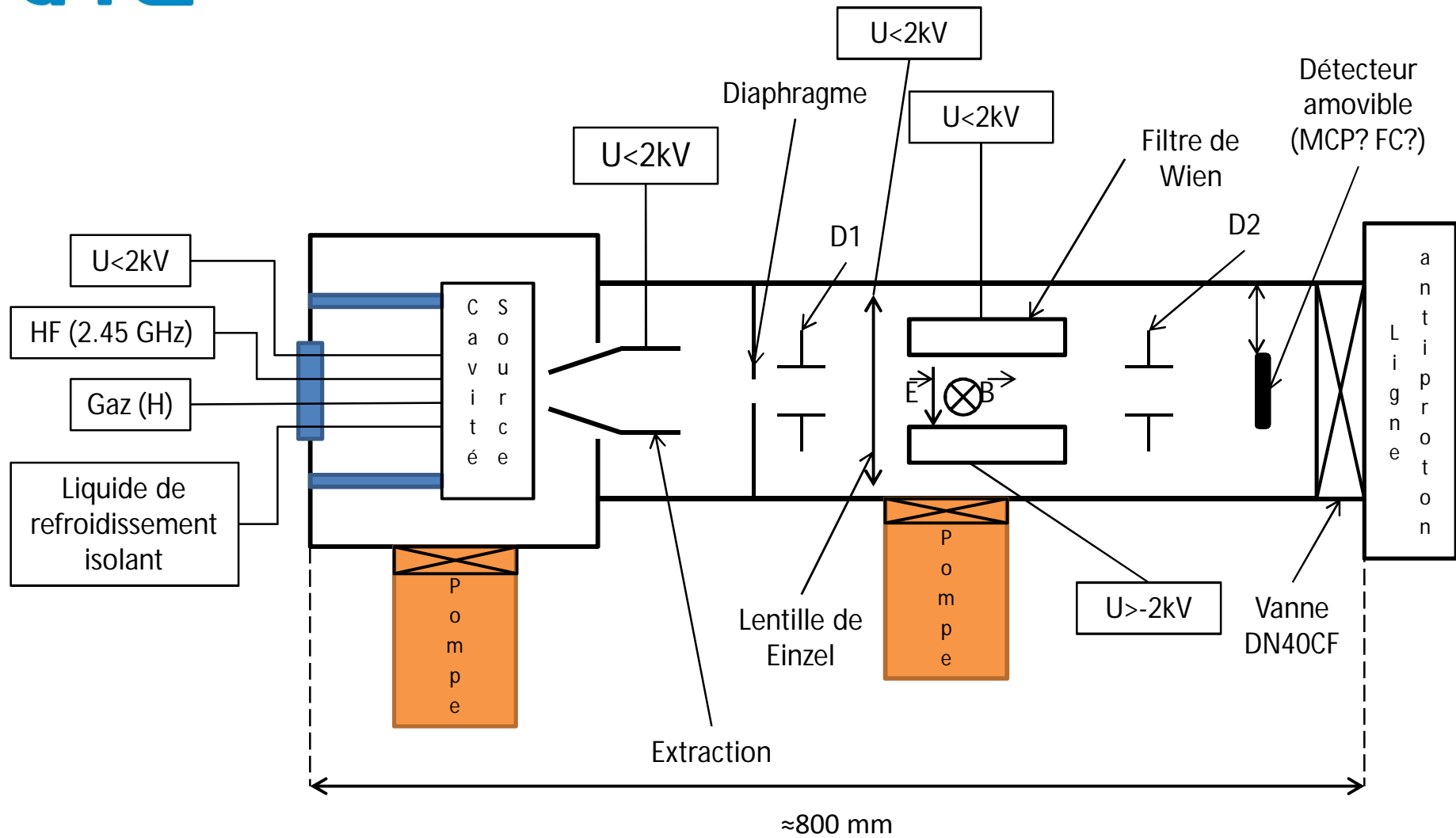
 <b>Bologne</b> M. Prevedelli	 <b>Gênes</b> <b>G. Testera</b> , V.Lagomarsino, Z.Zavatarelli, R. Vaccarone	 <b>Milan</b> M.Giammarchi, S.Cialdi, R.Ferragut, G.Consolati, F.Moia, F.Castelli, F.Prelz	 <b>Pavie</b> Bonomi, A. Fontana, L. Dassa, A. Rotondi, C. Riccardi
 <b>Trento</b> R. Brusa, S. Mariazzi, G. Nebbia, G. Ferrari	 <b>CERN</b> <u>M. Doser</u> J.Bremer, A. Dudarev, S. Haider, G. Burkhardt	 <b>Zurich</b> F. Merkt, S. Hogan	 <b>Univ. Zurich</b> C. Amsler, C. Canali, C. Regenfus, J. Storey
 <b>Heidelberg Univ.</b> A. Kellerbauer	 <b>Heidelberg MPI-K</b> M. Oberthaler	 <b>Prague</b> V. Petracek	 <b>Bergen Univ. Olso Univ.</b> H. Sandaker, J. P. Hansen O. Rohne
 <b>Moscou</b> S. Gninenko, A. Belov, V. Matveev	 <b>ipnl</b> UNIVERSITE DE LYON H. El Mamouni P. Lebrun P. Nedelec	 <b>Lab. A. Cotton Orsay</b> 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?
  - $E < \text{qlq keV}$
  - $F \sim 10^6 - 10^8 \text{ p/s}$



# Schéma de principe de la ligne proton basse énergie pour AEGIS



Pompe  
turbomoléculaire



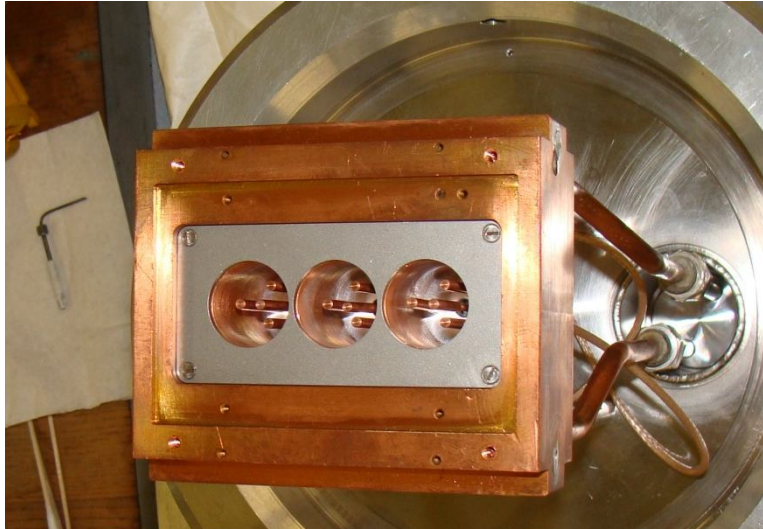
Isolant



Vanne

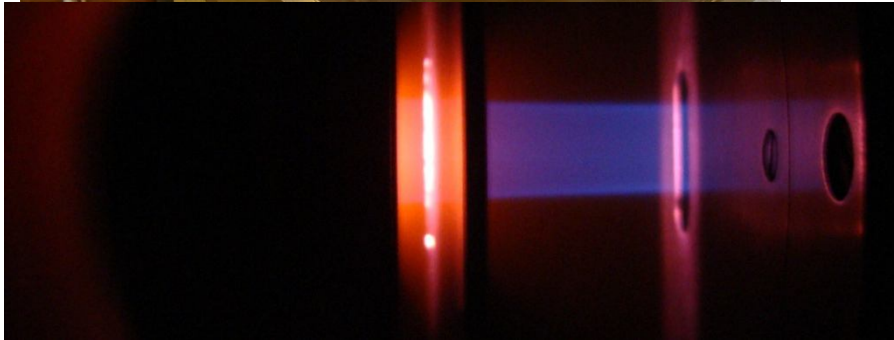
D1, D2 : Déflecteurs Y-Z

# Faisceau de proton: comment ?



Une compétence locale/régionale

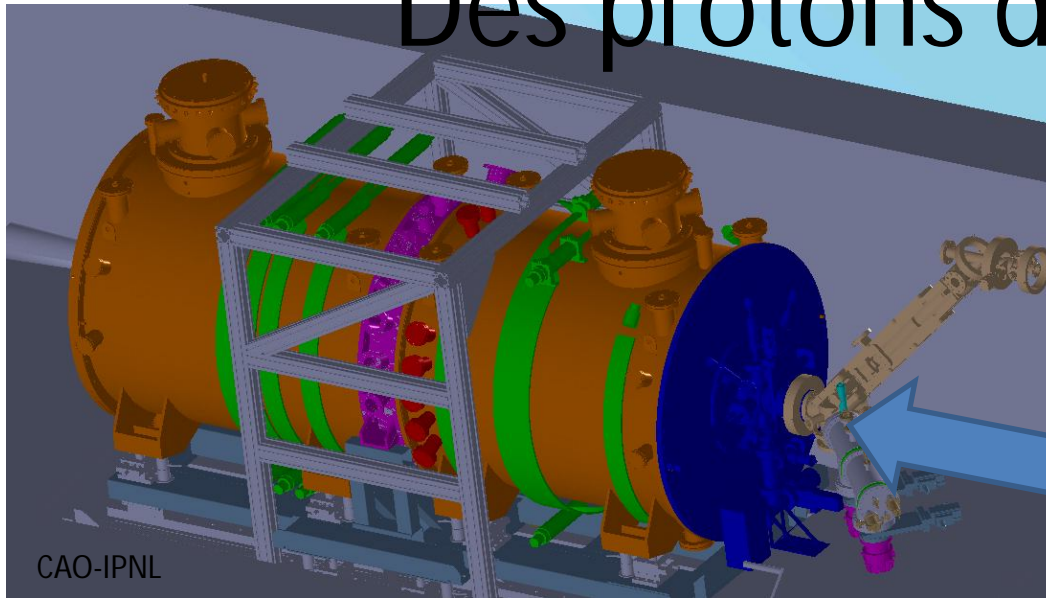
- IPNL/LPSC – COMIC
- P source 150kV – DIAM
- Implanter d'ions - ACE



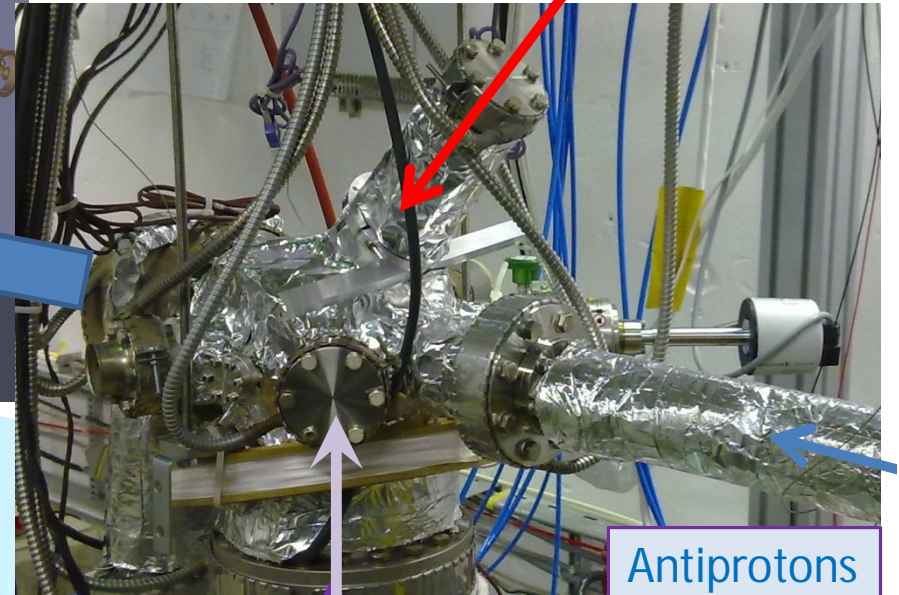
- Faisceau p IPNL/AEGIS
  - + simple ( $E \sim \text{qlq keV}$ ,  $F < 10^8$ )
  - Adaptation ligne AD/CERN



# Des protons dans AEGIS

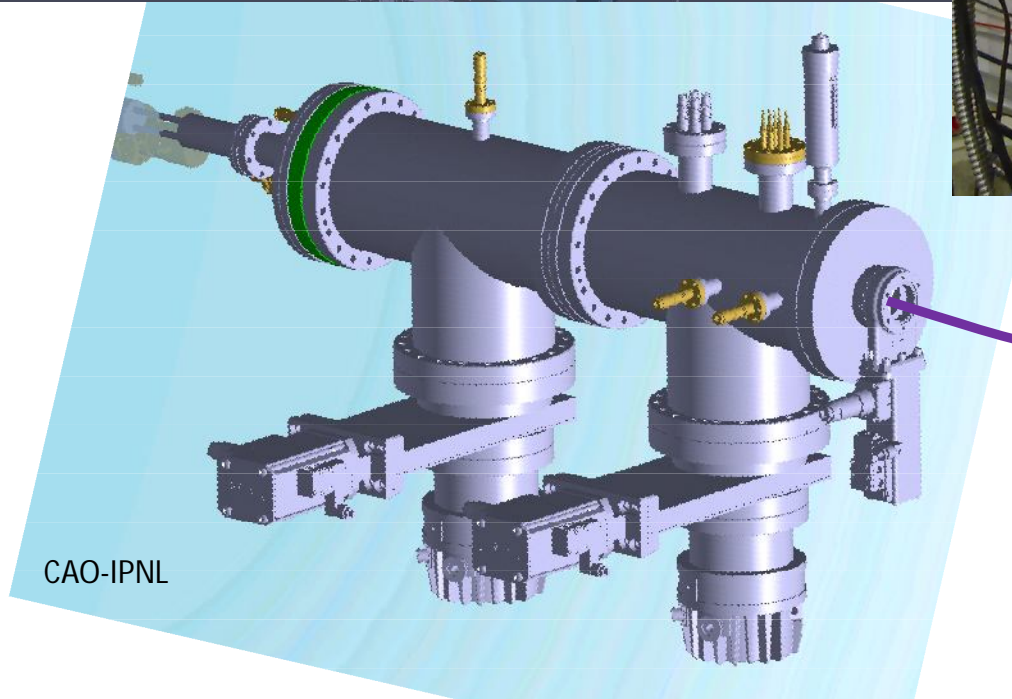


CAO-IPNL



Positrons  
To MC

Antiprotons  
From AD



CAO-IPNL

Protons  
to mixing chamber :

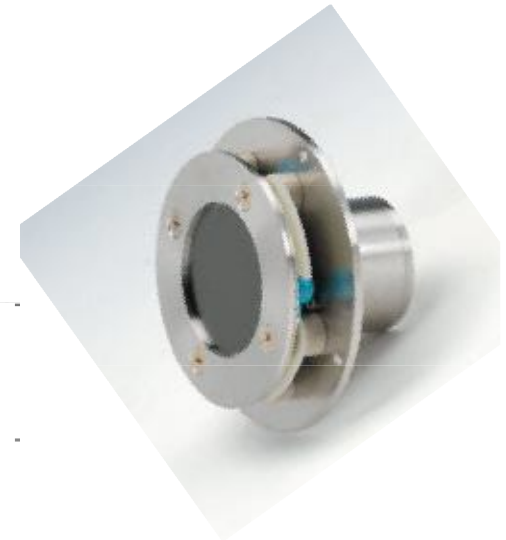
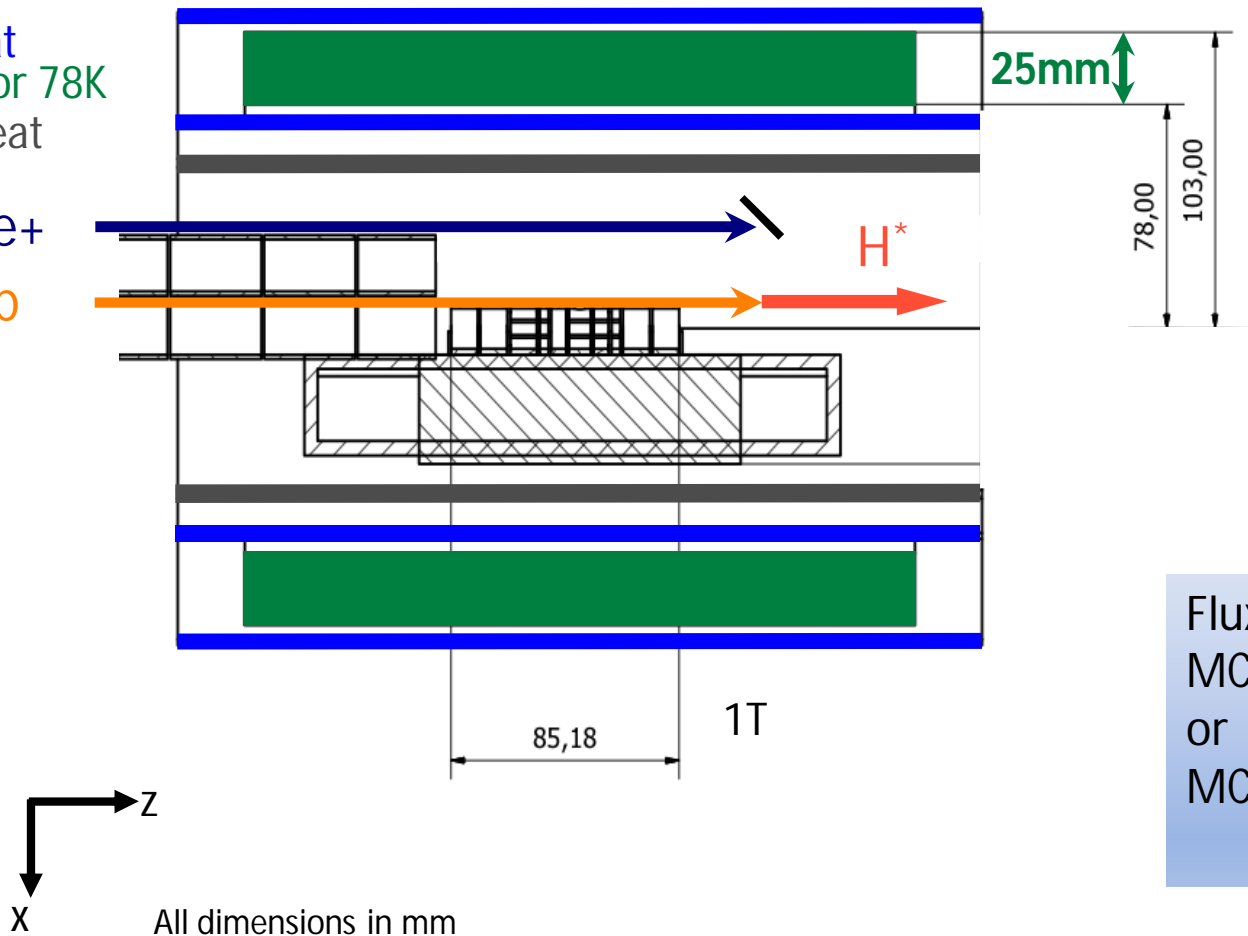
Les protons suivent  
le meme chemin dans AEGIS  
que les pbar



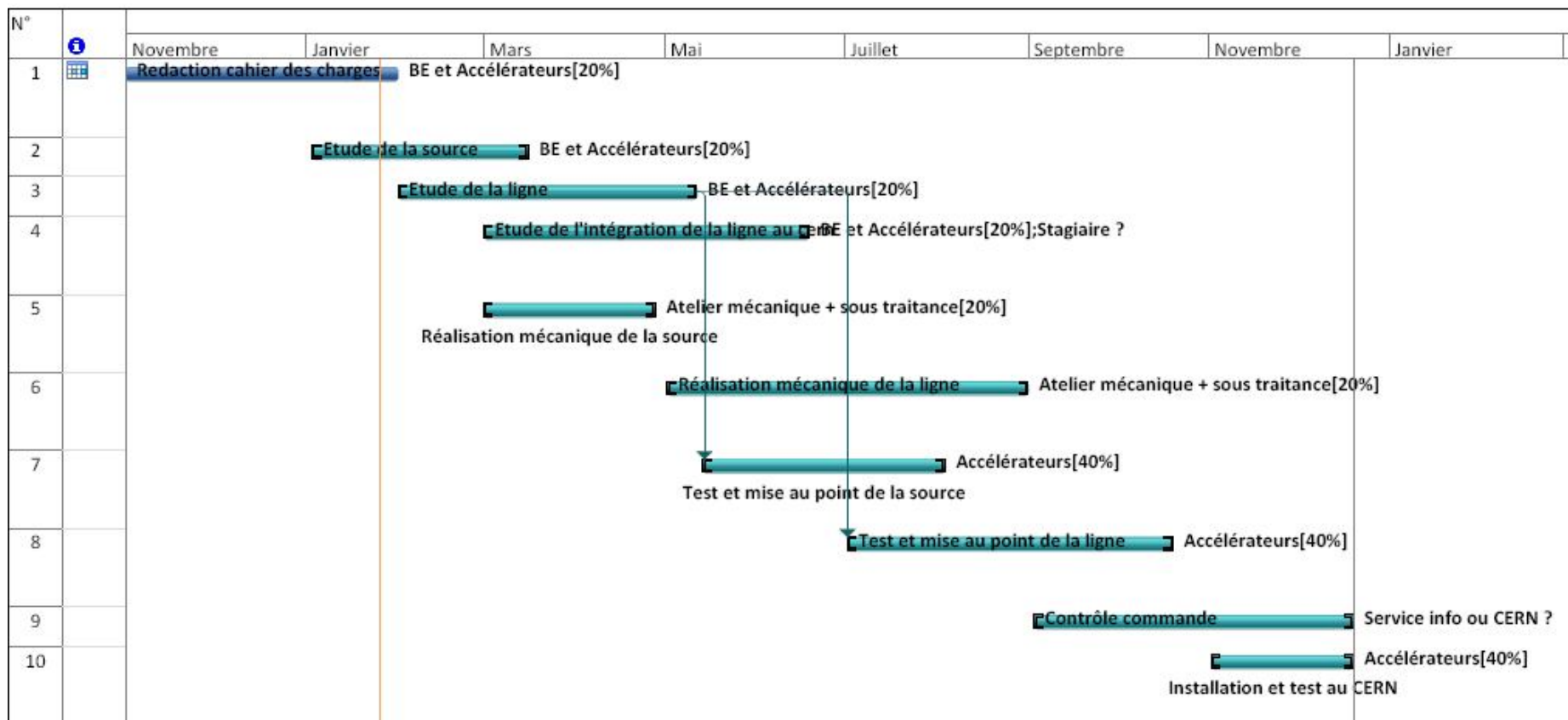
# H production and detection

4K anti-cryostat detector 78K  
1.5K heat shield

$e^+$   
 $p$



Flux of  $H^*$   
MCP – 2stages  
or  
MCP+Phosphore screen



Projet : aegis Date : Jeu 26/01/12	Tâche		Jalons externes		Report récapitulatif manuel	
	Fractionnement		Tâche inactive		Récapitulatif manuel	
	Jalon		Jalon inactif		Début uniquement	
	Récapitulative		Récapitulatif inactif		Fin uniquement	
	Récapitulatif du projet		Tâche manuelle		Échéance	
	Tâches externes		Durée uniquement		Avancement	



# AEGIS : participation/budget

- Source de protons pour AEGIS
  - Service Accélérateur : conception, réalisation
  - Service Mécanique : conception, réalisation, installation sur site.
  - Electronique + DAQ: intégration AEGIS (>2012)
  - Tests (IPNL)
  - Installation sur site (2013)

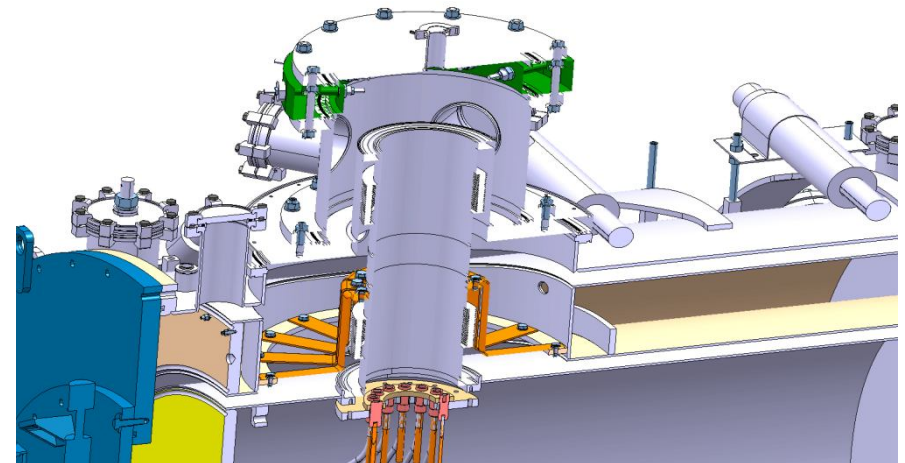
Budget : 60 kEuros





# AEGIS : participation/budget

- Coordination Intégration-CAO
  - Service Mécanique IPNL – BE
- Réalisations mécaniques – BE+Ateliers
  - Cheminée 5T (2011) – 5kEuro - IPNL
  - Cheminée 1T (2012)
    - 5 kEuros





# Calendrier

- Source proton :
  - R&D, pré-étude : Fin-2011
  - Design & construction : 2012
  - Installation 2013
  - Premier faisceau de p (de H?) : juillet 2013
- Coordination :
  - Mid-2010
  - Installation/intégration (→2012)

## The *AEGIS*: official schedule & beam time

year	Technical topics	Physics topics
2012	positron accumulation positron transfer positronium formation material studies with positrons	positronium temperature measurement positronium excitation positronium spectroscopy positronium formation, excitation & studies in B-field material studies with positrons
	antiproton trapping detector R & D with antiprotons	Rydberg antihydrogen formation temperature measurement of antihydrogen
2013	hydrogen formation detection of low- $n$ Hydrogen hydrogen beam formation manipulation of Rydberg positronium	Rydberg hydrogen formation hydrogen temperature de-excitation of Rydberg hydrogen positronium spectroscopy and related studies in B-field
2014	antihydrogen beam formation antihydrogen beam optimization cooling techniques	antihydrogen gravity measurement positronium spectroscopy and related studies
2015	manipulation of Rydberg antihydrogen	improved antihydrogen gravity measurement precision positronium spectroscopy and related studies
2016	trapping & manipulation of Rydberg antihydrogen	improved antihydrogen gravity measurement spectroscopy of trapped antihydrogen

year	beam time request	main goal
2012	May & June September-December	commissioning of $\bar{p}$ trapping, plasma diagnostics, detectors formation of Rydberg antihydrogen
2013	-	proton, positron, Ps and Hydrogen work without external beam
2014 and subsequent years	May - December	gravitational interaction and spectroscopic measurements with antihydrogen

# CONCLUSIONS

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- × **AEGIS : expérience physique fondamentale**
  - + **Collaboration internationale**
    - × Démarre en 2012 (e<sup>+</sup>, oPs, p) – 2013 (H) ; 2014 (Hbar)
    - × CERN, ...
    - × France: Lab. A. Cotton, IPNL
  - + **Techniques HEP ⇔ compétences IN2P3/IPNL**
    - × Faisceau p, Mécanique (BE, Atelier), DAQ, Qualité, ...
  - + **« Amusante & Formatrice »**
    - × Il y a plein de physique ! HEP, Ps, atomique, beams, laser, cryo, H, Hbar, ...
    - × Outreach / Grand Public
- × **Des extensions possibles (faisceau e<sup>+</sup>, ELENA) :**
  - + **Etudes oPs (fondamentales + matériaux)**
  - + **Violation de CPT, spectroscopie, comparaisons H-Hbar**

# Etats/soutiens

- L'expérience AEGIS
  - est en cours d'installation au CERN
  - Premiers pbar en 2011
  - Premier piégeage de pbar : 2012
  - Premiers H : 2013
  - Premiers Hbar : 2014
- IN2P3 - IPNL
  - Réalisation/utilisation de la source de protons (2012/2013) et détection
  - Participation à la construction de la mécanique
  - Participation aux runs (2012-2016)

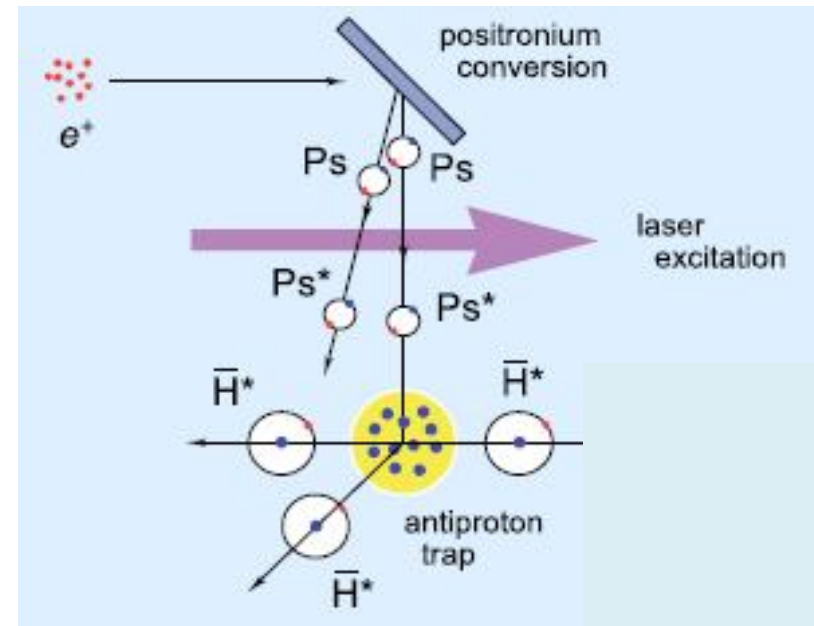
21/03/2012

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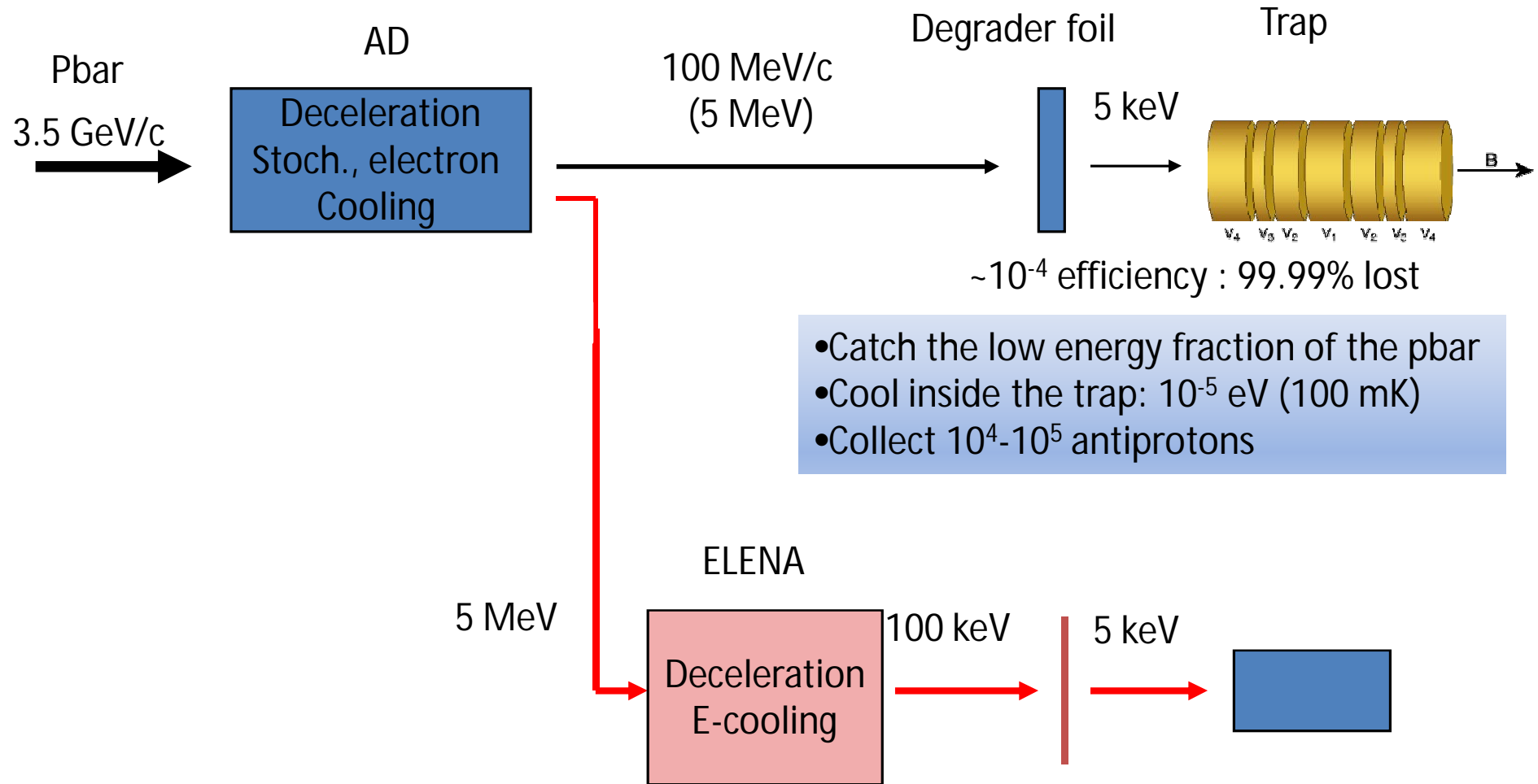
# The *AE g IS* experimental method

## 1. Antihydrogen Formation

1. Cold antiprotons ( $T \sim 0.1$  K)
2. Production of Rydberg positronium
3. Production of antihydrogen atoms



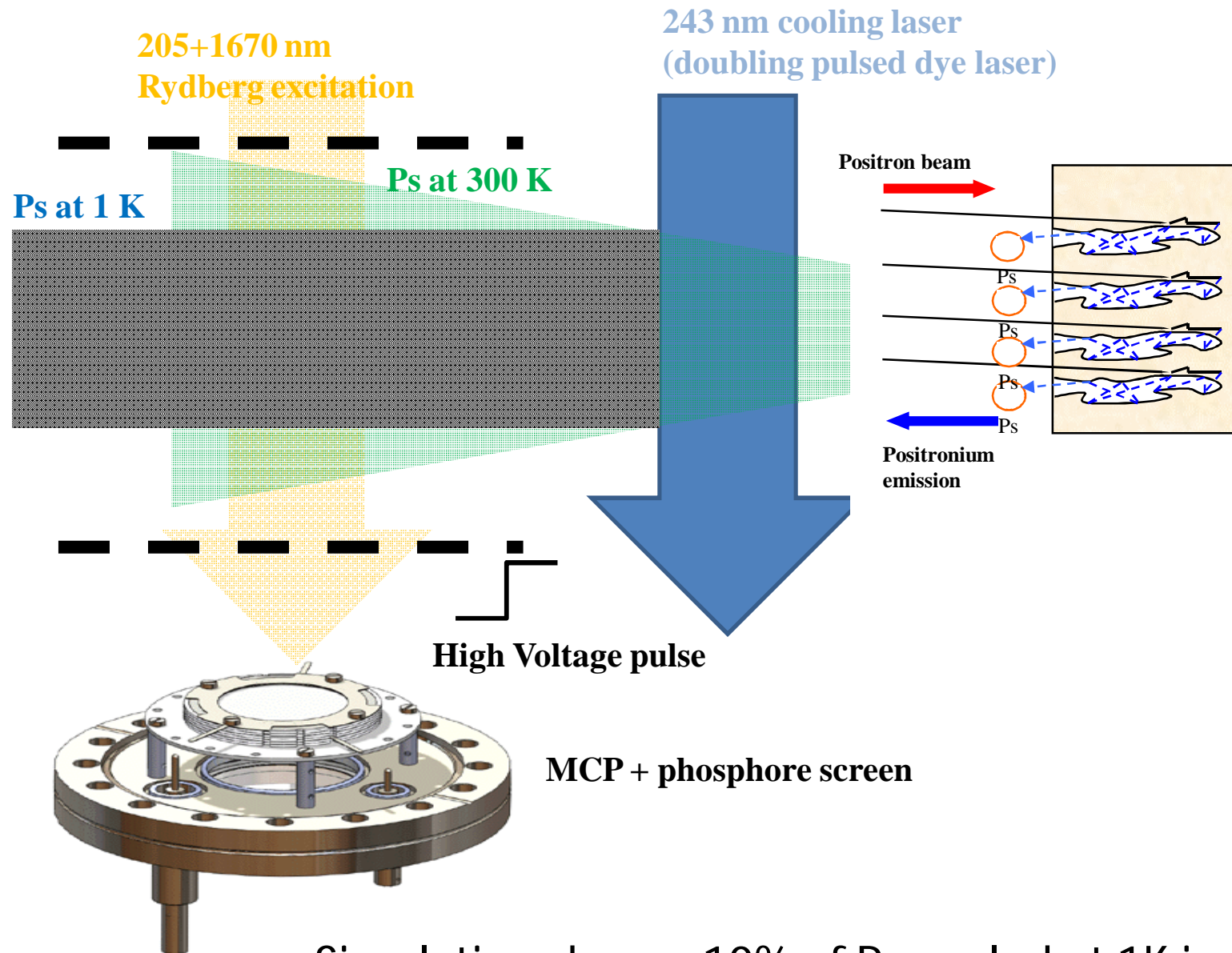
# Antiproton with ELENA



ELENA will provide ultra-low energy phase-space compressed beam enhancing number of usable pbars by up to **4 orders** of magnitude

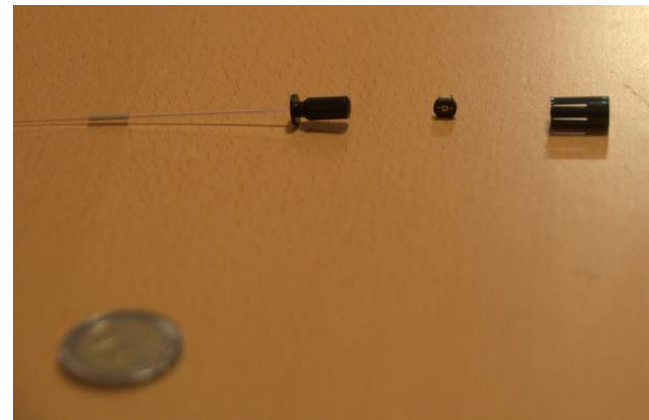
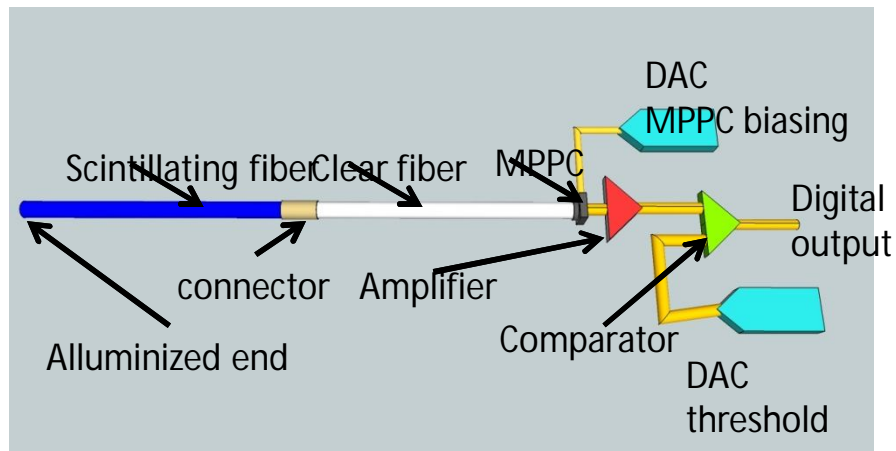
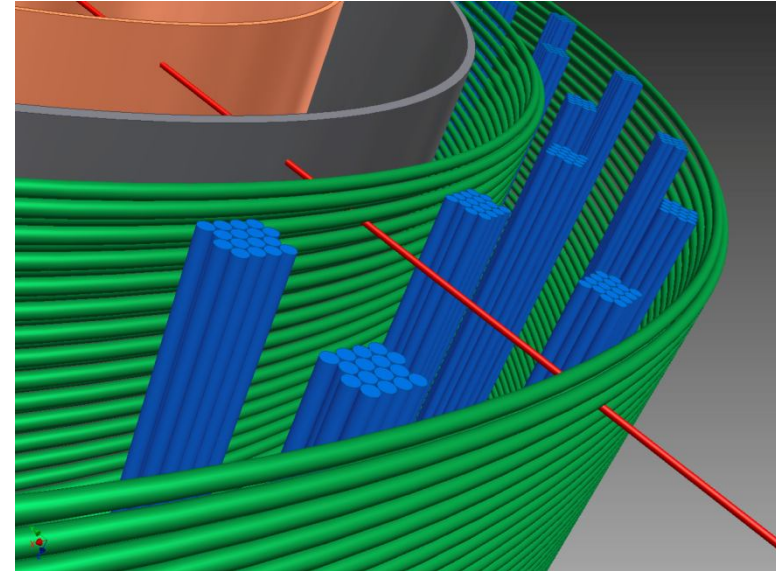
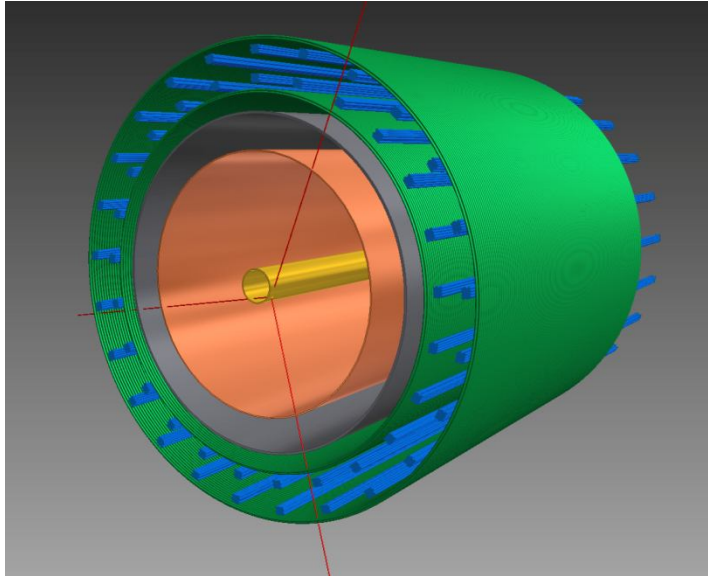


# Laser cooling of positronium



Simulation shows: 10% of Ps cooled at 1K in 200ns

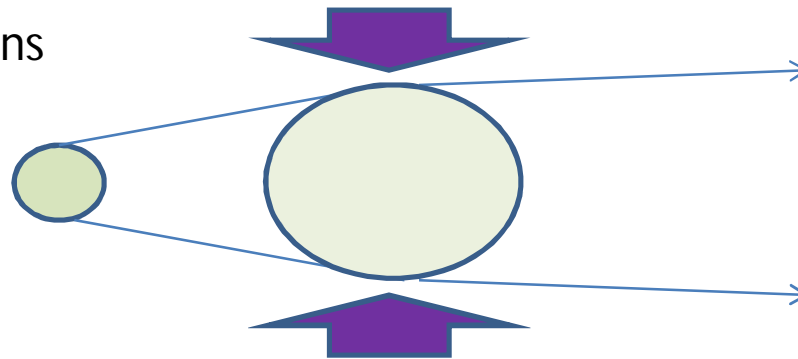
# The detector of the antihydrogen formation



# Refroidissement laser de l'hydrogène (transition 1s-2p) À 121,56 nm en régime quasi-continu

Intensité de saturation:  $7\text{W}/\text{cm}^2 \rightarrow 100\text{mW}$  sur une taille de faisceau de 1mm

$G = 2 \pi \times (100\text{MHz}) = 1/\text{lifetime} = 1/1.6 \text{ ns}$



Exemple: Dans l'expérience AEGLS, réduction de la vitesse transverse des atomes d'anti-hydrogène avant le déflectomètre Moiré.

50 m/s (100 mK)  $\rightarrow$  3 m/s (vitesse de recul)  $\rightarrow$  17 photons

Temps de transit typique dans le faisceau laser: 100  $\mu\text{s}$ .

Le laser est décalé de la moitié de la largeur naturelle pour optimiser l'effet Doppler durant le refroidissement.

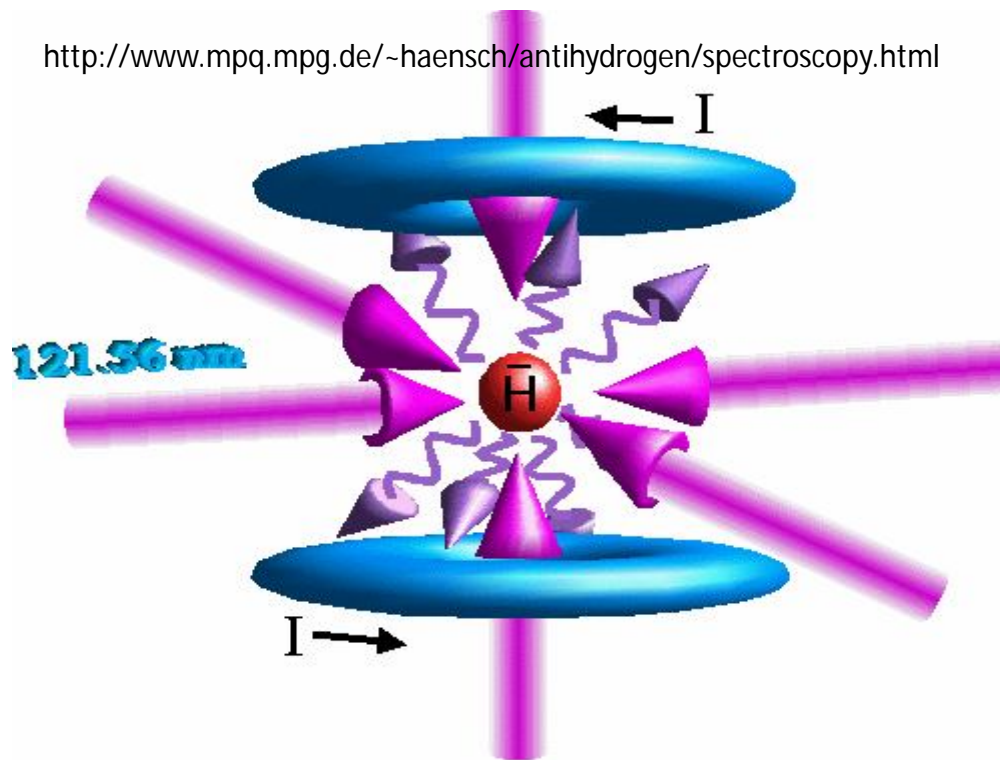
Il suffit de  $1/1000^{\text{e}}$  de l'intensité de saturation, pendant 100  $\mu\text{s}$ , pour réaliser le refroidissement 1D, soit une puissance d'environ 5 mW à  $\lambda = 121,6 \text{ nm}$

# Refroidissement laser dans un piège magnétique

Refroidissement optique de l'hydrogène atomique dans un piège magnétique ~8mK  
Faisceau unique à 121,5 nm (thermalisation 3D par collisions)

T. W. Hijmans and O. J. Luiten I. D. Setija and J. T. M. Walraven J. Opt. Soc. Am. B 6 2235 (1989)

<http://www.mpq.mpg.de/~haensch/antihydrogen/spectroscopy.html>



Appl. Phys. B 77, 713–717  
(2003)

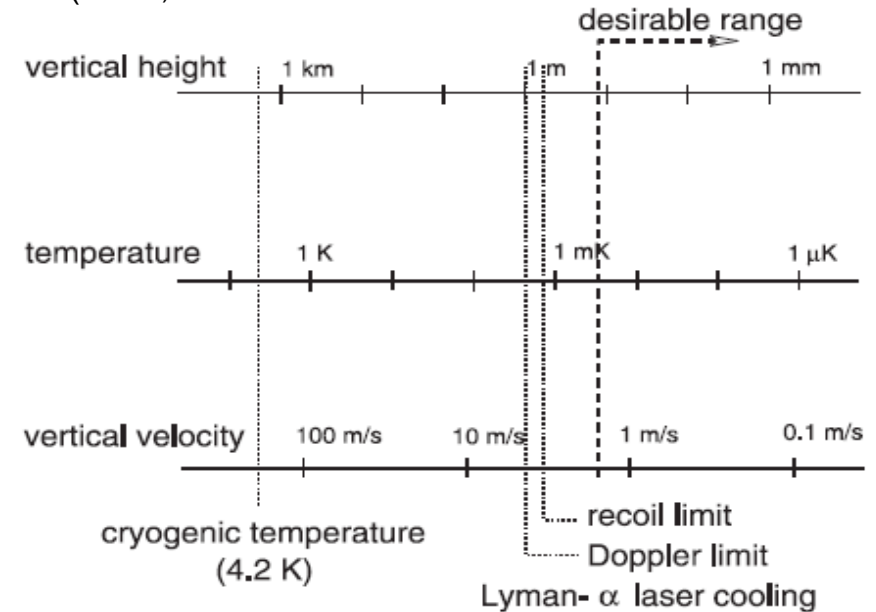
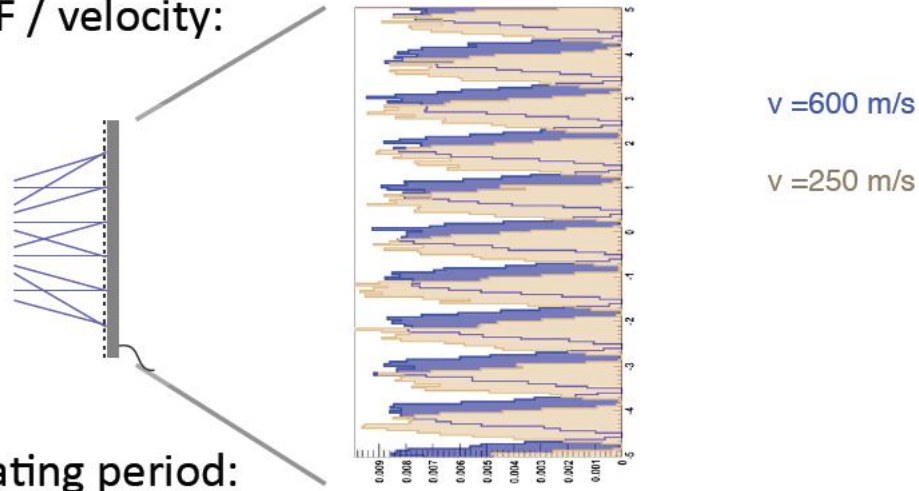


FIGURE 5 Orders of magnitude relevant for gravitational experiments with antihydrogen. The scale at the *bottom* gives the spread of vertical velocities,  $1\sigma = \sqrt{kT/m}$ , which corresponds to the temperature axis in the *middle*. The height  $kT/2\ mg$  to which antihydrogen atoms can climb against gravity is shown on the *upper scale*. Ultra-cold antihydrogen atoms are needed for gravitational experiments to be practical

# The *AEGIS* analysis method

- Detection of vertical annihilation position as a function of TOF / velocity:



- Binning modulo grating period:

