

Synthesis of Cold Antihydrogen in a Cusp Trap

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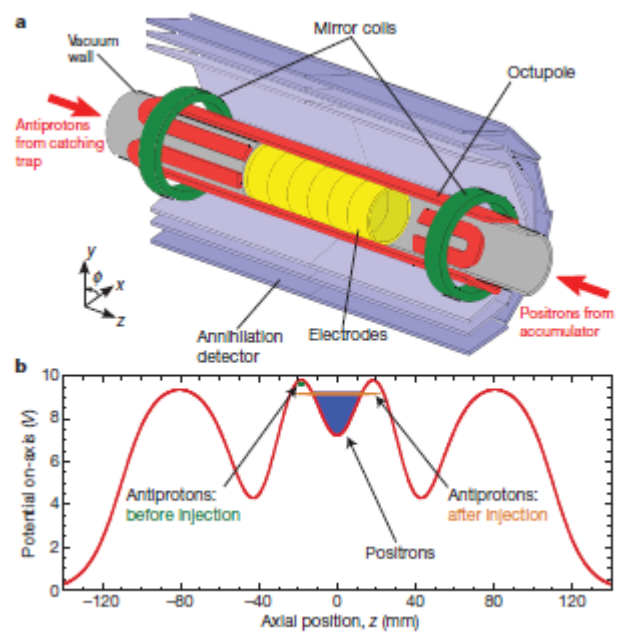


Figure 1 | The ALPHA central apparatus and mixing potential

ALPHA, Nature

17 novembre 2010

atomes \bar{H} piégés plus de 170 ms

LETTER

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Trapped antihydrogen

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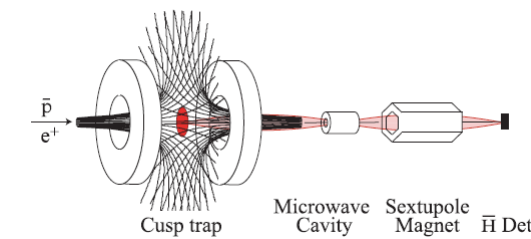
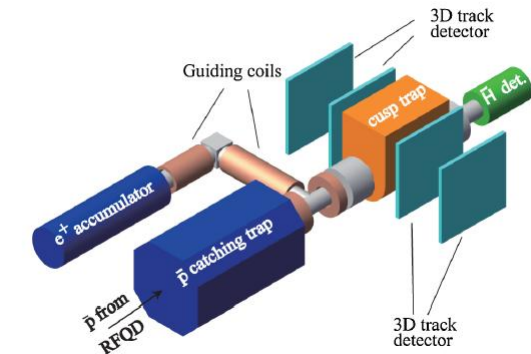
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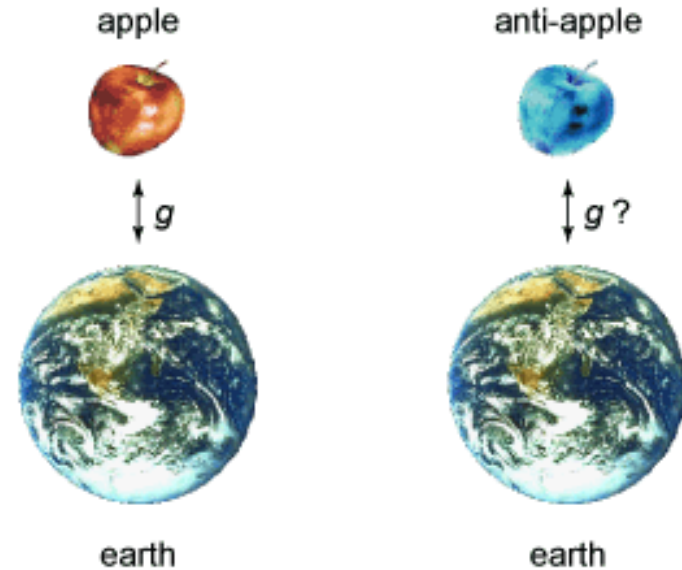
P. Debu - Irfu

ASACUSA, Phys Rev Lett 105

10 décembre 2010

Synthèse et extraction
d'un faisceau d'atomes \bar{H}





- **Motivation**
- **Limites indirectes**
- **Projets en cours**
- **GBAR**
- **Conclusions**

Test direct du Principe d'Equivalence avec l'antimatière

L'accélération transmise à un corps par un champ gravitationnel est indépendante de sa masse et de sa composition

masse inertielle = masse gravitationnelle

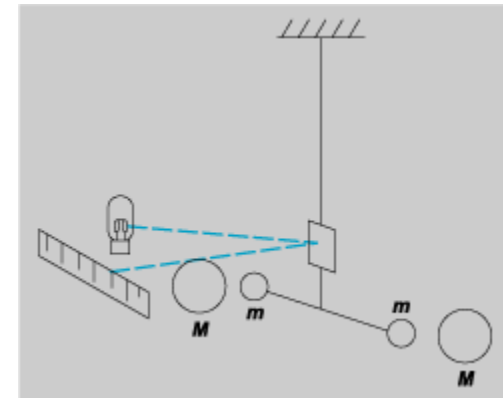
Testé pour la matière avec une très grande précision avec de nombreux matériaux

Principe d'équivalence faible (balance de torsion)

$$(\Delta a / a)_{\text{Be/Ti}} = (0.3 \pm 1.8) \times 10^{-13} \quad \text{S.Schlaminger et al, Phys Rev Lett 100 (2008) 041101}$$

Principe d'équivalence fort (Lunar Laser Ranging)

$$(\Delta a / a)_{\text{Terre/Lune}} = (-1.0 \pm 1.4) \times 10^{-13} \quad \text{J.G.Williams et al, Phys Rev Lett 93 (2004) 261101}$$



Limites indirectes

Considérations théoriques et limites indirectes sur une violation du principe d'équivalence par l'antimatière

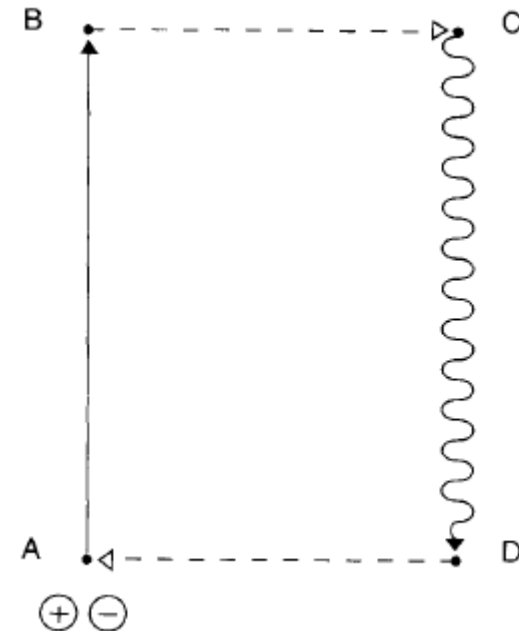
-Argument de Morrison (1958) :
antigravité en RG \rightarrow
violation de la conservation de l'énergie

si $m_G (+) = -m_G (-)$:

$$E_A = E_B = 2m_I c^2 = h\nu_C$$

$$h\Delta\nu_{CD} = h\nu_C (gL / c^2) = 2m_I gL$$

$$E_D = E_A + 2m_I gL$$



Limites indirectes

→ pas exclu ? voir :

G. Chardin et J.M. Rax, Phys Lett B282 (1992) 256

G. Chardin, Hyperfine Interactions 109 (1997) 83

→ introduire des champs gravi-vecteurs et gravi-scalaires non couplés aux photons pour différencier m_G et \bar{m}_G

(voir par exemple : *J. Scherk, Phys. Lett. B (1979) 265*)

$$V = -G \frac{mm'}{r} \underbrace{(1 \mp a \exp(-r/v) + b \exp(-r/s))}_{\text{supergravité : une contribution répulsive}}$$

Les tests avec la matière contraignent seulement $\sim |b-a|$

Limites indirectes

- Contenu en antimatière de la matière ordinaire (« argument de Schiff ») mais :

$$\rho_{\text{vide}} = \int_0^\Lambda \sqrt{k^2 + m^2} \frac{4\pi k^2}{2(2\pi)^3} dk \approx \frac{\Lambda}{16\pi^2} \sim 10^{73} \text{ GeV}^4 \text{ pour } \Lambda = E_p$$

$$\rho_{\text{critique}} \sim 10^{-47} \text{ GeV}^4$$

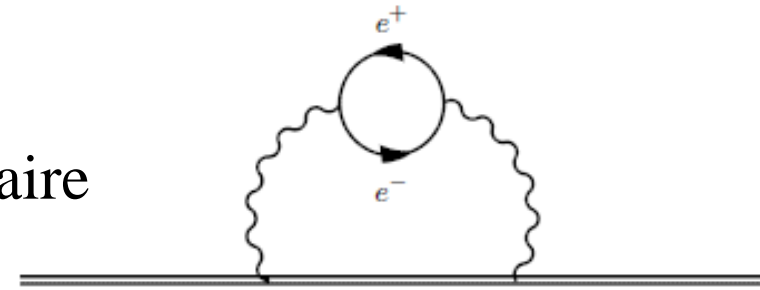


FIG. 2: Loop contribution to the electrostatic self-energy of the nucleus

$$\left| \frac{g_0 - |g_0|}{g_0} \right| \sim \left| \frac{g - g_{\Delta\text{Erad}}}{g} \right| \Rightarrow$$

Scenario	Argument	Bound on $ g_H - g_{\text{II}} /g_H$
Modification of GR	Lamb shift	$\lesssim 10^{-2}$
	Electrostatic self-energies of nuclei	$\lesssim 10^{-7}$
	Antiquarks in nucleons	$\lesssim 10^{-9}$
Scalar-vector	Radiative damping of binary systems	$\lesssim 10^{-4}$
	Scalar charges are not vector charges	$\lesssim 10^{-8}$
	Velocity dependence	$\lesssim 10^{-7}$

- Compensation exacte scalaire/vecteur impossible
(D.S.M.Alves et al SU-ITP-09/36)

Limites indirectes

-Mesures de η^\pm et Φ^\pm en fonction du temps par CPLEAR

Oscillations $K^0-\bar{K}^0$ dépendent de $\delta m_{\text{eff}} = M_{K^0} (g - \bar{g}) \frac{U}{c^2} \exp(-r / r_I) f(I)$

A. Apostolakis et al., Phys Lett B 452 (1999) 425

Summary of limits on $|g - \bar{g}|$ for spin 0, 1 and 2 interactions

	Source	Spin 0	Spin 1	Spin 2
Variation du potentiel en fonction du temps	Earth	6.4×10^{-5}	4.1×10^{-5}	1.7×10^{-5}
	Moon	1.8×10^{-4}	7.4×10^{-5}	4.8×10^{-5}
	Sun	6.5×10^{-9}	4.3×10^{-9}	1.8×10^{-9}
Introduction d'un potentiel absolu \longrightarrow	Galaxy	1.4×10^{-12}	9.1×10^{-13}	3.8×10^{-13}
	Supercluster	7.0×10^{-14}	4.6×10^{-14}	1.9×10^{-14}

-Mesure des fréquences cyclotron p (H^-) et \bar{p} dans un même champ B

R. Hughes and M. Holzscheiter, Phys Rev Lett 66 (1991) 854

G. Gabrielse et al. Phys Rev Lett 82 (1999) 3198

$$\omega = qB / 2\pi m + \alpha U / c^2 \quad |\omega - \bar{\omega}| / \omega = (9 \pm 9) \times 10^{-11} \rightarrow |g - \bar{g}| / g \leq 10^{-6}$$

Limite directe ?

-Temps d'arrivée d'1 (? : 90 % CL) neutrino et de 18 antineutrinos de la SN1987a

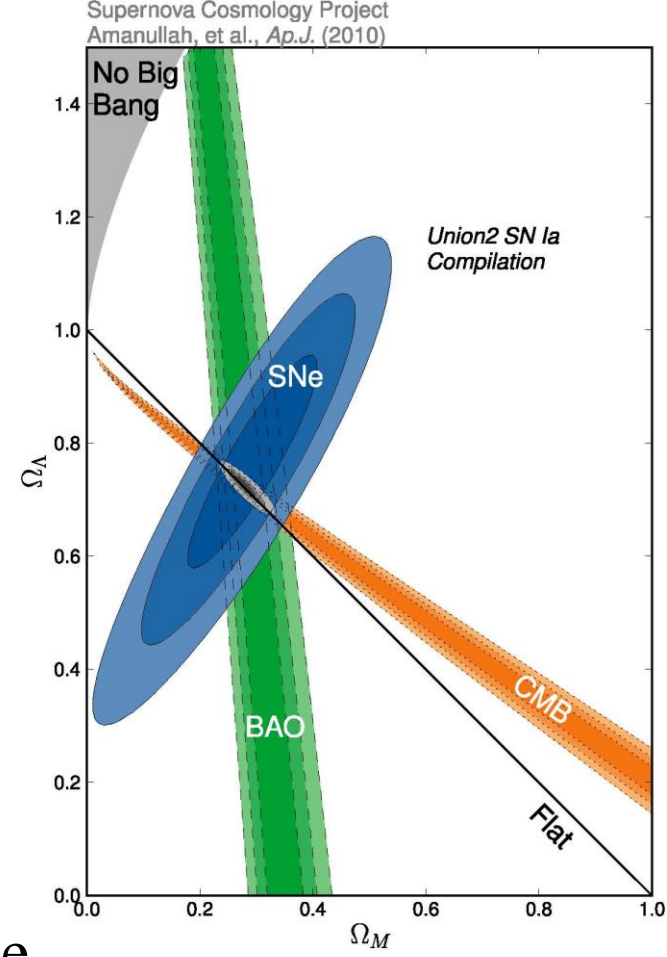
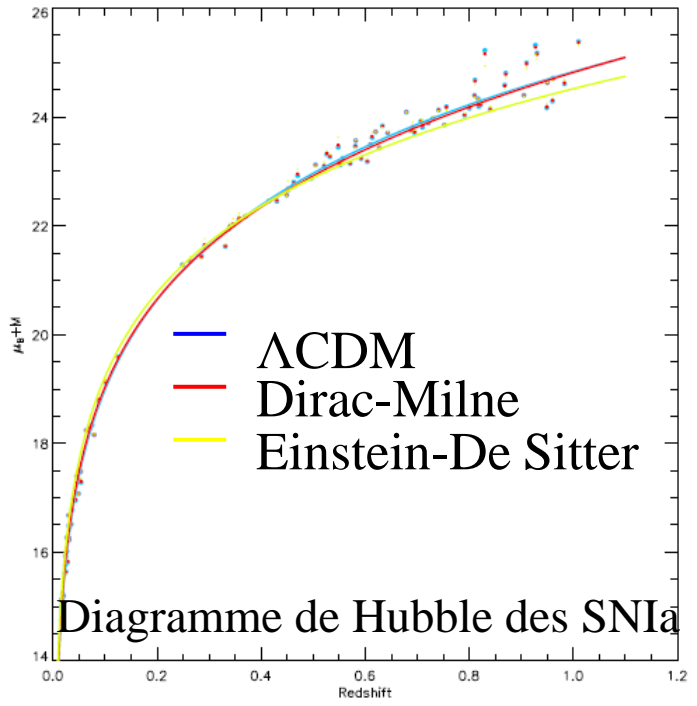
$$\text{délai gravitationnel : } \delta t = MG \left[-R / \sqrt{R^2 + b^2} + (1 + \gamma) \ln \left| R + \sqrt{R^2 + b^2} / b \right| \right]$$

$$|\delta t(\nu_e) - \delta t(\bar{\nu}_e)| / \delta t(\bar{\nu}_e) < 10^{-6} \rightarrow |\gamma(\nu_e) - \gamma(\bar{\nu}_e)| / \gamma(\bar{\nu}_e) < 10^{-6}$$

(S. Paksava et al. Phys Rev D 39 (1989) 1761)

Cosmologie

- Asymétrie matière antimatière
 - Accélération de l'expansion de l'univers
 - + Matière noire + inflation
- Y a-t-il une répulsion matière antimatière ?



→ Univers de Dirac Milne

-Tentative de construire une cosmologie avec :

- Symétrie matière-antimatière
- Mécanisme séparant matière et antimatière

(Thèse Paris XI d'A. Benoît-Lévy – dir G. Chardin (2009))

Tentatives et propositions passées

-**positrons** : *F. Witteborn and W. Fairbank, Phys Rev Lett 19 (1967) 1049)*

-**antiprotons** : *PS200 Proposal Los Alamos Report LA-UR 86-260*

-*Systématiques trop grandes* :

$$m_e g / e = 5.6 \times 10^{-11} \text{ V / m (une charge élémentaire à 5 m)}$$

-**antineutrons** : difficile de les ralentir suffisamment

T. Brando et al, Nucl. Instrum. Methods 180 (1981) 461

-**positronium** : temps de vie très court (142 ns) si $n = 1$

possibilité discutée s'il est excité $n \gg 1$ ($\tau \simeq (n / 25)^{5.236} \times 2.25 \text{ ms}$)

Pbs : refroidissement, polarisabilité, ionisation par rayonnement...

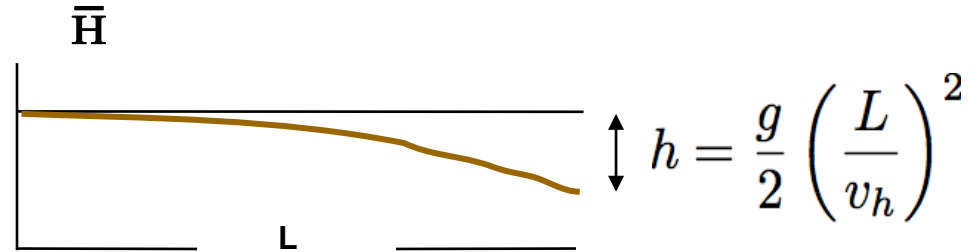
A.P. Mills, M. Leventhal, Nucl. Instrum. Meth. in Phys. Research. B192 (2002) 102

Systeme suivant $\bar{H} \rightarrow$ Projets en preparation

Principe :

Vol parabolique des \bar{H}

Interféromètre, déflectomètre, chute libre



-L = 1 m et $v_h = 1000$ m/s $\rightarrow h = 5 \mu\text{m}$ ($T(\bar{H}) \sim 4$ K ~ 0.3 meV)

\rightarrow *AGE : LOI FNAL en suspens - atomes \bar{H} (neutres)*

-L = 1 m et $v_h = 500$ m/s $\rightarrow h = 20 \mu\text{m}$ ($T(\bar{H}) \sim 100$ mK $\sim 7 \mu\text{eV}$)

\rightarrow *AEGIS : expérience CERN - atomes \bar{H} (neutres)*

-L = 0.1 m et $v_h = 0.5$ m/s $\rightarrow h = 20$ cm ($T(\bar{H}) \sim 15 \mu\text{K} \sim 1$ neV)

\rightarrow *Gbar : LOI CERN - \bar{H}^+ refroidis $\rightarrow \bar{H}$ lents*

P. Pérez et al, LOI CERN –SPSCI-038 (2007) Irfu, Riken, Tokyo U.

Antimatter Gravity Experiment at FNAL

- Flux \bar{p} at FNAL (4×10^{12} / jour) \gg CERN AD (2×10^{10} / jour)
- AGE Letter of Intent in 2009 (12 USA institutes)
- Status : staged – tests with matter required by FNAL committee

Aims :

-First step :

- produce \bar{H} at FNAL and measure \bar{g} to 1 % soon after with a three grating interferometer
- run a few months to reach 10^{-4} precision

-Second step :

- reach 10^{-9} precision with laser atomic (Raman) interferometer

- Additional physics : CPT test with spectroscopy

AGE proposed method

-Deceleration $\bar{p} \rightarrow 1 \text{ GeV}$ + degrader foils + trap (20 kV) ($\epsilon \sim 10^{-4}$)

-Cooling at 4 K with electrons

-Extraction at $\langle v \rangle \sim 1 \text{ km/s}$

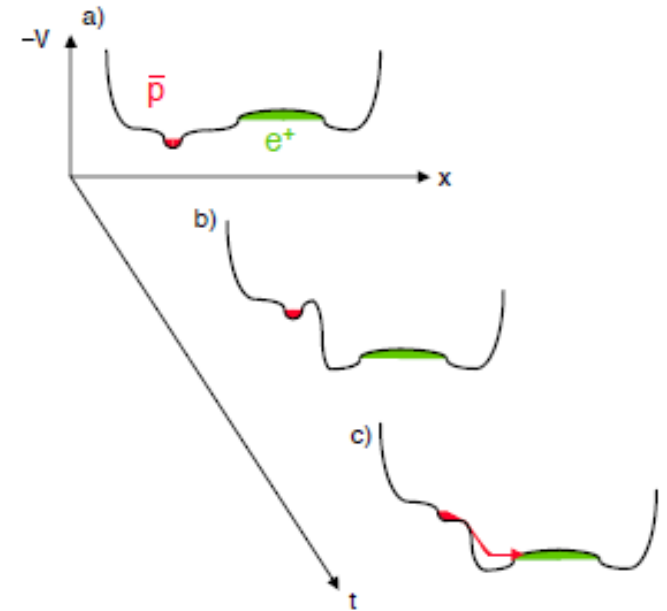
- \bar{H} production :

Interaction with positrons trapped

(produced by a ^{22}Na 50 mCi source : 8×10^6)

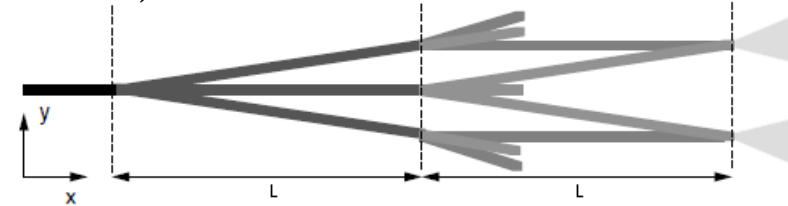
$$\Gamma(\bar{p} + 2e^+ \rightarrow \bar{H} + e^+) \approx 6 \times 10^{-13} \left(\frac{4.2 \text{ K}}{T} \right)^{9/2} \frac{n_e^2}{1 \text{ cm}^{-6}} \left[\text{s}^{-1} \text{ per } \bar{p} \right] \quad (\text{with here } n_e > 10^8 \text{ cm}^{-3}; T \approx 4 \text{ K})$$

45 % efficiency for $v = 1 \text{ km/s}$ and $L = 10 \text{ cm}$



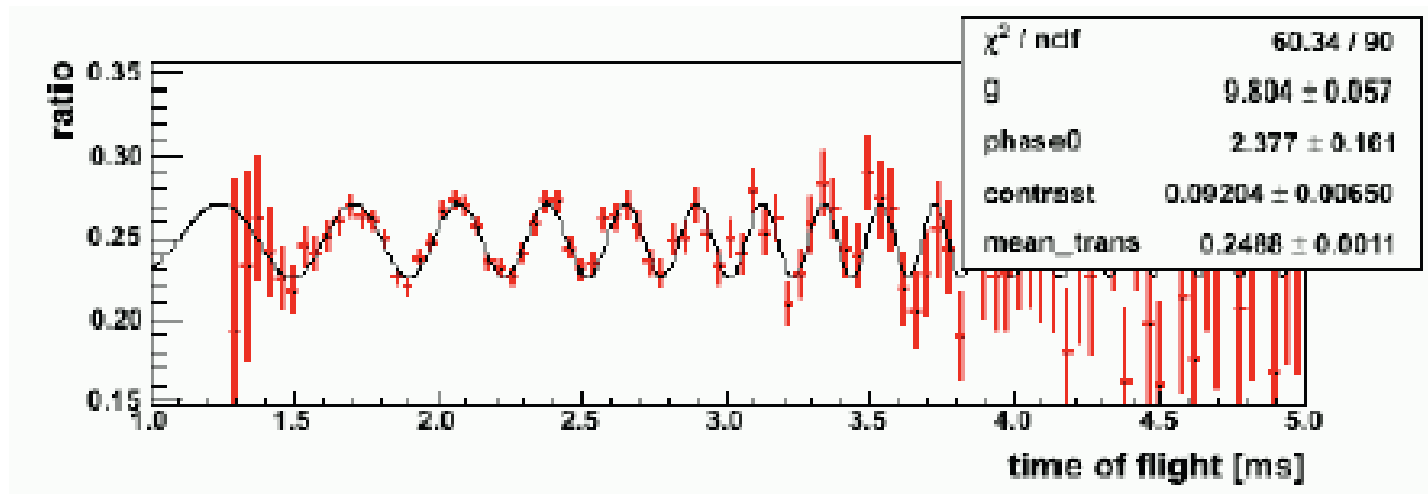
AGE first step

-Fly through 3 diffraction gratings (1 μm period)



-Vertical deflection $\mathbf{D} = \bar{g} \frac{L^2}{v^2}$

-Measure ratio of \bar{H} exiting interferometer vs time of flight
(10^6 extracted atoms (few hours) $\rightarrow \Delta g/g \approx .6\%$)



The *AE \bar{g} IS* experiment at AD

Antimatter Experiment: Gravity, Interferometry, Spectroscopy

Primary goal:

measurement of the Earth gravity acceleration on antihydrogen

Precision :

first goal : 1% with 10^5 antihydrogen atoms

higher accuracy in the future

Other physics :

high precision antihydrogen spectroscopy (CPT tests)

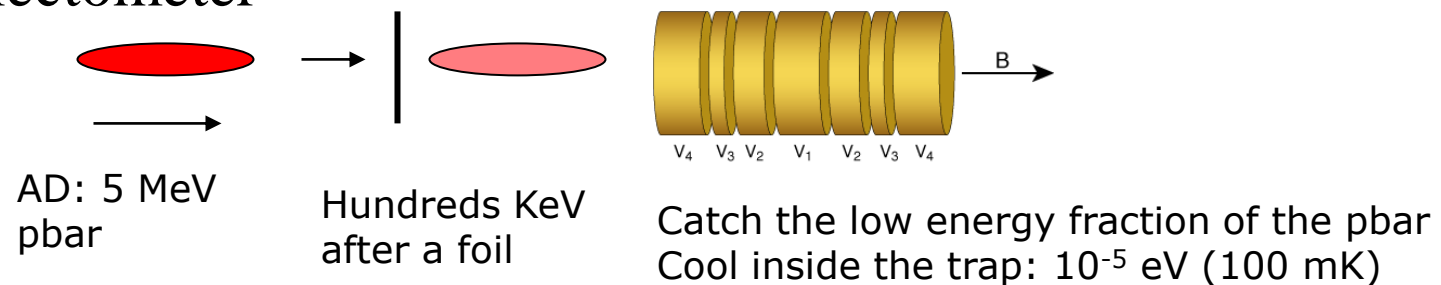
positronium physics (as by product)

AEGIS METHOD :

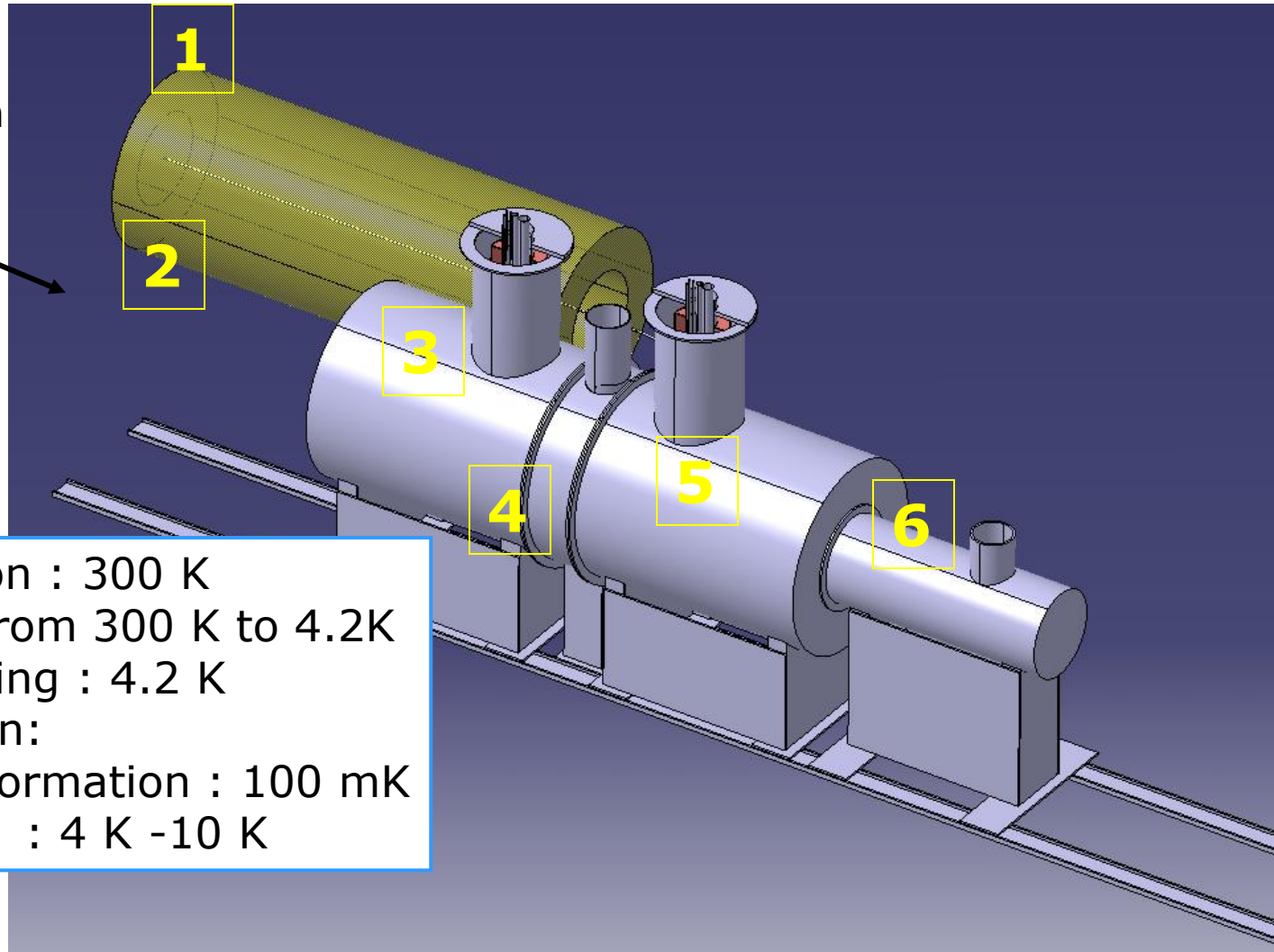
- Collect 10^4 - 10^5 extremely cold antiprotons ($T \sim 0.1\text{K}$) in a trap
- Accumulate a cloud of positrons in a trap: 10^8 (or more) in some minute
- Produce very slow ground state Ps sending the e^+ into a nanoporous target
- Produce Rydberg positronium via laser excitation
- Form cold (100 mK) antihydrogen atoms by the charge exchange process



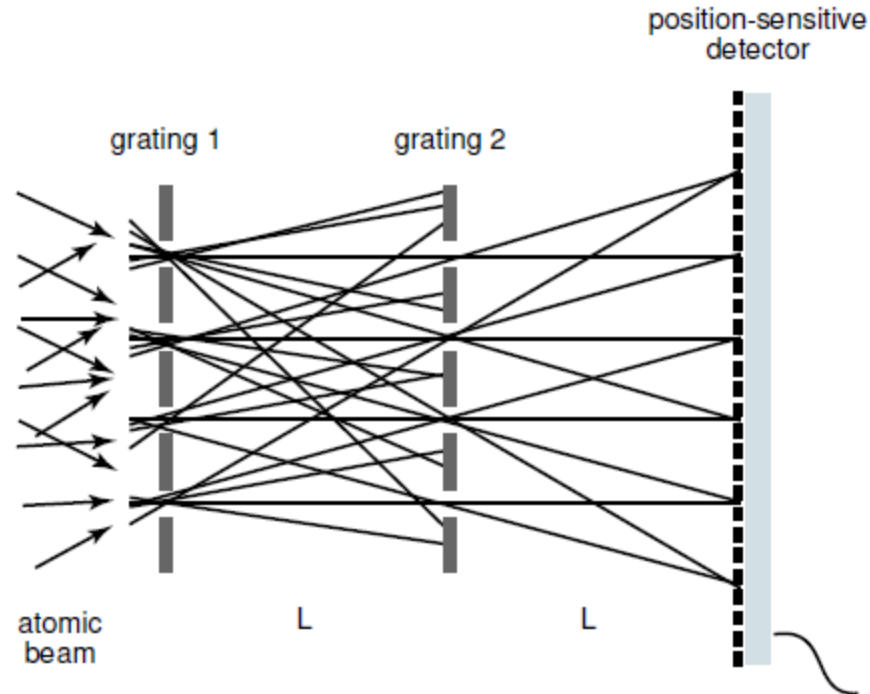
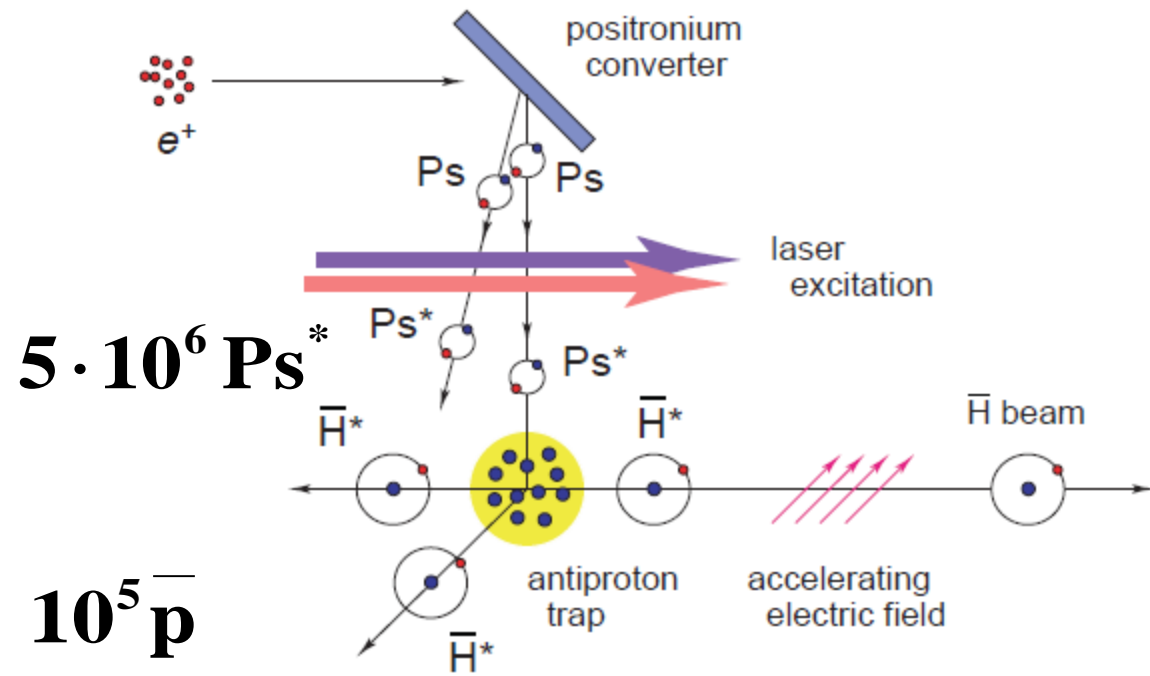
- accelerate the $\bar{\text{H}}^*$ to \sim few 100 m/s using Stark Effect
- get \bar{g} through a measurement of the $\bar{\text{H}}$ beam deflection with a Moiré deflectometer



AD antiproton
beam



- 1 e⁺ accumulation : 300 K
- 2 e⁺ transfer : from 300 K to 4.2K
- 3 pbar, e⁺ catching : 4.2 K
- 4 instrumentation:
- 5 antihydrogen formation : 100 mK
- 6 measurement : 4 K -10 K



$10^5 \bar{\text{p}}$

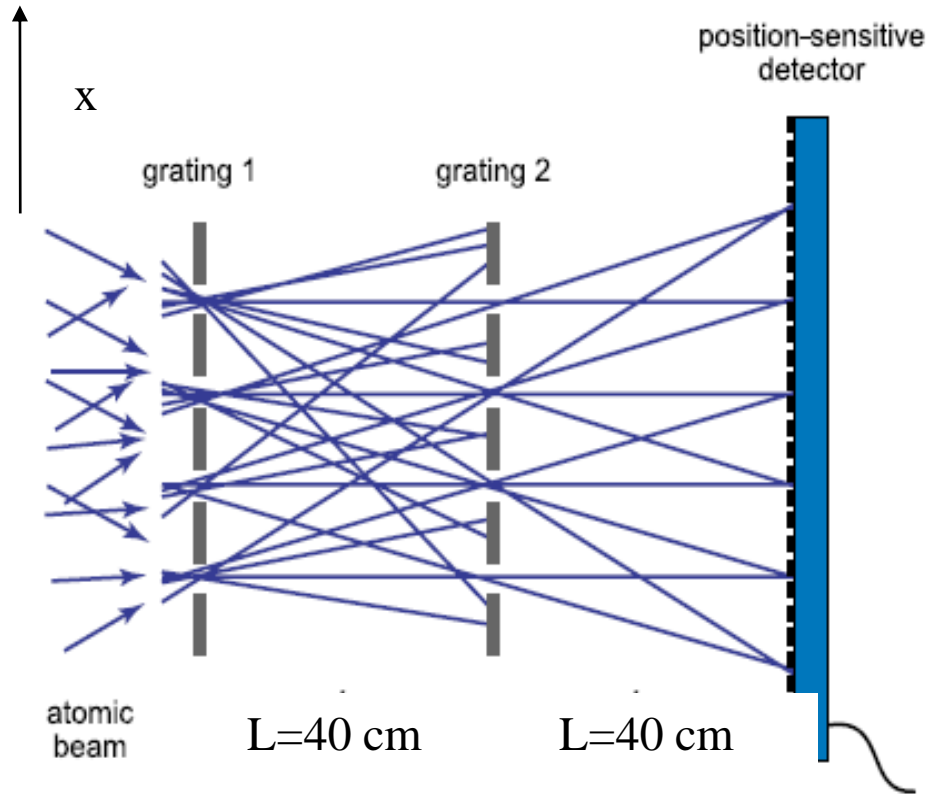
$\bar{\text{H}} \text{ 100mK}$

$v = 50 \text{ m / s}$

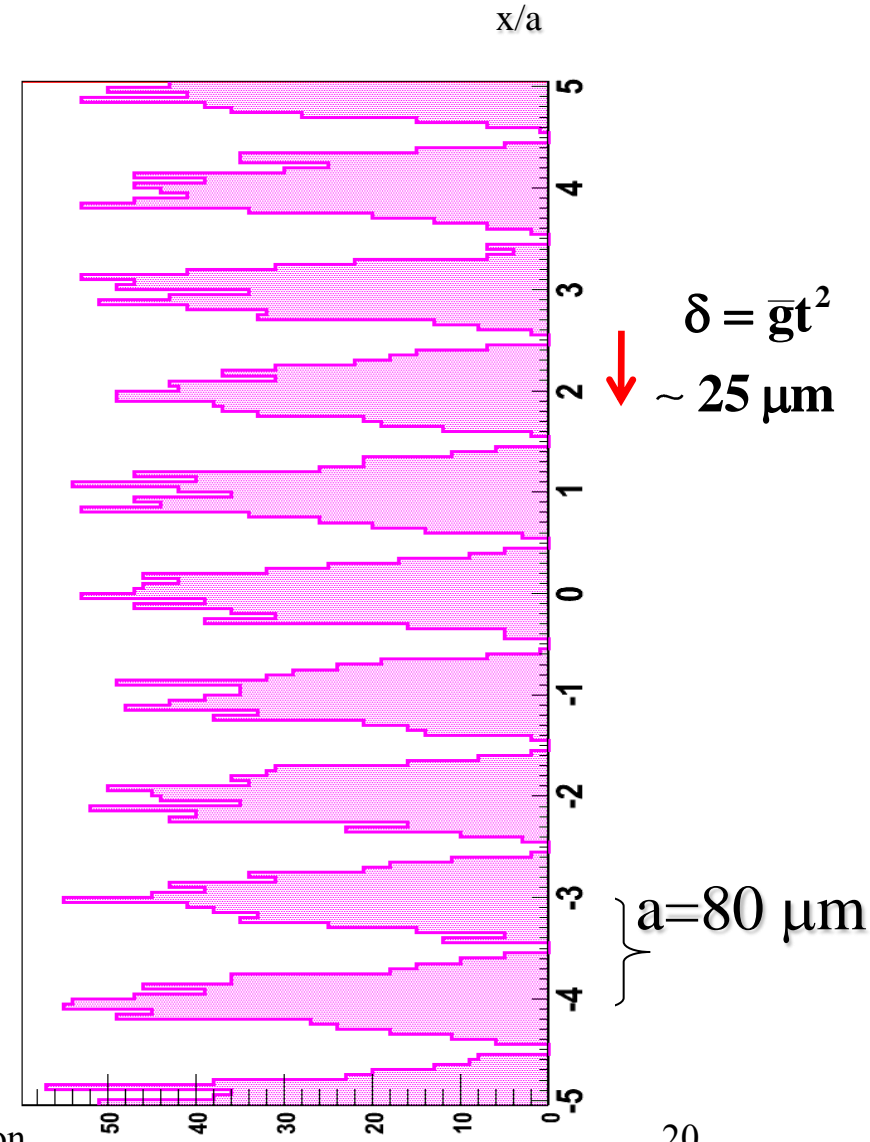
- The distribution of the vertical coordinates in the detector position shows a spatial modulation
- Extract g from this modulated distribution
- Use a position sensitive antihydrogen detector

- Time to prepare pbar and e^+ : few hundreds s
- Pulsed Antihydrogen production
- 100-1000 antihydrogen/(AEGIS cycle)

The Moiré deflectometer : principle of operation



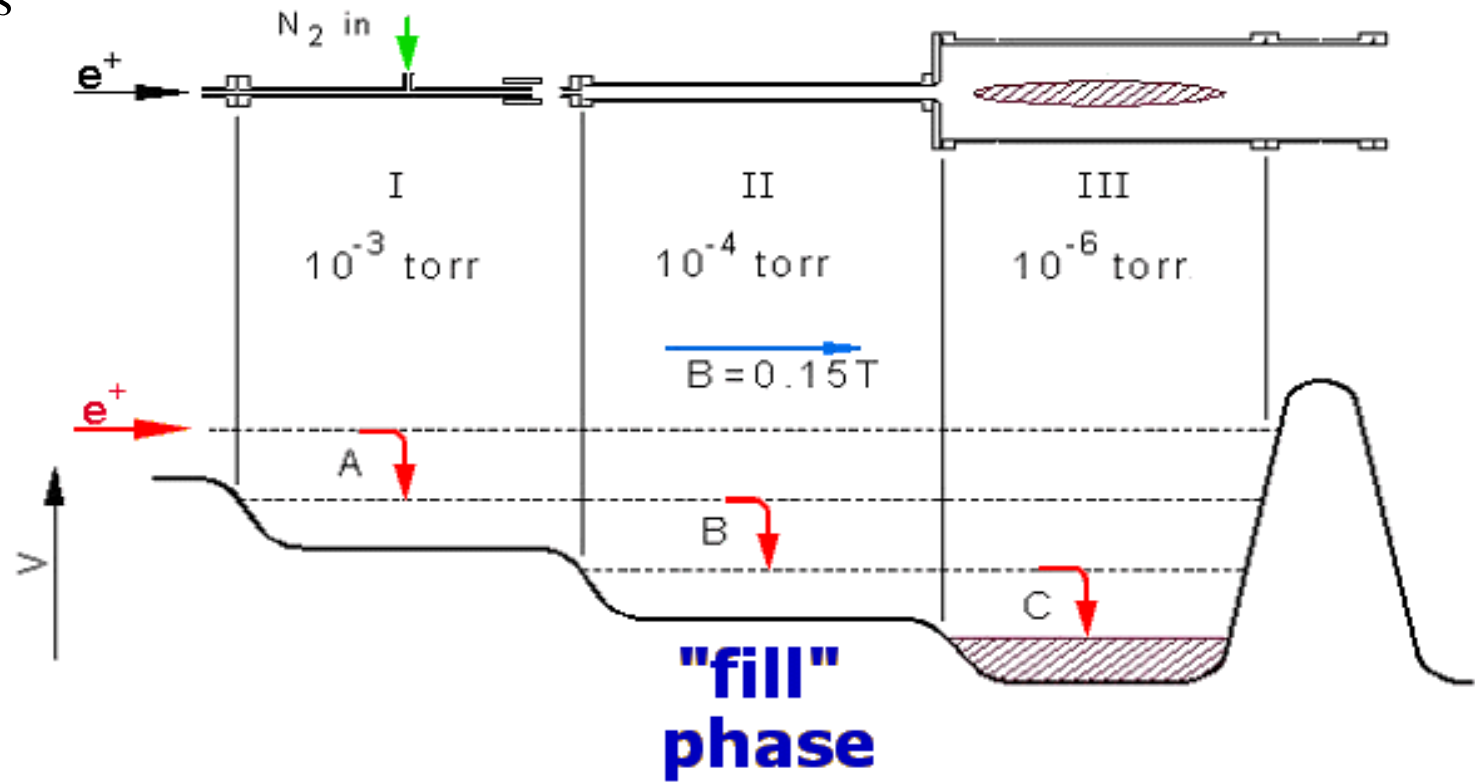
Counts vs vertical coordinate



grating period = $80 \mu\text{m}$; grating size = 20 cm (2500 slits)
 need $v_z \sim 500$ m/s and $v_T \sim 50$ m/s $\Rightarrow T \approx 100$ mK
 Simulation : $\delta \bar{g} / \bar{g} \approx 1\%$ $\Rightarrow \sim 10^5$ \bar{H} detected atoms
 ~ 2 weeks with ~ 1 useful \bar{H} /s

The positron accumulator: "Surko type"

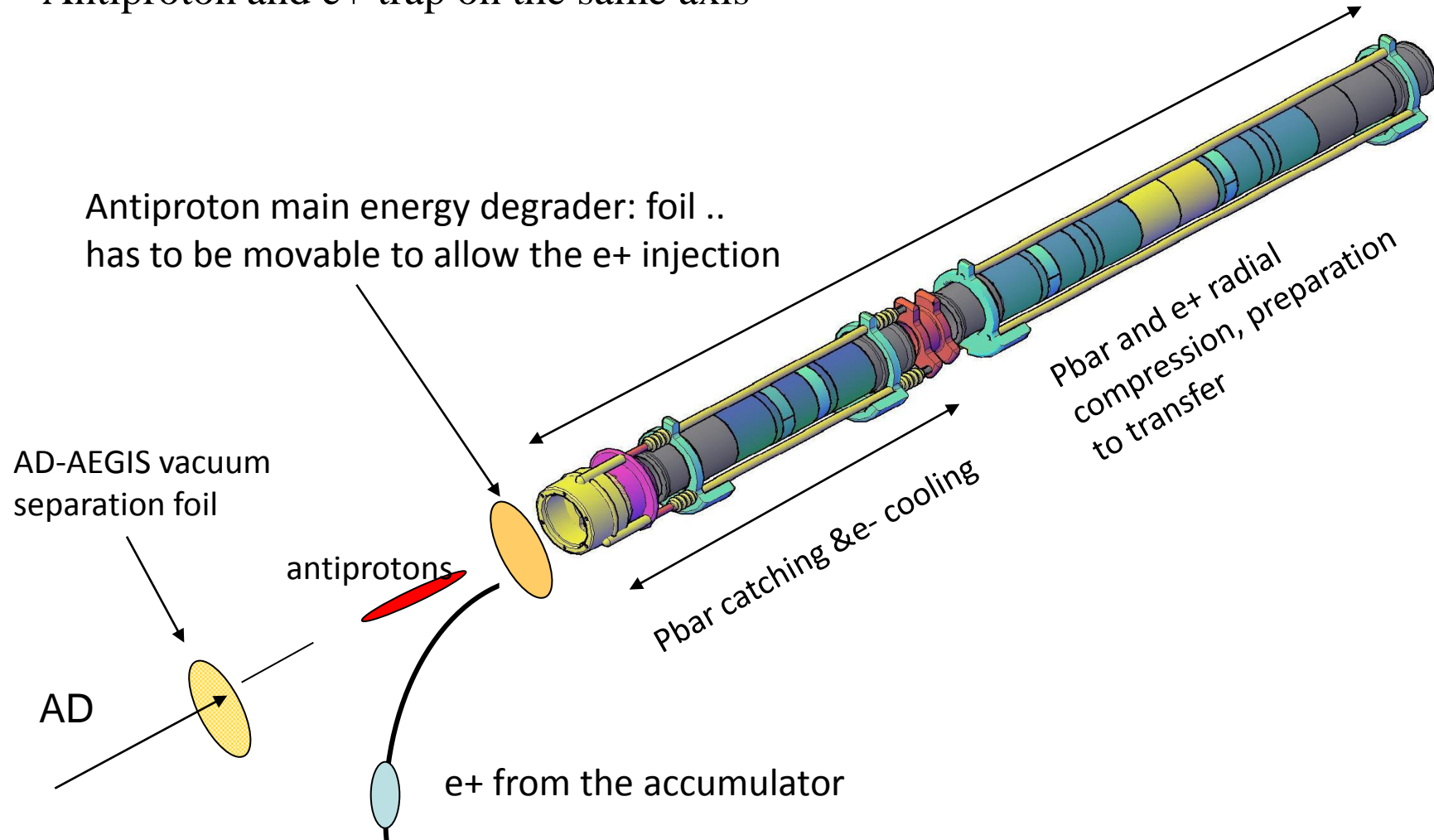
- ^{22}Na source: $> 50 - 100$ mC
- Moderation through solid neon
- Accumulation in trap
- Buffer gas cooling
- 3×10^8 e^+ in few minutes
- $B = 0.15 - 0.2$ T



The AEGIS trap design : the traps in the high (5T) field

B= 5 Tesla

Antiproton and e+ trap on the same axis



Toward ultracold (100 mK) antiprotons

Antiprotons in trap cannot be directly cooled to 100 mK

Cool antiprotons by collisions with a **partner particle stored in the same trap** (sympathetic cooling) that can be cooled

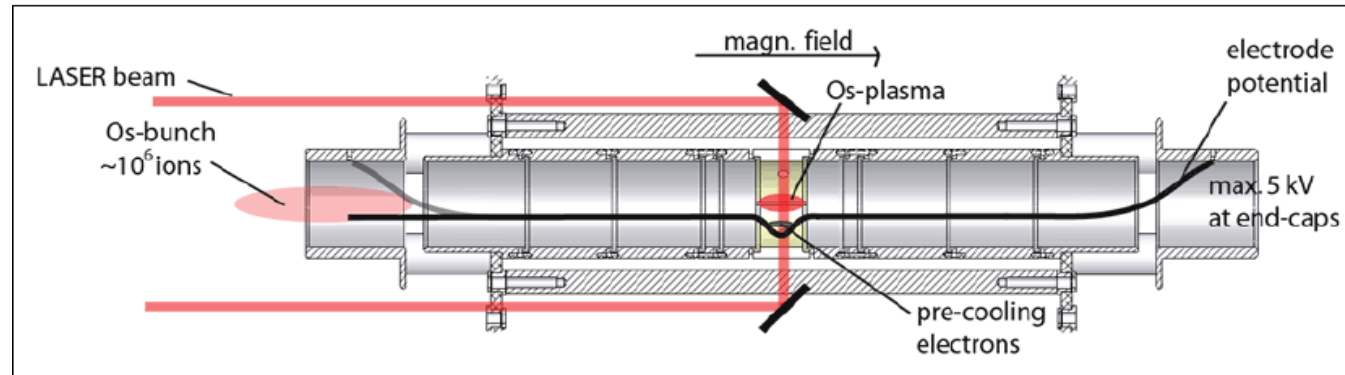
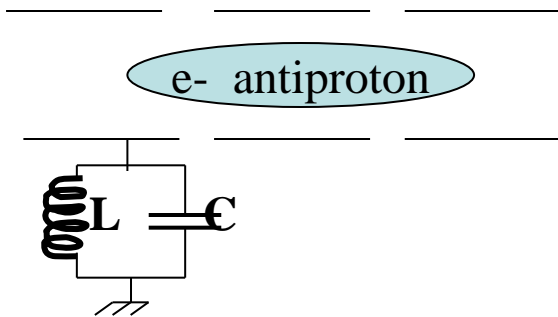
electrons

Negative ions: Os⁻

Resistive cooling with a resonant tuned circuit + radiation cooling

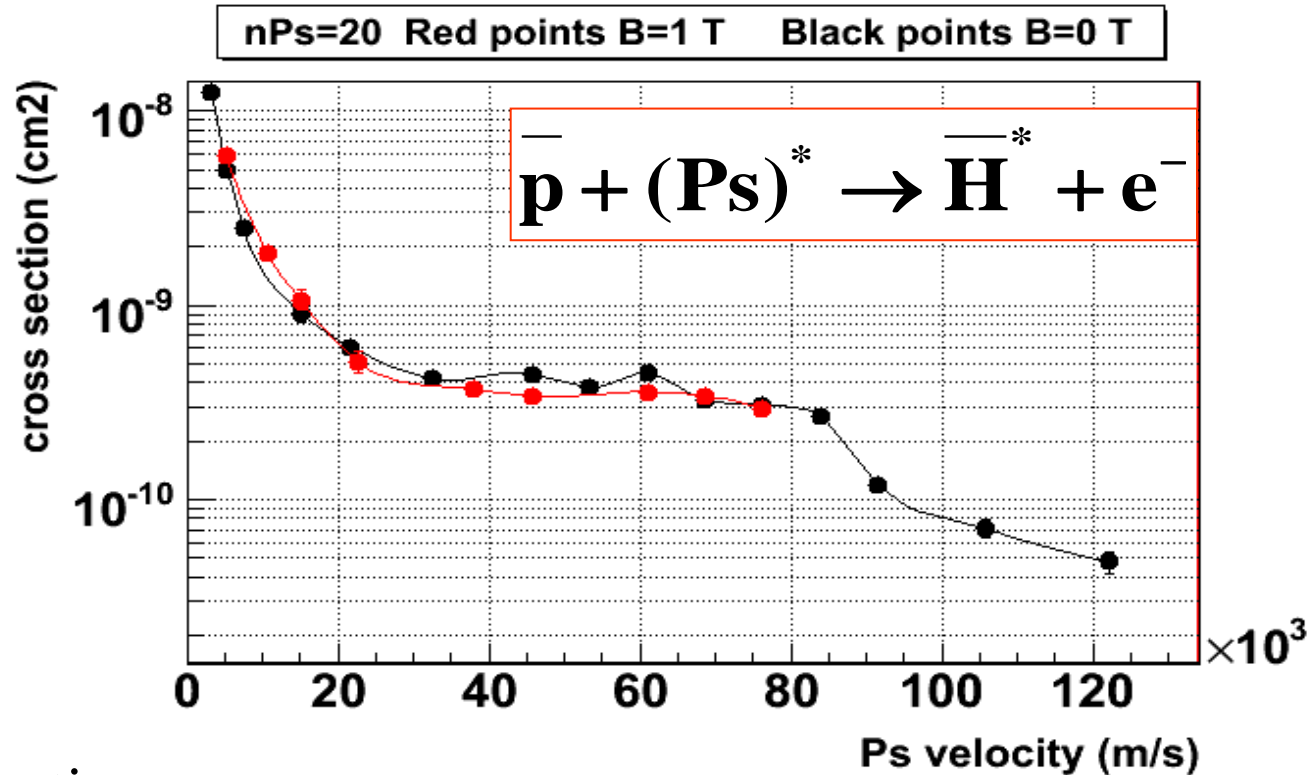
Laser cooling of Os⁻

Ultimate temperature :240 nK



•A demonstration of laser cooling of negative ions is needed

\bar{H}^* formation : Charge exchange cross section (CTMC calculation)



- High cross section
- Small effects due to 1 T magnetic field (new result, not included in the proposal: publication in preparation)
- Ps velocity of some tens Km/sec : about 100 K (10 meV)
- In progress: measurement of the positronium velocity distribution

AEGIS schedule

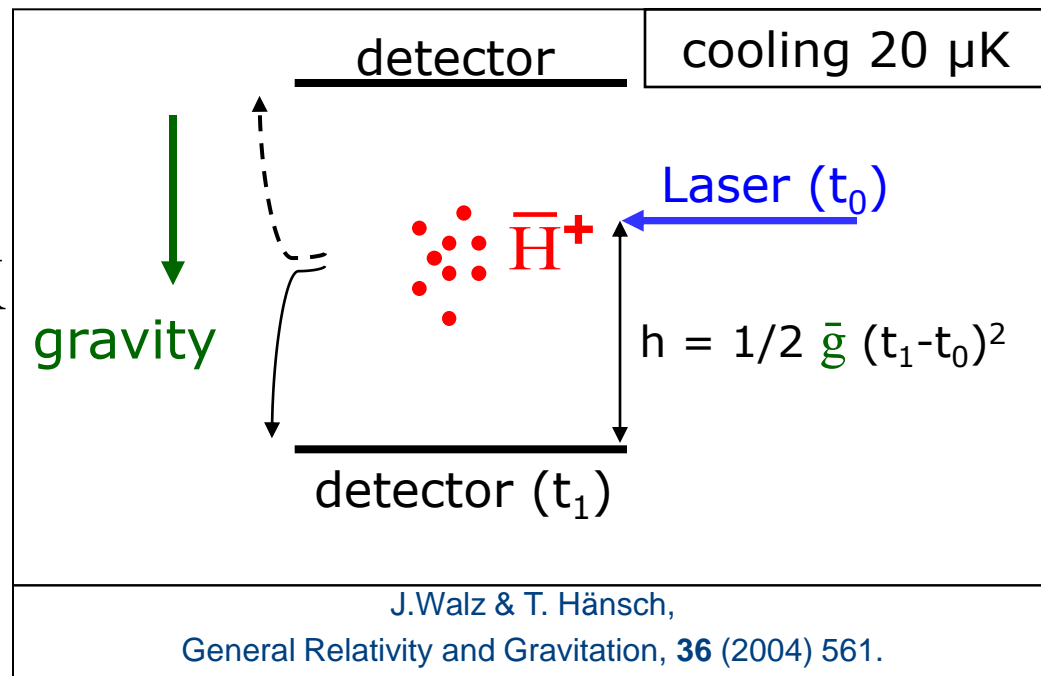
(from SPSC presentation in 2009)

2010	Start construction (magnet, cryostat, traps ...) & installation in the zone
2011 -2012	Run with and without antiprotons (e^+ commissioning) (catch, cool & transfer \bar{p} , e^+ accumulation and transfer) Complete construction and installation (antihydrogen detector, laser installation) Rydberg positronium & \bar{H} formation Cooling antiprotons to 100 mK Optimization of the antihydrogen beam
2014, 2015	Run with the grating system and the position sensitive detector

Effective schedule will depend on the funding availability

- Produce ion \bar{H}^+
- Capture ion \bar{H}^+
- Sympathetic cooling $20 \mu\text{K}$
- Photodetachment of e^+
- Time of flight

Error dominated by temperature of \bar{H}^+



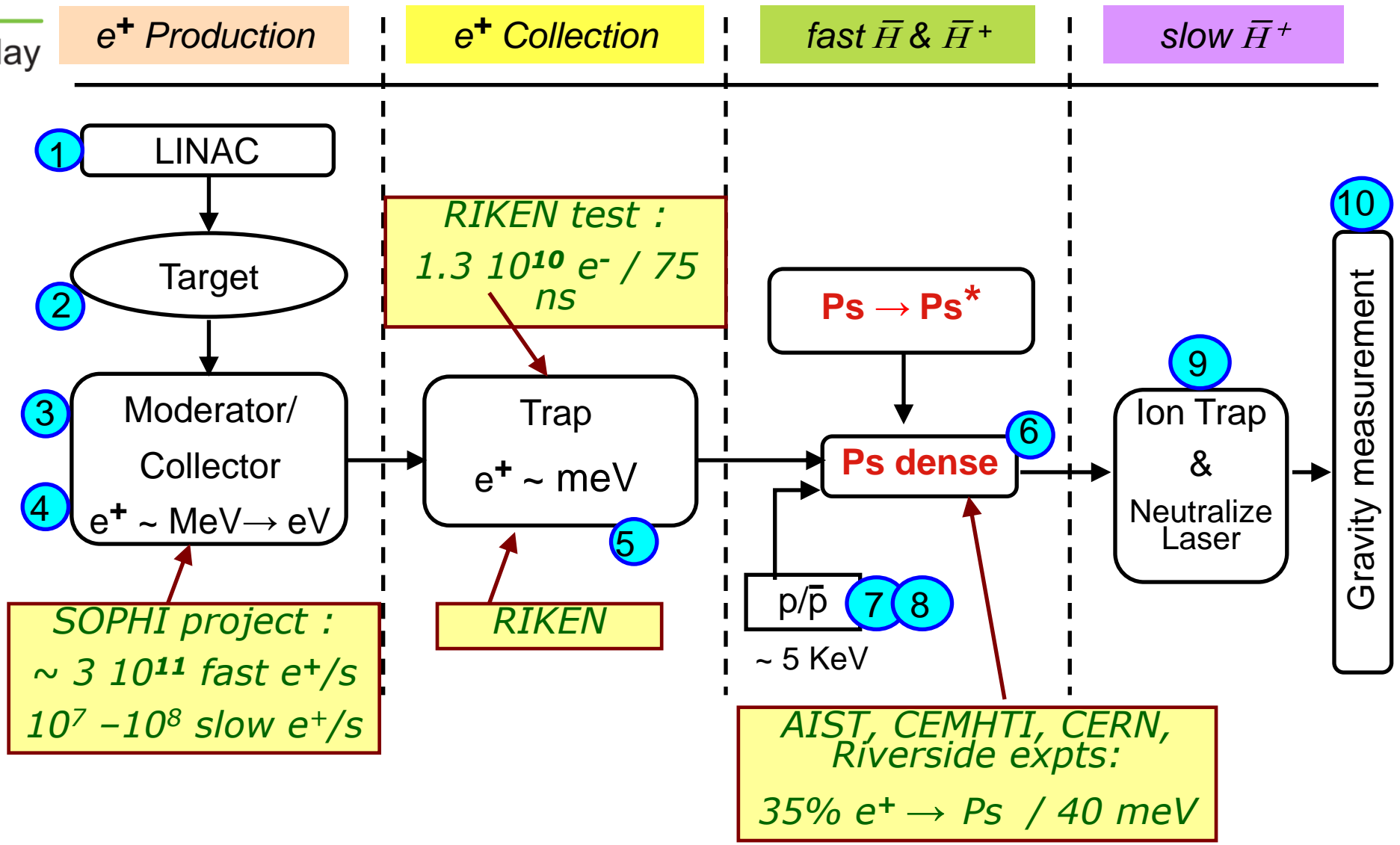
Relative Precision on \bar{g} :

\bar{H}^+ in ion trap	$\Delta g/g$
$5 \cdot 10^5$	0.001
10^4	0.006
10^3	0.02

$$h = 10 \text{ cm} \rightarrow \Delta t = 143 \text{ ms}$$

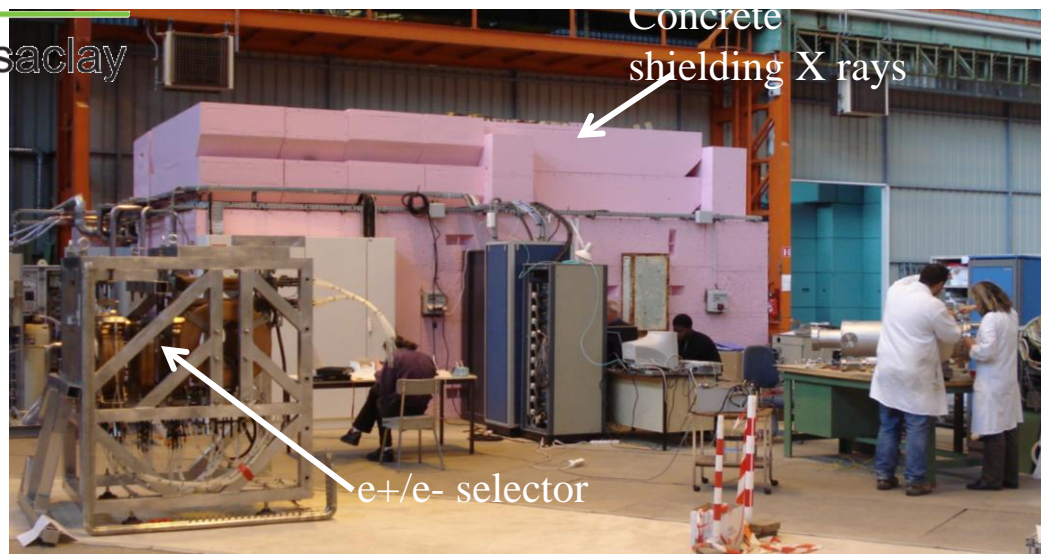
$$h = 1 \text{ mm} \rightarrow \Delta t = 14 \text{ ms}$$

Synoptic scheme



SOPHI Installation at Saclay (Nov'08)

Funded CEA-CG Essonne



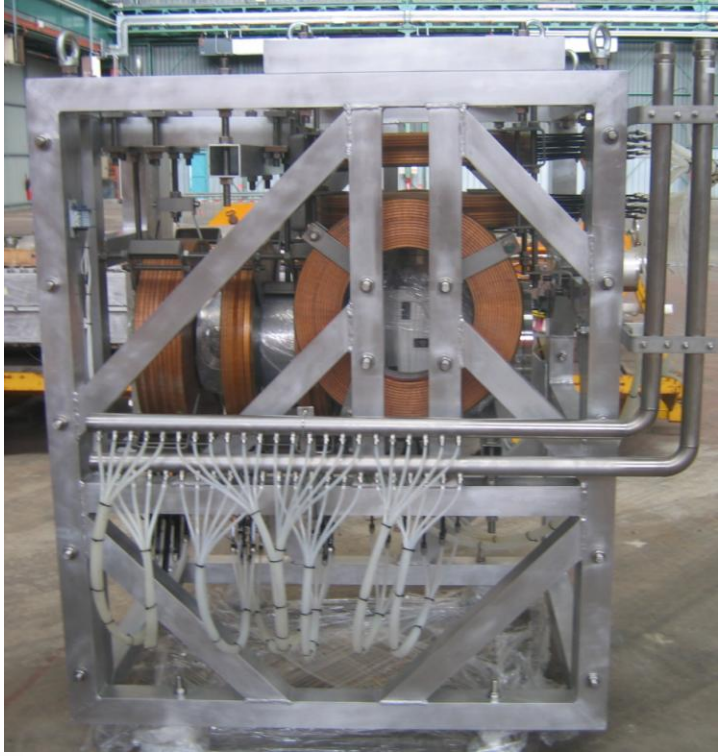
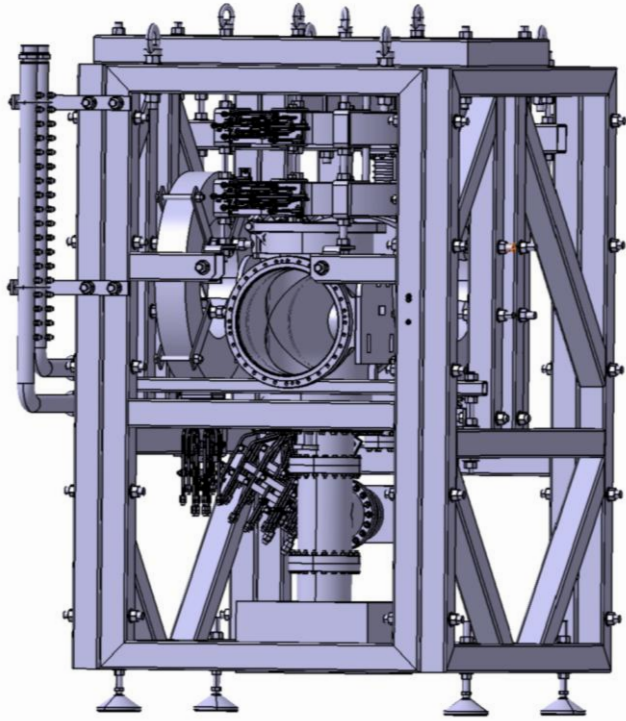
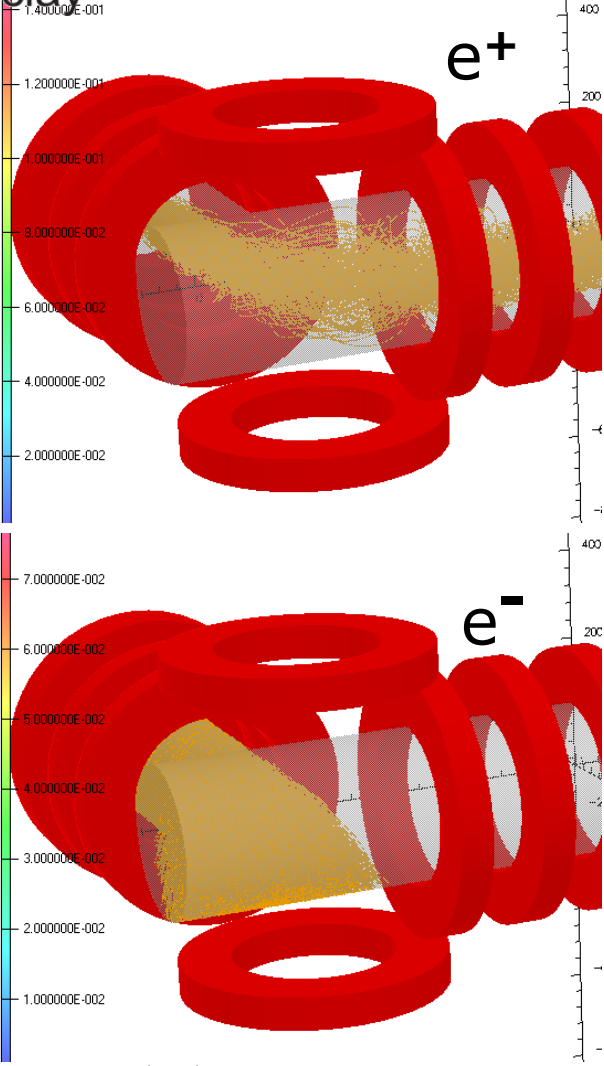
ANR 2006

Demonstrator e⁻ Linac

$E_c = 5.5 \text{ MeV}$

$I_{\text{measured}} = 0.14 \text{ mA}$

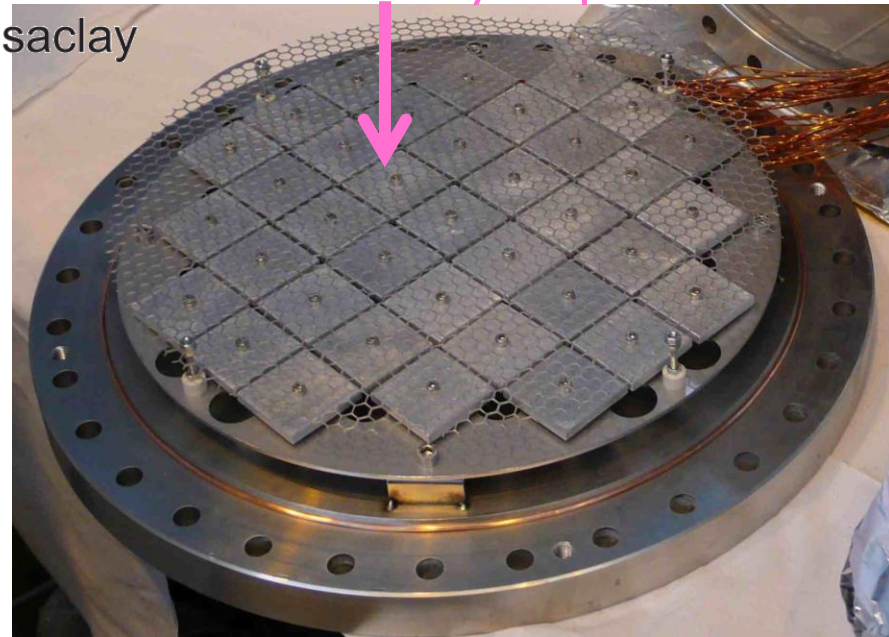
e^+/e^- selector



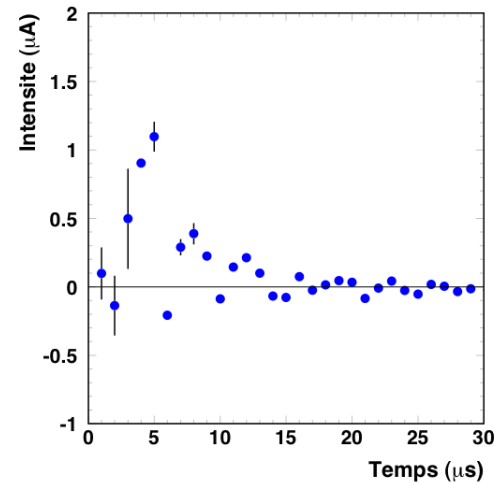
US Patent 2004
Brevet français 2005

Fast e^+ detection

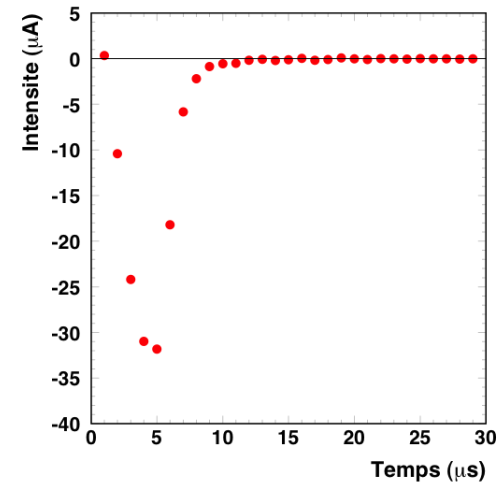
35 Faraday cups



First positrons measured end of 2009



e^+



e^-

expected positron yield from 1 mm W target at 5.5 MeV $\sim 1 \cdot 10^{-4}$ per electron

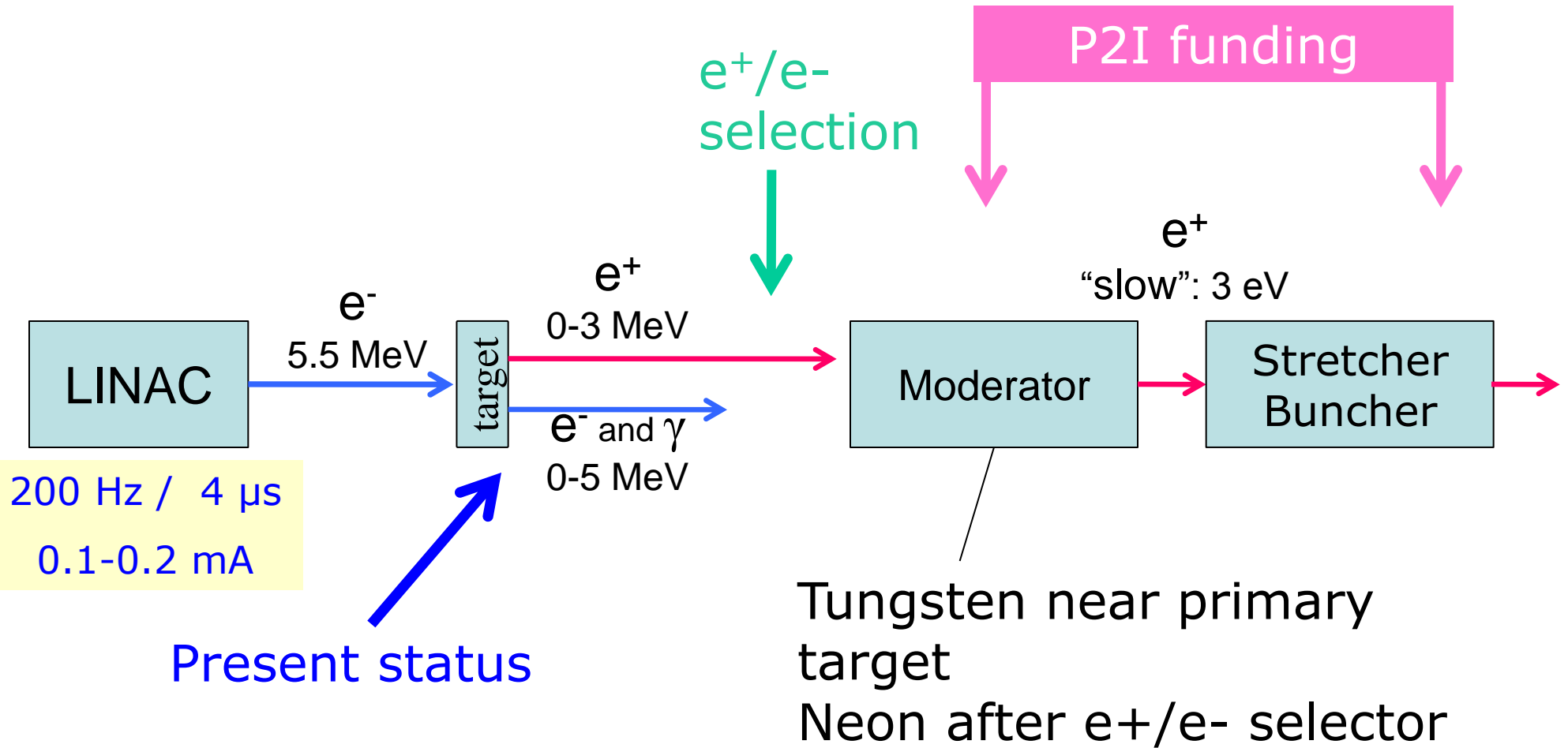
Linac peak current $\sim .12$ mA during 4 μ s

expected positron charge on pads 11-12 from simulation ~ 13 pC per burst

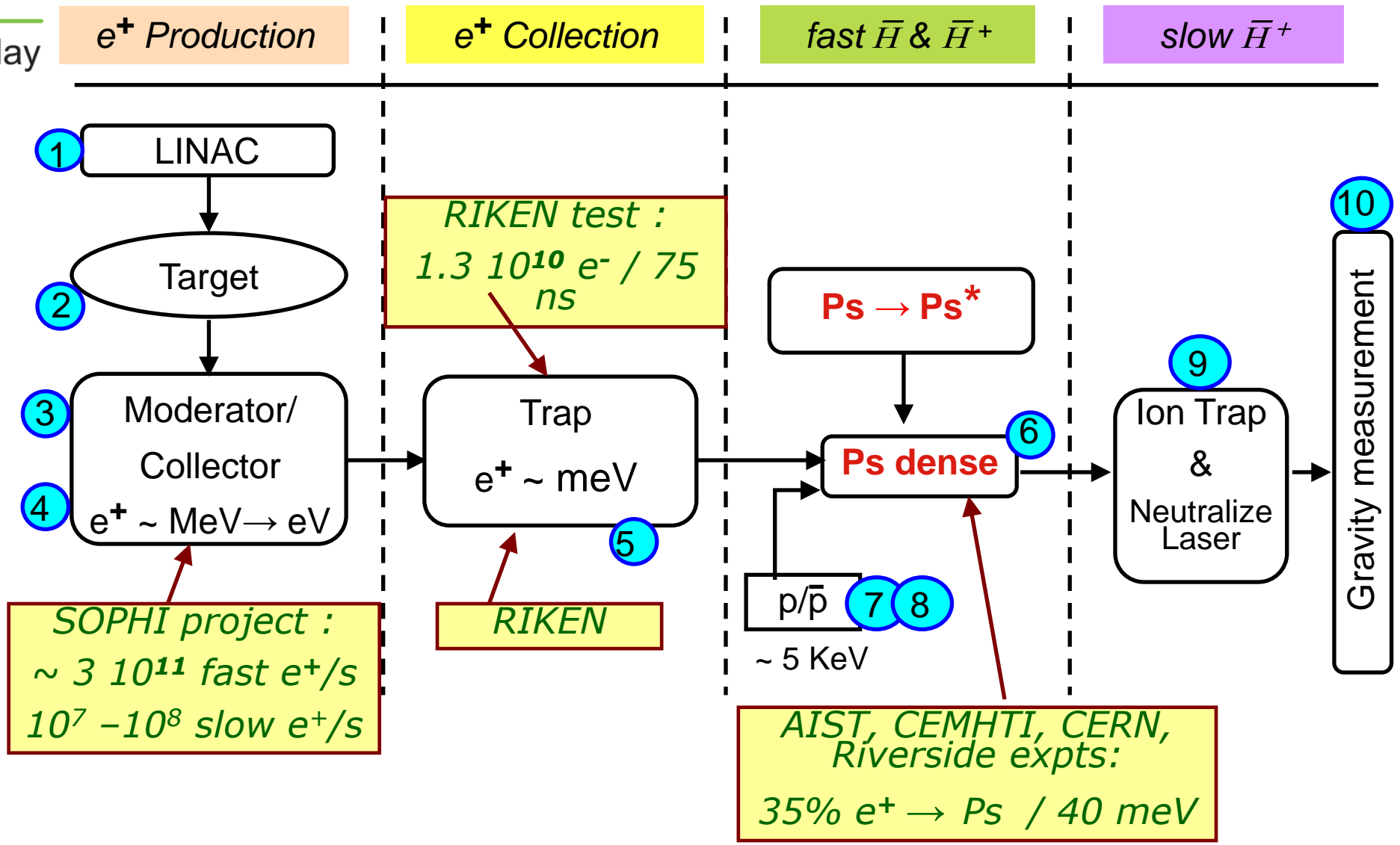
charge seen ~ 4 pC per burst :

- electron additional background ?
- LINAC energy below 5.5 MeV ?

Production and extraction of slow positrons



Synoptic scheme



RIKEN MultiRing Trap



電子プラズマを用いた陽電子蓄積装置 Development of a positron accumulator with an electron plasma

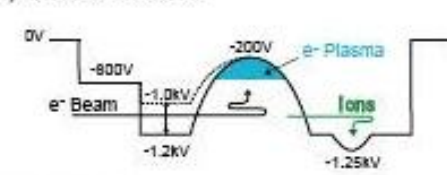
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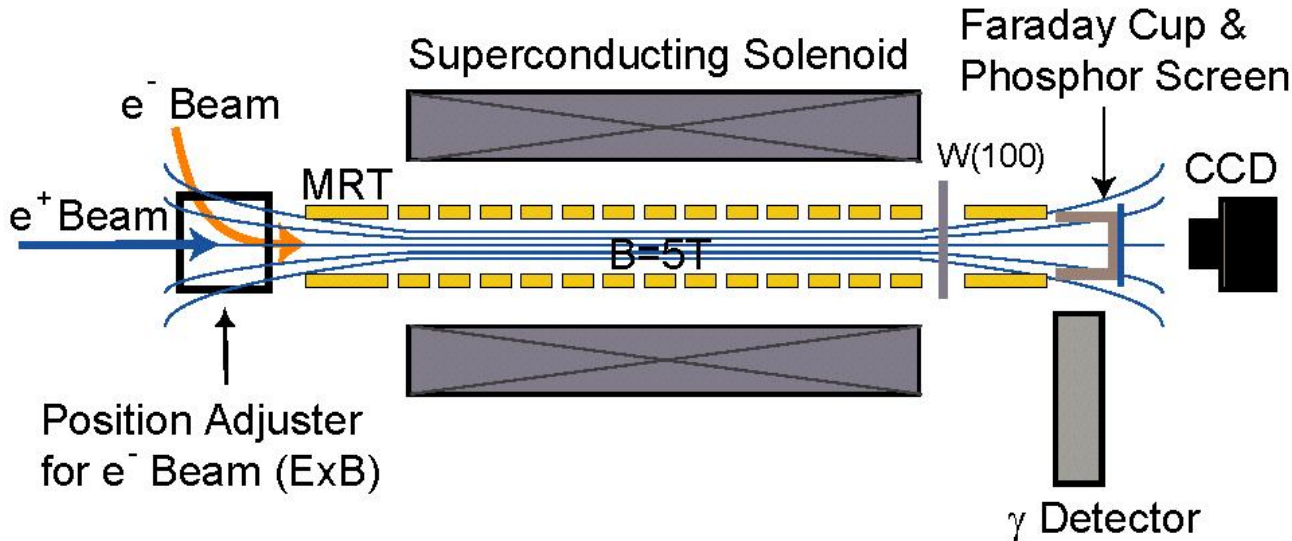
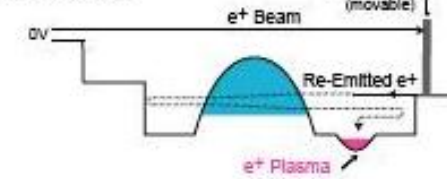
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東京大学大学院・総合文化 Institute of Physics, University of Tokyo, 3-8-1 Komaba, Meguro, Tokyo 153-8902, Japan†

a) e⁻ Plasma Formation

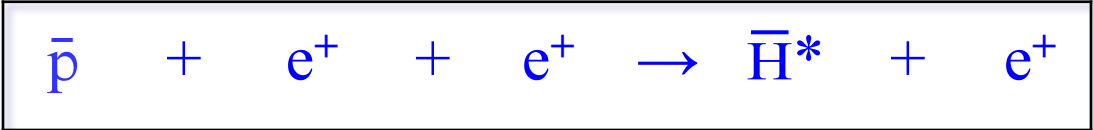


b) e⁺ Trapping

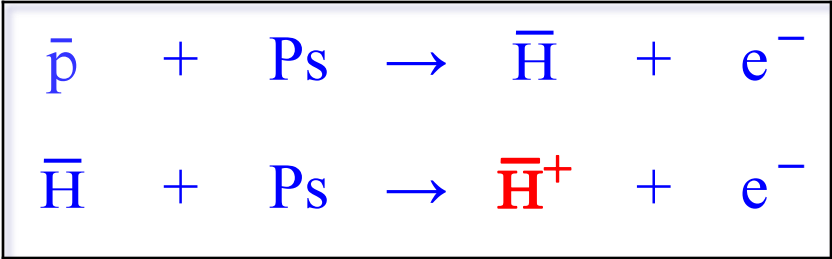
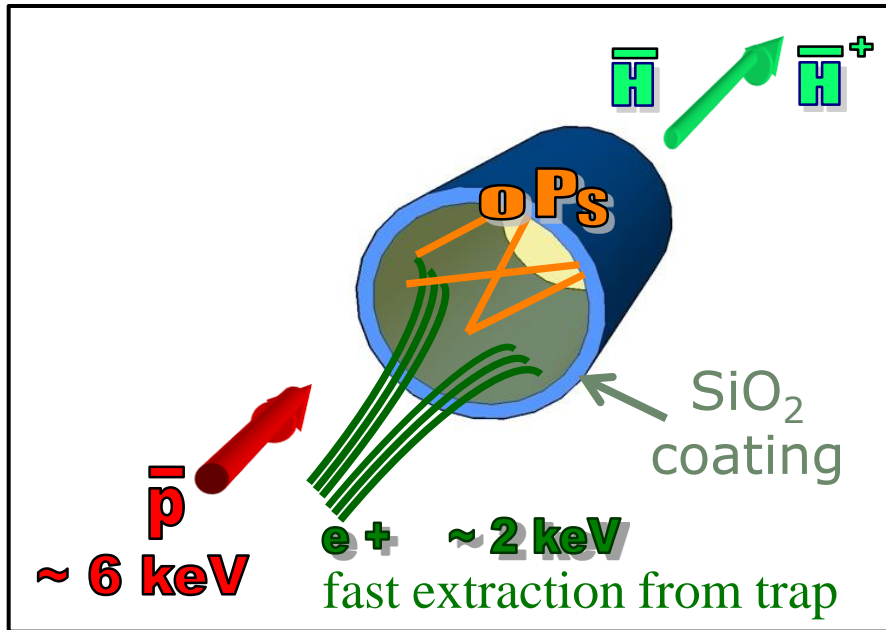


\bar{H} production via \bar{H}^+

Standard production

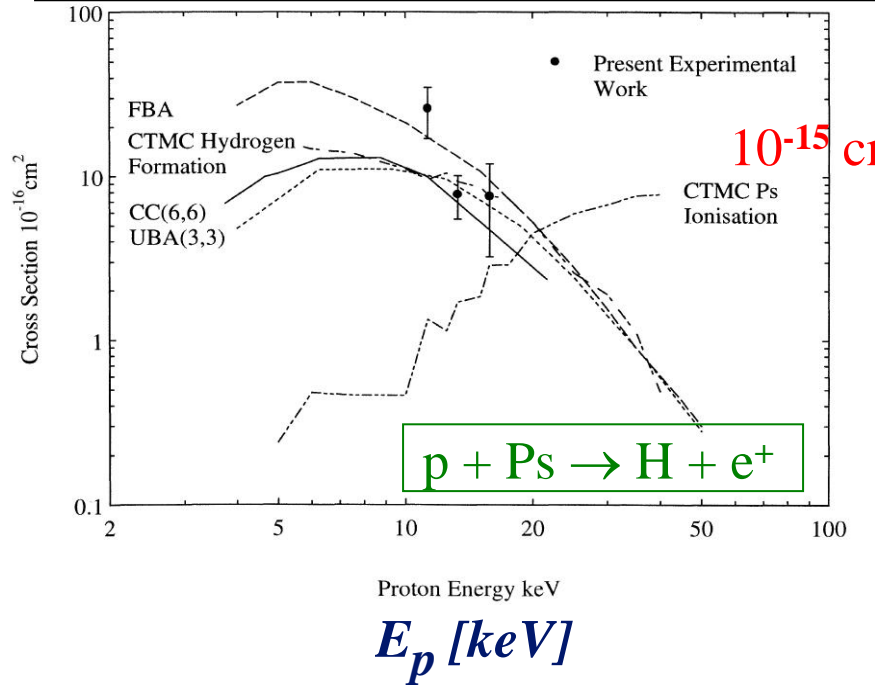


\bar{H}^+ Formation

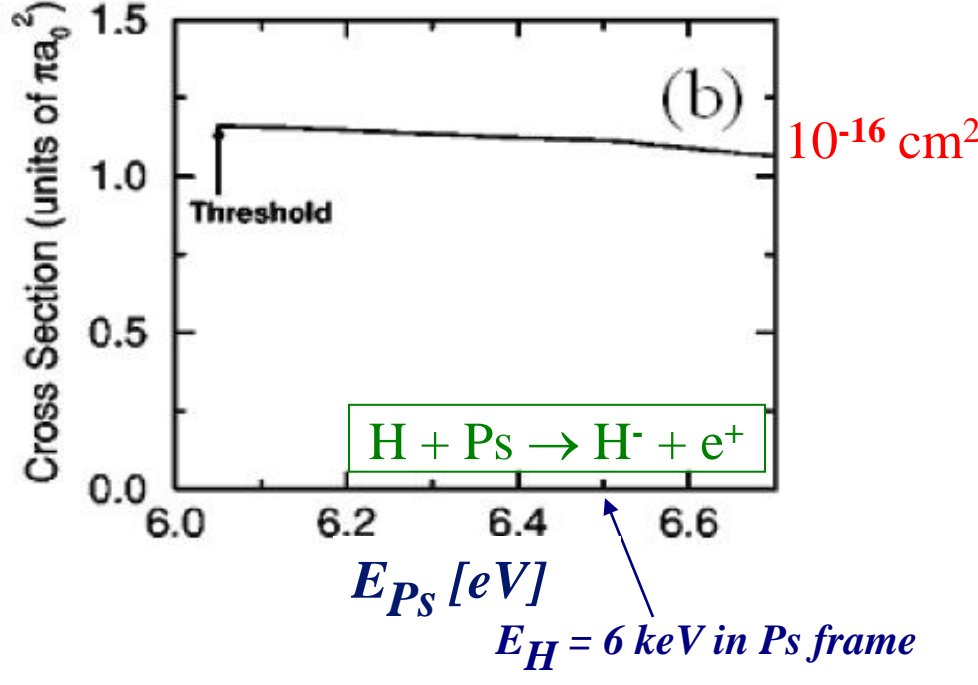


Cross-sections on PS

J. P. Merrison et al., Phys. Rev. Lett. **78**, 2728 (1997)



H.R.J. Walters and C. Starett, Phys. Stat. Sol. C, 1-8 (2007)



ASACUSA
12 AD shots \rightarrow
 e^+ from
Linac & Trap
11/01/2011

$10^7 \bar{p}$	}	$10^4 \bar{H}$
$10^{12} P_s / \text{cm}^2$		$1 \bar{H}^+$

cross-section $\propto n^4$
Excite fraction of Ps to $n=3$
 \downarrow
 $10 \bar{H}^+ ?$

Production of 10^{12} Ps/cm²

e⁺ from Na22 sources



e⁺ → Ps converter : eff. > 30%
 tube geometry to keep density
 (SiO₂ reflects Ps 100%)

Experiments with ETHZ e⁺ beam
 (A. Rubbia et al.)

L.Liszky et al., Appl. Phys. Lett. **92** (2008) 063114

to be tested with e⁺ pulses from trap

Dump 10^{11} e⁺ in 1 mm² section
 in $< \tau_{Ps}$

e⁺ trap
 accumulate 10^{11} e⁺
 during \bar{p} filling
 ~ 30'

RIKEN
 Tokyo
 Saclay

Linac
 10^8 slow e⁺/s

Saclay

Small size linac to fit AD

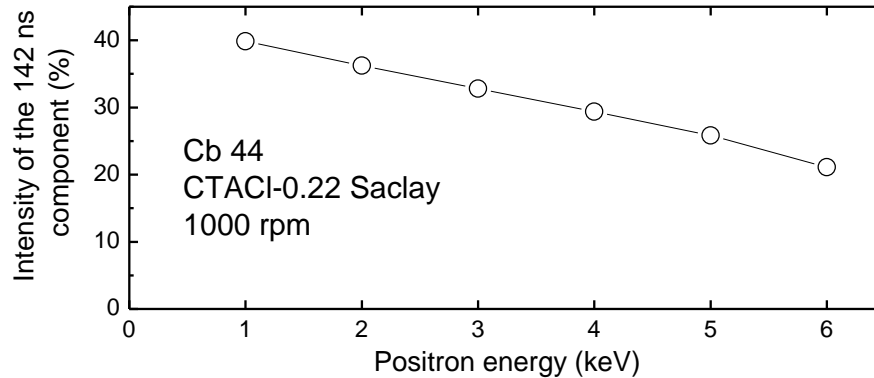
10 MeV/0.15 mA
 <E>~1.1 MeV, $8 \cdot 10^{11}$ s⁻¹

5.5 MeV/0.15 mA
 <E>~0.8 MeV, $2 \cdot 10^{11}$ s⁻¹

fast e ⁺ rate (s ⁻¹)	moderation efficiency	
10^{12}	10^{-4}	W
10^{11}	10^{-3}	Ar/Kr
$3 \cdot 10^{10}$	$3 \cdot 10^{-3}$	Ne

Yield of o-Ps : comparison CERN/UCR

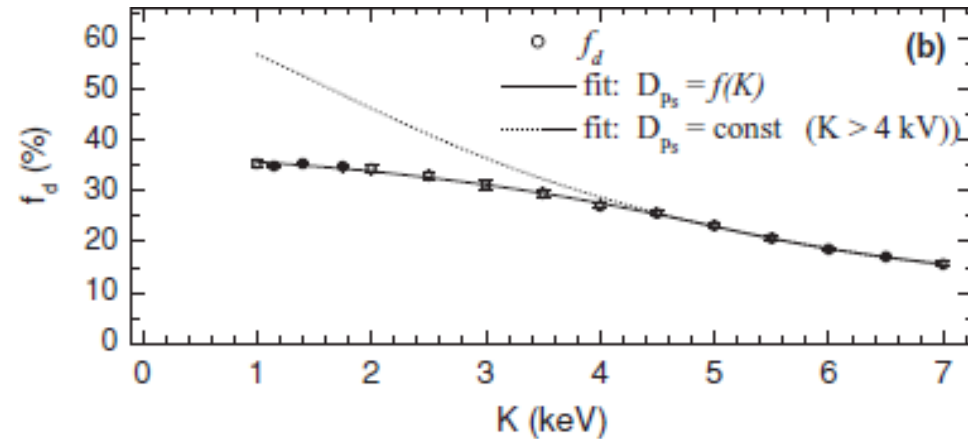
Measurement at CERN



$\sim 3.5 \times 10^5 \text{ e}^+ \text{ cm}^{-2}\text{s}^{-1}$

e^+ flux
x
 $\sim 10^{11}$

Measurement at UCR



$\sim 5.6 \times 10^{16} \text{ e}^+ \text{ cm}^{-2}\text{s}^{-1}$

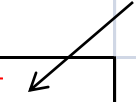
No loss in conversion efficiency in spite of the 10^{11} intensity factor

Efficiencies



Electrons						
Linac frequency (Hz)	Ie- (mA)	Ie- /pulse (mA)	pulse length (s)	Ne ⁻ / pulse	Ne ⁻ (s ⁻¹)	
200	1.40E-01	1.75E+02	4.00E-06	4.38E+12	8.75E+14	
Positrons						
ε (e ⁻ → e ⁺)	ε (transport)	ε (moderation)	Ne+fast / pulse	Ne+ fast (s ⁻¹)	Ne+ slow / pulse	Ne+ slow (s ⁻¹)
1.50E-04	0.8	1.00E-03	5.25E+08	1.05E+11	5.25E+05	1.05E+08
Positron Storage						
ε (trapping)	accum. time (s)	Ne+ stored				
0.2	1200	2.52E+10				
Positronium						
ε (e ⁺ → Ps)	volume tube (cm ³)	Ps density (cm ⁻²)	ε (excitation)			
0.35	0.01	8.82E+11	10			
\bar{H}						
N \bar{p} / pulse	σ(\bar{p} +Ps → \bar{H})	σ(\bar{H} +Ps → \bar{H}^+)	N \bar{H}	N \bar{H}^+		
1.00E+07	1.00E-15	1.00E-16	8.82E+04	7.78E+00		

every 20 minutes pulse



2011-2012



saclay

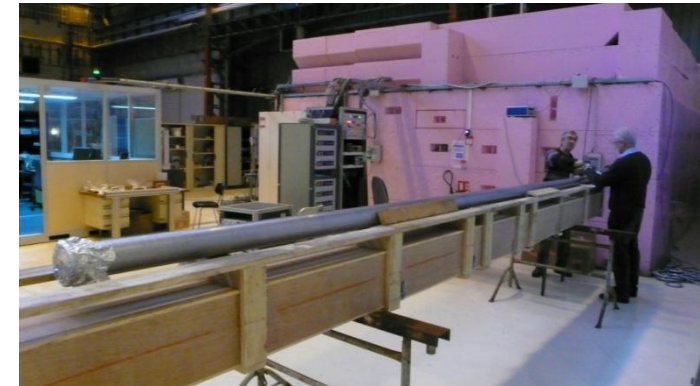
- Installation du piège de RIKEN
- Modération des positons, transport jusqu'au piège
- Piégeage des positons lents produits par le linac
- Optimisation de la production de positronium (linac, modérateur)
- Proposition CERN
(CSNSM, Irfu, LKB, Riken, Swansea, Tokyo Komaba, Tokyo U. of Science+ intérêt de ETHZ)
- Demande ANR refroidissement Be^+
- Décision sur ELENA ?***
- Applications sciences des matériaux (equipex PAM, ANR Parmes) ?*

2012-1013

- Excitation du positronium
- Conception piège $\bar{\text{H}}^+$ et photodétachement
- Conception du dispositif de mesure de chute.

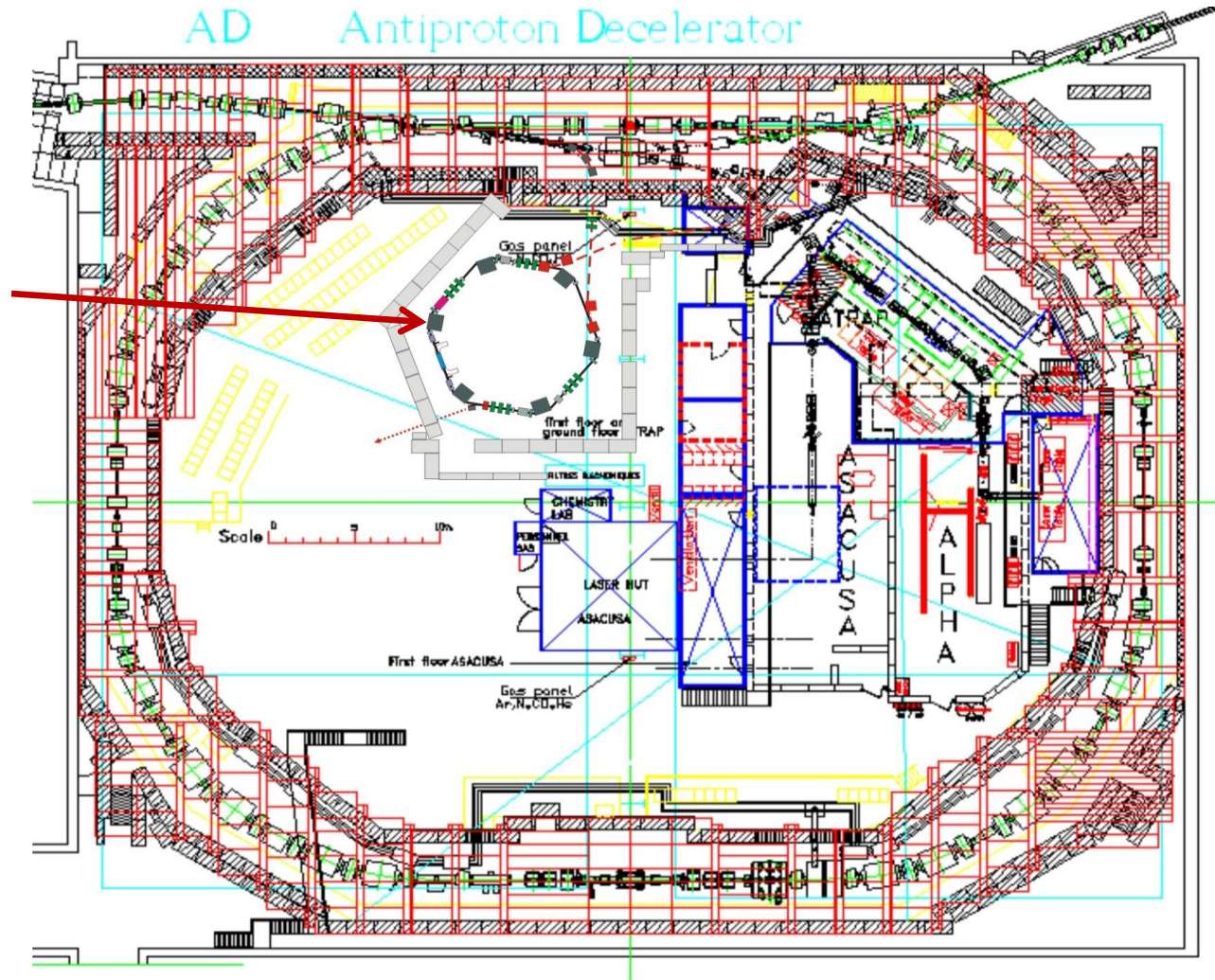
2014

- Installation au CERN et tests avec les $\bar{\text{p}}$





Bientôt ELENA (Extra Low ENergy Antiproton ring) ?



- **Nouvel anneau** en projet pour décélérer encore un peu plus les antiprotons de l'AD (**gain d'efficacité ~ 10** suivant les expériences)

- **AD:**
 - \bar{p} 5,5MeV, 1 ligne à la fois pendant 6, 12, 24h...

- **ELENA:**
 - \bar{p} **100 keV** en continu
 - possibilité de distribuer plusieurs lignes
 - **Nouvelle ligne possible**

- Décision Cern en 2011?

- Une mesure de la chute libre d'atomes d'antihydrogène serait le premier test direct du principe d'équivalence avec de l'antimatière.
- Les projets en préparation proposent des méthodes très différentes.
La proposition d'expérience pour Gbar est en cours de rédaction (CSNSM, *ETHZ*, IPCM, Irfu, LKB, Riken, Swansea, Tokyo Komaba, Tokyo U. of Science).
- Ces expériences ont une taille et un coût matériel modestes (hors production des \bar{H}), mais leur mise au point est longue et délicate (physique atomique, lasers, pièges, accélérateurs, science des matériaux, physique des particules).
- La construction d'Elena est très attendue par l'ensemble de la communauté anti H.