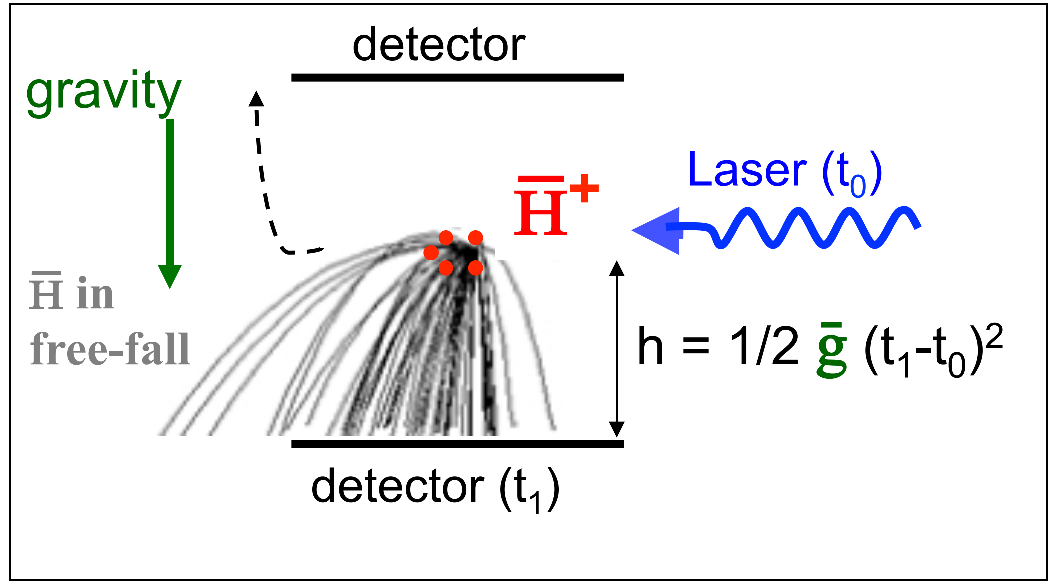
GBAR (Gravitational Behaviour of Antihydrogen at Rest)

Proposal CERN-SPSC-2011-029

Goal $\Delta\bar{g}/\bar{g} \sim 1\%$



Irfu

Laboratoire Kastler Brossel
Physique quantique et applications

RIKEN

Swansea University
School of Physical Sciences

CSNSM

ill NEUTRONS FOR SCIENCE®
Institut Laue-Langevin

東京理科大学
Tokyo University of Science

NARODOWE CENTRUM BADAŃ JĄDROWYCH
Świerk

UPPSALA UNIVERSITET

IPCMS

ETH ZÜRICH

東京大学
THE UNIVERSITY OF TOKYO

P.N.Lebedev Physical Institute of the Russian Academy of Science

JG|U
JOHANNES GUTENBERG UNIVERSITÄT MAINZ

GBAR dans l'IRFU

DIR: P. Debu
SPP: *B. Mansoulié*, P. Pérez, Y. Sacquin, B. Vallage
SEDI: L. Liszkay
SACM: J-M. Rey, P. Lévêque, , A. Chancé, D. Loucano et l'atelier du SACM
SIS: P. Bargueden, G. Dispau, Y. Lecout, P. Lotrus, J. Noury, J-Y. Roussé, Y. LeNoa
SIS(BE): P. Hardy, G. Coulloux
SPhN: *contacts avec J. Carbonell, V. Blideanu*

Etudiants: P. Grandemange, P.Comini
Postdocs: D. Brooke-Roberge, C. Roux (?) (ANR POSITRAP, Sept 2012)
Stagiaire: M. Haroche 1 an (centrale Paris) ?

<u>Aides ponctuelles:</u>
SACM: F. Peauger, A. France, G. Bourdelle, S. Langlois, R. Duperrier
SEDI: P. Legou, Y. Combet
SPP: R. Aleksan
<u>Audit</u>:
S. Joly, L. Rinolfi, H. Dzitko

Motivation

A direct test of the Equivalence Principle with antimatter

The acceleration imparted to a body by a gravitational field is independent of the nature of the body :

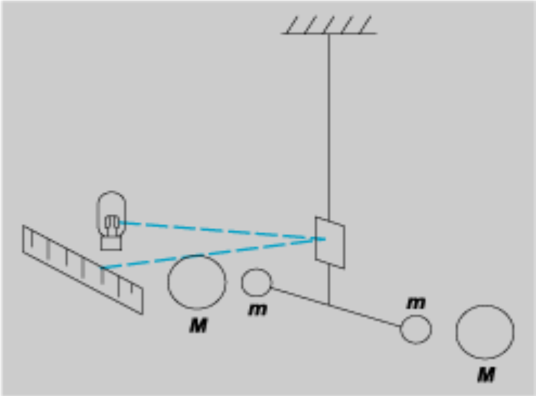
Inertial mass = gravitational mass

Tested to a very high precision with many materials

Weak Equivalence Principle (torsion pendulum)

$$\left(\Delta a / a\right)_{Be/Ti} = \left(0.3 \pm 1.8\right) x10^{-13}$$

S.Schlamminger et al, Phys Rev Lett 100 (2008) 041101



Strong Equivalence Principle (Lunar Laser Ranging)

$$\left(\Delta a / a\right)_{Earth/Moon} = \left(-1.0 \pm 1.4\right) x10^{-13}$$

J.G.Williams et al, Phys Rev Lett 93 (2004) 261101

CPT symmetry assumed

(see talk by E. Adelberger at gbar2011 workshop http://indico.in2p3.fr//event/gbar2011.fr)

Theory

$$\mathbf{V} = -\mathbf{G}\,\frac{\mathbf{mm'}}{\mathbf{r}}\left(\mathbf{1} \mp \mathbf{a}\ \mathbf{e}^{-\frac{r}{v}} + \mathbf{b}\ \mathbf{e}^{-\frac{r}{s}}\right)$$

Newton (the $-G\,\frac{mm'}{r}$ term)

Supergravity : one component of repulsive gravity (the $\mp a\,e^{-r/v} + b\,e^{-r/s}$ terms)

J. Scherk, Phys. Lett. B, 265 (1979).

Discussion and experimental constraints : *M. Nieto and T. Goldman, Phys. Rep.* ***205****, 221 (1991).*

Motivation for antigravity in General Relativity: *G. Chardin, Hyperfine Interactions* ***109****, 83 (1997).*

Lorentz and CPT violation in SME: *V. A. Kostelecký and J. D. Tasson, Phys. Rev.* ***D 83****, 016013 (2011).*

→ Toy model evades constraints

$$L = \underbrace{\tfrac{1}{2}\left(m + \tfrac{5}{3} N^w m^w \bar{c}^w_{TT}\right)}_{m_{\mathrm{i,eff}}} v^2 - gz\underbrace{\left(m + N^w m^w \bar{c}^w_{TT} + 2\alpha N^w (\bar{a}_{\mathrm{eff}})^w_T\right)}_{m_{\mathrm{g,eff}}}$$

matter: $m_{\mathrm{i,eff}} = m_{\mathrm{g,eff}}$, $\mathrm{a} = g$	**antimatter**: $m_{\mathrm{i,eff}} \neq m_{\mathrm{g,eff}}$, $\bar{\mathrm{a}} = g\left(1 - \frac{4 m^w N^w}{3m} \bar{c}^w_{TT}\right)$

Considérations théoriques

- **Antigravité en Relativité Générale**
  → violation de la conservation de l'énergie

- $m_G \neq \bar{m}_G$ possible si on ajoute des interactions (supergravité…)

- Pas d'antimatière dans l'univers visible
  → répulsion matière antimatière ?

- énergie noire + matière noire + inflation
  → théorie de la gravitation OK ?

Limites sur $(\bar{g}-g)/g$

Limites indirectes :

- Contenu en antimatière de la matière ordinaire : ~ 10^{-9}
- Mesures $\eta^{\pm}$ et $\Phi^{\pm}$ en fonction du temps par CPLEAR : qqs 10^{-9}
- Mesure fréquences cyclotron p (H^-) et $\bar{p}$ dans un même champ B : ~ 10^{-6}

Limite directe ?

-Temps d'arrivée d'1 neutrino (?) & 18 antineutrinos de SN1987a : ~ 10^{-6}

Pourquoi l'antihydrogène ?

-**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* :

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

-**antineutrons** : difficile de les ralentir suffisamment
T. Brando et al, NucI. Instrum. Methods 180 (1981) 461

-**positronium** : temps de vie très court (142 ns) si n = 1
possibilité discutée s'il est excité n>>1
Pbs : refroidissement, polarisabilité, ionisation par rayonnement…
A.P. Mills, M. Leventhal, NucI. Instrum. Meth. in Phys. Research. B192 (2002) 102

Low velocity for free fall measurement

Classical free fall: $$z = z^0 + {\color{red}v_z^0}\, t + \frac{1}{2}\, g t^2$$

Main perturbation

Desired range

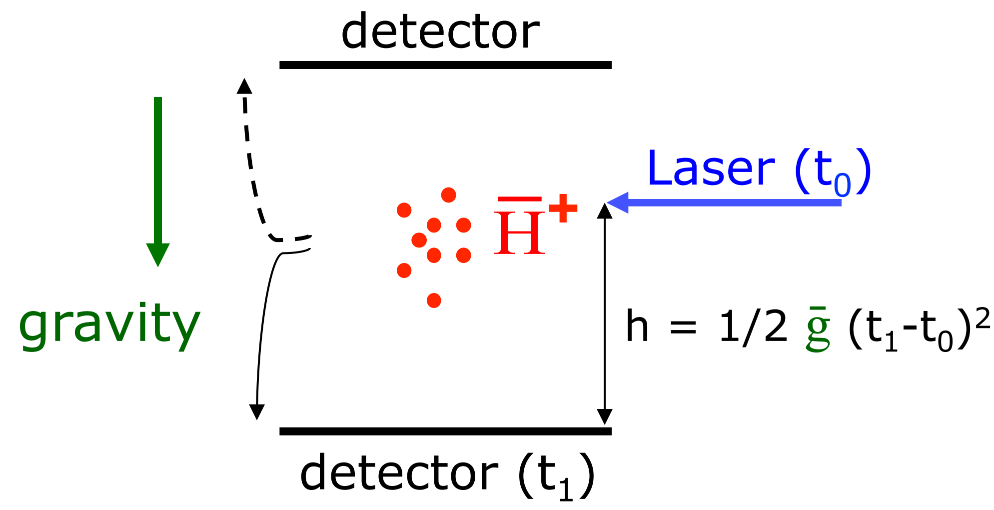
Velocity fluctuation	100 m/s	3 m/s	0.1 m/s
Temperature equivalent	1 K	1 mK	1 μK

Recoil limit of Ly_α laser cooling of $\overline{\mathrm{H}}$

Using $\bar{H}^+$ to get $\bar{H}$ atoms

- Produce ion $\bar{H}^+$
- Sympathetic cooling 10 µK
- Photodetachment of e^+
- Time of flight

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



J.Walz & T. Hänsch,
General Relativity and Gravitation, **36** (2004) 561.

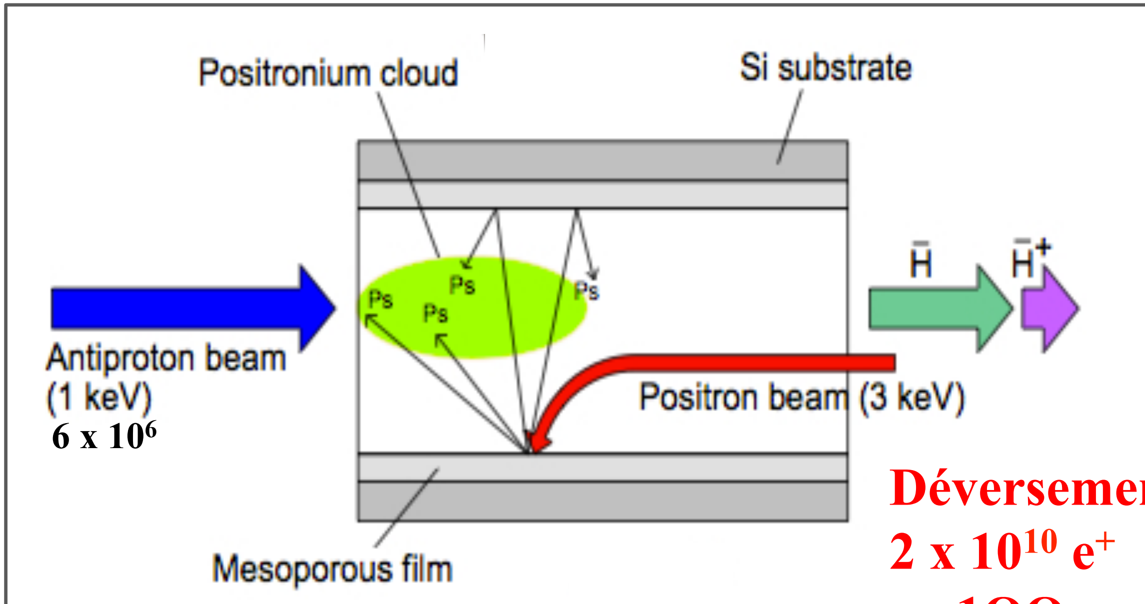
Relative Precision on $\bar{g}$:

$\bar{H}$ detected free falls	$\Delta g/g$
$1.5\ 10^5$	0.001
1500	0.01

h = 20 cm → Δt = 202 ms

h = 15 cm → Δt = 175 ms

Production des $\bar{H}^+$



Déversement de 2×10^{10} e^+ en 100 ns

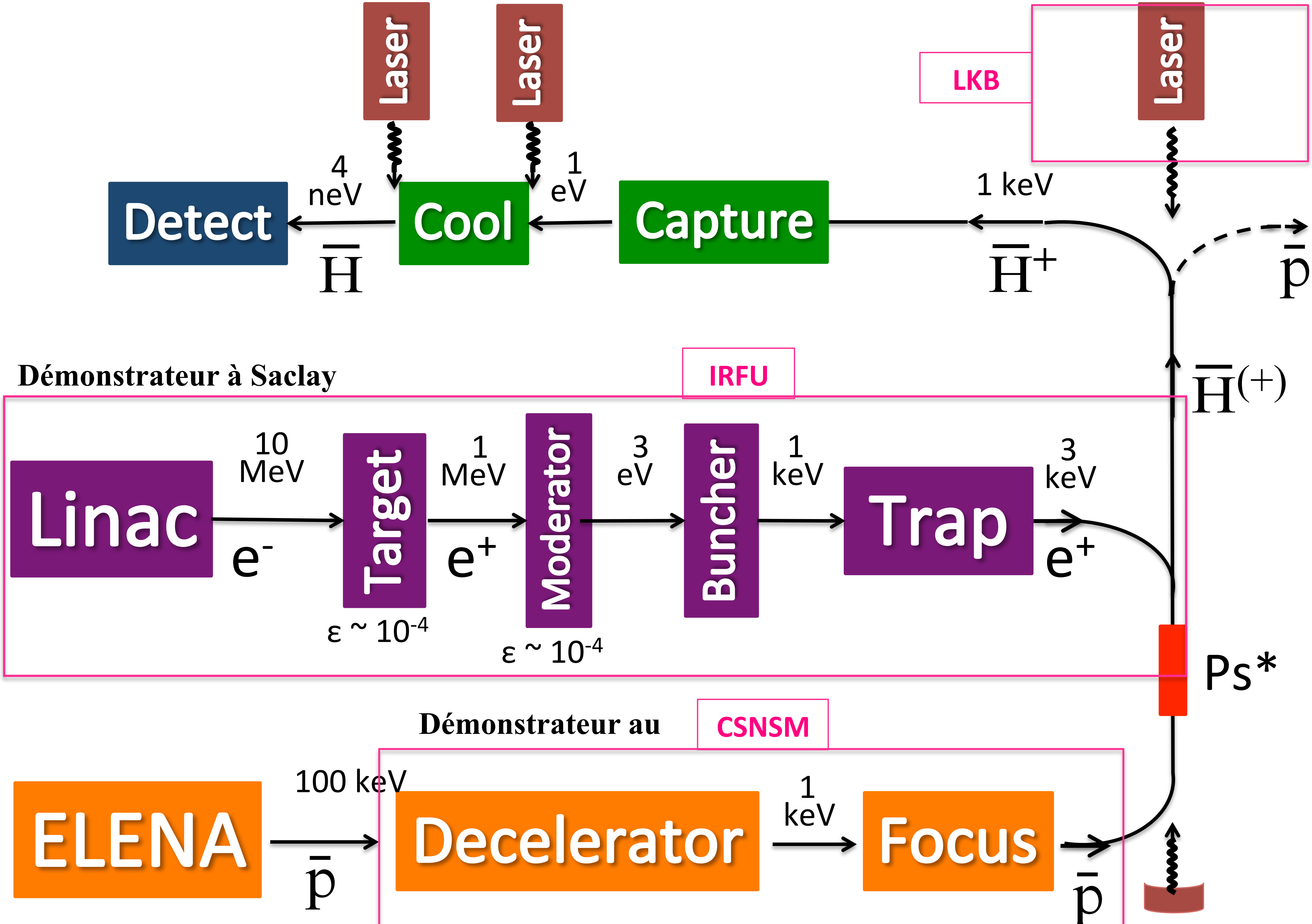
~ 1 mm

~ 1 cm

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

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

~ 0.3 $\bar{H}^+$ / pulse (~2 minutes)


Laser
Laser
Laser
LKB
4 neV
1 eV
1 keV
Detect
Cool
Capture
H̄
H̄+
p̄
Démonstrateur à Saclay
IRFU
H̄(+)
10 MeV
1 MeV
3 eV
1 keV
3 keV
Linac
Target
Moderator
Buncher
Trap
e-
e+
e+
ε ~ 10-4
ε ~ 10-4
Ps*
Démonstrateur au
CSNSM
100 keV
1 keV
ELENA
Decelerator
Focus
p̄
p̄

GBAR à Saclay

Recommandations CSTS SPP 5 mai 2010

1- Comprendre le déficit de e^+ rapides	mesures AIRIX (E = f(I))	04/2011
2- Réaliser ligne de transport e^+ lents	Financement P2I	06/2011
3- Recherche de collaborateurs et proposal CERN	GBAR proposal (14 instituts 40 physiciens)	09/2011

Actions supplementaires

ANR POSITRAP (600 k€), **DIM IFRAF** RESIMA (580 k€), **P2IO** (96 k€)
~~Equipex PAM, ANR PARMES (x2), demande postdoc **P2IO** (100 k€)~~
ERC Synergy (12.5 M€), ~~ANR SCOPE (x2)~~

Transport piège de Penning de RIKEN et installation
Contact NCBJ Swierk pour futur linac → nouveau collaborateur
Contact J. Walz (Mainz) → nouveau collaborateur

Thèses de P. Dupré et N. Ruiz
Workshop GBAR2011 60 participants/ 2 jours a l'IHP

Mesure E_{LINAC} avec spectro AIRIX

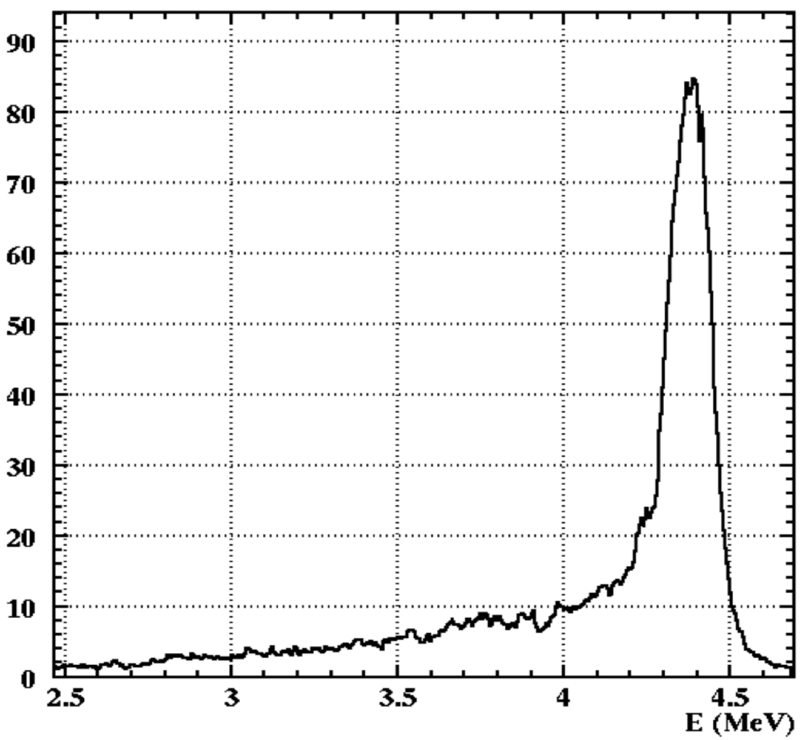


Figure 1 – measured e⁻ beam energy spectrum

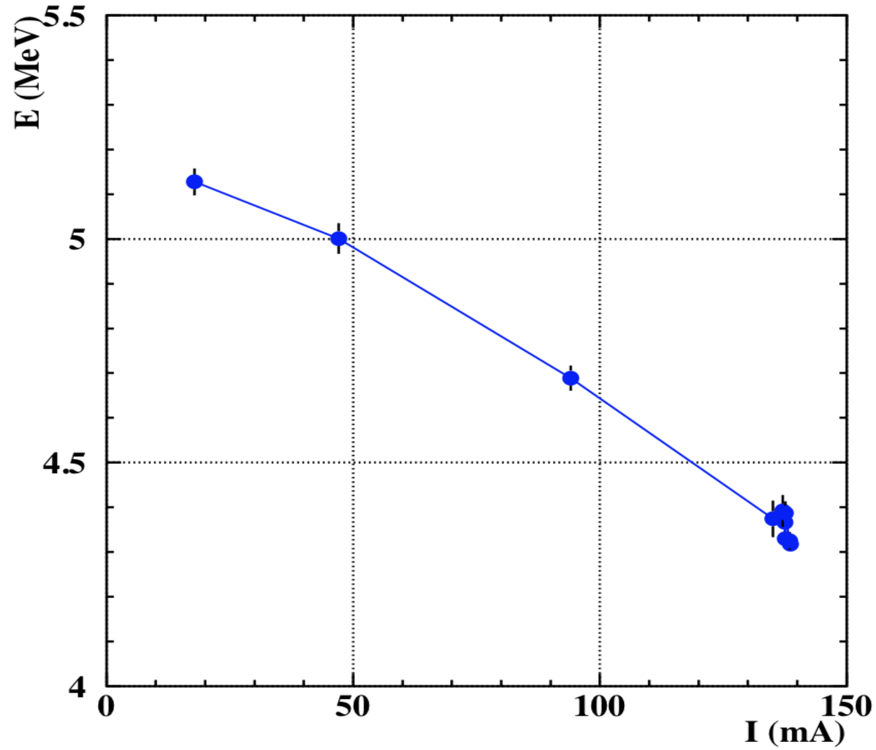


Figure 2 – measured e⁻ beam energy vs current

Intervention NCBJ sur regulation Linac

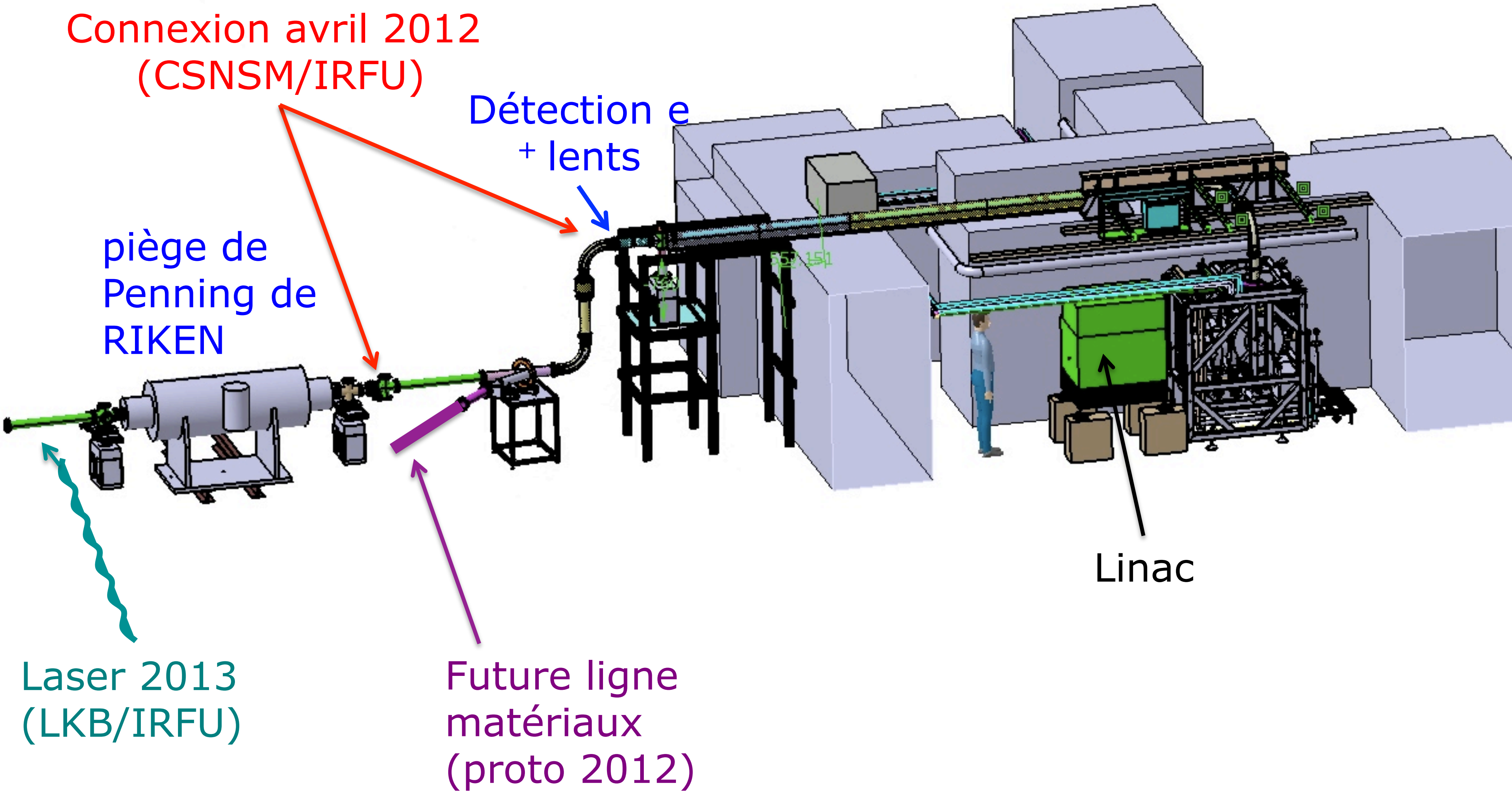
Conseil de L. Rinolfi (Cern) et aide de R. Aleksan

MoU entre NCBJ (Swierk, Pologne) et CEA/DSM

-> régulation linac (10 k€)

Effectué avril 2012 avec succès

-> stable a 200 Hz

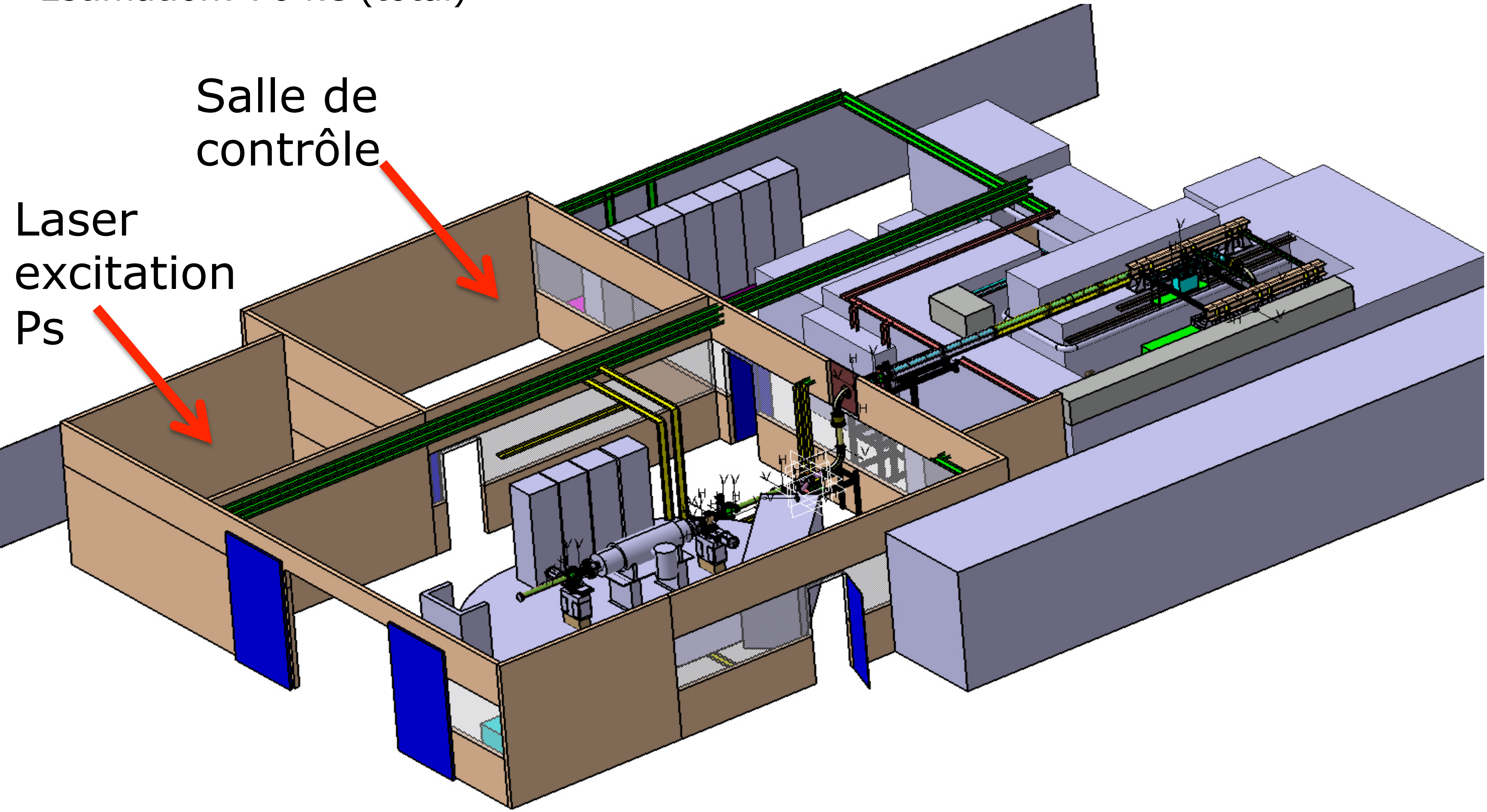

Connexion avril 2012
(CSNSM/IRFU)
Détection e
+ lents
piège de
Penning de
RIKEN
Linac
Laser 2013
(LKB/IRFU)
Future ligne
matériaux
(proto 2012)

Situation 5/04/2012

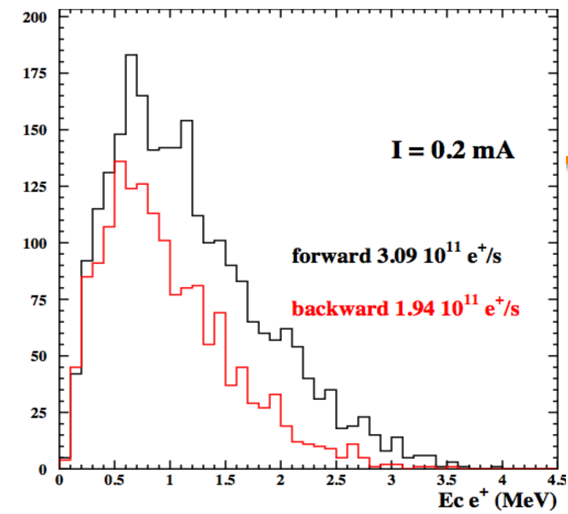
N. Ruiz, *Thesis, U. of Paris 6, (2011)*

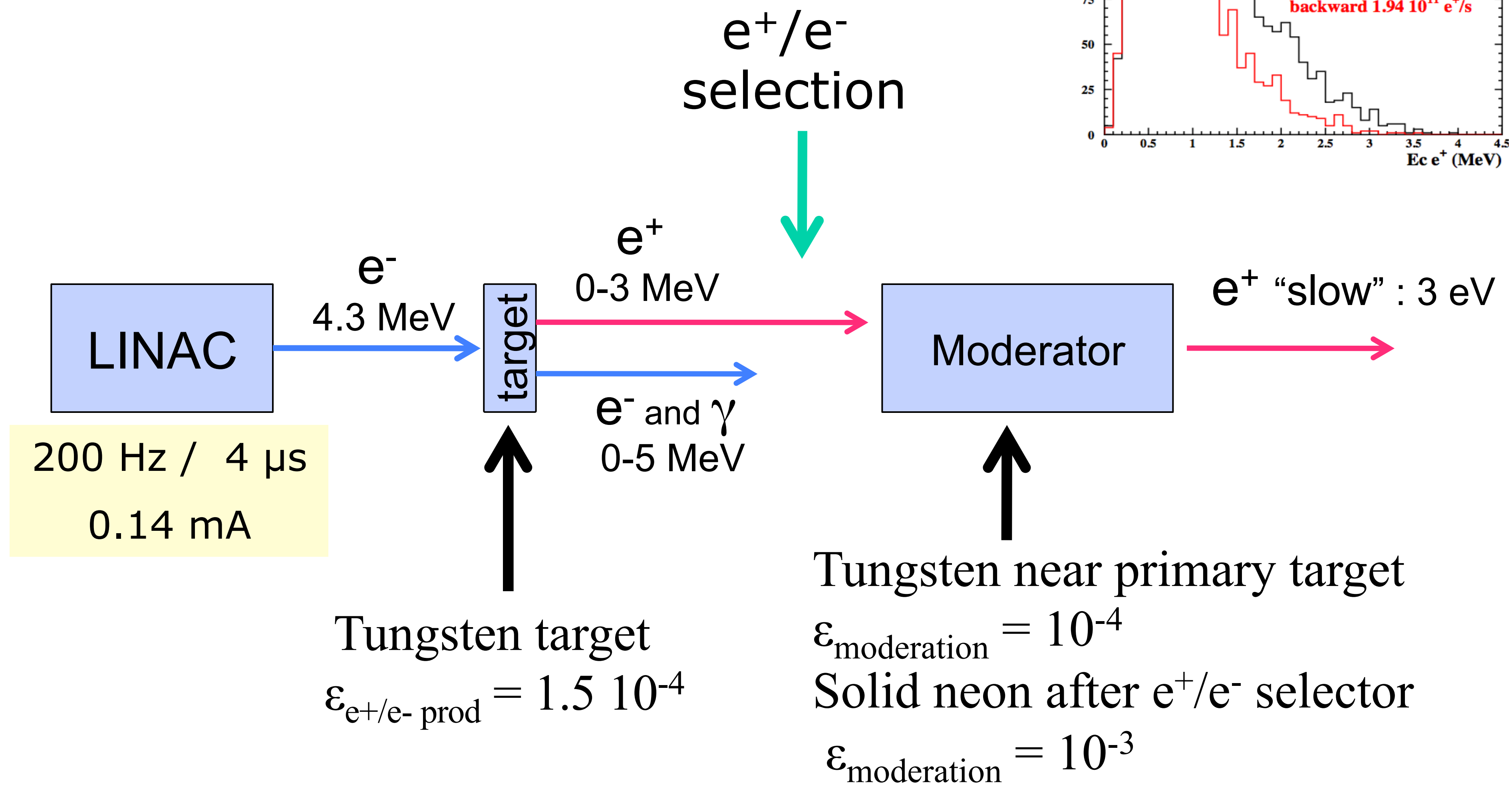
"Cabane" pour isoler les équipements

Recommandé par CLS juin 2011
Estimation: 70 k€ (total)



High intensity slow positrons source





moderation

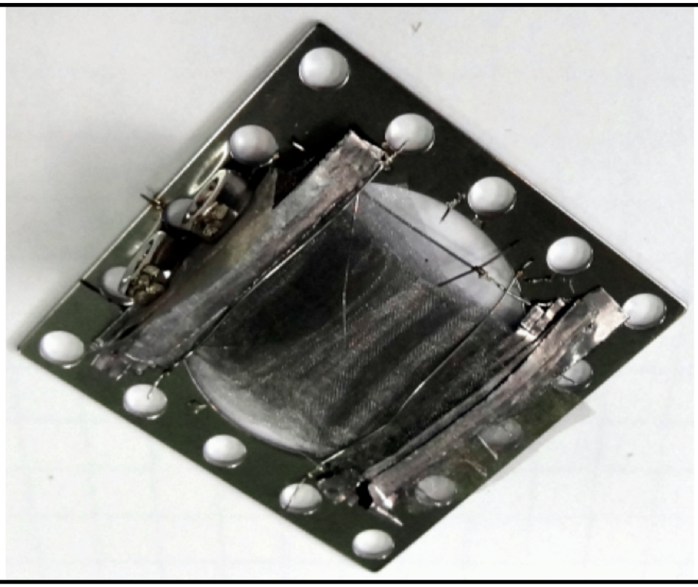


Figure 5 – tungsten mesh moderator

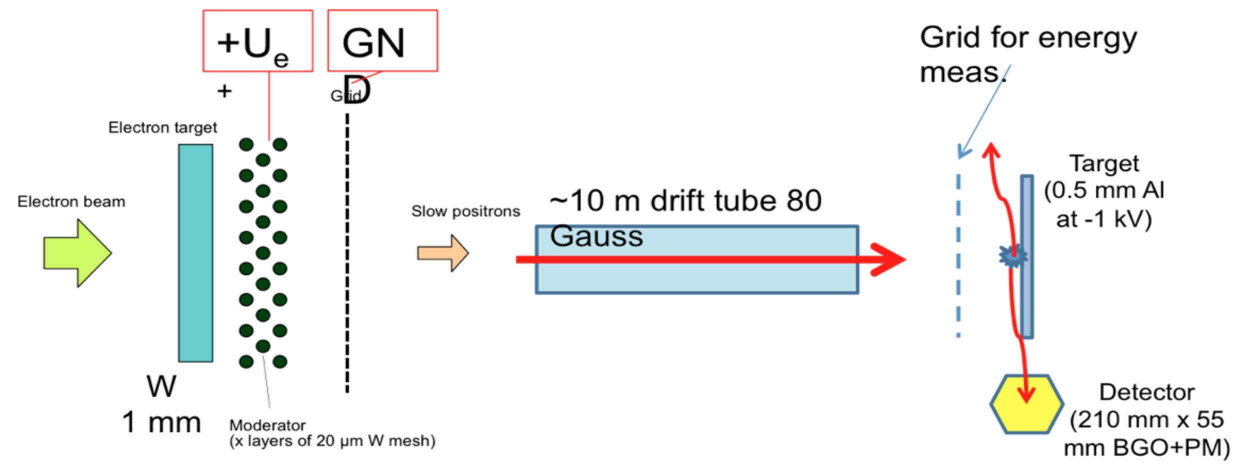
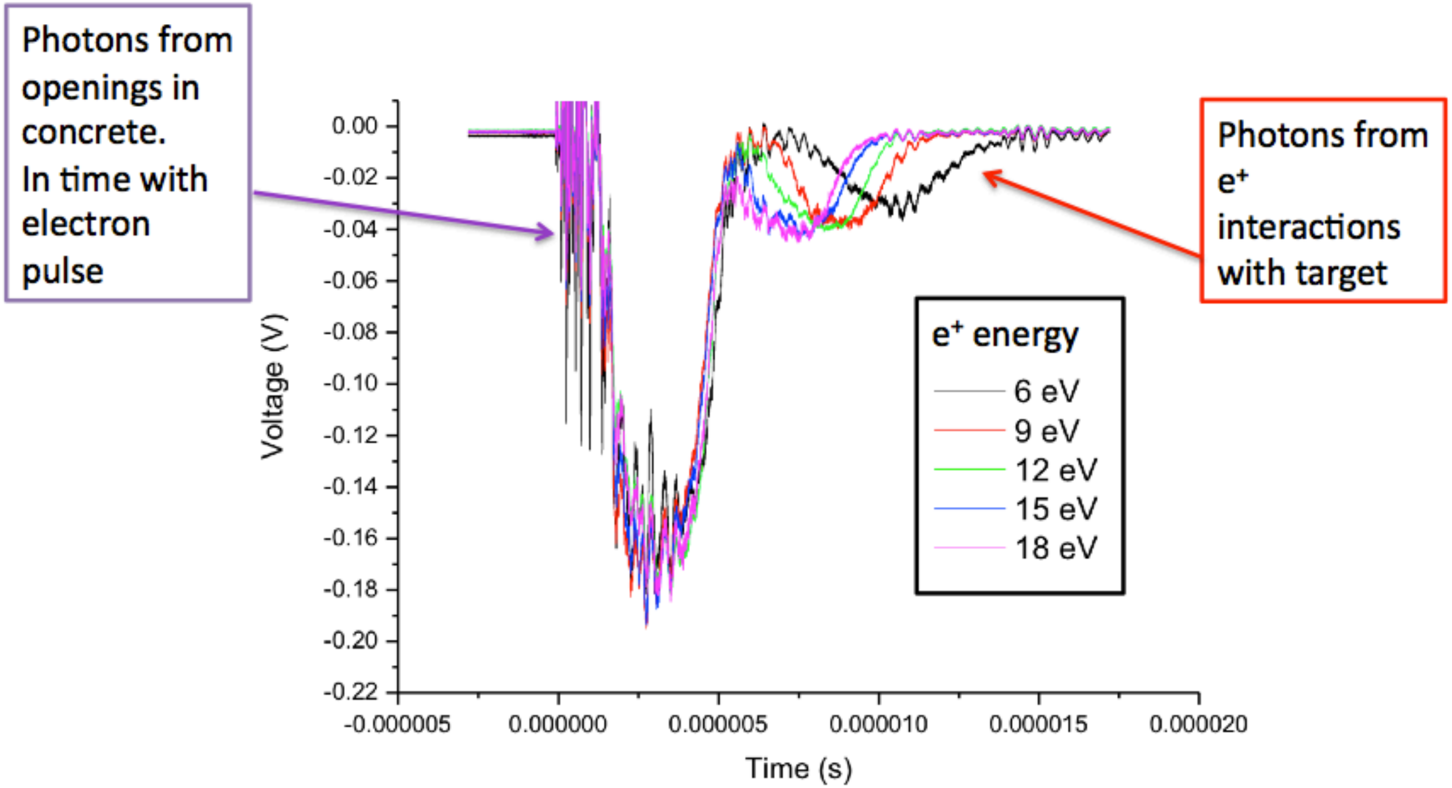


Figure 6 – principle of slow e^{+} detection

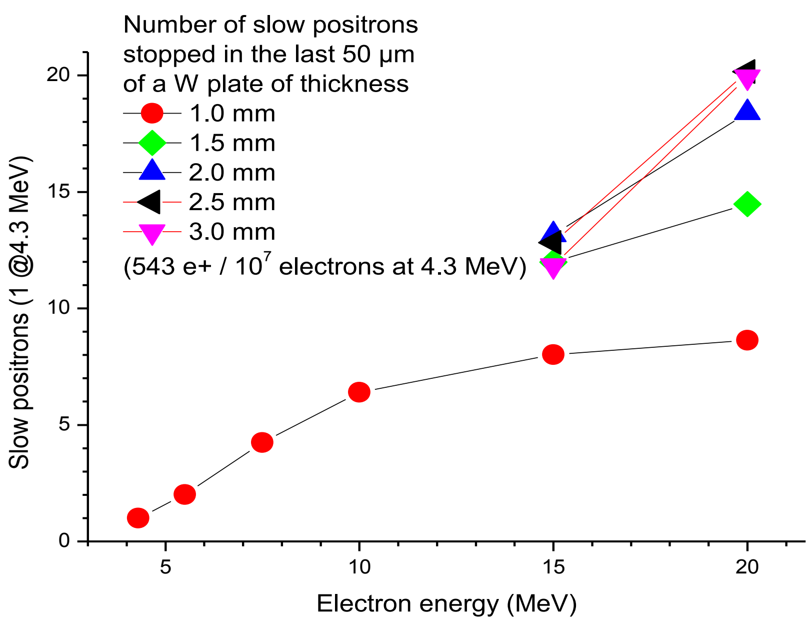
Slow positrons from Linac

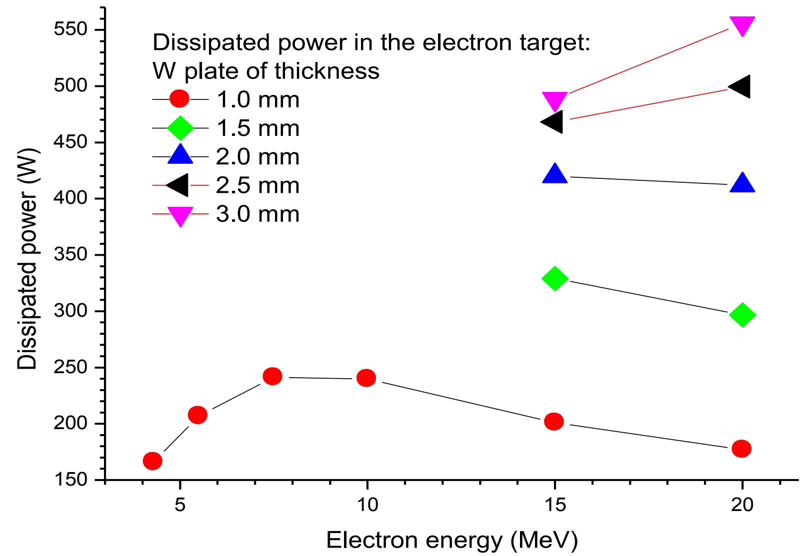


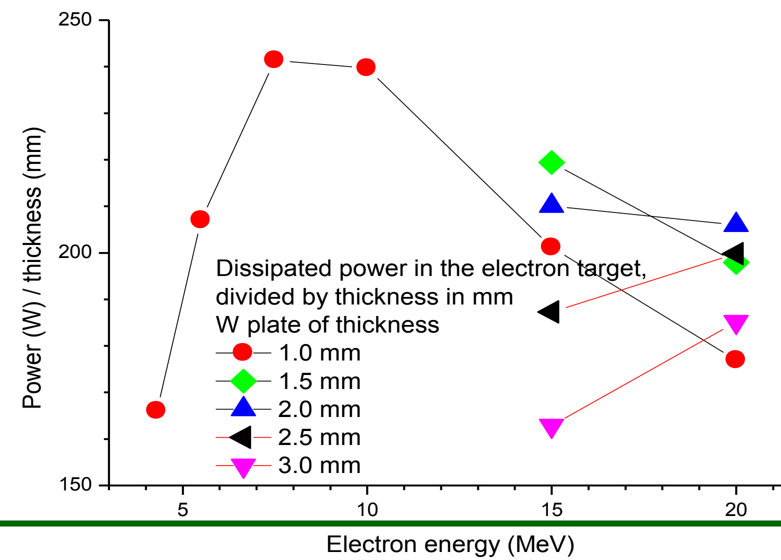
Moderator:
Basic annealing of W meshes →

Present slow e^+ rate	$3.2\ 10^6\ s^{-1}$
Extrap. to 10 MeV linac	$4.3\ 10^7\ s^{-1}$
target value	$2.8\ 10^8\ s^{-1}$

Slow positron yield and heating power vs. energy

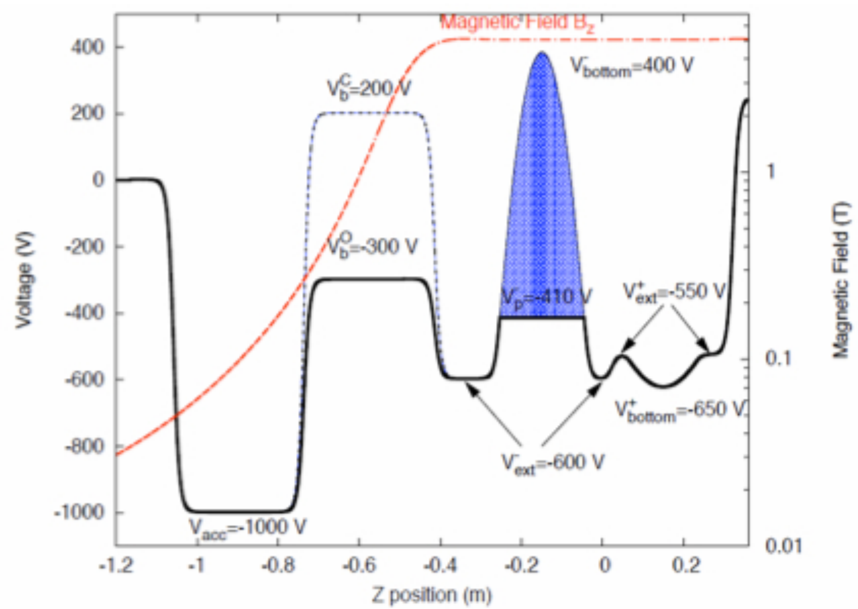


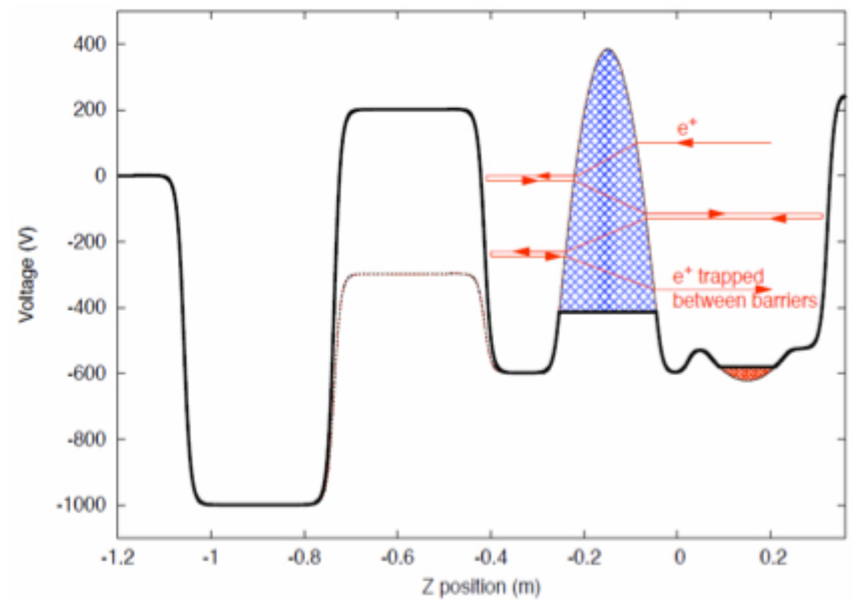




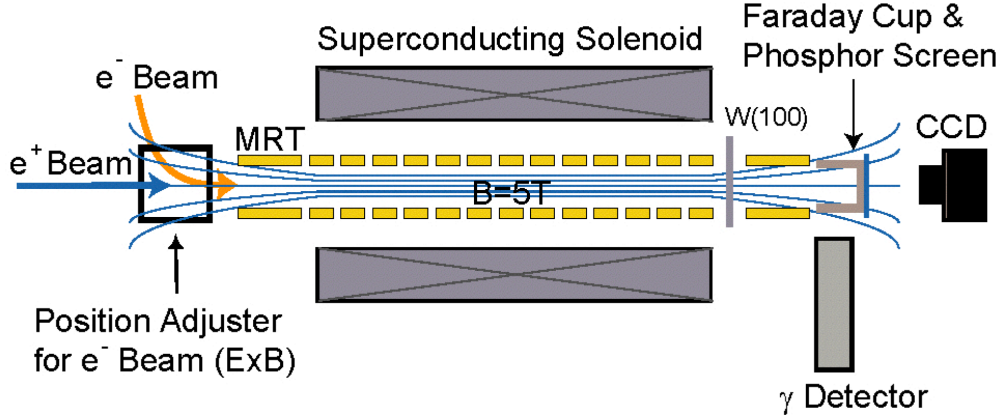
e^+ accumulation

RIKEN Penning trap adapted to pulses from Linac





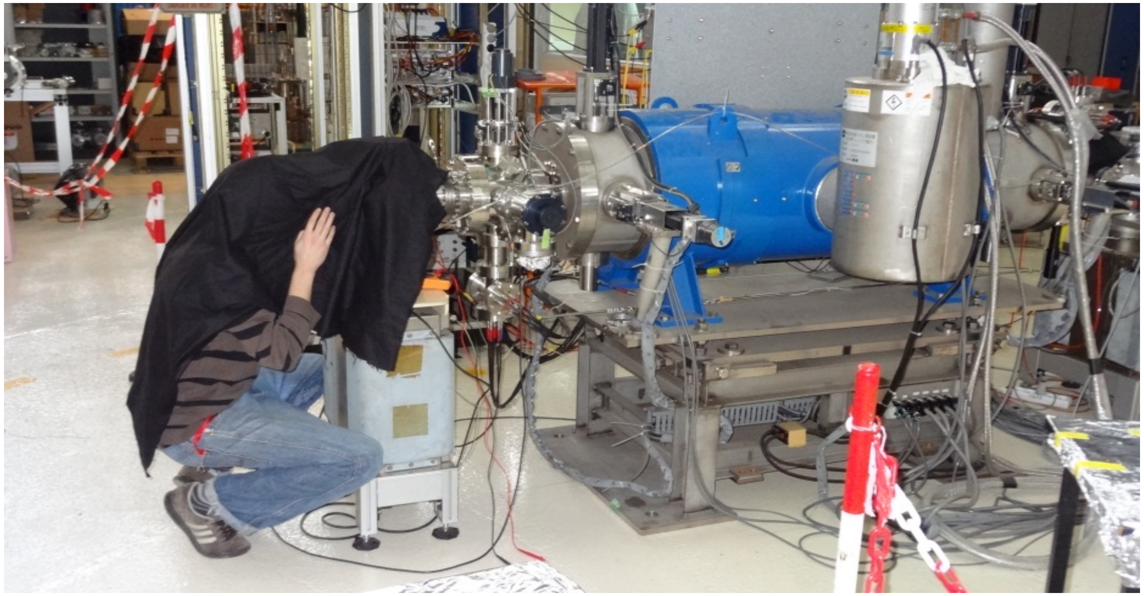
N. Oshima *et al.*,
Phys. Rev. Lett. 93, 196001 (2004)



P. Dupré, *Thesis, U. of Paris 6, (2011)*

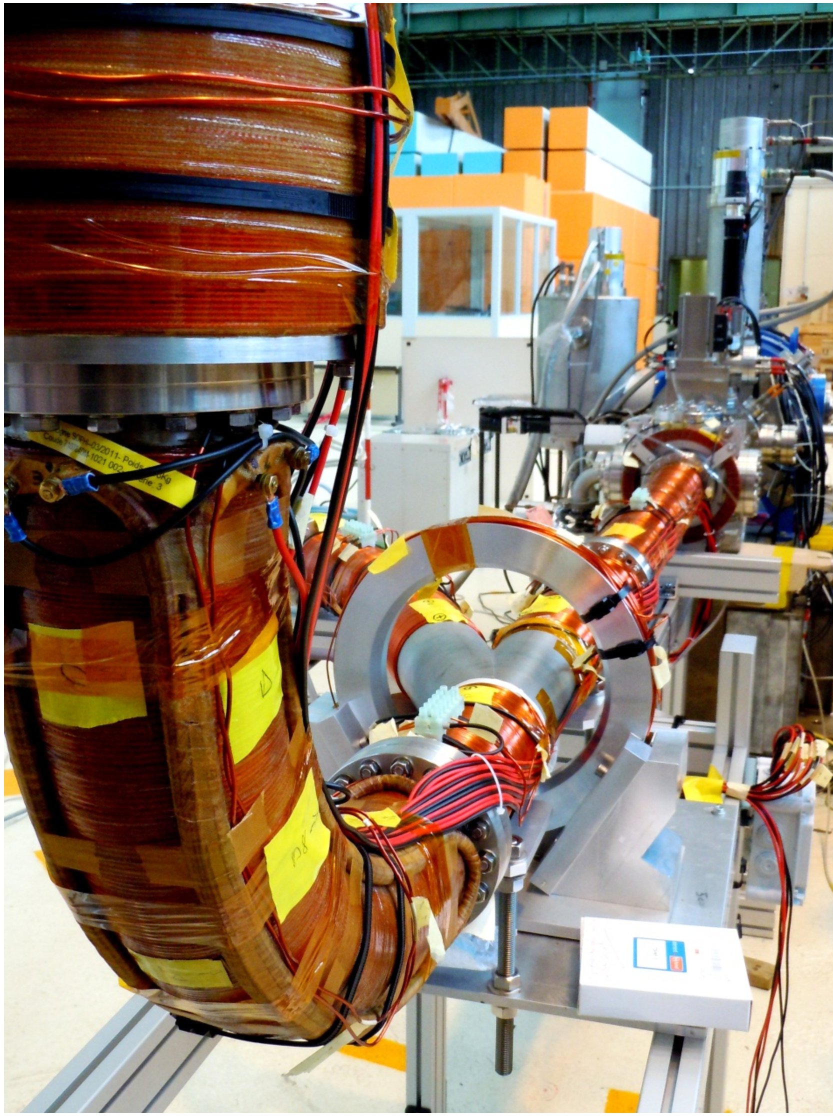
Expect ~ 70 % trapping efficiency
2 10^{10} $e^+$to be trapped

e^+ accumulation(2)



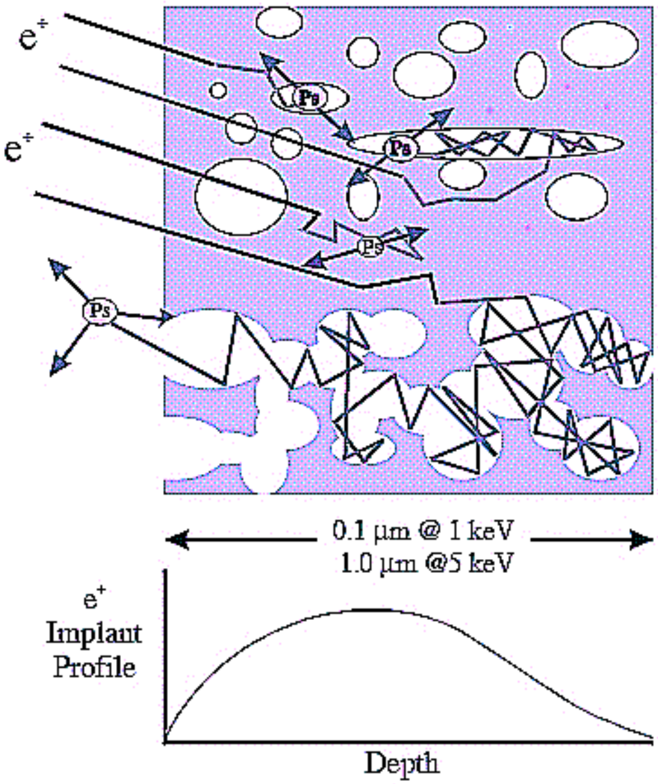
Electron spot coming from the electron gun on a phosphor screen

P. Grandemange, *These, (2013)*



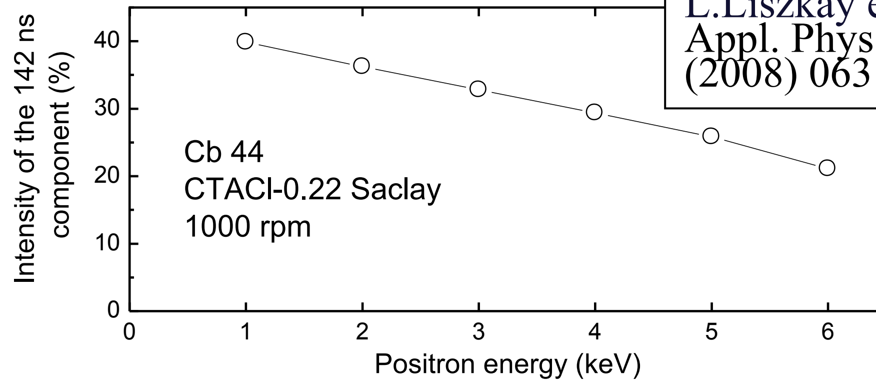
Efficient $e^+ \longrightarrow$ *o*-Ps conversion

Porous SiO_2



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

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

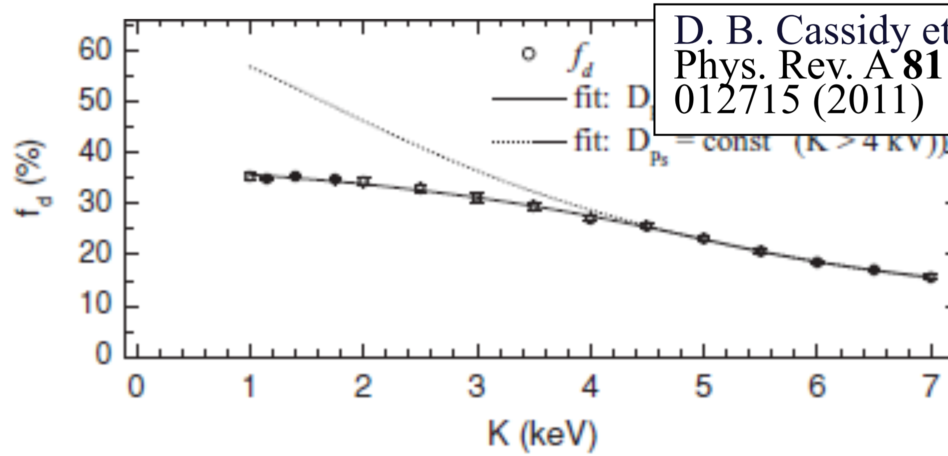


$\sim 3.5 \times 10^5\ e^+\ cm^{-2}s^{-1}$ e^+ flux

x

$\sim 5.6 \times 10^{16}\ e^+\ cm^{-2}s^{-1}$ $\sim 10^{11}$

D. B. Cassidy et al., Phys. Rev. A **81** 012715 (2011)



P. Comini

Sections efficaces production $\overline{\text{H}}$ & $\overline{\text{H}}^+$

- 2 questions : énergie optimale des $\bar{p}$ & état d' excitation optimal de Ps ?
- 2 réactions :
  - $\bar{p} + Ps(n_{Ps}, l_{Ps}) \longrightarrow \overline{H}(n_H, l_H) + e^-$ (3-corps)
  - $\overline{H}(n_H, l_H) + Ps(n_{Ps}, l_{Ps}) \longrightarrow \overline{H}^+ + e^-$ (4-corps)
- 1 même modèle théorique : Continuum Distorted Wave Final State (CDW-FS)
- Même niveau d'approximation pour les deux réactions

- CDW-FS en quelques mots :
  - Méthode perturbative avec description exacte des états asymptotiques :

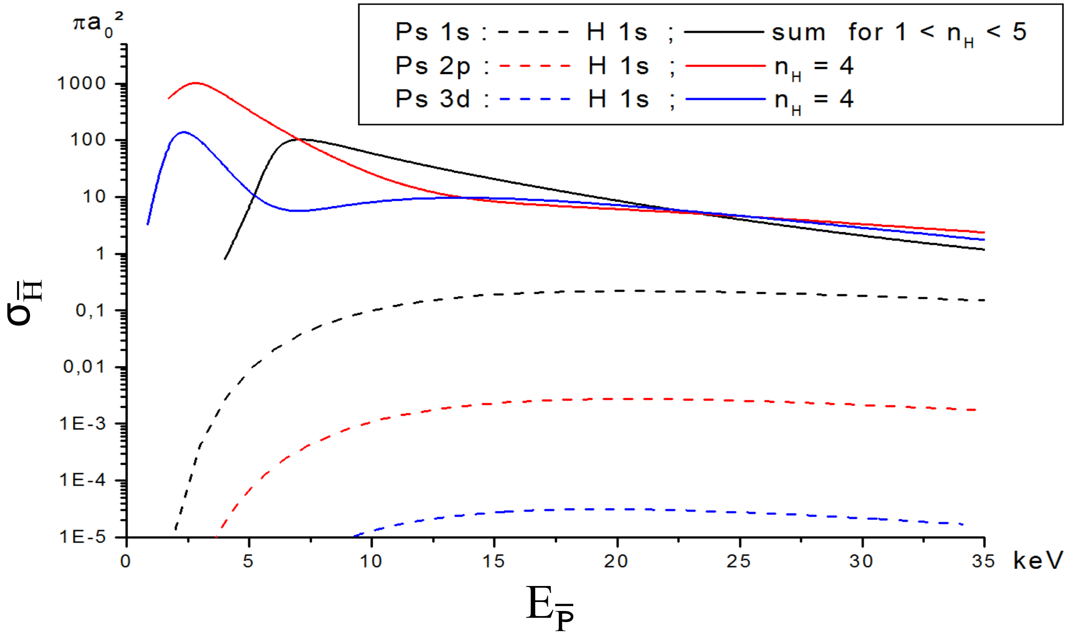
  état initial perturbé par un potentiel coulombien à courte portée ; les particules du continuum sont décrites par des fonctions d' onde de Coulomb, l' influence du potentiel coulombien réel à longue distance passant dans un terme de phase (d' où « distorted »).

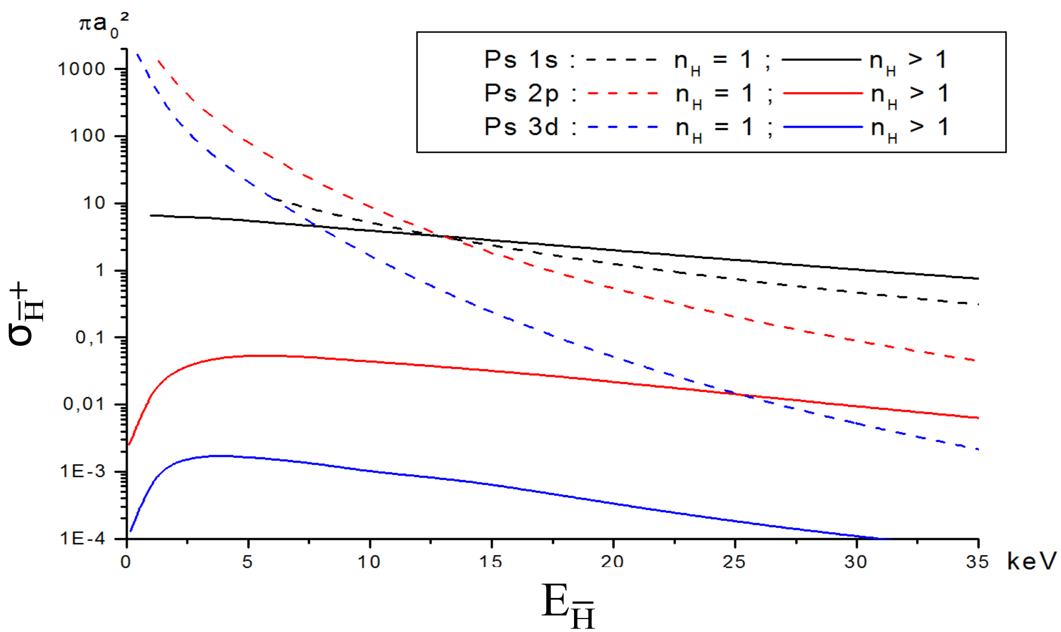
- Calculs pour les réactions inverses en matière ($\overline{H} \leftrightarrow H$; $\overline{H}^+ \leftrightarrow H^-$; etc)
- Outils principaux : développements en ondes partielles
- Étude de la réaction à 4 corps inspirée de :

  J. Hanssen, P.-A. Hervieux, O.A. Fojón and R.D. Rivarola, *Phys. Rev. A* **63,** 012705 (2001), *Positronium formation in positron-metastable-helium collisions*

P. Comini

Sections efficaces production $\overline{H}$ & $\overline{H}^+$



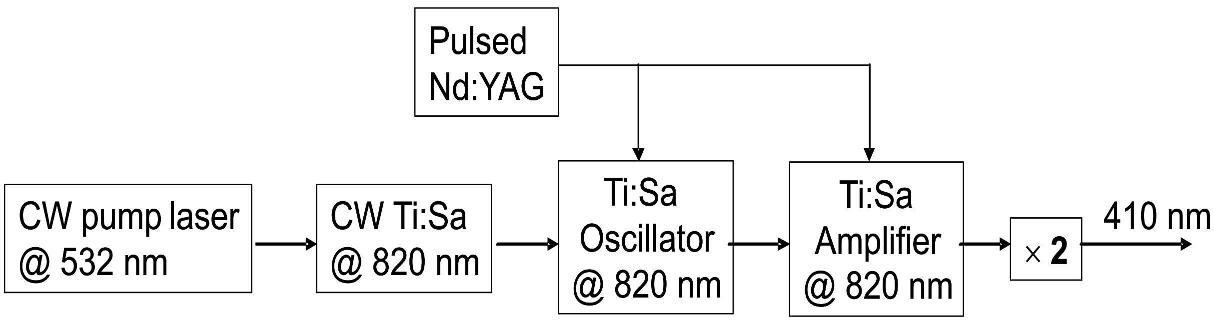


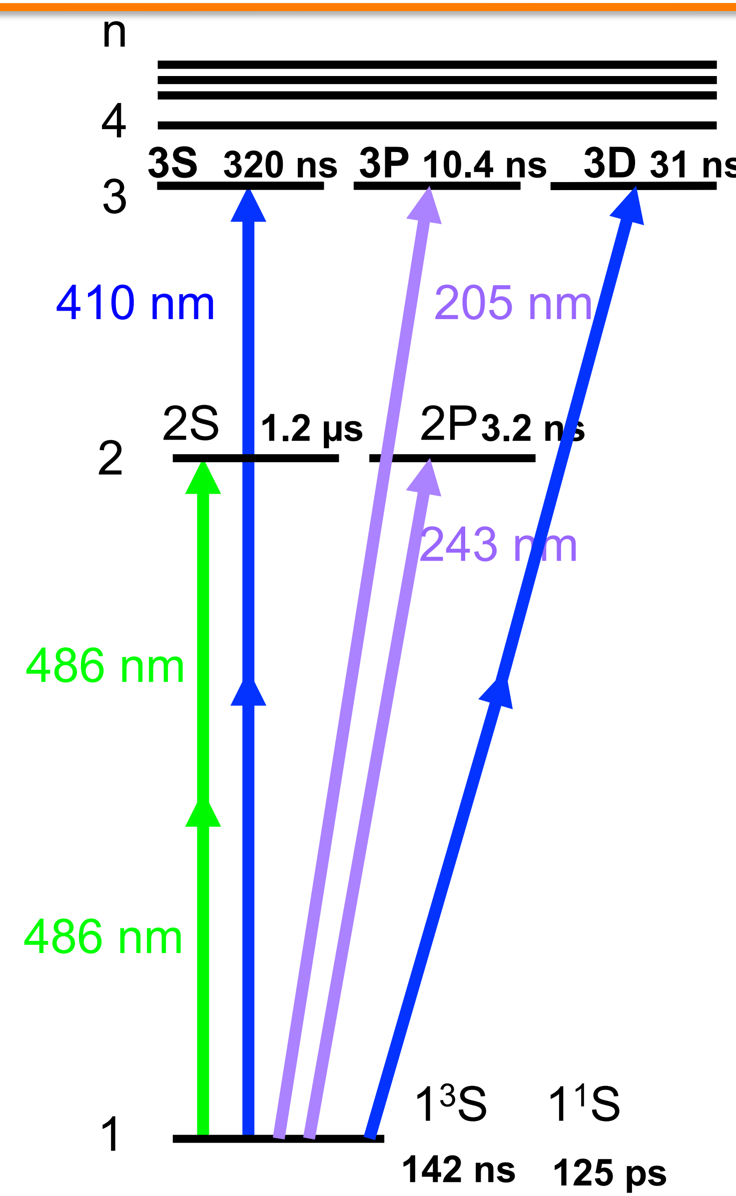
Ps excitation

3D level 10 times less affected by photoionization than 3S level

Excite 50% of Ps

Expect gain > 100 in $\overline{H}^+$ cross section





Will be tested in Saclay at Penning trap exit

Echéances

12/2012	piégeage e^+ (collab. CSNSM, RIKEN, Swansea)
12/2013	formation d’une cible de Ps (collab. ETHZ)
	ralentissement des (anti)protons (collab. CSNSM-P2IO)
12/2014	excitation Ps (collab. LKB)
	possibilité de mesurer les sections efficaces “matière”

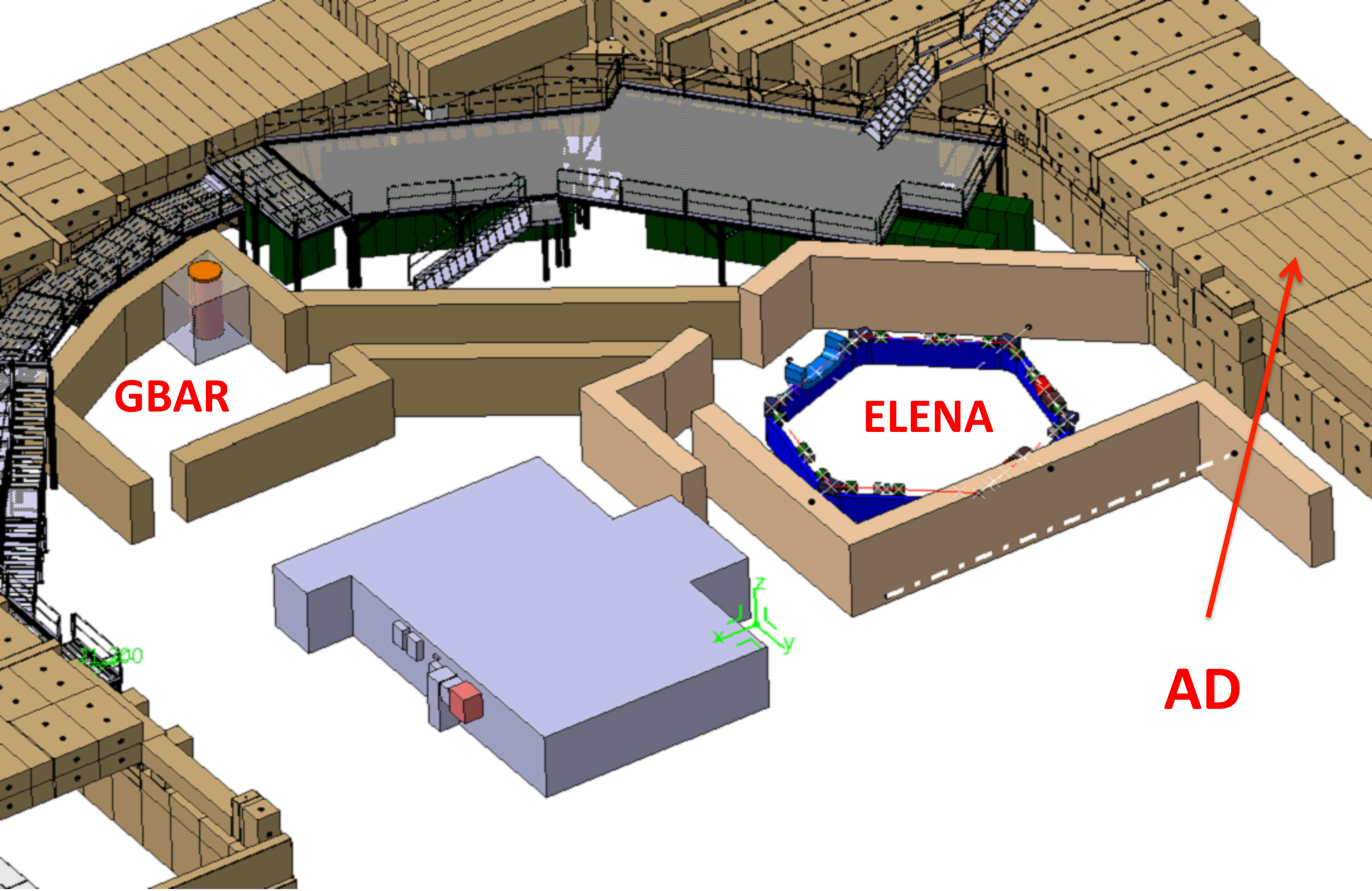
Collaboration GBAR

G. Chardin, P. Dupré, P. Grandemange, D. Lunney, V. Manea	**CSNSM, CNRS – Orsay , France**
A. Badertscher, P. Crivelli, A. Curioni, A. Marchionni, B. Rossi, A. Rubbia	**ETHZ, Zürich, Switzerland**
V. Nesvizhevsky	**ILL, Grenoble, France**
P-A. Hervieux, G. Manfredi	**IPCMS, Strasbourg, France**
P. Comini, P. Debu, L. Liszkay, , B. Vallage B. Mansoulié, P. Pérez, J-M. Rey, Y. Sacquin	**IRFU, CEA, Saclay, France**
J. Walz, F. Schmidt-Kaler	**Johannes Gutenberg Universität, Mainz, Germany**
A. Voronin	**Lebedev Phys. Institute, Moscow, Russia**
F. Biraben, P. Cladé, A. Douillet, A. Gérardin, S. Guellati, L. Hilico, P. Indelicato, A. Lambrecht, R. Guérout, J-P. Karr, F. Nez, S. Reynaud, V-Q. Tran	**Laboratoire Kastler-Brossel, CNRS – Paris, France**
S. Wronka, M. Staszczak	**Narodowe Centrum Badań Jądrowych (NCBJ), Otwock-Świerk , Poland**
A. Mohri, Y. Yamazaki	**Atomic Physics Laboratory, RIKEN, Japan**
M. Charlton, S. Eriksson, N. Madsen, D.P. van der Werf	**Swansea University, UK**
N. Kuroda, H. Torii	**University of Tokyo, Japan**
Y. Nagashima	**Tokyo University of Science, Japan**
P. Froelich	**Uppsala Universitaet, Sweden**

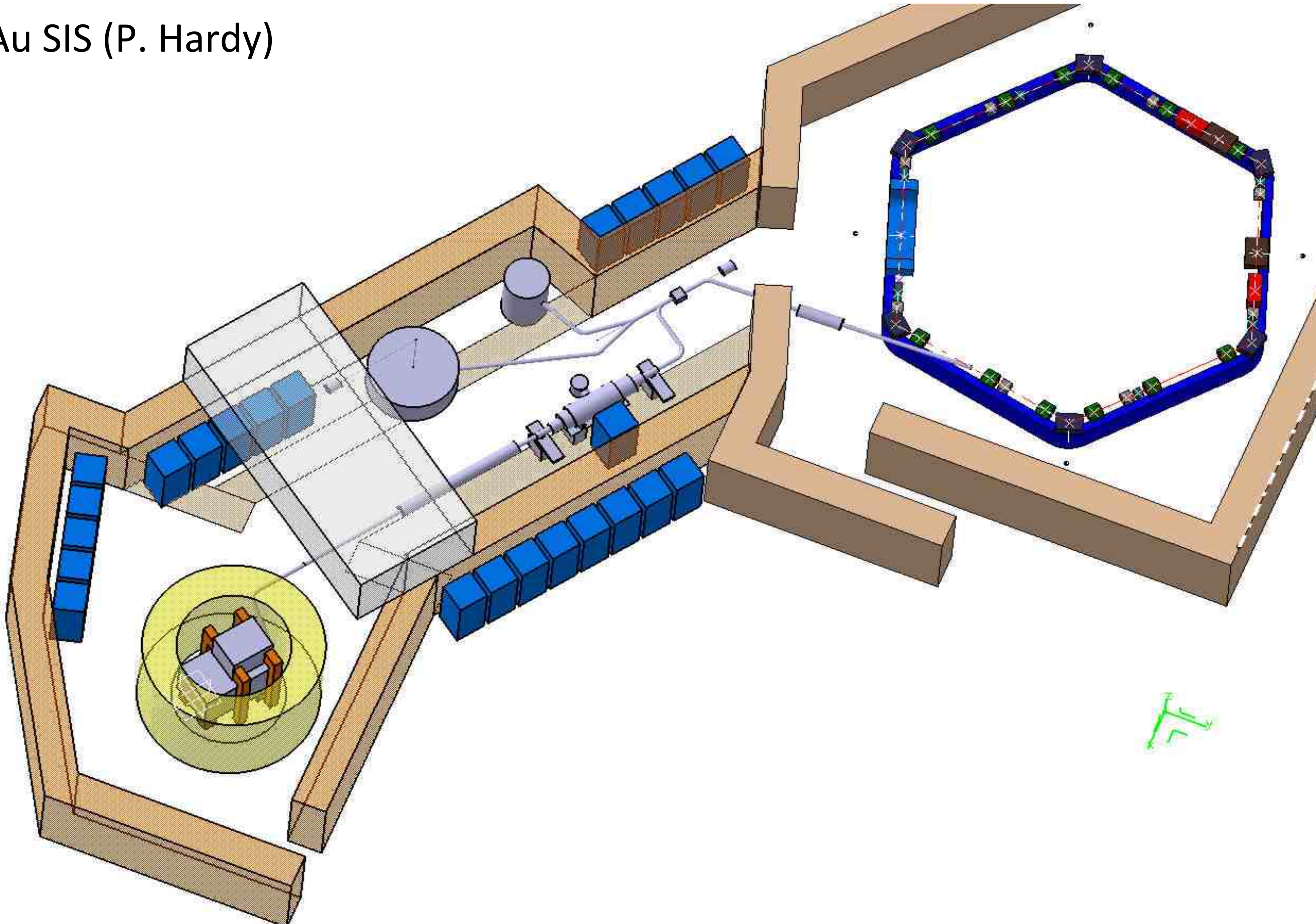
GBAR au CERN

- Proposal CERN-SPSC-P-342, 30/09/2011
- SPSC → MoU → réunion de collaboration 28/06
- RB → 30/05 → **GBAR accepté**,
  mais ELENA retardé 1 an (2017)

- Premières interactions avec équipe AD/ELENA
  - Estimation des besoins en services
  - Plan d'implantation ← SIS-BE


GBAR
ELENA
AD

Au SIS (P. Hardy)



Capture de Q:\Projets\SOPHI\300\3000\3000000_Implantation-CERN.CATProduct - 05/04/2012 15:22:15

Organisation de la collaboration

- 6 réunions plénières au LKB et au CERN

- MoU en préparation

→ Structure décisionnelle

→ Engagements financiers pour la construction

March 2012

Memorandum of Understanding

for the Construction of the GBAR/AD-XXX Experiment

between

The EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH, "CERN",
an Intergovernmental Organization having its seat at Geneva, Switzerland,
as Host Laboratory

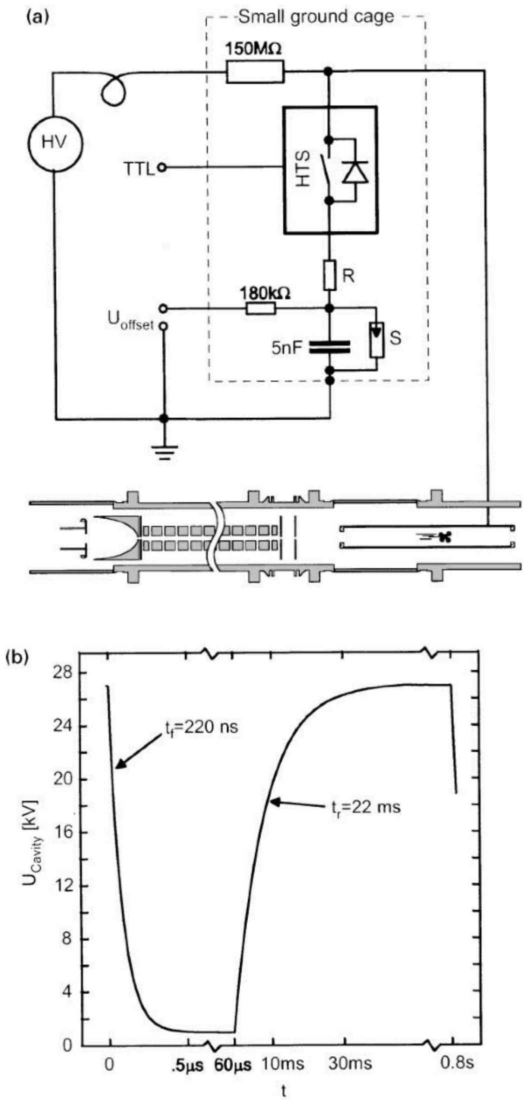
on the one hand,

and

the Collaborating Institutions/Funding Agencies of the GBAR Collaboration

on the other hand.

$\bar{p}$ deceleration

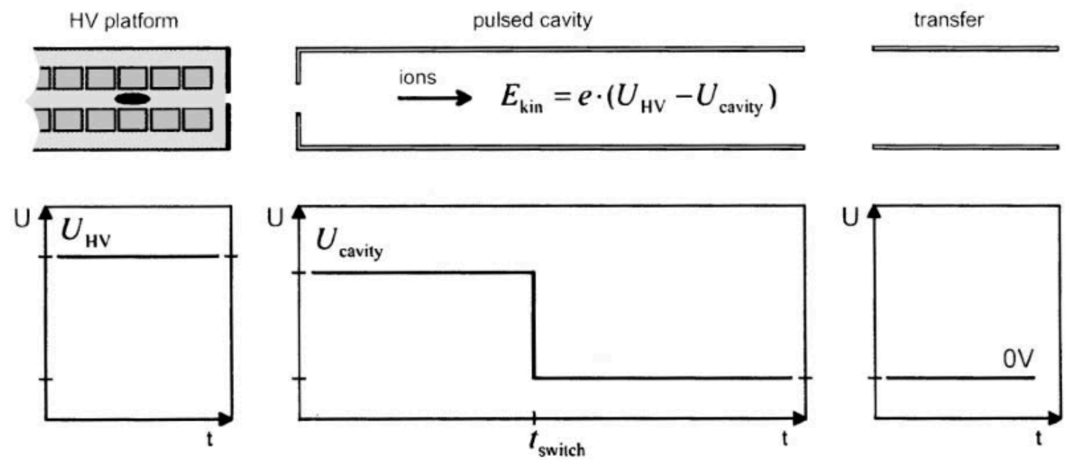


From 100 keV (ELENA) ⟶ 1 keV

Scheme adapted from ISOLTRAP

F. Herfurth et al., NIMA 469 (2001) 254.

drift tube



simulation underway for emittance optimization

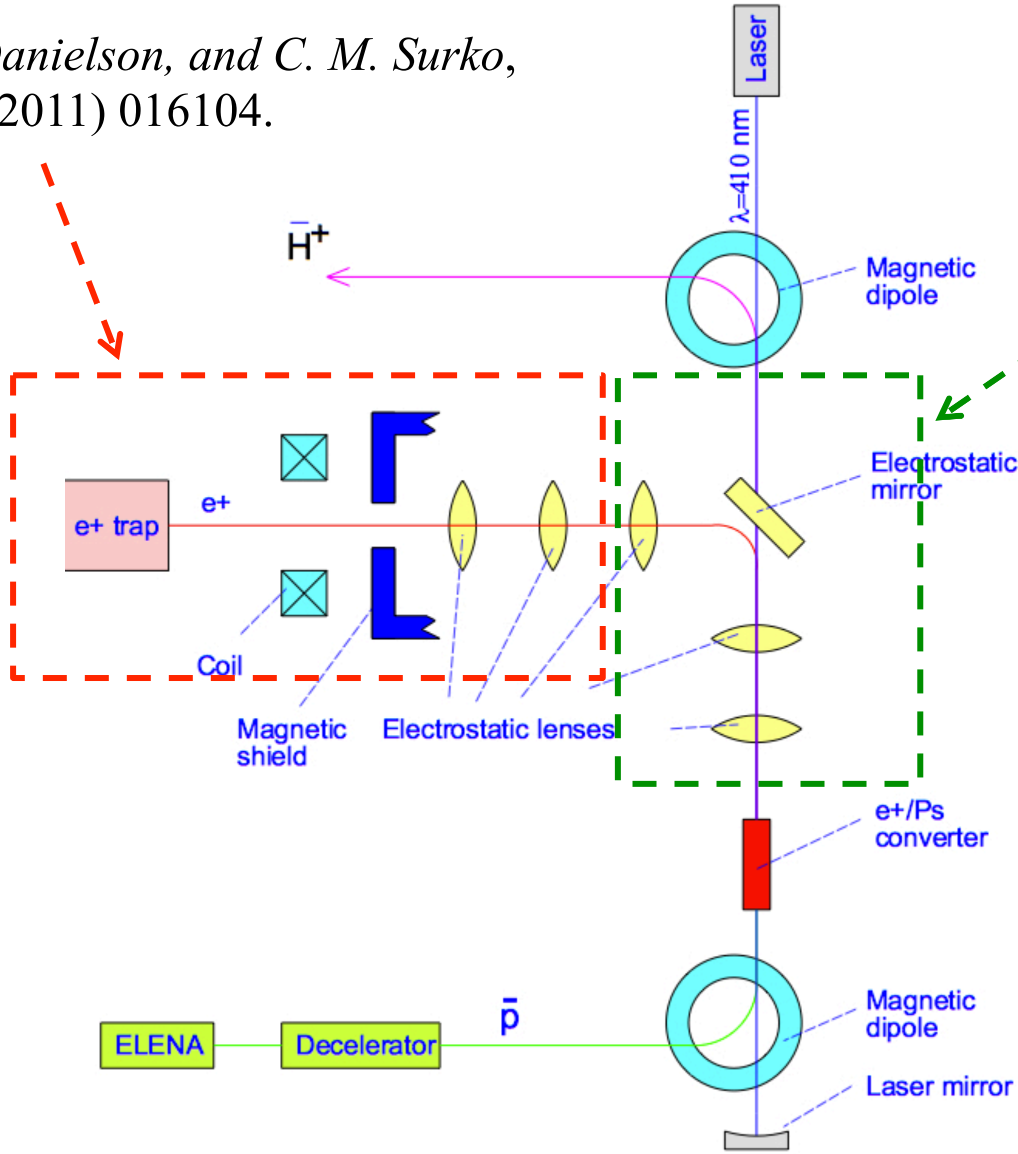
$\bar{p}$ accumulation trap can be added

Reaction region

T. R. Weber, J. R. Danielson, and C. M. Surko,
Rev. Sci. Inst. **82**, (2011) 016104.

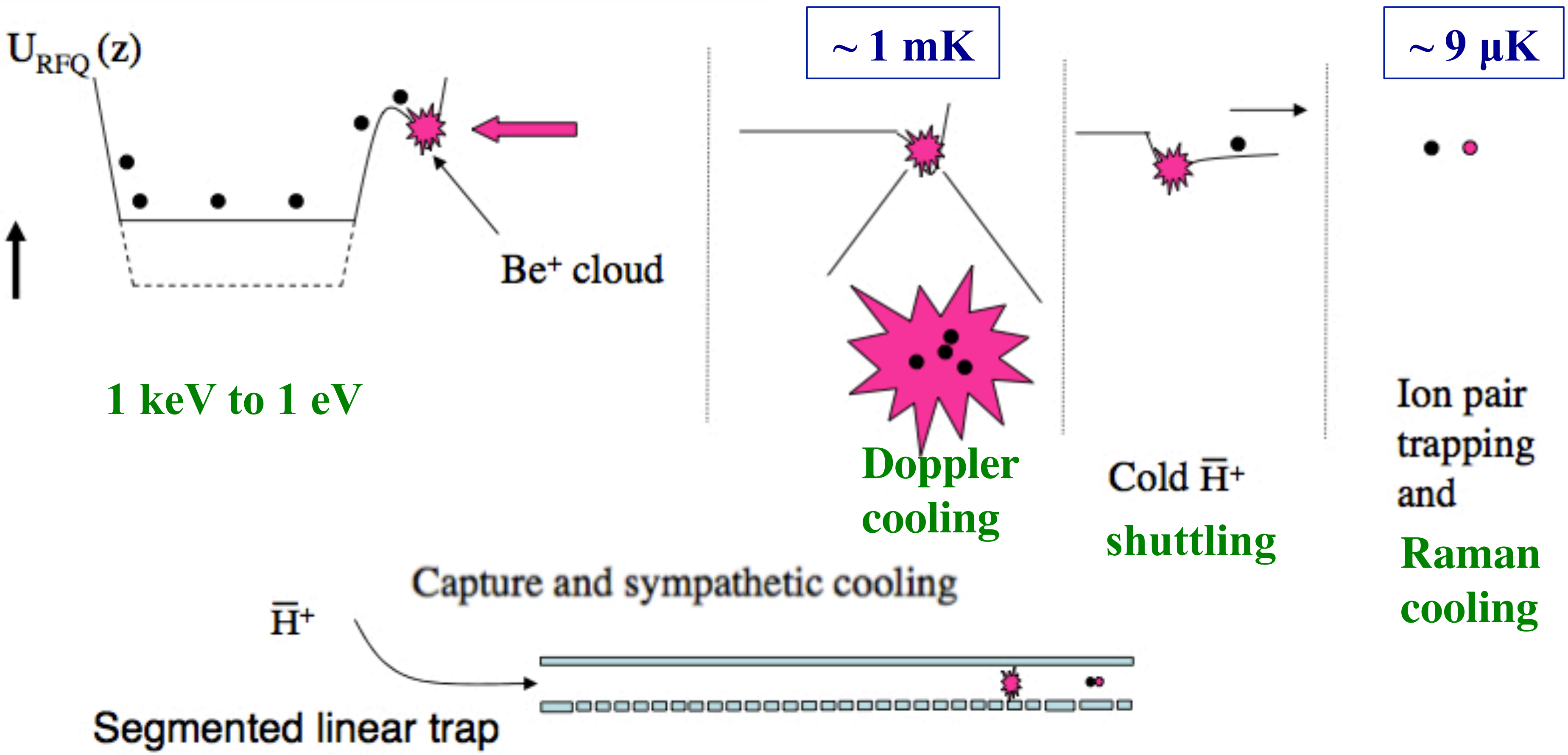
30 eV, 5 µs
↓
3 keV, 100 ns

D. W. Gidley et al.,
in New Directions in Antimatter Chemistry and Physics, pp. 151-71 (2001).



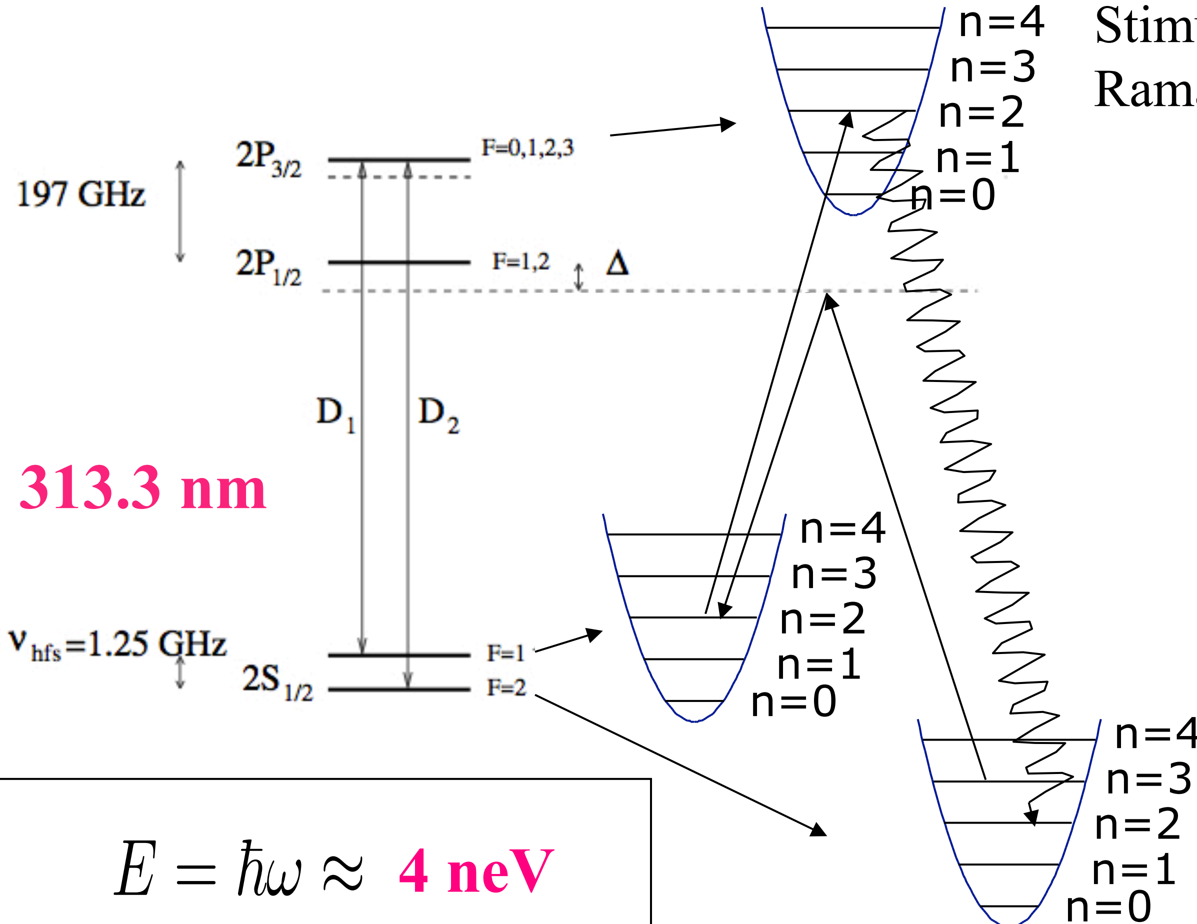
A. Chancé (SACM)

$\bar{H}^+$ cooling challenge



NIST group
*M. D. Barrett, …, D. Wineland, PRA **68**, 042302 (2003)*
Sympathetic cooling of $^9Be^+$ and $^{24}Mg^+$ for quantum logic

sub-Doppler cooling



Stimulated & Spontaneous Raman transitions

Cycle sequence:

F = 2, n
→ F = 1, n-1
→ F = 2, n-1
…
→ F = 2, n=0

quantum regime of coupled harmonic oscillators

$$E = \hbar\omega \approx \textbf{4 neV}$$

$$\Delta v = \sqrt{\frac{\hbar\omega}{2m}} \approx \textbf{0.44 ms}^{-1}$$

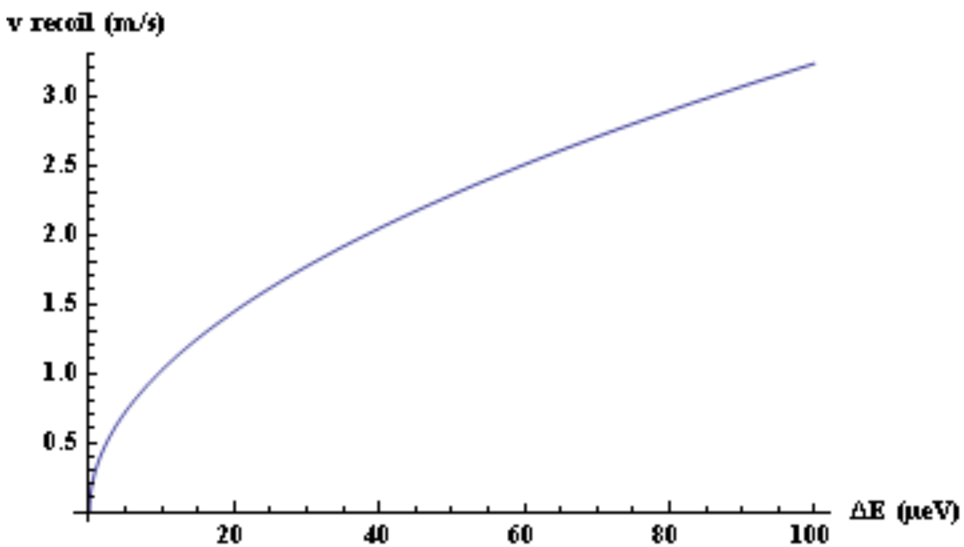
Photo detachment with minimal recoils

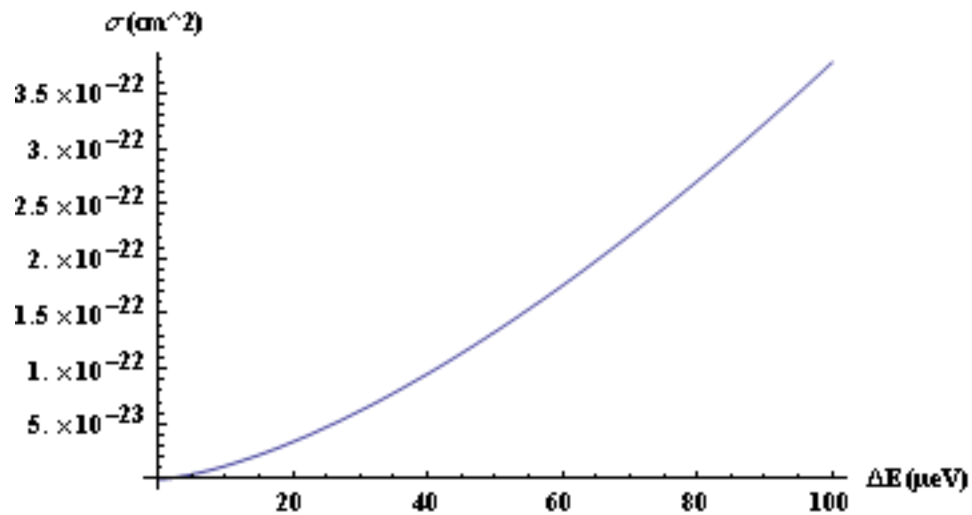
$\bar{H}^+$ binding energy 0.76 eV => $p_\gamma \sim 0.76$ eV/c close to threshold

Recoil due to absorption: $v_{recoil} = p_\gamma / m_H = 0.2$ m/s => 4 cm for 0.2 s fall

Recoil due to e^+ emission

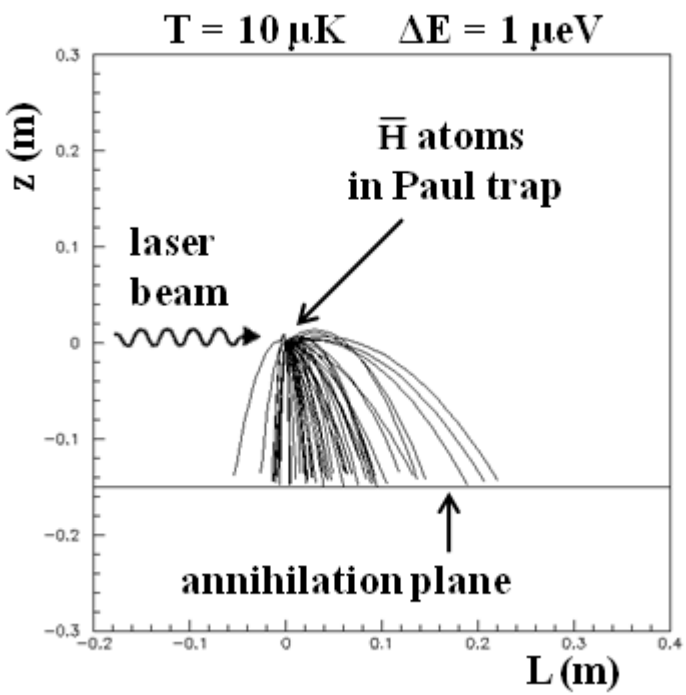
$E_c = E_\gamma - 0.76$ => $v_{recoil} = \sqrt{\frac{2 m_e E_c}{m_H}}$ ~ 0.3 m/s for $E_c = 1$ μeV

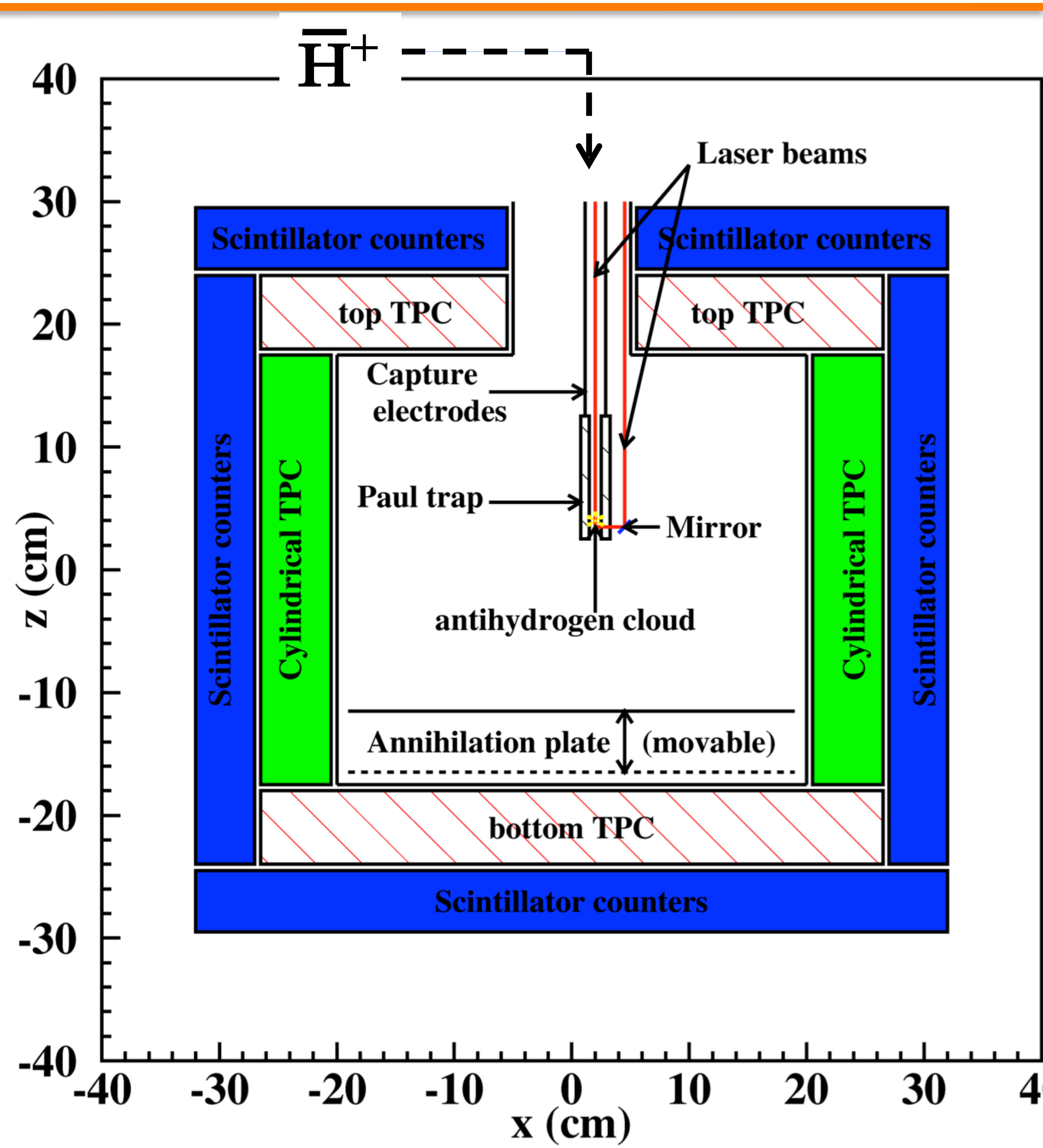




1 W laser, 150 μs shots, 99% efficiency

$\overline{\mathrm{H}}$ free fall detection





Detection	Requirement
TOF precision	150 µs
Annihil. vertex precision	2 mm
Background rejection	event topology

Echéances

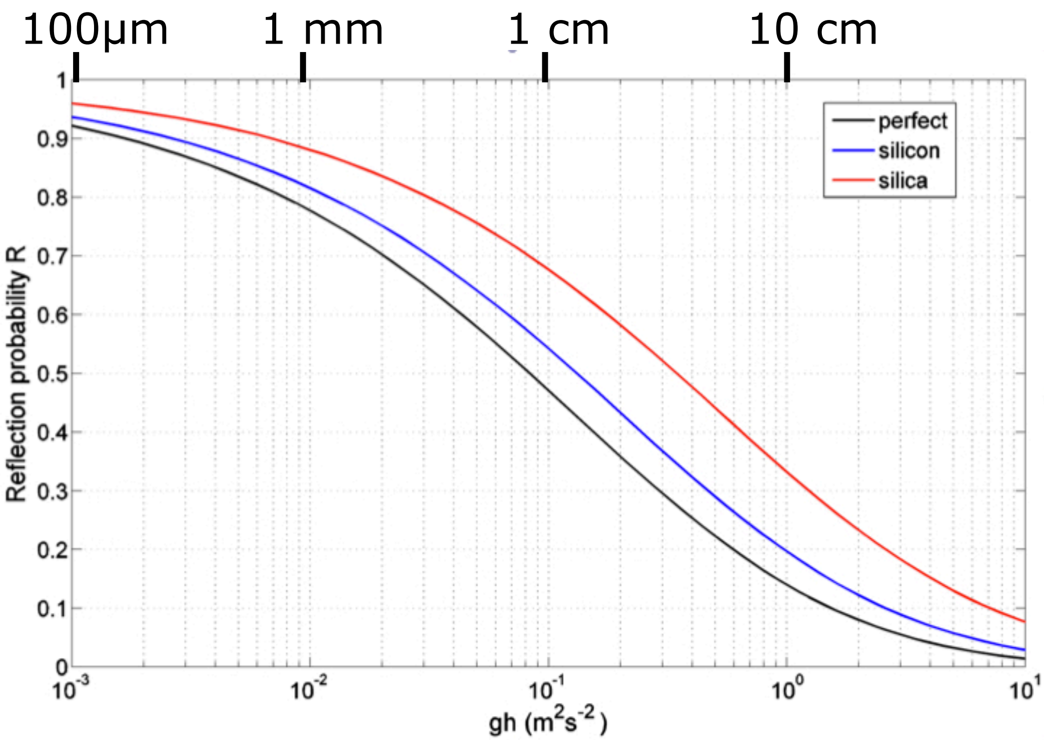
2012	MoU pour la construction de GBAR
12/2014	installation linac au CERN
2015	Commissioning
2016	Premiers faisceaux… et démarrage de la mesure de $\bar{g}$
2018	Spectroscopie gravitationnelle

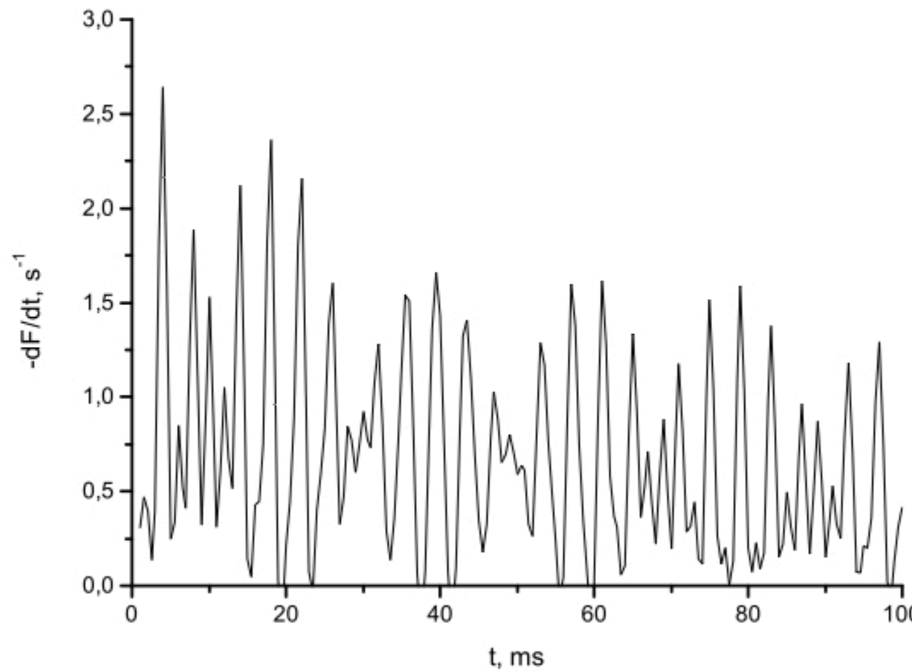
Perspective: towards higher precision on $\bar{g}$

Improve precision on $\bar{g}$ with spectroscopy of gravitational levels of $\overline{H}$:

- similar method as for UltraCold neutrons (ILL)
- only few events needed to reach ~10^{-3} precision !

A. Yu. Voronin, P. Froelich, and V. V. Nesvizhevsky, *Antihydrogen Clock*, Phys. Rev. A **83**, 032903 (2011)





GBAR et la concurrence

AEGIS a comme but une mesure de $\bar{g}$ à 1%.
Approuvé par le CERN en 2008.
Commence installation en 2012 sur AD et bénéficiera d'ELENA en 2017.
Utilise $\bar{H}$ neutre.
Avait prévu une température initiale de 100 mK et 10^5 évènements pour $\Delta\bar{g}/\bar{g}$ = 1%.
Rencontre des problèmes sur la faisabilité avec collisions sur Os^-.
Espoir d'atteindre 4K (méthode publiée par ATRAP en mars 2012)
Si très optimiste (tout le reste marche) → $\Delta\bar{g}/\bar{g}$ = 40% (si pas de bdf)
2012: commisioning e^+ & $\bar{p}$ traps
2013: Cern shutdown (essais avec matière: mesure production H, IPNL)
2015-2016: possibilité de première mesure ?

GBAR utilise $\bar{H}^+$ qui peut être refroidi à 9 µK, 1500 évènements → $\Delta\bar{g}/\bar{g}$ = 1%
Possibilité d'amélioration par spectroscopie gravitationnelle.
Pas de bruits de fond.
Utilisera ELENA qui sera mis en service en 2017.

ALPHA a tenté une mesure de la masse gravitationnelle de l'antihydrogène: $|m_g/m_i| < 100$ (non publié). Prévoit une adaptation pour mesurer $\bar{g}$ mais pas encore de proposal. **ATRAP** commence à mentionner la gravitation dans ses buts de physique
ASACUSA n'en parle pas

Expected efficiencies

Electrons						
Linac frequency	Mean current	Pulse current	Pulse duration	Electrons per pulse	Electron rate (s^{-1})	
300 Hz	0.2 mA	0.33 A	2 μs	4.2×10^{12}	1.25×10^{15}	
Positrons						
Production efficiency (at 10 MeV)	Transport efficiency	Fast positrons per pulse	Fast positron rate (s^{-1})	Moderation efficiency	Slow positrons per pulse	Slow positron rate (s^{-1})
5.5×10^{-4}	80 %	1.8×10^{9}	5.5×10^{11}	5×10^{-4}	9.2×10^{5}	2.8×10^{8}
Positron storage						
Trapping efficiency	Injection time	Stored positrons				
70 %	110 s	2.1×10^{10}				
Positronium						
Production efficiency	Tube section	Tube length	Positronium density	Loss fraction from Ps decay		
35 %	1 mm^2	1 cm	7.4×10^{11} cm^{-3}	0.5		
Antihydrogen positive ions						
Antiprotons per pulse	Deceleration and bunching efficiency	Production cross section of the $\overline{H}$ atom	Production cross section of the $\overline{H}^+$ ion	$\overline{H}$ per pulse	$\overline{H}^+$ per pulse	
6×10^{6}	80 %	4.4 10^{-16} cm^2	8.8 10^{-15} cm^2	3.9×10^{2}	0.32	
Antihydrogen atoms						
$\overline{H}^+$ Trapping efficiency	Cooling efficiency	cold $\overline{H}^+$ per pulse	Photodetachment efficiency	Detector acceptance	$\overline{H}$ events per pulse	$\overline{H}$ event rate (s^{-1})
100 %	70 %	0.2	99 %	65 %	0.14	1.3×10^{-3}

Investissements à négocier

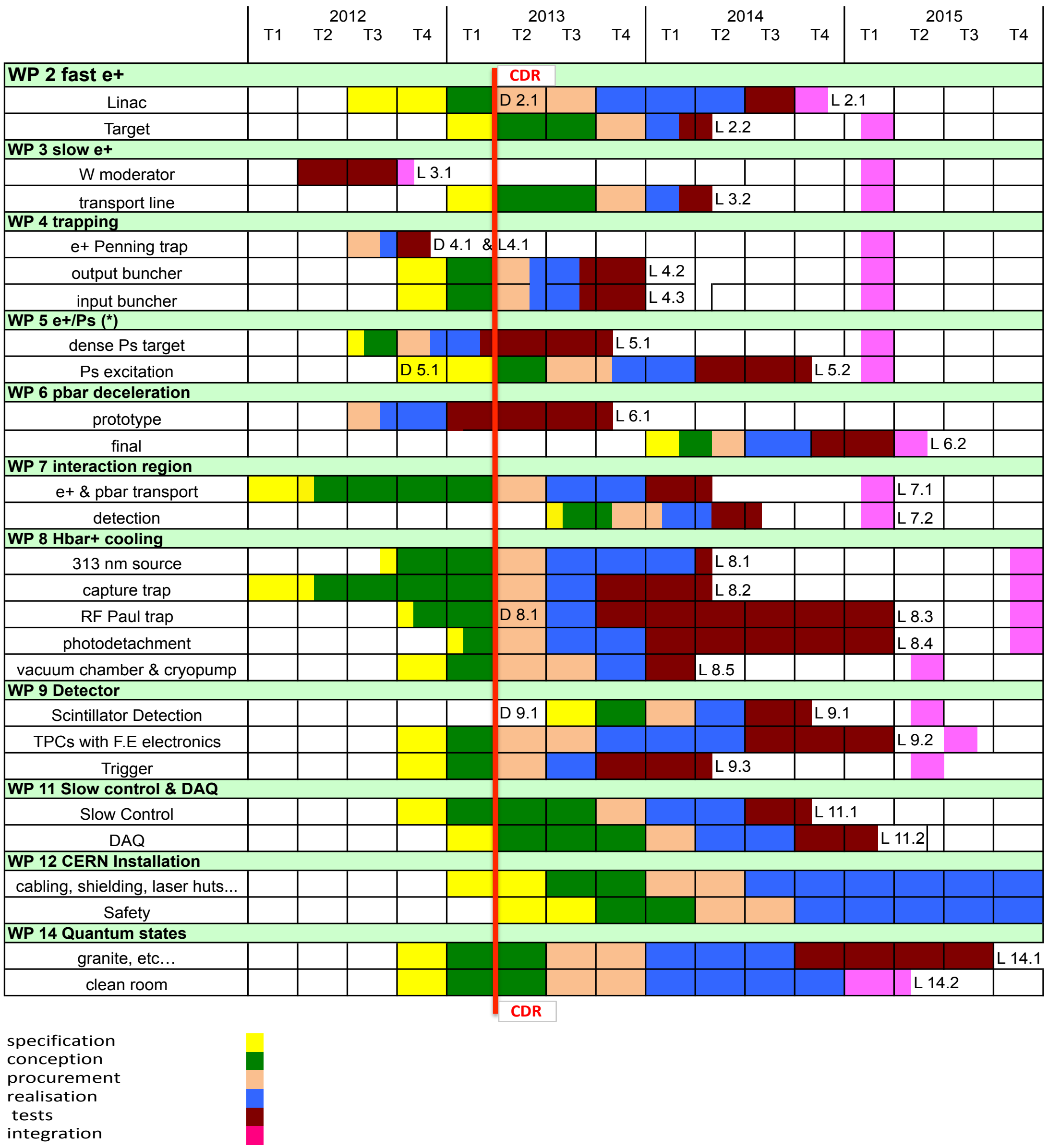
Work Package	Deliverables	Invest. Cost (k€)	Institutes
1- Management			IRFU, LKB, JGU
2- Fast e^+	Electron linac	500	NCBJ, IRFU
	Primary target	**50**	
3- Slow e^+	Neon moderator	-	IRFU, Swansea, TUS
	Tungsten moderator	**20**	
	Transport line	**100**	
4- e^+ accumulation	Input/output bunchers	200	RIKEN, IRFU, CSNSM, Swansea
	e^+ trap	-	
5- Positronium	e^+/Ps converter development	**60**	LKB, IRFU, ETHZ
	excitation laser	370	
6- Antiproton deceleration	$\bar{p}$ decelerator and focus	87	CSNSM, IRFU, LKB, Tokyo
7- $\bar{H}$ & $\bar{H}^+$ production	e^+ and $\bar{p}$ transport to interaction region, $\bar{H}$ & $\bar{H}^+$ detection	374	Swansea, IRFU, LKB
8- $\bar{H}^+$ cooling	313 nm sources	437	Mainz, LKB, ILL
	Traps and chamber	86	
	Photodetachment	127	
9- Detector	Trigger and veto scintillators, tracker system	500	ETHZ, IRFU, Mainz
10- Theory	Ps-H interactions, plasma trapping	20	IPCMS, Lebedev, Uppsala
11- Slow control, DAQ	Centralized slow control	**270**	IRFU
	DAQ	100	all
12- Installation at CERN		200	
13- Dissemination		-	
14- Quantum states	Granite support plate with active compensation, magnetic shield, clean room	300	ILL, All
Total		3801	

Ressources humaines

Hommes.an

Work Package	A1 total	A2 total	A1 Irfu	A2 Irfu
1- Management	7		7	
2- Fast e^+	11.3	6.1	1.1	0.5
3- Slow e^+	13.8	1.6	3.7	0.7
4- e^+ accumulation	12.8	1.6	3.9	0.8
5- Positronium	19.1	4.5	3.4	0.4
6- Antiproton deceleration	12.1	5.5	0.25	0.5
7- $\overline{H}$ & $\overline{H}^+$ production	9.9	1	1.25	
8- $\overline{H}^+$ cooling	26.4	11	0.25	
9- Detector	11.25	6.75	1.4	1.4
10- Theory	20			
11- Slow control, DAQ	17.5	11.3	11.5	5.3
12- Installation at CERN	16	17.4	7	5
13- Dissemination				
14- Quantum states	6	1		
Total	183.15	67.75	40.75	14.6

Planning



CDR	Conceptual Design Report, including specifications for each object
PRR	Product Readiness Review
L 2.1	Linac commissioned at CERN
L 2.2	Water cooled target, with W moderator holder and in situ annealing
L 3.1	Tungsten moderator
L 3.2	Slow positron transport line from moderator to trap input buncher
L 4.1	e+ pulsed beam from linac accumulated in RIKEN trap
L 4.2	buncher for fast positron plasma extraction from RIKEN trap
L 4.3	incoming pulse from linac bunched to 100 ns
L 5.1	e+/Ps converter in which Ps form a dense target of 10^12 at/cm3
L 5.2	Ps excitation laser beam focussed onto 1 mm diameter Ps target
L 6.1	prototype for decelerator tested with protons or H-
L 6.2	antiproton decelerator tested with H- ELENA beam
L 7.1	e+ and pbar beams focused onto Ps target
L 7.2	detectors for pbar, Hbar, Hbar+ & Ps, created in reaction chamber
L 8.1	laser for Be+ cooling
L 8.2	electrostatic deceleration and capture trap for Hbar+
L 8.3	RF Paul trap for Be+ and Hbar+ cooling
L 8.4	1665 nm laser for photodetachment of Hbar+ at threshold
L 8.5	cryopumped vacuum chamber for free fall measurement
L 9.1	Scintillators equipped with PM and power supplies
L 9.2	TPC for reconstruction of Hbar annihilation vertex
L 9.3	trigger system
L 11.1	slow control of entire experiment
L 11.2	DAQ for entire experiment
L 14.1	hardware for quantum states detection
L 14.2	clean room for quantum states hardware mounting

D 2.1 PRR for Linac

D 4.1 e+ accumulation with single trap OK

D 5.2 Choice of Ps excitation laser wavelength and antiproton ener

D 8.1 Paul trap geometry (planar/tubular)

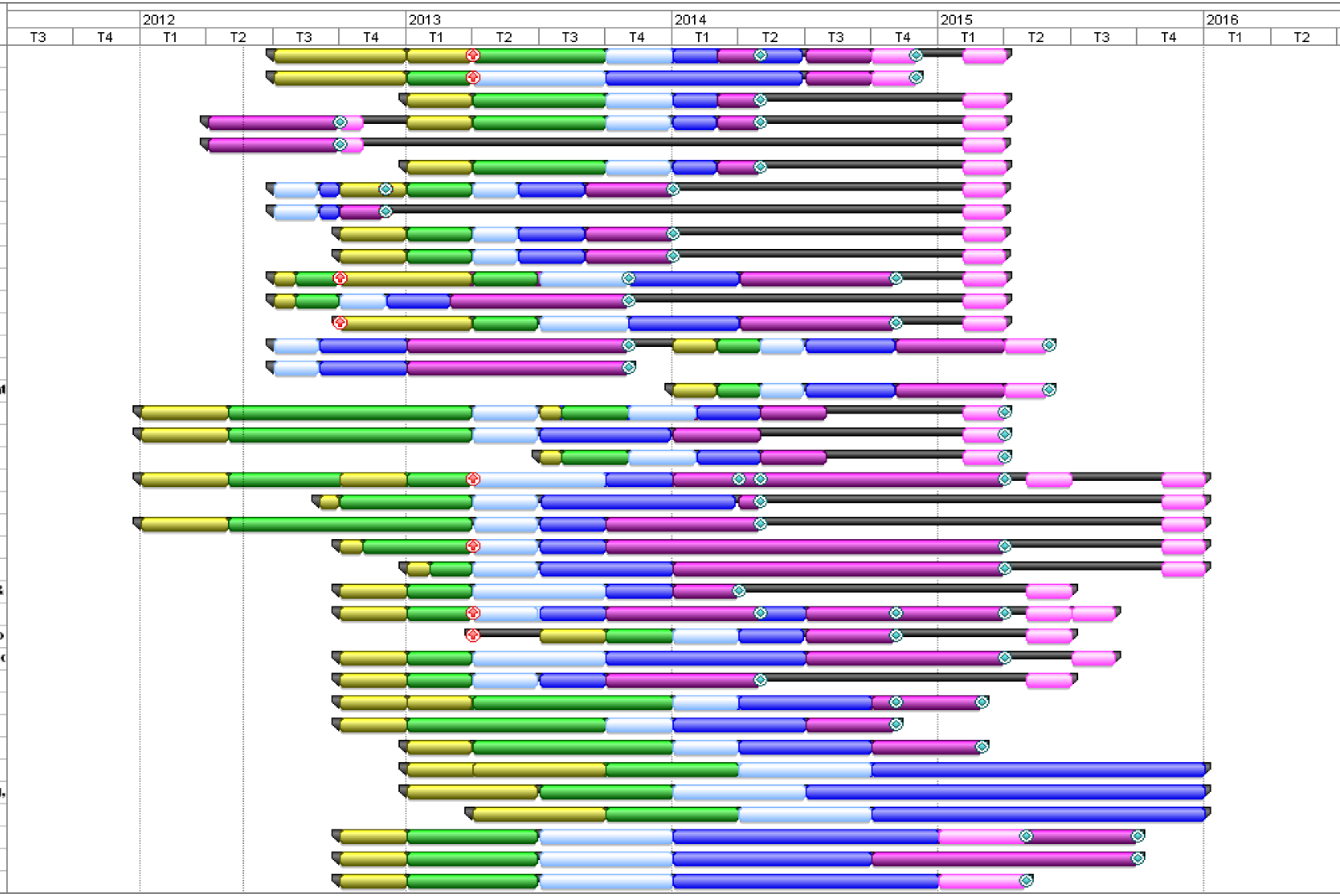
D 8.4 Optimal photodetachment energy (impact D 9.1)

D 9.1 Choice of detector and vacuum chamber sizes

Planning

(ms project, copyright R. Aleksan)

N°	WBS	Task Name
1	1	WP_2 fast e+
2	1.1	WP_2 LINAC
11	1.2	WP_2 Target
19	2	WP_3 slow e+
20	2.1	WP_3 Tungsten mod
25	2.2	WP_3 Transport line
33	3	WP_4 e+ trapping
34	3.1	WP_4 e+Penning Trap
41	3.2	WP_4 output buncher
49	3.3	WP_4 intput buncher
57	4	WP_5 e+/ Ps
58	4.1	WP_5 dense Ps Target
66	4.2	WP_5 Ps Excitation
75	5	WP_6 pbar deceleration
76	5.1	WP_6 Prototype
81	5.2	WP_6 Final pbar decelerat
89	6	WP_7 Interaction Region
90	6.1	WP_7 e+&pbar transport
98	6.2	WP_7 detection
106	7	WP_8 Hbar+ cooling
107	7.1	WP_8 313 nm source
115	7.2	WP_8 Capture Trap
123	7.3	WP_8 RF Paul Trap
132	7.4	WP_8 Photodetachment
140	7.5	WP_8 vacuum chamber &
148	8	WP_9 Detector
149	8.1	WP_9 Scintillator Detectio
158	8.2	WP_9 TPCs with front enc
166	8.3	WP_9 Trigger
174	9	WP_11 Slow control and DAQ
175	9.1	WP_11 Slow Control
182	9.2	WP_11 DAQ
189	10	WP_12 CERN Installation
190	10.1	WP_12 Cabling, shielding,
195	10.2	WP_12 Safety
200	11	WP_14 Quantum States
201	11.1	WP_14 Granite, etc...
208	11.2	WP_14 Clean Room



Requêtes

- *Approbation de GBAR par le CERN → projet IRFU avec “chef de projet” a plus de 50%*

- *support financier de l’IRFU pour les expériences a Saclay: “cabane expérimentale” dans Hall 126 (70 k€) ~50 k€ par an 2013-2015 et ~ 25 k€ par an de missions*

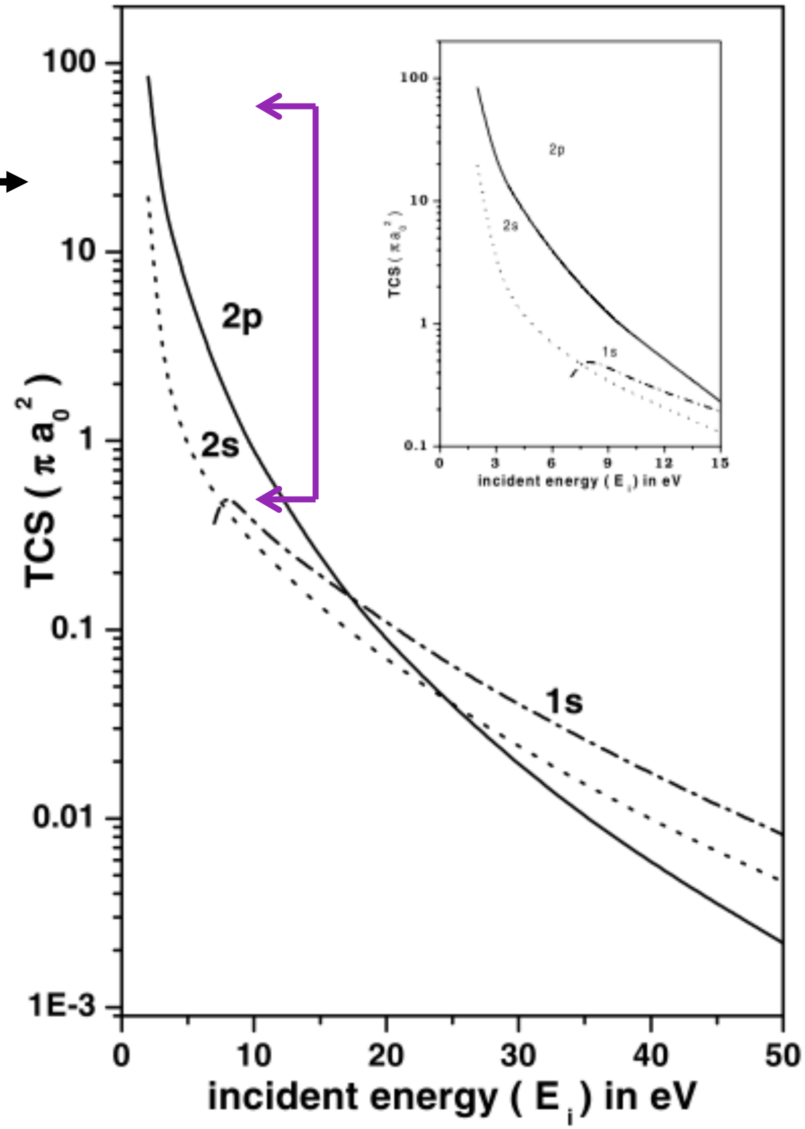
- *contribution de l’IRFU pour la construction de GBAR*

Backups

Increase cross-section of $\bar{H} + Ps \rightarrow \bar{H}^{+} + e^{-}$

use Ps excitation

Calculations for **n = 2** by:
S. Roy and C. Sinha, Eur. Phys. J. **D 47**, 327 (2008).



Binding energy of H^- = 0.76 eV

≈ same as Ps (n=3)

↓

Resonant enhancement

↓

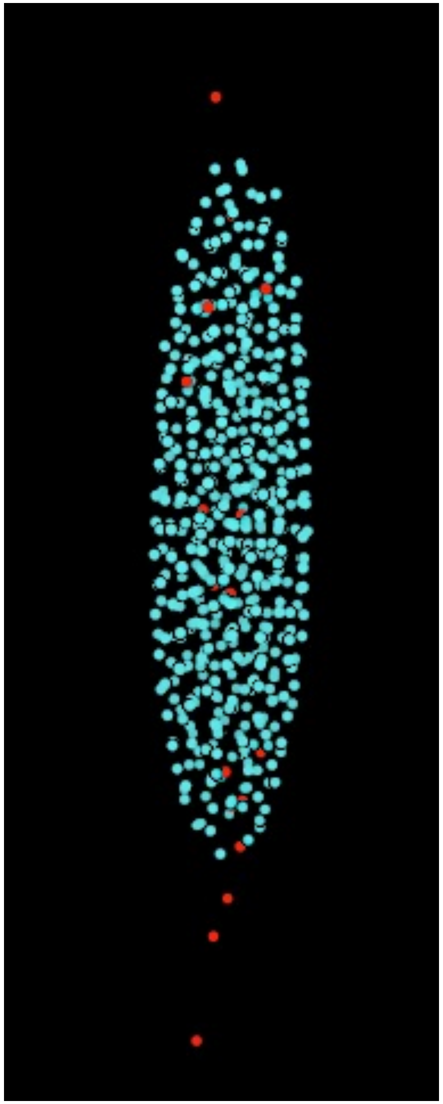
Excite fraction of Ps to n=3

*calculations underway for **n = 3***
to optimize $\bar{p}$ incident energy
We take: 8 10^{-15} cm^2

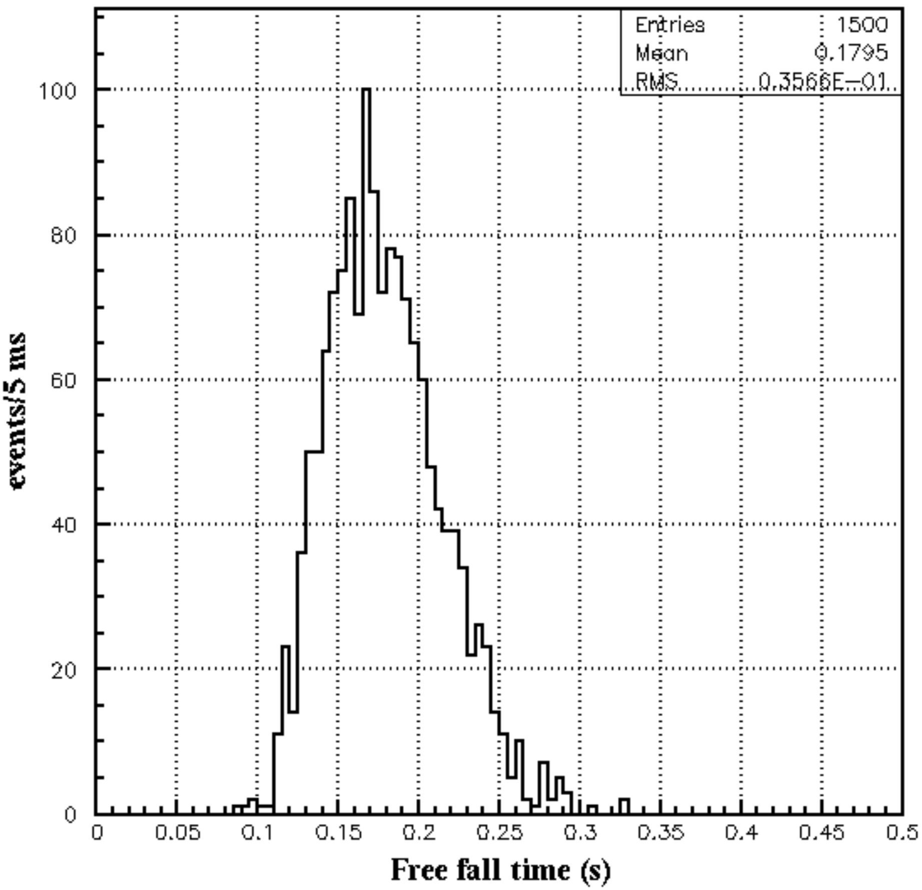
$\bar{H}^+$ sympathetic cooling

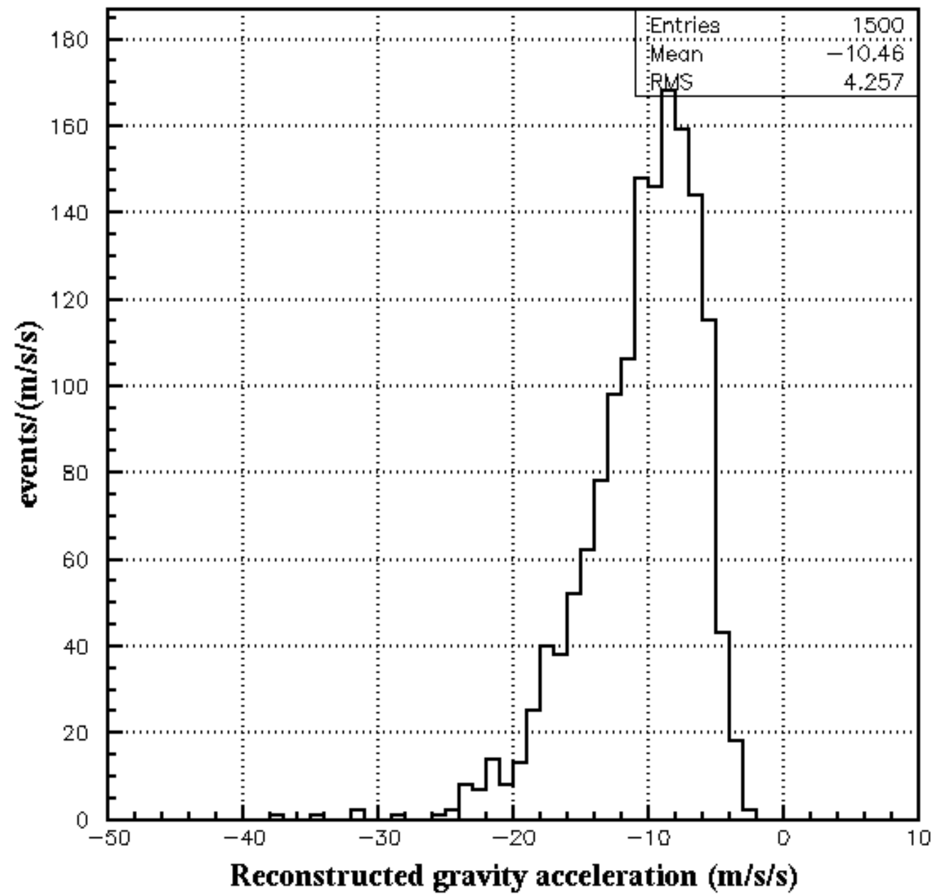
Simulation of Be^+ cooling in RF trap with micro-motion

→ determine trap parameters

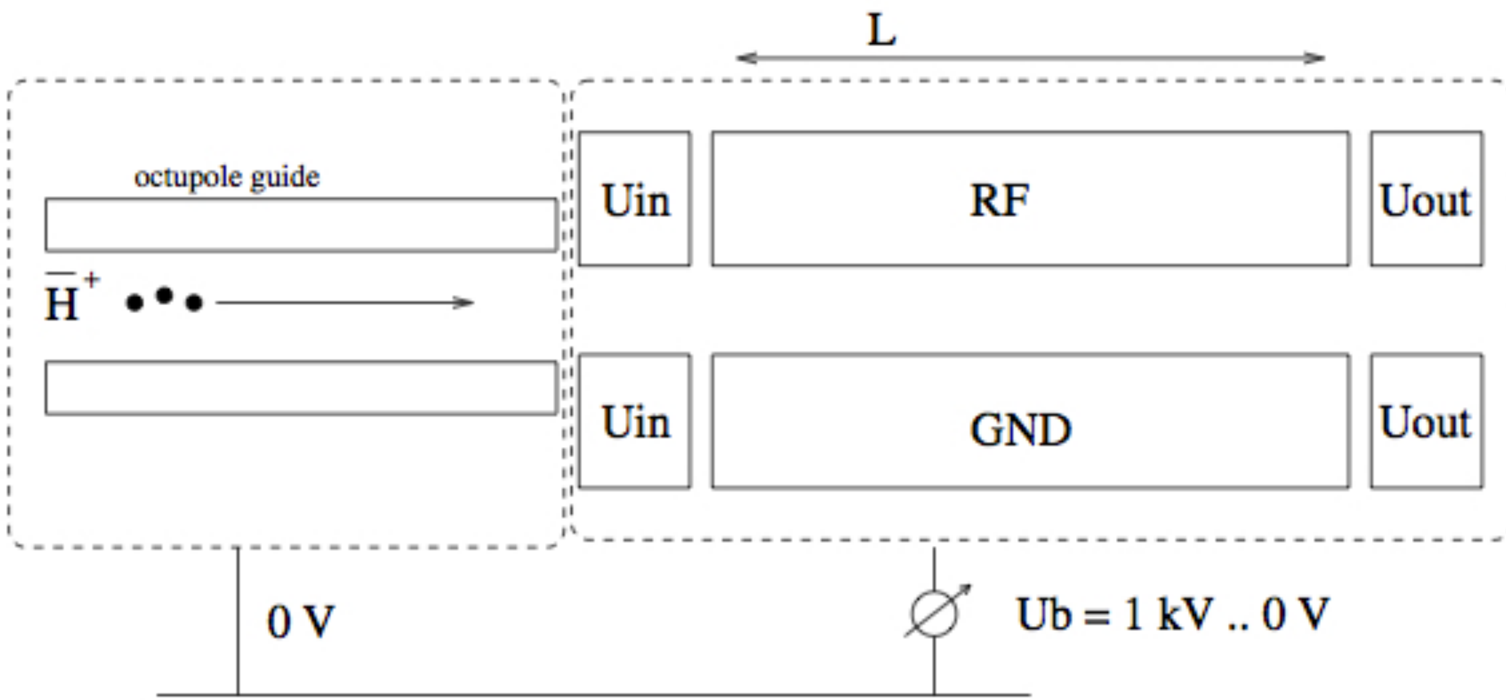


Free fall simulation





$\overline{H}^+$ deceleration



Emission of o-Ps from single shot lifetime measurement

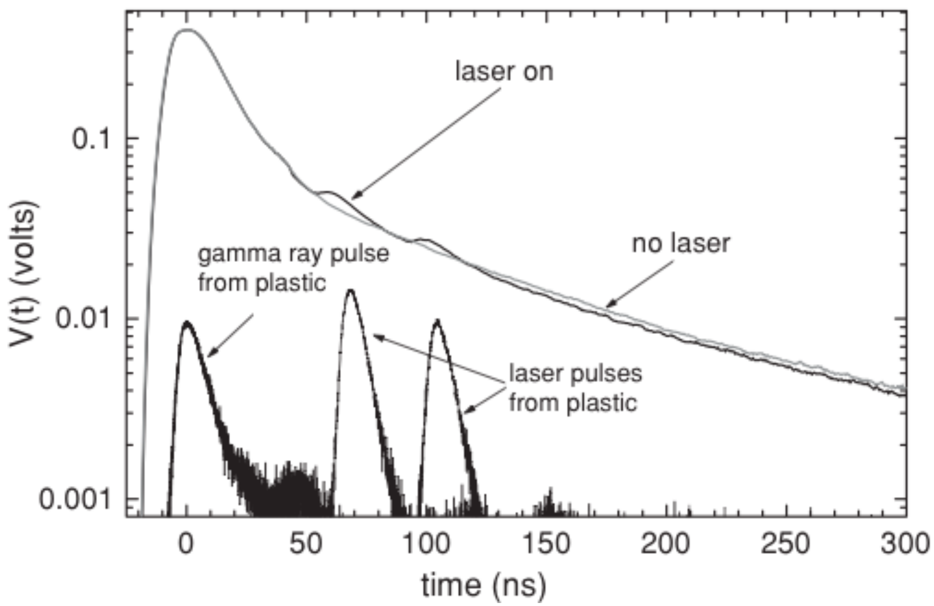
o-Ps | 243 nm laser pulse | excited state | optical transition to the ground state

$$1^3S_1[142ns] + h\nu_0 \rightarrow \left\langle 2^3P_j + 2^1P_0 \right\rangle [3.2ns]$$

in magnetic field:

~ 12 % decays to singlet state (with short lifetime)

$$\rightarrow 1^1S_0[125\,ps] + h\nu_0 \rightarrow 2\gamma$$



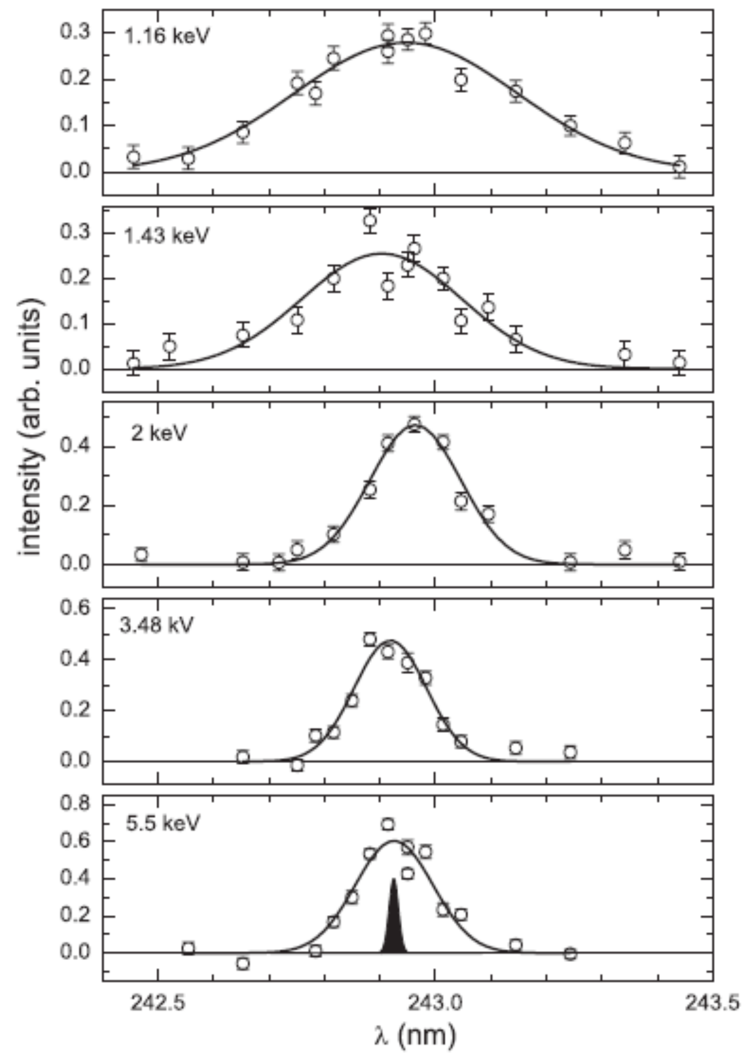
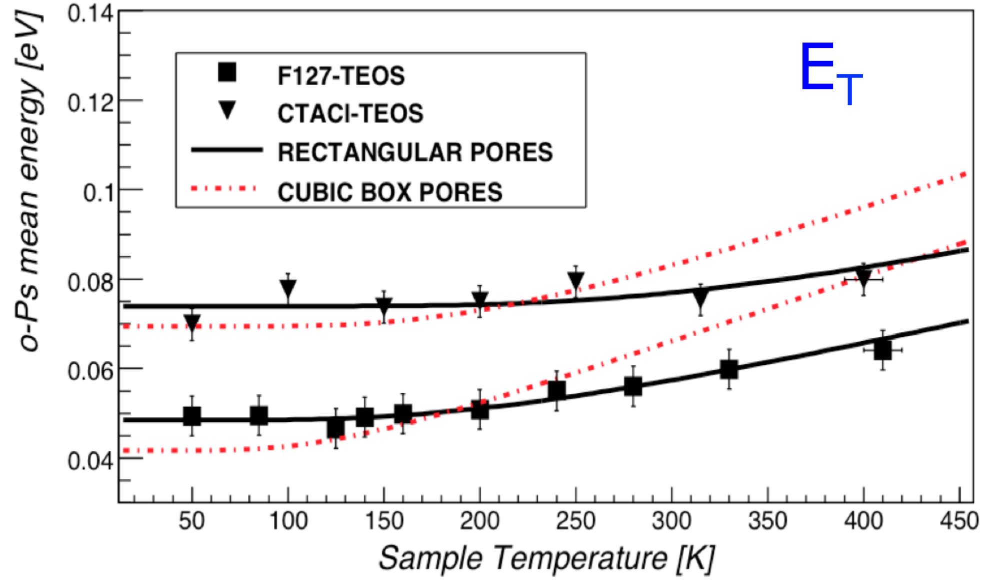


FIG. 9. Linewidth of the 1^3S-2^3P excitation of positronium

Energy of o-Ps : comparison CERN/UCR

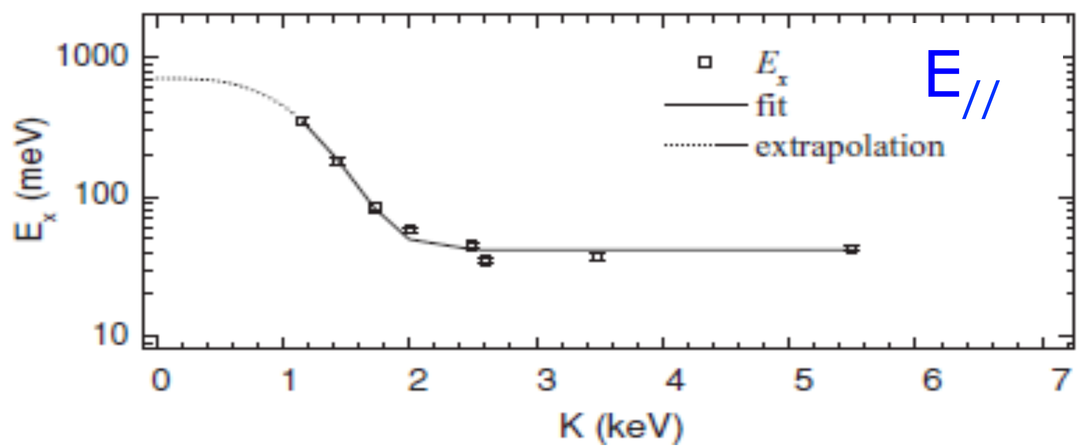
Measurement at CERN

P. Crivelli et al., Phys. Rev. **A 81**, 052703 (2010)

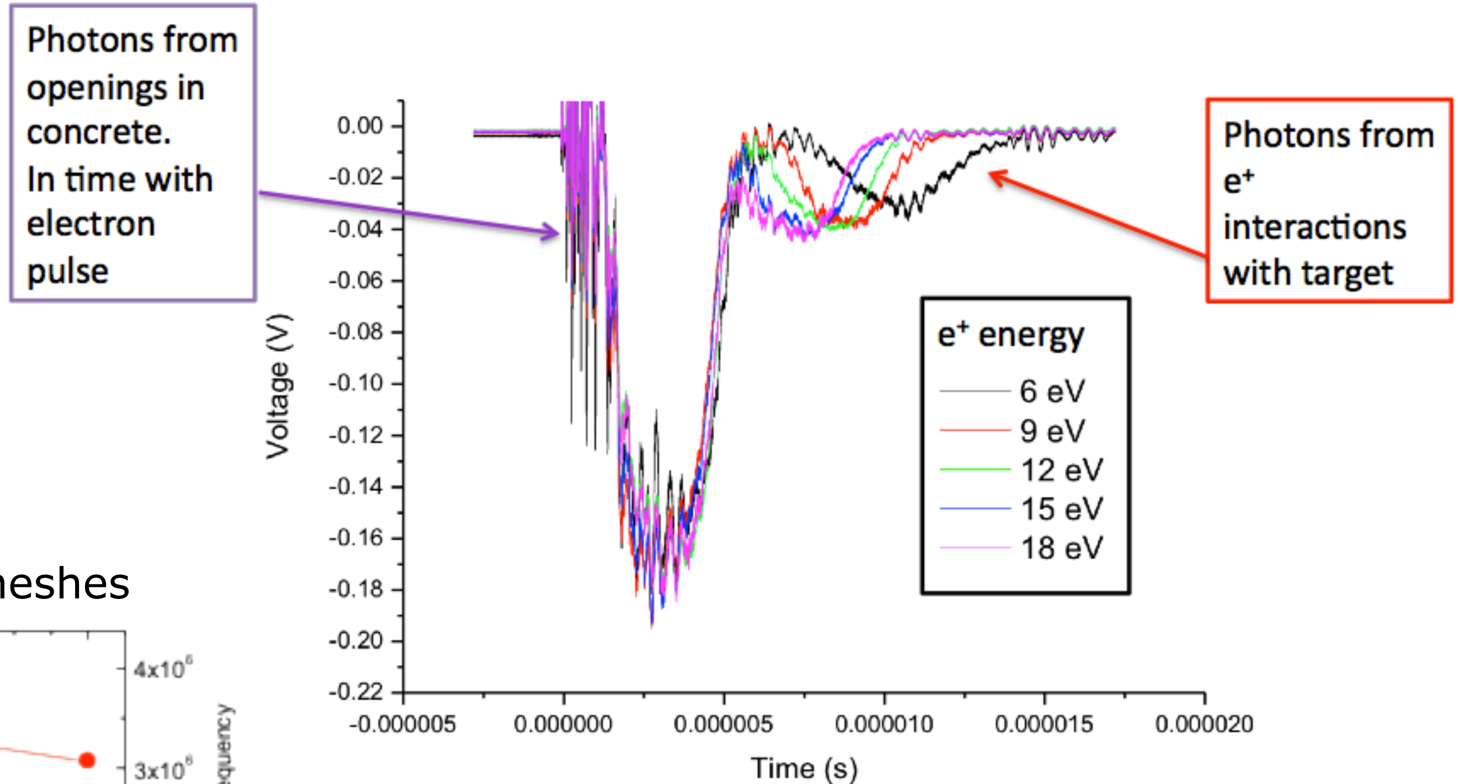


Measurement at UCR

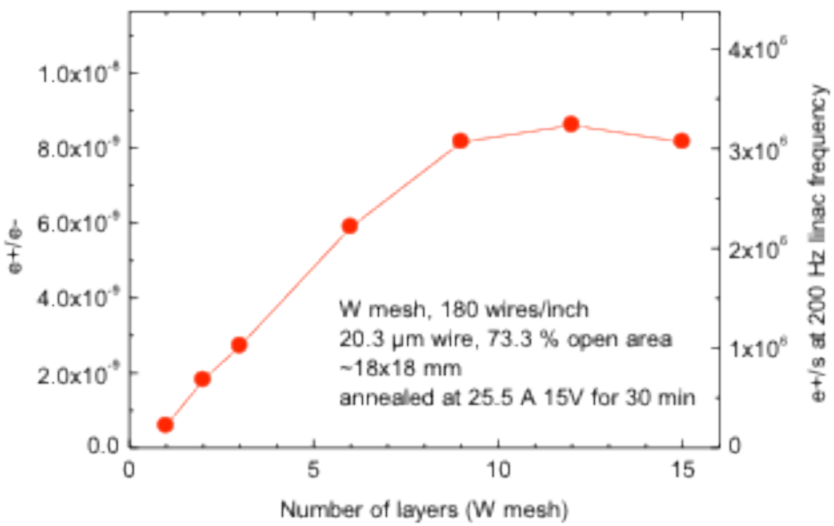
D. B.. Cassidy et al., Phys. Rev. **A 81**, 012715 (2010).



Detection of slow positrons from Linac



Basic annealing of W meshes



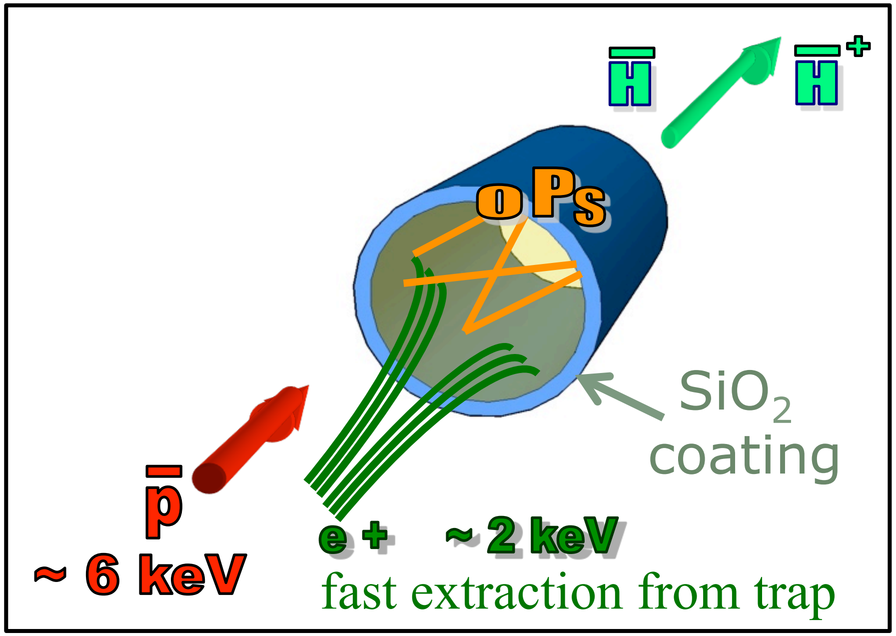
Present slow e^+ rate	$3.2\ 10^6\ s^{-1}$
with 10 MeV linac	$4.3\ 10^7\ s^{-1}$
target value	$2.8\ 10^8\ s^{-1}$

Dense Ps target

Dump 2×10^{10} e^+ in Ps converter in < τ_{Ps}=142 ns

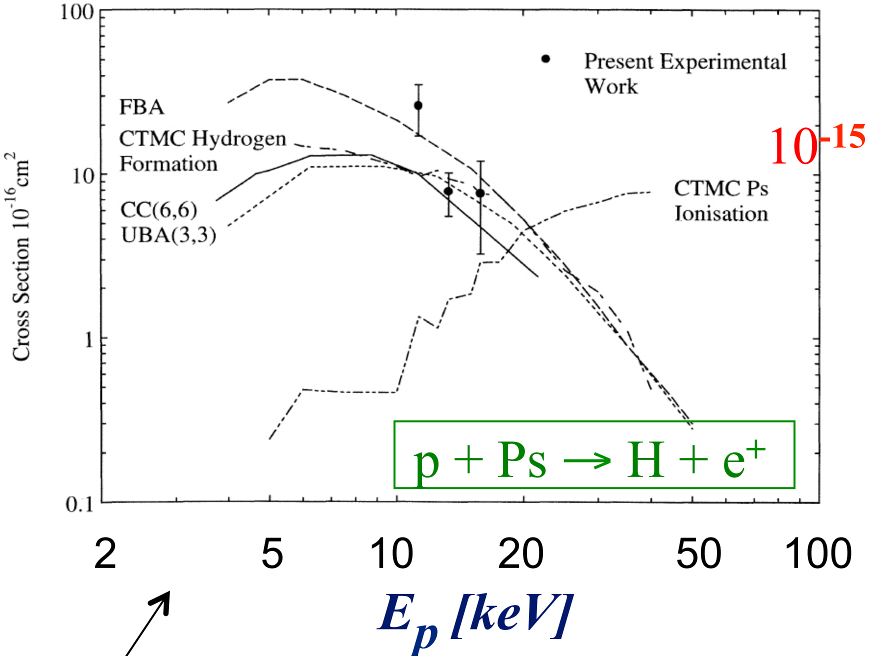
RIKEN test without buncher:
1.3 10^{10} e^- / 75 ns

tube geometry to keep density
(*SiO_2 reflects Ps*)

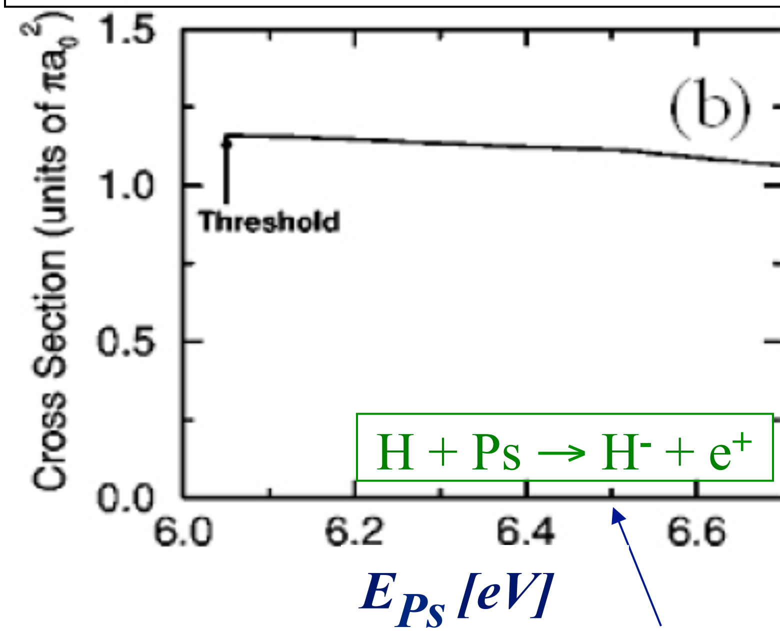


Cross-sections on Ps

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)



E_H = 6 keV in Ps frame

$n_H = 1 - \infty$

$10^7\ \bar{p}$

10^{12} Ps at/cm^2

$\Big\} \longrightarrow$

$10^4\ \bar{H}$

$1\ \bar{H}^+$