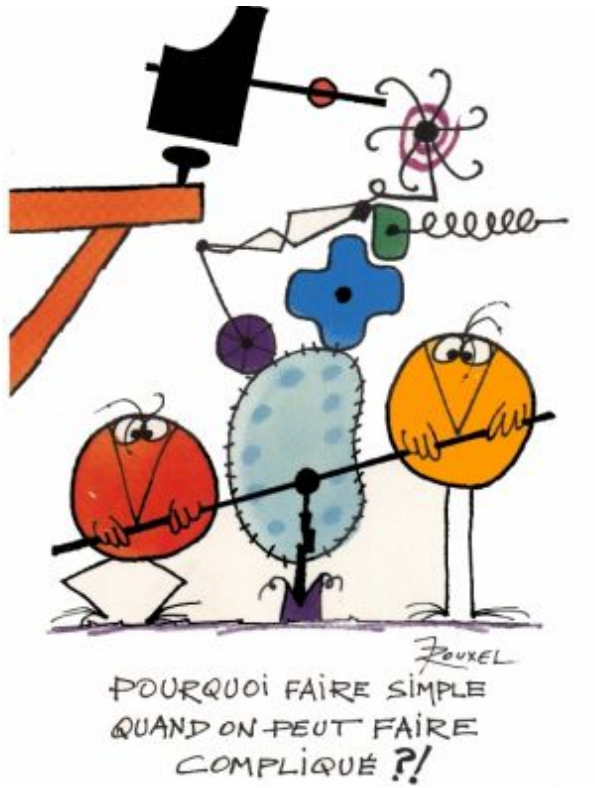
$\bar{G}$: a test of the Equivalence Principle: g =? $\bar{g}$

P. Debu, P. Dupré, L. Liszkay, B. Mansoulié, P. Pérez, J-M Rey, N. Ruiz, Y. Sacquin



L'équipe du SPP

Pascal Debu

Pierre Dupré

Bruno Mansoulié

Patrice Pérez

Nicolas Ruiz

Yves Sacquin

Tomoko Muranaka

Les equipes de l'IRFU

Jean-Michel Rey
Chef de Projet

SACM
SEDI
SIS
SENAC

Laszlo Liszkay
→ SEDI

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 very high precision with many kinds of materials by Eötvös type experiments.

Theory and Experiment

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

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

Newton — Supergravity: has component of repulsive gravity

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

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

Limits

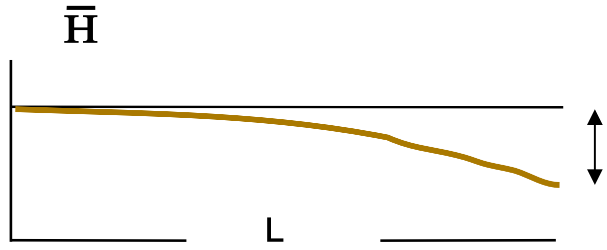
K_0 - $\bar{K}_0$	SN1987a	Cyclotron frequency p/$\bar{p}$

Direct Tests

Charged antimatter	*e^+ or $\bar{p}$ (e.m. shielding)*	
Neutral antimatter	*$\bar{n}$ hard to slow down*	*Ps short lifetime*
	$\bar{H}$ cooling limit mK	*$\bar{H}^+$ cooling limit μK*
	AEGIS(CERN)	This Project

No direct measurement exists

Principle of the experiment



$$h = \frac{g}{2}\left(\frac{L}{v_h}\right)^2$$

Parabolic flight of $\bar{H}$

- L = 1 m et v_h = 500 m/s → h = 20 μm

  → *AEGIS experiment with $\bar{\mathrm{H}}$ (neutral)*

- L = 0.1 m et v_h = 0.5 m/s → h = 10 cm

  → *Gbar project using $\bar{\mathrm{H}}^+$ to produce slow $\bar{\mathrm{H}}$*

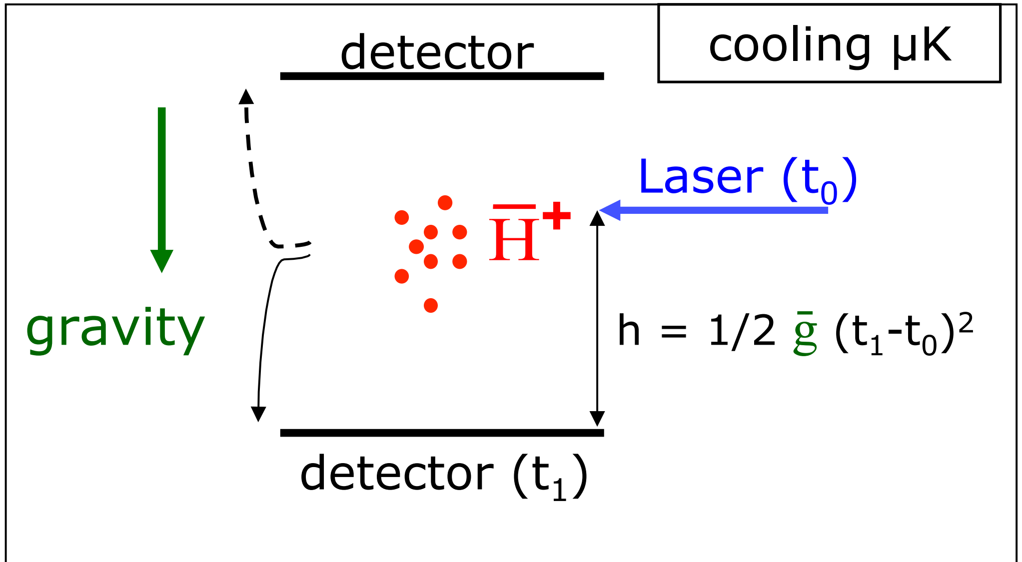
P. Pérez et al, LOI CERN –SPSCI-038 (2007) Irfu, Riken, Tokyo U.

- Precision depends on the spread of the initial vertical speed

$\bar{g}$ experiment using $\bar{H}^+$

- Produce ion $\bar{H}^+$
- Capture ion $\bar{H}^+$
- Sympathetic cooling 20 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 $\bar{g}$:

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

$h = 10$ cm → $\Delta t = 143$ ms

$h = 1$ mm → $\Delta t = 14$ ms

$\bar{H}$ Production via $\bar{H}^+$

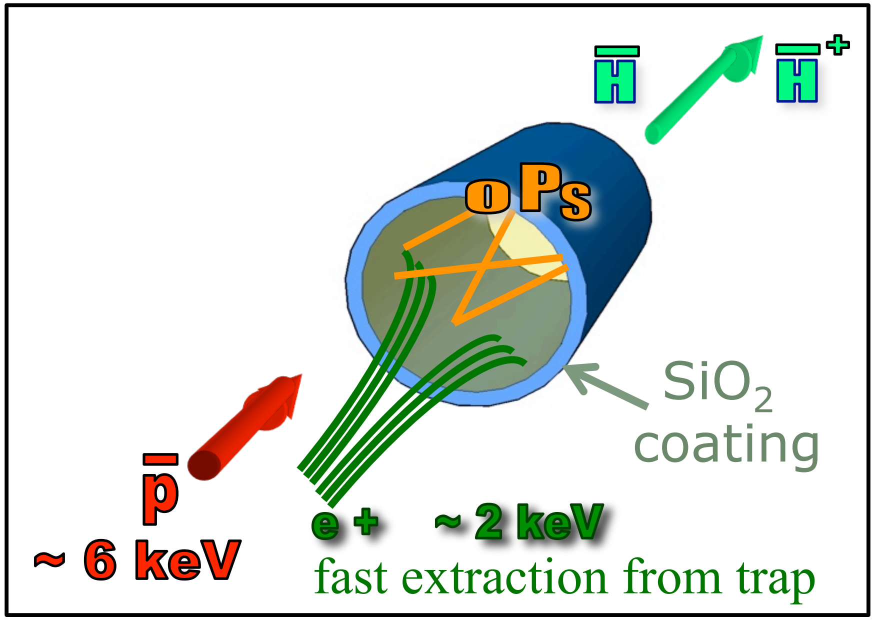
Standard production

$$\bar{p} + e^+ + e^+ \rightarrow \bar{H}^* + e^+$$

$\bar{H}^+$ Formation

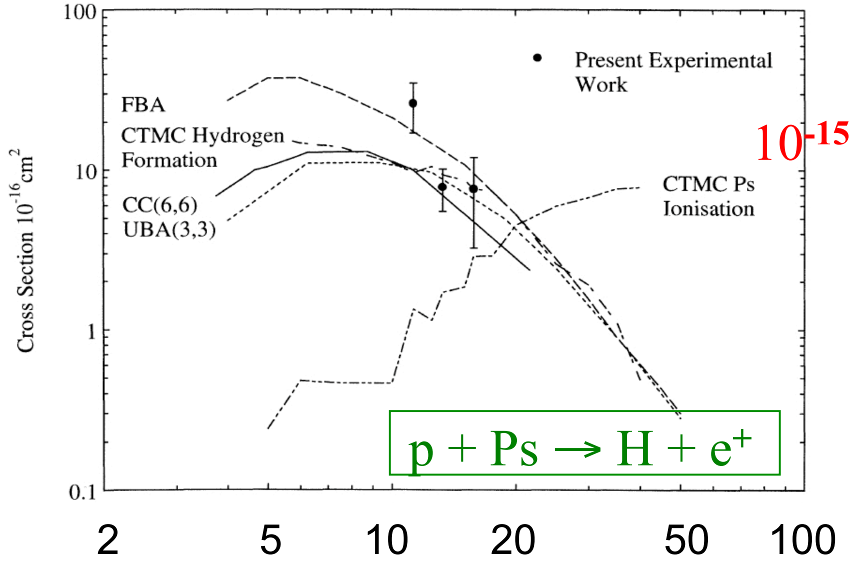
$$\bar{p} + Ps \rightarrow \bar{H} + e^-$$

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



Cross-sections on Ps

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

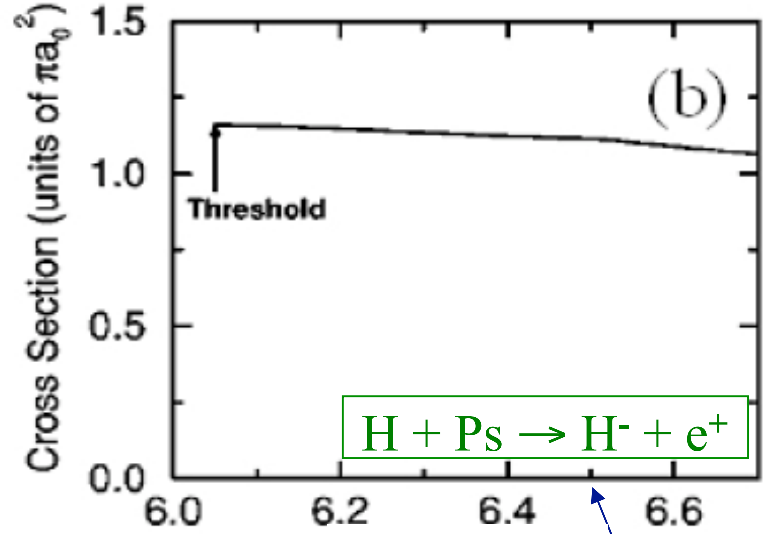


10^{-15} cm^2

$p + Ps \rightarrow H + e^+$

E_p [keV]

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



10^{-16} cm^2

$H + Ps \rightarrow H^- + e^+$

E_{Ps} [eV]

E_H = 6 keV in Ps frame

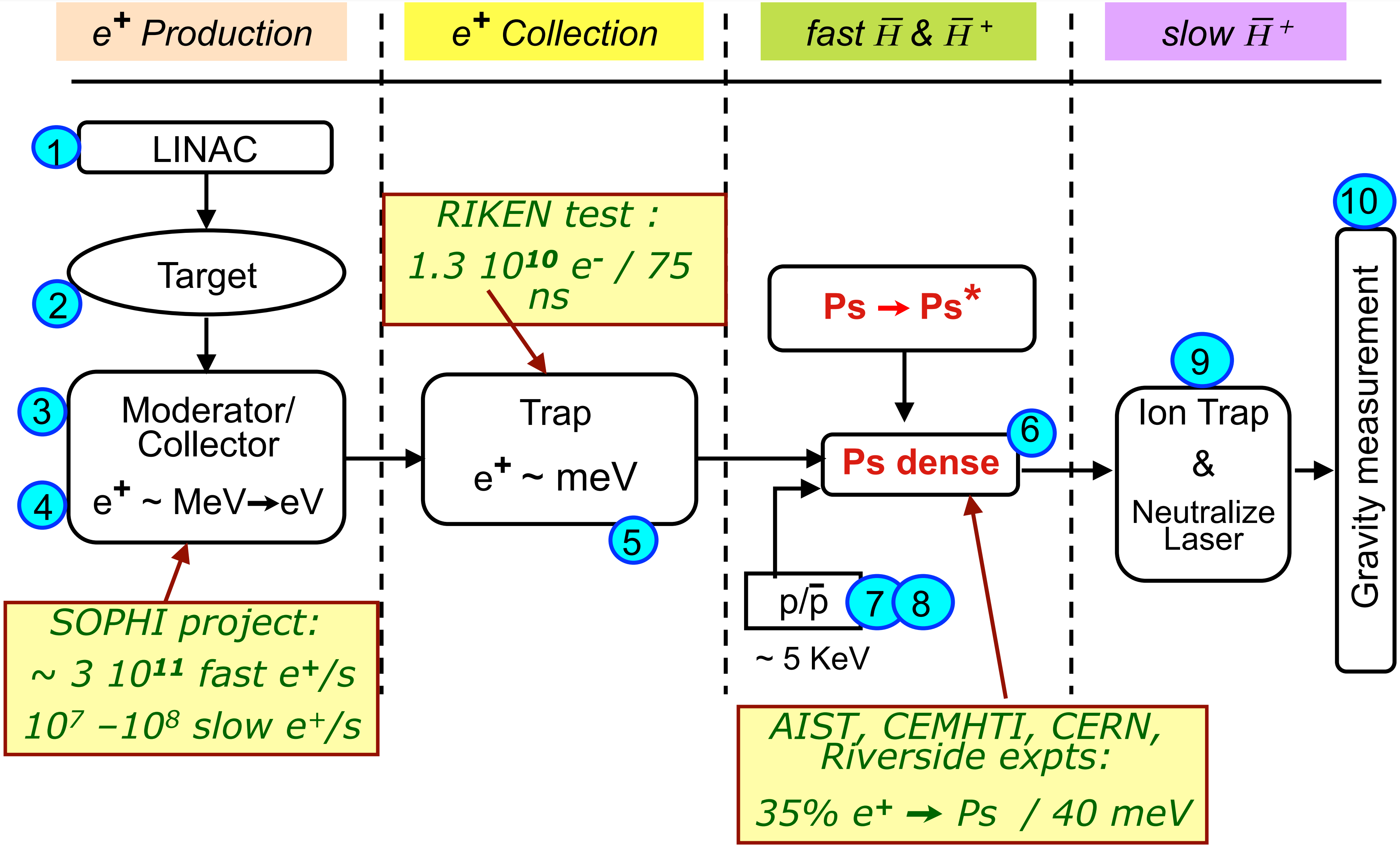
ASACUSA
12 AD shots → $10^7\ \bar{p}$

e^+ from Linac & Trap → 10^{12} Ps at/cm^2

} → $10^4\ \bar{H}$, $1\ \bar{H}^+$

if all Ps excited to n=3, expect × 80

Synoptic Scheme

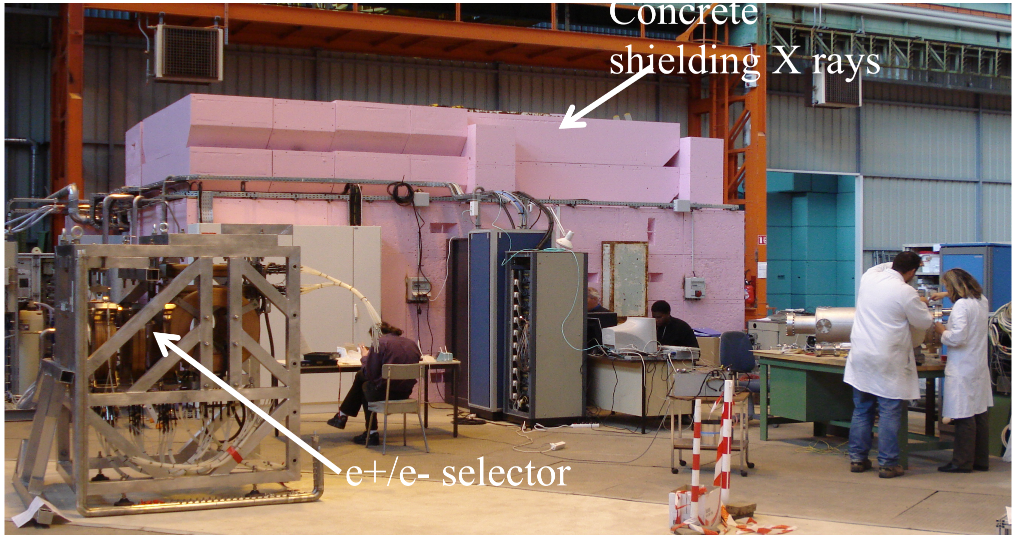


Efficiencies

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	$\sigma(\bar{p}+Ps \rightarrow \bar{H})$	$\sigma(\bar{H}+Ps \rightarrow \bar{H}^+)$	$N\bar{H}$	**$N\bar{H}^+$**		
1.00E+07	1.00E-15	1.00E-16	8.82E+04	**7.78E+00**		

↑ every 20 minutes pulse

Installation at Saclay (Nov'08 – May'09)



Funding CEA-CG Essonne

ANR 2006

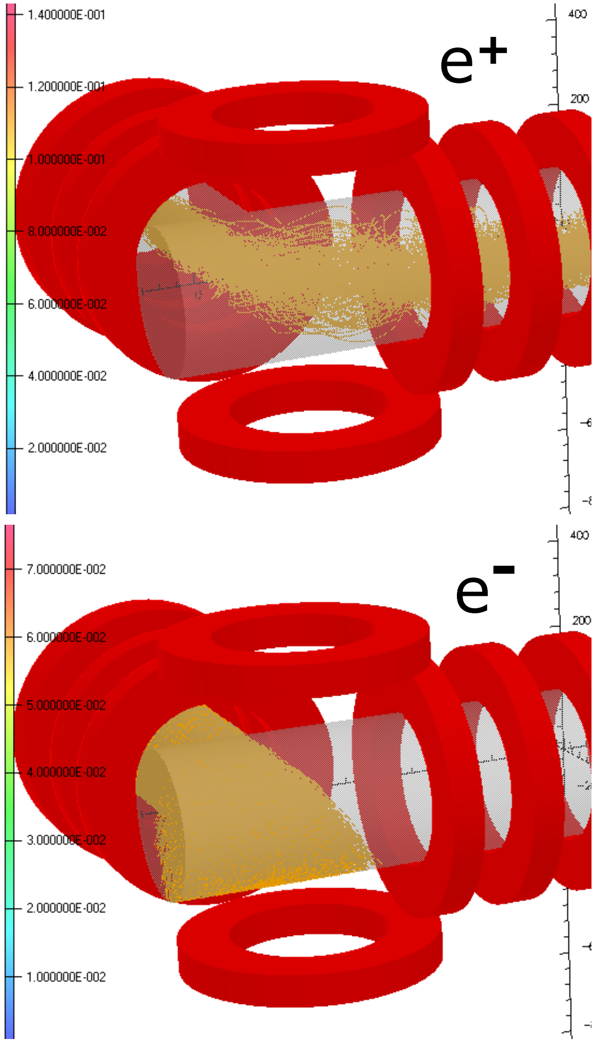
Demonstrator e^- Linac

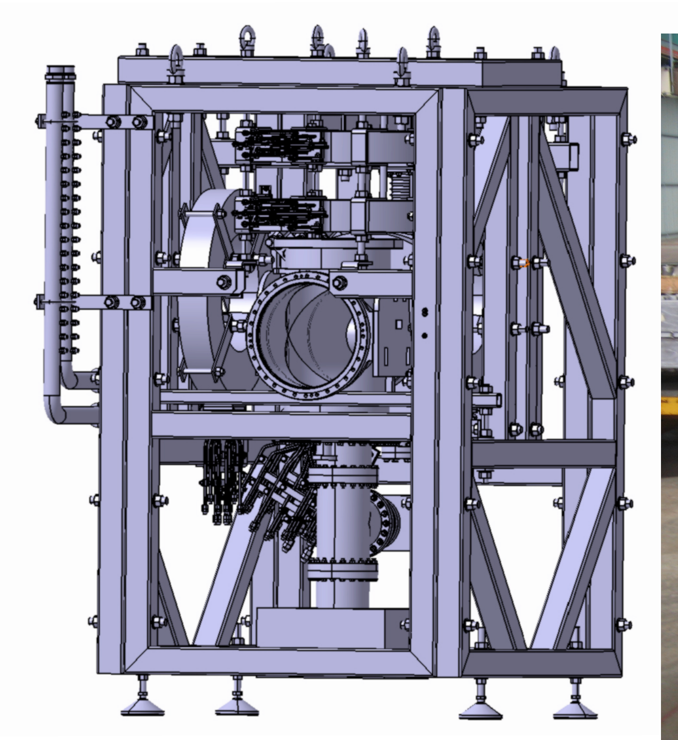
Ec = 5.5 MeV

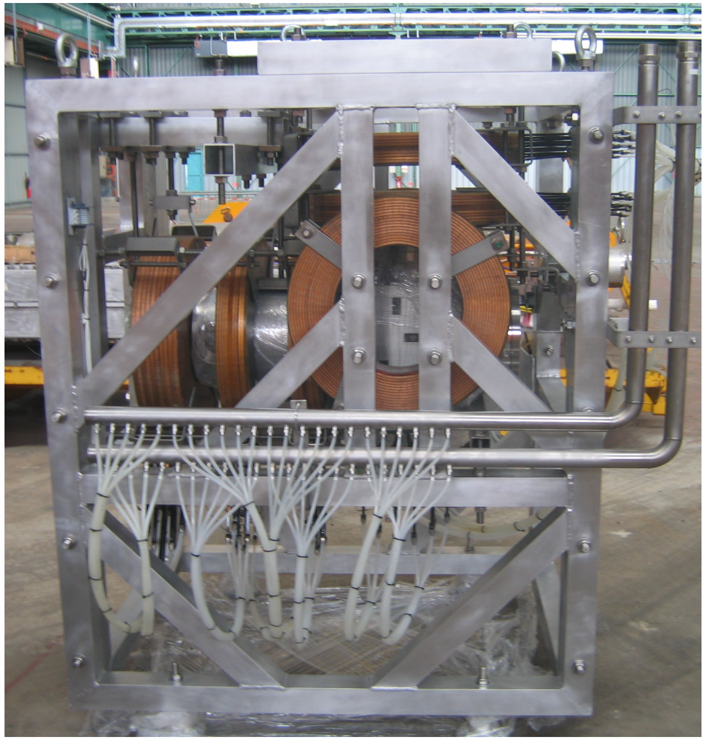
$I_{measured}$ = 0.14 mA

Hall 126 - New Paint and Counting Room

e^+/e^- selector


e+
e-
1.400000E-001
1.200000E-001
1.000000E-001
8.000000E-002
6.000000E-002
4.000000E-002
2.000000E-002
7.000000E-002
6.000000E-002
5.000000E-002
4.000000E-002
3.000000E-002
2.000000E-002
1.000000E-002
400
200





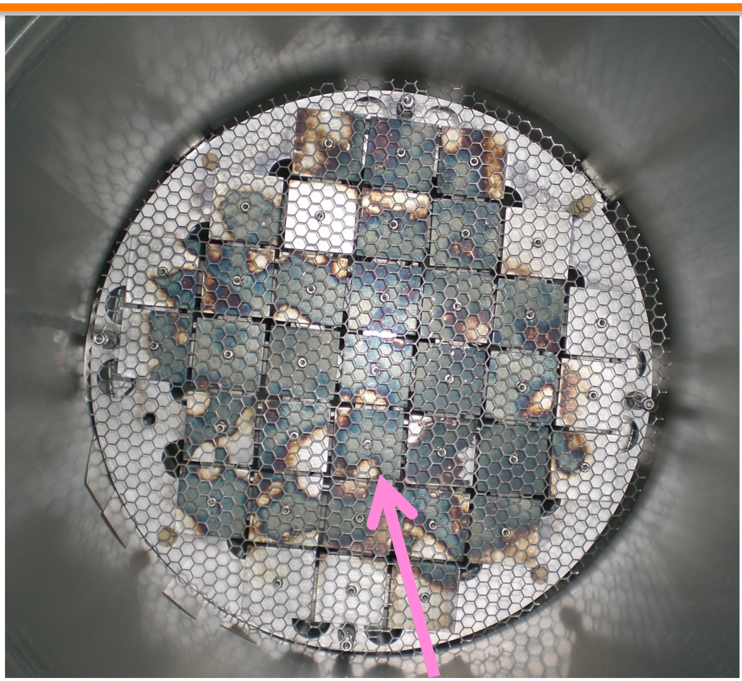
Reducing HF backgrounds

1.9 MW magnetron
located 1.5 m from e^+ detector

→Thick shielding !
HF noise reduced by factor 500

→particles are seen

Fast e^+ detection

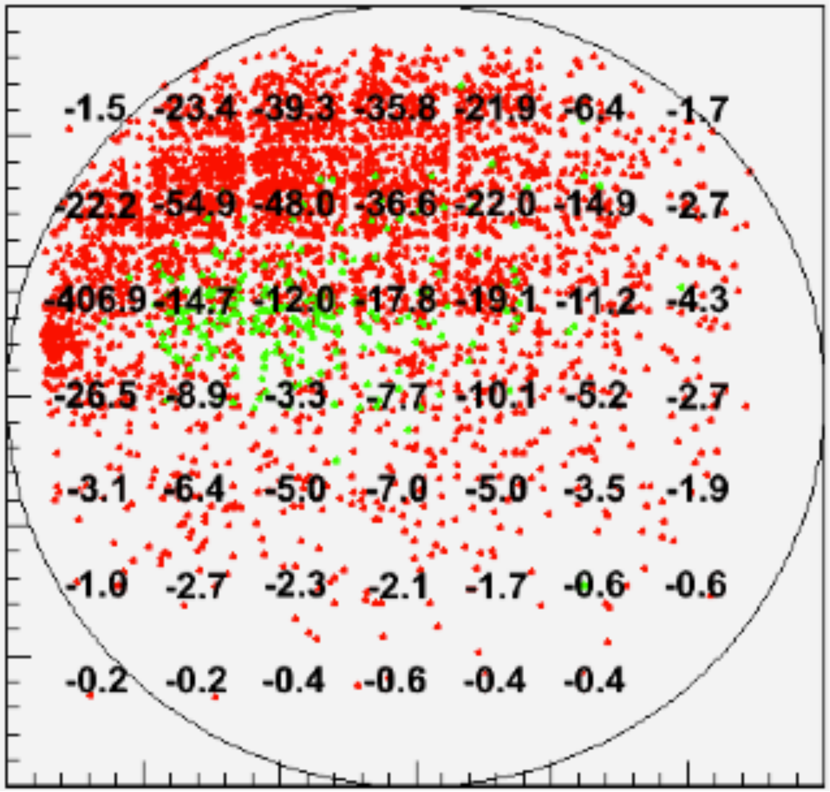


35 Faraday cups

Expected e^+ yield from 1 mm W target at 5.5 MeV ~ 1 10^{-4} per e^-

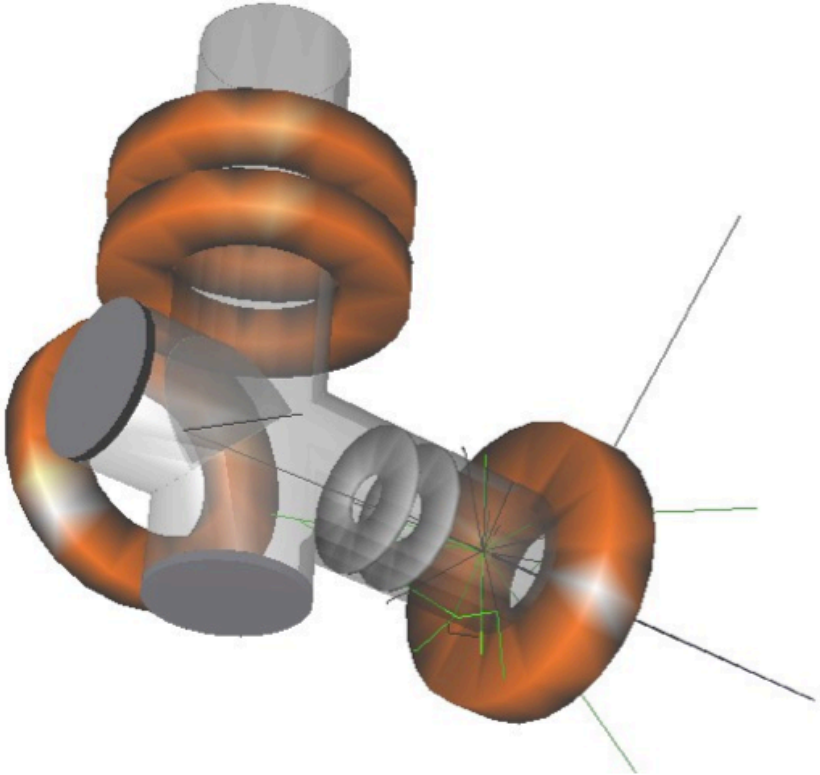
Linac peak current ~ .12 mA during 4 μs

GEANT4 simulation: **400 μm** target



e^- e^+

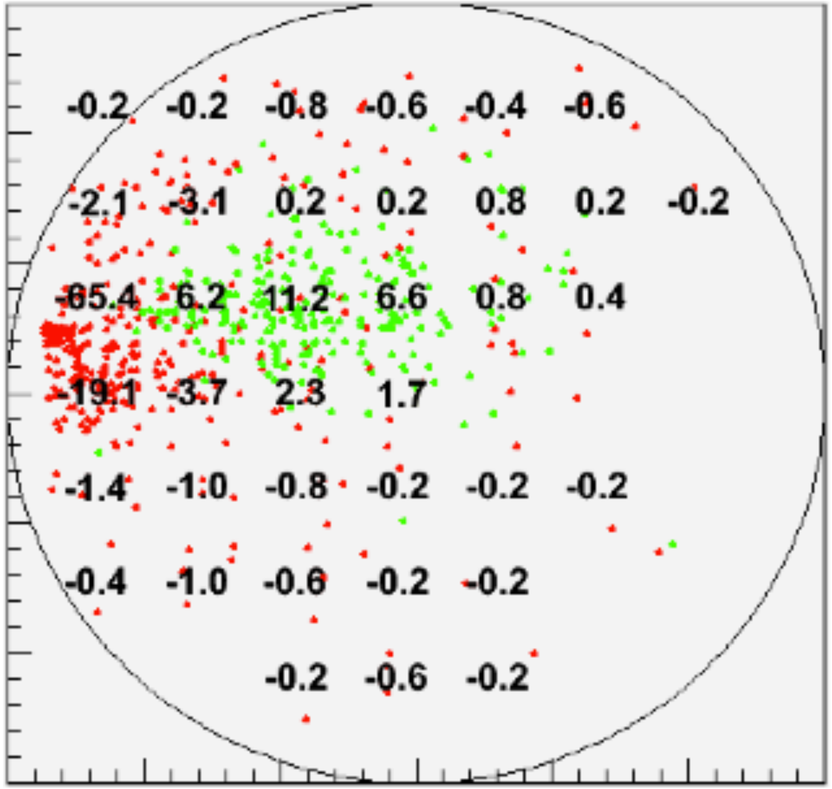
Improving S/N



electron additional background ?

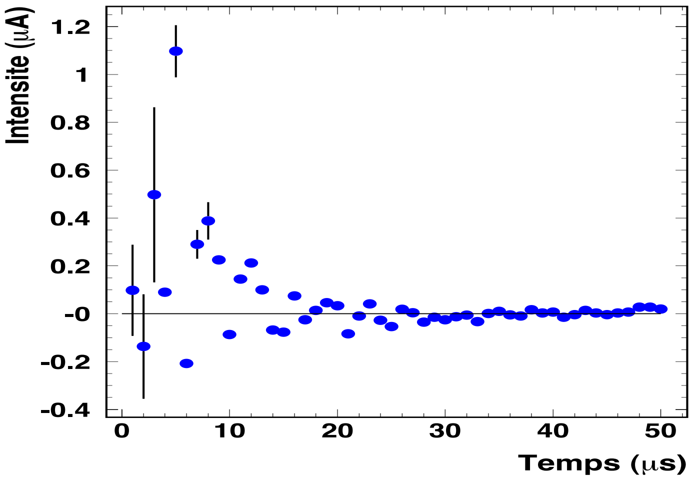
LINAC energy < 5.5 MeV ?

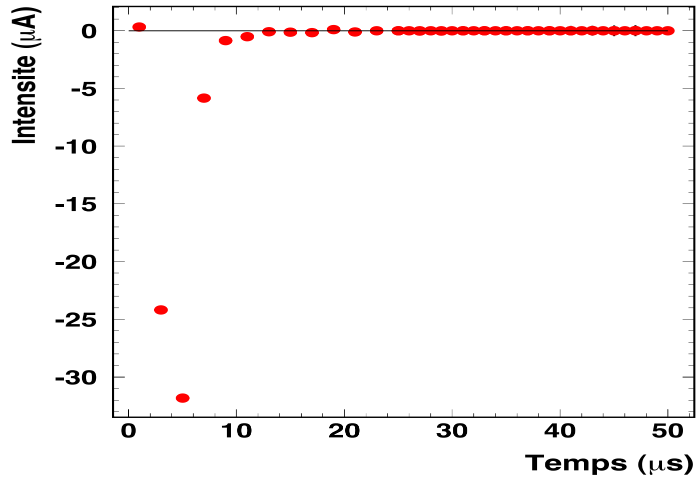
GEANT4 simulation: **1 mm** target



Expected e^{+} charge on pads 11-12
~ 13 pC per burst
charge seen ~ 4 pC per burst :

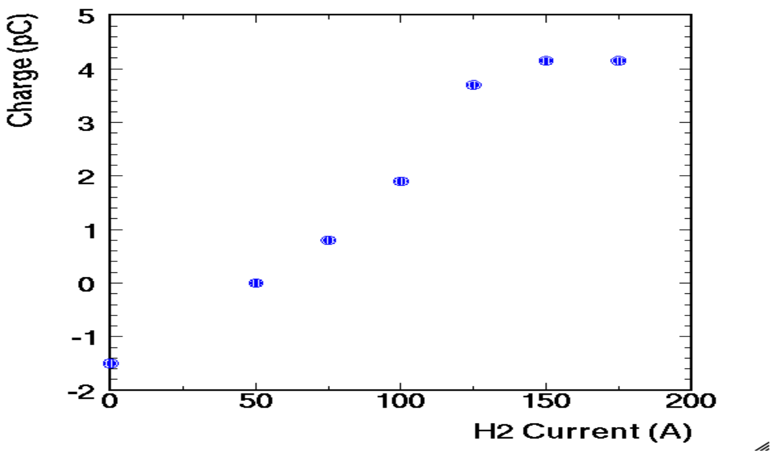
Fast e^+ detection

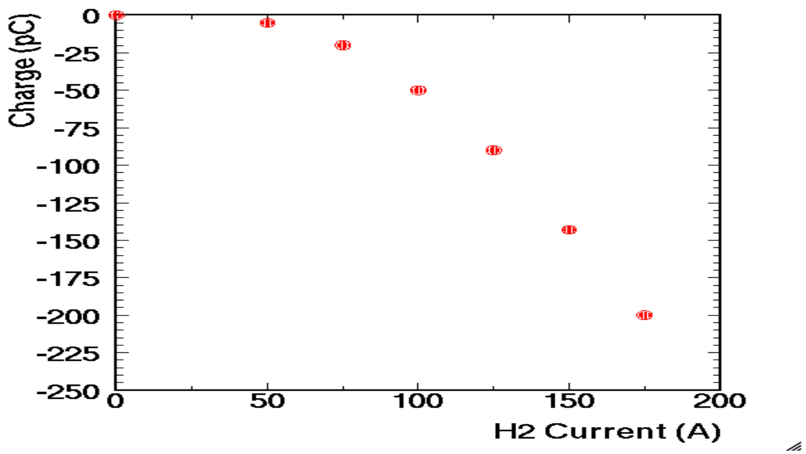




e^+

e^-





Short term (2010)

Water cooling

- New target holder
  → measure e^+ rate at 200 Hz (May-June 2010)

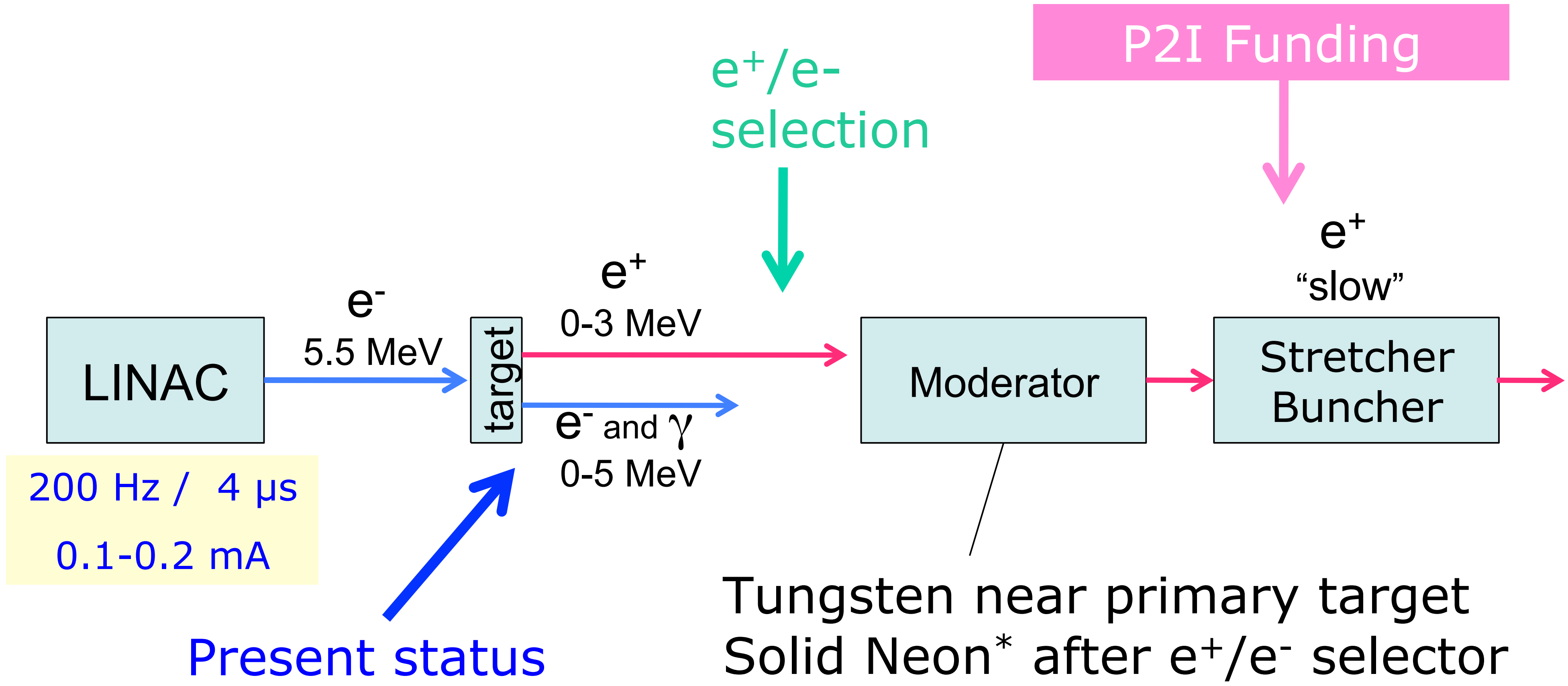
- Add focussing magnet around cathode

- Modify steering quad at linac exit

- Understand/measure
  E_{e-} vs I_{e-} and E_{e-} distribution

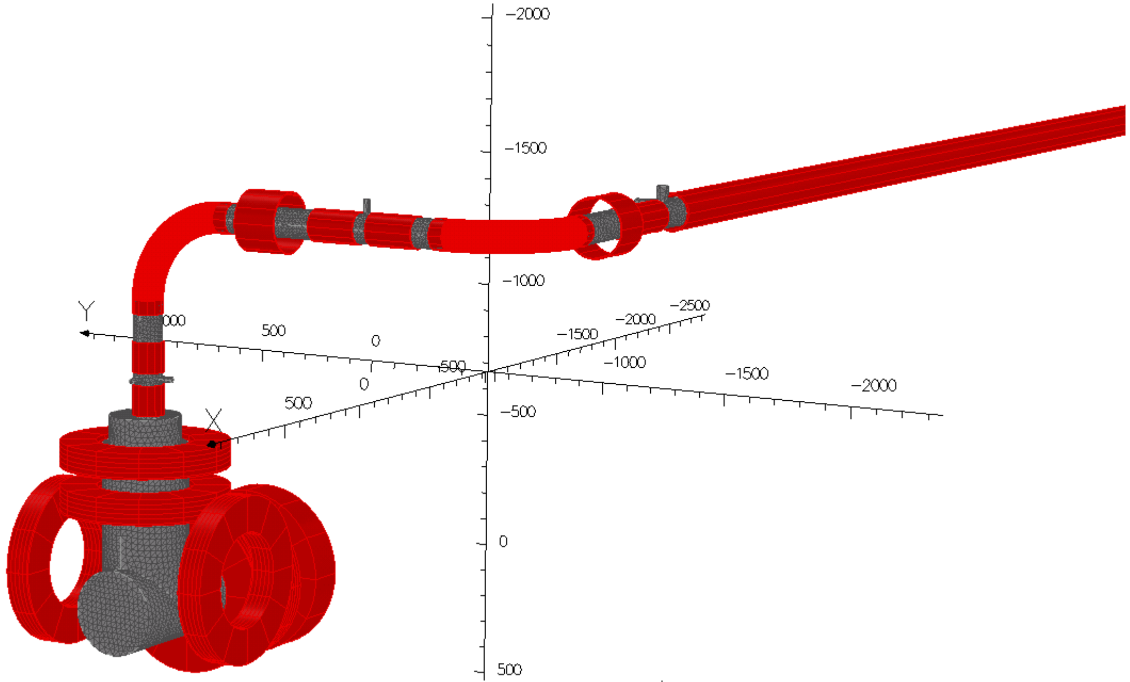
- Improve MC description

Production and extraction of slow positrons

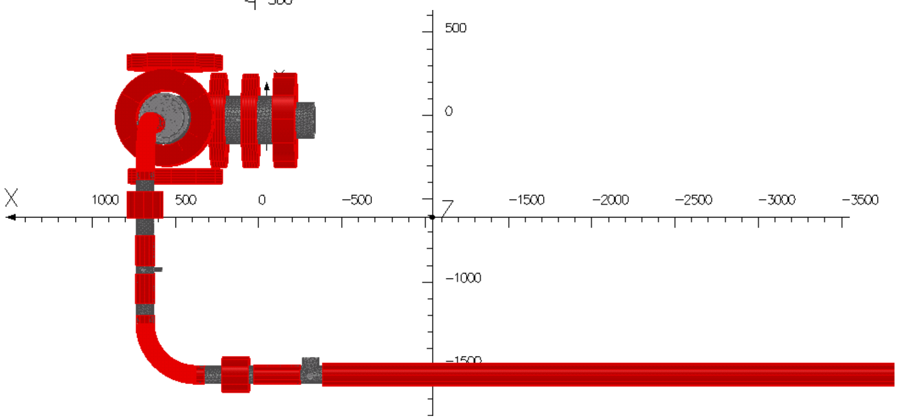


* Needed for $\overline{\mathrm{H}}$ expt. *(not yet funded)*

Extraction of slow positrons

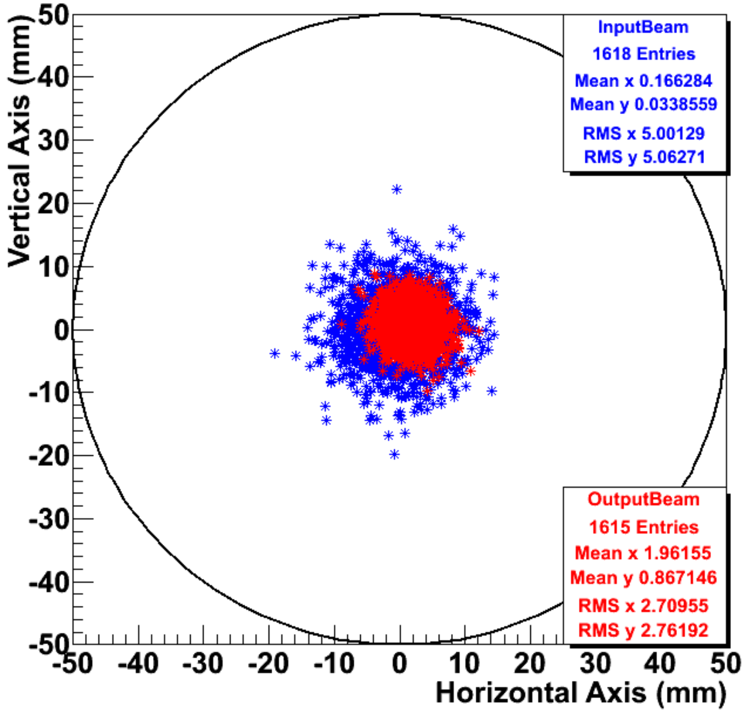


View from above →

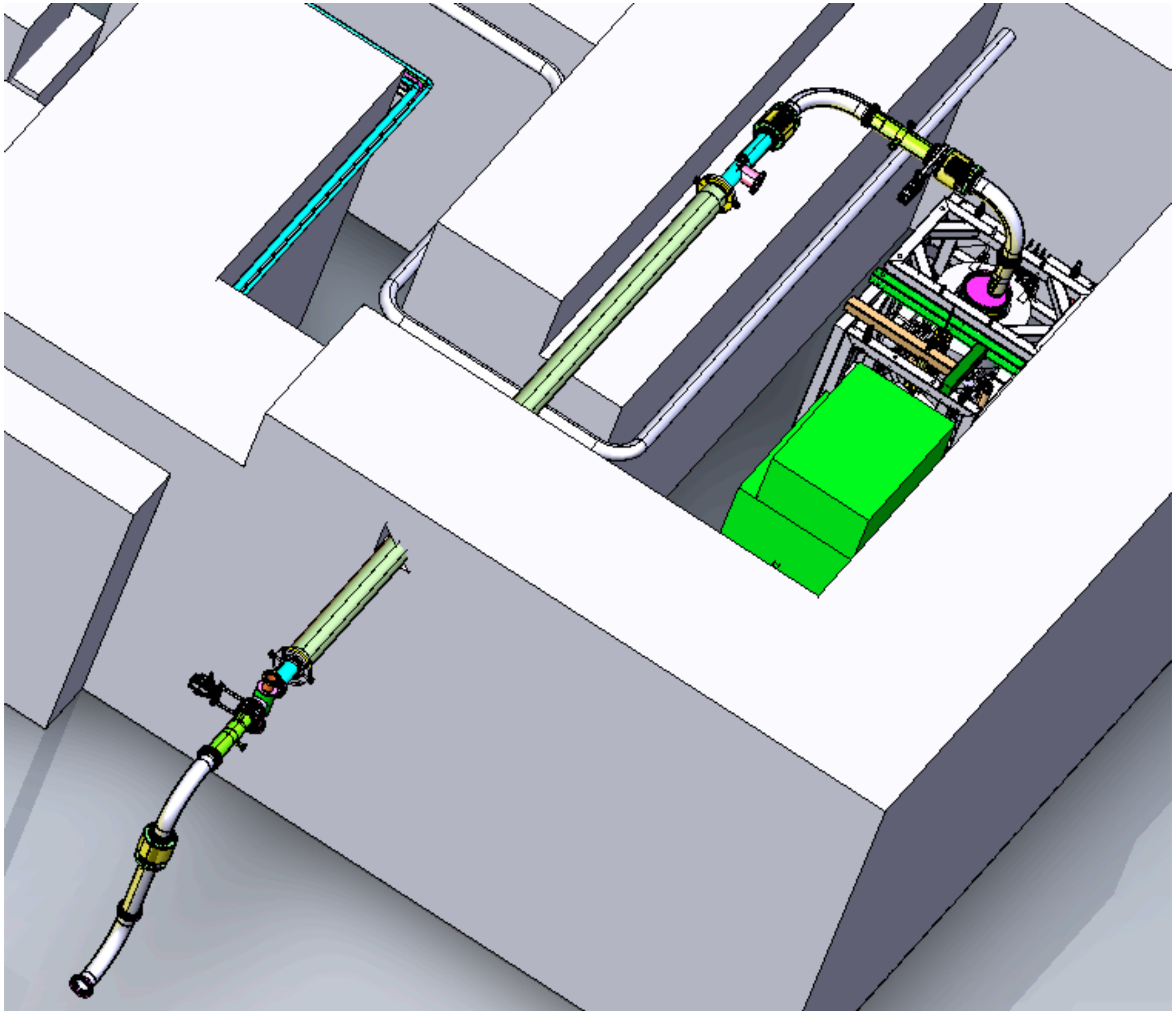


Magnetic field calculations with Tosca/Opera

N. Ruiz

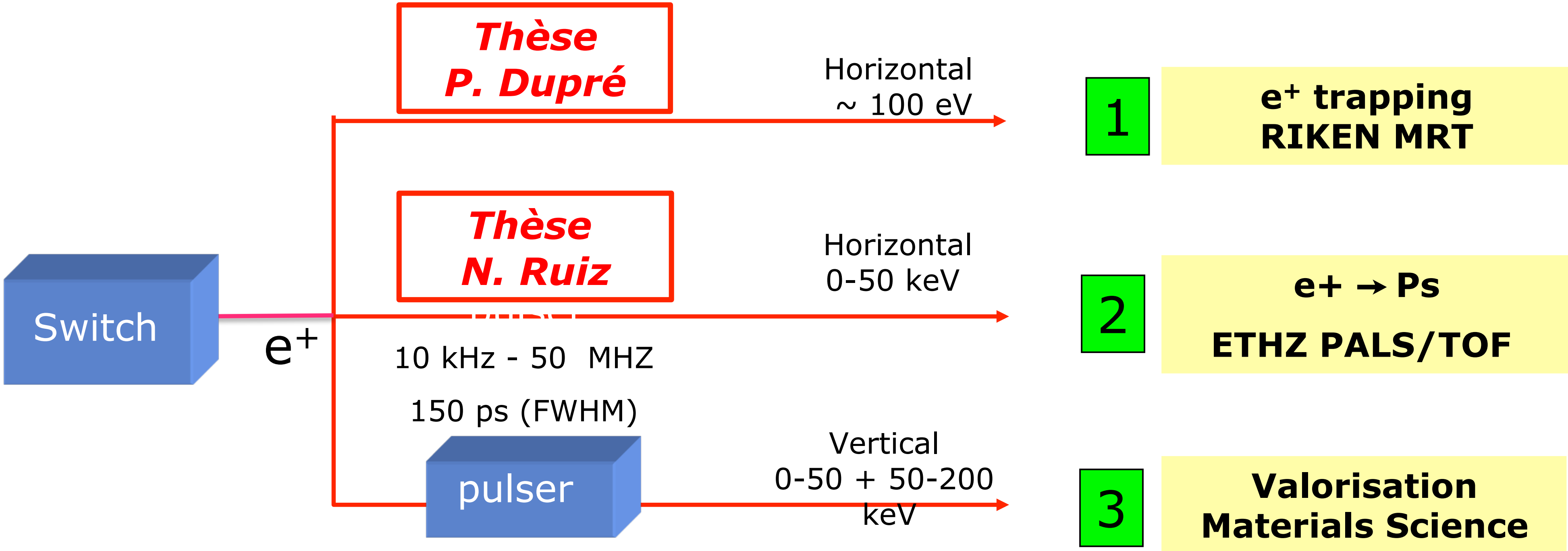


Implantation



Thesis
Nicolas
Ruiz

2-3 beam lines

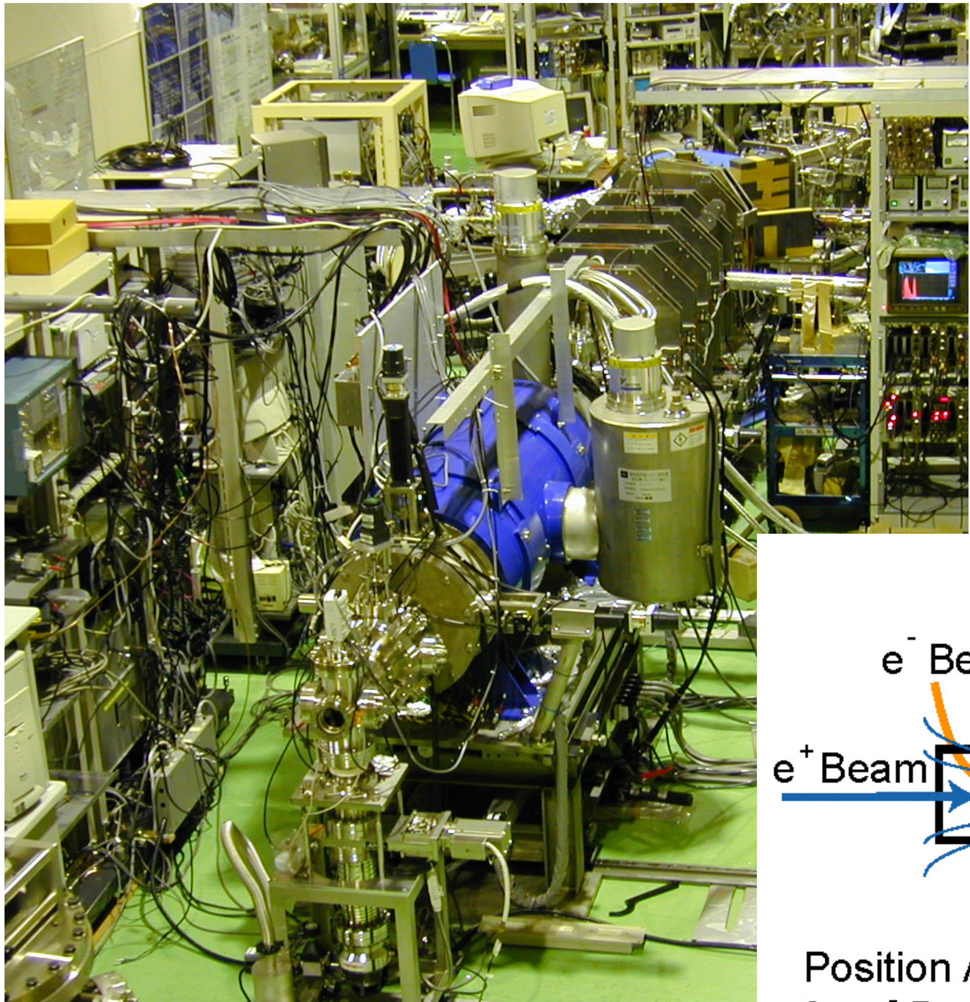


Line 2 also suitable for fundamental research:

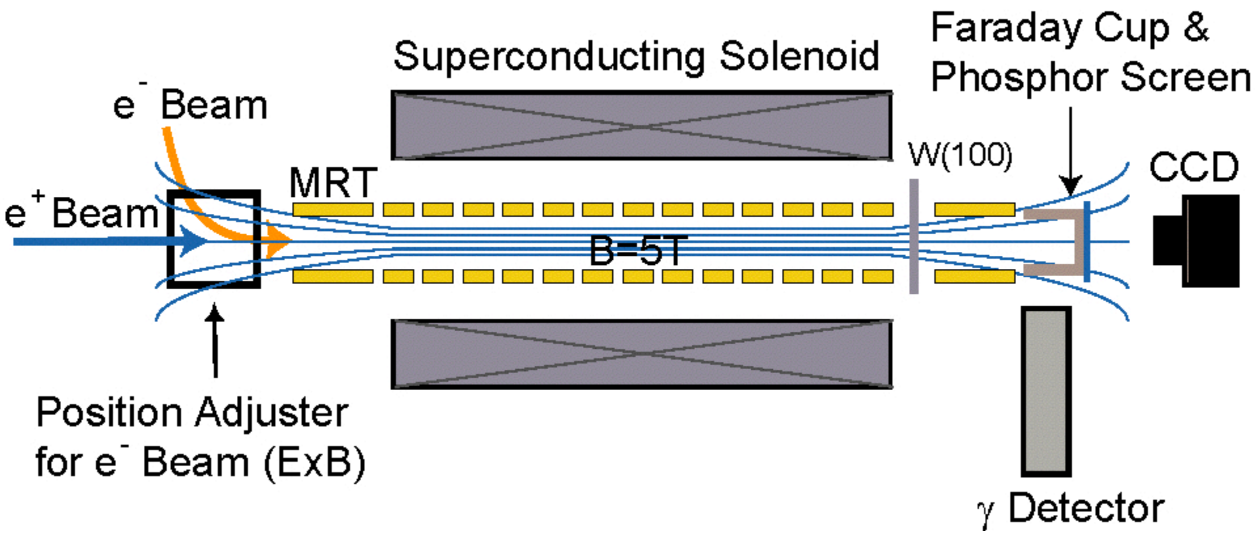
- Axions Ps → a + γ
- Mirror Universe Ps → invisible
- Excitation Ps → Ps*

RIKEN
MultiRing Trap

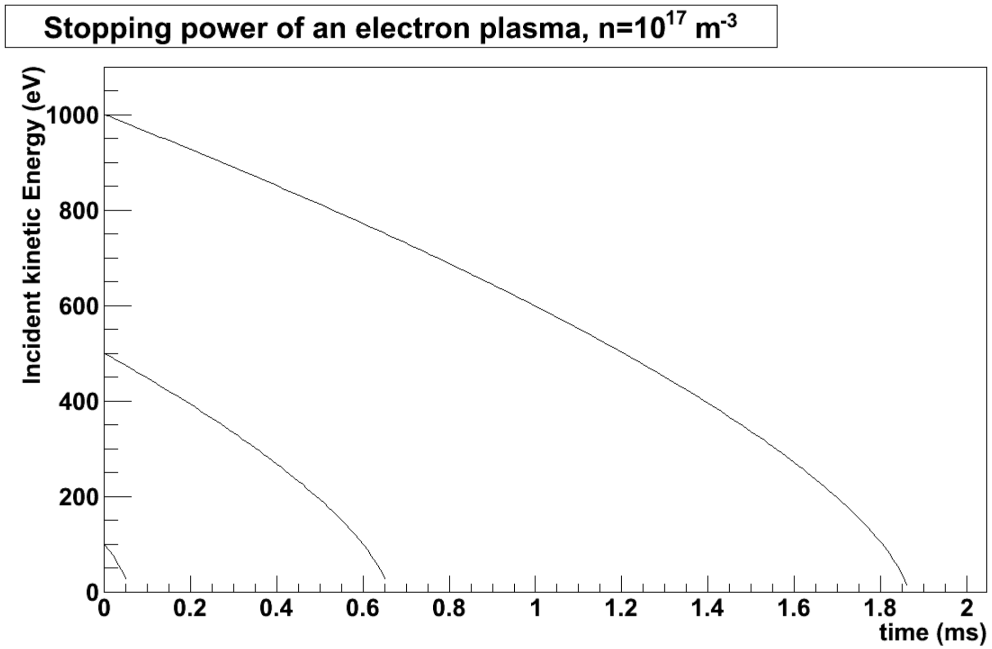
小島 隆夫*, 大島 永康*†, 新垣 恵*†, 毛利 明博*, 山崎 泰規*†
Takao M. Kojima*, Nagayasu Oshima*†, Megumi Niigaki†, Akihiro Mohri*, and Yasunori Yamazaki*†
理研原子物理研究室 *Atomic Physics Laboratory, RIKEN, 2-1 Hirosawa, Wako, Saitama 351-0198, Japan**

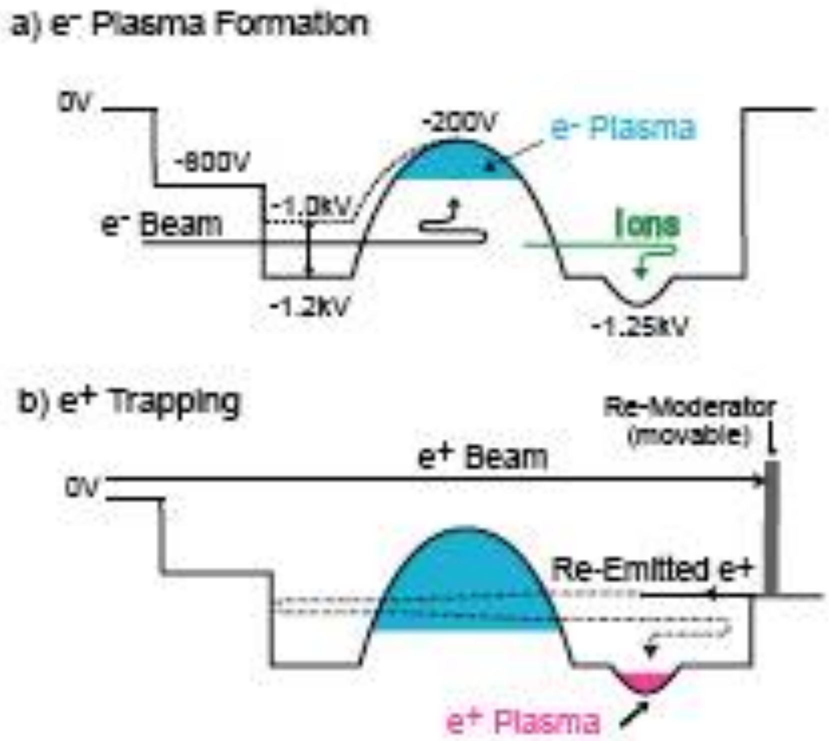


Thesis
Pierre
Dupré



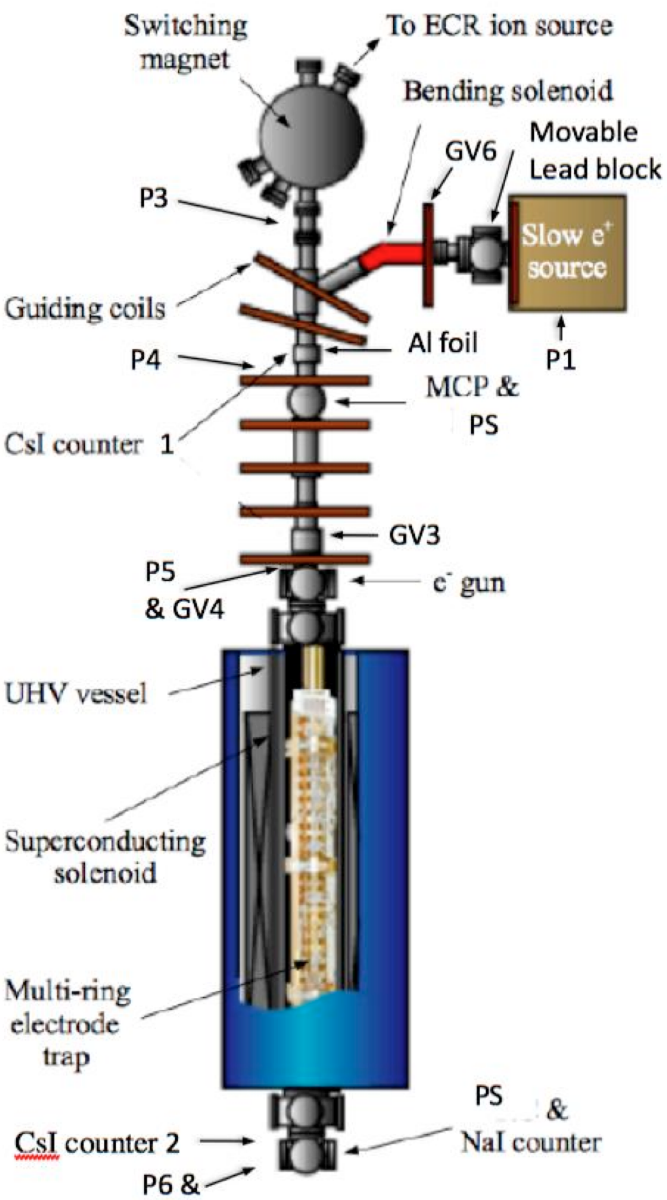
RIKEN trapping mechanism

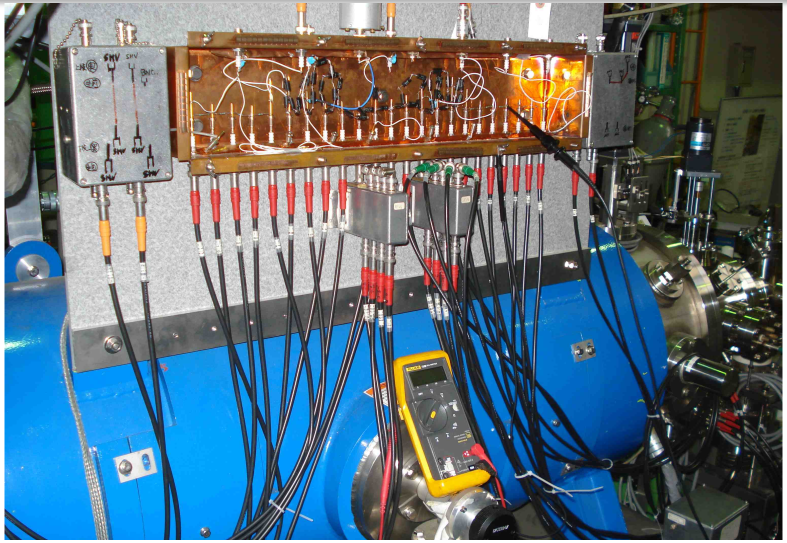


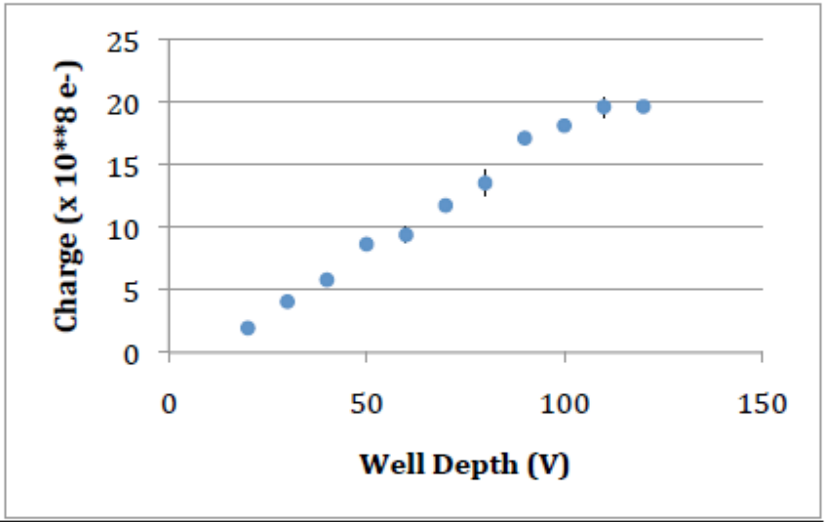


T confinement (s)	1	2	5	10	20	50	100	200	500	1000
Charge (x 10^8 e-)	11.5 ± 0.3	12.6 ± 0.1	11.0 ± 0.7	11.9 ± 0.3	11.6 ± 0.3	12.3 ± 0.2	11.5 ± 0.3	11.2 ± 0.7	11.0 ± 1.2	9.9 ± 1.2

Exercising the trap

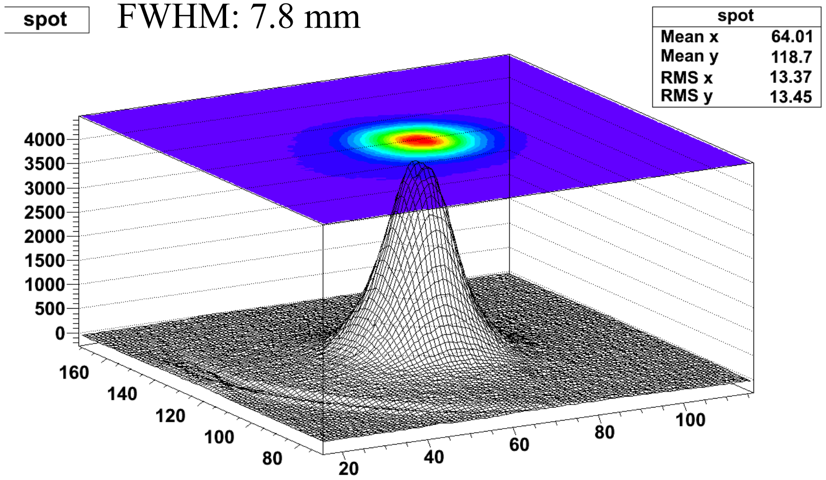




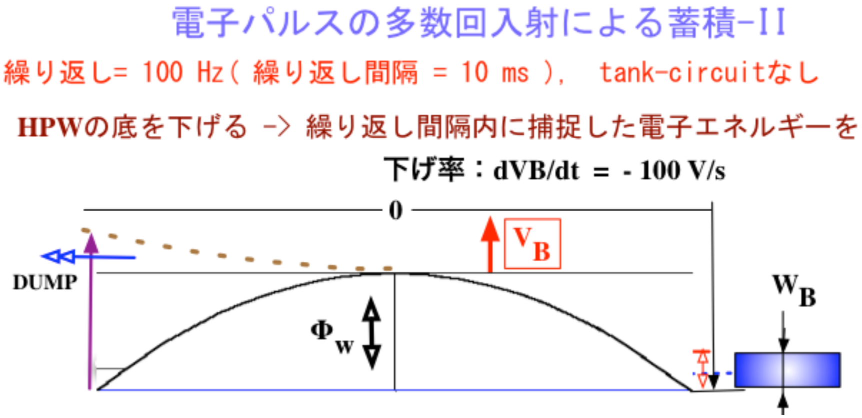


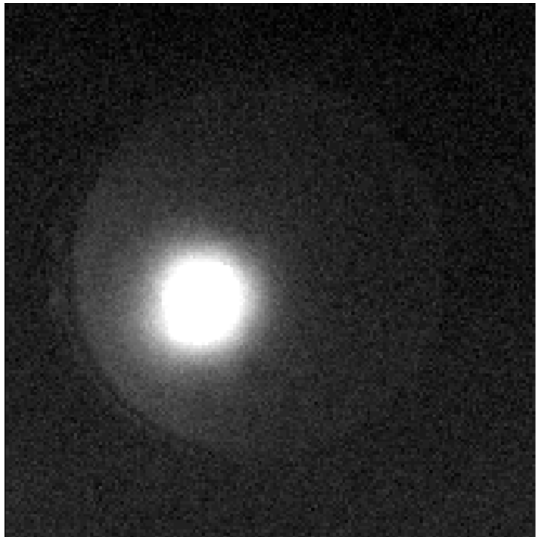
Experiments with electrons

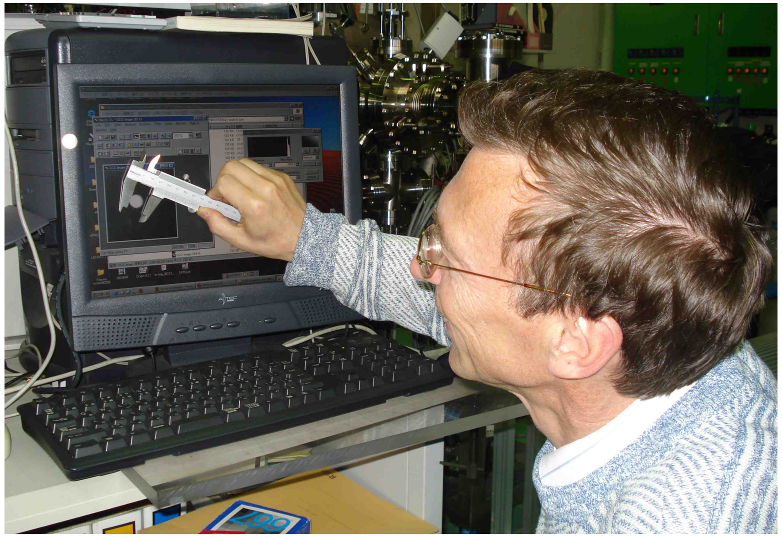
FWHM: 7.8 mm



V_{IN} = -1100 V Radius 0.5 mm
aspect ratio 350
density 9.7 10^{10} cm^{-3}
$\varepsilon_{damping}$ 59 %



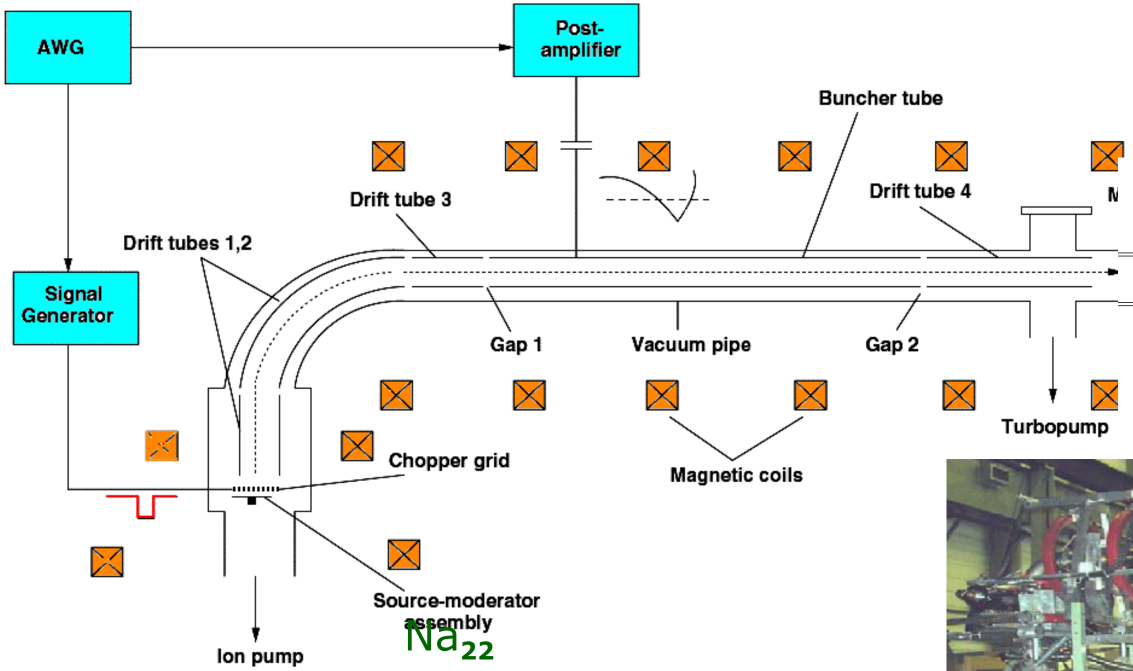


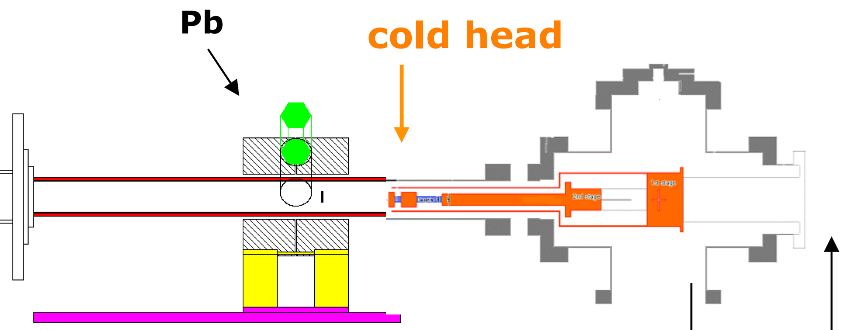


Slow e^+ beams: PALS/TOF

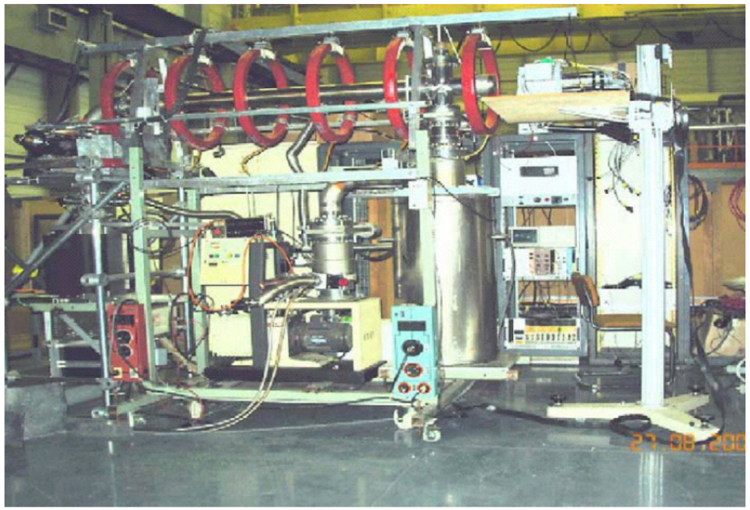
AIST Tsukuba
(R. Suzuki, T. Ohdaira)

E.T.H Zurich (A. Rubbia, U. Gendotti)
IRFU Saclay (P. Crivelli, L. Liszkay)





N. Alberola et al., Nucl. Instr. Meth. A 560 (2006) 524.

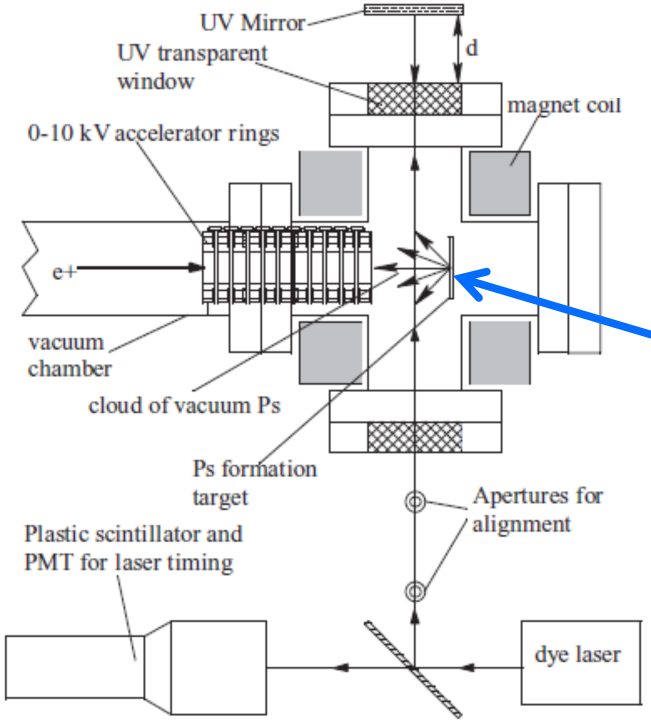


Emission o-Ps from single shot lifetime

PHYSICAL REVIEW A **81**, 012715 (2010)

Positronium cooling in porous silica measured via Doppler spectroscopy

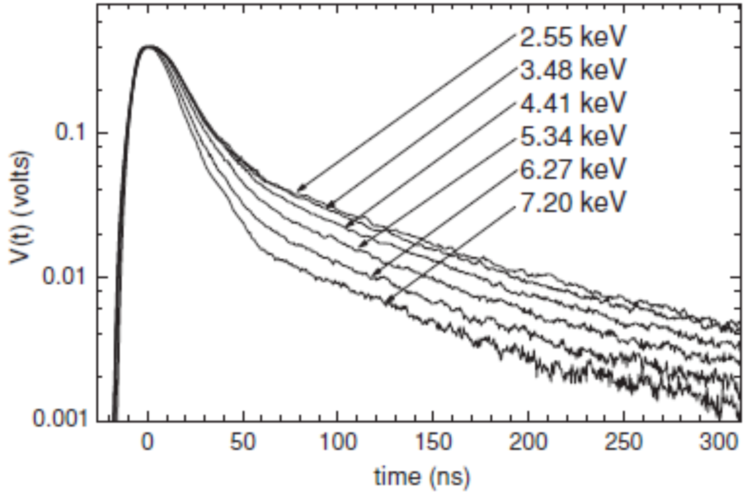
D. B. Cassidy,[1] P. Crivelli,[2] T. H. Hisakado,[1] L. Liszkay,[3,*] V. E. Meligne,[1] P. Perez,[3] H. W. K. Tom,[1] and A. P. Mills Jr.[1]
[1]*Department of Physics and Astronomy, University of California, Riverside, California 92521-0413, USA*
[2]*URFJ, Rio de Janeiro, Brazil*
[3]*CEA, Saclay, IRFU, F-91191 Gif-sur-Yvette Cedex, France*



Sample from Saclay

Laser : 243±5 nm
< 350 μJ/pulse

Experimental setup (UCR)

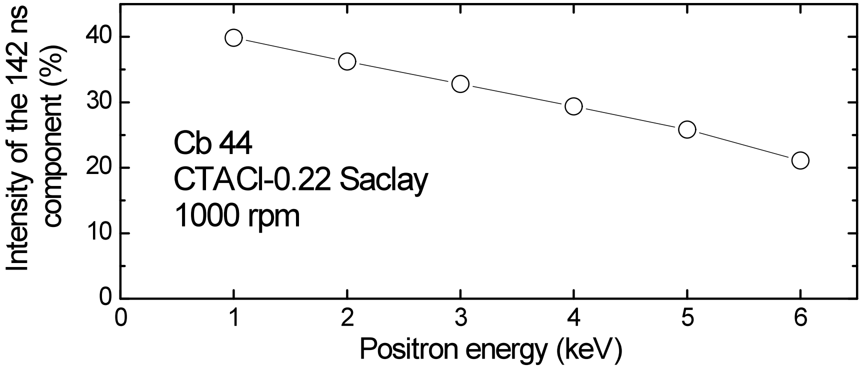


Data analysis : delayed fraction

$$f_d = \int_{50ns}^{300ns} V(t)dt \Big/ \int_{-50ns}^{300ns} V(t)dt$$

Yield of o-Ps : comparison CERN/UCR

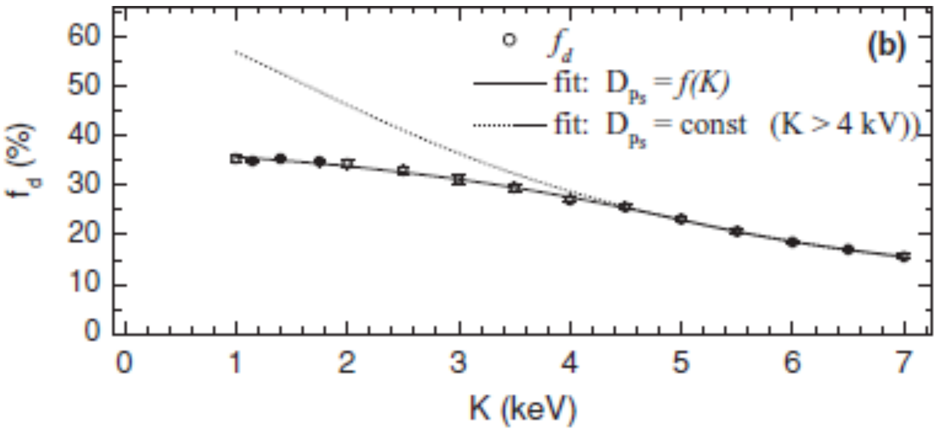
Measurement at CERN



~ 3.5 x 10^5 e^+ $cm^{-2}s^{-1}$

e^+ flux
x
~10^{11}

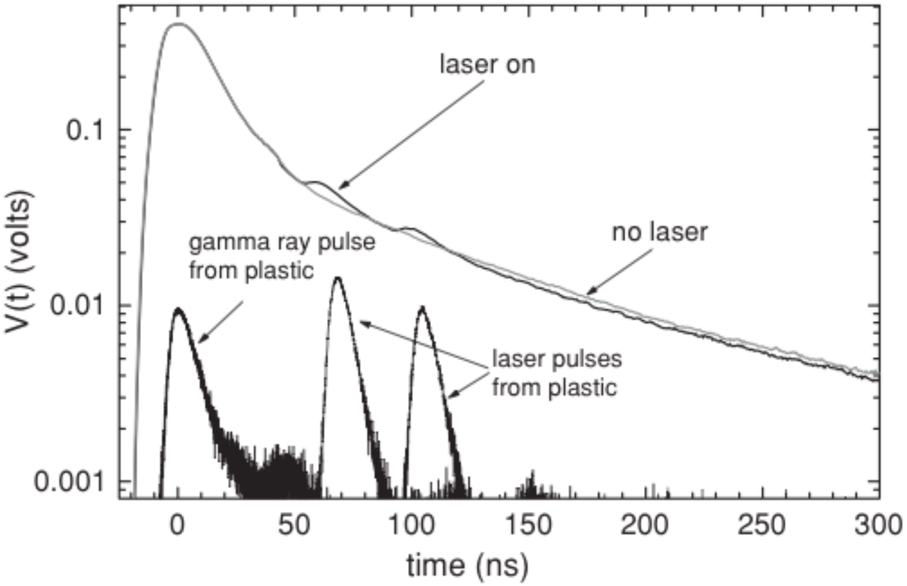
Measurement at UCR



~ 5.6 x 10^{16} e^+ $cm^{-2}s^{-1}$

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

Emission of o-Ps from single shot lifetime measurement



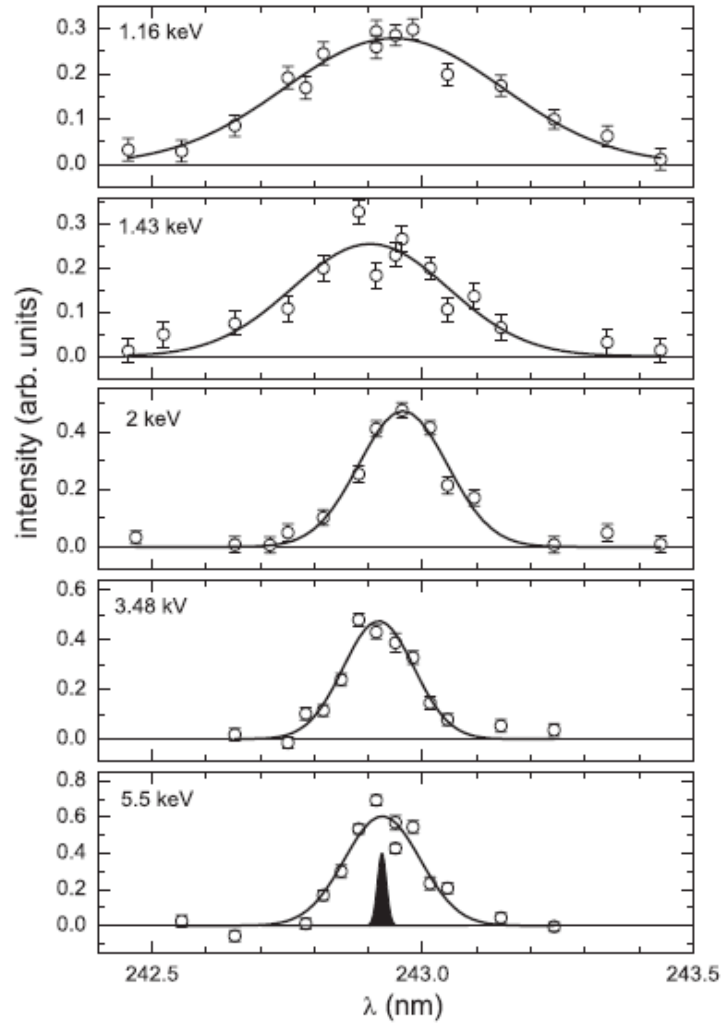
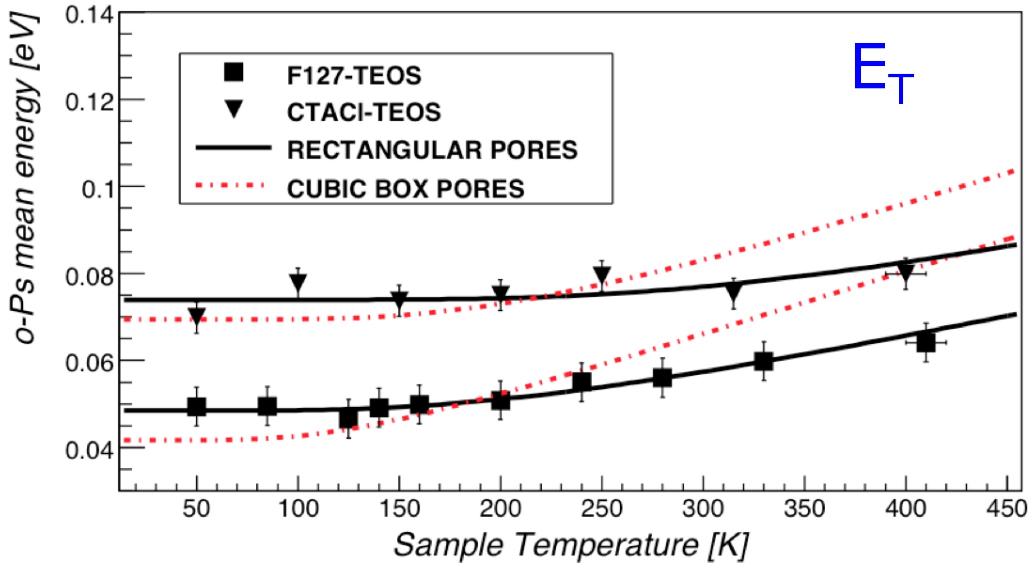
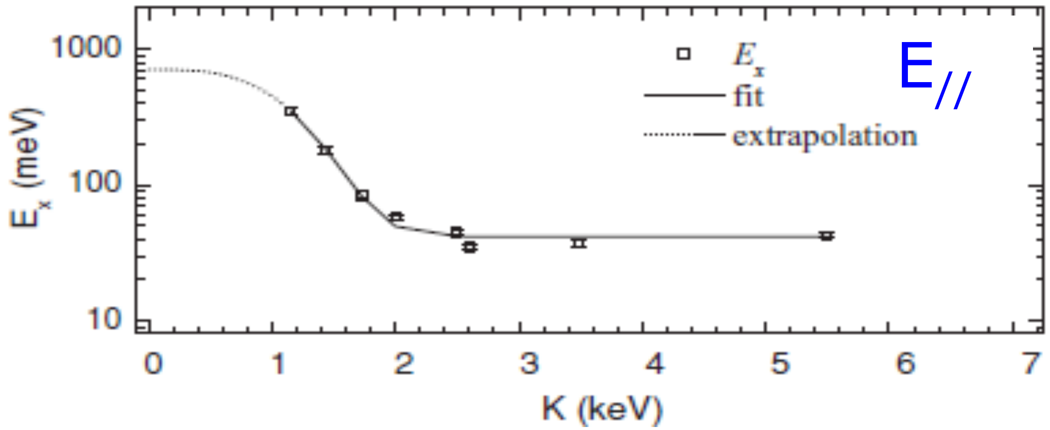


FIG. 9. Linewidth of the 1^3S-2^3P excitation of positronium

Energy of o-Ps : comparison CERN/UCR

P. Crivelli et al., accepted Phys. Rev. A (2010).





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

Short term perspectives

2010

- Linac stability improvement and energy measurement
- Slow e^+ beam line (with W moderator)
- Optimization of e^+ / Ps converter material
- Transfer of the RIKEN Penning trap at Saclay

  (ANR POSITRAP : IRFU-CSNSM-IPCMS UDS-RIKEN-SWANSEA)
- Participate to ELENA → enter the AD programme
- Formalize & enlarge the collaboration
- *Develop opportunities for Material Science applications*

2011

- RIKEN trap operational at Saclay
- Cryogenic moderation with solid Ne
- Trapping of e^+ from linac and Ps conversion

Longer term

Measurement of the H^- production
(or preferably $\overline{H}^+$ if accepted at CERN)

2011-2013	Build ELENA
2013	Study transfer to CERN
2014	Install at CERN

Efficiencies / Current Status

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

SELMA

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

1/4

Positron Storage

ε (trapping)	accum. time (s)	Ne+ stored
0.2	1200	2.52E+10

10^6 at RIKEN

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	$\sigma(\bar{p}+Ps \rightarrow \bar{H})$	$\sigma(\bar{H}+Ps \rightarrow \bar{H}^+)$	$N\bar{H}$	$N\bar{H}^+$
1.00E+07	1.00E-15	1.00E-16	8.82E+04	**7.78E+00**

every 20 minutes pulse

Improve/change Linac
Setup slow e^+ line (W & Ne)
Adapt trap to Linac
Measure Ps density
Find collaborators → atomic physics

“Requests”

Change status: R&D → Project
Join ELENA construction
Funding for next 2 steps:
- Neon moderation
- RIKEN trap installation (if ANR POSITRAP fails)

1 postdoc (Geant4 simulation)
½ PhD funding with CSNSM

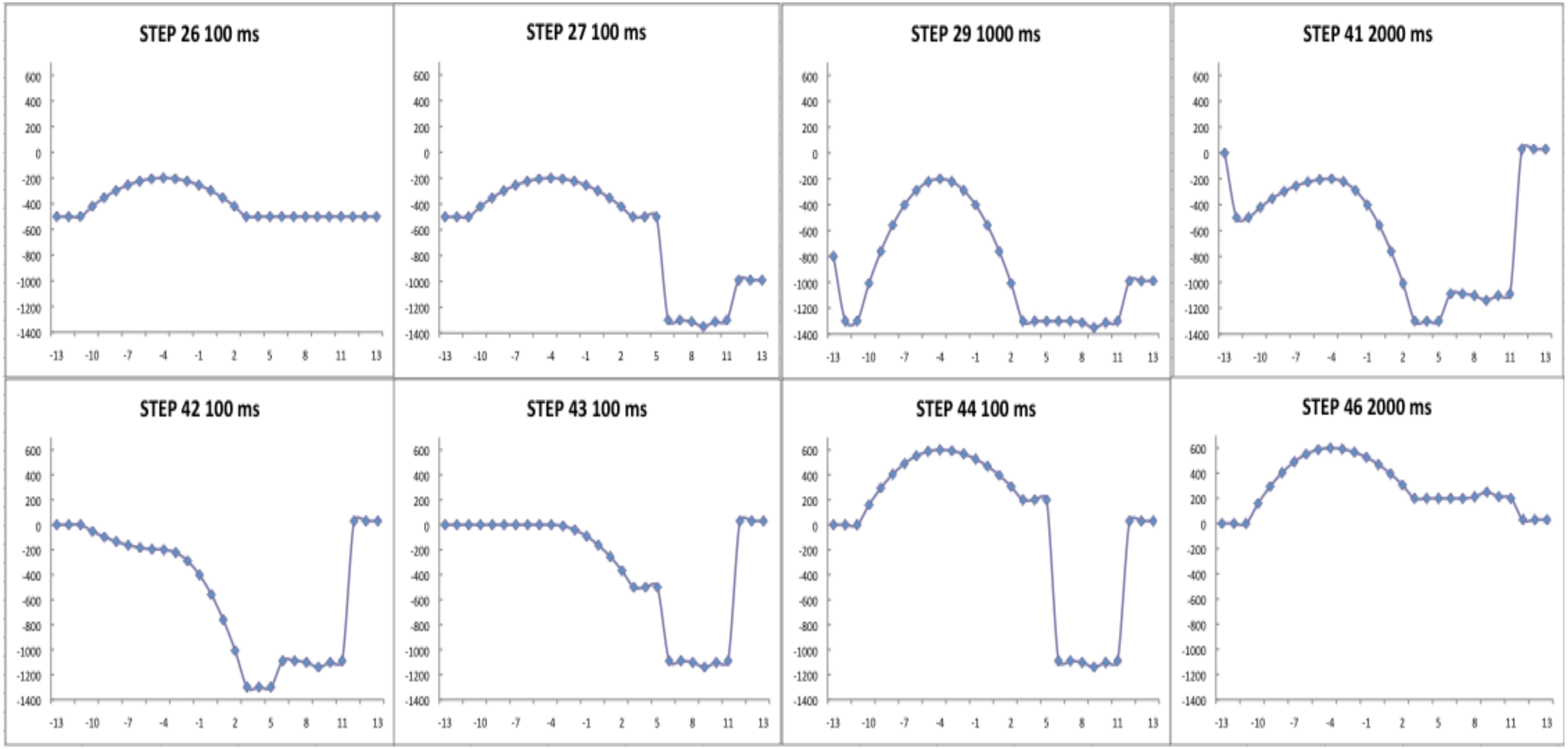
Backups

Competition : AEGIS

- Scheme "orthogonal" to ours:
  - We send keV $\bar{p}$ into a neutral Ps cloud "at rest"
  - They send Ps* onto charged $\bar{p}$ "at rest"
- We need lots of e^+ and keep efficiencies at high level all along!
- They must prepare very cold $\bar{p}$ (100 mK: is evaporative cooling applicable?)
- Etc…

- AEGIS is preparing for first data taking in 2011 on AD $\bar{p}$ beam line.

e^+ trapping: HV switching sequence



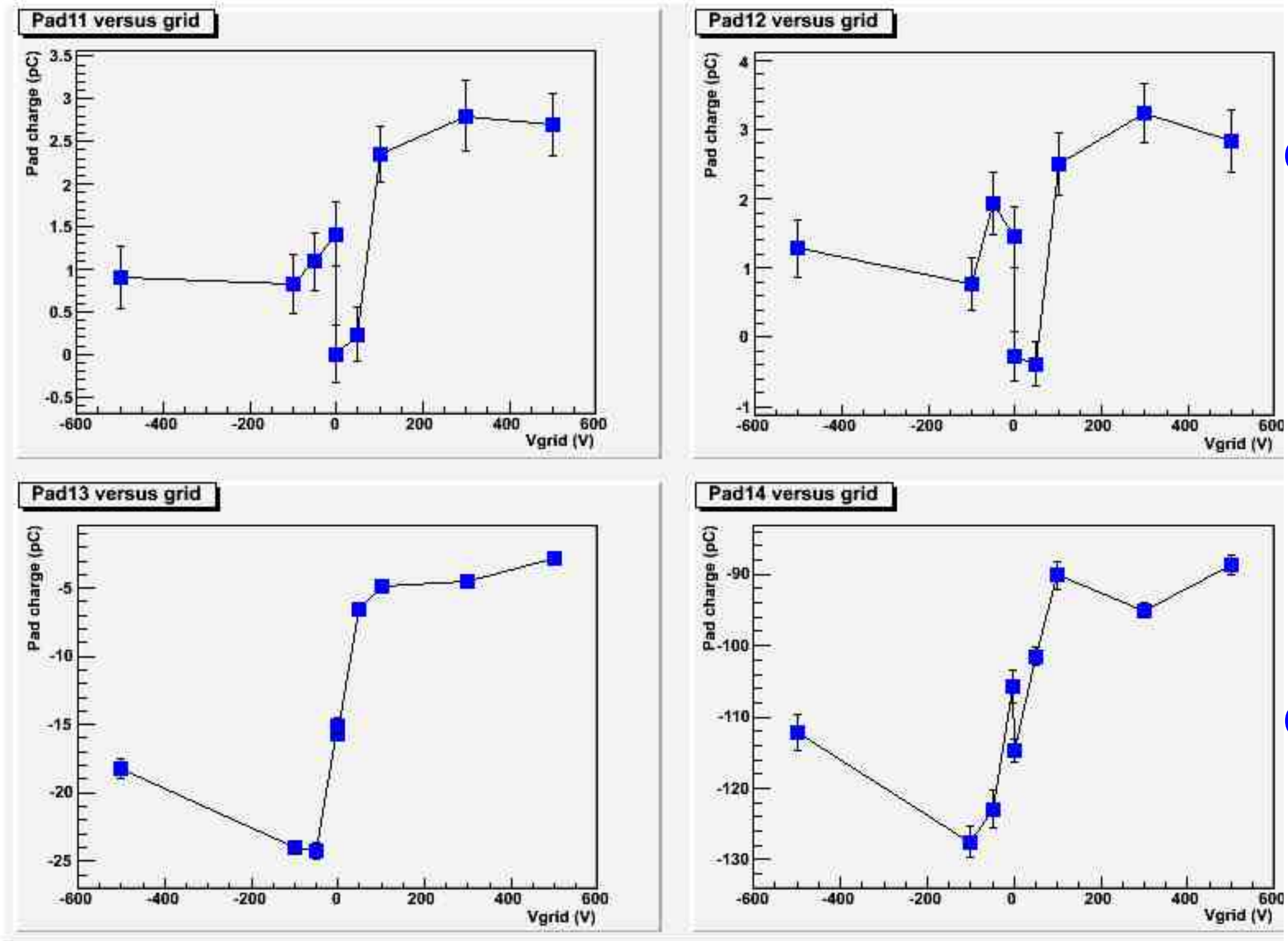
HV as a function of electrode number

Using the Grid

Secondary e^- are recovered for $HV_{GRID} < 0$

Study of charge vs HV_{GRID} gives information on e^- background and e^+ signal

HV<0 11’
HV>0 26’



e^+

e-

Production of 10^{12} Ps/cm^2

$e^+ \rightarrow$ Ps converter :   eff. > 30%
tube geometry to keep density
(*SiO_2 reflects Ps 100%*)

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

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

to be tested with e^+ pulses from trap

Dump 10^{11} e^+ in 1 mm^2 section
in $< \tau_{Ps}$

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

RIKEN
Tokyo
Saclay

Small size linacs to fit AD

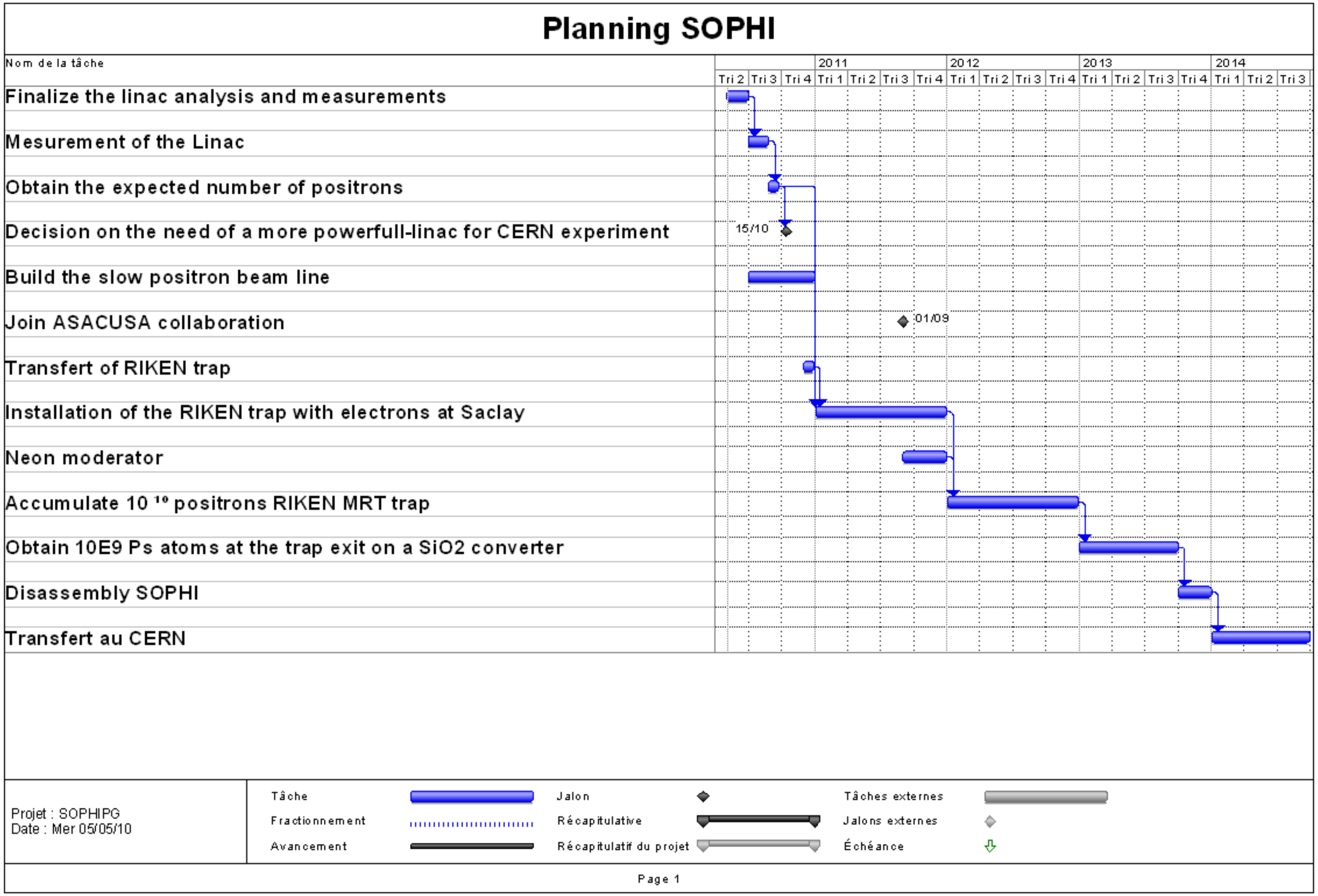
10 MeV/0.15 mA
<E>~1.1 MeV,   8 10^{11} s^{-1}

5.5 MeV/0.15 mA
<E>~0.8 MeV, 2 10^{11} s^{-1}

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

Linac
10^8 slow e^+/s

Saclay



Planning SOPHI
Nom de la tâche
2011
2012
2013
2014
Tri 2 Tri 3 Tri 4 Tri 1 Tri 2 Tri 3 Tri 4 Tri 1 Tri 2 Tri 3 Tri 4 Tri 1 Tri 2 Tri 3 Tri 4 Tri 1 Tri 2 Tri 3
Finalize the linac analysis and measurements
Mesurement of the Linac
Obtain the expected number of positrons
Decision on the need of a more powerfull-linac for CERN experiment
15/10
Build the slow positron beam line
Join ASACUSA collaboration
01/09
Transfert of RIKEN trap
Installation of the RIKEN trap with electrons at Saclay
Neon moderator
Accumulate 10 ¹⁰ positrons RIKEN MRT trap
Obtain 10E9 Ps atoms at the trap exit on a SiO2 converter
Disassembly SOPHI
Transfert au CERN
Projet : SOPHIPG
Date : Mer 05/05/10
Tâche
Fractionnement
Avancement
Jalon
Récapitulative
Récapitulatif du projet
Tâches externes
Jalons externes
Échéance
Page 1