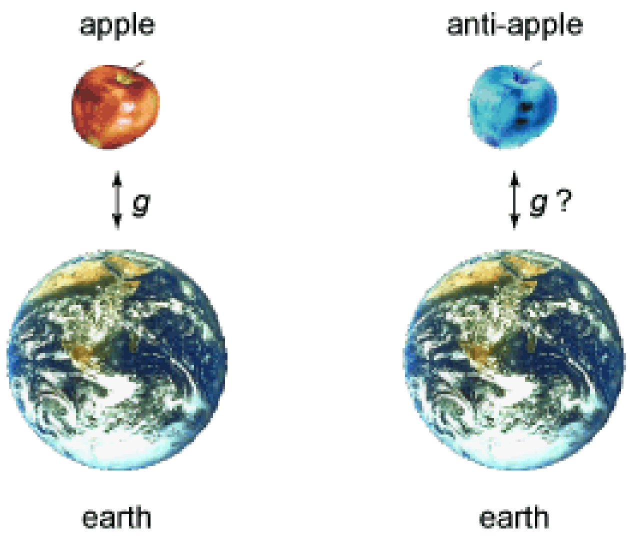
GBAR

Gravitational Behaviour of Antihydrogen at Rest

CERN AD-7
Approved 30/05/2012



- **Motivation**
- **Principle and goal of the experiment**
- **Experimental techniques**
- **Schedule and perspectives**

Outline

- **Motivation**
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Motivation

<u>A direct test</u> of the Equivalence Principle with antimatter

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

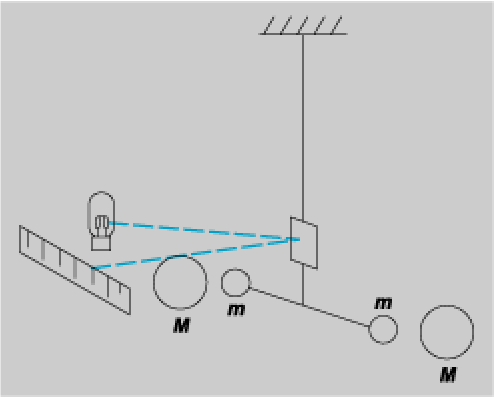
Inertial mass = gravitational mass

Tested to a very high precision with many materials

Weak Equivalence Principle (torsion pendulum)

$$\left(\Delta a / a\right)_{\mathrm{Be/Ti}} = \left(0.3 \pm 1.8\right) \mathrm{x} 10^{-13}$$

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



Strong Equivalence Principle (Lunar Laser Ranging)

$$\left(\Delta a / a\right)_{\mathrm{Earth/Moon}} = \left(-1.0 \pm 1.4\right) \mathrm{x} 10^{-13}$$

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

INDIRECT LIMITS
Theory and Experiments

Discussion and experimental constraints :

M. Nieto and T. Goldman, Phys. Rep. 205 (1991) 221

Morrison argument(1958) :

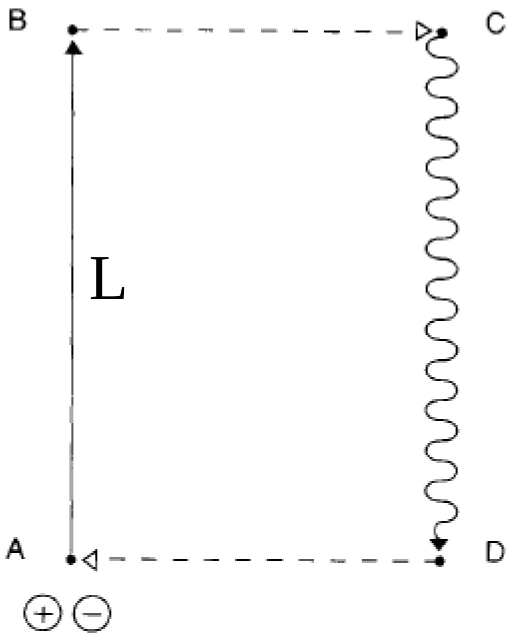
antigravity in General relativity → violation of Energy conservation

$$\text{if } m_G(+) = -m_G(-) :$$

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

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

$$E_D = E_A + 2m_I gL$$



→ *not excluded ? see :*

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

G. Chardin, Hyperfine Interactions 109 (1997) 83

INDIRECT LIMITS
Theory and Experiments

→ introduce new gravi-vector and scalar fields not coupled to γ
to distinguish m_G et $\overline{m}_G$

(seminal article: J. Scherk, Phys. Lett. B (1979) 265)

Field	Scalar	Vector
matter	attractive	repulsive
antimatter	attractive	attractive

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

Tests with matter only constrain |b-a|

INDIRECT LIMITS
Theory and Experiments

- Antimatter content of ordinary matter («Schiff argument»)

$$\left|\frac{g-\bar{g}}{g}\right| \sim \left|\frac{g-g_{\Delta Erad}}{g}\right| \qquad \Downarrow$$

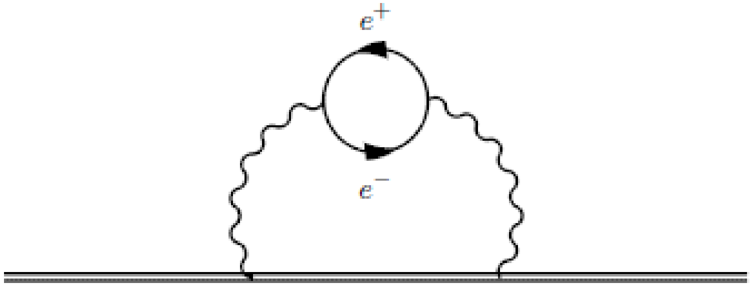


FIG. 2: Loop contribution to the electrostatic self-energy of the nucleus

Scenario	**Argument**	**Bound on** $\lvert g_H - g_{\bar{H}}\rvert / g_H$
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	$\lesssim 10^{-7}$

Exact scalar/vector cancellation impossible
(D.S.M.Alves et al SU-ITP-09/36)

INDIRECT LIMITS
Theory and Experiments

$\eta^{\pm}$ and $\Phi^{\pm}$ measurements as a function of time by CPLEAR

K^0-$\overline{K}^0$ oscillations depend upon $\delta m_{eff} = M_{K^0}(g-\overline{g})\frac{U}{c^2}\exp(-r/r_I)f(I)$

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

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

	Source	Spin 0	Spin 1	Spin 2
Potentiel variation with time →	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}
Use of an absolute potential →	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}

INDIRECT LIMITS
Theory and Experiments

Cyclotron frequency measururement of p (H^-) et $\bar{p}$ in the same magnetic field

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

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

$$\omega = qB/2\pi m + \alpha U/c^2 \quad |\omega - \bar{\omega}|/\omega = (9 \pm 9) x10^{-11} \rightarrow |g - \bar{g}|/g \leq 10^{-6}$$

A direct limit ???

Arrival time of one (? : 90 % CL) neutrino and18 antineutrinos from SN1987a (*S. Paksava et al. Phys Rev D 39 (1989) 1761*)

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

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

INDIRECT LIMITS
Theory and Experiments

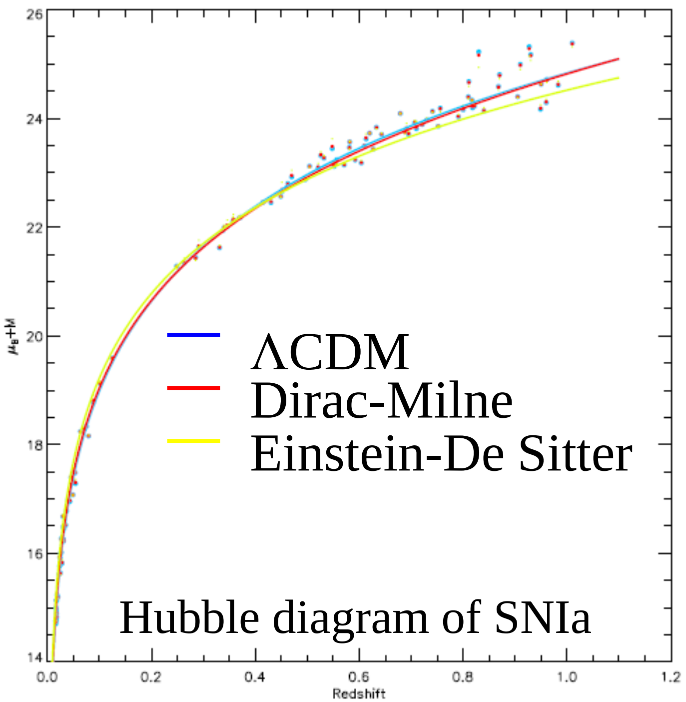
Cosmology :

-Matter antimatter asymmetry in the Universe

-Need of dark energy + dark matter + inflation

Is there a repulsive antimatter-matter interaction ???

Paris XI thesis - A. Benoît-Lévy
director G. Chardin (2009)



→ **Dirac Milne Universe**

Attempt to build a cosmology with

- matter antimatter symmetry content
- and a mechanism to separate matter and antimatter

SNIa ok

CMB ~ ok except at small l

Primordial nucleosynthesis ~ imperfect (excess of ^{3}He)

But no BAO acoustic peak at ~ 100 Mpc/h

Past Attempts and proposals

- **positrons**: *proposed by W. Fairbank*

tests with electrons: F. Witteborn and W. Fairbank, Phys Rev Lett 19 (1967) 1049

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

-Very hard : $m_e g / e = 5.6x10^{-11} V / m$ (one elementary charge 5 m away)

- **antineutrons**: hard to slow down

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

- **positronium**: short life time (142 ns) if n = 1

possibility if n>>1 $(\tau \simeq (n / 25)^{5.236} x\, 2.25 ms)$

Pbs: cooling, polarisability, ionisation…

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

To conclude :

All theoretical arguments have assumptions (CPT…)

No direct measurement available yet

Outline

- Motivation
- **Principle and goal of the experiment**
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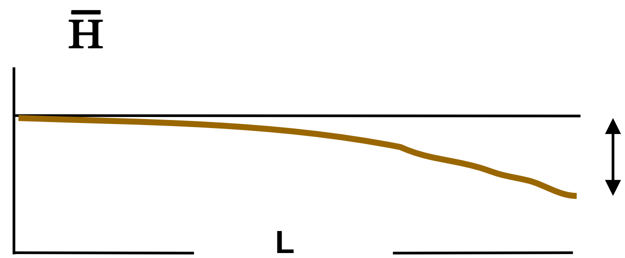
Next simplest system: $\bar{\mathrm{H}}$
Two experiments in preparation

Principle : parabolic flight

AEGIS : deflectometer
GBAR : duration of free fall



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

$$t = \sqrt{\frac{2h}{g}}$$

***AEGIS : cold antihydrogen** T($\bar{H}$) ~ 100 mK ~ 10 μeV*

- L = 1 m & v_h = 500 m/s → h = 20 μm

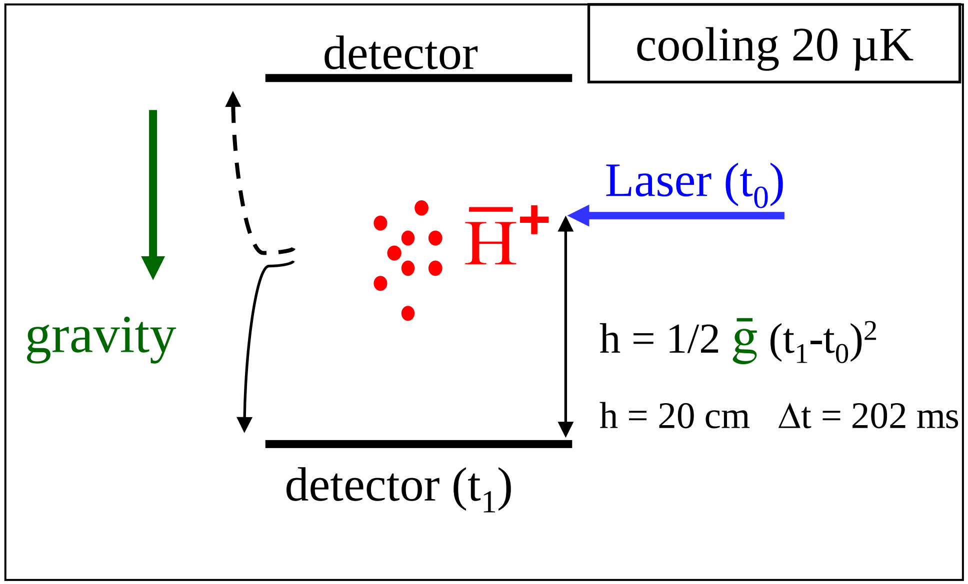
GBAR : produce first cold $\bar{\mathrm{H}}^+$ → very slow $\bar{\mathrm{H}}$ T($\bar{\mathrm{H}}$) ~ 10 μK ~ 1 neV

- L = 0.1 m & v_h = 0.5 m/s → h = 20 cm

Goal : phase 1 : $\Delta\bar{g}/\bar{g}$ ~ 1% ; phase 2 : $\Delta\bar{g}/\bar{g} < 10^{-3}$

Gbar : use $\bar{H}^+$ to get $\bar{H}$ atoms

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

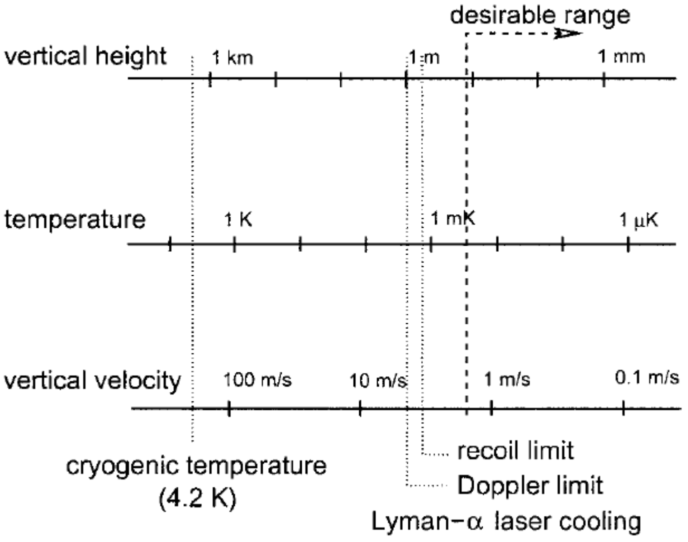


J.Walz & T. Hänsch,
General Relativity and Gravitation, **36** (2004) 561.

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

Relative Precision on $\bar{g}$:

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



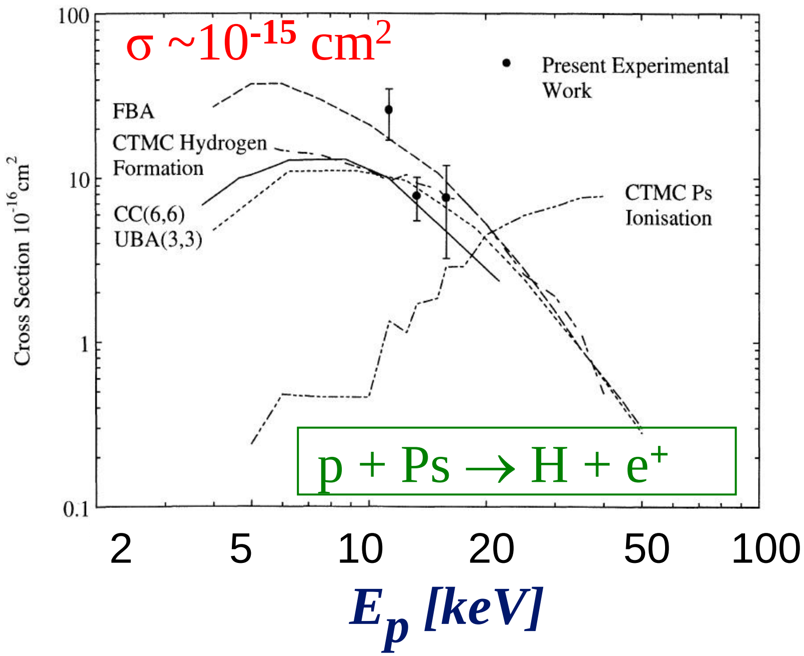
$\bar{H}^+$ production

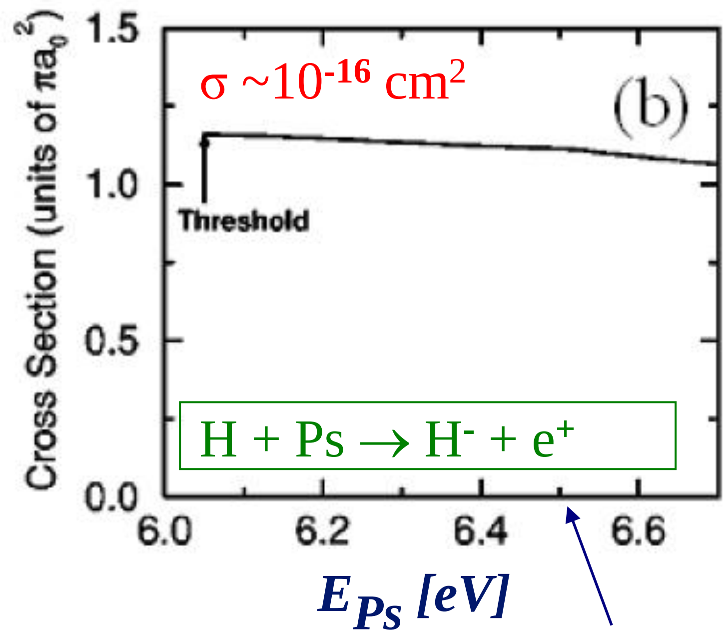
$$\bar{p} + Ps \rightarrow \bar{H} + e^-$$
$$\bar{H} + Ps \rightarrow \bar{H}^+ + e^-$$

Positronium
$Ps = e^+e^-$

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

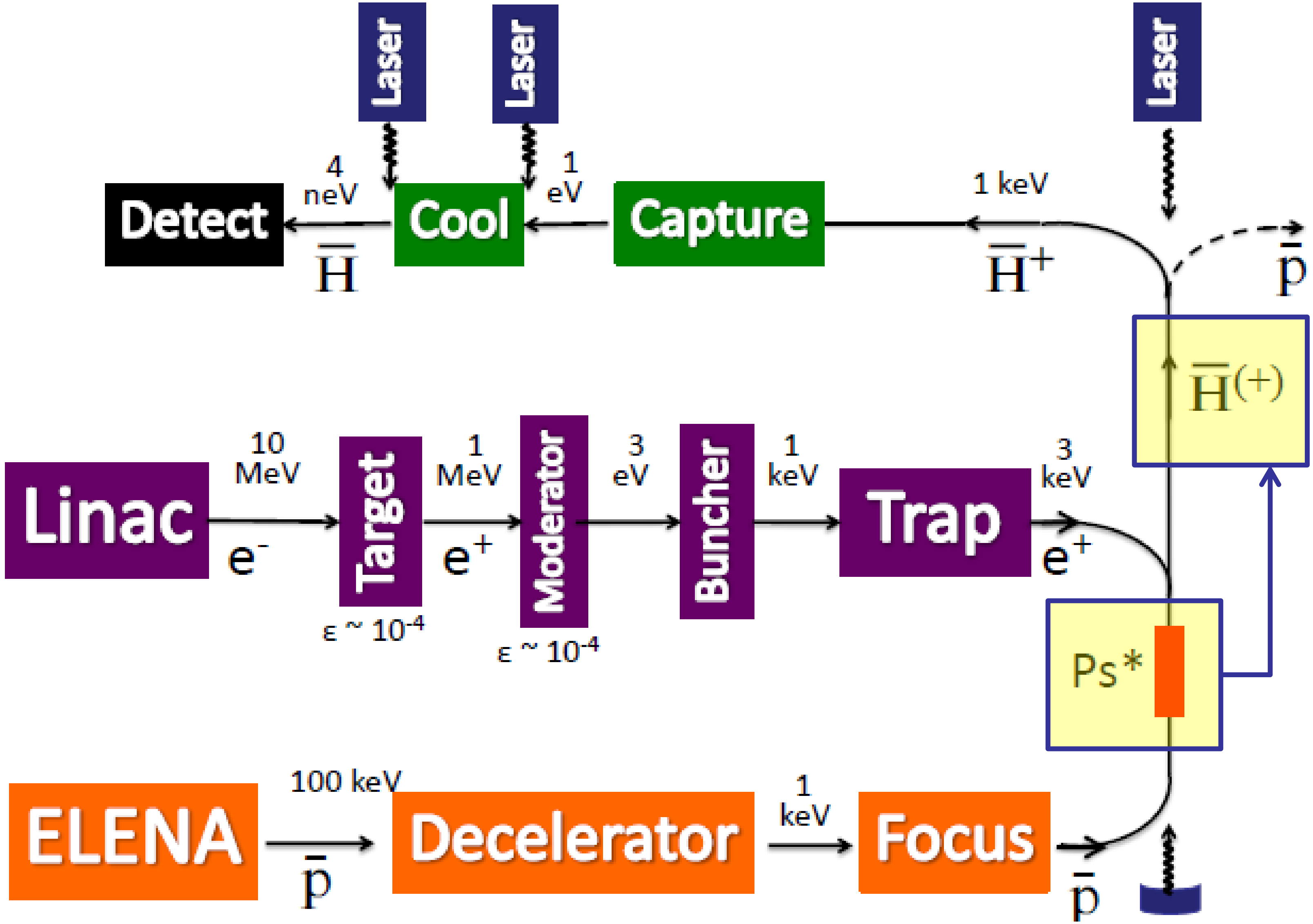
H.R.J. Walters and C. Starett, Phys. Stat. Sol. **C**, 1-8 (2007)





E_H = 6 keV in Ps frame

Synoptic Scheme



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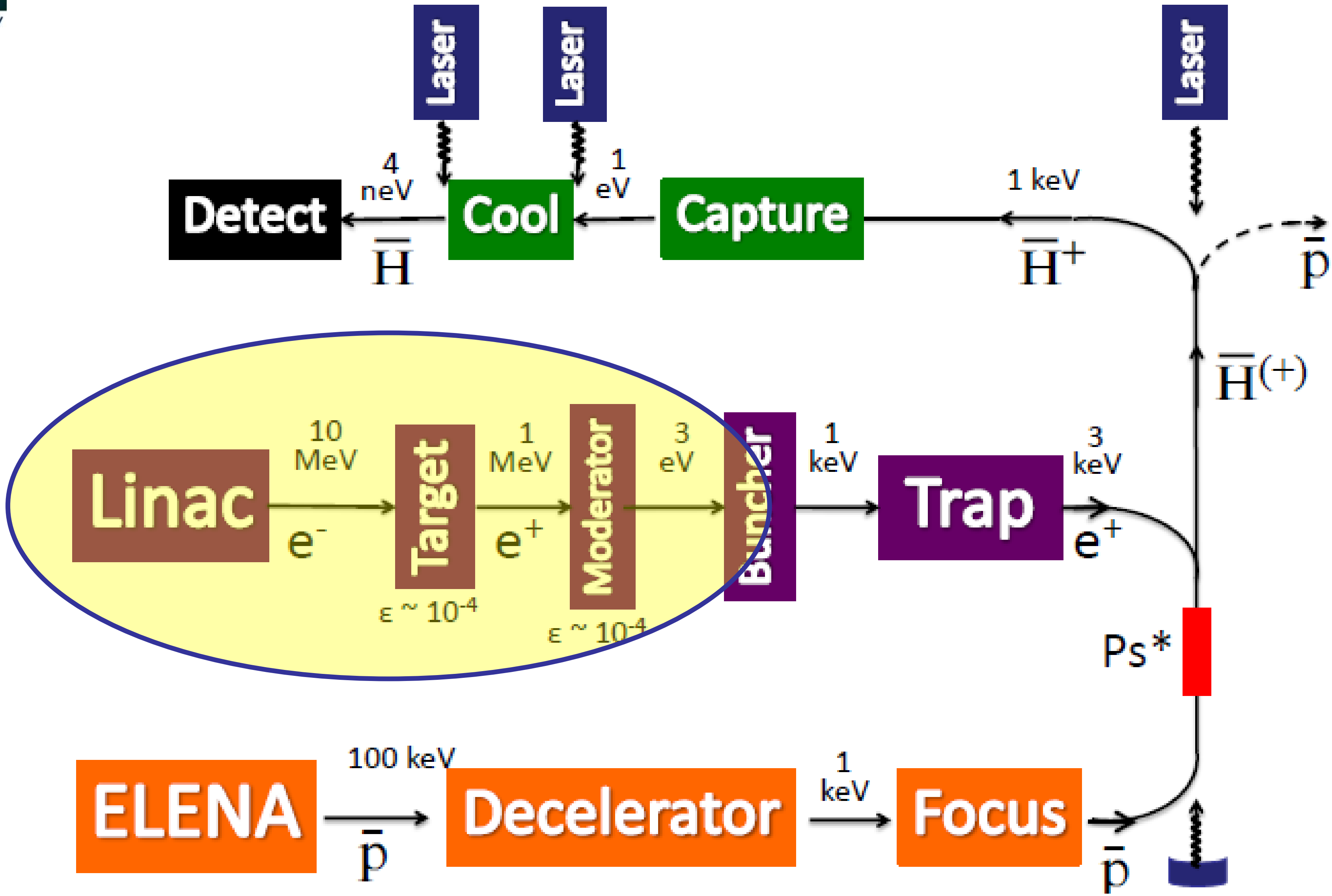
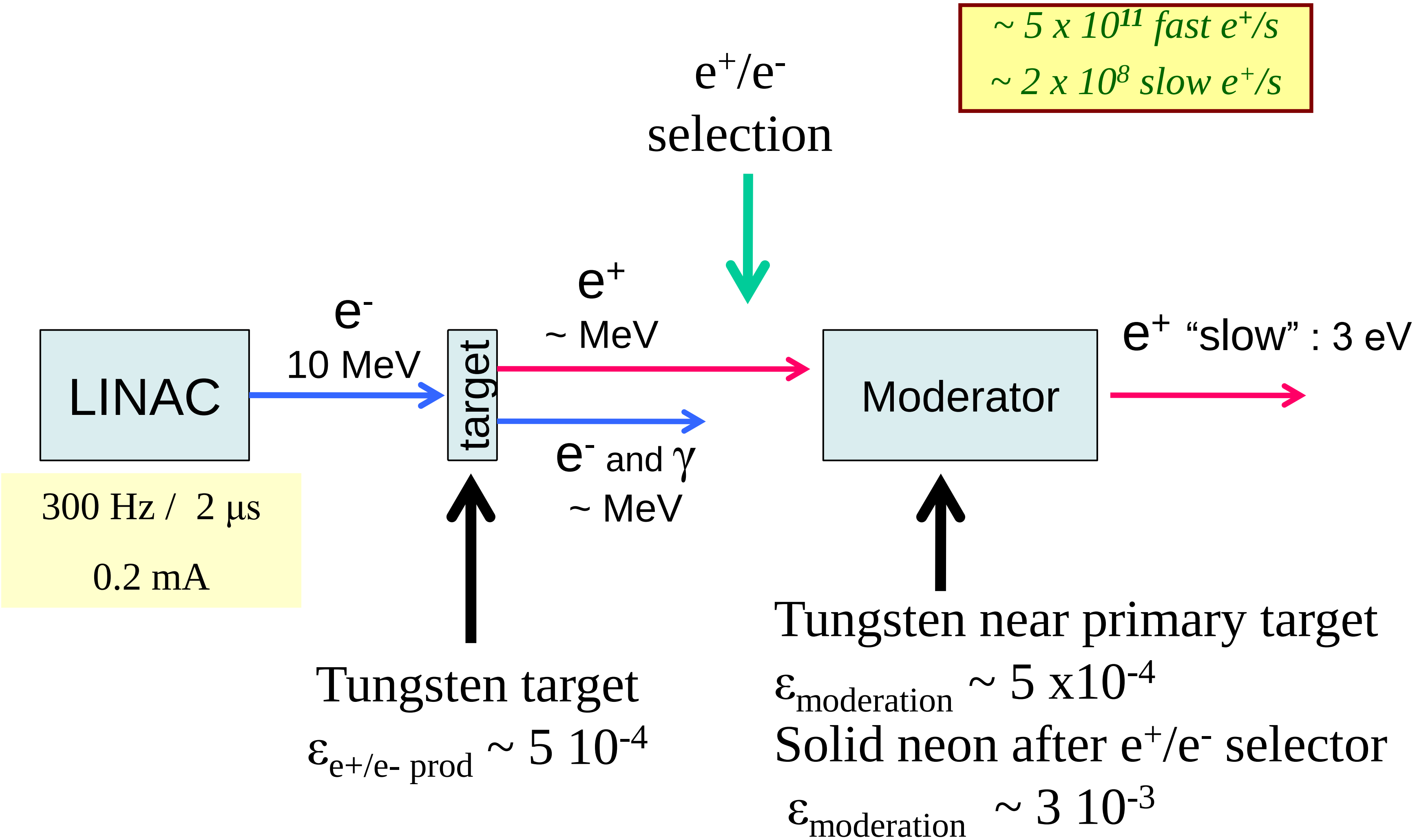
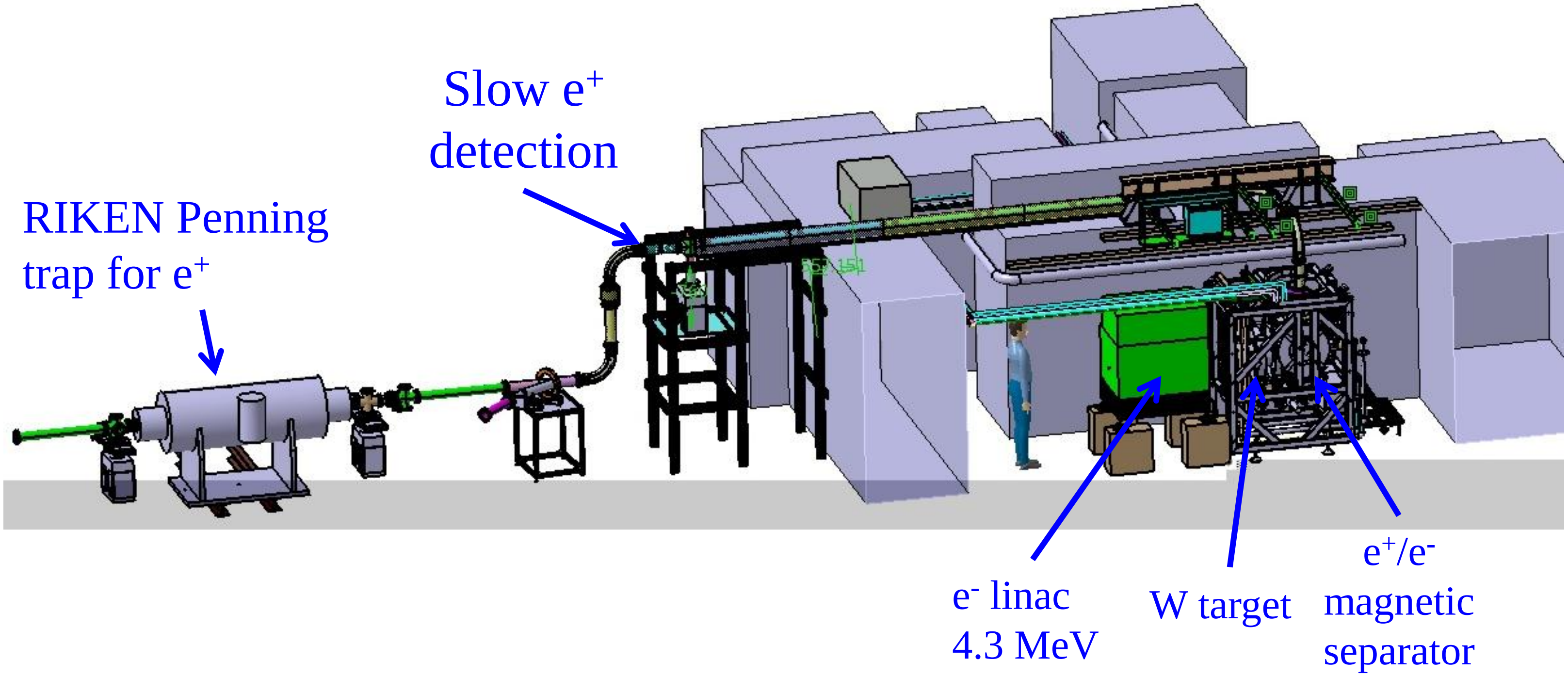


High intensity slow positrons source



Prototype at Saclay

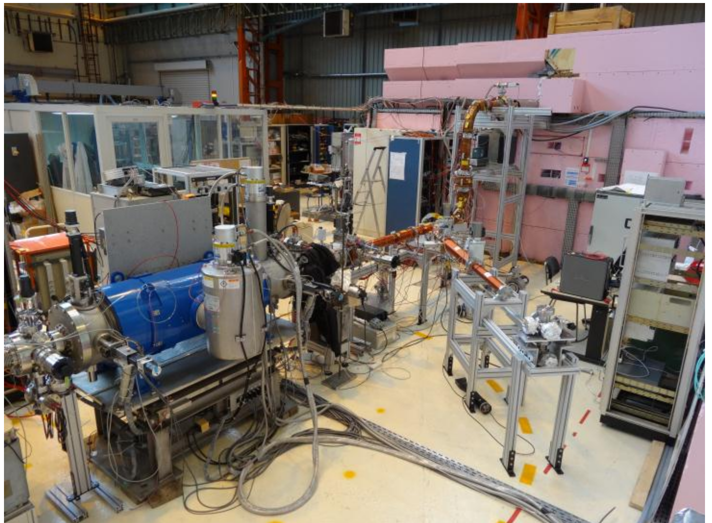


Present slow e^+ rate : ~ 4 10^6 s^{-1}

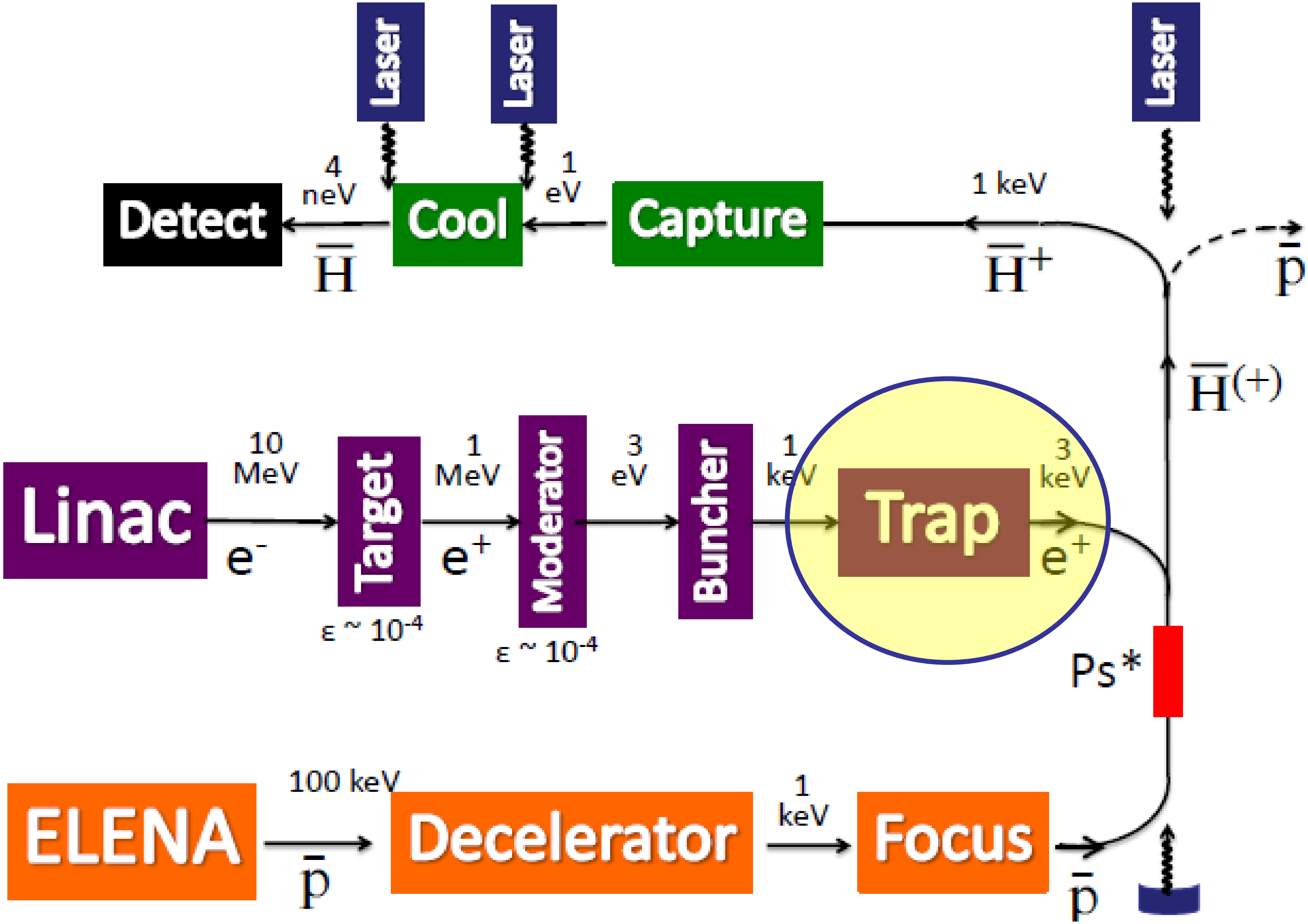
Extrap. to 10 MeV : ~ 5 10^7 s^{-1}

Target value : ~ 3 10^8 s^{-1}

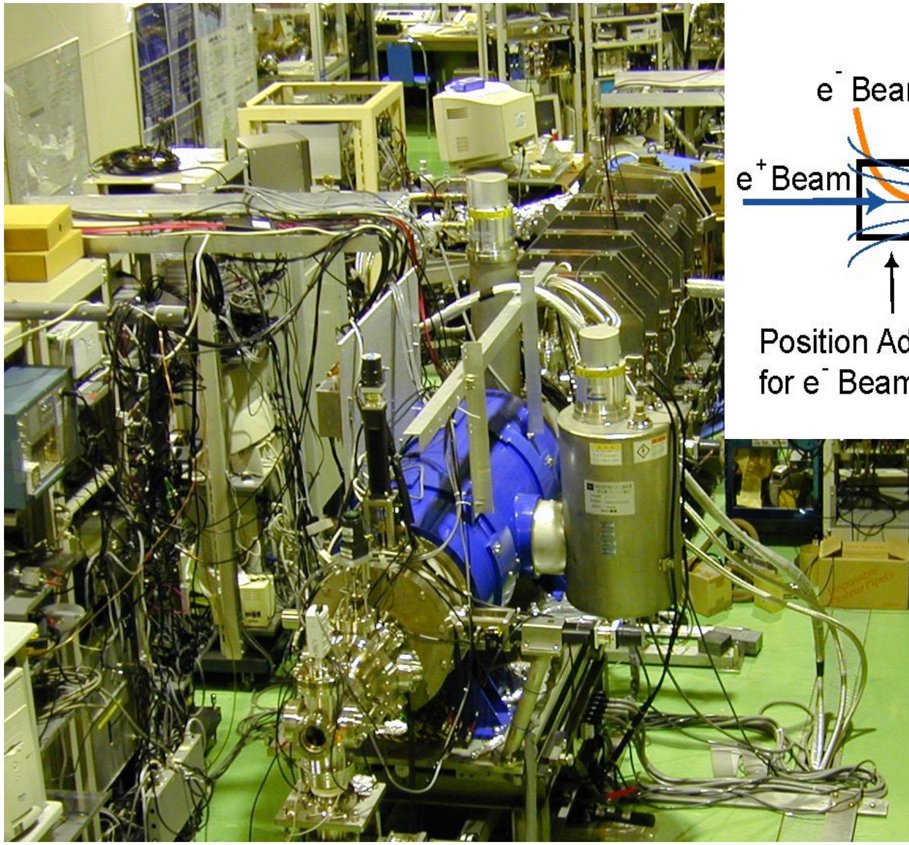
(higher energy, frequency, moderation)

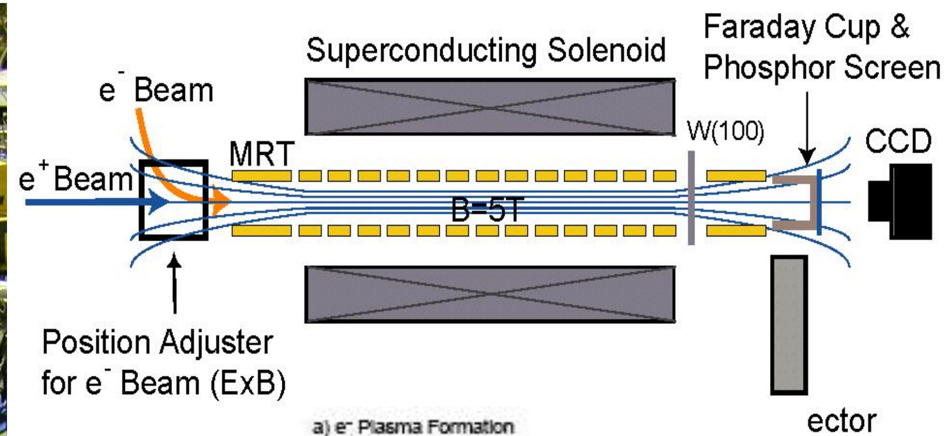


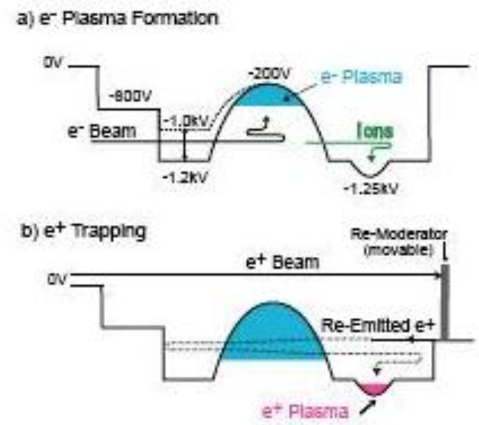
Synoptic Scheme



RIKEN Multi Ring Trap







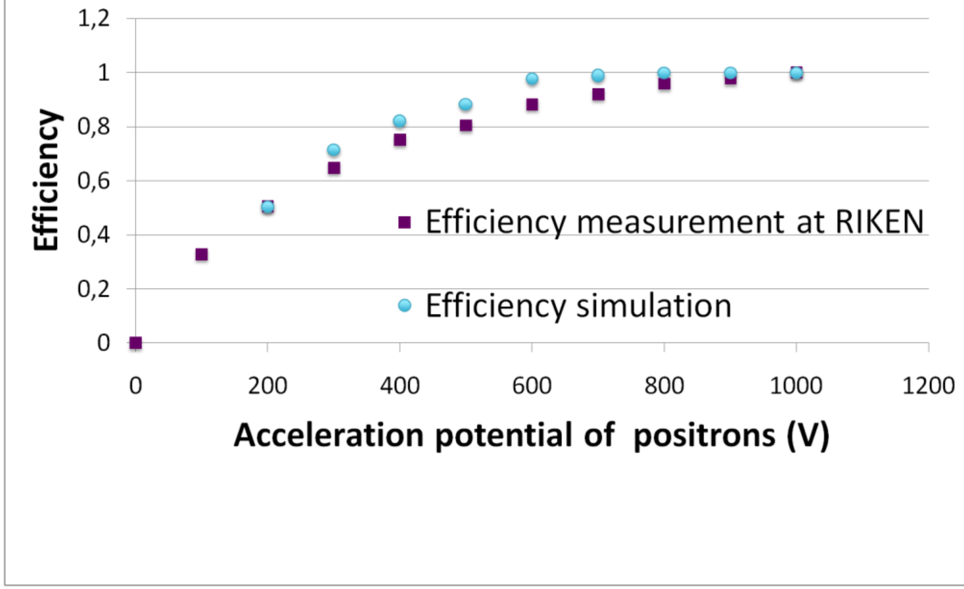
- Cooling by e^- plasma, 10^6 e^+ stored, trapping efficiency $\varepsilon_{trapping} \sim 1\%$

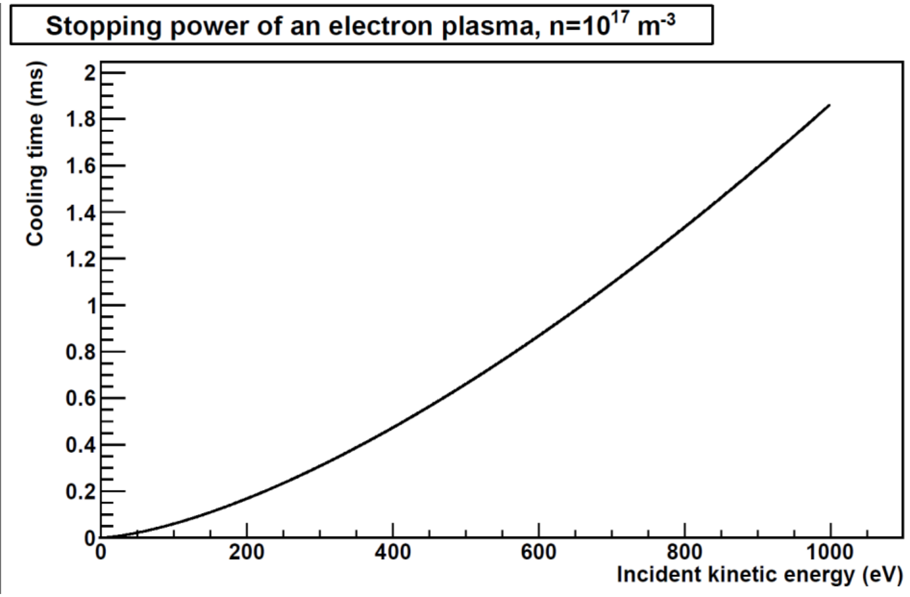
N. Oshima et al., Phys. Rev. Lett. **93 19** (2004)

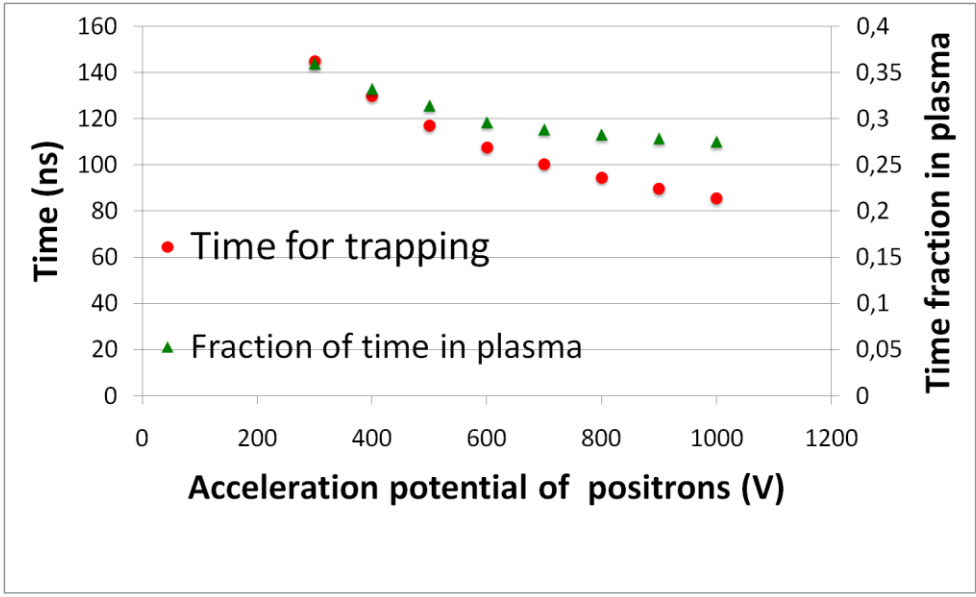
- **Trap now at Saclay: start test accumulation with pulsed e^+**

  $\varepsilon_{trapping} \approx 50\%$ expected, few 10^{10} e^+ needed

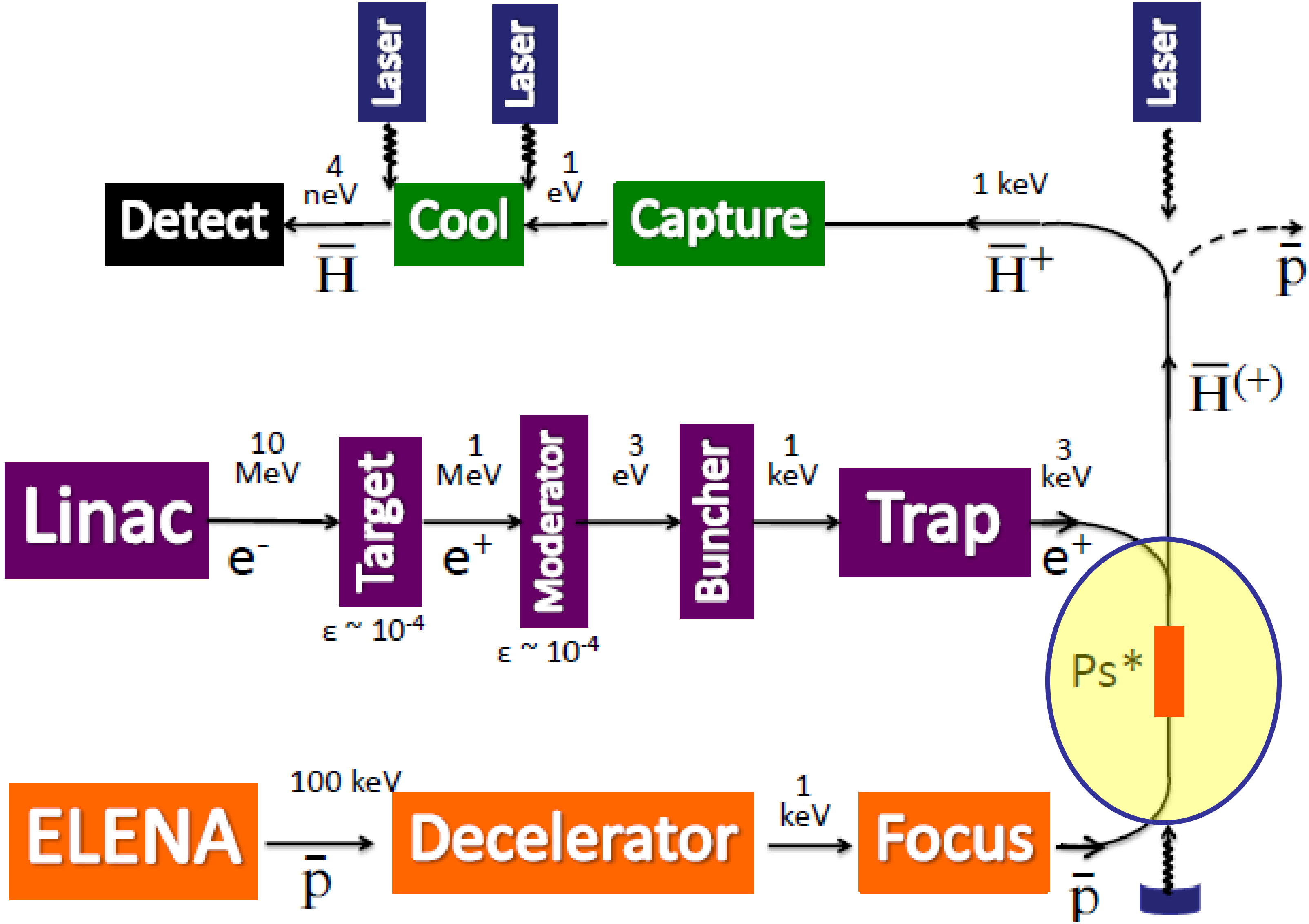
Trapping pulsed e+ beam







Synoptic Scheme



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

Positronium target is produced with a porous SiO_2 converter:

dump few 10^{10} e^++in less than ~ 140 ns onto converter

e^+ converter → Ps

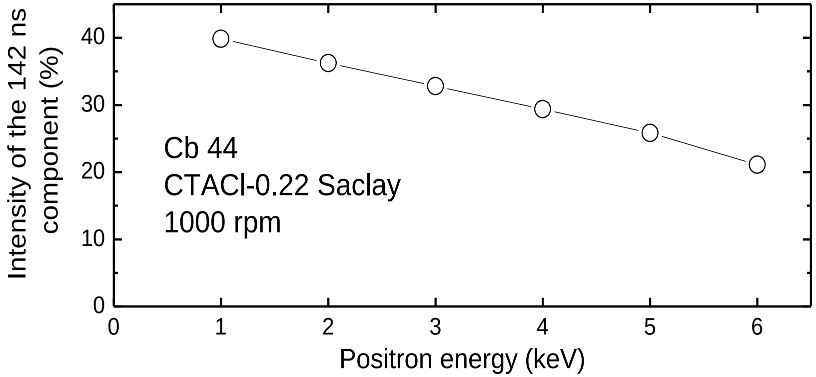
Experiments at CERN: Irfu/ETHZ (e^+ beam)
and at UCR Cassidy et al. (trap)

- Ps in fundamental state
- Ec ~40 meV
- **Efficiency of Ps production in vacuum > 30%**

Yield of o-Ps comparison CERN/UCR

Measurement at CERN

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



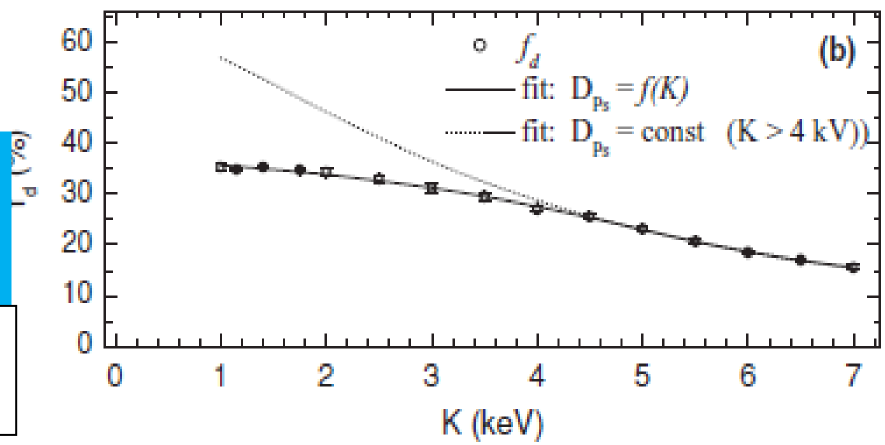
~ 3.5 x 10^5 e^+ $cm^{-2}s^{-1}$

e^+ flux x ~10^{11}

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

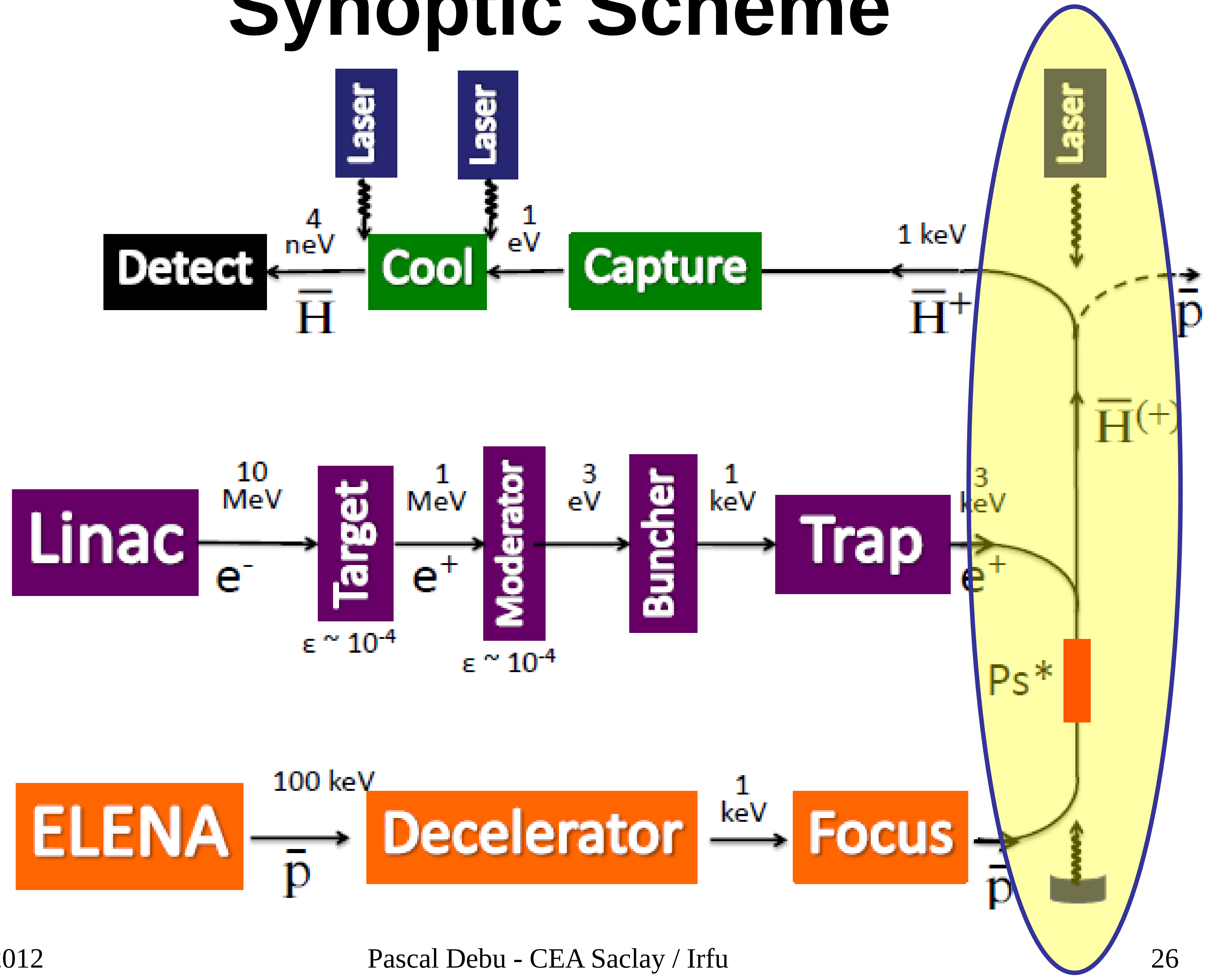
Measurement at UCR

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



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

Synoptic Scheme



$\bar{H}^+$ production

Linac
$3\ 10^8$ slow e^+/s

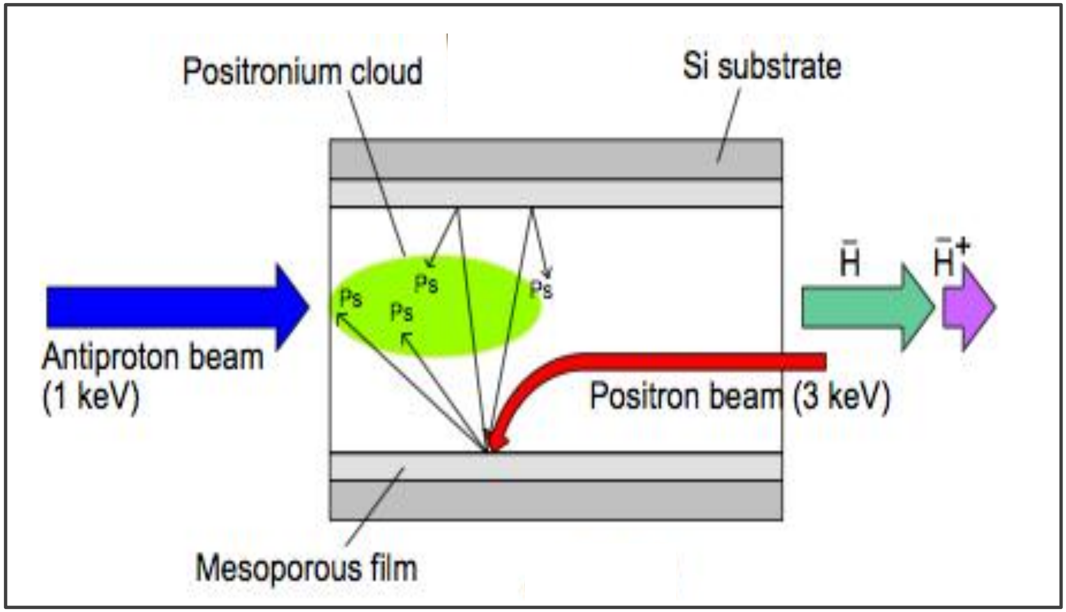
e^+ trap
accumulate ~ 2 10^{10} e^+
every $\bar{p}$ burst ~ 2'

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

RIKEN test :
1.3 x10^{10} e^- / 75 ns

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

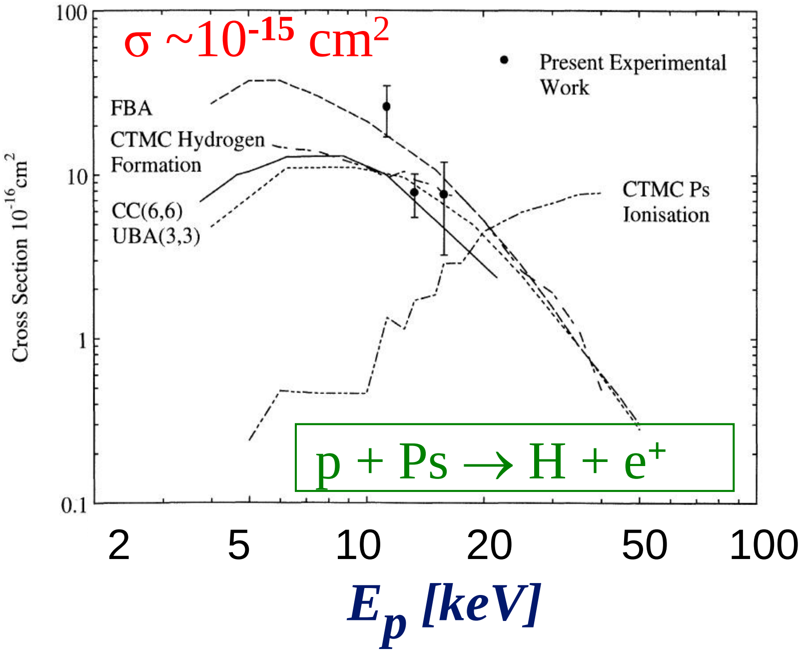
closed geometry to keep density
(*SiO_2 reflects Ps*)

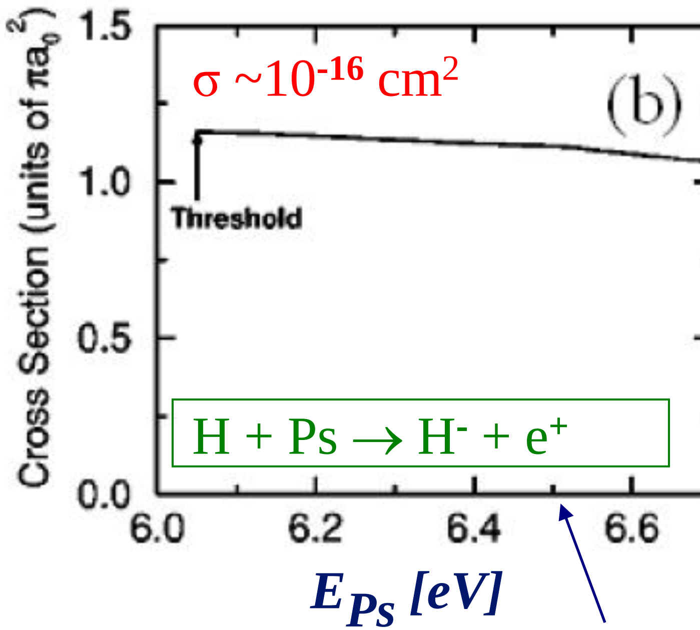


Cross-sections on Ps

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

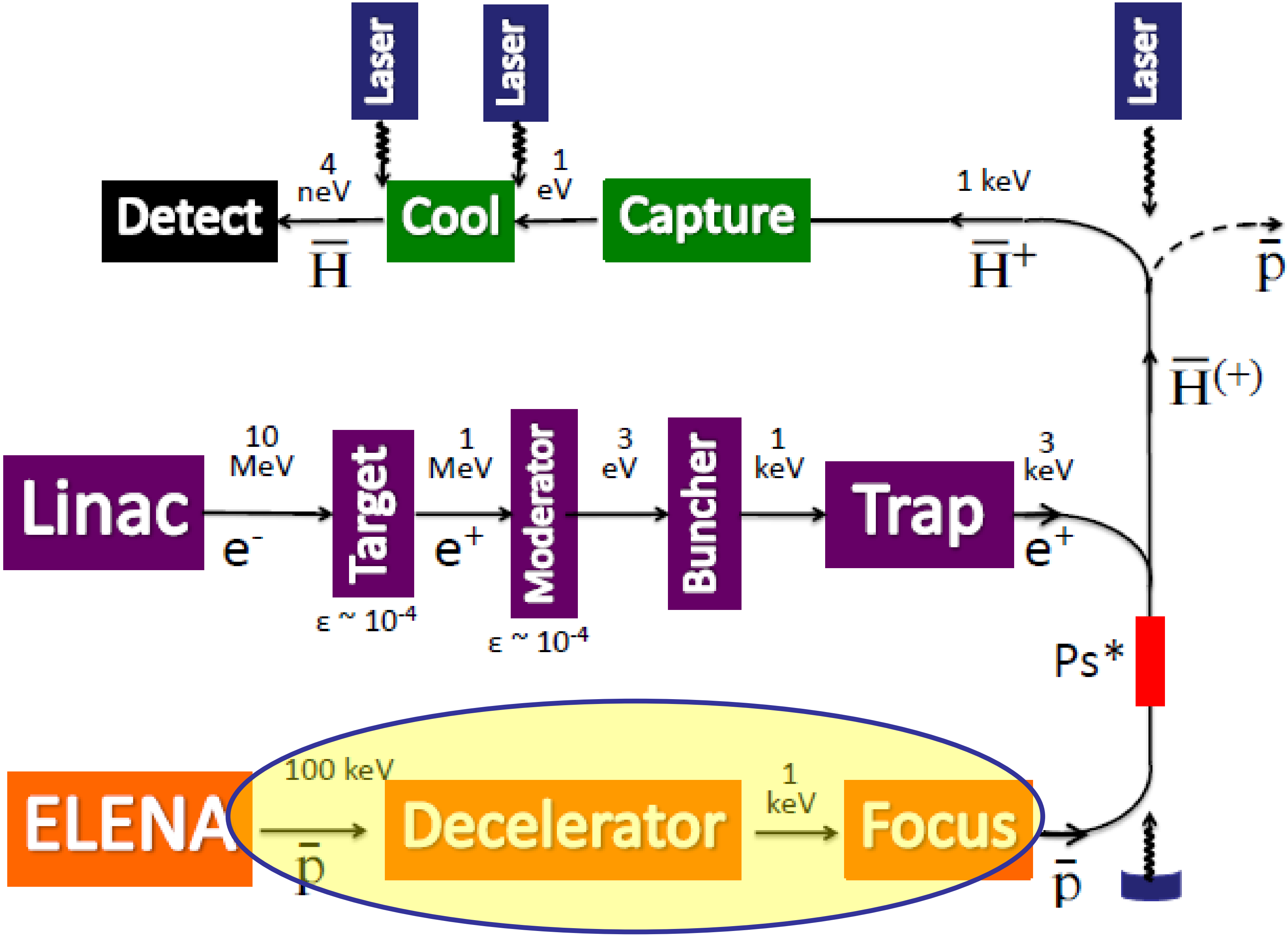
AD/Elena Facility CERN → $6\ 10^6\ \bar{p}$

$2\times10^{10}\ e^+$ from trap → 10^{12} Ps/cm²

} → $4\ 10^2\ \bar{H}$; $1\ \bar{H}^+$

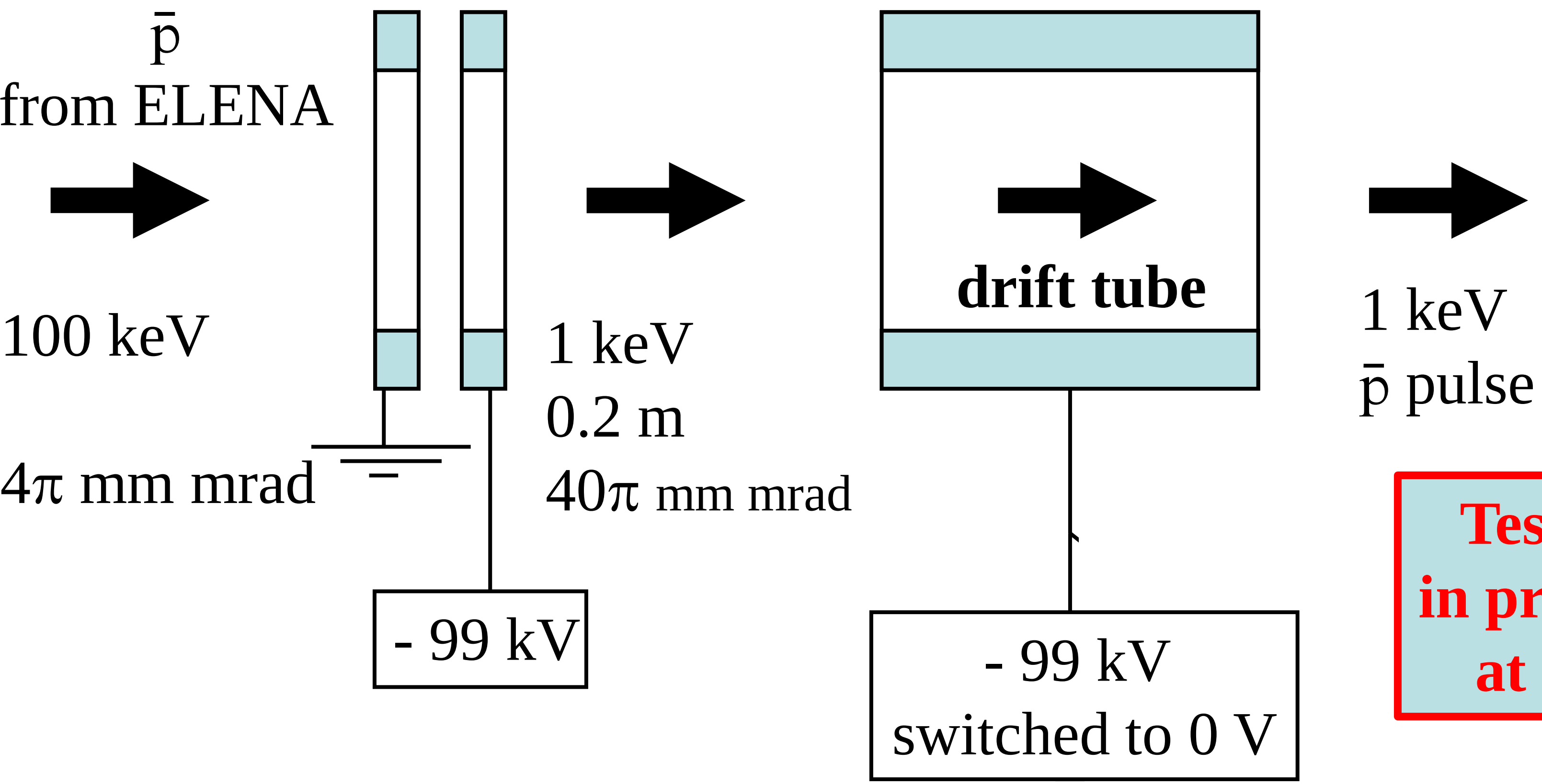
if fraction of Ps excited to n=3 expect × > 100

Synoptic Scheme



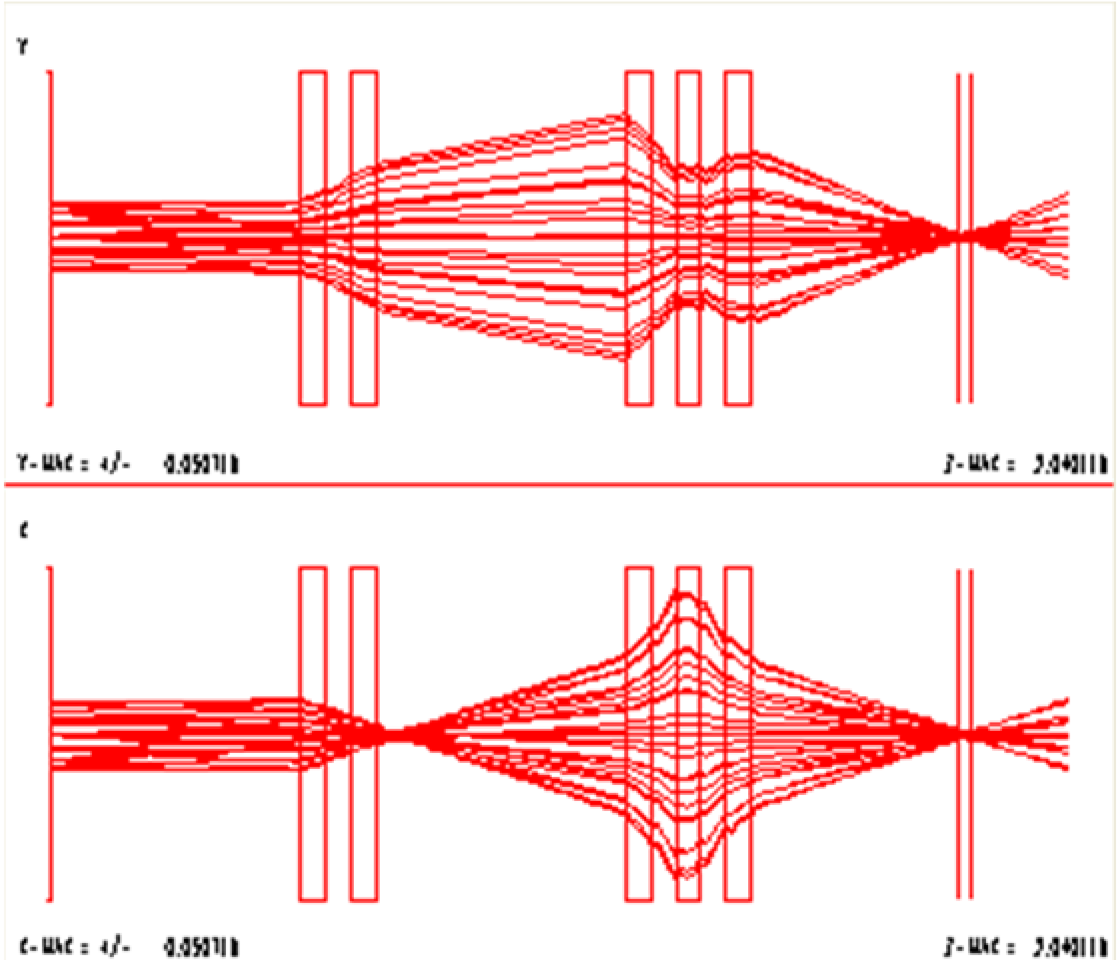
Deceleration & focusing of $\bar{p}$

Method used at ISOLDE :
60 keV ion beams delivered in 2 keV bunches of < 50 ns



Tests with p in preparation at CSNSM

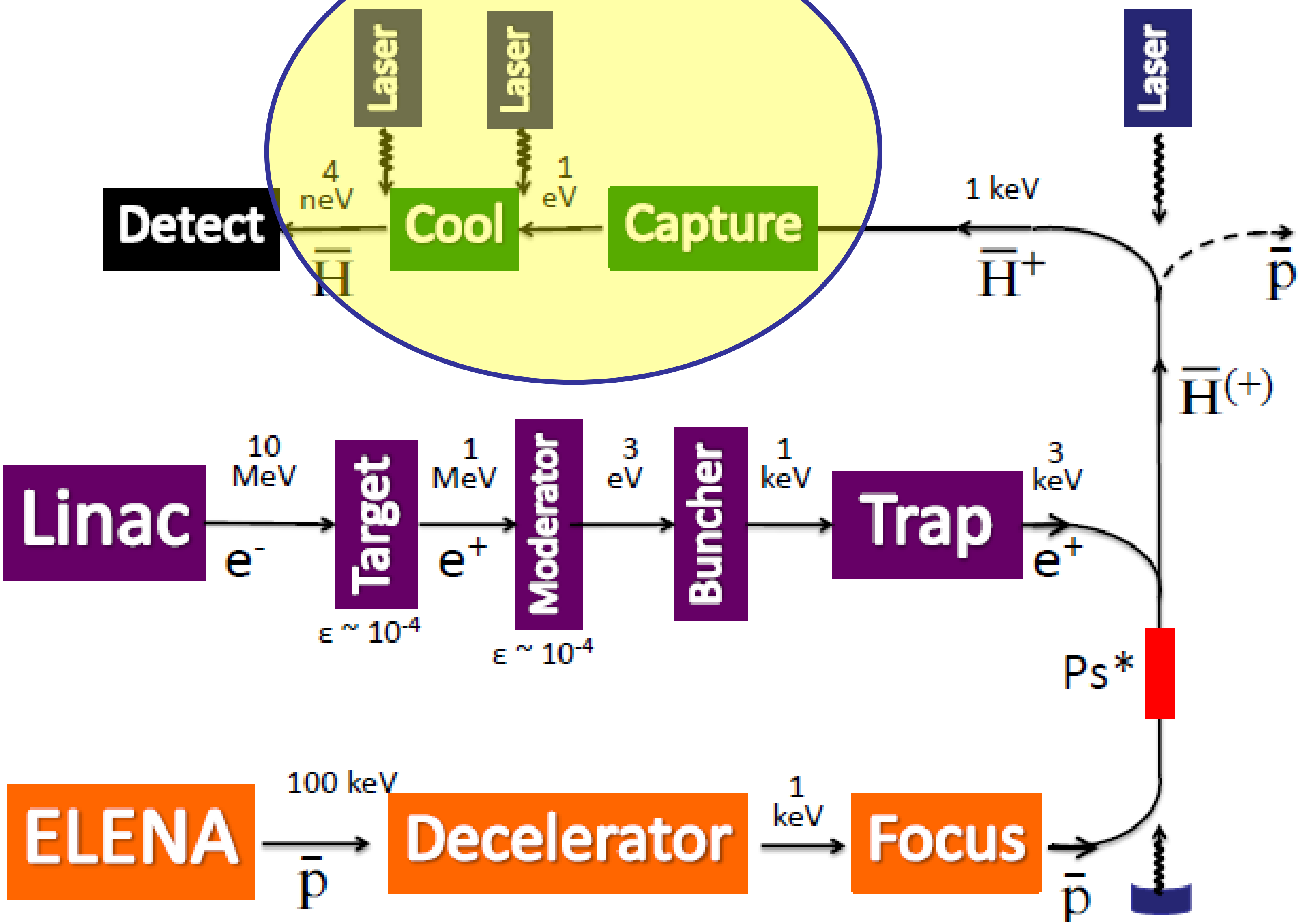
Transport to Ps* reaction chamber



Full simulation with SIMION

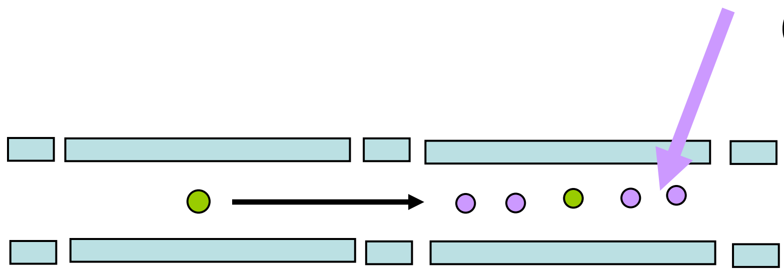
preliminary transmission: 44%

Synoptic Scheme



$\bar{H}^+$ cooling

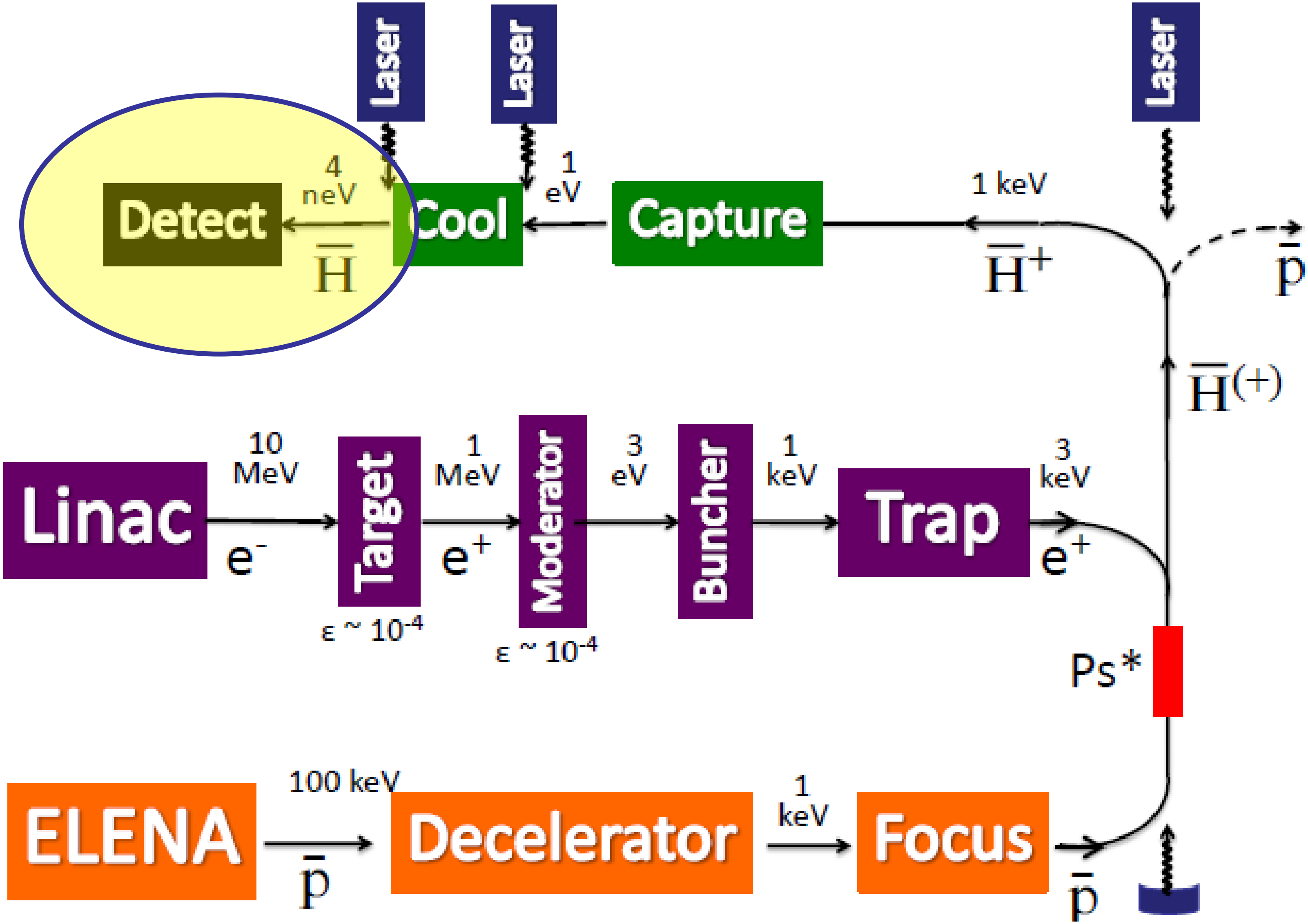
- Segmented RF Paul Trap, well depth ~1 eV
- Sympathetic cooling using Be^+ ions
  - Laser cooled Be^+ ions
  - Coulomb interaction of $\bar{H}^+$ and Be^+



- Be^+ Doppler cooling
  - Temperature ~ 1 mK
- Be^+ sub-Doppler cooling
  - Temperature ~ 10 μK

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

Synoptic Scheme



Photodetachment

$\bar{H}^+$ binding energy 0.76 eV => p_γ ~ 0.76 eV/c

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: γ must be very close to threshold

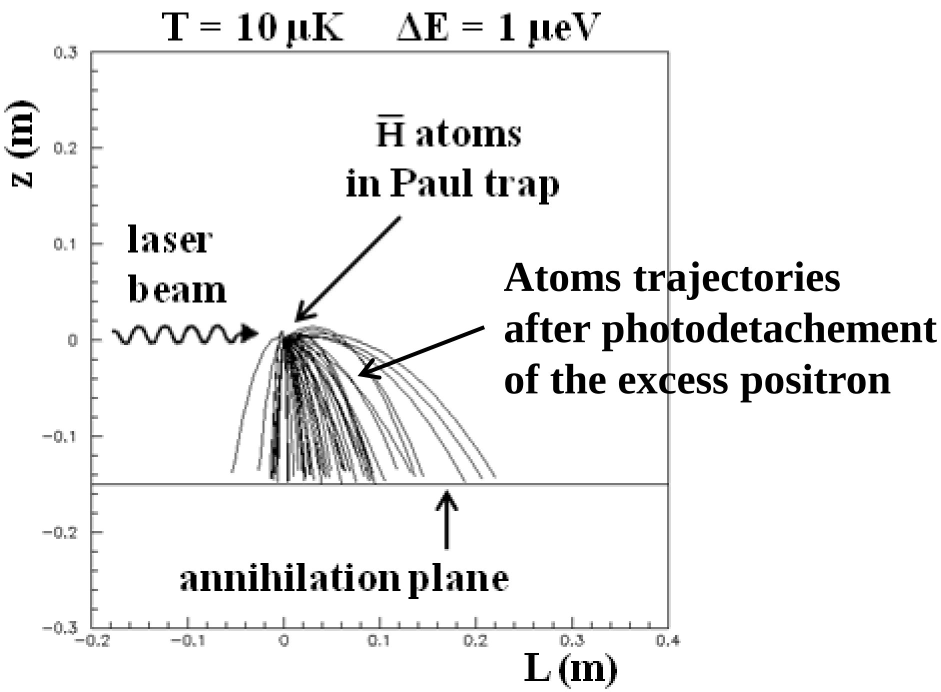
$E_c = E_\gamma - 0.76$ => $$v_{recoil} = \sqrt{\frac{2m_e E_c}{m_H}}$$ ~ 1 m/s for E_c = 10 μeV

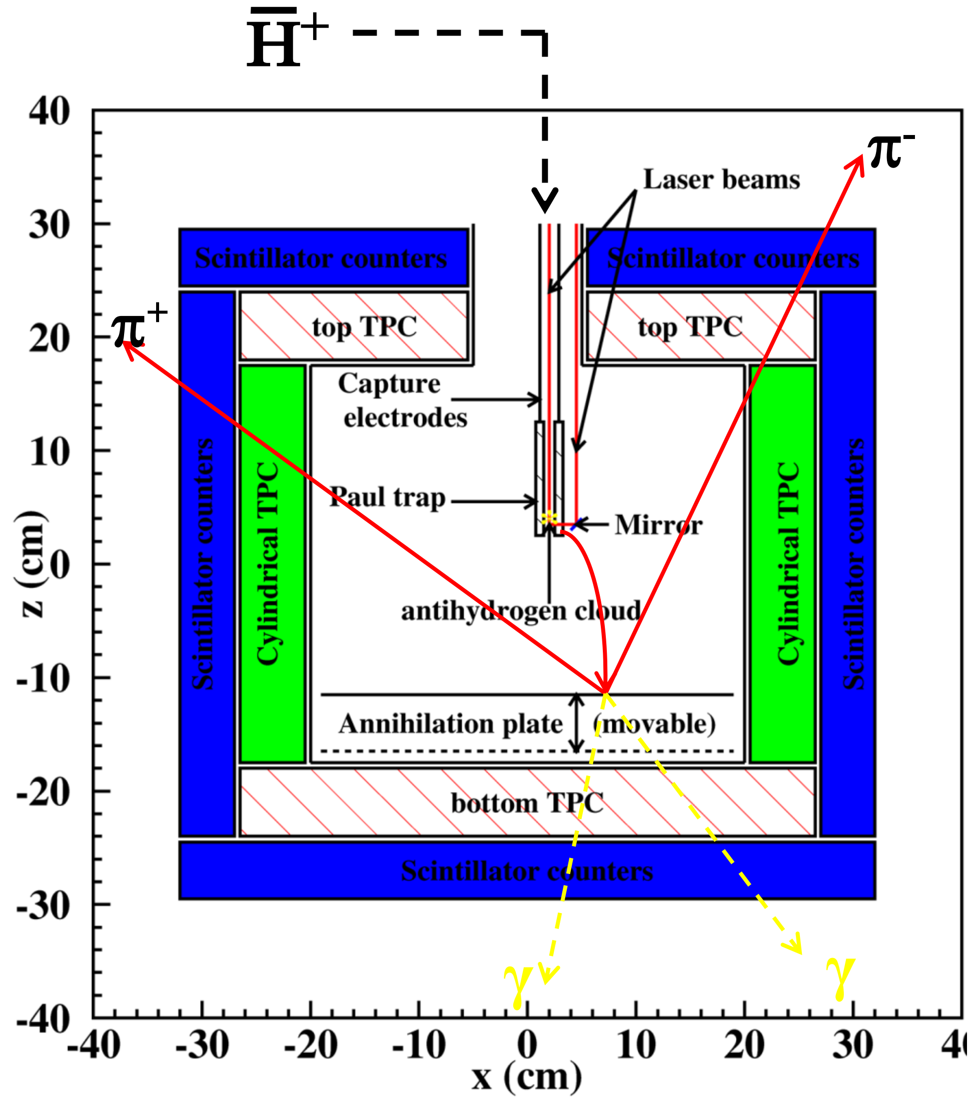
$\bar{H}$ free fall detection

-arrival position x,y (mm) => v_x, v_y
-TOF (140 ms)

=> cross-check of initial temperature

Free fall measurement





$$h = 1/2\ \bar{g}\ (t_1-t_0)^2+v_{z0}(t_1-t_0)$$

Aim : measure $\bar{g}$ to
1 % precison (first phase)
~ 1500 events needed

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}

A few weeks of running to get 1500 events

All details in :

P. Pérez et al, Proposal CERN - SPSC- 029 (2011)

Outline

- Motivation
- Principle and goal of the experiment
- Experimental techniques
- **Schedule and perspectives**

Perspective: beyond 1 % precision

Gravitational quantum states of Antihydrogen
A. Yu. Voronin, P. Froelich, and V. V. Nesvizhevsky,
Phys. Rev. A **83**, 032903 (2011)

- $\bar{H}$ Source:
  - very low temperature
  - high phase-space density
  - compact system

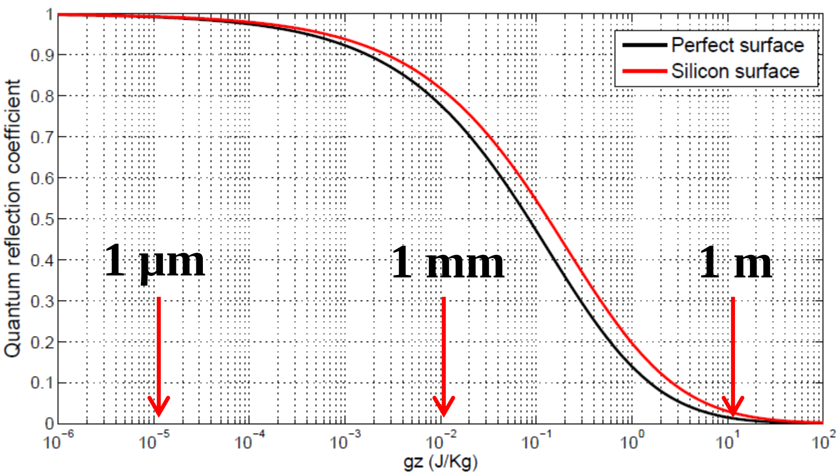
- Improve the precision on $\bar{g}$ with the spectroscopy of gravitational levels of $\bar{H}$ above the annihilation plane : similar method as for UCN neutrons (GRANIT spectrometer)

Towards a higher precision on $\bar{g}$

Put the detection plane at z very close to the Paul trap Center hight

⇩

Casimir effect



Reflection probability

Annihilation rate vs time

few tens of events needed to reach ~10^{-3} precision !

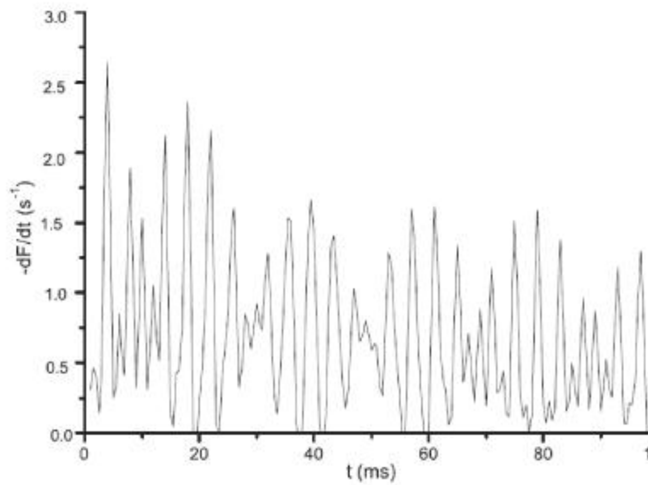
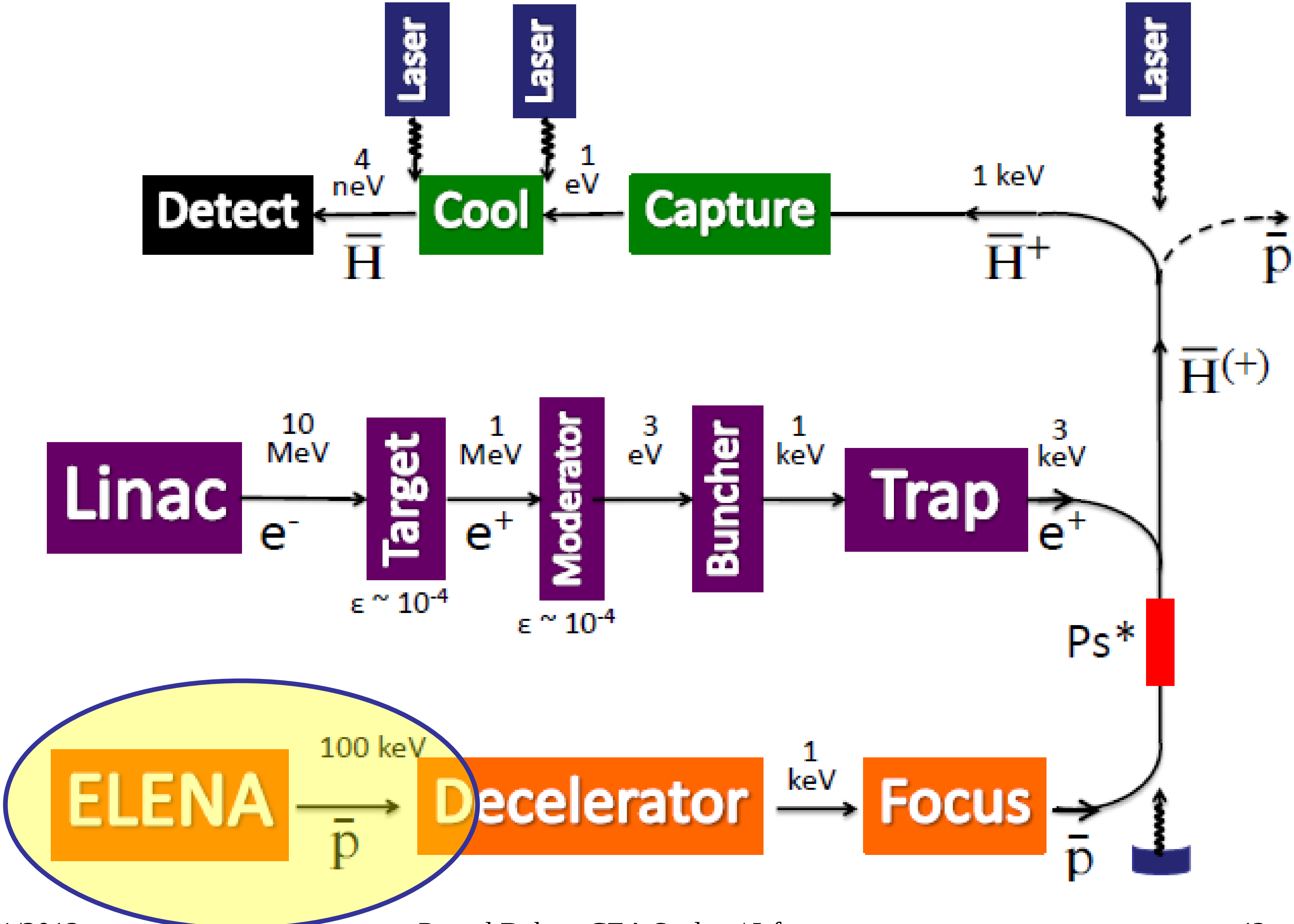


Figure 53: Evolution of the annihilation rate of $\overline{\mathrm{H}}$ atoms for a superposition of the 3 lowest gravitational states.

Synoptic Scheme



Coming soon : ELENA (Extra Low ENergy Antiproton ring)

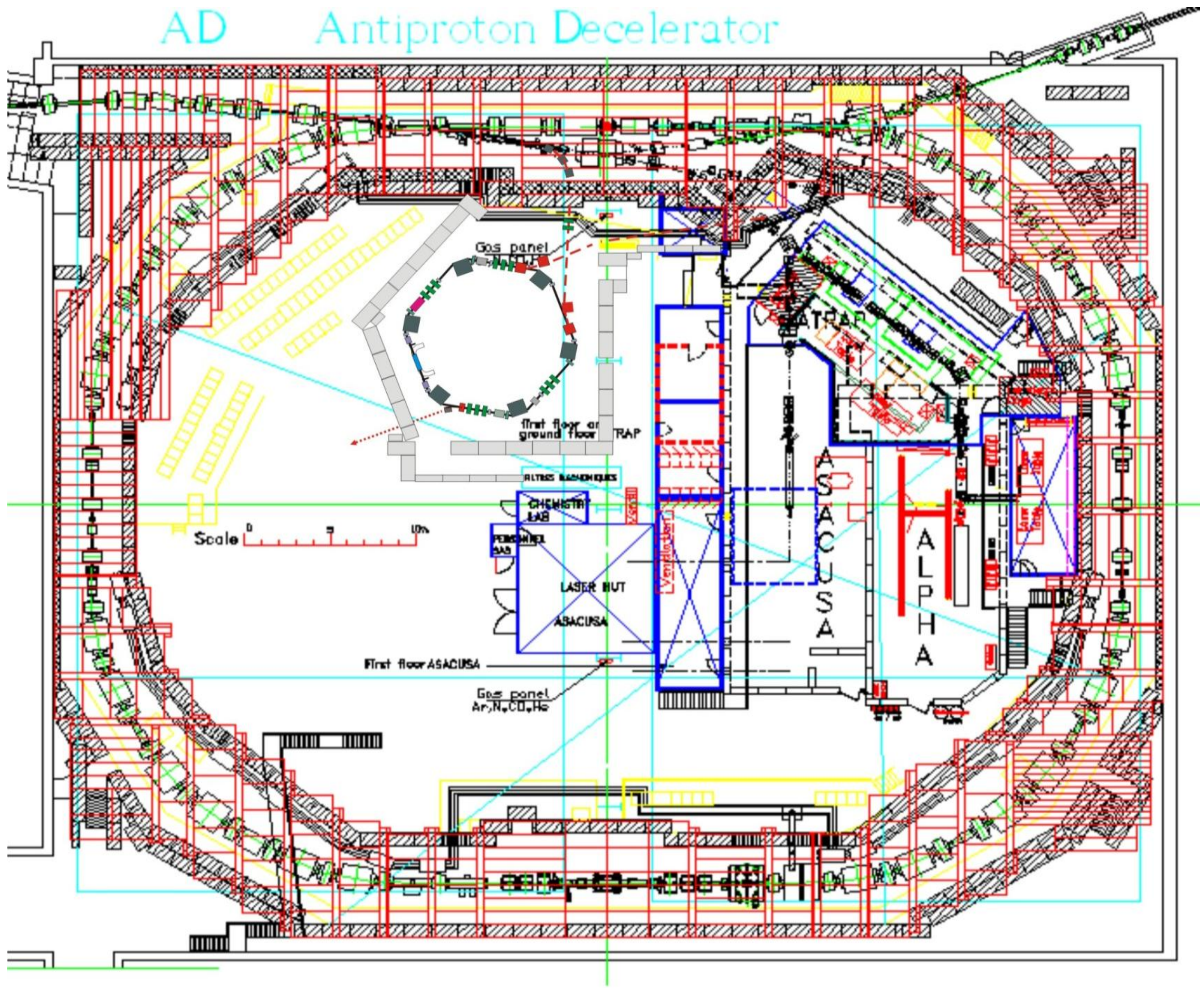
- **New ring under construction** to decelerate antiprotons from AD (**efficiency gain ~10** for antihydrogen ecperiments)

- **AD**:
  - ○ p̄ 5,5MeV, 1 line at a time during 6, 12, 24h…

- **ELENA**:
  - ○ p̄ **100 keV** continuous
  - ○ several extraction lines

- **Commissionning 2016**

- **Start physics in 2017**



GBAR Schedule

- **05/2012: approval by CERN Research Board**
- **12/2012: e+ trapping**
- **06/2013: deceleration technique demonstration with protons**
- **06/2014: Ps production and excitation**
- **06/2014: detector tests with cosmics**
- **12/2014: sympathetic cooling demonstration with matter (H_2^+)**
- **06/2015: Installation at CERN**
- **03/2016: Commissionning**
- **01/2017: ELENA starts and later… first measurements**

The GBAR collaboration

14 institutes
46 physicisists

Variety of physics fields

Particle
Accelerator
Plasmas and ions trapping
Cold atoms
Positronium
Material science
Cold neutrons
Theory

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