Laboratoire Kastler Brossel
Physique quantique et applications

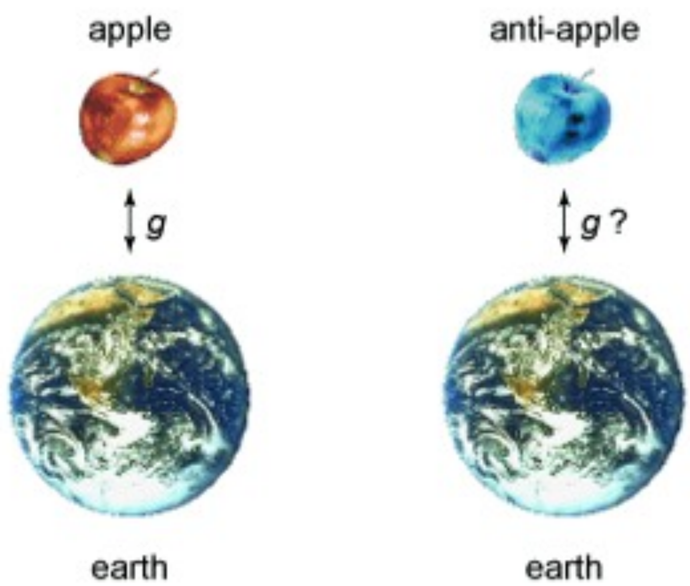
The Gbar project, or how does antimatter fall?

Paul Indelicato
For the GBAR collaboration

GBAR

Gravitational Behavior of Antihydrogen at Rest

irfu
cea
saclay
Laboratoire Kastler Brossel
RIKEN
Swansea University
School of Physical Sciences
IPCMS
CSNSM
東京大学
THE UNIVERSITY OF TOKYO
東京理科大学
Tokyo University of Science
ETH Institute for Particle Physics
NEUTRONS FOR SCIENCE®
Institut Laue-Langevin
EMMI
IFRAF
ENS



cnrs
UPMC
PARIS UNIVERSITAS

The GBAR collaboration

14 institutes
48 physicisists

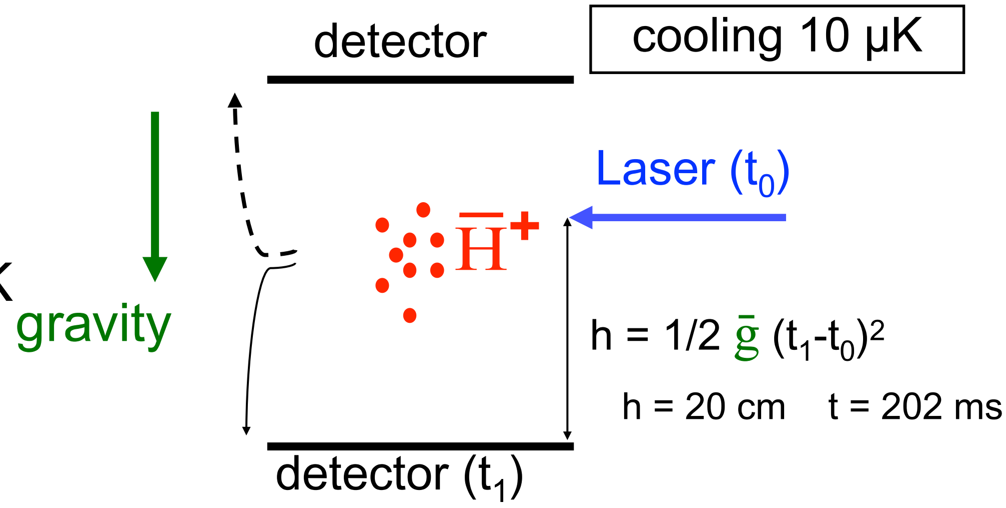
Variety of physics fields

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

Country	Institute	Members
FRANCE	**CSNSM**	G. Chardin, P. Dupré, P. Grandemange, D. Lunney, V. Manea
FRANCE	**ILL**	V. Nesvizhevsky
FRANCE	**IPCMS**	P-A. Hervieux, G. Manfredi
FRANCE	**IRFU**	P. Comini, P. Debu, L. Liszkay, B. Mansoulié, **P. Pérez**, Y. Sacquin, B. Vallage
FRANCE	**LKB**	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
GERMANY	**JGU**	J. Walz, F. Schmidt-Kaler
JAPAN	**RIKEN**	A. Mohri, Y. Yamazaki
JAPAN	**U. Tokyo**	N. Kuroda, H. Torii
JAPAN	**TUS**	Y. Nagashima
POLAND	**NCBJ**	S. Wronka
RUSSIA	**Lebedev**	A. Voronin
SWEDEN	**Uppsala**	P. Froelich
SWITZERLAND	**ETHZ**	A. Badertscher, P. Crivelli, A. Curioni, A. Marchionni, B. Rossi, A. Rubbia
UNITED KINGDOM	**Swansea**	M. Charlton, S. Eriksson, N. Madsen, D.P. van der Werf

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

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

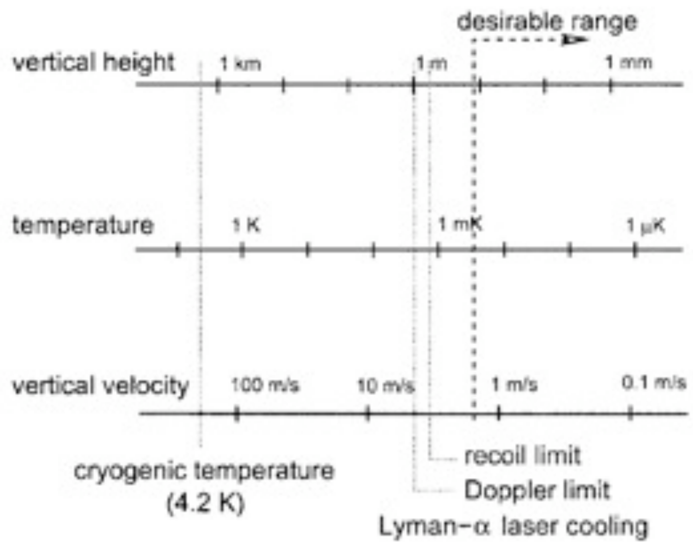


Error dominated by temperature of $\bar{H}^+$

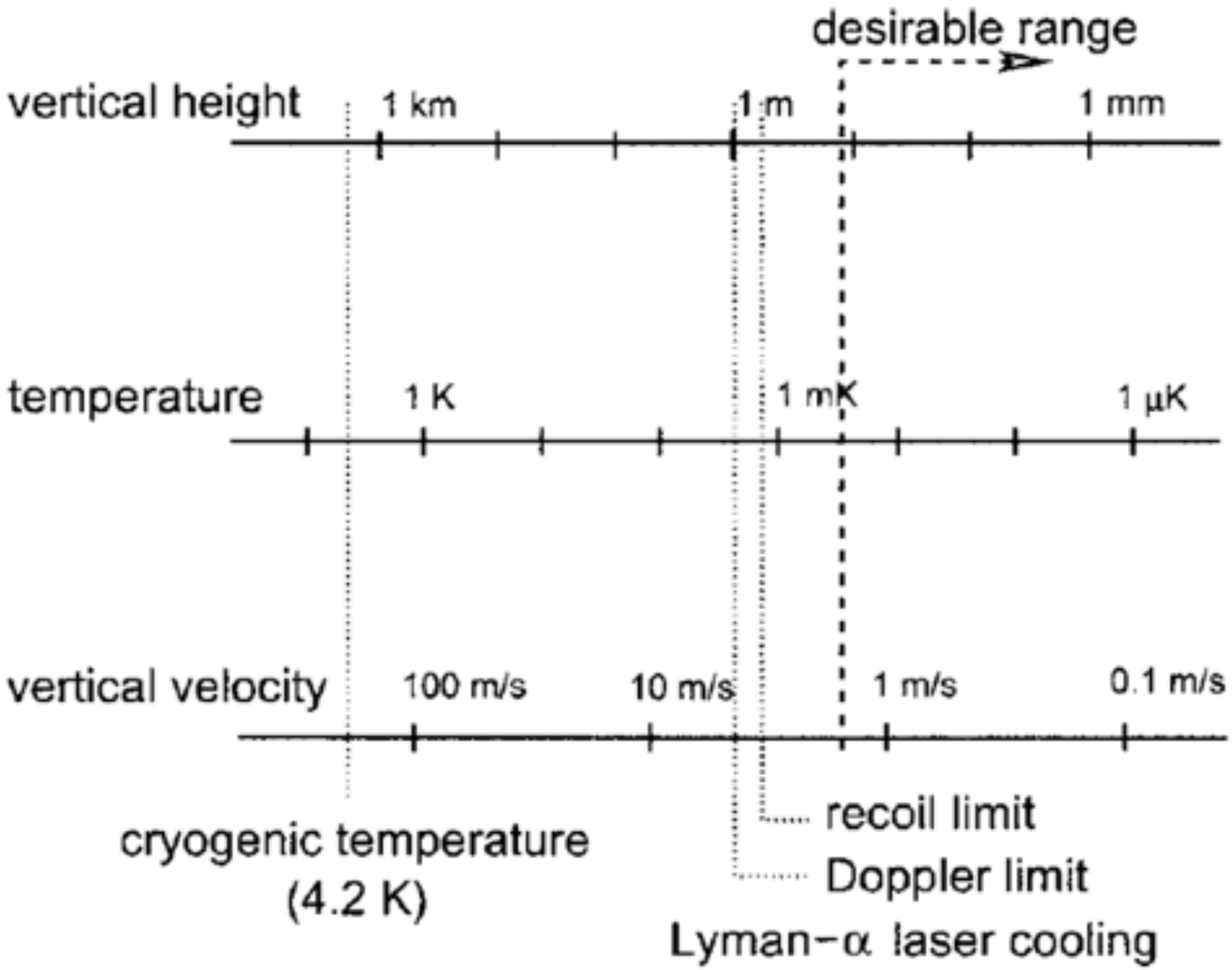
J.Walz & T. Hänsch,

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

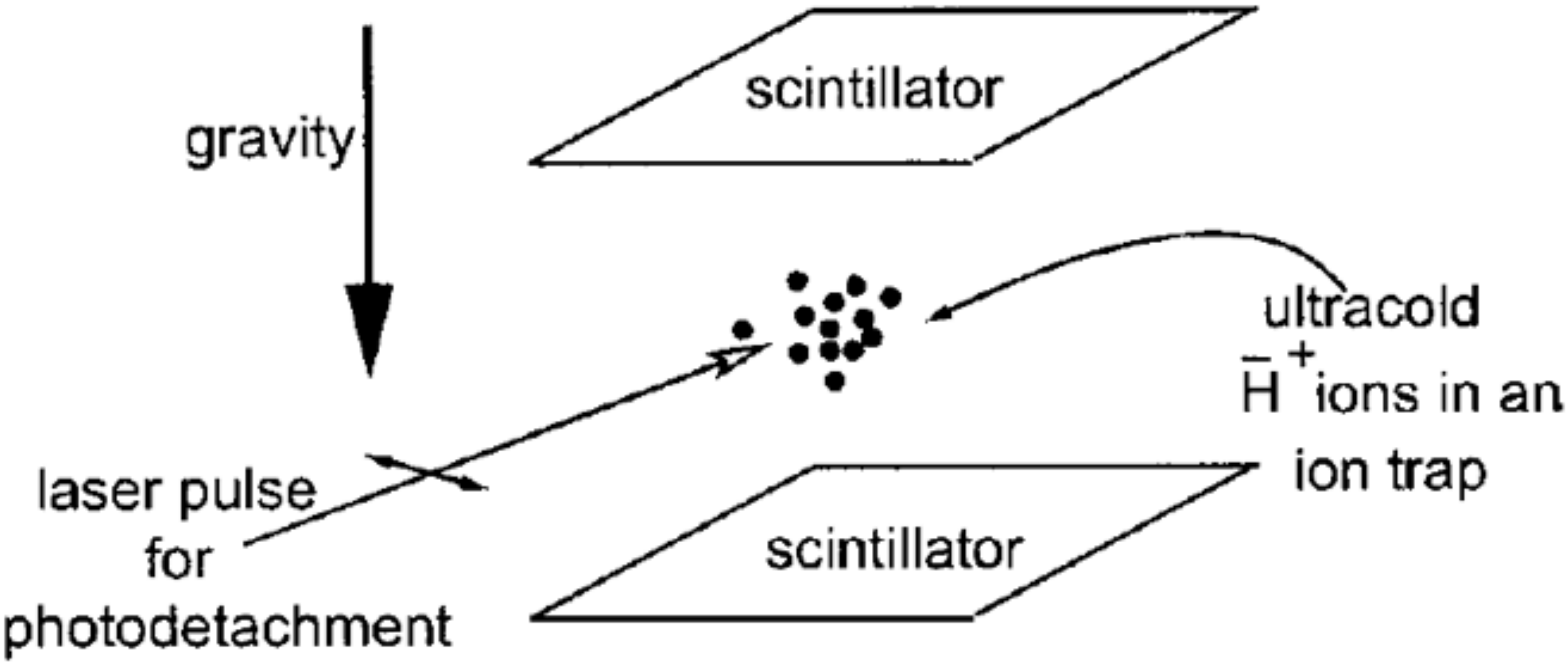


How to measure $\bar{g}$?



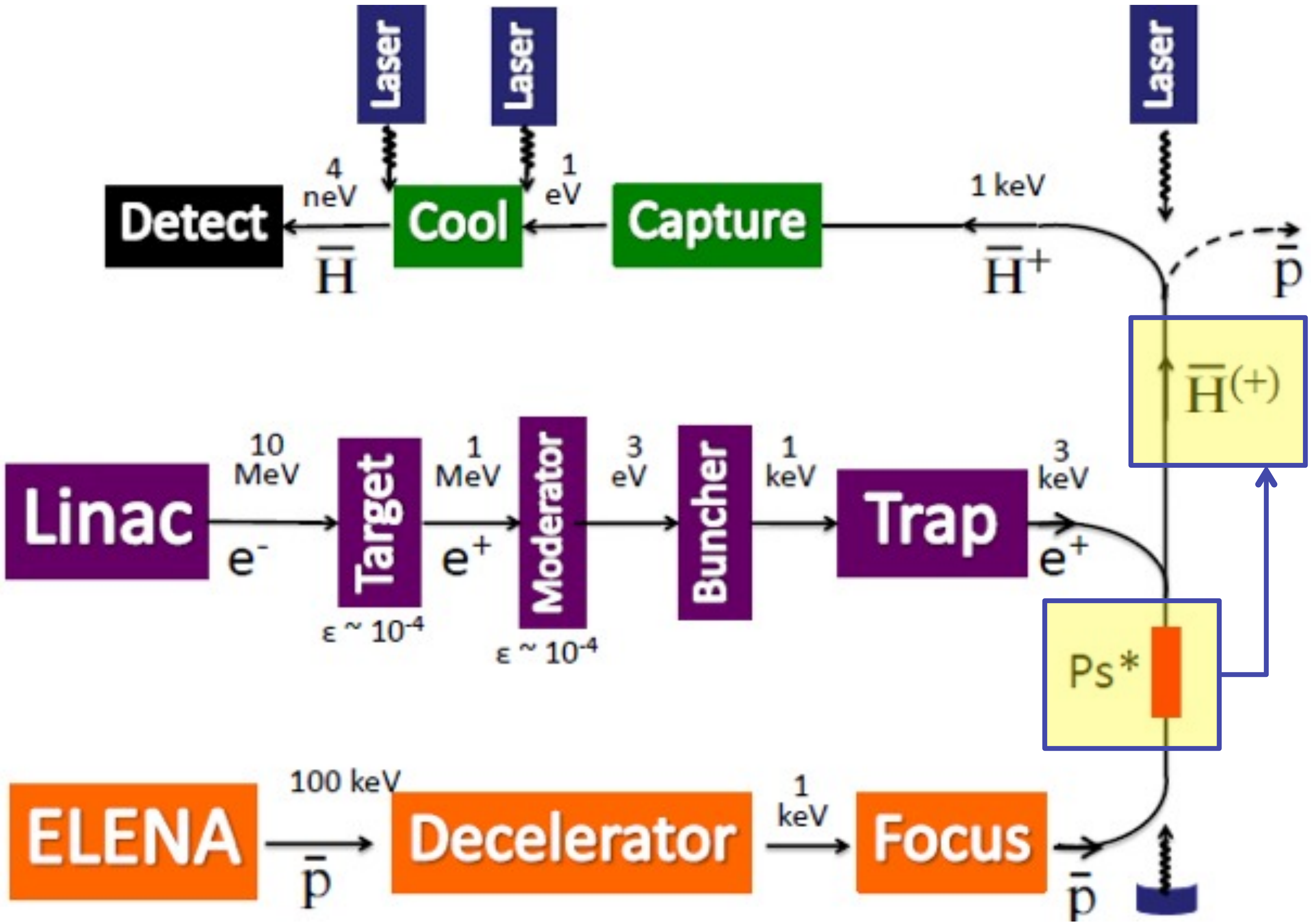
A Proposal to Measure Antimatter Gravity Using Ultracold Antihydrogen Atoms. J. Walz et T.W. Hänsch. General Relativity and Gravitation. **36** 561-570, (2004).

How to measure $\bar{g}$?



A Proposal to Measure Antimatter Gravity Using Ultracold Antihydrogen Atoms. J. Walz et T.W. Hänsch. General Relativity and Gravitation. **36** 561-570, (2004).

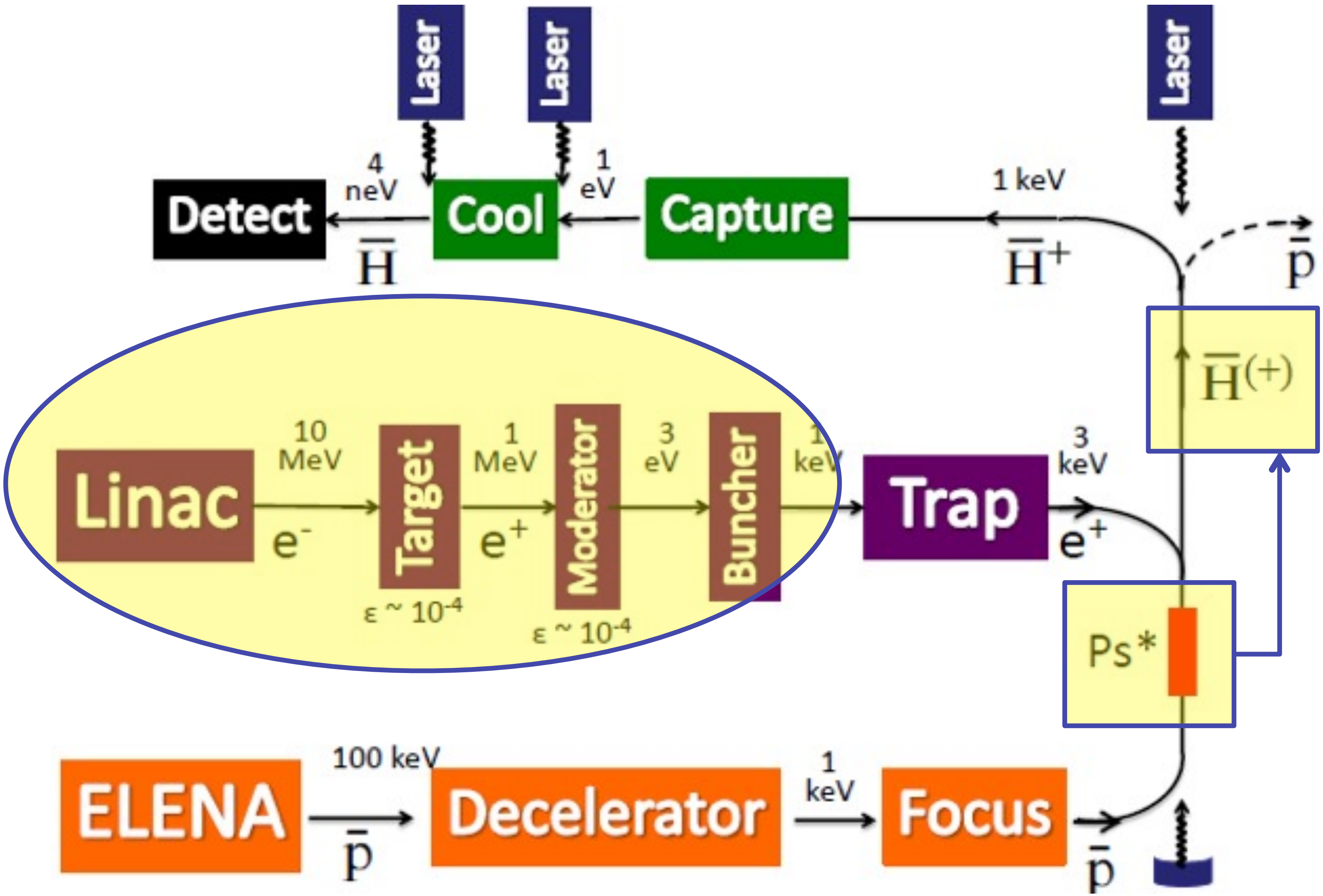
GBAR Synoptic Scheme



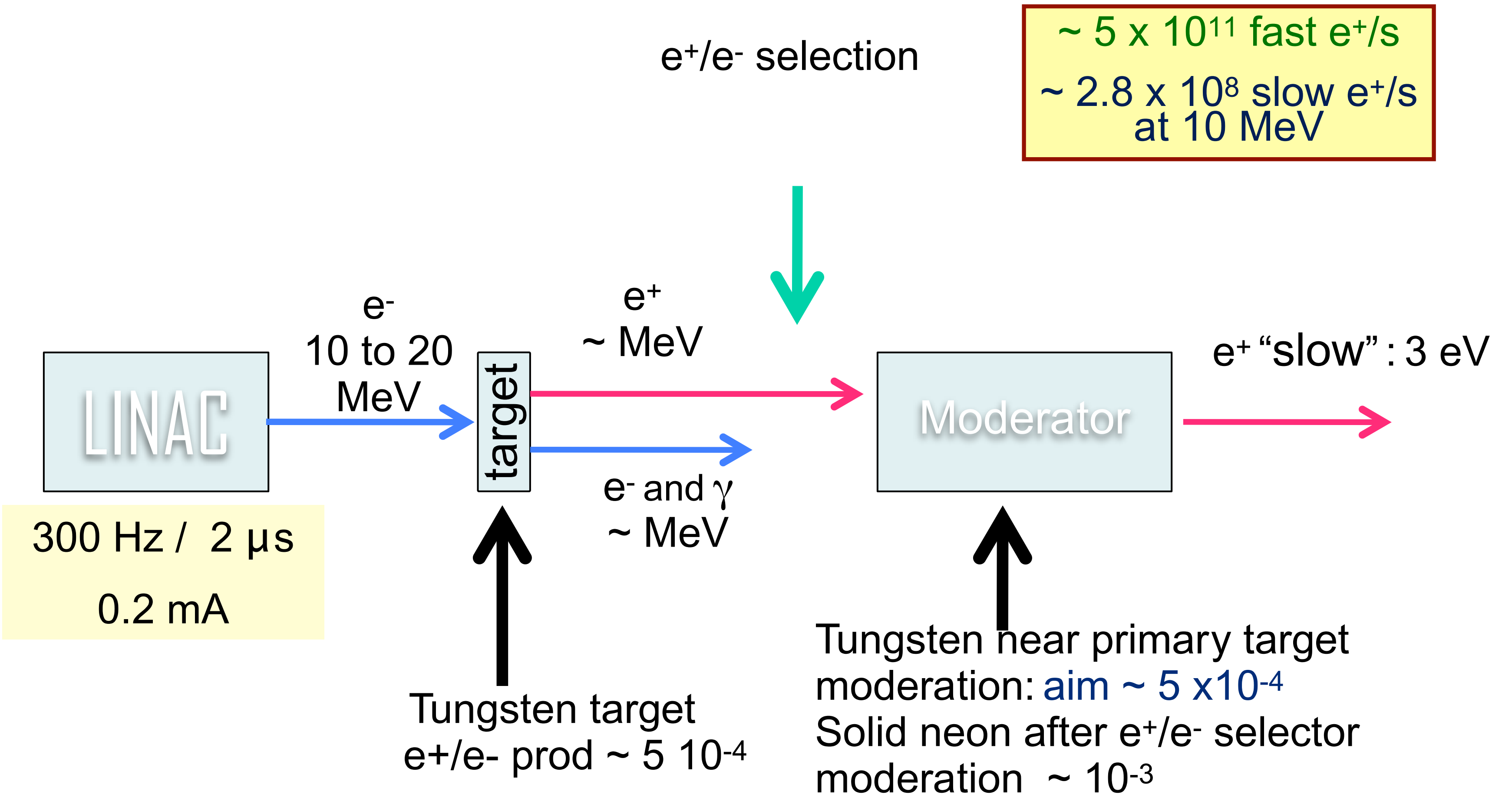
GBAR Schedule

- 05/2012: approval by CERN Research Board
- 12/2012: start e+ trapping tests
- 06/2013: deceleration technique demonstration with protons
- 06/2014: Ps production and excitation
- 06/2014: detector tests with cosmic rays
- 12/2014: sympathetic cooling demonstration with matter (H_2^+)
- 06/2015: Installation at CERN of the GBAR LINAC
- 03/2016: Commissioning of ELENA with p^+ and H^-
- 06/2017: AD/ELENA commissioning with $\bar{p}$ and later... first measurements

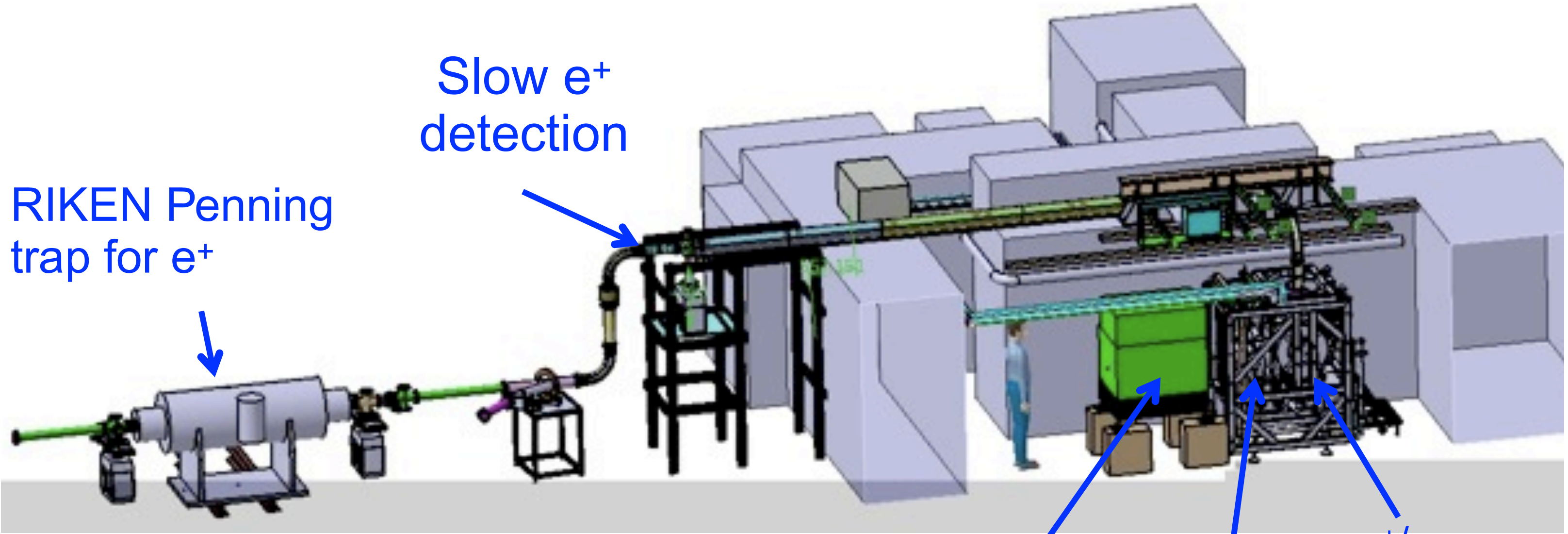
GBAR Synoptic Scheme



High intensity slow positrons source

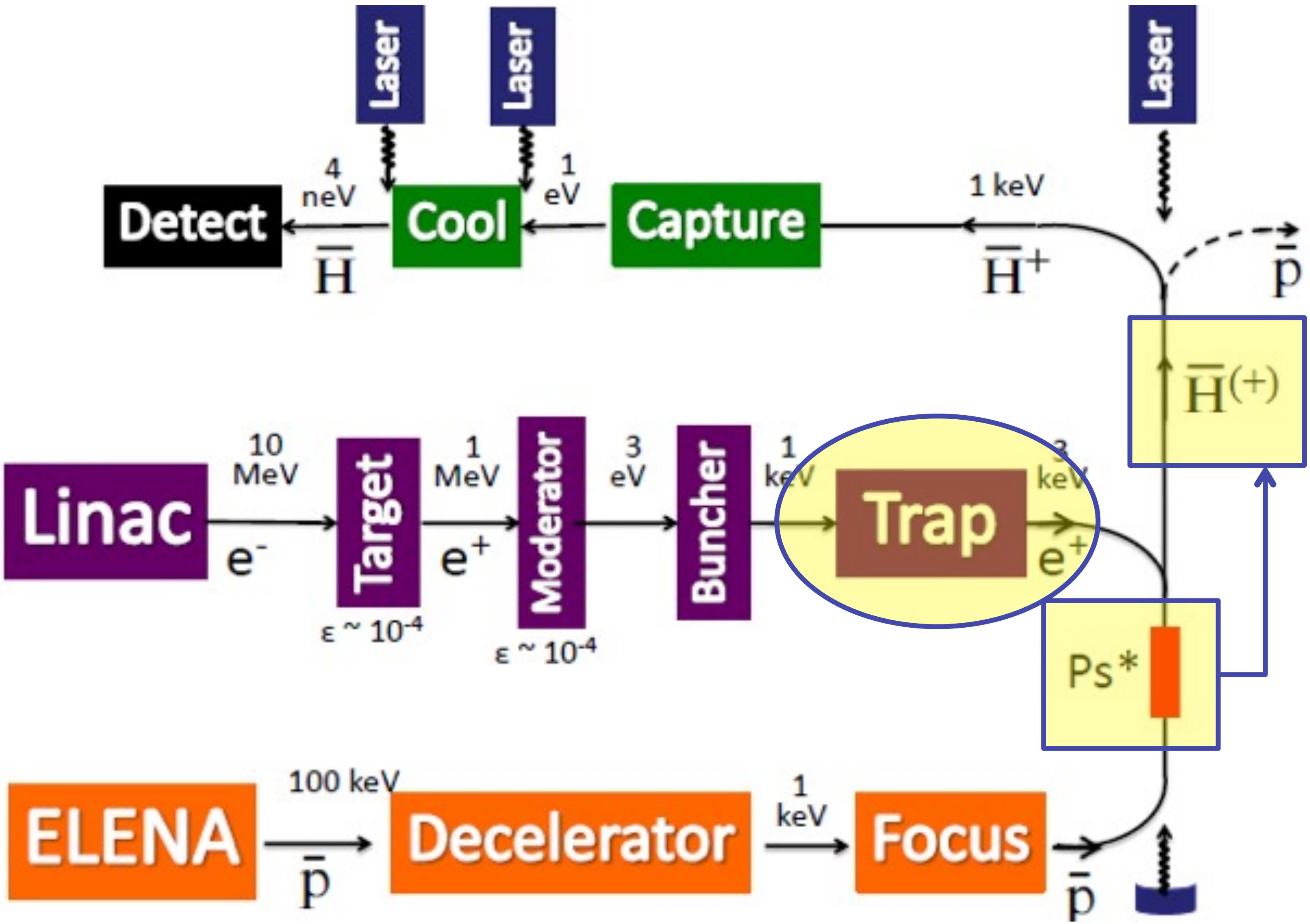


Prototype at Saclay

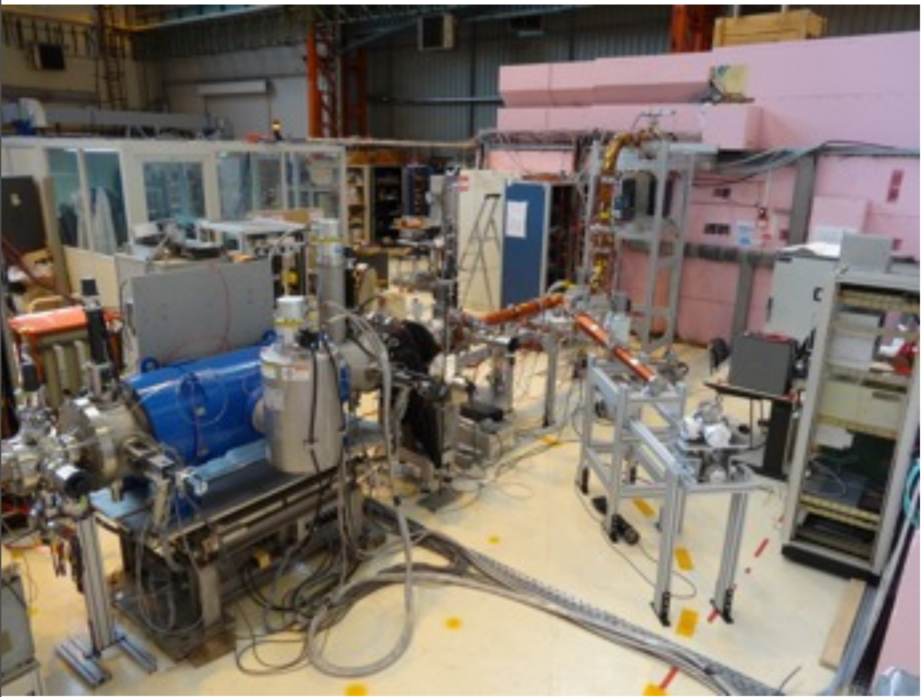


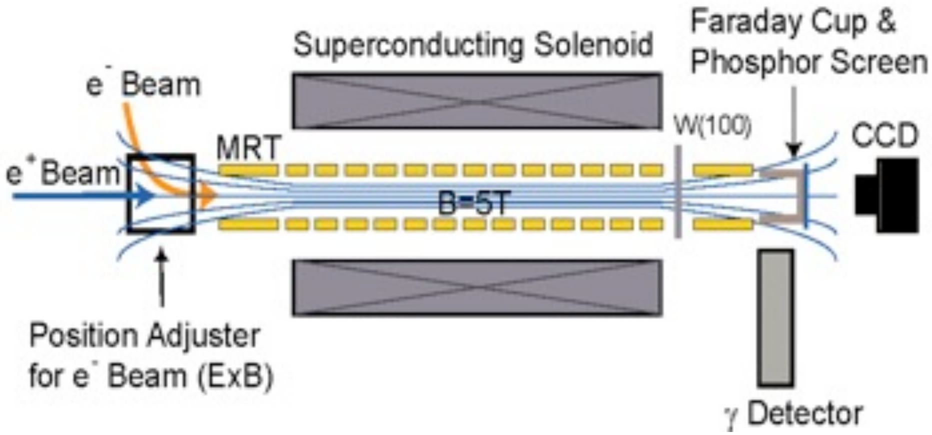
Present slow e^+ rate : ~ 3 10^6 s^{-1}
Extrap. to 10 MeV : ~ 5 10^7 s^{-1}
Target value : ~ 3 10^8 s^{-1}
(higher energy, frequency, moderation)

GBAR Synoptic Scheme



RIKEN Multi Ring Trap





•Trap now at Saclay:

we start accumulation with <u>pulsed e^+</u>

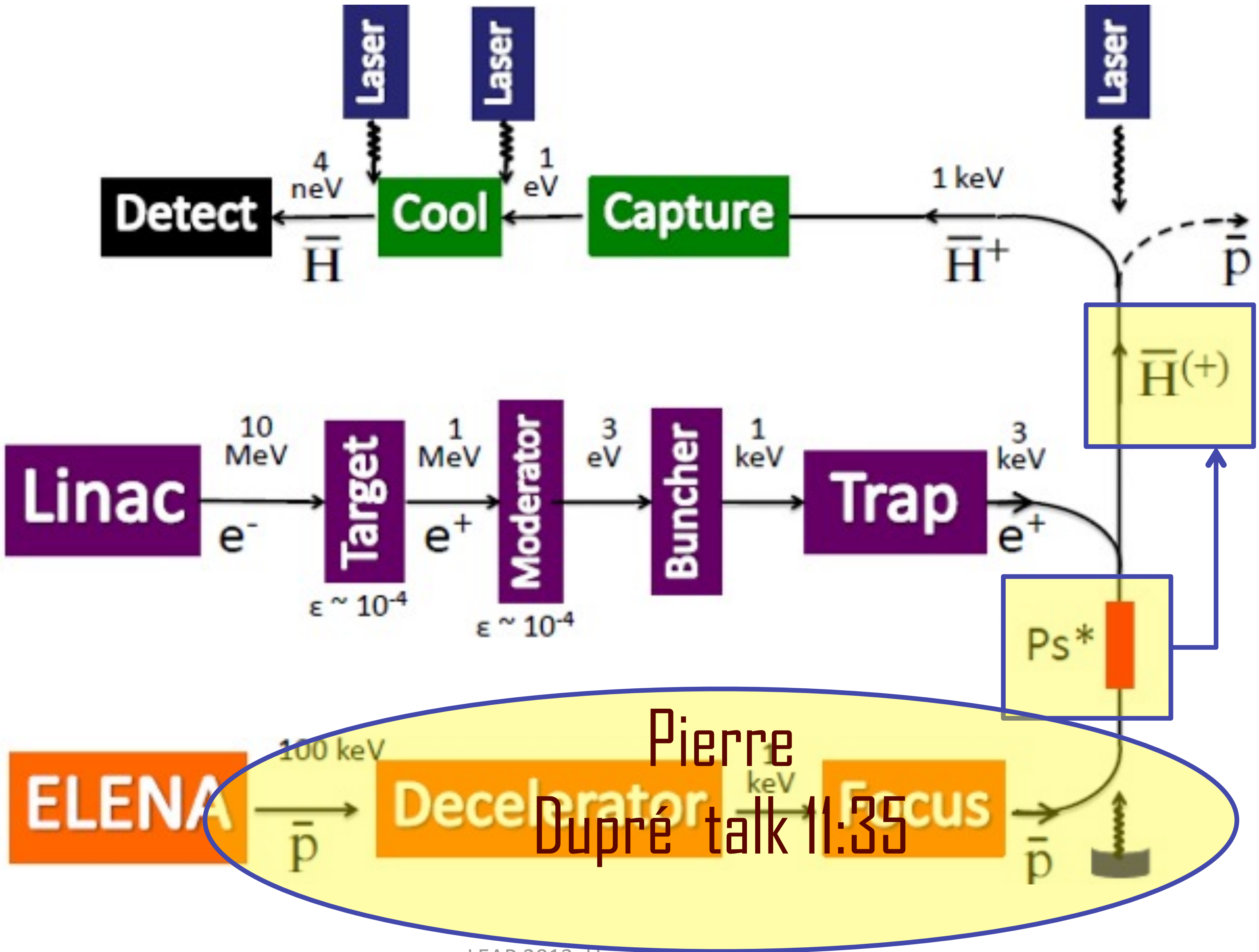
Simulation:

$\varepsilon_{trapping} \approx 50\%$ expected

The MRT at Saclay

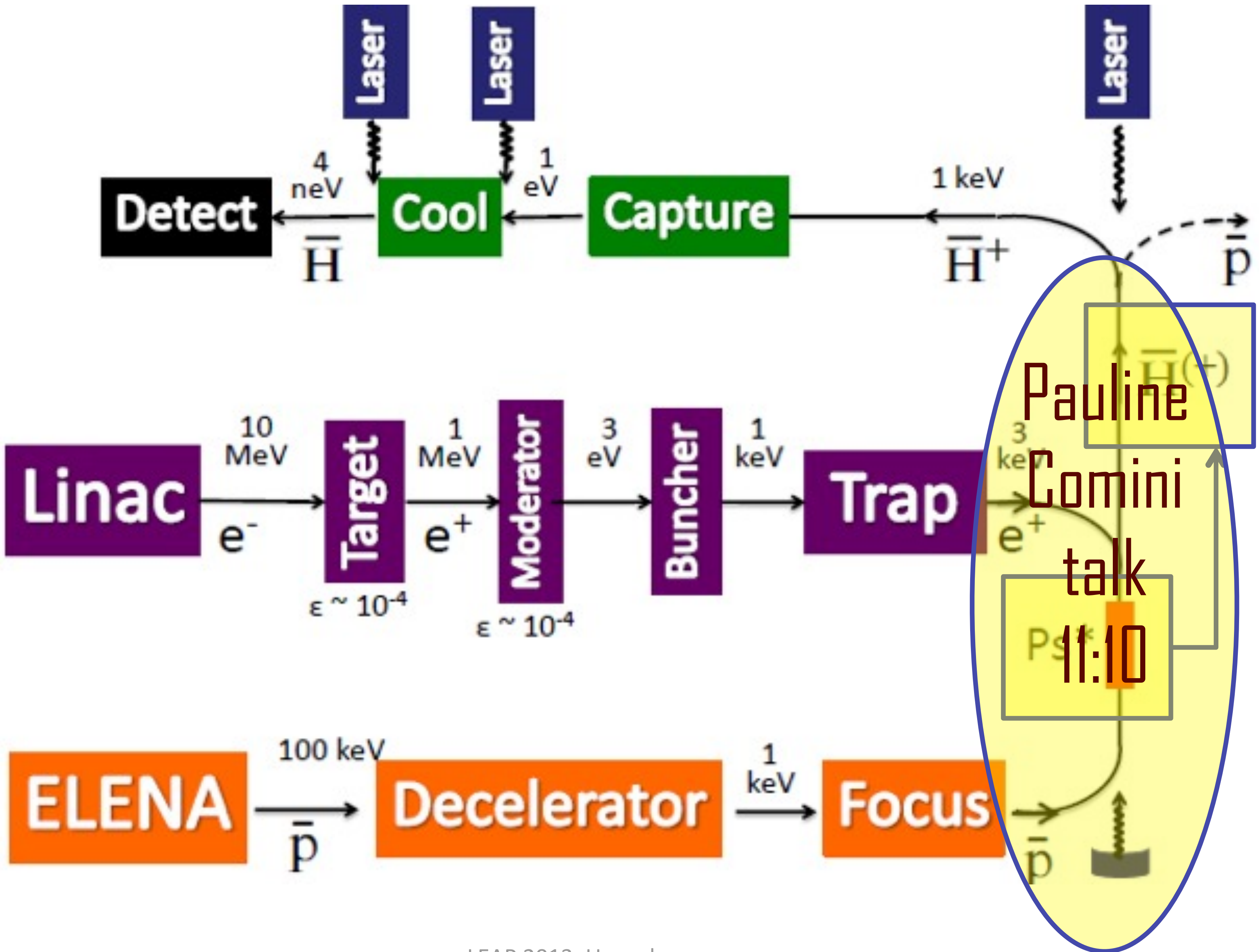
few 10^{10} e^+ needed

GBAR Synoptic Scheme



vendredi 14 juin 2013

GBAR Synoptic Scheme



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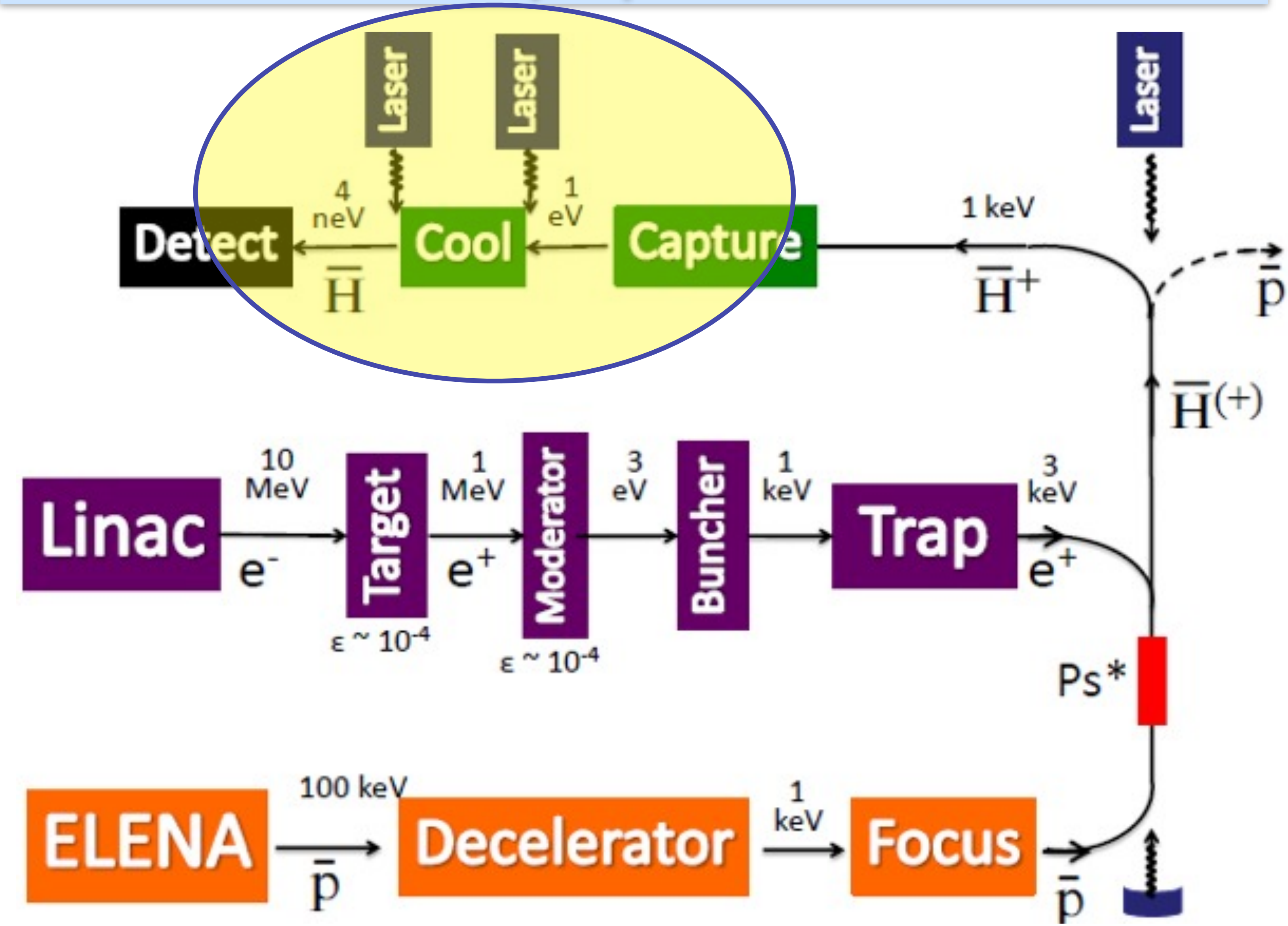

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H^+ sympathetic cooling

First step

- Capture into a Paul trap and cooling to the 1 mK range (Doppler cooling)
- Optional step: resistive cooling to 4K

Second step

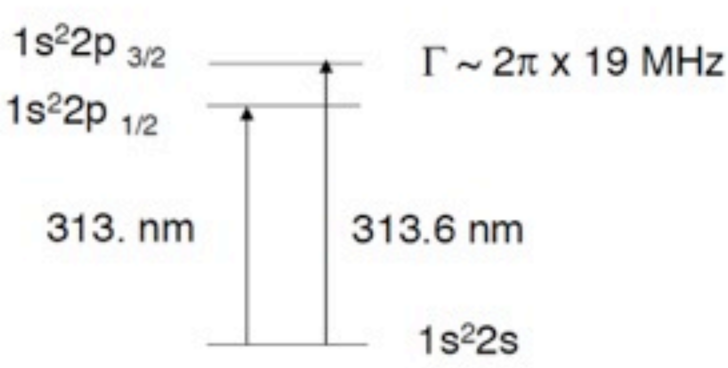
- Transfer to a 2 ion trap and Raman side-band cooling (~10 μK)

Ion choice

Beryllium

^{9}B 100% I=3/2

Be^{+} / $\bar{\mathrm{H}}^{+}$ $\quad \dfrac{m_1/q_1}{m_2/q_2} = 9$



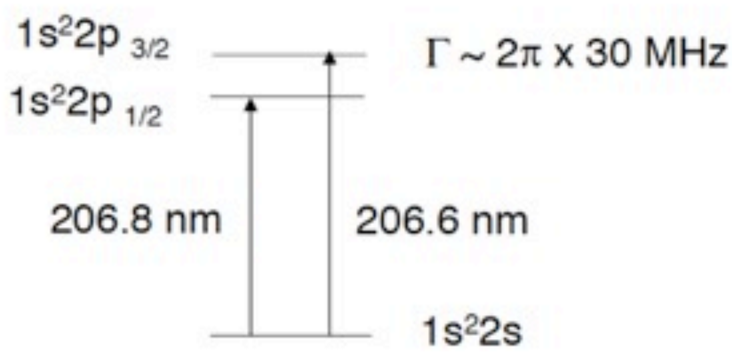
Be^{+} HFS = 1.25 GHz

Bore

^{10}B 19.9 % I=3

^{11}B 80.1 % I=3/2

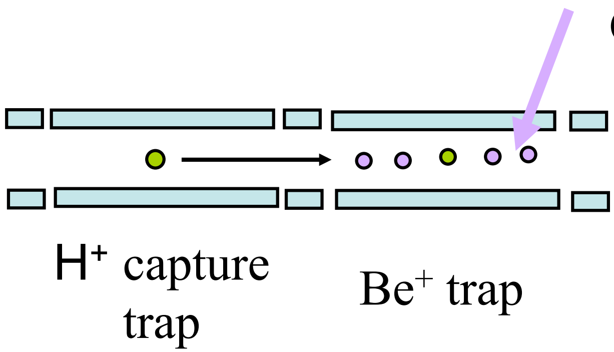
B^{2+} / $\bar{\mathrm{H}}^{+}$ $\quad \dfrac{m_1/q_1}{m_2/q_2} = 5.5$



B^{2+} HFS = 7.5 GHz

H^+ sympathetic cooling

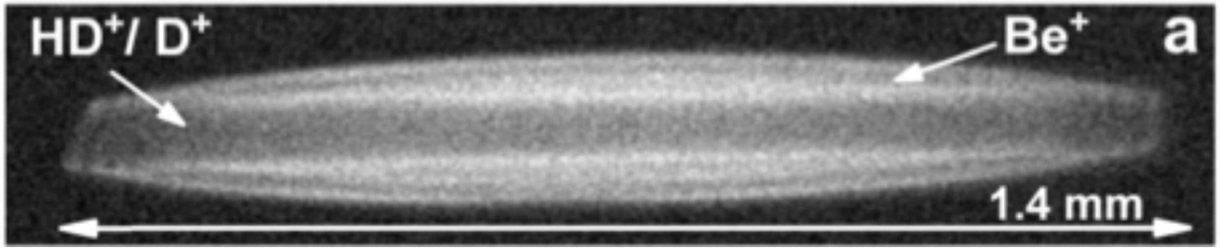
- Segmented RF Paul Trap, well depth ~1 eV
- Sympathetic cooling using Be^+ ions
  - ➢ Laser cooled Be^+ ions
  - ➢ Coulomb interaction of H^+ and Be^+



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

NIST group
M. D. Barrett, …, D. Wineland, PRA ***98****, 042302 (2003)*
Sympathetic cooling of $^9Be^+$ and $^{24}Mg^+$ for quantum logic

Sympathetic cooling by Be^+ ions

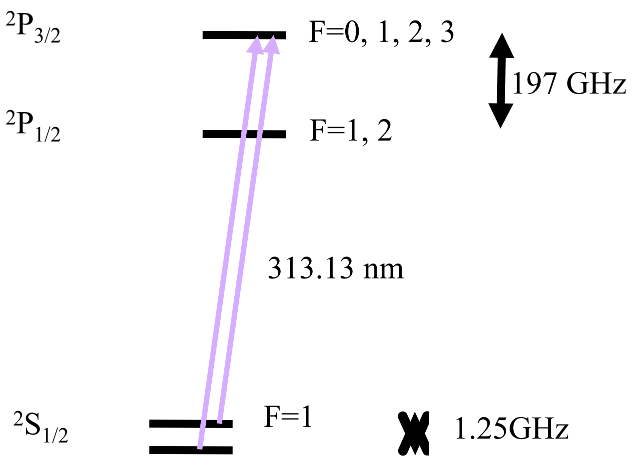


B. Roth et al., Phys. Rev. A **74**, 040501(R) (2006)

Better confinement of the ions

Non destructive measurement

Suppression of the second order Doppler effect



Sum of fiber lasers and frequency doubling

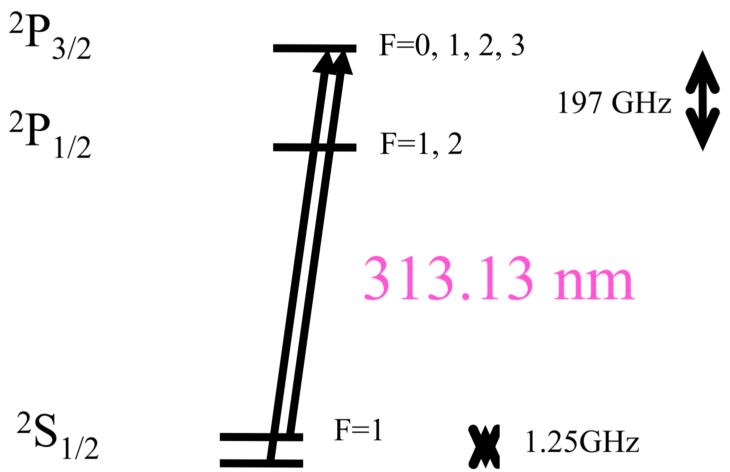
1560.4 nm + 1046 nm → 626.26 nm

626.26 x 2 → 313.13 nm, a few mW

NIST ~ 500 mW

Be^+ cooling

- Why Be^+?
  - Be^+ has a m/q of 9, Mg^+ of 24…
  - H_2^+ has a m/q of 2, HCI: Ar^{13+} 40/13~3, H-like: A/(Z-1)~2
  - For a Paul trap, one needs m/q in a range of 10 maximum



Laser cooling and repumping

Temperature : Doppler limit

$$k_B T = \frac{\hbar\Gamma}{2}$$

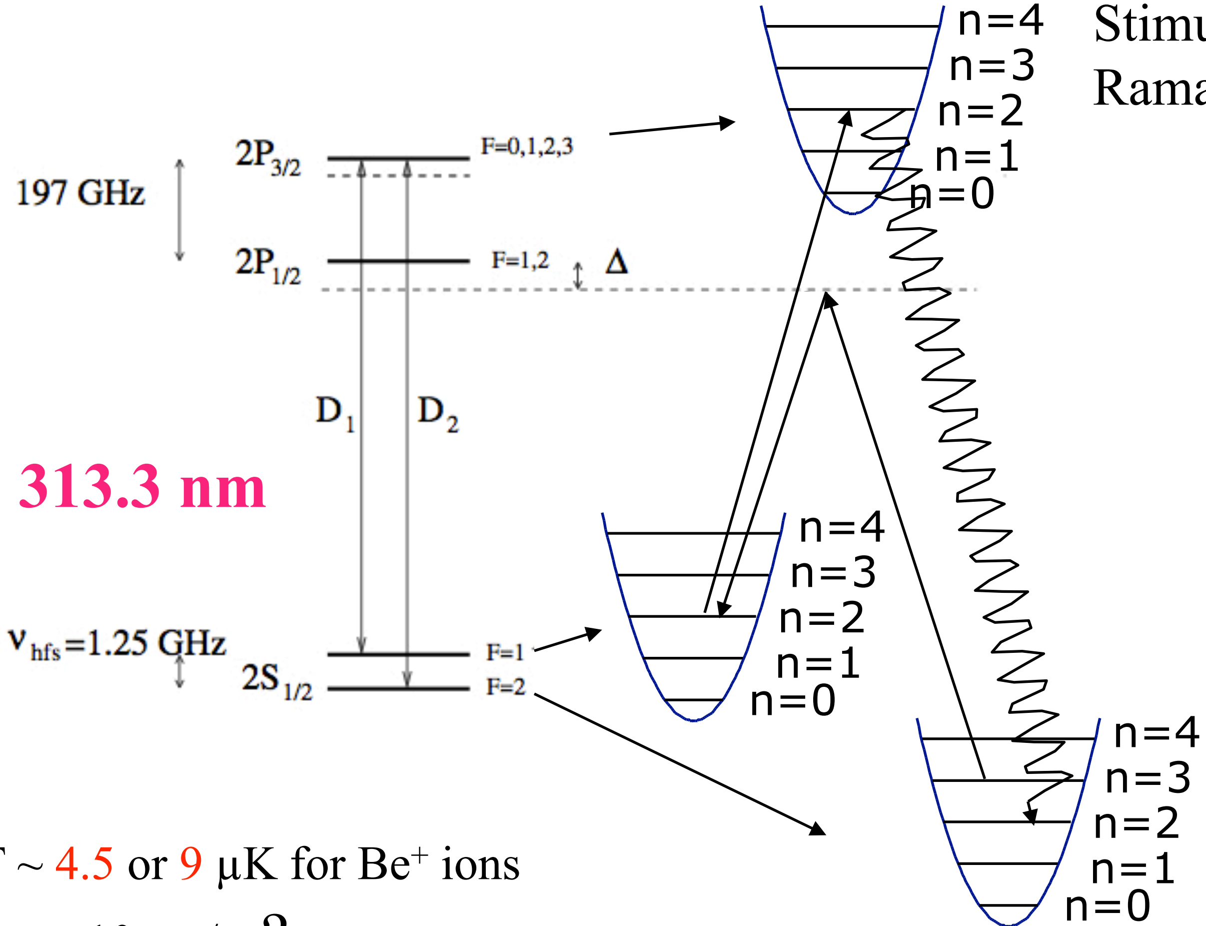
~ 0.5 mK

Be^+ sub Doppler cooling

- *M. D. Barrett, …, D. Wineland, PRA **98**, 042302 (2003) Sympathetic cooling of $^9Be^+$ and $^{24}Mg^+$ for quantum logic*
- *Serge Haroche Lectures, Collège de France 2006*
- *JOSA B **20**, vol 5, special issue*

Problem: photoionisation of H^+ by the cooling UV laser

Stimulated & Spontaneous Raman transitions



Cycle sequence:

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

Results

$\bar{n} = 0.03(2)$

$p_0 = 0.97(2)$

T ~ 4.5 or 9 μK for Be^+ ions

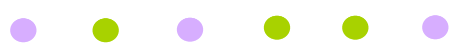
v ~ 10 cm/s ?

Sub Doppler cooling requirements

- Steep trapping potentiel to resolve macromotion sidebands

$\omega_x, \omega_y, \omega_z$ in the > MHz range

- Linear ion chain



N ions $\Longrightarrow$ 3 N phonon modes

3 N eigen frequencies

Raman side-band cooling for each mode !

The complexity increases with N

Only a few ions in the chain !

Main issues

$\bar{H}^+$ production

Creation time spread ?

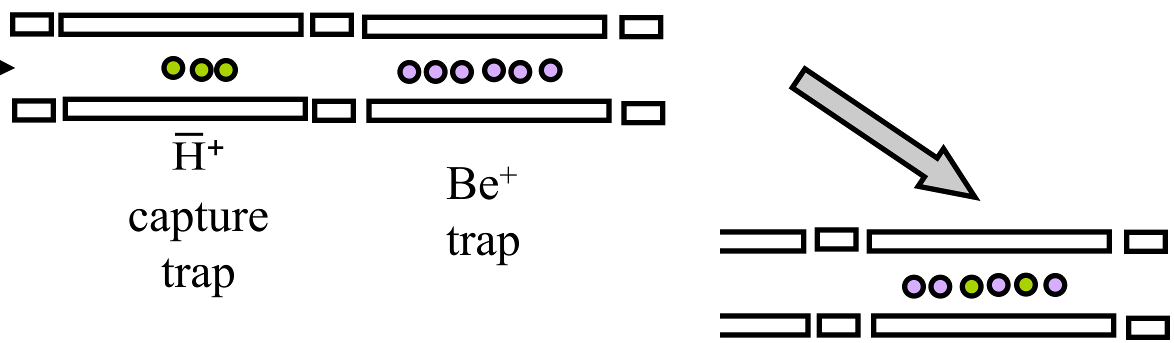
Position spread ?

Velocity spread ?

Energy spread ?

Segmented RF Paul Trap
Well depth ~ 1 eV

Sympathetic cooling by laser cooled Be^+ ions



Trap environment
room temperature
no cryogenics

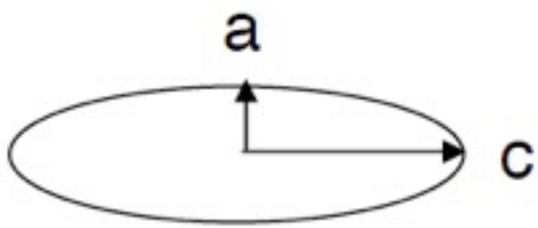
Cold matter : ion cloud only !

How many ions?

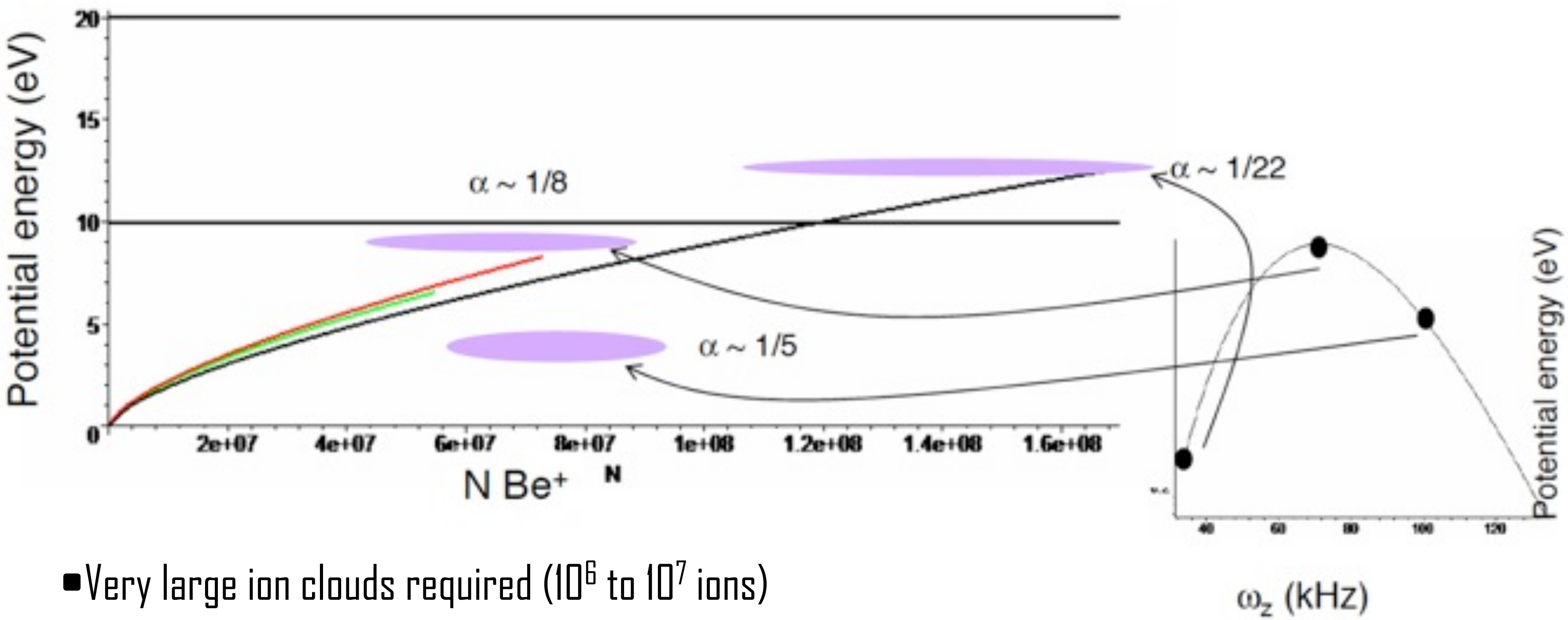
Trap transverse depth ~ 20 eV

r_0=3.5 mm

V_{RF} = 444 V Ω = 22 MHz $q(\bar{H}^+)$=0.36 $q(Be^+)$=0.04



$\omega_z(Be^+)$ → Be^+ cloud aspect ratio α=a/c



- Very large ion clouds required (10^6 to 10^7 ions)
- Time for cooling must be investigated (simulations) → Resistive cooling to 4K first?
- Test experiment with H_2^+ or p^+

GBAR Synoptic Scheme

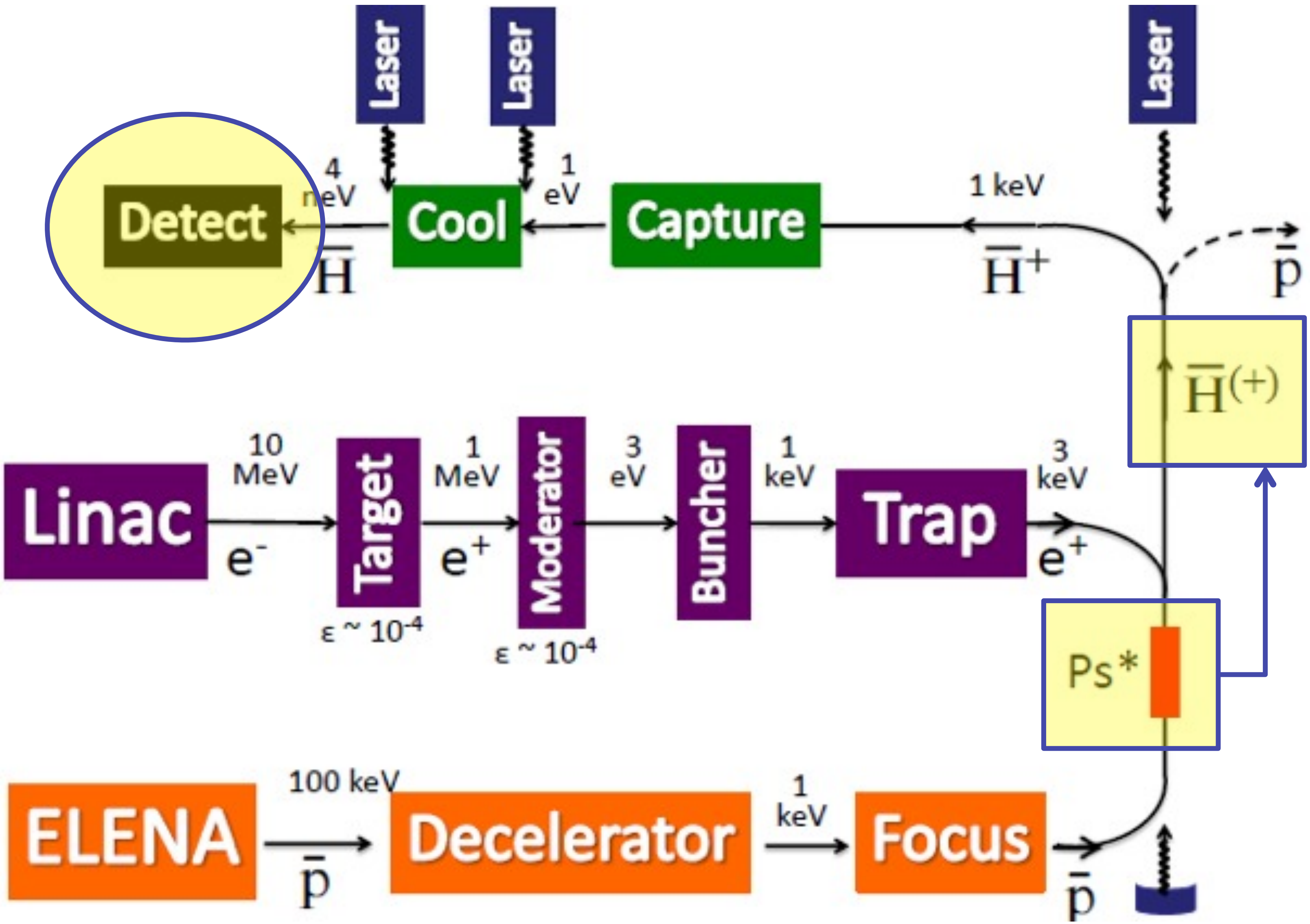


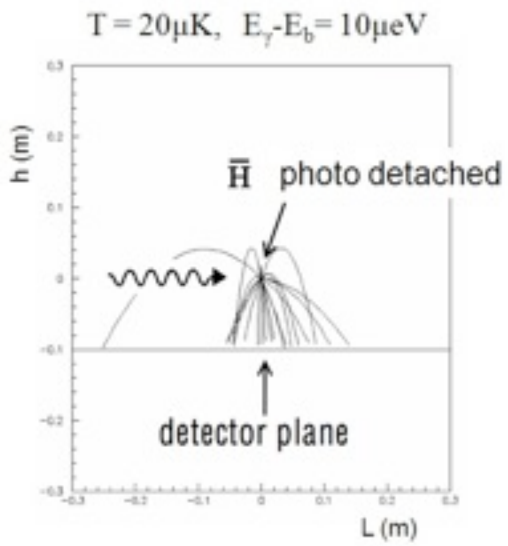
Photo-detachment

$\bar{H}^+$ 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 very close to threshold

$$E_c = E_\gamma - 0.76 \Rightarrow \quad v_{recoil} = \sqrt{\frac{2 m_e E_c}{m_H}} \quad \sim 0.3 \text{ m/s for } E_c = 1\ \mu\text{eV}$$

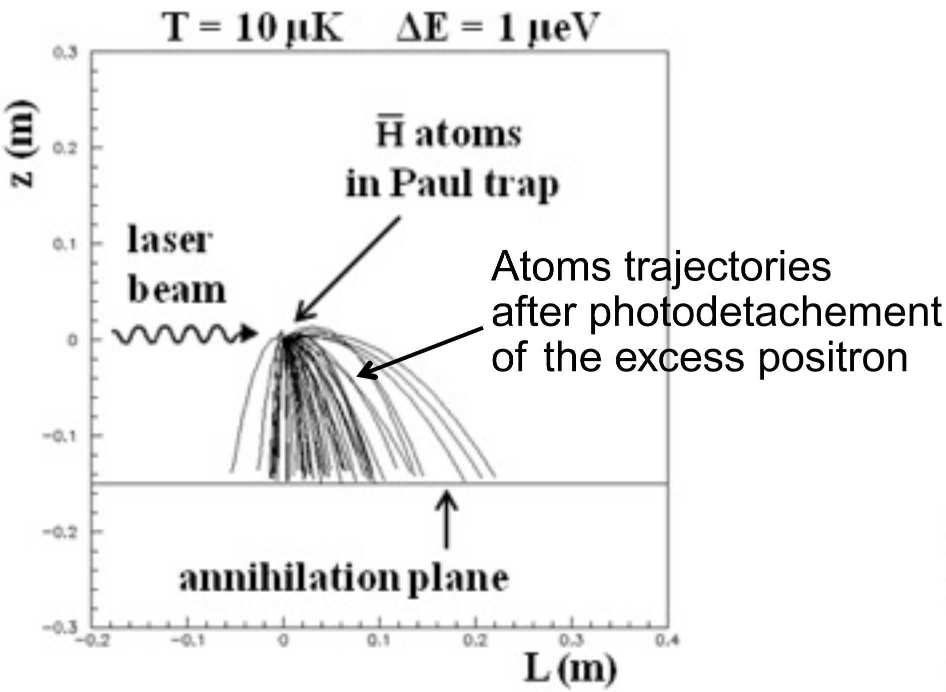


$\bar{H}$ free fall detection

-ejected e^+ direction => sign(v_z)
-arrival position x,y (mm) => v_x, v_y
-TOF (140 ms)

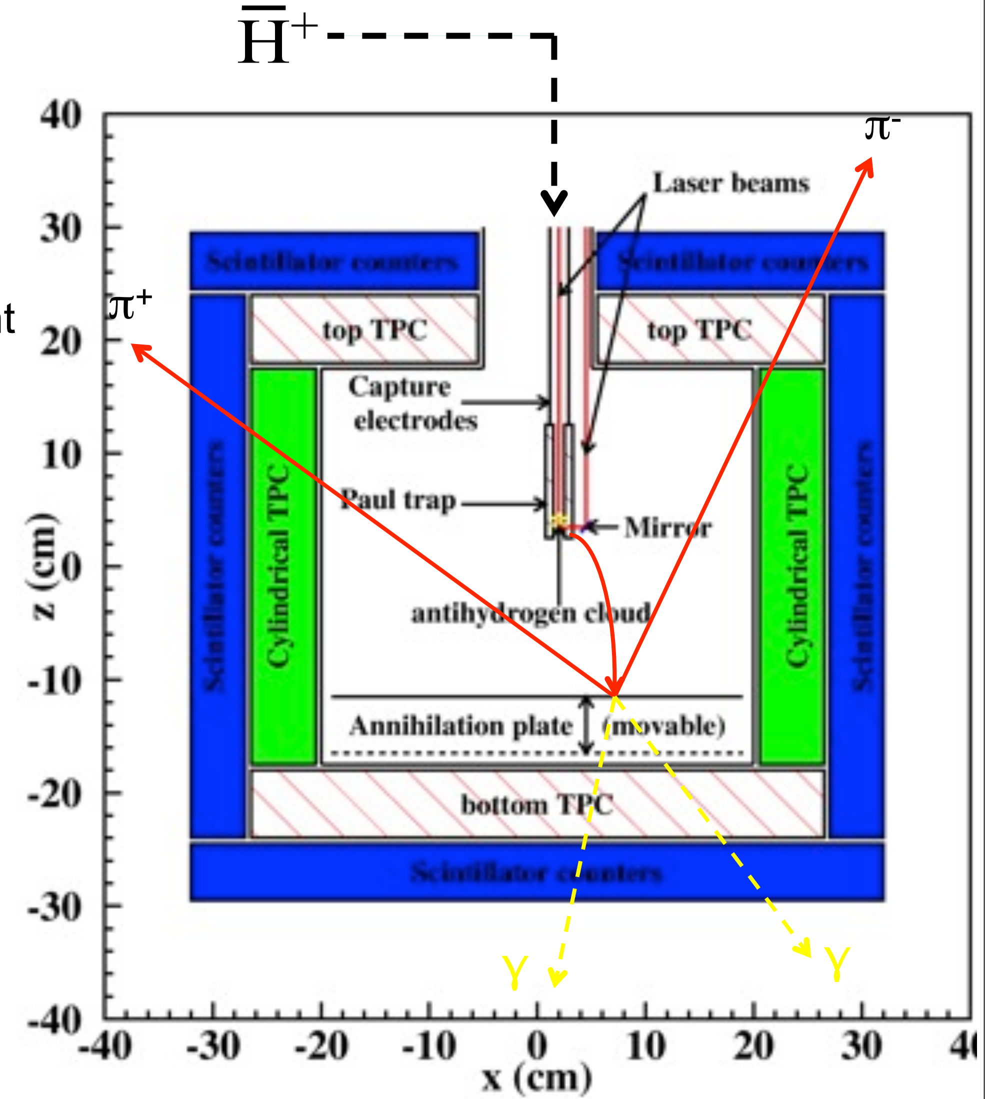
=> cross-check of initial temperature

Free fall measurement



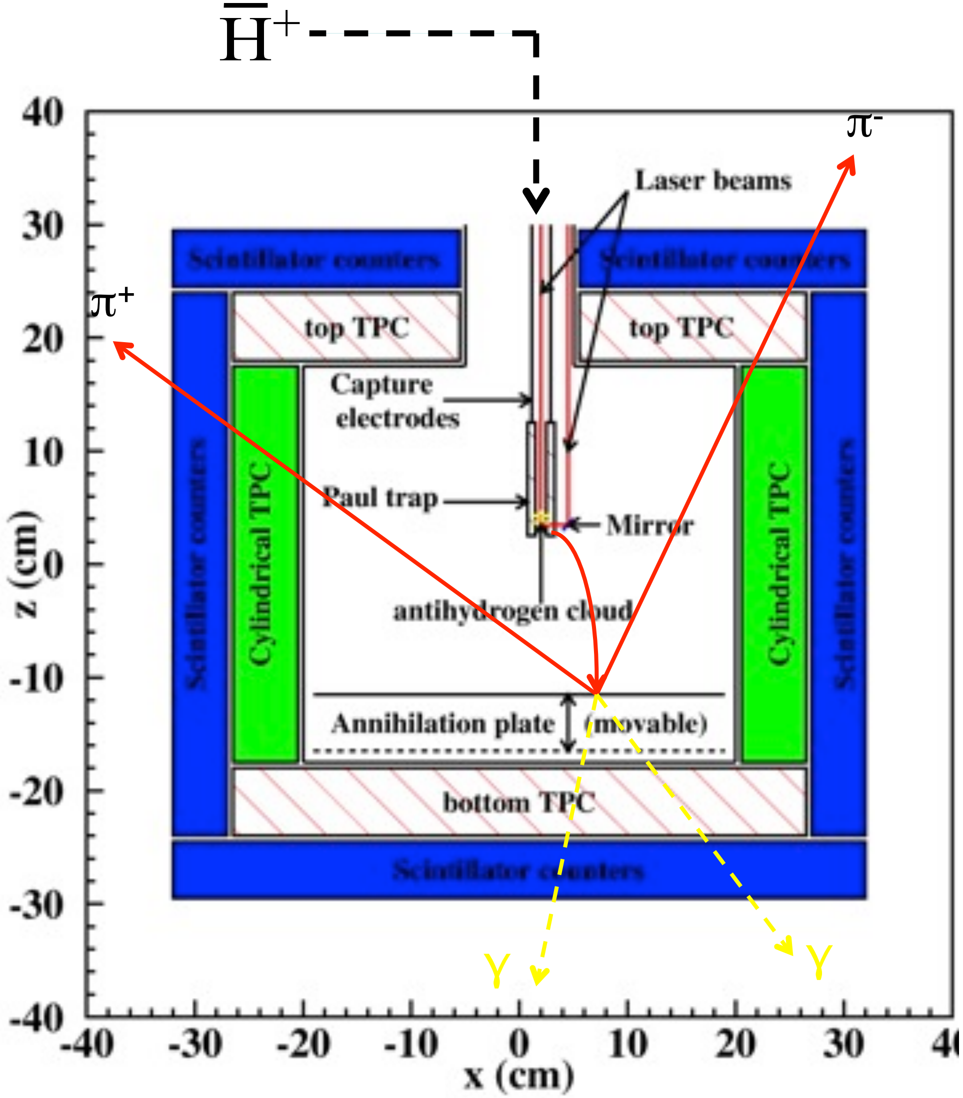
$h = 1/2\, \bar{g}\, (t_1-t_0)^2+v_{z0}(t_1-t_0)$

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



Free fall measurement

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



Efficiencies

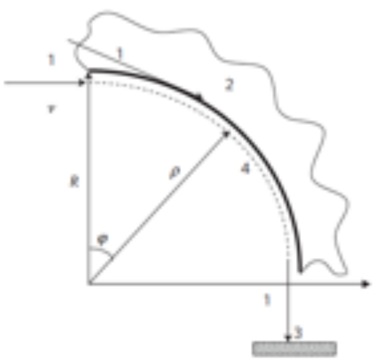
Electrons						
Linac frequency	Mean current	Pulse current	Pulse duration	Electrons per pulse	Electron rate (s^{-1})	
300 Hz	0.2 mA	0.33 A	2 µs	4.2×10^{12}	1.25×10^{15}	
Positrons						
Production efficiency (at 10 MeV)	Transport efficiency	Fast positrons per pulse	Fast positron rate (s^{-1})	Moderation 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 $\bar{H}$ atom	Production cross section of the $\bar{H}^+$ ion	$\bar{H}$ per pulse	$\bar{H}^+$ 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						
$\bar{H}^+$ Trapping efficiency	Cooling efficiency	cold $\bar{H}^+$ per pulse	Photodetachment efficiency	Detector acceptance	$\bar{H}$ events per pulse	$\bar{H}$ event rate (s^{-1})
100 %	70 %	0.2	99 %	65 %	0.14	1.3×10^{-3}

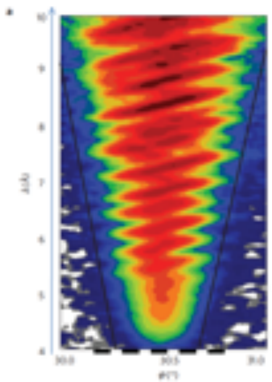
A few weeks of running to get 1500 events

All details in : P. Pérez et al, Proposal CERN - SPSC- 029 (2011)

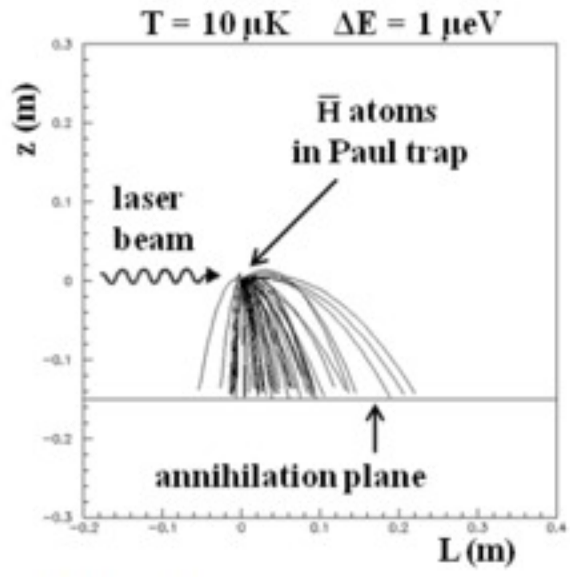
Casimir effect and quantum reflexion

- The potential due to the Casimir effect may create quantum reflexion at the surface of matter (the detector)
- The very slow antihydrogen atoms may bounce on the surface
- Already observed with neutrons (Quantum states of neutrons in the Earth's gravitational field. V.V. Nesvizhevsky et al Nature. 415 297-299, (2002).) and cold atoms
- Could be used to make more accurate measurements (Neutron whispering gallery. V.V. Nesvizhevsky, et al. Nature Physics. 6 114-117, (2010)) with quantum effects





Quantum reflection of antihydrogen



Quantum reflection of antihydrogen atoms from the Casimir potential of the detection plate

- suppresses close contact with the plate and therefore prevents annihilation
- would bias the free fall measurement, if not properly accounted for

Evaluations already done :

- Casimir-Polder potential for real plates
- Quantum reflection of cold antihydrogen atoms as a function of their energy, to be taken into account in the data analysis.

*G. Dufour, A. Gérardin, R. Guérout, A. Lambrecht, V.V. Nesvizhevsky, S. Reynaud, A.Yu. Voronin, **PRA 87** 012901 (2013)*

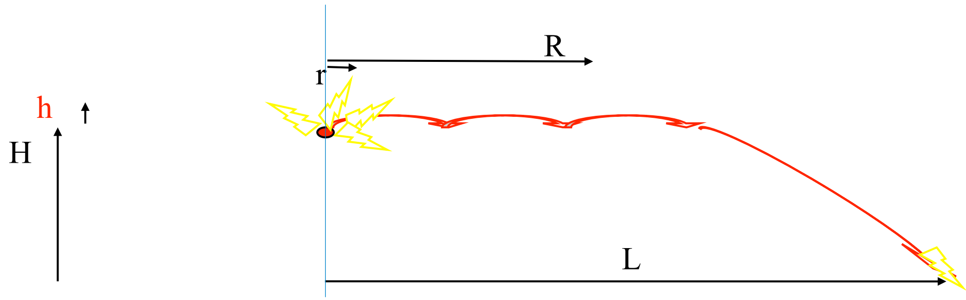
*G. Dufour, RG, AL, VVN, SR, AYuV, **PRA 87** 022506 (2013)*

Quantum reflection of antihydrogen

Quantum reflection of antihydrogen can be used for storing and manipulating antimatter with matter boundaries as well as for improving the test of the equivalence principle in evolutions of GBAR

*A.Yu. Voronin, V.V. Nesvizhevsky, S. Reynaud, **J. Phys. B 45** (2012) 165007*

For example, quantum reflection can be used for improving the accuracy in the measurement of the free fall acceleration (despite the degraded statistics)



Conclusion

- Antigravity must be studied experimentally using neutral objects
- The gbar project consist in making a source of antihydrogen+ ions (antimatter equivalent of H^-) using the AD, ELENA, a trap and a linac to produce antielectrons
- Project accepted by the CERN committee
- Accuracy aimed at in the first phase: 10^{-3} for 1500 events
- Accuracy possible using quantum reflection: 10^{-5}

Gbar

Does Antimatter imply Antigravity ?

Ladies and gentlemen Welcome.