The GBAR antimatter gravity experiment

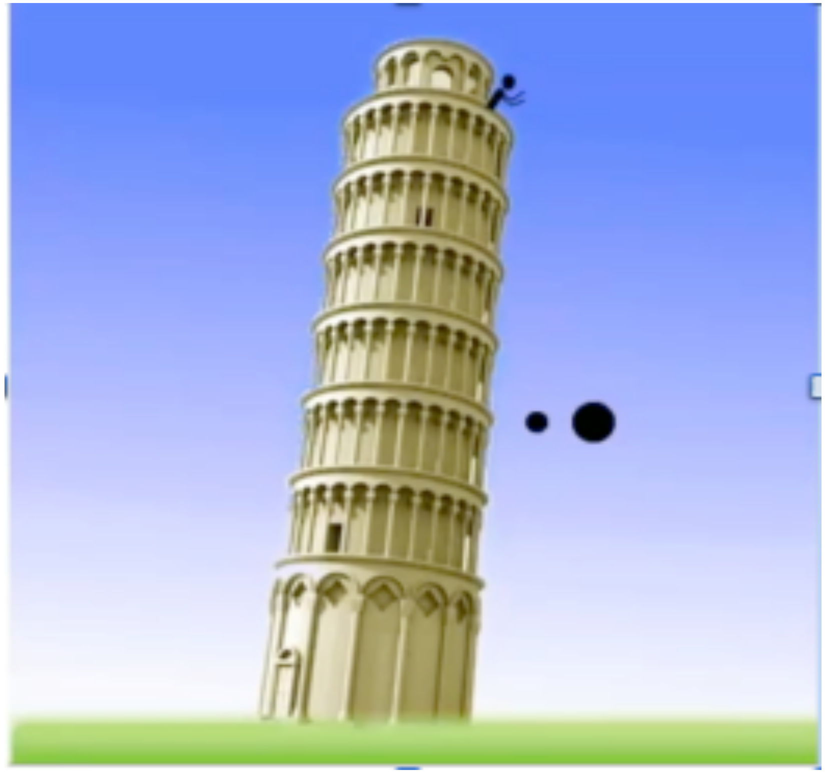
Equivalence Principle

"The trajectory of a point mass in a gravitational field depends only on its initial position and velocity, and is independent of its composition and structure."

$$\vec{P} = m_G \vec{g}$$
$$\vec{F} = m_I \vec{a}$$

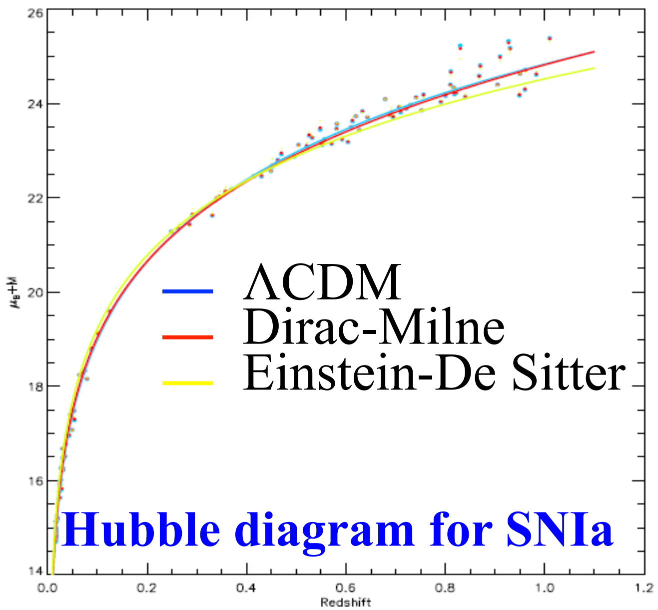
Apollo 15 – 1971

Galileo – 1602



Why study gravitation and antimatter?

- It has never been measured!
- No quantum theory of gravity
  - Big Bang model → same quantity of matter and antimatter, but Antimatter not seen!
  - energy content: matter (4%), dark matter(22%), dark energy (74%) of **unknown nature**
  - antigravity or modified gravity?



Attempts to construct cosmology with matter-antimatter symmetry + mechanism to keep them apart: gravitational repulsion

negative gravitational masses? gravitational dipoles?

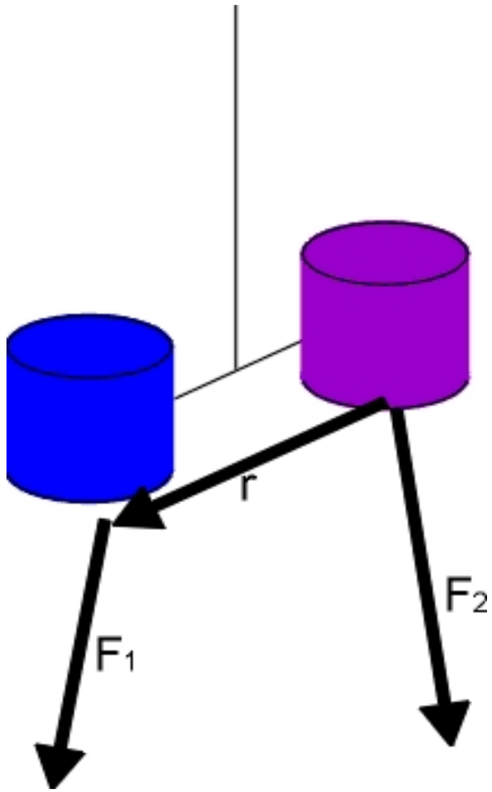
Quantum theories (superstrings, SUSY, …) contain scalar and vector terms on top of tensor → components of repulsive gravity

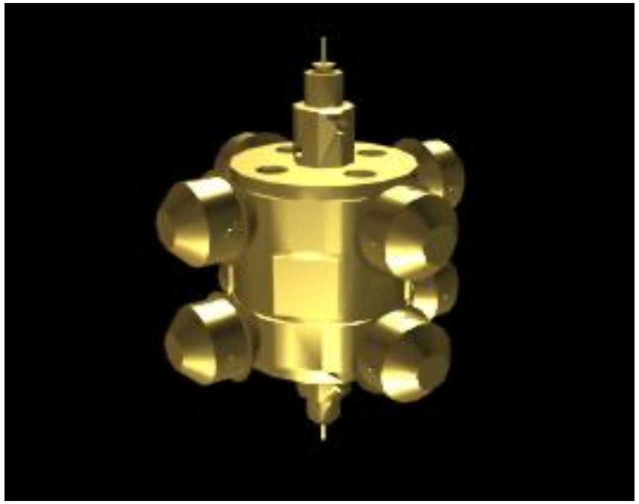
→ gravity may be more complicated than classically thought.

→ antimatter may behave differently in a gravity field generated by matter (the Earth)

Matter Experiments: best constraint

Torsion balance (Eötwash)





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

Antimatter Experiments: example constraints

- Cyclotron frequency of p & $\bar{p}$ in same B field

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

$$\omega = qB / 2\pi m + \alpha U / c^2 \qquad |\omega - \bar{\omega}| / \omega = (9 \pm 9) x10^{-11}$$

$$\rightarrow |g - \bar{g}| / g \leq 5 10^{-6}$$

- Arrival time of 1 (? : 90 % CL) neutrino and 18 antineutrinos from SN1987a

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

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

Antimatter Experiments: prospects

- Positrons (e^+) or Antiprotons ($\bar{p}$)

  gravity force on $e^\pm$

  ~ force from 1 elementary electric charge at 5 m

$$\frac{m_e g}{e} = 5.6\ 10^{-11}\ V\ /\ m$$

- Antineutrons

  difficult to slow down and keep enough

- Neutrinos

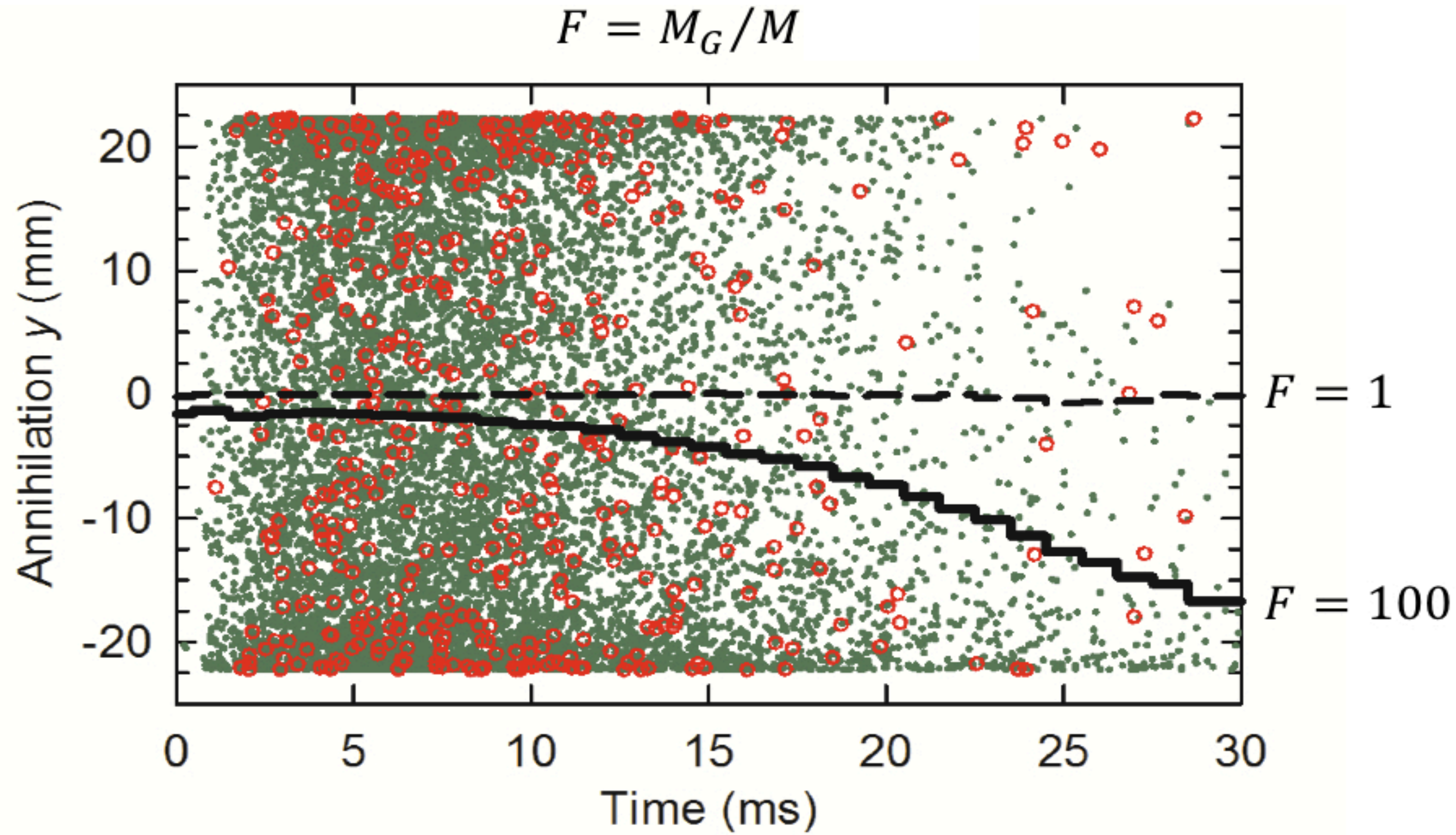
  wait for next supernova ?

- Positronium (e^+e^-)

  Lifetime 142 ns, cooling, ionisation by black body radiation, project by D. Cassidy at UCL

Antimatter Experiments: ALPHA result

Antihydrogen



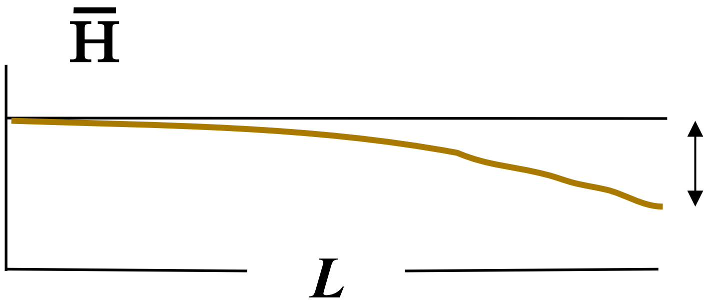
Green dots---simulated annihilations

Red circles---434 Observed annihilations

Position of annihilation vertex during release of trapping field

Antimatter Experiments: Antihydrogen gravity

$$m_i \vec{a} = m_g \vec{g}$$



$$h = v_z^0 t + \frac{1}{2}\frac{m_g}{m_i} g t^2 = v_z^0 \left(\frac{L}{v_h}\right) + \frac{1}{2}\frac{m_g}{m_i} g \left(\frac{L}{v_h}\right)^2$$

	AEGIS : $\bar{H}$ beam	GBAR : cooled $\bar{H}^+$ → slow $\bar{H}$
L	1 m	0.1 m
h	20 µm	20 cm
v_h	500 m/s	0.5 m/s
T_H	100 mK ~ 7 µeV	20 µK ~ 7 neV

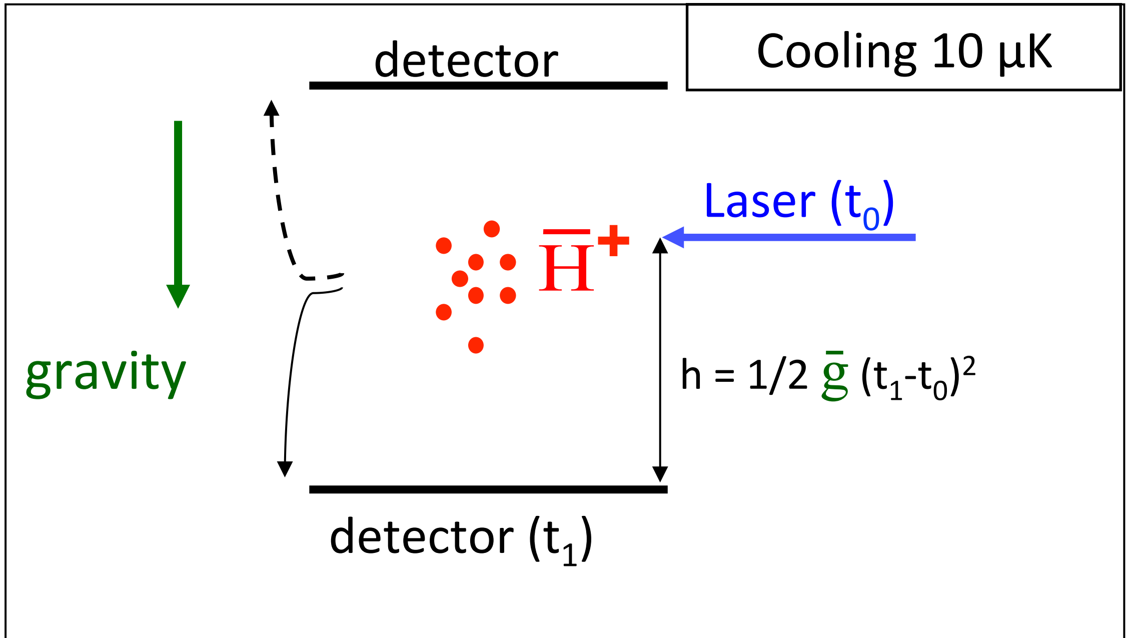
Goal

$$\frac{\Delta g}{g} \leq 1\%$$

Gravitational Behaviour of Antihydrogen at Rest

GBAR principle: cool $\bar{H}^+$ to get ultra-slow $\bar{H}$

- $\bar{H}^+ = \bar{p}\, e^+ e^+$
- Capture $\bar{H}^+$ in trap
- Sympathetic cooling with Be^+ → 10 μK
- Photodetachment of e^+
- Time of flight



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

h = 10 cm → Δt = 143 ms

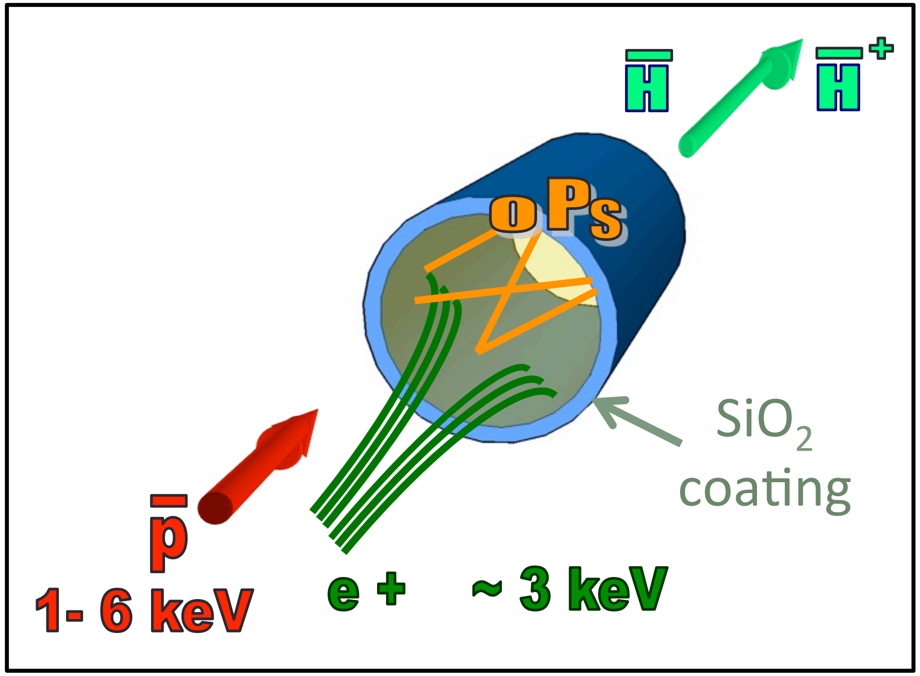
h = 1 mm → Δt = 14 ms

GBAR principle: $\bar{H}^+$ production

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

$\bar{H}^+$ Formation

Reaction first demonstrated by G. Gabrielse (2004)



bound e^+e^-

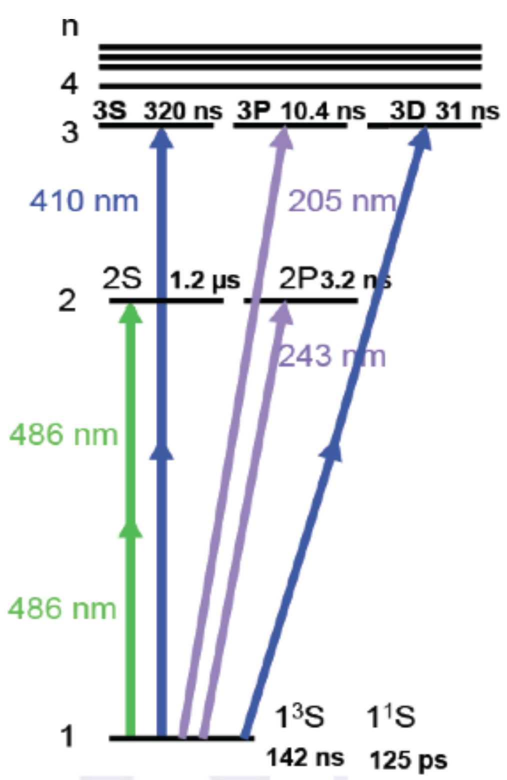
$$\bar{p} + Ps \rightarrow \bar{H} + e^-$$

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

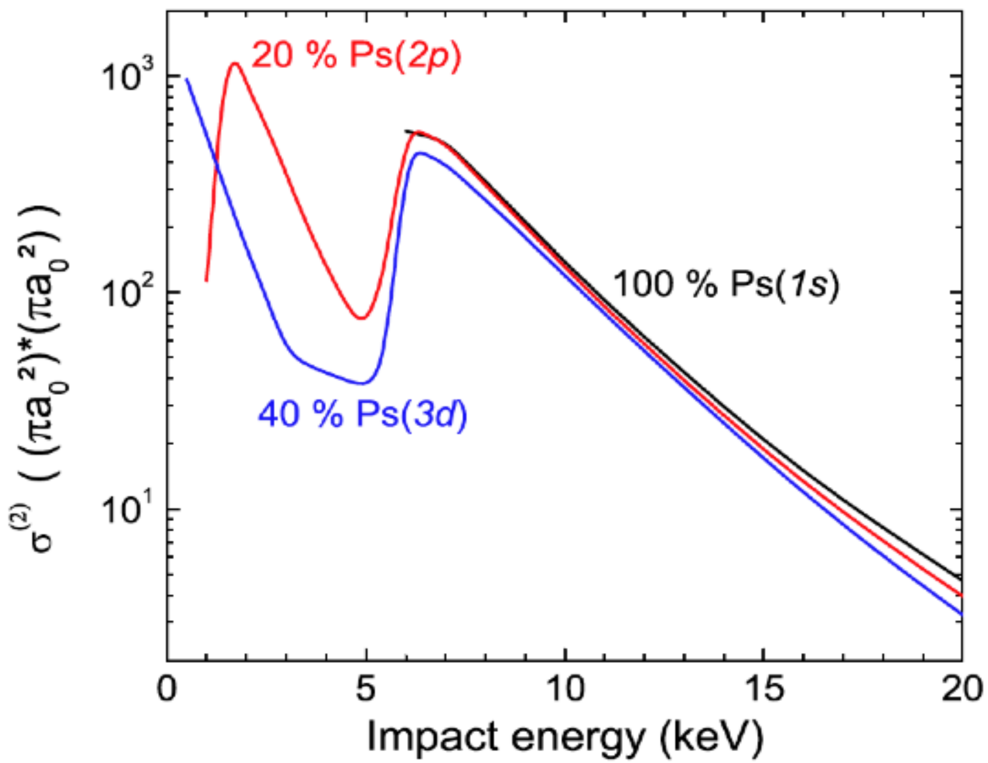
*P. Pérez & A. Rosowsky, NIM **A 532**, 523-532 (2004)*

$$\left.\begin{array}{l} 10^7\ \bar{p} \\ 10^{12}\ P_S/cm^2 \end{array}\right\} \longrightarrow \begin{array}{l} 10^4\ \bar{H} \\ 1\ \bar{H}^+ \end{array}$$

a possibility to enhance $\overline{\mathrm{H}}^+$ production

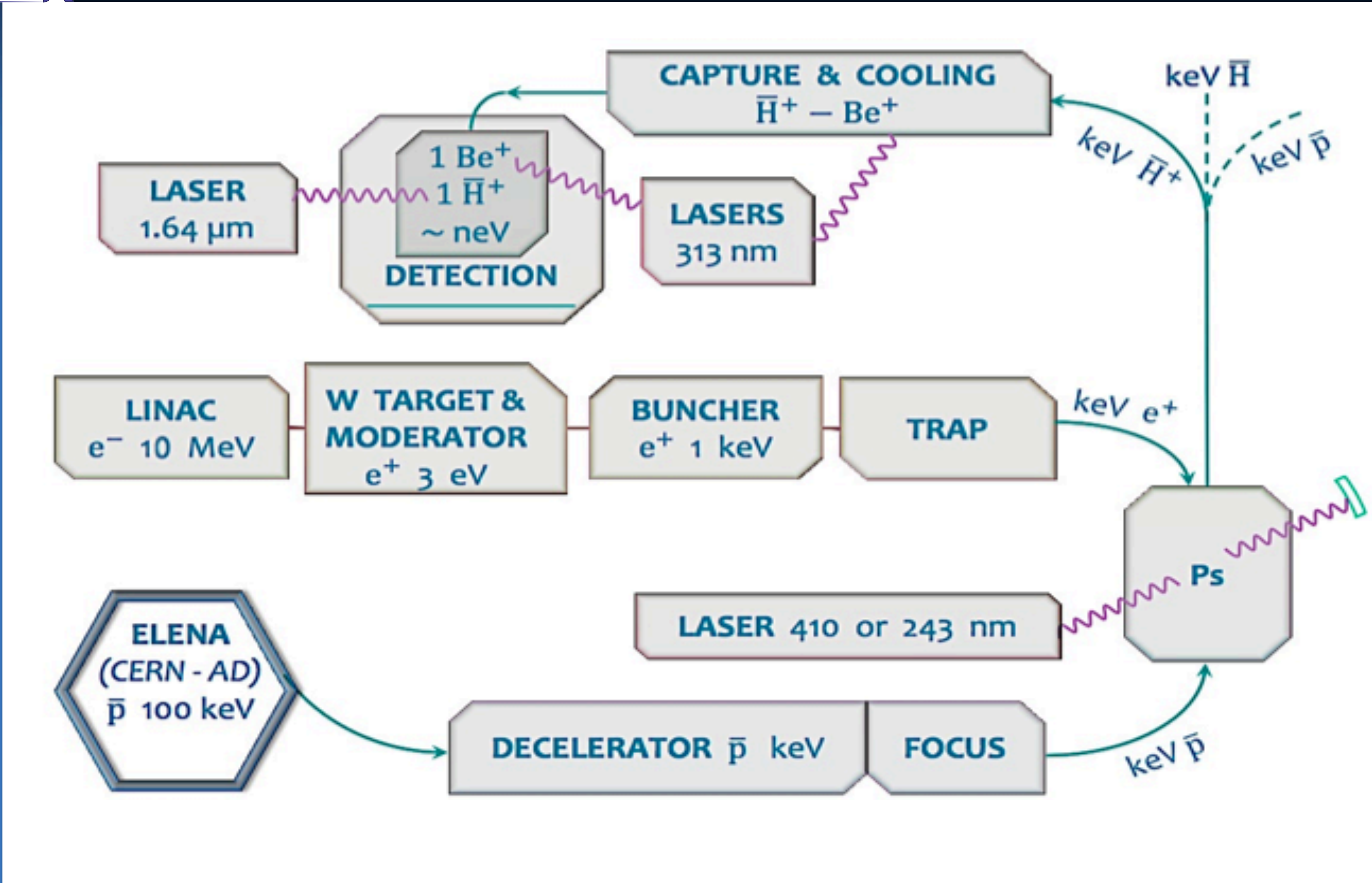


- $\bar{p} + Ps(n_{Ps}, l_{Ps}) \longrightarrow \overline{H}(n_H, l_H) + e^-$ (3-body)
- $\overline{H}(n_H, l_H) + Ps(n_{Ps}, l_{Ps}) \longrightarrow \overline{H}^+ + e^-$ (4-body)

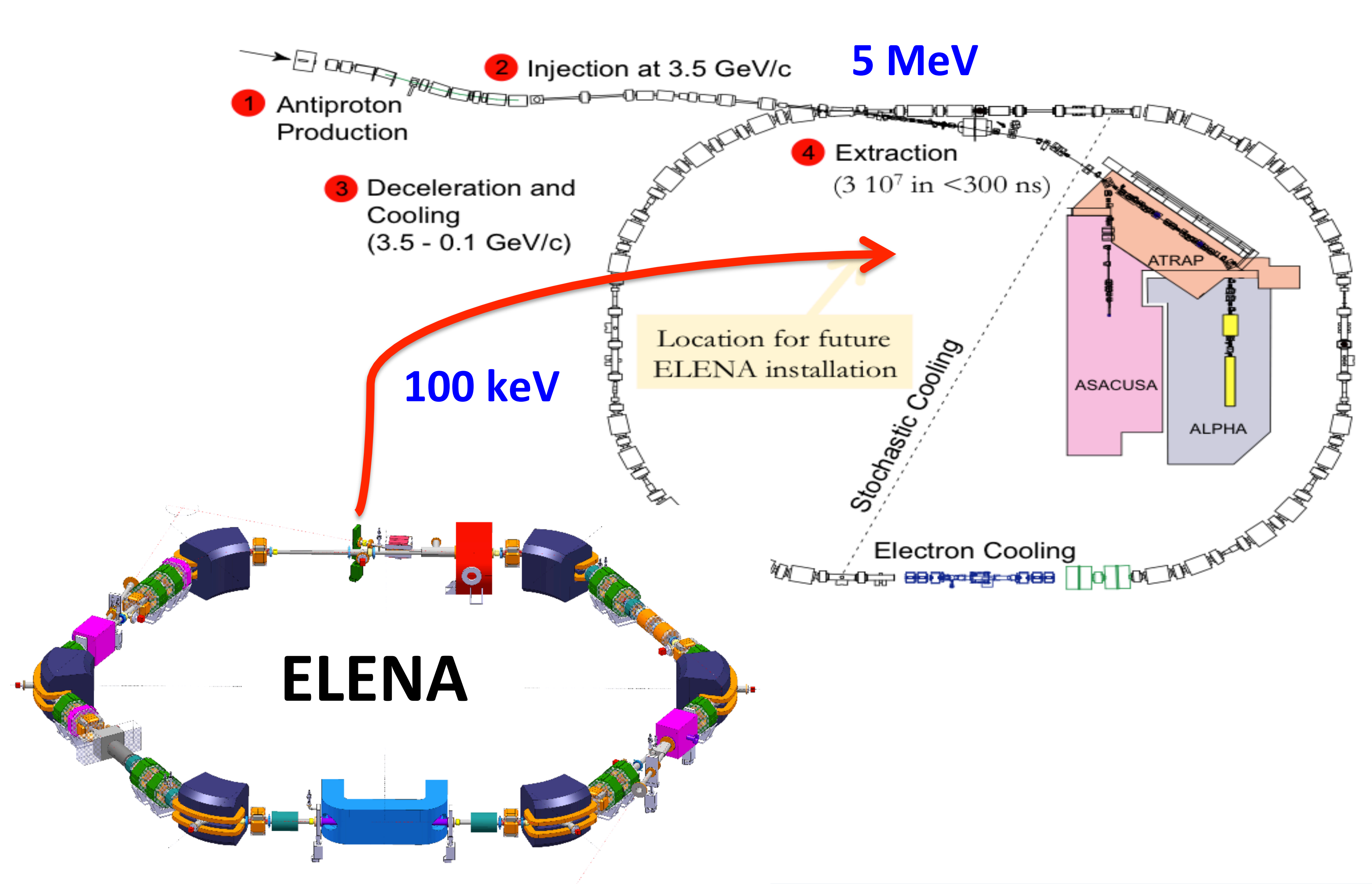


P. Comini and P-A. Hervieux, J. Phys.: Conf. Ser. **443**, 012007 (2013)
P. Comini, P-A. Hervieux and F. Biraben, LEAP 2013

GBAR overall scheme

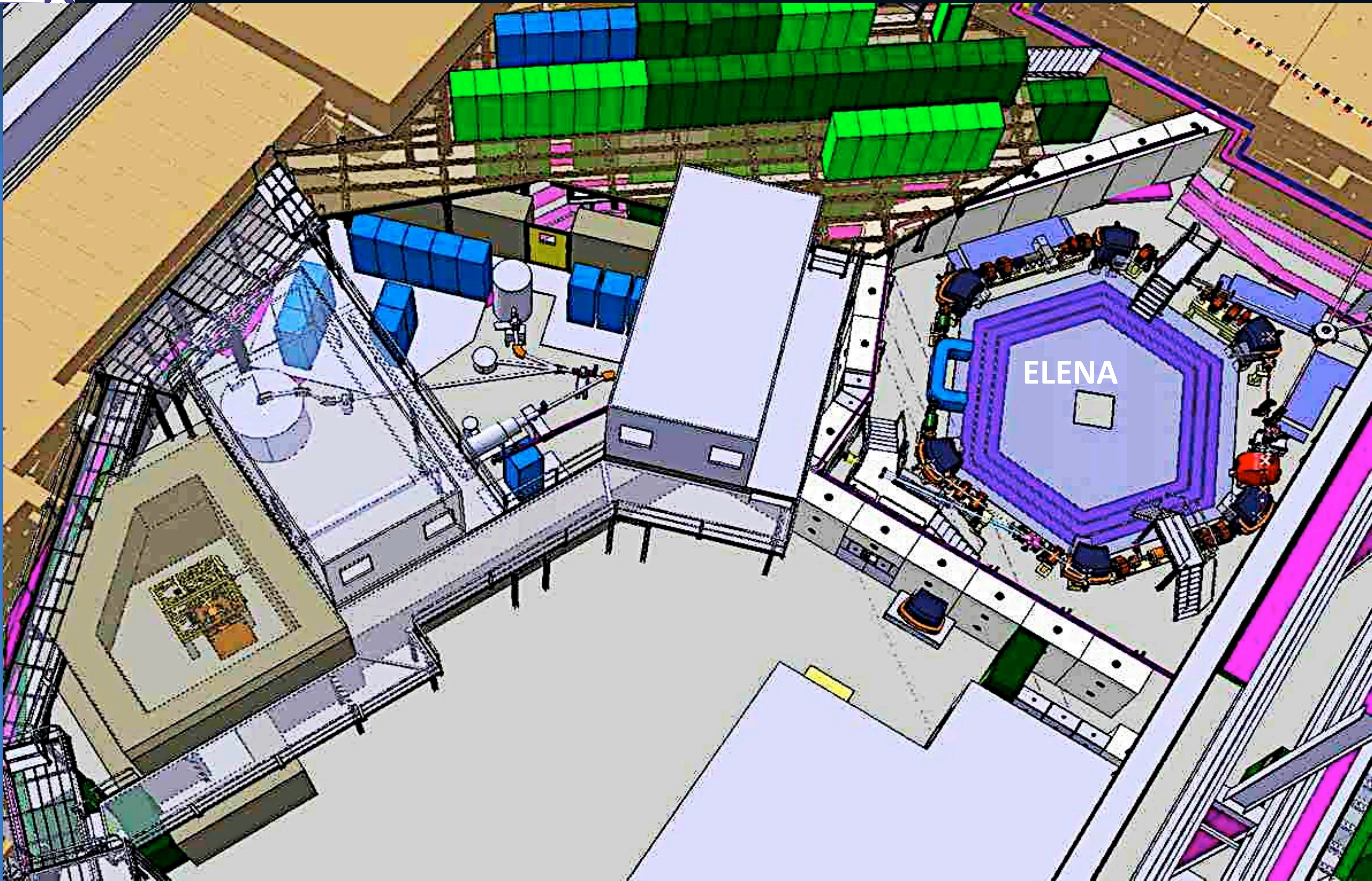


Antiprotons: CERN AD / ELENA



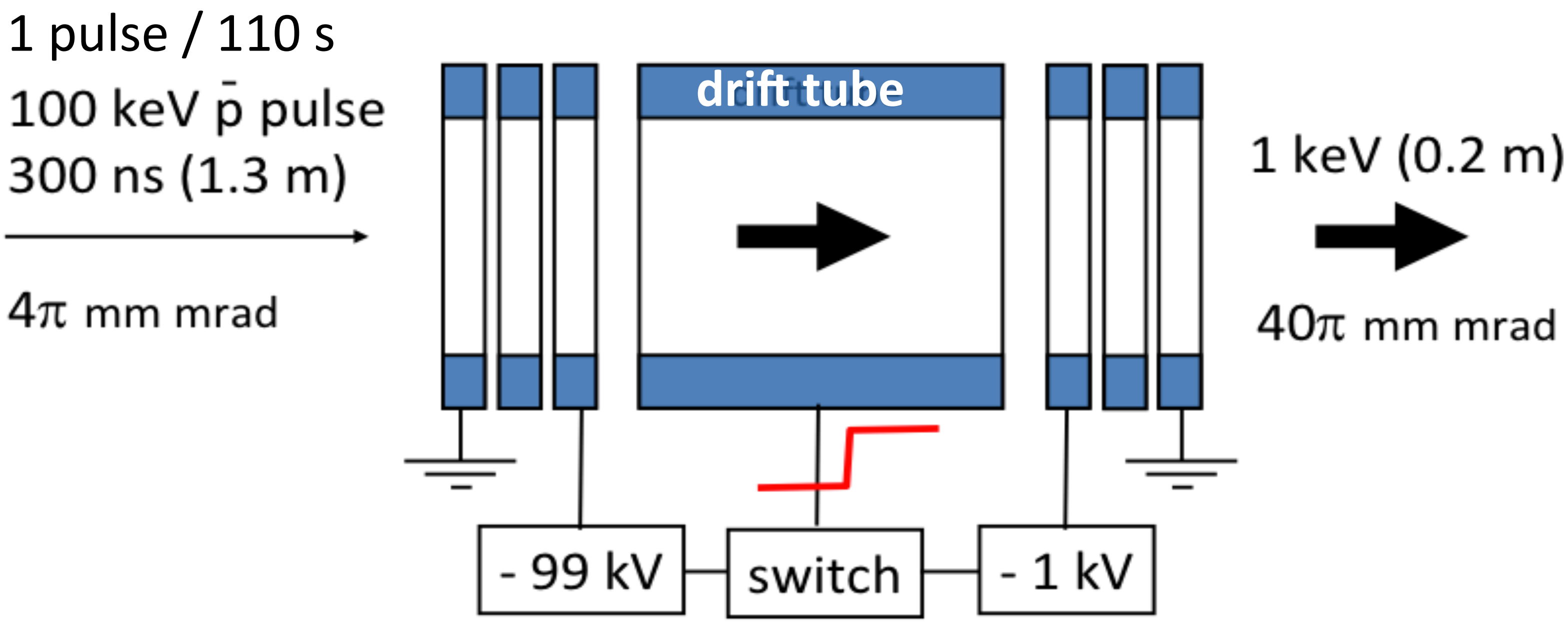
Layout

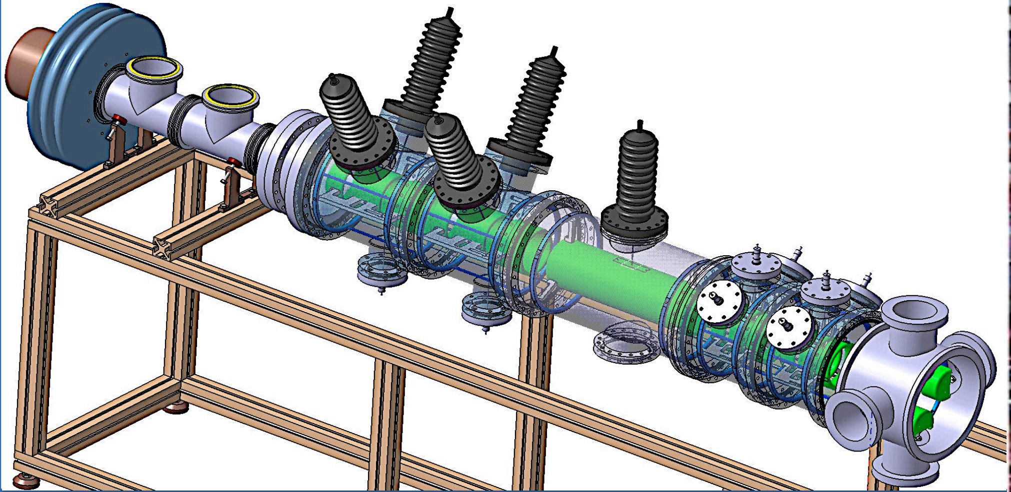
O. Choisnet
F. Butin

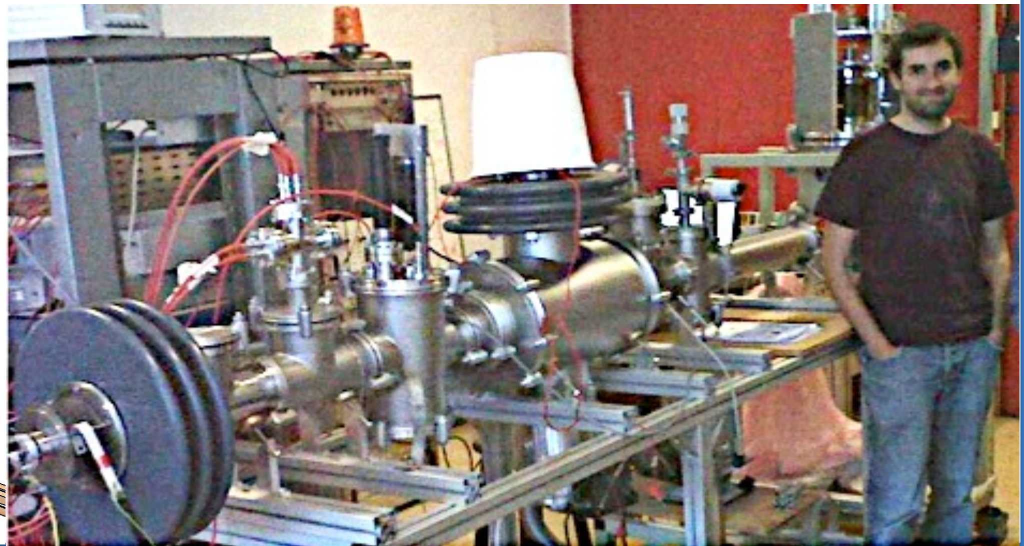


GBAR antiproton decelerator

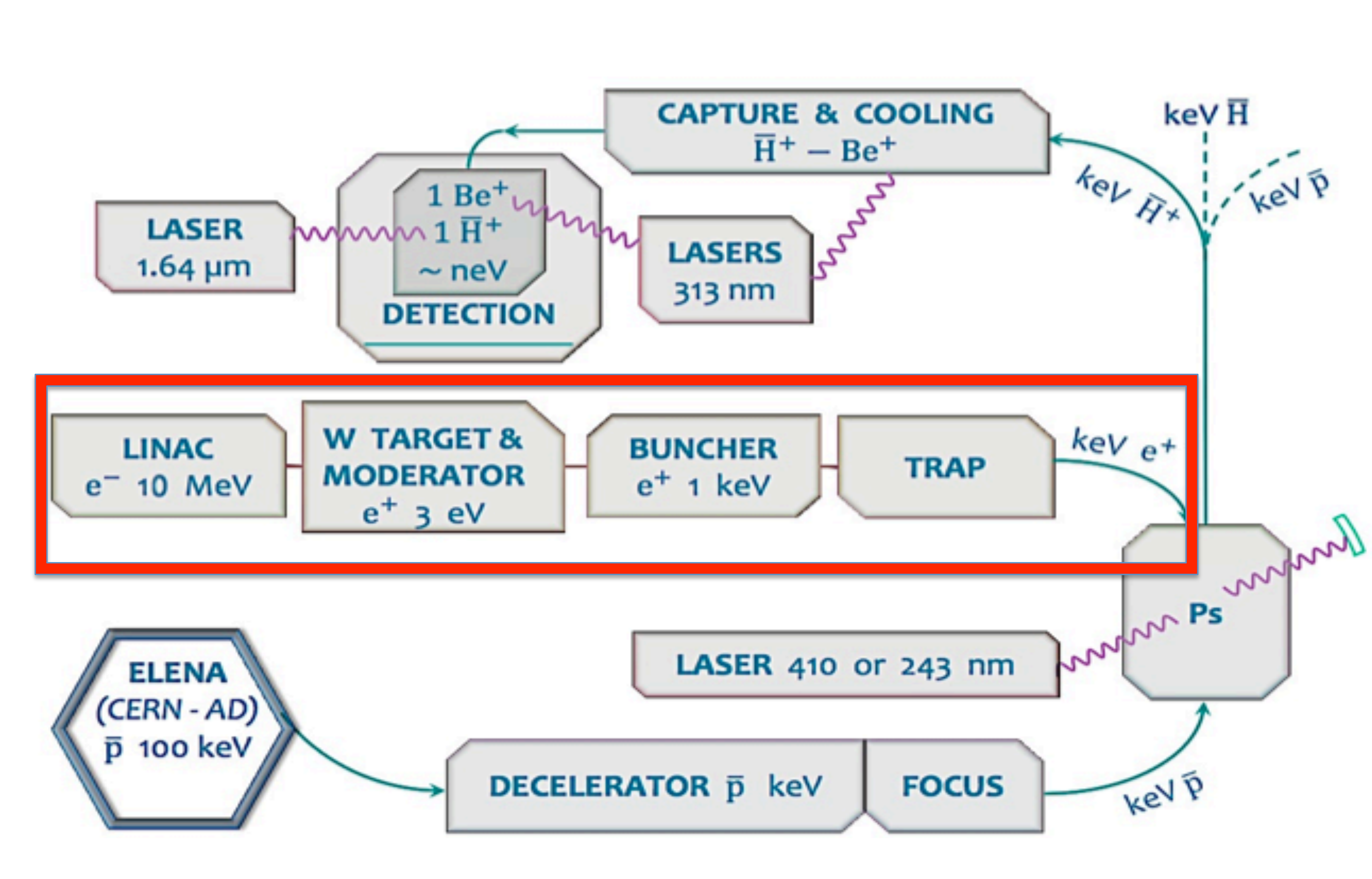
D. Lunney
P. Dupré



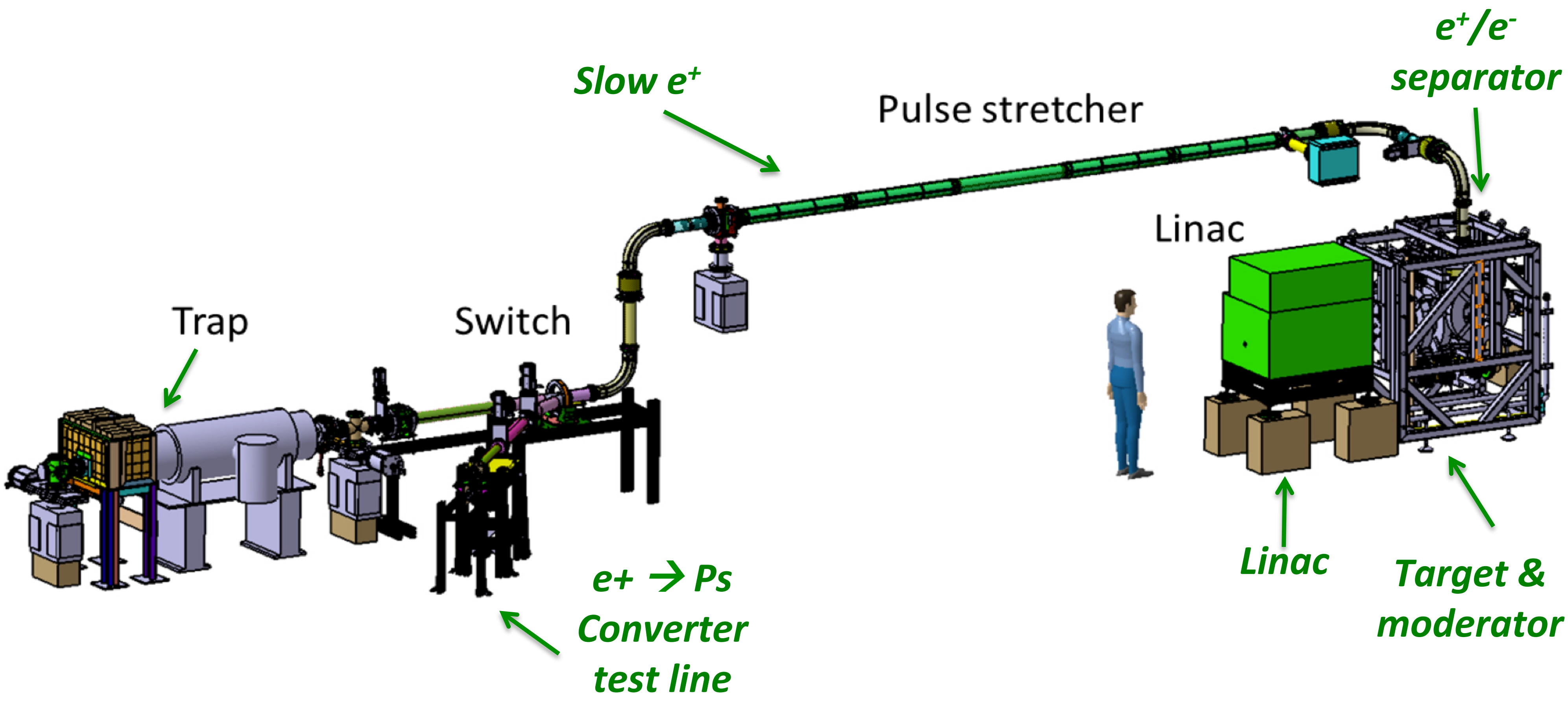




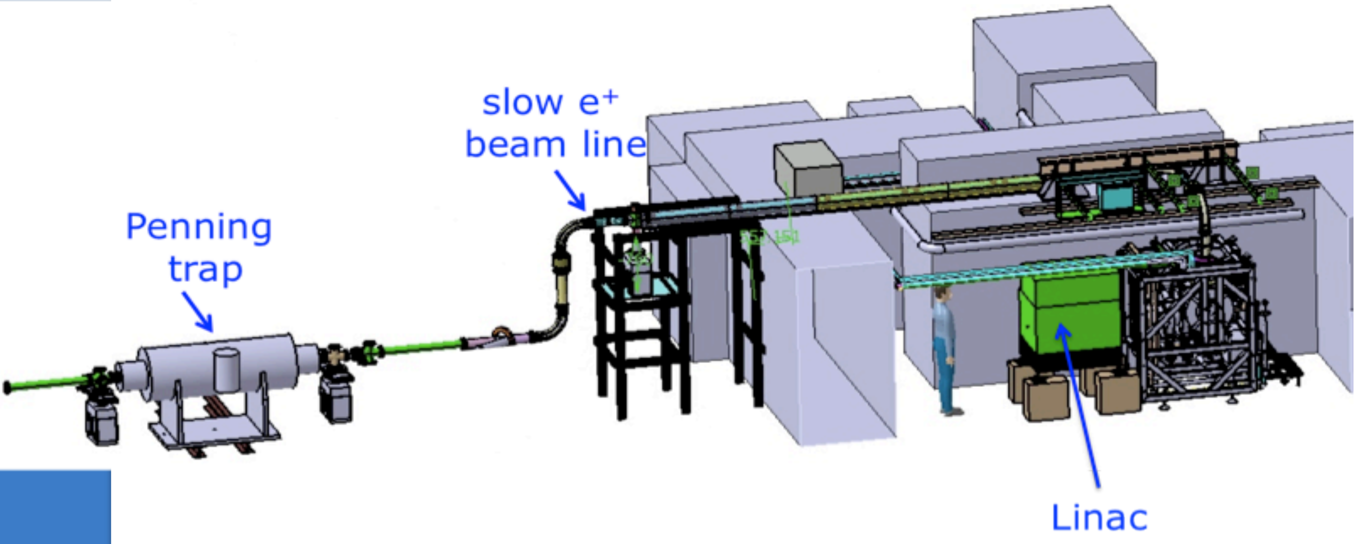
Positron production and storage



e+/Ps demonstrator at Saclay

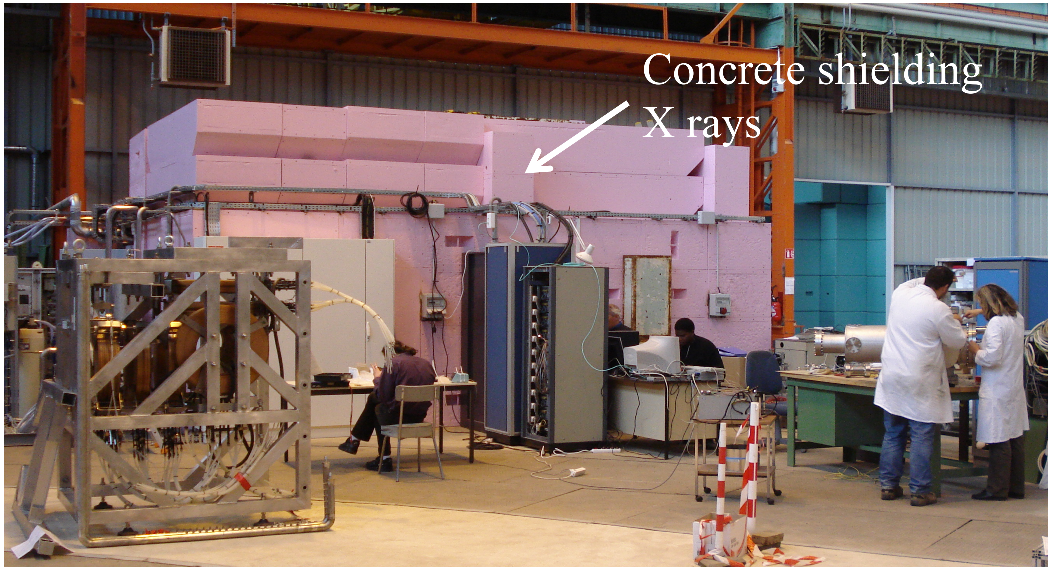


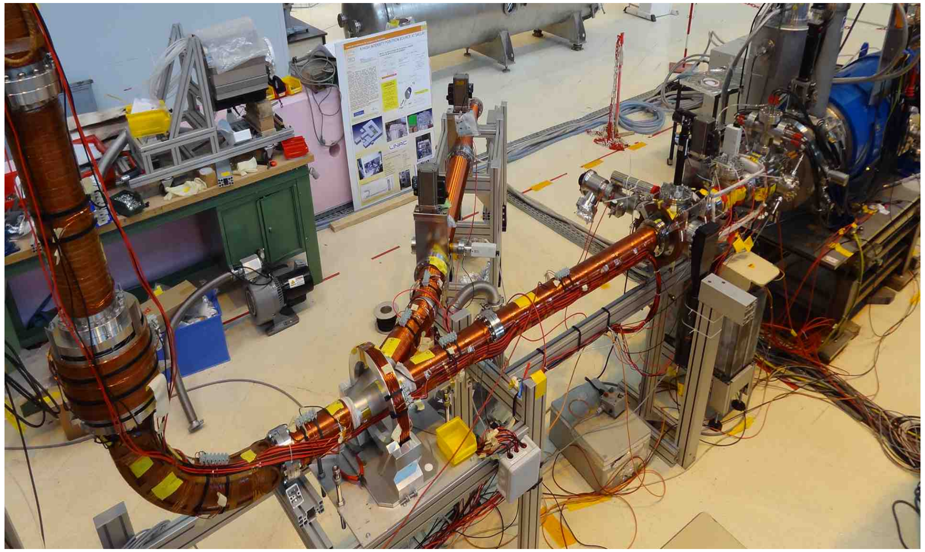
e+/Ps demonstrator at Saclay



- 4.3 MeV / 200 Hz / 2.5 µs / 120 µA
- 3 10^6 slow e^+/s
- with first W mesh moderator
- Penning trap on beam line (from RIKEN)
- First trapping trials
- Secondary beam line
- → moderator developments
- → e+/Ps converters
- Ps* laser being prepared at LKB (Paris)

e+/Ps demonstrator at Saclay

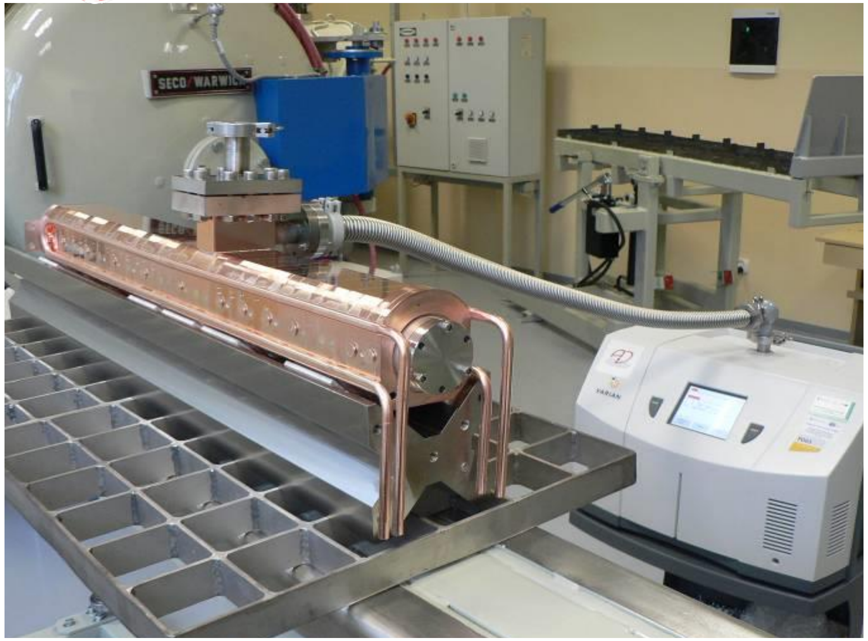


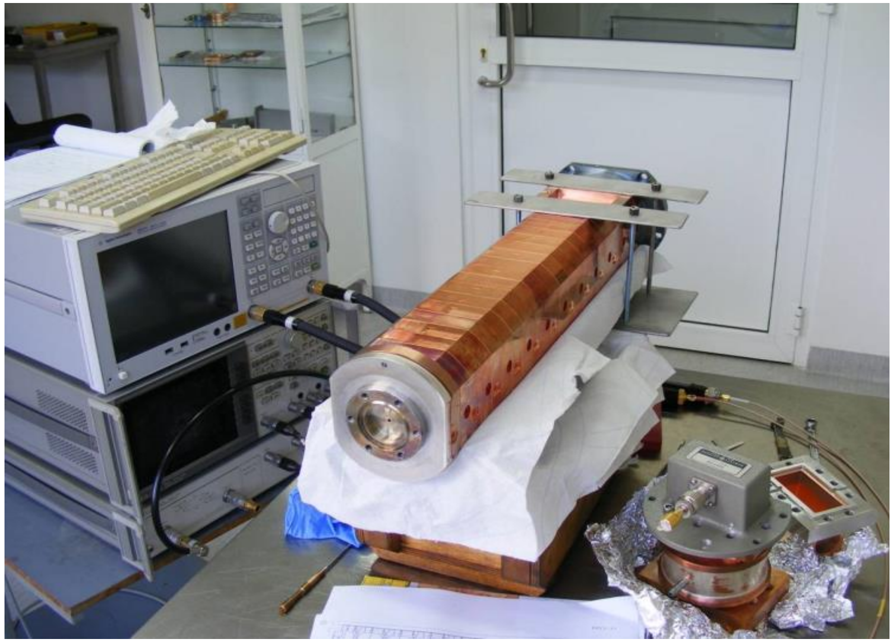


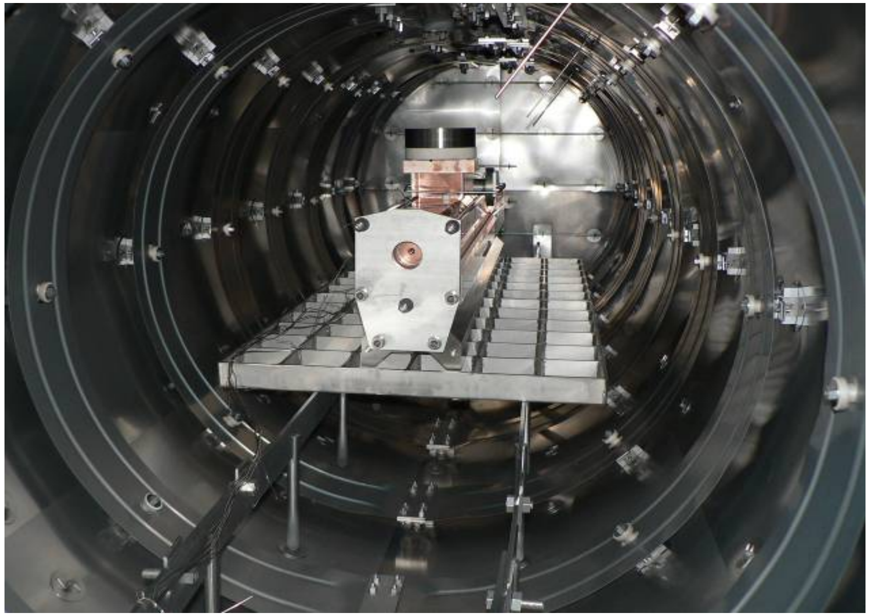
e$^-$ Linac   Ec = 4.3 MeV   I = 0.14 mA

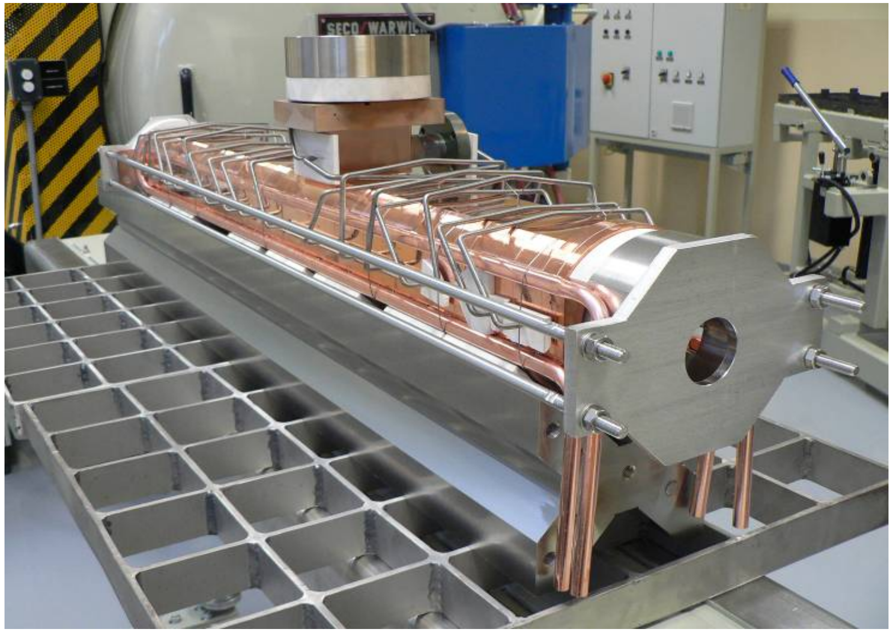
NCBJ workshops

S. Wronka
P. Krawczyk

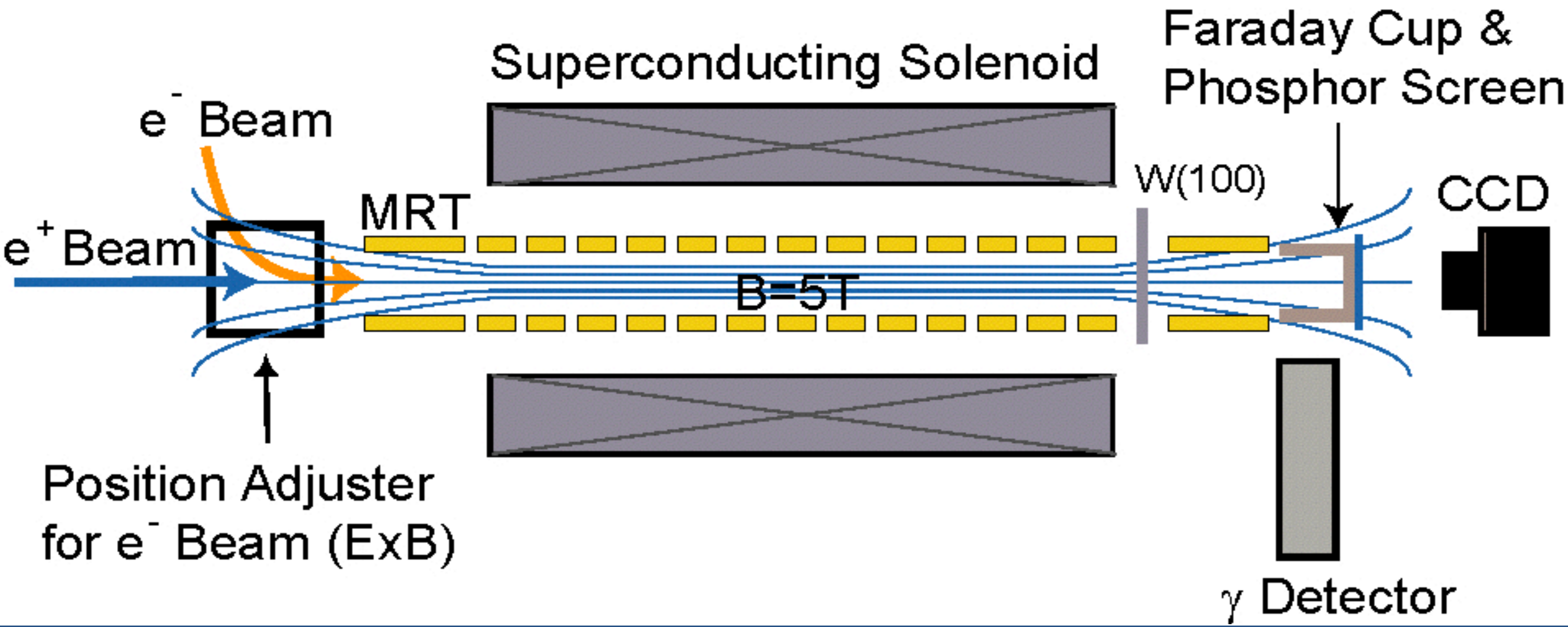






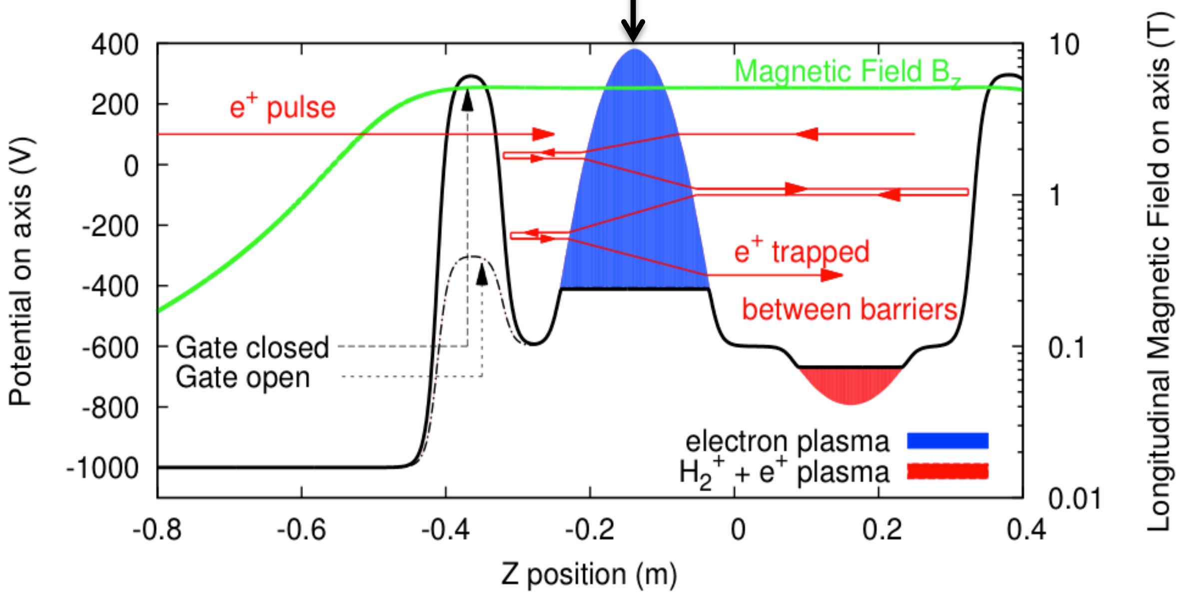


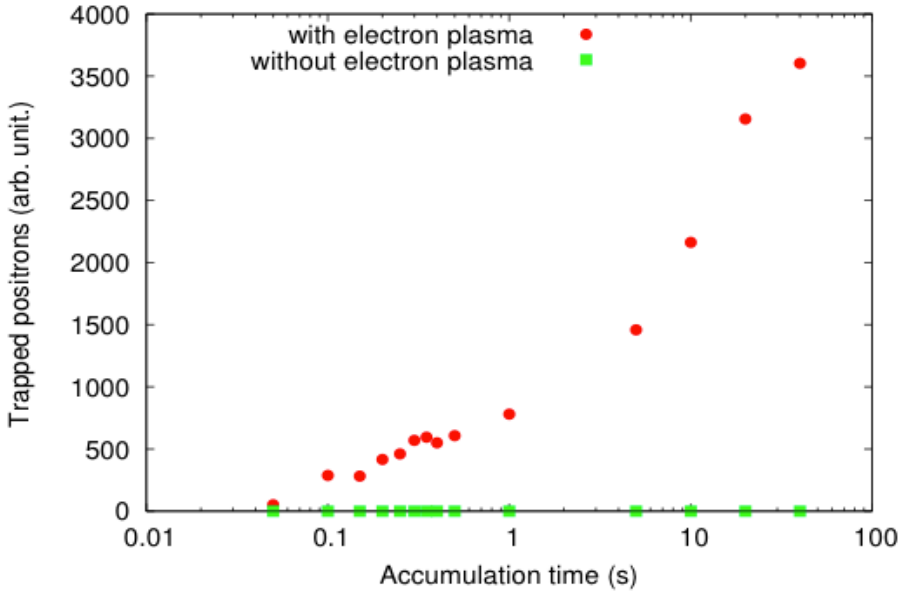
RIKEN Multi-Ring Trap



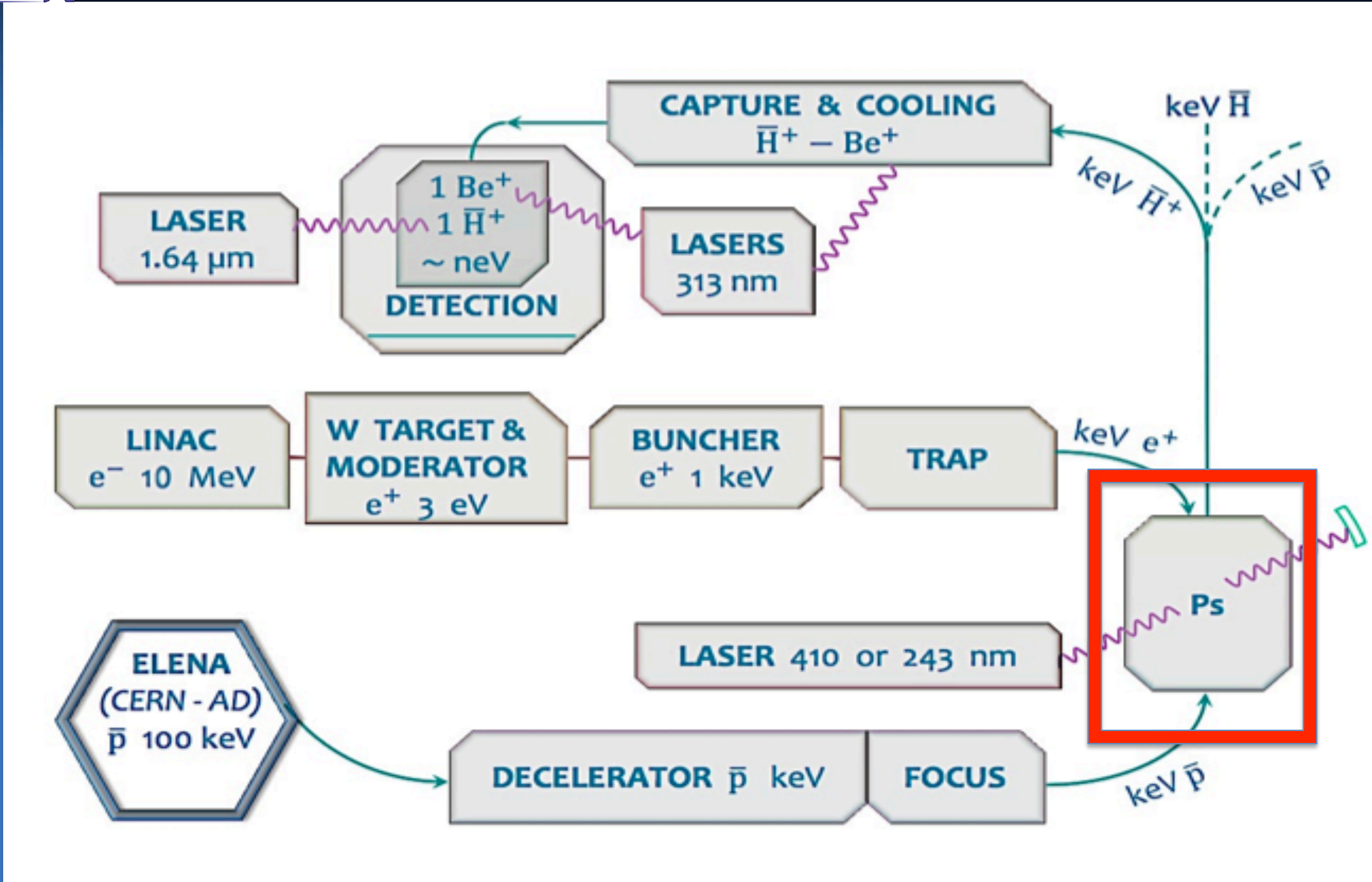
e^+ trapping

electron plasma for cooling

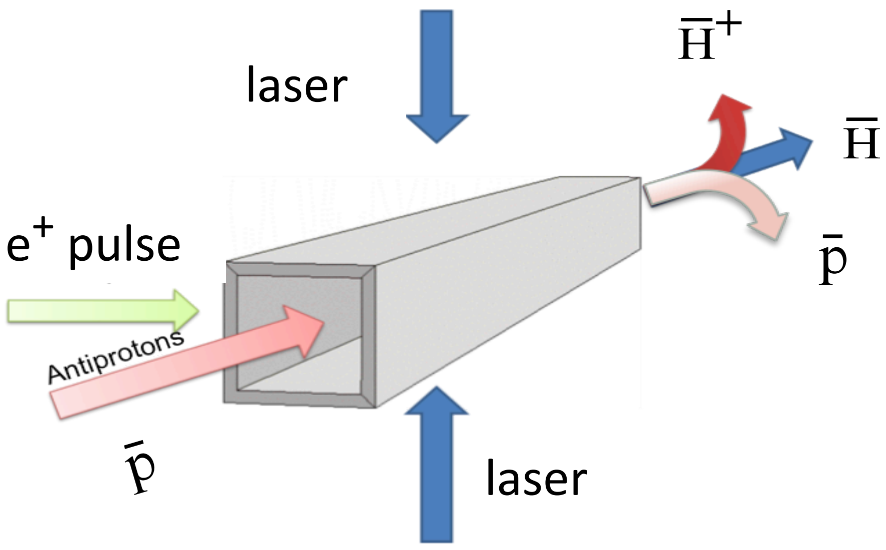


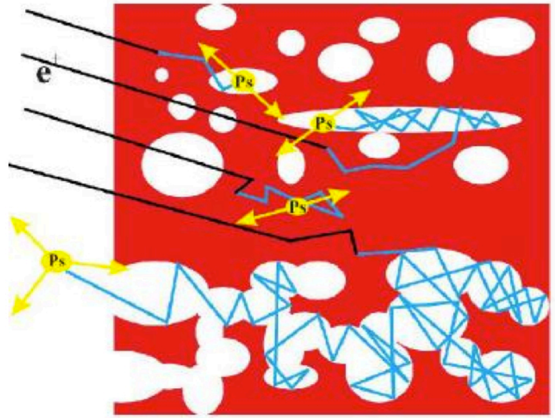


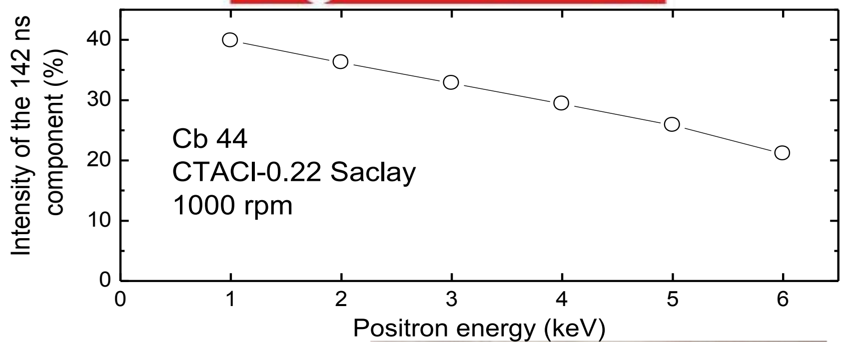
Positronium production



Ps formation





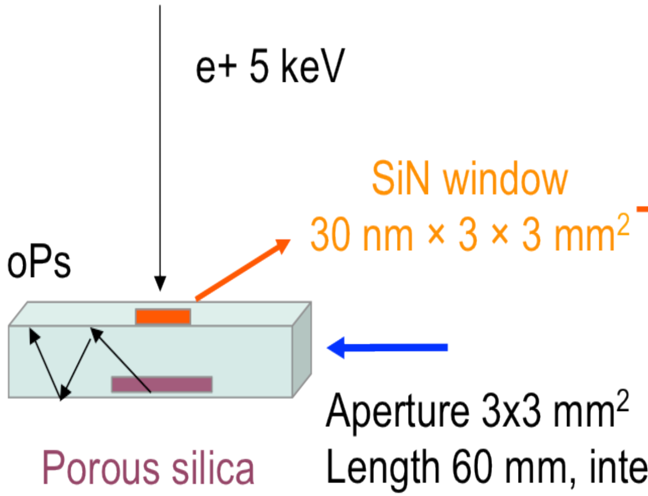


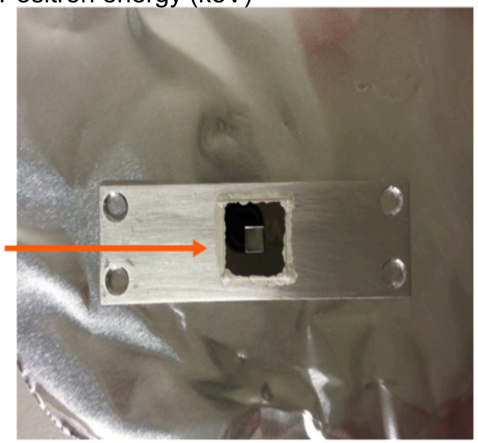
1 mm × 1 mm × 2 cm
Si with mesoporous SiO_2 coating

Test on ETHZ beam line

Transmission @ 5 keV ~ 100%
Ps formation efficiency as for bare SiO_2
Same Ps lifetime distribution

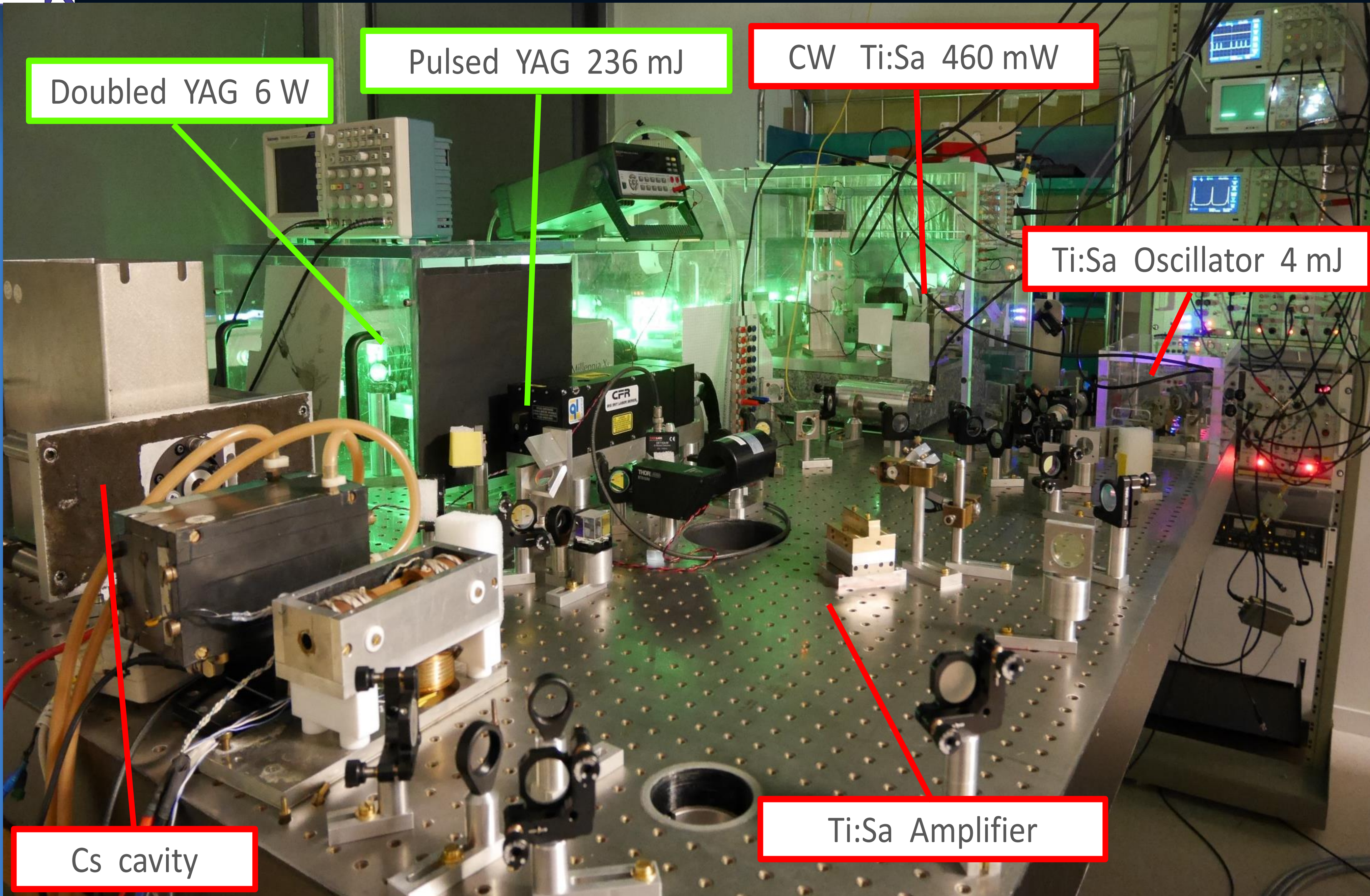
P. Crivelli, WAG2013



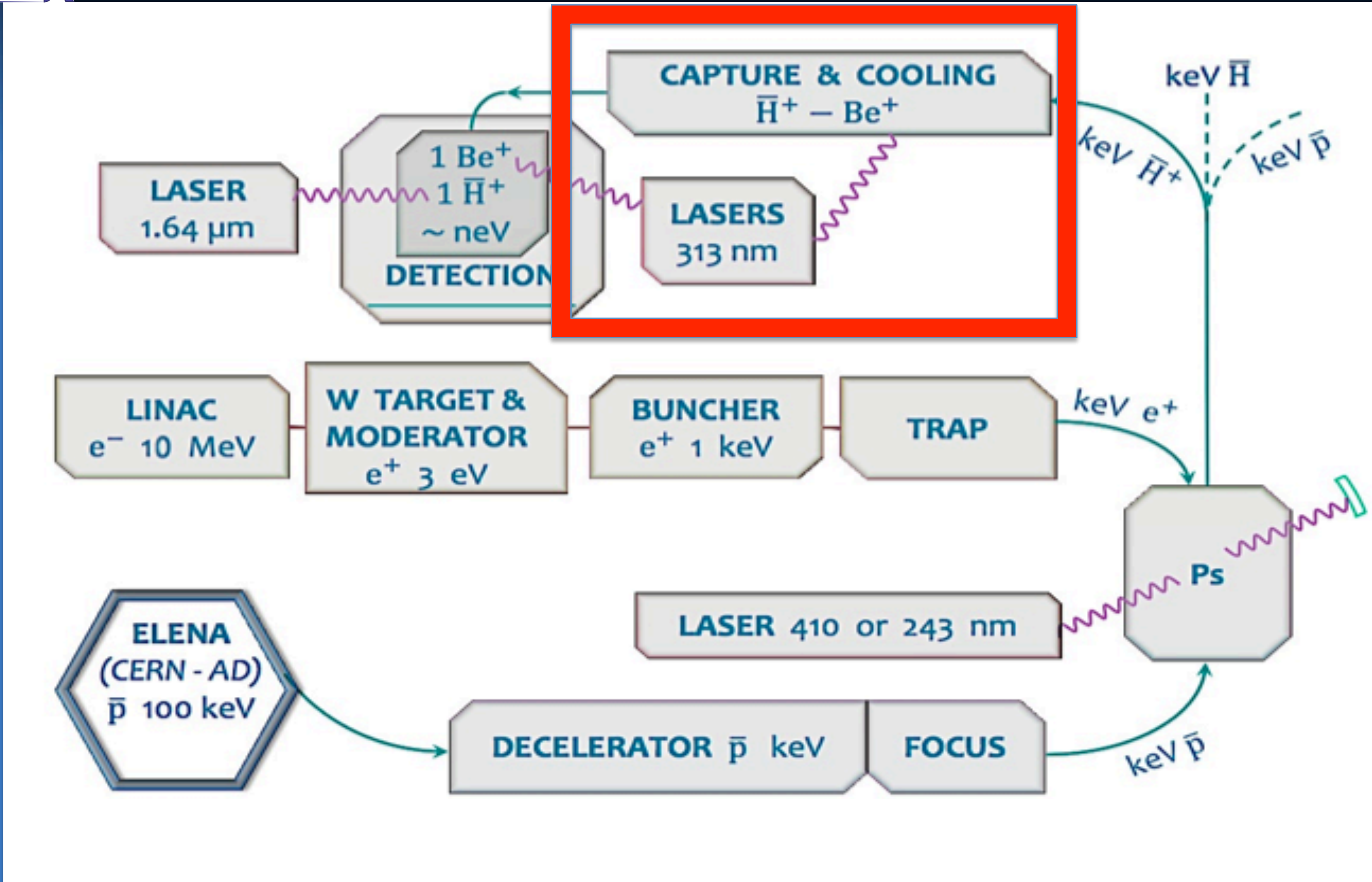


Aperture 3x3 mm²
Length 60 mm, internal walls coated with SiO2

Ps excitation laser (n=3)



Capture and cooling of $\bar{H}^+$



$\bar{H}$ with v < 1 m/s ?

L. Hilico et al., Int. Journal Mod. Phys: Conf. Series, 30 (2014) 1460269.

Cooling challenges

Reaction chamber → Capture + Cooling → Cold trapped $\bar{H}^+$

Kinetic energy 1 .. 6 keV
Temperature 60 .. 300 eV
700 000 K

÷ $10^{10..11}$

Trapped particle
Temperature 3 neV
20 µK

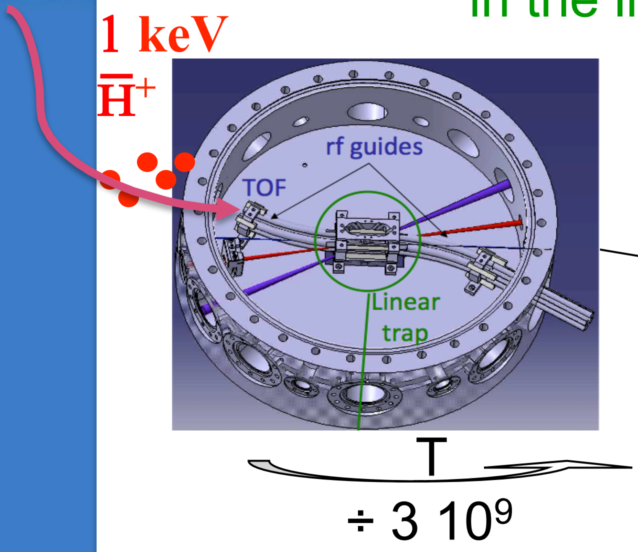
Classical world → Frontiers of Quantum world

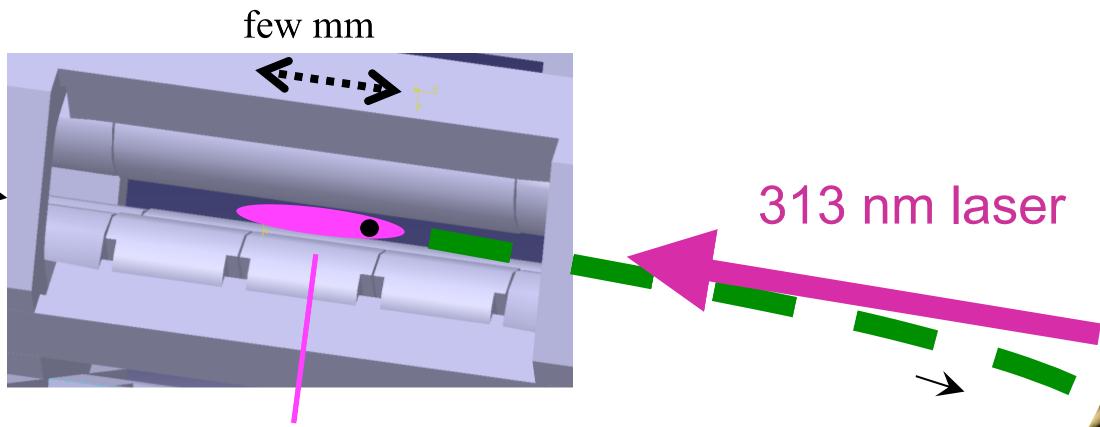
NIST D. Wineland
Innsbruck R. Blatt

L. Hilico
F. Schmidt-Kaler

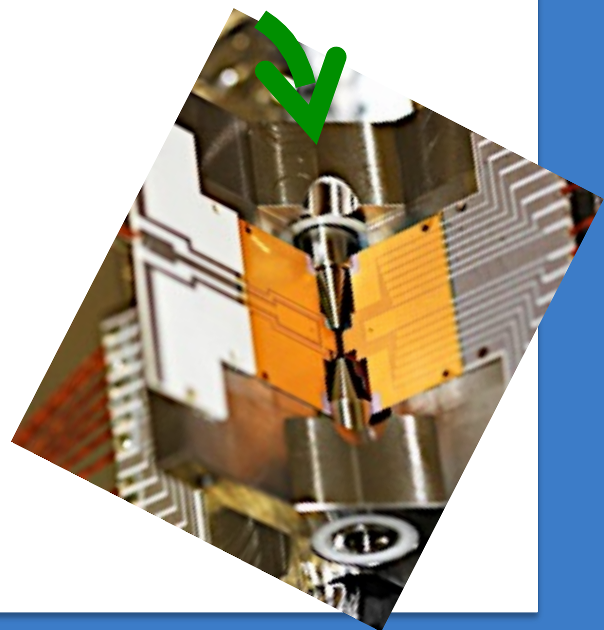
Two cooling steps

First step Capture and sympathetic Doppler cooling by laser cooled Be^+ ions in the linear **capture trap** (Paul trap, r_0 = 3.5 mm, Ω = 13 MHz)





> 10 000 laser cooled Be^+ ions
100 neV, T ~ mK



Second step

Transfer and ground state cooling of a $Be^+/\overline{H}^+$ ion pair in the **precision trap**

tests with H_2^+ / H^+ REMPI source

$\bar{H}^+$ cooling simulations

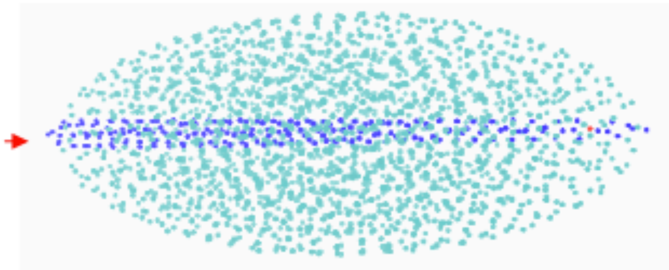
L. Hilico

9/1 mass ratio : bad mechanical coupling
9/2 mass ratio : much better mechanical coupling

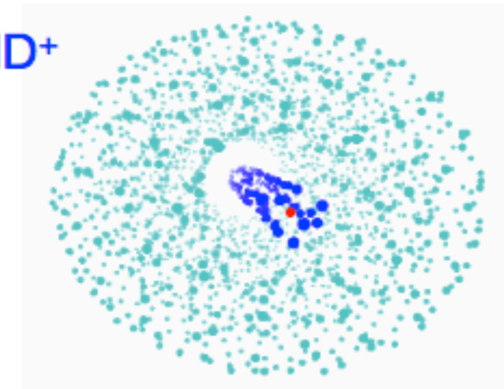
→ Idea : try an intermediate ion 9 / 3 / 1

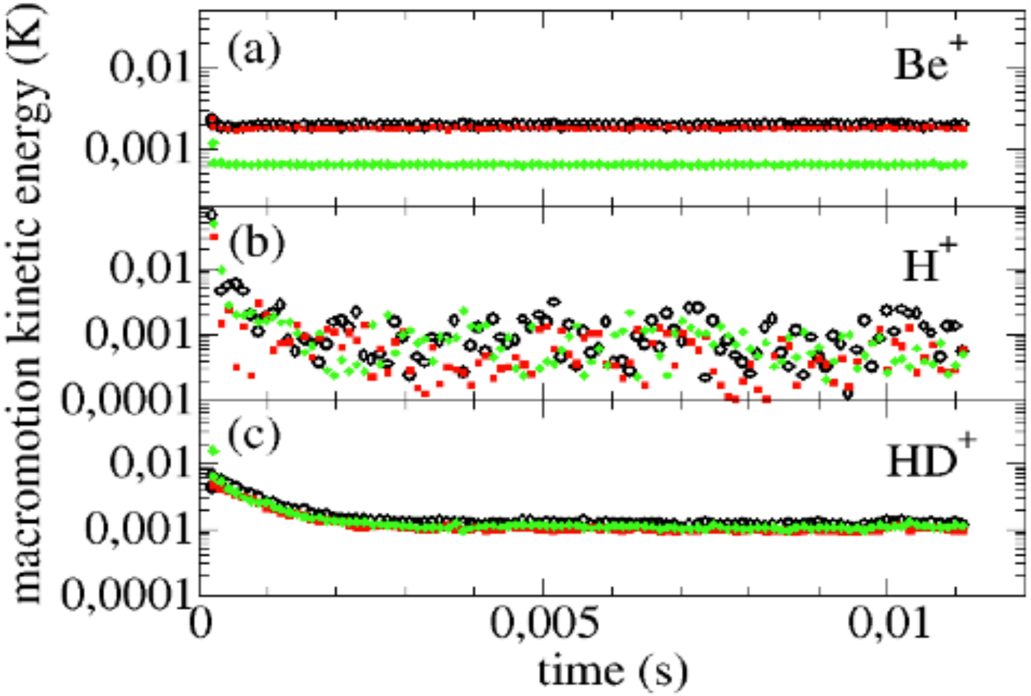
C. B. Zhang, D. Oenberg, B. Roth, M. A. Wilson, and S. Schiller, Phys. Rev. A 76, 012719 (2007).
L. Hilico et al., IJMPCS 2014

few meV $\bar{H}^+$



1800 Be^+
200 HD^+
1 $\bar{H}^+$

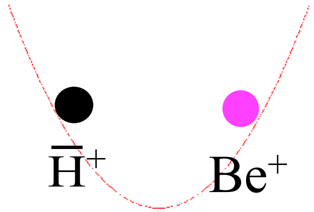




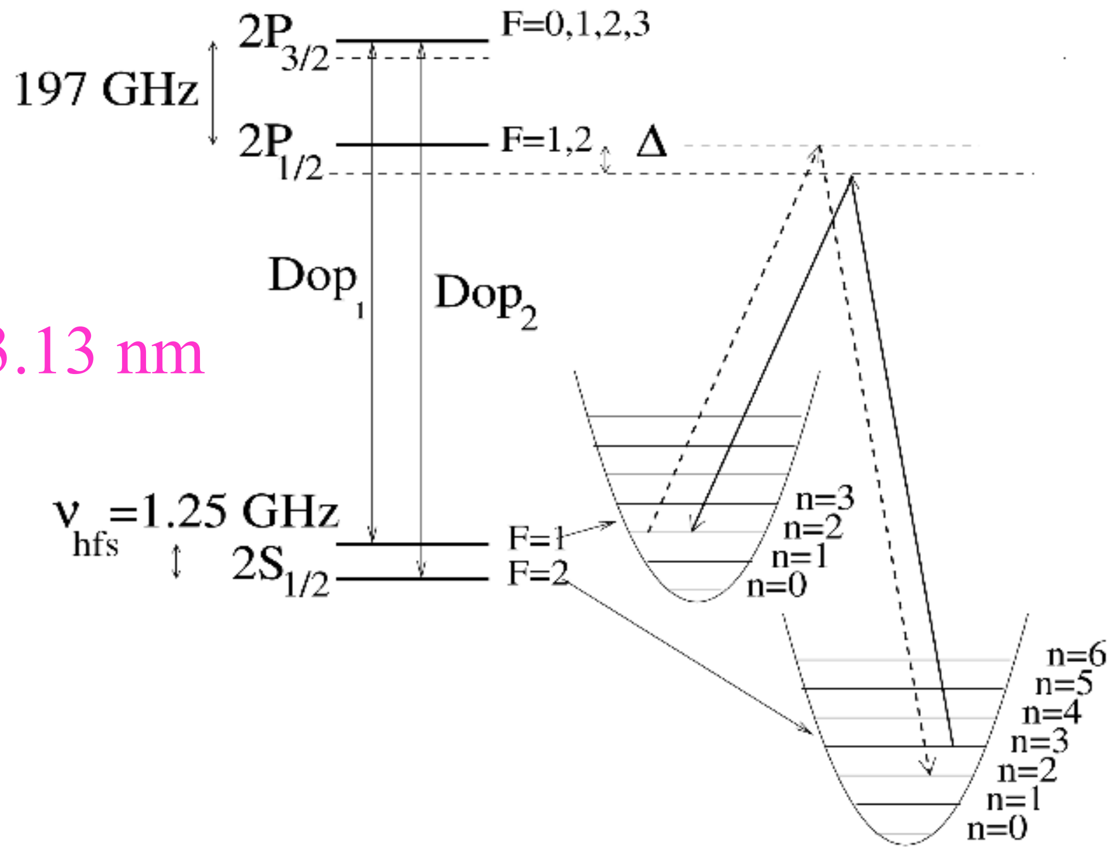
X
Y
Z

L. Hilico et al., (2014)
arXiv:1402.1695 [physics.atom-ph]

Raman side band cooling



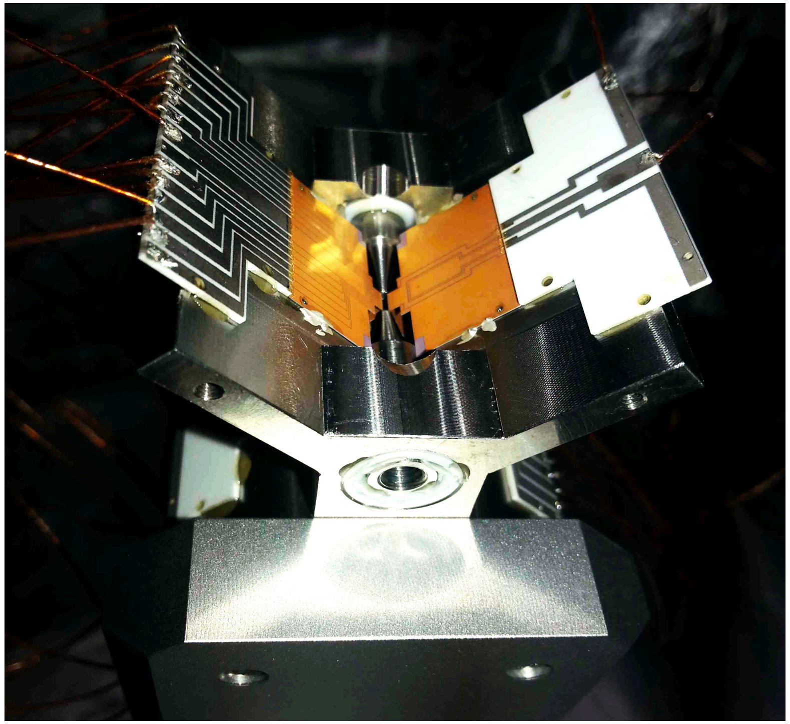
313.13 nm

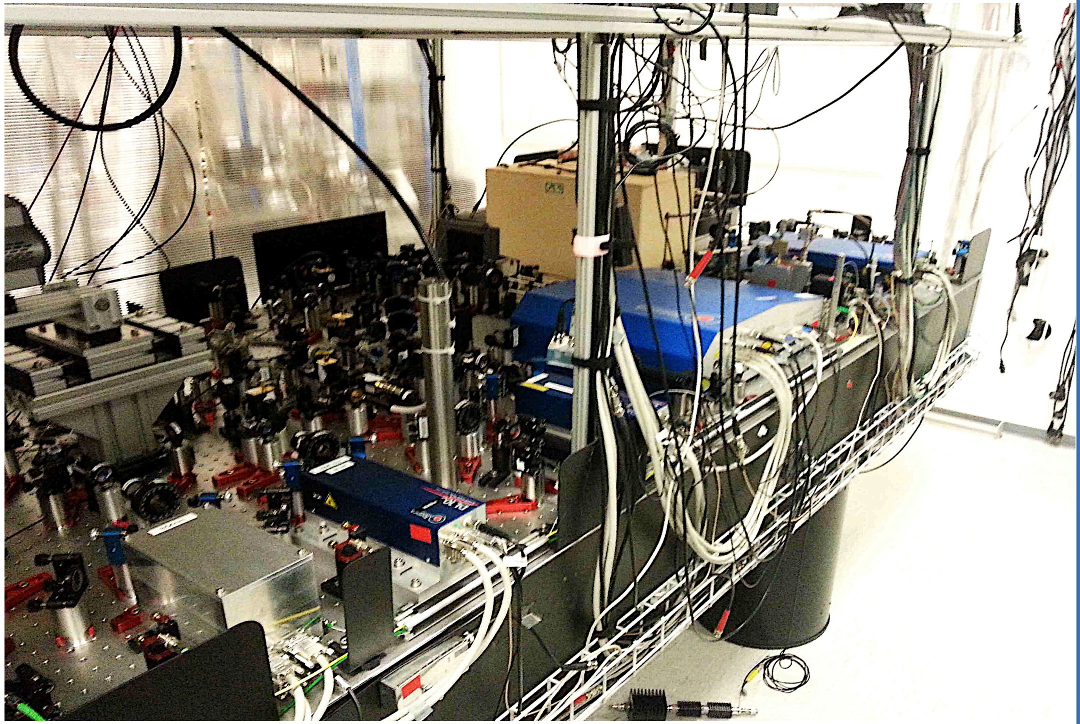


Precision trap

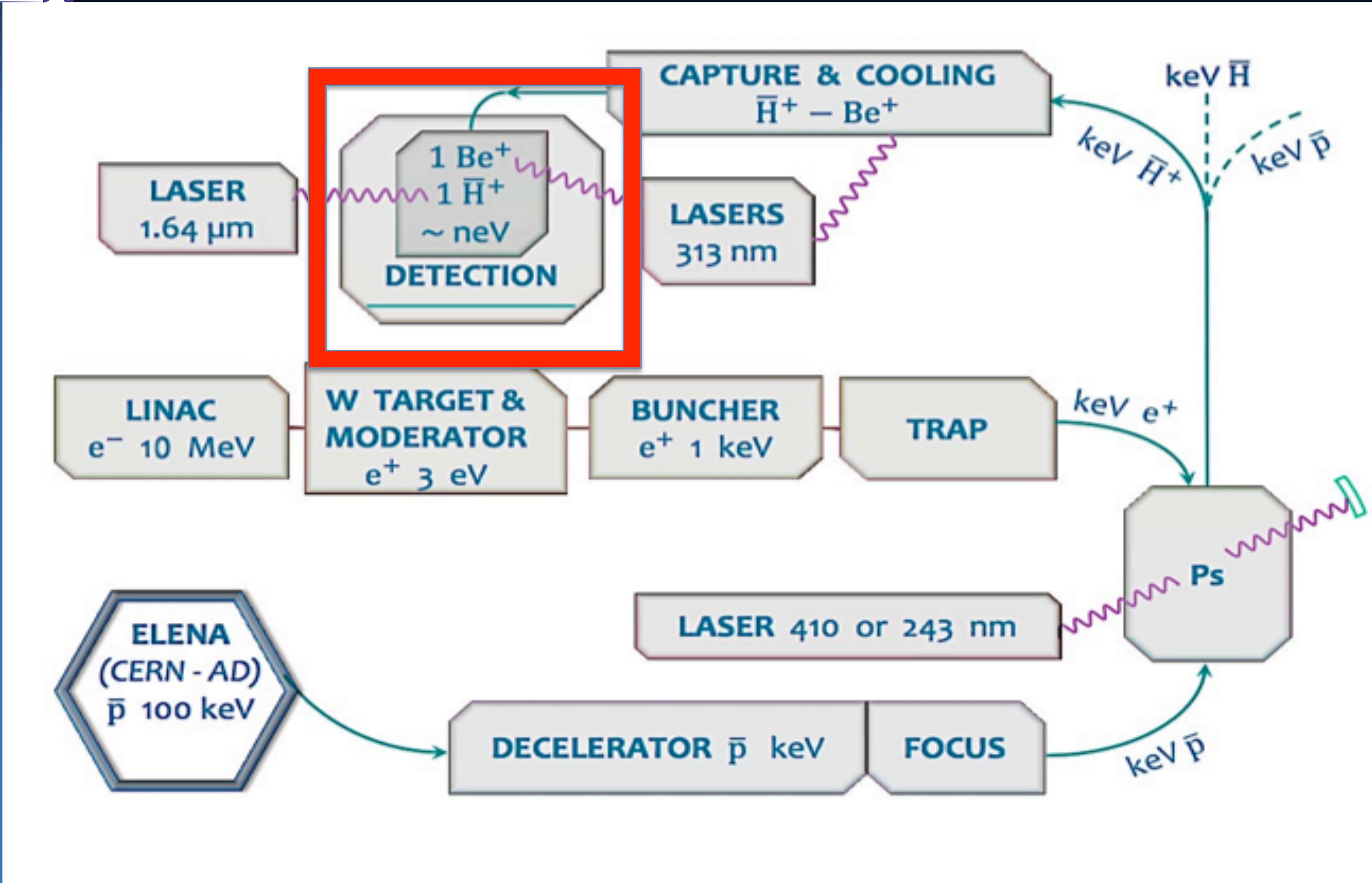
S. Wolf
F. Schmidt-Kaler

Precision trap being prepared at Mainz
Laser table ready for tests with Ca^+/Be^+, later Sr^+/Be^+

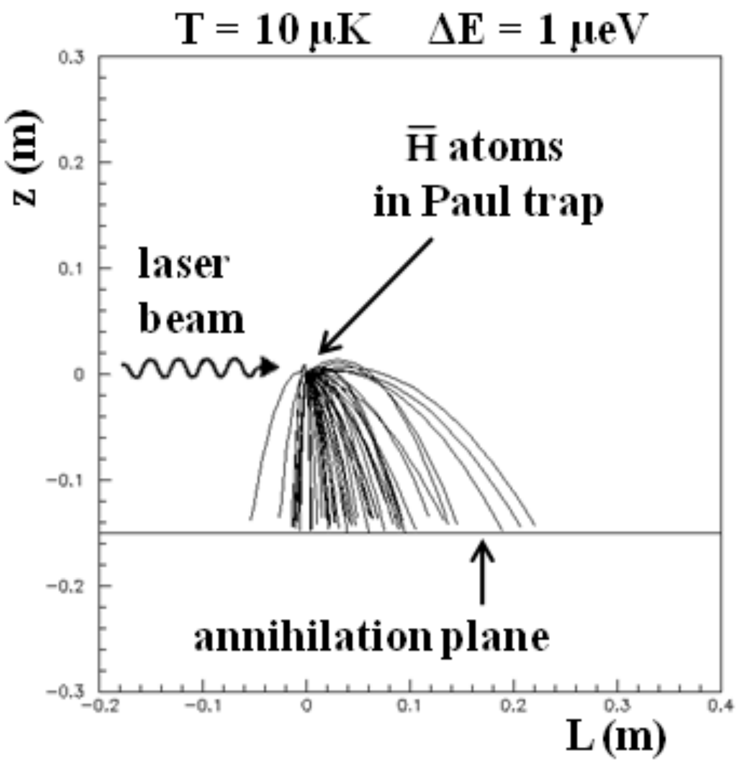


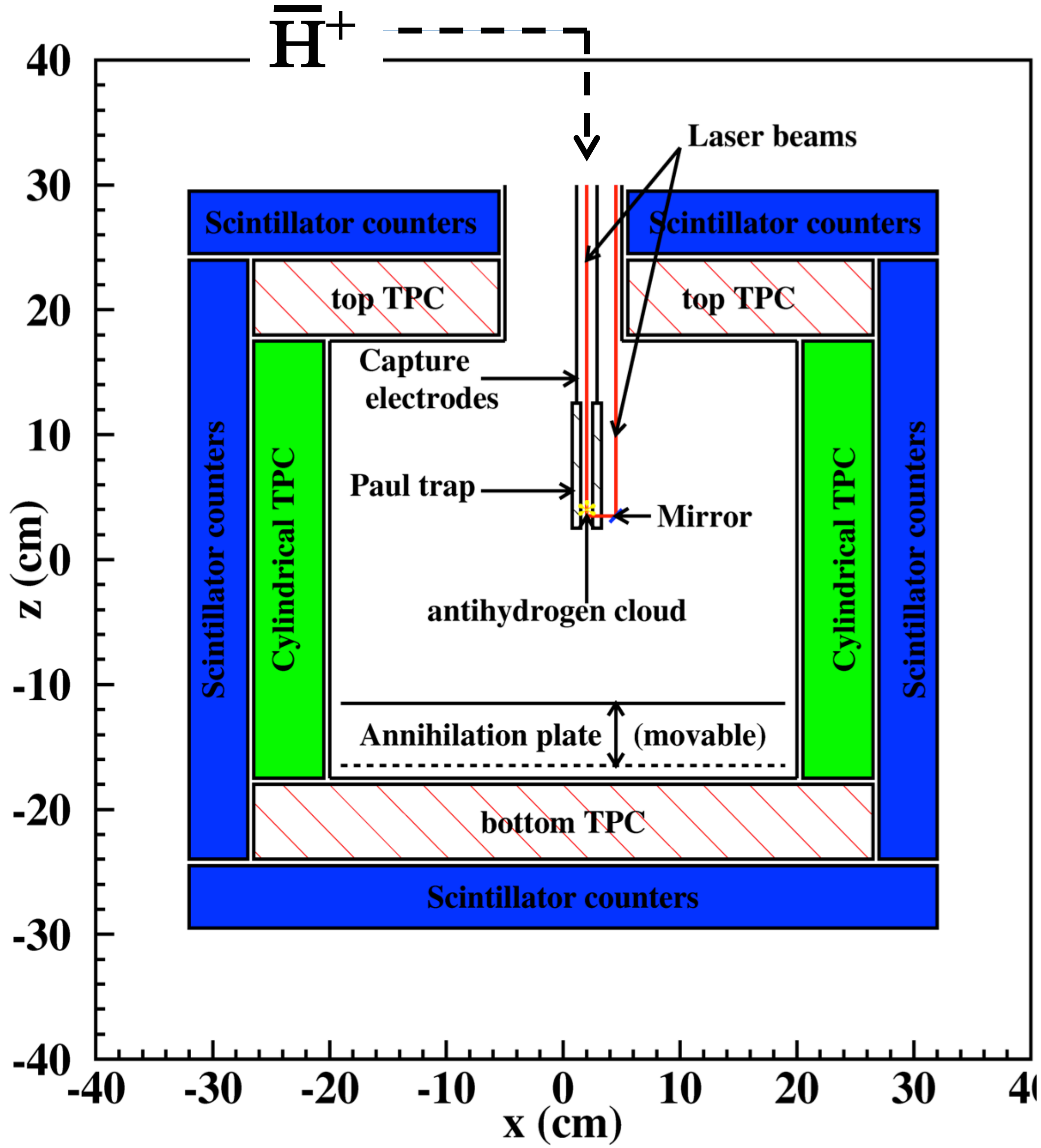


$\bar{H}$ free fall detection



$\bar{H}$ free fall detection





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

MicroMegas detector

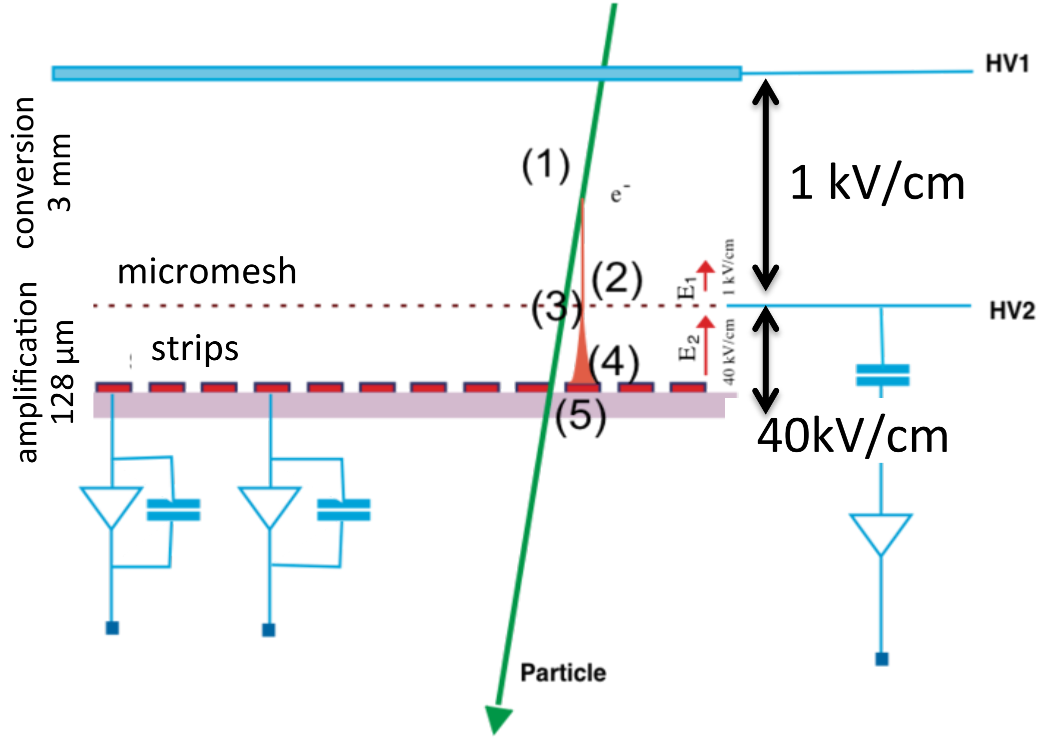
D. Banerjee, P. Crivelli
S. Aune, B. Vallage

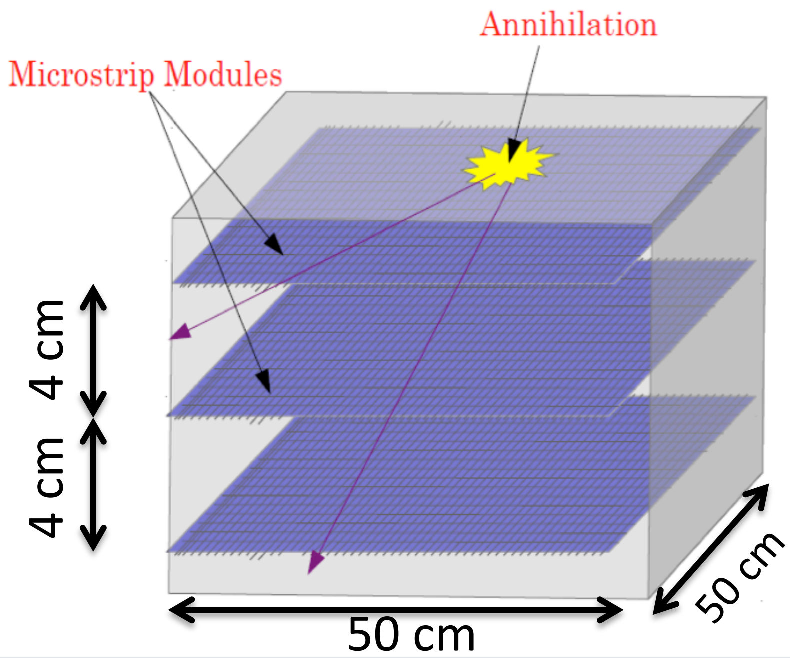
Argon Isobutane (95% , 5%)

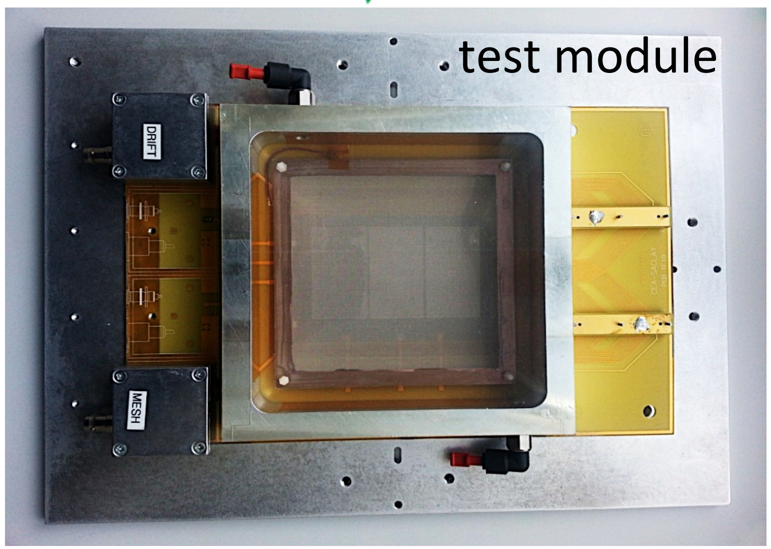
Pitch of strip ~ 400 microns

X and Y strips give track position directly

Genetic multiplexing of strips
S. Procureur et al, NIM **A** 729 (2013) 888

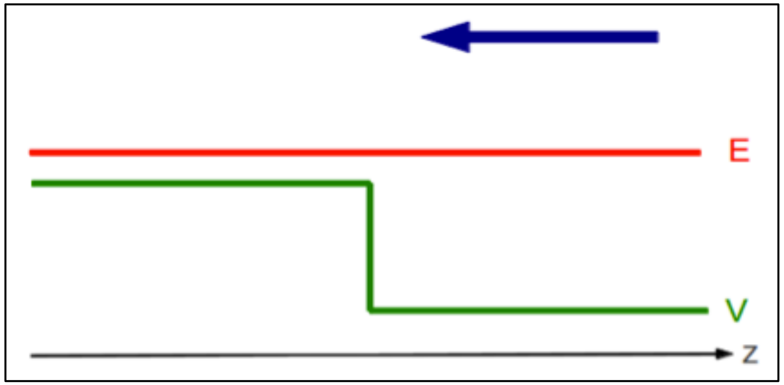






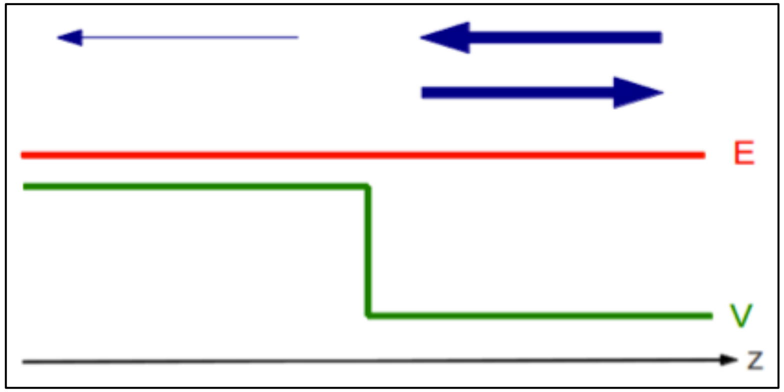
Quantum reflection on a step

G. Dufour, et al.



plane wave incident on a potential step:

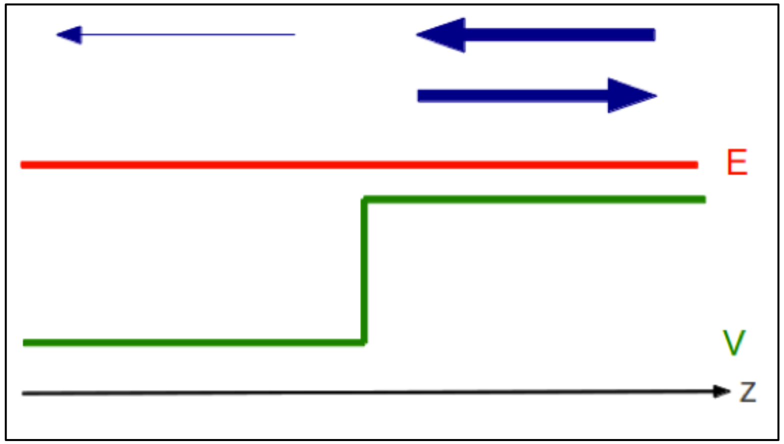
$$\Psi_{in}(z) \propto \exp(-ikz) \text{ with } k = \sqrt{2m(E - V)} / \hbar$$



wave function partly transmitted, partly reflected

reflection: $r_{12} = \dfrac{k_2 - k_1}{k_1 + k_2}$

transmission: $t_{12} = \dfrac{2\sqrt{k_1 k_2}}{k_1 + k_2}$



reflection from attractive potential

Reflection probability unchanged when $1 \leftrightarrow 2$

$$|r_{12}|^2 = |r_{21}|^2$$

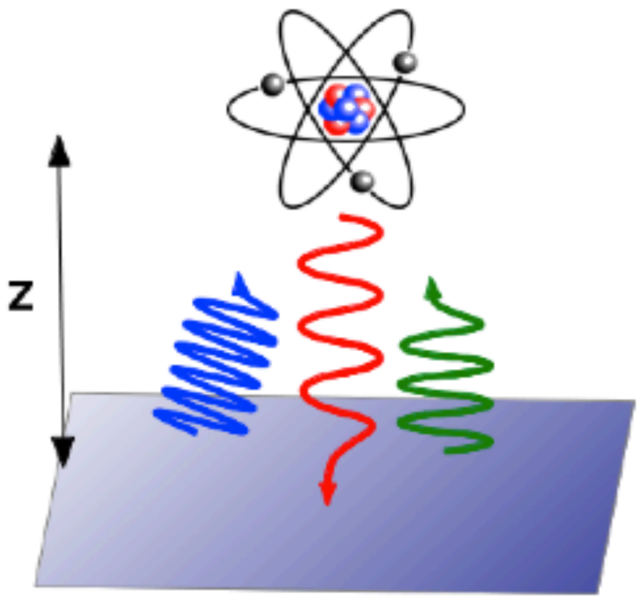
The Casimir - Polder force

G. Dufour et al., Int. Journal Mod. Phys: Conf. Series, 30 (2014) 1460265.

Electromagnetic (EM) modes are modified when the atom comes close to the detector:

⇒ the EM ground state (vacuum) energy changes

⇒ attractive Casimir-Polder force between atom and detector



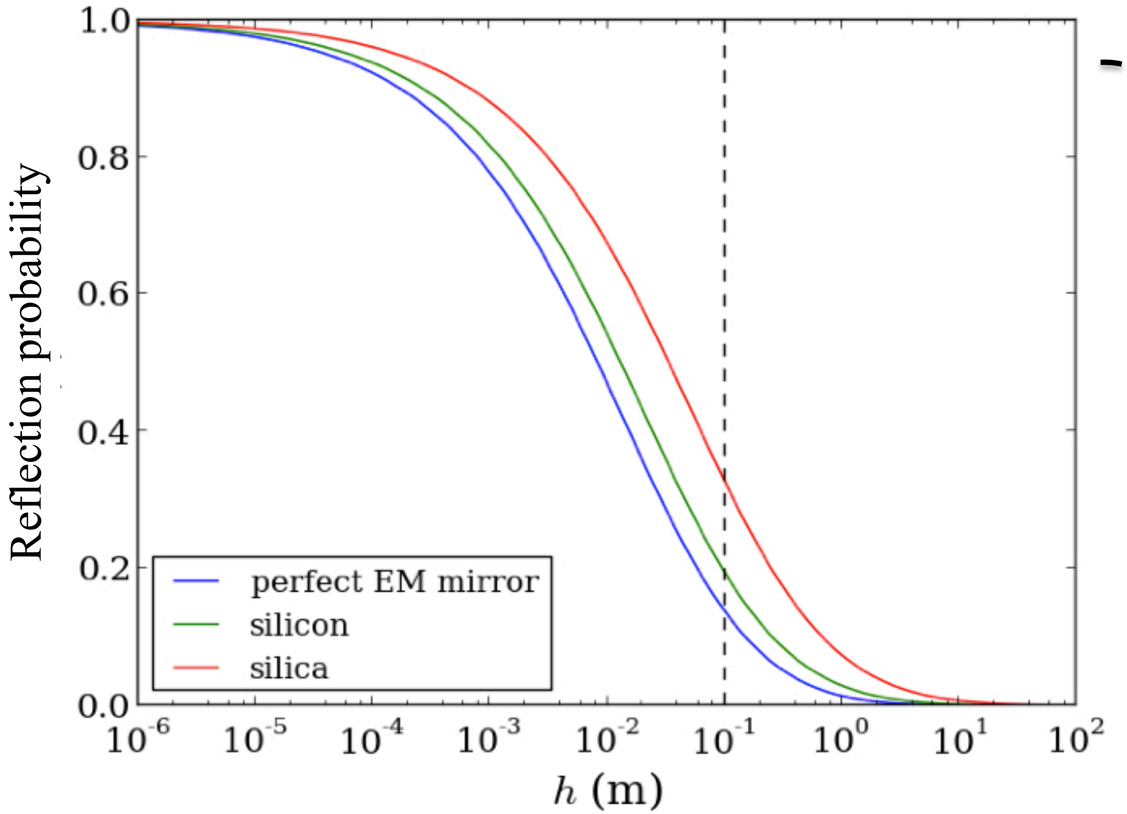
Casimir 1948 : long-range interaction energy between an atom and a perfectly conducting mirror:

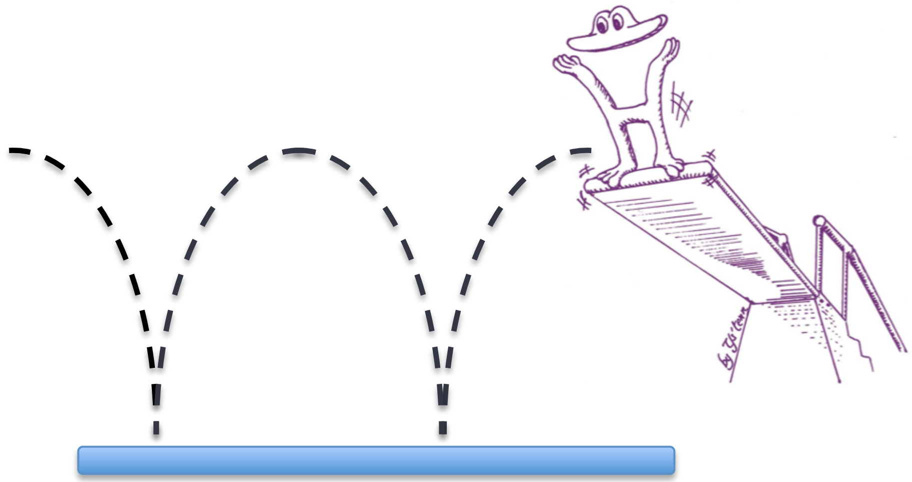
$$V^*(z) = -\frac{3\hbar c}{8\pi z^4}\frac{\alpha(0)}{4\pi\epsilon_0} = -\frac{C_4^{perfect}}{z^4}$$

For H and $\overline{\mathrm{H}}$, $C_4^{perfect} \approx 73.6\ E_h a_0^4$

$V(35\ \mathrm{nm}) \approx$ - $mg \times 10$ cm

Spectroscopy of gravitational states



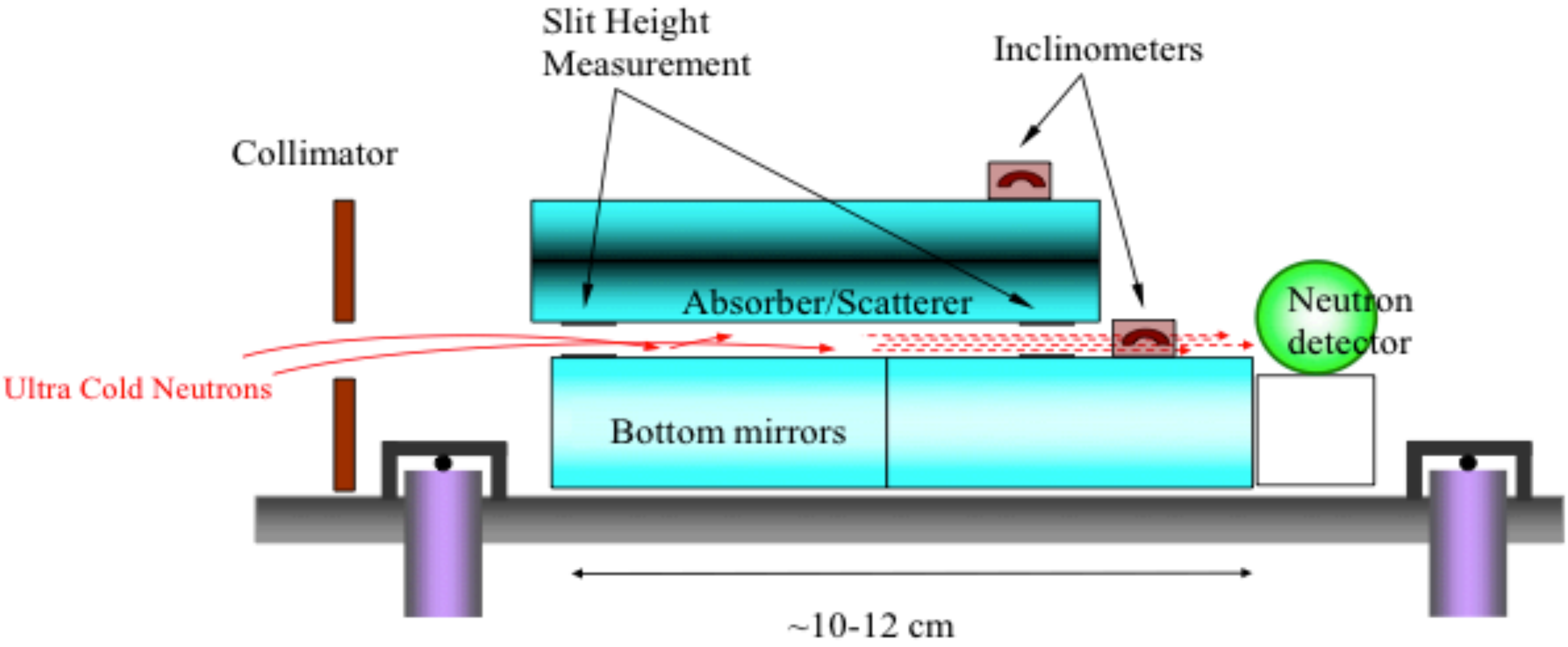


altitudes are quantized
→ spectroscopy
i.e. improved precision

already demonstrated with ultra cold neutrons at ILL (*V. Nesvizhevsky*)

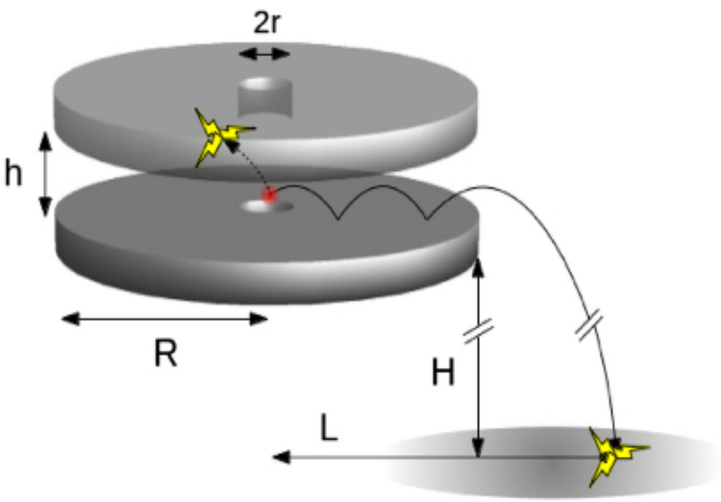
Gravitational States of Neutrons

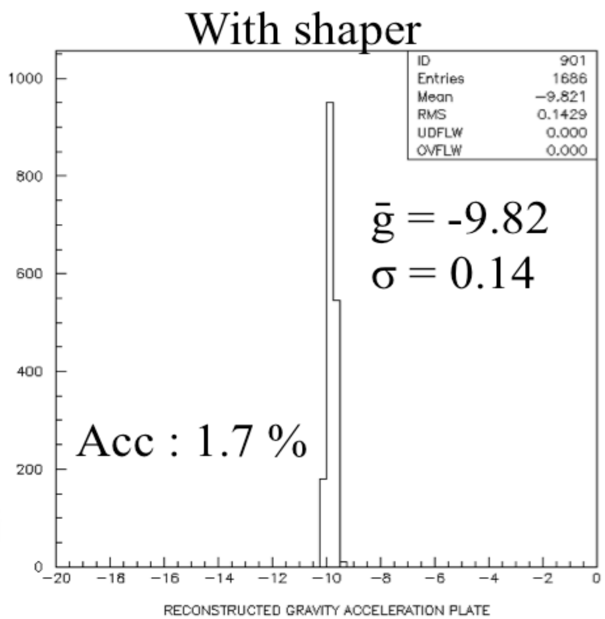
V. Nesvizhevsky et al., Nature 415, 297 (2002)

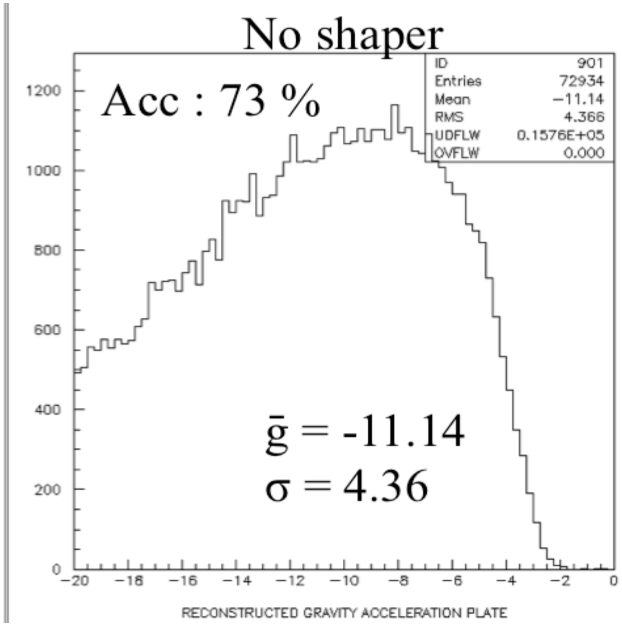


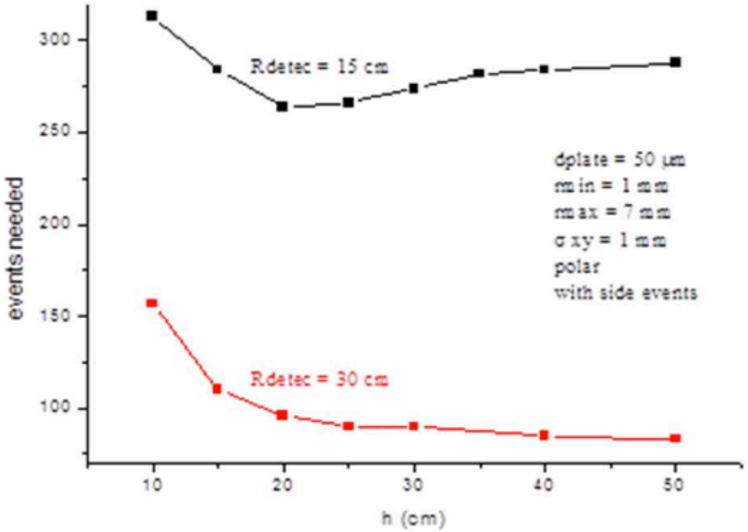
Velocity selector

G. Dufour et al., Eur. Phys. J. C 74 (2014) 2731









First simulations → optimise dimensions with experimental constraints

h = 50 µm

H = 20 cm , Rdetector = 20 cm

Shaper Rmin = 1 mm, Rmax = 7 mm

→ need 150 produced $\overline{H}^+$ for Δg/g = 1%

10 times less than in proposal

15 institutes ~ 50 researchers

new collaborators welcome!

2015 start installation

2016 ELENA commissioning with p and H^-

2017 first antiprotons for GBAR