Gravitational Behavior of Antihydrogen at Rest

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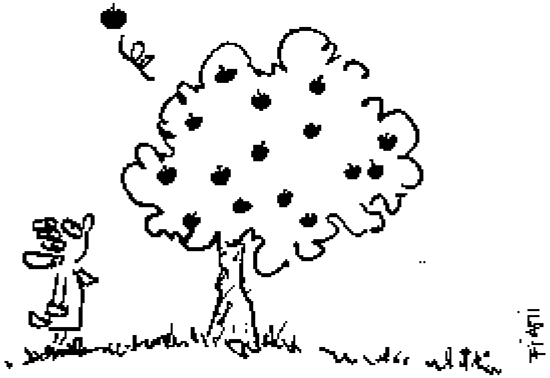
Outline

- Motivations and related projects
- Principle of the experiment
- Producing antimatter ions
- The ion trappers' mission
- Perspectives

ISAAC NEWTON AND THE ANTIAPPLE



Motivations

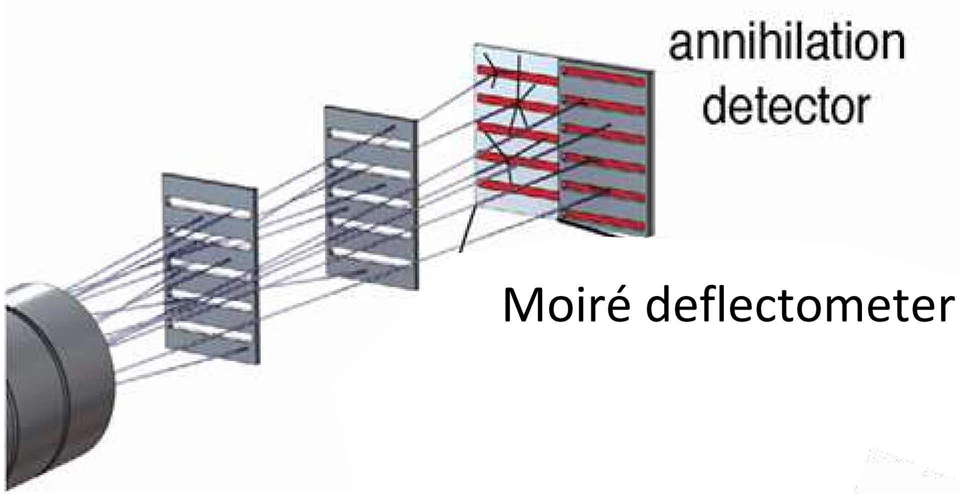
- Answer the question How does antimatter falls ?

~~Charged antimatter~~

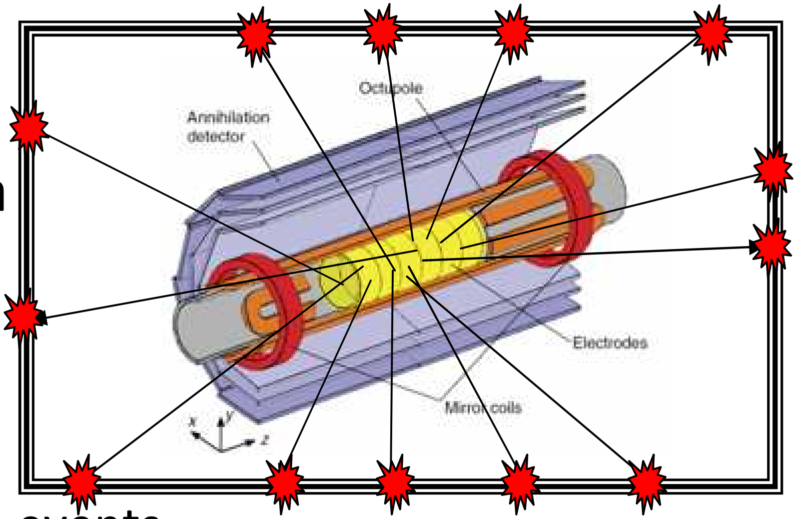
Neutral antimatter ~~$\bar{n}$~~ $\bar{H}$ $Ps = e^+e^-$

Related projects

- AEgIS (IN2P3)



- Alpha

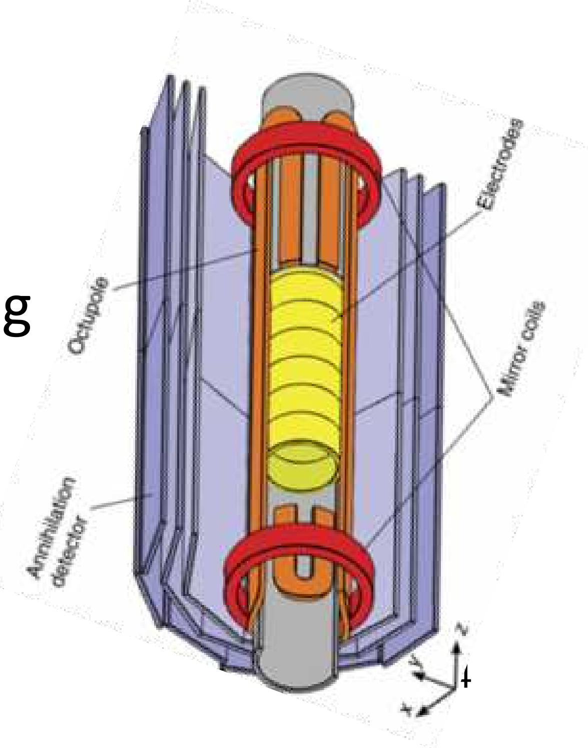


343 events

$-65 \le \bar{g}/g \le 110$

Nature Communications 4, 1785 (2013)

Alpha-g



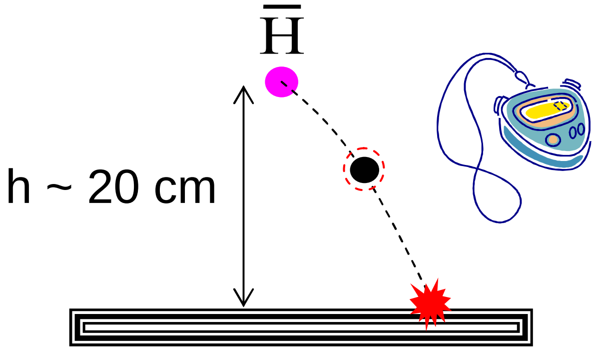
GBAR concept

- Measure the free-fall time of a $\bar{\mathrm{H}}$ atom

If atom at rest : $v_f \sim 2$ m/s

Requirement : $\Delta v_{iz} \ll 1$ m/s ↔ $T \ll 100\ \mu$K

<u>Goal:</u> $T = 20\ \mu$K → 1% on $\bar{g}$ with a few 10^3 atoms



Laser cooling ?

$\lambda = 121$ nm

Doppler limit $\Gamma = 2\pi\ 100$ MHz $T_D = 2400\ \mu$K

Recoil limit $T_R = 650\ \mu$K

- How to produce ultra-cold $\bar{\mathrm{H}}$?

From the ideas to the GBAR proposal

J. Walz and T. Hänsch, General Relativity and Gravitation **36**, 561 (2004)
P. Pérez and A. Rosowsky, NIMA **545**, 20 (2005)
P. Pérez *et al*., CERN-SPSC-P-342 (2011) ; accepted (2012).

1. produce an $\bar{\mathrm{H}}^+$ ion ($\bar{\mathrm{p}}^- \mathrm{e}^+ \mathrm{e}^+$):

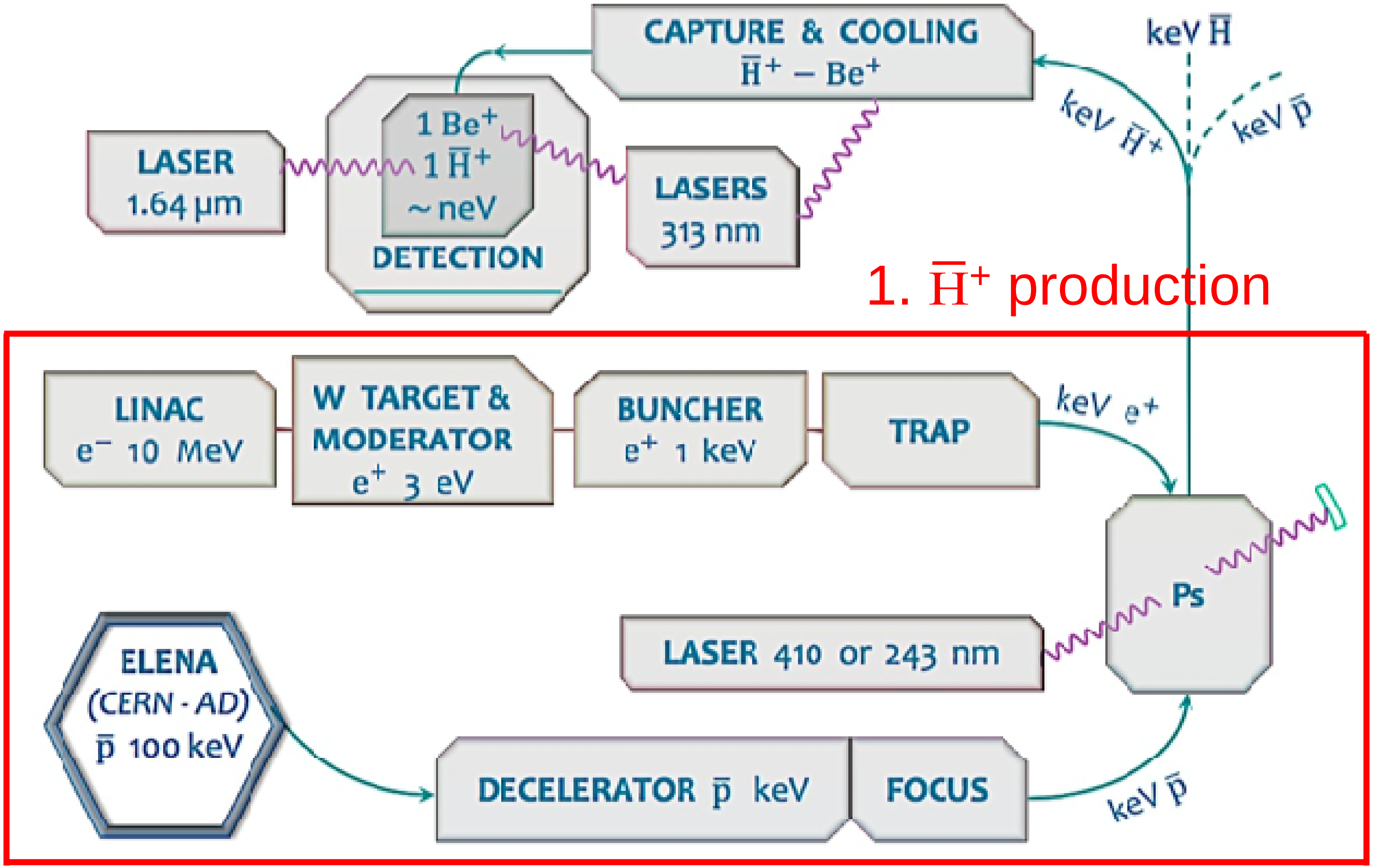
$$Ps^* + \bar{p} \rightarrow \bar{H}^* + e^-$$

$$Ps^* + \bar{H}(1s) \rightarrow \bar{H}^+ + e^-$$

2. **Trapping and sympathetic cooling of $\bar{\mathrm{H}}^+$**

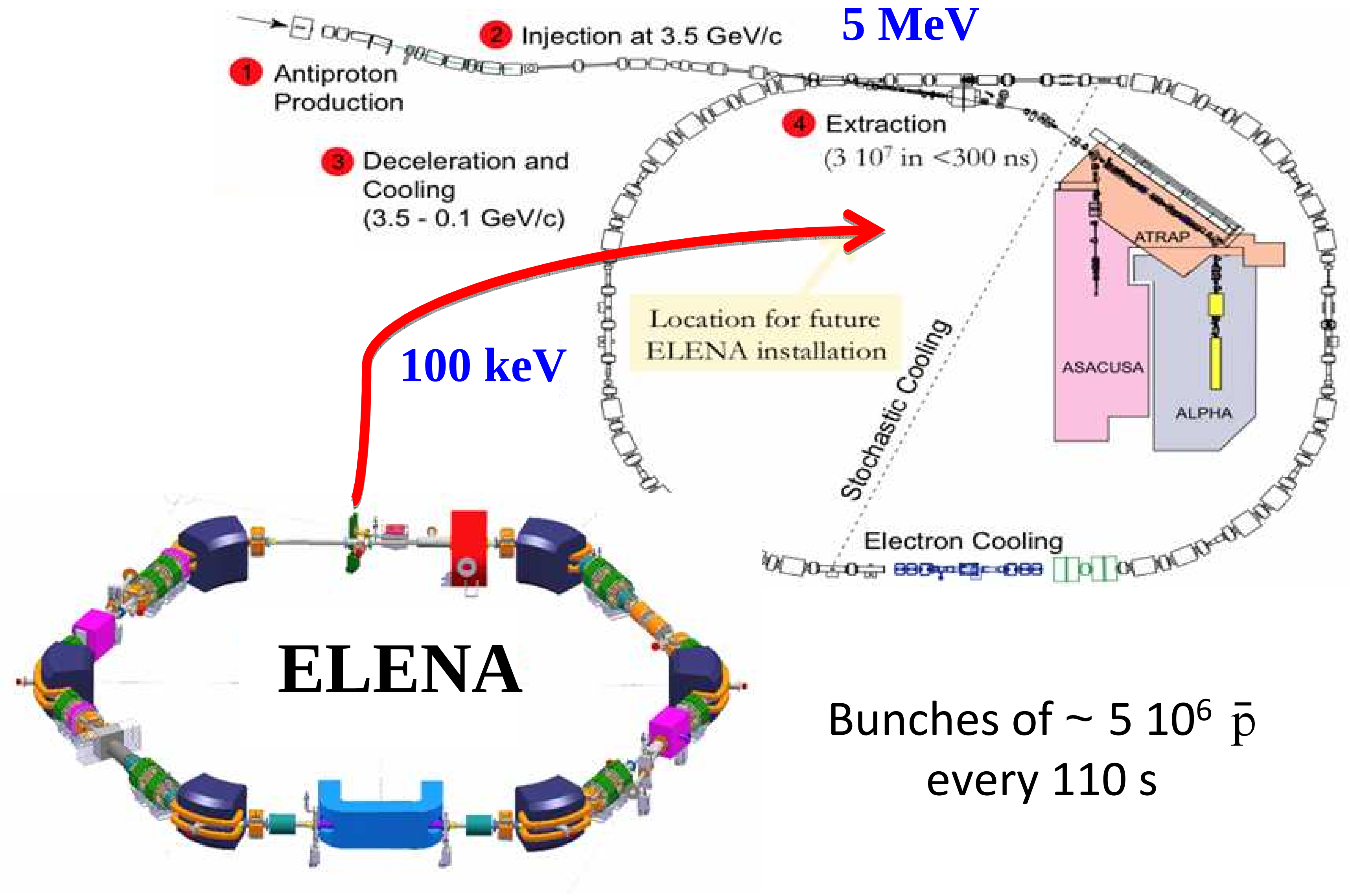
3. photodetachment at threshold (λ = 1.64 µm)

Experimental scheme



1. $\bar{H}^+$ production

Antiprotons : AD and ELENA



Bunches of ~ 5 10^6 $\bar{\text{p}}$ every 110 s

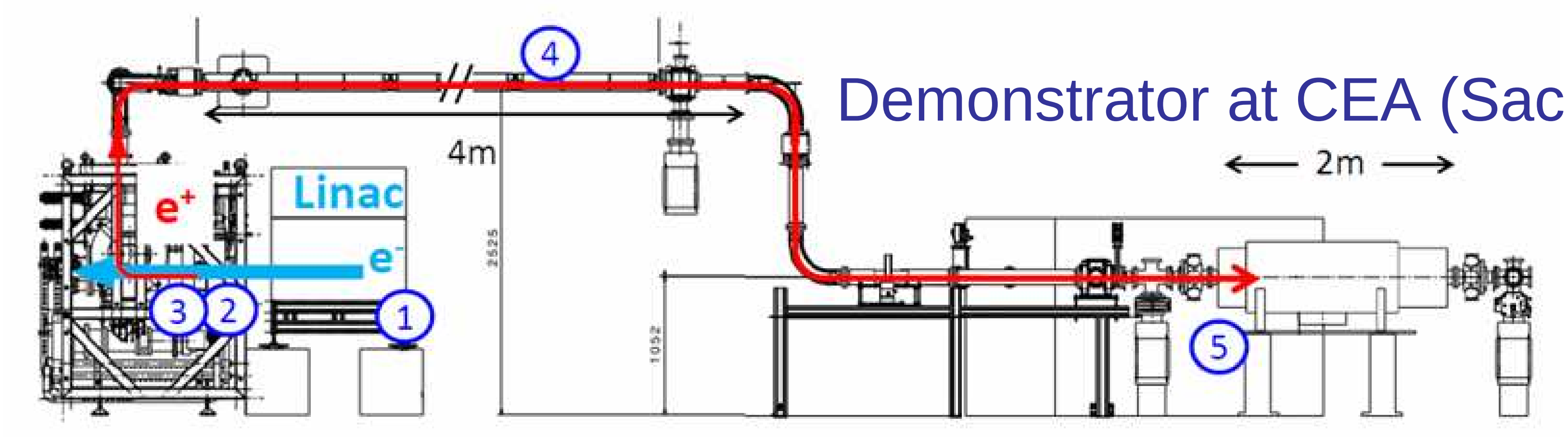
Production of positrons

- ➢ Requirement : produce a large number of Ps atoms

→ Intense source of positrons + accumulation

‘usual’ source: $^{22}\mathrm{Na} \rightarrow {}^{22}\mathrm{Ne} + e^{+} + \nu_e + \gamma$ too small intensity

LINAC source: MeV e^{-} and W e^{-}/e^{+} converter OK

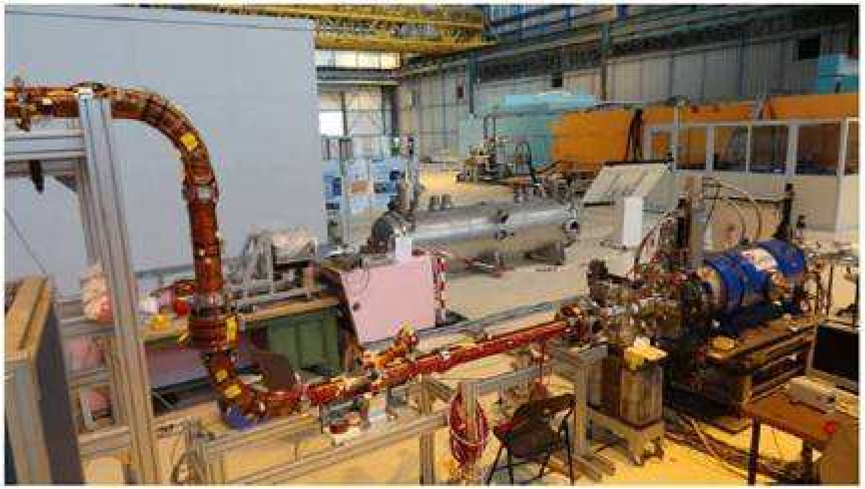


Demonstrator at CEA (Saclay)

1. Linear accelerator of e^{-} (4.3 MeV)
2. e^{+}/e^{-} convertor (tungsten target)
3. Moderator (tungsten mesh) MeV → eV
4. Transport line (solenoids)
5. Penning-Malmberg trap (B = 5T) (RIKEN, Tokyo); cooling by e^{-}

Positrons at CEA

L. Liszkay
C. Corbel
P. Debu
P. Dupré
P. Grandemange
P. Pérez
J.-M. Rey
J.-M. Reymond
N. Ruiz
Y. Sacquin
B. Vallage

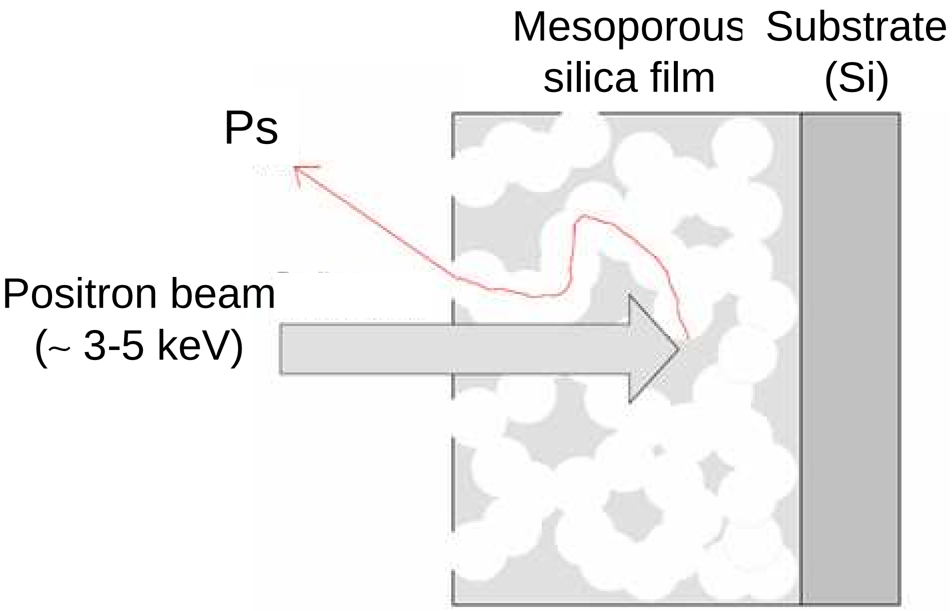


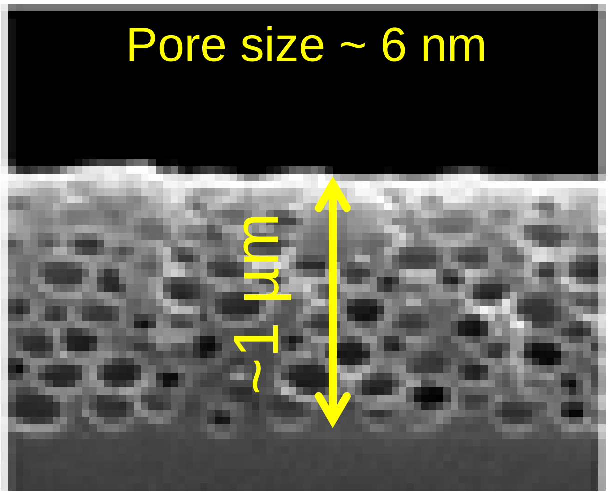
Slow positron flux 3 10^6 s^{-1}

Positrons at CERN

- New Linac under construction 9 MeV 10^8 s^{-1}
- Positron accumulation needs to be improved (Goal: > 10^{10} e^+ in 110 s)
- Construction of a buffer gas trap to reduce e^+ energy before entering the Penning-Malmberg trap

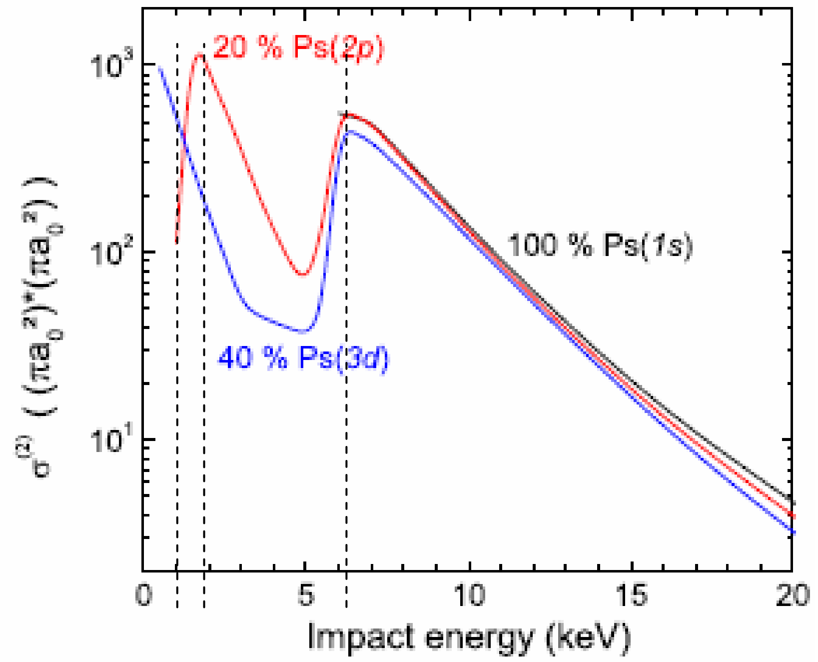
Conversion e^+ / Ps



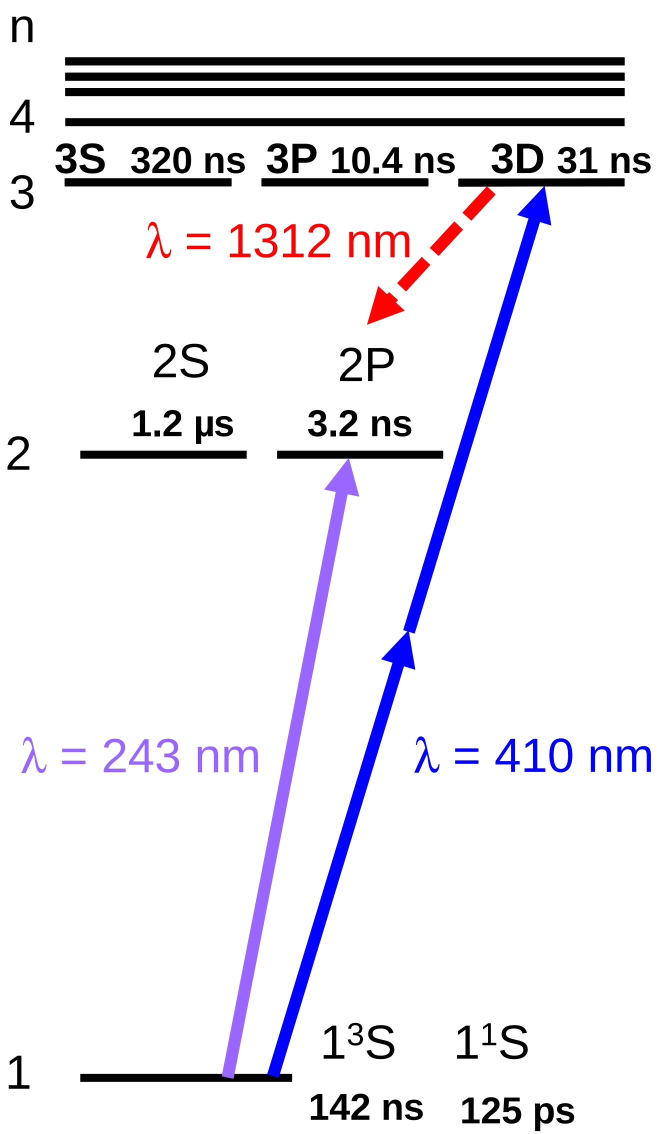


- Excellent conversion efficiency (> 30% !)
- Ps energy: < 0.1 eV

$\overline{\mathrm{H}}^+$ production cross-sections



P. Comini and P.-A. Hervieux, New J. Phys. **15**, 095022 (2013)
See also A.S. Kadyrov, M. Charlton et al., PRL **114**, 183201 (2015)

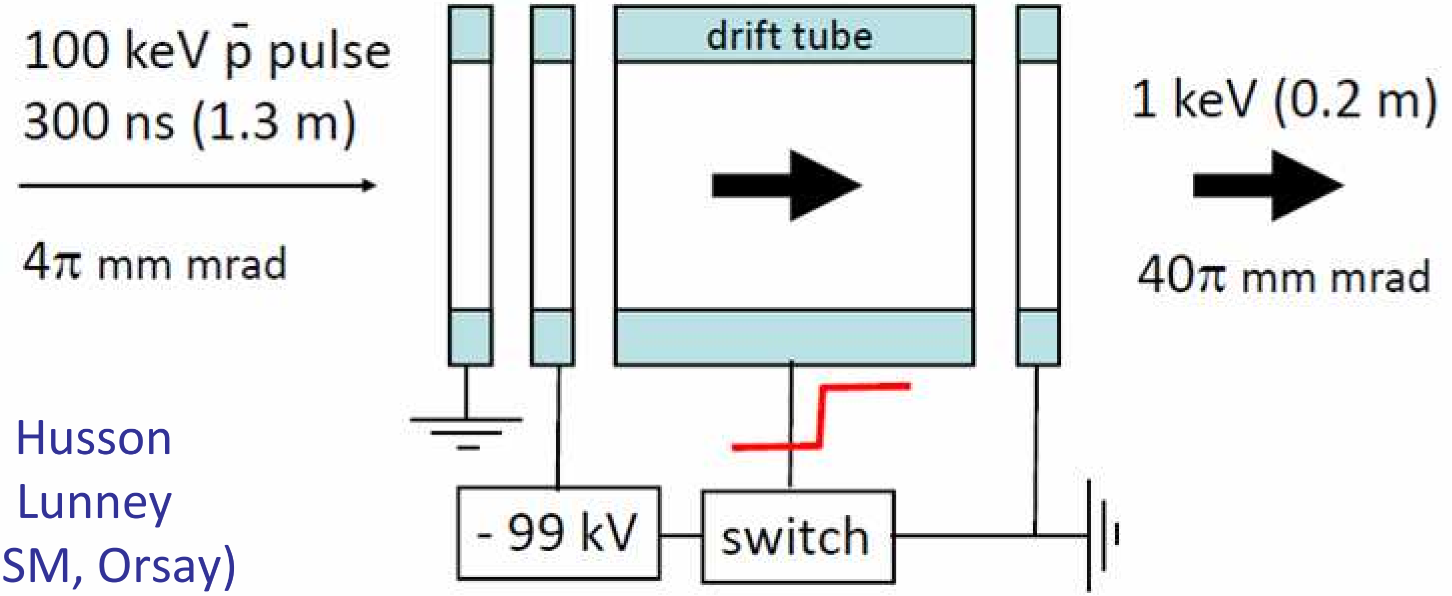


Possible choices : Ps(3d) at 6 keV or 1 keV
Ps(2p) at 2 keV

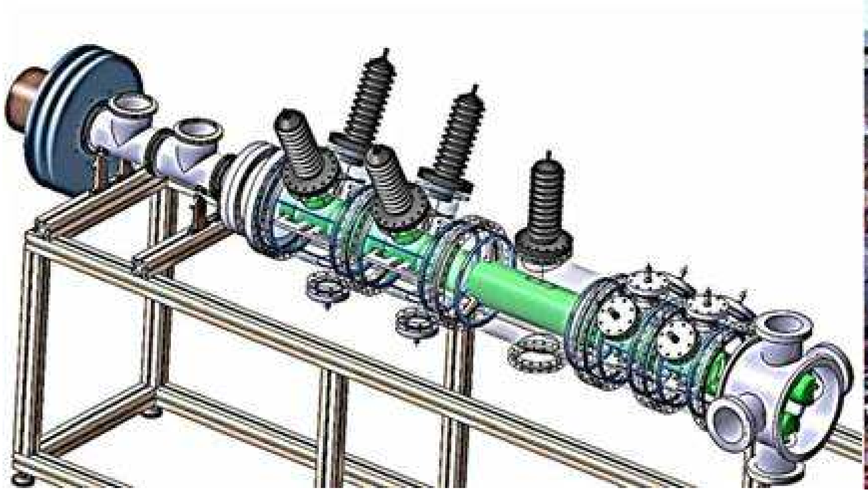
Estimated production yield :

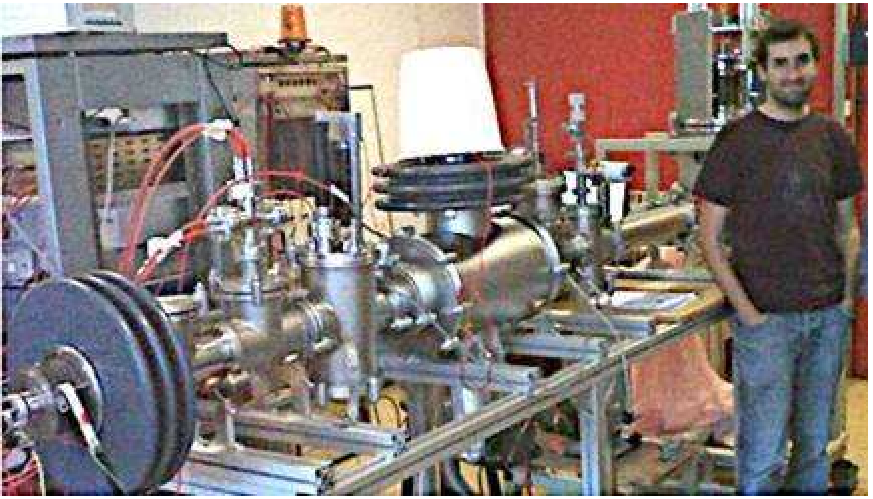
$$\left.\begin{array}{r} 5.\,10^{6}\ \ \bar{p} \\ 3.10^{10}\ e^{+} \rightarrow 10^{12}\ \mathrm{Ps/cm^{2}} \end{array}\right\} \longrightarrow \boxed{\begin{array}{c} \mathbf{10^{4}\ \overline{H}} \\ \mathbf{1\ \overline{H}^{+}} \end{array}}$$

Antiproton decelerator



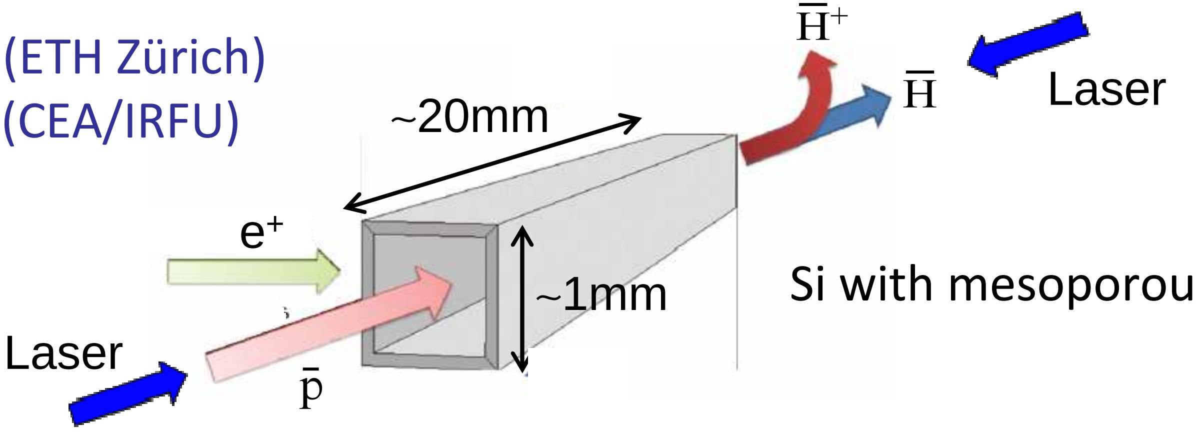
A. Husson
D. Lunney
(CSNSM, Orsay)





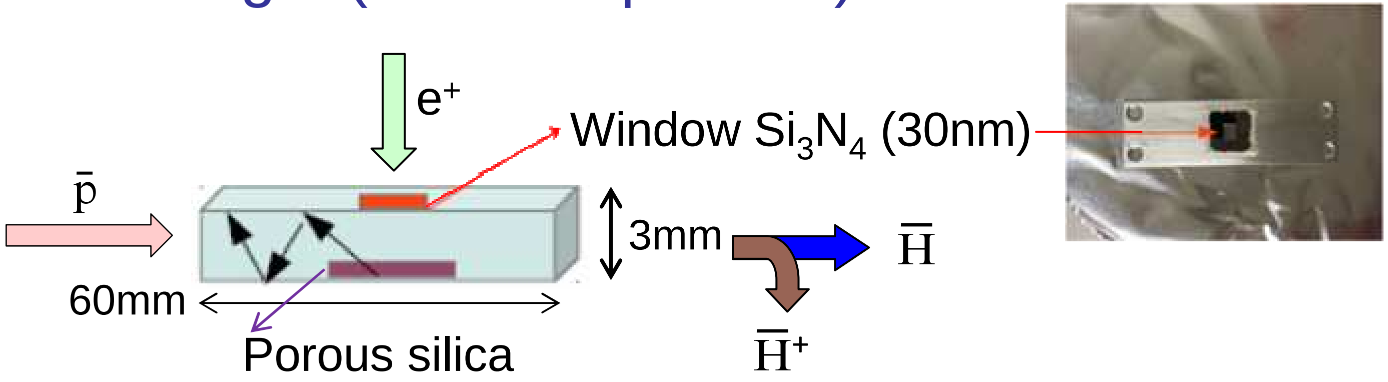
Interaction chamber

P. Crivelli (ETH Zürich)
L. Liszkay (CEA/IRFU)



Si with mesoporous SiO_2 coating

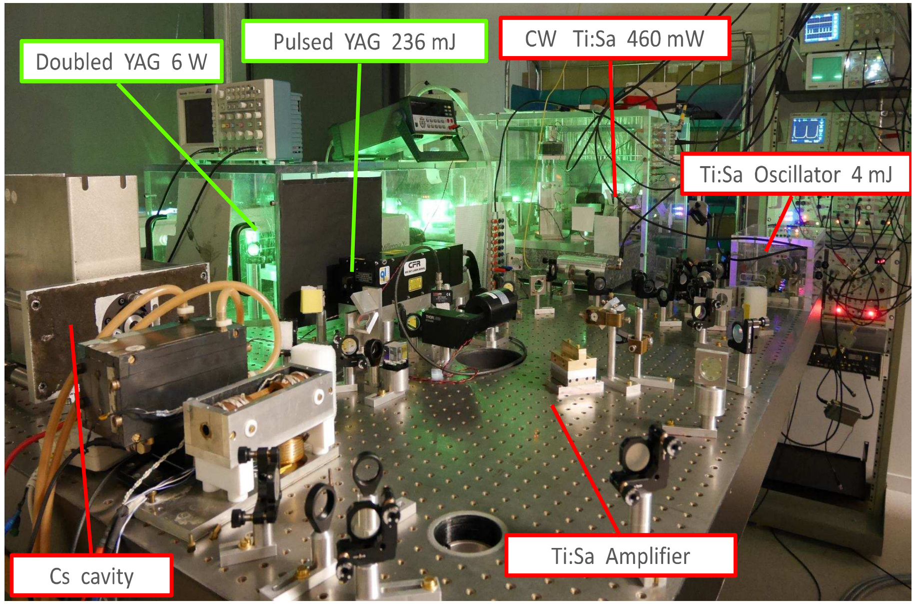
Test target (first with protons)



- N.B. Momentum of $\bar{H}^+$ quasi identical to that of $\bar{p}$

Pulsed laser for Ps(3d)

P. Comini, F. Nez (LKB)

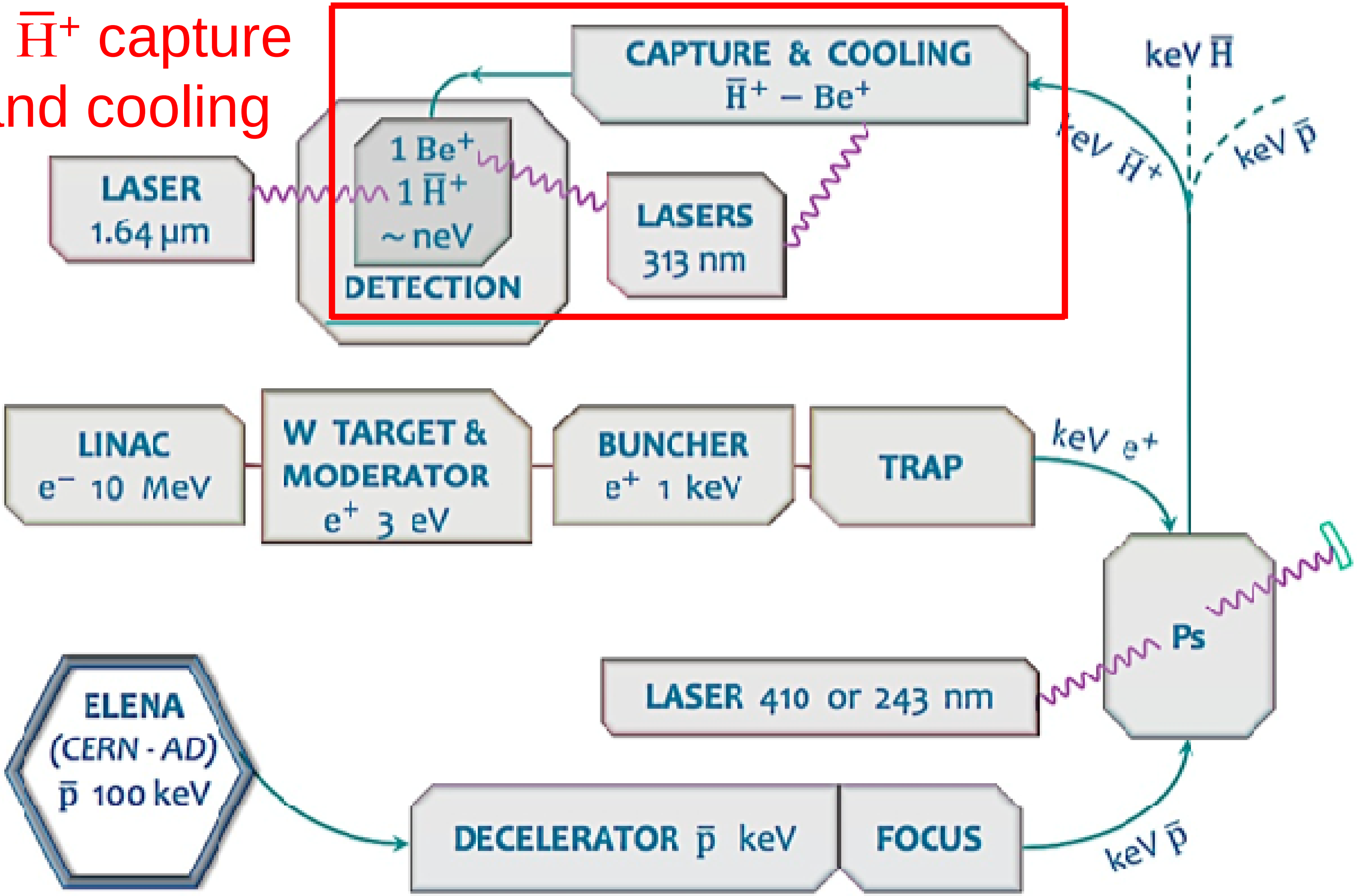


- $\Delta t \sim 9$ ns, E = 4 mJ @ 820 nm
  $\Rightarrow \sim 2$ mJ @ 410 nm expected (LBO crystal)

- Linewidth of the same order as 1s-3d transition in Ps (2nd-order Doppler effect ~ 30 MHz)

Experimental scheme

2. $\bar{H}^+$ capture and cooling



The ion trappers’ mission

- $\sim$ 1 $\bar{H}^+$ ion every 100s

  $E_{moy}(\bar{H}^+) \cong E_{moy}(\bar{p}) \sim$ 1-6 keV (depending on chosen Ps state)
  $\Delta E\ (\bar{H}^+) \cong \Delta E(\bar{p}) \sim$ 200-300 eV $\sim$ **10^6 K**
  $\Delta t_{creation} \sim$ 10-20 ns, $\Delta x \sim \Delta y \sim$ 1mm, $\Delta z \sim$ 10mm

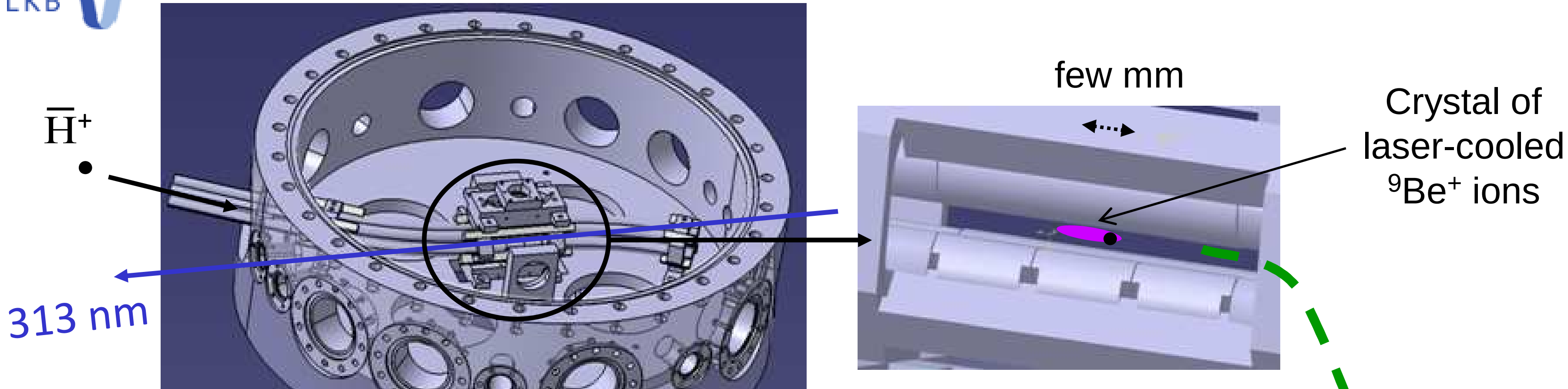
- Objective: trap and cool to T $\sim$ **20 µK** $\sim$ neV

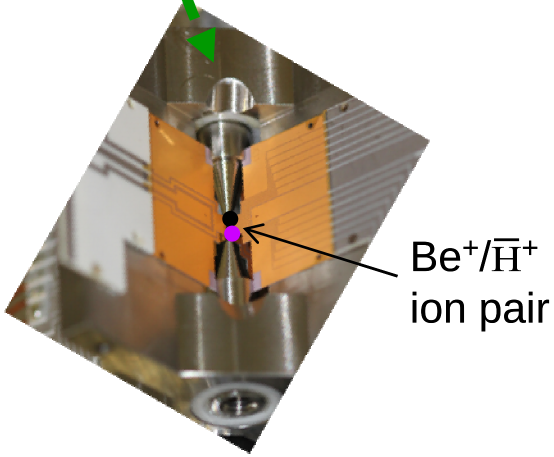
11 orders of magnitude with efficiency close to 100% …

- Strategy: sympathetic cooling by laser-cooled ions in RF (Paul) traps

- Trapping well depth $\sim$ 20 eV
  → pre-cooling of $\bar{p}$ required

Two-stage cooling scheme





1. Macroscopic “capture trap” (our team, LKB)

Doppler sympathetic cooling to T ~ 10 mK

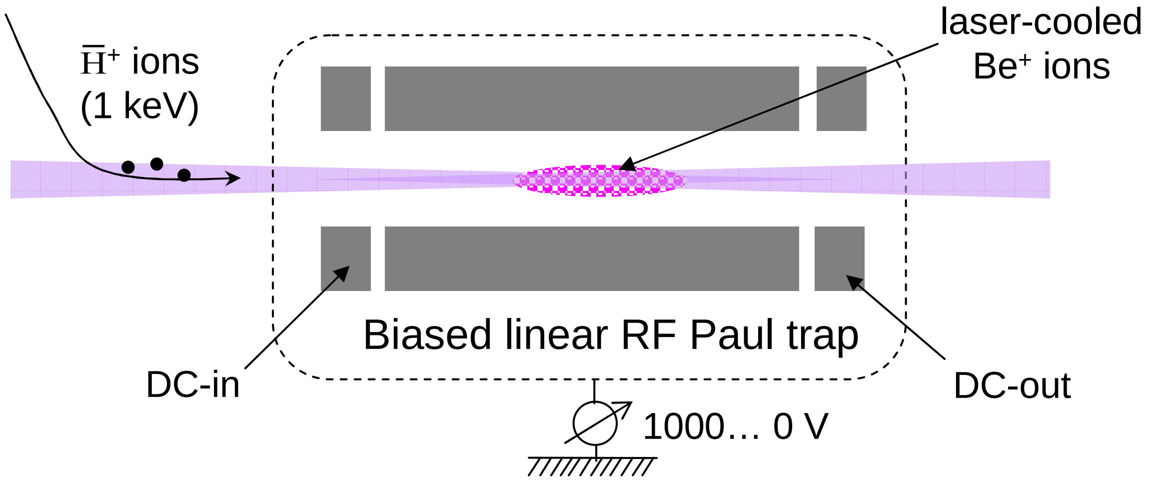
2. Micro-fabricated “precision trap” (F. Schmidt-Kaler, Mainz)

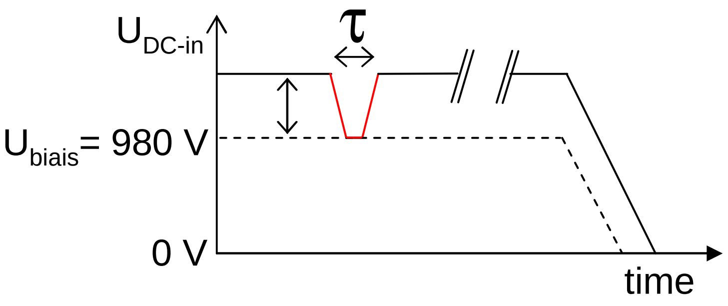
Raman sideband cooling to the motional ground state

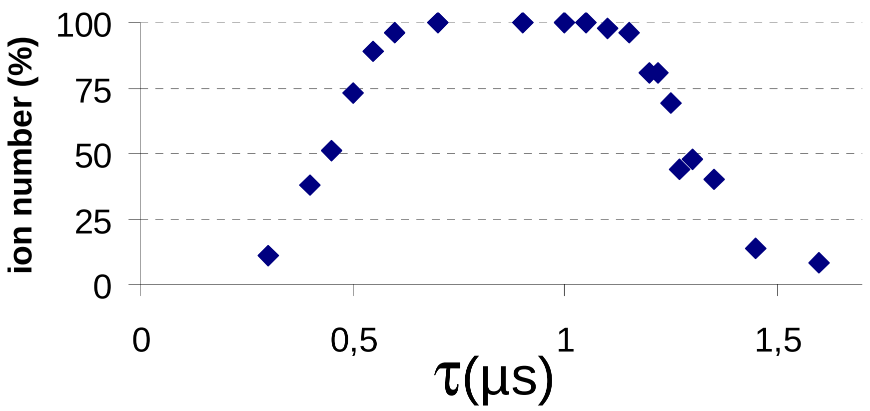
$$T_z = 20\,\mu\mathrm{K} \ \text{ corresponds to } \ \omega_z \approx 2\pi\times 400\,\mathrm{kHz} \Rightarrow \Delta v_z = \sqrt{\frac{\hbar\omega}{2m}} \approx 0.3\,\mathrm{m.s}^{-1}$$

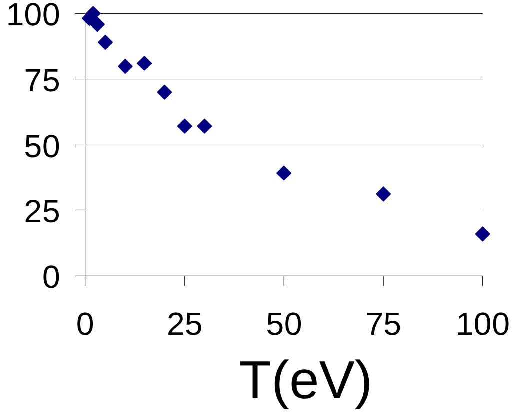
Simulations of ion intake

- One possible way: play the ‘drift tube’ trick with the trap itself



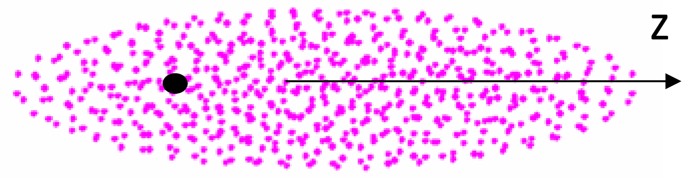






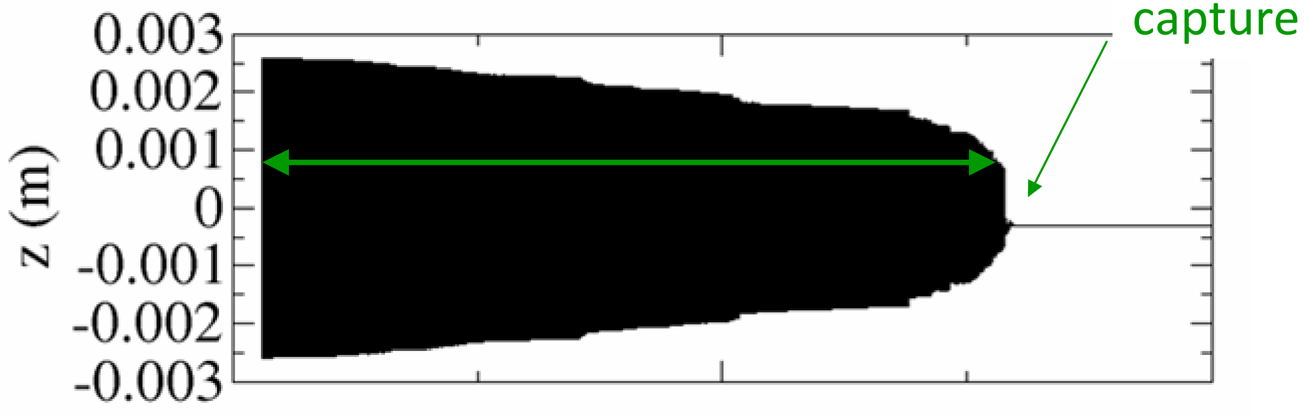
Capture and sympathetic cooling

Numerical simulations



Be$^+$

- Exact time dependent trapping fields
- From 100 to 15360 Be$^+$ ions
- Exact Coulomb forces



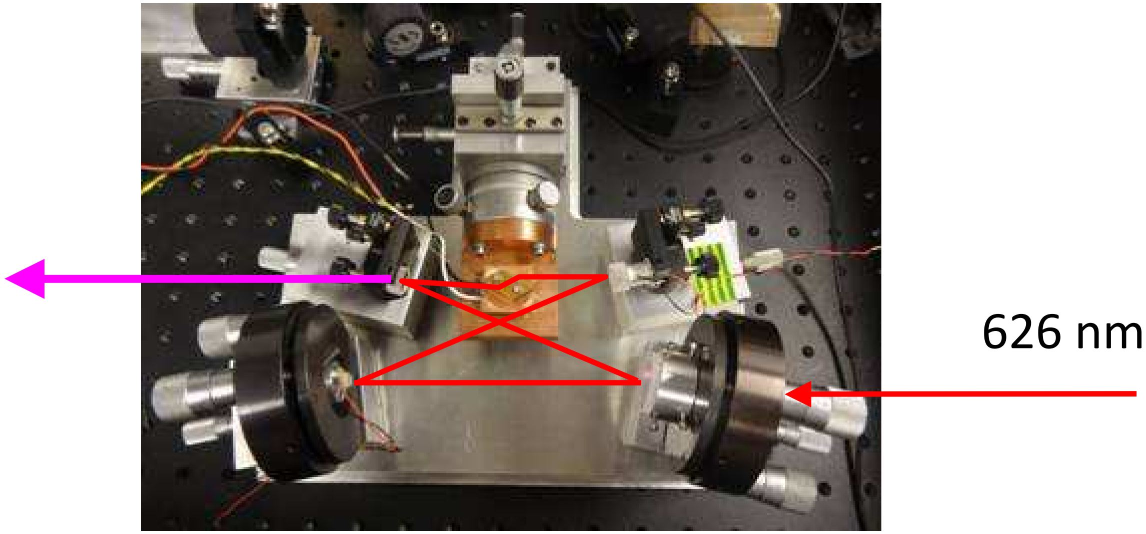
Capture time ≈ energy^2

initial energy	150 meV	7 ms
	1.5 eV	700 ms
	10 eV	30 s

Work in progress

Linear rf ion trap

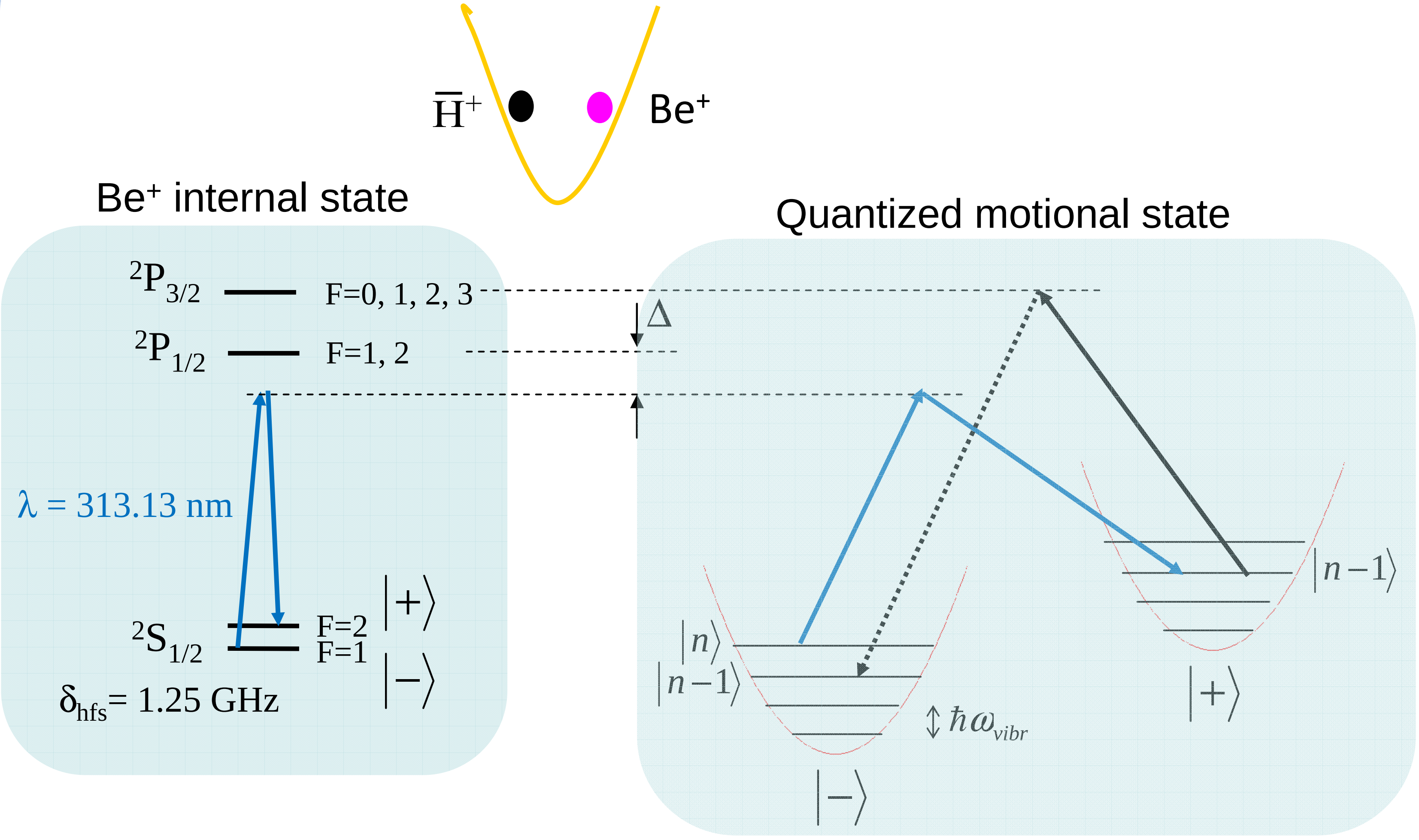
Vacuum vessel



313 nm
1 .. 100 mW

626 nm 0.1 … 2 W

Raman sideband cooling of Be$^+$



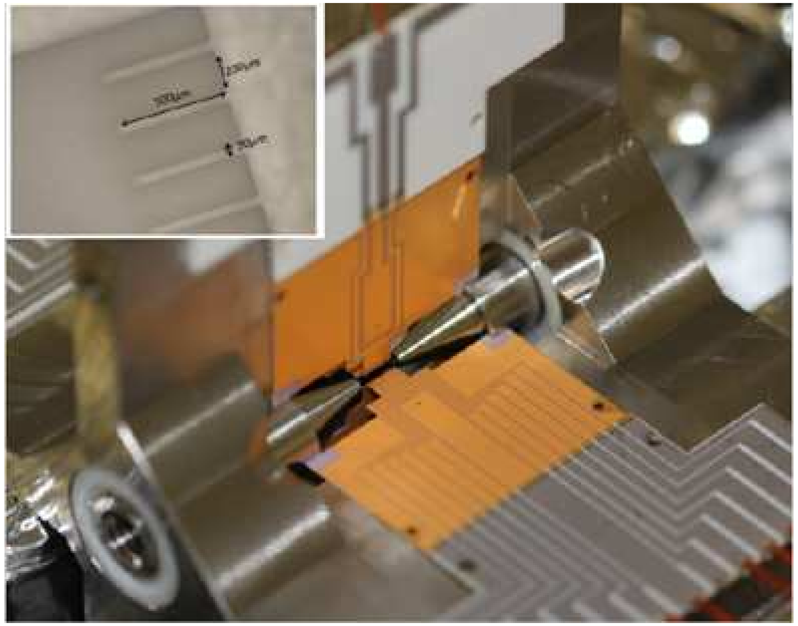
- Initialization in the motional ground state of single ions or few-ion strings

  ⇒ quantum manipulations, optical ion clocks

- Requires a tightly confining trap (Lamb-Dicke regime) and several lasers

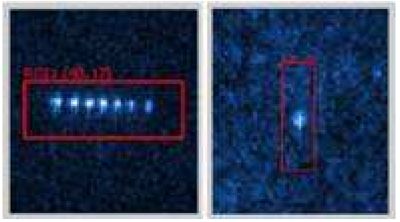
‘Precision trap’ for ground-state cooling

S. Wolf, F. Schmidt-Kaler (Mainz)

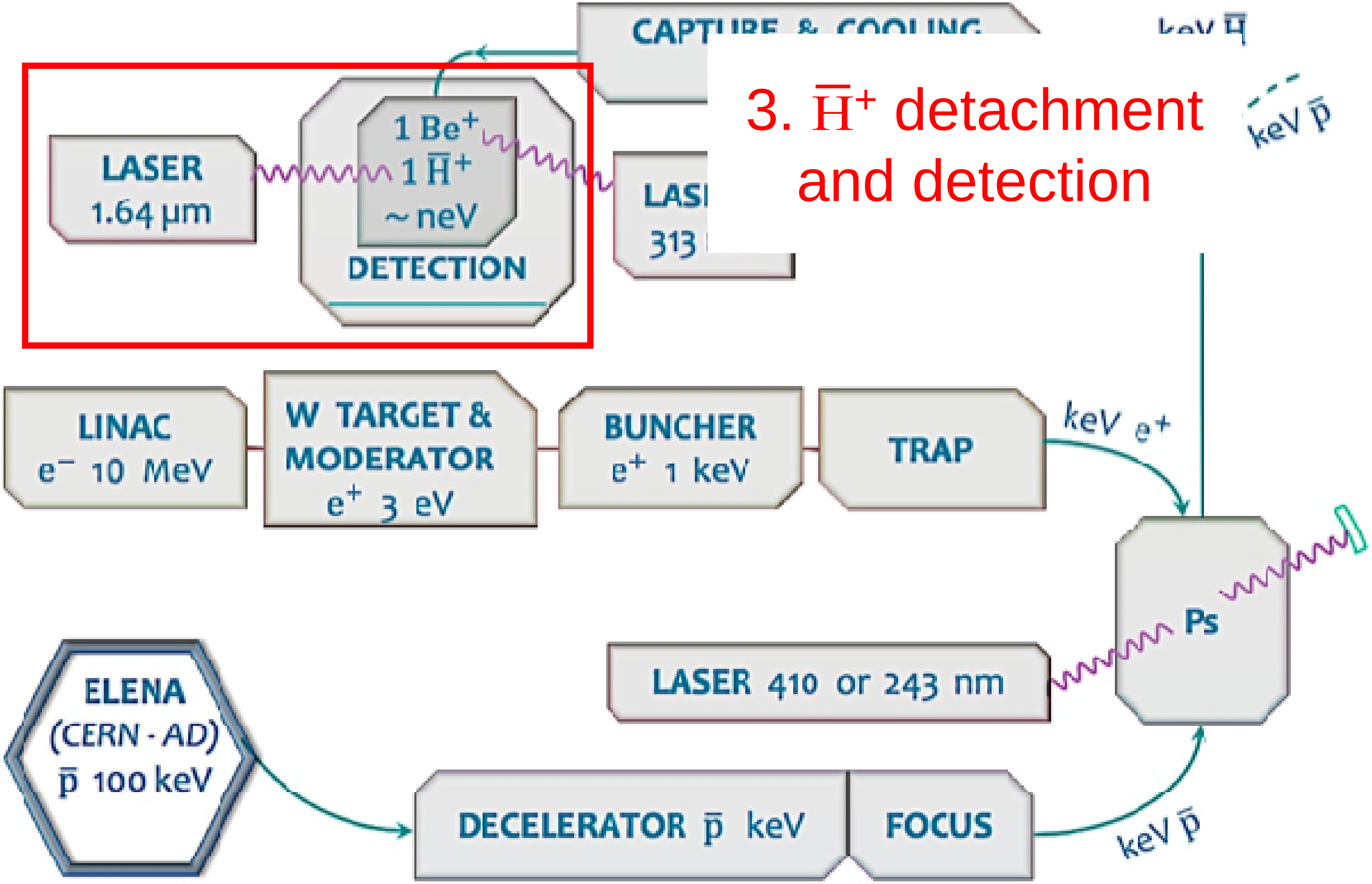


- Symmetric trap fields
- Few µm precision fabrication
- Segmented electrodes for versatile axial potentials
- Time-dependent potentials: fast digital/analog converter boards controlled by FPGA

First Ca$^+$ ions

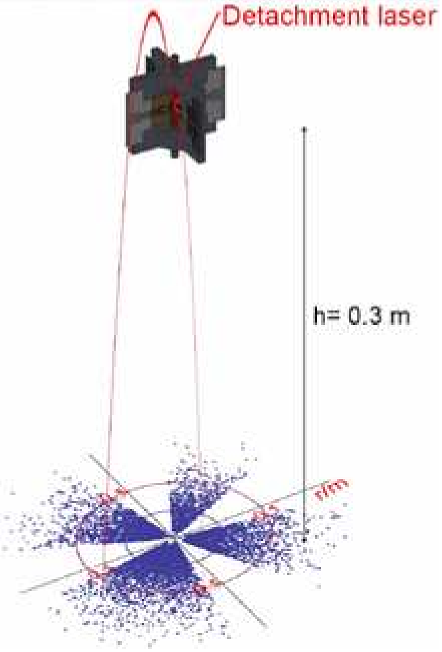


Experimental scheme



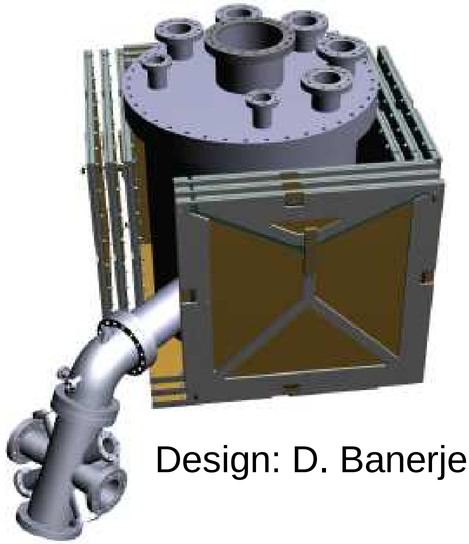
3. $\bar{H}^+$ detachment and detection

Finally : Photodetachment and detection



Phototodetachment (λ = 1.64 µm) $\overline{\mathrm{H}}^+ + h\nu \rightarrow \overline{\mathrm{H}} + e^+$

- Horizontal beam
- Just above threshold to minimize recoil from positron ejection
- But $\sigma \rightarrow 0$ like $(E\text{-}E_{thr})^{3/2}$
- Best compromise: ΔE ~ 1 µeV.
  Photon recoil ~ 0.2 $\mathrm{m.s}^{-1}$ Positron recoil ~ 0.3 $\mathrm{m.s}^{-1}$
  Photodetachment time ~ 150 µs with 1W over $(10\mu\mathrm{m})^2$
- Commercial source: cw OPO pumped by fiber laser (2W).



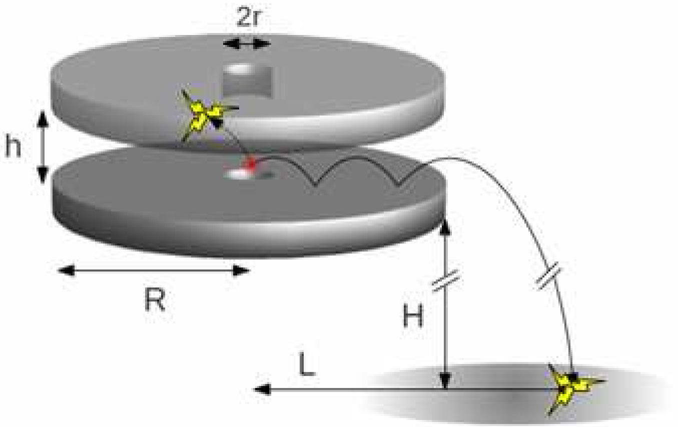
Detection

- $p\text{-}\bar{p}$ annihilation emits charged pions (π^+, π^-)
- Time Projection Chambers: trajectories of charged particles
  precision on the annihilation vertex ~ 1 mm
- Scintillating detectors to get precise annihilation time

Design: D. Banerjee (ETH Zurich)

Possible improvements

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



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)

G. Dufour, P. Debu, A. Lambrecht, V.V. Nesvizhevsky, S. Reynaud, A.Yu. Voronin, Eur. Phys. J. C **74** (2014) 2731

A.Yu. Voronin, V.V. Nesvizhevsky, S. Reynaud, J. Phys. B **45** (2012) 165007
G. Dufour et al., Adv. High Energy Phys. (2015) 379642

- Laser anti$\bar{g}$ravimeter

How to use antiatom interferometry to mesure $\bar{g}$?

The GBAR collaboration

CSNSM

ETH Eidgenössische Technische Hochschule Zürich

ILL NEUTRONS FOR SCIENCE

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Physique quantique et applications

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The University of Tokyo, Komaba

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