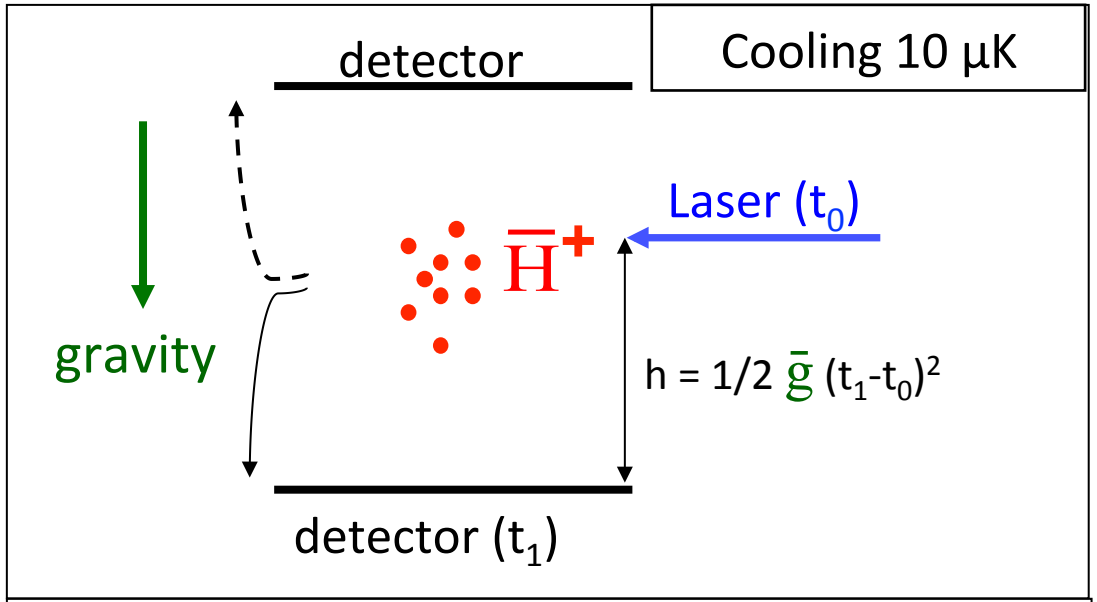
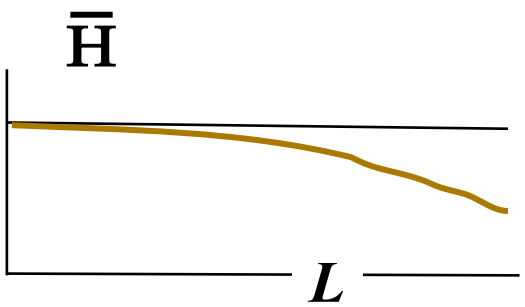
# GBAR principle: cool $\bar{H}^+$ to get ultra-slow $\bar{H}$

- $\bar{H}^+ = \bar{p}\, e^+ e^+$
- Sympathetic cooling with $Be^+ \rightarrow 10\ \mu K$
- Photodetachment of $e^+$
- Time of flight




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

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




$$h = v_z^0 t + \frac{1}{2}\frac{m_g}{m_i} g t^2$$

| | |
|---|---|
| L | 0.1 m |
| h | 10 cm |
| $\Delta t$ | 143 ms |
| $v_h$ | 0.5 m/s |
| $T_H$ | 20 µK ~ 7 neV |

*Goal*

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

# A recipe to produce anti ions

Standard $\bar{H}$ production via 3-body process

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

bound $e^+e^-$ → 3-body

demonstrated by ATRAP (2004) →

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

**Idea for GBAR**: 2nd charge exchange reaction →

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

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

Binding energy of $\bar{H}^+$ = 0.75 eV = energy level of Ps(n=3)

→ Expect cross-section enhancement if Ps excited to n=3

# $\bar{H}^+$ production

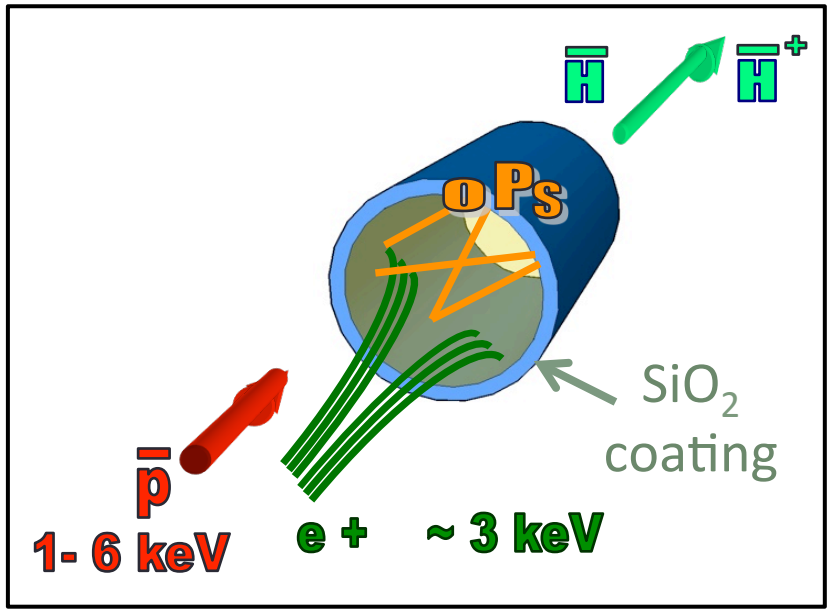
CERN provides per bunch every 110 s →

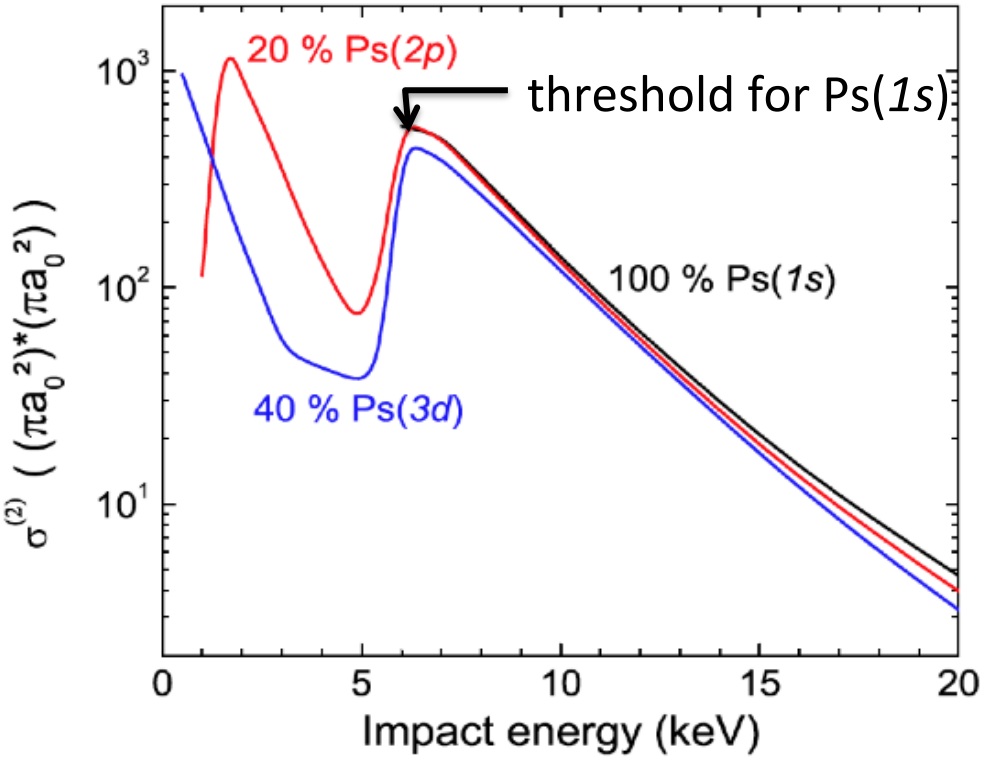
~0.5 $10^7$ $\bar{p}$

$10^{12}$ $P_S$ /cm$^2$

} → $10^4$ $\bar{H}$

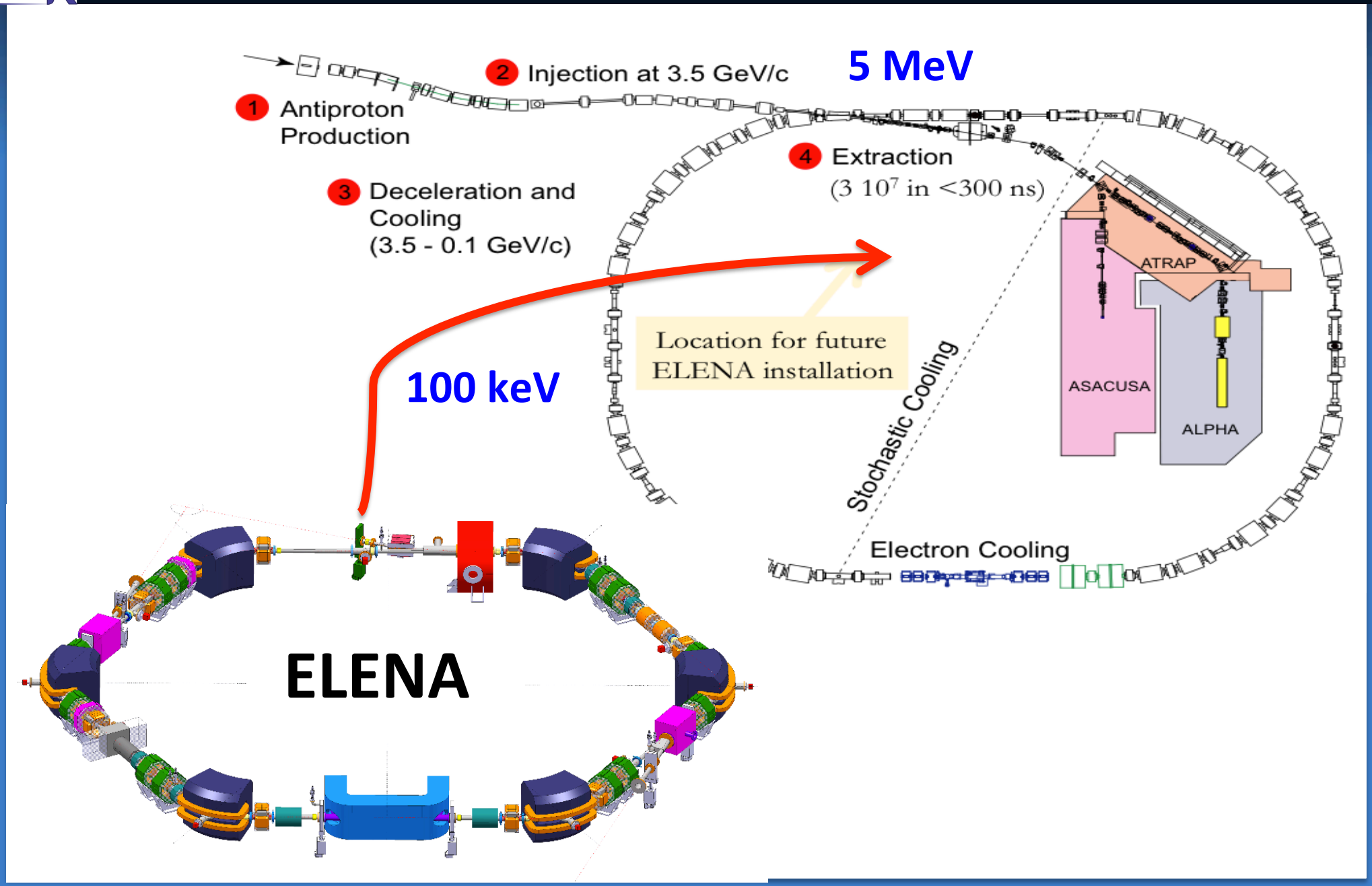
1 $\bar{H}^+$



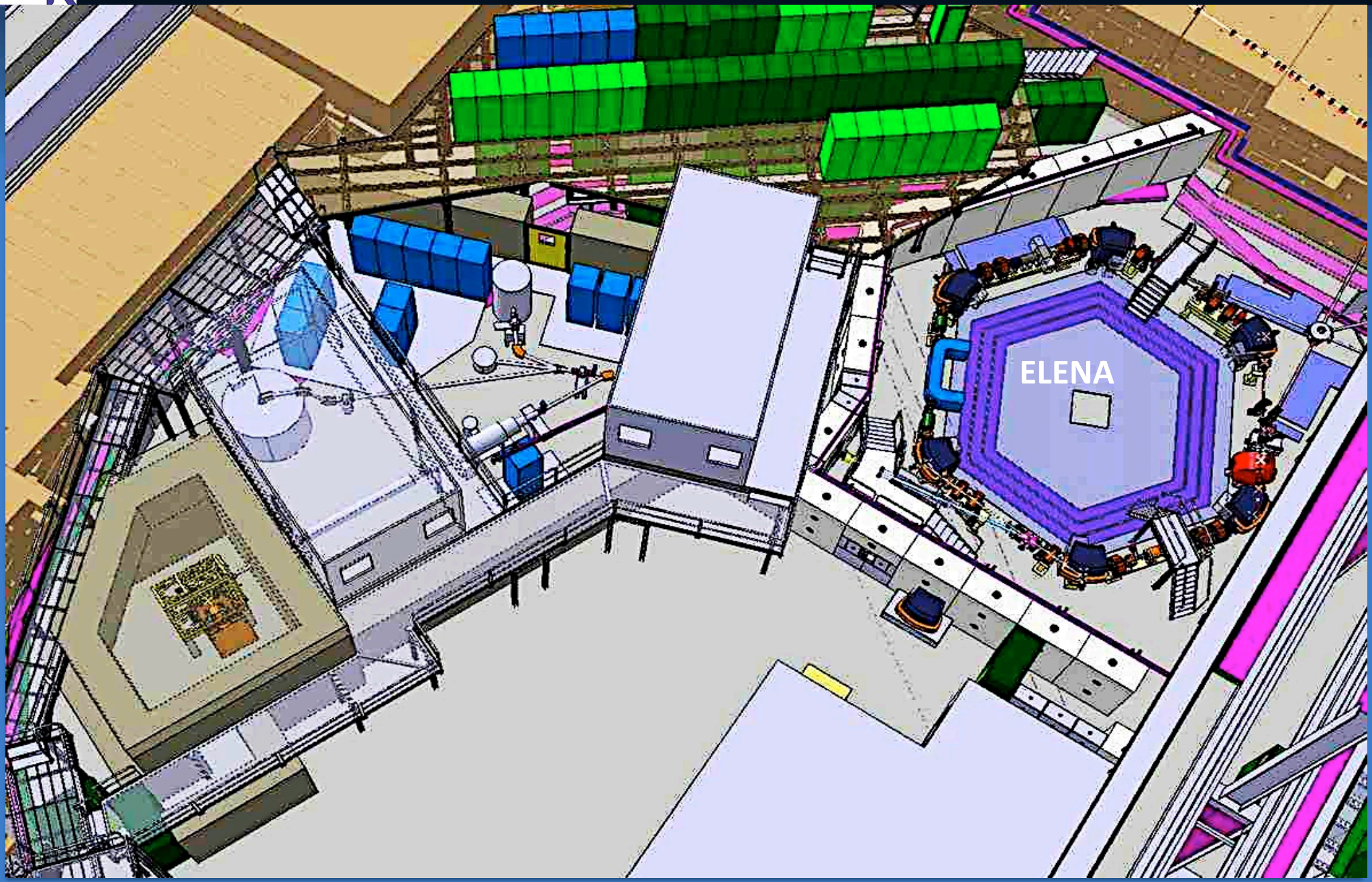

*P. Comini and P-A. Hervieux*, J. Phys.: Conf. Ser. **443**, 012007 (2013)
*P. Comini, P-A. Hervieux and F. Biraben,* LEAP 2013

# Antiprotons: CERN AD / ELENA



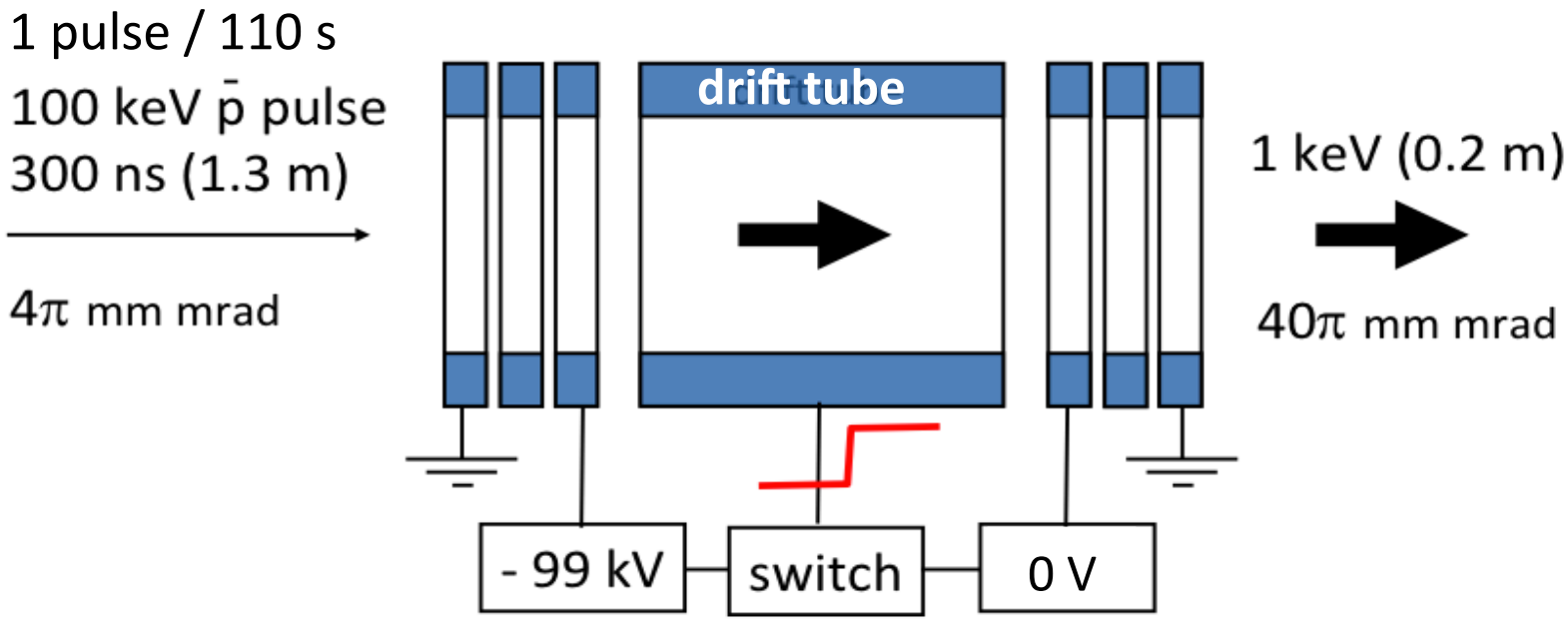
# Layout

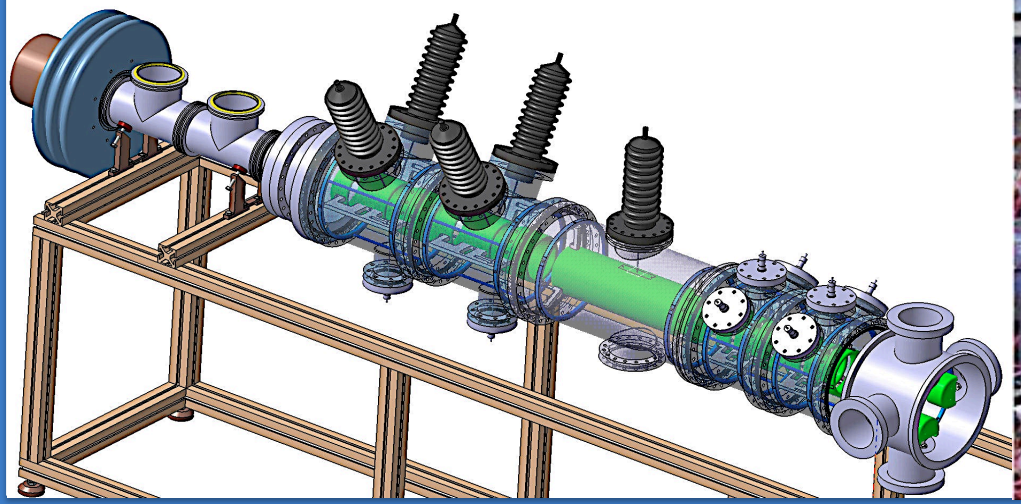
O. Choisnet
F. Butin

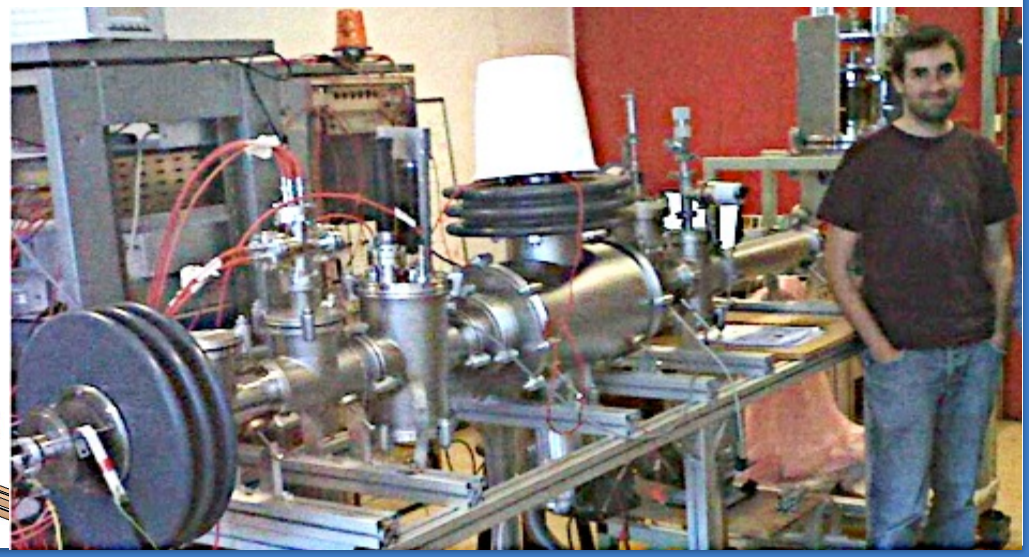


# GBAR antiproton decelerator

D. Lunney
P. Dupré

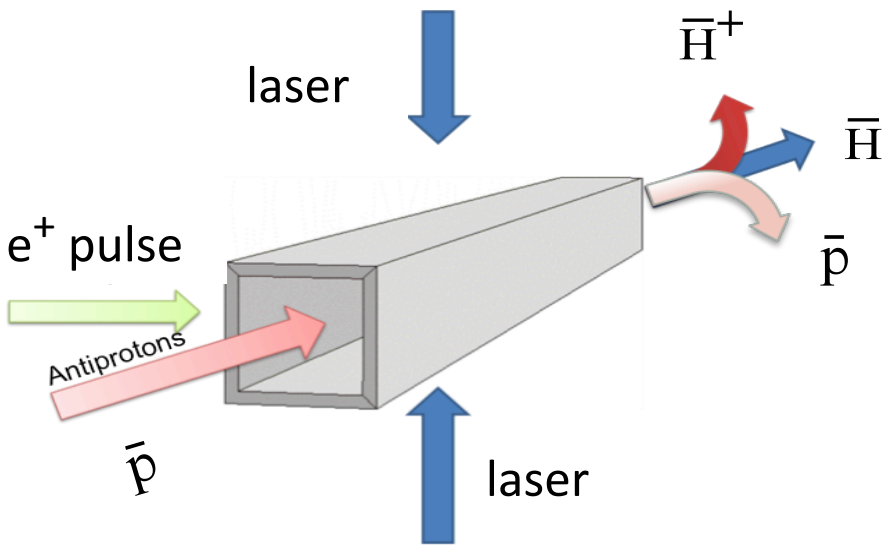


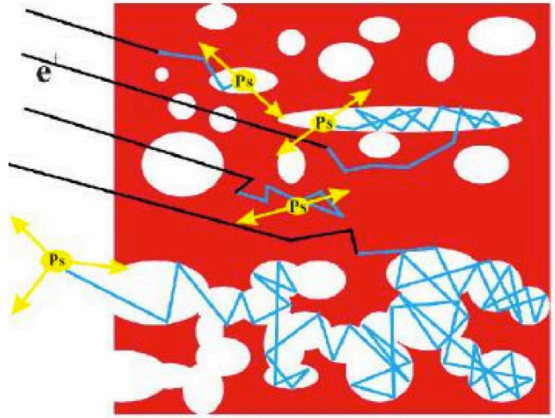



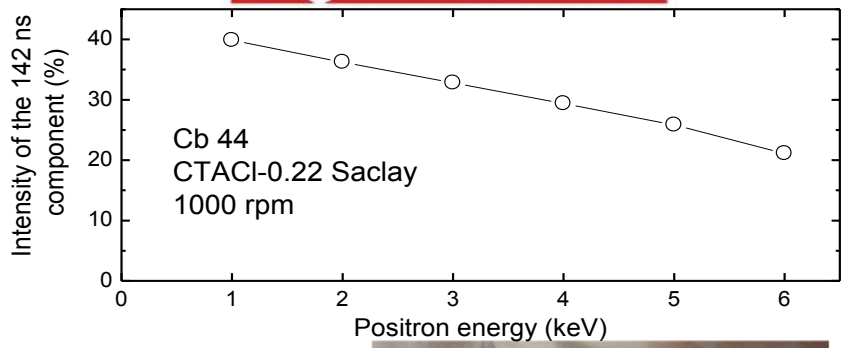


# Ps formation

P. Crivelli
L. Liszkay



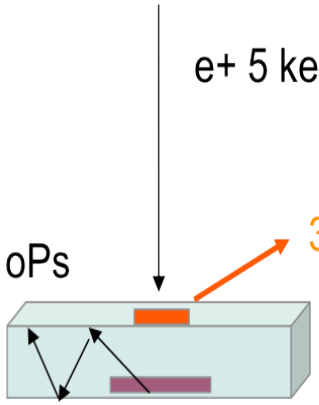



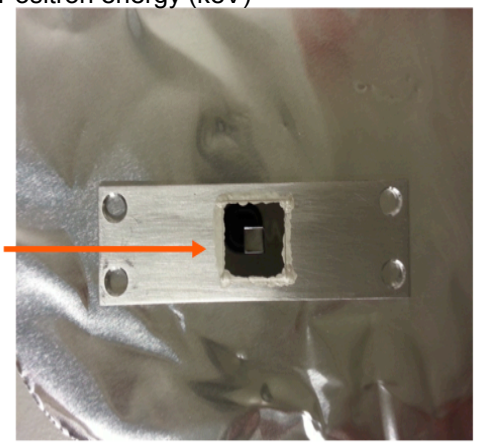

1 mm × 1 mm × 2 cm
Si with mesoporous $SiO_2$ coating

<u>Test on ETHZ beam line</u>
Transmission @ 5 keV ~ 100%
Ps formation efficiency as for bare $SiO_2$
Same Ps lifetime distribution

P. Crivelli, WAG2013

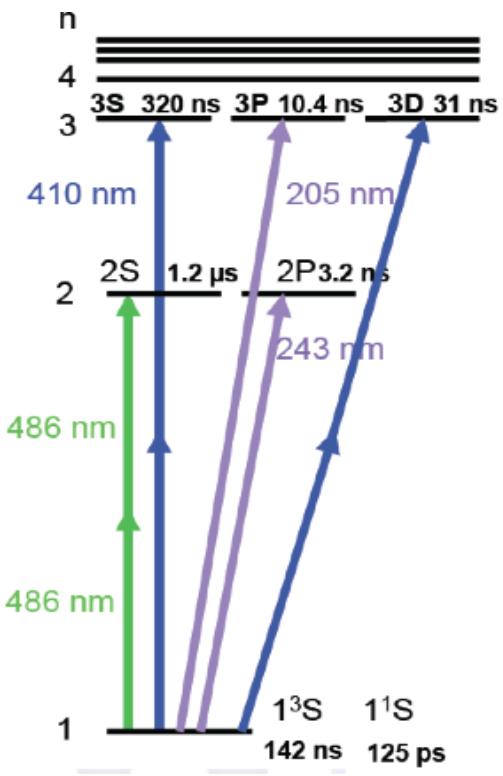


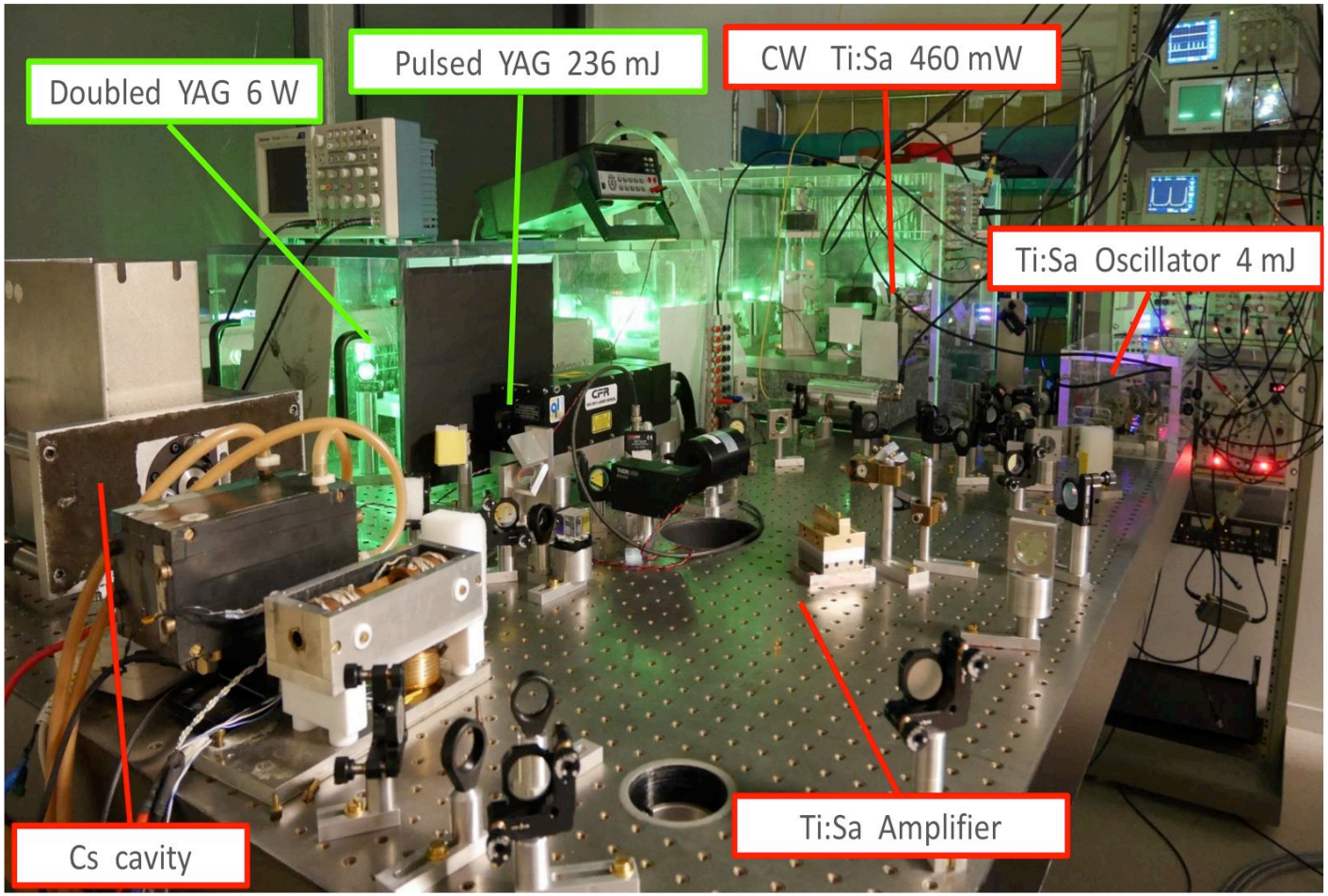

SiN window
30 nm × 3 × 3 $mm^2$



Aperture 3x3 $mm^2$
Length 60 mm, internal walls coated with SiO2

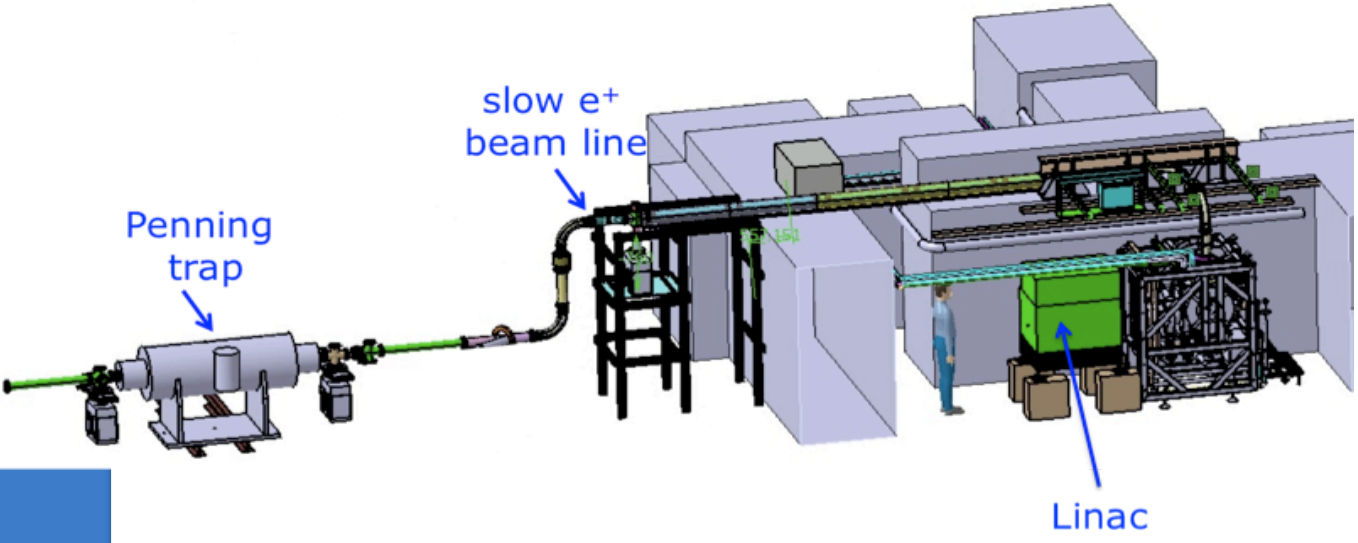
# Ps excitation laser (n=3)




Presently developed at LKB – Paris
To be tested at Saclay

# e+/Ps demonstrator at Saclay



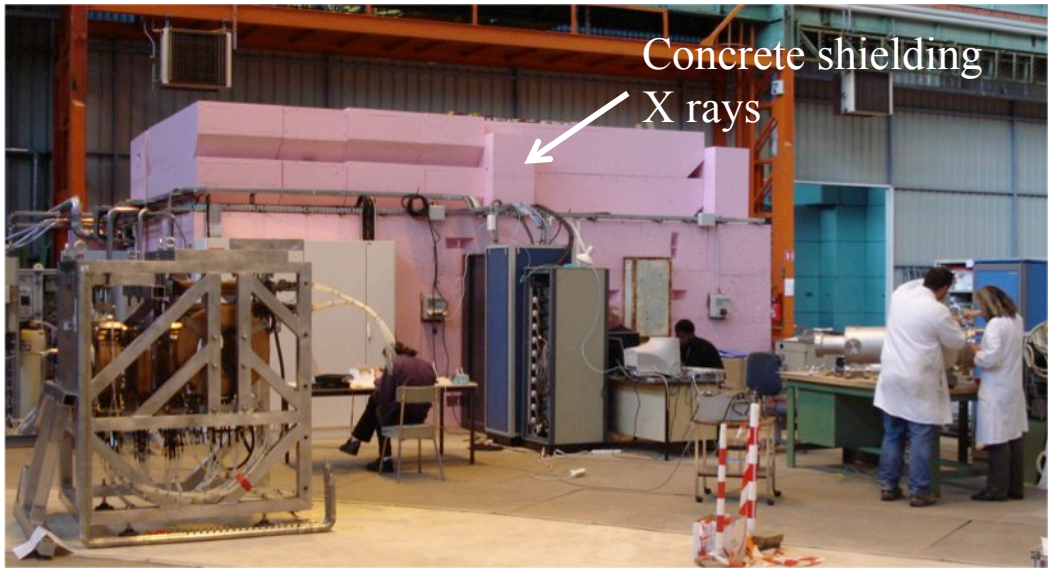

- 4.3 MeV / 200 Hz / 2.5 µs / 120 µA
- 3 $10^6$ slow $e^+$/s
- with first W mesh moderator

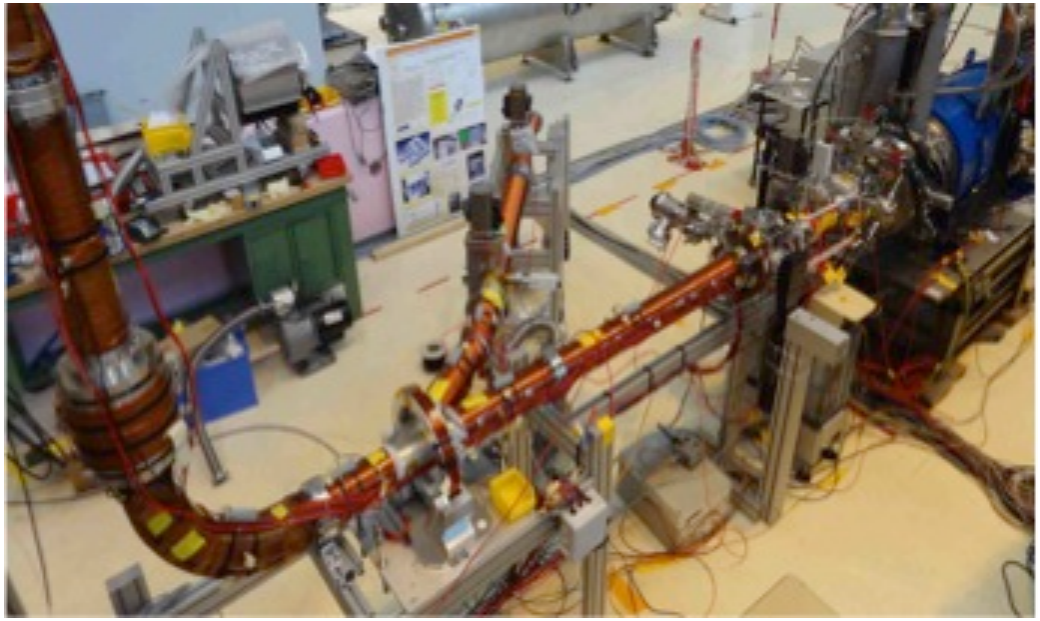
- Penning trap on beam line (from RIKEN)
- First trapping trials

- Secondary beam line
- → moderator developments
- → e+/Ps converters

- Ps* laser being prepared at LKB (Paris)

# e+/Ps demonstrator at Saclay



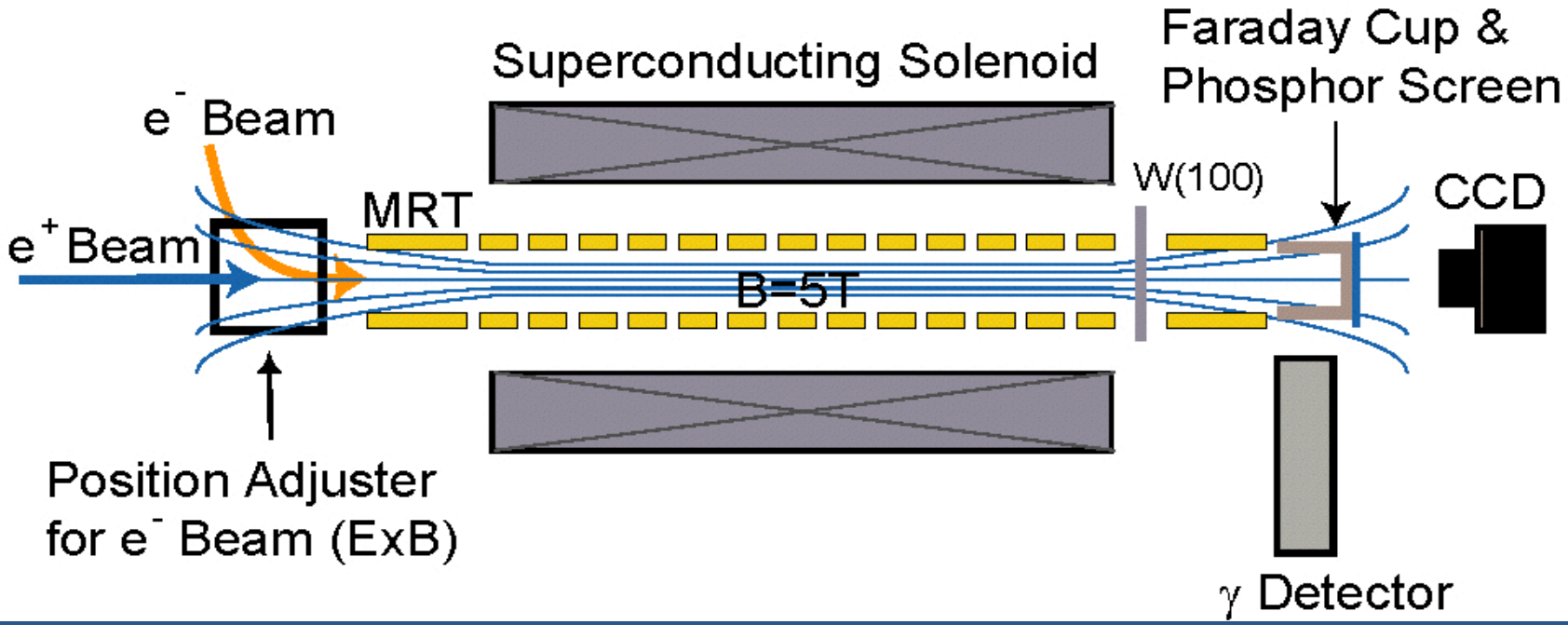



$e^-$ Linac  Ec = 4.3 MeV  I = 0.14 mA

**CERN version: 10 MeV, 0.2 mA**
**Built by NCBJ Warsaw**
**→ 1-3 $10^8$ $e^+$/s**

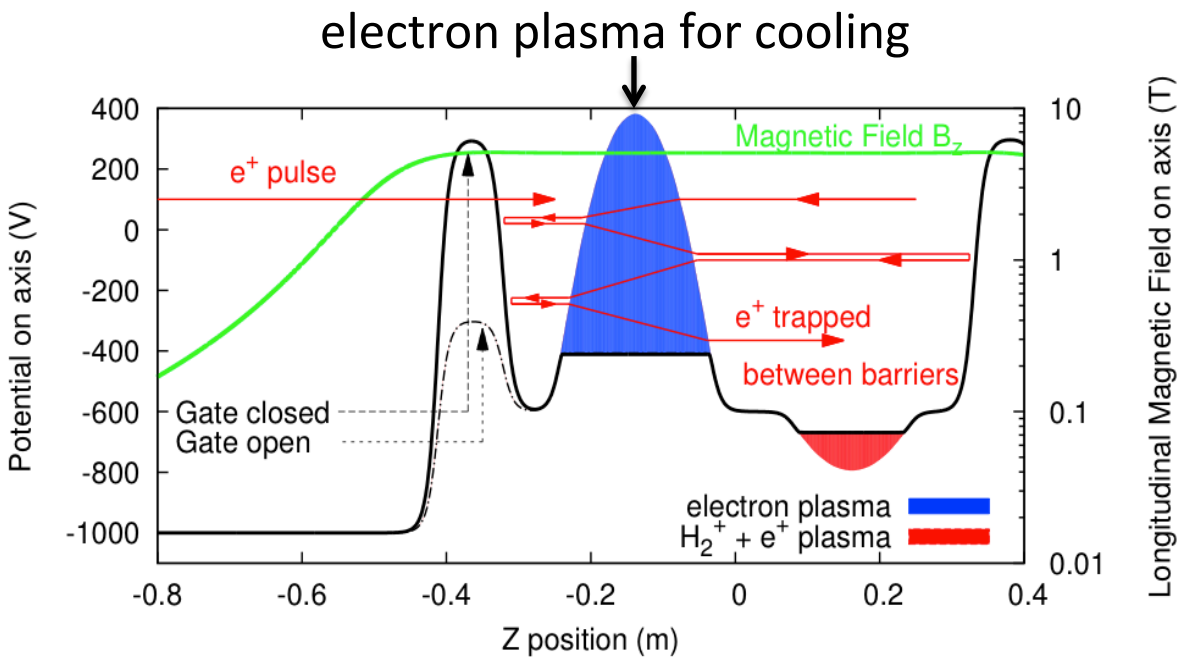
# RIKEN Multi-Ring Trap

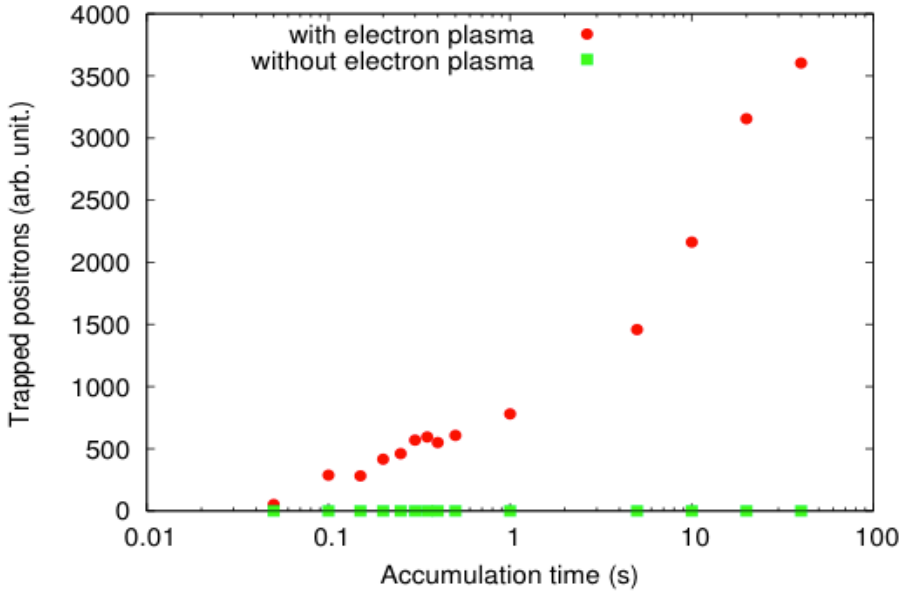
Must accumulate 3 $10^{10}$ $e^+$ in 110 s

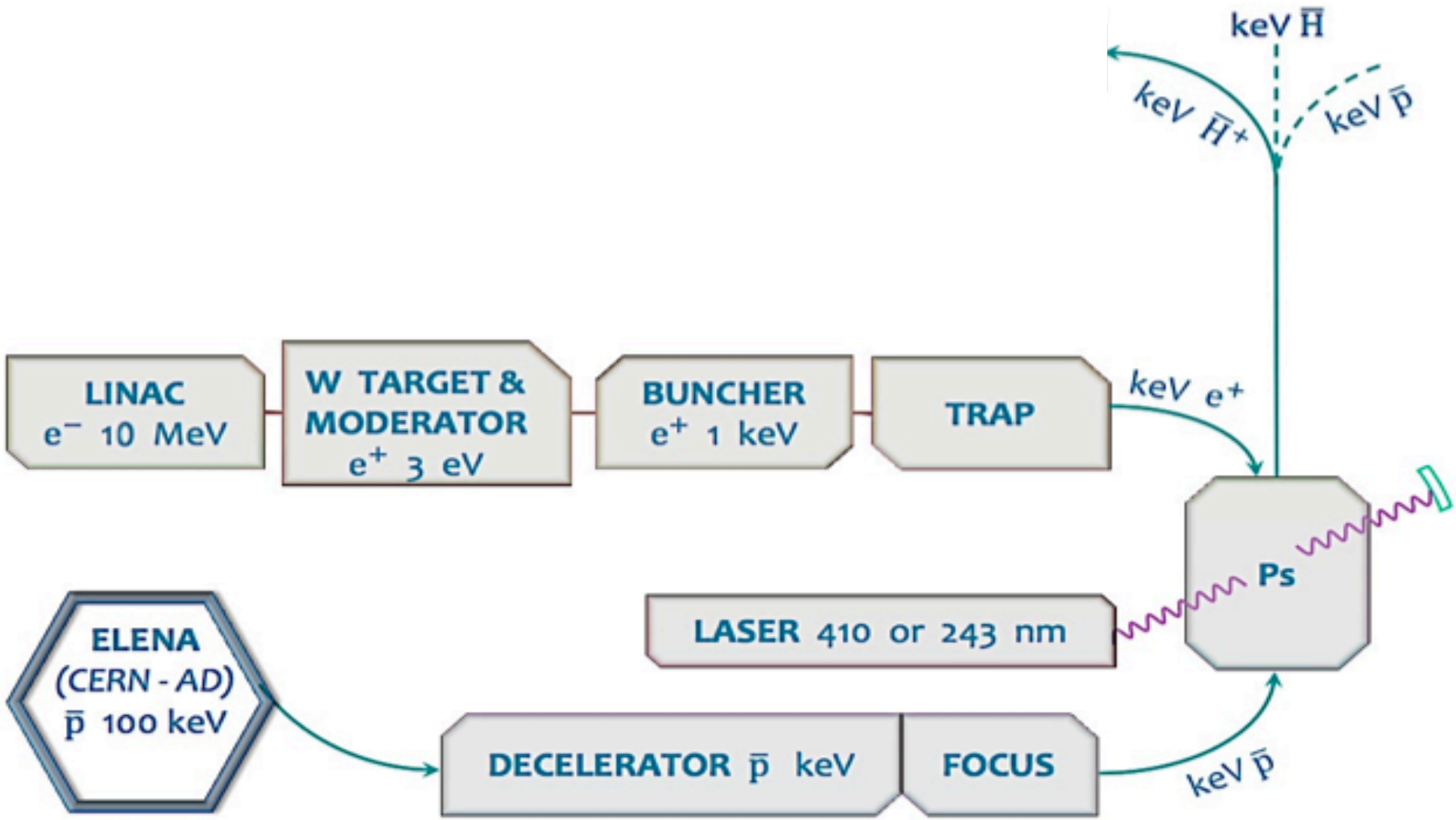
# $e^+$ trapping

P. Dupré
P. Grandemange



# $\overline{H}^+$ production scheme

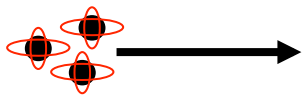


# $\bar{H}$ with v < 1 m/s ?

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 particule
Temperature 3 neV
20 μK

Classical world

Frontiers of
Quantum world

NIST D. Wineland
Innsbruck R. Blatt

# $\bar{H}^+$ cooling simulations

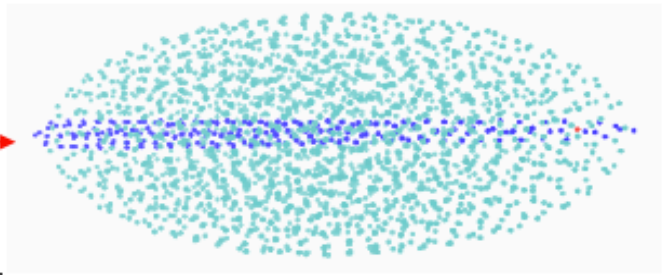
L. Hilico

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

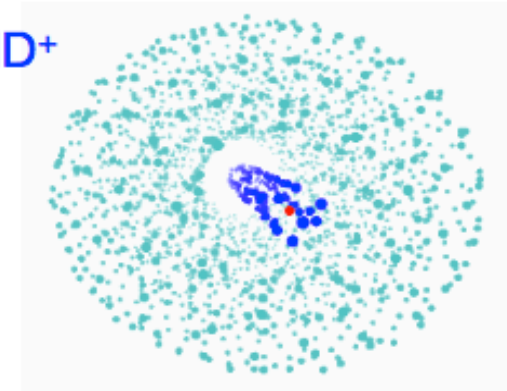
Idea : try an intermediate ion 9 / 3 / 1

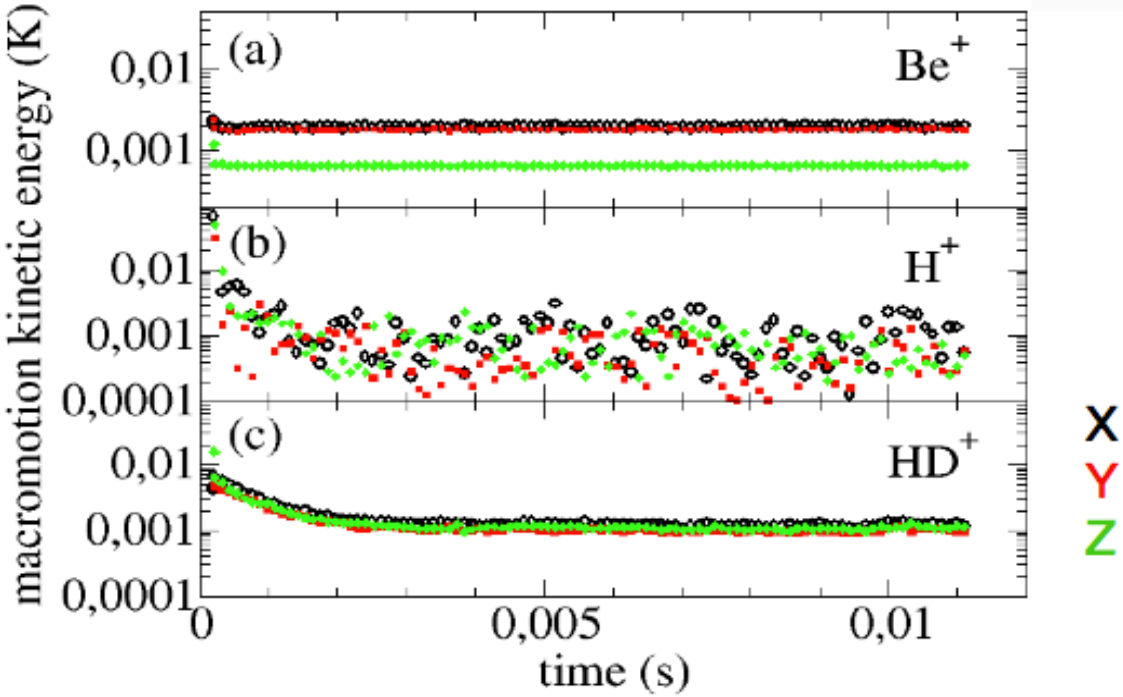
C. B. Zhang, D. Oenberg, B. Roth, M. A. Wilson, and S. Schiller, Phys. Rev. A 76, 012719 (2007).
L. Hilico et al., IJMPCS 2014

few meV $\bar{H}^+$



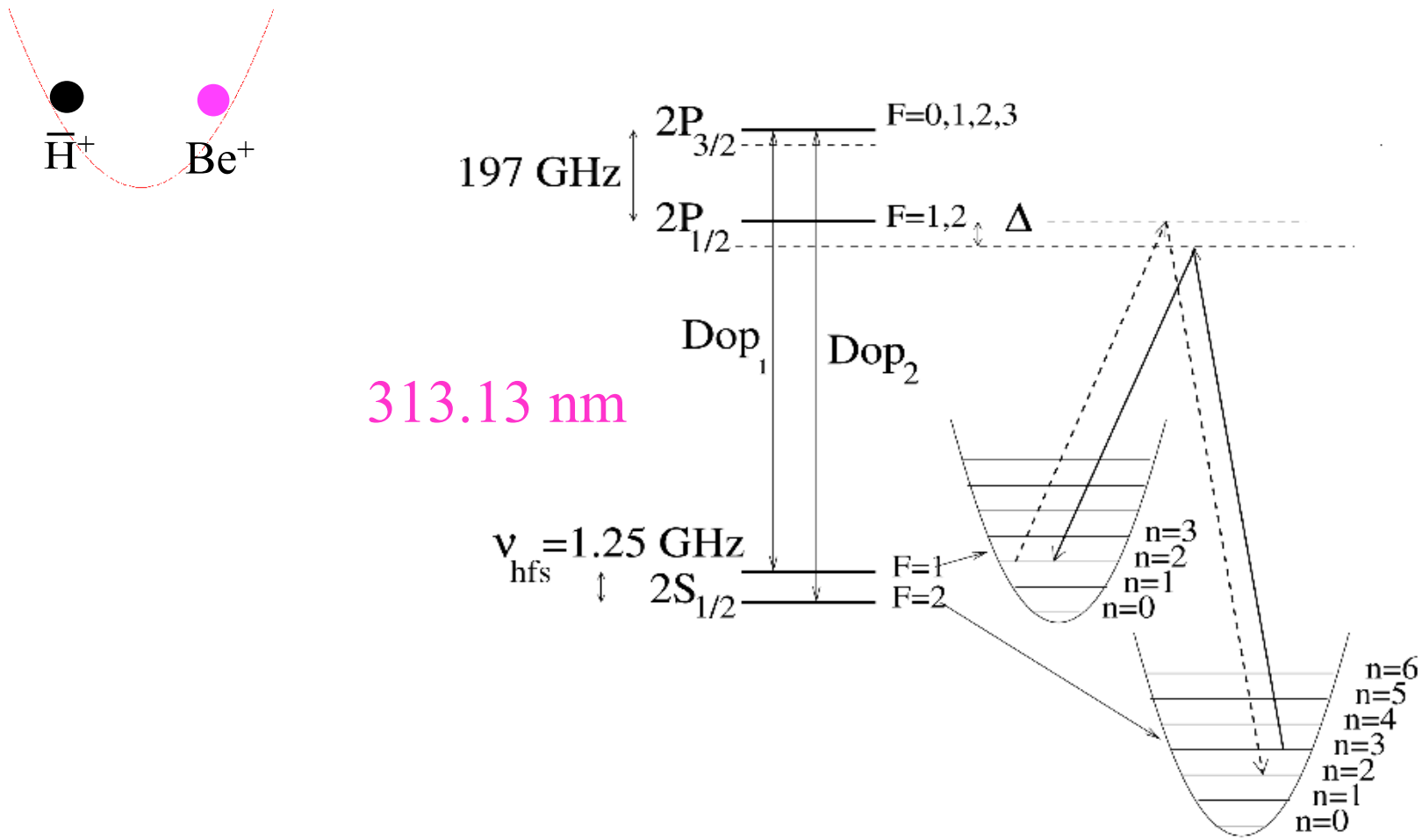
1800 $Be^+$
200 $HD^+$
1 $\bar{H}^+$






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

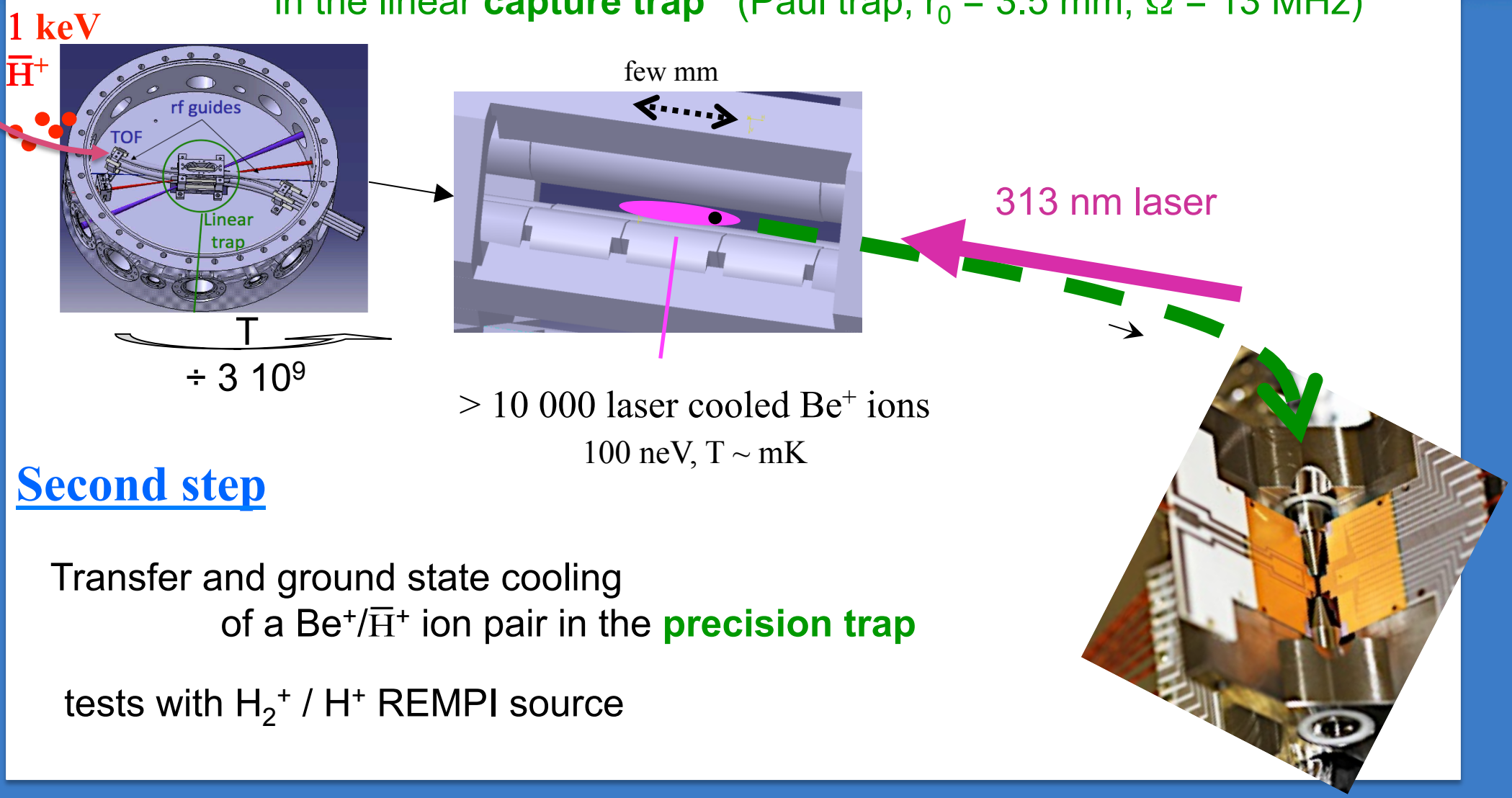
# Raman side band cooling



# Two cooling steps

L. Hilico
F. Schmidt-Kaler

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




**Second step**

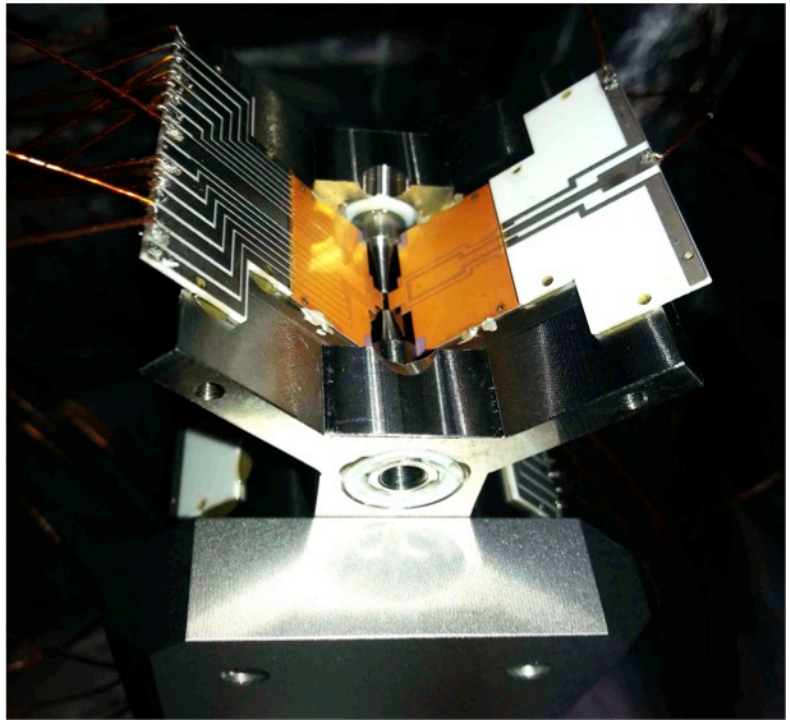
Transfer and ground state cooling of a $Be^+/\bar{H}^+$ ion pair in the **precision trap**

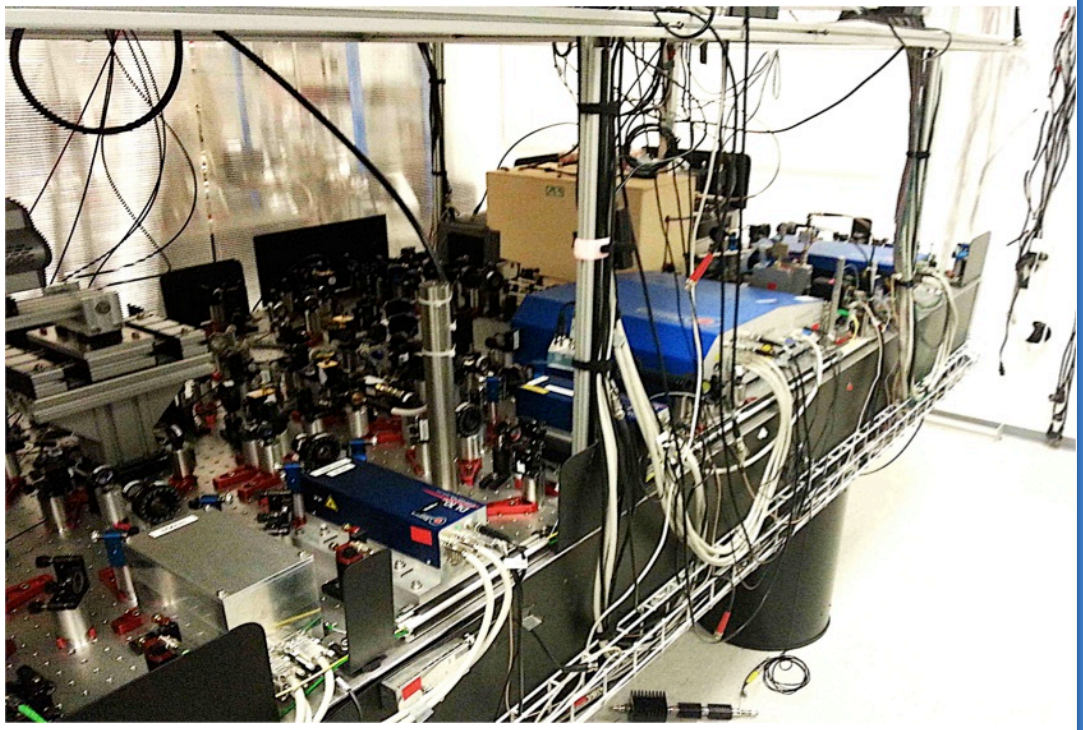
tests with $H_2^+$ / $H^+$ REMPI source

# Precision trap

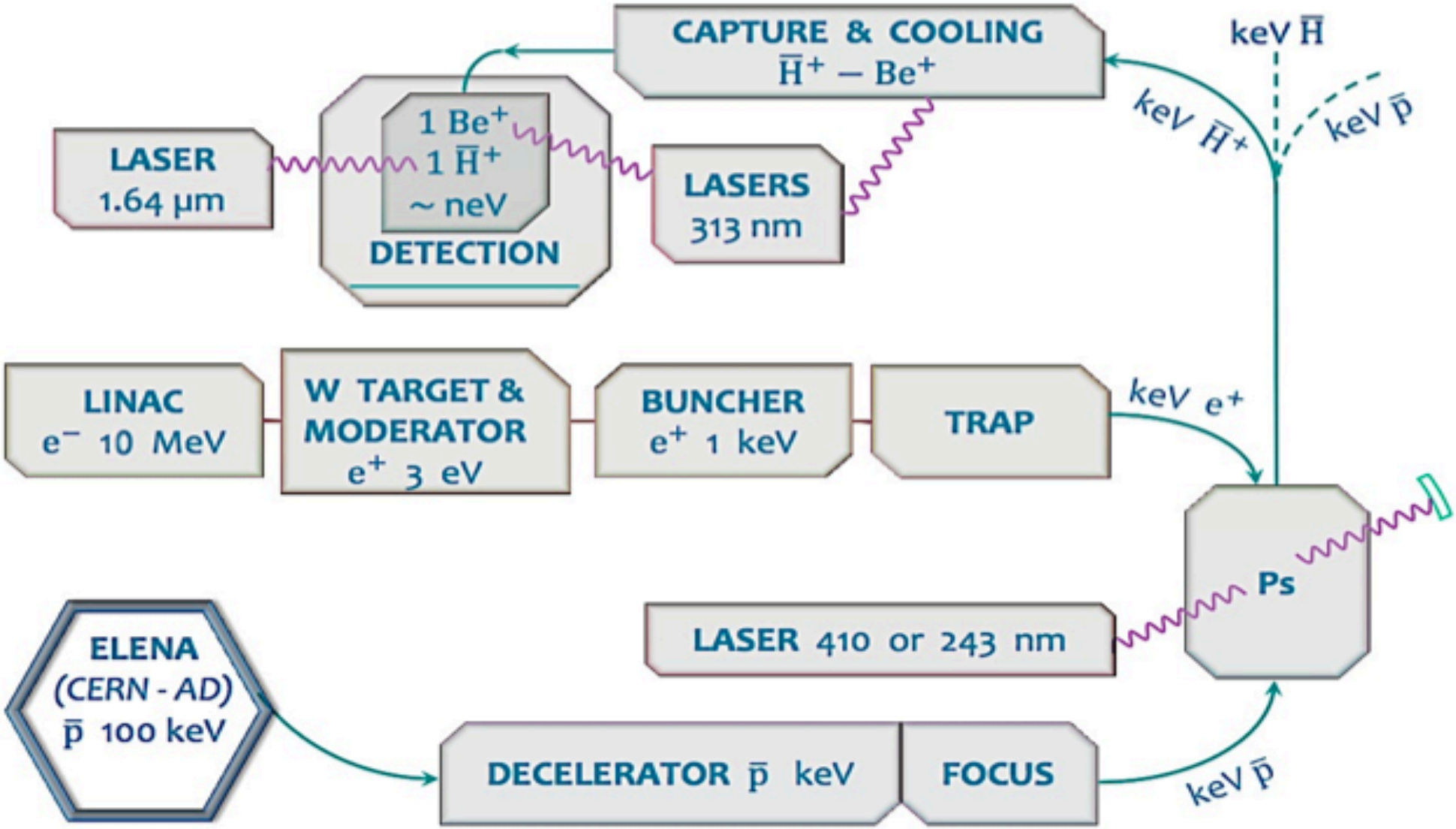
S. Wolf
F. Schmidt-Kaler

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

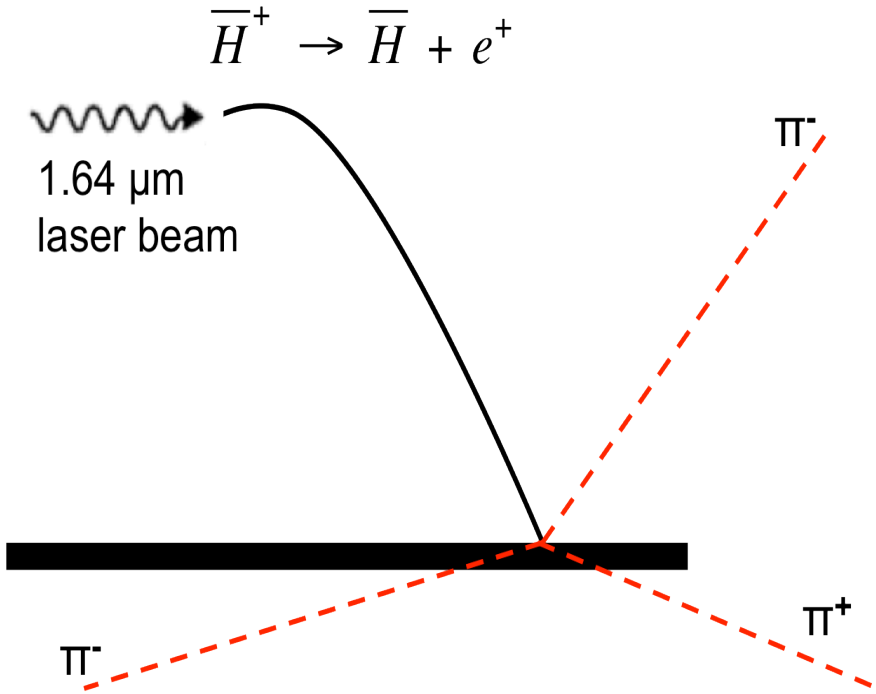


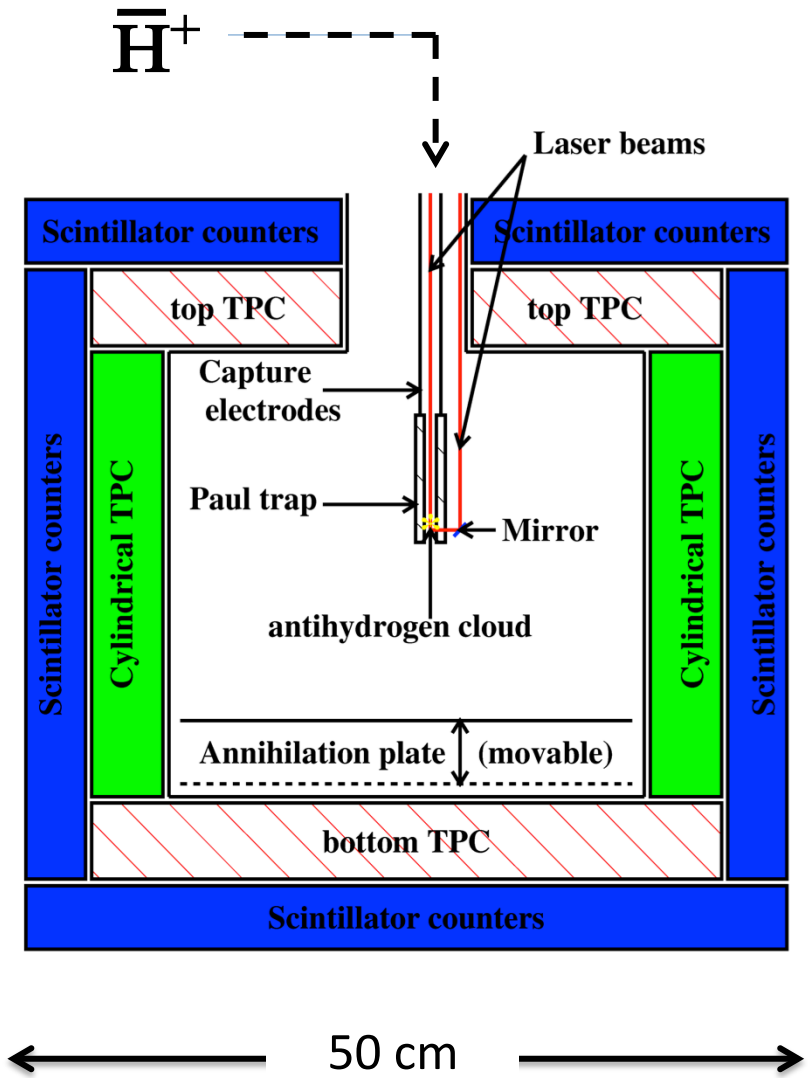


# GBAR overall scheme



# $\overline{H}$ 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

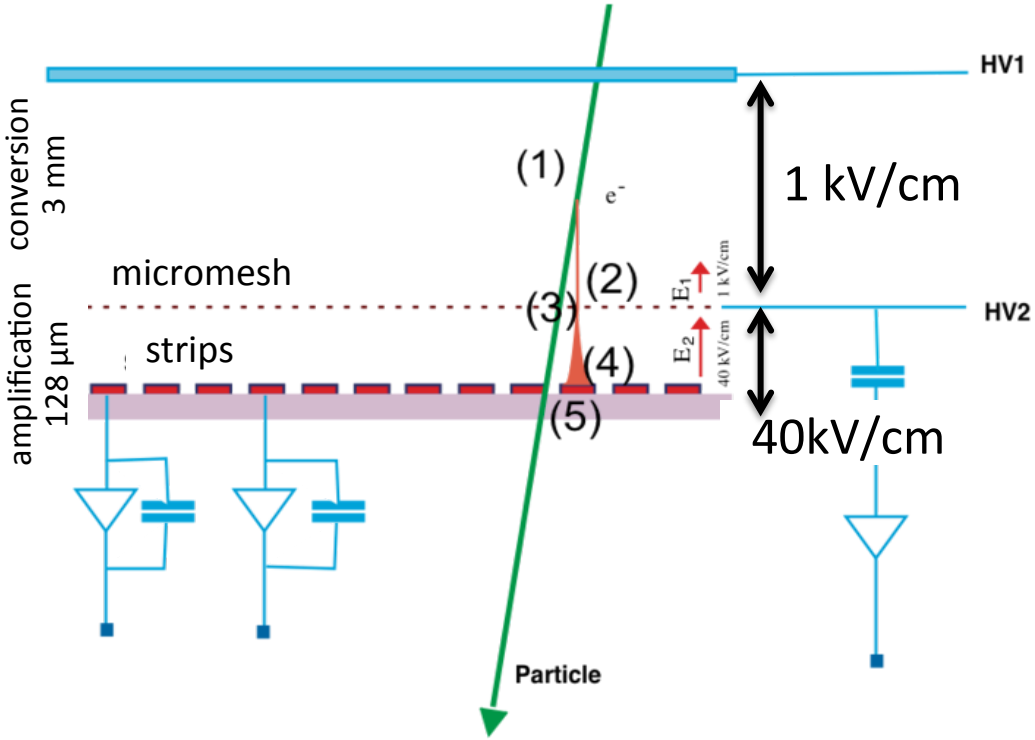
Argon Isobutane (95% , 5%)

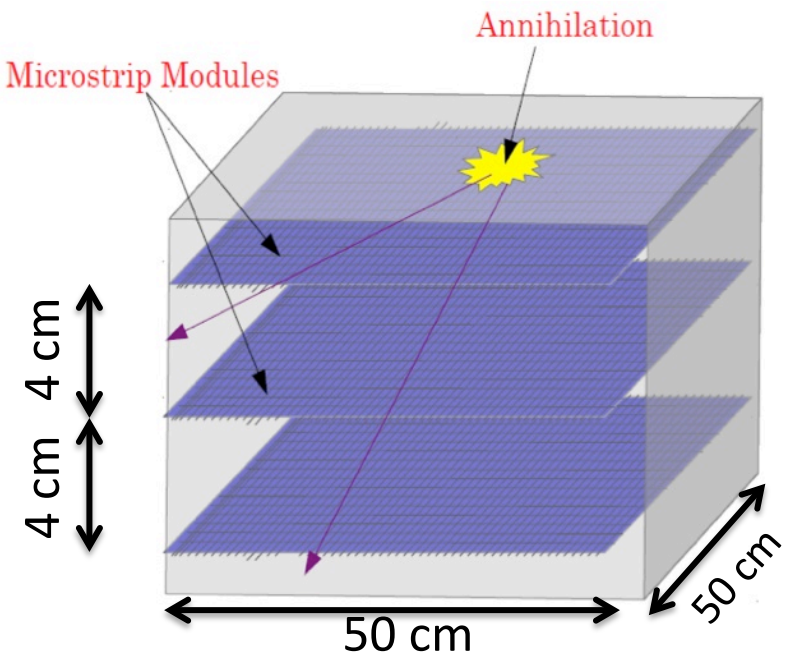
Pitch of strip ~ 400 microns

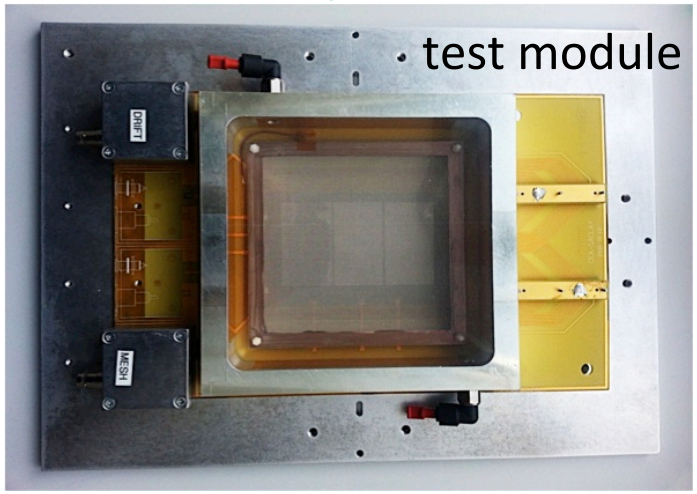
X and Y strips give track position directly

Genetic multiplexing of strips

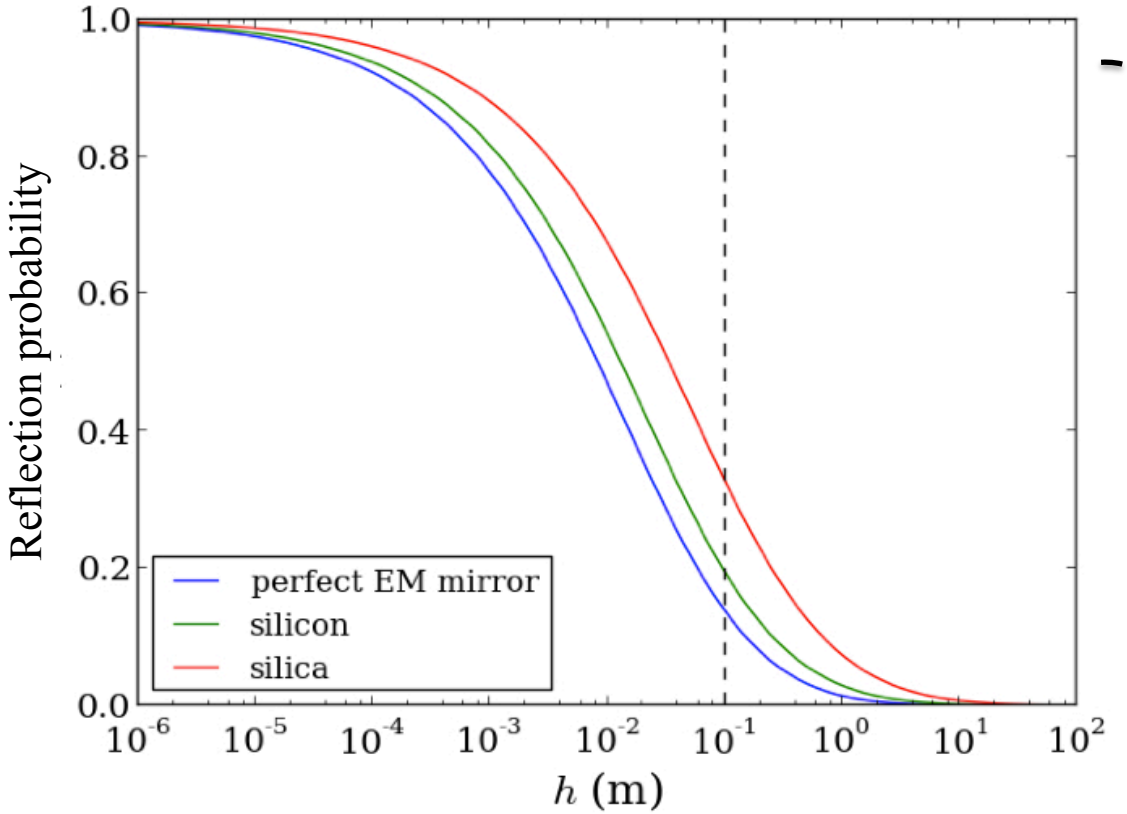
S. Procureur et al, NIM **A** 729 (2013) 888

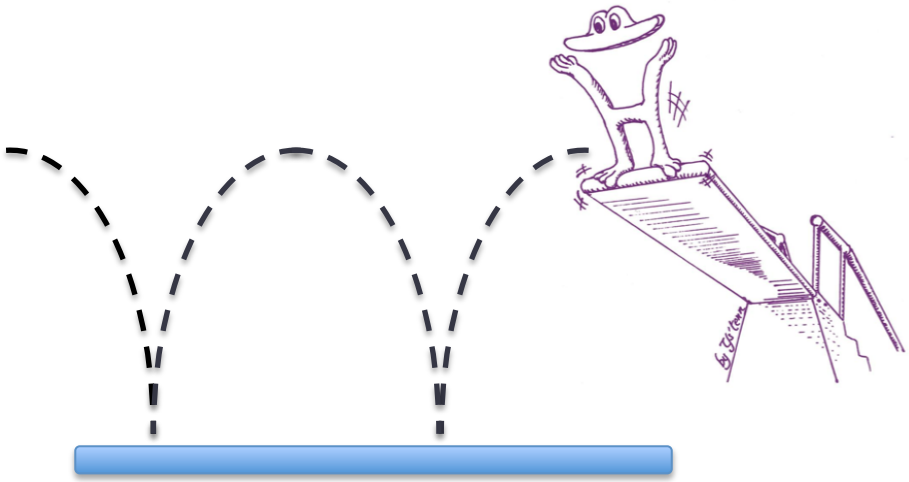


# Spectroscopy of gravitational states



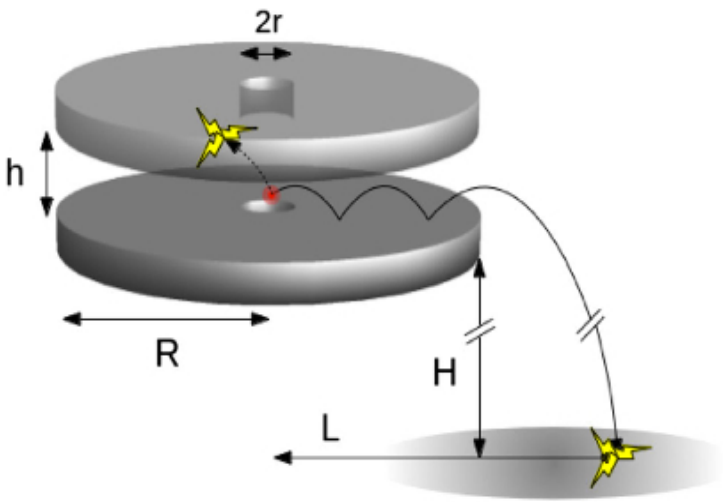



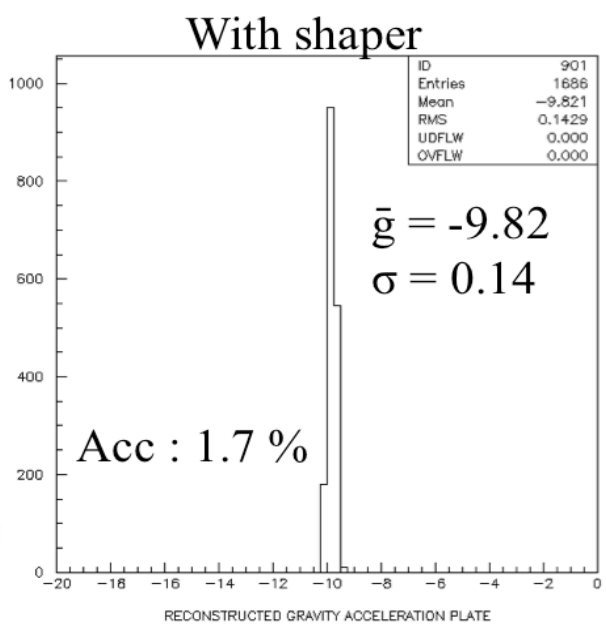
altitudes are quantized
→ spectroscopy
i.e. improved precision

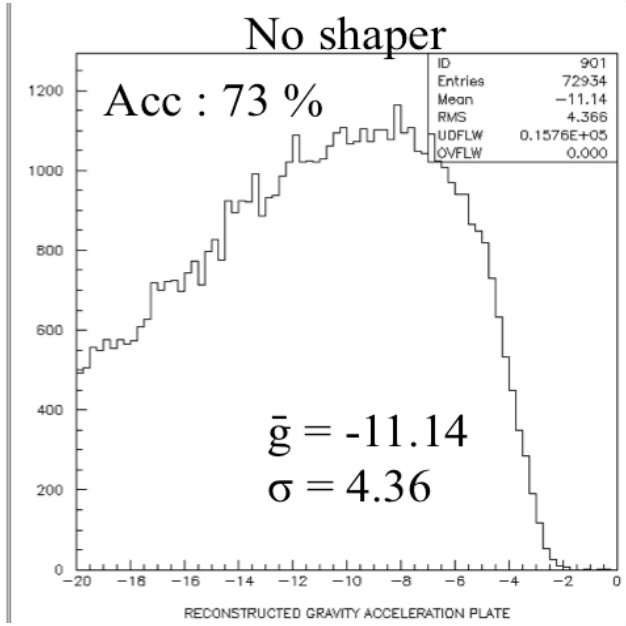
already demonstrated with ultra cold neutrons at ILL (*V. Nesvizhevsky*)

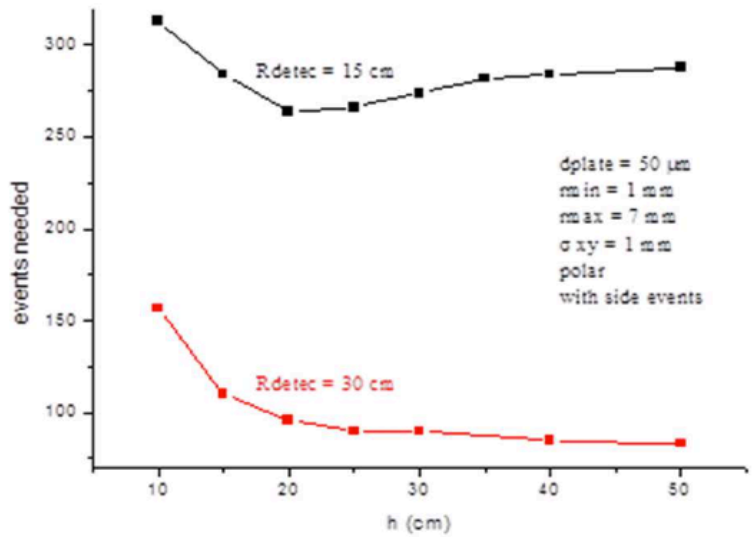
# Velocity selector

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

2015 start installation
2016 ELENA commissioning with p and $H^-$
2017 first antiprotons for GBAR