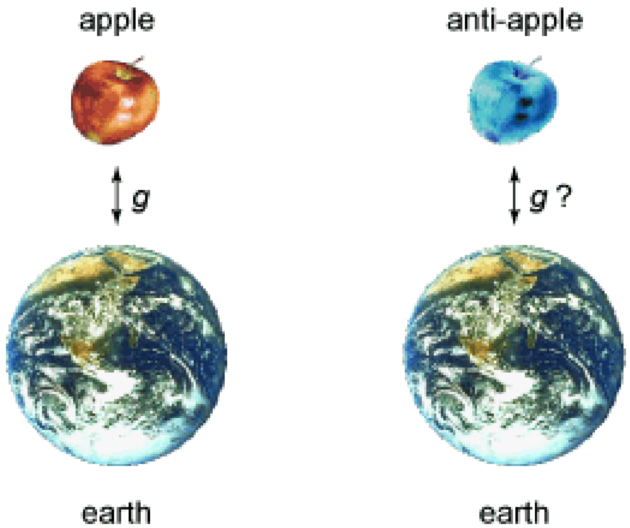
GBAR

Gravitational Behaviour of Antihydrogen at Rest



- **Motivation & goal**
- **Principle of the experiment**
- **Experimental techniques**
- **Perspective**

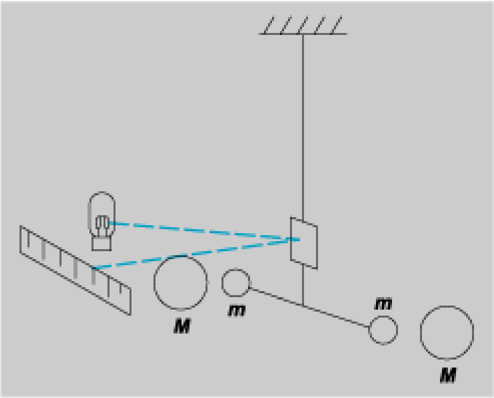
Motivation

<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)

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

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

Strong Equivalence Principle (Lunar Laser Ranging)

$$\left(\Delta a / a\right)_{Earth/Moon} = \left(-1.0 \pm 1.4\right) x10^{-13}$$

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

Theory (1)

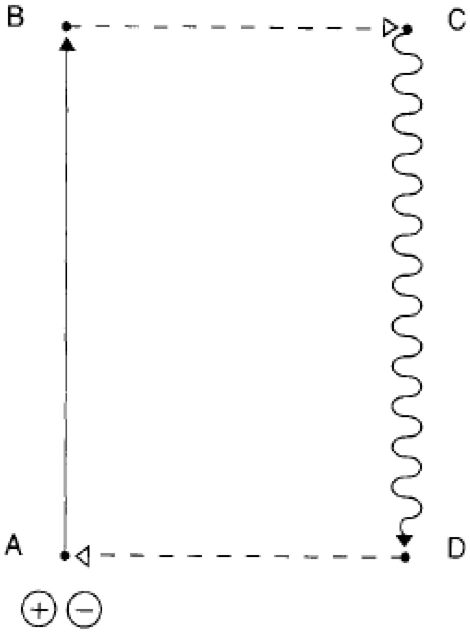
Morrison argument (1958) :
antigravity in General Relativity
→ violation of energy conservation

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

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

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

$$E_D = E_A + 2m_I gL$$



Theory (2)

→ new gravi-vector and gravi-scalar fields coupled to baryon number
→ distinguish m_G and $\bar{m}_G$
(J. Scherk, Phys. Lett. B (1979) 265)

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

Tests with matter give only limits on ~ |b-a|

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

Theory (3)

Anti matter content of ordinary matter
(Schiff argument)

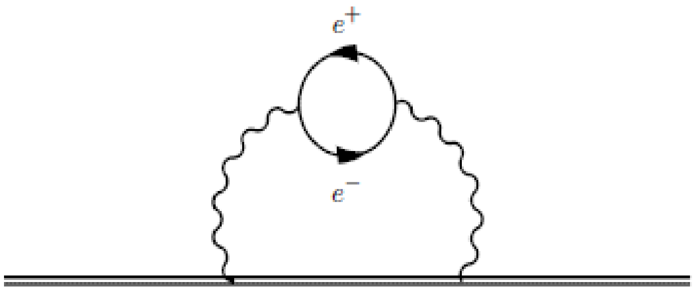


FIG. 2: Loop contribution to the electrostatic self-energy of the nucleus

$$\left|\frac{g-\bar{g}}{g}\right| \square \left|\frac{g-g_{\Delta Erad}}{g}\right| \Rightarrow$$

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	$\lesssim 10^{-7}$

(D.S.M. Alves et al SU-ITP-09/36)

Theory (4)

Standard Model Extension (*Kostelecky et al*)
based models for analysis of CPT&LI tests escape these arguments
J.D. Tasson Int. J. Mod. Phys. Conf. Ser. 30, 1460273 (2014)
But are sensitive to other tests (atomic interferometry and
best : bound kinetic energy of nuclei : $(\bar{g}-g)/g < 10^{-6} - 10^{-8}$
but model dependant limit)
M. Hoensee et al, Phys.Rev.Lett. 111, 151102 (2013)

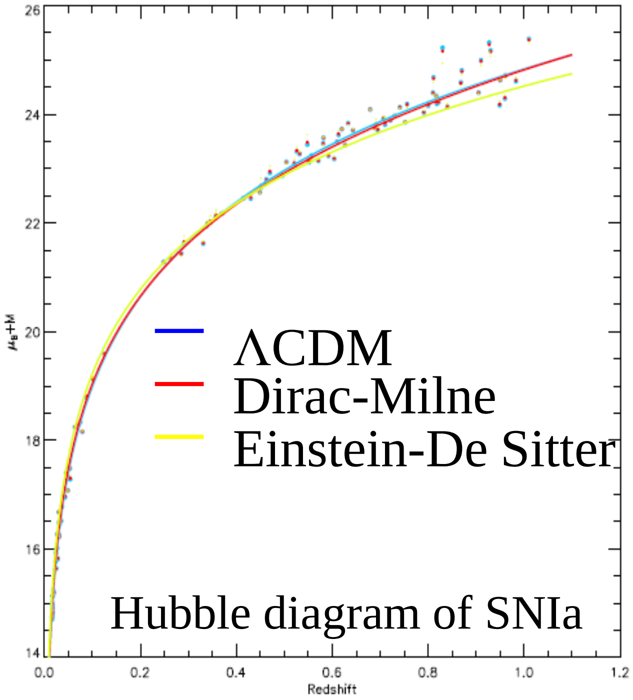
Autres modèles → voir références WAG 2015

"In conclusion whether or not one now accepts the existence of non-Newtonian gravitational forces, the possibility of new non-inverse-square and/or composition-dependent components of gravity must be thoroughly studied"
Nieto – Goldman *PHYSICS REPORTS (Review Section of Physics Letters) 205, No. 5(1991)*

Cosmology

- Matter-antimatter asymmetry in the Universe ???
- RG OK but with dark energy, dark matter and inflation…

- Could there be a matter-antimatter repulsive force?



→ Dirac Milne Universe

Attempt to build a cosmology with:

- Matter-antimatter symmetry
- Mechanism to separate matter from antimatter

PhD Thesis Paris XI ,A. Benoît-Lévy – dir G. Chardin (2009)

Experiment (1)

- $\eta^{\pm}$ et $\Phi^{\pm}$ as a function of time: CPLEAR

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

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

Potential variation with time

Need an absolute potential →

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

Source	Spin 0	Spin 1	Spin 2
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}
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}

Experiment (2)

Cyclotron frequency of p (H^-) and $\bar{p}$ in the same B

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

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

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

Arrival time of 1 (? : 90 % CL) neutrino and 18 antineutrinos from SN1987A in Kamiokande

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

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

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

Past attemtps and proposals

- **positrons** : *F. Witteborn and W. Fairbank, Phys Rev Lett 19 (1967) 1049)*

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

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

-**antineutrons** : difficult to slow down
T. Brando et al, NucI. Instrum. Methods 180 (1981) 461

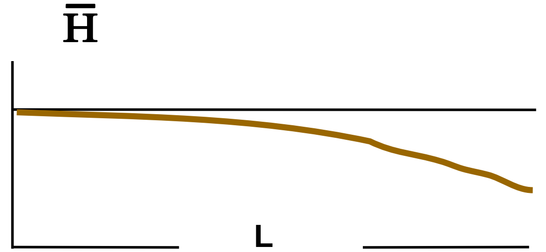
-**positronium** : short life time (142 ns) if n = 1
Maybe possible if excited n>>1 $\tau \approx (n/25)^{5.326} \cdot 2.25$ ms)
Pbs : cooling, polarisability, ionisation from thermal radiation…
A.P. Mills, M. Leventhal, NucI. Instrum. Meth. in Phys. Research. B192 (2002) 102
Project by D. Cassidy at Cambridge UK
(described in G. Dufour et al, Adv. In High Energy Physics 2015/ID379642)

Next simplest system: $\bar{H}$

Principle :

Parabolic flight of $\bar{H}$

Deflectometre or freel fall time



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

- L = 2 cm et $v_h \sim 100$ m/s (E($\bar{H}$) $\lesssim$ 540 mK ~ 50 μeV)

  → *ALPHA : - atoms $\bar{H}$ (neutral)*

- L = 1 m et $v_h \sim 50$ m/s → h = 20 μm (T($\bar{H}$) ~ 100 mK ~ 10 μeV)

  → *AEGIS : - atoms $\bar{H}$ (neutral)*

- L = 0.1 m et $v_h = 0.5$ m/s → h = 20 cm (T($\bar{H}$) ~ 10 μK ~ 1 neV)

→ ***Gbar :*** **cold $\bar{H}^+$** → very slow $\bar{H}$

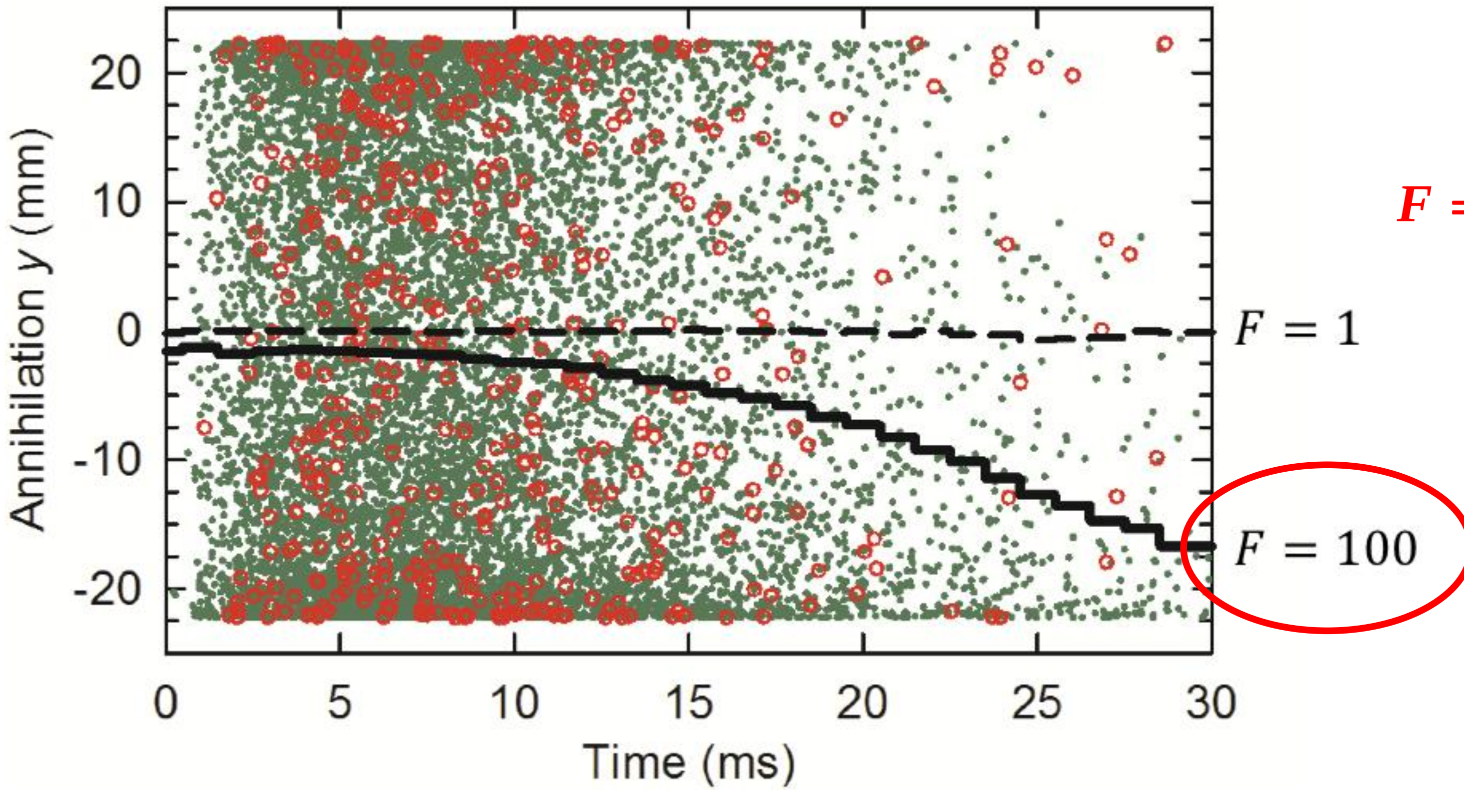
Goal : phase 1 : $\Delta\bar{g}/g \sim 1\%$; phase 2 : $\Delta\bar{g}/g < 10^{-3}$

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

Experiment (3)

Antihydrogen

$F = M_G / M$



$$F = \left| \frac{\bar{g}}{g} \right| \sim\leq 100$$

Green dots---simulated annihilations

Red circles---434 Observed annihilations

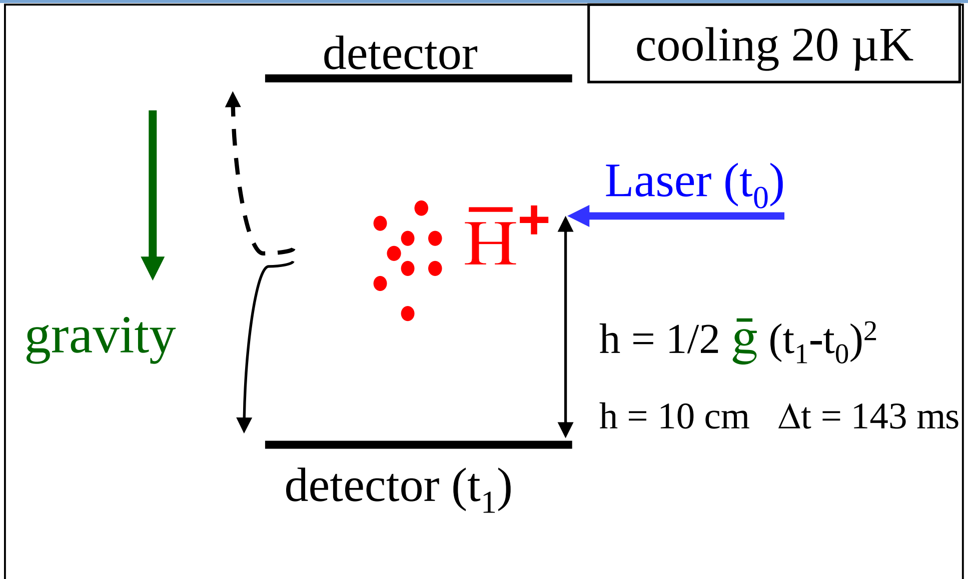
Vertical position of annihilation vertex during release of trapping field

The ALPHA collaboration

Nature comms 2013 (4:1785 | DOI: 10.1038/ncomms2787)

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

- Produce ion $\bar{H}^+$
- Capture ion $\bar{H}^+$
- Sympathetic cooling 20 µK
- Photo-detachment of e^+
- Measure fall time



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

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

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

Production of anti ions

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

$$\bar{p} \quad + \quad e^+ \quad + \quad e^+ \quad \longrightarrow \quad \bar{H}^* \quad + \quad e^+$$

Use positronium !!!

bound e^+e^- → 3-body

demonstrated by ATRAP (2004) →

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

Idea for GBAR: 

2nd charge exchange reaction →

$$\bar{H} \quad + \quad Ps \quad \longrightarrow \quad \bar{H}^+ \quad + \quad e^-$$

*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

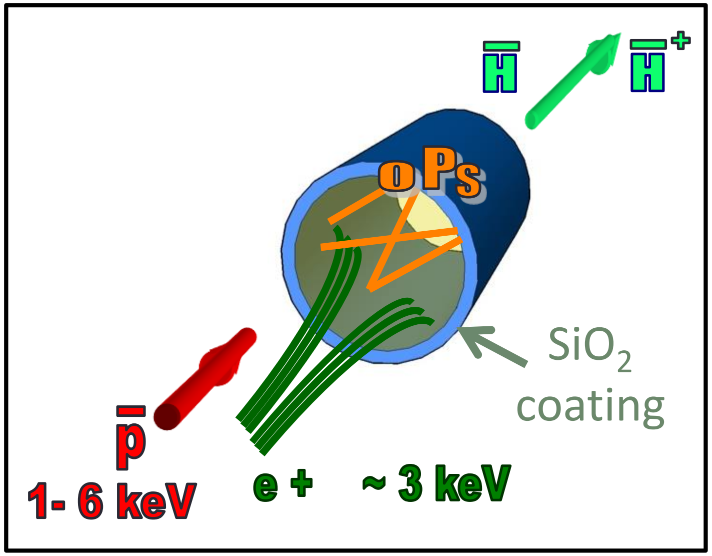
$\bar{H}^+$ production yield

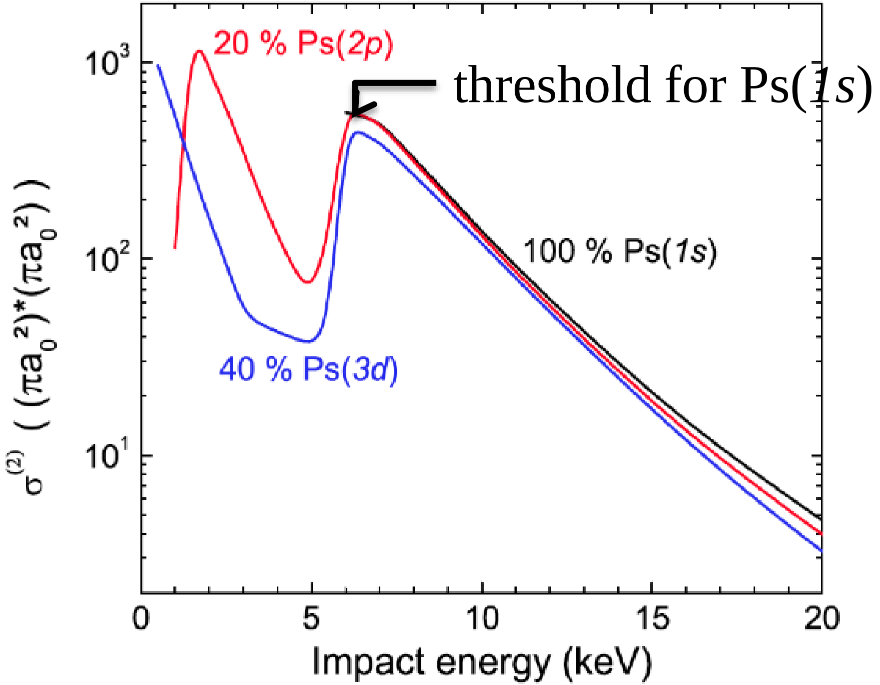
CERN provides per bunch every 110 s
dump 3×10^{10} e^+ On a SiO2 porous surface

→ ~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

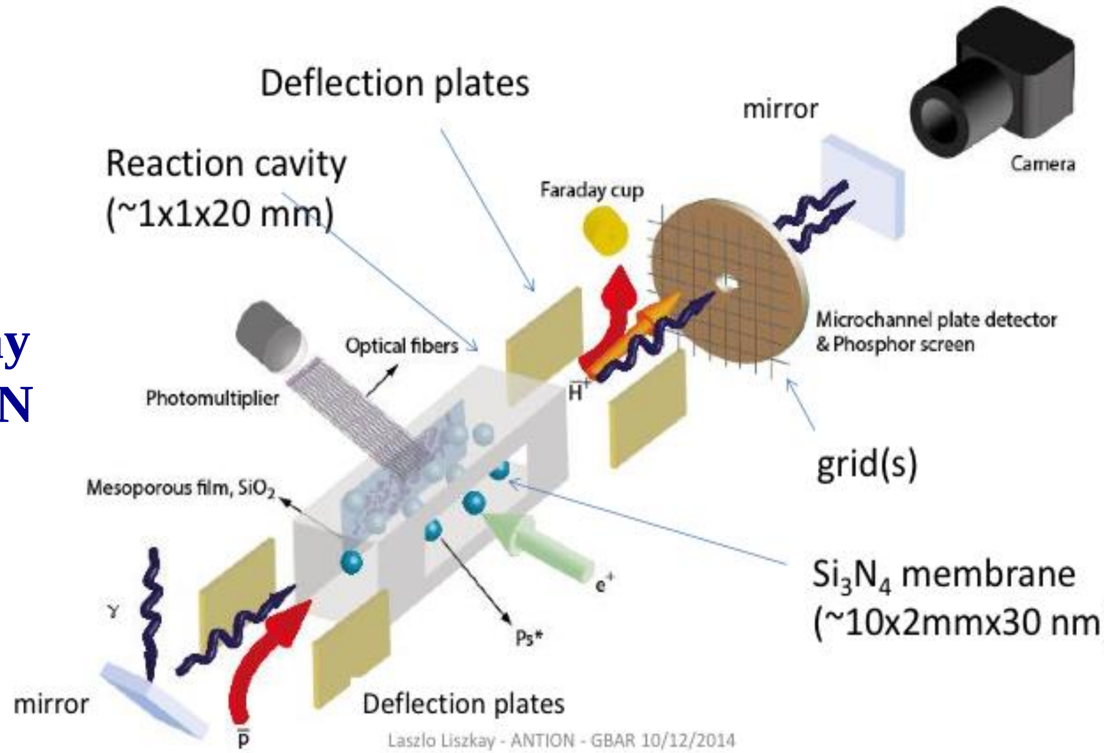
(anti) Ion Production cross-section

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

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

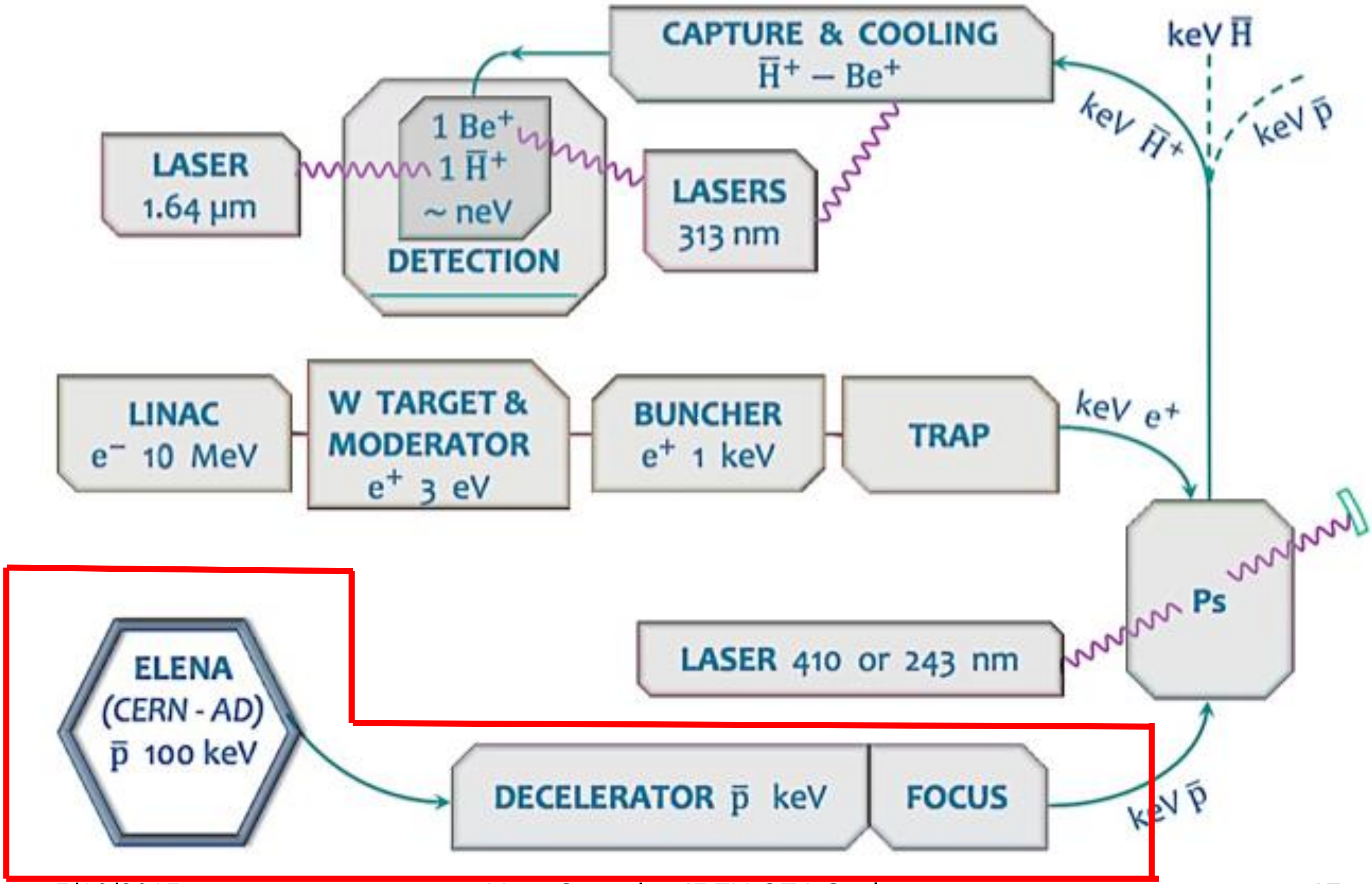
ANR
funding

2015-2016 : protons at Saclay
2016-2017 : protons at CERN
2017-… : antiprotons

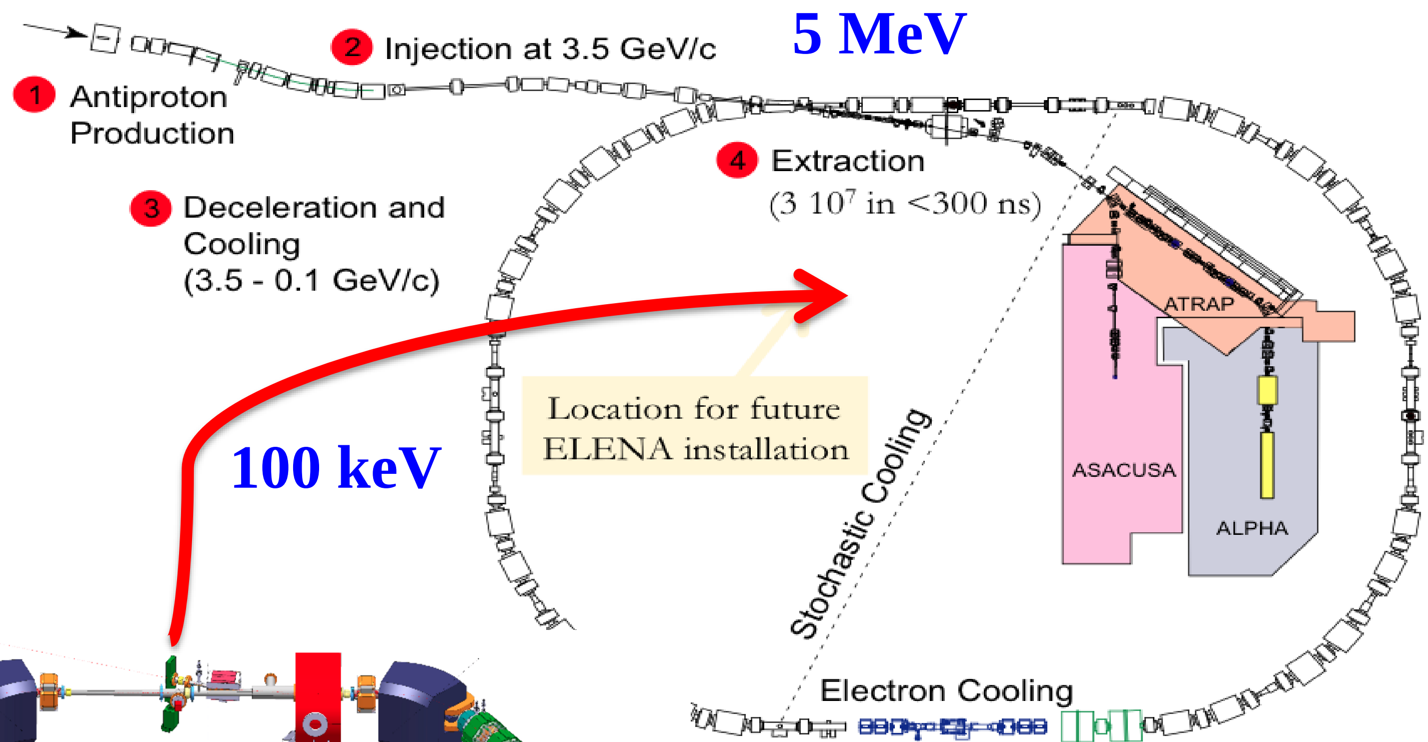


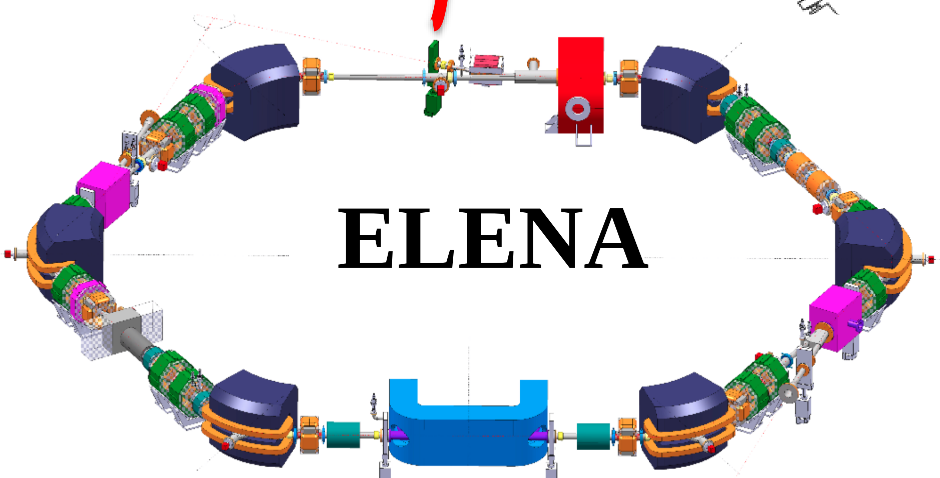
p source ~ 1 μA
(CSNSM)

Experimental Scheme



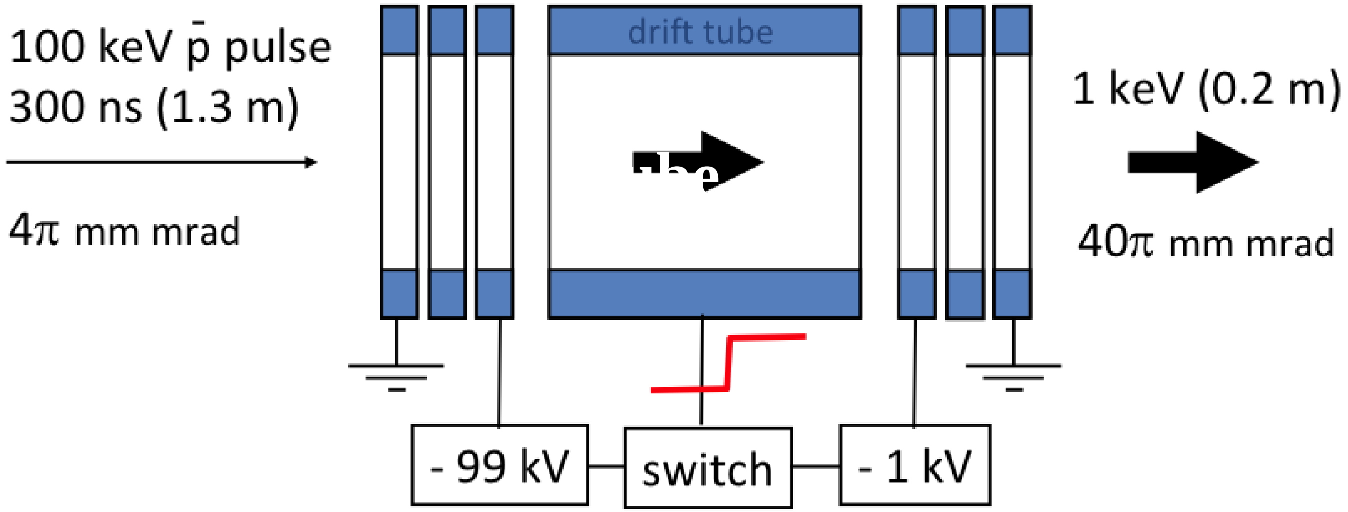
Antiprotons: CERN AD / ELENA

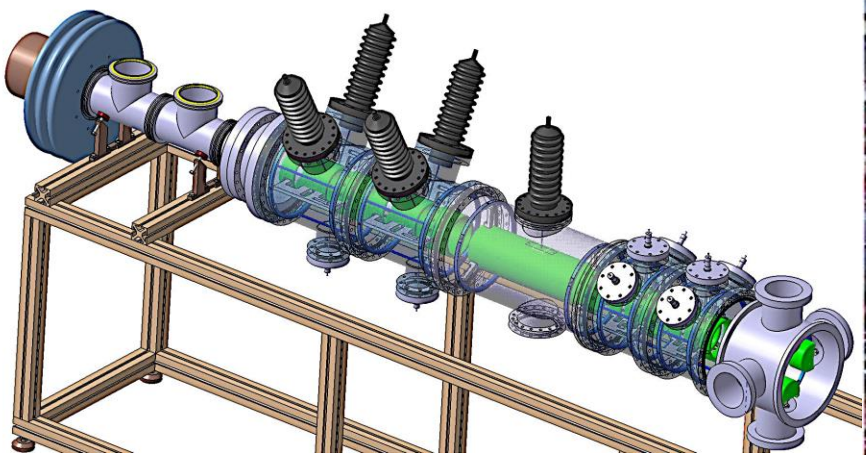




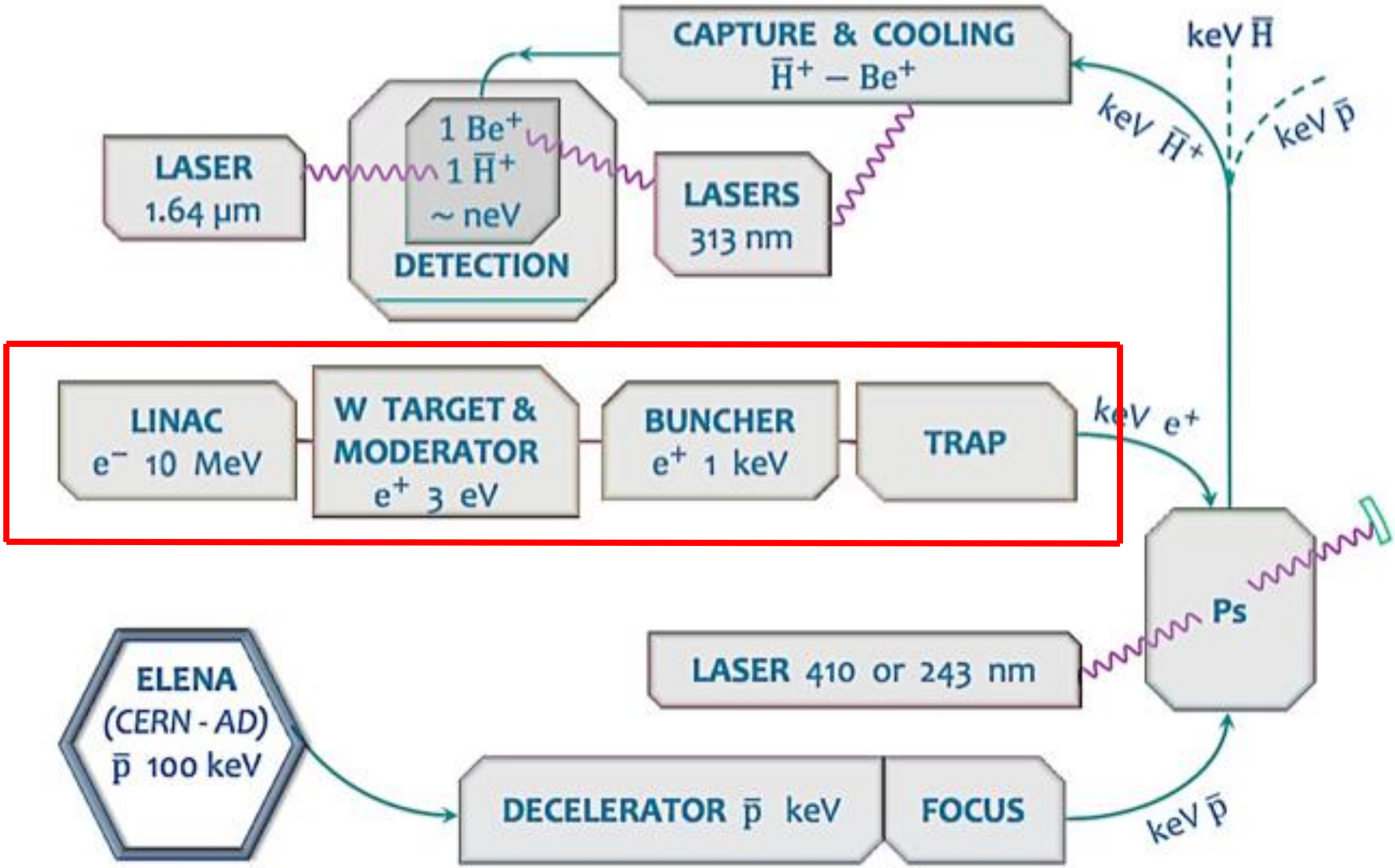
GBAR antiproton decelerator

1 pulse/ 110 s





Experimental Scheme

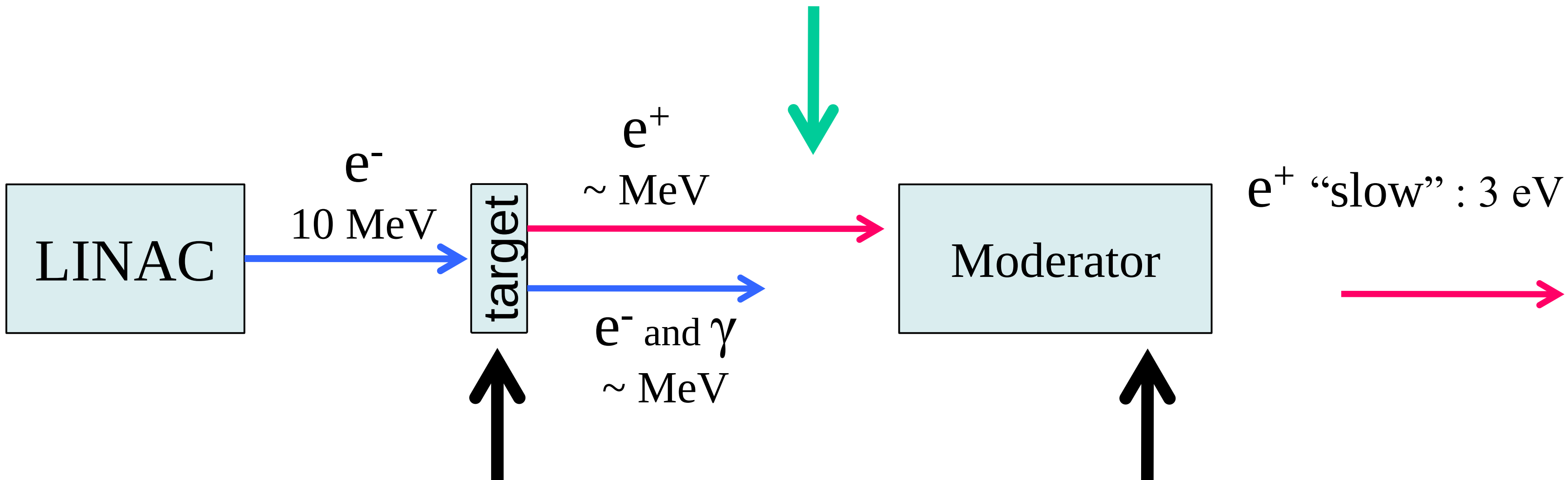


High intensity slow positrons source

~ 5 x 10^{11} fast e^+/s

~ 2 x 10^{8} slow e^+/s

e^+/e^- selection



Tungsten target

$\varepsilon_{e+/e-\ prod} \sim 5\ 10^{-4}$

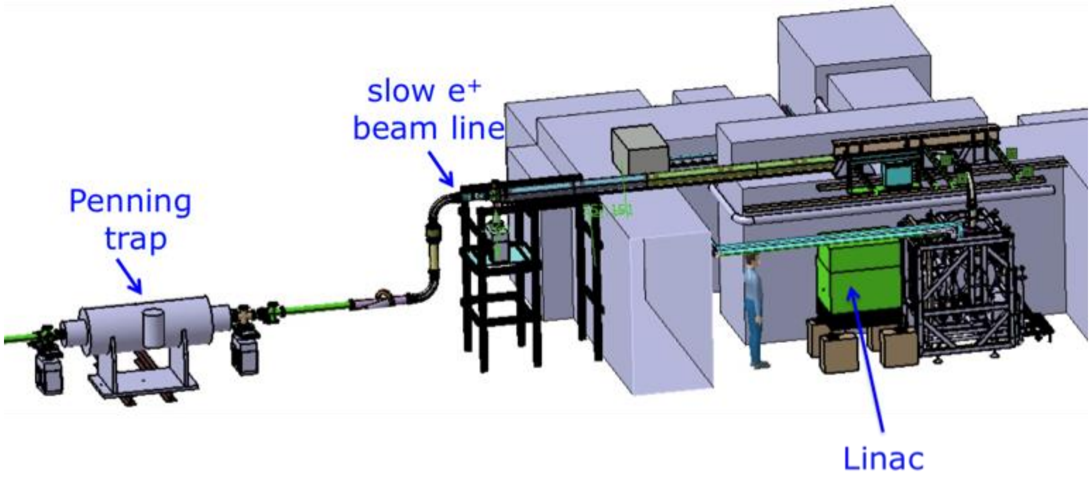
Tungsten near primary target

$\varepsilon_{moderation} \sim 5\ x10^{-4}$

Solid neon after e^+/e^- selector

$\varepsilon_{moderation} \sim 3\ 10^{-3}$

e^+ / Ps demonstrator at Saclay



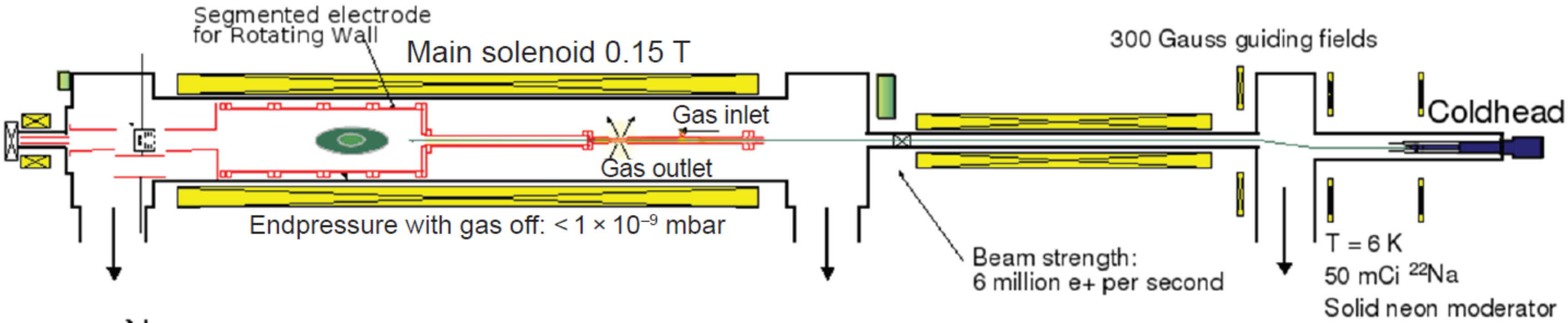
- **4.3 MeV / 200 Hz / 120 µA**
- **3 10^6 slow e^+/s**
- **with W mesh moderator**
- **target value : 2 10^8 s^{-1}**

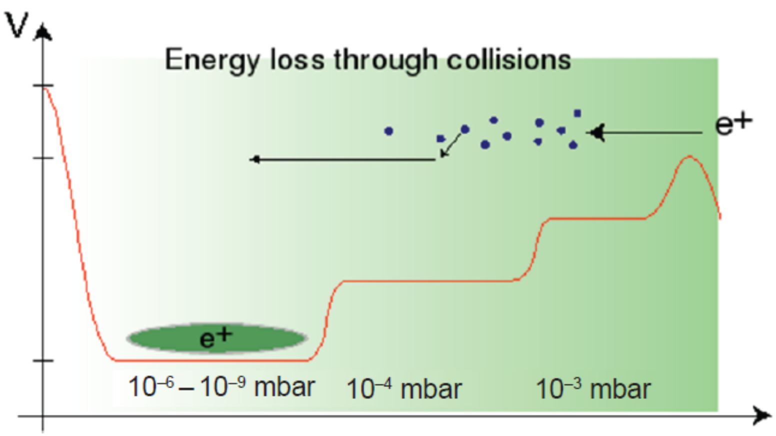
e^+ trapping

A two stage accumulation being realized at Saclay:

1. **buffer gas trap to cool positrons with Nitrogen**
2. **accumulator**

Alpha buffer gas system





Positron – Nitrogen reactions:

$$e^+_{(<8\ \mathrm{eV})} + N_2 \rightarrow e^+ + N_2^{\mathrm{rot/vib}}$$

$$e^+_{(>8\ \mathrm{eV})} + N_2 \rightarrow Ps + N_2^+$$

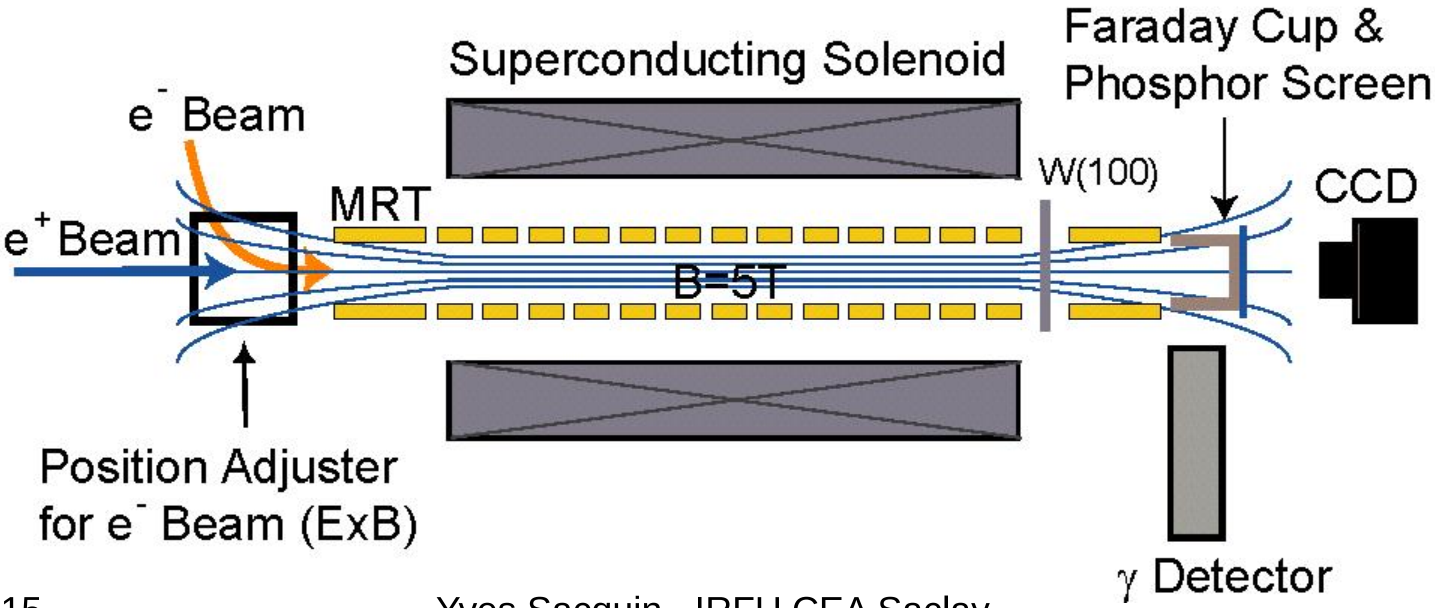
$$e^+_{(8\text{–}11\ \mathrm{eV})} + N_2 \rightarrow e^+ + N_2^*$$

last reaction: positrons lose ~9 eV
but rate below Ps formation at E > 11eV→ 3 eV window

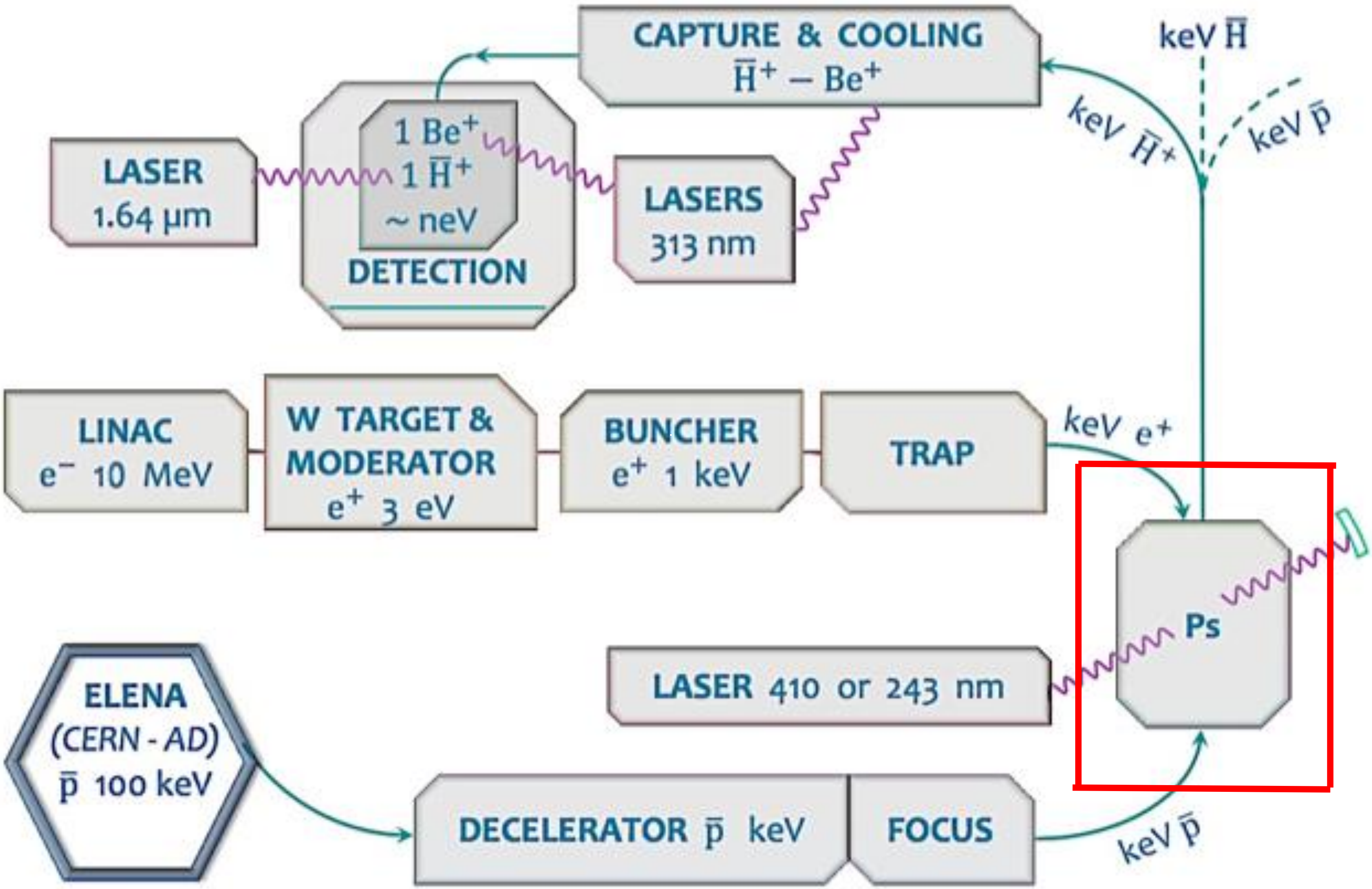
RIKEN Multi-Ring Trap

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

N. Oshima → e^- cooling



Experimental Scheme



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

e^+ to Positronium converter is a porous SiO_2 surface:

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

e^+ + converter → oPs

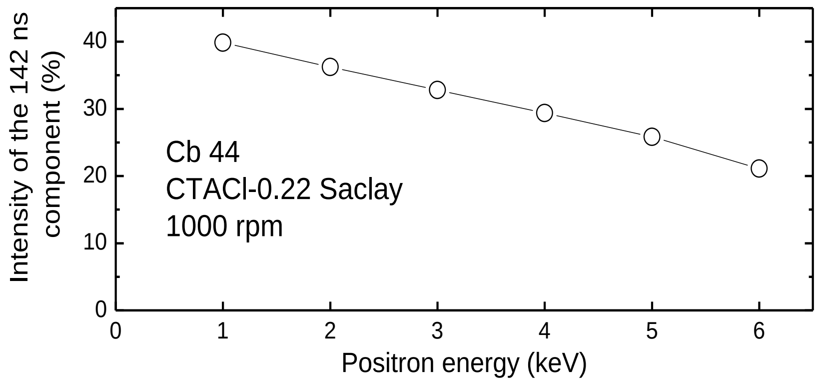
Experiments at CERN: Irfu/ETHZ (e^+ beam)
and at UCR Cassidy et al. (trap)

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

Yield of o-Ps

Measurement at CERN

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

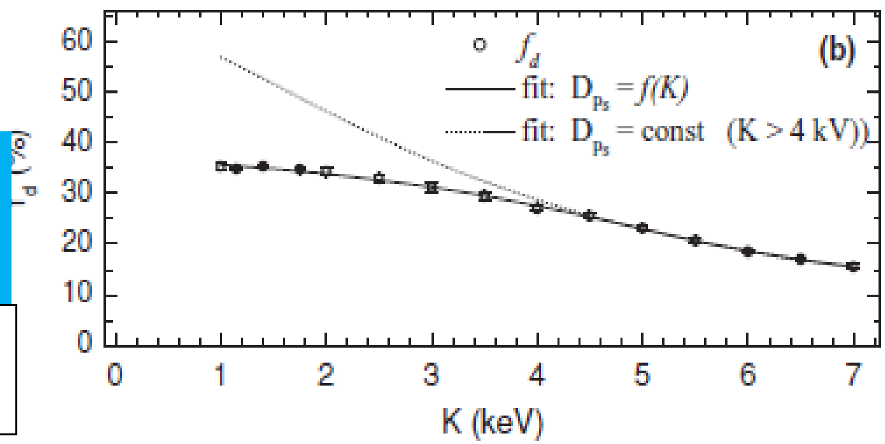


~ 3.5 x 10^5 e^+ $cm^{-2}s^{-1}$

e^+ flux x ~10^{11}

Measurement at UCR

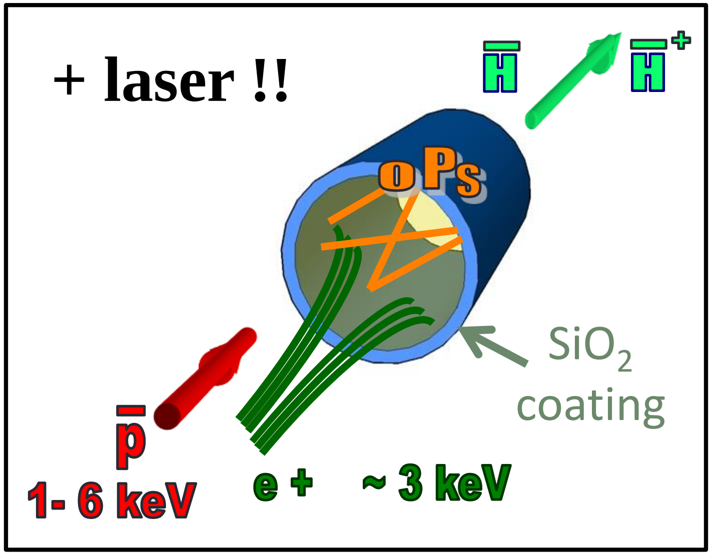
D. B. Cassidy et al., Phys. Rev. A **81** 012715 (2011)



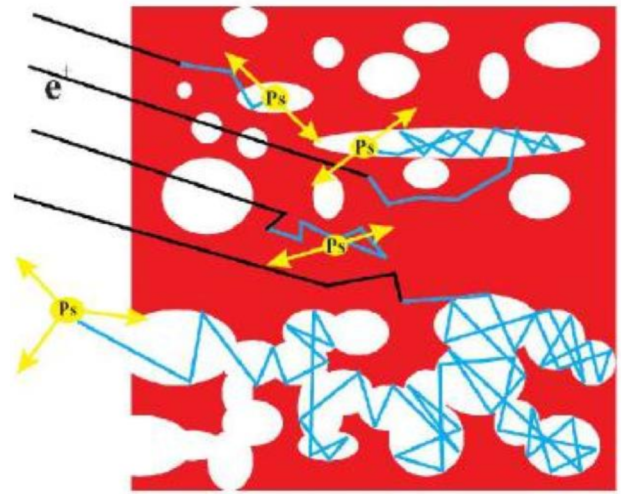
~ 5.6 x 10^{16} e^+ $cm^{-2}s^{-1}$

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

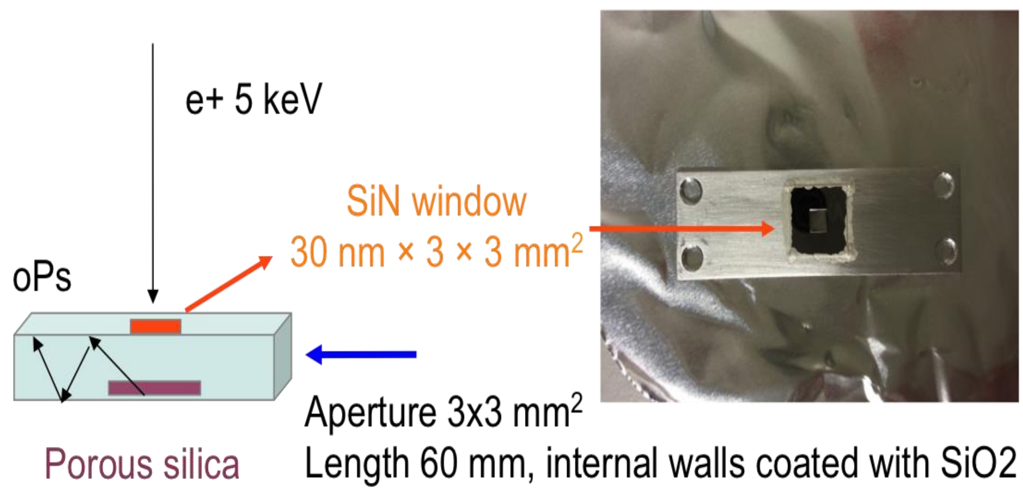
Ps formation



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

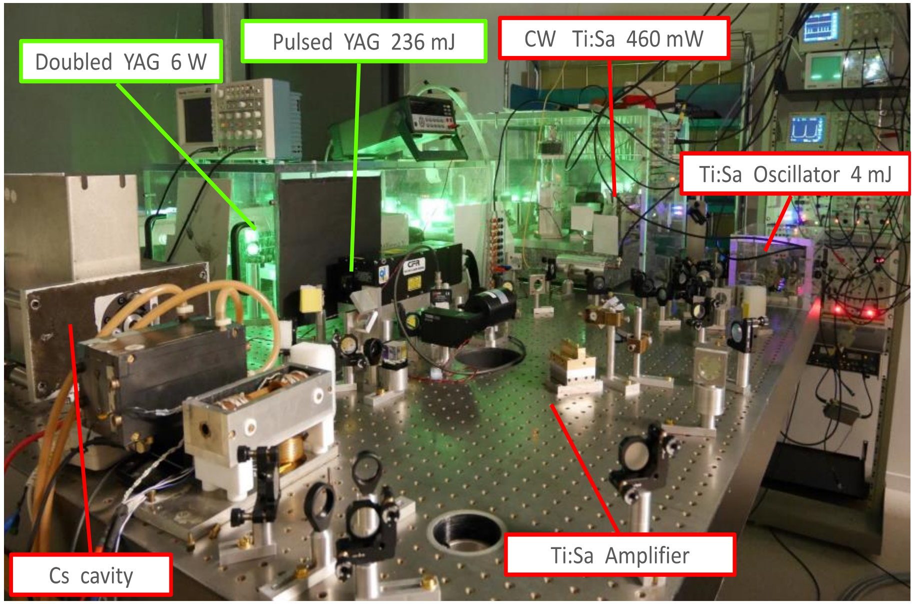


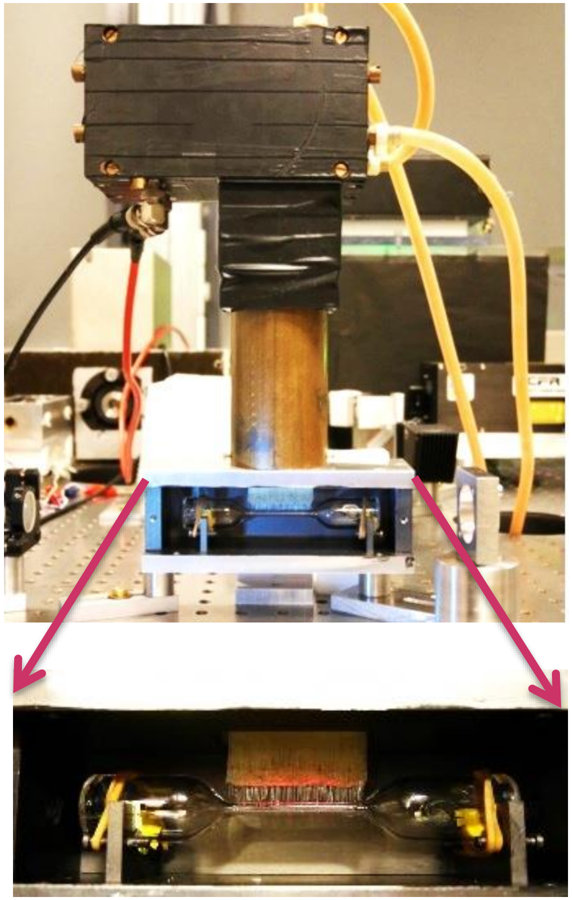
<u>Test on ETHZ beam line</u>
Transmission @ 5 keV ~ 100%
Ps formation efficiency as for bare SiO_2
Same Ps lifetime distribution

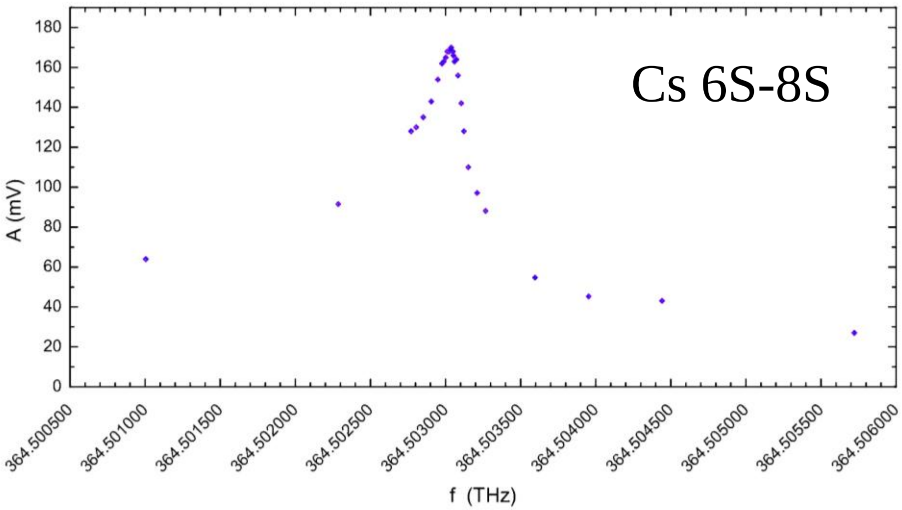


P. Crivelli, WAG2013

Ps excitation (3d) laser at LKB

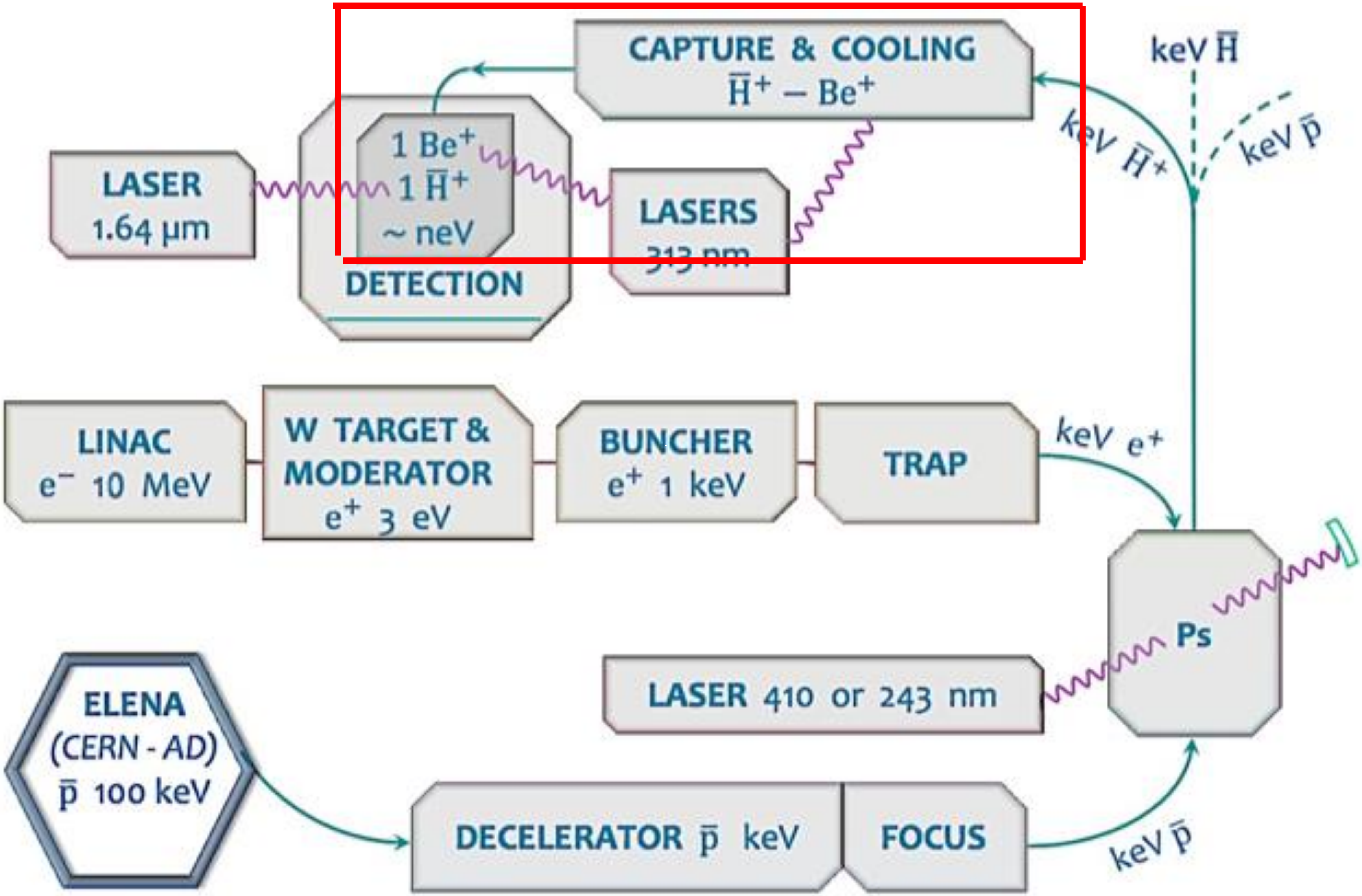






Cs cell with fiber optic bundle conditions similar to Ps*
→ ready for Ps* measurements

Experimental Scheme

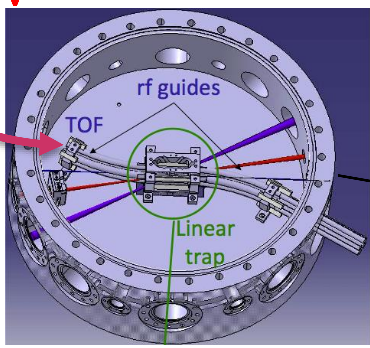


$\bar{H}^+$ with v < 1 m/s: from 700000 K to 20 µK !!!

Done in 2 steps

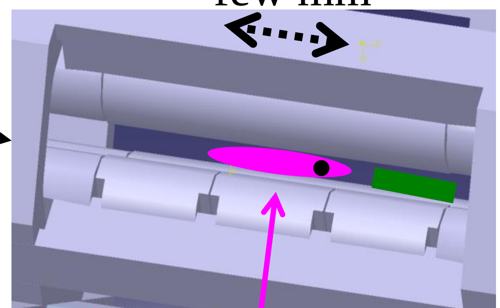
First step Capture and sympathetic cooling by Doppler laser cooled Be^+ ions in the linear **capture trap**

1 keV
$\bar{H}^+$



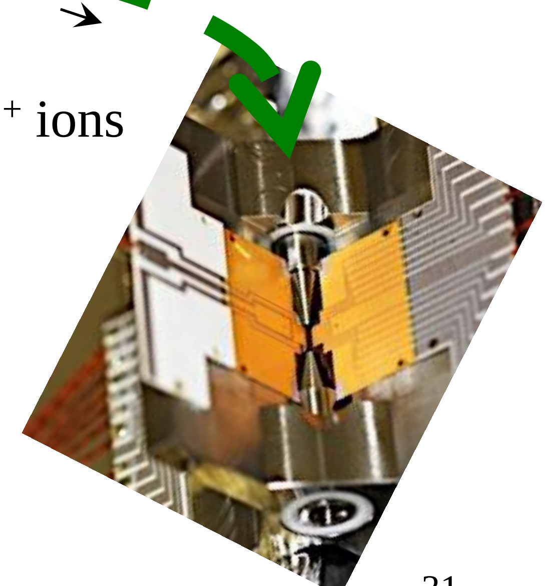
T÷ 10^{11}

few mm



313 nm laser

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



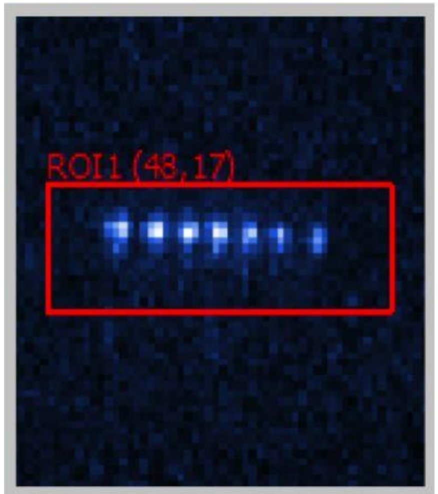
Second step

Transfer and ground state cooling of a Be^+/H^+ ion pair in the **precision trap**

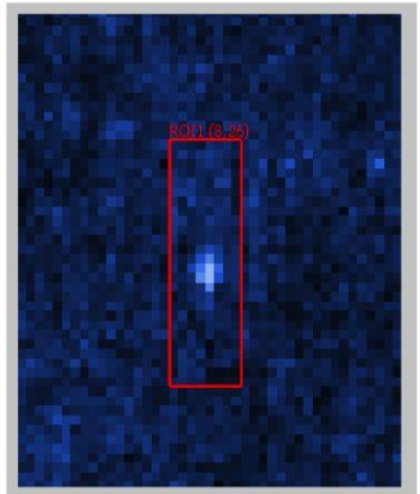
tests with H_2^+ / H^+ REMPI source

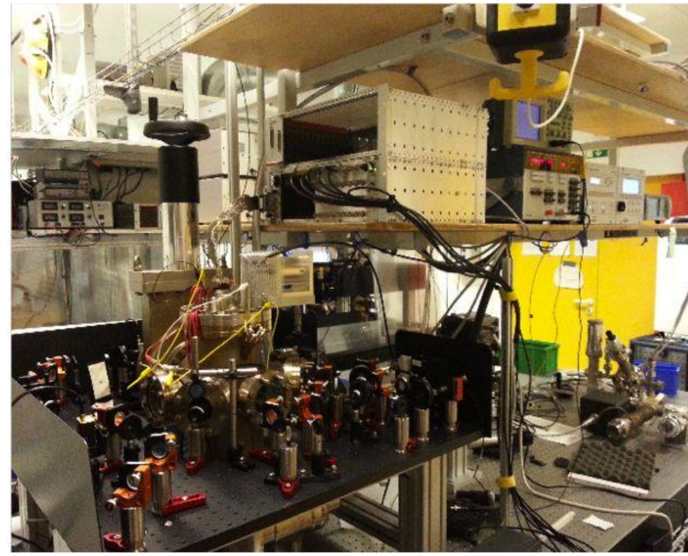
Precision trap

First Ca^+ ions and linear ion crystals trapped at Mainz



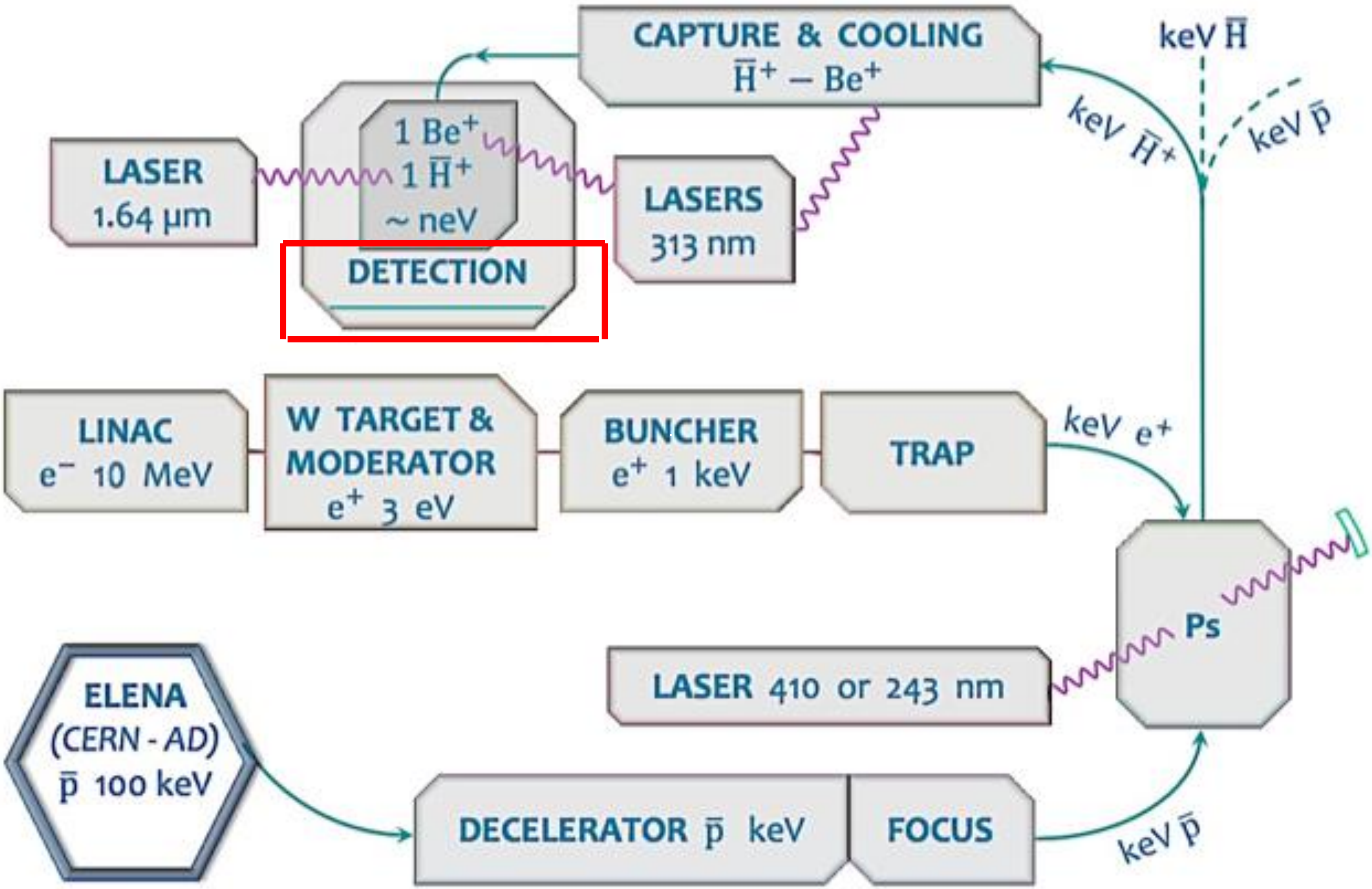
First ion crystals


First single ions



2015: capture trap construction and tests of cooling of Ca^+/Be^+,
transport of ions between traps
2016: cooling of H_2^+ with Be^+/HD^+ mixture
2017: transport to CERN

Experimental Scheme



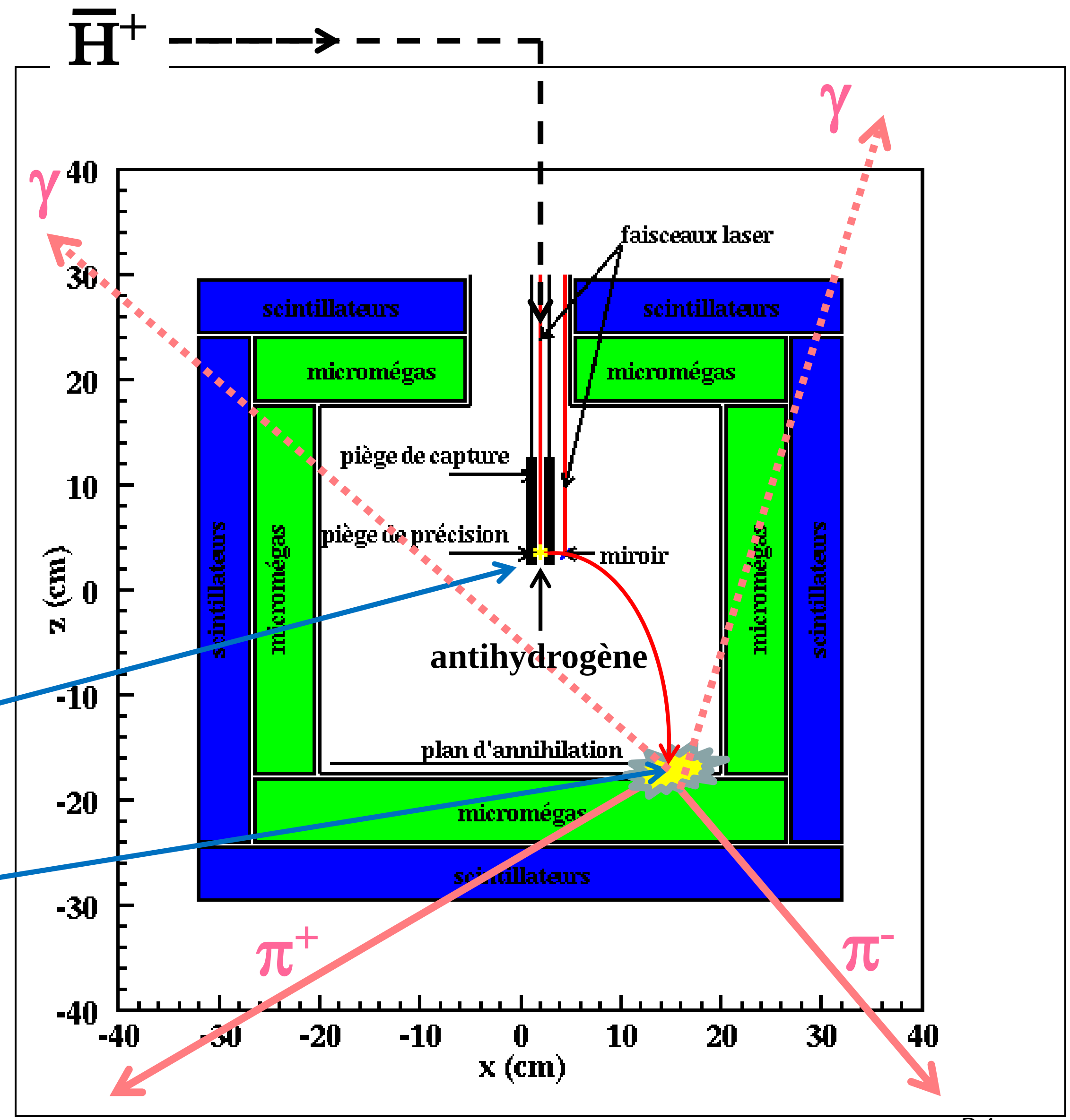
Free Fall

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

Detection	Requirement
TOF	150 µs
Annihilation vertex	2 mm
Background rejection	event topology

Laser shot
t_0

annihilation
t_1



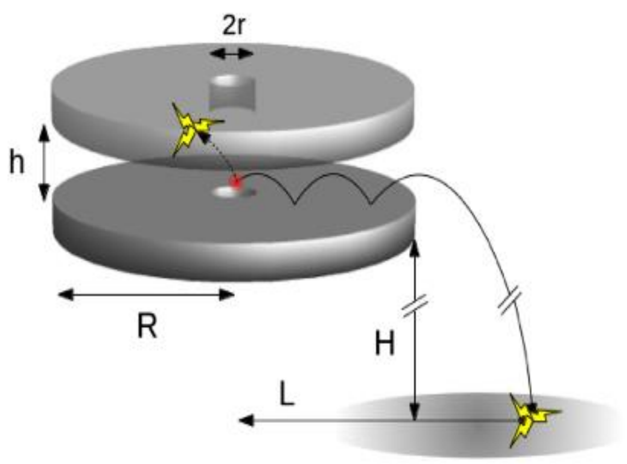
Free fall height h = 20 cm

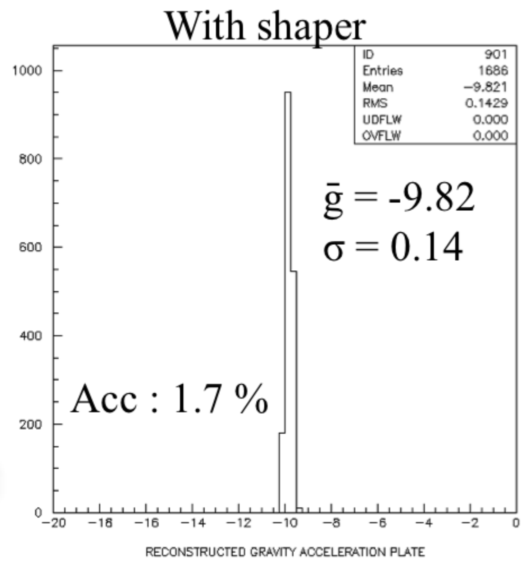
$$h = 1/2\ \bar{g}\ (t_1-t_0)^2+v_{z0}(t_1-t_0)$$

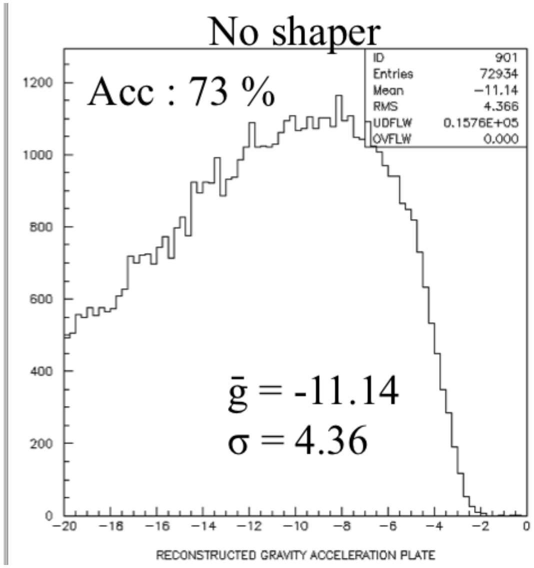
Reduce needed statistics !!!

Velocity selector

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







Simulations → optimize dimensions with experimental constraints

Selector : h = 50 μm Rmin = 1 mm, Rmax = 7 mm

H free fall = 20 cm , Ø detector = 40 cm

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

10 times less than in proposal

Towards < 1 ‰ precision

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

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

- **Improve the precision on $\bar{g}$ with the <u>spectroscopy</u> of gravitational levels of $\bar{\mathrm{H}}$ above the annihilation plane :**

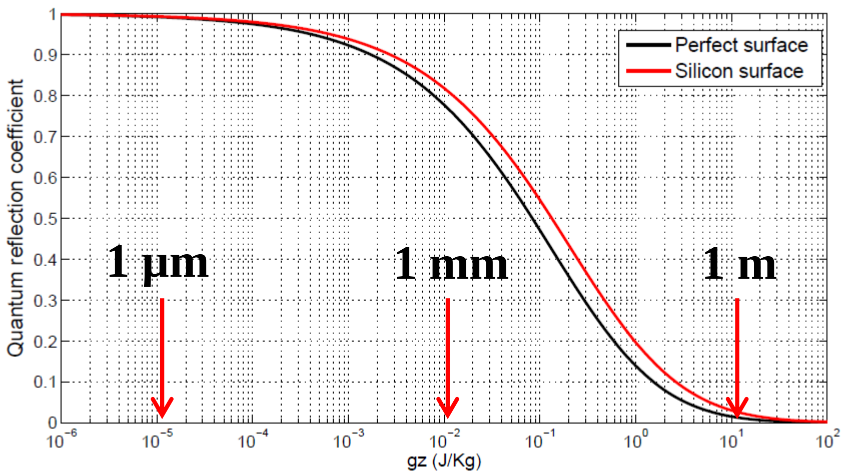
similar method as for UCN neutrons (GRANIT spectrometer)

Reflection of $\bar{H}$ atom

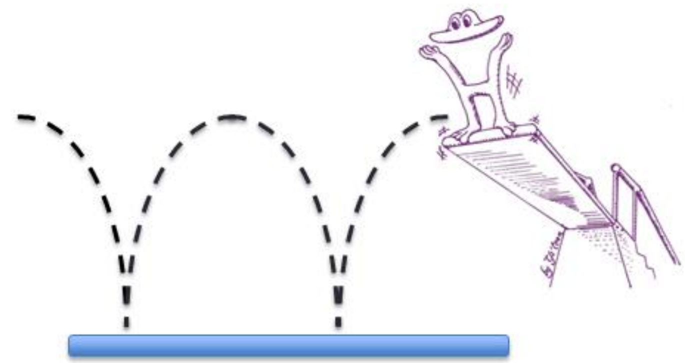
Casimir-Polder attractive force

+

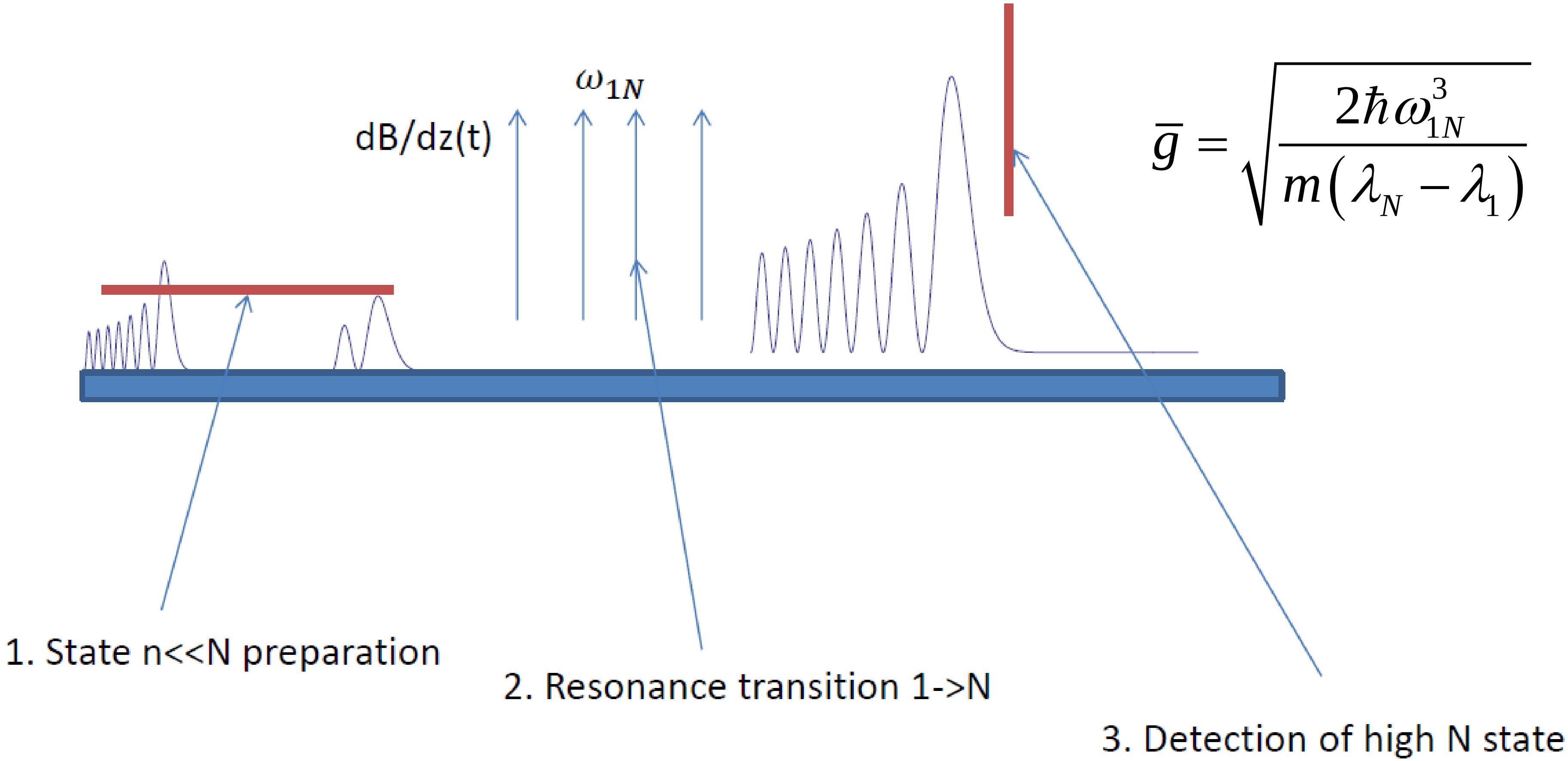
quantum reflection



Reflection probability
of $\bar{H}$ atom



Principle



$$\bar{g} = \sqrt{\frac{2\hbar\omega_{1N}^{3}}{m\left(\lambda_N - \lambda_1\right)}}$$

To measure flux of annihilation events at height of Nth state as a function of frequency

~100 events needed
to reach ~10^{-3} statistical precision
!

G.Dufour et al, Adv. High Energy Phys. 2015 ID379642

The GBAR collaboration

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Perspectives

- **2015 Start installation at CERN**
- **2016 ELENA Commissionning with p and H^-**
- **2017 First $\bar{p}$ for GBAR**

16 institutes ~ 50 researchers

new collaborators welcome!

THANKS FOR YOUR ATTENTION !