Weighting Antihydrogen

- **Objective**

- **Motivation**
  - ✓ **Theory**
  - ✓ **Experiment**

- **Experiments with $\overline{\mathrm{H}}$**
  - ✓ **ALPHA**
  - ✓ **GBAR**
  - ✓ **AEGIS**

- **Conclusion**

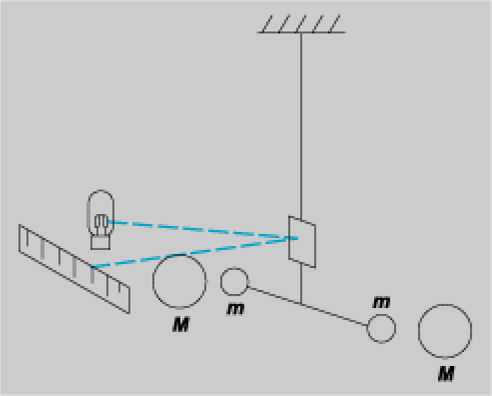
Objective

A direct test 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)

$$\left(\Delta a / a\right)_{\mathrm{Be/Ti}} = \left(0.3 \pm 1.8\right) \mathrm{x} 10^{-13}$$

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

Strong Equivalence Principle (Lunar Laser Ranging)

$$\left(\Delta a / a\right)_{\mathrm{Earth/Moon}} = \left(-1.0 \pm 1.4\right) \mathrm{x} 10^{-13}$$

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

The measured parameter: ḡ

Gravitational acceleration on Earth of antihydrogen atoms

$$F_z = G\frac{M_T}{R_T^2}m_g$$

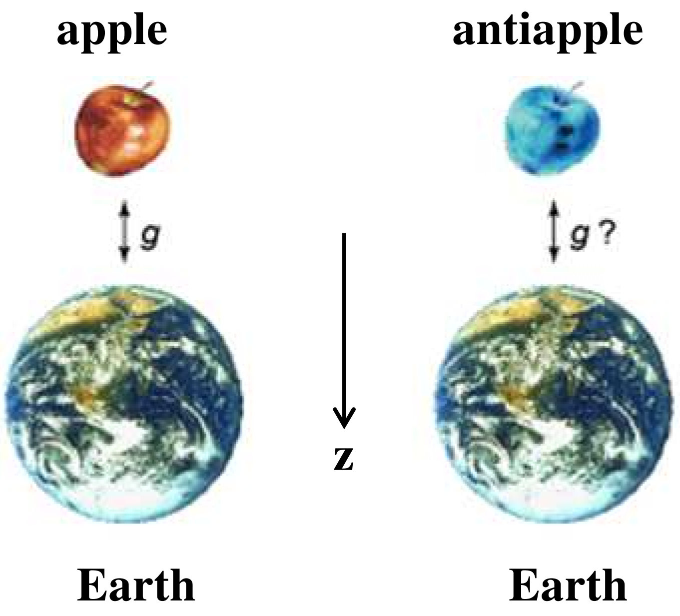
$$F_z = m_i a$$

$$g \equiv a = \frac{F_z}{m_i} = G\frac{M_T}{R_T^2} = 9{,}8\ m/s^2$$

$$\uparrow$$

$$\boxed{m_g = m_i}$$

Equivalence principle



$$\bar{F}_z = G\frac{M_T}{R_T^2}\bar{m}_g$$

$$\bar{F}_z = \bar{m}_i\bar{a}$$

$$\boxed{\bar{g}} \equiv \bar{a} = \frac{\bar{F}_z}{\bar{m}_i} = G\frac{M_T}{R_T^2}\frac{\bar{m}_g}{\bar{m}_i} = g\frac{\bar{m}_g}{\bar{m}_i}$$

$$\boxed{???\ \bar{m}_g = \bar{m}_i\ ???}$$

Antimatter

particules				antiparticules	
electron	e^-	●	●	e^+	positron
proton	p	⊕	⊖	$\bar{p}$	antiproton
neutron	n	○	○	$\bar{n}$	antineutron
photon	γ	●	●	γ	photon

↑

Same inertial mass

→ Same lifetime

Opposite charges

CP violation (1964) J. Christenson, J. Cronin, V. Fitch, R. Turlay:

Decay rates of particles and antiparticles to CP even states can be (slightly) different

Example: $\Gamma\left(K^0 \to \pi^+\pi^-\right) \neq \Gamma\left(\overline{K}^0 \to \pi^+\pi^-\right)$

➔ ∃ small matter antimatter differences in the Standard Model

- Objective

- **Motivation**
  - ✓ **Theory**
  - ✓ Experiment

- Conclusion

Antimatter&gravitaion
Theory (1)

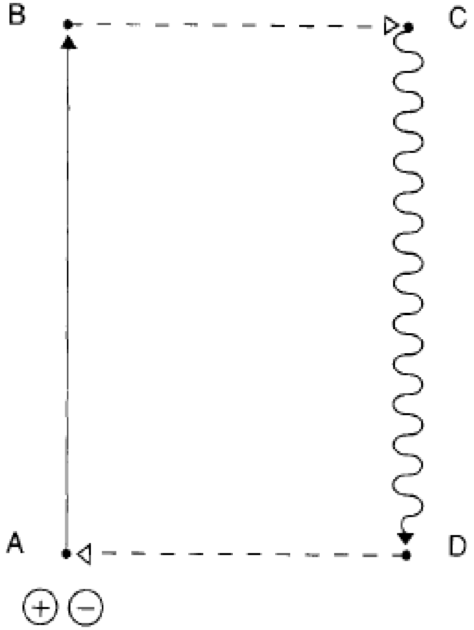
Morrison argument (1958):
antigravity in General Relativity
(or any difference between matter and antimatter)
→ violation of energy conservation

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

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

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

$$E_D = E_A + 2m_I gL$$



Theory (2)

Supergravity:

→ new gravi-scalar and gravi-vector fields coupled to baryon number

→ distinguish m_G and $\overline{m}_G$

J. Scherk, Phys. Lett. B (1979) 265, S. Belluci & V. Faraoni Phys. Lett. B (1996) 55

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

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

But exact cancellation scalar/vector impossible (4-velocity dependance)

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

Theory (3)

Antimatter content of ordinary matter (Schiff argument)

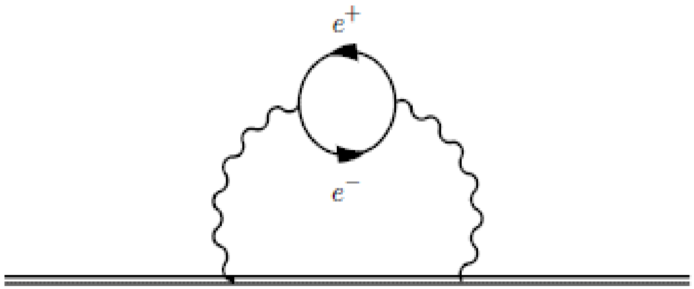


FIG. 2: Loop contribution to the electrostatic self-energy of the nucleus

$$\left|\frac{g-\bar{g}}{g}\right| \sim \left|\frac{g-g_{\Delta E\mathrm{rad}}}{g}\right| \Rightarrow$$

Scenario	Argument	Bound on $\lvert g_{\mathrm{H}} - g_{\overline{\mathrm{H}}}\rvert / g_{\mathrm{H}}$
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*):

- models for analysis of CPT&LI tests can escape these arguments

Ex: Isotropic Parachute Model *J.D. Tasson Int. J. Mod. Phys. Conf. Ser. 30, 1460273 (2014)*
escapes: Morrison & Schiff arguments
+ cyclotron frequency, K system tests (see experimental limits)
but remains sensitive to velocity dependance tests (bound systems like nuclei…)

One still gets $(\bar{g}-g)/g < 10^{-6} - 10^{-8}$

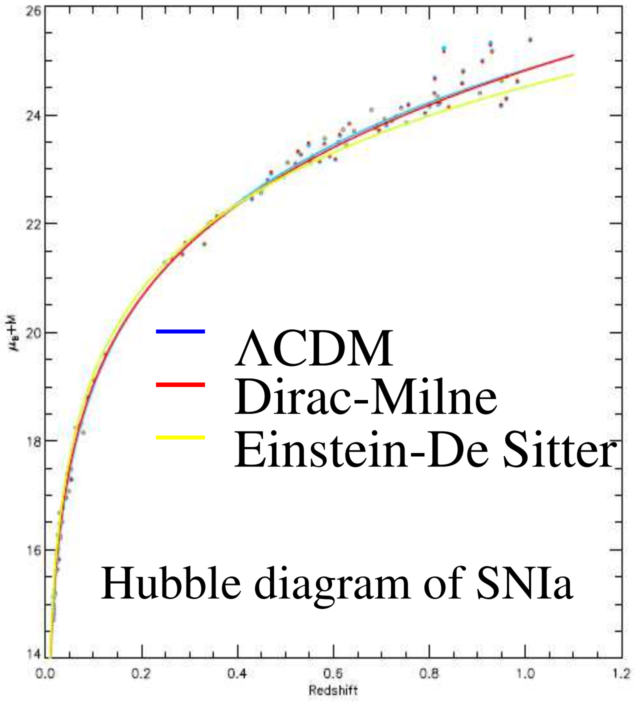
- but model dependant limit (*M. Hoensee et al, Phys.Rev.Lett. 111, 151102 (2013)*)

Other models → see WAG 2015

Cosmology

- Matter-antimatter asymmetry in the Universe ???
- Cannot be explained by CP violation in the standard model
- GR OK (at cosmological scales) but with dark energy, dark matter and inflation… and tensions at small scales

→ need new model ?



Hubble diagram of SNIa

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)

Conclusion: Theory

- “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)*

- However **expected effects are quite small**

- A 1 % experiment is a “textbook experiment” **and should be a first step towards higher precision**

- **Objective**

- **Motivation**
  - ✓ **Theory**
  - ✓ **Experiment**

- **Conclusion**

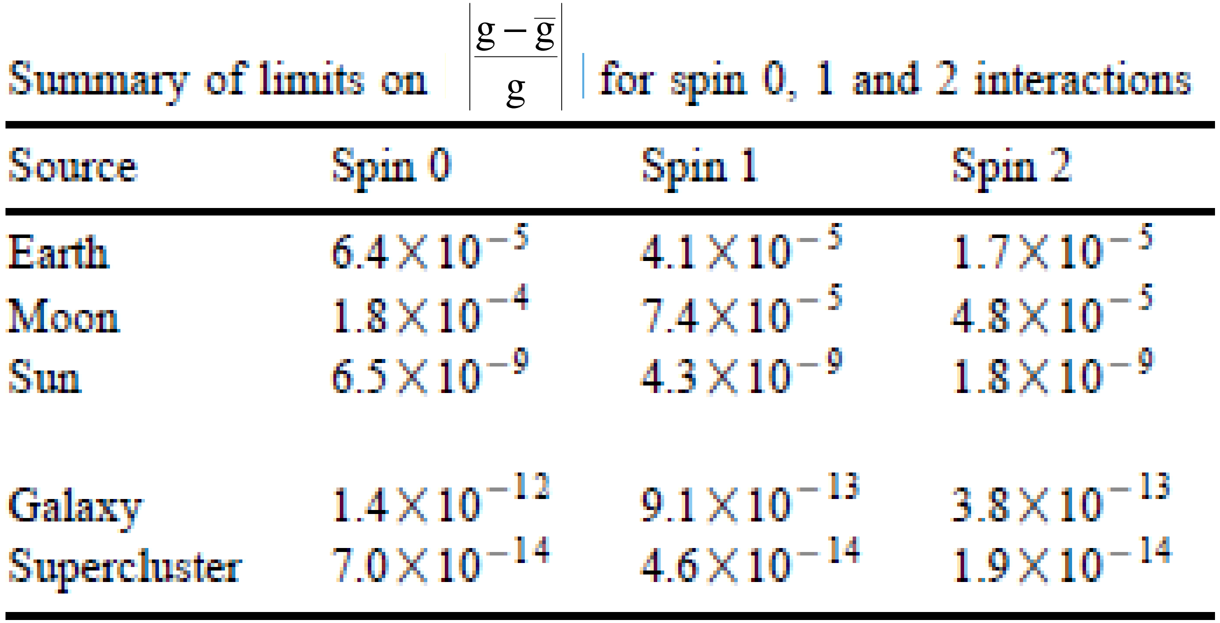
Experiments: indirect limits (1)

Study CP violation parameters $\eta^{\pm}$ et $\Phi^{\pm}$ of the K^0-$\overline{K}^0$ system

as a function of time (CPLEAR)

K^0-K^0 oscillations depend on $$\delta m_{\mathrm{eff}} = M_{K^0}\left(\frac{g-\overline{g}}{g}\right)_I \frac{GM}{rc^2}\exp\left(-r/r_I\right)f(I)$$

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



Summary of limits on $\left|\frac{g-\overline{g}}{g}\right|$ 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}

Potential variation with time

Need an absolute potential →

Experiments: indirect limits (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

$$\omega = qB/2\pi m + \alpha \underbrace{U/c^2}_{\text{local supercluster}} \qquad |\omega-\bar{\omega}|/\omega = (9\pm 9)\text{x}10^{-11} \rightarrow \underbrace{|g-\bar{g}|/g \le 10^{-6}}_{\text{assuming CPT}}$$

Experiments: a direct limit ?

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

post-newtonian parameter (1 in GR)

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

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

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

Past attempts and proposals (1)

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

Very difficult: equivalent electric field $eE = m_e g$

$E = m_e g / e = 5{,}6 \times 10^{-11}$ V / m (one elementary charge at 5 m)

- **antiprotons** : *PS200 Proposal Los Alamos Report LA-UR 86-260*
  but could not be performed

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

Past attempts and proposals (2)

- **positronium**: bound e^+ - e^- system → neutral system

short annihilation life time (142 ns) if n = 1 but increases as n^3
but radiative lifetime much lower (~ /100)
except for circular states ($m = l = n\text{-}1$) $\tau \simeq (n/25)^{5.236} \times 2.25\ \text{ms}$
→ Principle:
- excite Ps to high n,
- use stark effect acceleration to produce a beam,
- then excite to circular state to have null electric dipole moment to decrease sensitivity to stray electric fields

Pbs: cooling, thermal radiation → quenching, ionization

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 (2015) 379642

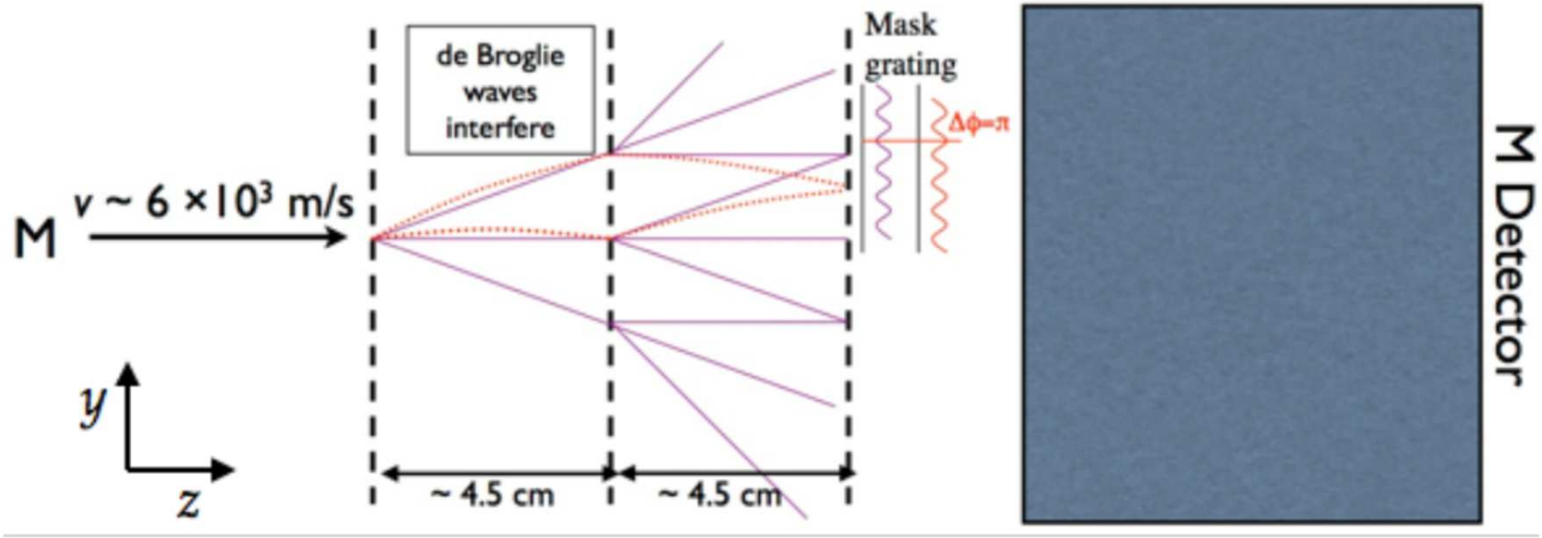
Past attempts and proposals (3)

- **Muonium (M)**: bound μ^+ - e^- system → neutral system

M beam at PSI (muons stopped in superfluid He)

3 grating interferometer :

100 nm pitch, $\Delta\Phi = 0.02$, **0.4 nm gravitational deflection**

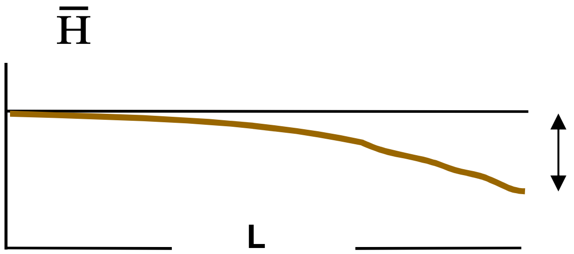


D.M. Kaplan et al, IIT-CAPP 16-1 (2016).

Next simplest system: $\bar{H}$

Principle for ~% measurement:

Parabolic flight of $\bar{H}$



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

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

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

- L = 1 m et v_h ~ 500 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 $\bar{H}$

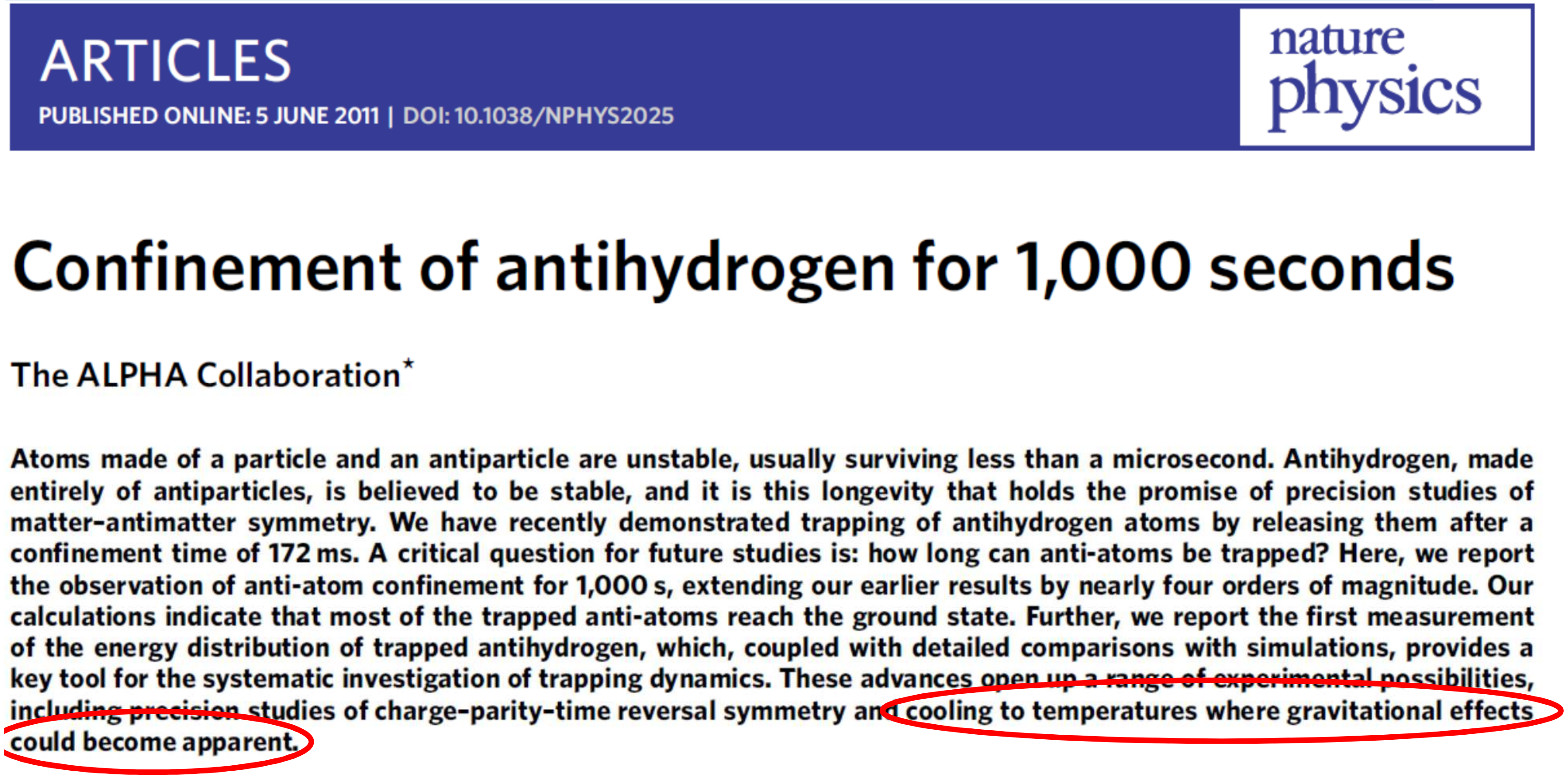
Objectives in a first step: sign of $\bar{g}$ and then $\Delta\bar{g}/g$ of order a few 10^{-2}

CERN
Antiproton Decelerator Hall

AEGIS
ALPHA
ASACUSA
ATRAP
BASE
GBAR

Experiments with $\overline{\mathrm{H}}$

- **ALPHA**
- GBAR
- AEGIS



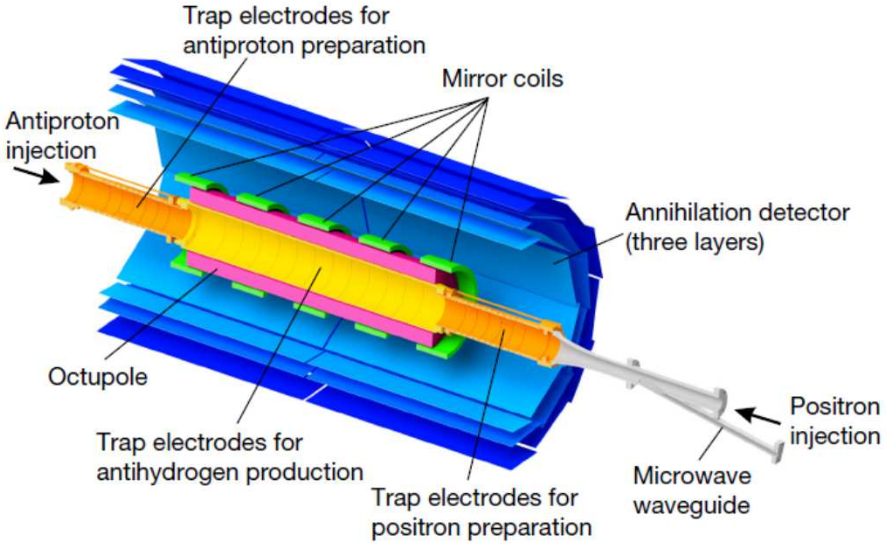
ARTICLES
nature physics

| DOI: 10.1038/NPHYS2025

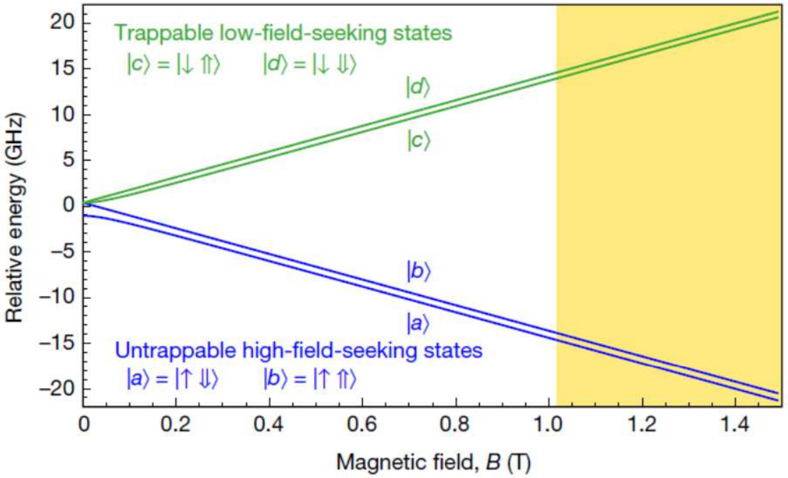
Confinement of antihydrogen for 1,000 seconds

The ALPHA Collaboration*

Atoms made of a particle and an antiparticle are unstable, usually surviving less than a microsecond. Antihydrogen, made entirely of antiparticles, is believed to be stable, and it is this longevity that holds the promise of precision studies of matter–antimatter symmetry. We have recently demonstrated trapping of antihydrogen atoms by releasing them after a confinement time of 172 ms. A critical question for future studies is: how long can anti-atoms be trapped? Here, we report the observation of anti-atom confinement for 1,000 s, extending our earlier results by nearly four orders of magnitude. Our calculations indicate that most of the trapped anti-atoms reach the ground state. Further, we report the first measurement of the energy distribution of trapped antihydrogen, which, coupled with detailed comparisons with simulations, provides a key tool for the systematic investigation of trapping dynamics. These advances open up a range of experimental possibilities, including precision studies of charge–parity–time reversal symmetry and cooling to temperatures where gravitational effects could become apparent.



Observation of the hyperfine spectrum of antihydrogen

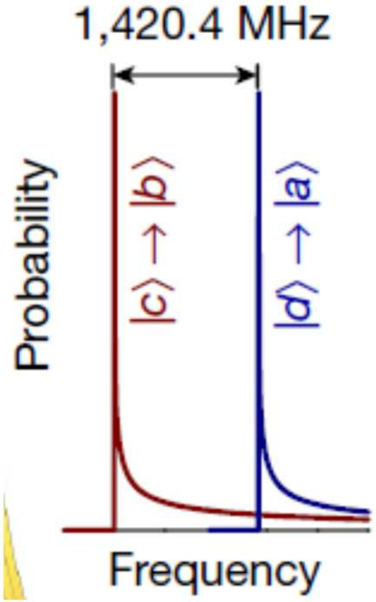


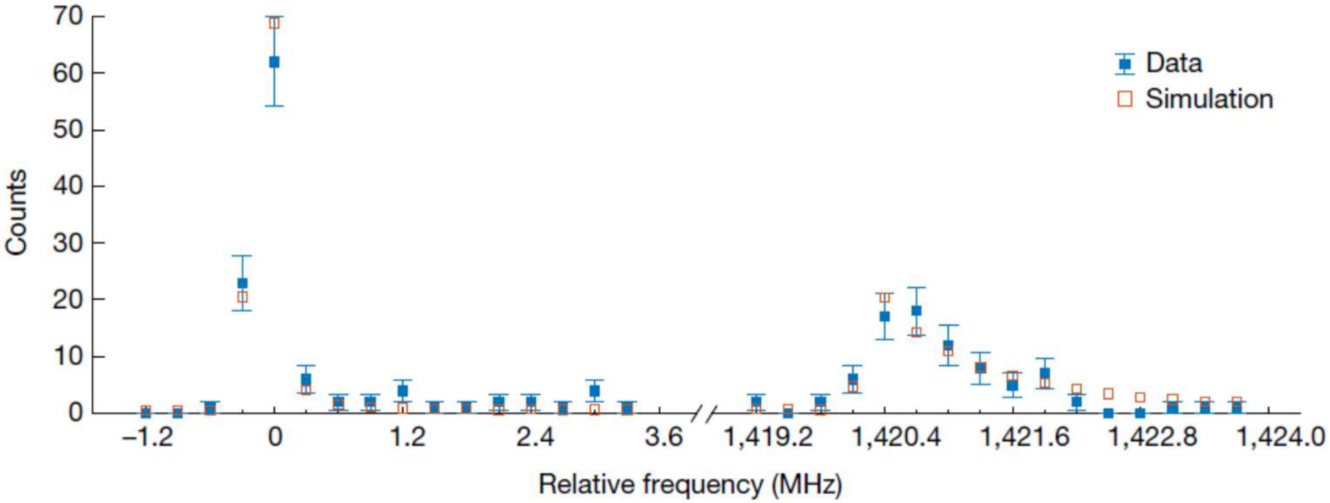
Nature 548 (2017) 66

194 events

Δf = 1420.4 ± 0.5 MHz

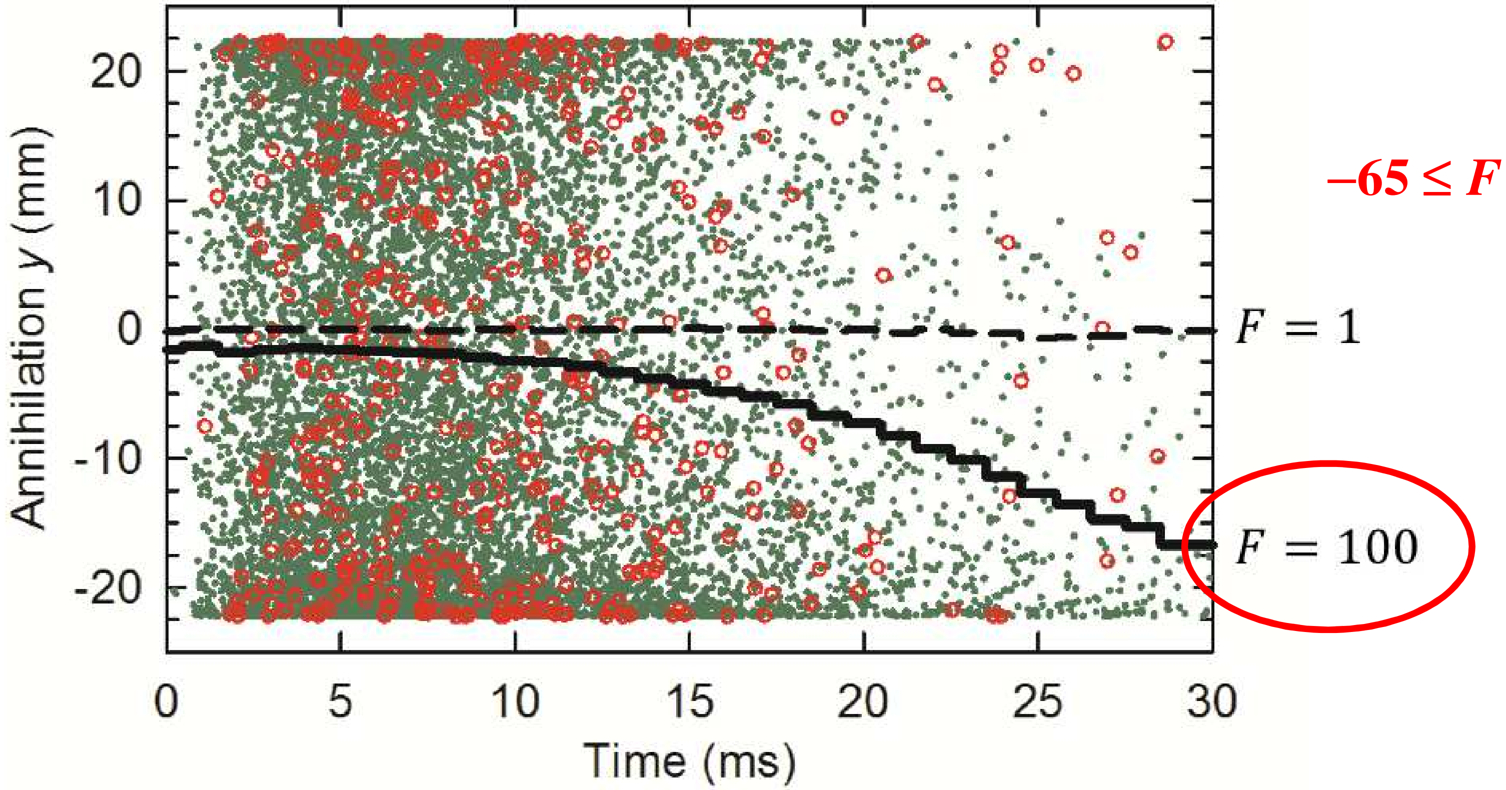
Hydrogène : 1420.40575178 MHz





First direct limit on $\bar{g}$

Antihydrogen $F = M_G/M$



$$-65 \leq F = \frac{\bar{g}}{g} \leq 110$$

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)

Project for a new detector: ALPHA-g

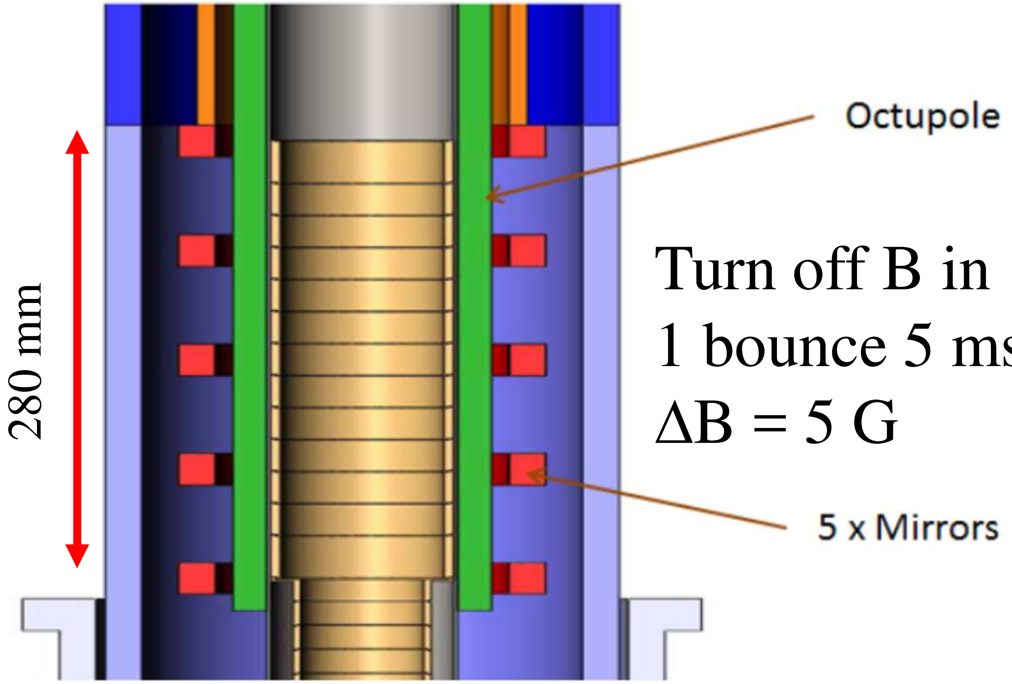
Antimatter gravity measurement with increasing precision

SPSC-P325-ADD-1

T=500 mK

- First step:
1T mirror B field :
up-down measurement

- Second step:
1kG mirror B field :
1 % measurement



Turn off B in 10 s
1 bounce 5 ms
ΔB = 5 G

$$P = mg \text{ et } F_z = \mu_B \partial B / \partial z$$

$$\mu_B = 5.8\times 10^{-5} \text{ eV/T} \Rightarrow 18 \text{ G/m} \Leftrightarrow 1\text{g}$$

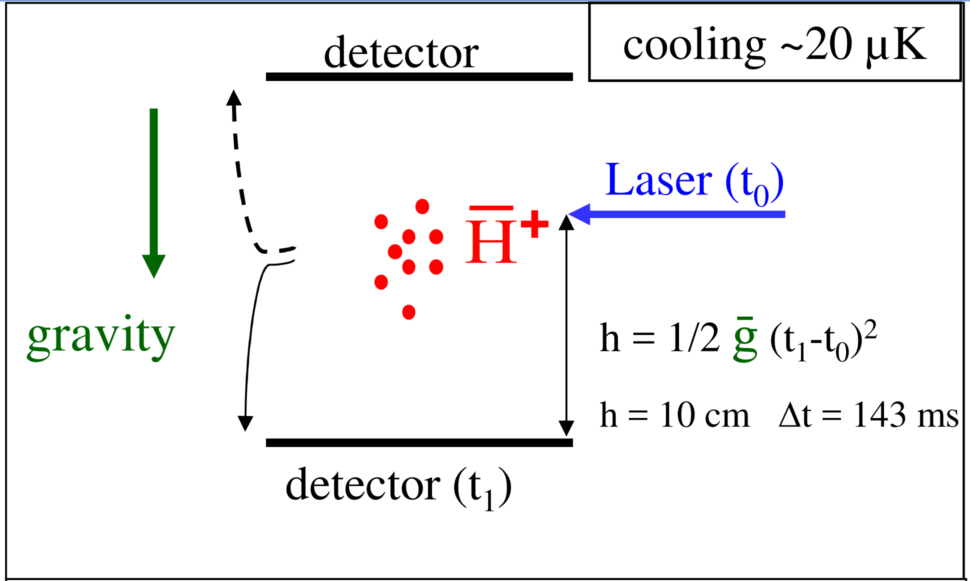
$$\Delta B = 5 \text{ G} \Leftrightarrow \Delta h = 280 \text{ mm}$$

Experiments with $\overline{\mathrm{H}}$

- ALPHA
- **GBAR**
- AEGIS

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

- Produce ion $\bar{H}^{+}$
- Capture ion $\bar{H}^{+}$
- Sympathetic cooling 20 µK
- Photodetachment of e^{+}
- Time of flight



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

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

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

Production of anti ions

Use positronium !

bound e^+e^- → 3-body

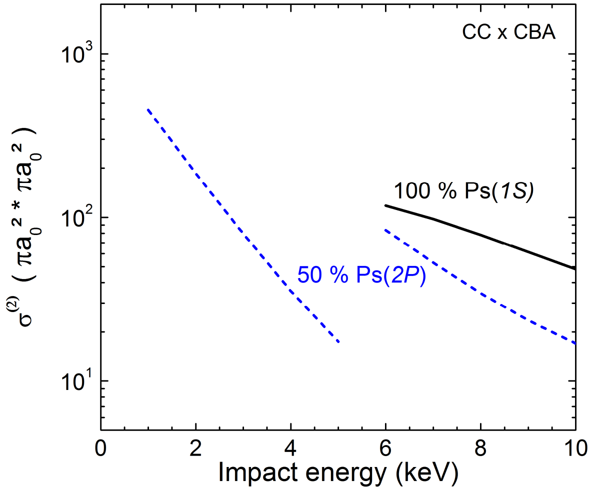
demonstrated by ATRAP (2004) → $\bar{p} + Ps \rightarrow \bar{H} + e^-$

Idea for GBAR:

2nd charge exchange reaction → $\bar{H} + Ps \rightarrow \bar{H}^+ + e^-$

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

Cross-section enhancement
if Ps excited to n>1



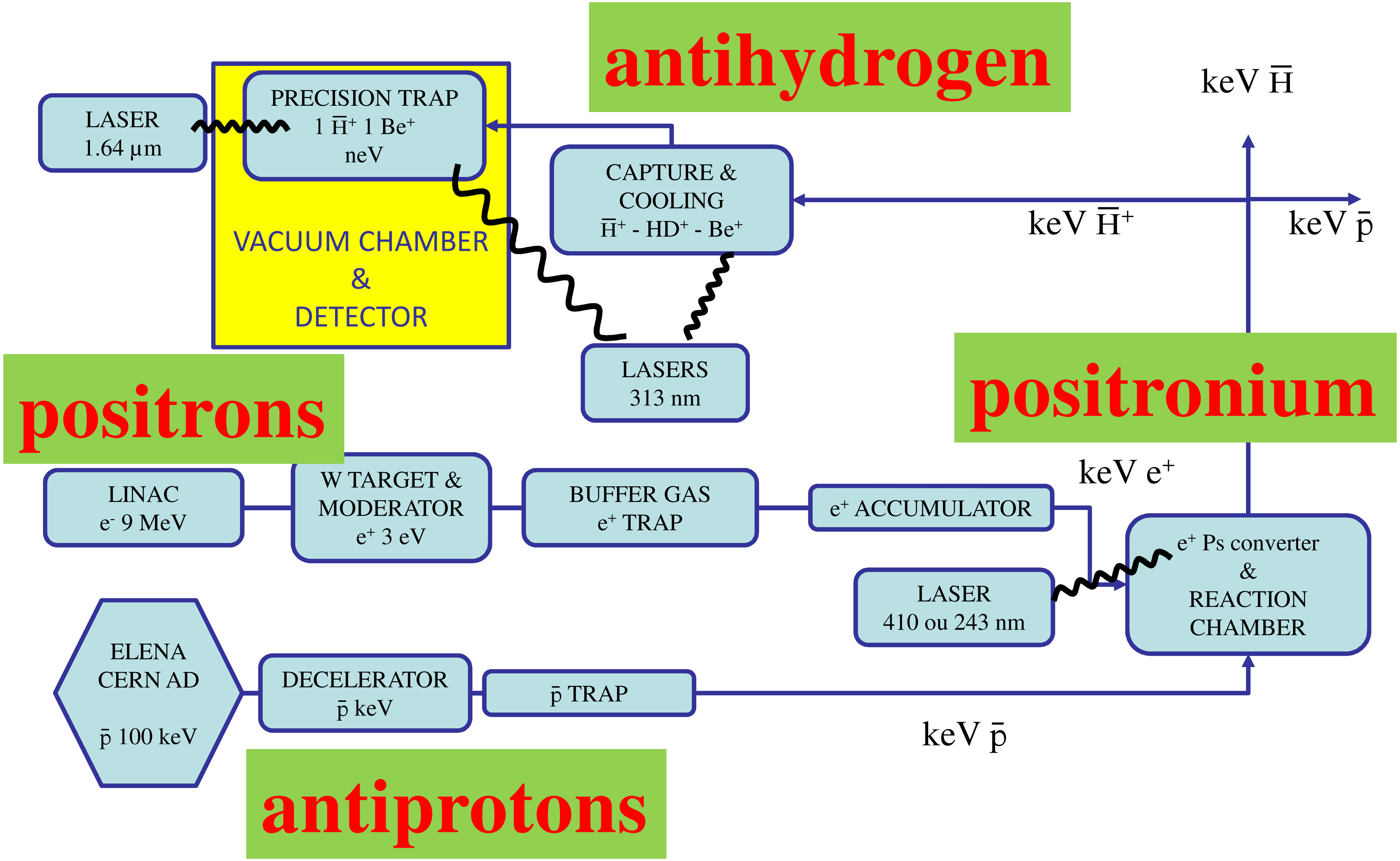
P. Comini, Private Communication

CERN every 110 s → $\sim 0.5\ 10^7\ \bar{p}$

dump $3\text{x}10^{10}$ e^+ on a SiO2 porous surface → 10^{12} Ps /cm²

$\left.\begin{matrix} \sim 0.5\ 10^7\ \bar{p} \\ 10^{12}\ Ps/cm^2 \end{matrix}\right\} \rightarrow \begin{matrix} 10^4\ \bar{H} \\ 1\ \bar{H}^+ \end{matrix}$

GBAR experimental scheme



antihydrogen

keV $\bar{H}$

LASER
1.64 µm

PRECISION TRAP
1 $\bar{H}^+$ 1 Be^+
neV

VACUUM CHAMBER
&
DETECTOR

CAPTURE &
COOLING
$\bar{H}^+$ - HD^+ - Be^+

keV $\bar{H}^+$

keV $\bar{p}$

LASERS
313 nm

positrons

positronium

keV e^+

LINAC
e^- 9 MeV

W TARGET &
MODERATOR
e^+ 3 eV

BUFFER GAS
e^+ TRAP

e^+ ACCUMULATOR

e^+ Ps converter
&
REACTION
CHAMBER

LASER
410 ou 243 nm

ELENA
CERN AD

$\bar{p}$ 100 keV

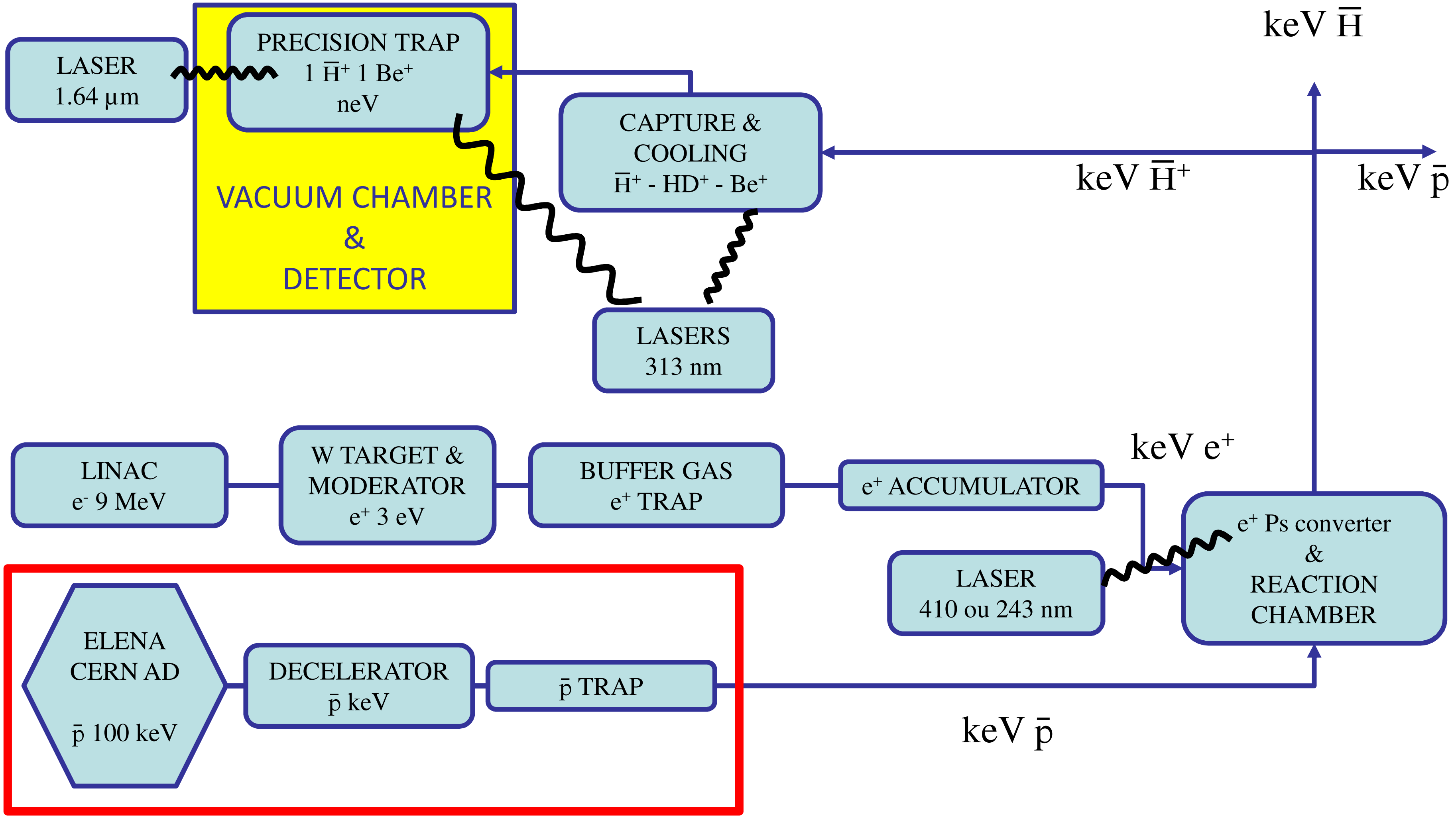
DECELERATOR
$\bar{p}$ keV

$\bar{p}$ TRAP

keV $\bar{p}$

antiprotons

GBAR experimental scheme



LASER
1.64 µm

PRECISION TRAP
1 $\bar{H}^+$ 1 Be^+
neV

VACUUM CHAMBER
&
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CAPTURE &
COOLING
$\bar{H}^+$ - HD^+ - Be^+

LASERS
313 nm

keV $\bar{H}$

keV $\bar{H}^+$

keV $\bar{p}$

LINAC
e^- 9 MeV

W TARGET &
MODERATOR
e^+ 3 eV

BUFFER GAS
e^+ TRAP

e^+ ACCUMULATOR

keV e^+

LASER
410 ou 243 nm

e^+ Ps converter
&
REACTION
CHAMBER

ELENA
CERN AD

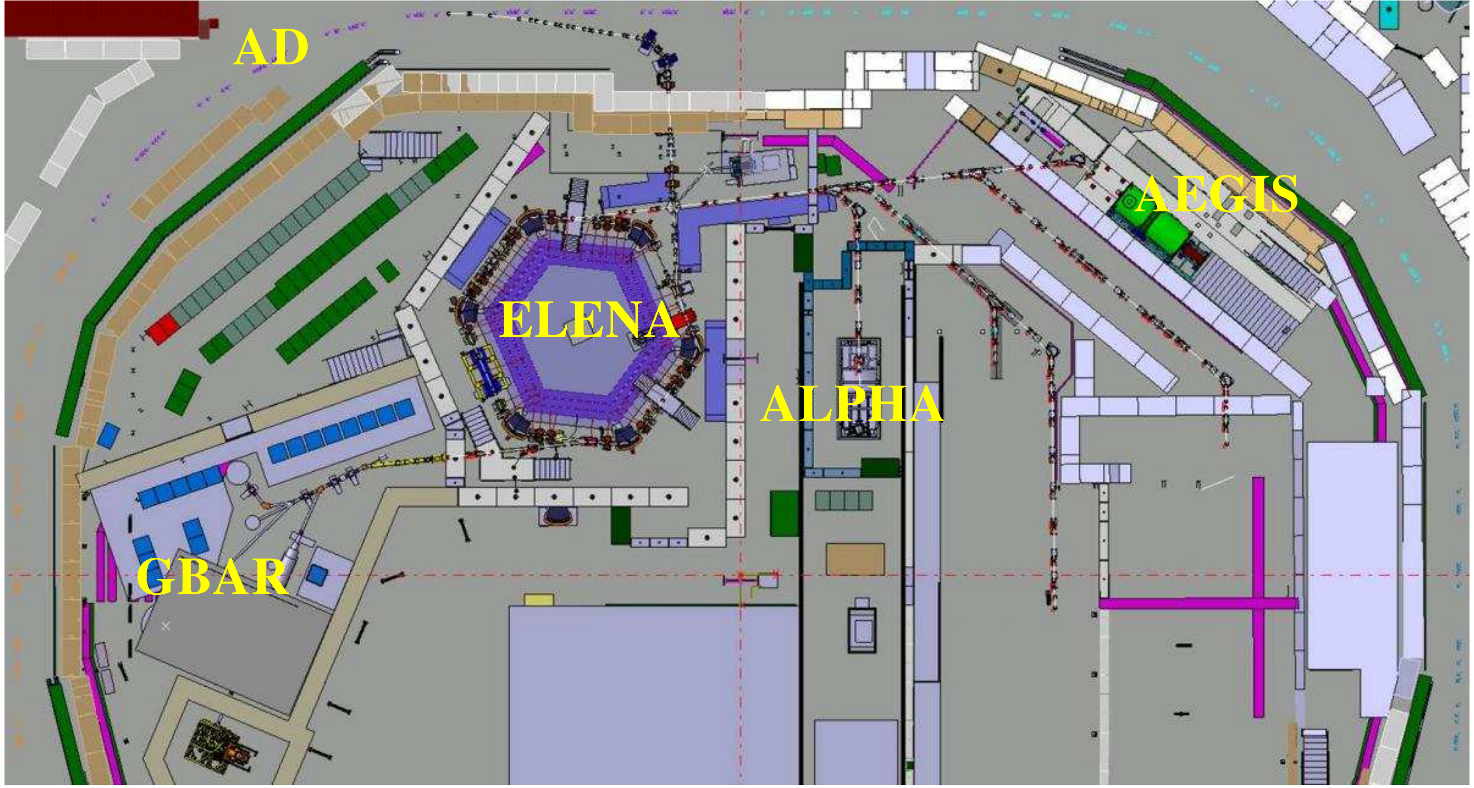
$\bar{p}$ 100 keV

DECELERATOR
$\bar{p}$ keV

$\bar{p}$ TRAP

keV $\bar{p}$

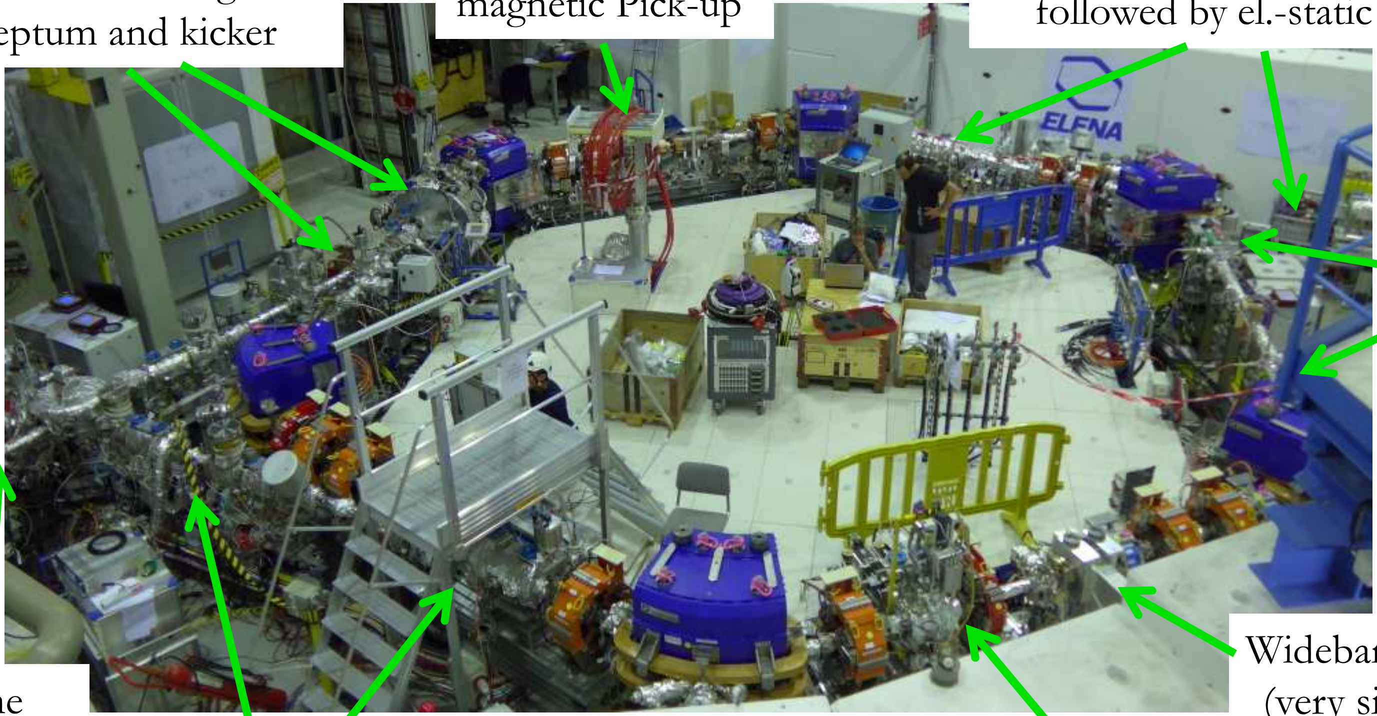
Antiprotons: CERN AD / ELENA



AD : 5 MeV $\bar{p}$

ELENA : 100 keV $\bar{p}$
but still not slow enough for GBAR
need additional deceleration (CSNSM)
and trapping (U. Seoul & IBS South Korea)

ELENA



Injection with magnetic septum and kicker

High sensitivity magnetic Pick-up

Extraction towards new experimental zone (fast deflector) followed by el.-static transfer lines

Compensation solenoids for (not yet Installed) cooler

Wideband RF cavities (very similar to new PSB cavities)

Scraper to measure emittance

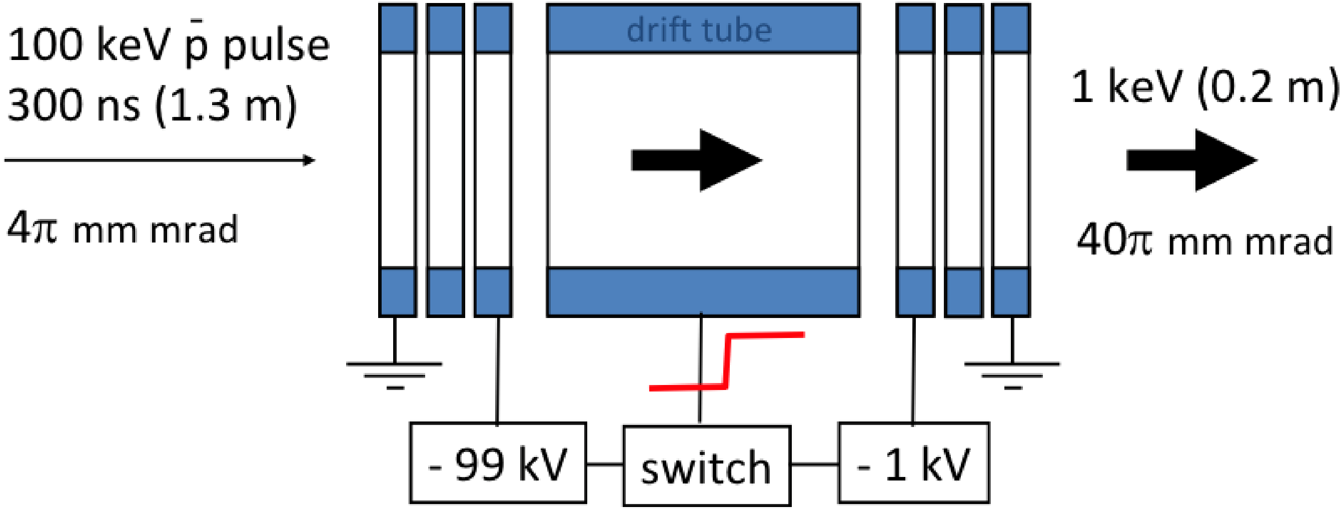
Extraction towards existing experiments

Line From AD

- Deceleration of antiprotons from 5.3 MeV to 100 keV to improve efficiency of experiments
- Circumference 30.4 m (1/6 the size of the AD), magnetic ring and electrostatic extraction lines
- Challenges related to low energy as field quality of magnets operated with very low fields

GBAR antiproton decelerator

1 pulse/ 110 s



100 keV $\bar{p}$ pulse

300 ns (1.3 m)

4π mm mrad

drift tube

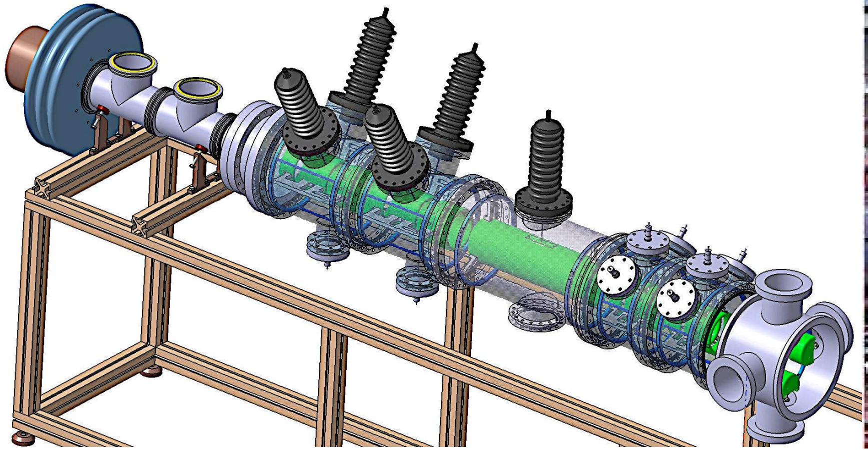
1 keV (0.2 m)

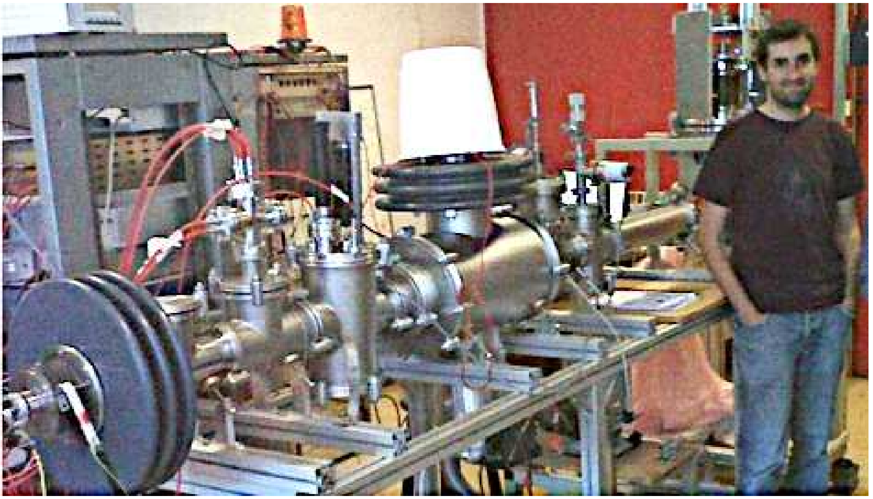
40π mm mrad

- 99 kV

switch

- 1 kV





Antiproton trap

Receive and catch the antiproton bunches from ELENA with GBAR decelerator

Cool antiprotons and reduce the size of the beam

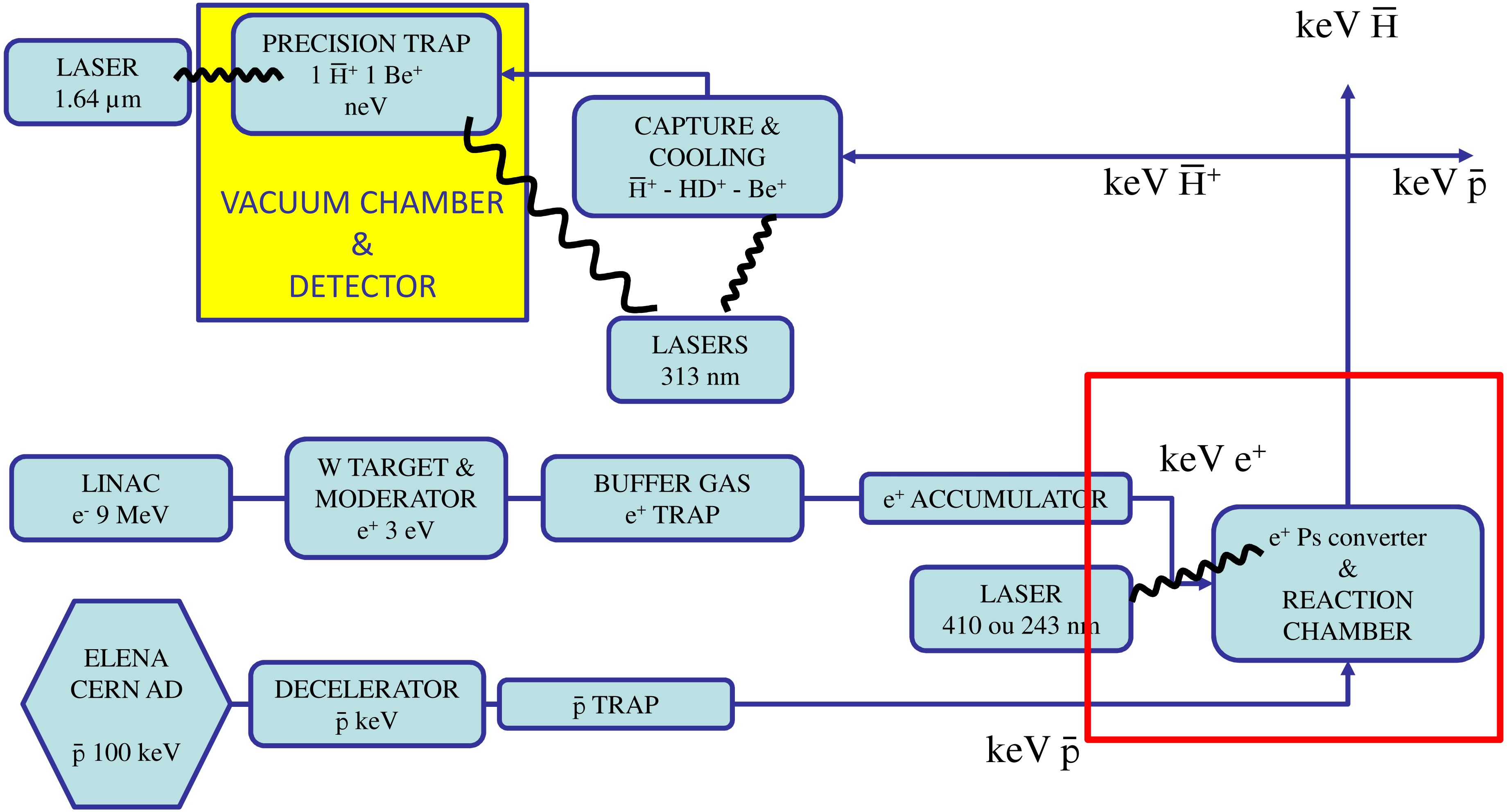
Catch additional bunches while manipulating beam size

Inject to GBAR reaction chamber

Recapture unused antiprotons from the reaction chamber

Input	Output
Antiproton energy: 1-6 keV	Antiproton energy: 10 -100 eV
$\Delta E = 300$ eV	$\Delta E = 15$ eV
# Antiprotons/cycle : 4 x 10^6	# Antiprotons : 1 x 10^7
Emittance : 40 π mm mrad	Radial beam size : 1 mm
bunch length : ~ 270 ns	bunch length : ~ 100 ns
cycle time : 110s	

GBAR experimental scheme



LASER
1.64 µm

PRECISION TRAP
1 $\bar{H}^+$ 1 Be^+
neV

VACUUM CHAMBER
&
DETECTOR

CAPTURE &
COOLING
$\bar{H}^+$ - HD^+ - Be^+

LASERS
313 nm

keV $\bar{H}$

keV $\bar{H}^+$

keV $\bar{p}$

LINAC
e^- 9 MeV

W TARGET &
MODERATOR
e^+ 3 eV

BUFFER GAS
e^+ TRAP

e^+ ACCUMULATOR

keV e^+

LASER
410 ou 243 nm

e^+ Ps converter
&
REACTION
CHAMBER

ELENA
CERN AD

$\bar{p}$ 100 keV

DECELERATOR
$\bar{p}$ keV

$\bar{p}$ TRAP

keV $\bar{p}$

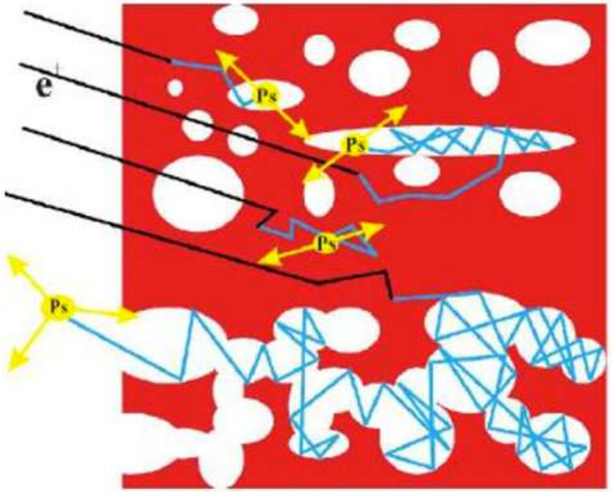
Production of 10^{12} Ps/cm^2

Ps: positronium bound state of $e^+ e^-$: para-Ps 125 ps ; ortho-Ps 142 ns
(S=0) (S=1)

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

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

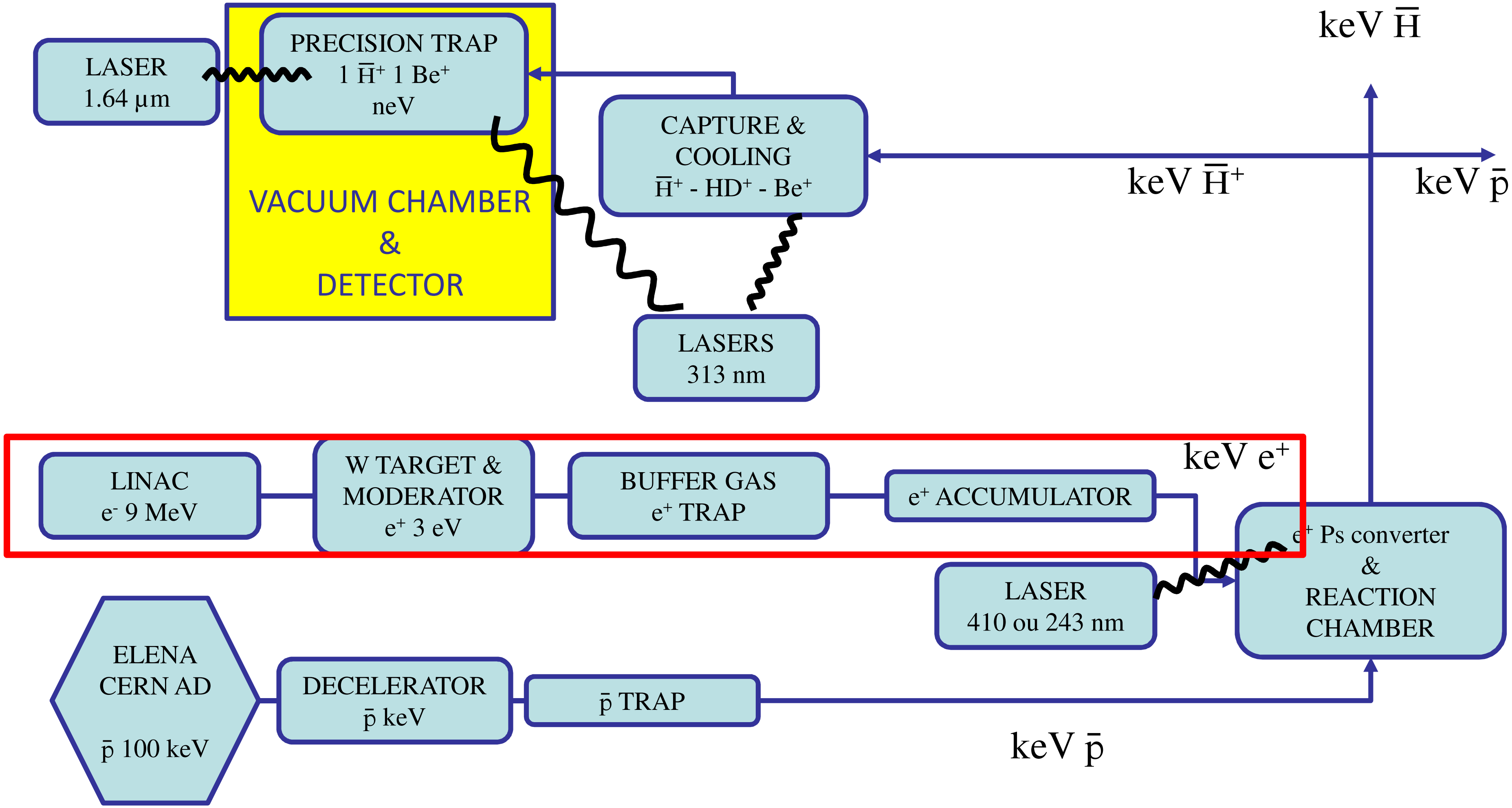
e^+ + converter → Ps



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

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

GBAR experimental scheme



LASER
1.64 µm

PRECISION TRAP
1 $\bar{H}^+$ 1 Be^+
neV

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ELENA
CERN AD

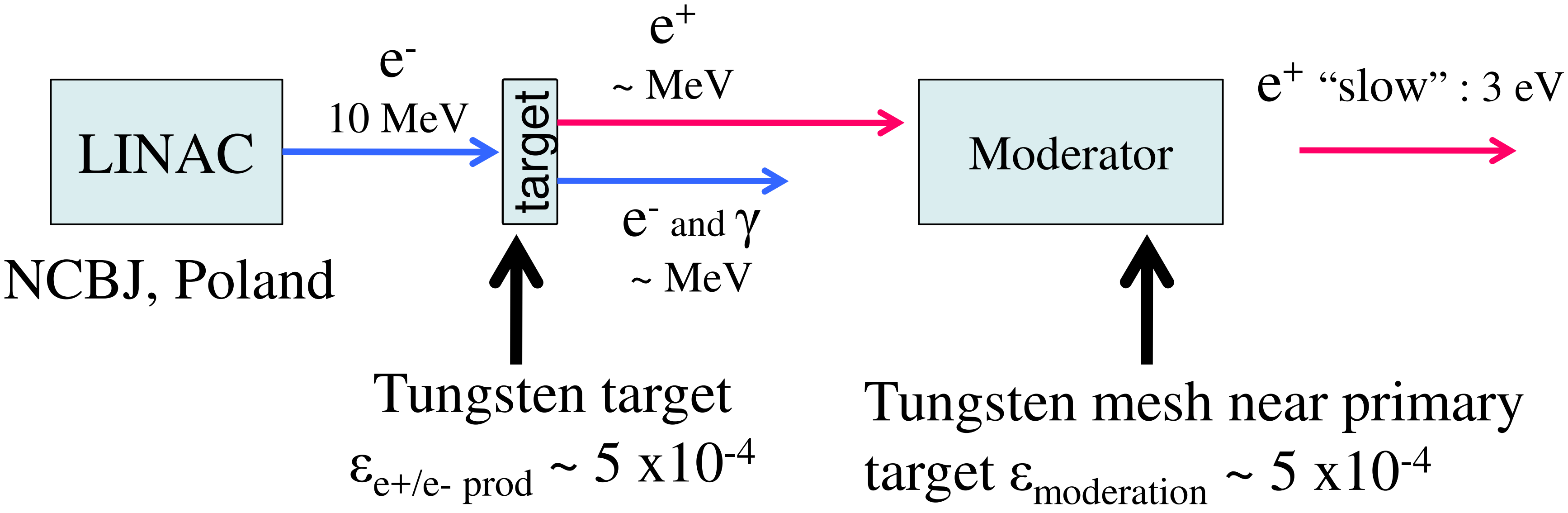
$\bar{p}$ 100 keV

DECELERATOR
$\bar{p}$ keV

$\bar{p}$ TRAP

keV $\bar{p}$

High intensity slow positrons source



LINAC

NCBJ, Poland

e^- 10 MeV

target

e^+ ~ MeV

e^- and γ ~ MeV

Moderator

e^+ "slow" : 3 eV

Tungsten target $\varepsilon_{e+/e-\ prod}$ ~ 5×10^{-4}

Tungsten mesh near primary target $\varepsilon_{moderation}$ ~ 5×10^{-4}

~ 5×10^{11} fast e^+/s

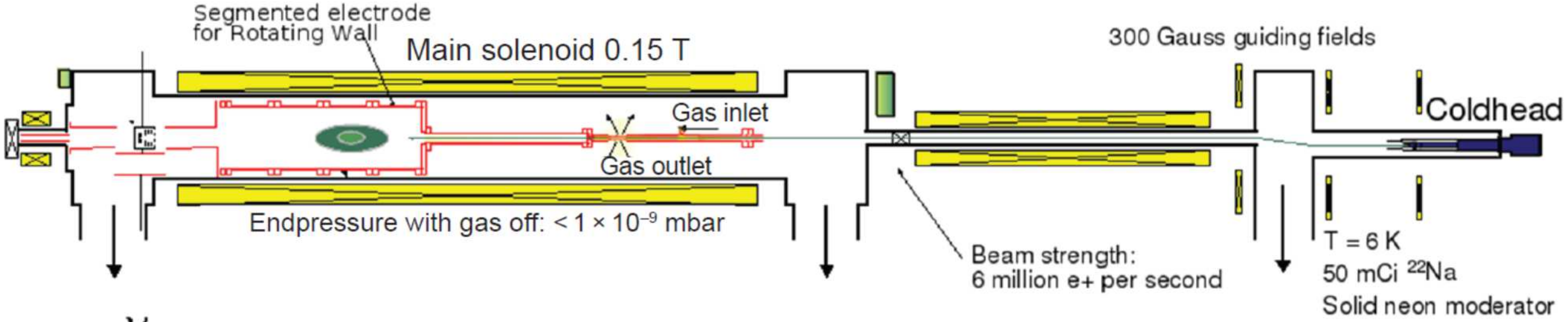
~ 2×10^{8} slow e^+/s

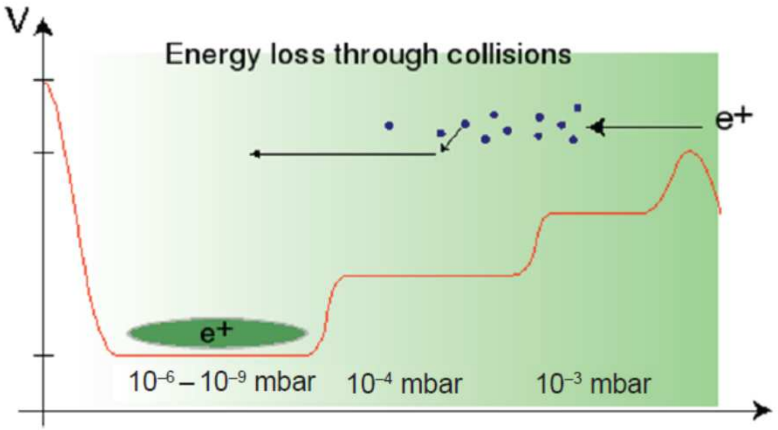
e^+ trapping

A two stage accumulation at Saclay:

1. **buffer gas trap to cool positrons with Nitrogen**
2. **Accumulator: RIKEN multiring trap**

Alpha buffer gas system





Positron – Nitrogen reactions:

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

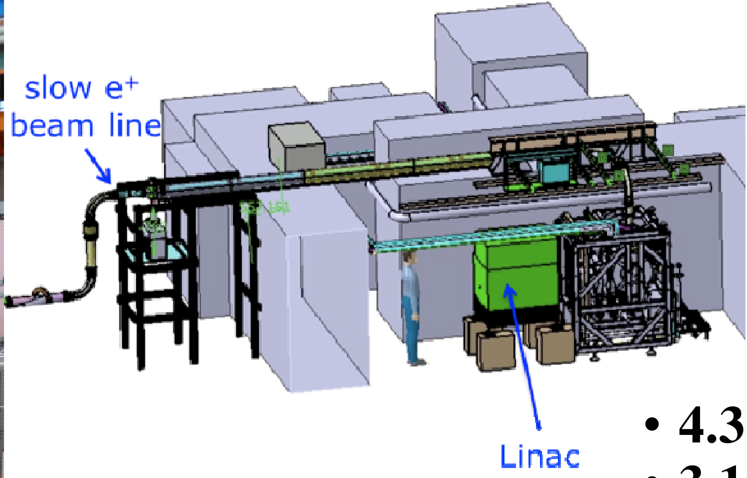
$$e^+_{(>8.8\ \mathrm{eV})} + N_2 \rightarrow Ps + N_2^+$$

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

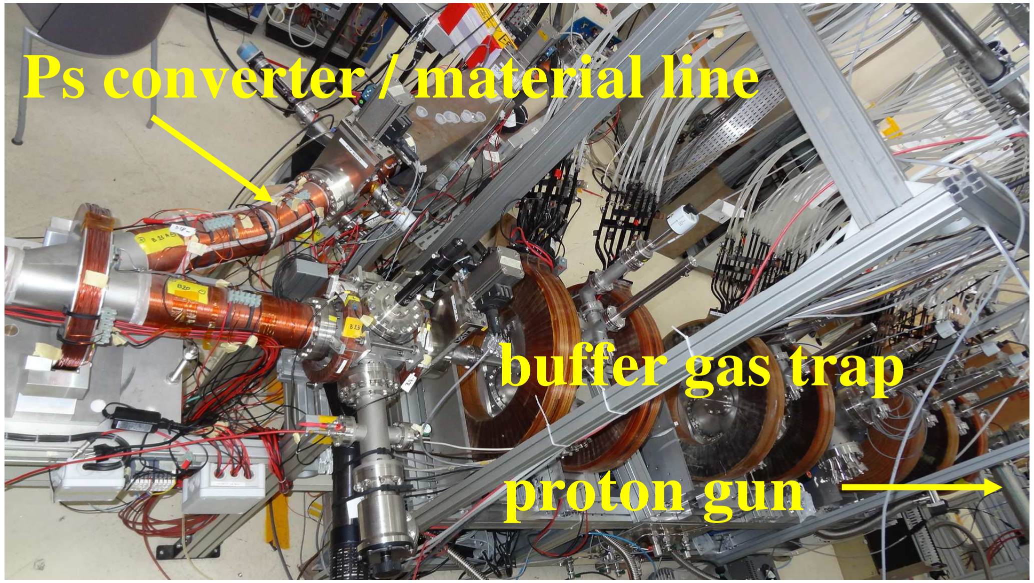
$$e^+_{(>15.6\ \mathrm{eV})} + N_2 \rightarrow e^+ + e^- + N_2^+$$

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

Installation at Saclay: e^+, Ps, p, H

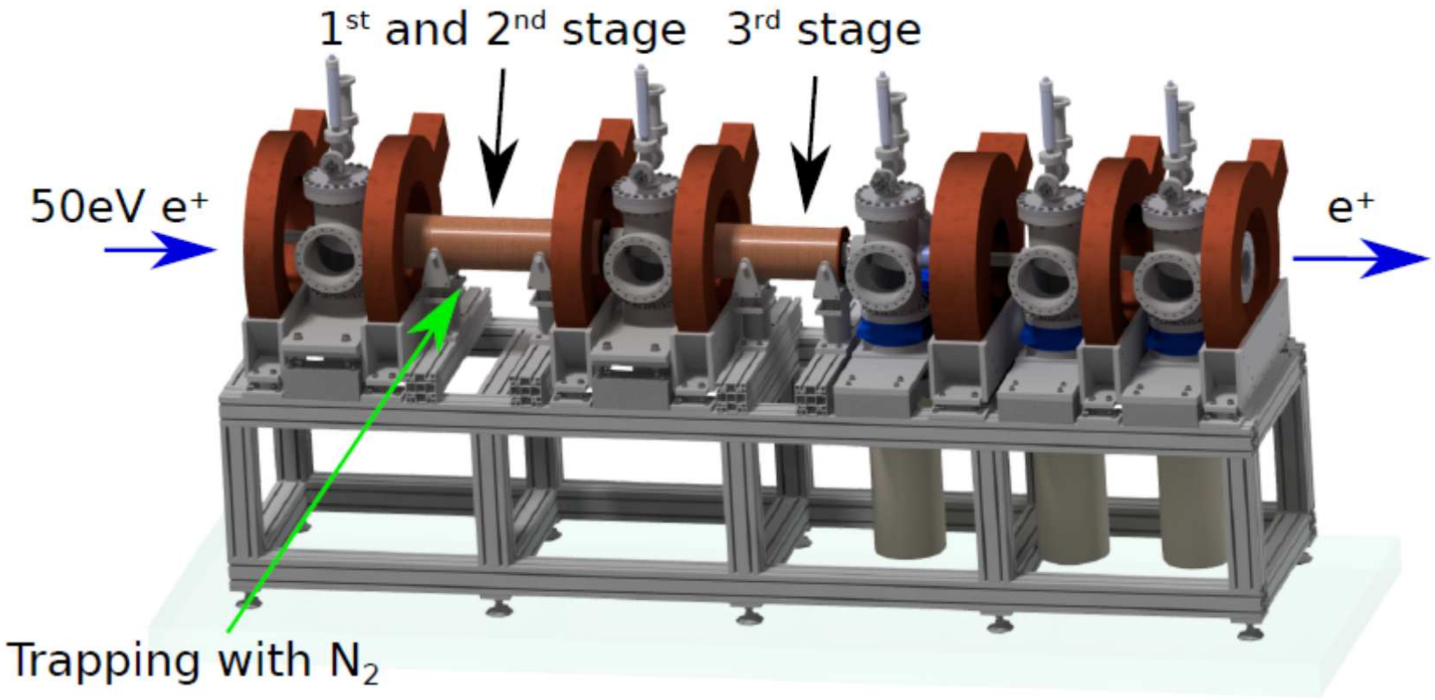


- 4.3 MeV / 200 Hz / 120 µA
- 3 10^6 slow e^+/s



e^+ trapping

Buffer gas trap: commissioning at Saclay

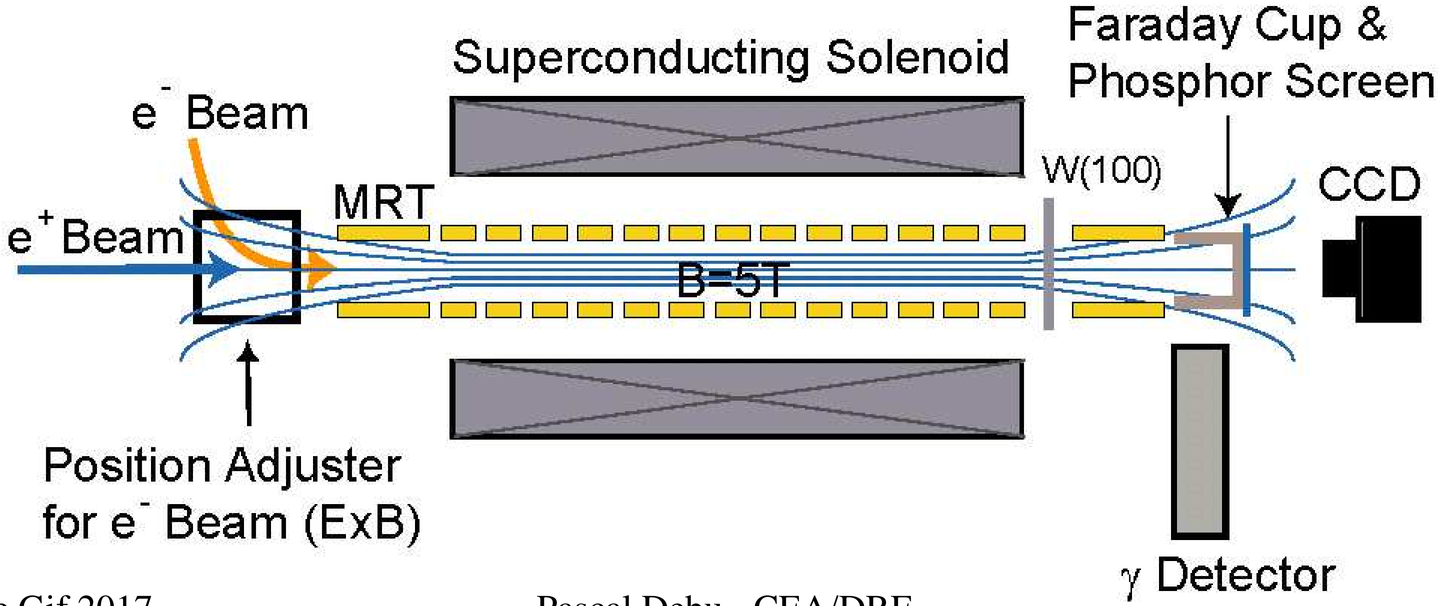


Maximum expected trapping efficiency 30 %
Measured 10 %

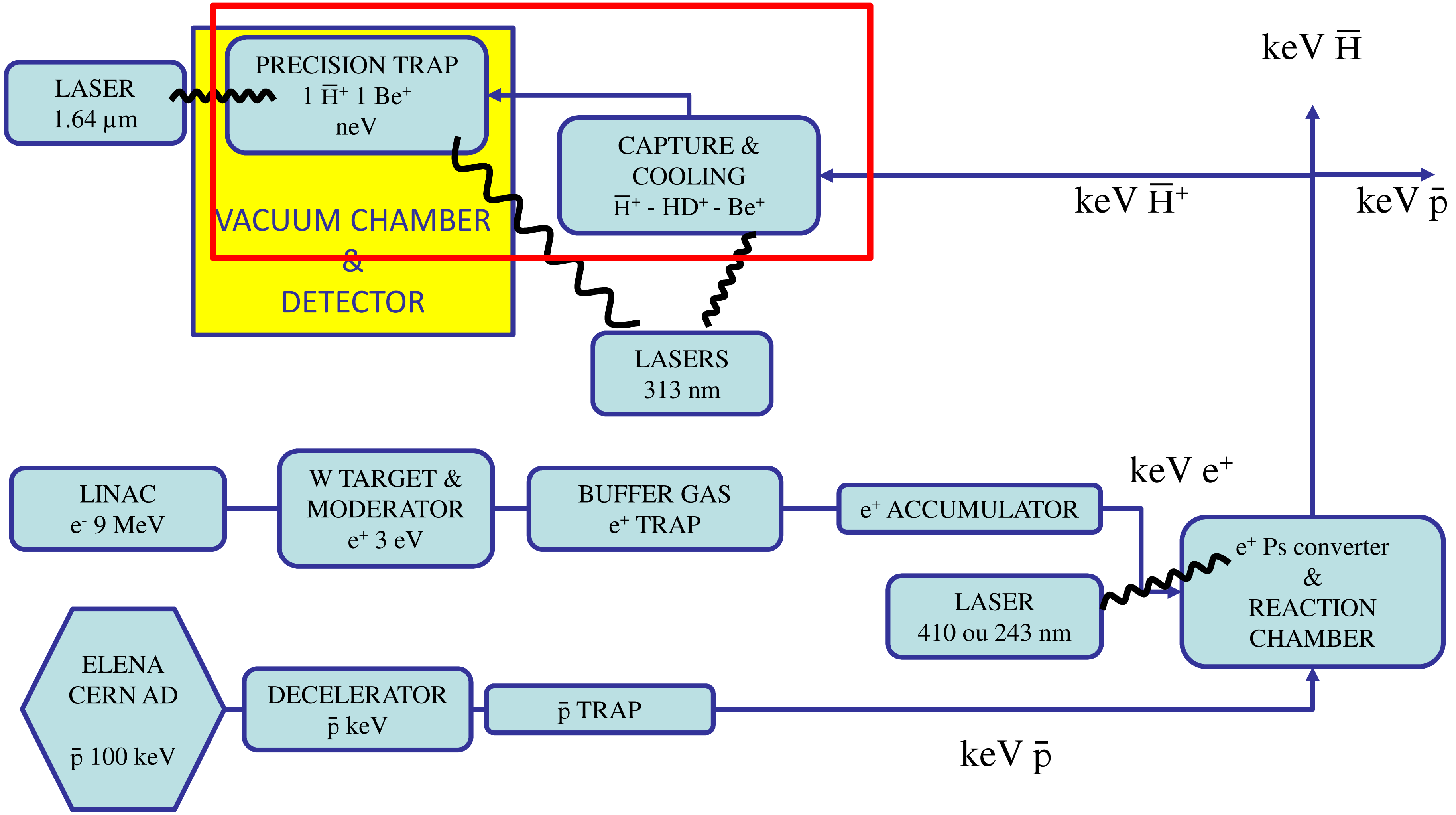
RIKEN Multi-Ring Trap

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

N. Oshima → e^- cooling



GBAR experimental scheme



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$\bar{p}$ keV

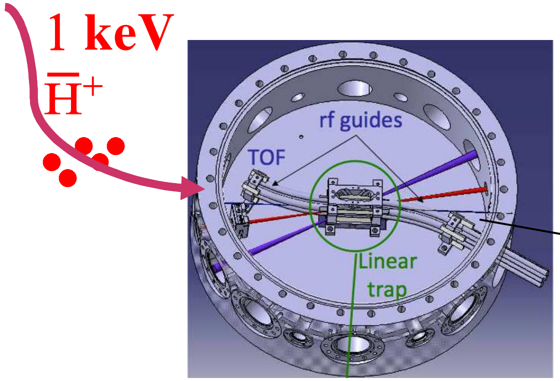
$\bar{p}$ TRAP

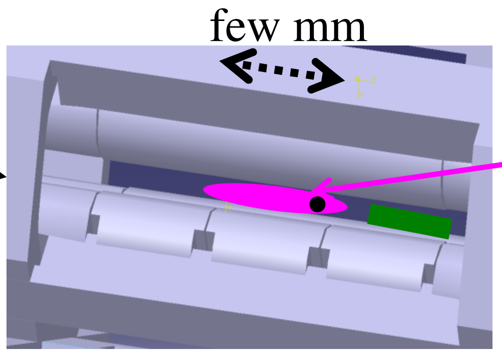
keV $\bar{p}$

$\overline{H}^+$ with v < 1 m/s: from 500 000 K to 20 μK !

Done in 3 steps (Mainz & LKB)

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



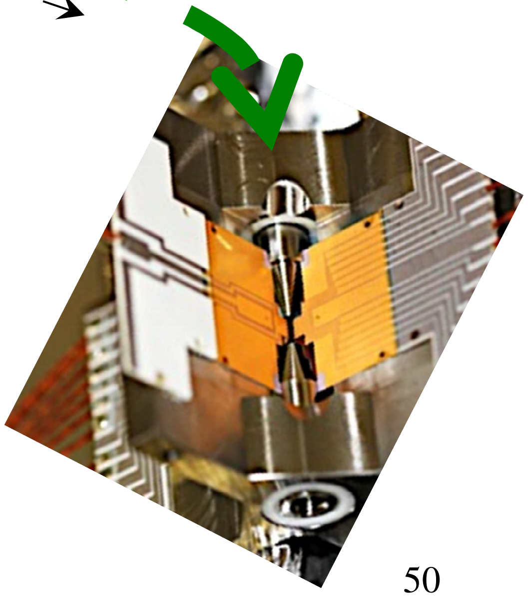


> 10 000 laser cooled Be^+ ions
100 neV, T ~ mK

313 nm laser

Second step

Transfer and ground state cooling to 100 μK of a Be^+/H^+ ion pair in the **precision trap**
Raman side band cooling



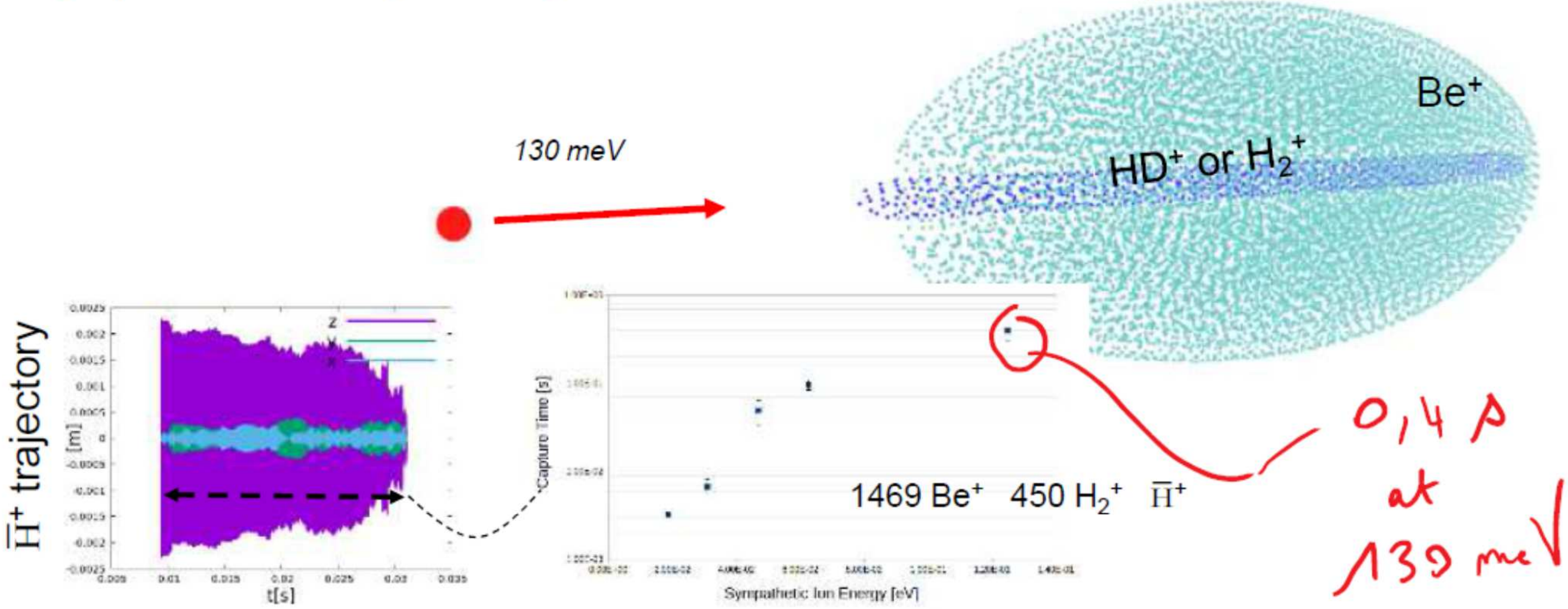
Third step

Adiabatic ramp down to 20 μK

Sympathetic cooling: full simulation

Sympathetic cooling of $\bar{H}^+$ by laser cooled Be^+ only **does not work**

Sympathetic cooling of $\bar{H}^+$ by laser cooled Be^+ and HD^+ or H_2^+ **should work**



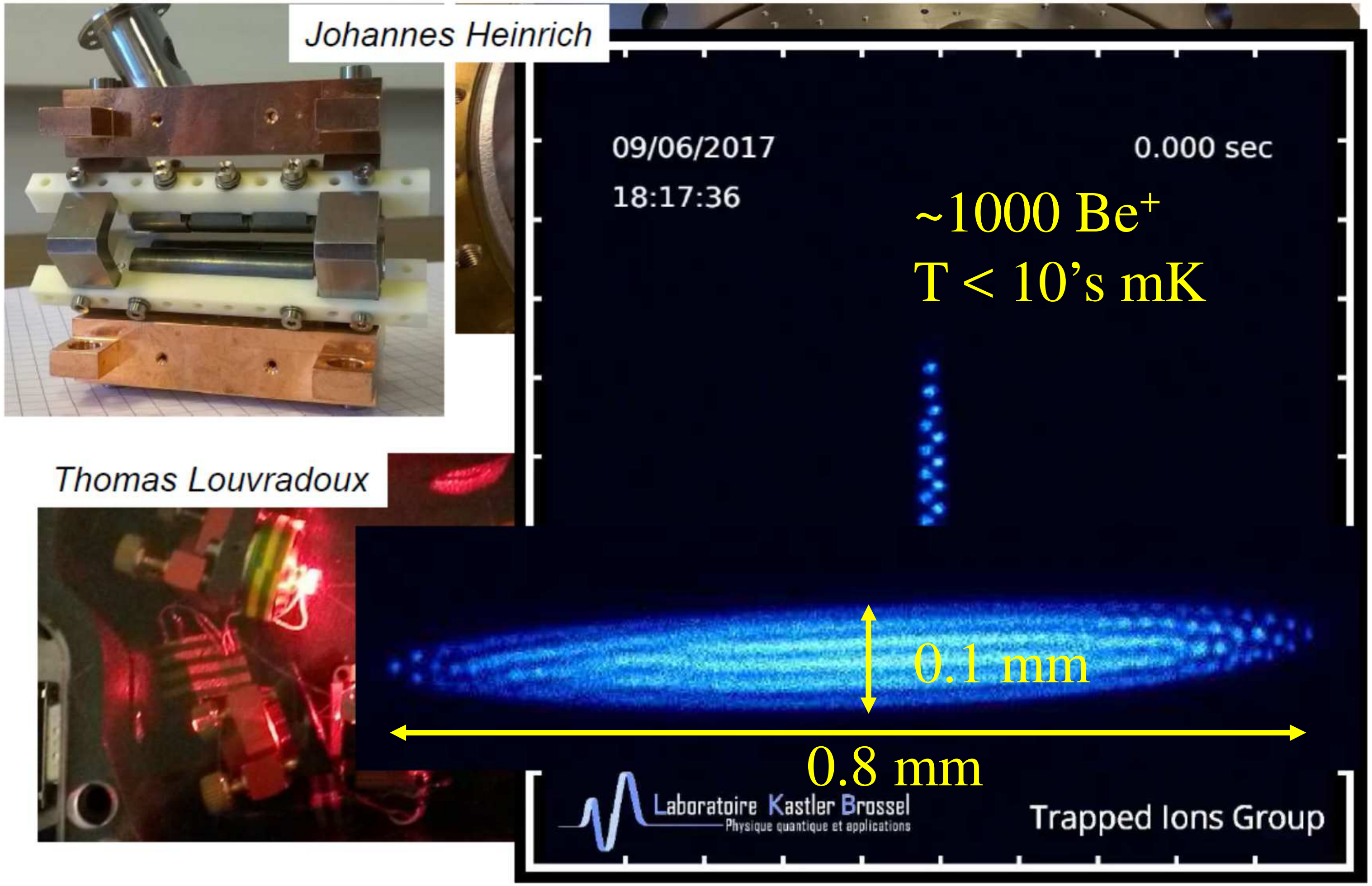
0,4 s
at
130 meV
~1500K

Experimental tests with $^{88}Sr^+/^{9}Be^+$ at MPQ (Univ Denis Diderot)

$^{88}Sr^+/^{27}Al^+/^{9}Be^+$

L. Hilico

Sympathetic cooling: in progress!



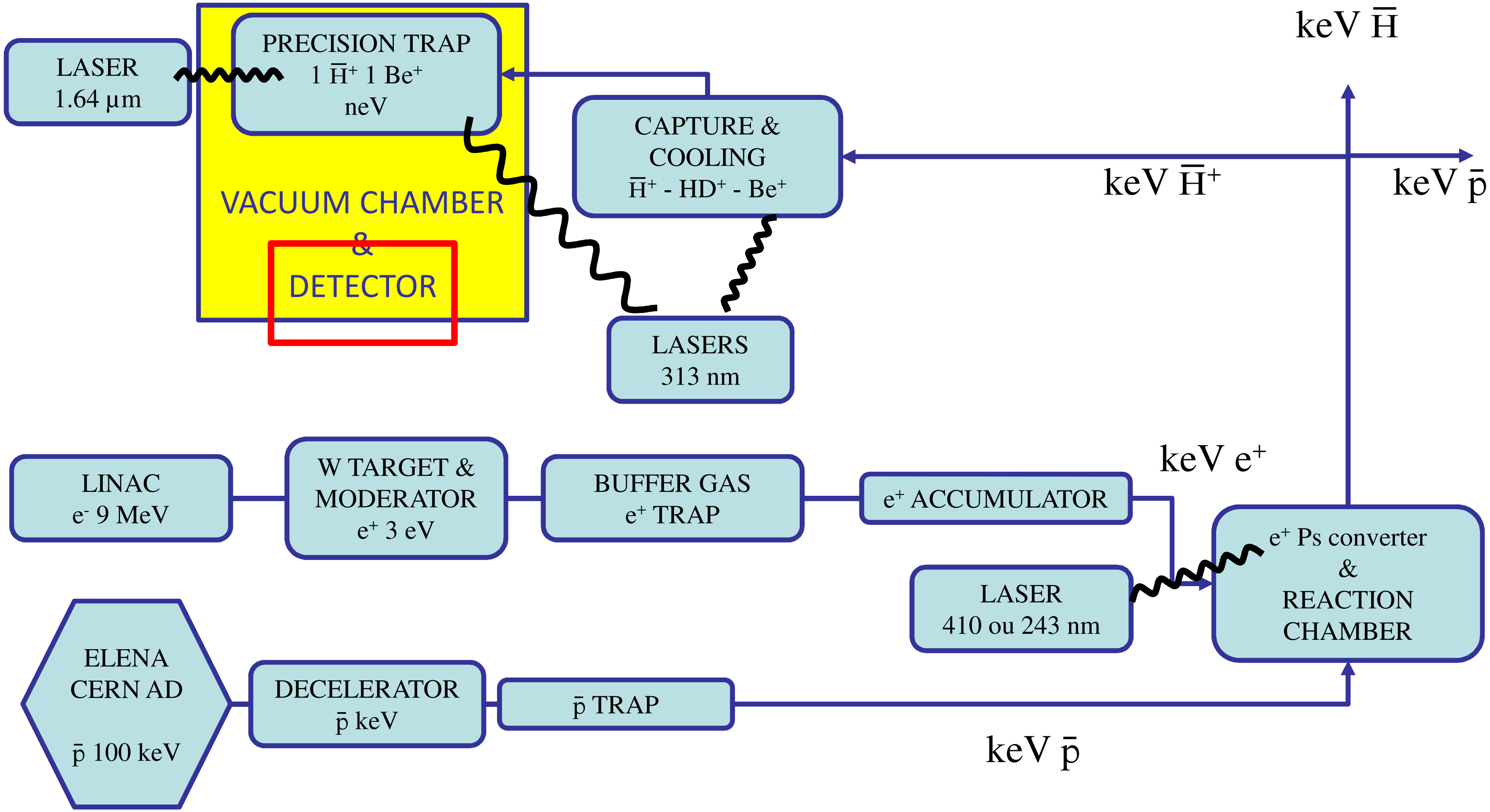
~1000 Be^+

T < 10's mK

0.1 mm

0.8 mm

GBAR experimental scheme



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$\bar{p}$ keV

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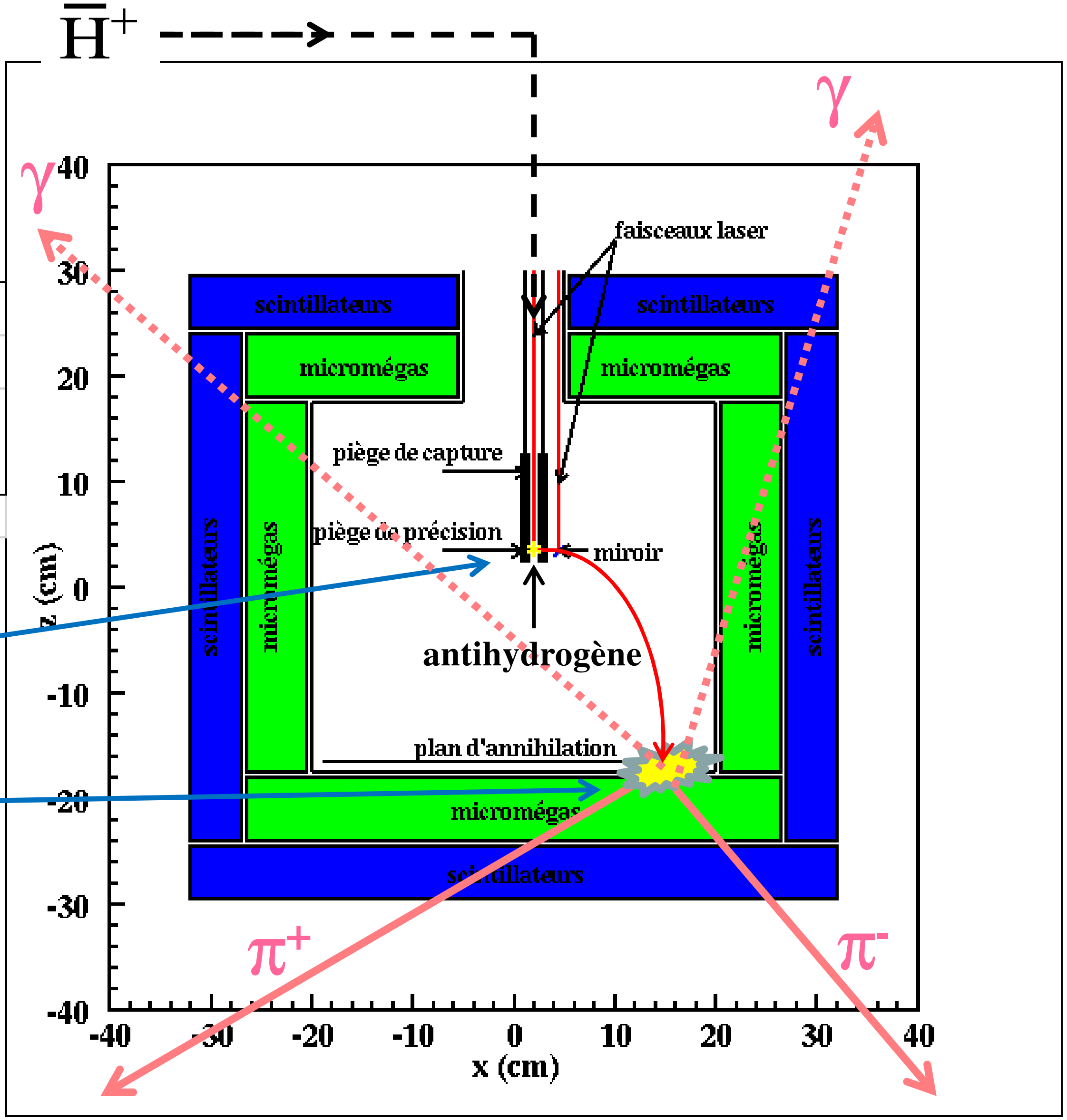
keV $\bar{p}$

Simple free fall

can measure $\bar{g}$ to 1 %
with ~ 1500 events

TOF	150 µs
Annihilation vertex	2 mm
Background rejection	event topology & sci. counters



Laser shot
t_0

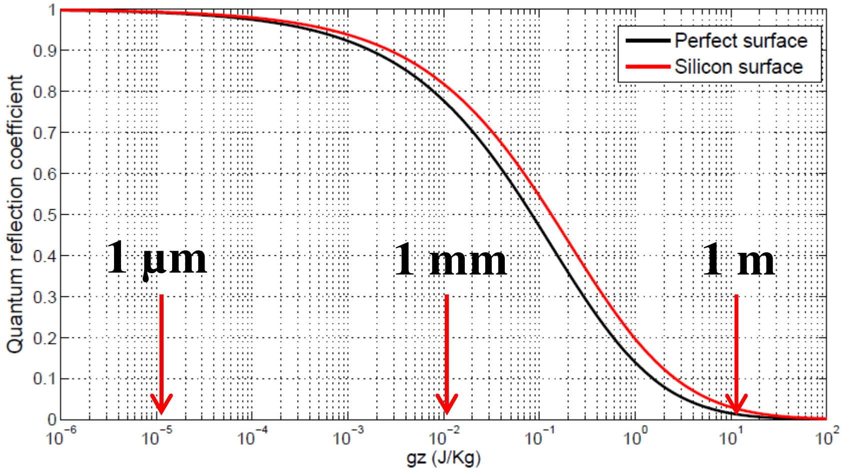
annihilation
t_1

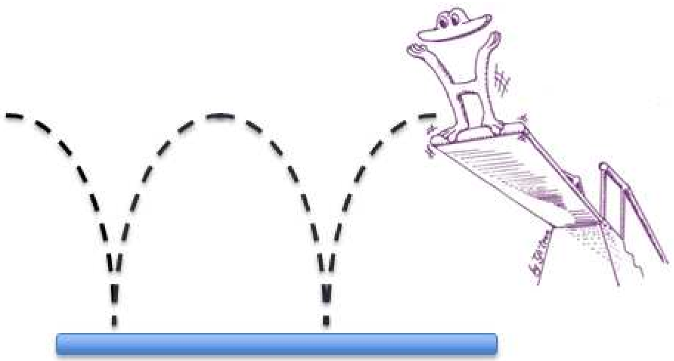
Free fall height h = 20 cm

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

Towards better sensitivity: reflection of $\bar{\mathrm{H}}$

Casimir attractive force
+
quantum reflection





Reflection probability
of $\bar{\mathrm{H}}$ atom

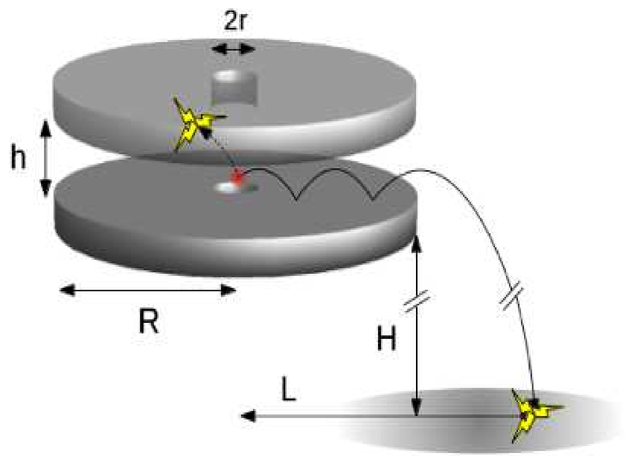
G. Dufour et al, *Quantum reflection of antihydrogen from the Casimir potential above matter slabs*, Phys. Rev. A 87, 2013

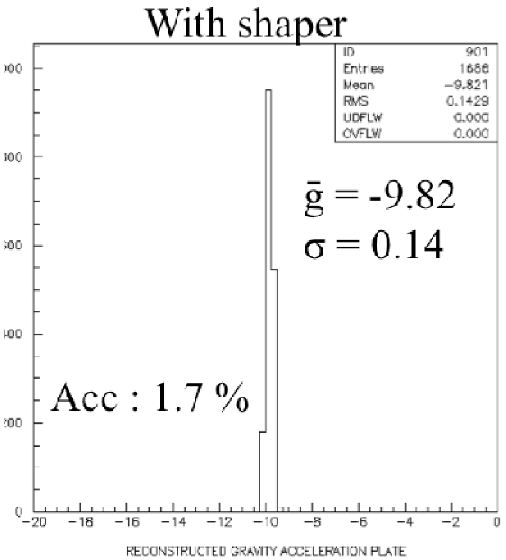
Reduce needed statistics !!!

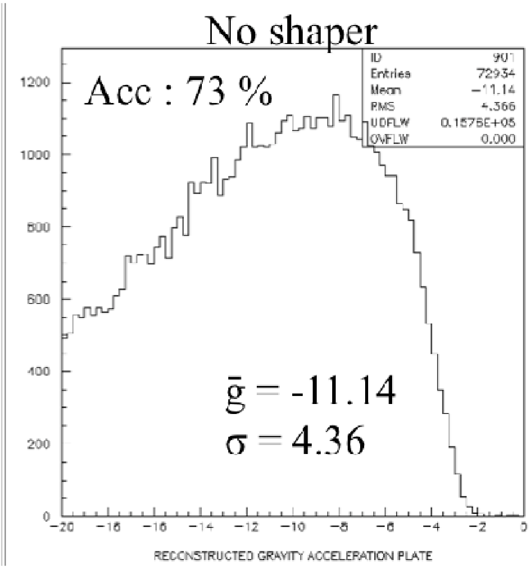
Velocity selector

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

$\overline{g}_m = 2h/\left(t_1 - t_0\right)^2$ **is a biased estimate of** $\overline{g}$







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 $\overline{\mathrm{H}}^+$ for Δg/g = 1%

10 times less than in proposal

Towards < 1 ‰ precision

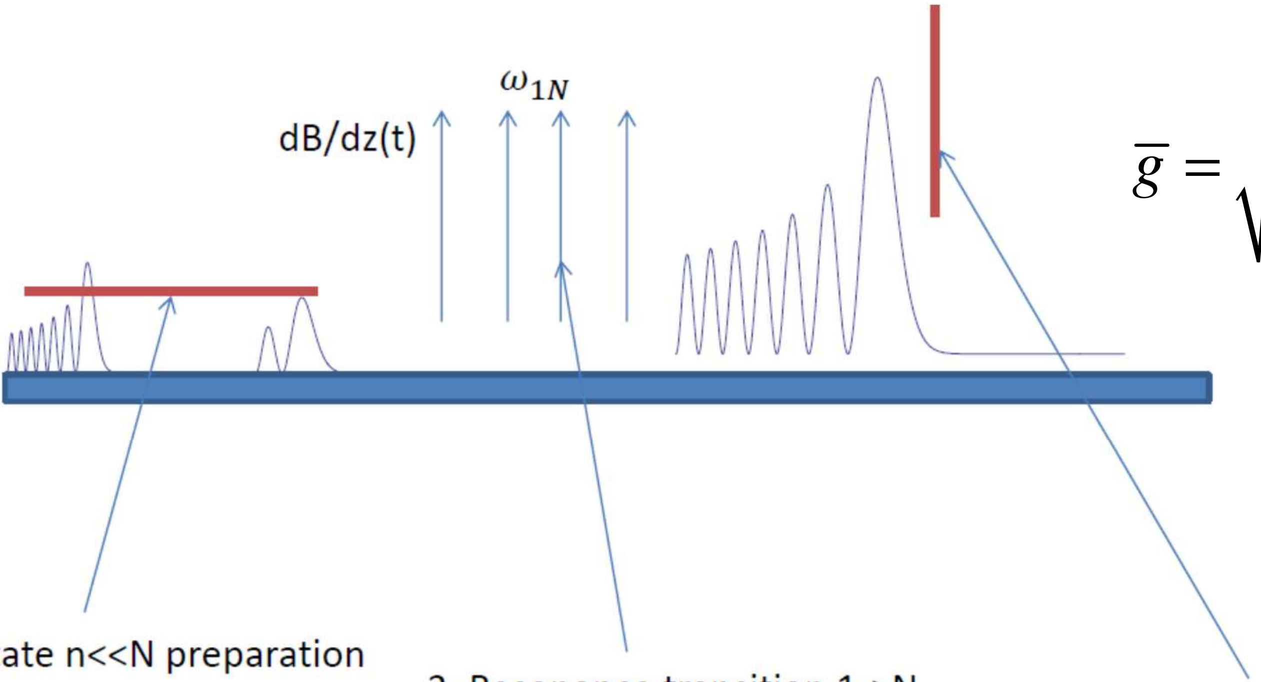
Gravitational quantum states of Antihydrogen
A. Yu. Voronin, P. Froelich, and V. V. Nesvizhevsky,
Phys. Rev. A **83**, 032903 (2011)

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

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

similar method as for UCN neutrons at ILL
(GRANIT spectrometer)

Principle



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

1. State n<<N preparation

2. Resonance transition 1->N

3. Detection of high N state

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
studies on systematics to reach 10^{-6} (?)

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

GBAR status

- ANTION project: matter cross sections measurement
  - ✓ Buffer gas and proton source working
- LINAC installed at CERN, commissioning end of september
- ELENA: H- & p in, beam monitors not yet operational
- $\bar{p}$ decelerator connected to ELENA
- Ps excitation laser (3d) tested
- Tests for $\bar{H}^+$ cooling under way
- Free fall detector:

TOF plane installed & 3 micromegas planes under tests

Many GBAR parts get ready for move to CERN
in the following months

Experiments with $\overline{\mathrm{H}}$

- ALPHA
- GBAR
- **AEGIS**

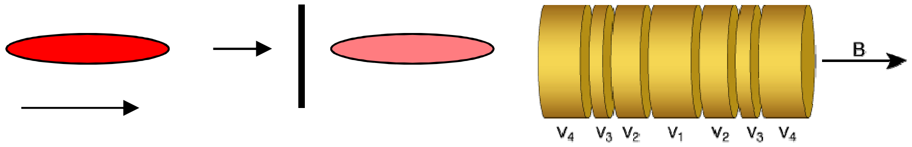
The *AE* $\bar{g}$ *IS* experiment at AD
Antimatter Experiment: Gravity, Interferometry, Spectroscopy

Thanks to Michael Doser and Pierre Lansonneur for the material provided

Primary goal:
measurement of the Earth gravity acceleration on antihydrogen

Precision :
first goal : few % with 10^5 antihydrogen atoms
higher accuracy in the future

AEGIS Method



AD: 5 MeV $\bar{p}$

Hundreds keV after a foil

Catch the low energy fraction of the pbar
Cool inside the trap: 10^{-5} eV (100 mK)

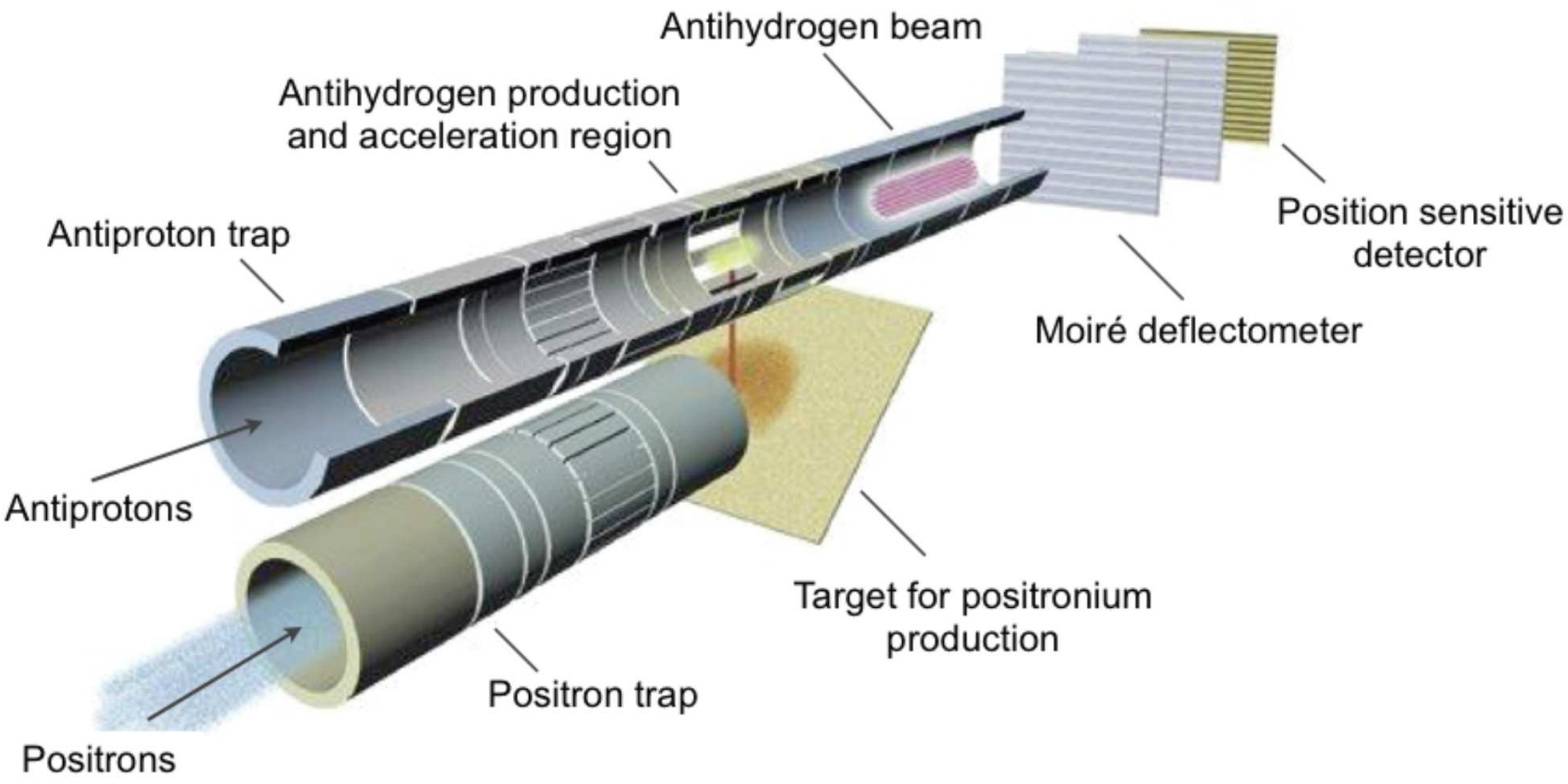
- **Collect 10^4-10^5 extremely cold antiprotons (T~0.1K) in a trap**
- Accumulate a cloud of positrons in a trap: 10^8 (or more) in some minute
- Produce very slow ground state Ps sending the e^+ into a nanoporous target
- Produce Rydberg positronium via laser excitation
- Form cold (100 mK) antihydrogen atoms by the charge exchange process

$$\bar{\mathbf{p}} + (\mathbf{Ps})^* \rightarrow \bar{\mathbf{H}}^* + \mathbf{e}^- \quad (\bar{\mathbf{H}}^* : \textbf{Rydberg state n } \approx \mathbf{30})$$

- accelerate the $\bar{H}^*$ to ~ few 100 m/s using Stark Effect
- get $\bar{g}$ through a measurement of the $\bar{H}$ beam deflection with a Moiré deflectometer

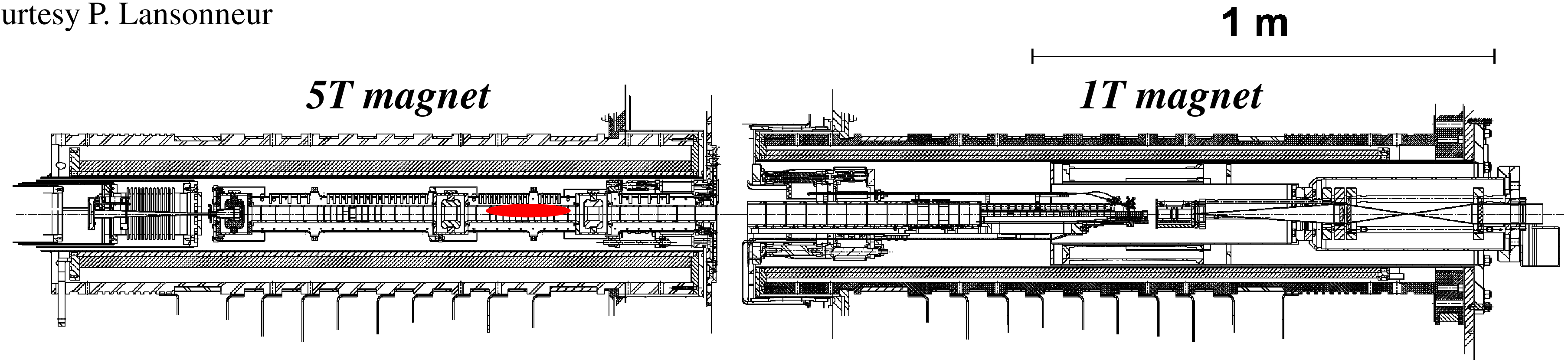
Schematic of the detector

Courtesy P. Lansonneur

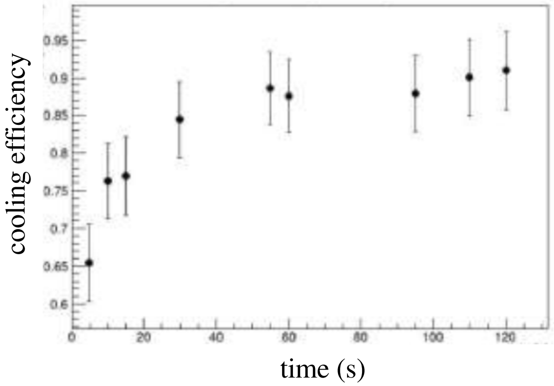


Antiprotons manipulation

Courtesy P. Lansonneur



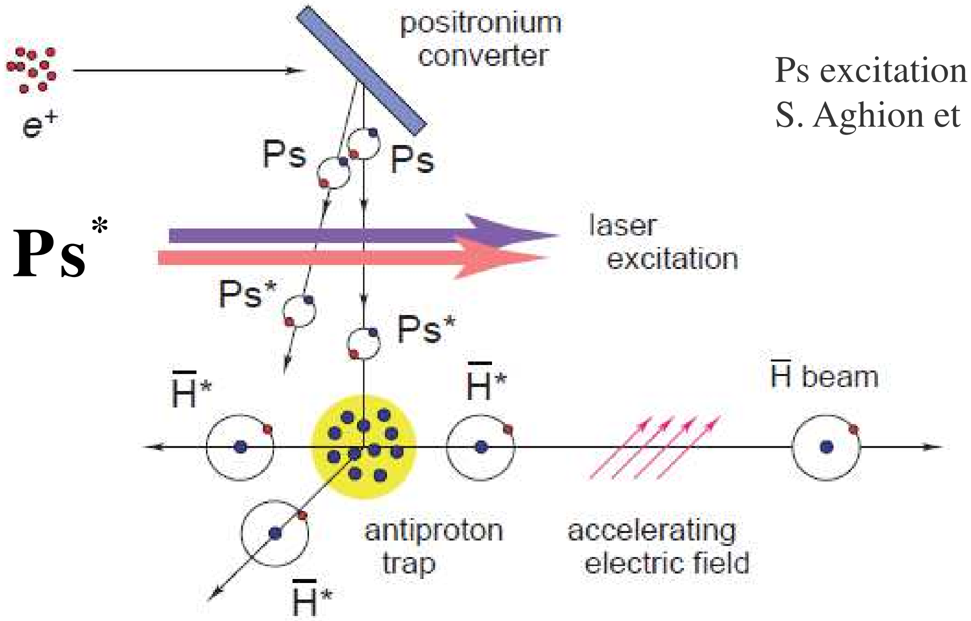
sympathetic cooling of antiprotons
with 10^8 electrons
T~ 1 K



Procedure

1/ electrons loaded into the trap (approx. 10^8)
2/ antiprotons catching
3/ antiprotons sympathetic cooling with electrons
4/ antiprotons compression (« rotating wall »)
5/ ballistic transfer toward 1T region eff. ≥ 90%
~ 3.5 10^5 $\bar{p}$ in prod. trap
6/ antihydrogen production

$\overline{\mathrm{H}}$ formation and acceleration



Ps excitation to n=3 and n=15
S. Aghion et al., PRA 94 (2016) 012507

$$5 \cdot 10^6\ \mathrm{Ps}^*$$

$$10^5\ \overline{\mathrm{p}}$$

$$\overline{\mathrm{H}}^*\ 100\,\mathrm{mK}$$

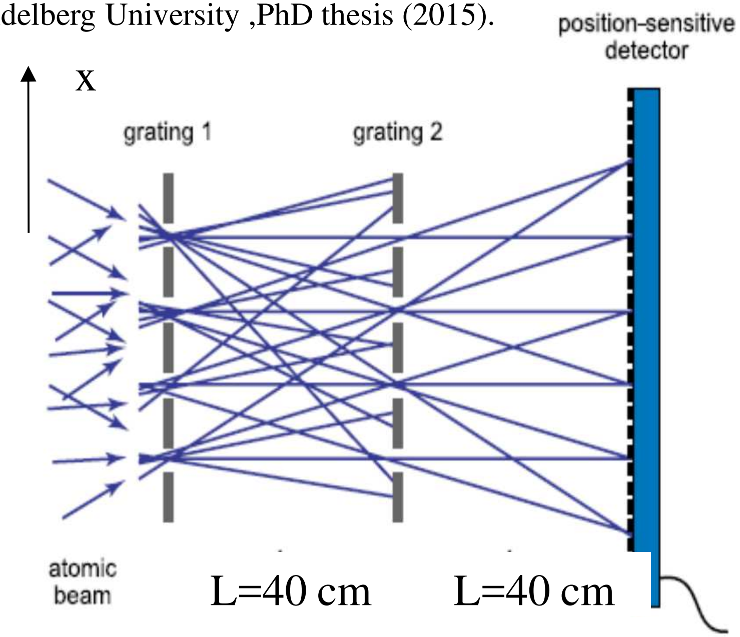
$$\mathrm{v} = 50\,\mathrm{m/s}$$

- •Time to prepare pbar and e^+: few hundreds s
- •Pulsed Antihydrogen production
- •100-1000 antihydrogen/(AEGIS cycle)

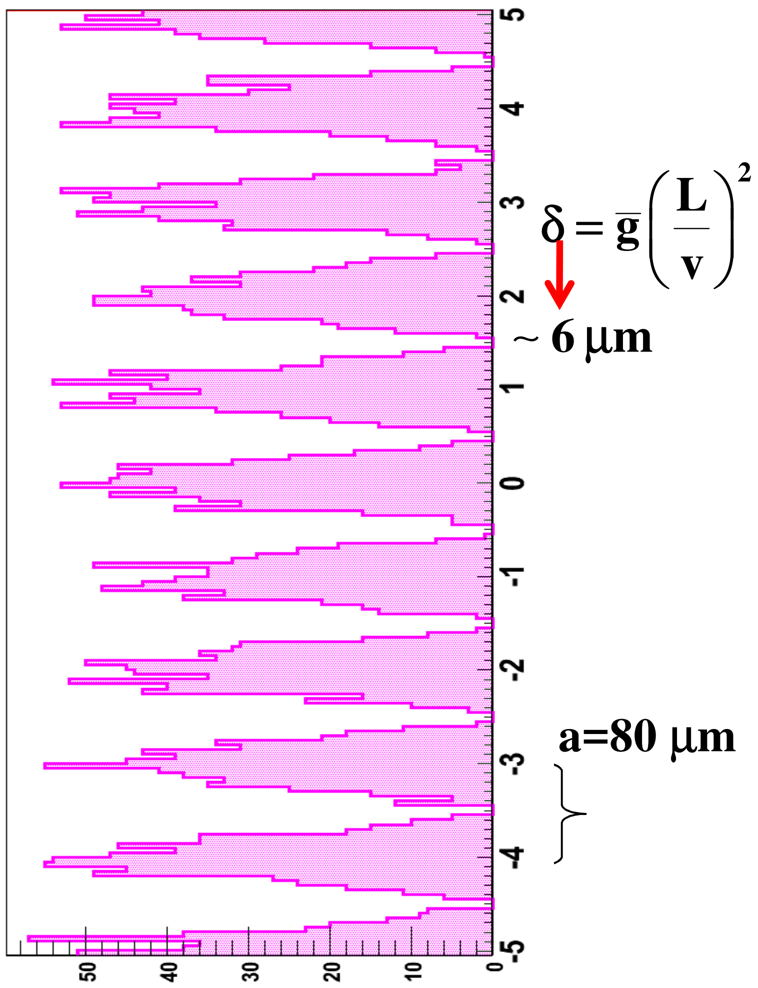
The Moiré deflectometer: principle of operation

P. Braunig, *Atom Optical Tools for Antimatter Experiments*
Heidelberg University ,PhD thesis (2015).

Courtesy P. Lansonneur



Counts vs vertical coordinate



$$\delta = \bar{g}\left(\frac{L}{v}\right)^2$$

$\sim 6\ \mu m$

$a = 80\ \mu m$

- The distribution of the vertical coordinates in the detector position shows a spatial modulation
- Extract $\bar{g}$ from this modulated distribution
- Use a position sensitive antihydrogen detector

$$\mathbf{v_z \sim 500\ m/s\ ;\ v_T \sim 50\ m/s \Leftrightarrow T \approx 100\ mK}$$

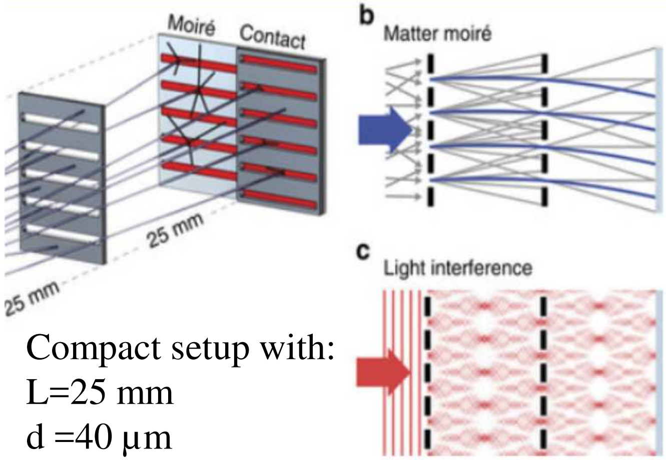
$$\mathbf{\delta\bar{g} / \bar{g} \simeq 1\% \Rightarrow \sim 10^5\ \bar{H}\ detected\ atoms}$$

~ 2 weeks with ~ 1 useful $\bar{H}$/s

The Moiré deflectometer: proof of principle

Nature Communications 5 (2014) 4538

moiré deflectometer to measure deflection by minute forces

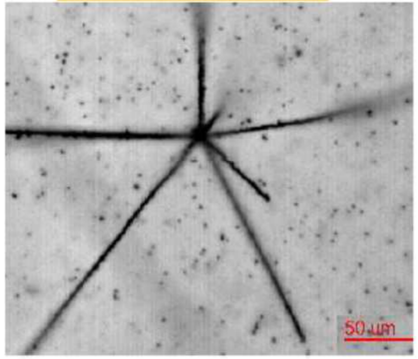


Compact setup with:
L=25 mm
d =40 µm
w = 12 µm

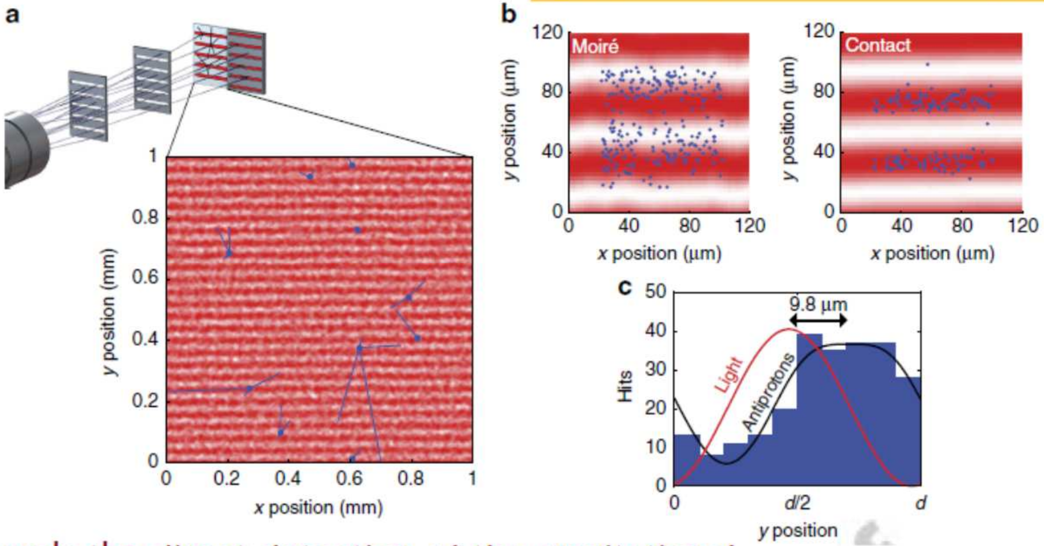
Visibility of 71%; mean force of ~500 aN

Compatible with a Lorentz force from 1 mT or 30 V/cm

J Instr. 9 (2014) C01061



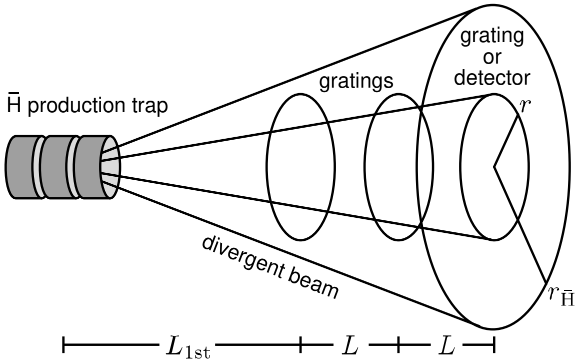
Aghion, S. et al., Nat. Commun. 5:4538 (2014).



Crucial step towards the direct detection of the gravitational acceleration of antihydrogen with the AEgIS experiment $\Delta z = g\tau^2$

Measurement precision

- Shot noise limit:



d – grating period
η – grating open fraction
V – visibility
τ – time of flight
r – radius
$L_{1\mathrm{st}}$ – distance to first grating
L – distance between gratings
N_{det} – no. of detected atoms
N_{prod} – no. of produced atoms

$$a_{\min} = \frac{d}{2\pi V \tau^2 \sqrt{N_{\mathrm{det}}}} = \underbrace{\frac{\enclose{circle}{d}}{2\pi V \eta r}}_{\text{gratings}} \times \underbrace{\frac{2(L_{1\mathrm{st}} + 2L)}{\enclose{circle}{L^2}}}_{\text{geometry}} \times \underbrace{\frac{\enclose{circle}{2kT}}{m} \frac{1}{\sqrt{N_{\mathrm{prod}}}}}_{\text{source}}$$

⇒ small grating period
large distance
low temperature

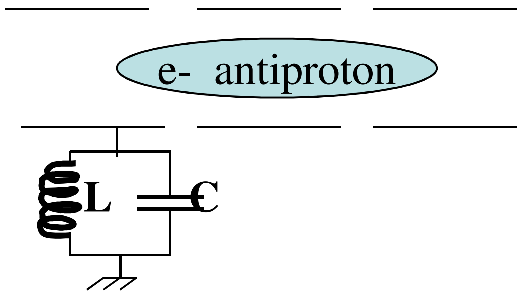
Toward ultracold (100 mK) antiprotons

Antiprotons in trap cannot be directly cooled to 100 mK

Cool antiprotons by collisions with a partner particle stored in the same trap (sympathetic cooling) that can be cooled

electrons

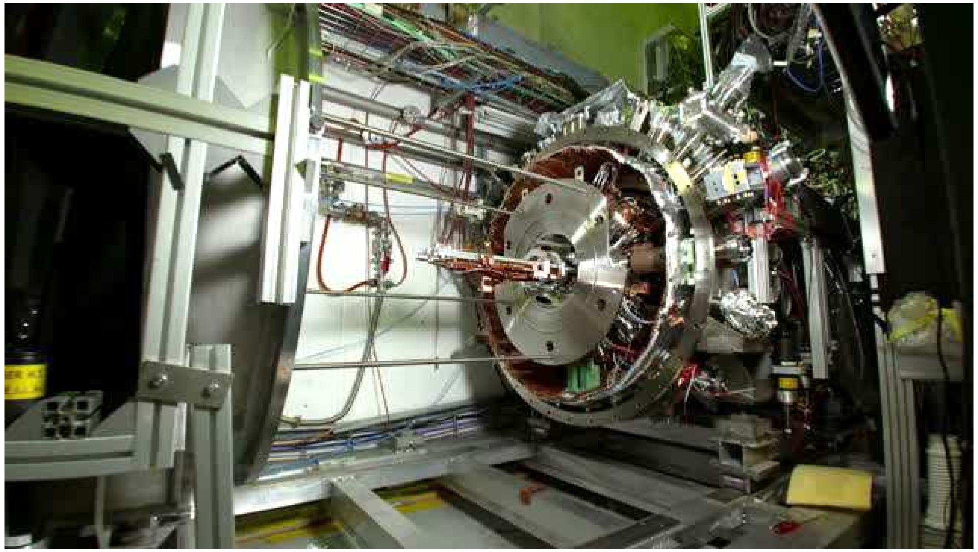
Resistive cooling with a resonant tuned circuit + radiation cooling



Negative ions needed
(atomic or molecular)

Study in progress

AEGIS status



Last runs:

→ Na22 source 10^8 e^+ per 300 s
→ Ps formation in the production region

→ o-Ps excitation to n = 3
(outside from the main apparatus)

→ 10^5 antiprotons in the production trap
→ Compression at 4,5 T to r = 260 µm

→ Tests of detectors for anti-hydrogen

Outlook for 2017/2018: anti-hydrogen production by charge exchange

2019 → 2021: long LHC shutdown (no antiproton beam)

- Objective

- Motivation
  - ✓ Theory
  - ✓ Experiment

- **Conclusion**

Conclusion: Theory

- “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)*

- However **expected effects are quite small**

- A 1 % experiment is a “textbook experiment” **and should be a first step towards higher precision**

Conclusion: $\overline{\mathrm{H}}$ Experiments

- **ALPHA:**
  - **has put first direct limits on $\bar{g}$**
  - **has a project to do a first ~ 100% measurement with a vertical detector and then 1 %**
  - **has a long term project for a precise measurement with interferometry**
- **AEGIS has crossed important steps towards a ~ 10 % measurement**
- **GBAR has started installation at CERN and aims at measuring $\bar{g}$ to $10^{-2} \rightarrow 10^{-4} - 10^{-6}$ (?) precision**

All these experiments are very challenging !