GBAR and Antimatter Gravity measurement

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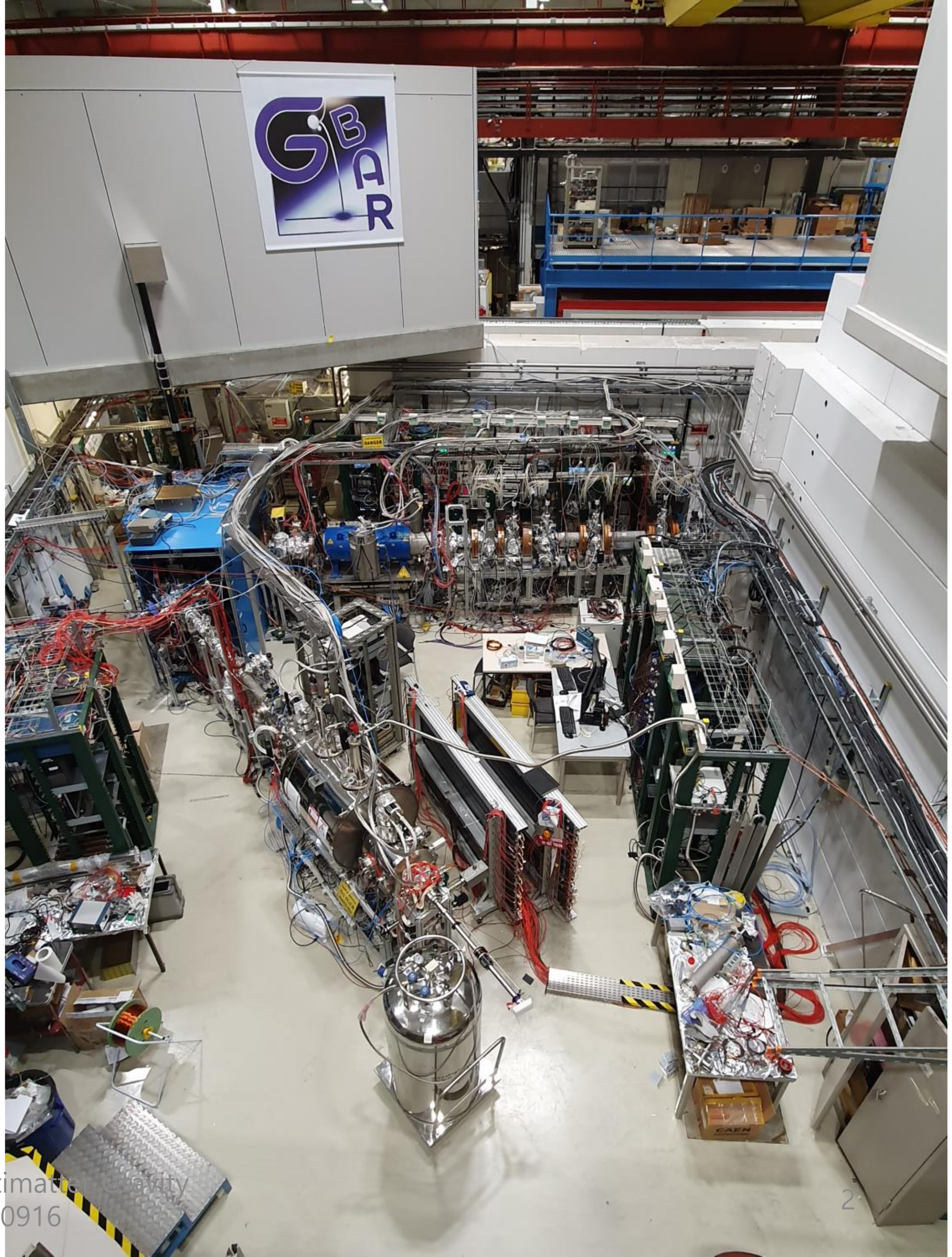


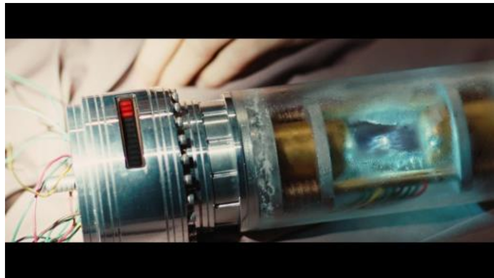
Original image via Husky Press

Antimatter

- Just after the discovery of electron by J. J. Thomson, there was questions why there's no negative gold although there's negative electricity (1898)..
- After prediction by Dirac equation in 1927, antiparticles as a pair of particle had detected (positron 1932, antiproton 1955…)
- The question of anti-gravity raised at 1950s and have continuing interests about antimatter's gravity..
- For a period of 100 years, the tested properties and interactions of antimatter are agreed with the standard model which based on CPT symmetry.
- But the universe near neighborhood is totally matter dominant without any trace or remnant of antimatter and shows no proof of symmetry..

: We are not worried about antimatter comet for example..

- With hardness of production and cooling of antimatter, there can be unknown properties of antiparticles.
- This mysterious status attracts much attention from the public. (with huge applications and fictions)



Antimatter gravity

- Arguments about antigravity were started about 1960

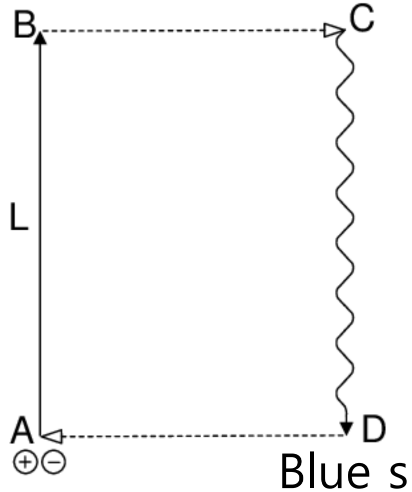
- P. Morrison (1958) : violation of energy conservation

← not only tensor but with scalar and vector (component of repulsive gravity) may required..

- other arguments by L.I. Schiff(1959), M.L. Good(1961) (M. M. Nieto and T. Goldman, Physics Reports, Volume 205, Issue 5, p. 221-281)

- Villata "General relativity and CPT are compatible only with repulsive gravity" M. Villata, *EPL* **94**, 20001 (2011).

$\Delta E = 0$



Blue shift

- Above arguments are mainly about antigravity..

Motivation : Cosmological mysteries

★Our understanding is very incomplete and limited..

- Matter and antimatter asymmetry

- Matter domain in observable Hubble volume : $n_B \gg n_{\bar{B}}$

- The standard model predicts equal amount of matter and antimatter in the universe after Bigbang..

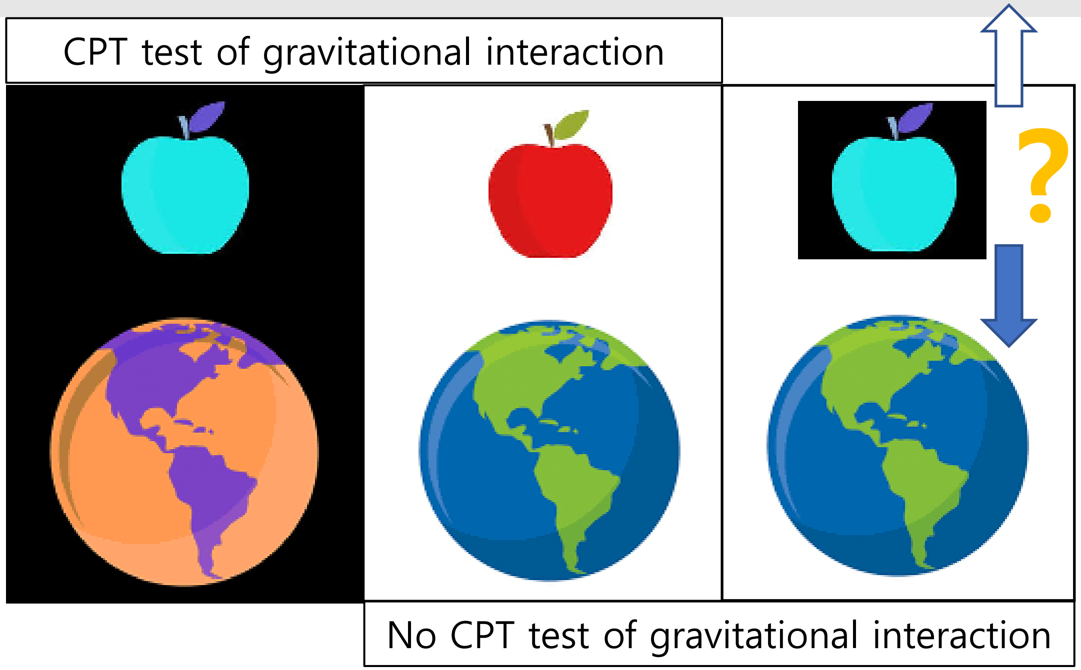
- Unknown nature for most energy contents of universe

- Dark energy : 69.4%, Dark matter : 26.1%, Ordinary matter : 4.5%...
- Hard to link dark energy to particle physics, no measurement of dark matter..

- Some attempts to make a cosmological model to explain the asymmetry and to keep them apart by gravitational repulsion..

A. Benoit-Levy and G.Chardin, A&A 537, A78(2012), M.Villata, Astrophys. Space Sci. 339, 7 (2012), D. S. Hajdukovic, Int. J. Theor. Phys. 49, 1023 (2010)) can give new sight related to Dark energy and Dark matter..

Test of Weak Equivalence Principle



- $m_I = m_G \ (F = m_I a = -G m_G m'_G / r^2)$,
- $m_I = \overline{m_I} \ (by\ CPT)$
- $m_G = m_I = \overline{m_I} =? \ \overline{m_G}$

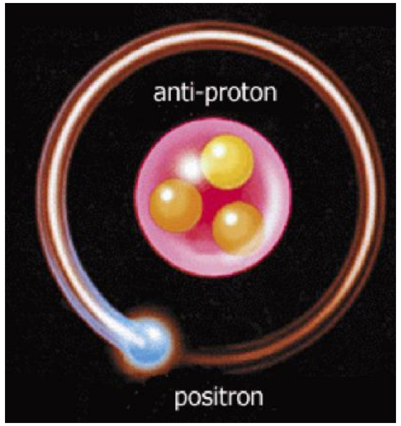
- Weak Equivalence Principle :

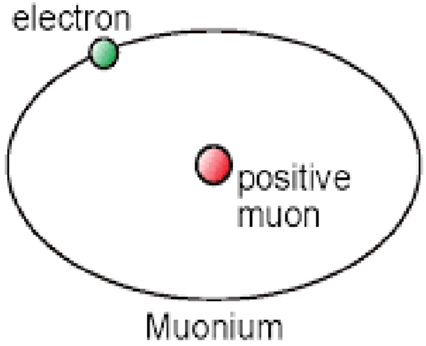
"The trajectory of a point mass in a gravitational field depends only on its initial position and velocity, and is independent of its composition and structure"

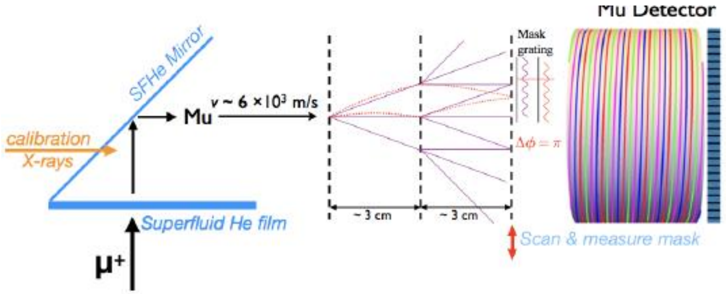
: The gravitational acceleration is not distinguishable with other acceleration locally <m_g=m_i>equivalence between the inertial mass and the gravitational mass

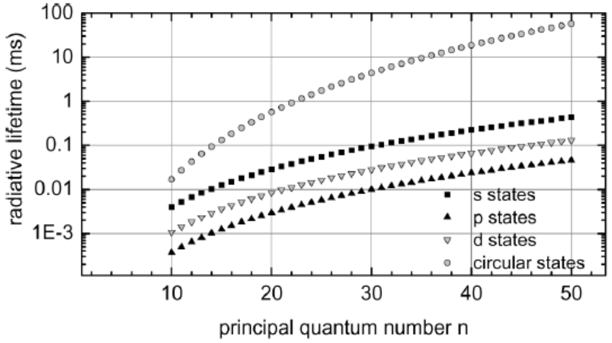
- Test between matter and earth has upper limit $\Delta(m_g/m_i)/(m_g/m_i)_{Be/Ti}$ = $(0.3\pm1.8)e^{-13}$ (Eötvös)
- Previous attempts (positron, antiproton..) are failed because of relatively small interaction compared with effects by electric charge (patch effect, gas charges..)

Test of WEP by neutral exotic atom







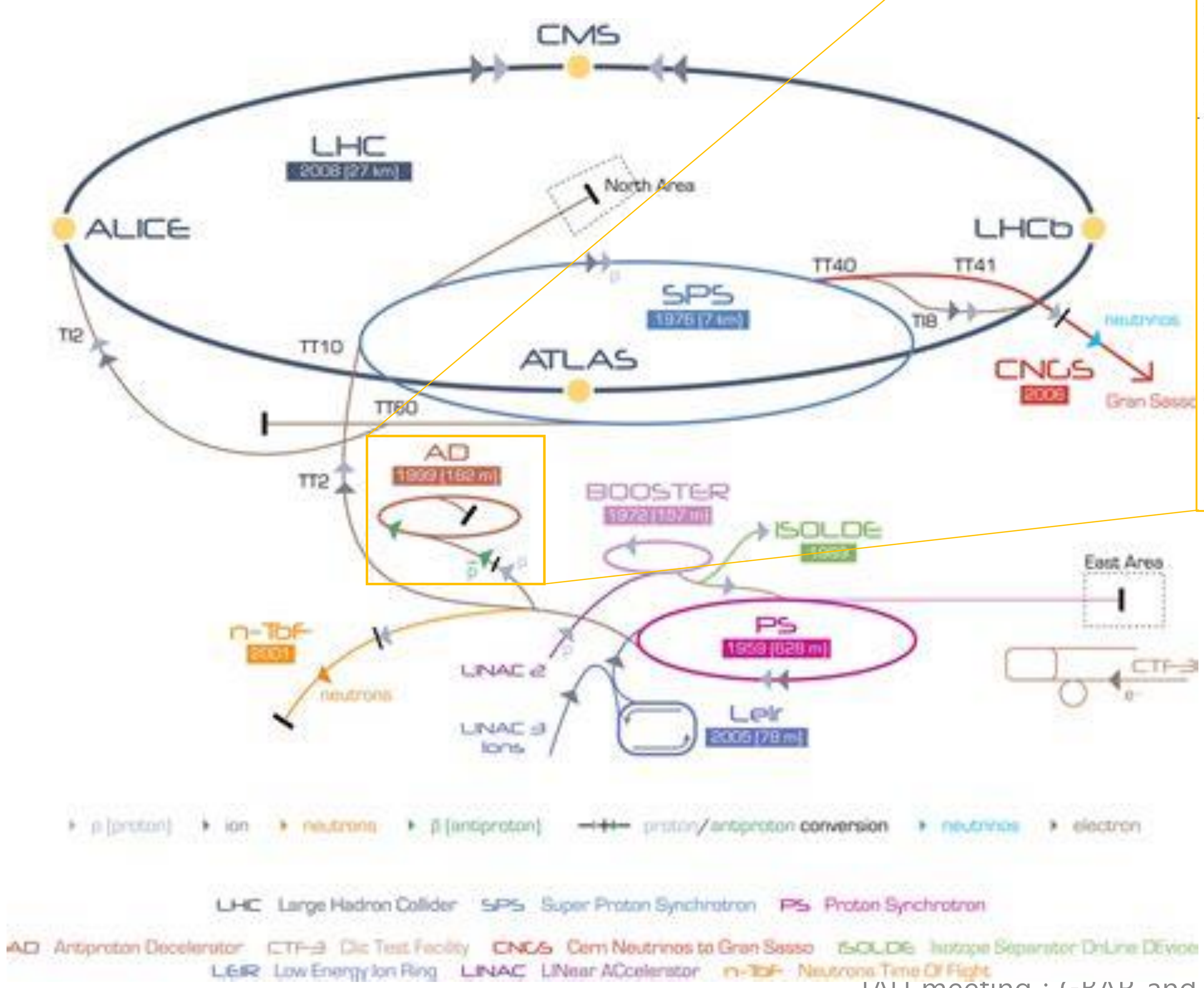


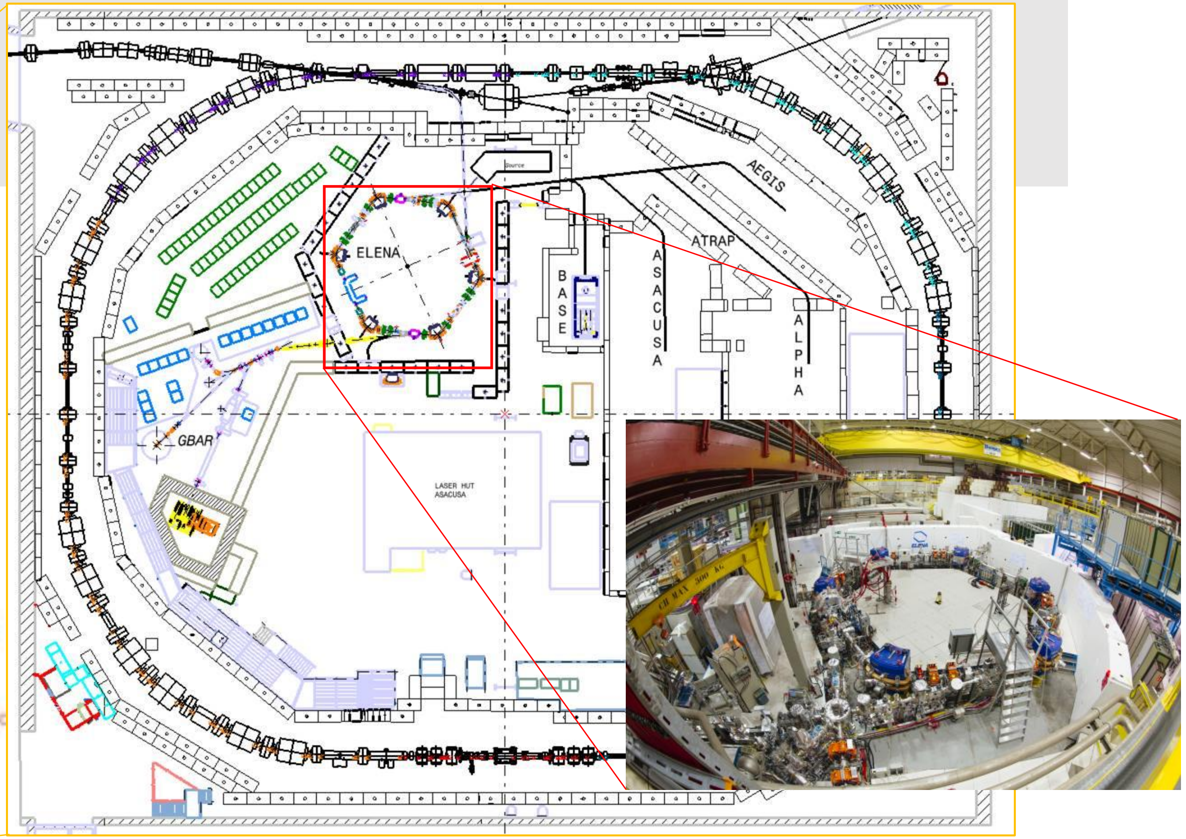
- Neutral exotic atom-based experiment has been prepared : Positronium (e^+e^-), Muonium(μ^+e^-) and Antihydrogen($\bar{H}$).

- Three constructing experiments using $\bar{H}$ will be compared.

- Conceptual design of gravity measurement by muonium atom at Mage collaboration(muonium beam by superfluid He film to get monochromatic direction (1% precision goal) T. J. Philips, *EPJ Web of Conferences* **181**, 01017 (2018)
- Positronium atom with long-lived Rydberg states (D. B. Cassidy and S. D. Hogan, *Int. J. Mod. Phys.*: *Conf. Ser.* **30**, 1460259 (2014))

AD & ELENA





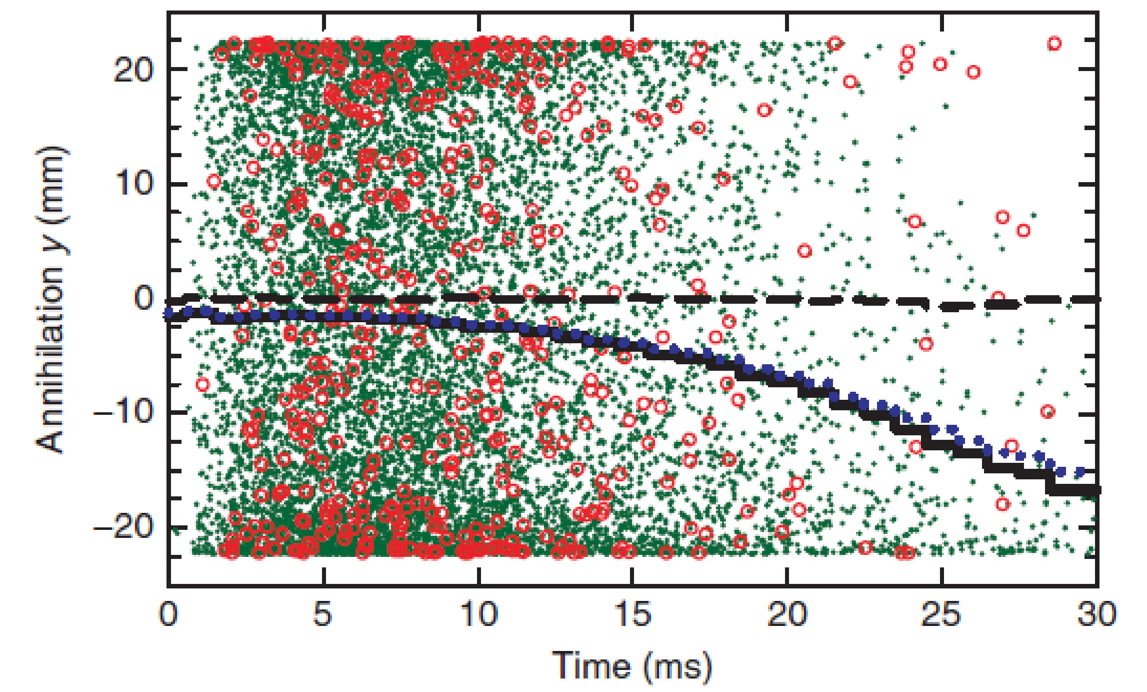
- Unique facility : low energy antiproton beam provider

- 26 GeV/c proton + Iridium target → 3.5GeV/c antiproton.
- 5.3MeV (100MeV/c) antiproton beam $2x10^7$#/120s

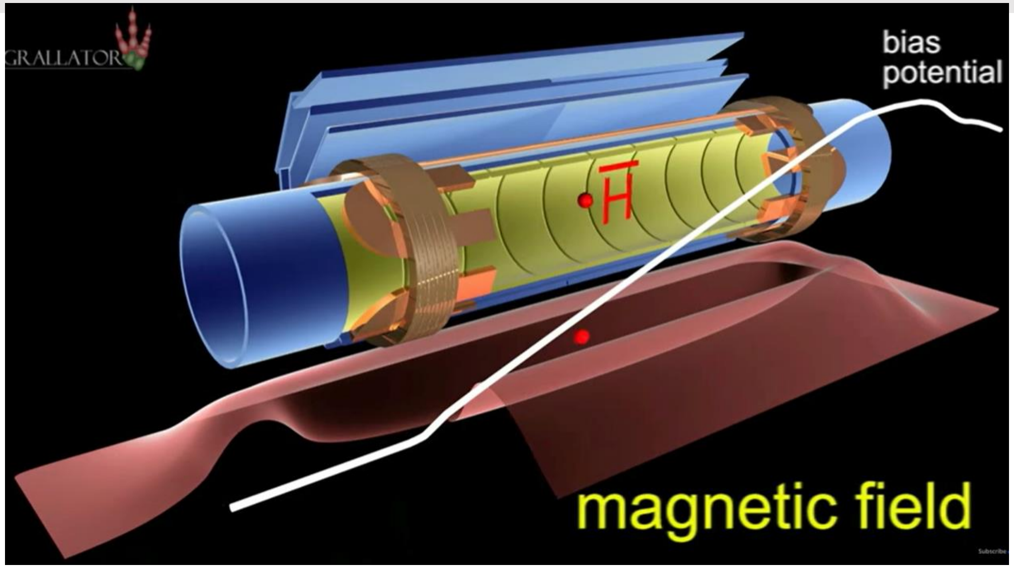
- ELENA : 100keV antiproton beam (σ<100ns, $0.5x10^7$#/120s : ¼ bunches) (commissioning during last beam time with GBAR experiment)

Previous measurement of antimatter gravity

Nature communications, 4, 1785 (2013)



Red circle : real data (434 annihilation points)
Green point : simulation
Black solid line : averaged simulation (F=100)
Blue dotted line : averaged simulation with detector smearing (F=100)
Black dashed line : averaged simulation (F=1)



- Only one anti-hydrogen experiment was done - ALPHA experiment

: -65 < F (= m_g/m_i) < 110 (95% significance level)

- The apparatus is not for gravity measurement : no control for vertical direction.

: Too high temperature (0.5K at 0ms), vertical trapping is not optimized

- Need to cool down & make better magnetic field

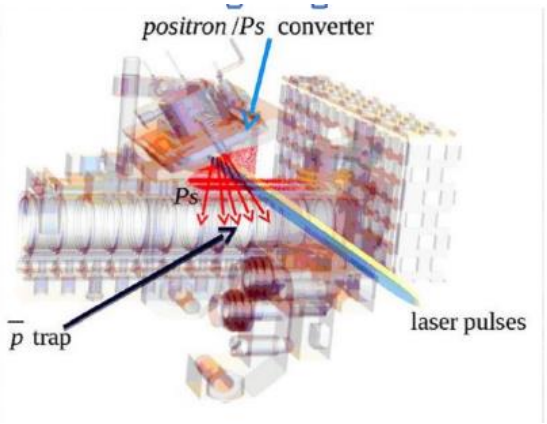
Gravity test approaches

AEGIS

- Antihydrogen production :
cold antiproton + excited o-Ps

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

- The antihydrogen production cross section is proportional to n_{ps}^{4} (=quantum number).
- The Rydberg Ps has longer lifetime than o-Ps (τ=142ns)



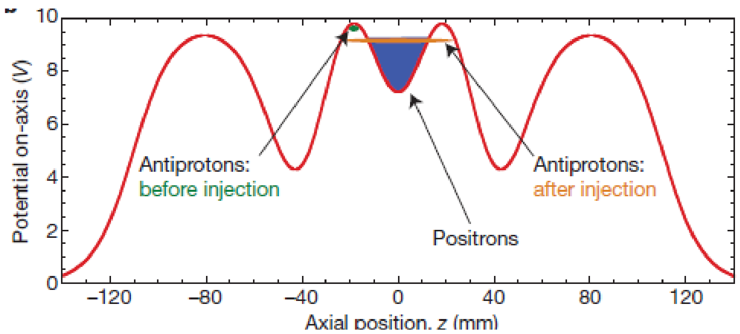
ALPHA-g

- Antihydrogen production :
cold antiproton + positron

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

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

- Nested-well potential for mixing.
- Antihydrogen production &trapping(ΔE = -μ • B) by octupole field in same trap



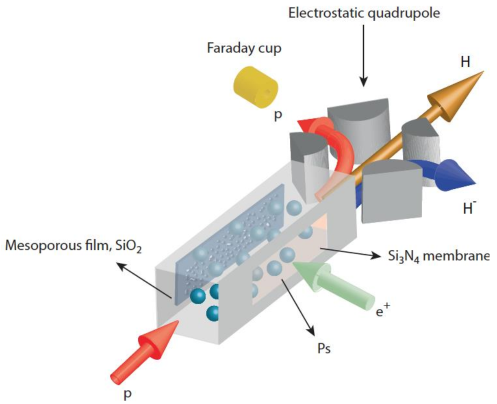
GBAR

- Antihydrogen ion production :
antiproton + positronium x 2

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

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

- The antihydrogen ion production cross section is proportional to ρ_{ps}^{2}.
- Produce dense o-Ps cloud by cavity shaped positronium target.



Gravity test approaches

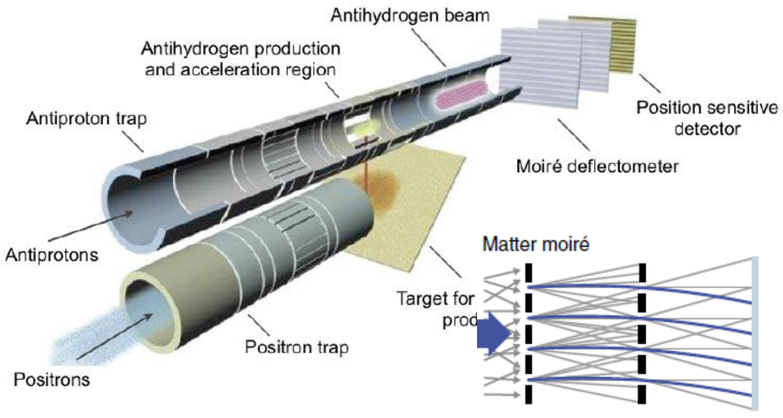
AEGIS

- Pulsed Antihydrogen beam (2021)
- Moire deflectometer tested by $\bar{p}$. (nature communications 5, 4538 (2014)

→ Pattern will be compared with one from light

- Aim : ~100mK (v~40m/s)

\- 1% precision with 1000# $\bar{H}$.

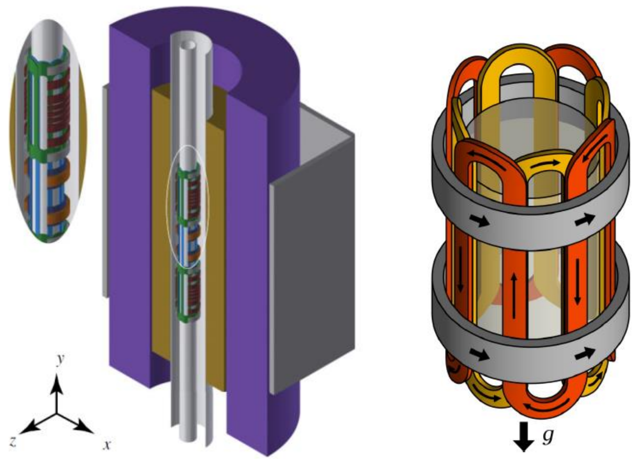


ALPHA-g

- Antihydrogen trapping (0.5K)

\+ Vertical trap (280mm long)

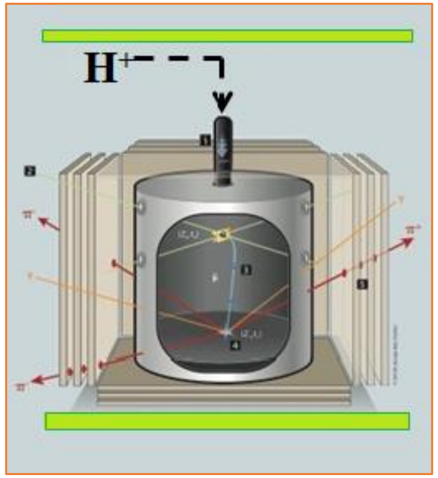
- Aim (1%) : sub-50mK (v~28m/s) temperature by extra cooling by laser & precise measurement of magnetic field



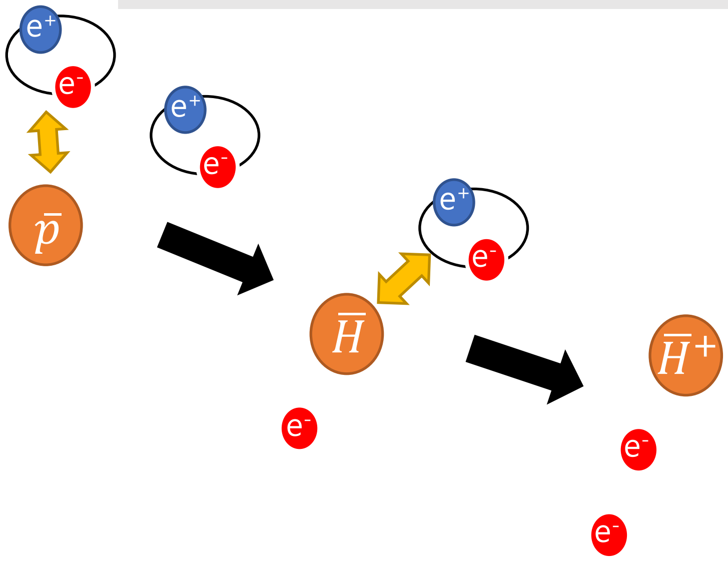
GBAR

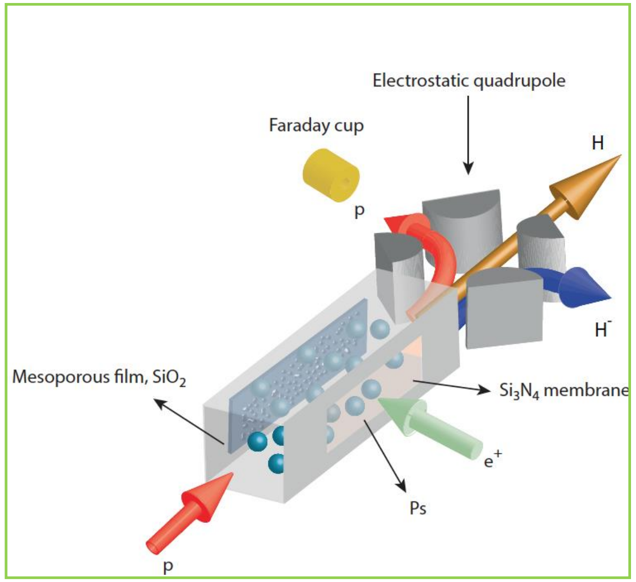
- Antihydrogen ion production
- Trapping and cooling antihydrogen ion.
- Classical Freefall test (z=0.25m)
- Aim : 10uK (v~0.4m/s)

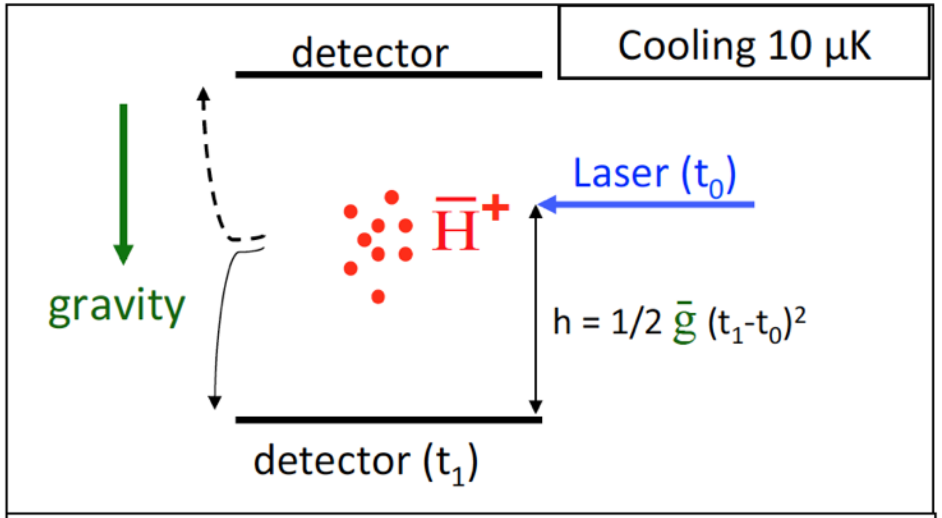
\- 1% precision with 1500# $\bar{H}$.



GBAR experiment approach







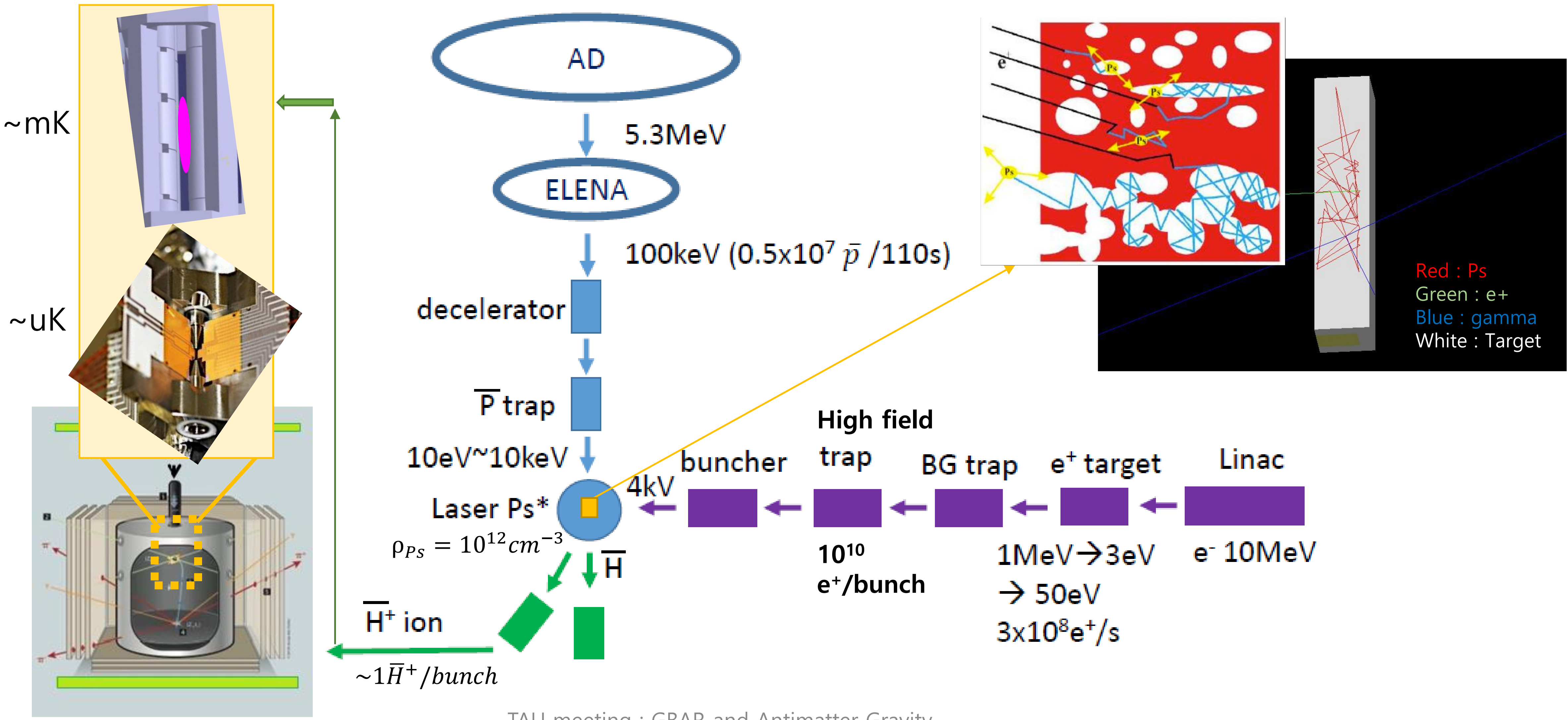
J.Walz & T. Hänsch,
General Relativity and Gravitation, **36** (2004) 561.

- GBAR (Gravitational Behaviour of Antihydrogen at Rest) experiment aims a direct measurement of the gravitational acceleration of antihydrogen at terrestrial gravitational field by a classical freefall test.
- Antihydrogen ion production is required to get ultra-cold antihydrogen.
- Double charge exchange process between antiproton beam and dense positronium cloud

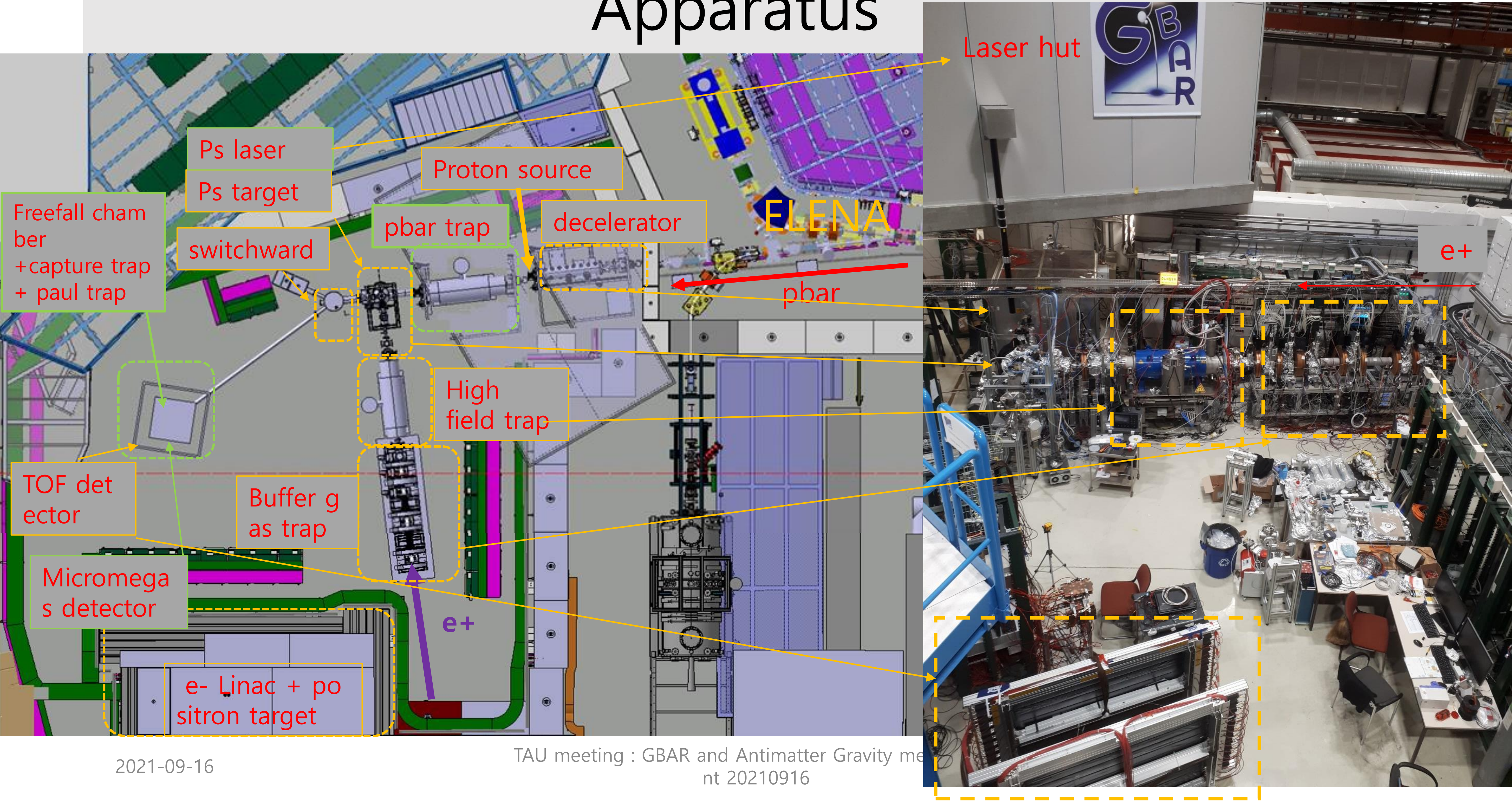
$$\bar{p} + Ps \rightarrow \bar{H} + e^-$$
$$\bar{H} + Ps \rightarrow \bar{H}^+ + e^-$$

- Cooling antihydrogen ion down to 10uK range (ultra-cold) with Be^+ to get extremely slow velocity.
- After dropping (by photo-detachment laser) one positron, let the ultra-cold antihydrogen freefall.

Experiment Scheme

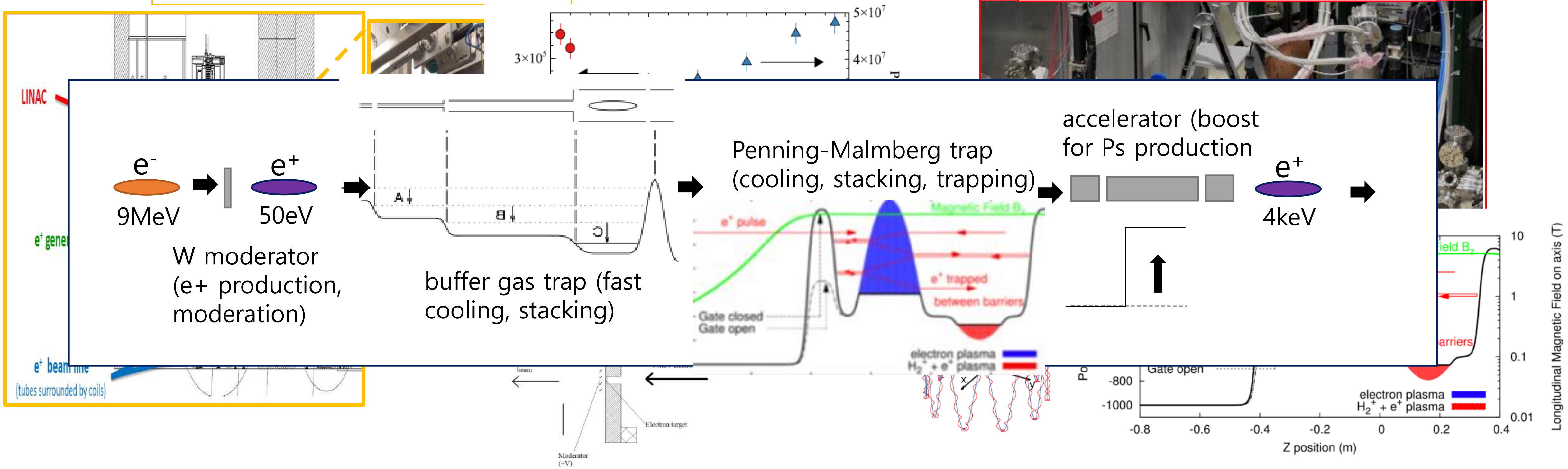


Apparatus

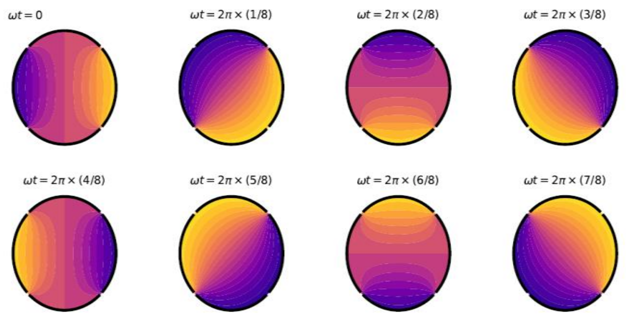


Laser hut
Ps laser
Ps target
Proton source
Freefall cham ber +capture trap + paul trap
pbar trap
decelerator
ELENA
switchward
e+
pbar
High field trap
TOF det ector
Buffer g as trap
Micromega s detector
e+
e- Linac + po sitron target

Positron beam for Ps production

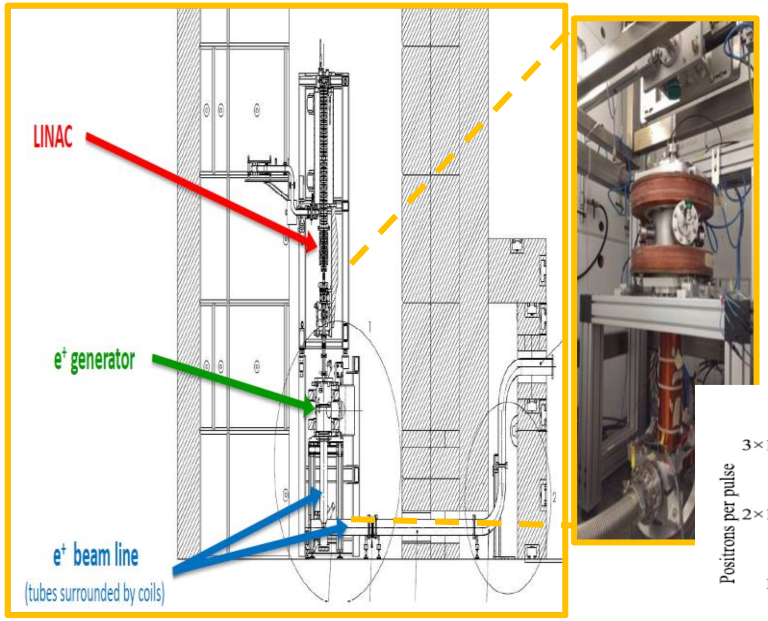


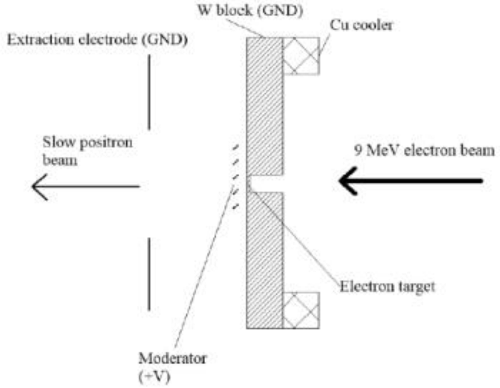
- Positron beam : (Near monoenergetic low energy by W moderator) positron beam generated from bremsstrahlung-induce pair production by 300Hz 9MeV e- linac with a goal to 3 x $10^8 e^+/s$ ←To achieve above radioactive sources ($<10^7$ e^+/s)
- Buffer-gas trap for positron accumulation with small energy spread
- Positron accumulation by high field trap : goal to $1x10^{10}$ e^+ (110s) with electron cooling
- Positron acceleration &bunching by electrostatic lenses with resistor chain

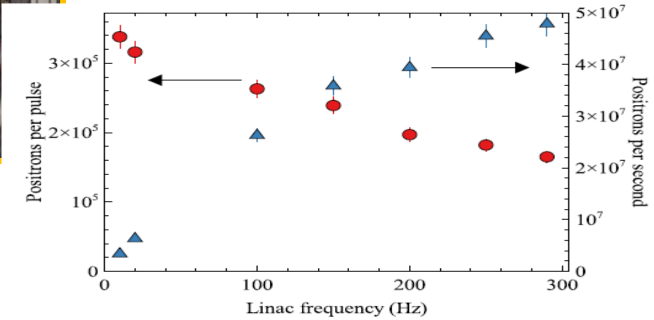


Positron beam for Ps production

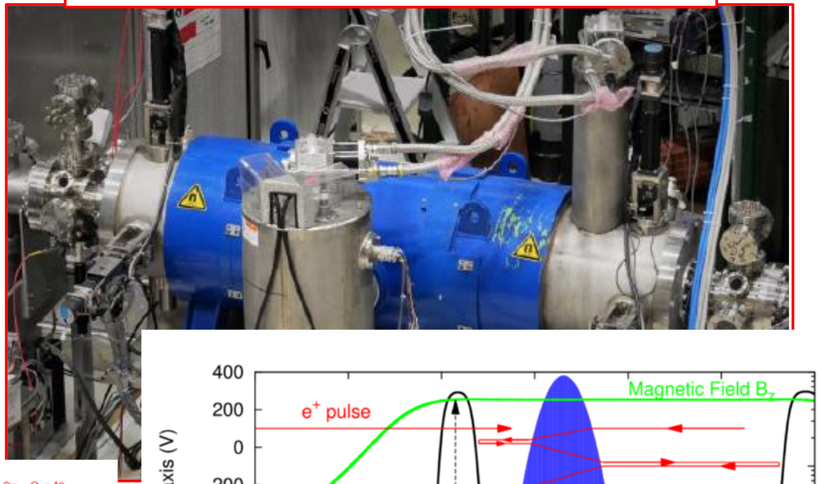
Linac and positron target

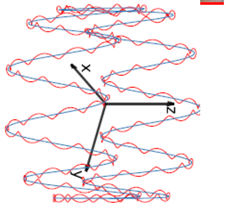


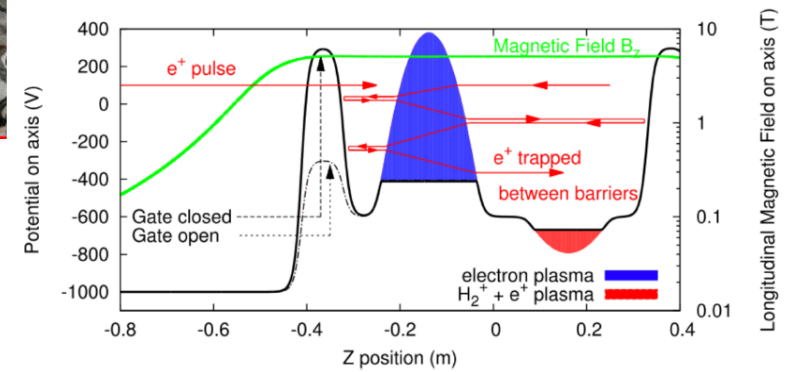




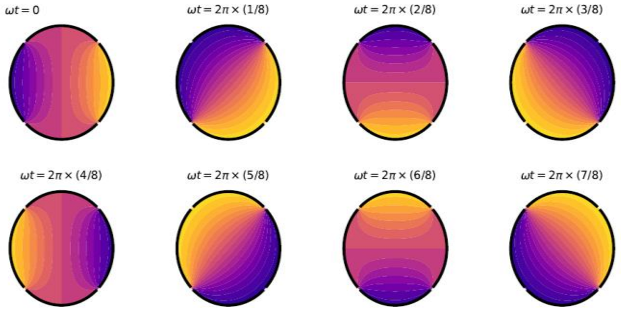
Positron high field trap



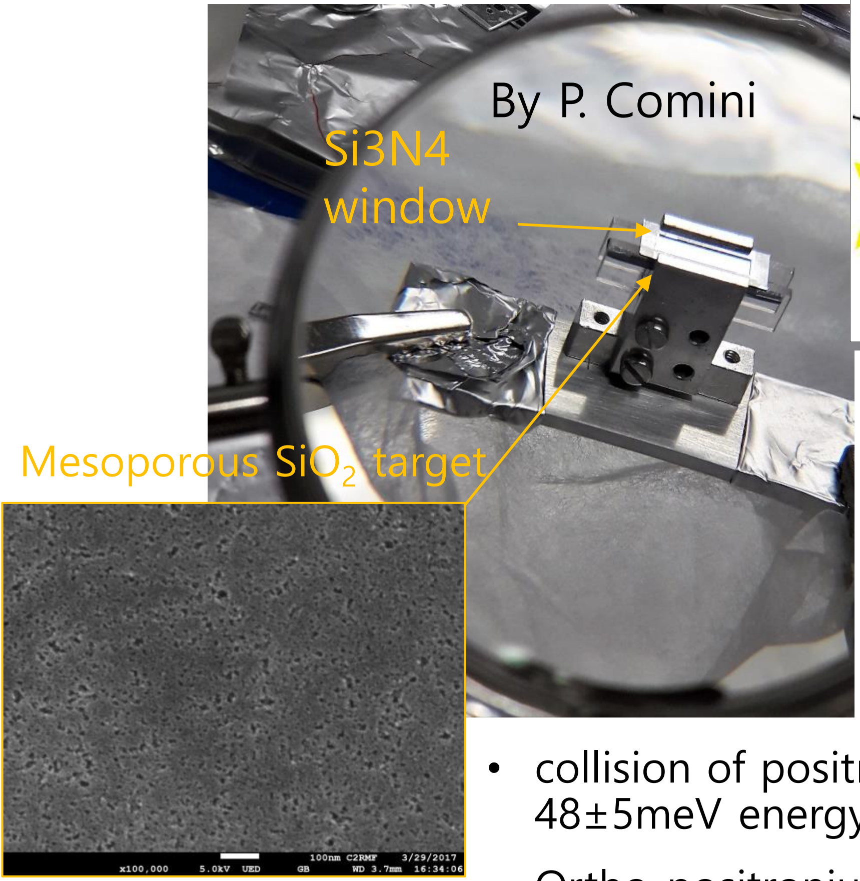


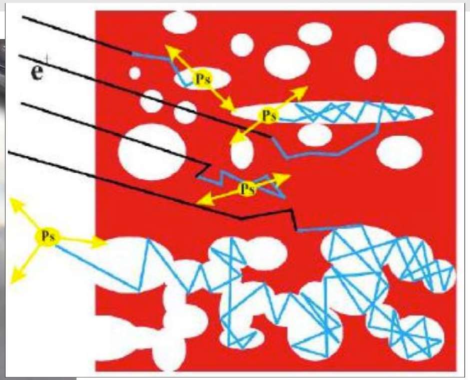


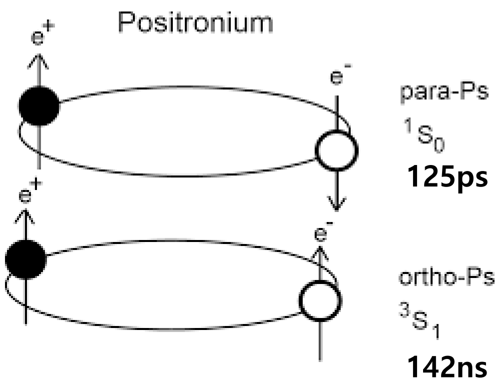
- Positron beam : (Near monoenergetic low energy by W moderator) positron beam generated from bremsstrahlung-induce pair production by 300Hz 9MeV e- linac with a goal to 3 x 10^8e⁺/s ←To achieve above radioactive sources (<10^7 e⁺/s) M. Charlton et al., Nuclear Inst. and Methods in Physics Research, A 985 (2021) 164657 **A** (2020)
- Buffer-gas trap for positron accumulation with small energy spread & fast cooling
- Positron accumulation by high field trap : goal to 1x10^{10} e⁺ (110s) with electron cooling & compression by rotating wall (detail is in thesis S. Niang, Paris Saclay-University, France (2020))
- Positron acceleration &bunching by electrostatic lenses with resistor chain

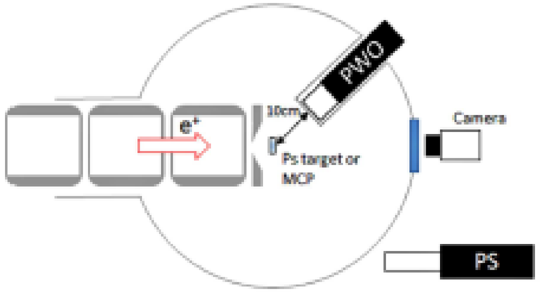


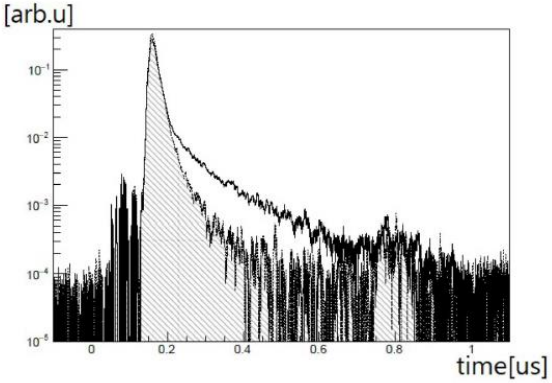
o-Ps production for antihydrogen production

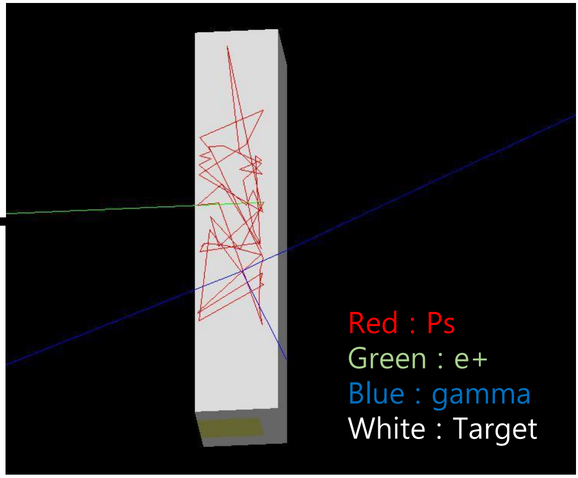






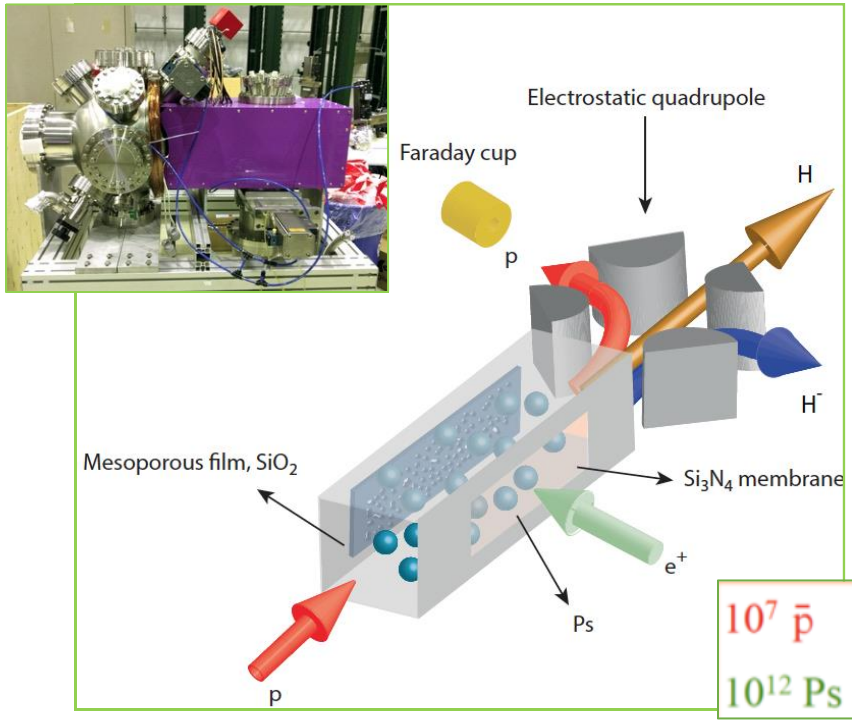


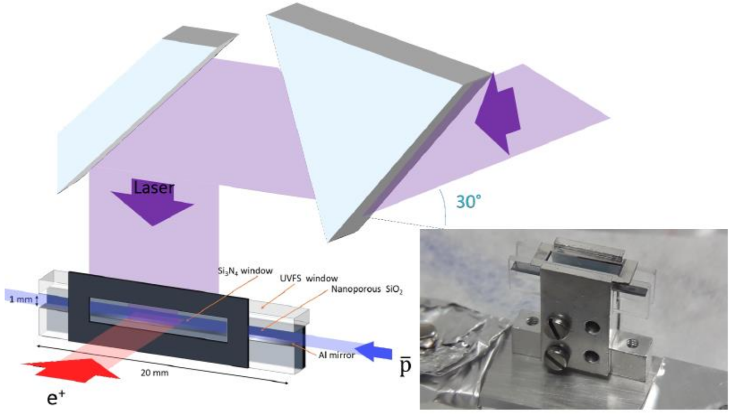




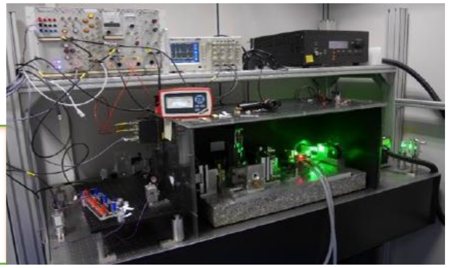
- collision of positron to mesoporous silica target SiO_2 generates positronium(30% o-Ps production rate, 48±5meV energy (PRA81, 052703))
- Ortho-positronium with 142 ns lifetime can be used for interaction with p-bar beam
- Positronium target with cavity shape ($1x1x10mm^3$) is prepared to make high density ($10^{12}cm^{-3}$ density required) positronium cloud.
- SSPALS based on $PbWO_4$ crystal detector for pulse beam detection

Antihydrogen production

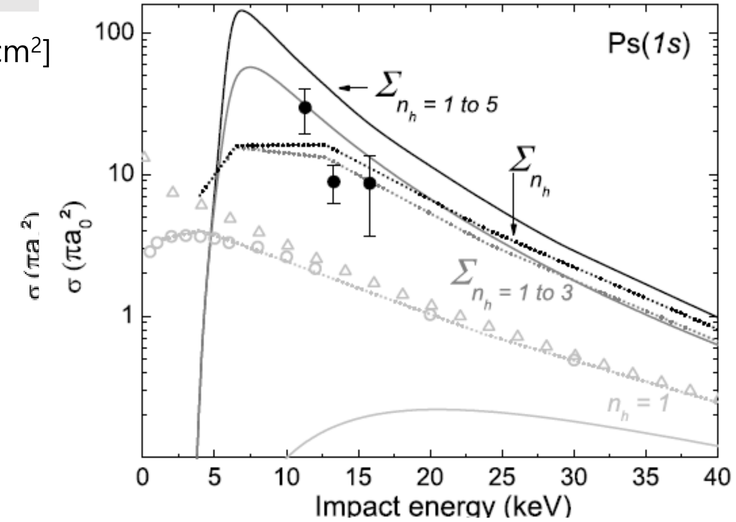


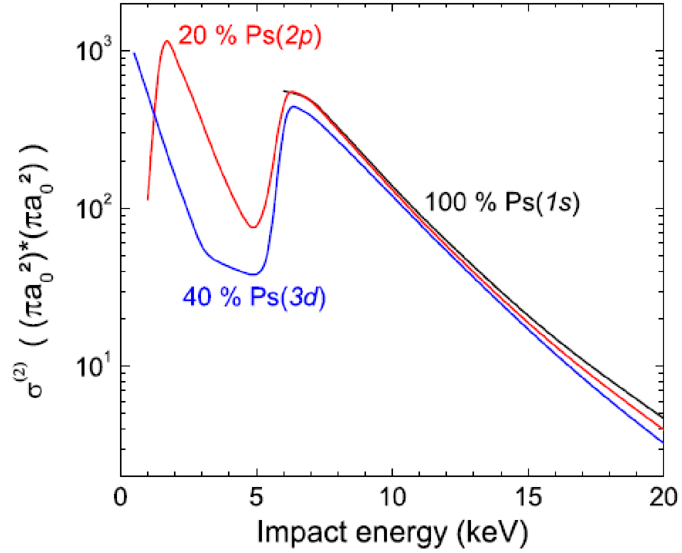


$10^7\ \bar{p}$, 10^{12} Ps at/cm² } → $10^4\ \bar{H}$, $1\ \bar{H}^+$



[$10^{-16}cm^2$]

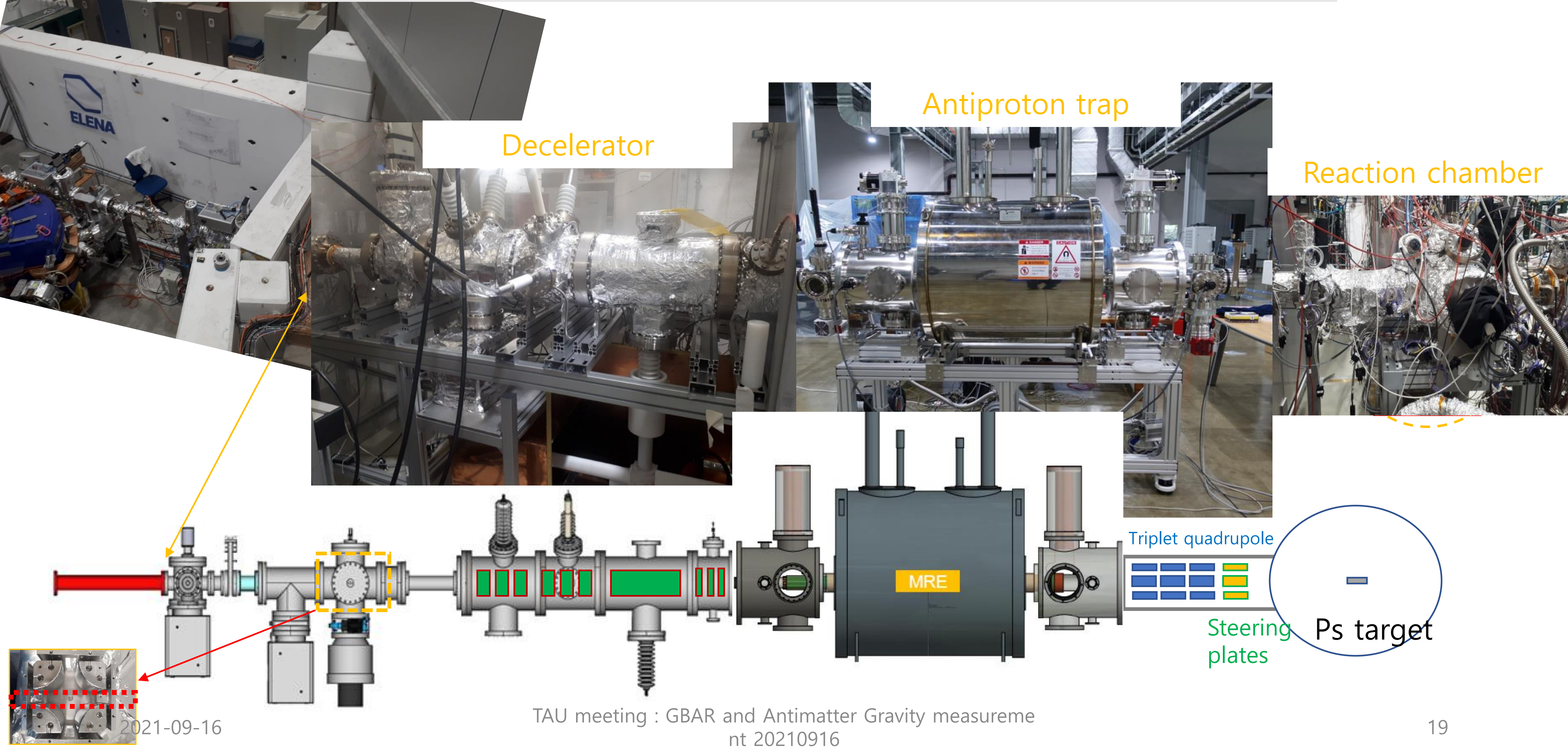




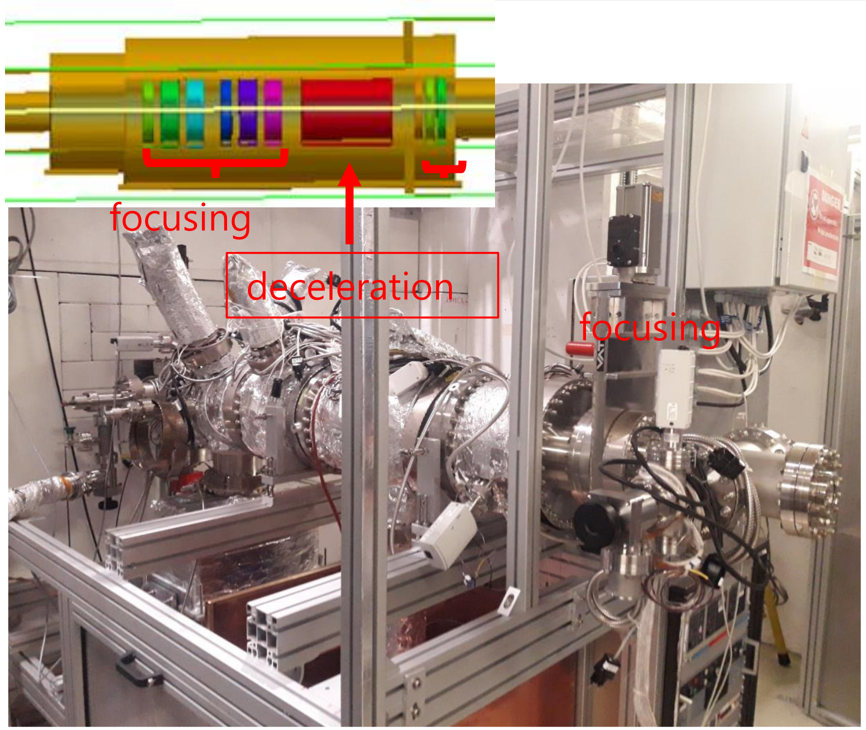
- $\bar{H}^+$ production can be maximized with Ps(2p, 3d or 1s)
- 10^{12}Ps/cm³ inside of target cavity
- About 1# $\bar{H}^+$expected for every 2 minute (1 cycle of AD)
- Study to optimize the production is ongoing for double charge exchange.
- The expected $\bar{H}$ number will be changed by new paper of cross-section : New J. Phys. 23 (2021) 029501
- A main goal of GBAR in this year is the production of $\bar{H}$ and H.

P.Comini et. al, Hyperfine Interactions, 228, 159-165 (2014)

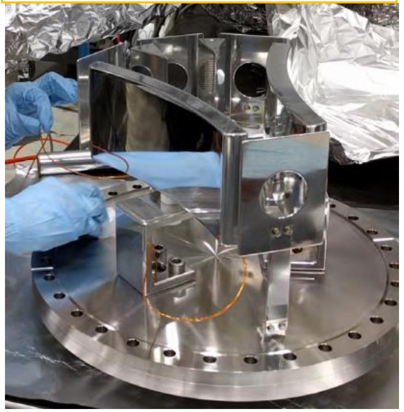
Antiproton and proton beam line

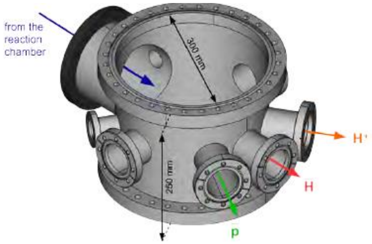


Antiproton and proton beam line

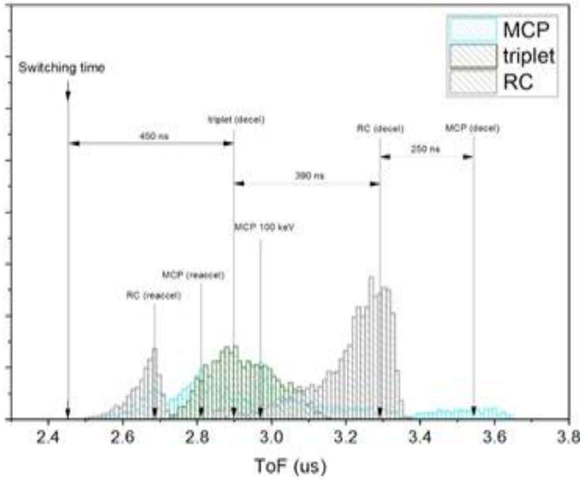


Switchward

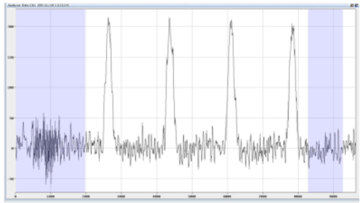


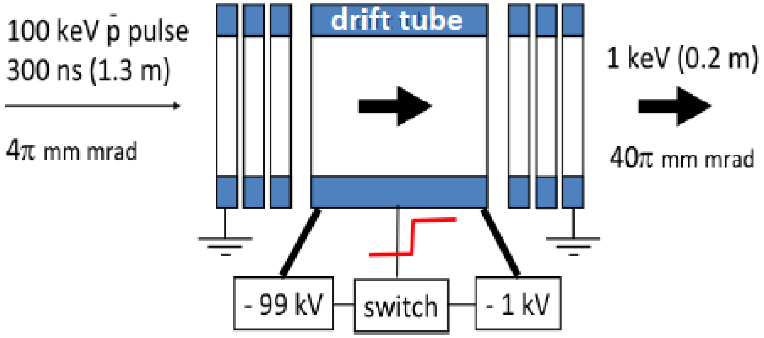


Antiproton beam deceleration test& simulation

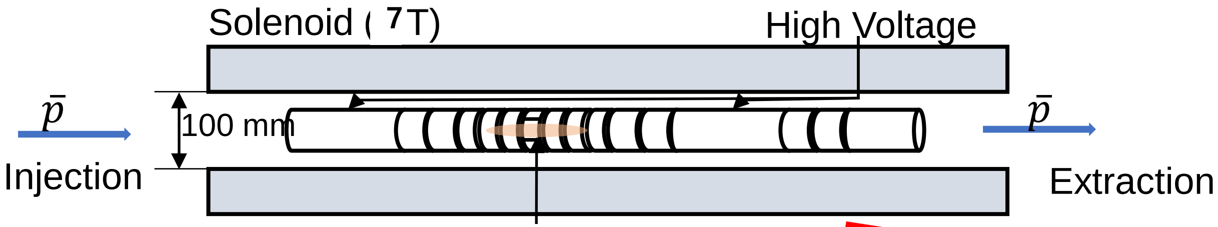


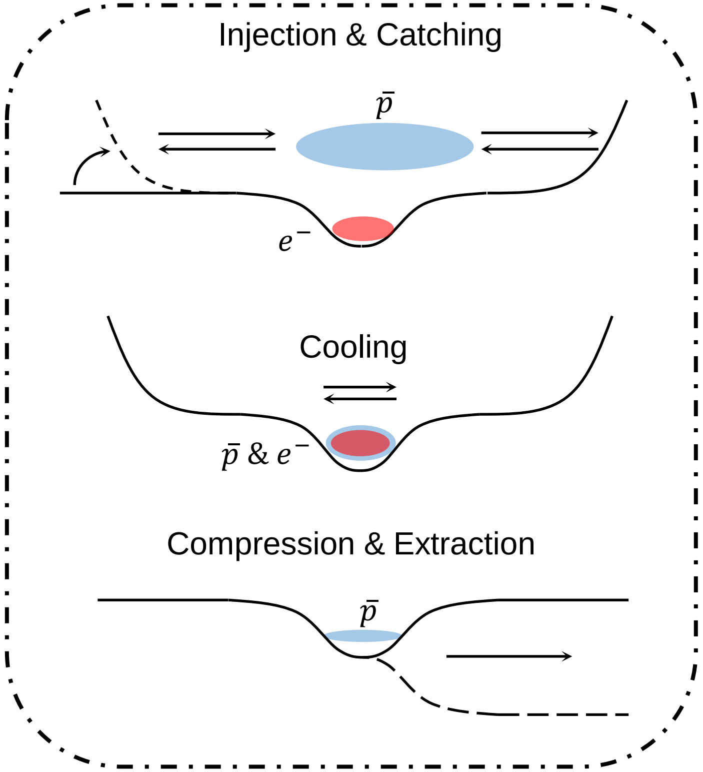
- First beam from ELENA was tested with decelerator in the GBAR line before LS2. A. Husson et al., [Nuclear Inst. and Methods in Physics Research, A 1002 (2021) 165245 **A** (2021)]
- Deceleration by electrostatic tube with switching circuit from 100keV (300ns) to 1~10keV with high efficiency: Has been tested now.
- Switchward to separate antihydrogen ion from antihydrogen and antiproton

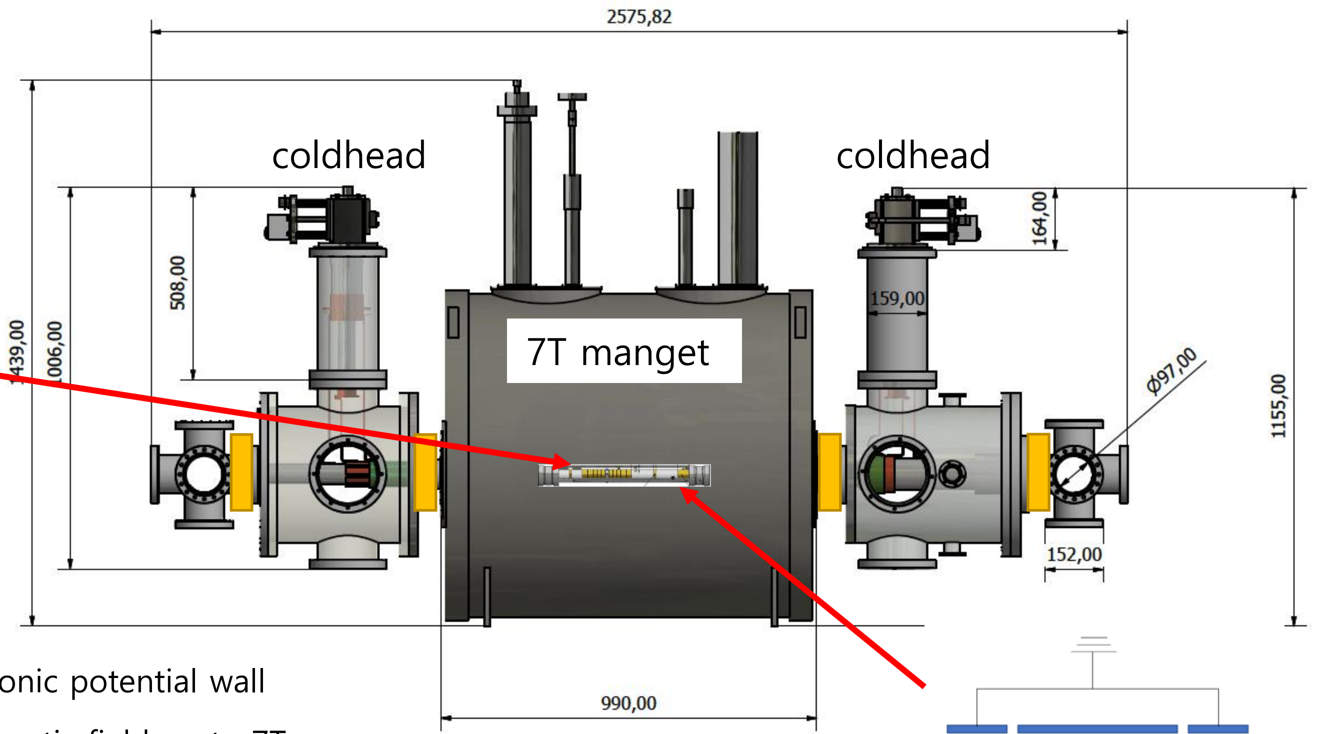


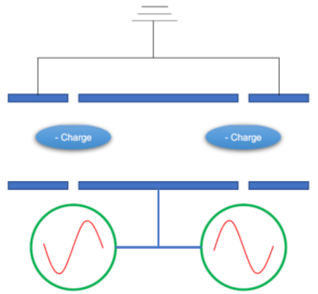


Antiproton trap



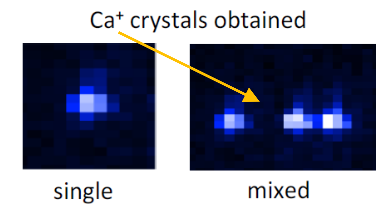


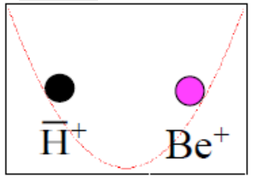


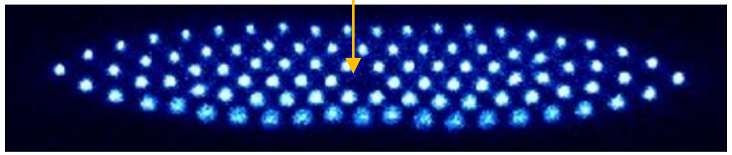


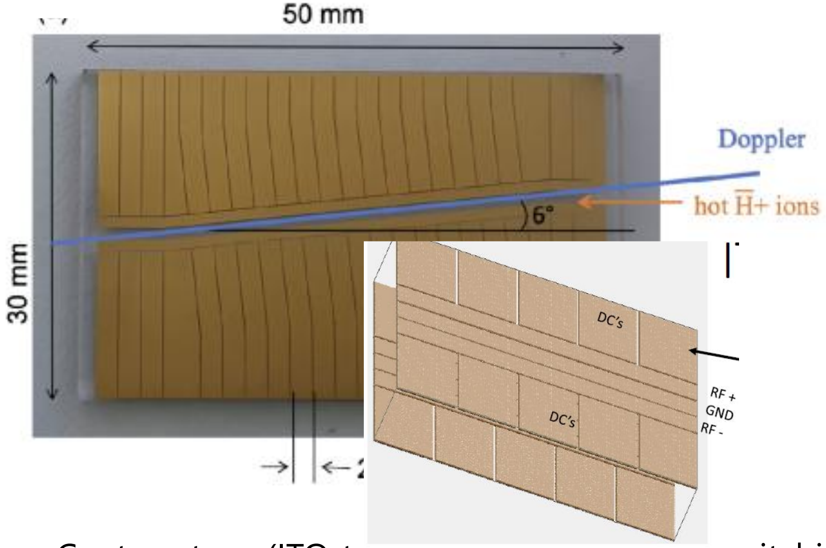
- Axial trapping by harmonic potential wall
- Radial trapping by magnetic field up to 7T
- Cooling by cyclotron radiation + electron cooling
- Compression by cylindrical electrodes and rotating wall
- Acceleration with bunching by inner double gap bunching system : test setup in IBS
- Beam size <1mmx1mm in reaction target with length <100ns, ΔE<25eV
- Electron trapping has been studied currently.
- Trap + recycler can improve antihydrogen production

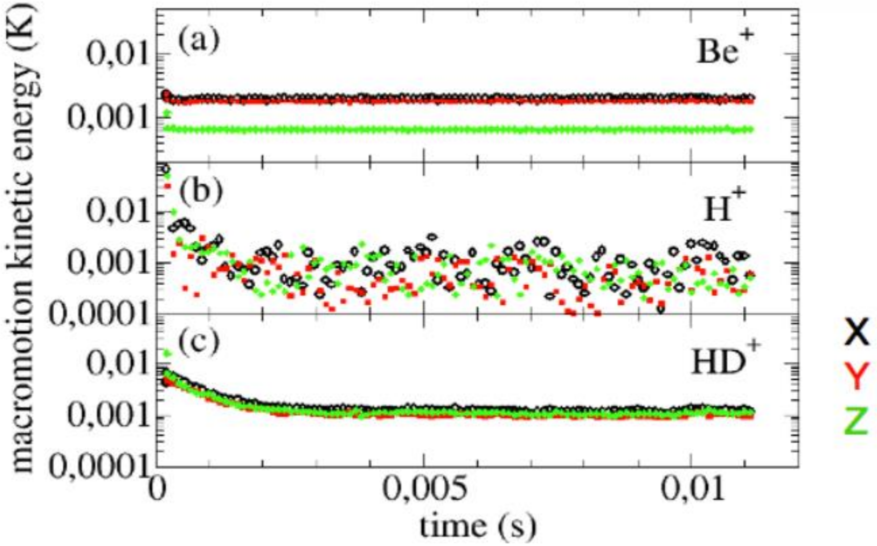
Cooling traps

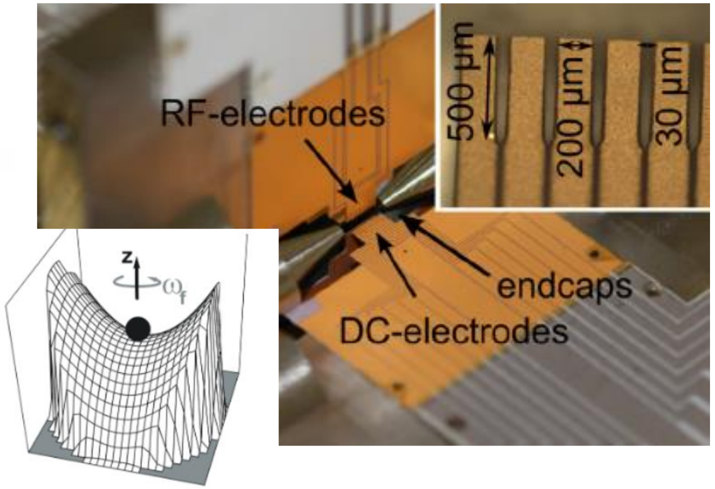


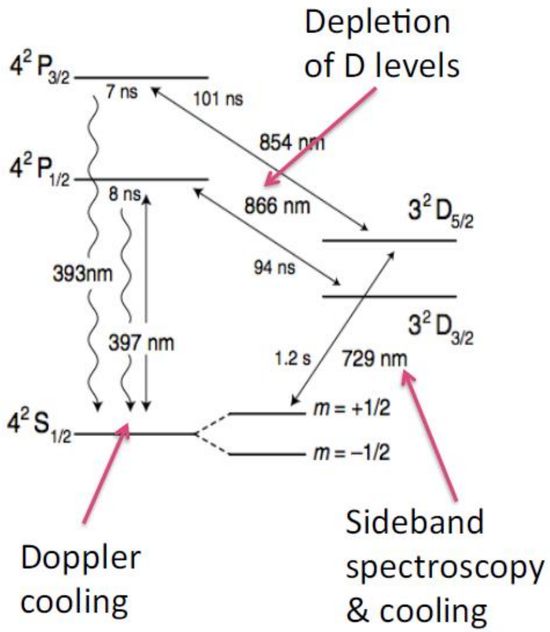












1. Capture trap (ITO trap) : capturing by DC switching+ rf voltage electrodes

Sympathetic Doppler cooling by cooled Be+ ions (>10,000 laser(313nm) cooled Be⁺/HD⁺ ions (Wigner crystal), 100 neV, T~mK by rf heating)

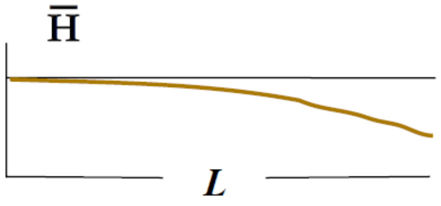
(L. Hilico et. al., Int. J. Mod. Phys. Conf. Ser. 30, 1460269 (2014))

← HD⁺ to reduce mass ratio for better coupling in simulation (similar charge to mass ratio required)

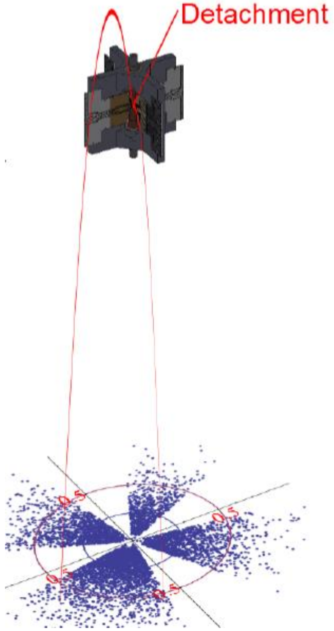
- 2. Precision trap : ion as a quantum harmonic oscillator, Raman sideband cooling for $Be^+/\overline{H}$ ion pair to T~10uK. (W. Schnitzler et. al, Physical Review Letters 102, 070501 (2009).)

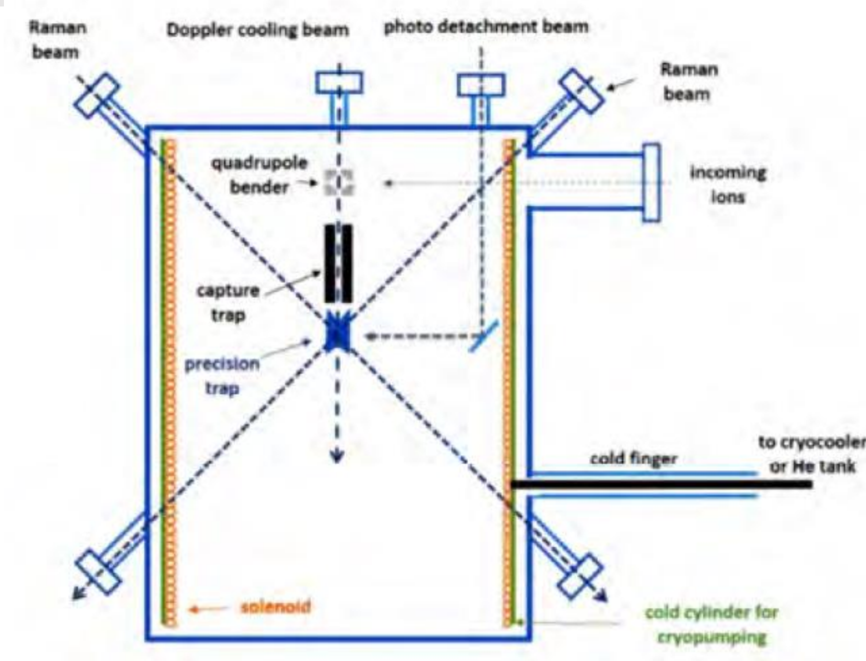
Freefall measurement

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



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

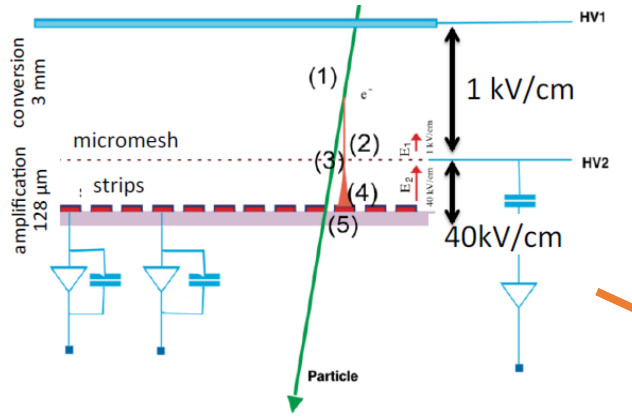


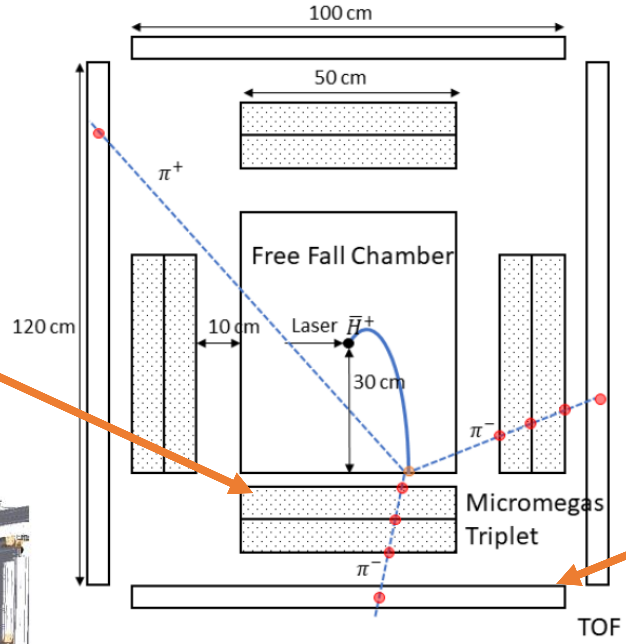


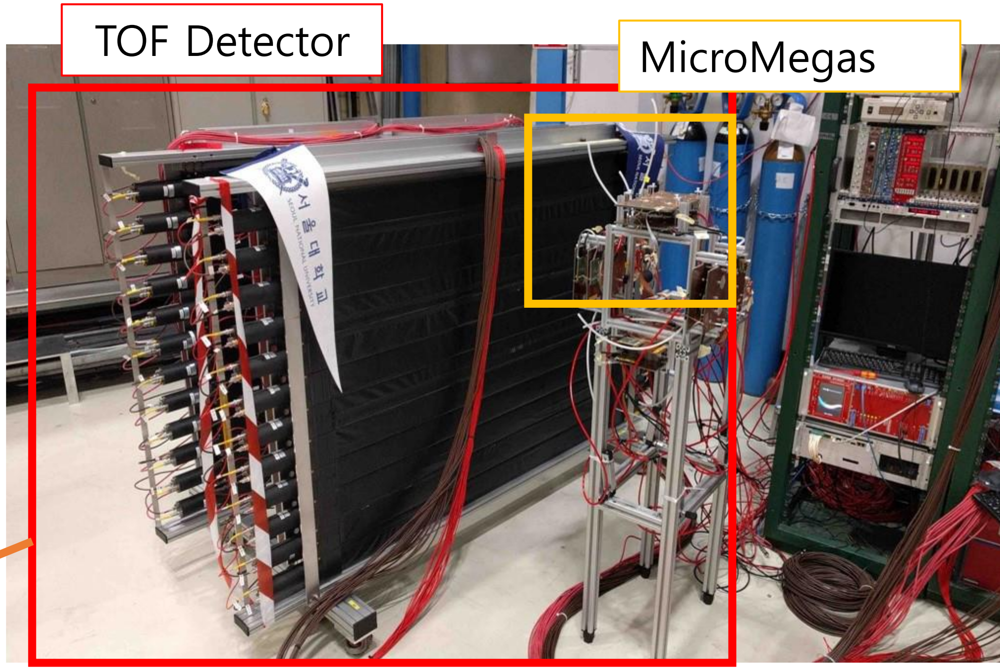
- Initial direction : temperature (0.44m/s for 1MHz) + photon recoil(0.24m/s) + positron emission (~0.3m/s for E_c = 1ueV)
- Length :10cm, height : 30cm (cf Aegis : L = 1m, h = 20um)
- Small magnetic field gradient, UHV, etc for systematic uncertainties have been studied
- Freefall time : about 500ms for $|\bar{g}| = g$
- uncertainty : $(\Delta z_0, \Delta v_{z0} t \ll z), \frac{\Delta \bar{g}}{\bar{g}} \cong \sqrt{(\frac{\Delta z}{z})^2 + (\frac{2\Delta t}{t})^2}$~0.4 (for single $\bar{H}$), Δz(T(10uK),ΔE(1ueV):positron emission)

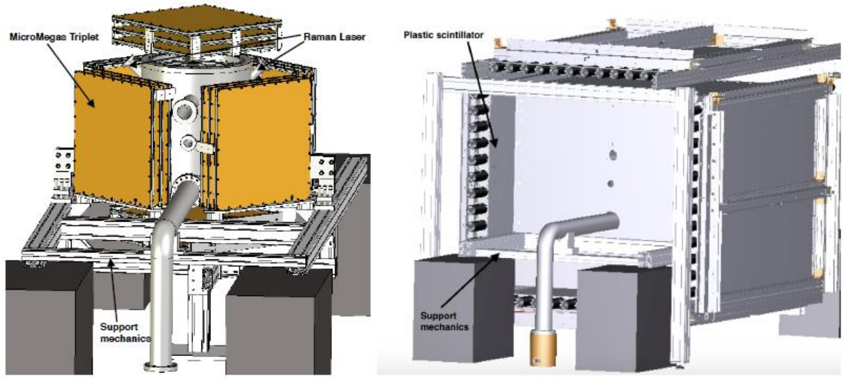
better description in G. Dufour et. al., Eur. Phys. J. C (2014) 74:2731

Freefall measurement



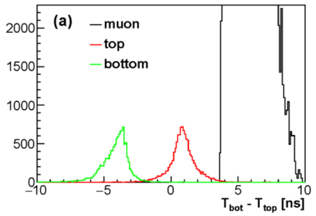


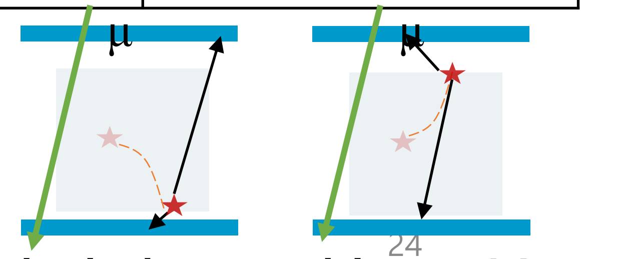




Temperature	Sign decision
10uK	~30 events
1mK	~6000 events

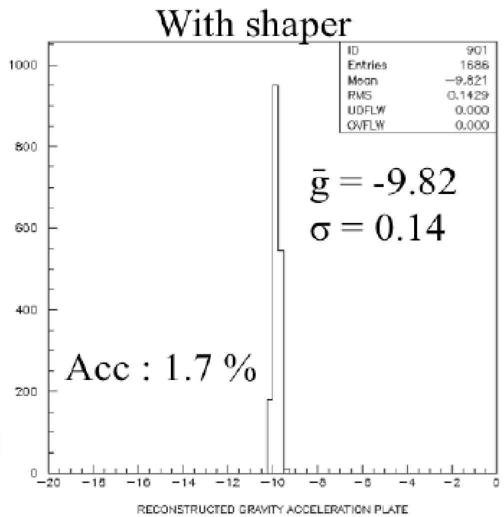
- Estimated number to measure 1% precision is 1500# detection of freefall antihydrogen (10uK)
- Simulation with deep learning has been studied
- Almost all cosmic ray background can be removed.

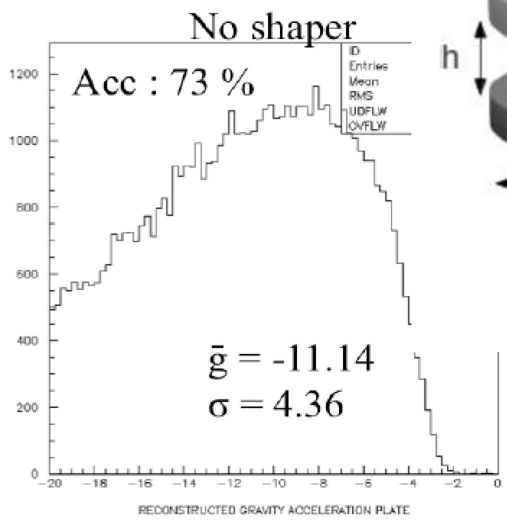


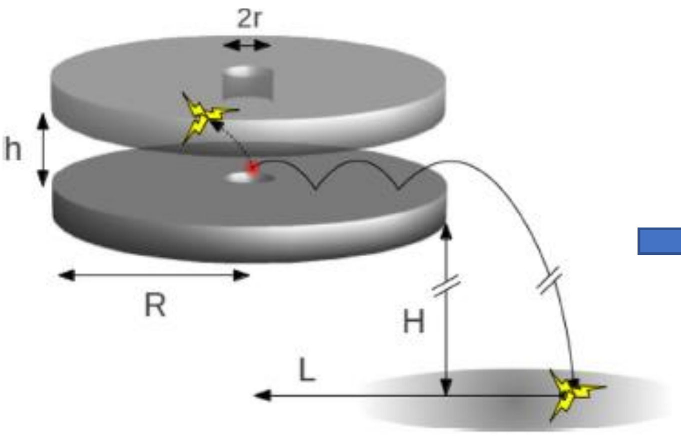


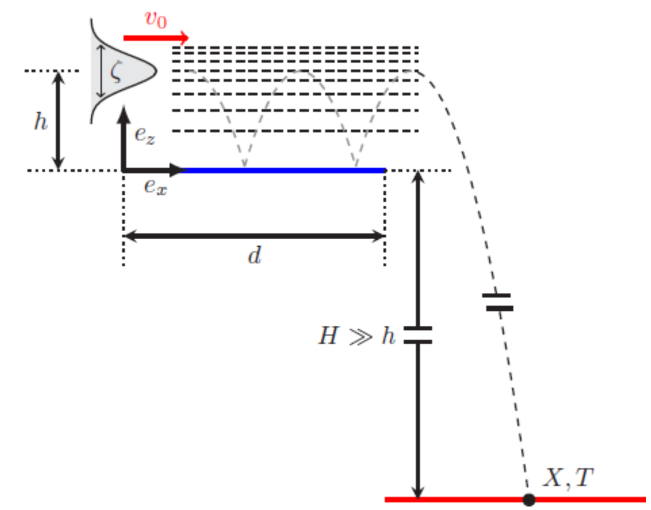
Chamber bottom annihilation Top annihilation

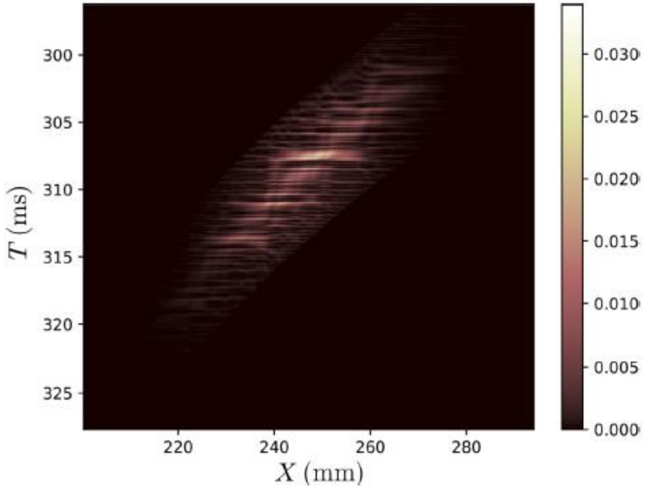
Further improvement











- Can be improved with proper shaper
- Quantum bouncing of antihydrogen (by Casimir-polder fore) : demonstrated with ultra cold neutron (V. V. Nesvizhevsky et. al., *Nature* **volume 415**, pages297–299 (2002)) :

+ shaping the distribution of velocity : precision be below 10^{-3} (G. Dufour et. al., Eur. Phys. J. C (2014) 74:2731)

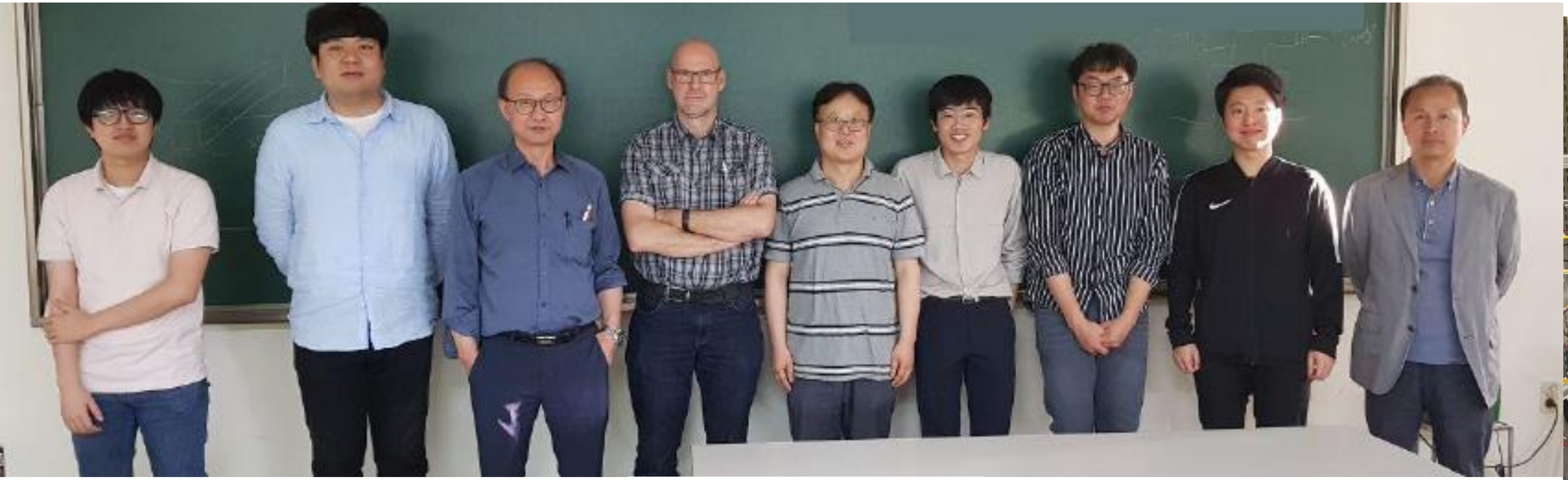
- Quantum interference to improve the accuracy (10^{-5}) : detail is in P.-P. Crepin, Phys. Rev. A 99,042119

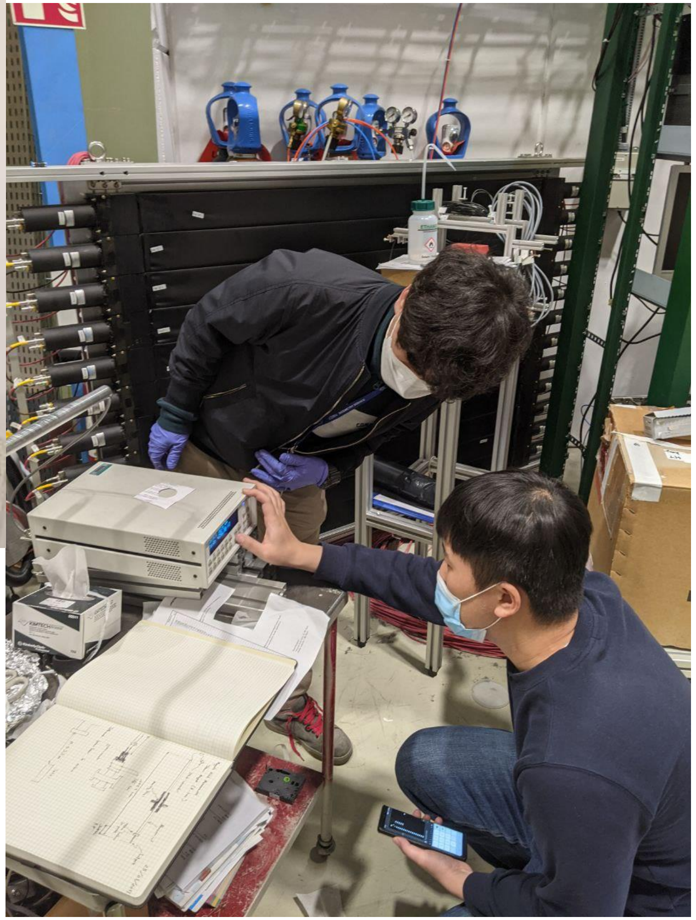
GBAR collaboration

70 members
18 institutes
8 countries

Korean group
4 Institutes
6 Ph. D
7 GS

GBAR Korean collaboration





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conclusion

- After the discovery of antimatter, there was arguments about antigravity.
- Recently, unprecedent experimental efforts are arose and the oretical rebellion started.
- Currently, experiments to measure the antihydrogen gravitatio nal acceleration with 1% precision have competed.
- GBAR experiment will measure gravitational acceleration by cl assical freefall test using ultra-cold antihydrogen.

Thank you

Motivation to study antihydrogen

- One of the best particle for fundamental physics as a direct tool of comparison

: neutral antimatter composed of only antiparticles

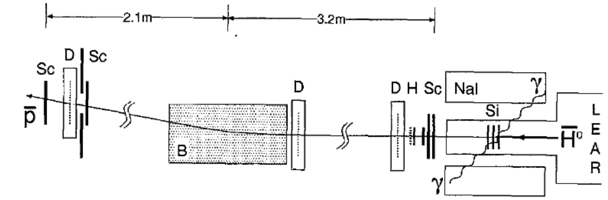
- CPT test between matter and antimatter

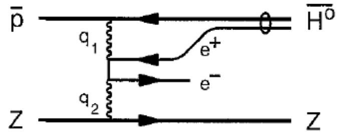
: Can extend Standard model

- Weak equivalence principle (WEP) test by antimatter

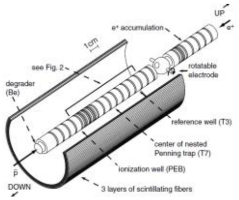
: The gravitational interaction between matter and antimatter (antimatter and antimatter) has never been tested. → WEP is only proven between matter and matter.

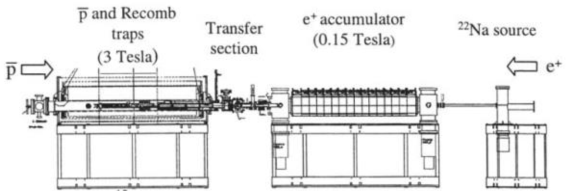
Recent breakthroughs of $\overline{\mathrm{H}}$

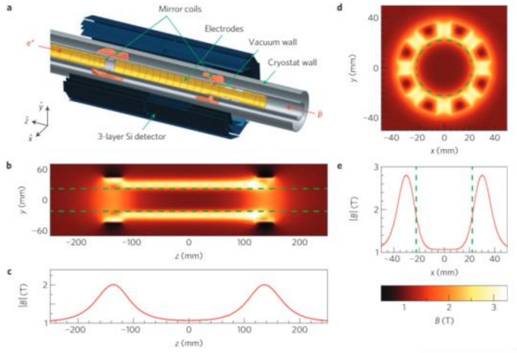


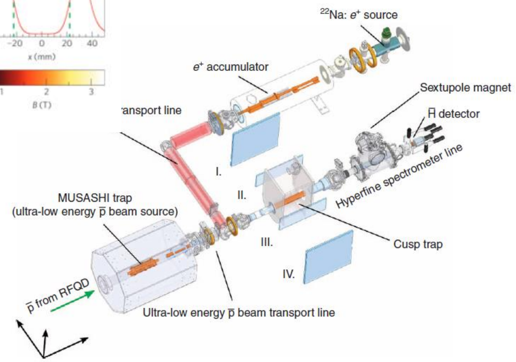


- 1995 : First production of antihydrogen at LEAR (Phys. Lett. B 368, 251) with stochastic cooling and electron cooling
- 2002 : Cold antihydrogen production at ATHENA(Nature 419, 456-459), ATRAP(Phys, Rev. Lett 89, 213401)
- 2010~2011 : Trapping antihydrogen (Nature 468, 673) up to 1000s (Nature physics, 7, 558-564) at ALPHA
- 2013 : Antihydrogen gravity test by ALPHA (Nature communications 4, 1785)
- 2014 : antihydrogen beam source by ASACUSA (Nature communications 5, 3089)
- 2021 : Antihydrogen laser cooling by ALPHA(Nature 592, 35-42)









CPT test

- Spectroscopy of antihydrogen

1S-2S transition : hydrogen 4.2e^{-15}

– antihydrogen $2x10^{-10}$(2017) → 2x 10^{-12} (2018)

Hyperfine splitting : observed 2% ($2P_{1/2}$-$2P_{3/2}$)

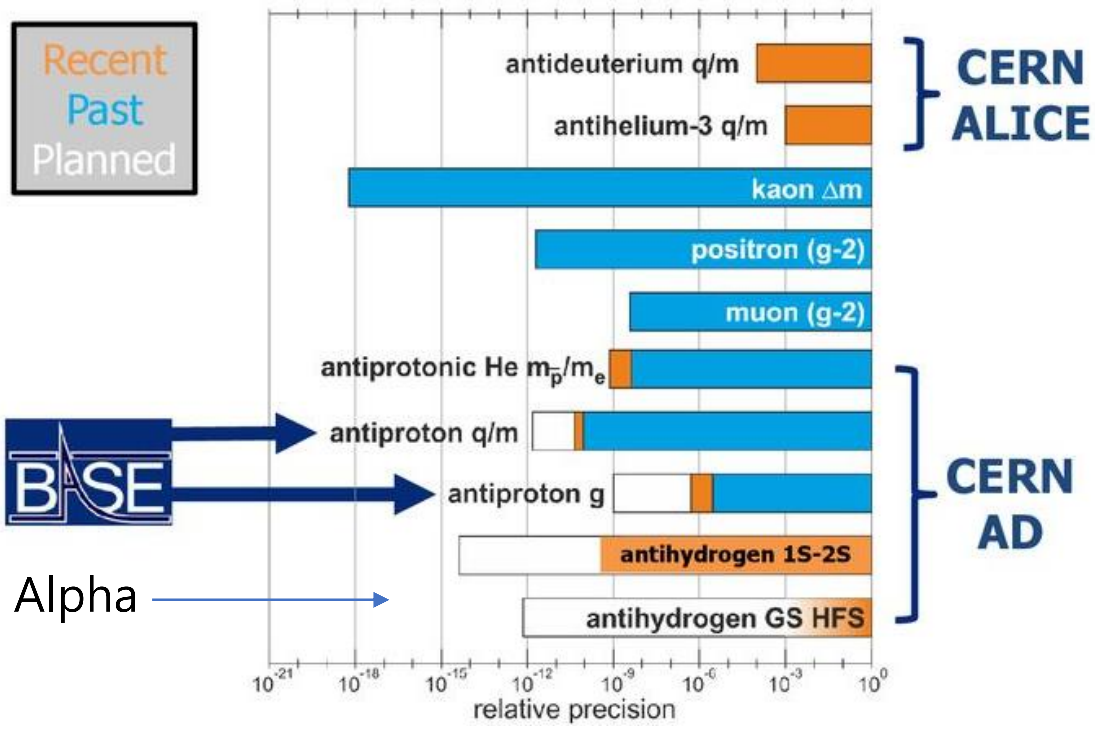
(nature 548, 66-69 (2017), nature 578, 375 (2020)) by ALPHA

- Lamb shift : agreed a level of 11% ($2S_{1/2}$-$2P_{1/2}$) (nature 578, 375 (2020)) by ALPHA

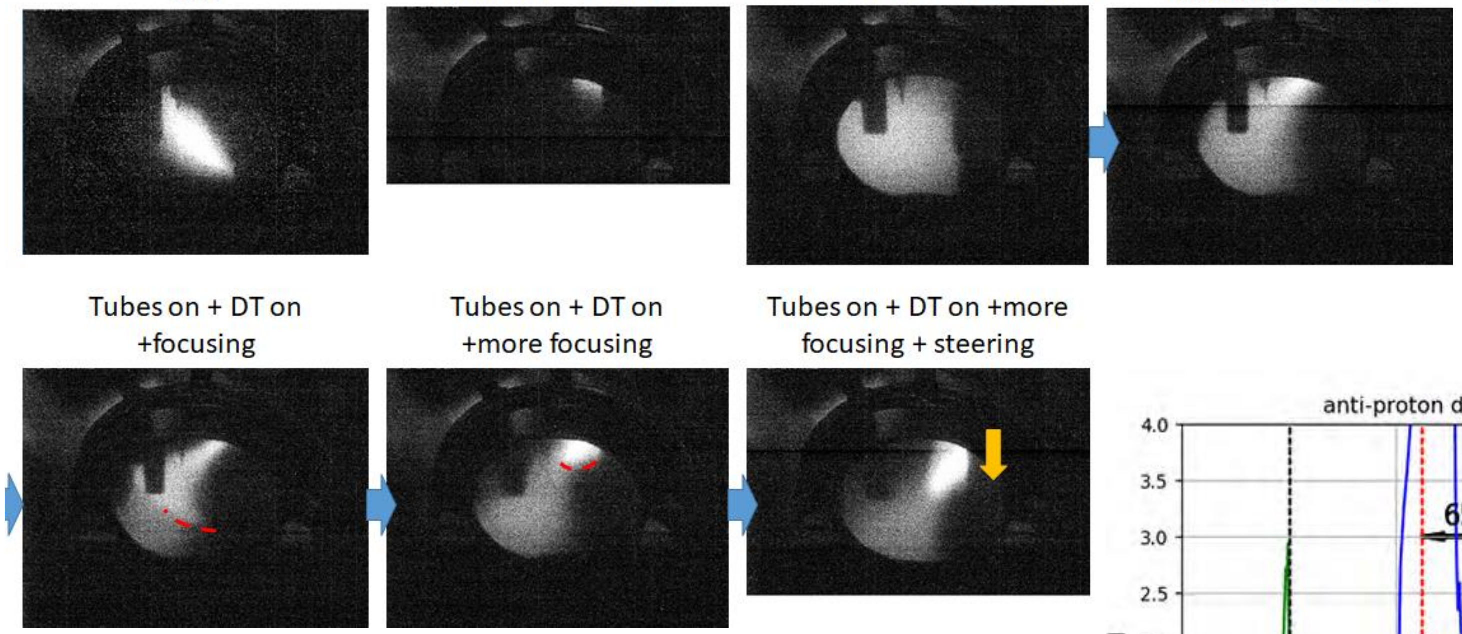
- Proton & antiproton CPT test by BASE

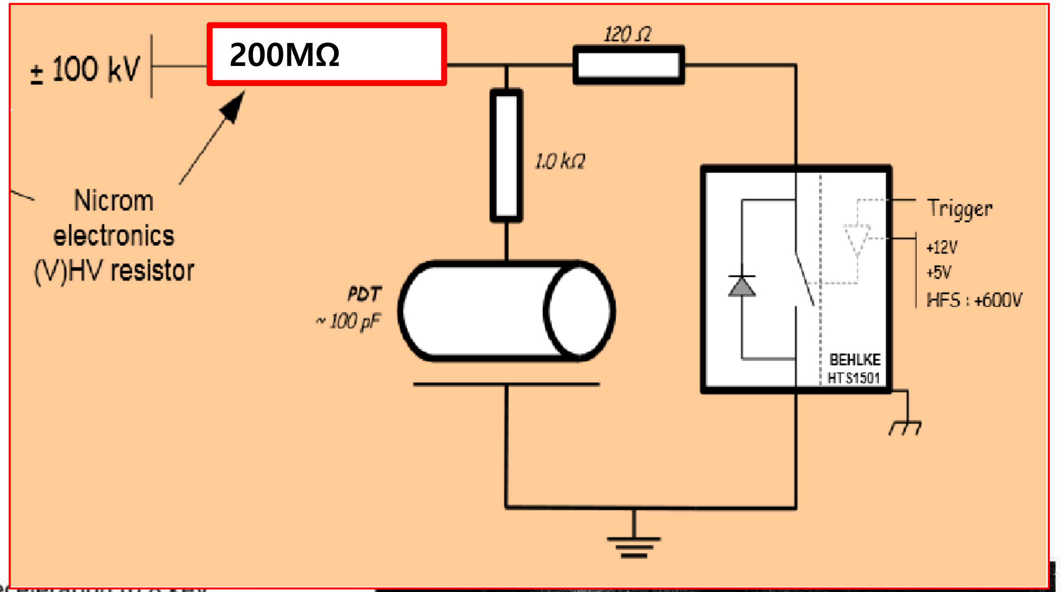
(nature 524, 196-199 (2015)) and updated information is not in the slide.

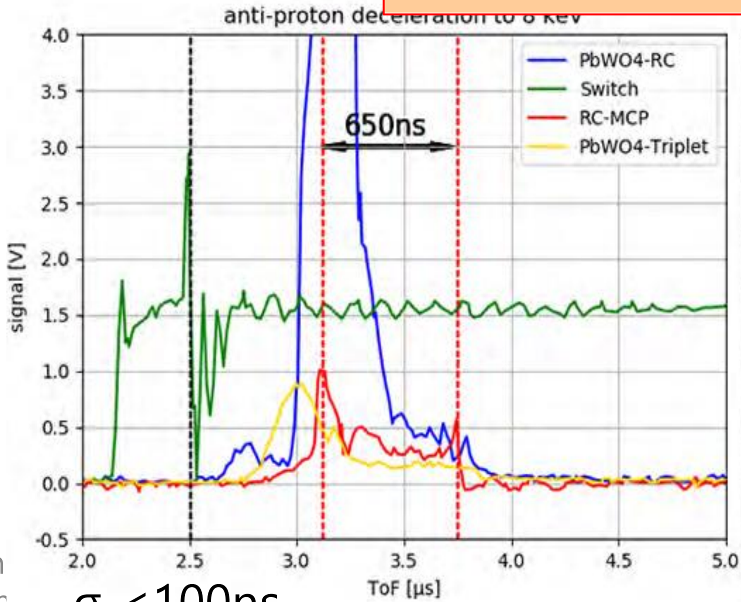
- Antideuteron, antihelium, muon, positron, kaon..
- (There's also many fantastic results for exotic antiprotonic helium, etc..)



Elena beam test before LS2







σ <100ns

- Elena beam test without antiproton trap : 3m tube without any optics

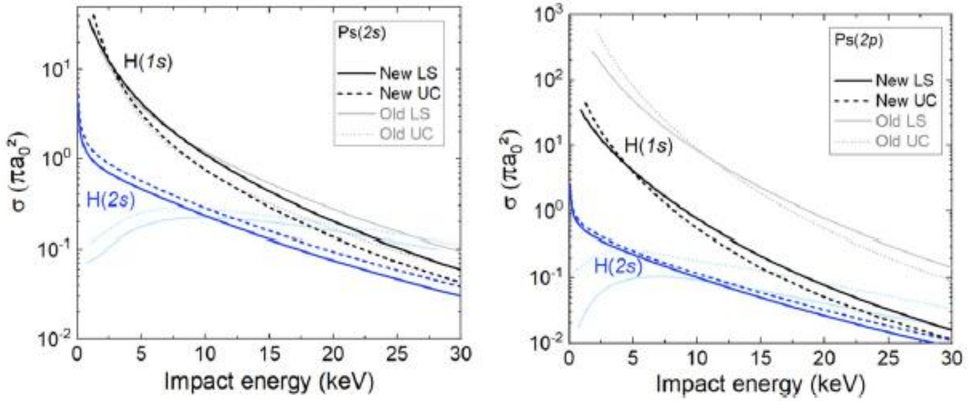


Figure 2. Antihydrogen ion production cross sections from positronium excited in a state $n_p = 2$ as a function of antihydrogen impact energy. See the caption of figure 1 for the detailed legend of the graph.