Status of the GBAR experiment and possible penning trap usage

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GBAR experiment

Motivation

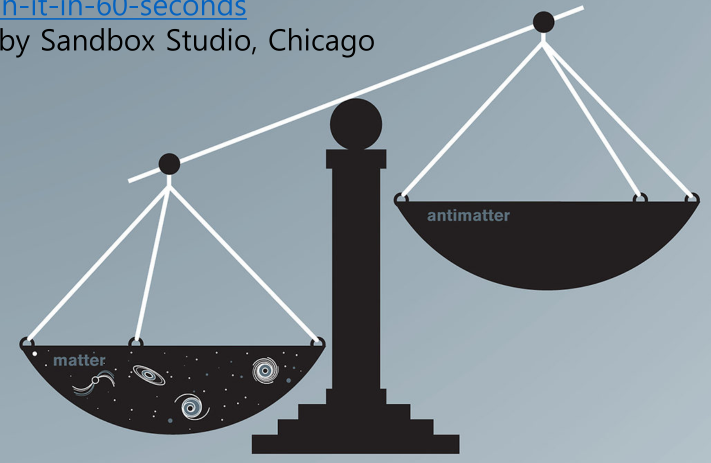
Interest to antimatter and their **interaction** & **property**

- Matter and antimatter asymmetry

- Different with expectation by Bigbang and Standard Model, the amount of matter and anti-matter is not equal although all parameters are symmetric.
- Matter domain in observable Hubble volume : $n_B \gg n_{\bar{B}}$

(baryon/photon ratio : $0.6e^{-9}$(observed) $\gg$ 10^{-18}(expect))

From https://www.symmetrymagazine.org/article/october-2005/explain-it-in-60-seconds
Illustration by Sandbox Studio, Chicago



- Weak Equivalence Principle(WEP) :

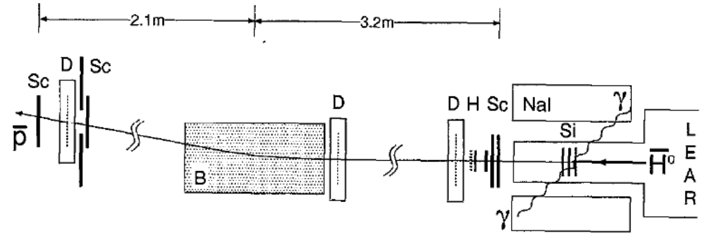
"The trajectory of a point mass in a gravitational field depends only on its initial position and velocity, and is independent of its composition and structure"

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

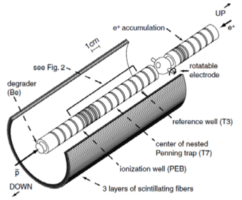
- Test between matter and earth $\Delta(m_g/m_i)/(m_g/m_i)_{Be/Ti}$ = $(0.3\pm1.8)e^{-13}$ (Eötvös)
- **Never well tested before** (positron, antiproton..) are failed because of relatively small interaction compared with effects by electric charge (patch effect, gas charges..)

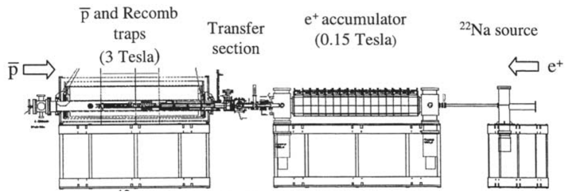
Breakthroughs of $\bar{p}$ & $\bar{H}$

- 1995 : First production of antihydrogen at LEAR (Phys. Lett. B 368, 251) with stochastic cooling and electron cooling

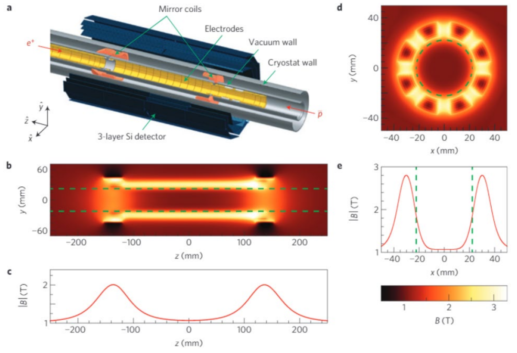


- 2002 : Cold antihydrogen production at ATHENA(Nature 419, 456-459), ATRAP(Phys, Rev. Lett 89, 213401)

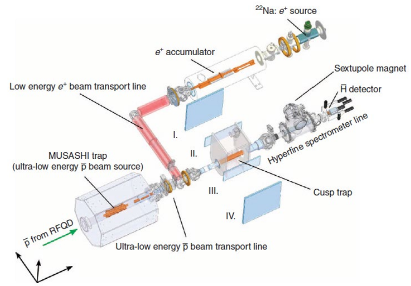




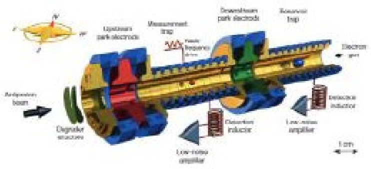
- 2010~2011 : Trapping antihydrogen (Nature 468, 673) up to 1000s (Nature physics, 7, 558-564) at ALPHA



- 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)
- 2022 : **WEP**$_{CC}$ test using antiproton by BASE (Nature, 601, 53-57 (2022))



CPT test by $\bar{p}$ & $\bar{H}$

- Spectroscopy of antihydrogen

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

– antihydrogen 2×10^{-10}(2017) → 2×10^{-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

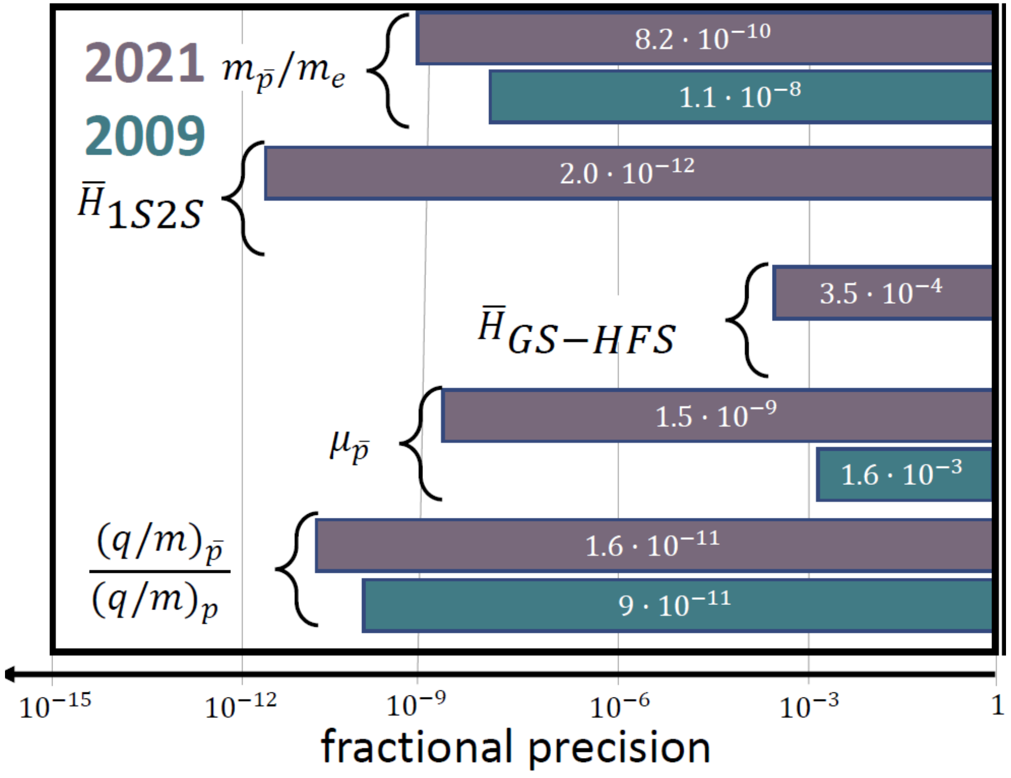
- Proton & antiproton CPT test by BASE

(nature 524, 196-199 (2015), Nature, 601, 53-57 (2022))

- Antideuteron, antihelium, muon, positron, kaon..

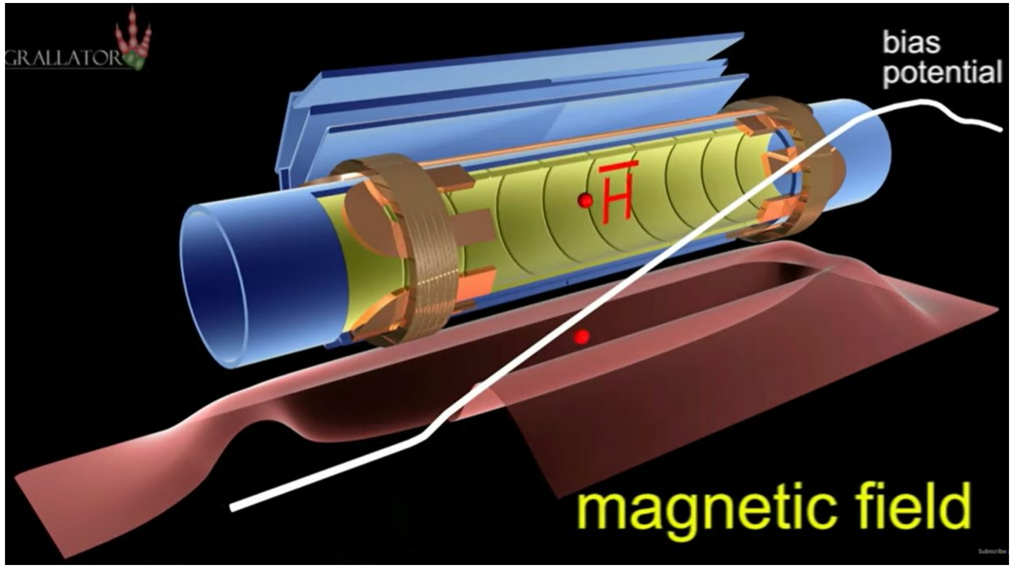
- (There's also many fantastic results for exotic antiprotonic helium, etc..)

From Stefan Ulmer's slide (ADUC)

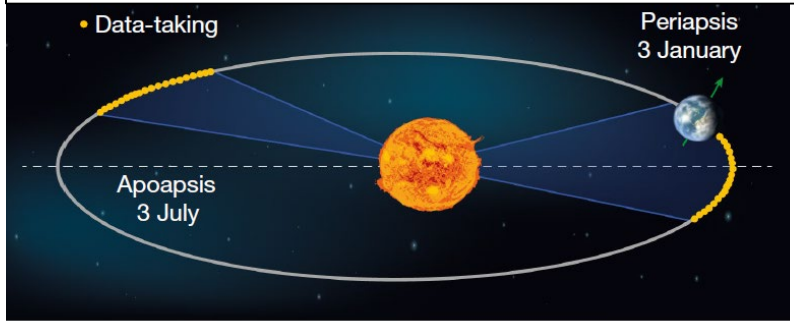


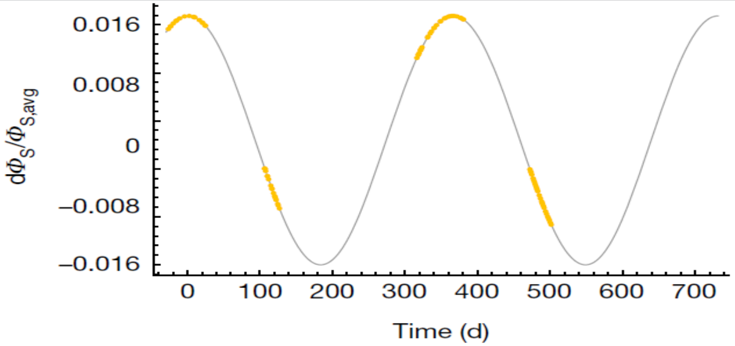
WEP test

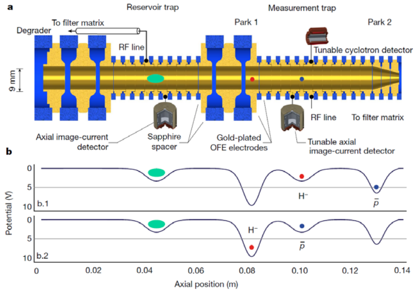
ALPHA experiment
Nature communications, 4, 1785 (2013)



BASE experiment
Nature, 601, 53-57 (2022)







- ALPHA experiment

Anti-hydrogen free-fall experiment was done for WEP_{ff} test : -65 < F (= m_g/m_i) > 110 (95% significance level) excluded.

- Base experiment

Antiprotons cyclotron clock measurement was done for WEP_{cc} test : $\left|\alpha_{g.D} - 1\right| < 0.030$ (CL 0.68)

(Reference for better understanding of each WEP - M.Charlton, et. al., arxiv:2022.09348 (2022))

WEP$_{ff}$ test approaches

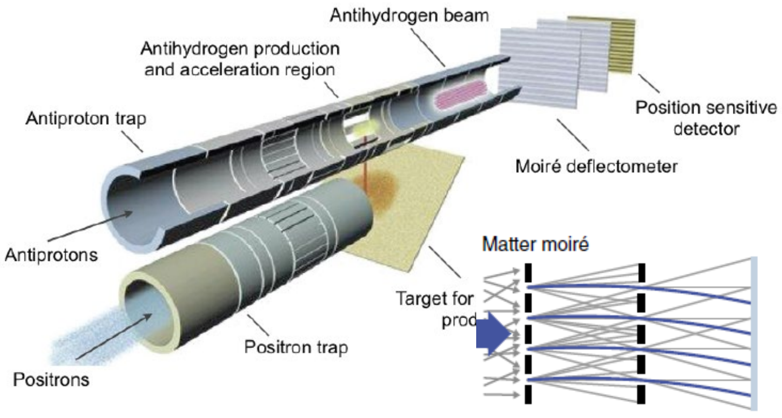
AEGIS

- 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# $\bar{H}$.

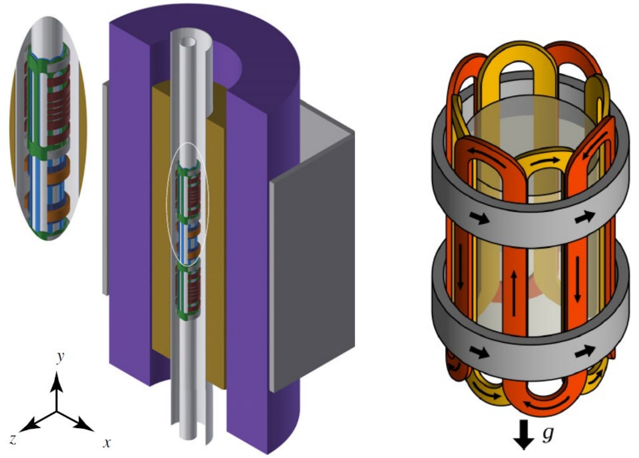


ALPHA-g

- Antihydrogen trapping (0.5K)

\+ Vertical trap (280mm long)

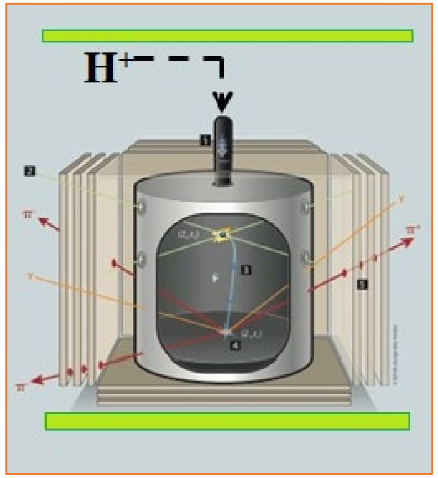
- Aim (1%) : sub-50mK (v~28m/s) temperature by extra cooling by laser & precise measurement of magnetic field



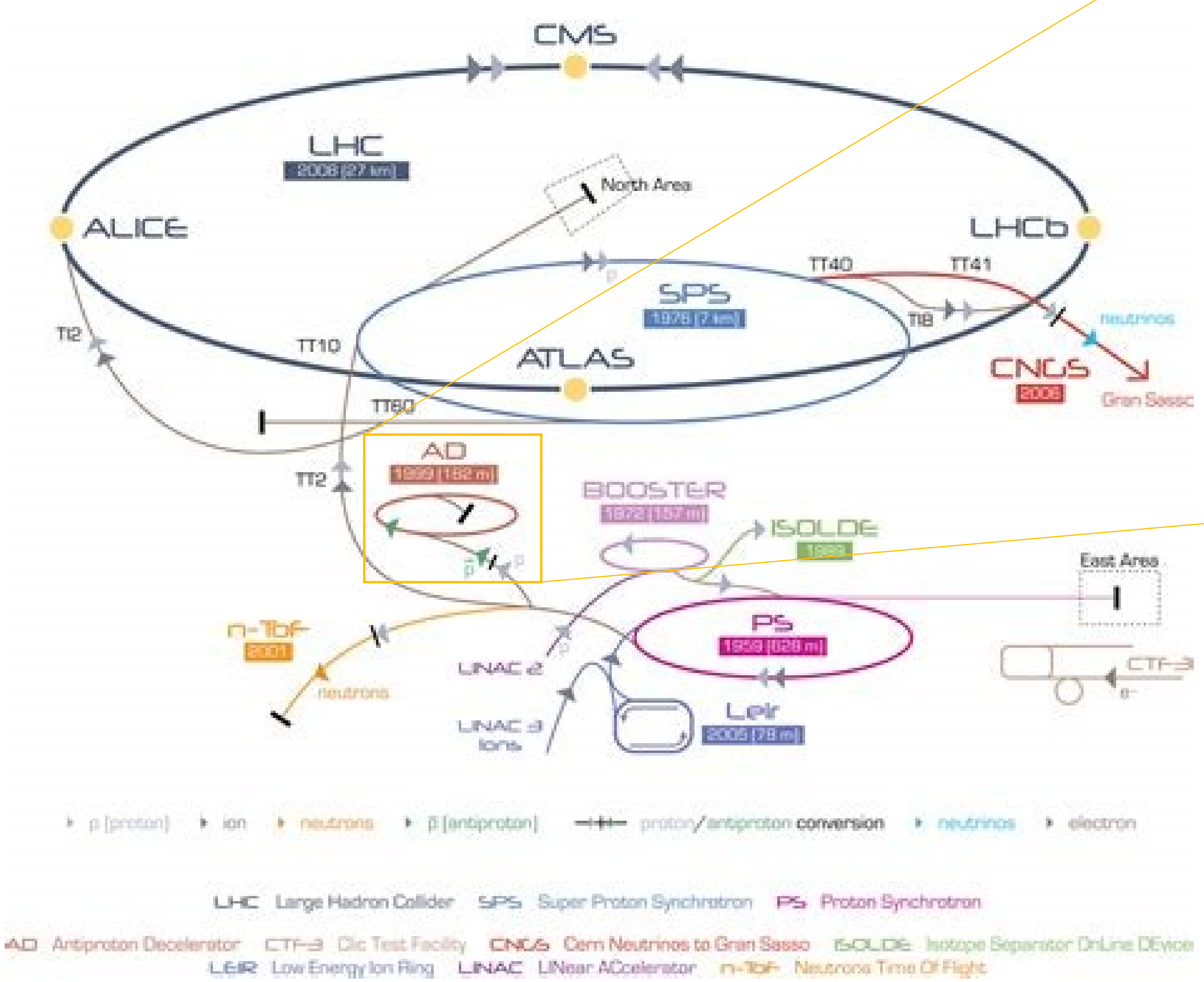
GBAR

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

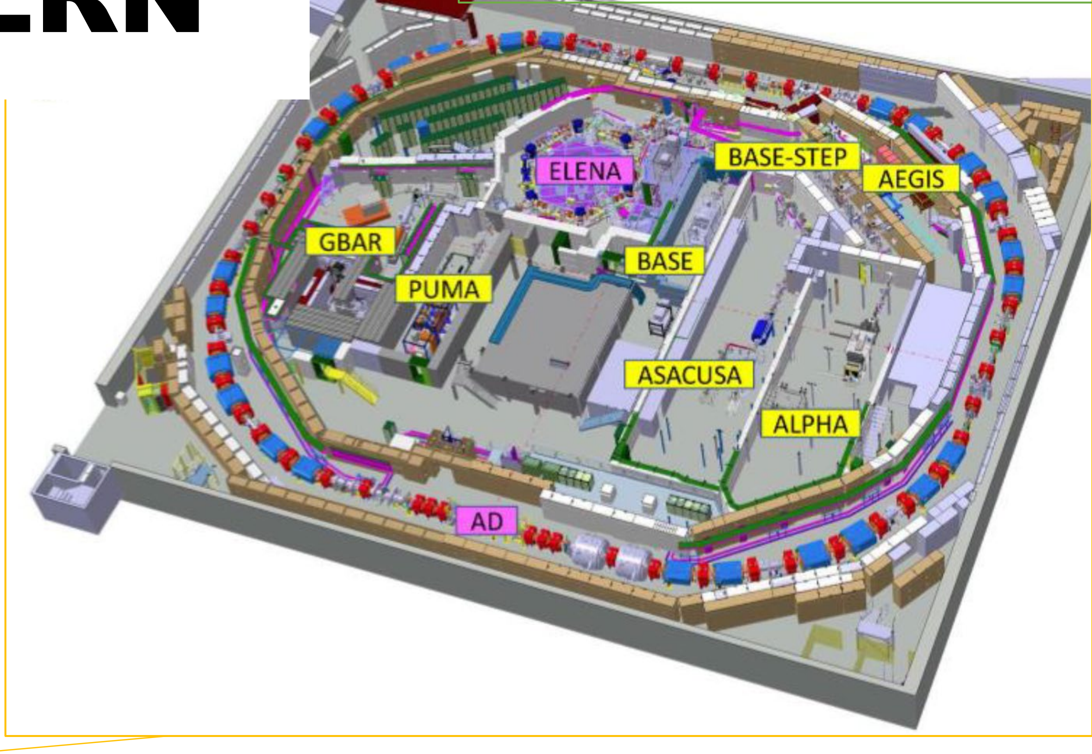
- 1% precision with 1500# $\bar{H}$.
- Capable to reach 0.001%



Antiproton factory at CERN

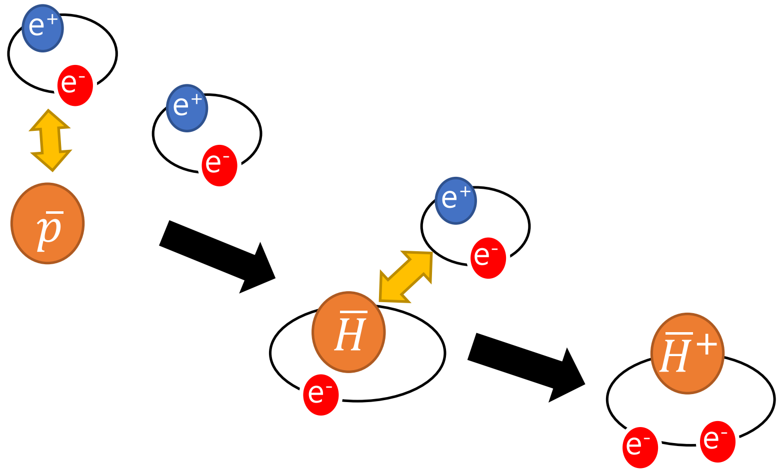


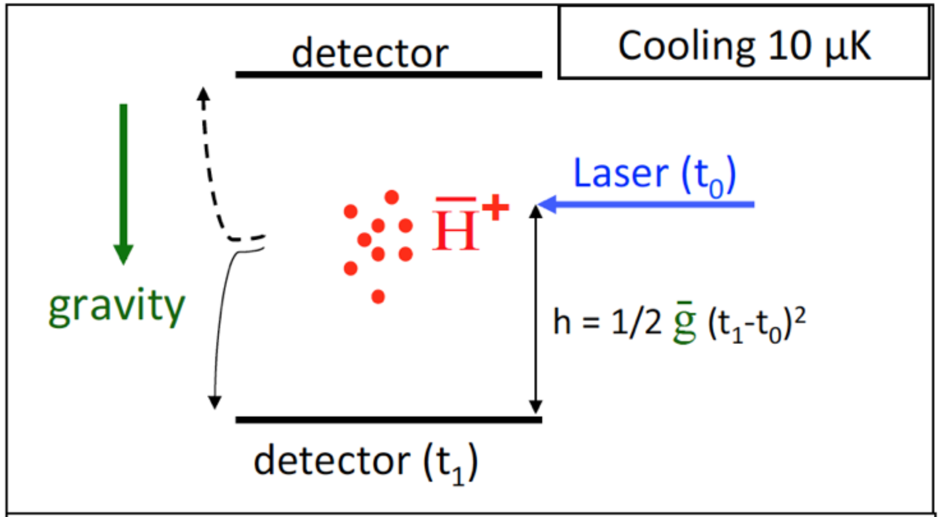
From Stefan Ulmer's slide



- AD : Unique low energy antiproton beam Facility
  5.3MeV (100MeV/c) antiproton beam 2x10^7#/120s
- ELENA : additionally decelerated 100keV antiproton beam (σ<100ns, 0.5x10^7#/120s : ¼ bunches) (improved during 2022)
- 6 collaborations for fundamental physics research : AEGIS, ALPHA, ASACUSA, BASE, **GBAR**, PUMA

GBAR experiment approach





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

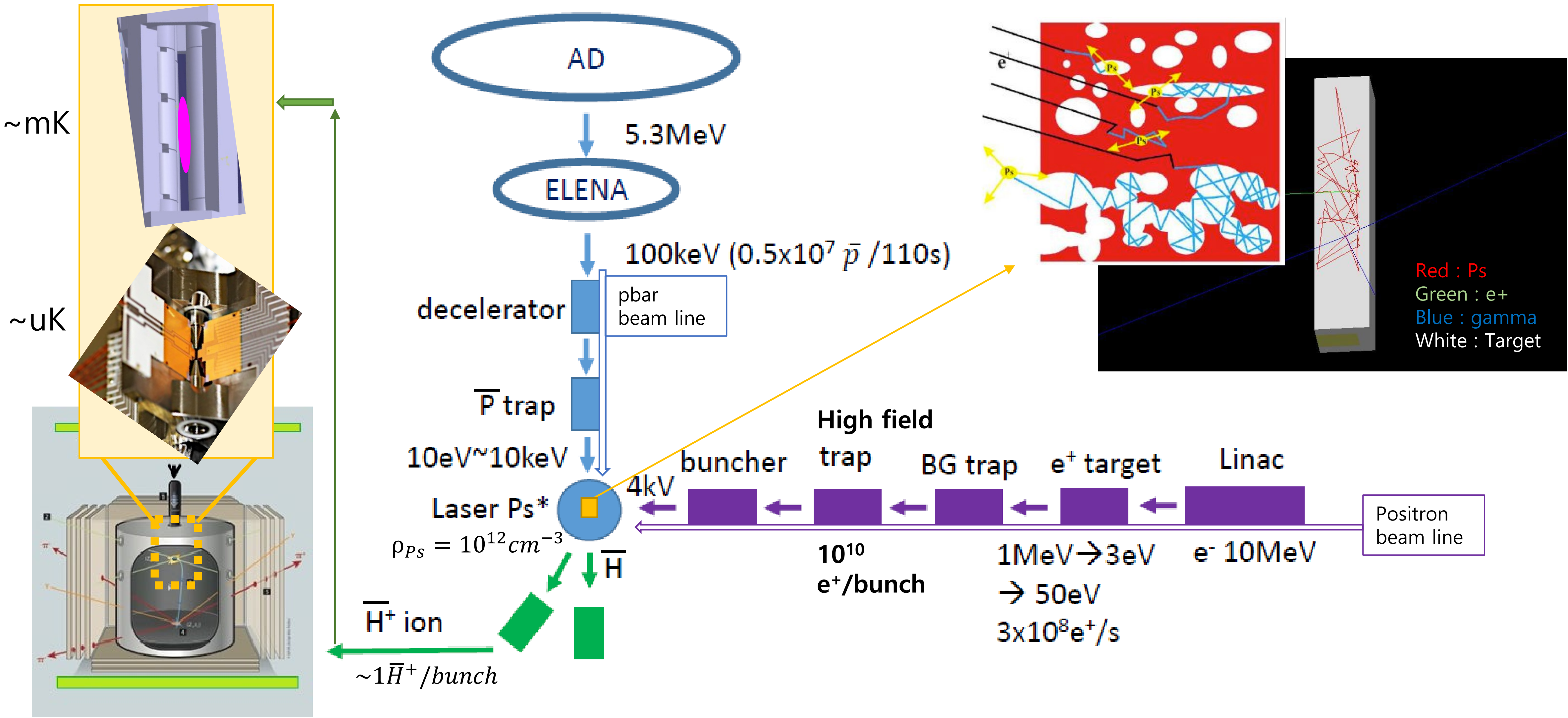
- GBAR (Gravitational Behaviour of Antihydrogen at Rest) experiment aims a direct measurement of the gravitational acceleration of antihydrogen at terrestrial gravitational field by a classical freefall test (universality of free-fall WEP (WEP_{ff})
- Antihydrogen ion production is required to get ultra-cold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

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

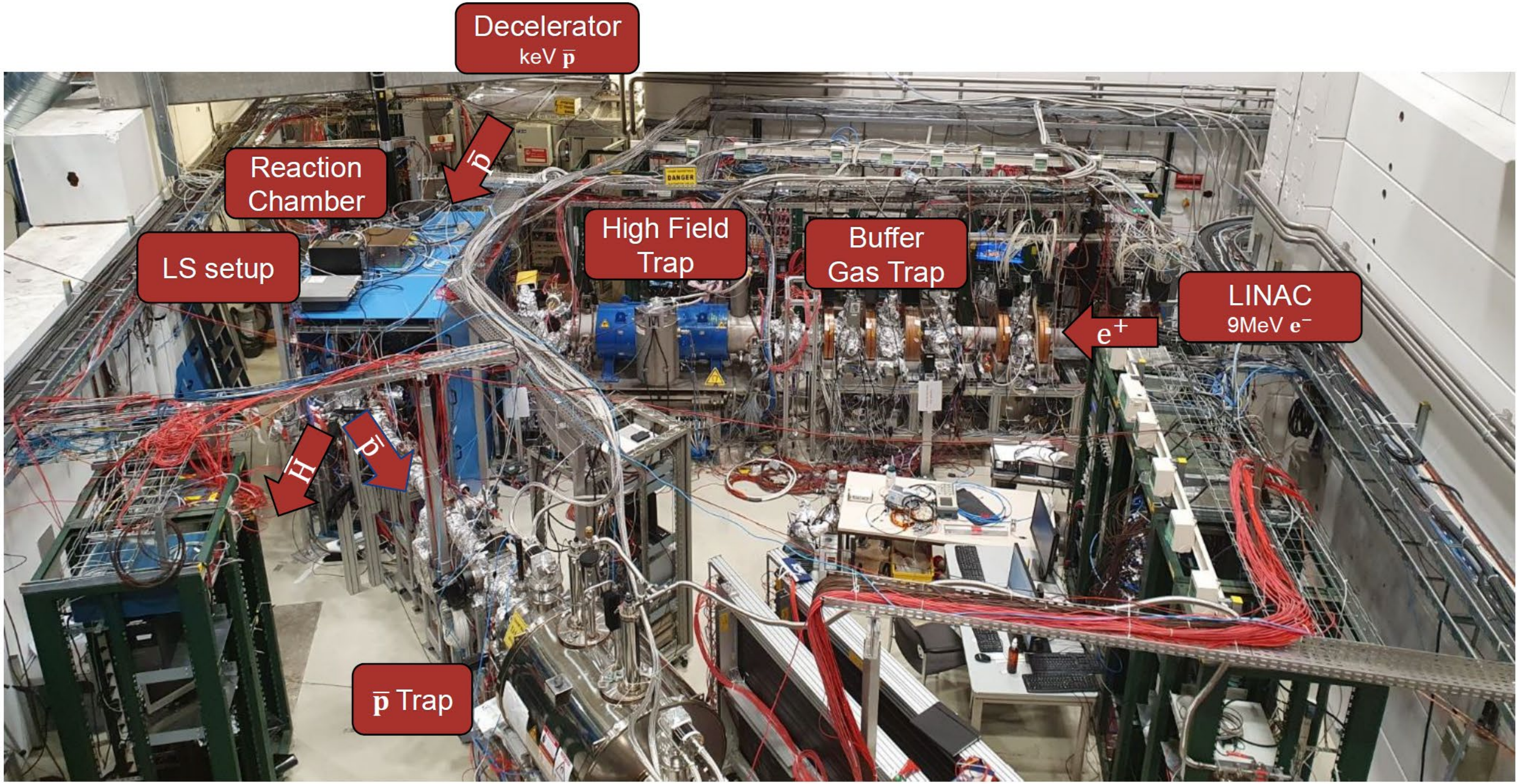
$$\bar{H} + Ps \rightarrow \bar{H}^{+} + e^{-}$$: Second **milestone**

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

Experiment Scheme

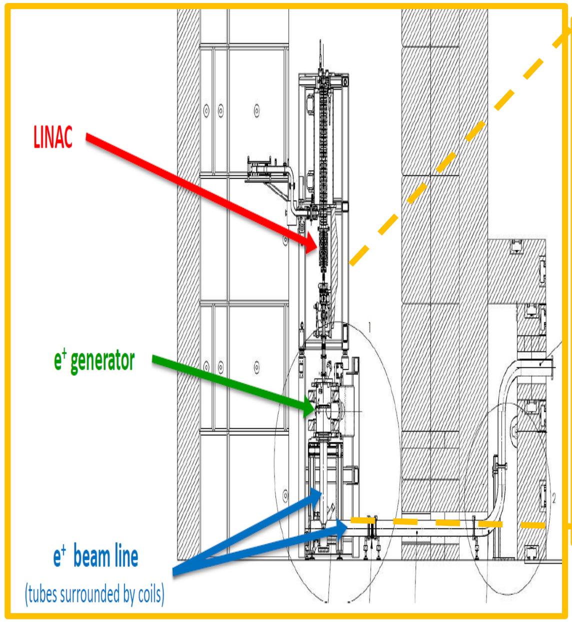


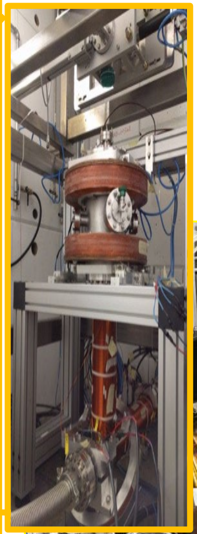
Experiment setup (2022)

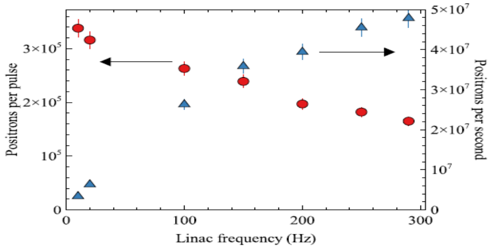


Positron beam for Ps production

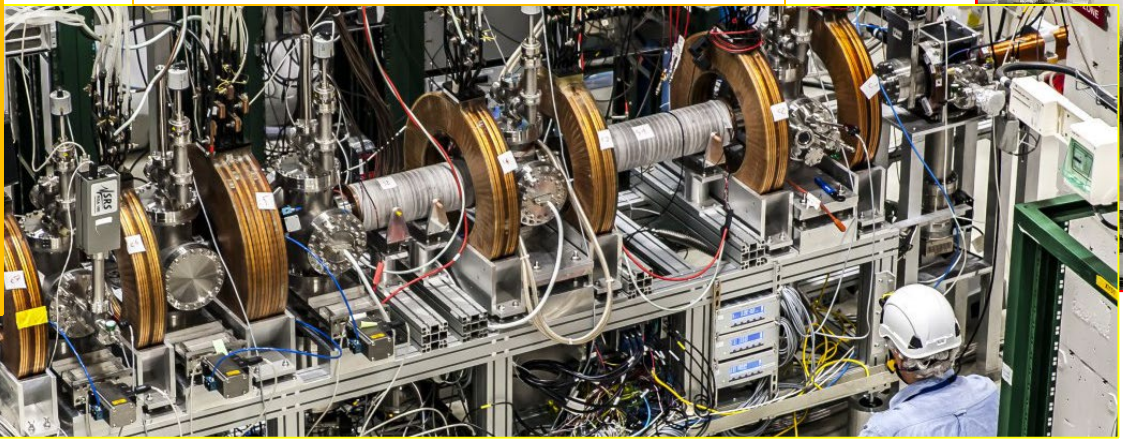
Linac and positron target



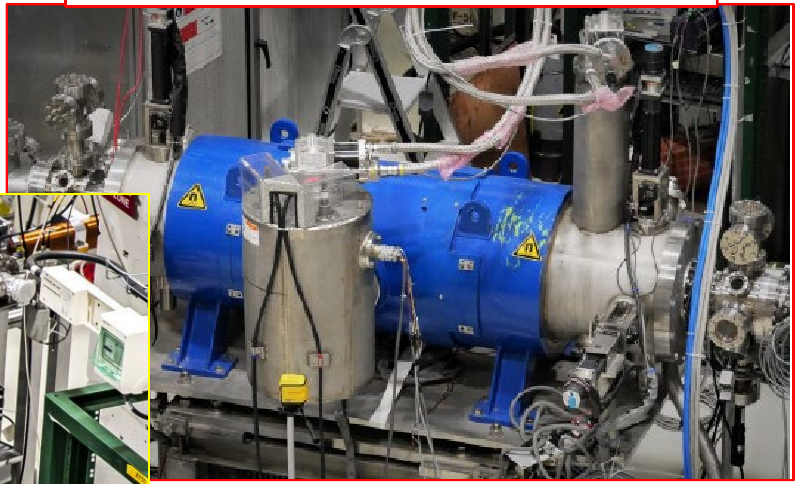




Buffer Gas trap

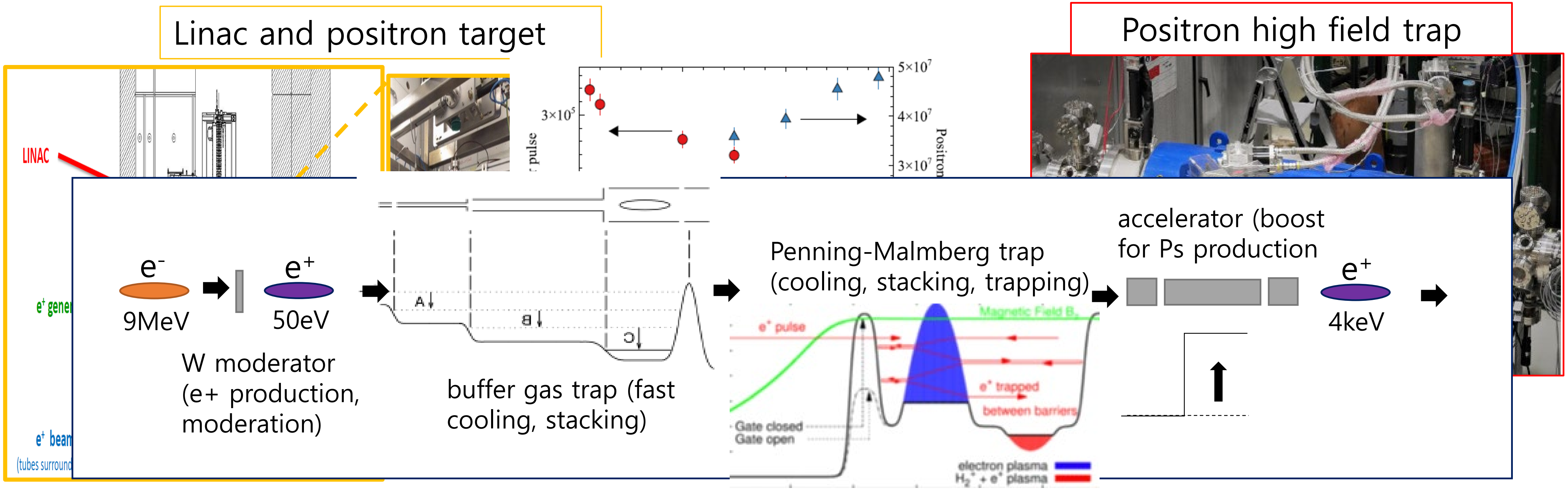


Positron high field trap



- 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 $10^8 e^+$/s
- Buffer-gas trap for positron accumulation with small energy spread → Ne re-moderator
- Positron accumulation by high field trap : goal to 1×10^{10} e^+ (110s) with electron cooling
- Positron acceleration &bunching by electrostatic lenses with resistor chain

Positron beam for Ps production



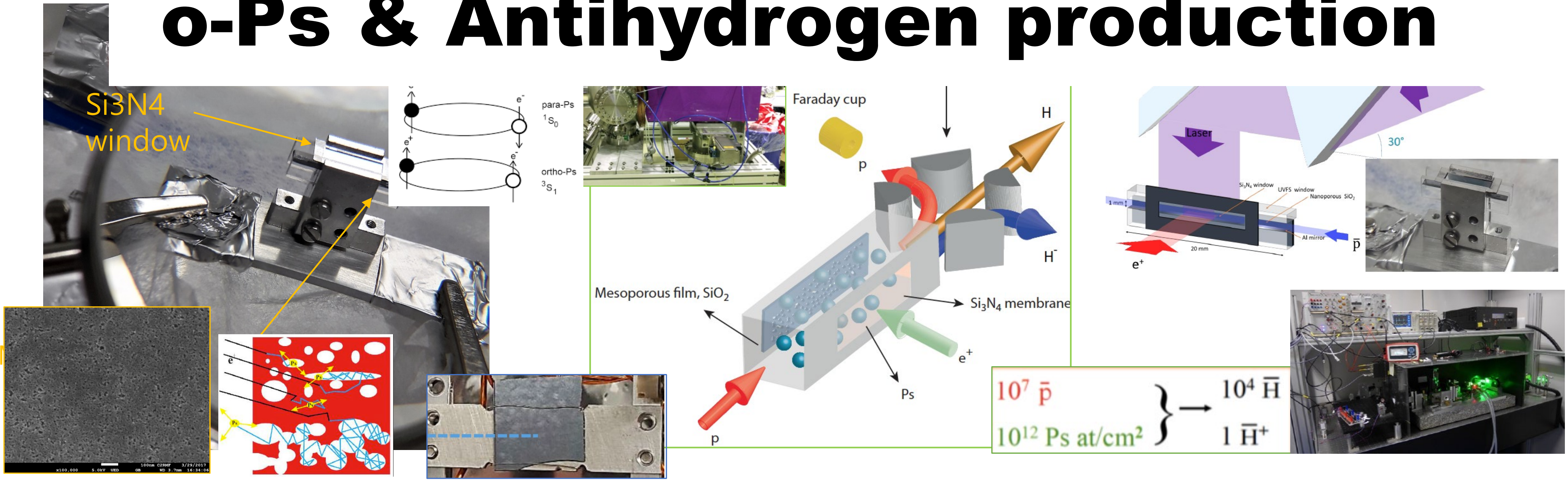
During 2022

- Positron beam intensity : 2.9 x 10^7 e^+/s (200Hz) Nucl. Inst. and Meth. A 985 (2021) 164657
- Positron accumulation : 1.5 x 10^8 e^+/AD cycle, 1.4(2) x 10^9 e^+/1100s Nucl. Inst. and Meth. A 1040 (2022) 167263

New activity (after 2022)

Ne moderator for better efficiency will be added in the buffer gas Trap

o-Ps & Antihydrogen production

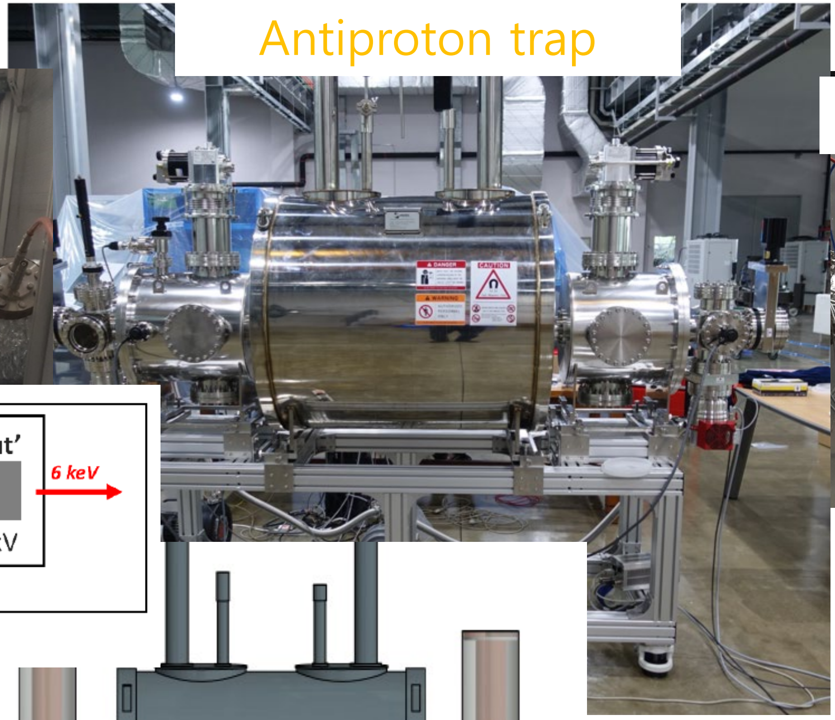


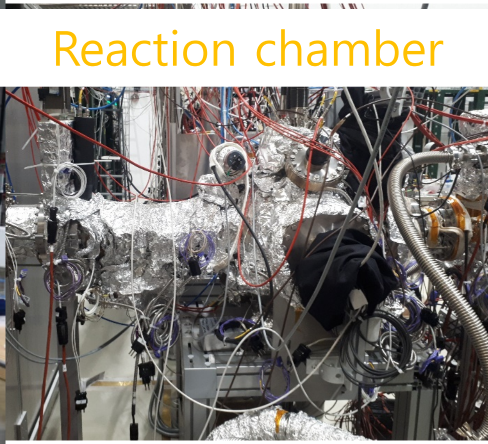
- Positronium target with cavity shape ($1x1x10mm^3$, $2x2x20mm^3$) is planed to make high density ($10^{12}cm^{-3}$ required) positronium
- About 1# $\bar{H}^+$aimed for every 2 minute (1 cycle of AD)
- The expected $\bar{H}^+$ number depends on excitation of Ps : New J. Phys. 23 (2021) 029501

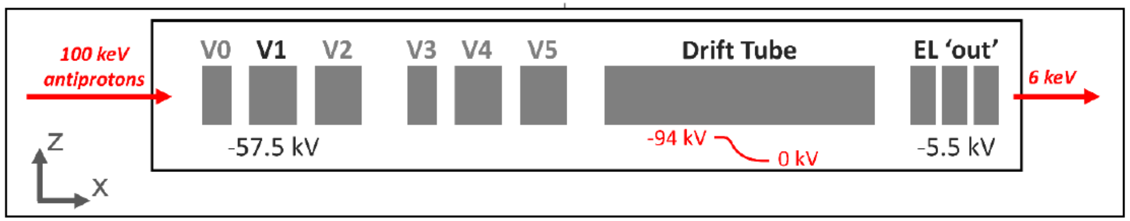
During 2022

- 9.1 x 10^6 o-Ps / AD cycle
- Flat target was used for higher o-Ps amount

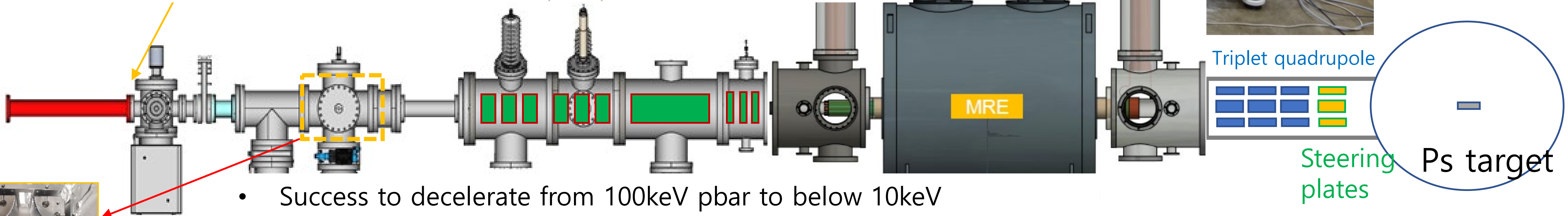
Antiproton beam line

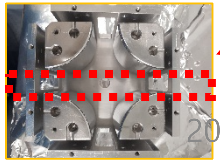






A. Husson et al., *NIMA* **1002** 165245 (2021)

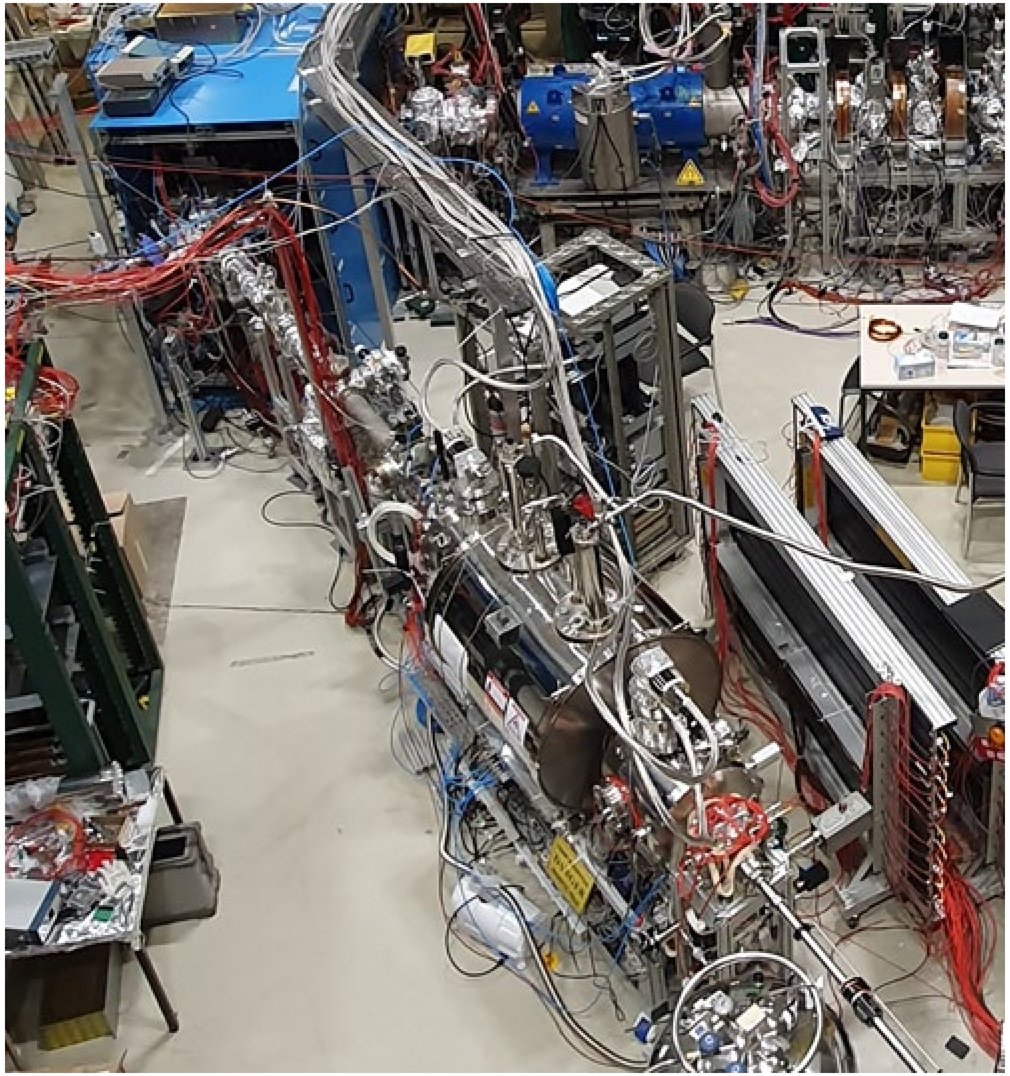


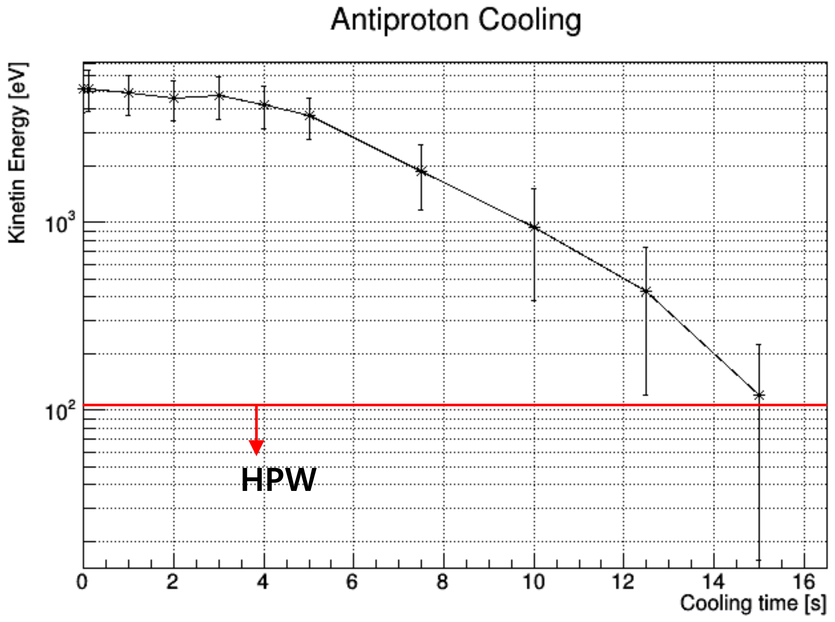


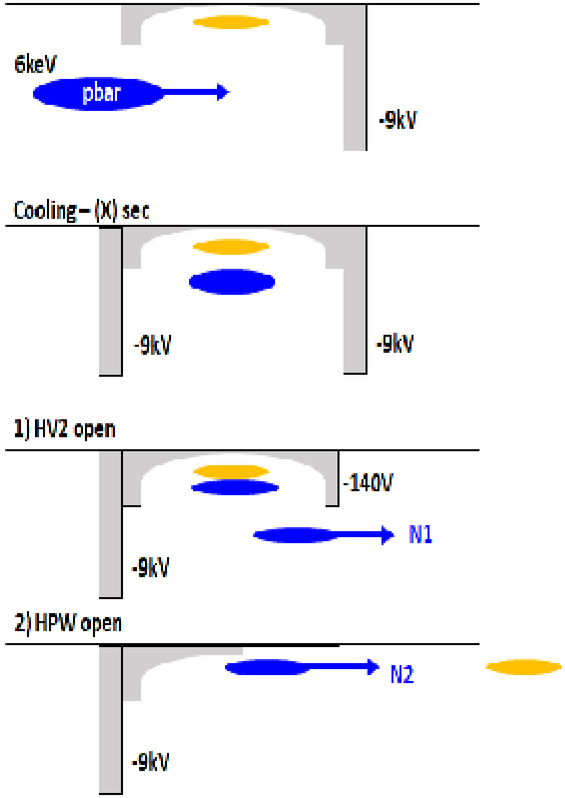
- Success to decelerate from 100keV pbar to below 10keV
- Stable operation for a year (commissioning done)

Antiproton trap

From B.C.Lee

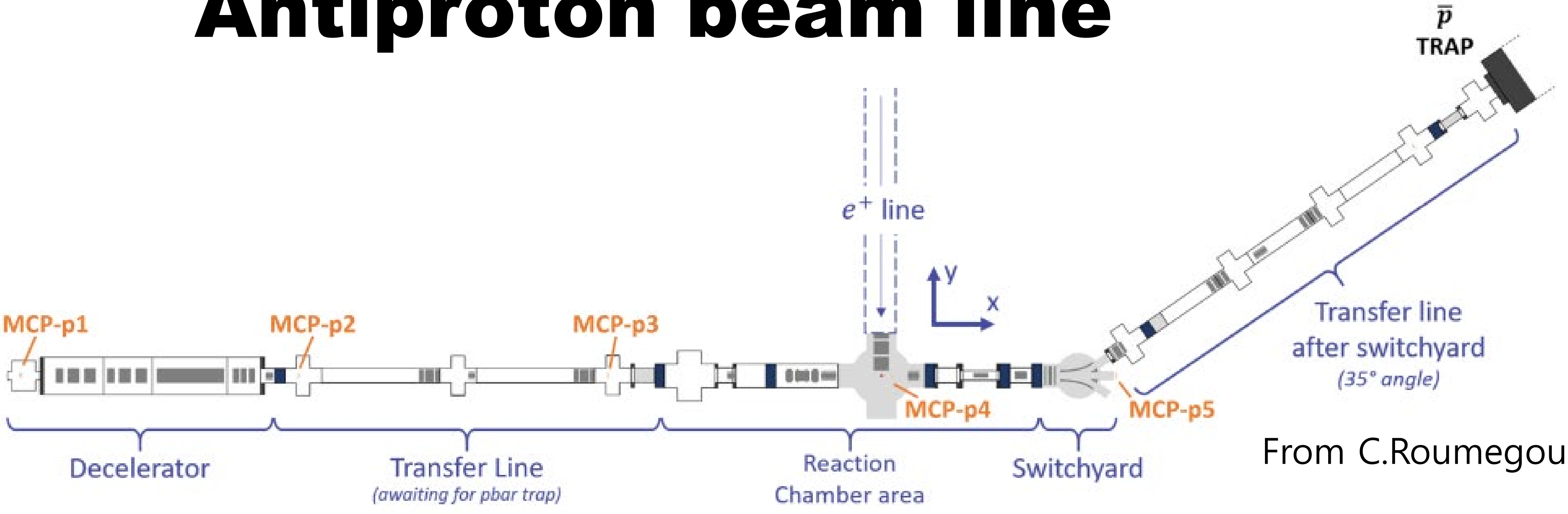






- $N_{\bar{p}} \sim 10^5$, $N_e \sim 10^7$, $B = 5T$
- MRE : T = 14K, P ~10^{-10}mbar
- 6keV → 1keV : 10sec / 6keV → 100eV : 15sec
- One experiment, one shot for each data point
- Error was given by sigma of the fitting function
- Only limited beam time was given

Antiproton beam line



From C.Roumegou

- During 2022

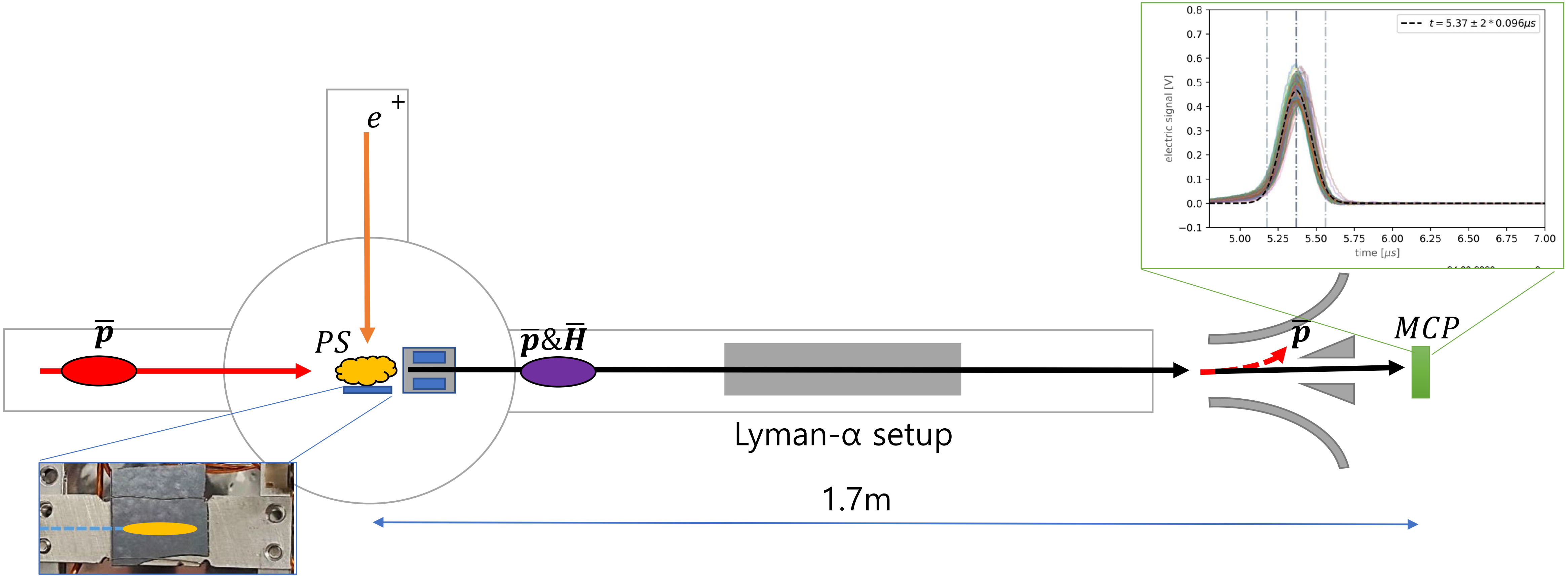
Transfer line is place for beam tuning (Antiproton trap is installed at the end of beam line for development)

- Initial beam intensity : 7 x 10^6 pbar per cycle

- Beam intensity in the target : 3 x 10^6 pbar per cycle

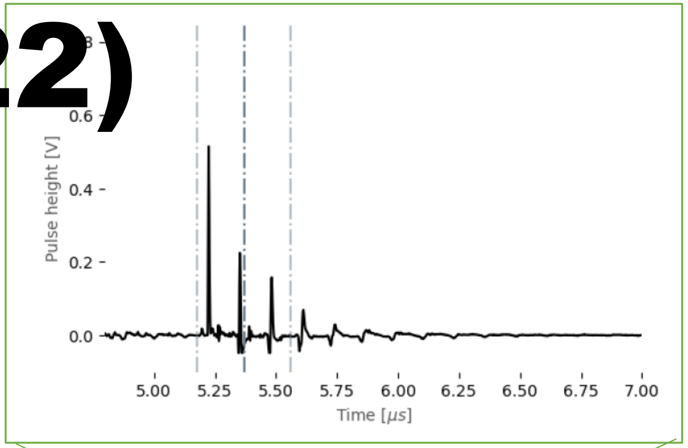
- At the antihydrogen detector (MCP) : ~30% transmission efficiency

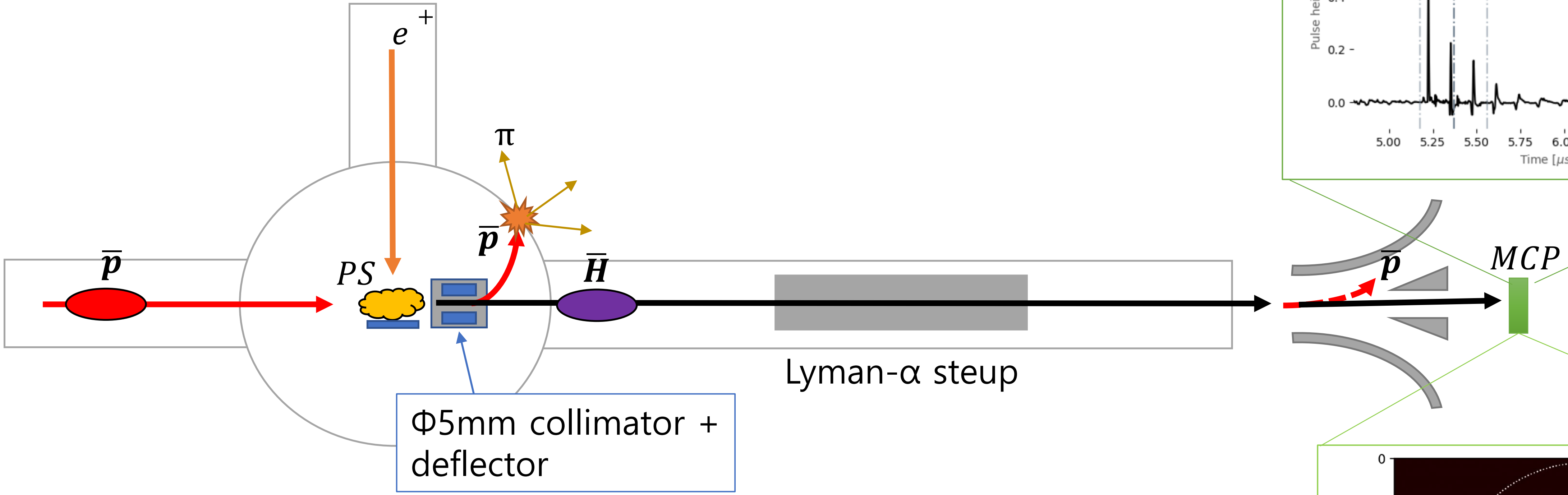
Antihydrogen production scheme (2022)

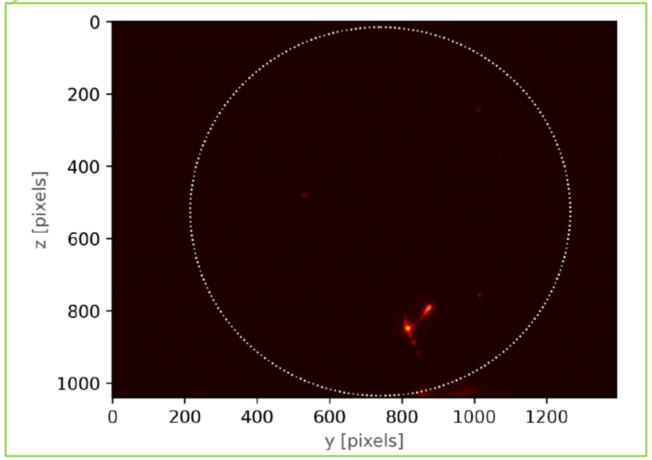


- Squeezing positron beam to make long shape
- Flat reaction target (no cavity type) for o-Ps production for more o-Ps production and easy guiding of antiproton beam
- Antiproton with KE 6keV and σ_t<100ns hits the produced o-Ps (τ=142ns) by time synchronization

Antihydrogen detection (2022)

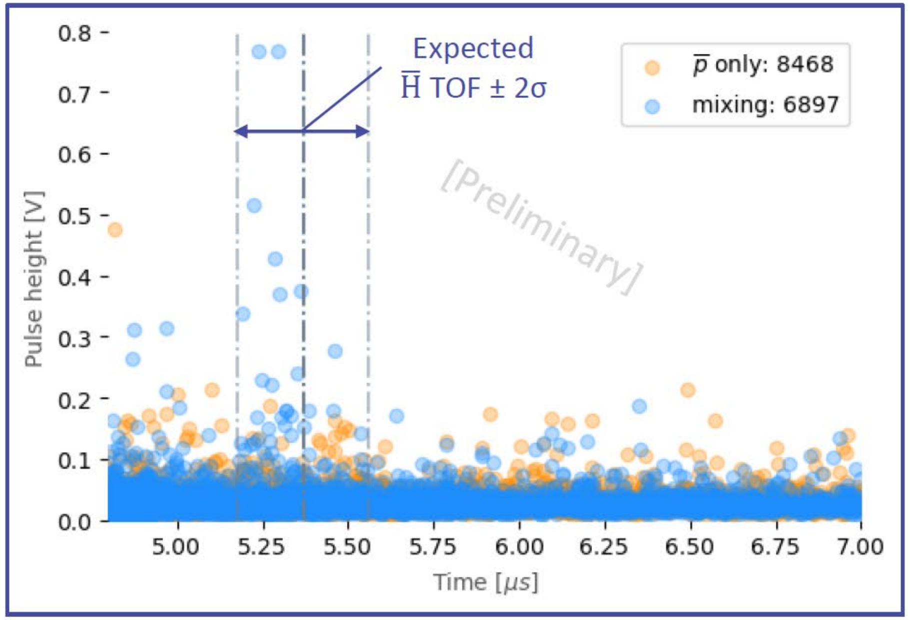


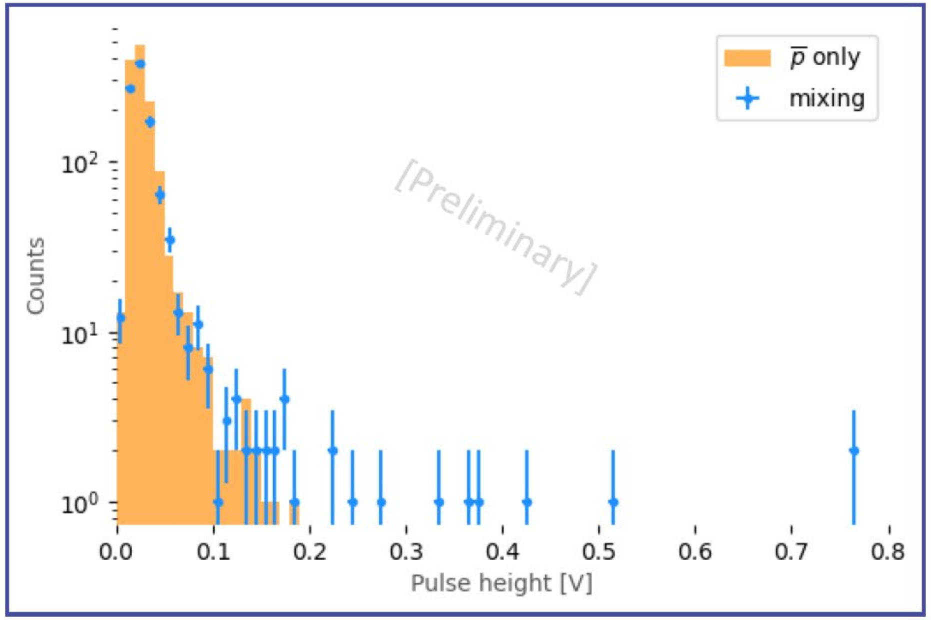




- Antiproton is focused at the reaction target with small emittance for the transmission of antihydrogen until MCP at 1.7m distance after the reaction
- Antiproton beam just after reaction is deflected by electric deflector and hits vacuum chamber.
- By 1.7m travel length, contamination of pion and γ background (generated at Reaction chamber) is reduced in the MCP signal.

Data taking & analysis





- Data taking runs

Signal : mixing (H-bar production) :6897#

Background : pbar only : 8468#, positron only 447#

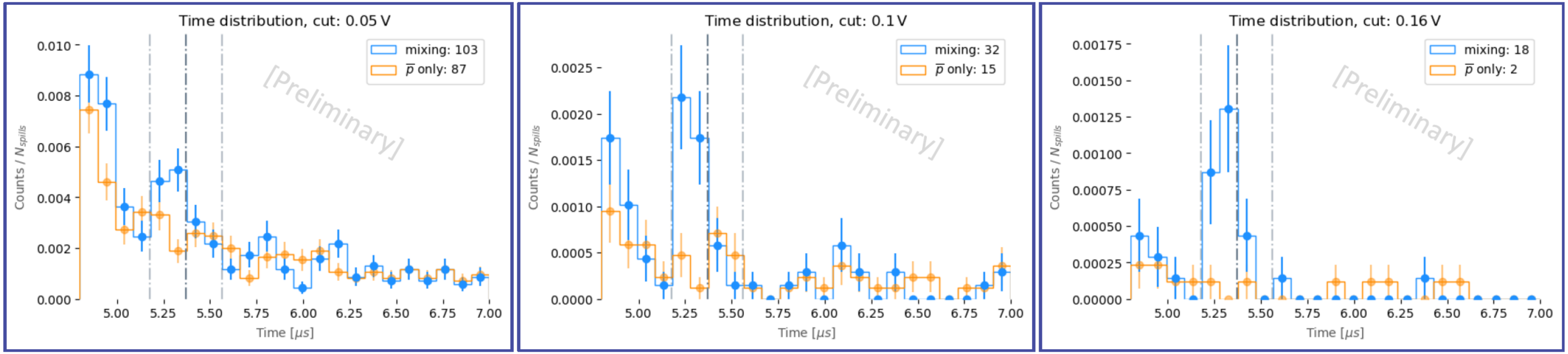
- Data analysis

Electric signal from MCP is (only) used for data analysis for this preliminary result

Maximum signal In the signal time window (selected by Time of Flight with 2σ window) is selected

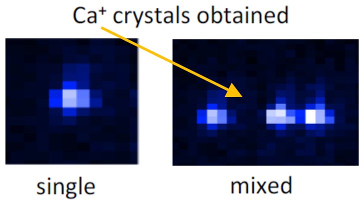
Signal and background show different in pulse height distribution

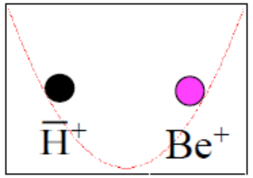
Preliminary result

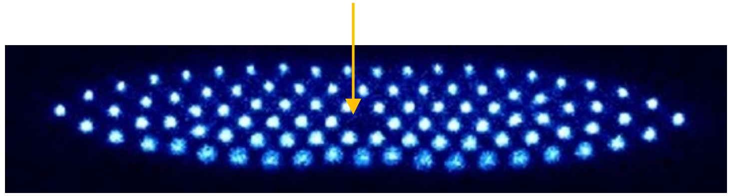


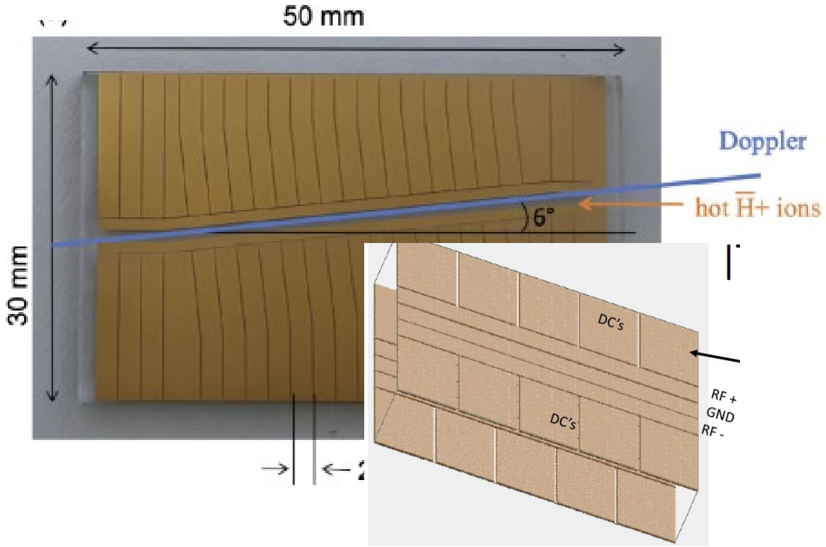
- Antihydrogen above 3σ is detected
- (First) production of antihydrogen by charge exchange between o-Ps and antiproton **beam**
- Expected antihydrogen production rate ~1.1+-0.4 $\bar{\mathrm{H}}$ per 100 spills and measured value's order seems roughly matched (no measurement for the cross-section yet)

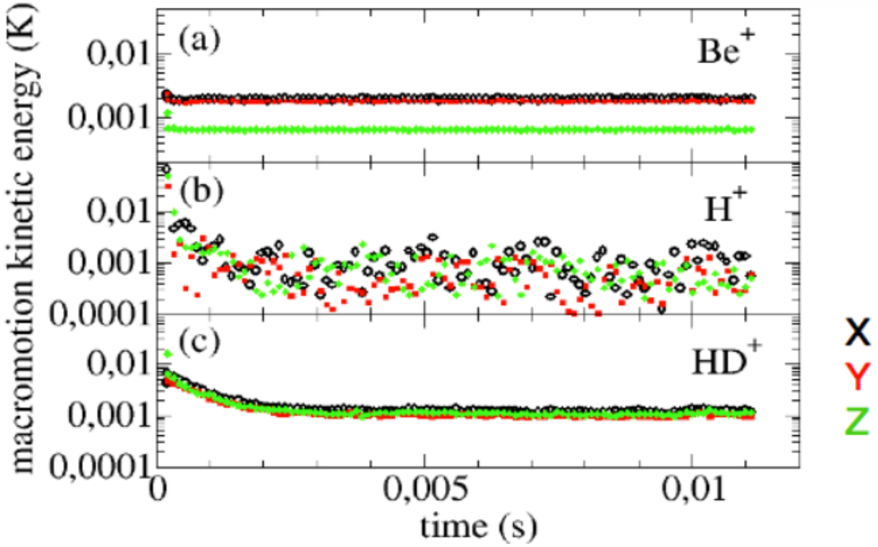
Cooling traps

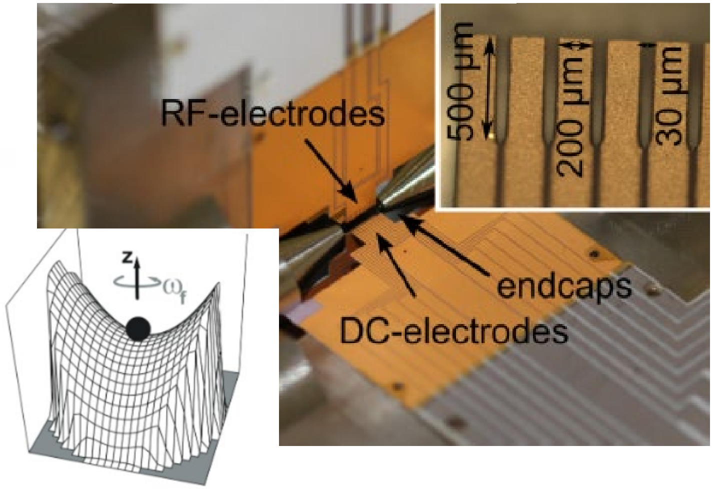












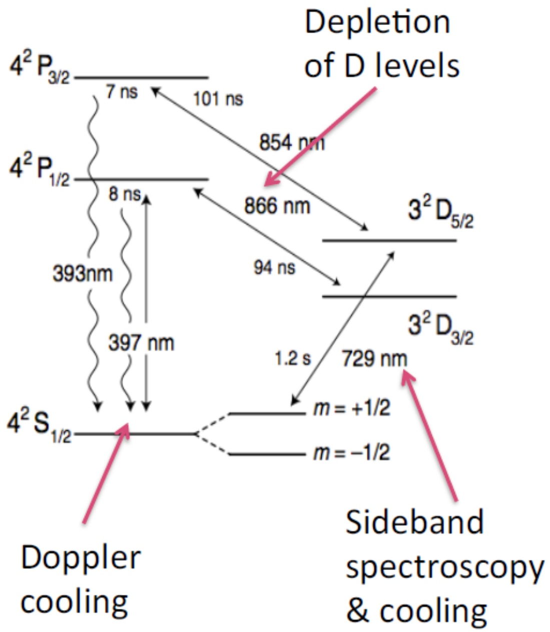
1. Capture trap (ITO trap) : capturing by DC switching+ rf voltage electrodes

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))

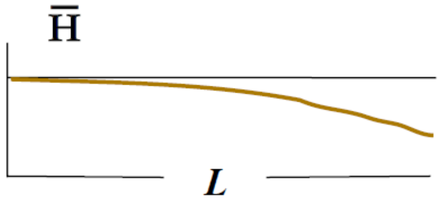
← HD^+ to reduce mass ratio for better coupling in simulation (similar charge to mass ratio required)

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

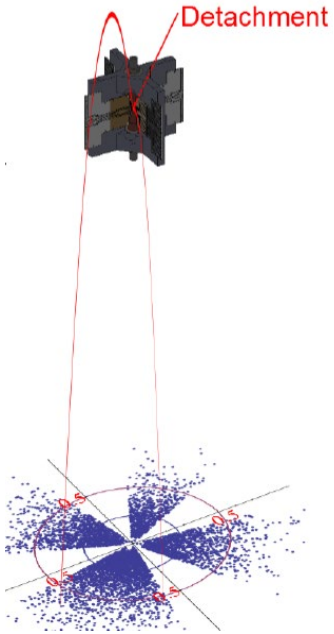


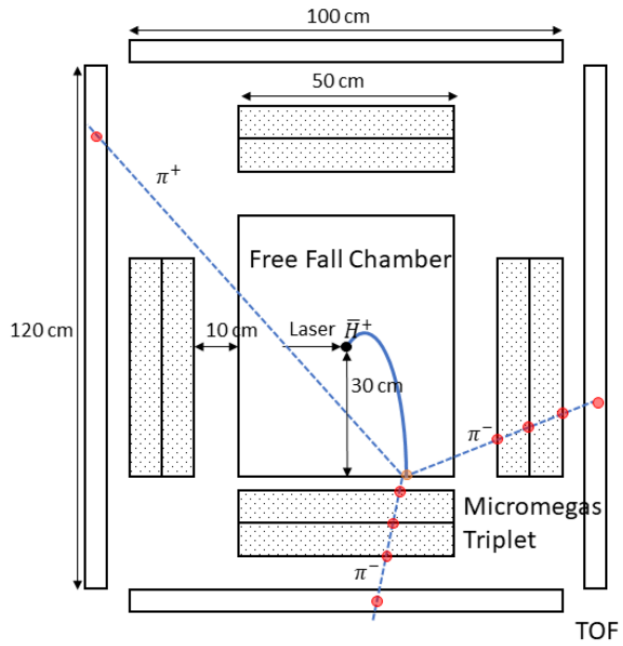
Freefall measurement

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



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

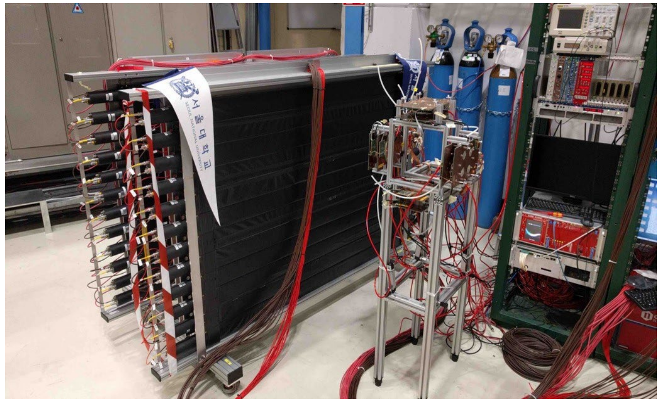




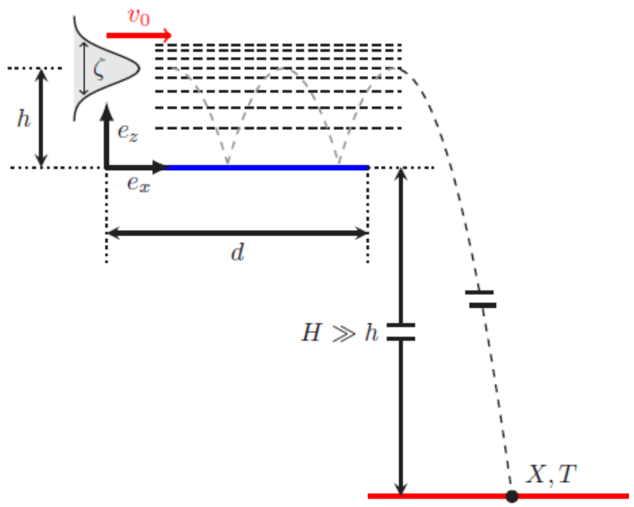
- Initial direction : temperature (0.44m/s for 1MHz) + photon recoil(0.24m/s) + positron emission (~0.3m/s for E_c = 1ueV)
- Length :10cm, height : 30cm (cf Aegis : L = 1m, h = 20um)
- Small magnetic field gradient, UHV, etc for systematic uncertainties have been studied
- Freefall time : about 500ms 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)

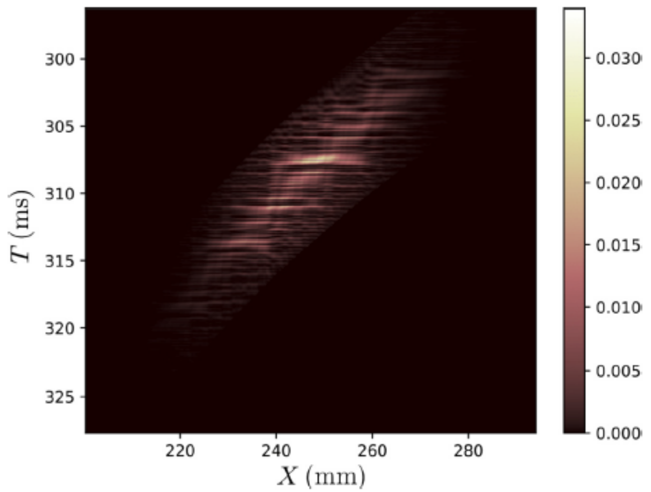
better description in G. Dufour et. al., Eur. Phys. J. C (2014) 74:2731

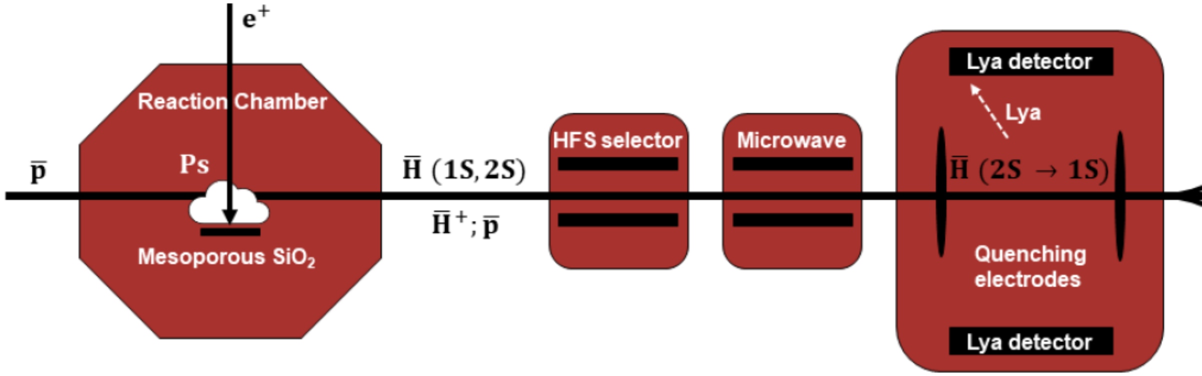
- Estimated number to measure 1% precision is 1500# detection of freefall antihydrogen (10uK)



Outlook for physics in GBAR







- Can be improved with proper shaper
- Quantum bouncing of antihydrogen (by Casimir-polder fore)

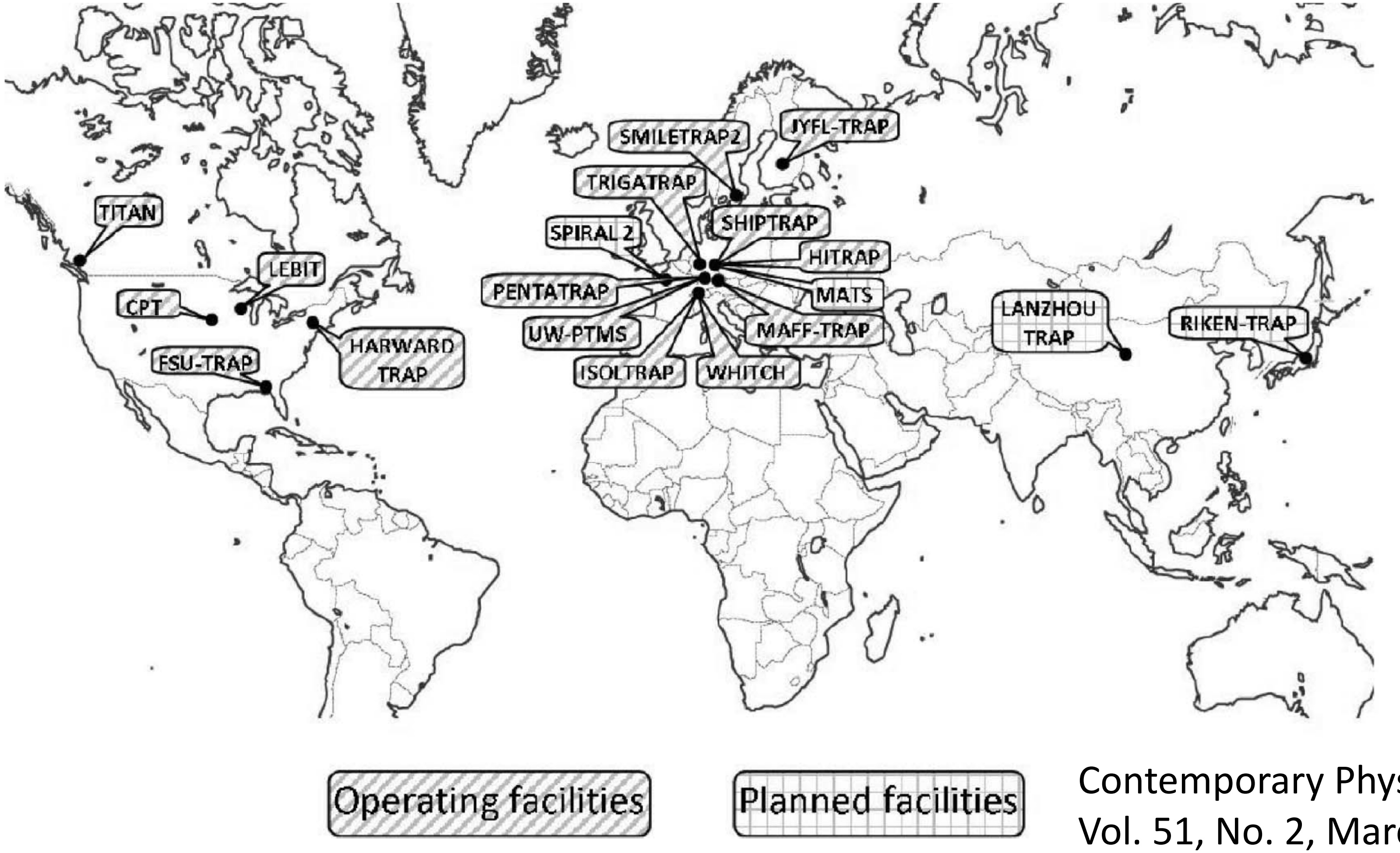
: ultra cold neutron demonstration (*Nature* **volume 415**, pages297 (2002))

+ velocity shaping : precision below 10^{-3} (Eur. Phys. J. C (2014) 742731)

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

- Device was commissioned in 2021 by hydrogen
- First attempt of $\bar{H}$ Lamb shift measurement is aimed
- GBAR can produce $\bar{H}$(2S) uniquely

Possible penning trap usage



Contemporary Physics
Vol. 51, No. 2, March–April 2010, 149–175

Penning trap usage in GBAR exp (possible new trap)

- The antiproton trap is a penning trap for accumulation & cooling for antiproton plasma production

- (Electron) sympathetic cooling, compression, acceleration

- CPT test : Antihydrogen molecule for the precision test

(phys. rev. A **98**, 010101(R))

- Antihydrogen ion production, cooling, detection(non-destructive)

: Zeeman frequency, Zeeman hyperfine frequency, vibrational frequency 103 more precision for m(e^+)/m($\bar{p}$)- m(e^-)/m(p) than $\mathrm{H}\&\bar{\mathrm{H}}$

- $\bar{H}^+ + \bar{\mathrm{p}}(100\mathrm{Kelvin}) \rightarrow \bar{H}_2^- + e^+$

~10T magnet required for Zeeman effect

Mass spectroscopy for neutrino study

Candidate search for Relic neutrino search

: (Nuclear Physics A 1031 122594 (2023) : about resonant relic neutrino absorption)

- Possible model : Echo experiment
- IBS is an institute with capability of relic neutrino search

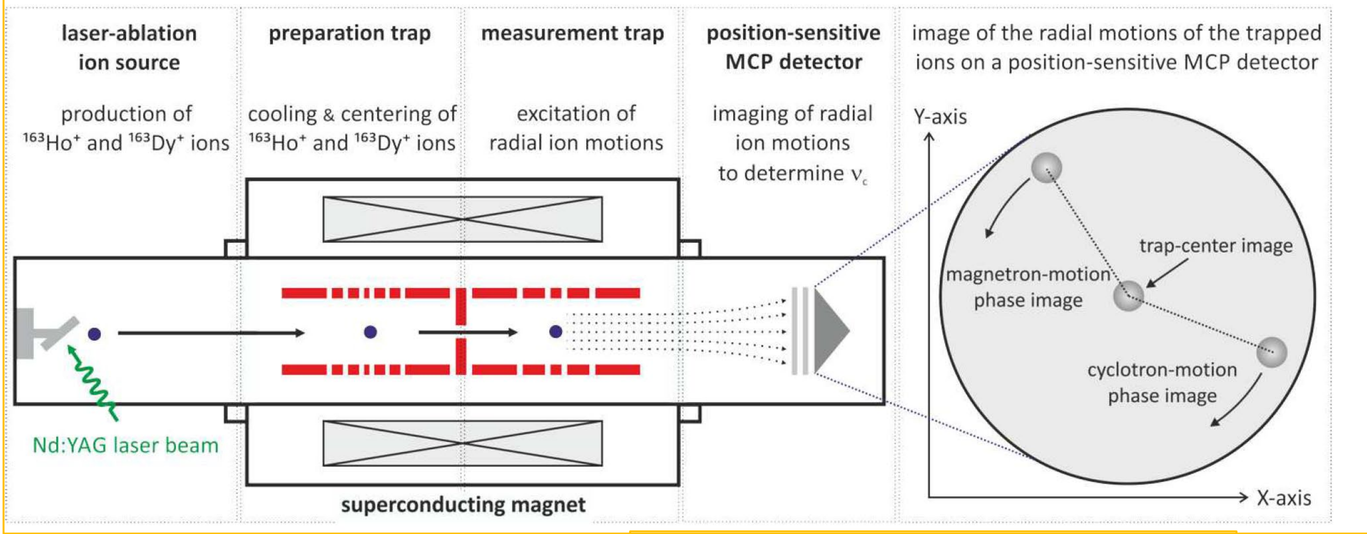
: low temp calorimeter with MMC

: Skillful for rare detection study

- missing part : mass spectroscopy and target production

- Target material : neutron injection (reactor) to ${}^{N}_{Z-1}A$ target
- Long life time
- ~7T magnet (commercial, ,<1ppm (+-10cm) required)
- gbar(<=3.75ppm (0,0, +-40cm), +-10ppm(Φ50x80)

)



SHIPTRAP as an example

- Required precision down to δm/m ~ <E-8 (PI-ICR), E-10 by (FT-ICR)

ex) 159Dy→159Tb : m(159Dy) =158925745.96 +-1.544, m(159Tb) = 158925353.707 +-1.184

Capture cross section σ (Dy158 neutron capture)= 43+-6millibarn (dy158: abundance 0.096%)

Uncertainty (TOF-ICR) $\delta m/m \sim 1/(\gamma_c T_{RF} (N)^{0.5})$: N ~few hundreds#

Mass spectroscopy in nuclear physics

- Short life time candidate for the nuclear physics
- For nuclear structure study, nuclear astrophysics study,
- On-line for short-lived beta decaying nuclei
- Destructive : PI-ICR technique to $\delta m/m < 10^{-8}$ for $\tau < 1s$

Table 1 Penning-trap mass spectrometers at radioactive ion beam facilities[a]

Name	Year	Location	Facility	Reaction(s)
ISOLTRAP	1987–present	ISOLDE, CERN	ISOL	Spallation, fission
CPT	1998–2009	ATLAS, ANL	In-flight	Transfer, fusion–evaporation
CPT	2009–present	CARIBU, ANL	ISOL	^{252}Cf fission
SHIPTRAP	2004–present	SHIP, GSI	In-flight	Fusion–evaporation
JYFLTRAP	2004–present	JYFL, Jyväskylä	IGISOL	Various
LEBIT	2005–present	NSCL, MSU	In-flight	Fragmentation
TITAN	2007–present	ISAC, TRIUMF	ISOL	Spallation, fission
TRIGATRAP	2017–present	TRIGA, Mainz	Reactor	Fission

Annu. Rev. Nucl. Part. Sci. 2018. 68:45–74

Future plan

GBAR experiment (short term : before LS3)
- Increasing o-Ps density
- Cross-section measurement (Antihydrogen production)
- Lyman-α (antihydrogen) measurement
- Antiproton recycler preparation
- Antihydrogen ion production

Development in IBS
- Design a new penning trap and development

backup

- The average thermal neutron flux inside the crystal is around 3.5×1013 n/cm2sec for all cases over 60 cm of the crystal length.
- "These ideas can be summarized in the strong equivalence principle (SEP), which states that: 1. WEP is valid for self-gravitating bodies as well as for test bodies. 2. The outcome of any local test experiment is independent of the velocity of the (freely falling) apparatus. 3. The outcome of any local test experiment is independent of where and when in the universe it is performed."

  Reference: https://www.physicsforums.com/threads/weak-and-strong-equivalence-what-is-the-difference-really.363402/