GBAR experiment

Center for Underground Physics
IBS

Bongho Kim

Motivation

: **Interest of antimatter** about their **interaction** & **property**

❖ Gravitational Behavior of Antihydrogen at Rest (GBAR)

- First test of gravity in the realm of antimatter
- Test of Weak Equivalence Principle (WEP) for antimatter

:<m_g=m_i>equivalence between the inertial mass and the gravitational mass (for matter $\Delta(m_g/m_i)/(m_g/m_i)_{Be/Ti} = (0.3\pm1.8)10^{-13}$))

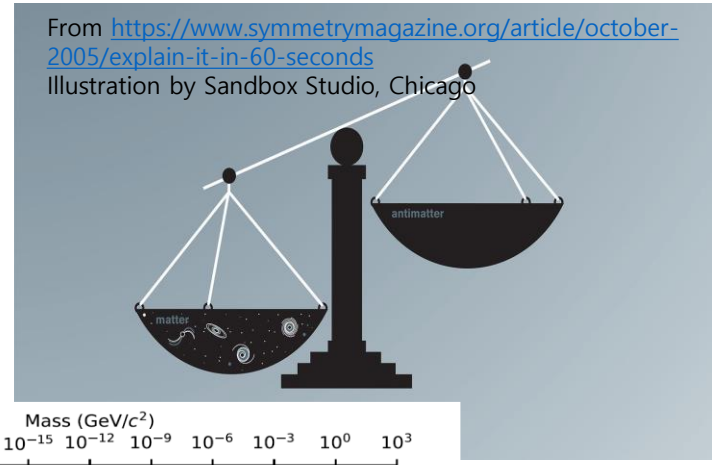
❖ Matter and antimatter asymmetry

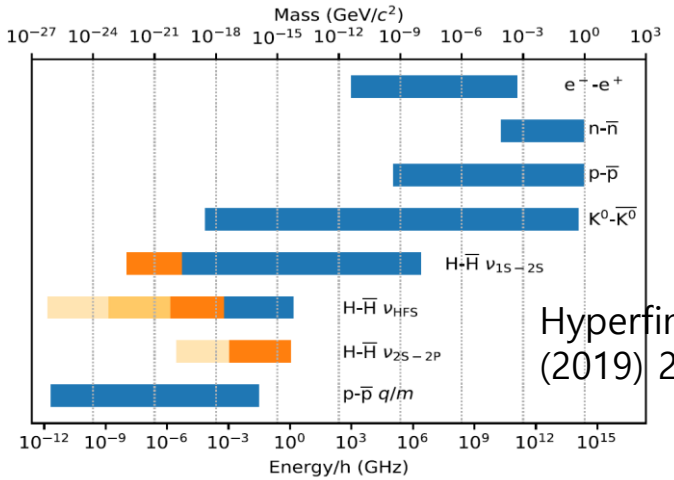
- Different with expectation by Bigbang and Standard Model,

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

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

→ Many CPT test has been performed between matter and antimatter

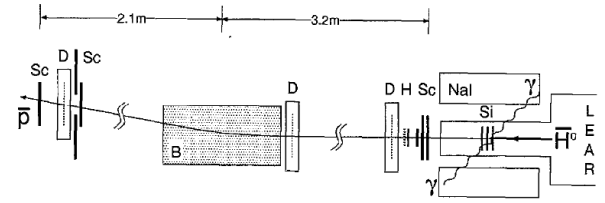


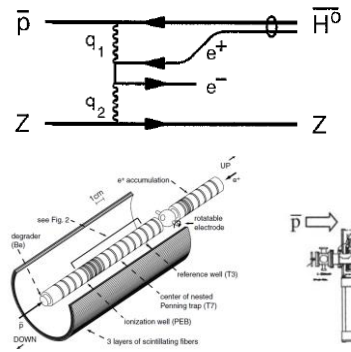


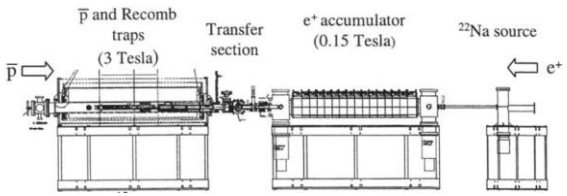
Hyperfine interaction (2019) 240:5

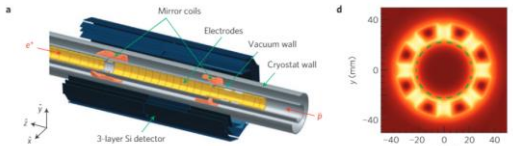
Recent breakthroughs of $\overline{H}$

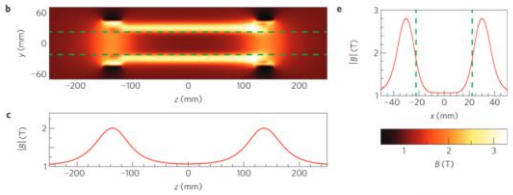
- 1995 : First production of antihydrogen at LEAR (Phys. Lett. B 368, 251) with stochastic cooling and electron cooling
- 2002 : Cold antihydrogen production at ATHENA(Nature 419, 456-459), ATRAP(Phys, Rev. Lett 89, 213401)
- 2010~2011 : Trapping antihydrogen (Nature 468, 673) up to 1000s (Nature physics, 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)

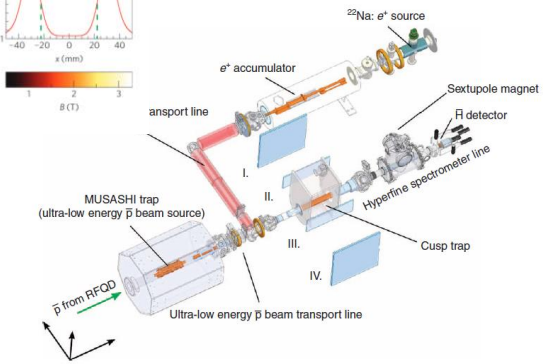












CPT test

- Spectroscopy of antihydrogen

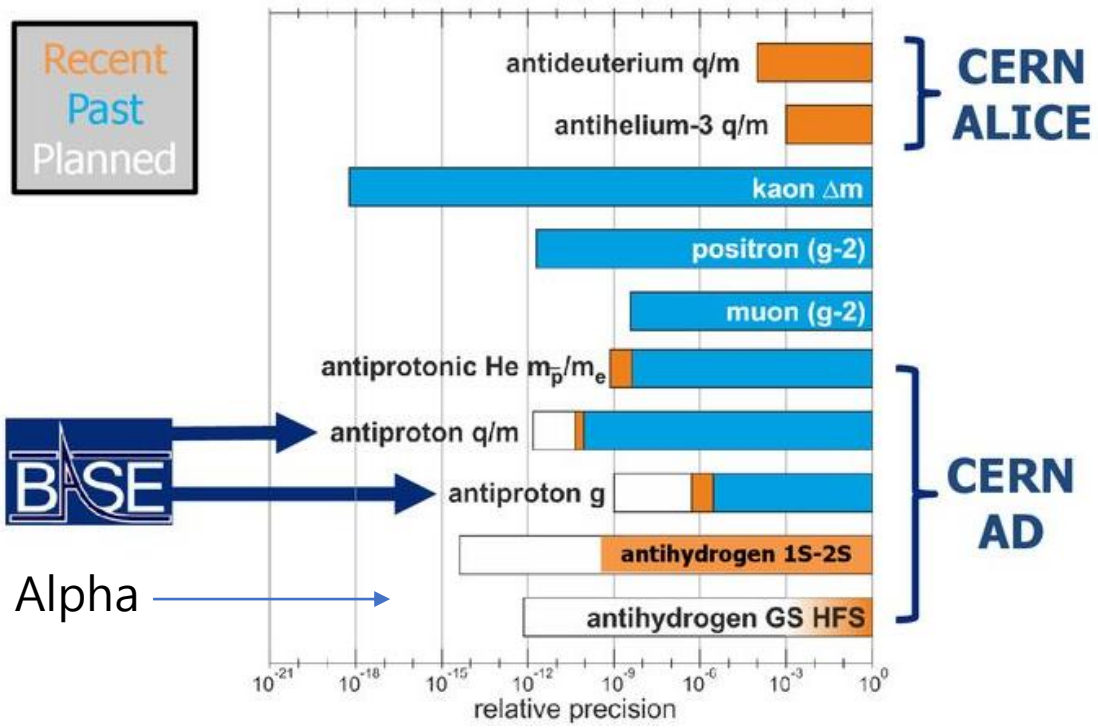
1S-2S transition : hydrogen $4.2e^{-15}$ – antihydrogen $2x10^{-10}$(2017) → $2x\ 10^{-12}$ (2018)

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

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

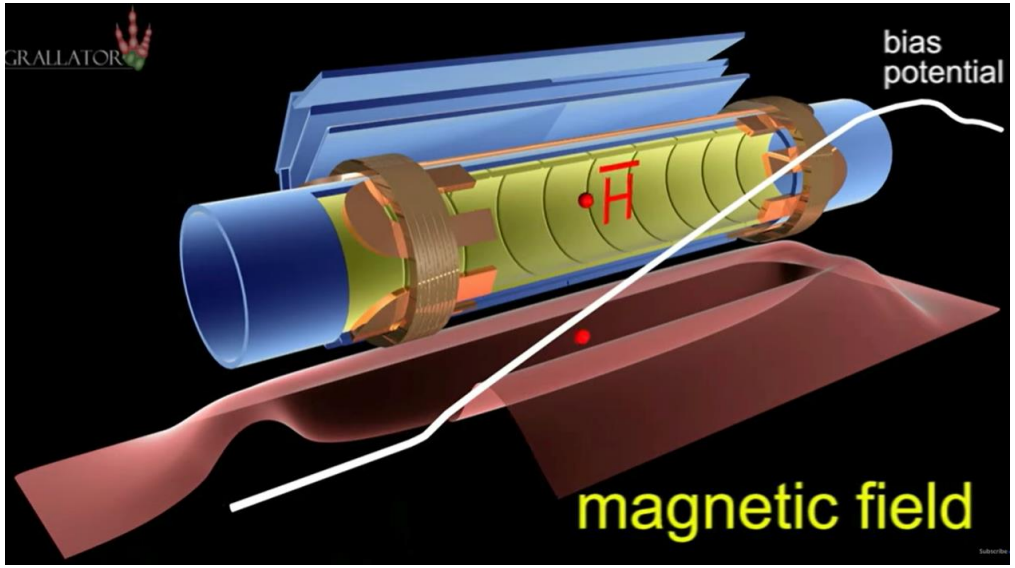
- Lamb shift : agreed a level of 11% ($2S_{1/2}$-$2P_{1/2}$) (nature 578, 375 (2020)) by ALPHA

- Proton & antiproton CPT test by BASE (nature 524, 196-199 (2015))
- WEP_{cc} BASE experiment, Nature, 601, 53-57 (2022)
- (There's also many fantastic results for exotic antiprotonic helium, etc..)

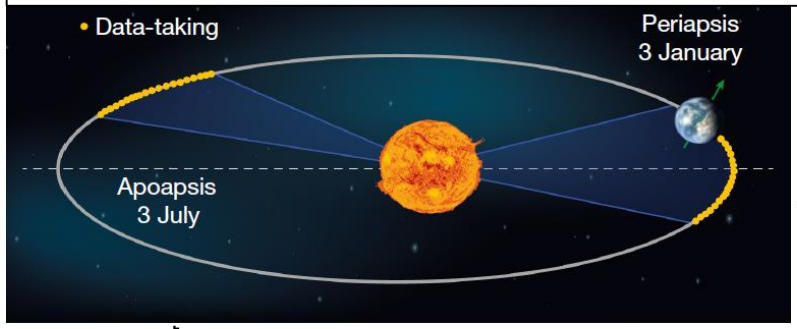


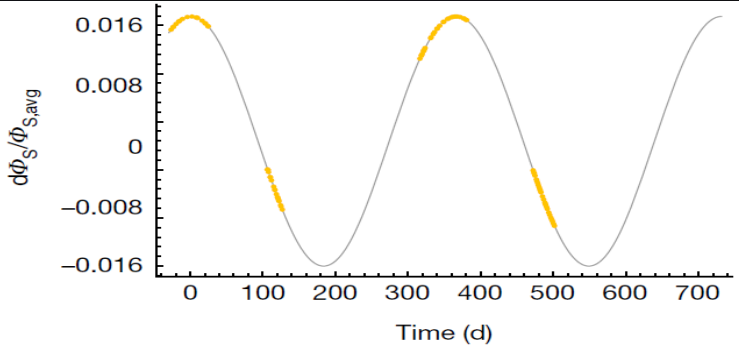
WEP test

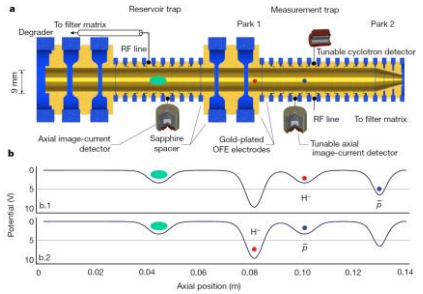
ALPHA experiment
Nature communications, 4, 1785 (2013)



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 : $|\alpha_{g.D} - 1| < 0.030$ (CL 0.68)

(Reference for better understanding of each WEP - M.Charlton, et. al., arxiv:2002.09348 (2022))

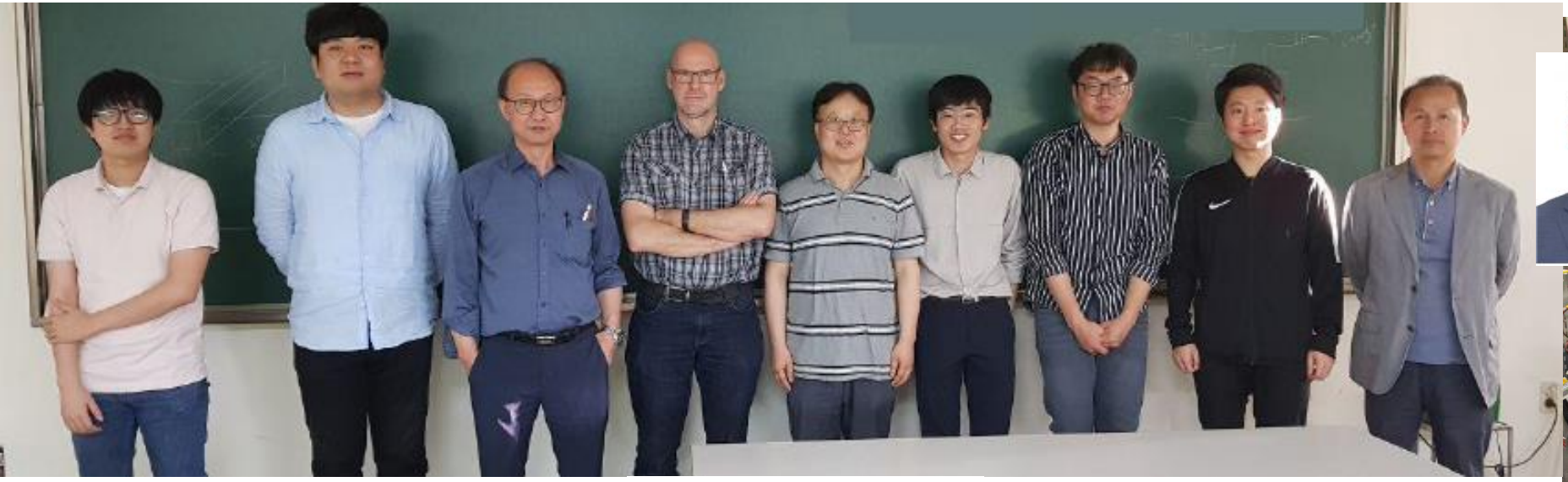
➔ Direct WEP_{ff} test for meaningful precision region is an interesting topic

GBAR collaboration

70 members
18 institutes
8 countries

Korean group
4 Institutes
6 Ph. D
7 GS

GBAR Korean collaboration



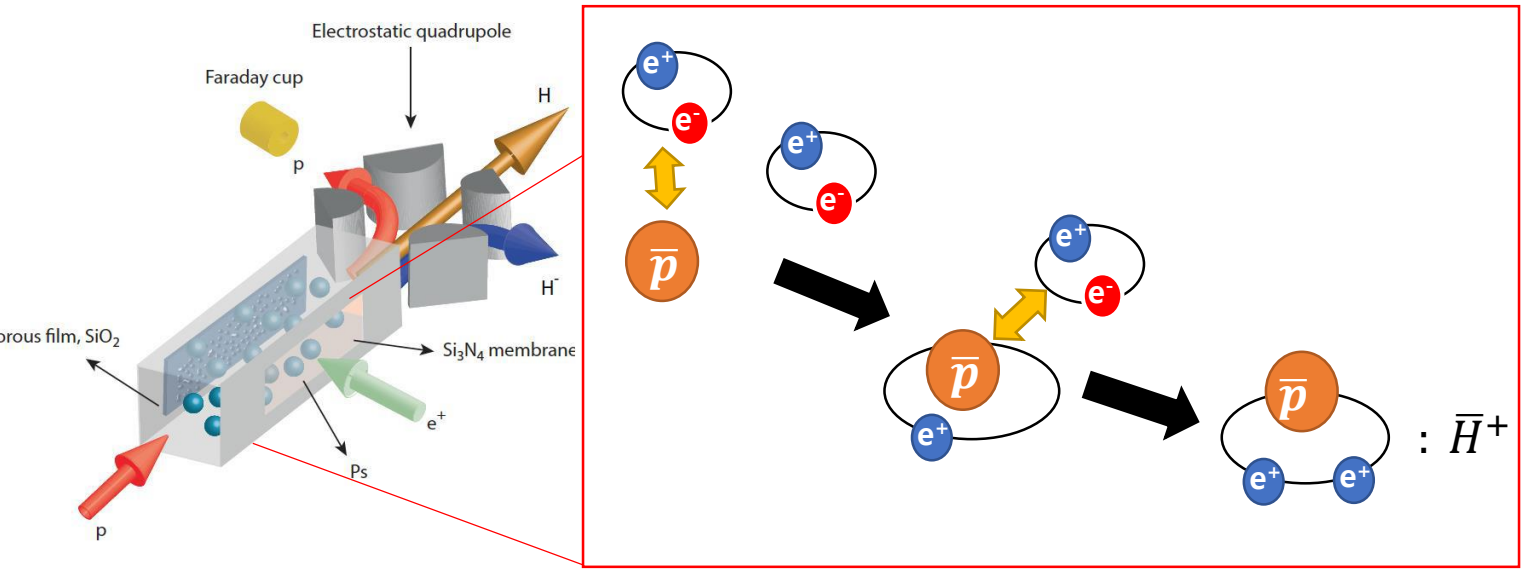
서울대학교 SEOUL NATIONAL UNIVERSITY

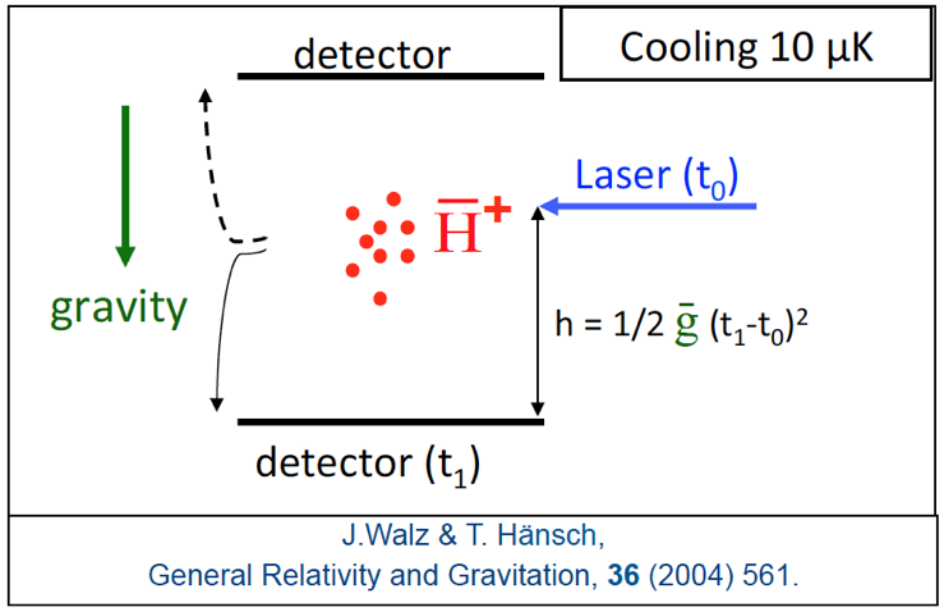
KOREA UNIVERSITY

ibs Institute for Basic Science

UNIST

GBAR overview





- Direct measurement of the gravitational acceleration of antihydrogen (universality of free-fall WEP (WEP_{ff}) below 1%
- $\bar{H}^+$ is required to get ultra-cold $\bar{H}$ (1500#) which can go below **10^{-5}** precision for WEP_{ff}(only ultracold antihydrogen can reach)
- Double charge exchange process between antiproton beam and dense positronium cloud

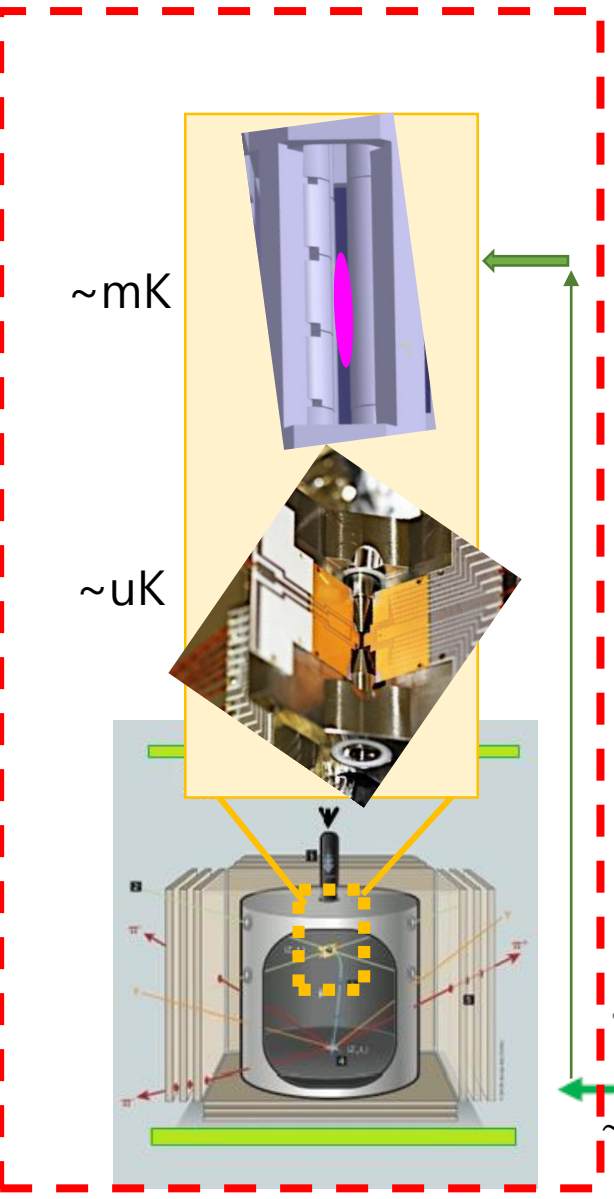
$\bar{p} + Ps \rightarrow \bar{H} + e^-$: **1st milestone**
$\bar{H} + Ps \rightarrow \bar{H}^+ + e^-$: **2nd milestone**

with

- Enough intensity of e^+ & $\bar{p}$
- Good beam phase-space

- Cooling antihydrogen ion down to **10uK** range (ultra-cold) with Be^+ to get extremely slow velocity : 3rd **milestone**
- After dropping one of e^+ (by photo-detachment laser), let the ultra-cold antihydrogen **freefall**.

Experiment Scheme



3.5→0.1GeV/c

AD

5.3MeV

ELENA

100keV ($0.5\times10^7\ \bar{p}$ /110s)

decelerator

pbar beam line

$\overline{P}$ trap

10eV~10keV

Laser Ps*

$\rho_{Ps} = 10^{12} cm^{-3}$

4kV

$\overline{H}$

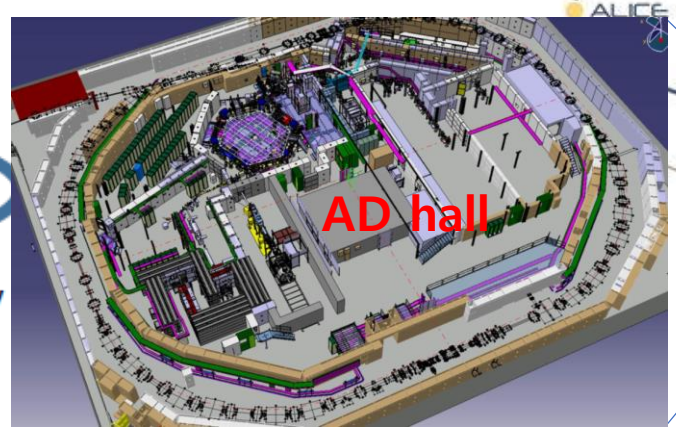
$\overline{p}$

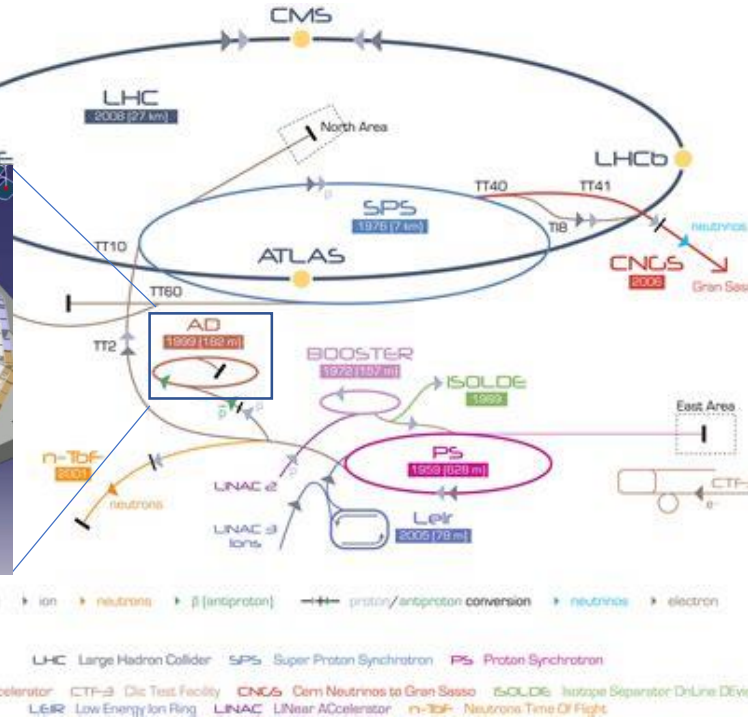
$\overline{H}^+$ ion

$\sim 1\bar{H}^+/bunch$

Lyman-α

Recycler $\#(\bar{p})$ x10





High field trap

Ne remoderator

buncher

BG trap

e^+ target

Linac

Positron beam line

10^{10} e^+/bunch

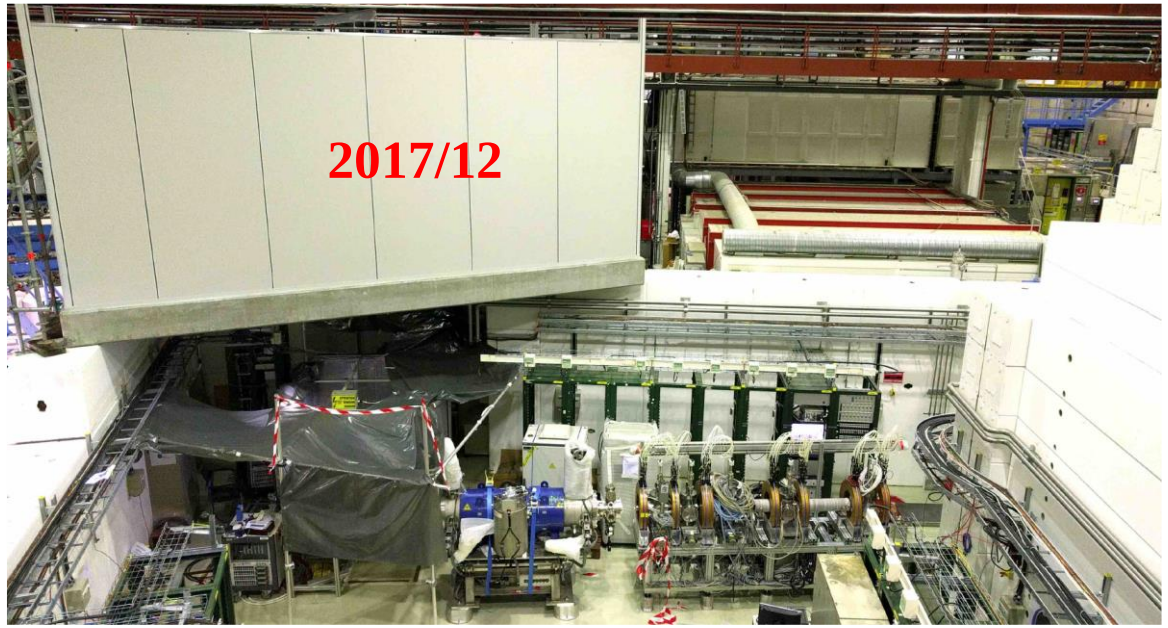
1MeV→3eV → 50eV

$3\times10^8 e^+/s$

e^- 10MeV

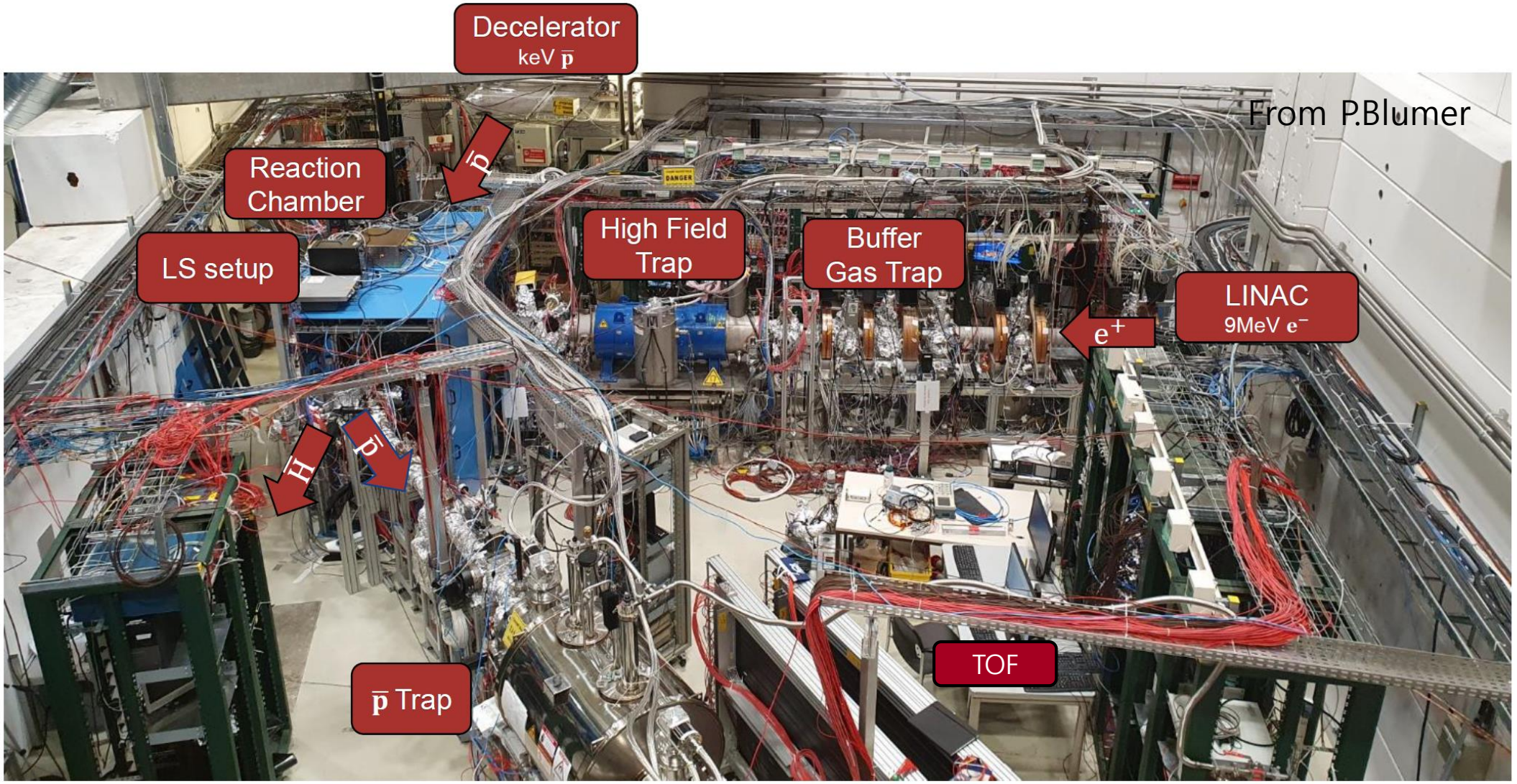
: after 2023

Experimental setup



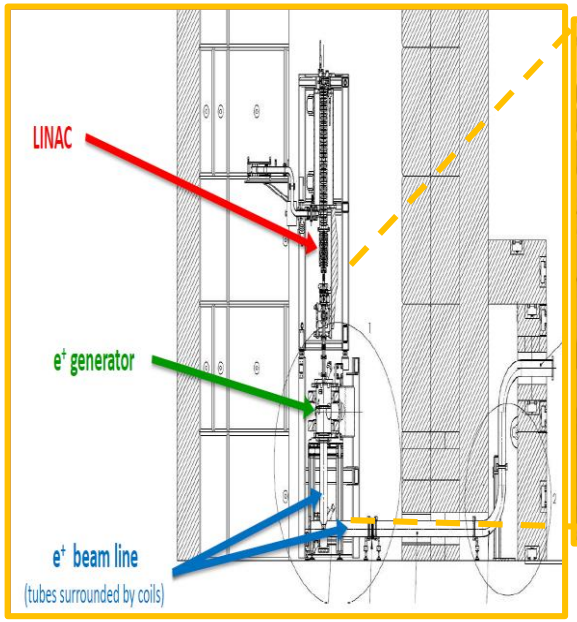
- 2007 : Letter Of Interest to CERN
- 2011 : Proposal to CERN
- 2016 : SNU & IBS joined MOU
- 2016-2018 : Experiment Installation
- 2019-2021 : Development of each devices

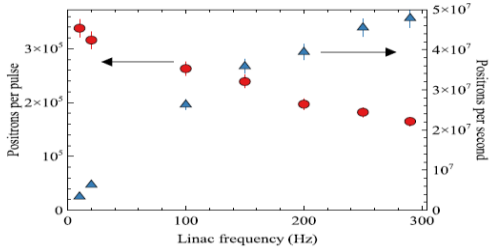
Experiment setup (2022)



Positron beam line

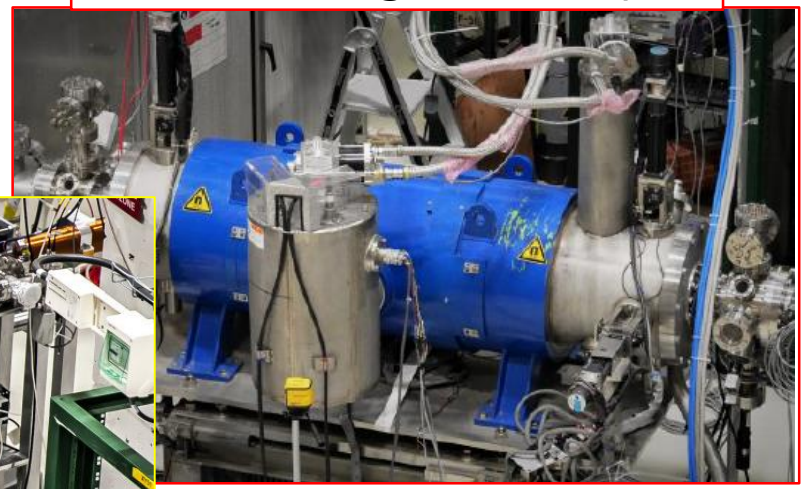
Linac and positron target





Buffer Gas trap

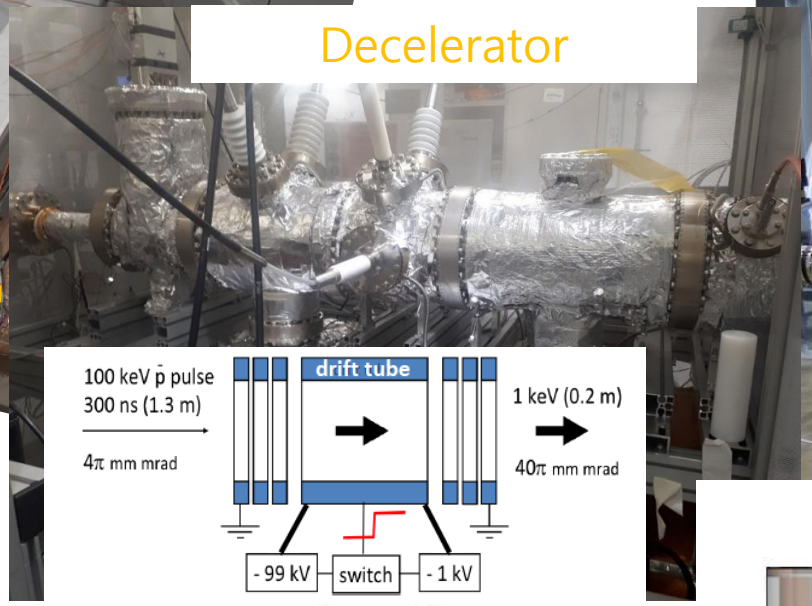
Positron high field trap



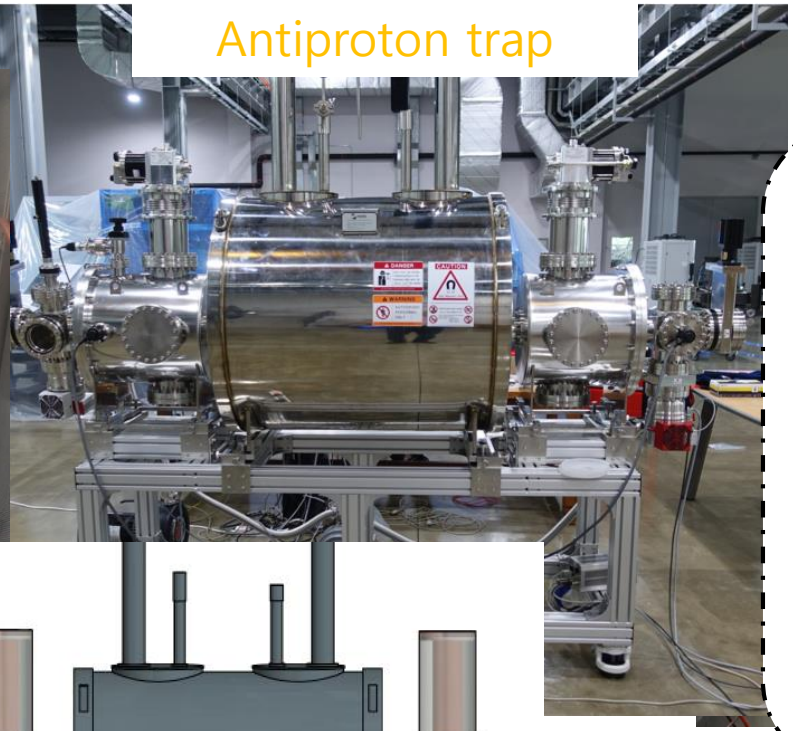
- Positron beam : (Near monoenergetic low energy by W moderator) positron beam generated from bremsstrahlung-induce pair production by 300Hz 9MeV e- linac with a goal to 3 x $10^8 e^+/s$
- Buffer-gas trap for positron accumulation with small energy spread → Ne re-moderator
- Positron accumulation by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

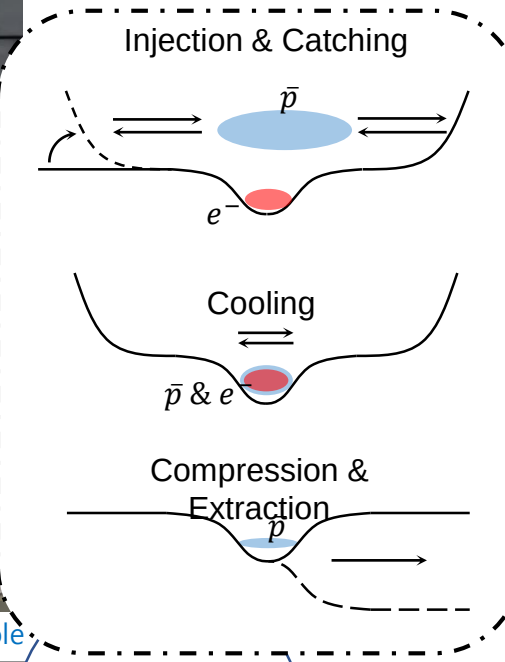
Antiproton and proton beam line

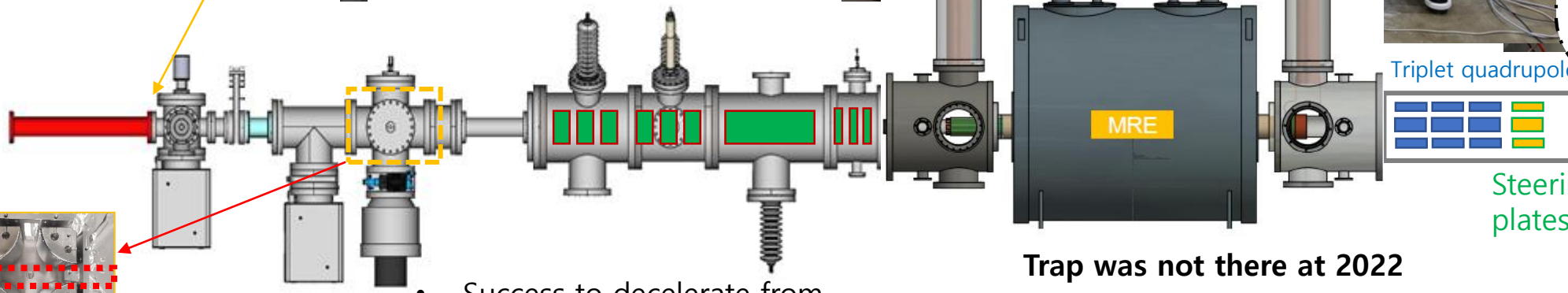
Decelerator

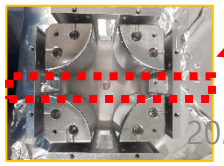


Antiproton trap





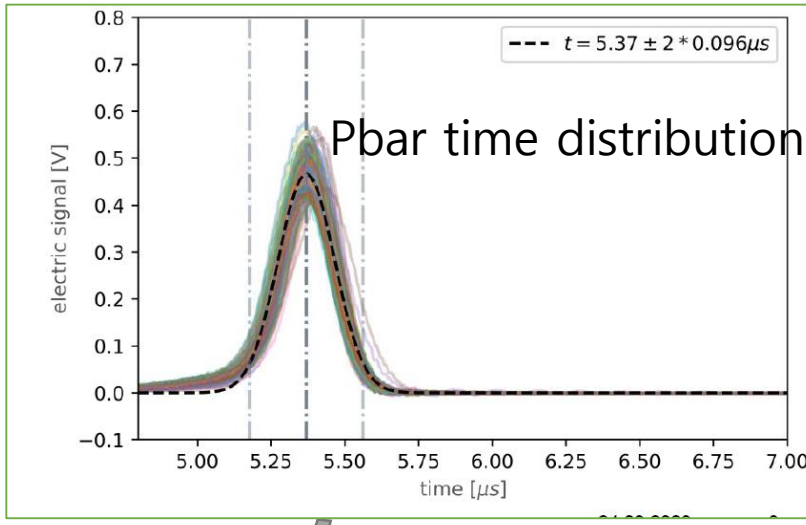




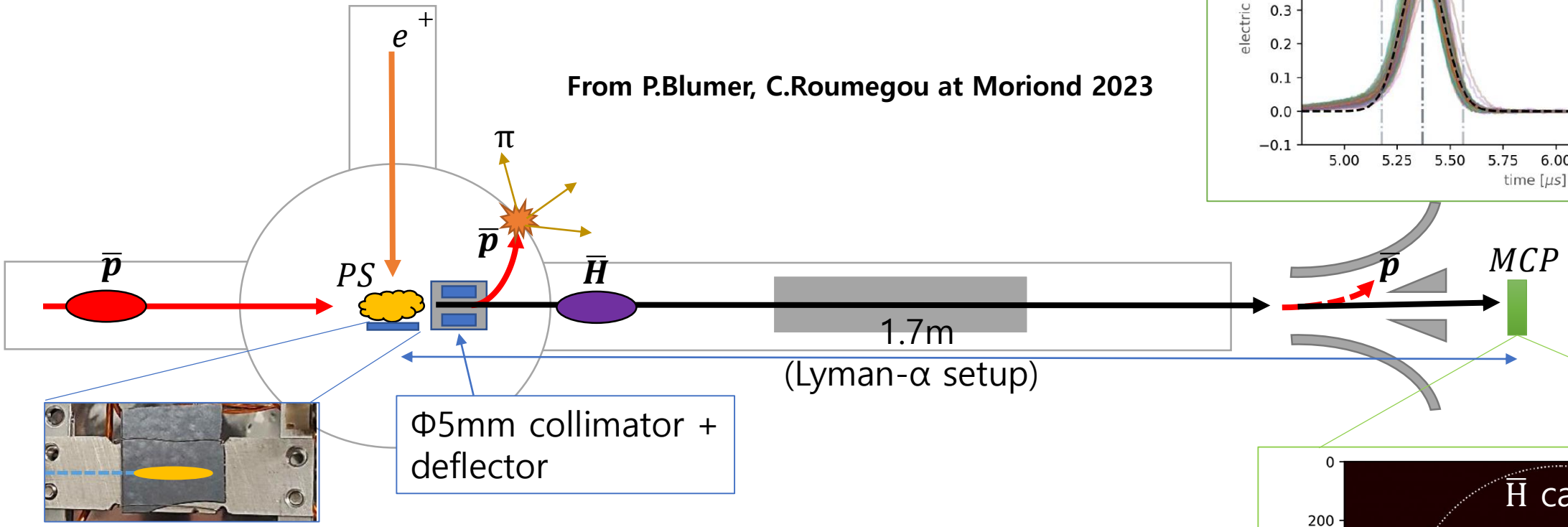
Trap was not there at 2022

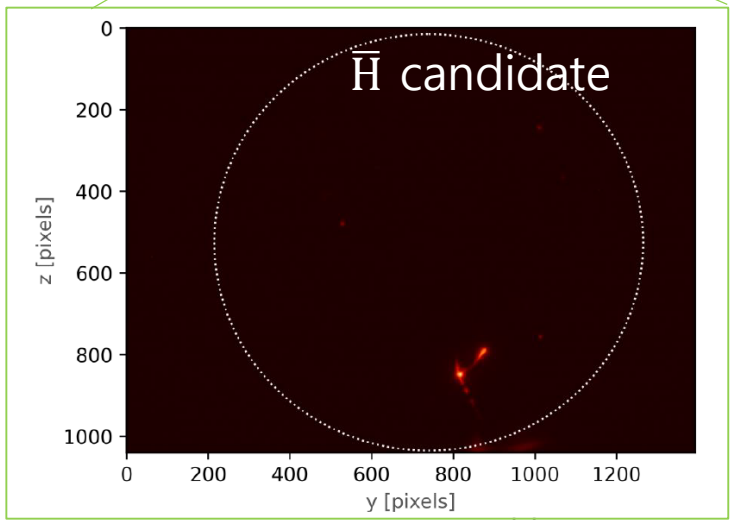
- Success to decelerate from 100keV pbar to below 10keV

$\bar{H}$ production (2022)



From P.Blumer, C.Roumegou at Moriond 2023

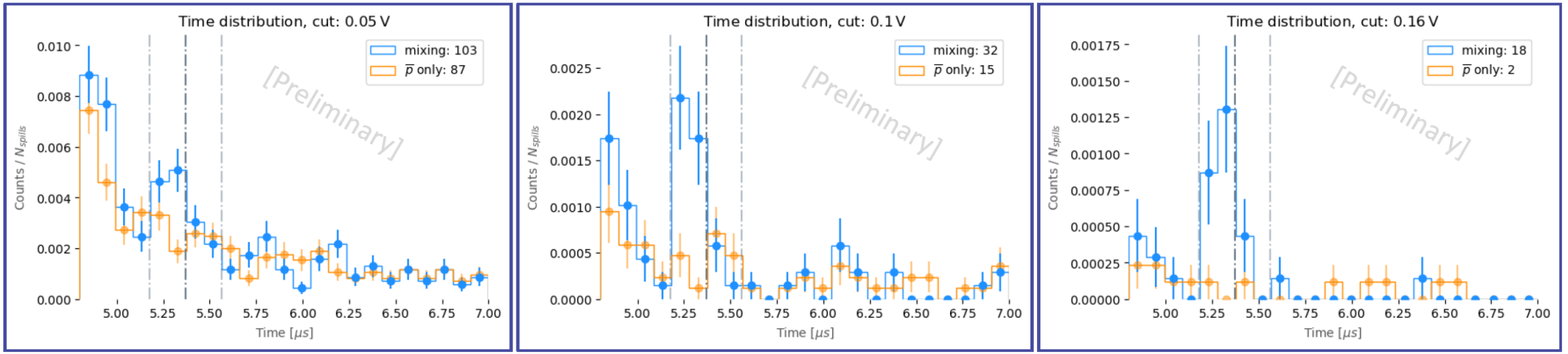




- $\bar{p}$ is tuned at the reaction target for the transmission of antihydrogen until MCP at 1.7m distance after the reaction
- $\bar{p}$ beam just after reaction(BG is deflected by electric deflector and hits vacuum chamber.
- By 1.7m travel length, contamination of pion and γ background (generated at Reaction chamber) is reduced in the MCP signal.

$\bar{H}$ production (Preliminary)

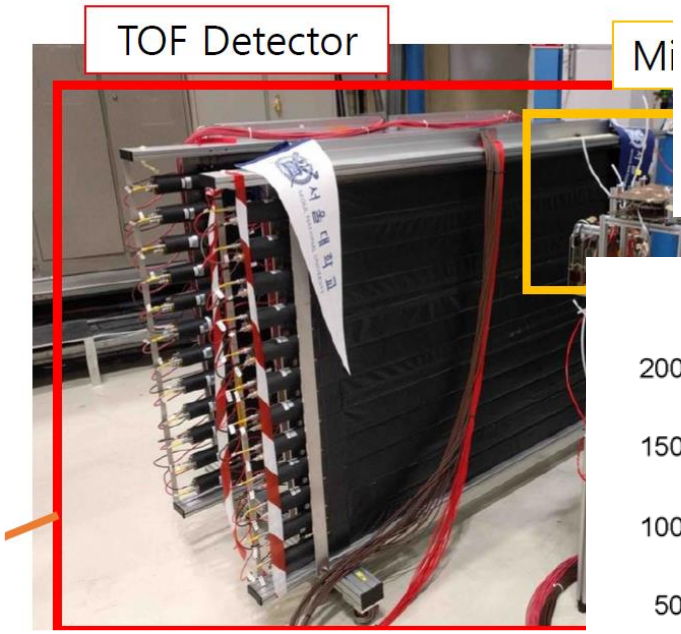
From P.Blumer, C.Roumegou at Moriond 2023

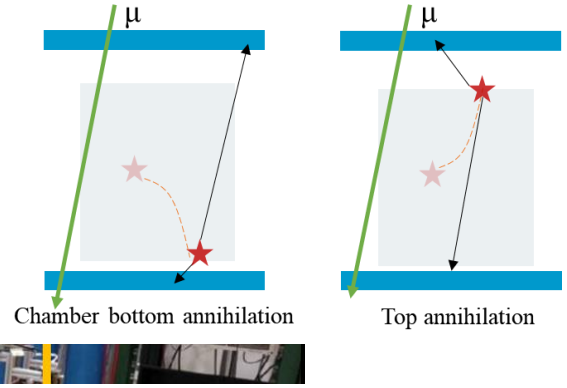


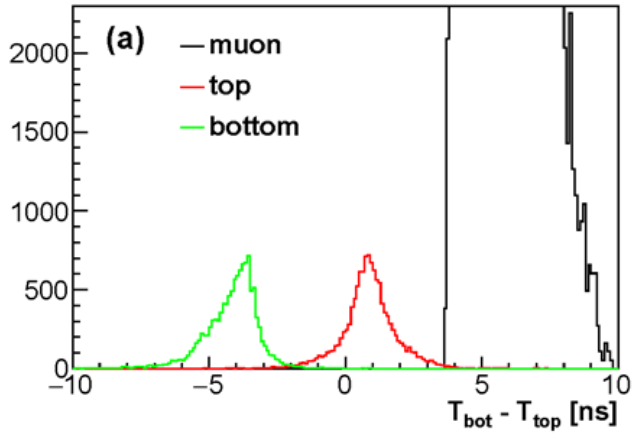
- Antihydrogen above 3σ is detected (which is **1st milestone**)
- (First) production of antihydrogen by charge exchange between o-Ps and antiproton **beam**
- Expected antihydrogen production rate ~1.1+-0.4 $\bar{H}$ per 100 spills seems roughly matched with calculated value (no measurement for the cross-section yet)

KGBAR group

- **Freefall detection**







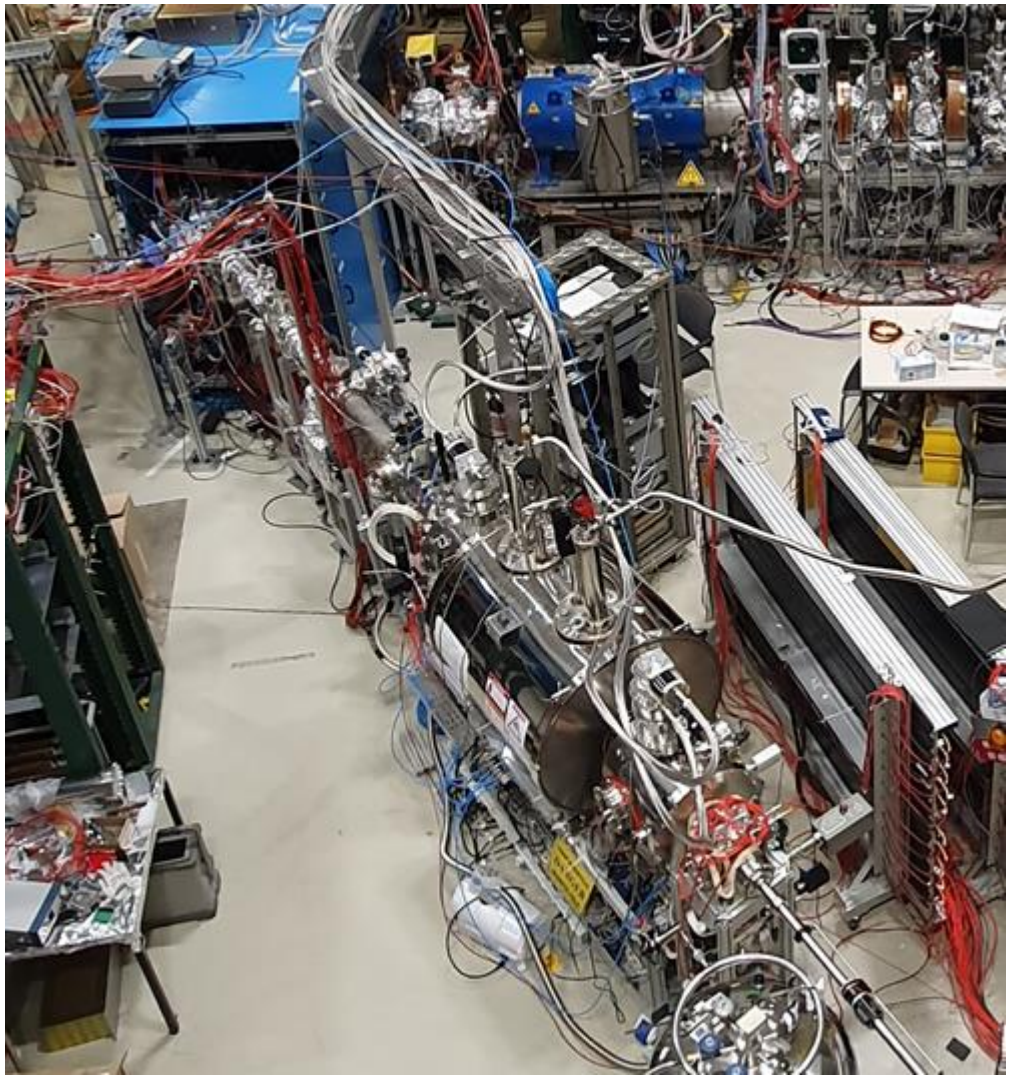
- Time of Flight (TOF) detector has been installed for freefall detection
- Hardware and simulation well prepared and it can measure sign of gravitational acceleration by 30#

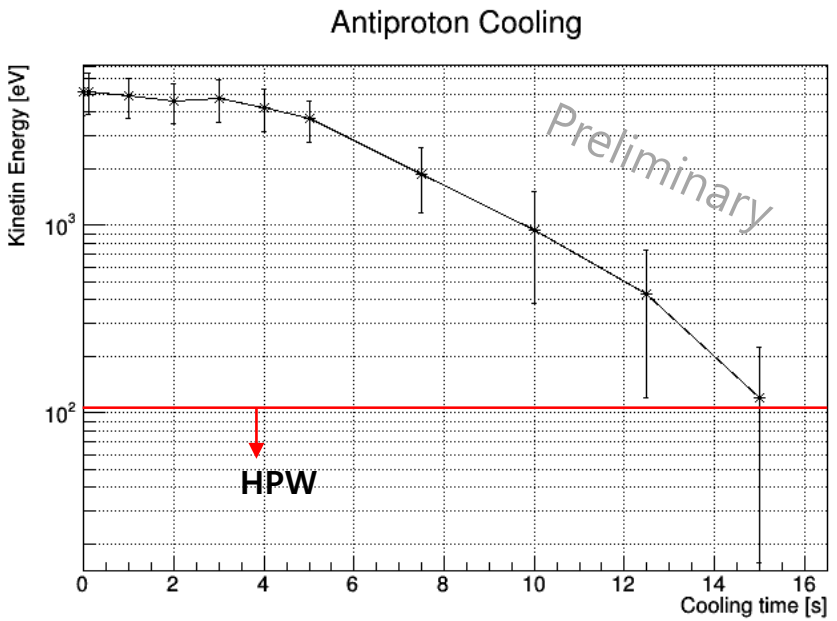
$\bar{H}^{0,+}$ production

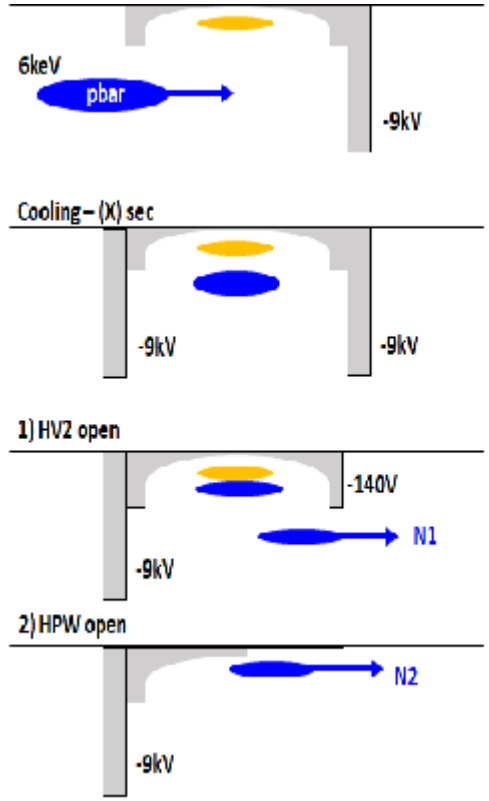
- Antiproton trap has been developed from floor plan level for $\bar{p}$ **beam reprocessing**.
- After demonstration by $\bar{p}$ &e^- , it was mounted at final position.
- Operation : Trapping, Accumulation, Compression, Bunching

Antiproton trap (2022)

From B.C.Lee



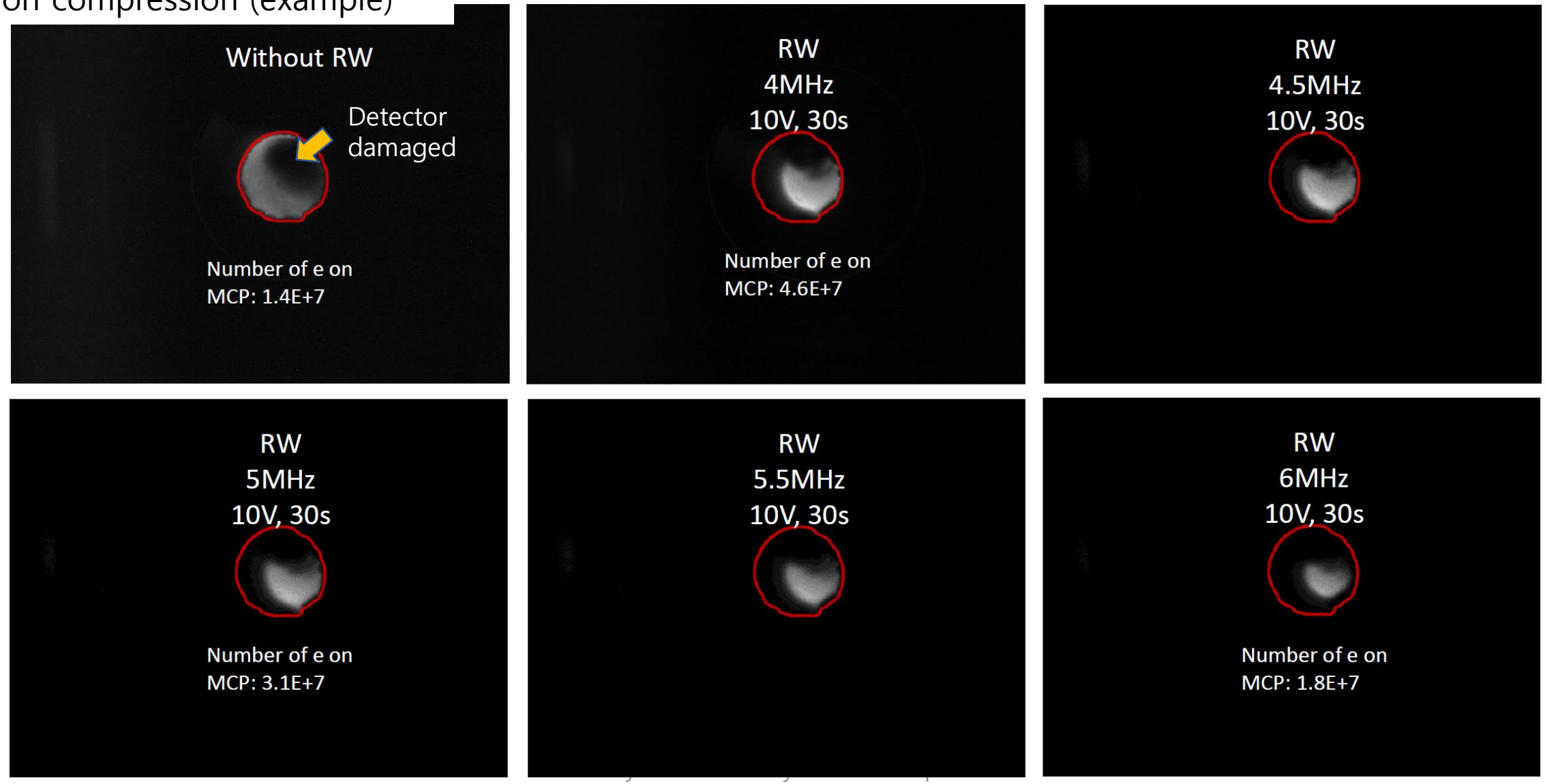




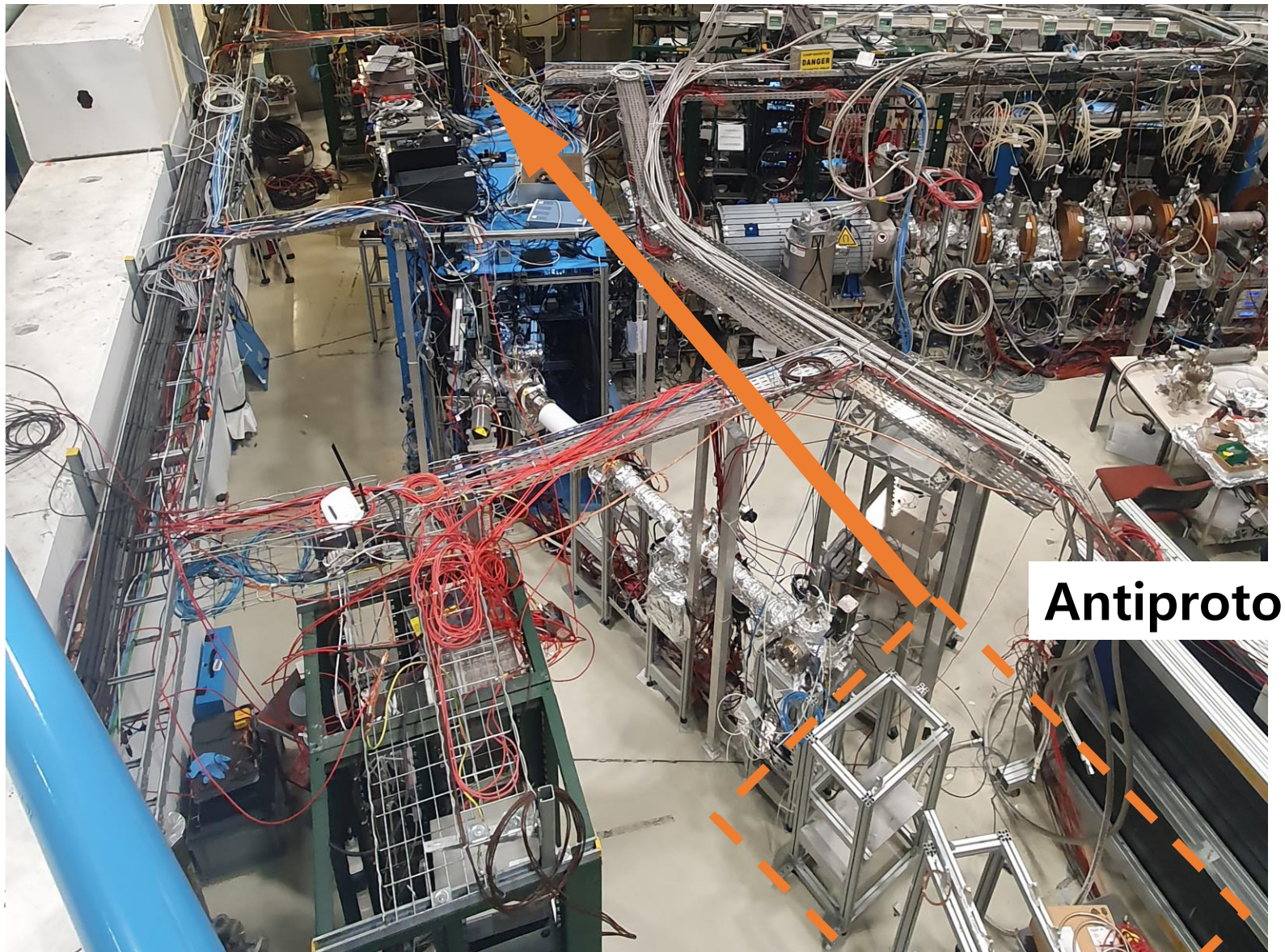
- $N_{\bar{p}} \sim 10^5$, $N_e \sim 10^7$, B = 5T (7T)
- MRE : T = 14K, P ~10^{-10}mbar
- 6keV → 1keV : 10sec / 6keV → 100eV : 15sec
- Antiproton trap's **trapping and cooling** performance has been developed.
- One experiment, one shot for each data point
- Only limited beam time was given
- Pressure level will be improved

Antiproton trap (2022)

Electron compression (example)

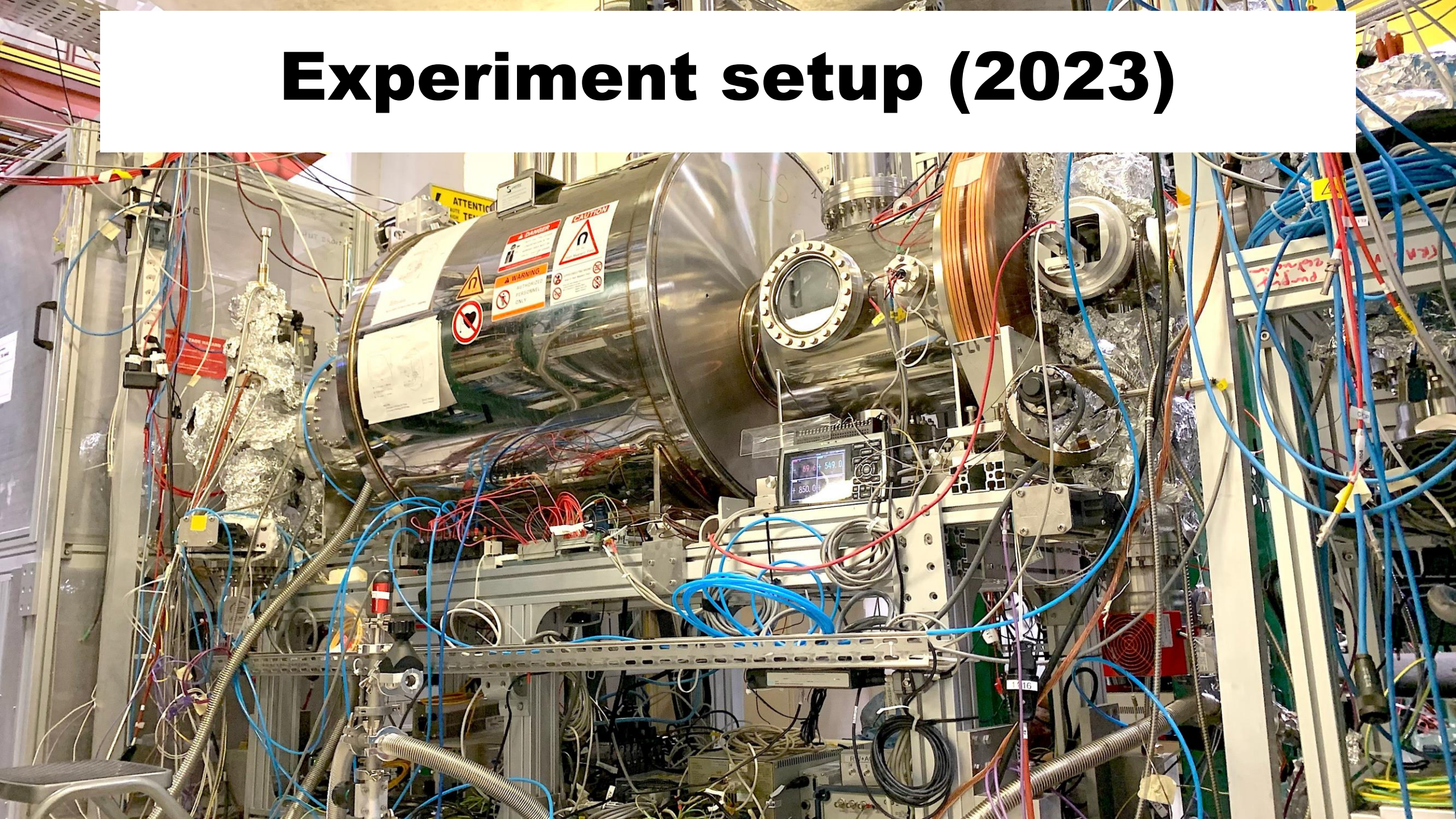


Experiment setup (2023)



Antiproton trap in final position

Experiment setup (2023)



Summary and Prospect

Summary

- GBAR experiment aims to confirm WEP_{ff} and to measure gravitational acceleration of $\bar{H}$ below 1%
- GBAR succeeded to achieve first milestone which is production of $\bar{H}$.
- KGAR team has developed TOF detector & antiproton trap successfully and will test all operation of antiproton trap in this year.

Plan before long shutdown (LS3)

- Increase source intensity with re-moderator & better compression (o-Ps x 100) and $\bar{p}$ recycler ($\bar{p}$ x10) for $\bar{H}^+$production.
- $\bar{H}^+$ production and cross-section measurement

Prospect

- First $\bar{H}$ freefall measurement to 1% precision from GBAR experiment : probably after LS3
- CPT test by $\bar{H}$ beam (Lyman-α) is planed before LS3
- Development freefall test with quantum bouncing of anti-hydrogen for 10^{-5} precision
- Development of new penning-malmberg trap at RAON for mass spectroscopy ($\delta m/m \sim 10^{-6}$) from 2023 (with CENS, RAON)

BACKUP

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

- 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

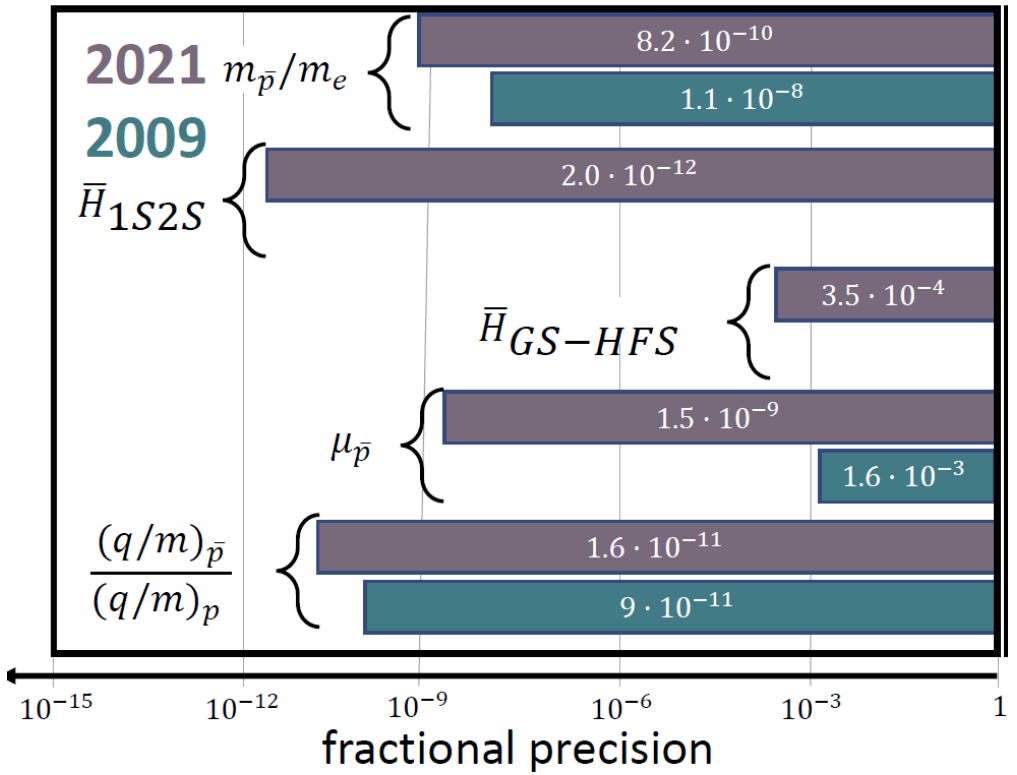
- Proton & antiproton CPT test by BASE

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

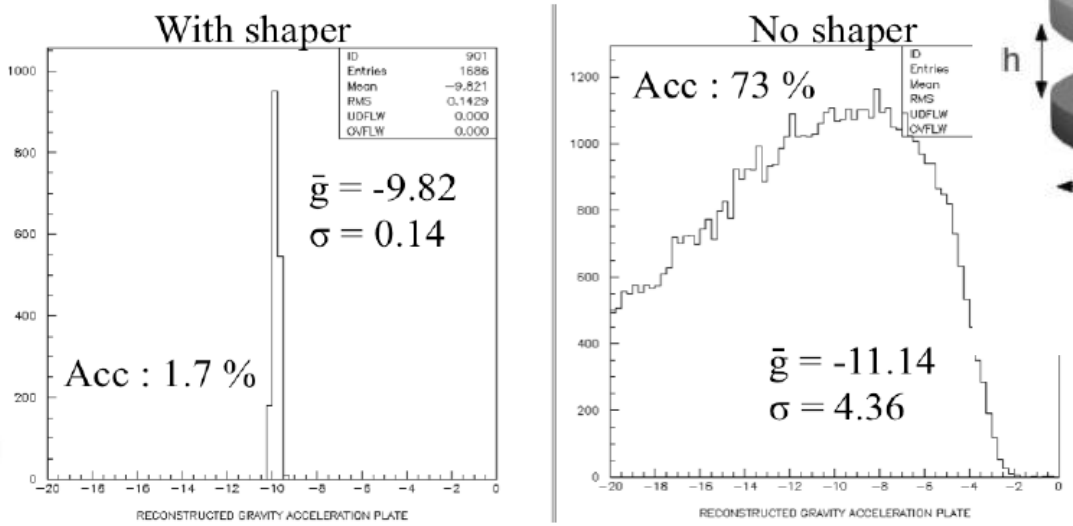
- Antideuteron, antihelium, muon, positron, kaon..

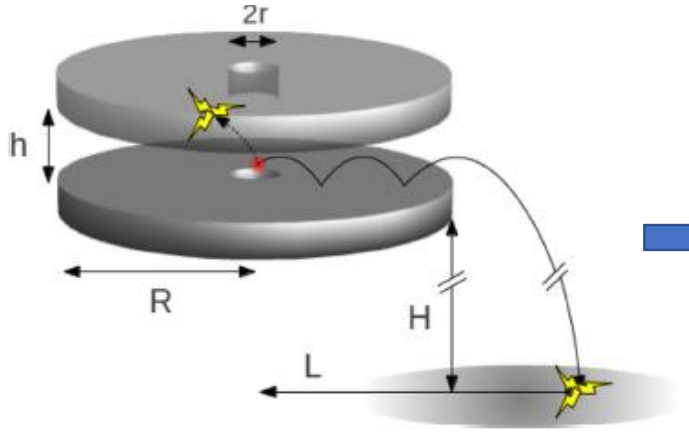
- (There's also many fantastic results for exotic antiprotonic helium, etc..)

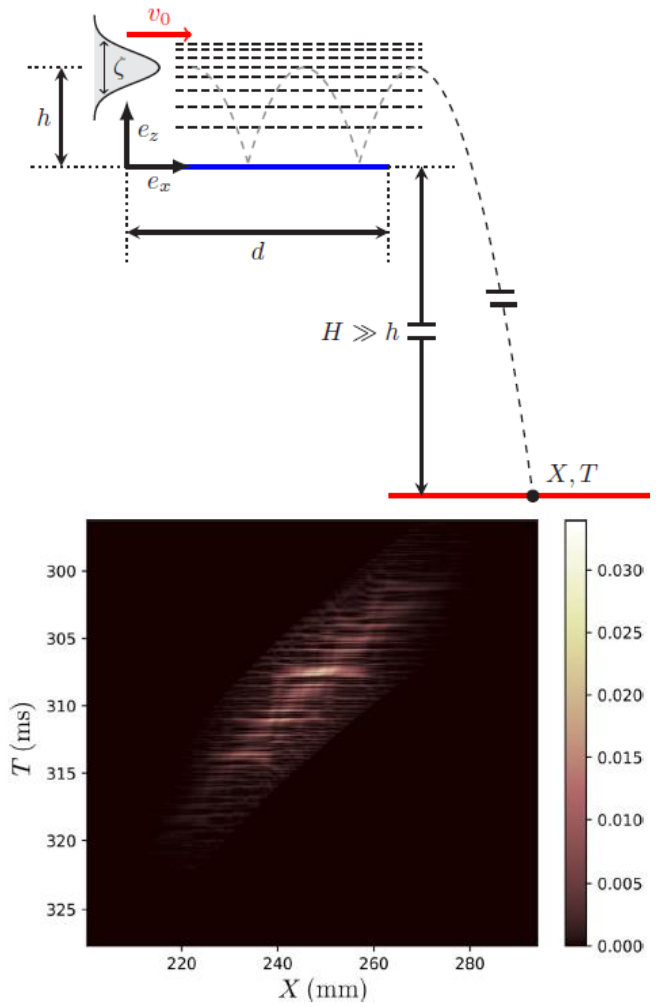
From Stefan Ulmer's slide (ADUC)



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

WEP_{ff} test approaches

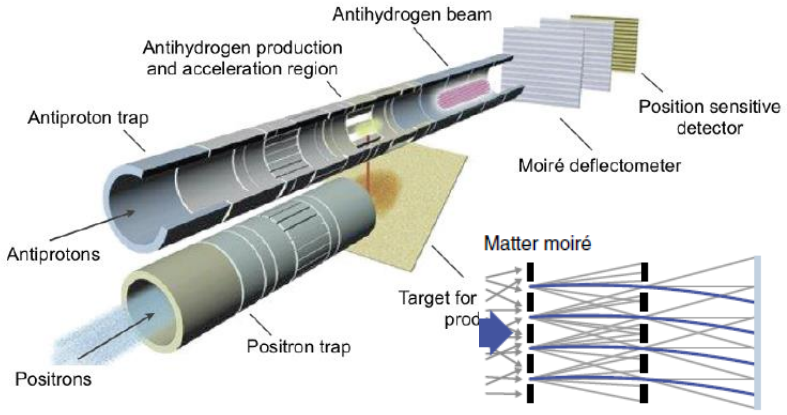
AEGIS

- 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# $\bar{H}$.

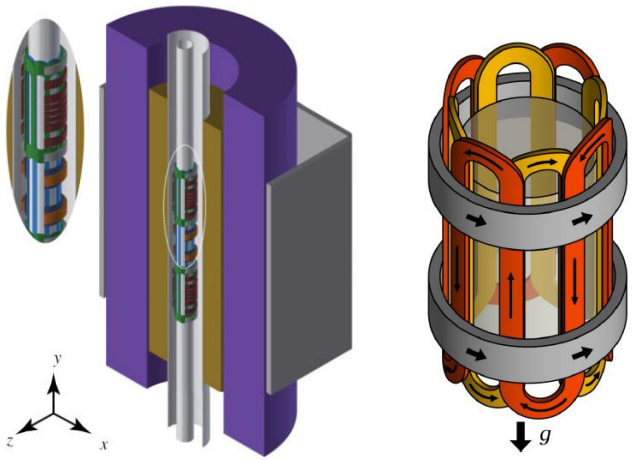


ALPHA-g

- 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# $\bar{H}$.