GBAR experiment

Center for Underground Physics
Institute of Basic Science

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Contents

INTRODUCTION

Motivation

❖ **Matter and Antimatter asymmetry**

- Different with expectation by BIGBANG and Standard Model,

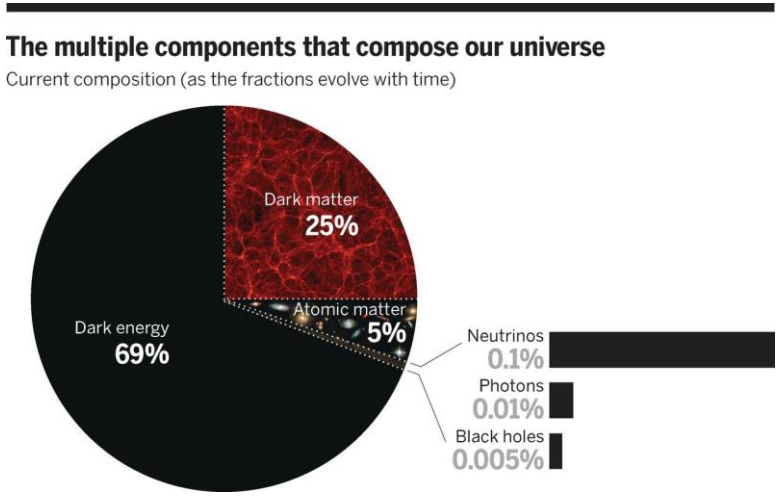
Matter domain in observable Hubble volume : $n_B \gg n_{\bar{B}}$

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

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

❖ Dark matter and Dark energy

- We do not understand 94% of the mass energy density



❖ Antimatter's fundamental properties are not fully measured

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

➔ CPT and WEP test with antimatter by precision test

Motivation

From Stefan Ulmer's slide (ADUC)

Check fundamental interaction between matter & antimatter

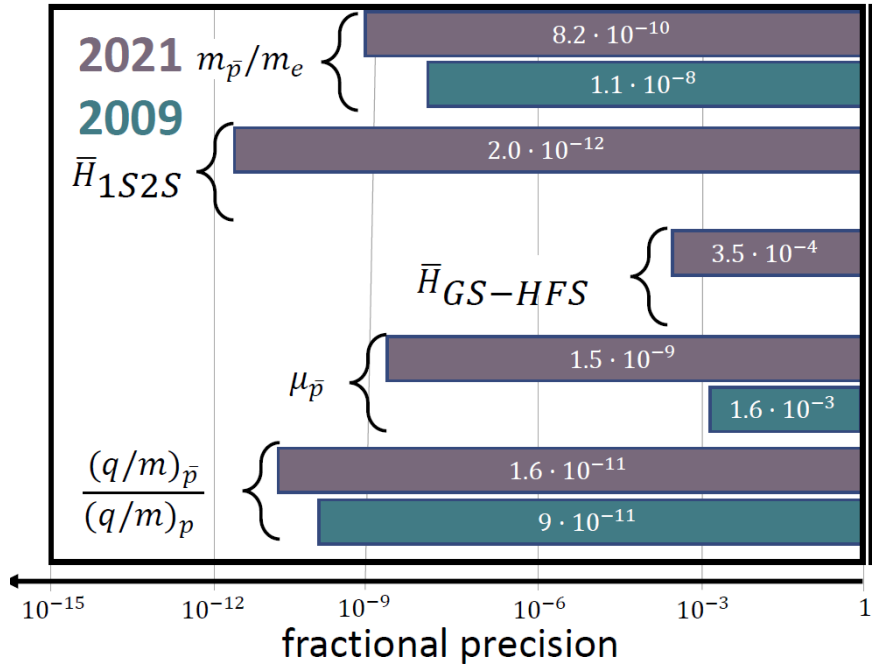
- Weak Equivalence Principle(WEP) :

$$m_I = m_G \; (F = m_I a = -G m_G m'_G / r^2)$$

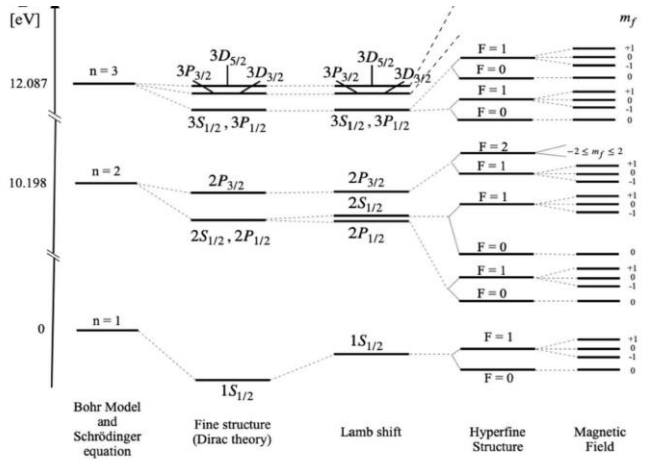
$$m_I = \overline{m_I} \; (by \; CPT)$$

$$m_G = m_I = \overline{m_I} = ? \, \overline{m_G}$$

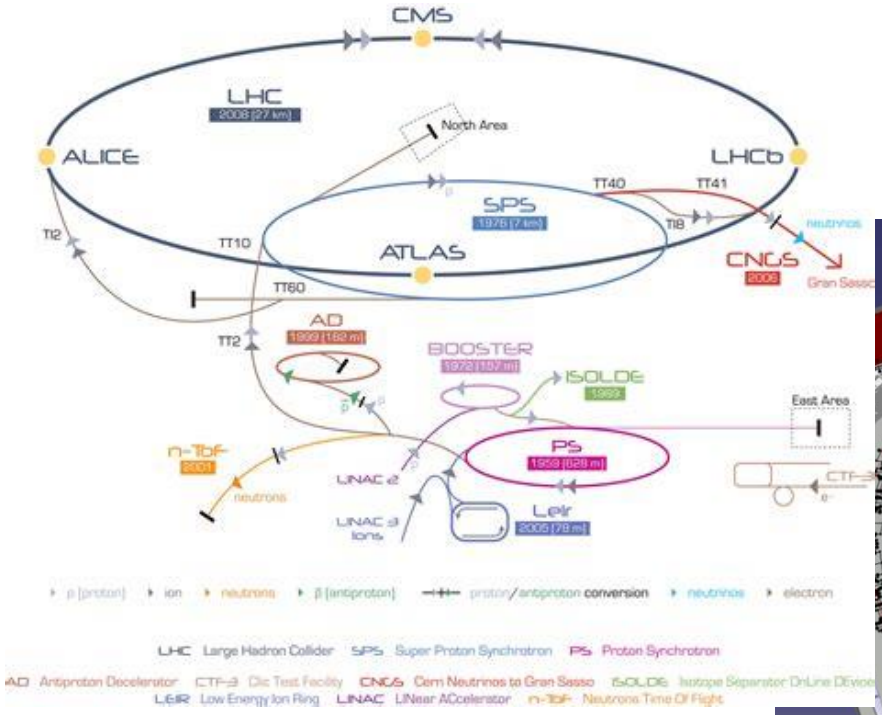
(for matter $\Delta(m_g/m_i)/(m_g/m_i)_{Be/Ti} = (0.3 \pm 1.8)10^{-13}$)

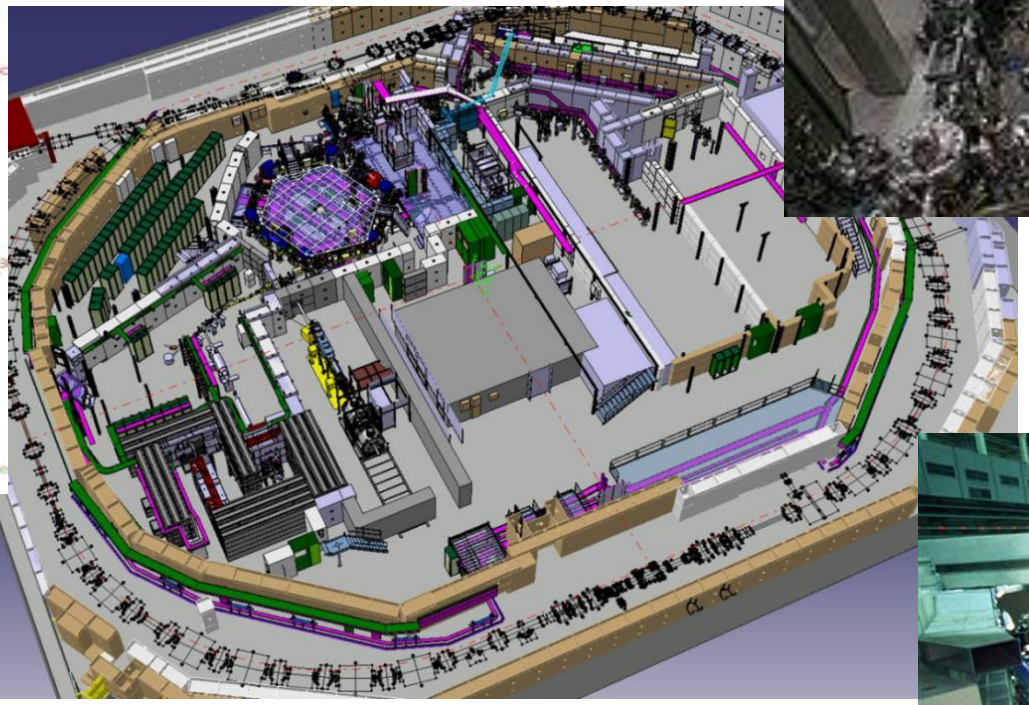


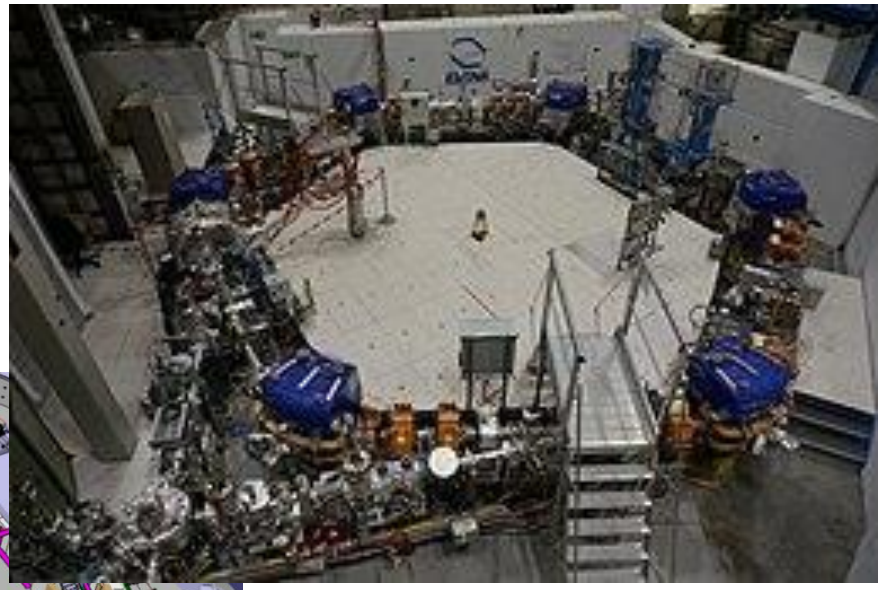
- Many CPT test has been performed between matter and antimatter especially by proton & antiproton and hydrogen and antihydrogen



AD &ELENA at CERN







Only existing facility of low energy $\bar{p}$

- 1982 ~ 1996) LEAR (AA + AC)
- 2000 ~ now) Antimatter Factory

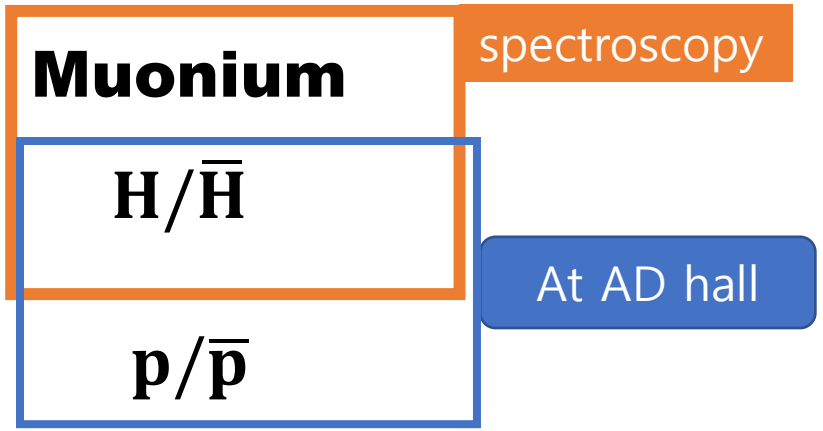
(AD + ELENA)

: 6 experiments (AEGIS, ALPHA, ASACUSA, BASE, GBAR, PUMA)

- Future) FLAIR at FAIR?

CPT test

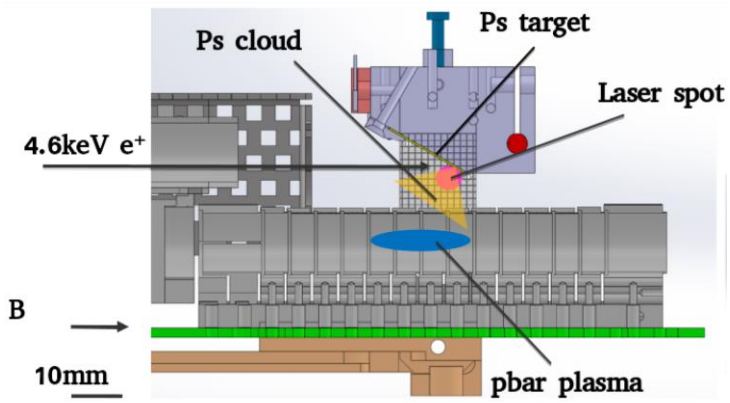
	High energy	Low energy
Meson	Kaon D meson B meson (neutral meson oscillation)	
Lepton	Neutrino oscillation	Positronium
Baryon		



WEP_{ff} test approaches

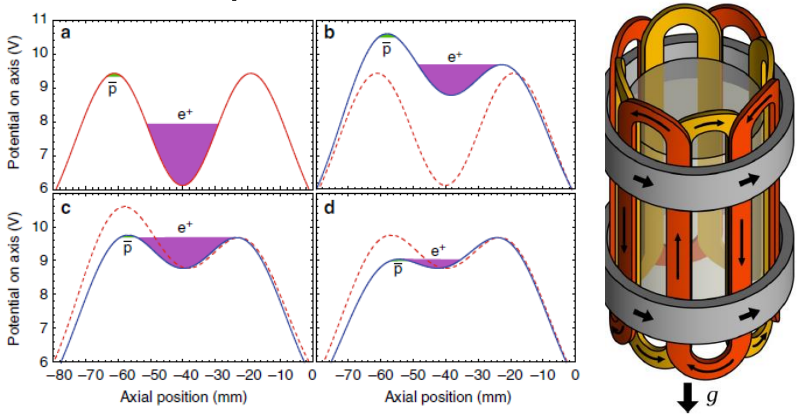
AEGIS

- e^+ : ^{22}Na source
- $\bar{p}$ → degrader foil
- $\bar{p} + Ps^*(Rydberg) \rightarrow \bar{H}^* + e^-$
- Reaction in trap
- Pulsed Antihydrogen beam



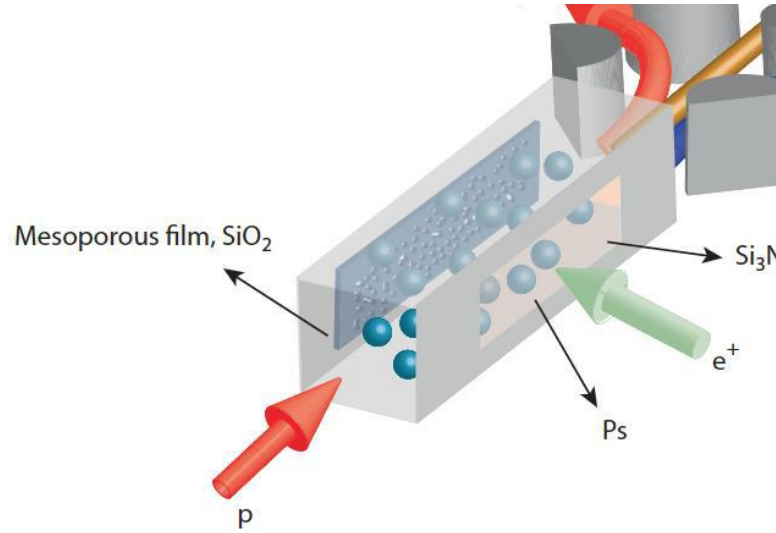
ALPHA-g

- e^+ : ^{22}Na source
- $\bar{p}$ → degrader foil
- $\bar{p} + e^+ + e^+ \rightarrow \bar{H} + e^+$
- Reaction in trap
- Antihydrogen trapping by penning-Ioffe trap (octupole)



GBAR

- e^+ : e^- Linac + W target
- $\bar{p}$ + decelerator + $\bar{p}$ trap
- $\bar{p} + Ps \rightarrow \bar{H} + e^-$
  $\bar{H} + Ps \rightarrow \bar{H}^+ + e^-$
- Reaction btw $\bar{p}$ beam + $Ps^{(*)}$ with excitation laser



WEP_{ff} test approaches

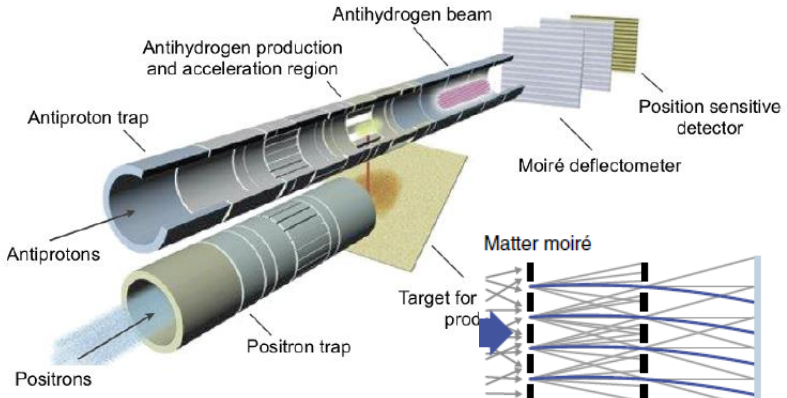
AEGIS

- **Cold $\bar{H}$ beam** by cold antiproton E (100mK)
- Moire deflectometer tested by $\bar{p}$. (nature communications 5, 4538 (2014)

→ Pattern will be compared with one from light

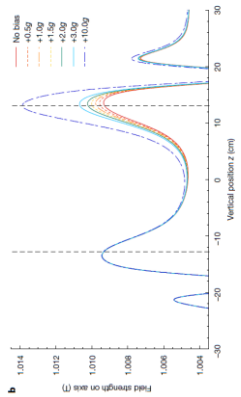
- Aim : ~100mK (v~40m/s)

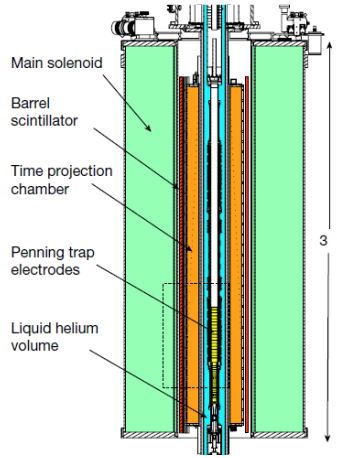
- 1% precision with 1000# $\bar{H}$.



ALPHA-g

- **Cold $\bar{H}$** in the trap by evaporative cooling (0.5K)
- Vertical trap (280mm long)
- Aim (1%) : sub-50mK (v~28m/s) temperature by laser cooling& precise measurement of magnetic field

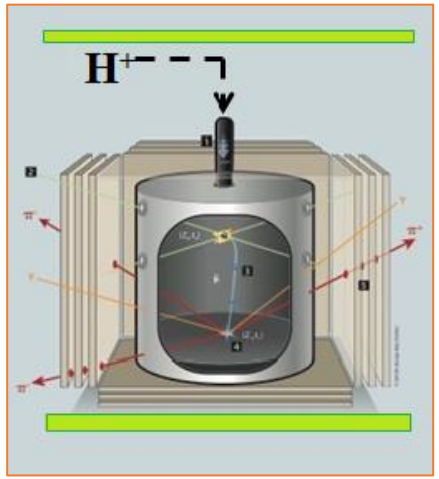




GBAR

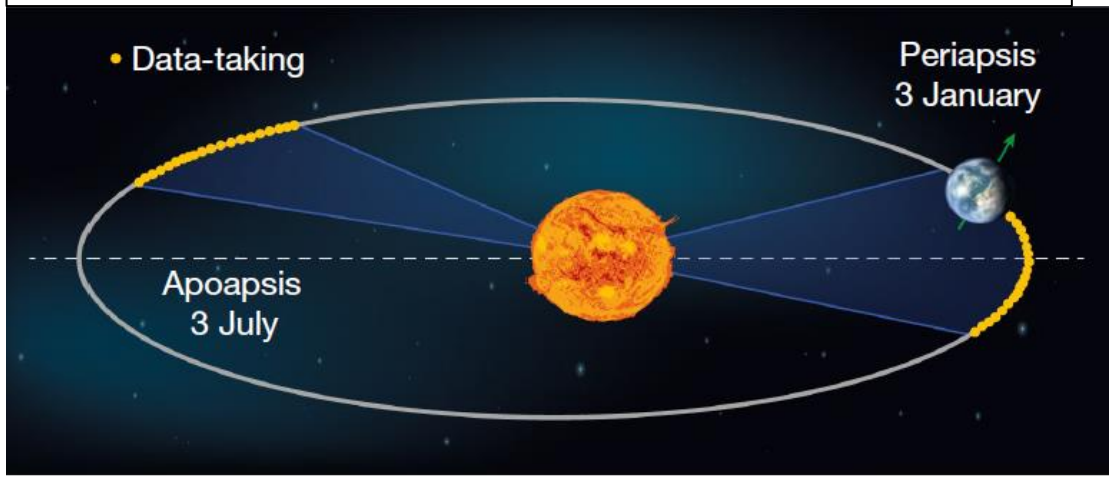
- Trapping and cooling $\bar{H}^+$ at paul trap.
- **Ultra-cold $\bar{H}^+$** by Sympathetic cooling by Be ion (10uK)
- Classical Freefall test (z=0.25m)
- Aim : 10uK (v~0.4m/s)

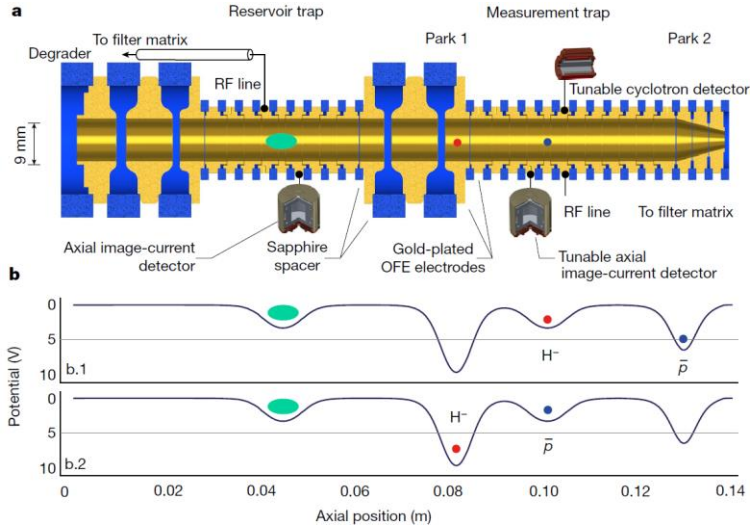
- 1% precision with 1500# $\bar{H}$.

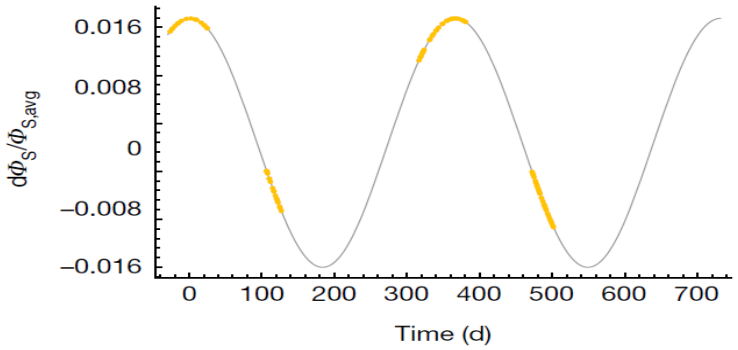


Antiproton WEP test

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







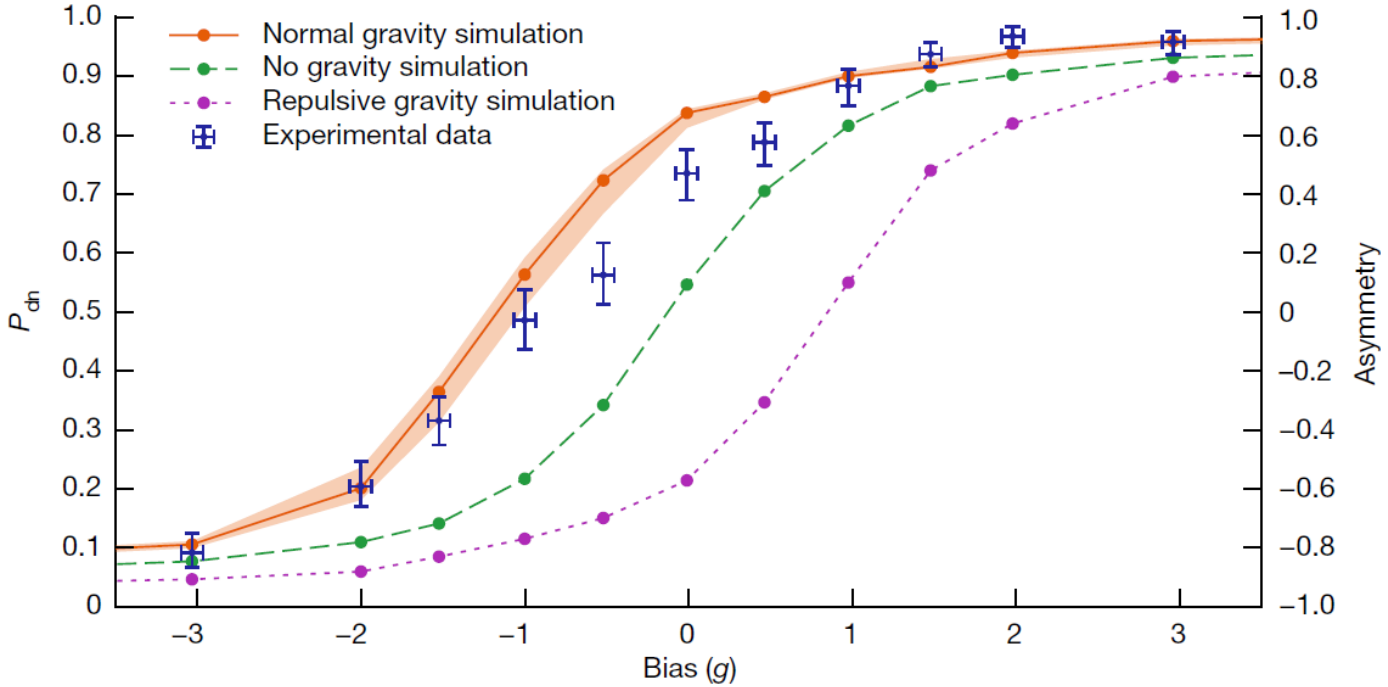
- **Base experiment**

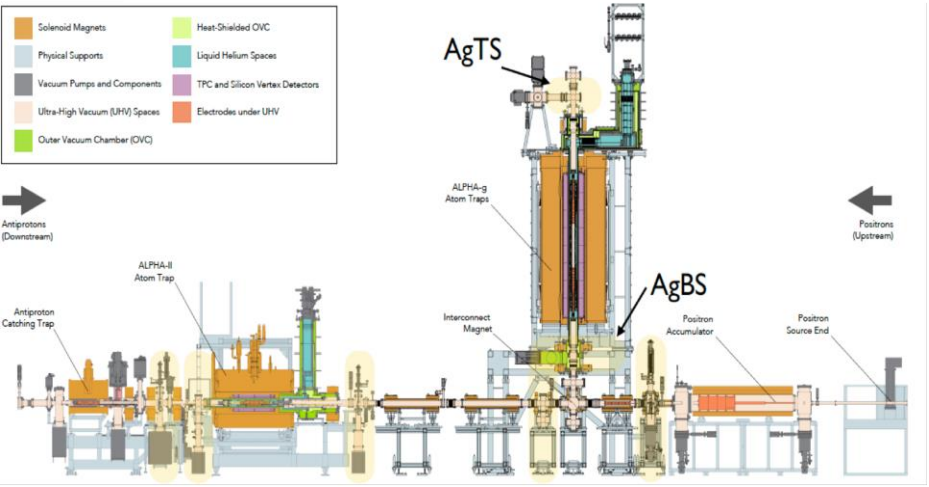
Antiprotons cyclotron clock measurement was done for WEP_{cc} test : $|\alpha_{g,D} - 1| < 0.030$ (CL 0.68)

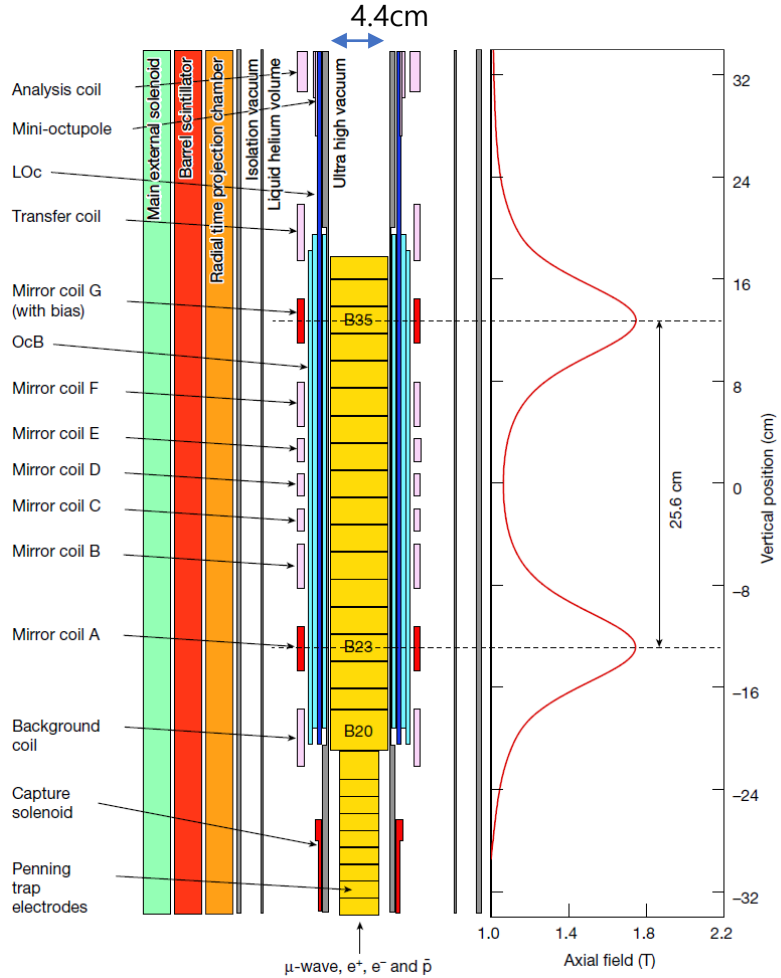
←Limit on scalar and tensor interaction $\frac{\nu_{c,\bar{p}} - \nu_{c,p}}{\nu_{c,avg}} = \frac{3\Phi}{c^2}(\alpha_g - 1)$

(Hughes R. J. & Holzscheiter M. H, PRL 66, 854 (1991))

Anti-Hydrogen WEP test







- **ALPHA-g experiment**

2013 : proof-of-principle experiment

2018 : Alpha-g magnet constructed

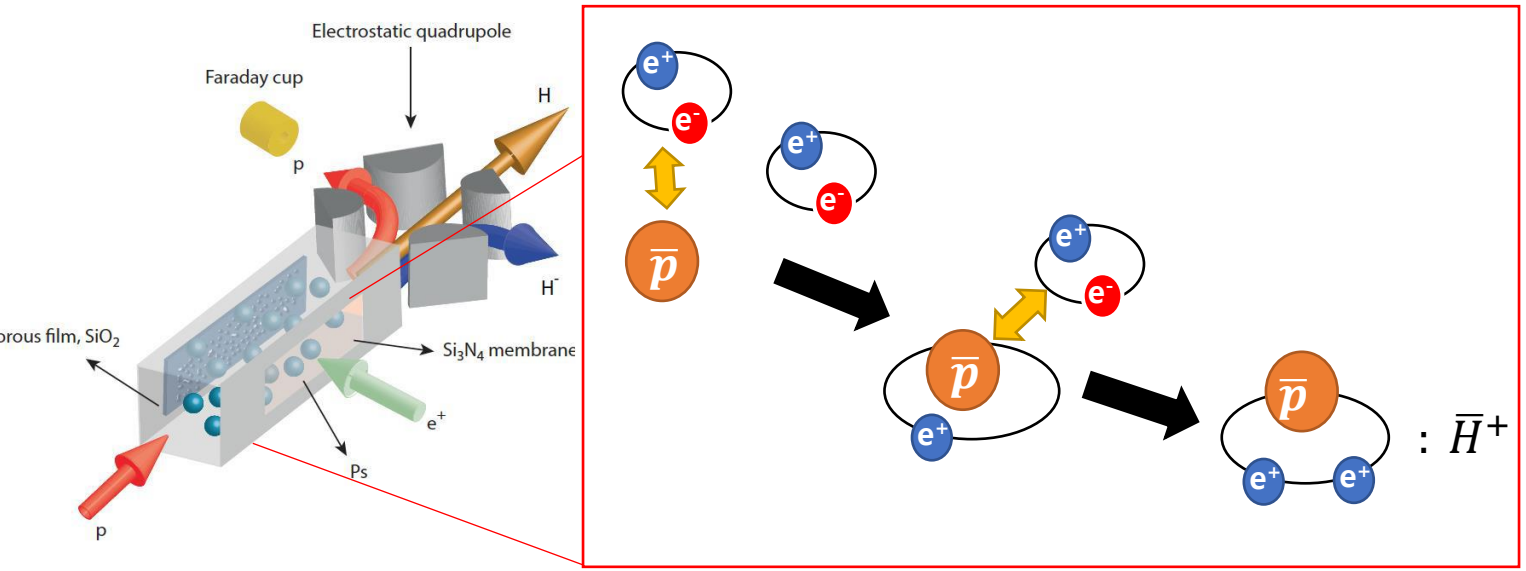
2023 : Rule out Repulsive antigravity by $\bar{H}$ with T <0.5K (**Nature 621, 716-722 (2023)**)

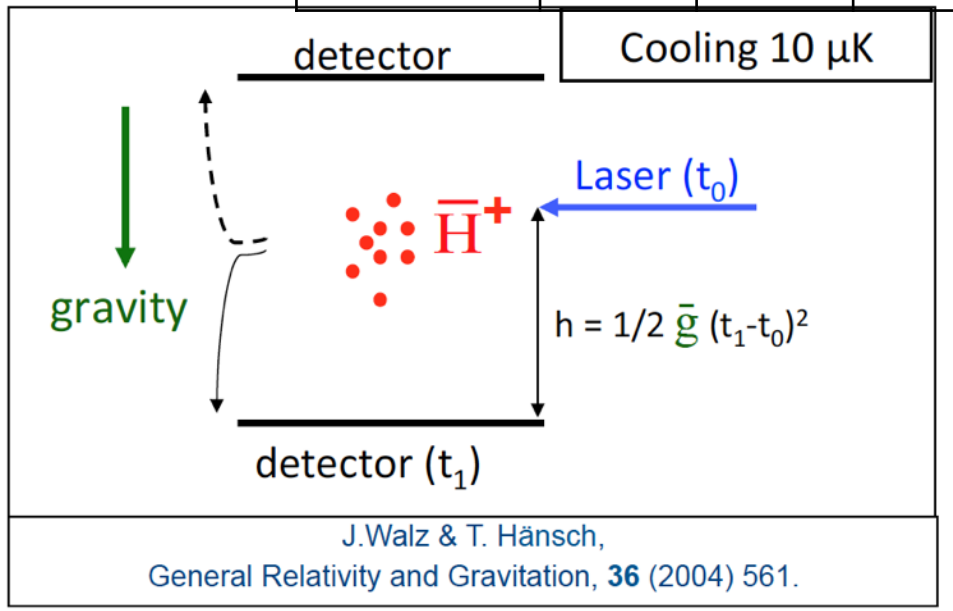
$$a_{\bar{g}} = (0.75 \pm 0.13 \pm 0.16) \times g$$

Experimental Detail

GBAR experiment

Velocity fluctuation	100m/s	3m/s	0.1m/s
Temperature	1K	1mK	1uK





- Direct measurement of the gravitational acceleration of anti-hydrogen (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 anti-hydrogen can reach)
- Double charge exchange process between anti-proton beam and dense positronium cloud (<2x2x20mm³ cavity)

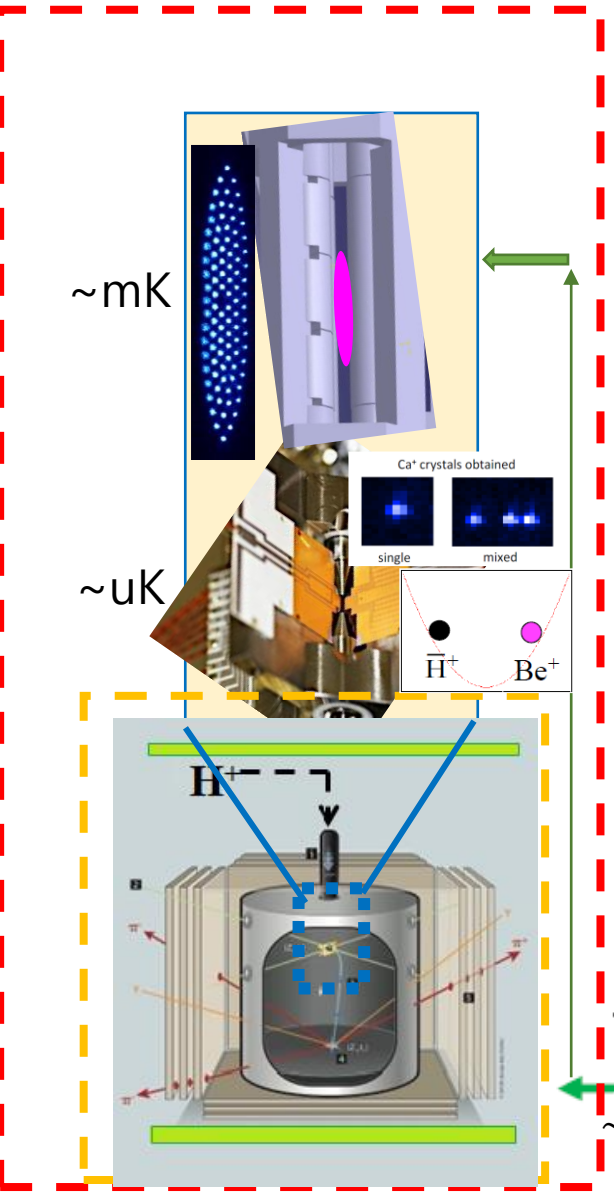
$\bar{p} + Ps \rightarrow \bar{H} + e^-$: **1st milestone**
$\bar{H} + Ps \rightarrow \bar{H}^+ + e^-$: **2nd milestone**

with

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

- Cooling anti-hydrogen 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 anti-hydrogen **freefall**.

Experiment Scheme

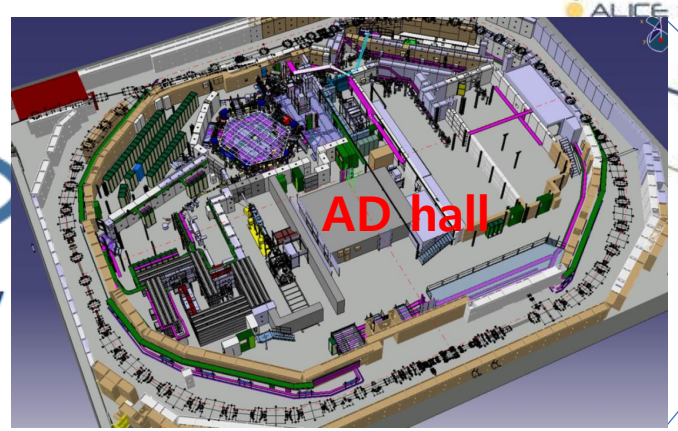


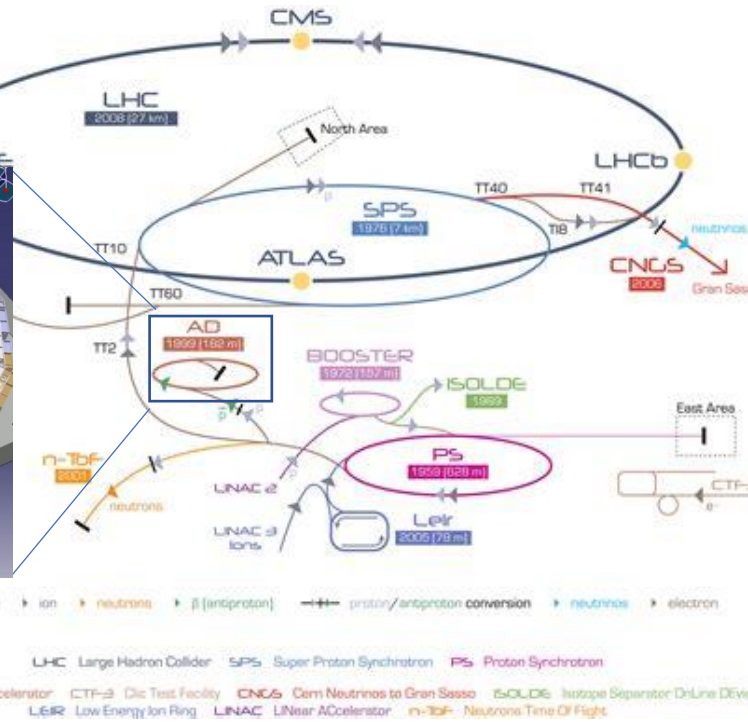
3.5→0.1GeV/c

AD

5.3MeV

ELENA





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

decelerator

Anti-proton beam line

$\bar{P}$ trap

10eV~10keV

Laser Ps*

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

4kV

High field trap

buncher

BG trap

Ne remoderator

e^+ target

Linac

Positron beam line

10^{10} e^+/bunch

1MeV→3eV → 50eV

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

e^- 10MeV

$\bar{H}$

$\bar{p}$

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

$\bar{H}^+$ ion

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

Lyman-α

: after 2023

: Korean team involved

GBAR collaboration

CSNSM

ETH Eidgenössische Technische Hochschule Zürich

ILL NEUTRONS FOR SCIENCE

IPCMS

Irfu - CEA Saclay
Institut de recherche sur les lois fondamentales de l'Univers

JGU JOHANNES GUTENBERG UNIVERSITÄT MAINZ

P.N.Lebedev Physical Institute of the Russian Academy of Science

Laboratoire Kastler Brossel
Physique quantique et applications

NCBJ NATIONAL CENTRE for NUCLEAR RESEARCH Świerk

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ibs Institute for Basic Science

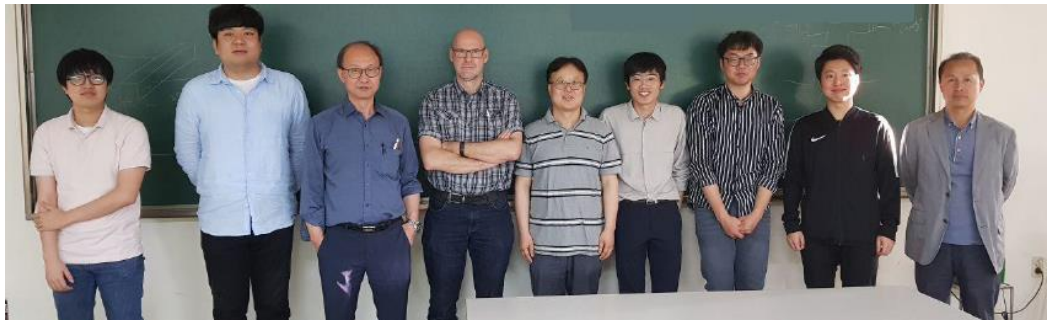
東京大学 大学院総合文化研究科・教養学部 The University of Tokyo, Komaba
Graduate School of Arts and Sciences, College of Arts and Sciences

東京大学 THE UNIVERSITY OF TOKYO

KOREA UNIVERSITY

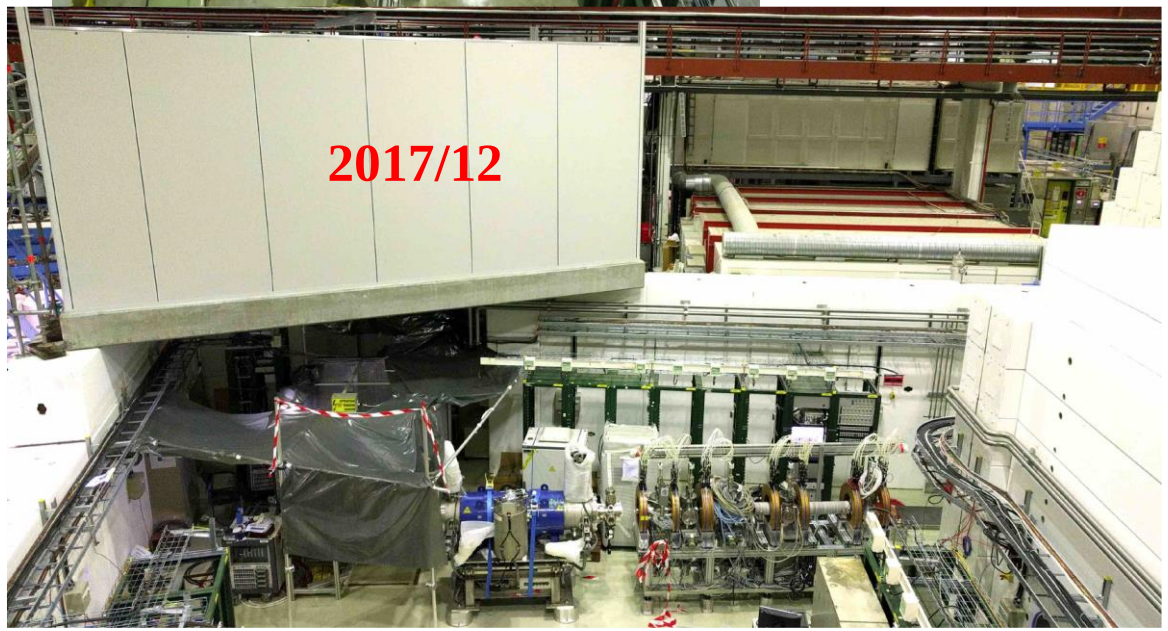
UNIST ULSAN NATIONAL INSTITUTE OF SCIENCE AND TECHNOLOGY

70 members
18 institutes
8 countries



Korean group
4 Institutes (IBS, KNU, SNU, UNIST)
6 Doctors (IBS : B.Kim, J.Lee, Y.Ko
KNU : E.Kim
SNU : S.Kim
UNIST : M.Jung)
5 GS (1 graduated)
→ 2 students staying at CERN normally
: Device development + operation

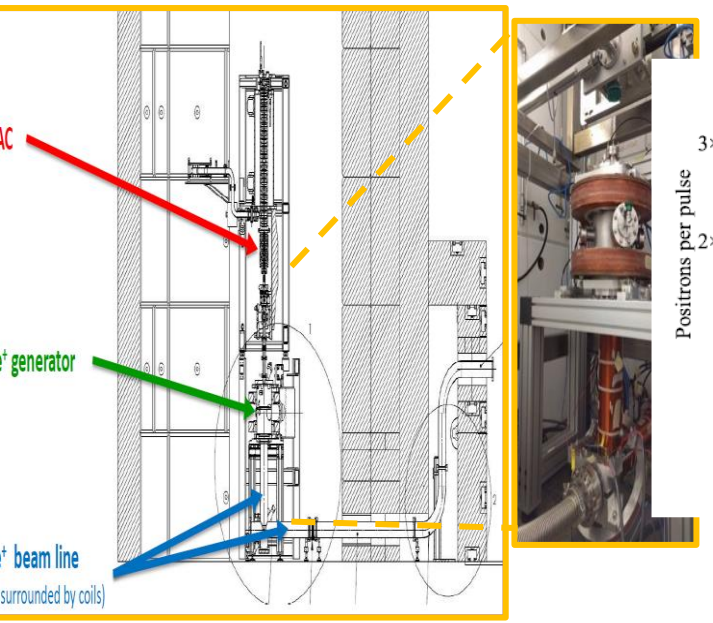
Experimental setup (past)

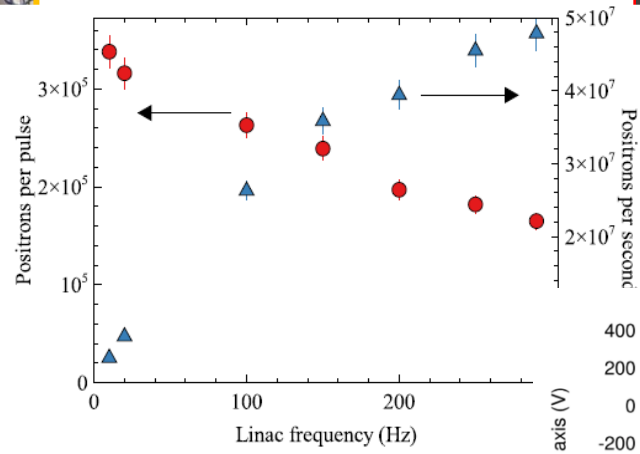


- 2007 : Letter Of Interest to CERN
- 2011 : Proposal to CERN
- 2016 : SNU & IBS joined MOU
- 2016-2018 : Experiment Installation
- 2019-2021 : Development of each devices

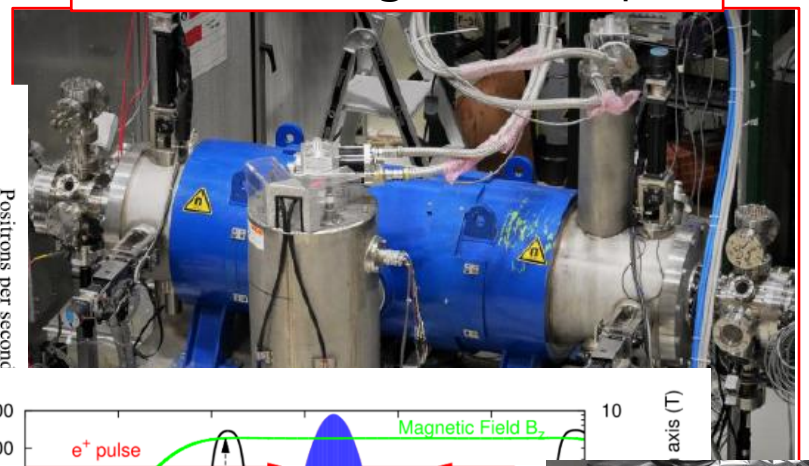
Positron beam for Ps production

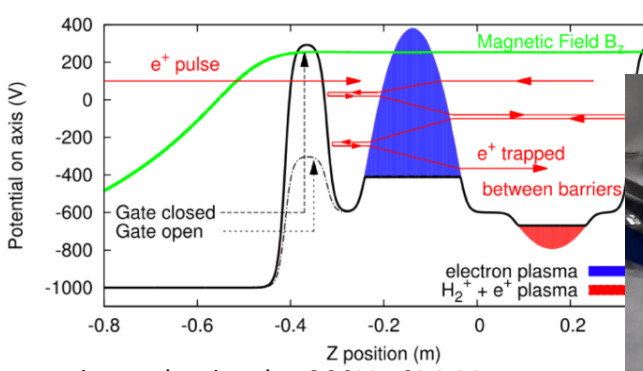
Linac and positron target

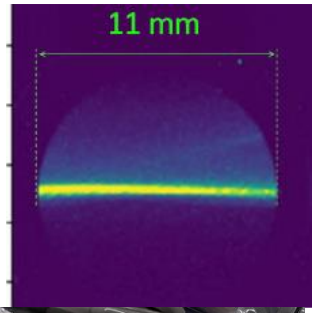


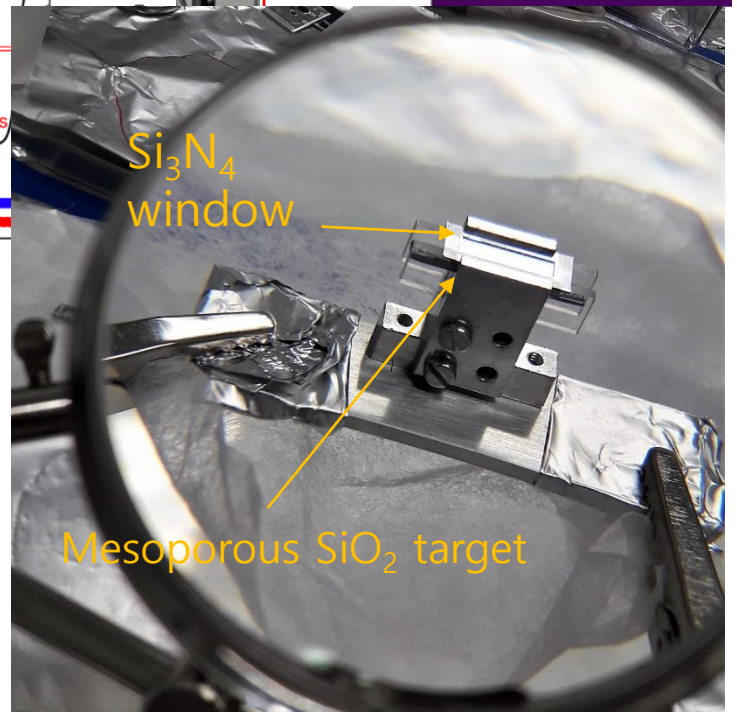


Positron high field trap



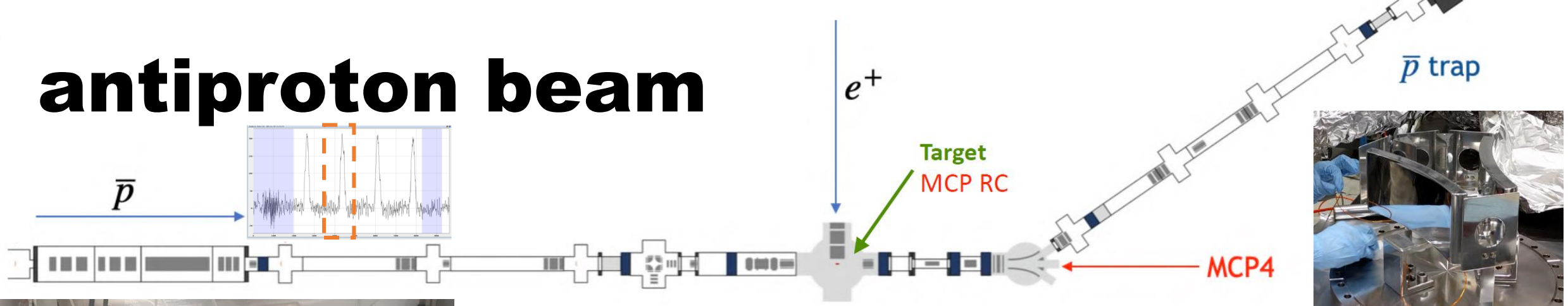




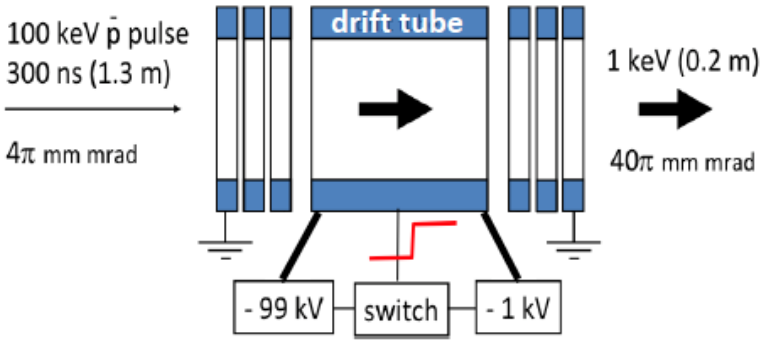


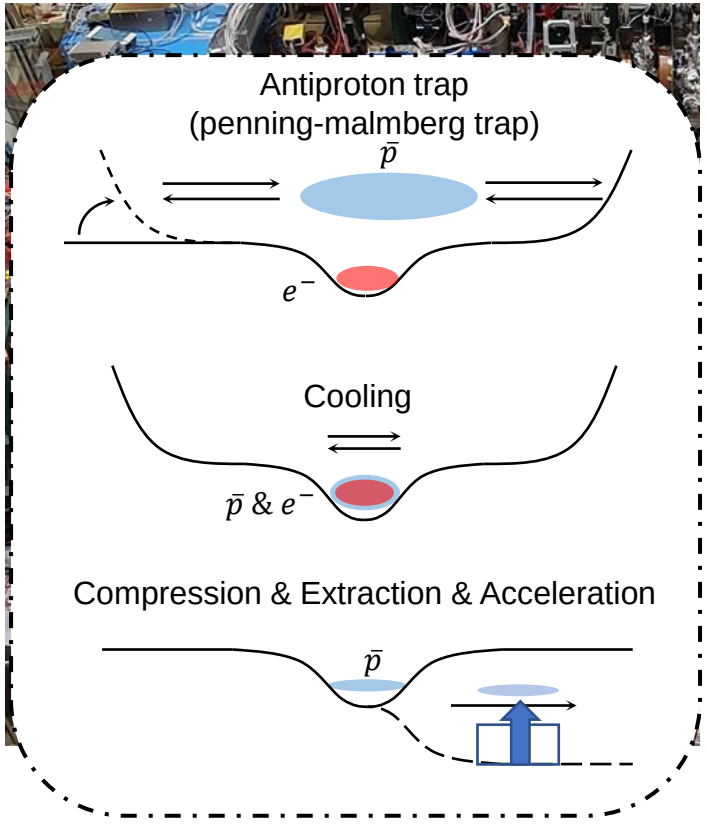
- Positron beam : monoenergetic positron beam generated from bremsstrahlung-induce pair production by 300Hz 9MeV e^- Linac with W moderator → a goal to 3 x $10^8 e^+$/s (commissioning in this year); M.Charlton et al., NIM A 985, 164657 (2020)
- Positron accumulation by high field trap : goal to 1x10^{10} e^+ (110s) with electron cooling (1.4xe^9 e+/1100s achieved); NIM A 1040 (2022) 167263
- Positron acceleration & guiding by electrostatic lenses to reaction target (2 x 10mm^2)
- SiC re-moderator has been prepared for better trapping efficiency

antiproton beam



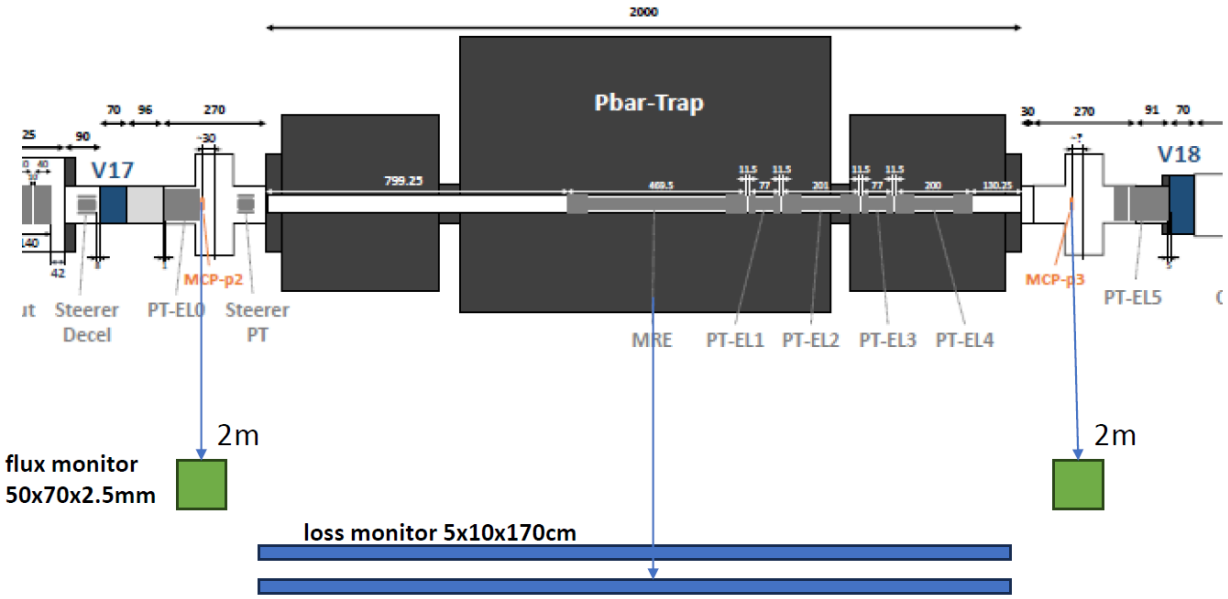
A. Husson et al., NIMA 1002 (2021)165245

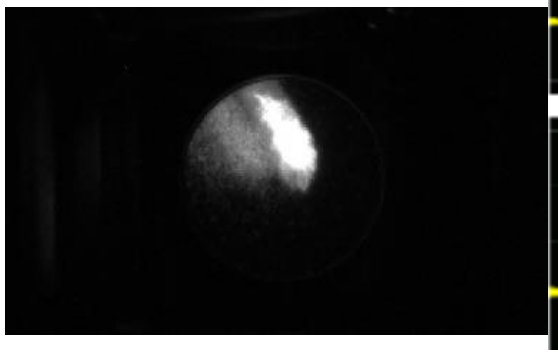


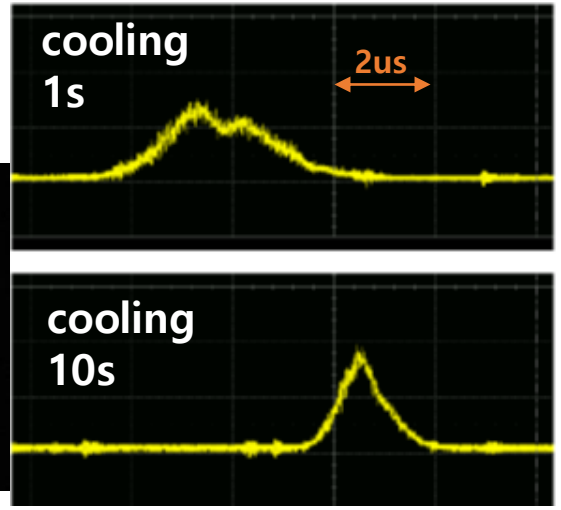


- ELENA commissioning (2021) with GBAR
- Deceleration test from 100keV to 4keV was succeeded. (NIM A 1002 (2021)165245)
- The decelerated antiproton beam passed reaction target hole 2mmx2mm (~10%)
- Antiproton trap being ready to get $\bar{p}$ beam (JINST 17 T10003 (2022))
- Succeed to guide proton beam to antiproton trap (2022)
- Trapping & cooling test of antiproton trap by $\bar{p}$ was done.

Antiproton trap

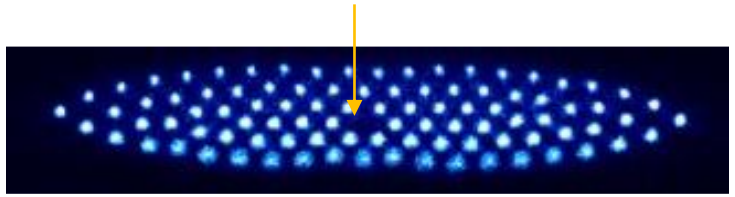


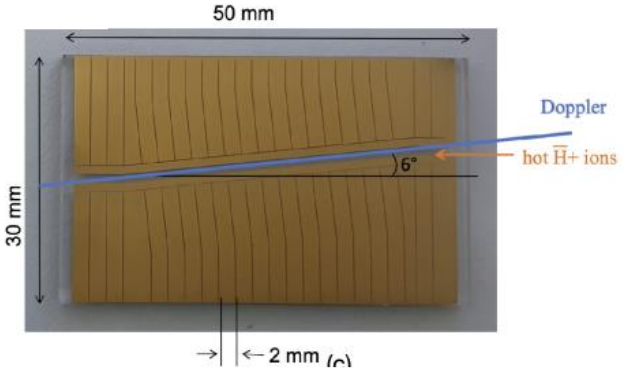


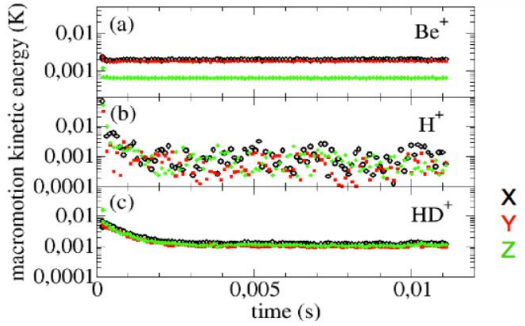


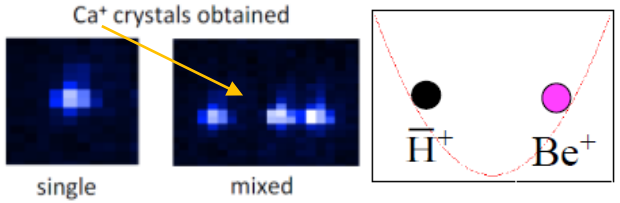
- Many efforts has spent from design & hardware preparation level
- T_{center} = 14K, P <1.0E-10mbar
- e^- loading capacity>10^8#
- e^- cooling succeeded
- e^- adiabatic extraction & guiding succeeded
- FPGA, sequence control development
- Proper detection system prepared for 2023 beam time

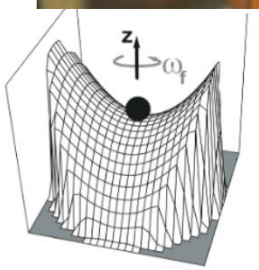
Cooling traps and photo-detachment

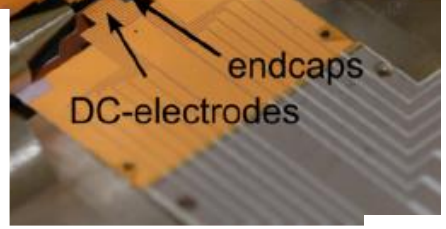


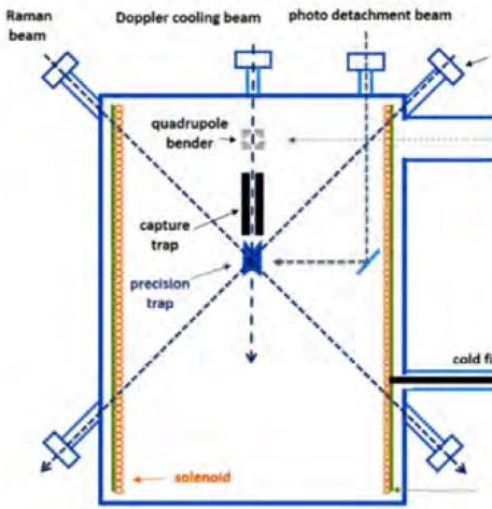










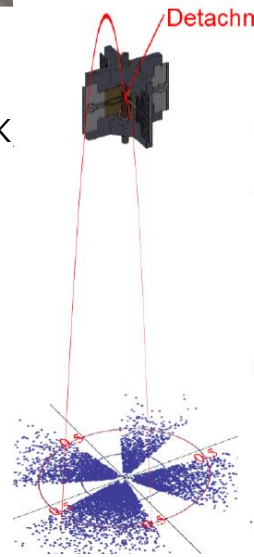


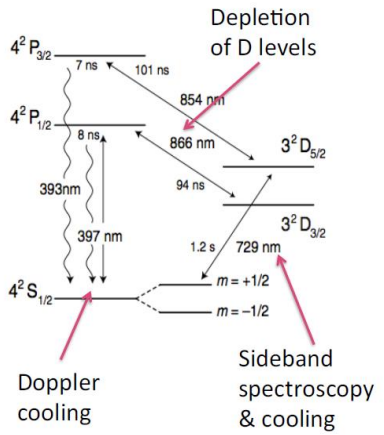
1. Capture trap (ITO trap) : capturing by DC switching+ rf voltage electrodes

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))

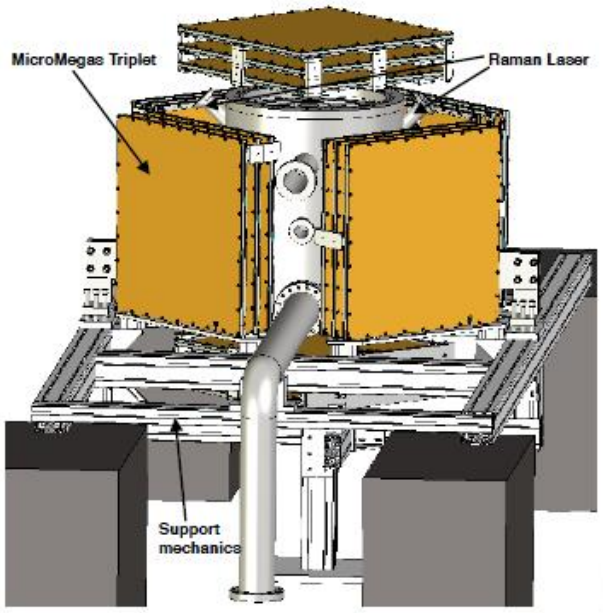
← HD^+ to reduce mass ratio for better coupling in simulation (similar charge to mass ratio required)

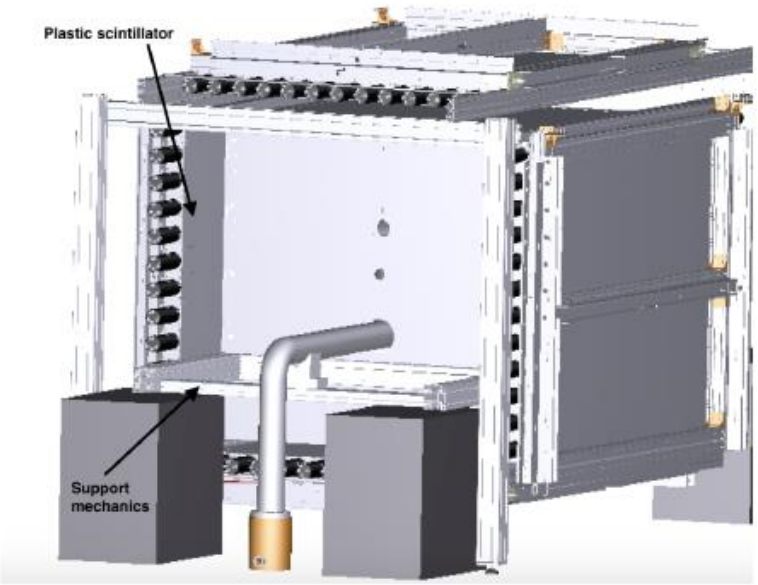
- 2. Precision trap : ion as a quantum harmonic oscillator, Raman sideband cooling for $Be^+/\bar{H}$ ion pair to T~10uK. (W. Schnitzler et. al, Physical Review Letters 102, 070501 (2009).)
- Initial direction : temperature (0.44m/s for 1MHz) + photon recoil(0.24m/s) + positron emission (~0.3m/s for E_c = 1ueV)

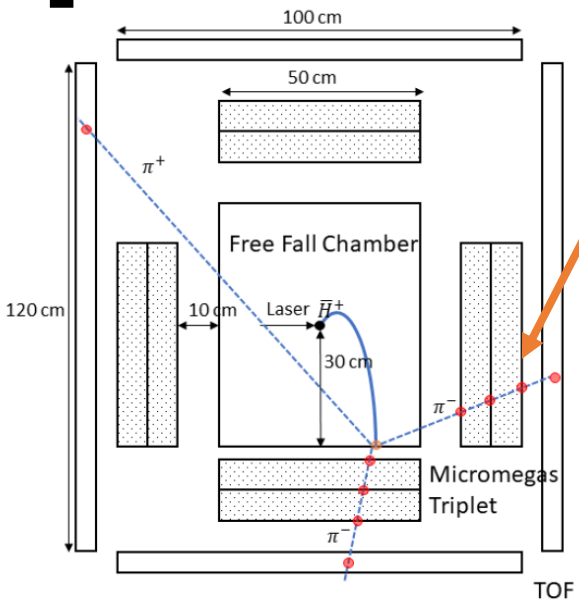


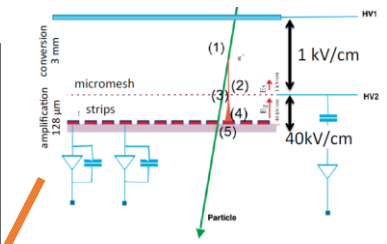


Freefall detection preparation



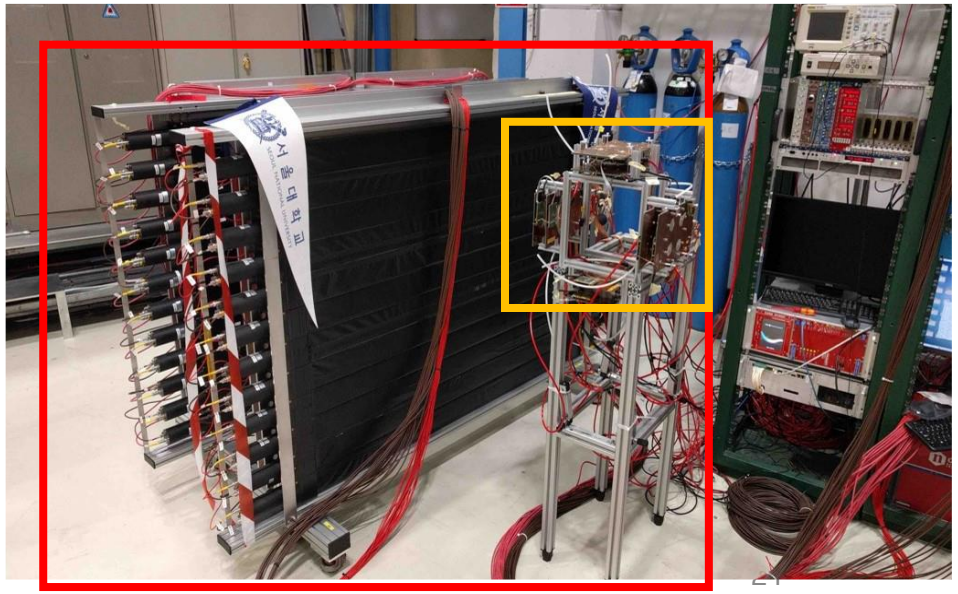




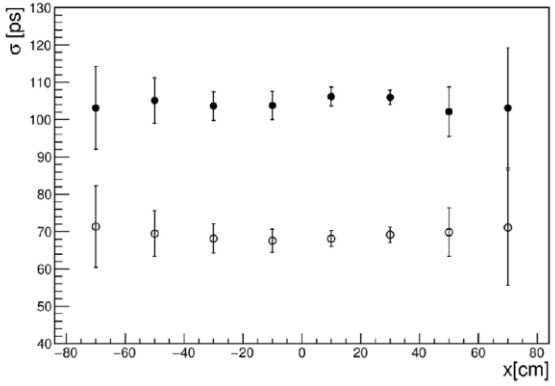


- 50x50 cm2 active area
-XY resistive readout
- Drift gap: 6mm, Amp gap: 128um

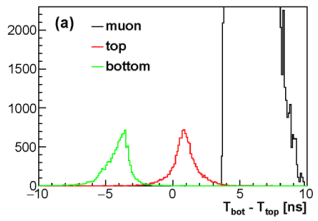
- MM(Micro-Megas) as a tracker and TOF(Time of Flight) detector as a timing detector tested by antiproton beam annihilation
- MM and TOF detector tested by antiproton beam annihilation
- (Cooling) laser hut for anti-hydrogen ion cooling was built and FFC is installed.
- Cooling trap (to go to ~mK) and precision trap (to go to ~10uK) ha s been studied in local group

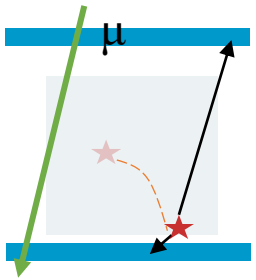


TOF detector development

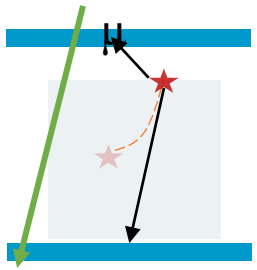


Temperature	Sign decision
10uK	~30 events
1mK	~6000 events



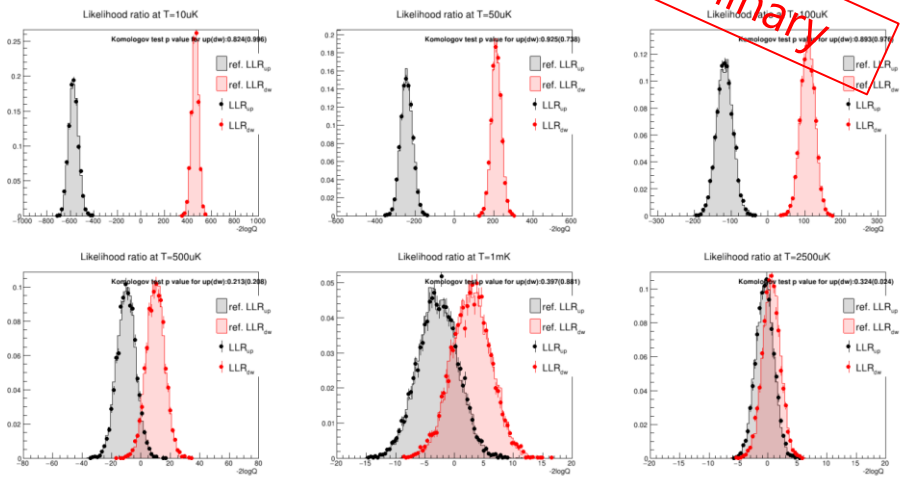


bottom annihilation



Top annihilation

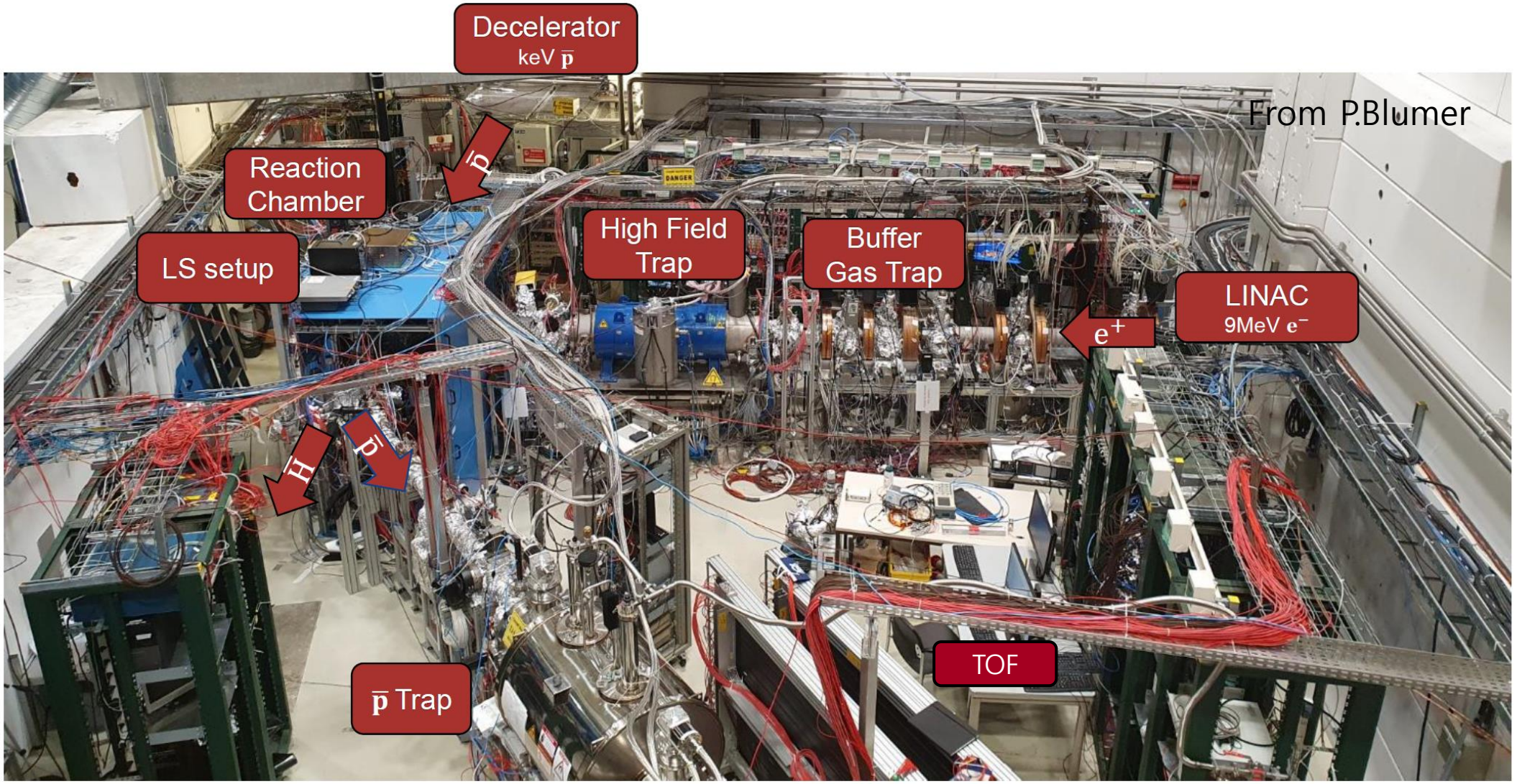
Preliminary



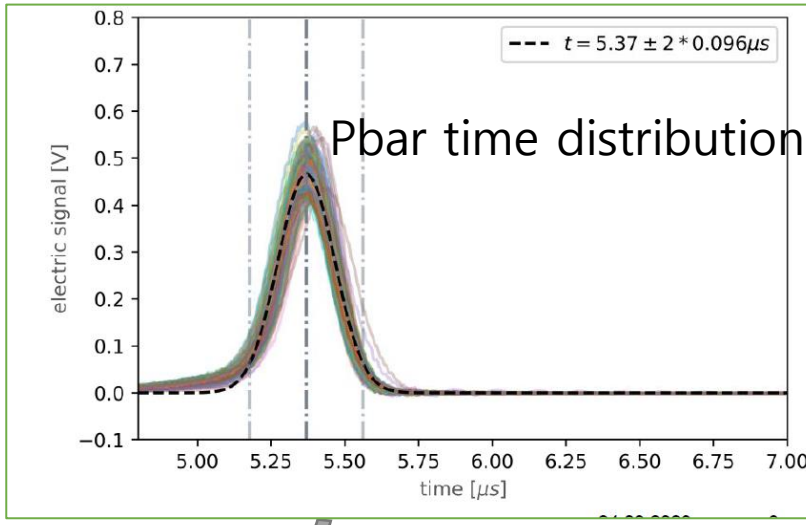
- TOF performance study was done by cosmic ray muon and achieved enough time precision (NIM A973 (2022) 164162)
- Simulation based on Geant4 with deep learning has been studied
- Estimated $\bar{H}$ number to measure 1% precision is 1500# detection of freefall $\bar{H}$ with 10uK
- Almost all cosmic ray background can be efficiently removed.

Current Status

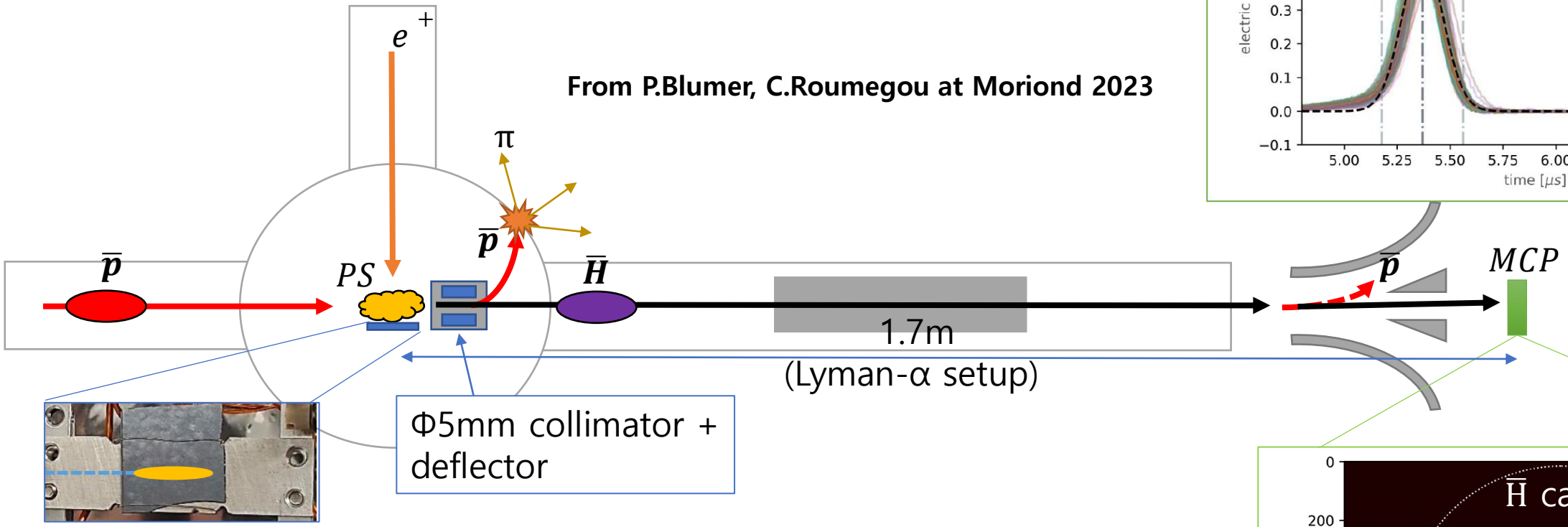
Experiment setup (2022)

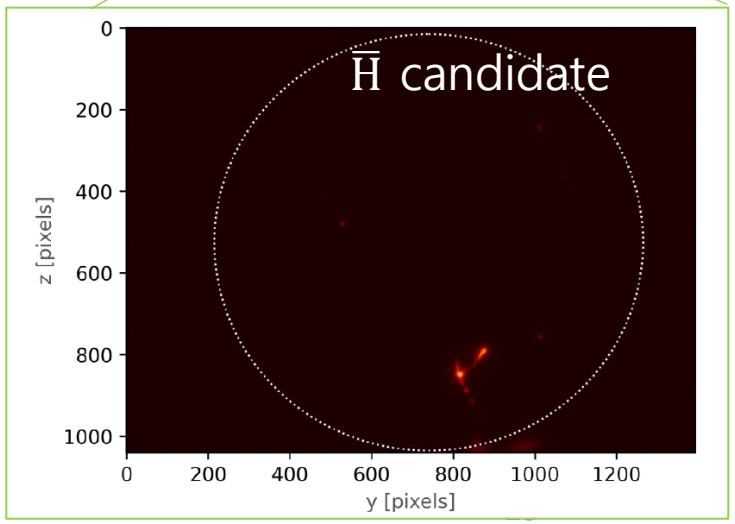


$\bar{H}$ production (2022)



From P.Blumer, C.Roumegou at Moriond 2023

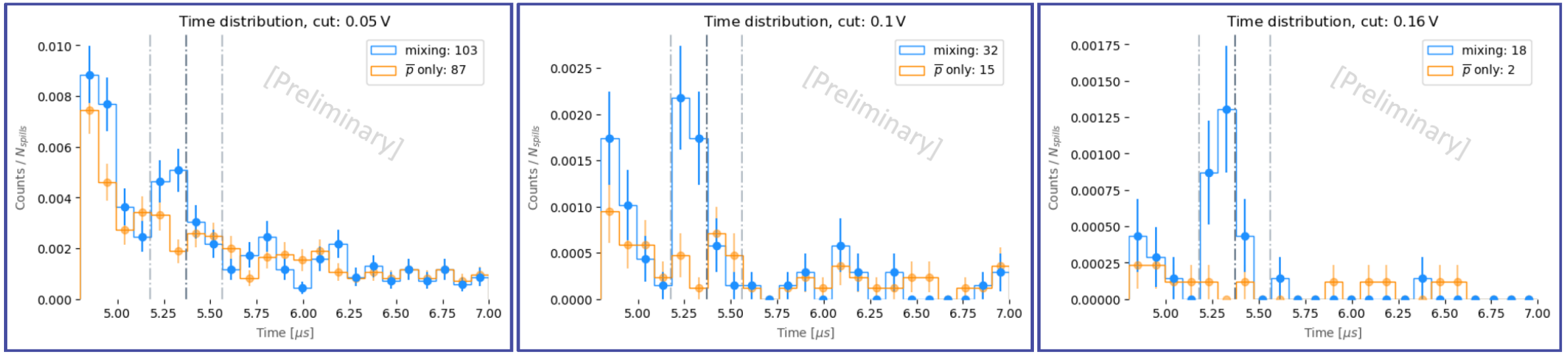




- $\bar{p}$ is tuned at the reaction target for the transmission of antihydrogen until MCP at 1.7m distance after the reaction
- $\bar{p}$ beam just after reaction(BG) is deflected by electric deflector and hits vacuum chamber.
- By 1.7m travel length, contamination of pion and γ background (generated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

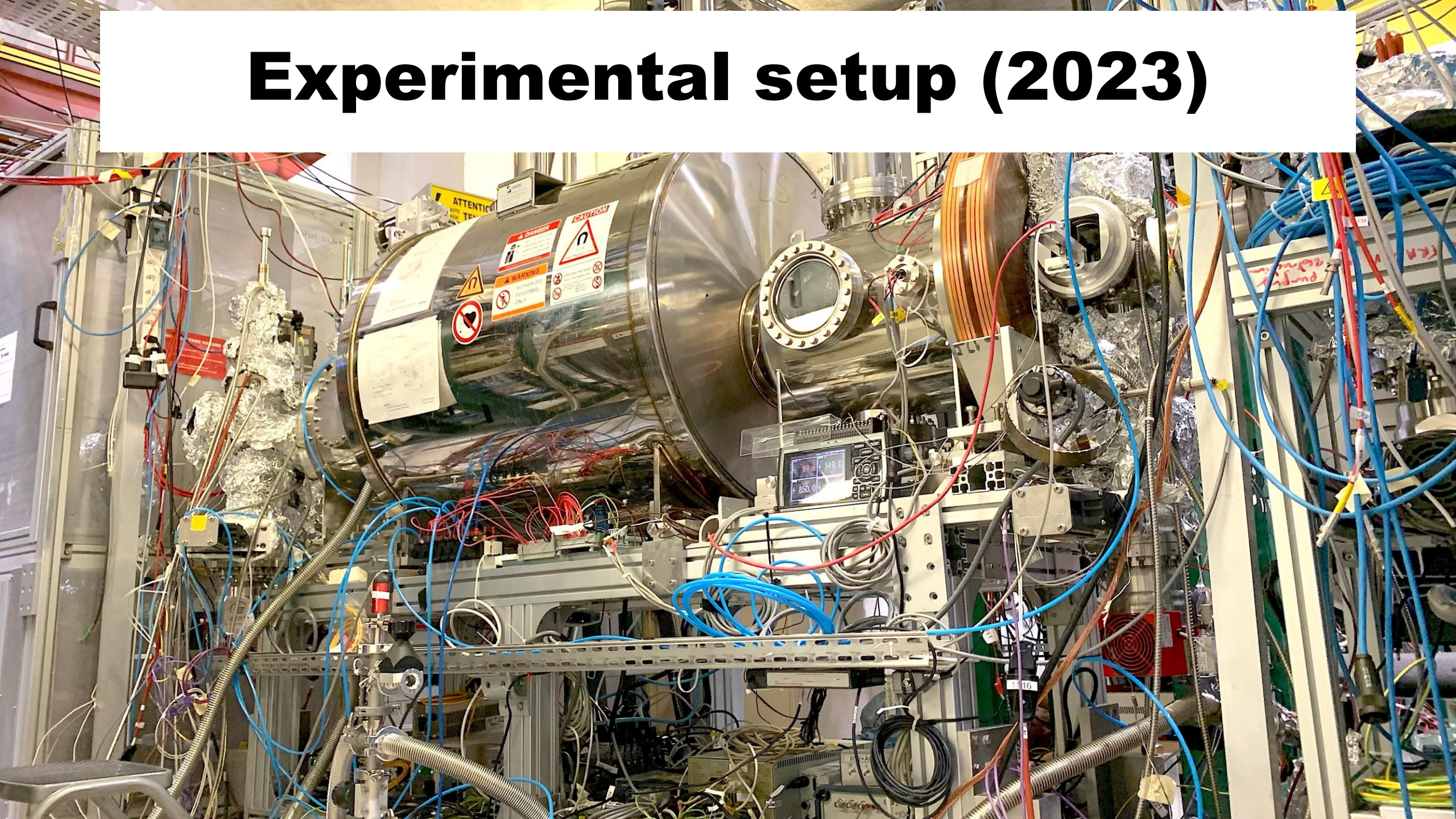
$\bar{H}$ production (2022)

From P.Blumer, C.Roumegou at Moriond 2023

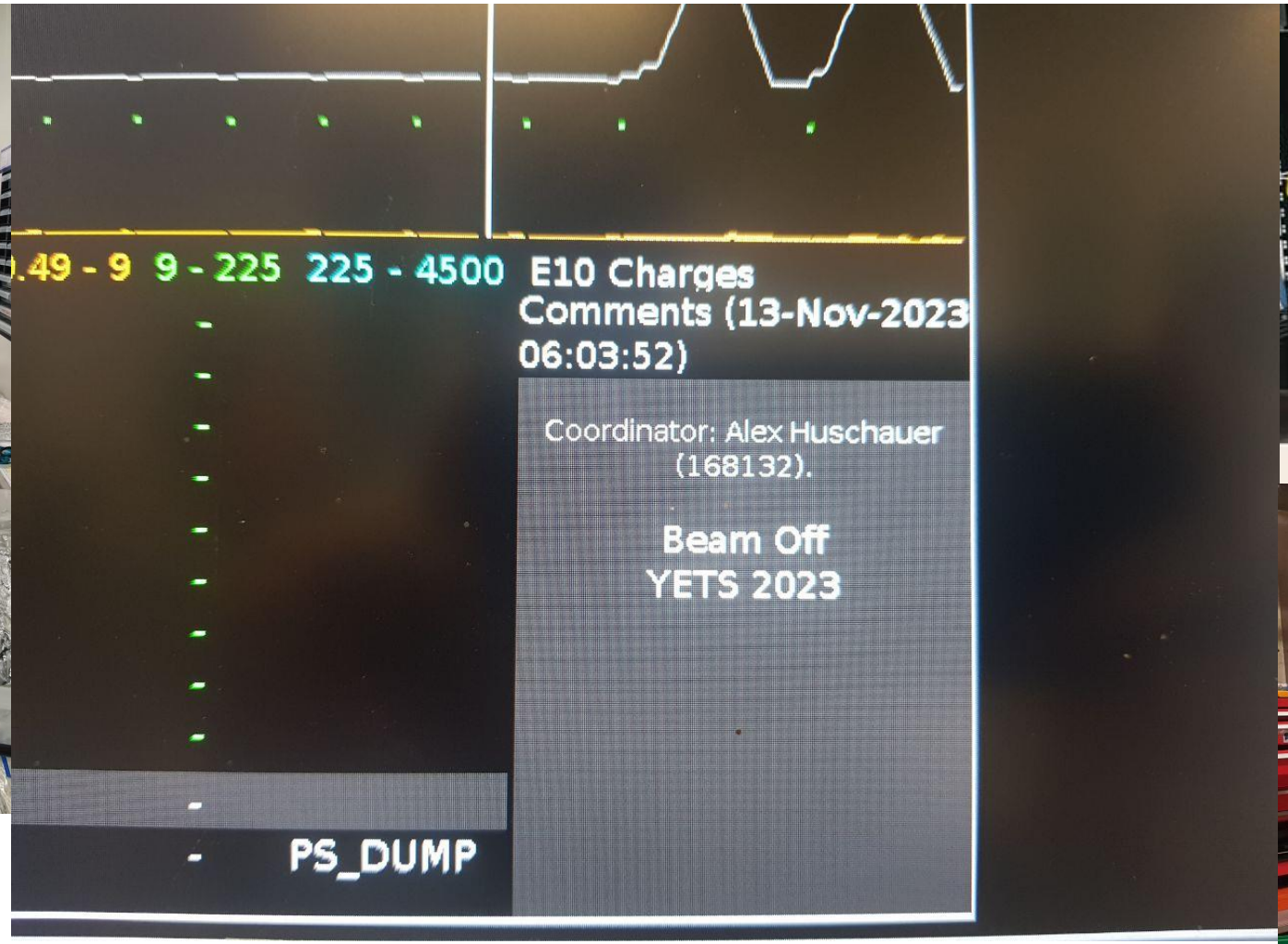


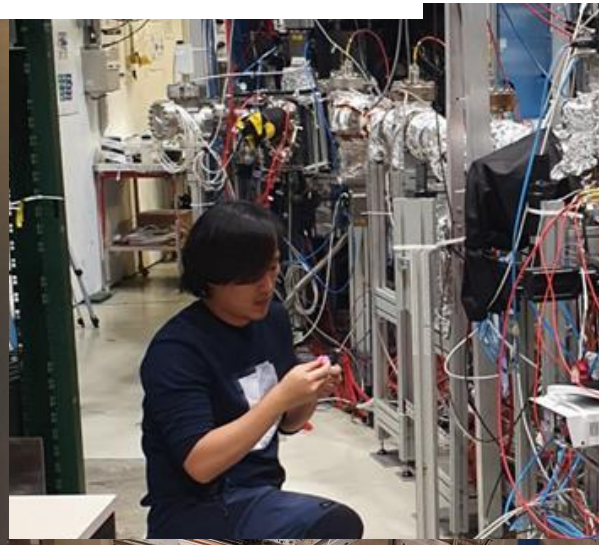
- Antihydrogen above 3σ is detected (which is **1st milestone**)
- (First) production of antihydrogen by charge exchange between o-Ps and antiproton **beam**
- Expected antihydrogen production rate ~1.1+-0.4 $\bar{H}$ per 100 spills seems roughly matched with calculated value (no measurement for the cross-section yet)
- Published at Eur. Phys. J. C 83, 10004 (2023)

Experimental setup (2023)



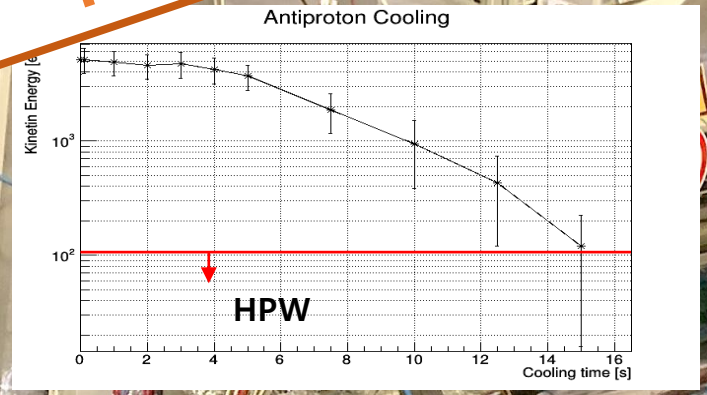
Experimental setup (2023)

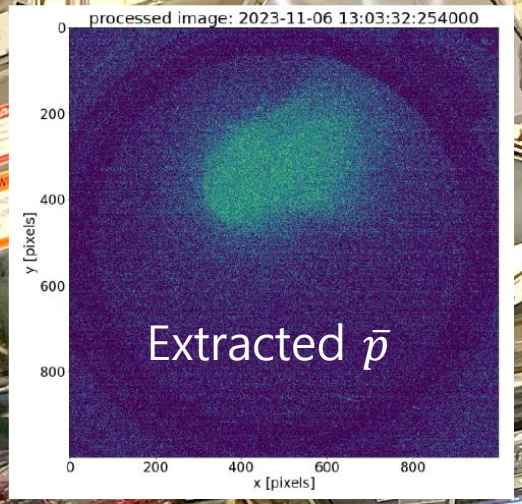


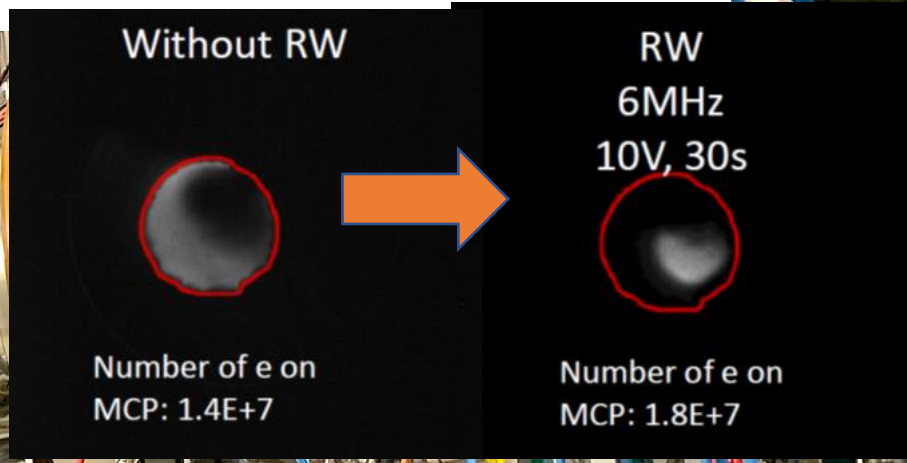


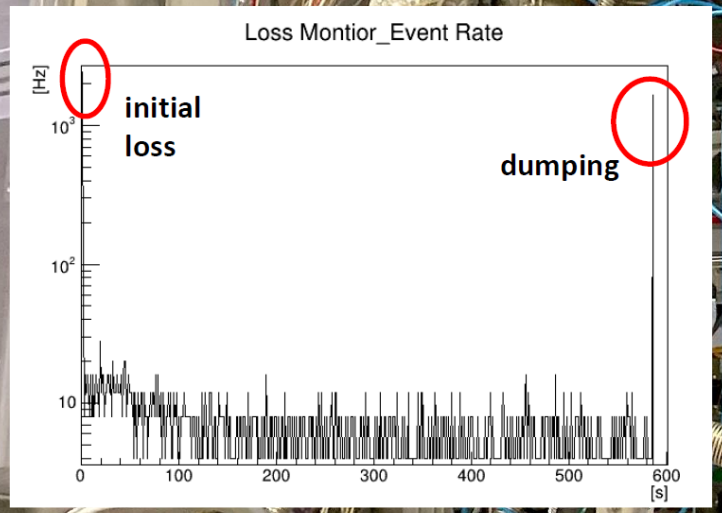
$\bar{p}$ trap demonstration (2023)

Preliminary









Operation	Process	Parameter
Trapping	70%	Efficiency($\bar{p}$)
Deceleration	60%	Efficiency($\bar{p}$)
Cooling	50%	e^-& $\bar{p}$ cooling, life time
Compression	45%	e^-& $\bar{p}$ compress, life time
Bunching	15%	Acceleration, bunching

- Antiproton trap was installed to final position at Sep. 2023
- Full operation has been checked and 35% efficiency has been shown during 2023 (1.8×10^6/110s)
- Try to produce $\bar{H}$ using $\bar{p}$ beam from antiproton trap
- Aim to achieve world best accumulation of $\bar{p}$ (now ~4×10^6 $\bar{p}$)

Plan and expectation

Plan of 2024

- Demonstration & cross-section expectation of $\bar{\boldsymbol{H}}^{+}$ by $H + Ps \rightarrow H^{-} + e^{+}$ experiment
- Antiproton trap commissioning (+ H^{-} cooling test?)

Plan before LS3 (until 2025)

- $\bar{\boldsymbol{H}}^{+}$ production & cross-section measurement (with enough condition of Ps and $\bar{\mathrm{p}}$: x1000 intensity (from 2022))
- Ready for free fall test ?
- Lamb-shift measurement

Antiproton beam line development

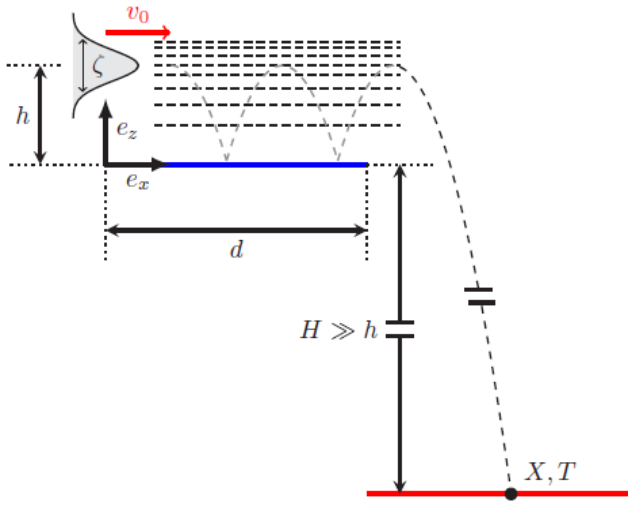
- Decelerator : French group (Orsay University (D.Lunney))
- Antiproton trap : Korean group
- FKPPL from 2023
- Recycler and recycling : Started from French group and now being Collaborated with Korean group → Recycler will be made at IBS
- What's done and planed : Reproduce antiproton beam from ELENA to well tuned beam for antihydrogen ion production

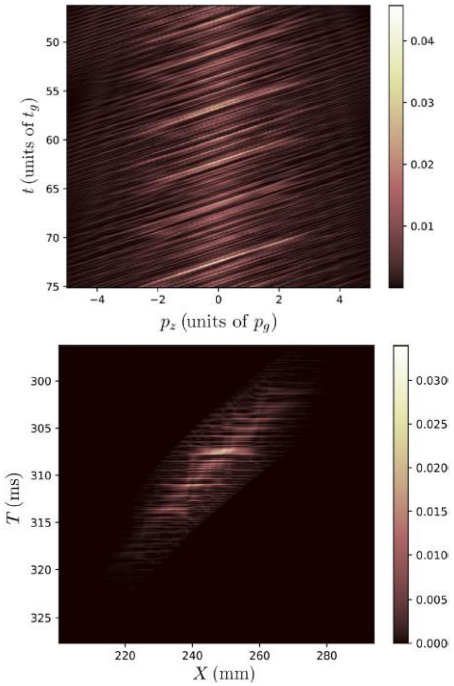
→

Decelerator		+ antiproton trap				+ recycler
Energy	T width	σ_r(at RC)	ΔE	T width	Efficiency	Intensity
<10keV	<100ns	<1mm	~10eV	56ns	~90%	X 10

- Current production rate requires much more input (>> x 100)
- Future plan : increasing antiproton intensity to x10 by recycler (2024, 2025)

Outlook for physics in GBAR



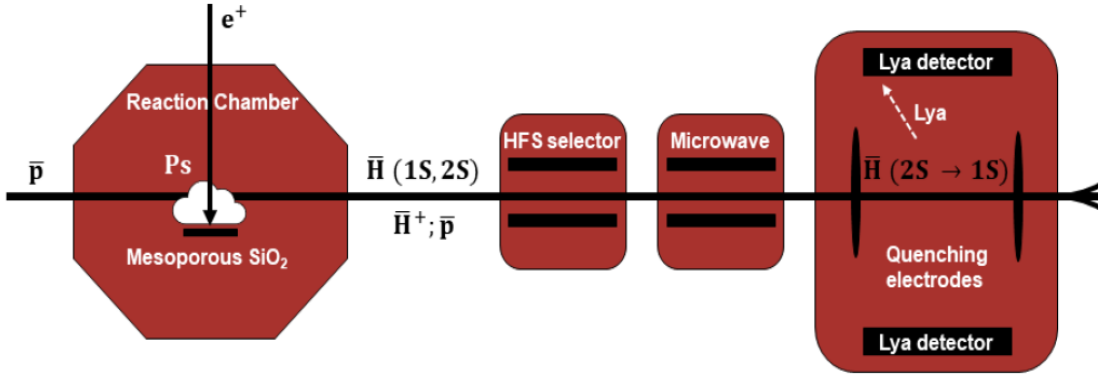


- Can be improved with proper shaper
- Quantum bouncing of antihydrogen (by Casimir-polder force)

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

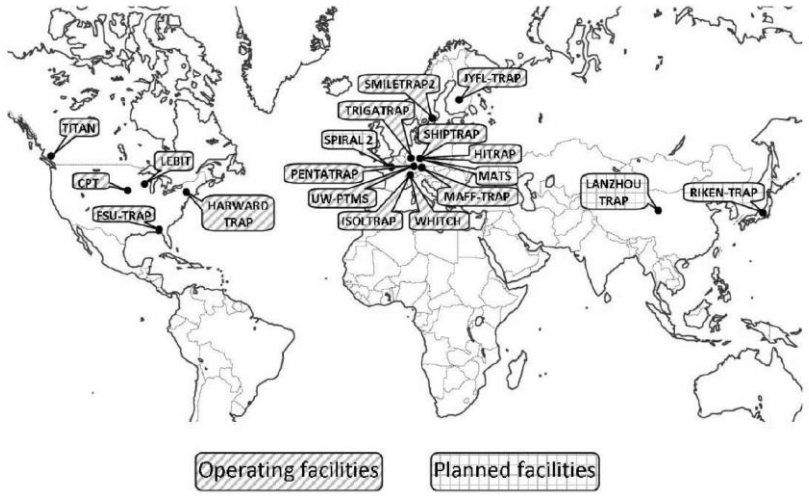
+ velocity shaping : precision below 10^{-3} (Eur. Phys. J. C (2014) 742731)

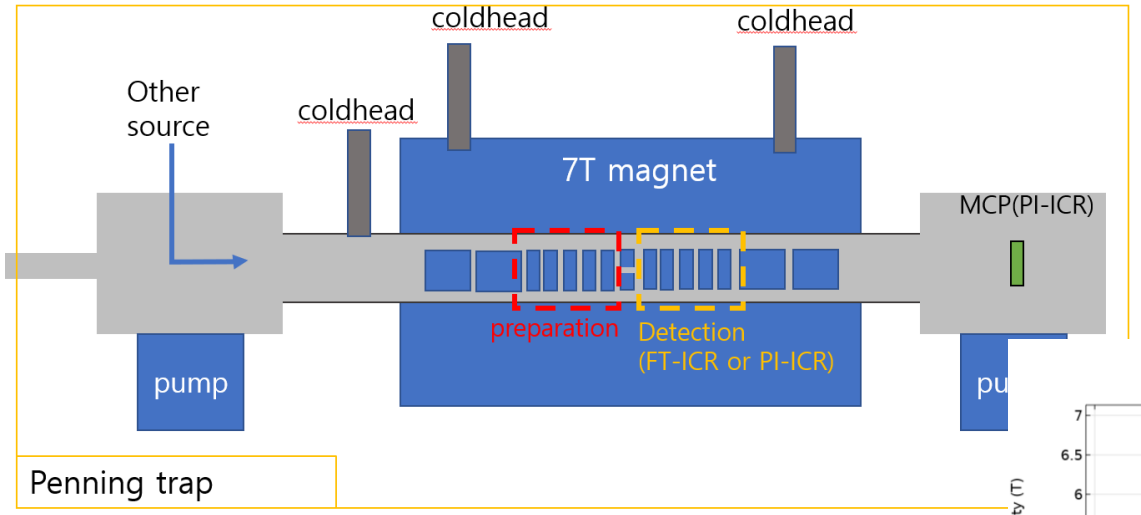
- Quantum interference to improve the accuracy (10^{-5}) : Phys. Rev. A 99,042119

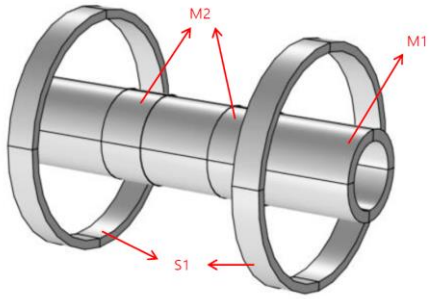


- Device was commissioned in 2021 by hydrogen
- First attempt of $\bar{H}$ Lamb shift measurement by Ramsey technique is aimed
- GBAR can produce $\bar{H}$(2S) and possibly measure a level of 100ppm
- Do more CPT test?

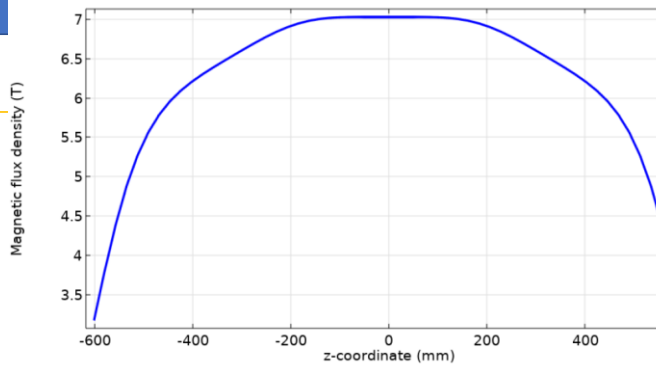
Further development

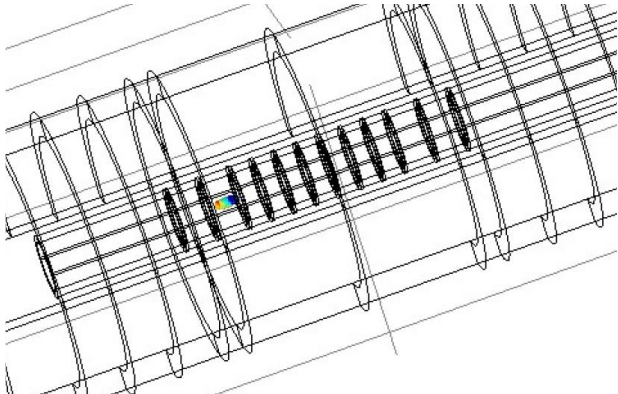






Magnetic field (R=0)





- We have technology for low temperature UHV penning-malmberg trap development

➔ Aim to make a penning trap for mass spectroscopy (at RAON?)

- Magnet production : end of 2024
- Possible assembly of the penning trap : middle of 2025
- Simulation study : COMSOL simulation for design study (injection, trapping, extraction)
- Precision detection technique will be developed by reference sources

: PI-ICR(ion cyclotron resonance) ($\delta m/m < 10^{-7}$) by position sensitive MCP detector

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 do commissioning next 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 penning trap for mass spectroscopy ($\delta m/m \sim 10^{7}$) from 2023 (with CENS, RAON?)

Backup

CPT test at AD

From Stefan Ulmer's slide (ADUC)

- Spectroscopy of antihydrogen

 - 1S - 2S transition : (hydrogen 4.2e^{-15}) CPT with antihydrogen : 200 ppt (2017) → 2 ppt (Nature 557, 71-75 (2018))

 - 1S- 2P transiton : 16 ppb (nature 578, 375 (2020))

 - Hyperfine splitting : observed 2% ($2P_{1/2}$-$2P_{3/2}$) : 250ppm

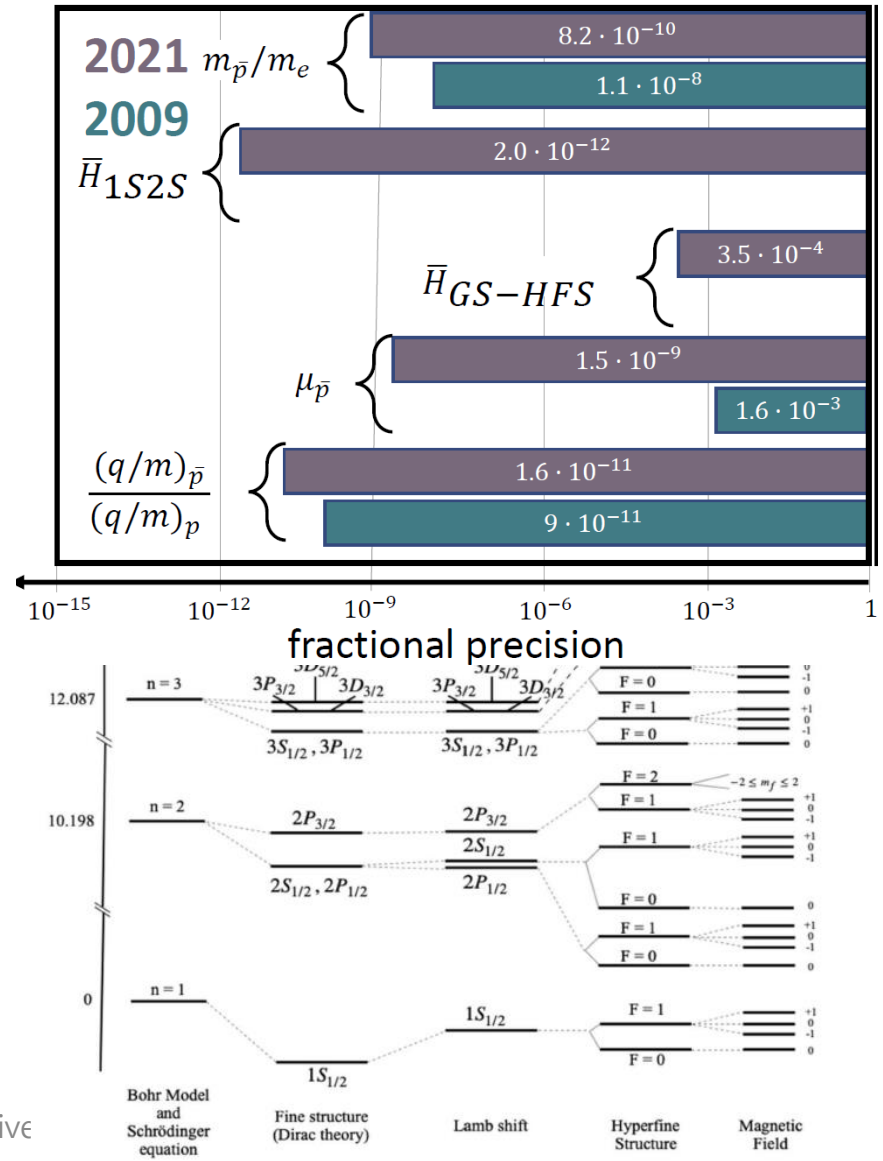
(nature 548, 66-69 (2017), nature 578, 375 (2020)) by ALPHA

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

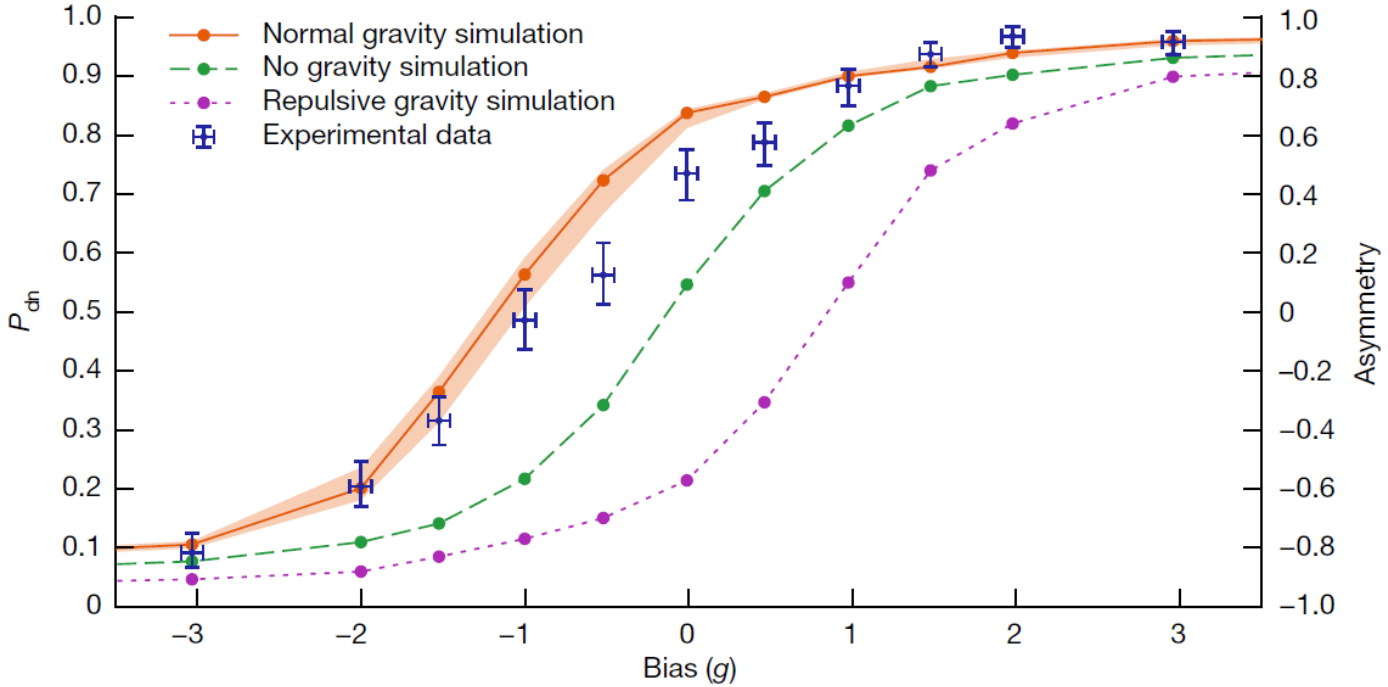
- Proton & antiproton CPT test by BASE

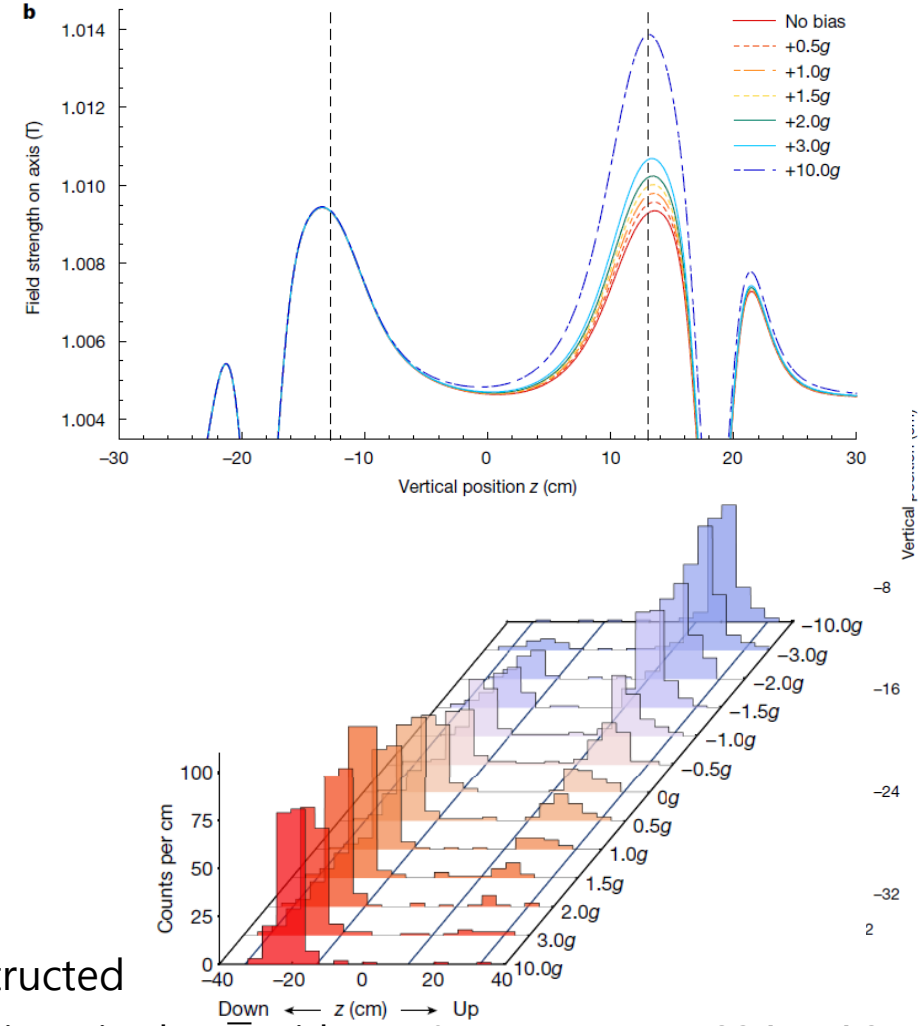
- g-factor : 1.5 ppb (nature 524, 196-199 (2015))

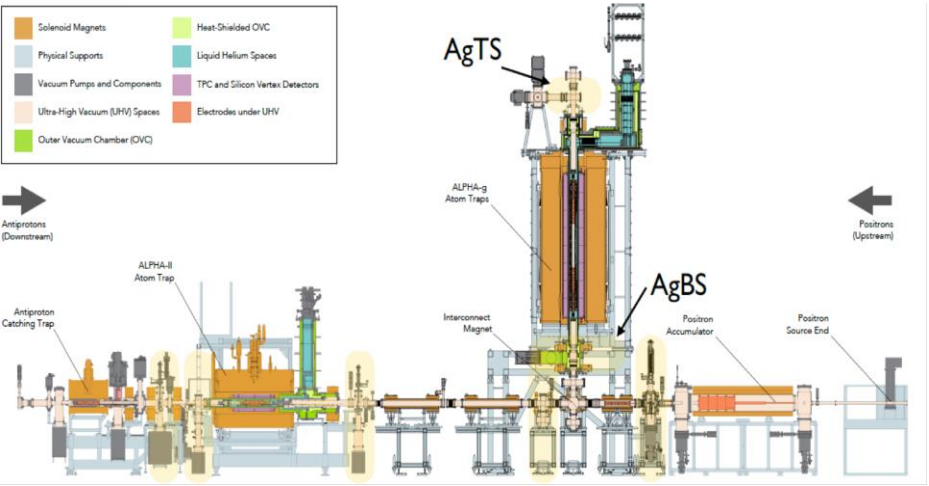
- m/q ratio : 16 ppt (nature 601, 53-57 (2022))



Antihydrogen WEP test







- ALPHA experiment

2018 : Alpha-g magnet constructed

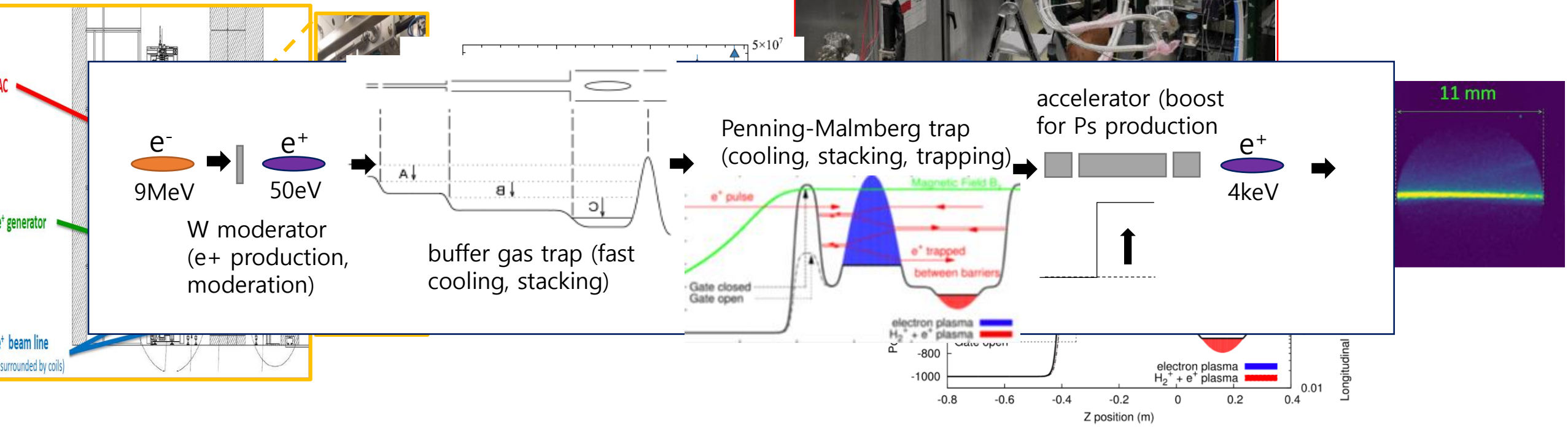
2023 : Rule out Repulsive antigravity by $\bar{H}$ with T <0.5K (**Nature 621, 716-722 (2023)**)

$$a_{\bar{g}} = (0.75 \pm 0.13 \pm 0.16) \times g$$

Positron beam for Ps production

Linac and positron target

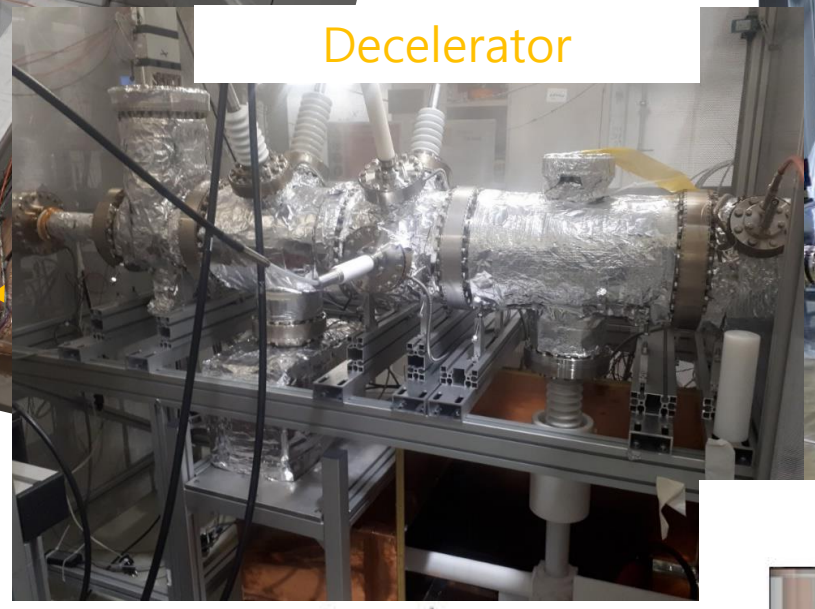
Positron high field trap



- Positron beam : monoenergetic positron beam generated from bremsstrahlung-induce pair production by 300Hz 9MeV e- linac with W moderator → a goal to 3 x $10^8 e^+/s$ (commissioning in this year) M.Charlton et al., NIM A 985, 164657 (2021)
- Positron accumulation by high field trap : goal to 1x10^{10} e^+ (110s) with electron cooling (1.4xe^9 e+/1100s achieved) (NIM A 1040 (2022) 167263
- Positron acceleration &bunching by electrostatic lenses to reaction target (2 x $10mm^2$)
- SiC re-moderator has been prepared for better trapping efficiency

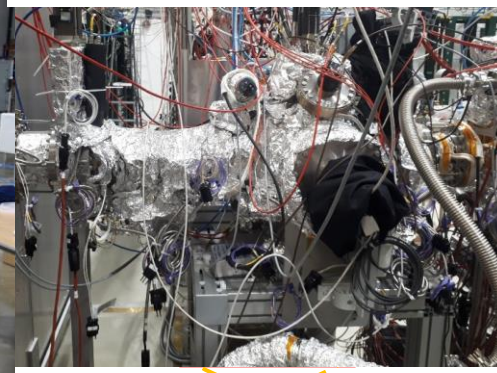
Antiproton beam line

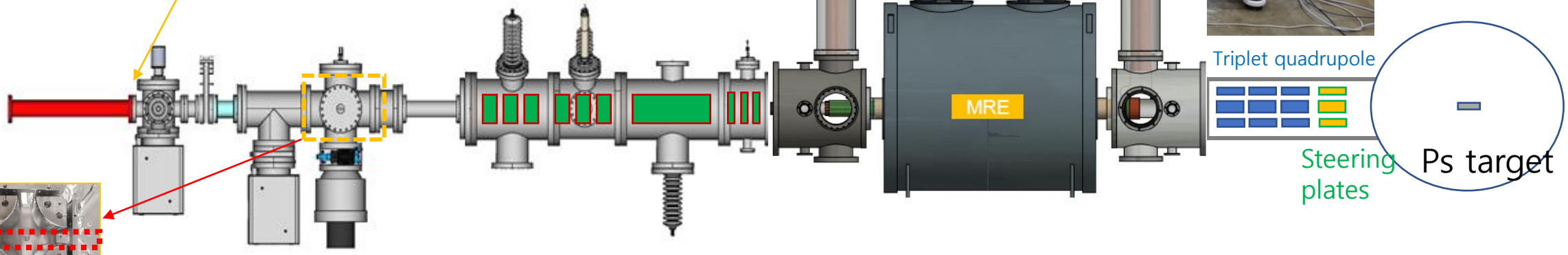
Decelerator



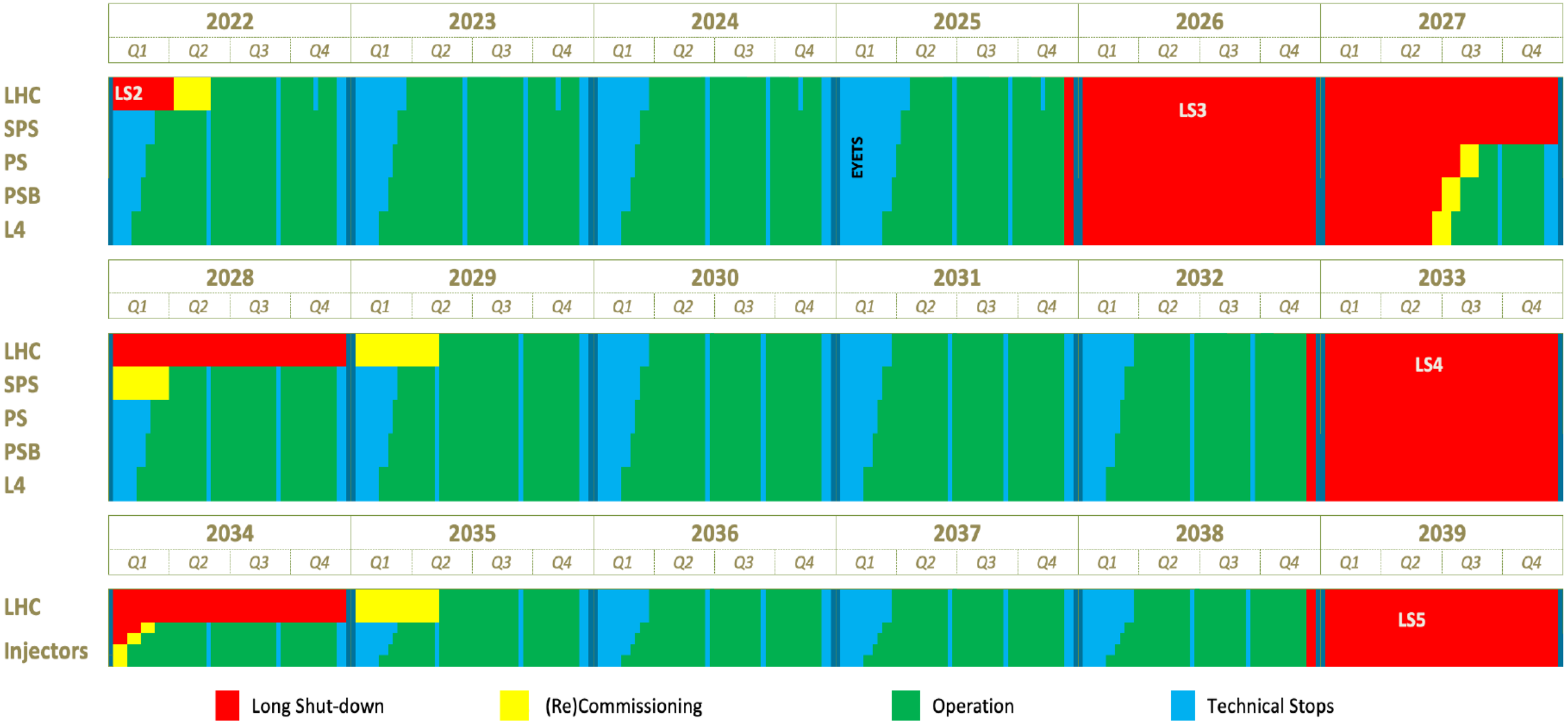
Antiproton trap

Reaction chamber

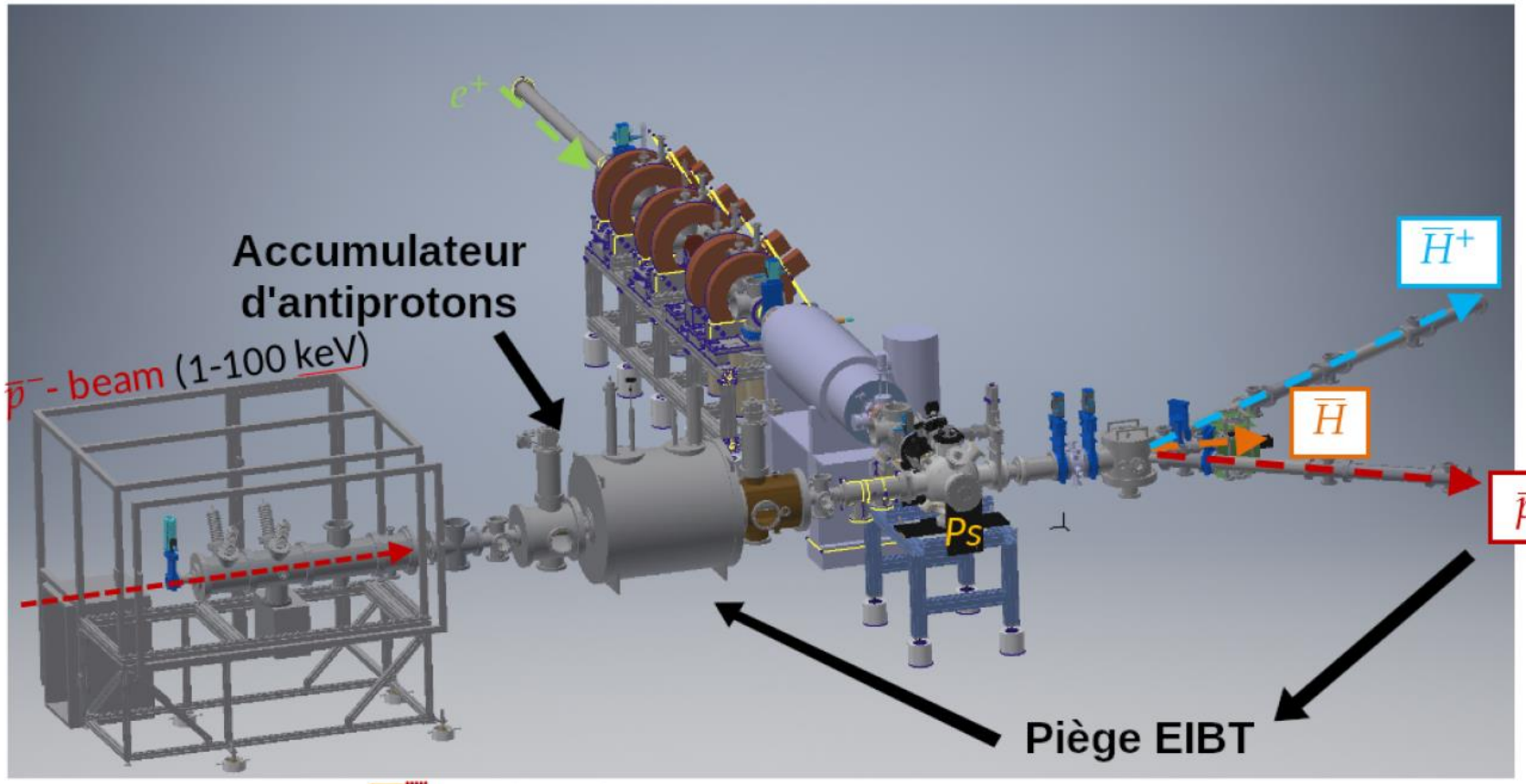


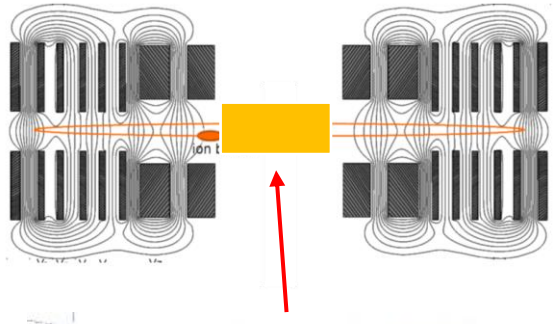


Long Term Schedule for CERN Accelerator complex



Antiproton beam with addition of recycler





$\bar{p}^-$: Anti-Protons $\overline{H}^{\square}$: Anti-Hydrogen e^-: Electrons

p^+: Protons $\overline{H}^+$: Anti-Hydrogen ion e^+: Positrons Ps: Positronium

100keV pbar beam→ Deceleration → Trap&Cool&compress → Target ← Reflection