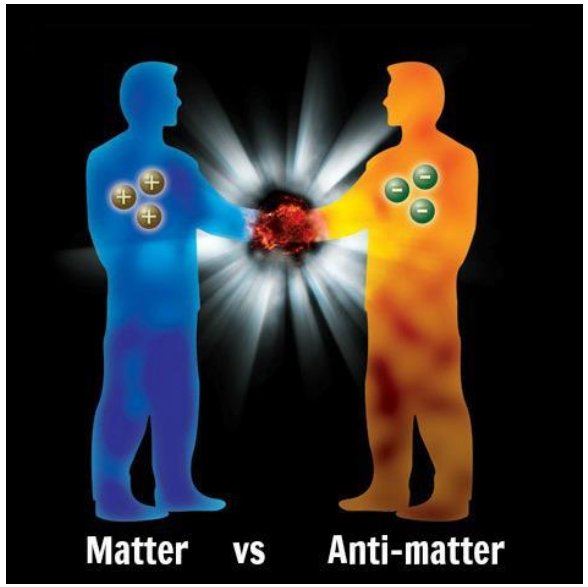
The status of the GBAR experiment

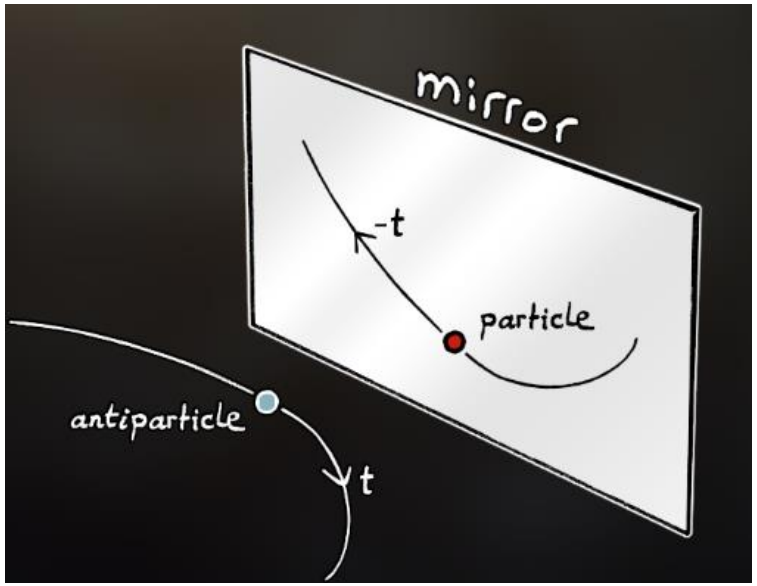
Center for Underground Physics
Institute of Basic Science

Bongho Kim

Introduction : Antimatter

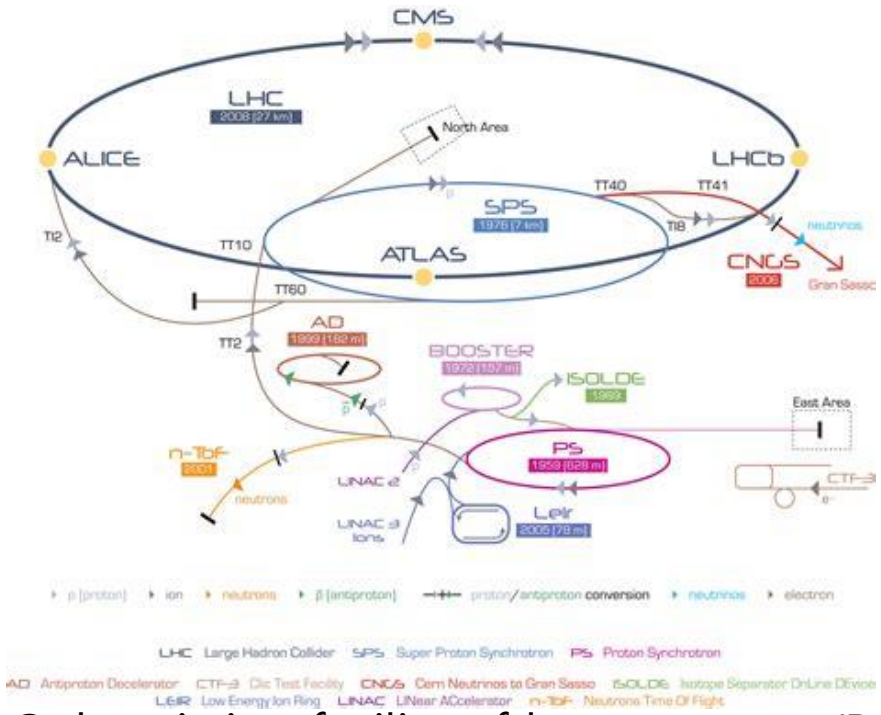


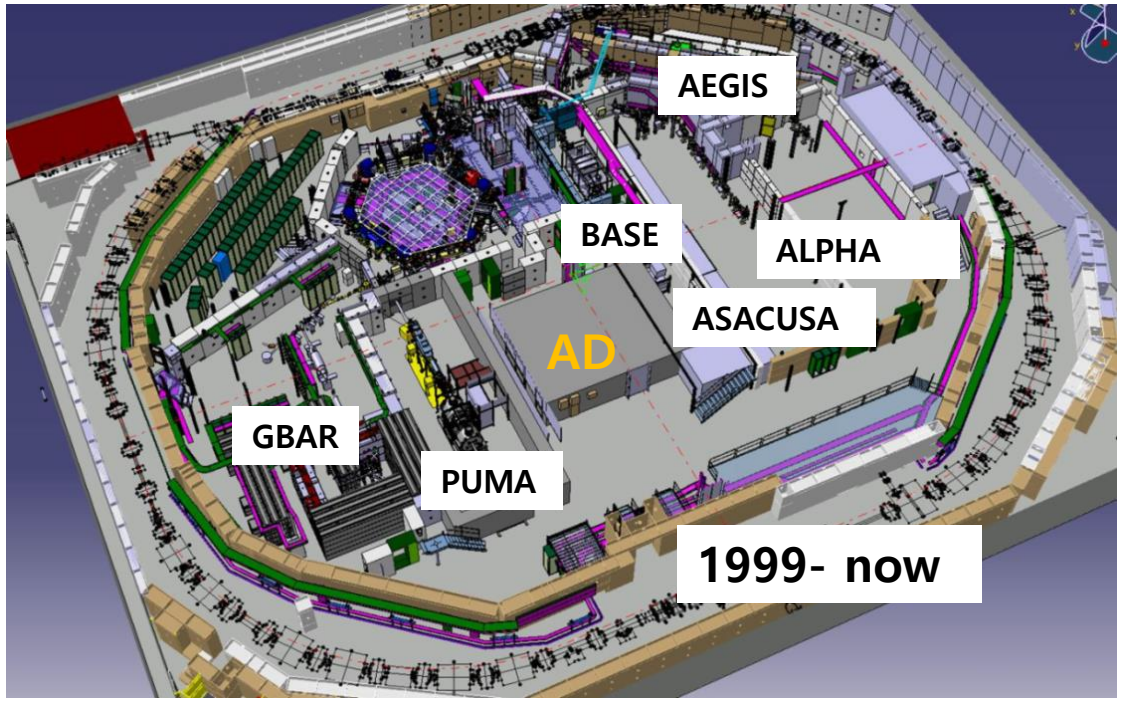
From https://www.symmetrymagazine.org/article/october-2005/explain-it-in-60-seconds
Illustration by Sandbox Studio, Chicago



- In 1928, solution of Dirac equation with negative energy predicts antimatter and the antimatter is experimentally confirmed in 1932
- Antimatter is partner of matter for CPT reversal, but our universe is matter dominant universe
- Currently measure CP violation is not enough to explain this asymmetry
- Efforts to check CPT symmetry have given by measuring fundamental property of matter and antimatter

Low energy Antiproton beam facility

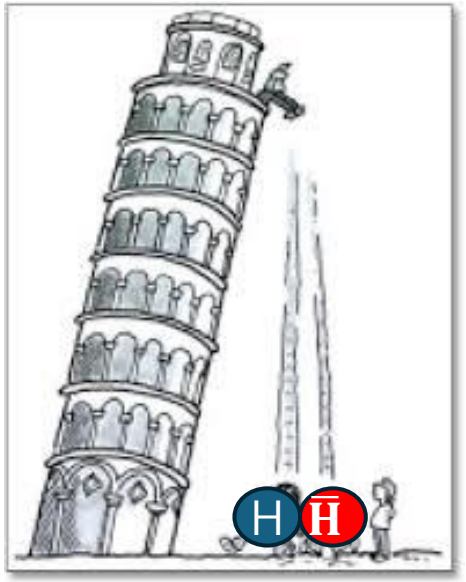




AD : Only existing facility of low energy $\bar{p}$ (PANDA at FAIR has higher energy)

- Antiproton Decelerator (AD) + ELENA : Antiproton Factory (for high statistics)
- For precision measurement by Electromagnetic and Gravitational property, **deceleration, cooling and trapping** techniques are important
- 26GeV/c proton → 3GeV/c antiproton to 0.1GeV/c at AD → 5.3MeV(0.1GeV/c) to 100KeV at ELENA

GBAR experiment



GBAR needs to **cool** the anti-atom to ~**1neV** (10uK)

- GBAR : Gravitational Behaviour At Rest

Freefalling antimatter (anti-hydrogen) in terrestrial gravitational field

+ CPT test by measuring atomic structure : Lamb shift measurement

=Check fundamental interaction between matter & antimatter

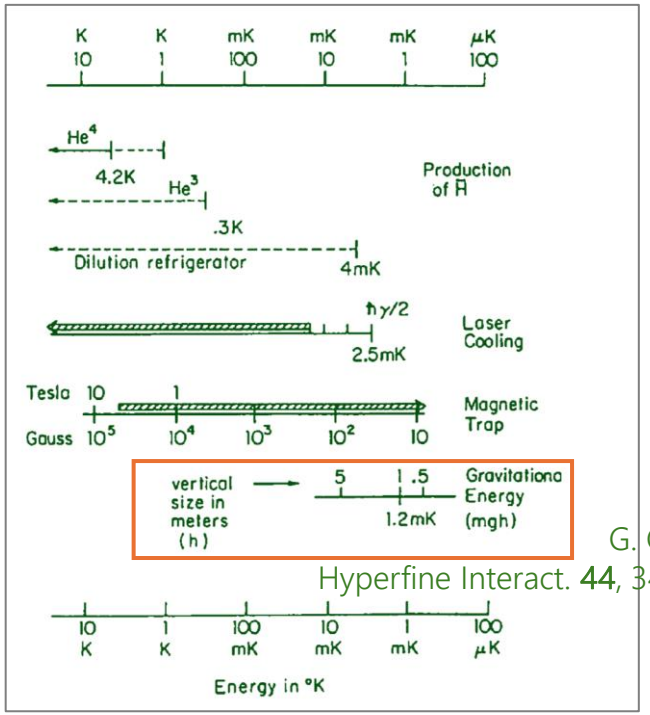
- Weak Equivalence Principle(WEP) :

$$m_I = m_G \ (F = m_I \mathrm{a} = -Gm_G m'_G / r^2)$$

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

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

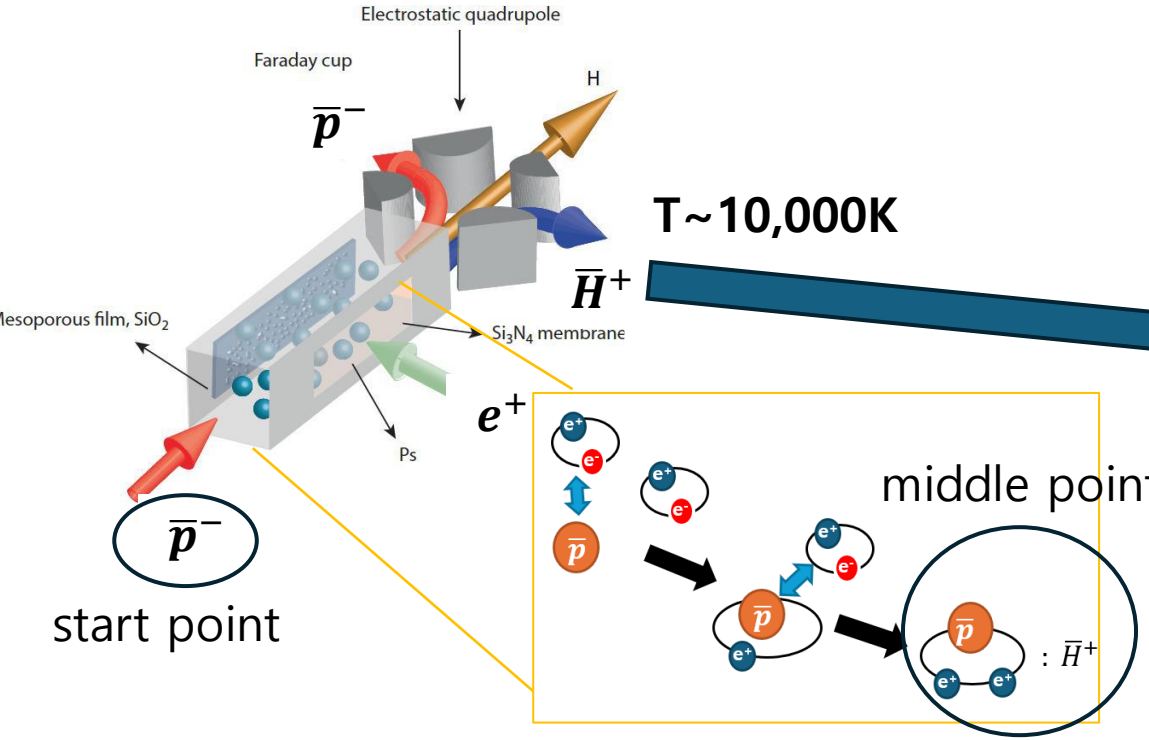
(for matter $\Delta(m_g/m_i)/(m_g/m_i)_{Be/Ti} = (0.3 \pm 1.8)10^{-13}$)



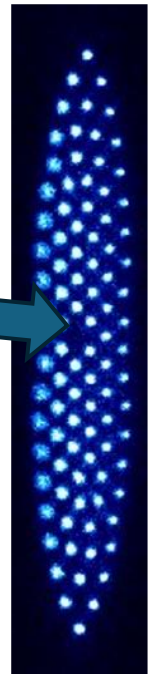
G. Gabrielse
Hyperfine Interact. **44**, 349 (1988)

GBAR experiment

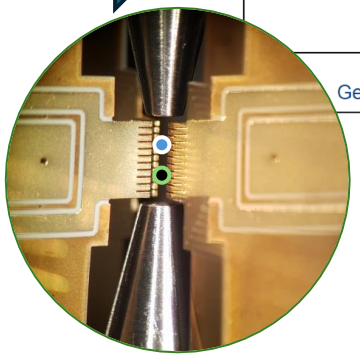
Velocity fluctuation	100m/s	3m/s	0.1m/s
Temperature	1K	1mK	1uK

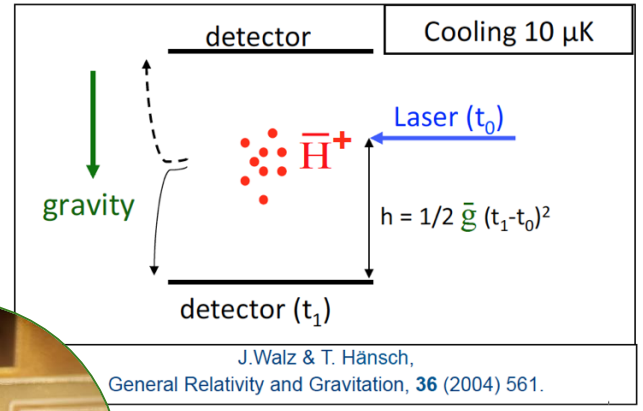


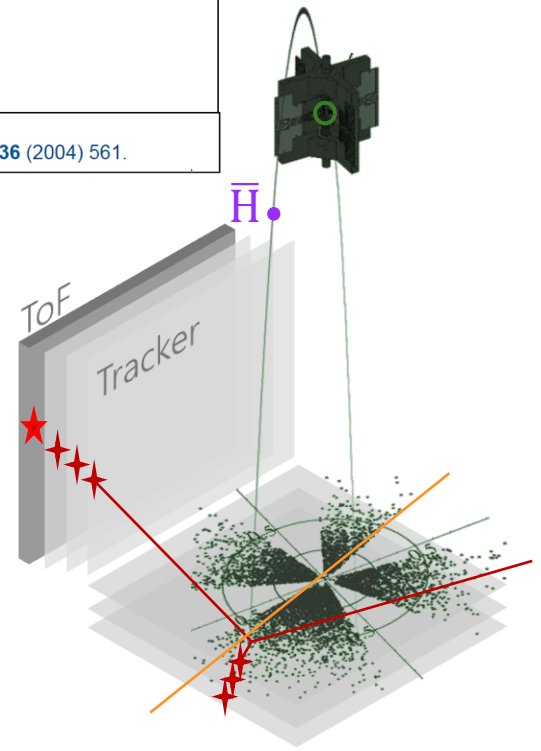
T~10,000K



T~mK→uK



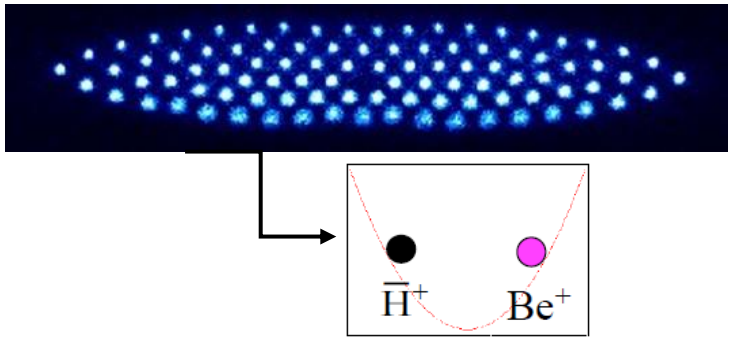


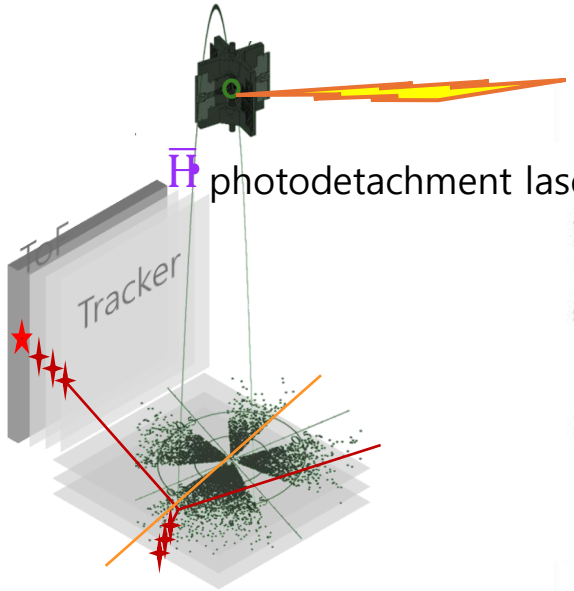


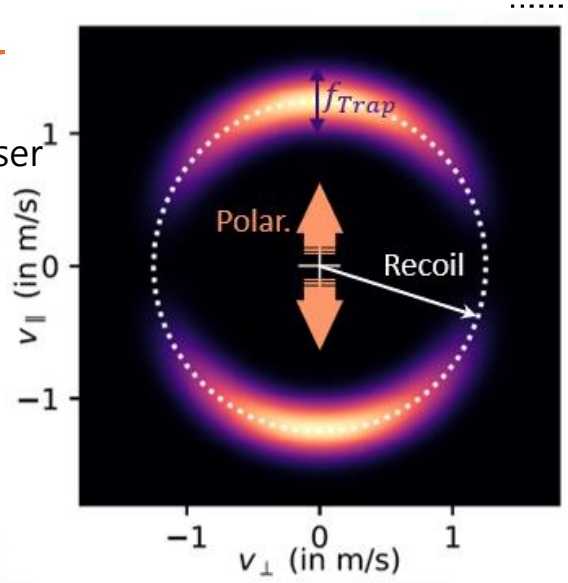
- Double charge exchange process between $\bar{p}$ beam and dense Ps cloud (<1x1.5x10mm³ cavity)
  $\bar{p} + Ps \rightarrow \bar{H} + e^-$: 1st milestone
  $\bar{H} + Ps \rightarrow \bar{H}^+ + e^-$: 2nd milestone
  with Enough intensity of e^+ & $\bar{p}$
  Good beam phase-space

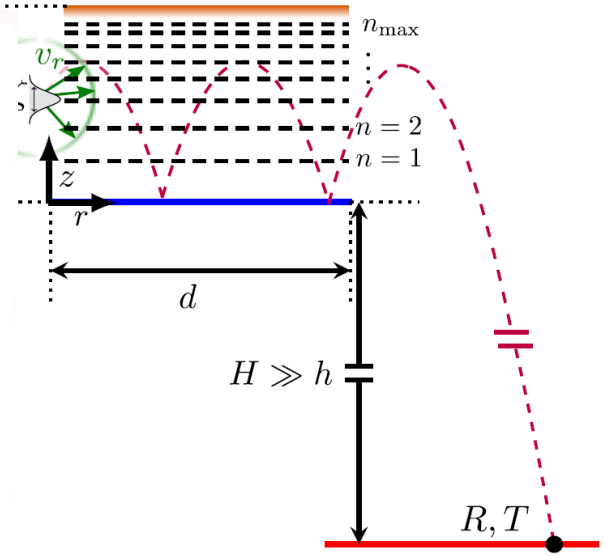
- Cooling anti-hydrogen ion down to **10uK** range by doppler cooling : 3rd **milestone**
- After dropping one of e^+ (by photo-detachment laser), let the ultra-cold anti-hydrogen **freefall**.
- Direct measurement of the gravitational acceleration ($m_H g \sim 10^{-7} eV/m$) of anti-hydrogen (WEP_{ff}) below 1%
- $\bar{H}^+$ is required to get ultra-cold $\bar{H}$ which can go below 10^{-5} precision

Quantum reflection and levitation









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

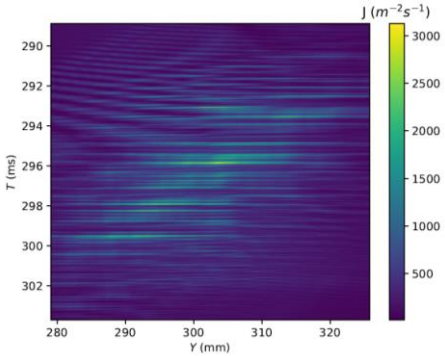
Sympathetic Doppler cooling by cooled Be^+ ions (>10,000 laser(313nm) cooled Be^+/HD^+ ions (Wigner crystal), 100 neV, T~mK by rf heating) (L. Hilico et. al., Int. J. Mod. Phys. Conf. Ser. 30, 1460269 (2014))

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).)

3. Photo detachment and free-fall

4. Polarization and Shaping with 0.1% uncertainty for 10,000 event (O.Rousselle et al, Eur. Phys. J. D **76**, 209 (2022))

5. Quantum bouncing by Casimir-Polder potential vs Gravitational potential 10^{-5} precision (G. Dufour et al., Eur. Phys. J. C (2014) 74: 2731)



GBAR collaboration

CSNSM

ETH Eidgenössische Technische Hochschule Zürich

NEUTRONS FOR SCIENCE

IPCMS

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

JG|U JOHANNES GUTENBERG UNIVERSITÄT MAINZ

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

Laboratoire Kastler Brossel
Physique quantique et applications

NATIONAL CENTRE for NUCLEAR RESEARCH Świerk

RIKEN

Stockholm University

Swansea University Prifysgol Abertawe

서울대학교 SEOUL NATIONAL UNIVERSITY

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

KOREA UNIVERSITY

ibs Institute for Basic Science

東京大学 THE UNIVERSITY OF TOKYO

POSTECH
POHANG UNIVERSITY OF SCIENCE AND TECHNOLOGY

Collaboration :

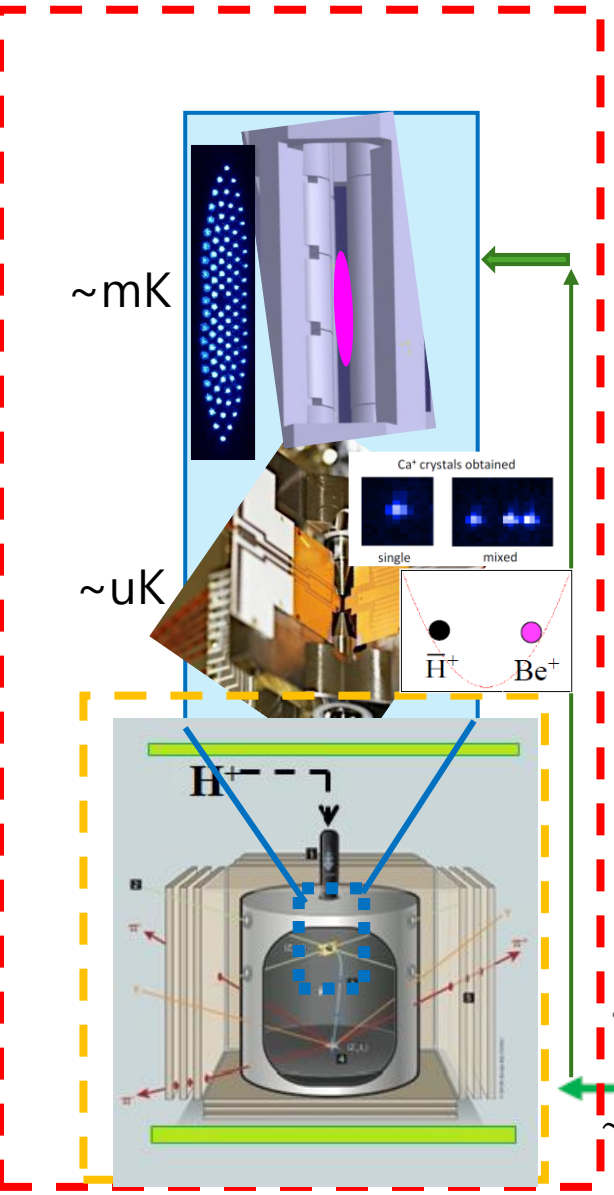
8countries ,18institutes, 64members

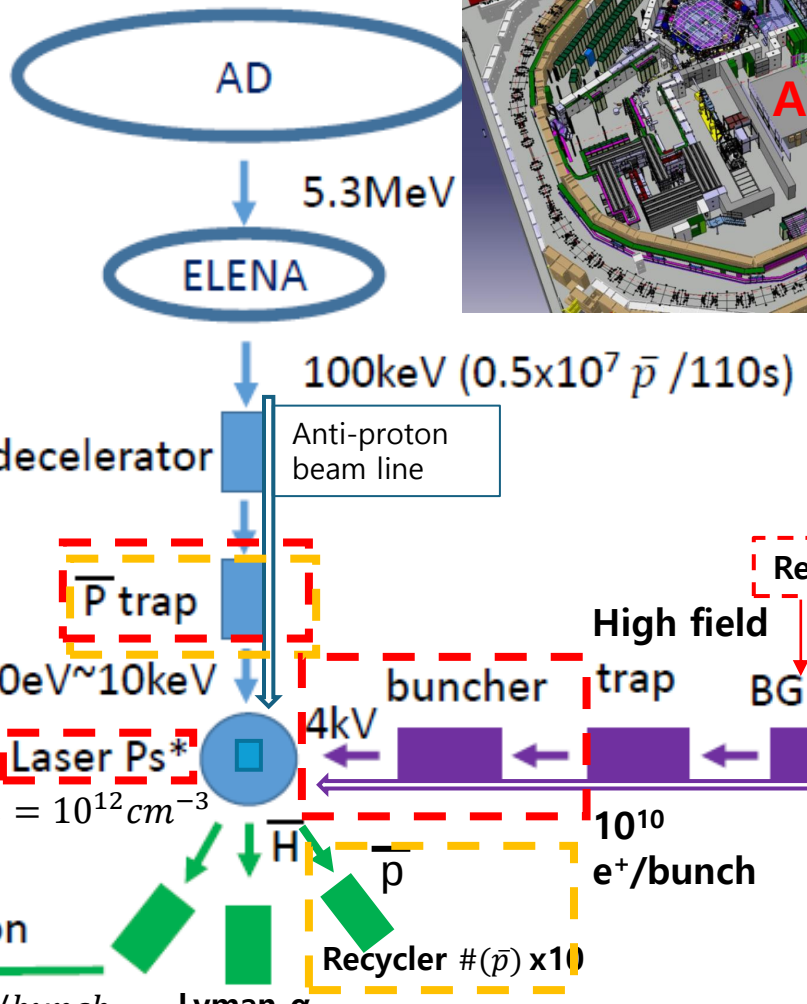
Korean team

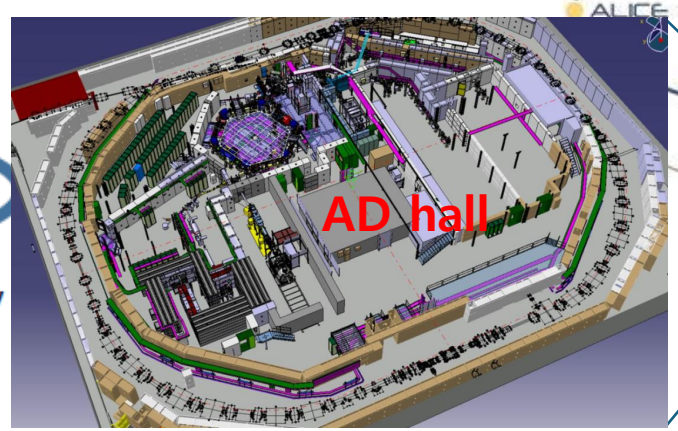
Senior : 6

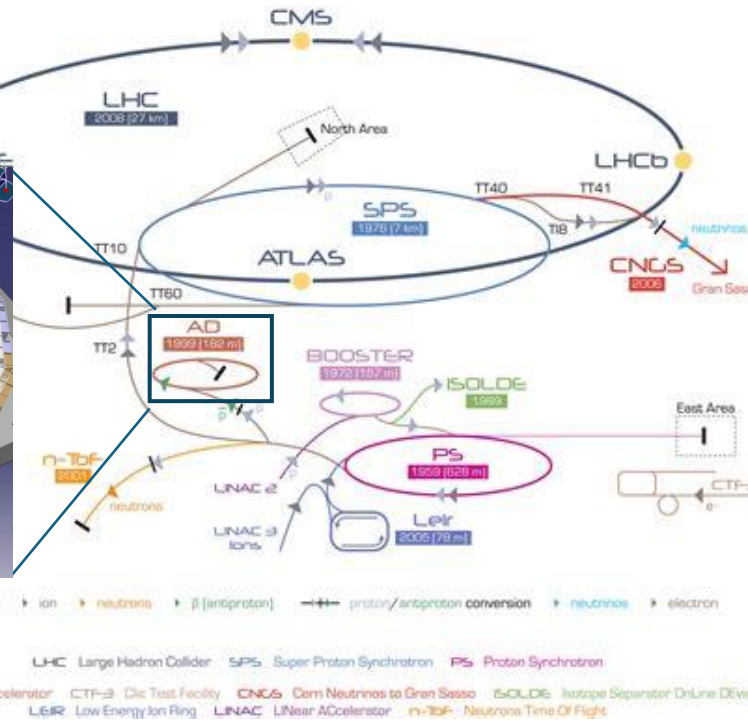
Students : 3 ~~(+2 : graduated)~~

Experiment Scheme





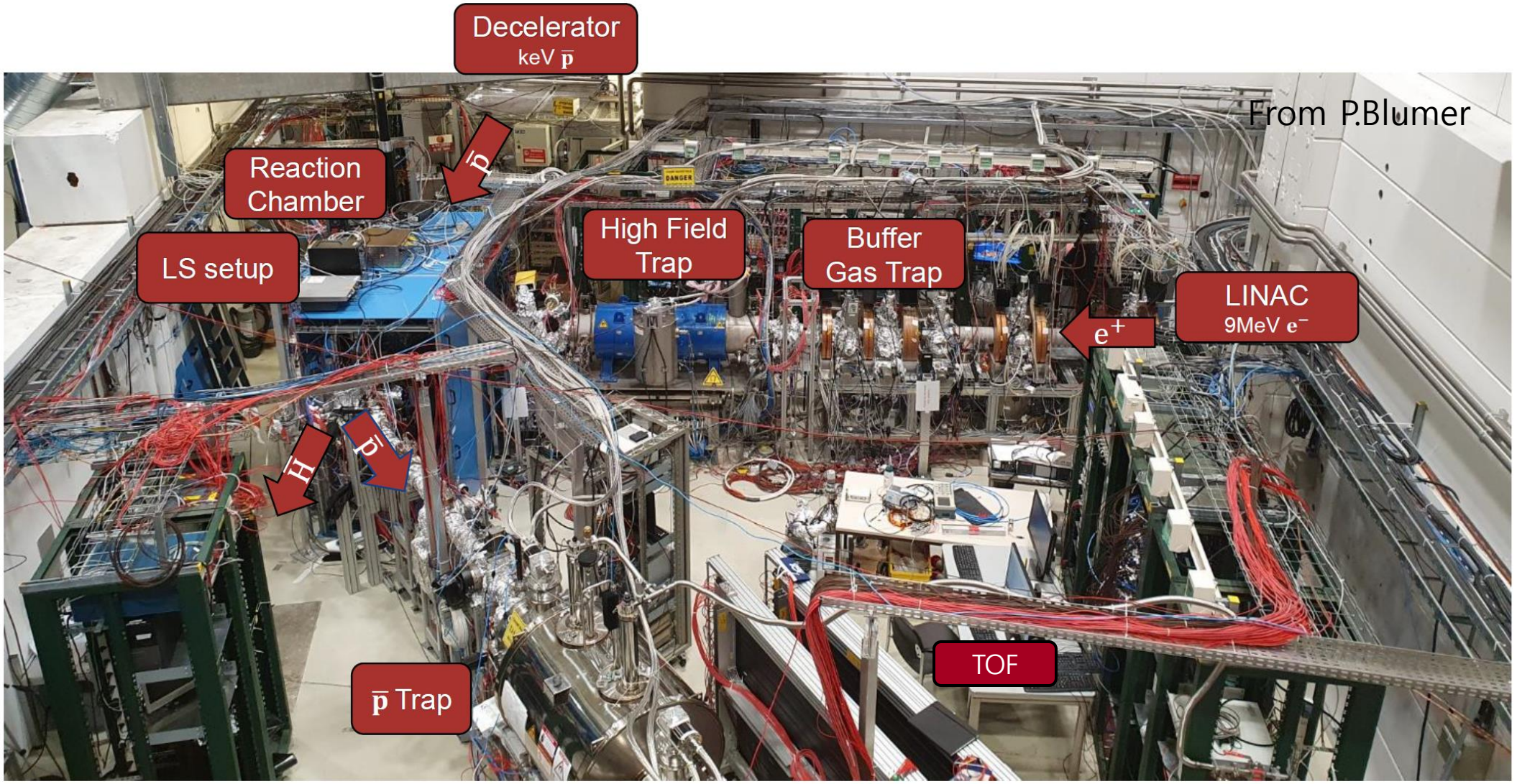




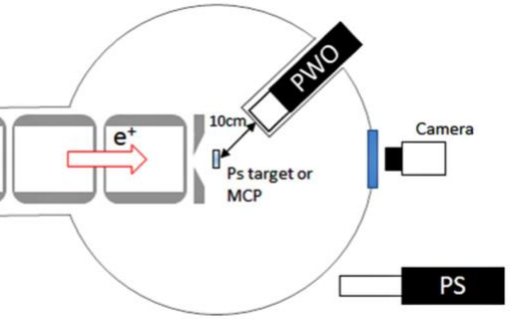
: Currently developed

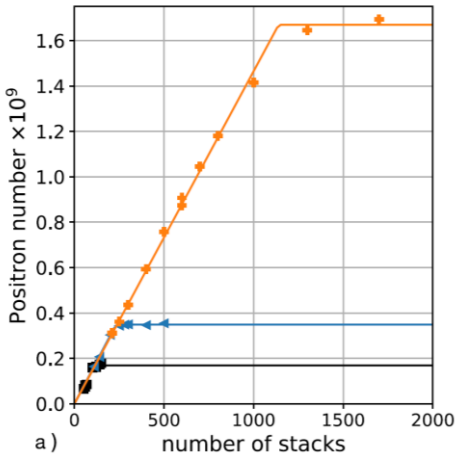
: Korean team involved

Experiment setup (2022)



Positron beam line





The GBAR collaboration,
Nucl. Instr. Meth. A **1040**, 167263 (2022)

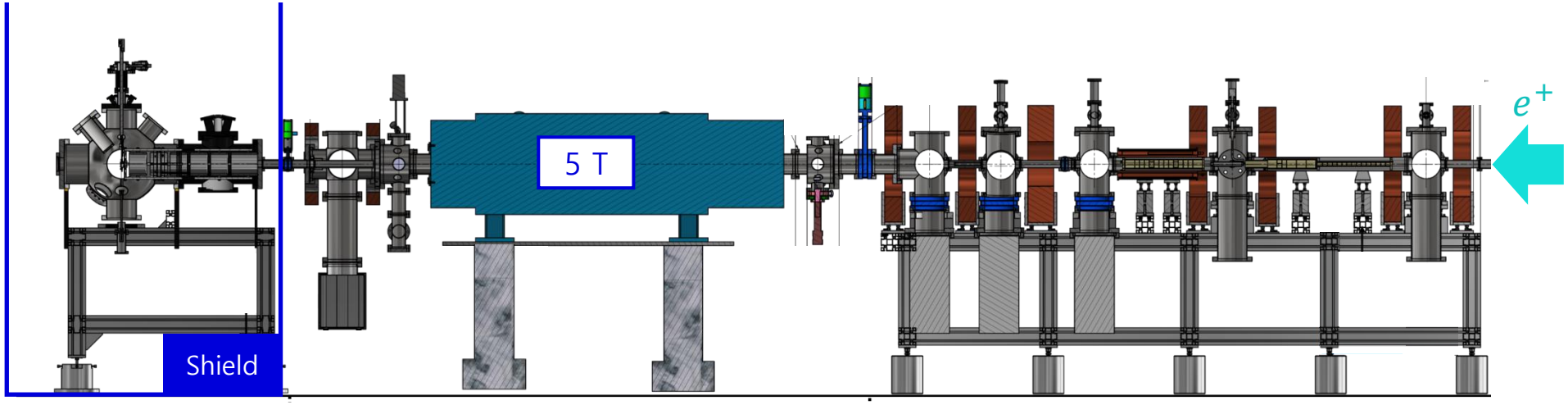
N_2/CO_2« Surko » trap
Pulsed operation
Transfer to HFT every 1 s

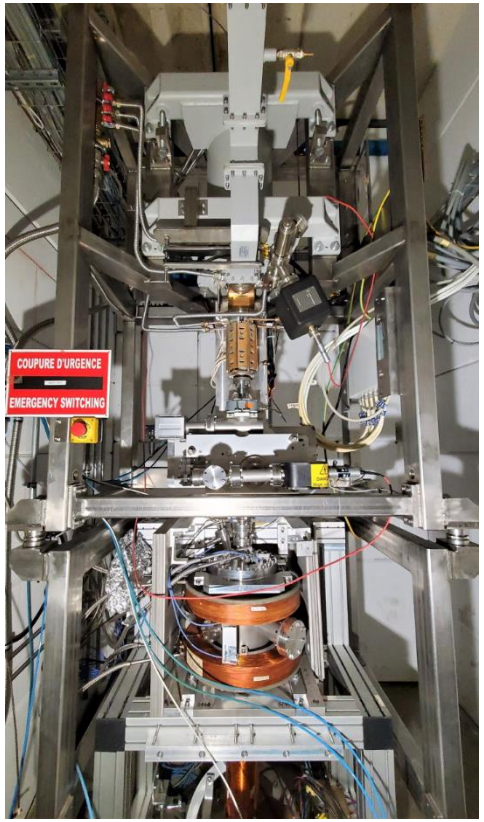
$1.4\ 10^9$ in 1100 s in 2021

9 MeV e^-
300 mA
200 Hz
W target & moderator

3×10^7 slow e^+ /s

The GBAR collaboration,
Nucl. Instr. Meth. A **985**, 164657 (2021)





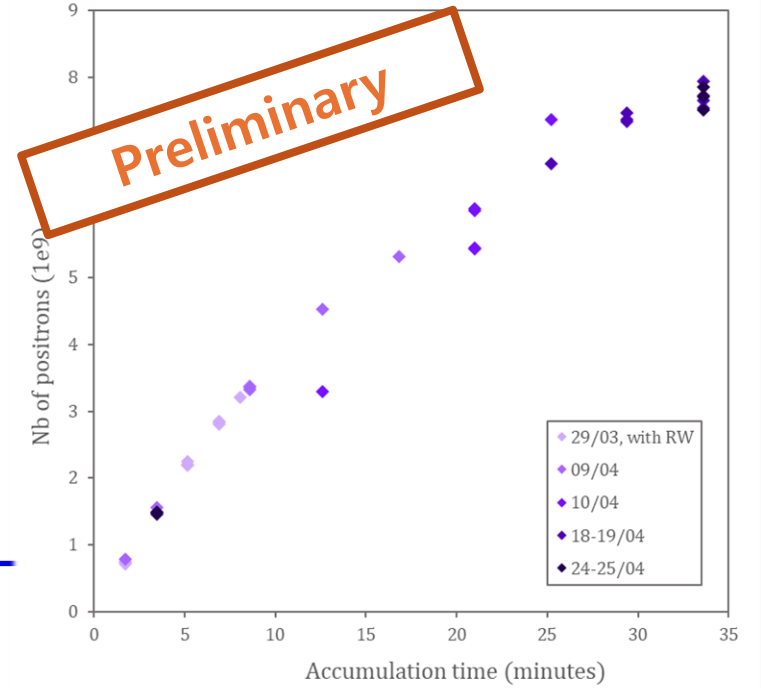
RC

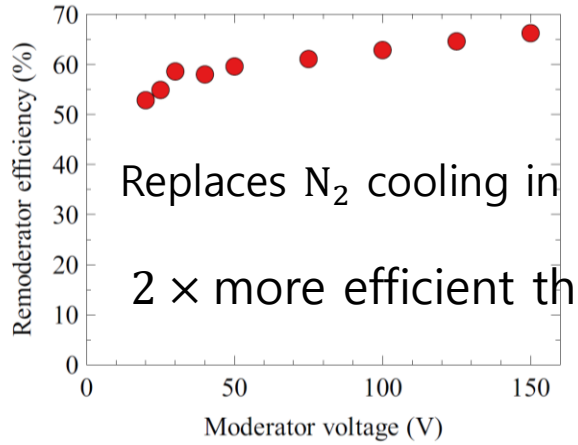
HFT

BGT

LINAC

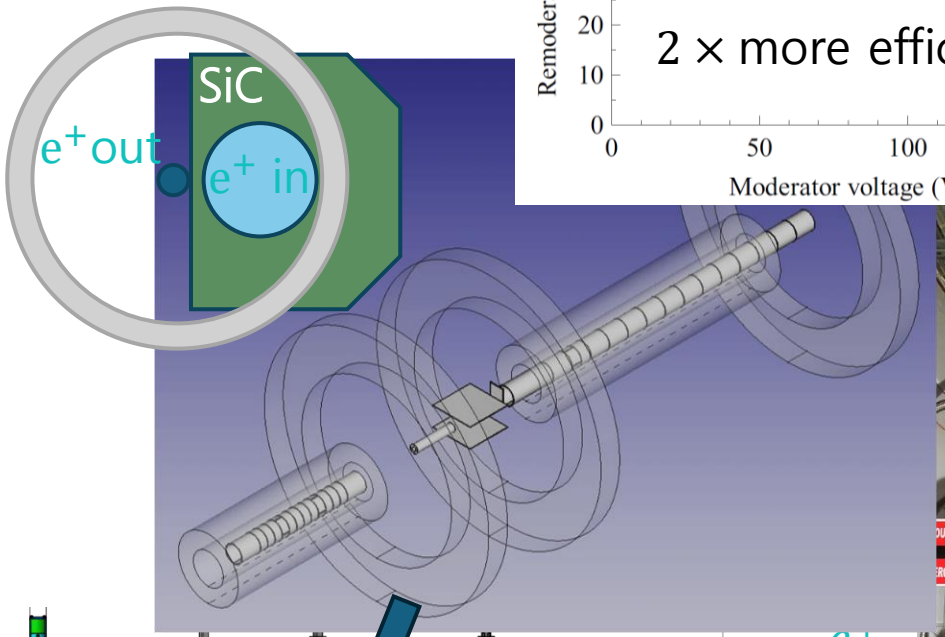
Positron beam line

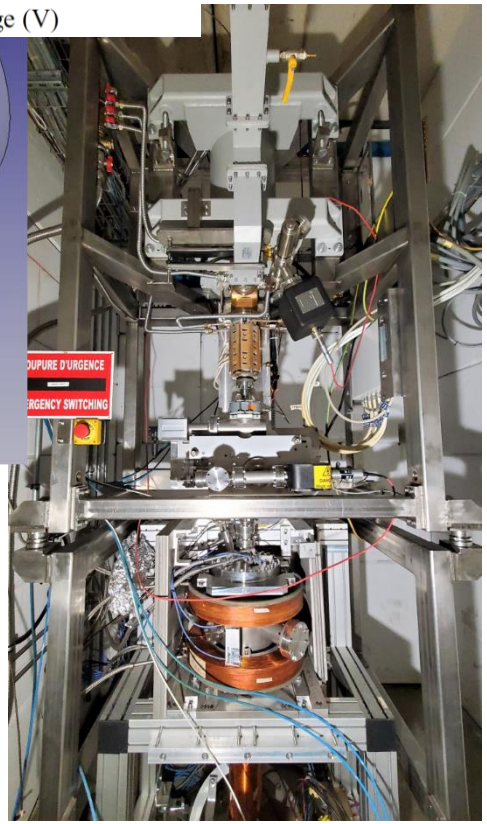


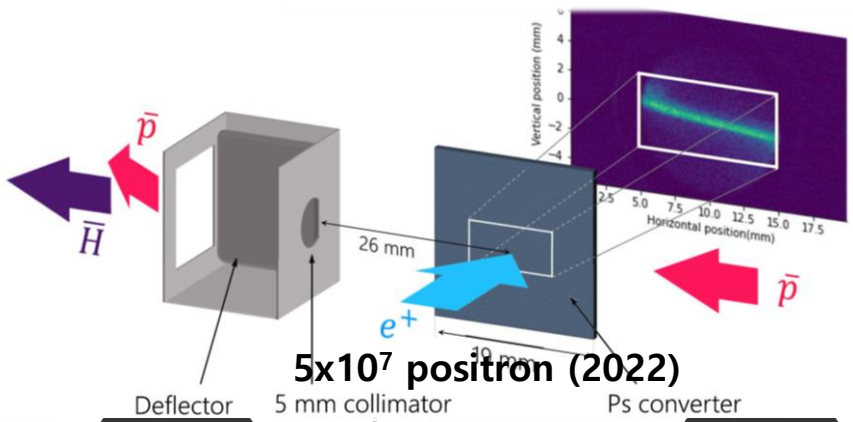


Replaces N_2 cooling in BGT. CO_2 kept.

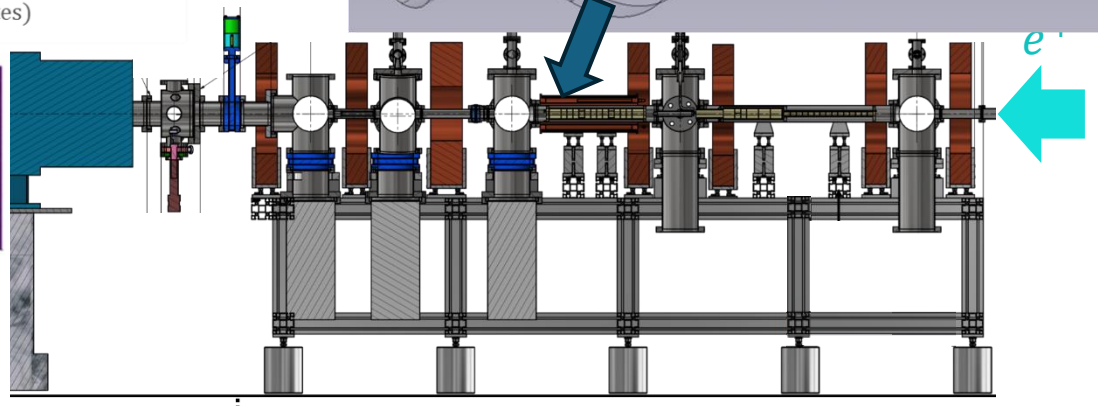
2 × more efficient than former BGT







5x10⁷ positron (2022)

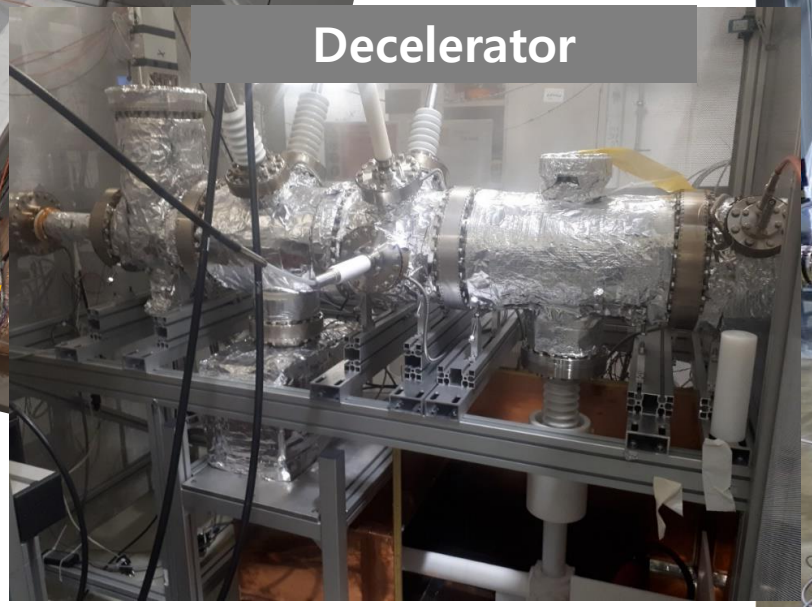


RC HFT BGT LINAC

Antiproton beam line

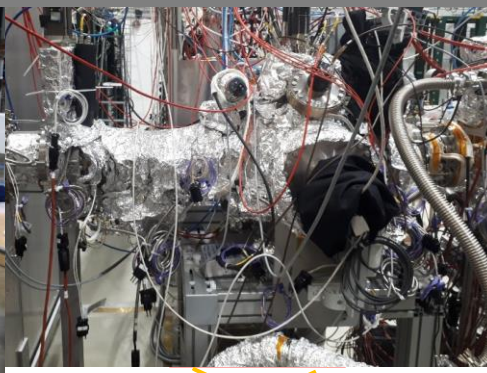
Detail information in Poster session :
WG3-03 / 71 by Byungchan LEE

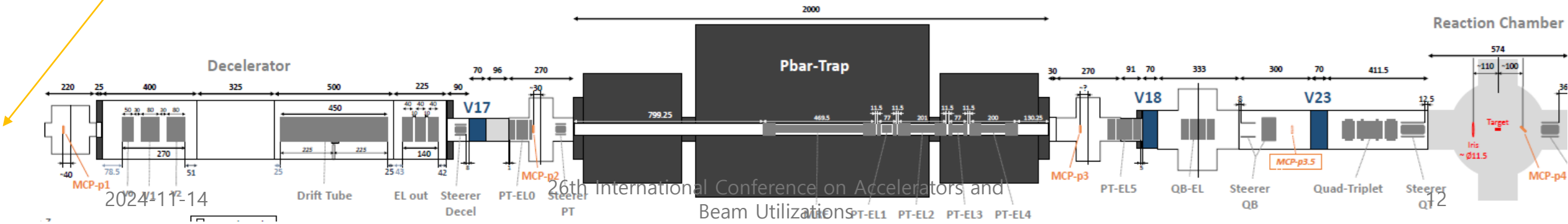
Decelerator



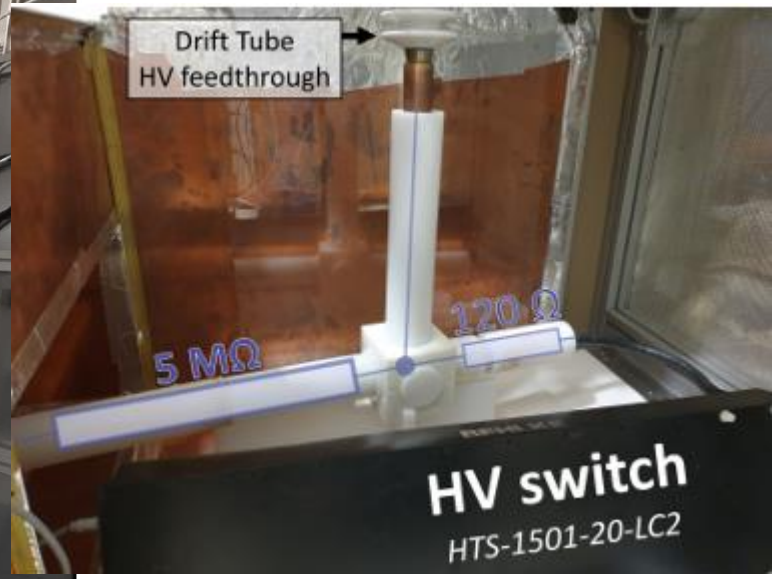
Antiproton trap

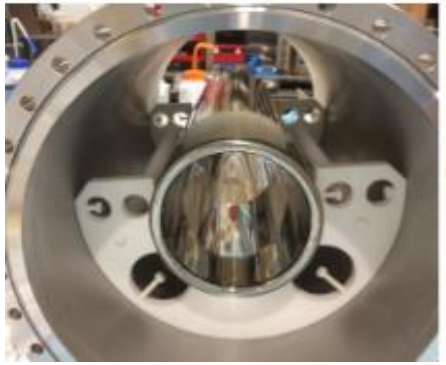
Reaction chamber

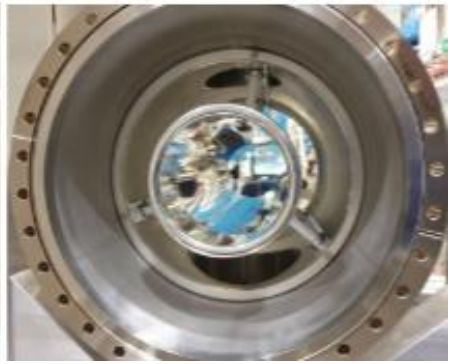


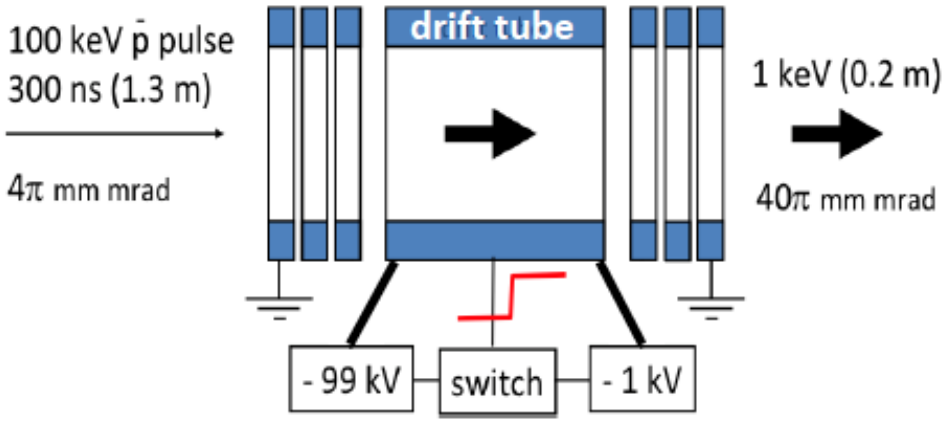


GBAR Decelerator



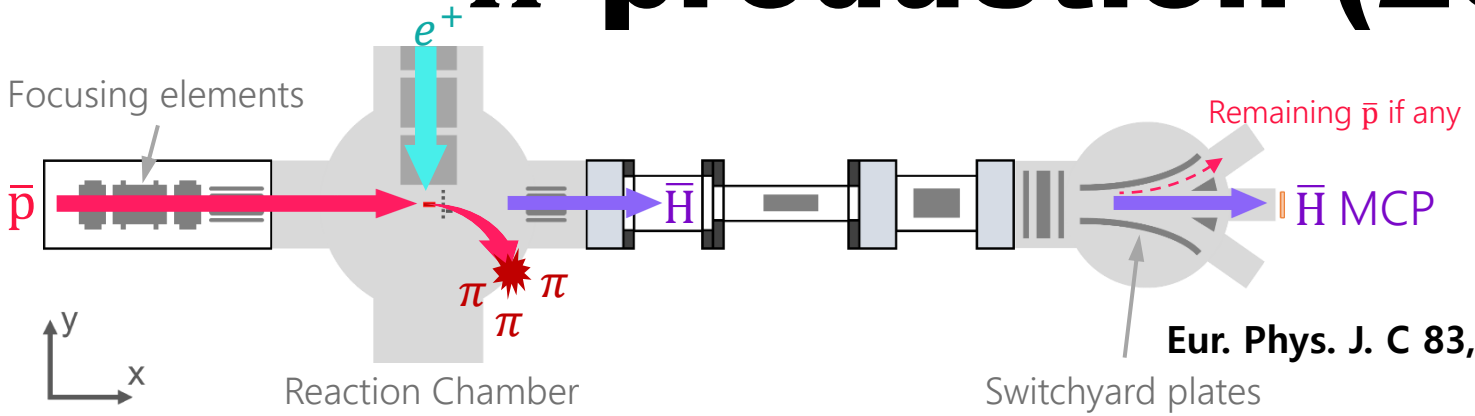


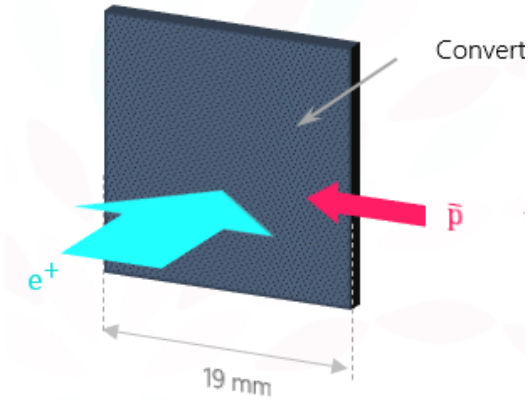




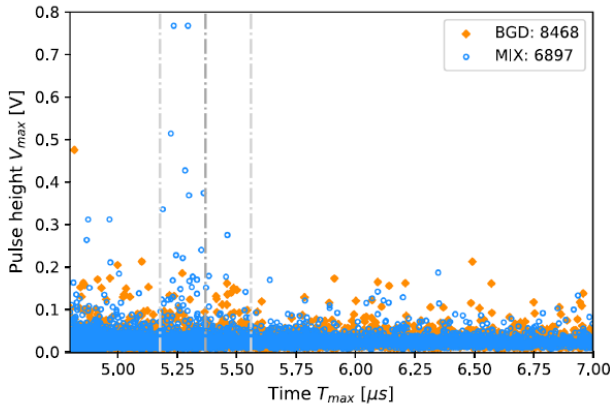
- GBAR decelerator
- Drift tube with –HV with fast-switching when pbar beam is in the tube
- Higher efficiency and mono-energy expected compared with Degrading foil
- With 100keV→1keV deceleration, emittance is increased about 10 times

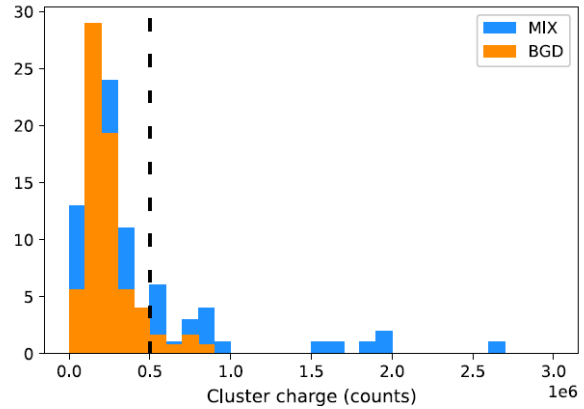
$\bar{H}$ production (2022)

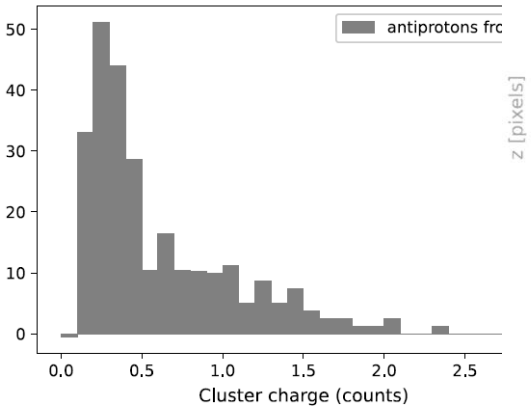


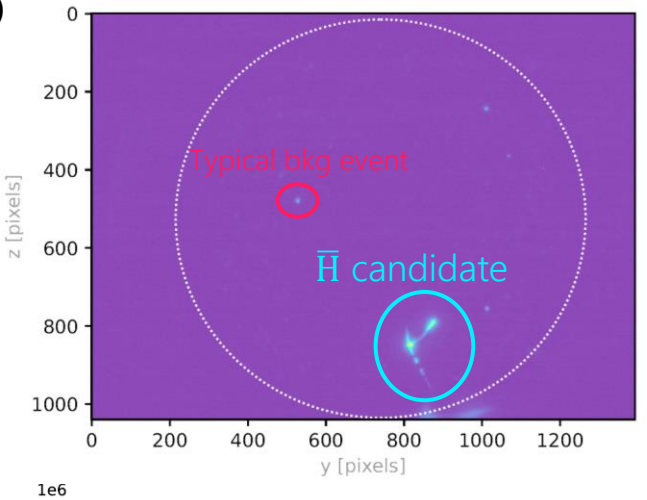


Eur. Phys. J. C 83, 10004 (2023)



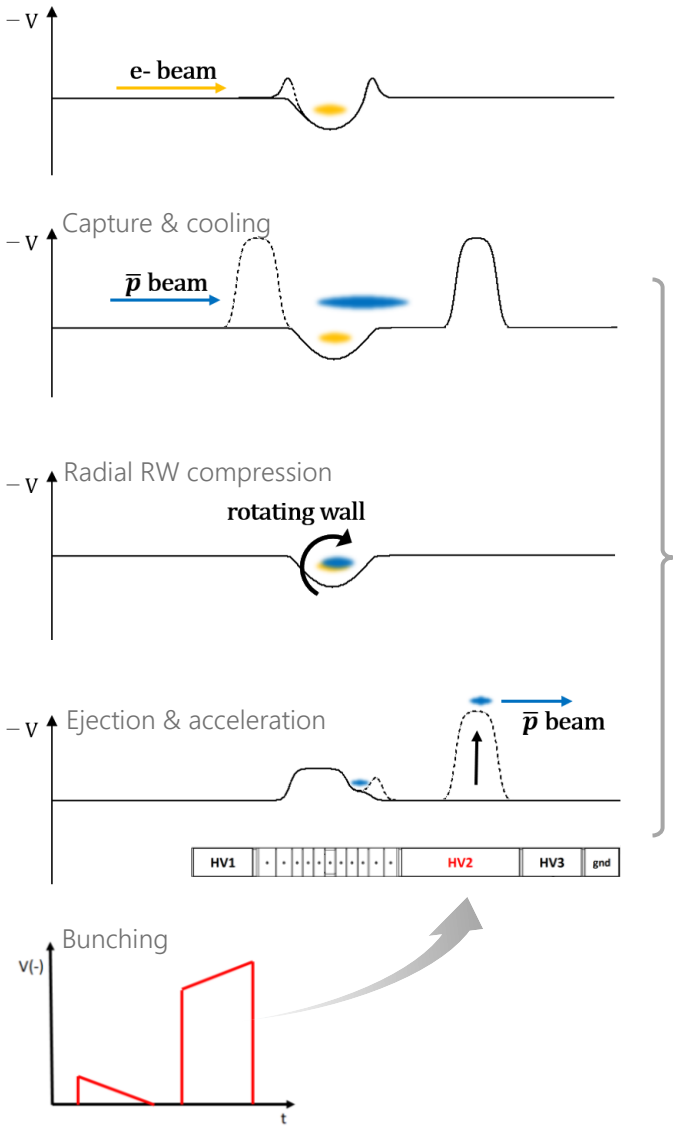


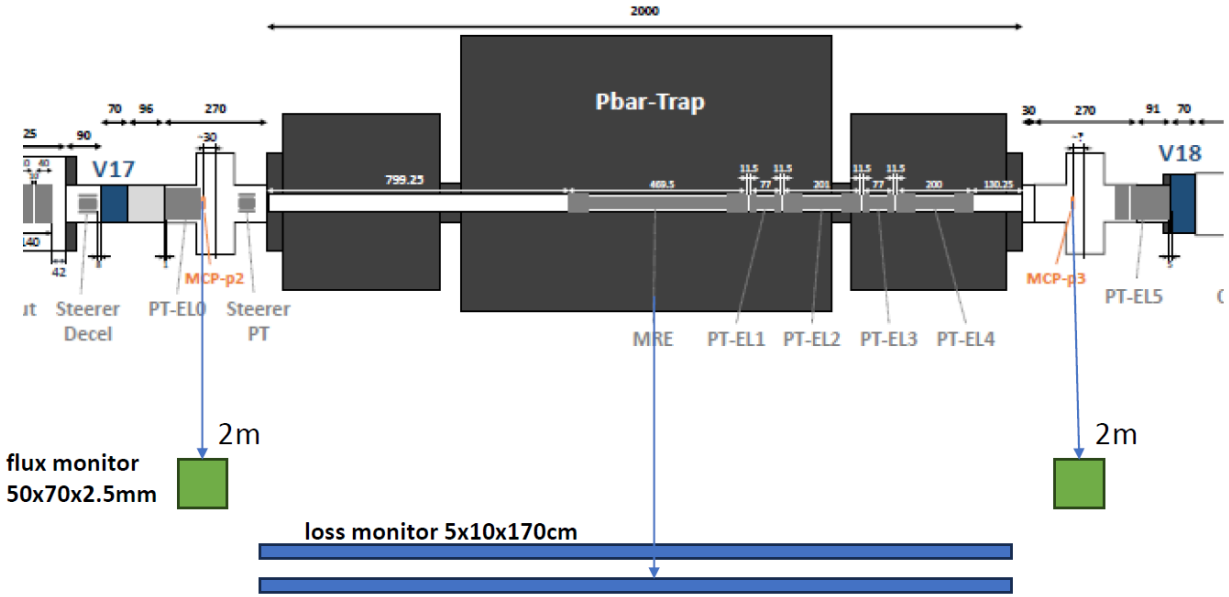




- Produced antihydrogen is detected above 3σ (which is **1st milestone**)
- About 6.8x10^6 oPs (5x10^7 e$^+$) and 3x10^6 pbar
- (First) production of antihydrogen by charge exchange between o-Ps and antiproton **beam**
- higher intensity with **better emittance** by pbar trap required $\bar{H}^+$ **production** (**2nd milestone**)

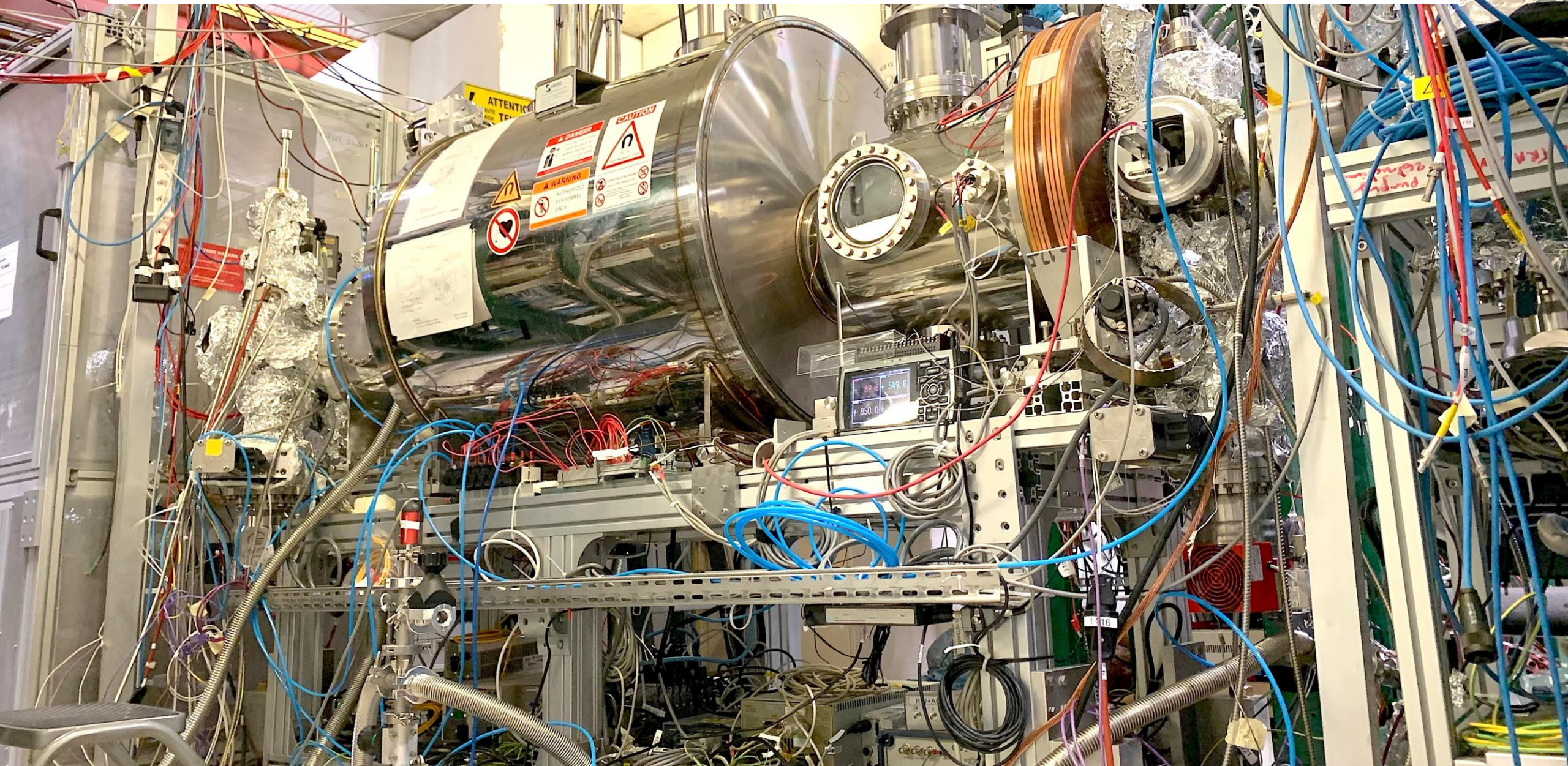
Antiproton trap





- Penning-malmberg trap (5T; 7T max) for antiproton beam reprocessing
- Function : Trapping, cooling, compression, acceleration, bunching and accumulation
- Goal : Producing antiproton beam with good beam parameters (higher intensity with accumulation, good phase-space & time spread for double charge reaction, small energy spread, etc)
- Injection and extraction simulation by WARP has been developed (Kyoung-Hun Yoo et al 2022 JINST 17 T10003)

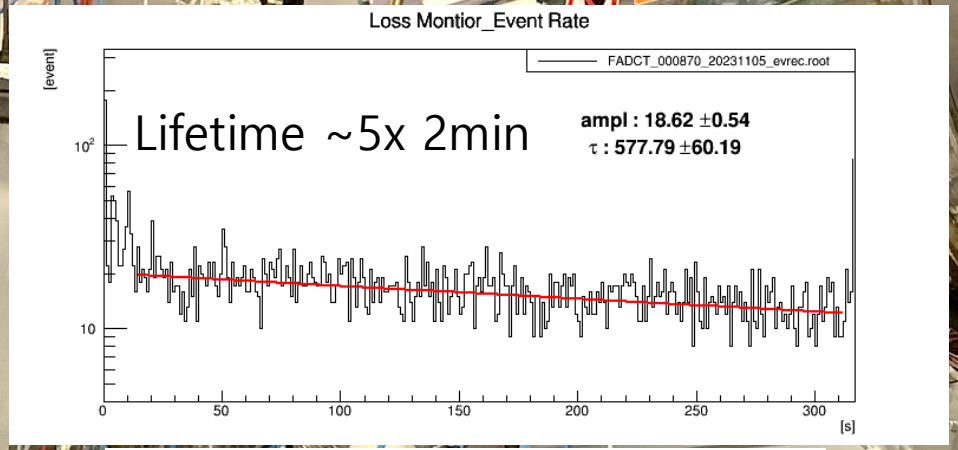
Antiproton trap installation (2023)

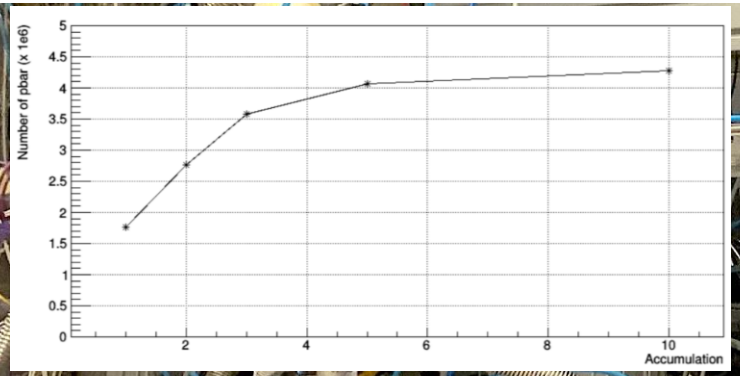


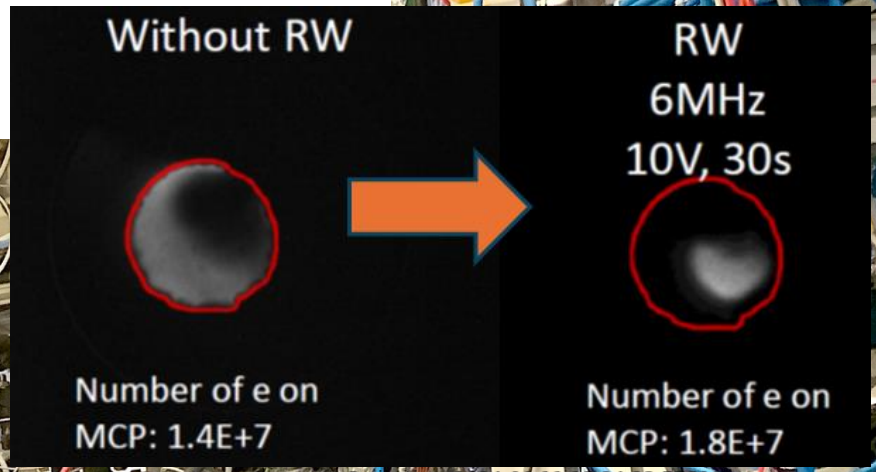
Antiproton trap operation

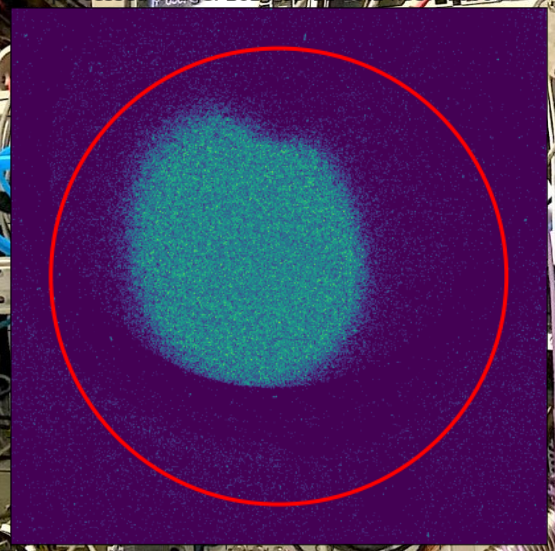
Preliminary

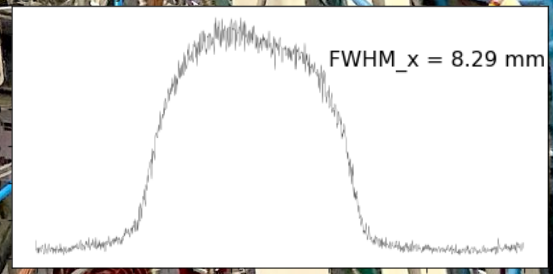
- Trapping efficiency : 60% of ELENA injection
- Reprocessed beam from trap : ~5x10^6#($\bar{p}$/2min)

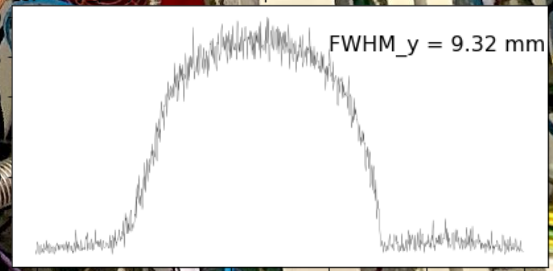












SUMMARY

- Many efforts are given to study fundamental property of antimatter with possible CPT test
- Deceleration, Cooling and Trapping is important technology for precision measurement
- GBAR aims to make ~10uK anti-hydrogen for WEP test below 1% by free-falling antihydrogen in terrestrial gravitational field
- GBAR produces antihydrogen as first milestone and has improved antiproton beam line and positron beam line for antihydrogen ion production as second milestone

THANK YOU VERY MUCH

감사합니다

BACKUP

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- Overview
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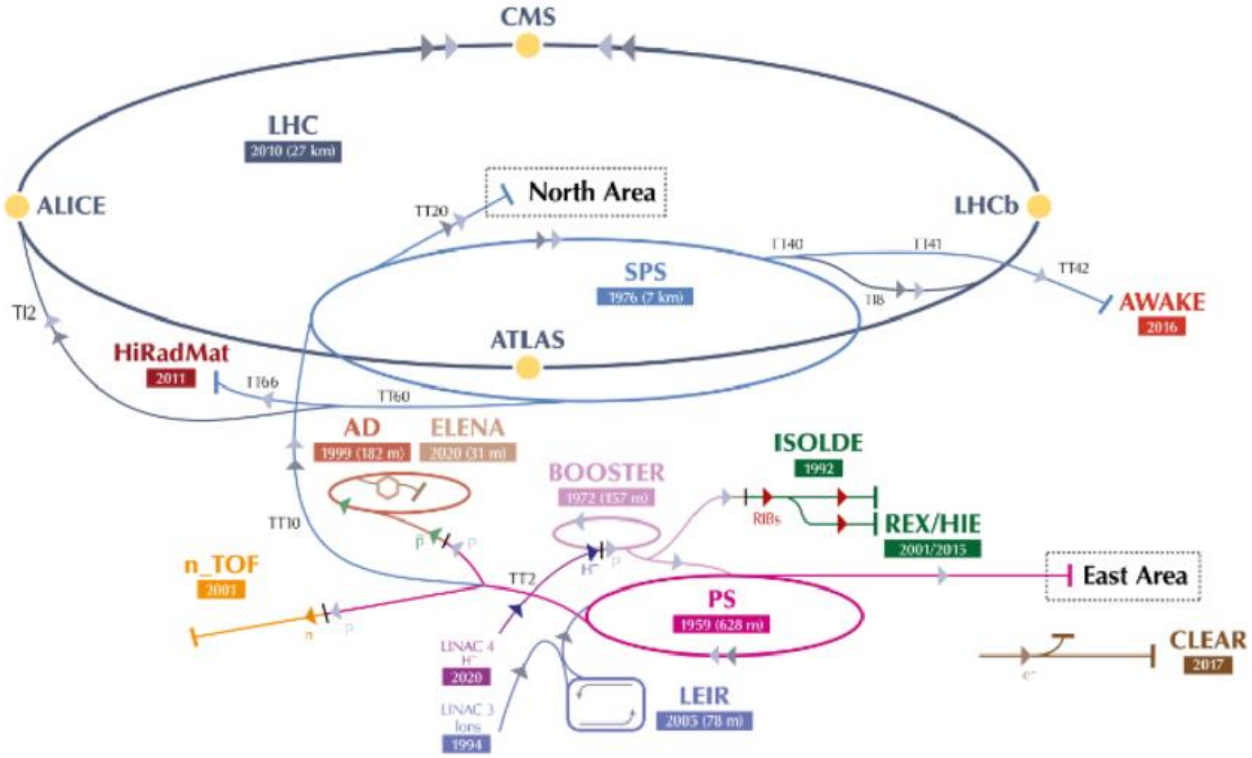
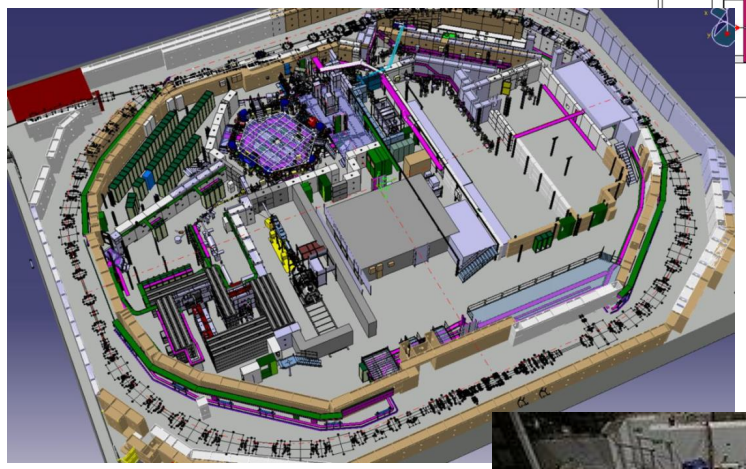
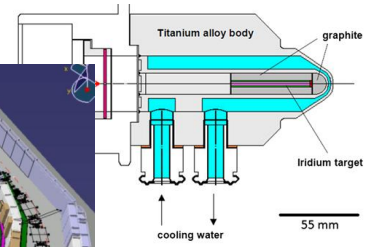
Low energy Antiproton beam facility







Production : Linac4(H^-) →Booster(H^-)→PS(p, 26GeV/c)→ iridium target →$\bar{p}$ (3.5GeV/c)

- Cooling : 3.5GeV/c → 100MeV/c→100keV