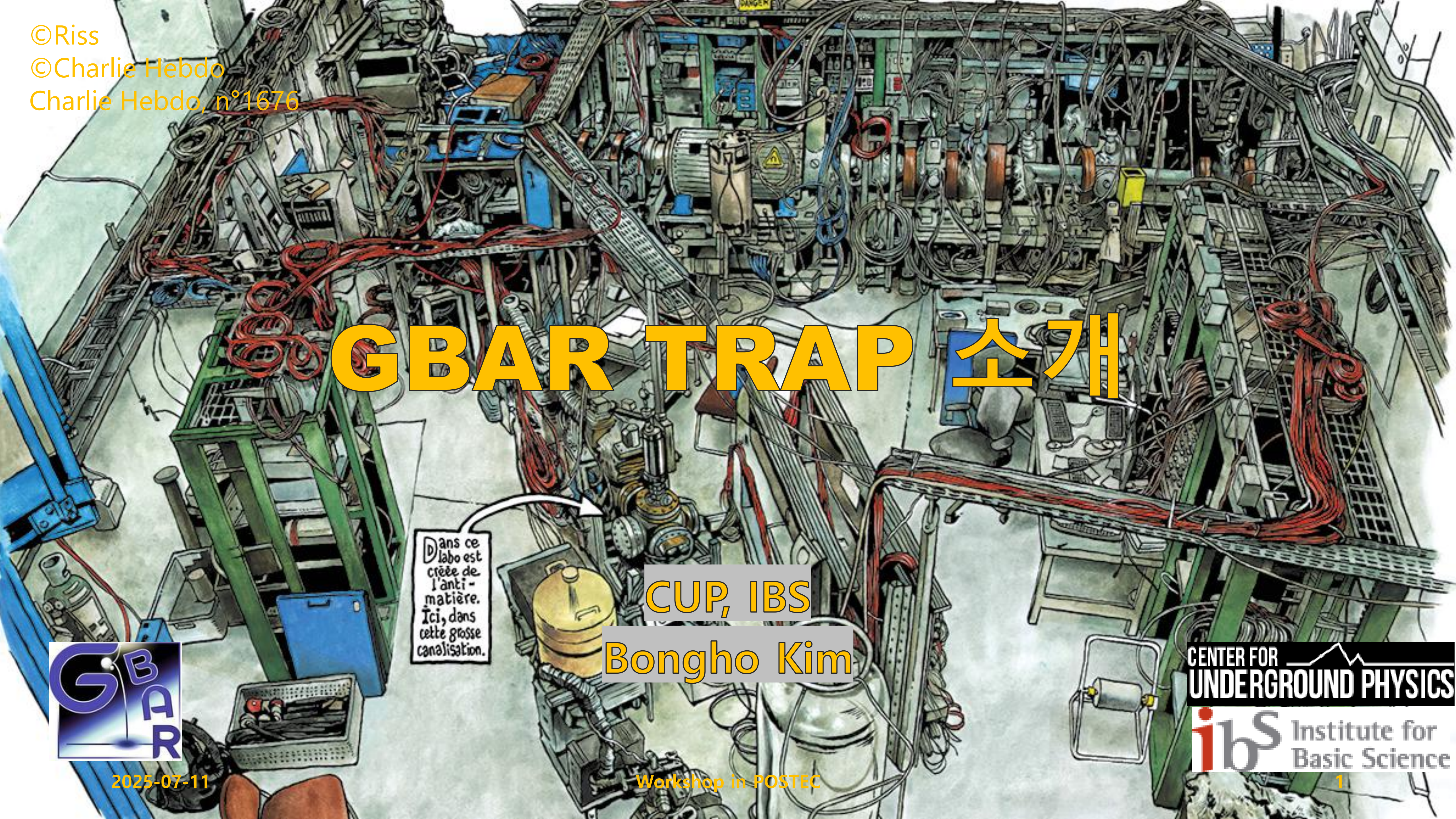
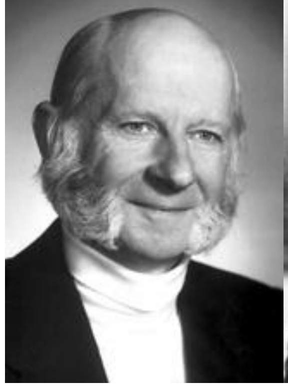


GBAR TRAP 소개

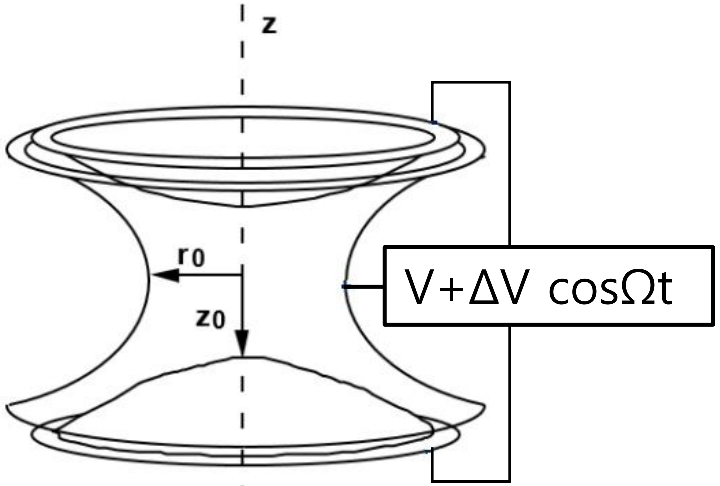
CUP, IBS
Bongho Kim

(Ion) TRAP



Principle

- Charged particles can be trapped in specific area by electromagnetic field
- Only possible to make saddle point by electrostatic potential $\varphi = Ar^2 + Bz^2$, $A + B = 0$ (simplest quadratic potential case)
- One direction confinement by applying potential



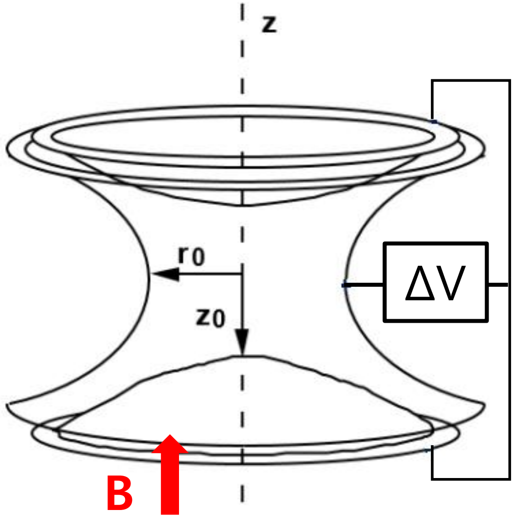
- Radial confinement

- RF field at endcap : Paul trap

: oscillate the electric field between radial and axial direction

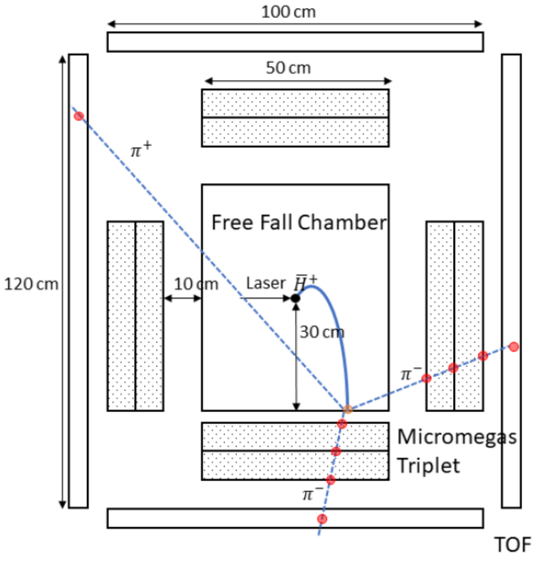
- Magnetic field : **Penning trap**

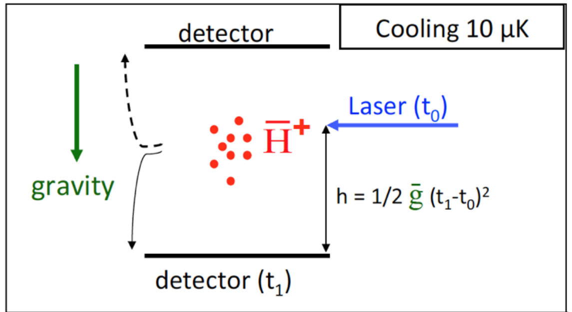
: confinement to plane perpendicular to magnetic field (cyclotron motion)



© Wikibooks / Theresa Knott

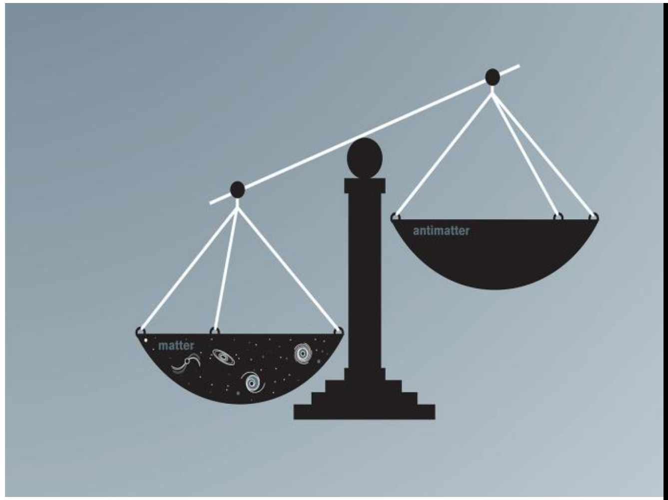
Usage of the Ion traps for antimatter in the GBAR experiment

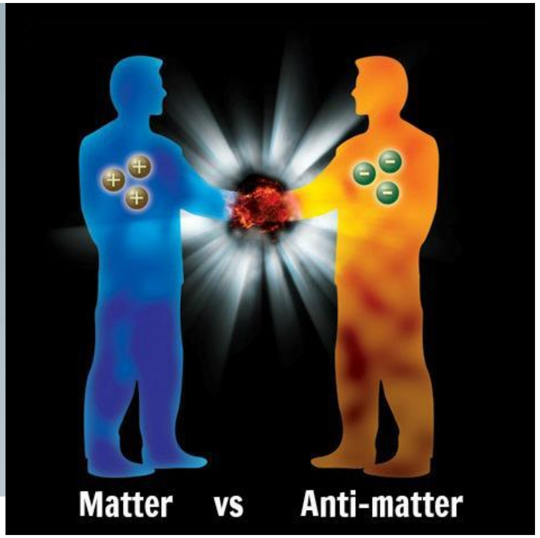


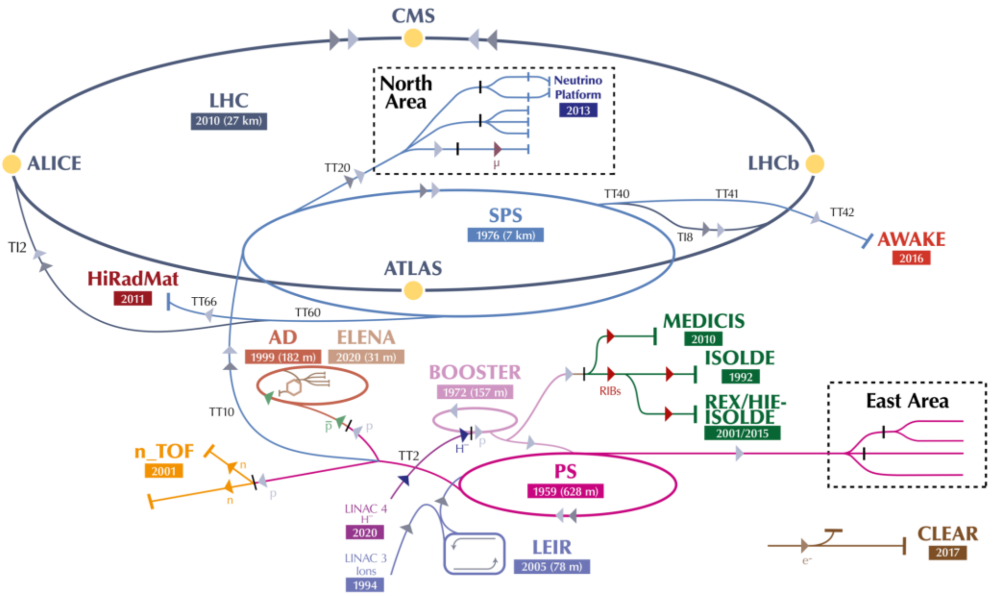


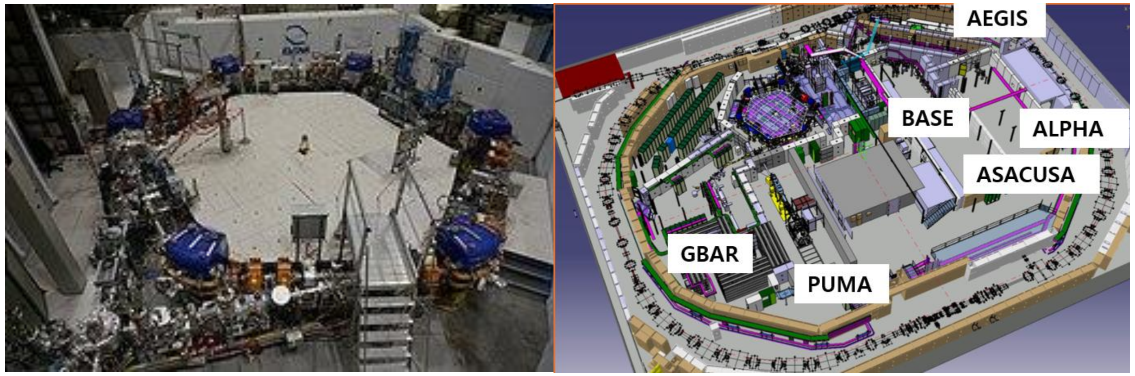
J.Walz & T. Hänsch, General Relativity and Gravitation, **36** (2004) 561.

Antimatter









❖ Matter and Antimatter asymmetry

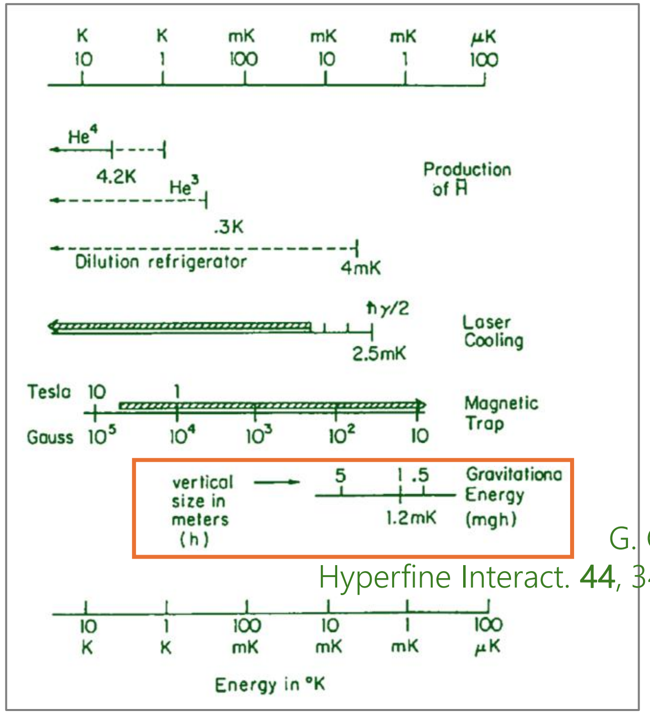
- We live in matter dominant universe
- Different with expectation based on CPT theorem and Standard Model, Matter domain (baryon asymmetry) in observable Hubble volume : $n_B \gg n_{\bar{B}}$

(baryon-to-photon ratio : 0.6e^{-9}(observed) ≫ 10^{-18}(expect))

❖ AD at CERN : Only existing facility of low energy $\bar{p}$

- $p\,(26GeV/c) + N(iridium) \rightarrow \bar{p} + X\ldots$
- Collecting $\bar{p}$ (p~3.5GeV/c)
- providing low energy $\bar{p}$ beam ~ 4x10^7 $\bar{p}$/2min

WEP test of antimatter



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

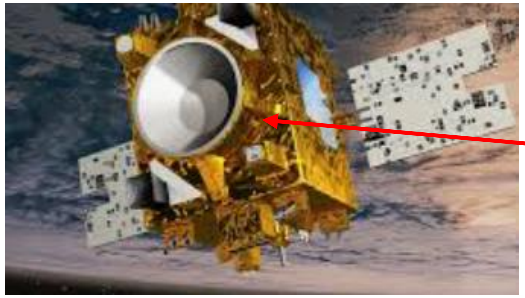
- Test of the WEP has been performed to high precision for **matter**

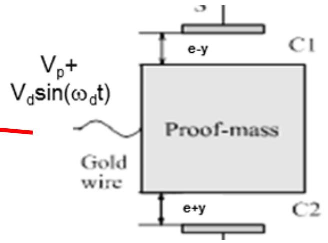
$\eta(Ti;Pt) = \Delta(m_g/m_i)/(m_g/m_i)_{Be/Ti} = (-1.5 \pm 2.3(stat) \pm 1.5(syst)) \times 10^{-15}$ (MICROSCOPE mission)

- With absent of enough **antimatter**, cold temperature for single anti-matter is required to sense gravitational interaction with earth (only one measured value $\boldsymbol{a_{\bar{g}} = (0.75 \pm 0.13 \pm 0.16) \times g}$)
- The gravitational potential for 1m is about milli-Kelvin temperature and we need to cool down the anti-matter to ultra-cold temperature

Relative strengths	Gravity	Weak	Electromag.	Strong (fundamental)	Strong (effective)
		(electroweak)			
2 quarks *up* at 10^{-18} m	10^{-41}	0.8	1	25	—
2 quarks *up* at 3×10^{-17} m	10^{-41}	10^{-4}	1	60	—
2 protons in the nucleus	10^{-36}	10^{-7}	1	—	20

https://ftae.ugr.es/index.php/pages/particles





GBAR TRAPs : to handling the rare particles

- **Penning-Malmberg trap**

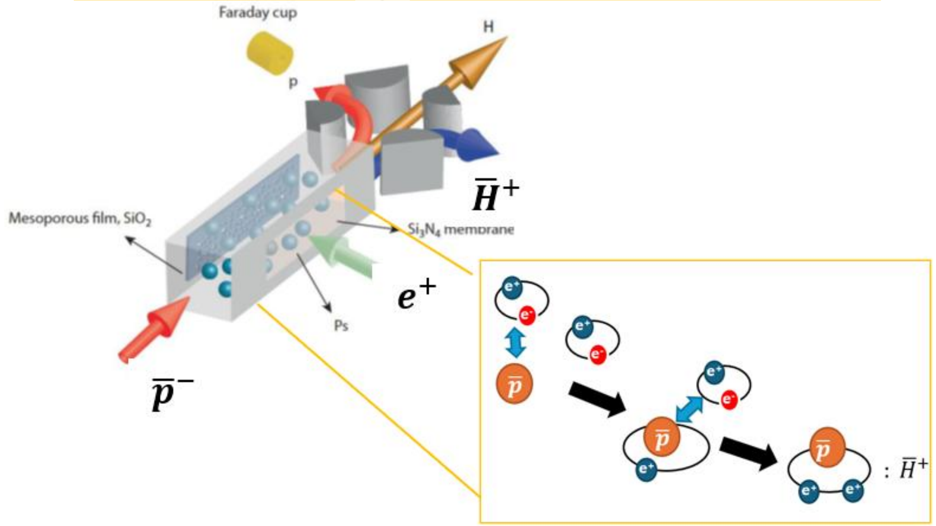
- **Buffer Gas trap** : fast cooling & trapping of positron (DC → Pulse)

- **High field trap** (positron accumulation trap) : large amount accumulation of positron for intense e^+ beam

- **Antiproton trap** : Efficient trapping & cooling & accumulation of antiproton for better antiproton beam

➔ **To produce first man-made antihydrogen ion!**

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



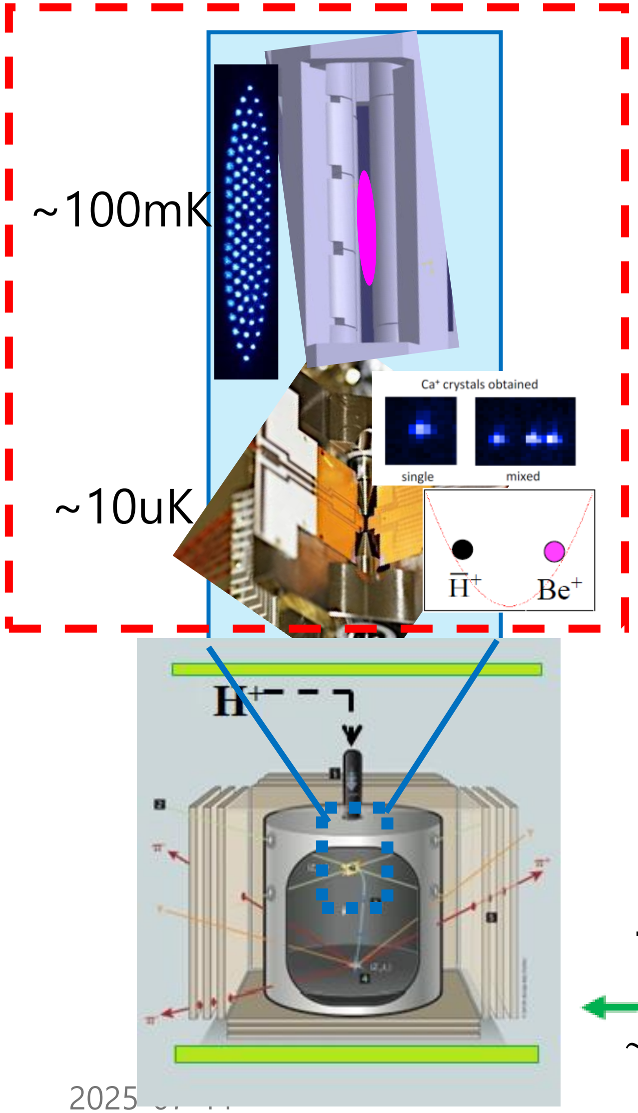
- **Paul trap**

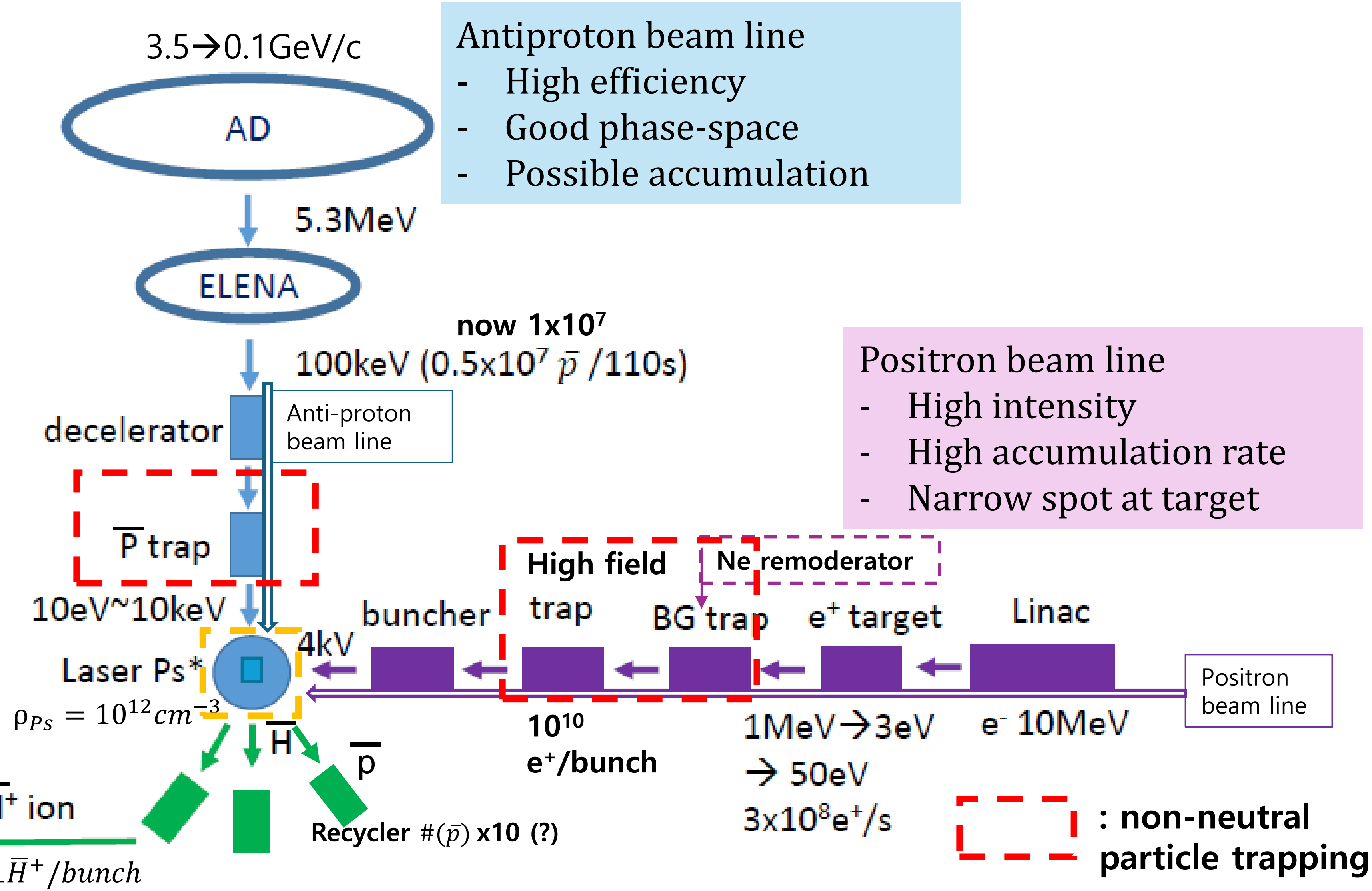
- **Capture trap** : fast & soft cooling (~100mK)

- **Precision trap** : cooling to nano-eV(~10uK) level

➔ **To produce ultra-cold antihydrogen ion!**

Experiment Scheme

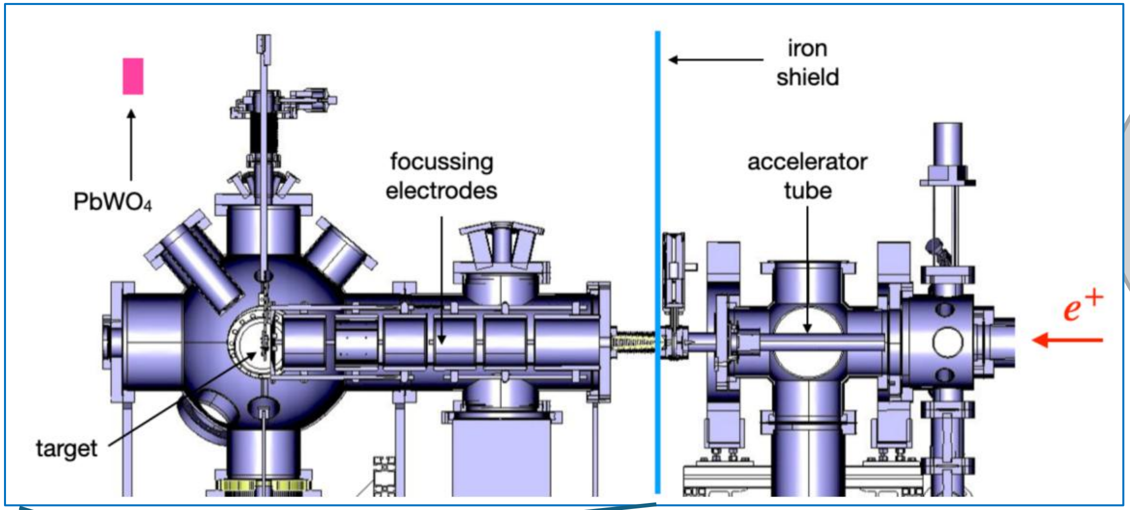


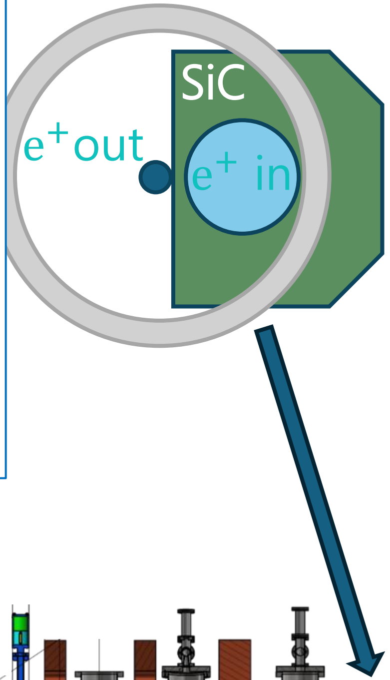


Positron beam line

Performance of linac-based positron sources.

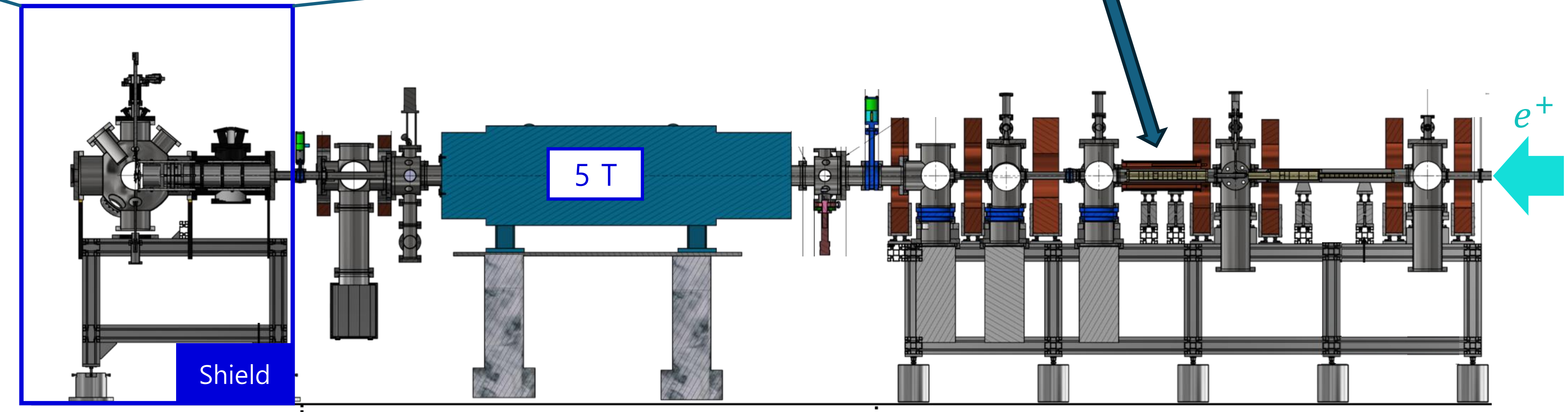
Linac	e^- energy MeV	e^- beam power W	Slow e^+ flux 10^7 e^+/s	Efficiency 10^{-7} e^+/e^-
Oak Ridge [33]	180	55 000	10	0.53
Livermore [34]	100	11 000	1000	16
ETL, Japan [35]	75	300	1.0	6
KEK [36]	55	600	5	7.3
Ghent [37]	45	3800	2	0.4
Giessen [38]	35	3500	1.5	0.2
Mitsubishi, Japan [39]	18	16	0.077	1.35
GBAR, CERN	9	2500	5	0.28
Saclay, CEA [40]	4.3	300	0.2	0.05

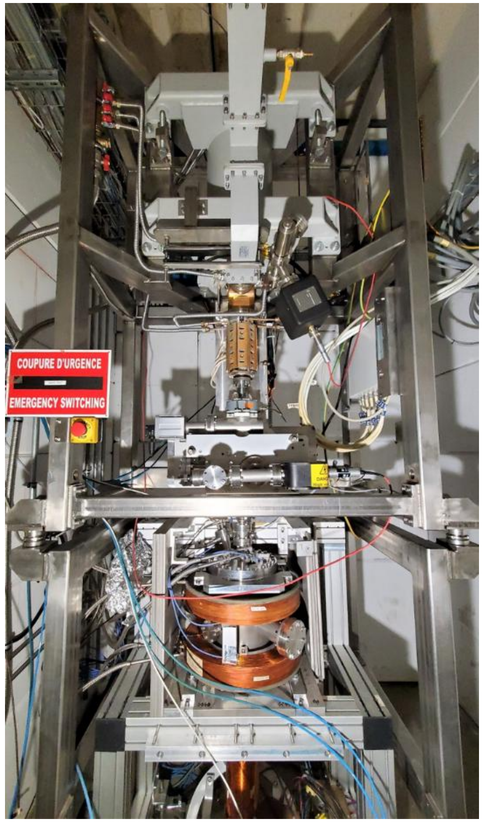




9 MeV e^-
300 mA
200 Hz
W target & moderator

3×10^7 slow e^+ /s

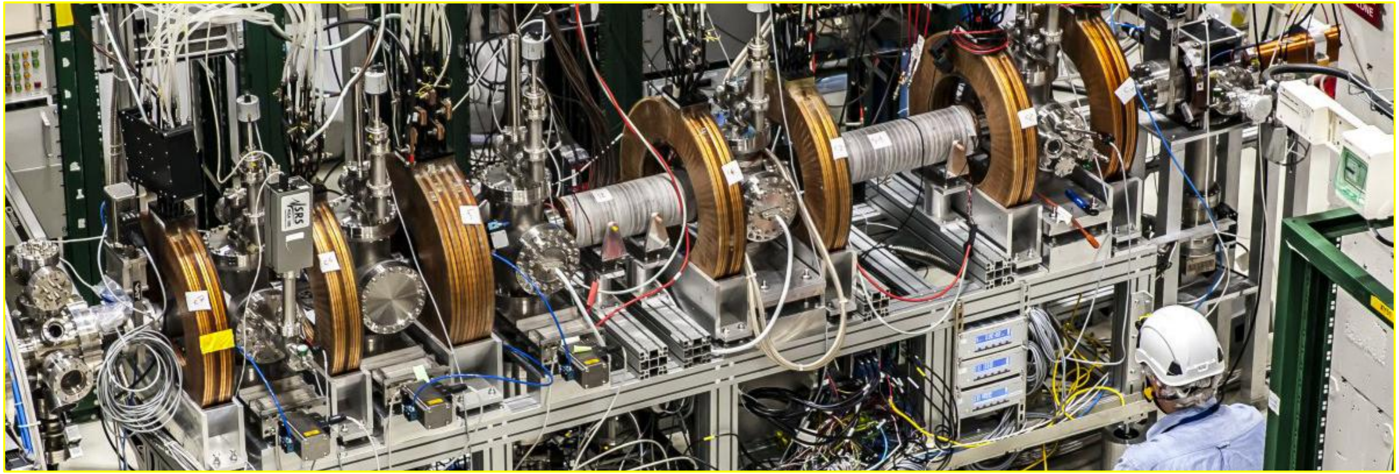




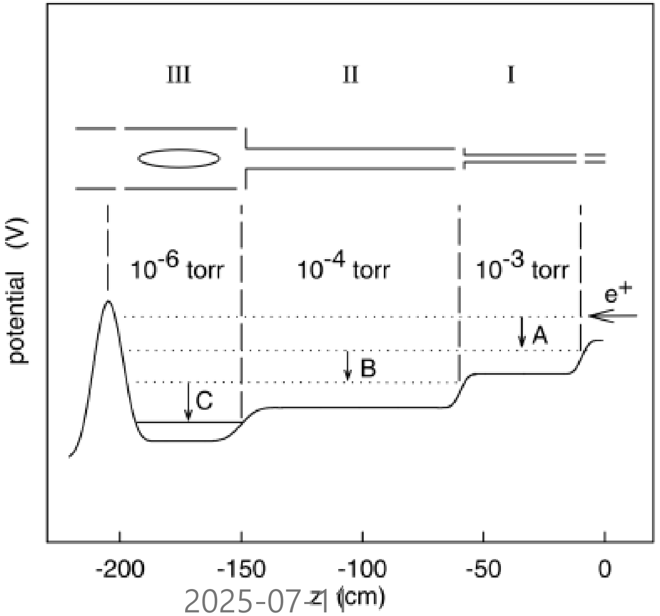
RC HFT BGT LINAC

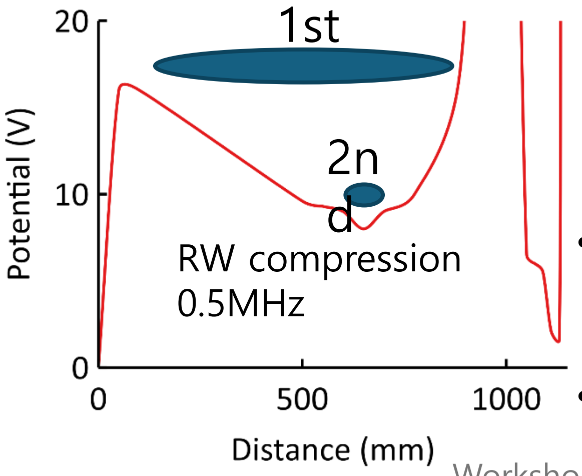
Buffer Gas trap

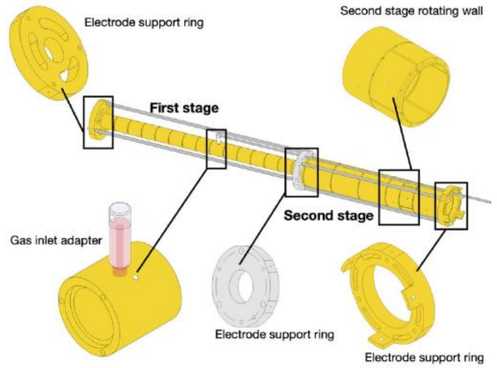
Gas	τ_a (s)	τ_c (s)	E_v (eV)	$\dot{n}/n_{max}$ (s^{-1})
SF_6	2190	0.36	0.076, 0.188	10
CF_4	3500	1.2	0.157	10
CO_2	3500	1.3	0.291, 0.083	4
CO	2400	2.1	0.266	< 0.2
N_2	6300	115	0.292	< 0.2



Name	Reaction	Energy threshold
Annihilation	$e^+ + N_2 \rightarrow {N_2}^+ + 2\gamma$	-
Electronic scattering	$e^+ + N_2 \rightarrow N_2 + e^+$	-
Rotational excitation	$e^+ + N_2 \rightarrow {N_2}^{rot} + e^+$	~ 1 meV
Vibrational excitation	$e^+ + N_2 \rightarrow {N_2}^{vib} + e^+$	~ 0.3 eV
Electronic excitation	$e^+ + N_2 \rightarrow {N_2}^* + e^+$	8.59 eV
Positronium formation	$e^+ + N_2 \rightarrow {N_2}^+ + Ps$	8.78 eV
Ionisation	$e^+ + N_2 \rightarrow {N_2}^+ + e^+ + e-$	15.6 eV

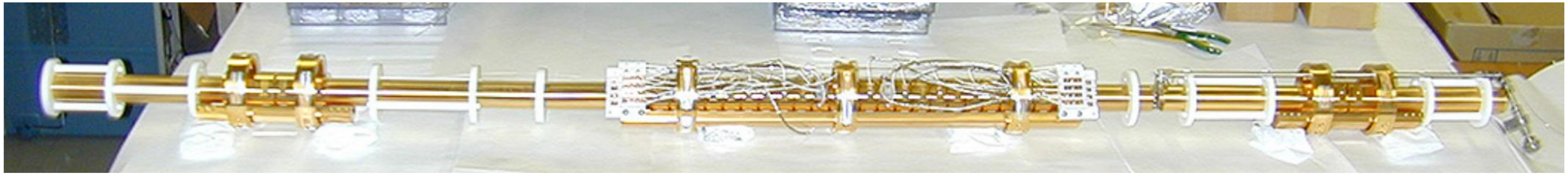


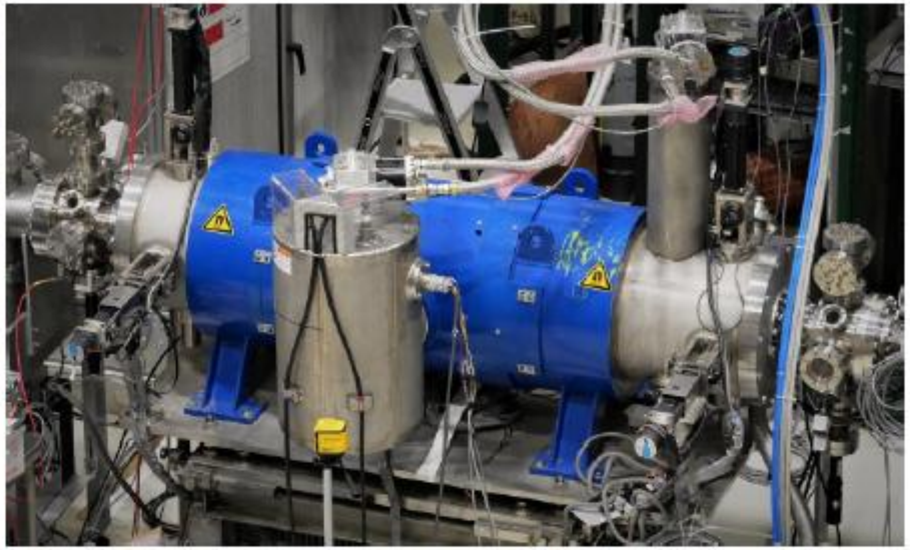


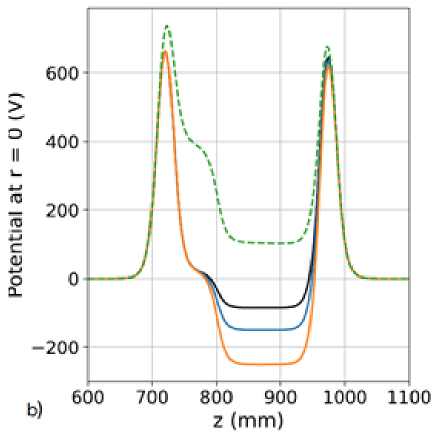


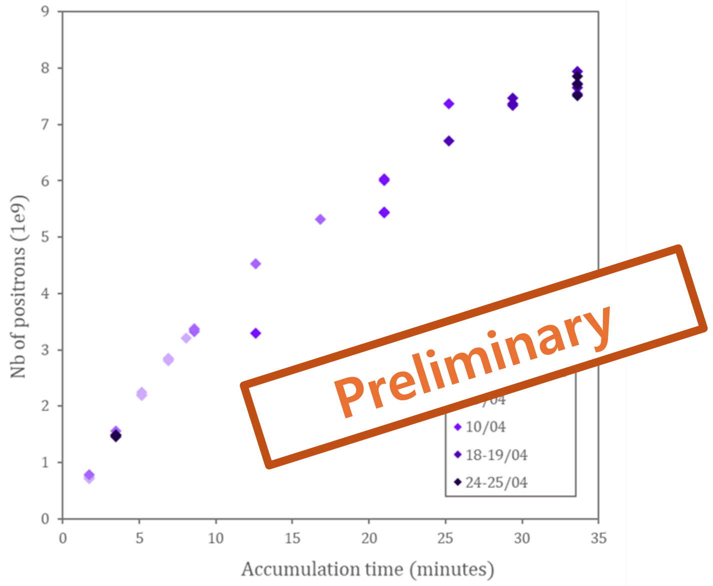
- modified Surko (buffer gas) trap:
  SiC remoderator (capture) + CO_2 (cooling)
  125 ms accumulation (2^{nd} stage) 125 ms (3rd stage)
- Many coils with water cooling to guide and trap the positrons

Positron High Field Trap





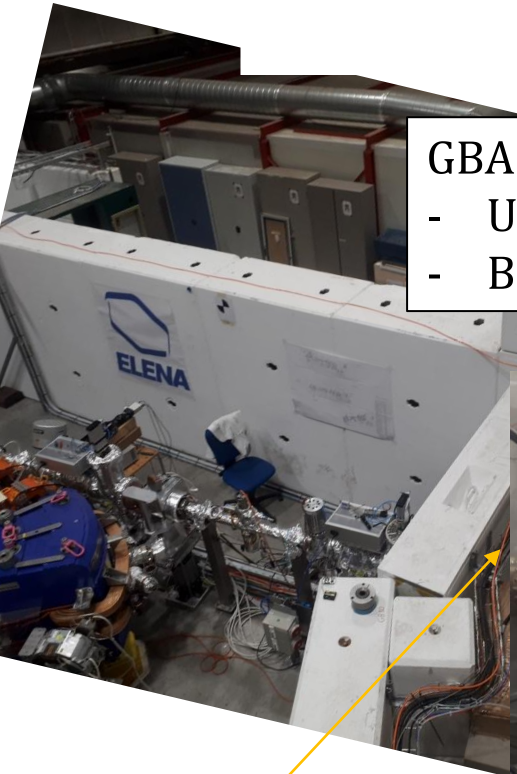


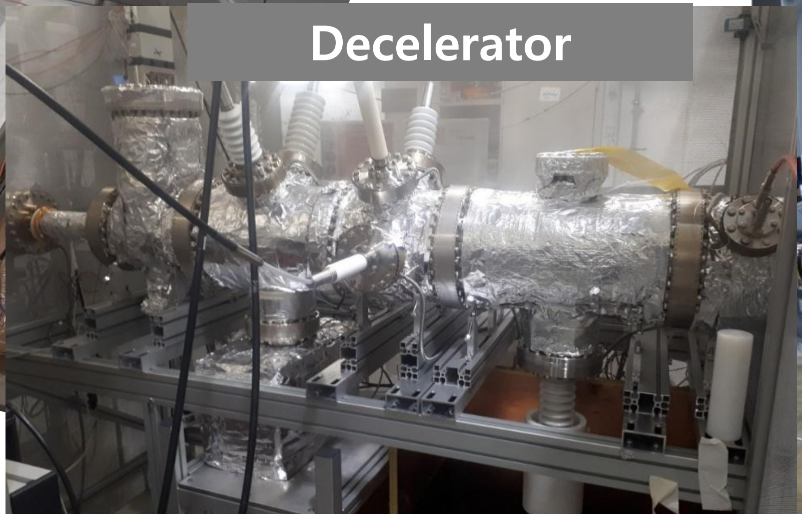


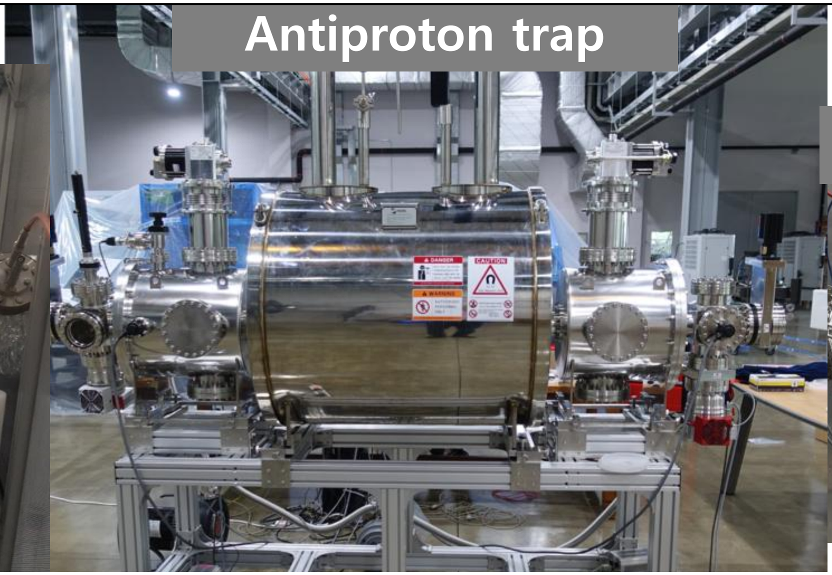
- high field trap (HFT): 5T Penning-Malmberg trap with 27 electrodes
- **maximum ~9x10^9 positrons trapped so far in ~35 minutes,**
  more than 5x10^8 in 2 minutes (ELENA cycle)
- Eject accumulated positron to 500eV to accelerator for positronium production

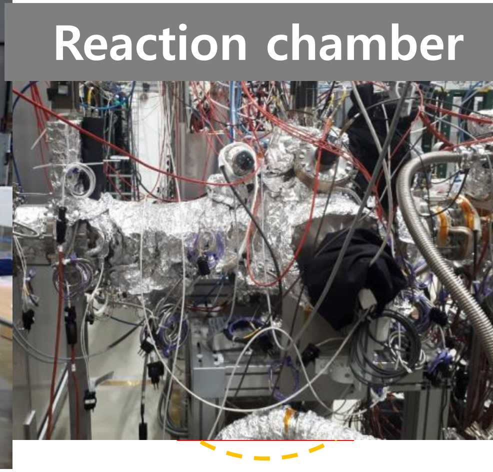
Antiproton beam line

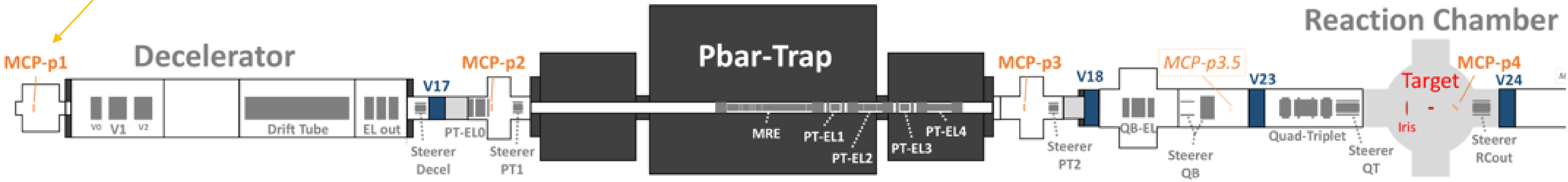
GBAR Antiproton beam line
- Unique system without degrading foil for higher efficiency
- Beam re-processing apparatus with trapping & cooling & re-acceleration for better beam parameters







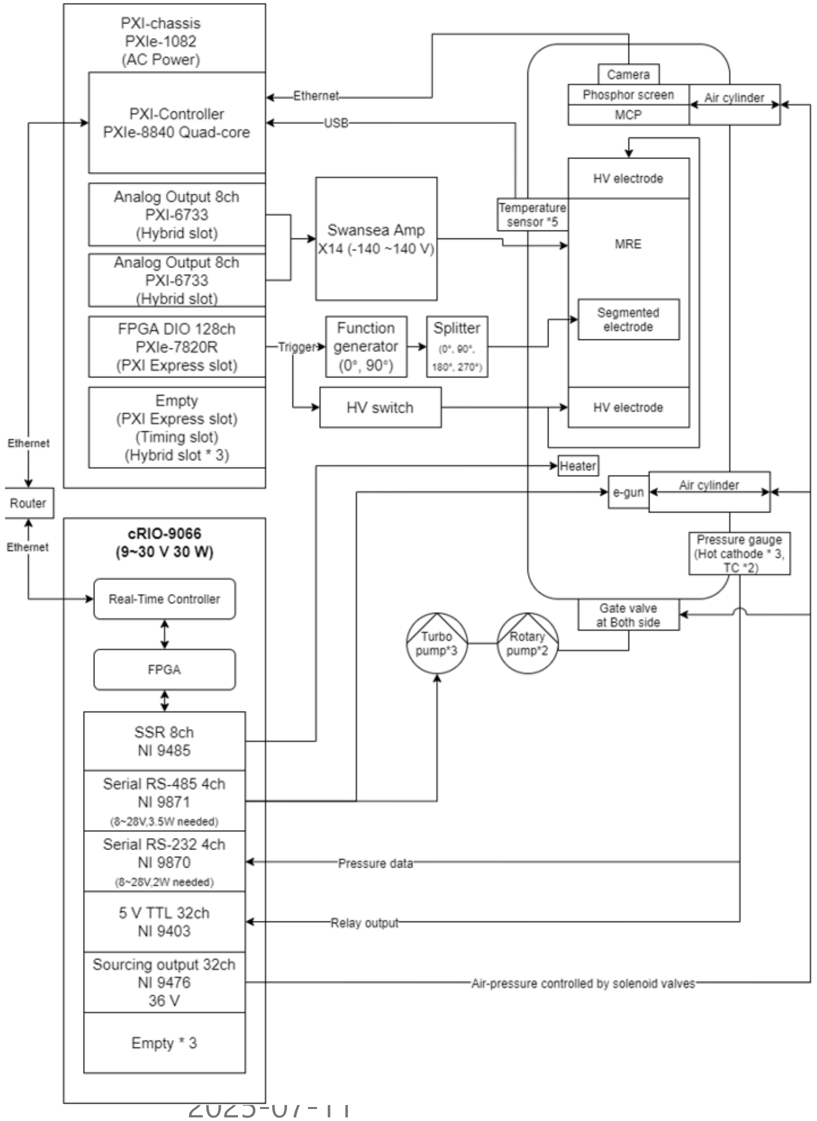


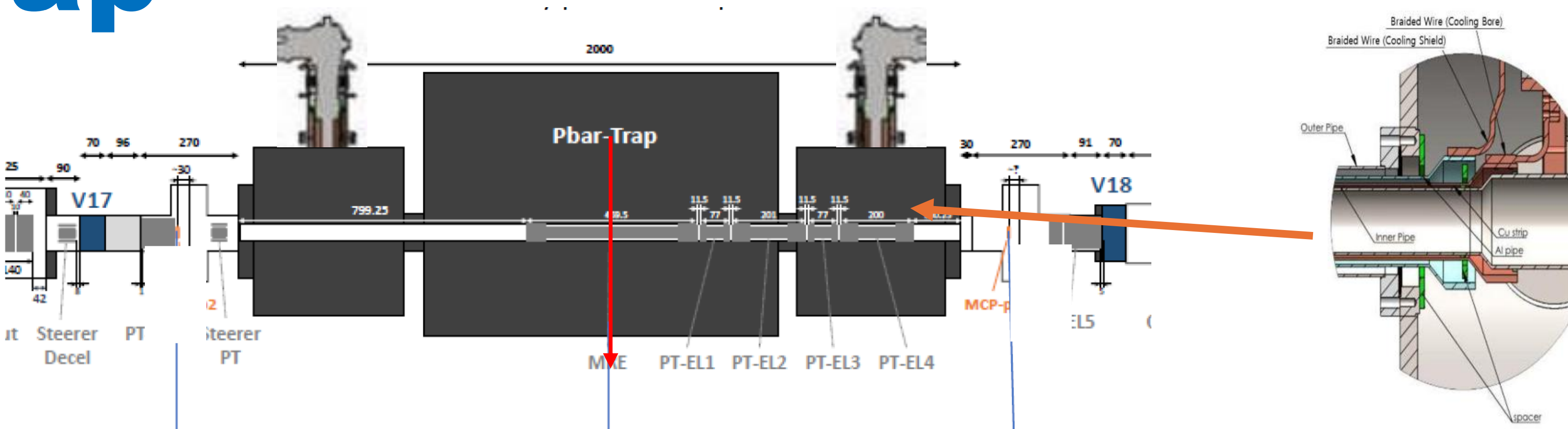


Antiproton trap

Made by Korean GBAR team!

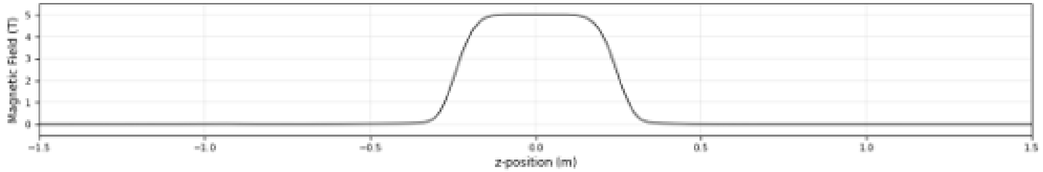
Antiproton trap

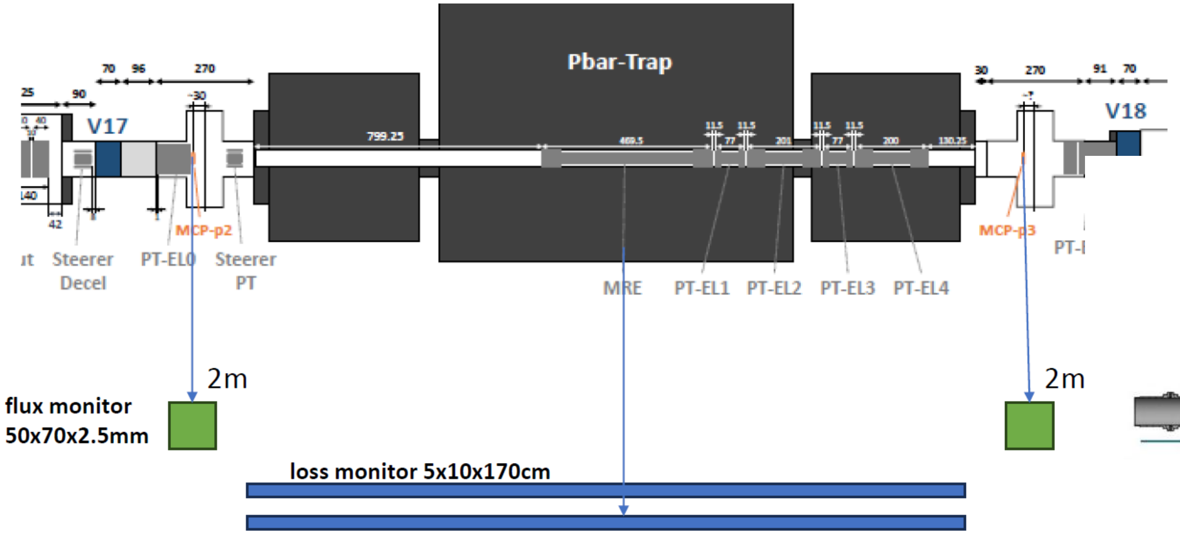


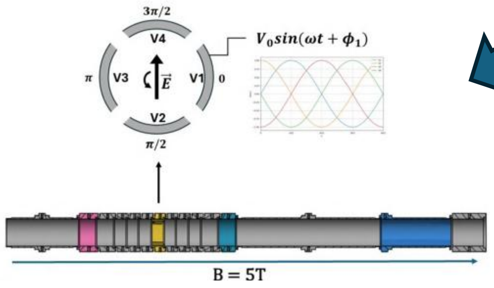


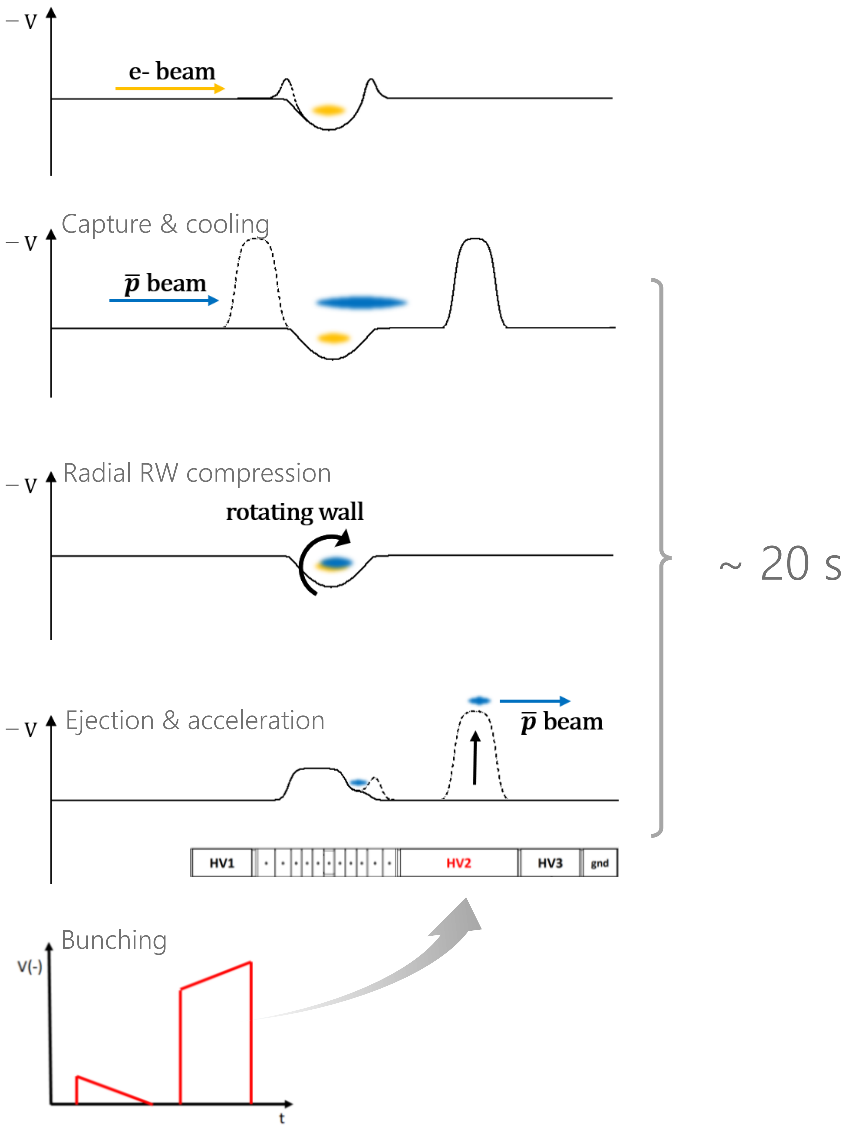
- Penning-Malmberg trap (5T; 7T max) for antiproton beam reprocessing
- Temperature at Multi-Ring-Electrode (MRE) is about 14K (2 x Coldhead with outer and inner vacuum chamber system)
- Pressure at MRE is about 10-12mbar (2 x Turbopump with 2 stage backing pump + 1 x Neg pump)
- PXI (sequence controller) + cRIO (FPGA + safety controller) system

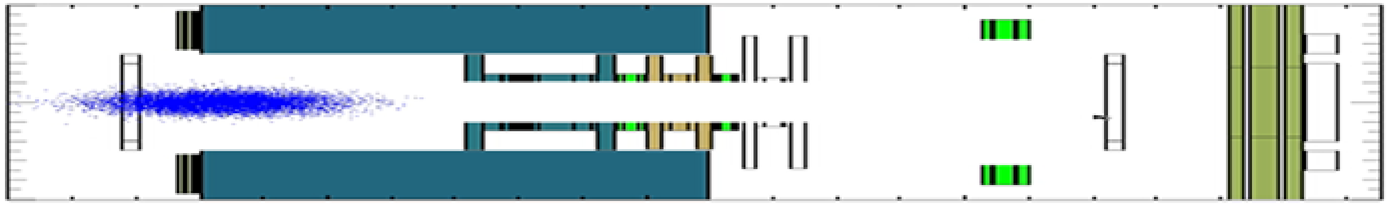
Antiproton trap









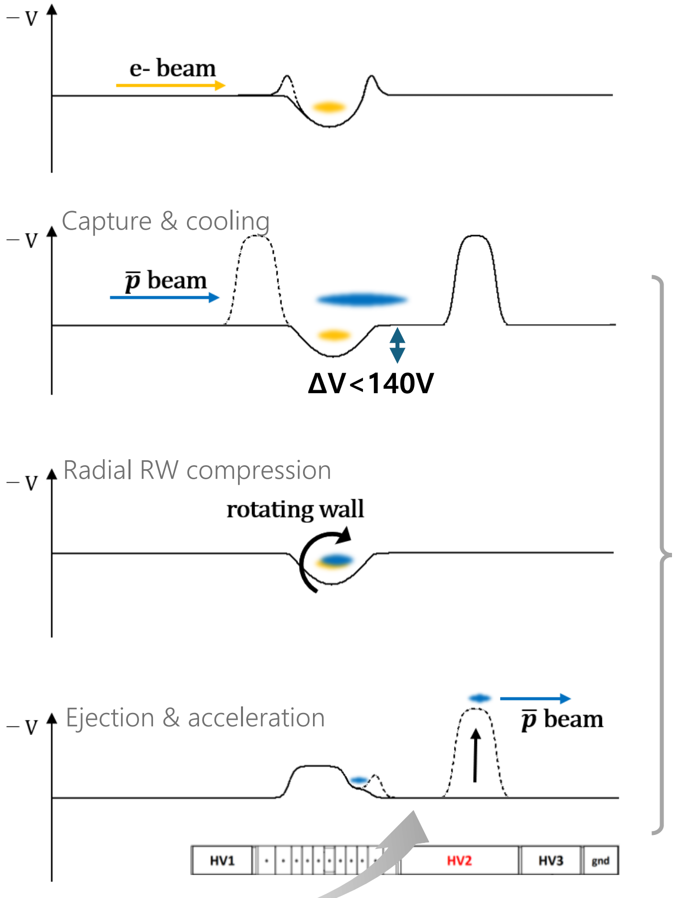


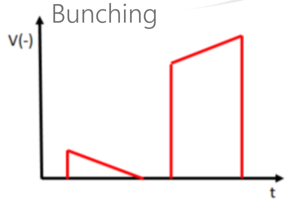
- Function : Trapping, cooling (sympathetic cyclotron cooling), compression, acceleration, bunching and accumulation
- Injection and extraction simulation by WARP has been developed (Kyoung-Hun Yoo et al 2022 JINST 17 T10003)
- Diagnostics : Plastic scintillators (Flux monitor, pion counter(loss monitor)), MCPs (2D beam profile monitor)

Antiproton trap

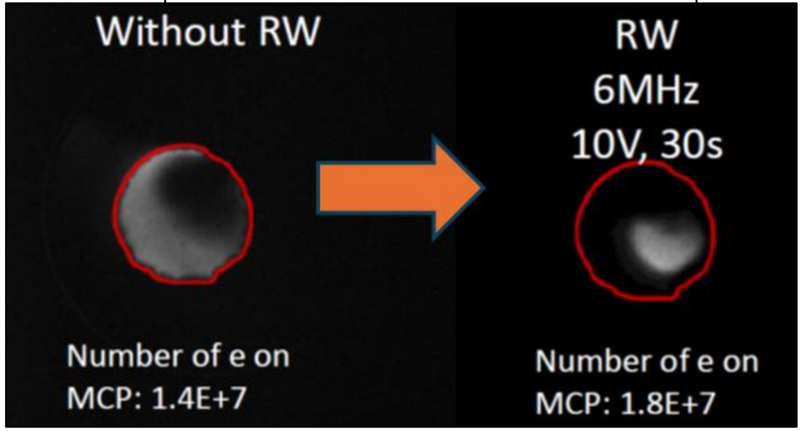
By B.C.Lee, K.H.Park, D.H.Won

Preliminary

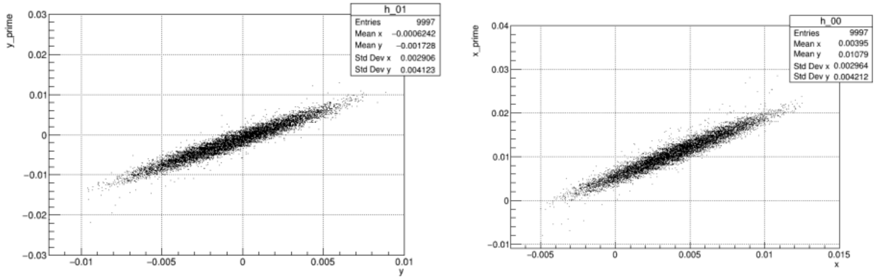




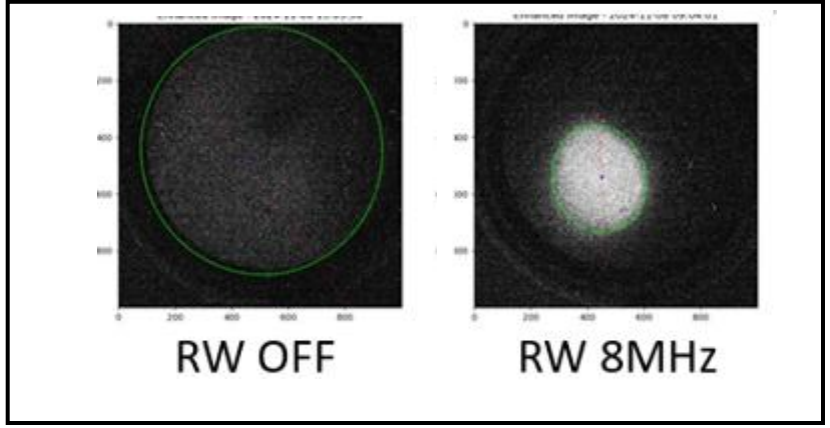
e- compression



~ 20 s



$\bar{p}$ compression



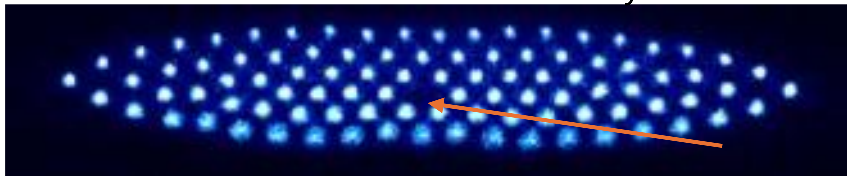
2024 comissioning

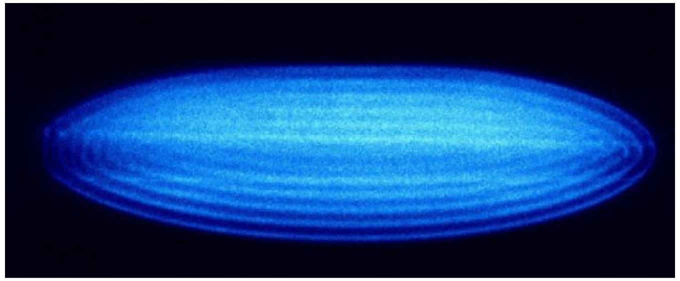
Beam Intensity	$(4.9 \pm 0.4) \times 10^6$
Extraction efficiency (/ELENA)	$(43 \pm 4)\%$
Beam size (σ_x)	2.71mm
Beam size (σ_y)	2.99mm
Bunch length (FWHM)	80ns

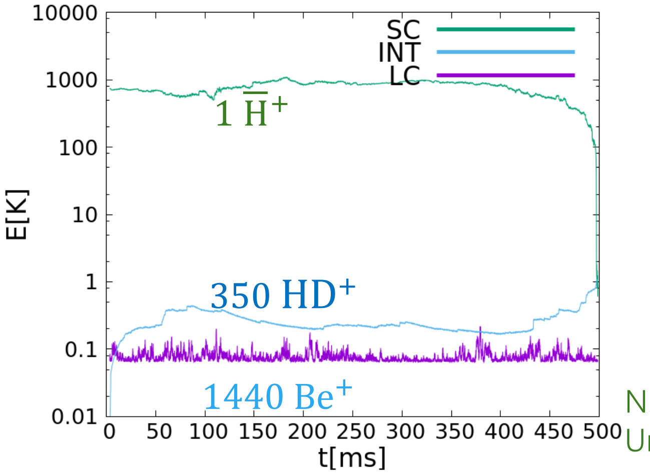
- e- accumulation & compression : enough accumulation(~10x #($\bar{p}$)) with possible compression
- Cooled $\bar{p}$ trapping : 55% of injection from ELENA (Temp measurement is planned), τ>10min
- $\bar{p}$ compression : Simulation based on extracted beam data expects the density is near designed value
- Re-accelerated $\bar{p}$ beam status : Success to pass through target cavity above 1×10^6 $\bar{p}$ /ELENA pulse

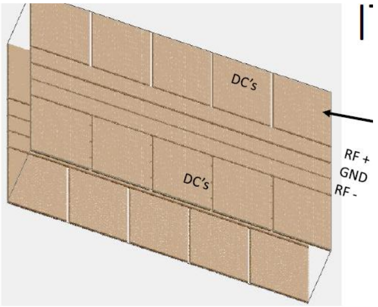
Capture Trap

Be⁺ crystal

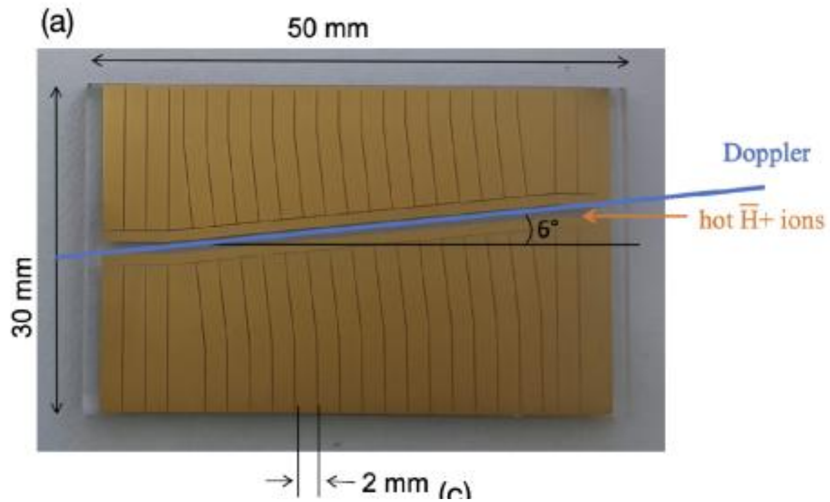


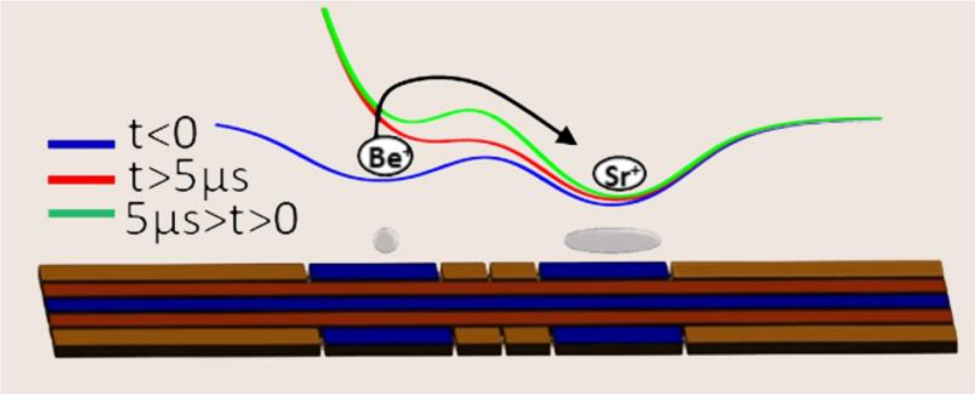


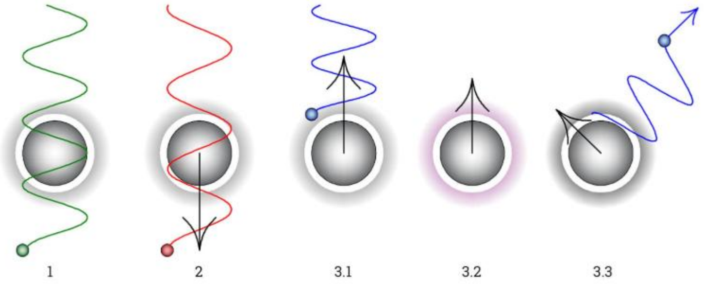




N. Sillitoe, PhD thesis, 2017
Uni. Pierre et Marie Curie - Paris VI







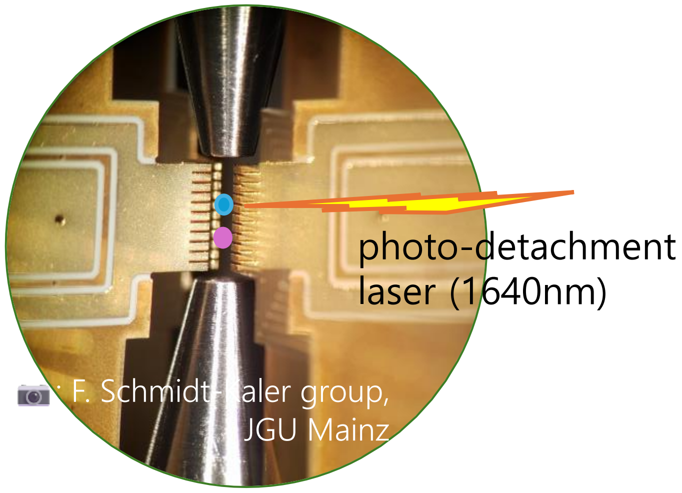
Capture trap : capturing by DC switching+ rf voltage electrodes

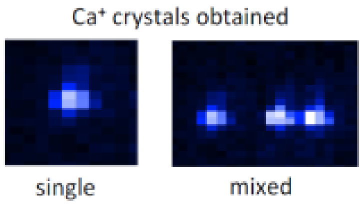
Sympathetic Doppler cooling by cooled Be^+/HD^+ ions

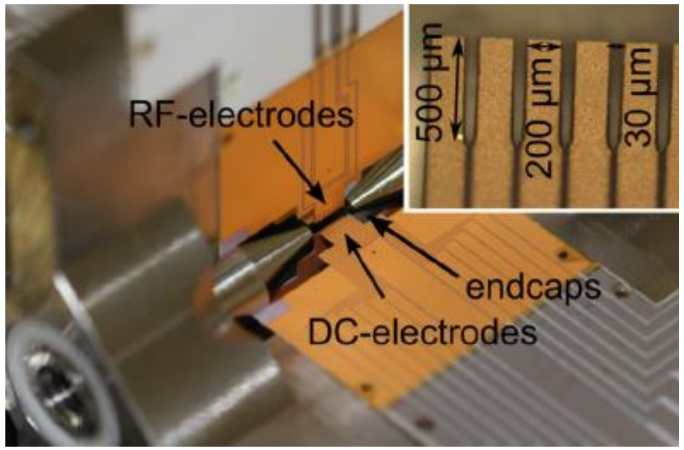
(>1,000 laser(313nm), T~100mK limited by rf heating)

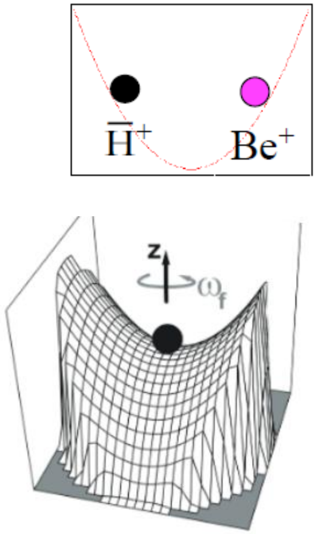
Cooling is limited by recoil energy by photon emission

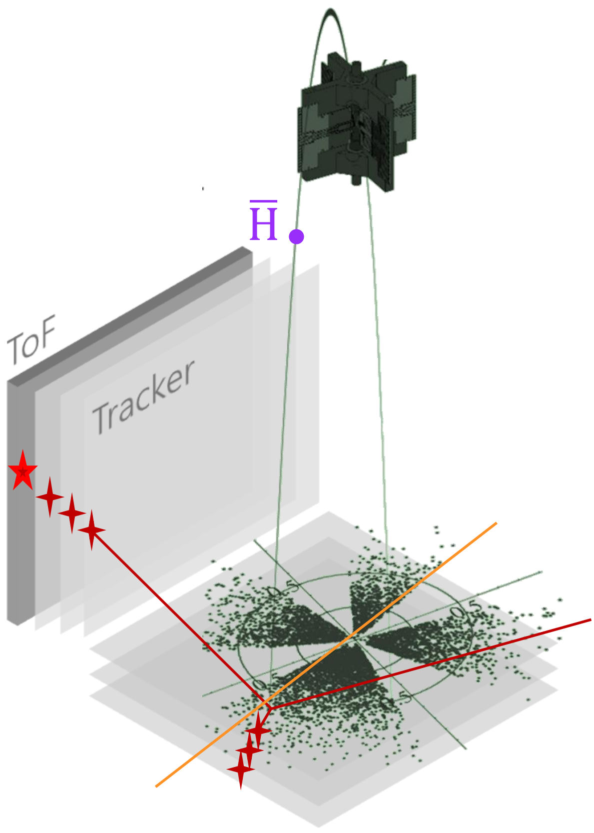
Precision Trap











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).)
Photo detachment finally produces ultra-cold and-atom and then the atom free-falls

Penning traps for precision measurement

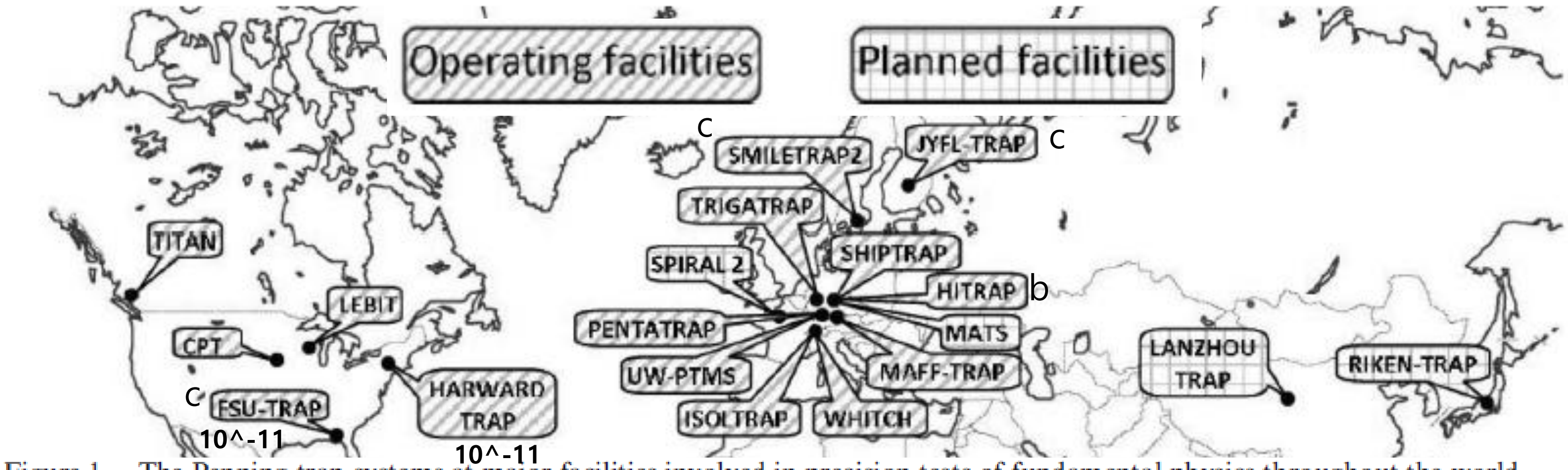


Figure 1. The Penning trap systems at major facilities involved in precision tests of fundamental physics throughout the world. The abbreviations stand for the installations situated at the following states: *America*: TITAN – Vancouver (Canada), CPT – Argonne (USA), LEBIT – Michigan (USA), MIT/FSU-TRAP – Florida (USA), Harvard-TRAP – Harvard (USA). *Europe*: ISOLTRAP – Geneva (Switzerland), WITCH – Geneva (Switzerland), SHIPTRAP – Darmstadt (Germany), HITRAP – Darmstadt (Germany), MATS –Darmstadt (Germany), TRIGA- TRAP – Mainz (Germany), PENTATRAP – Heidelberg (Germany), UW-PTMS – Heidelberg (Germany), SMILETRAP2 – Stockholm (Sweden), JYFLTRAP – Jyväskylä (Finland), Spiral2-TRAP – Caen (France), MAFF/MLL-TRAP – München (Germany). *Asia*: Lanzhou-TRAP – Lanzhou (China), RIKEN-TRAP – Tokyo (Japan).

Contemp.Phys. **51 (2010) 149-175**

Table 1. Fields of application and the generally required relative uncertainty on the measured mass $\delta m/m$ to probe the corresponding physics.

Field of Science	$\delta m/m$
General physics & chemistry	$\lesssim 10^{-5}$
Nuclear structure physics – separation of isobars	$\lesssim 10^{-6}$
Astrophysics – separation of isomers	$\lesssim 10^{-7}$
Weak interaction studies	$\lesssim 10^{-8}$
Fundamental constants	$\lesssim 10^{-9}$
CPT tests	$\lesssim 10^{-10}$
QED in highly-charged ions – b separation of atomic states	$\lesssim 10^{-11}$
Neutrino physics c	$\lesssim 10^{-11}$

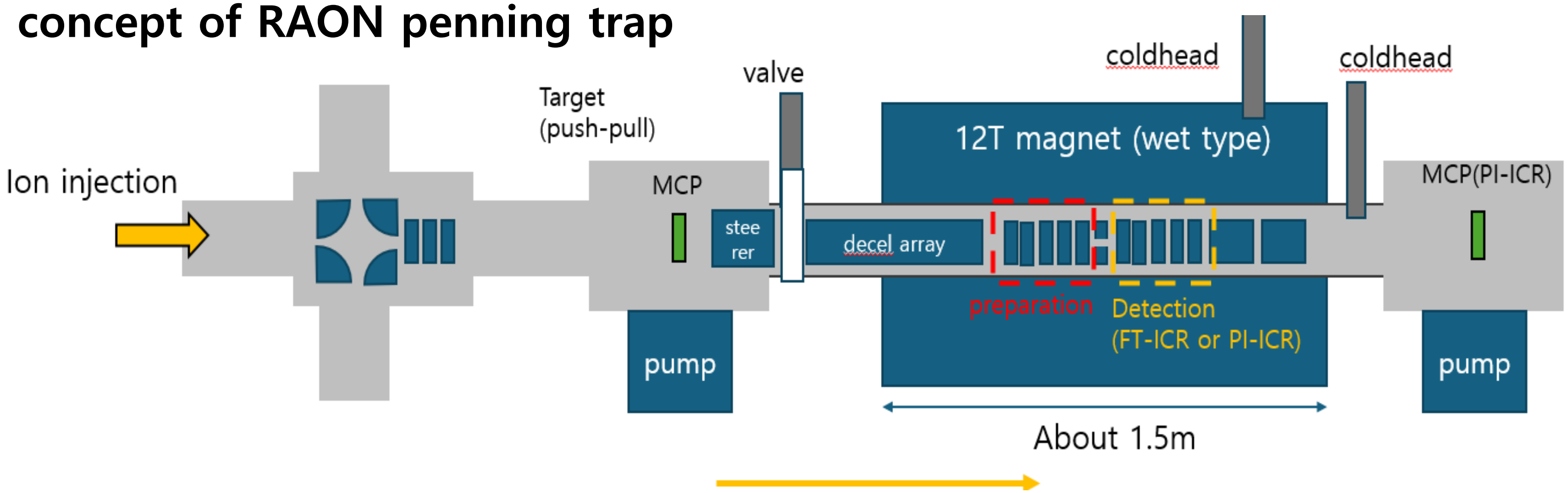
Annu. Rev. Nucl. Part. Sci. 2018. 68:45–74

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

Extend to new Penning trap at RAON

concept of RAON penning trap



- **Penning trap is the device to measure the mass of particle most precisely (by cyclotron motion $(f \propto B/m)$)**
- **Goal of the project**

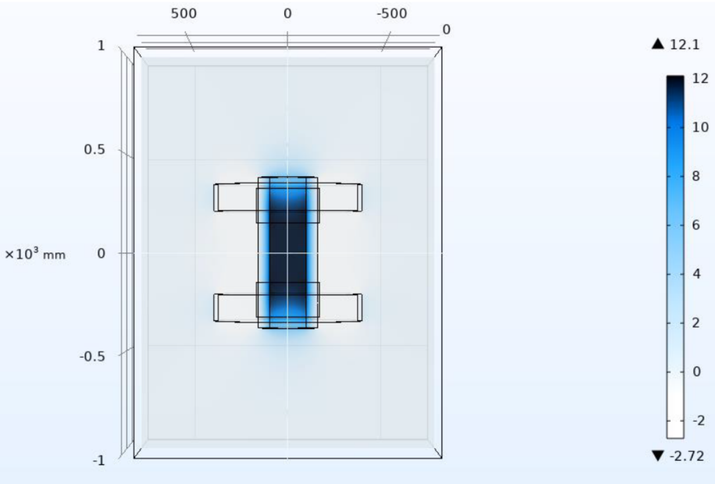
  - development of penning trap at ISOL beam line in RAON for nuclear ($\Delta m/m<10^{-6}$) and particle physics ($\Delta m/m<10^{-9}$)

  - Aim to develop first demonstration firstly.
- **In charge** : By Bongho Kim (+1 postdoc + one student near future?)

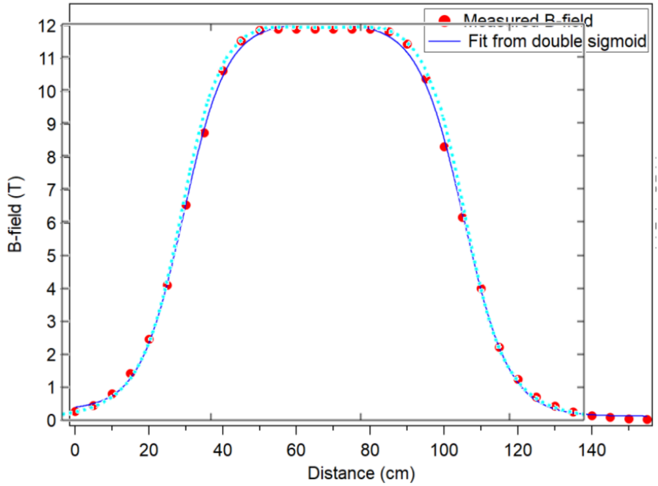
– experienced by development of antiproton trap (Penning-Malmberg trap) from AtoZ at GBAR experiment

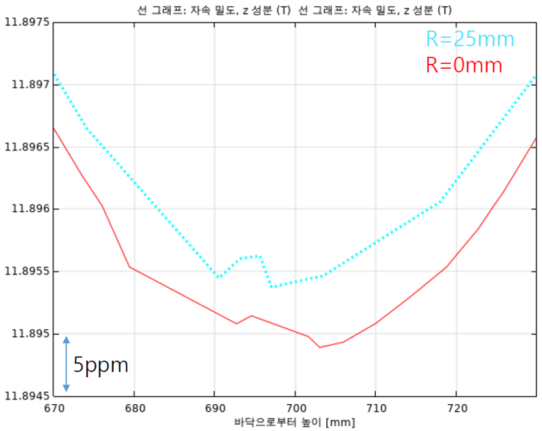
Extend to new Penning trap at RAON

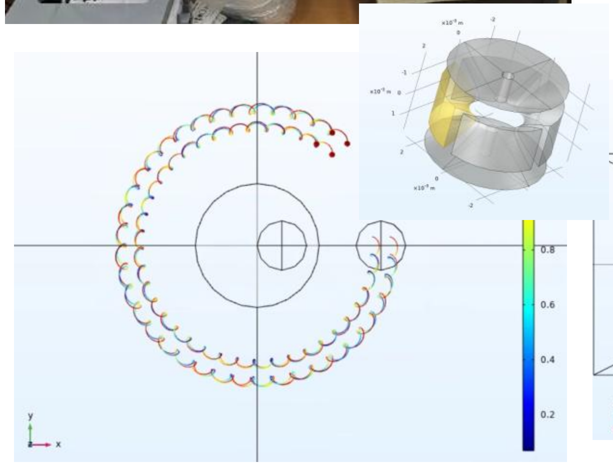
COMSOL Magnetic simulation

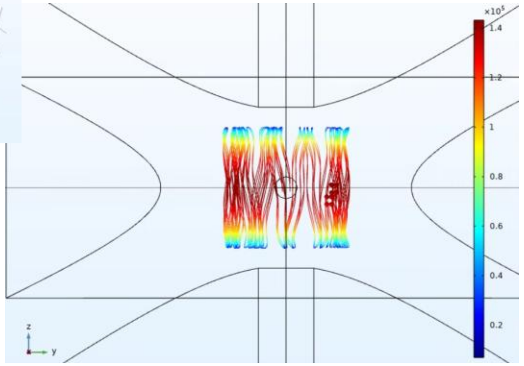


Red: Measured B field (CHIP)
Fitted from double sigmoid
Cyan: Simulation









- 12T magnet with ppm precision will be used
- Energizing and homogeneity test is planed in this year
- Basic simulation for B-field and E-field with particle motion has been prepared
- Still in design stage and many help needed

Conclusion

- The ion trap is the best tool to trap and control charged particle
- As one of application, the ion trap has been used for antimatter as rare particle
- The GBAR experiment has developed ion traps successfully and Korean GBAR group has developed penning-Malmberg trap
- Based on the developed technology and skill, the new penning trap will be developed at RAON

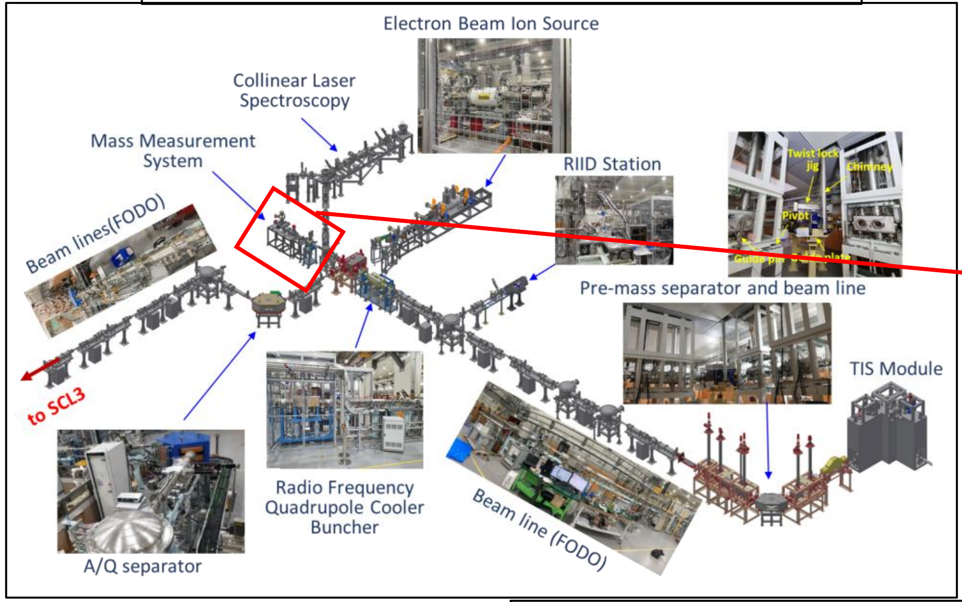
Thank you ☺

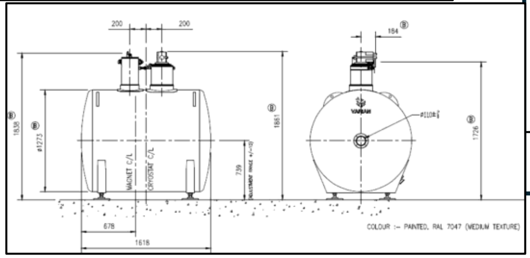
P. Adrich[1], P. Blumer[2], G. Caratsch[2], M. Chung[3], P. Cladé[4], P. Comini[5], P. Crivelli[2], O. Dalkarov[6], P. Debu[5], A. Douillet[4,7], D. Drapier[4], P. Froelich[8,20], N. Garroum[4,21], S. Guellati-Khelifa[4,9], J. Guyomard[4], P-A. Hervieux[10], L. Hilico[4,7], P. Indelicato[4], S. Jonsell[8], J-P. Karr[4,7], B. Kim[11], S. Kim[12], E-S. Kim[13], Y.J. Ko[11], T. Kosinski[1], N. Kuroda[14], B.M. Latacz[5,22], B. Lee[12], H. Lee[12], J. Lee[11], E. Lim[13], L. Liszkay[5], D. Lunney[15], G. Manfredi[10], B. Mansoulié[5], M. Matusiak[1], V. Nesvizhevsky[16], F. Nez[4], S. Niang[15,22], B. Ohayon[2], K. Park[11,12], N. Paul[4], P. Pérez[5], C. Regenfus[2], S. Reynaud[4], C. Roumegou[15], J-Y. Roussé[5], Y. Sacquin[5], G. Sadowski[5], J. Sarkisyan[2], M. Sato[14], F. Schmidt-Kaler[17], M. Staszczak[1], K. Szymczyk[1], T.A. Tanaka[14], B. Tuchming[5], B. Vallage[5], A. Voronin[6], D.P. van der Werf[18], D. Won[12], S. Wronka[1], Y. Yamazaki[19], K-H. Yoo[3], P. Yzombard[4]

BACKUP

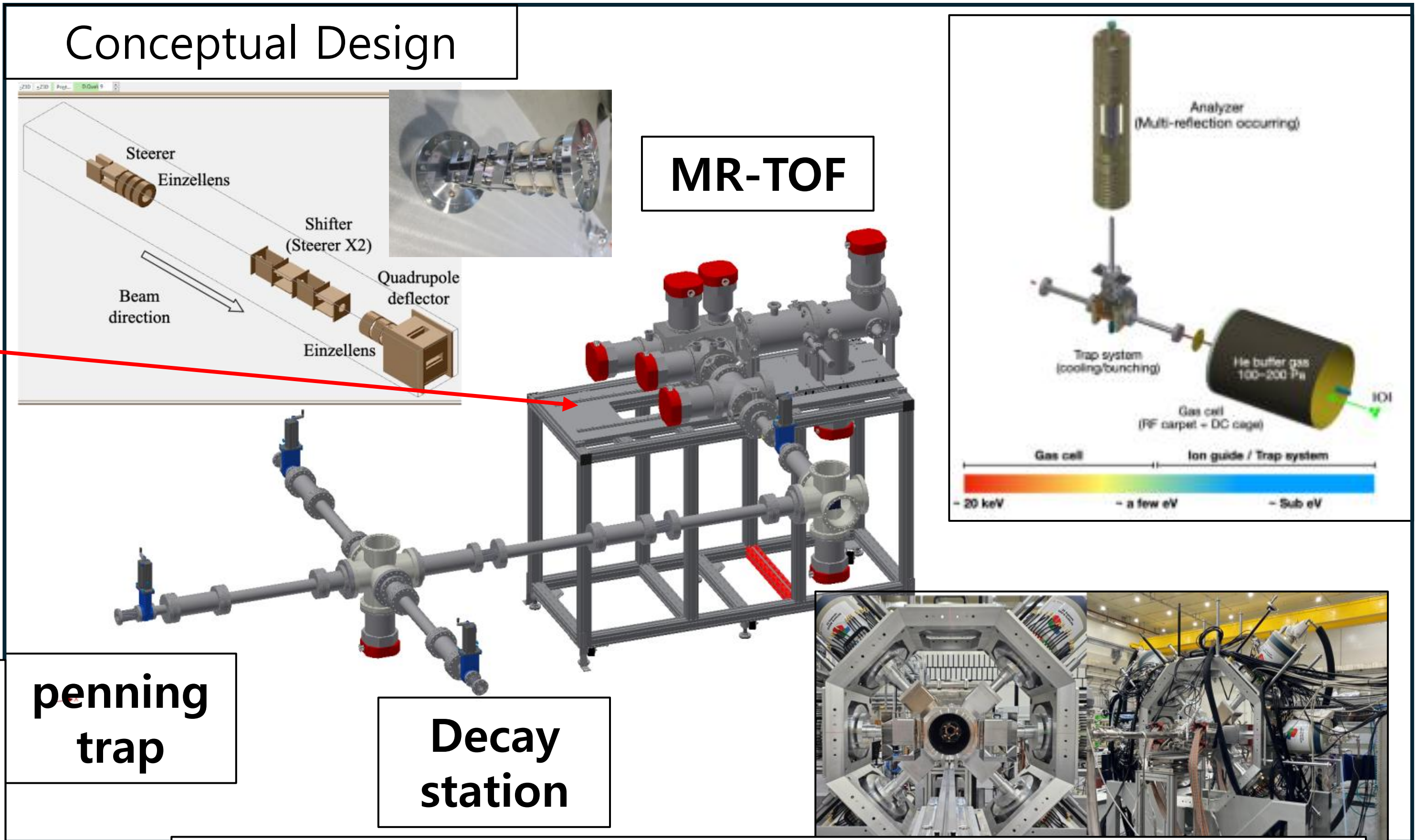
Additional ad : HIPPE beamline @ RAON

ISOL facility @ RAON





Conceptual Design

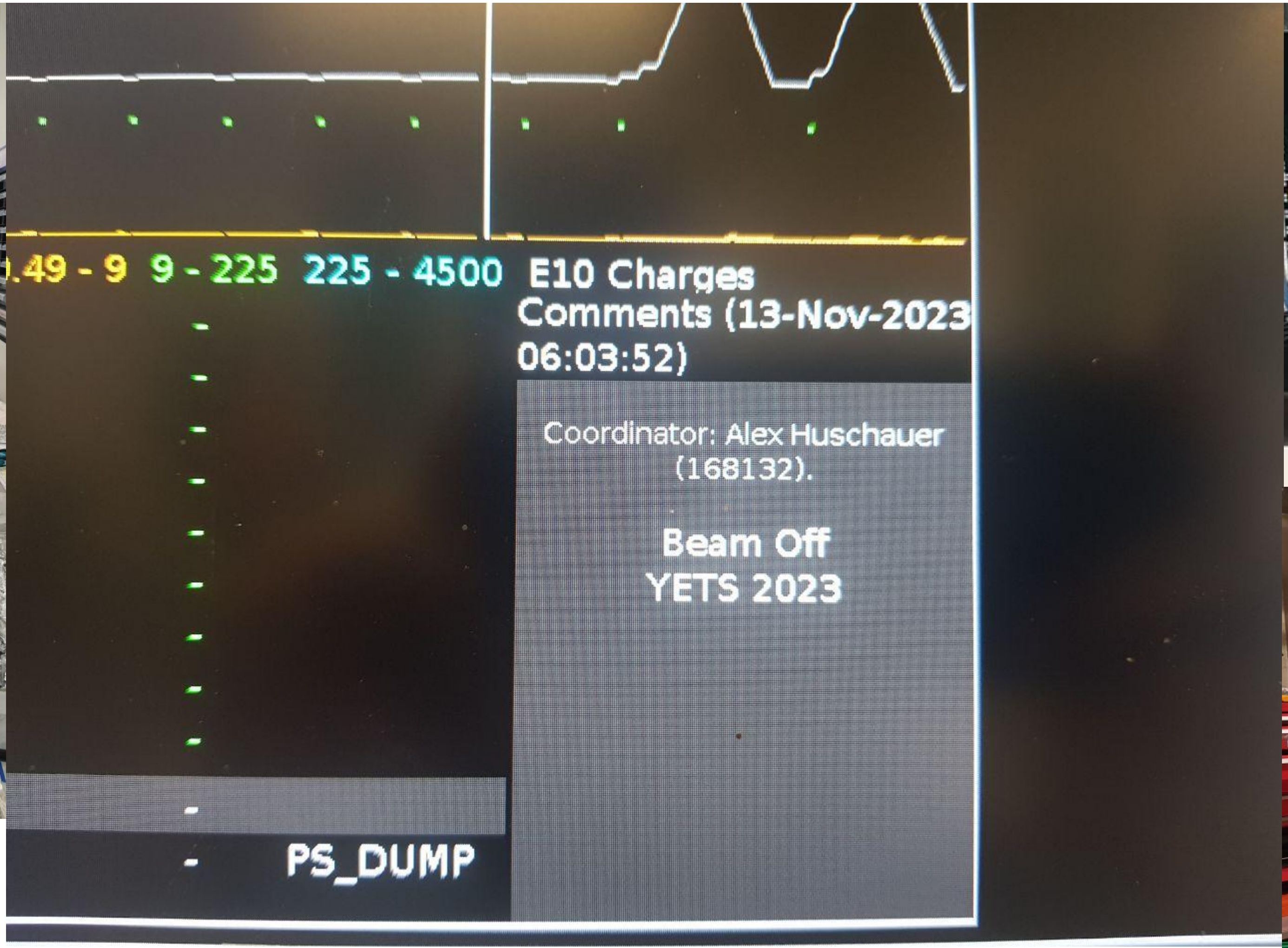


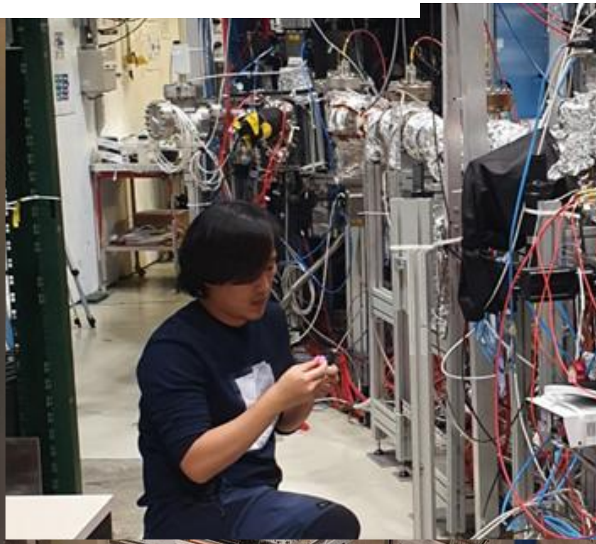
J. Ha[1], B. H. Kim[2], Y. H. Kim[1], J. Y. Moon[3], H. I. Bae[4] ,A. Chekhovska[1], S. Choi[5], K. I. Hahn[1], Y. Son[1,5], J. Yang[2,3],D. Won[3]

[1]Center for Exotic Nuclear Studies, Institute for Basic Science, Daejeon, Korea
[2]Center for Underground Physics, Institute for Basic Science, Daejeon, Korea
[3]Institute for Rare Isotope Science, Institute for Basic Science, Daejeon, Korea
[4]Yonsei University, Seoul, Korea
[5]Seoul National University, Seoul, Korea

- High Purity High Precision Experimental beamline (HIPPE) project initiated
- For precision decay spectroscopy and precision mass measurement

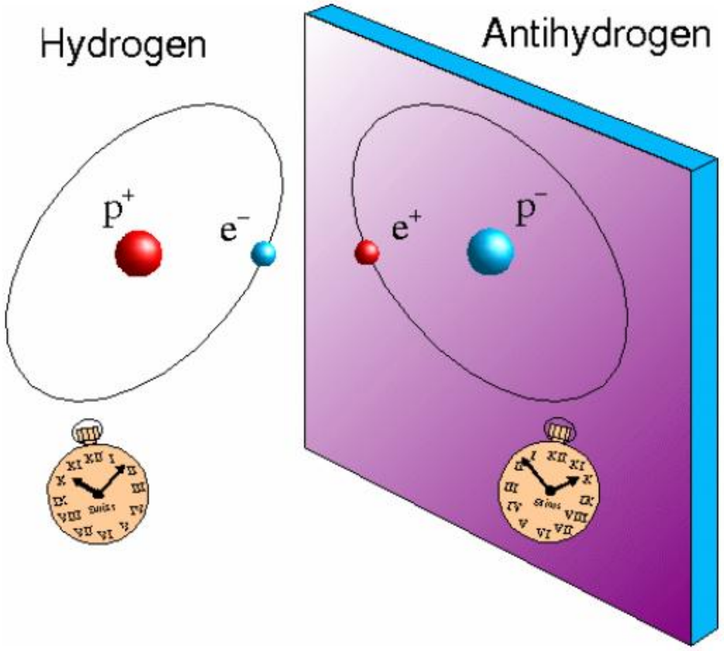
Experimental setup (2023)





Motivation

from http://www2.mpq.mpg.de/~haensch/antihydrogen/introduction.html



Check fundamental interaction between matter & antimatter

- Weak Equivalence Principle(WEP) :

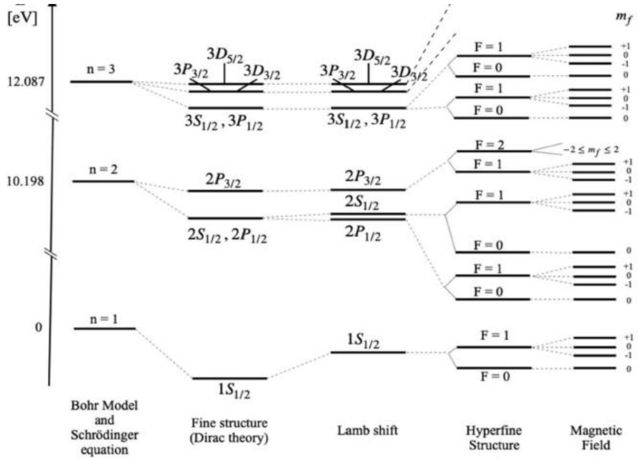
$$m_I = m_G \ (F = m_I a = -G m_G m'_G / r^2)$$

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

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

(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



CPT test at AD

- 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 transition : 16 ppb (nature 578, 375 (2020)) by ALPHA

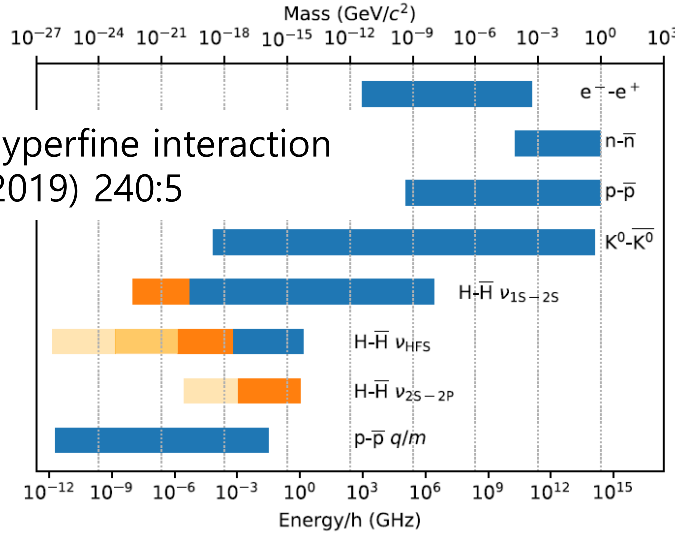
 - Hyperfine splitting : observed 2% ($2P_{1/2}$-$2P_{3/2}$) : 250ppm

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

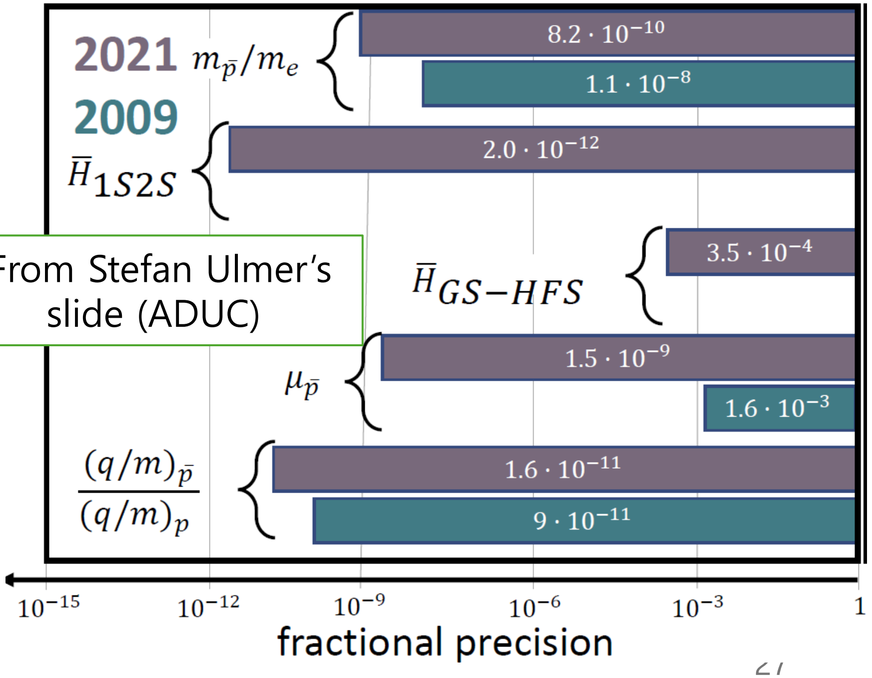
 - Lamb shift : agreed a level of 11% ($2S_{1/2}$-$2P_{1/2}$) (nature 578, 375 (2020)) by ALPHA

- 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))



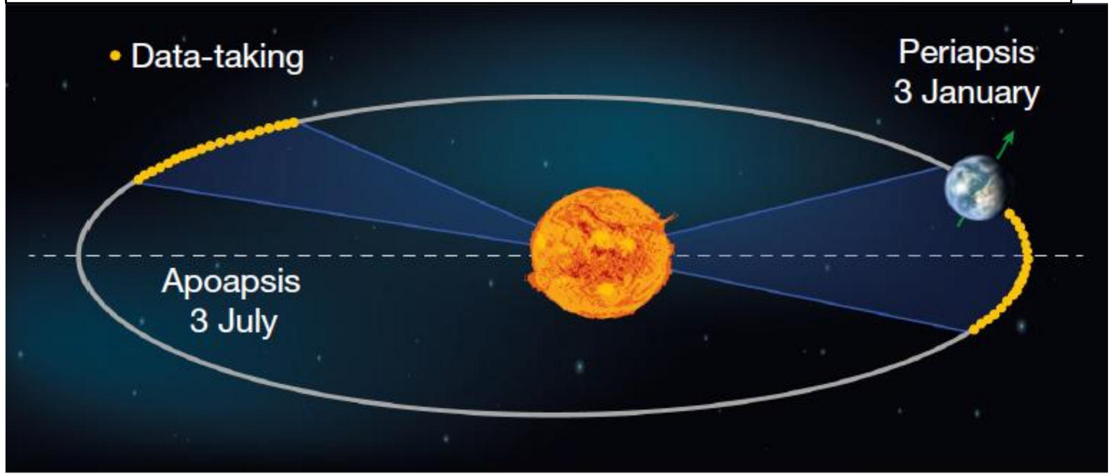
Hyperfine interaction
(2019) 240:5

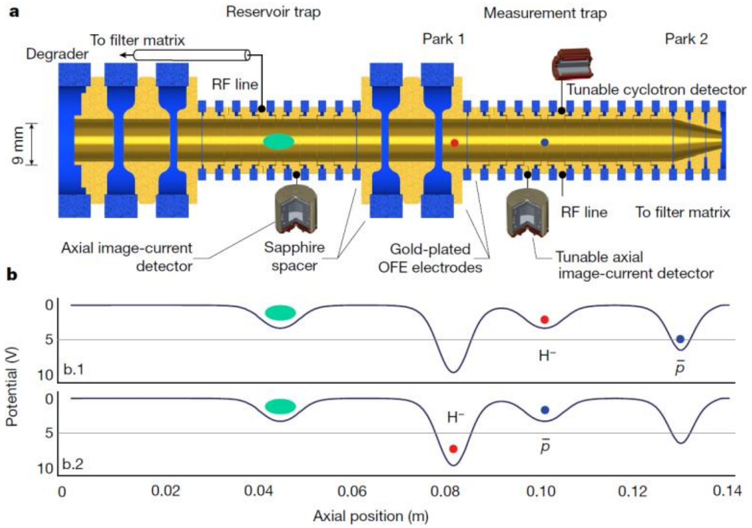


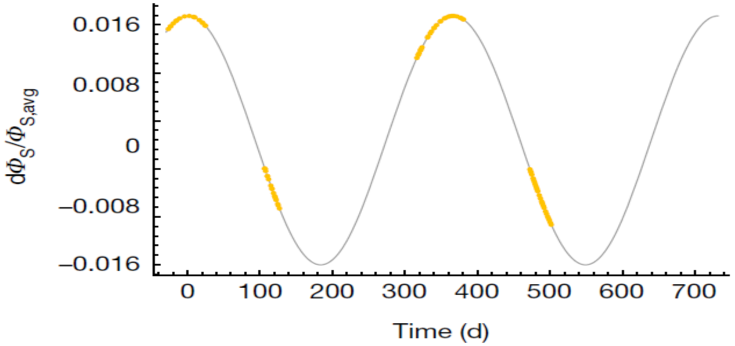
From Stefan Ulmer's
slide (ADUC)

Antiproton WEP test

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







- **Base experiment**

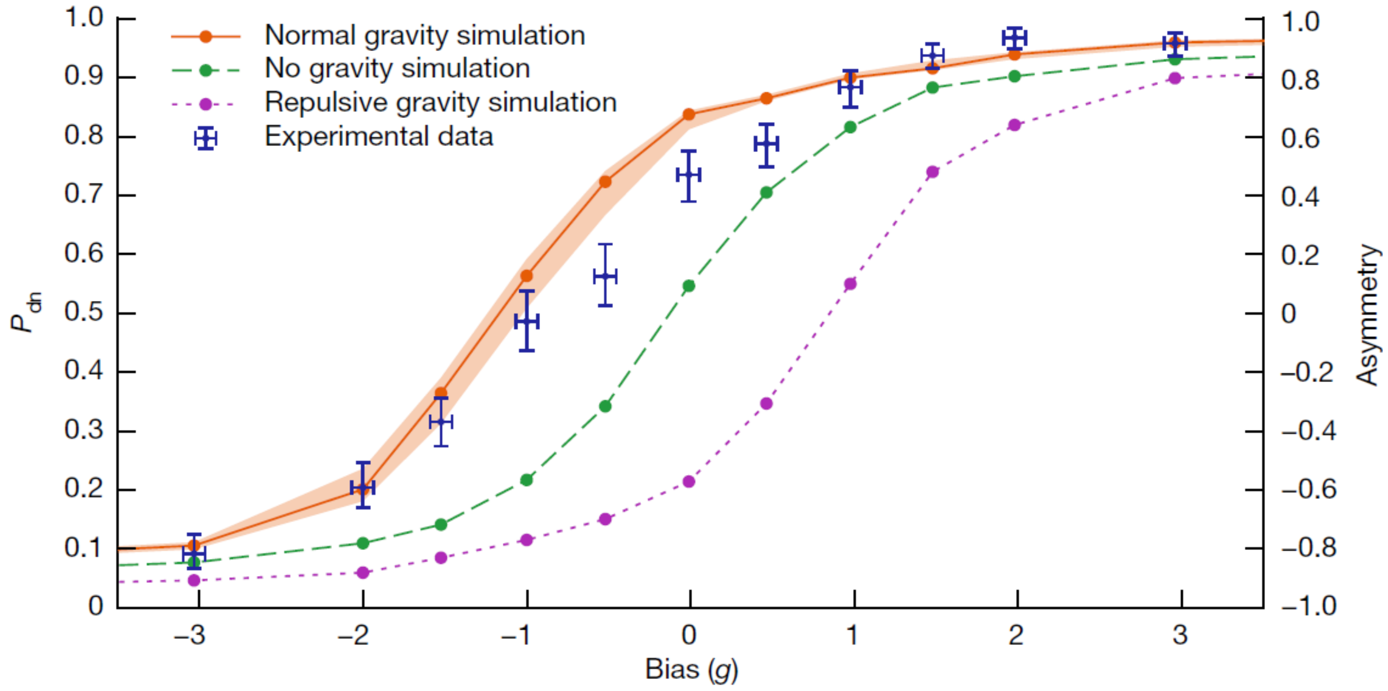
Antiprotons cyclotron clock measurement was done for WEP_{cc} test : $|\alpha_{g,D} - 1|$<0.030 (CL 0.68)

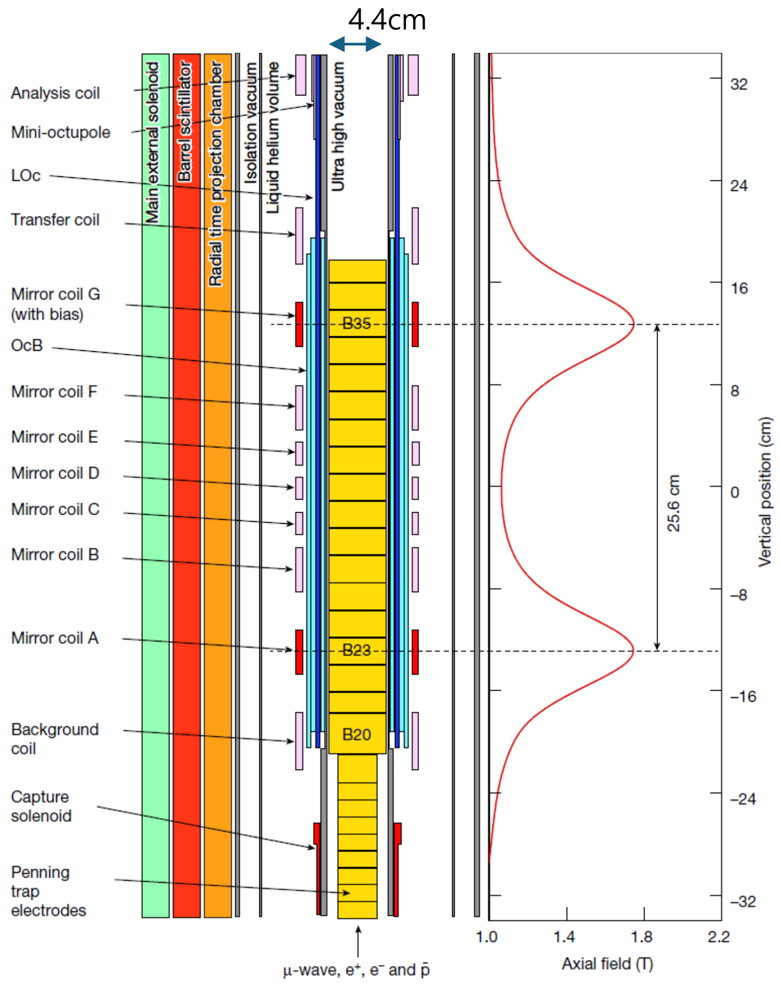
$$\frac{\nu_{c,\bar{p}} - \nu_{c,p}}{\nu_{c,avg}} = \frac{3\Phi}{c^2}(\alpha_g - 1)$$

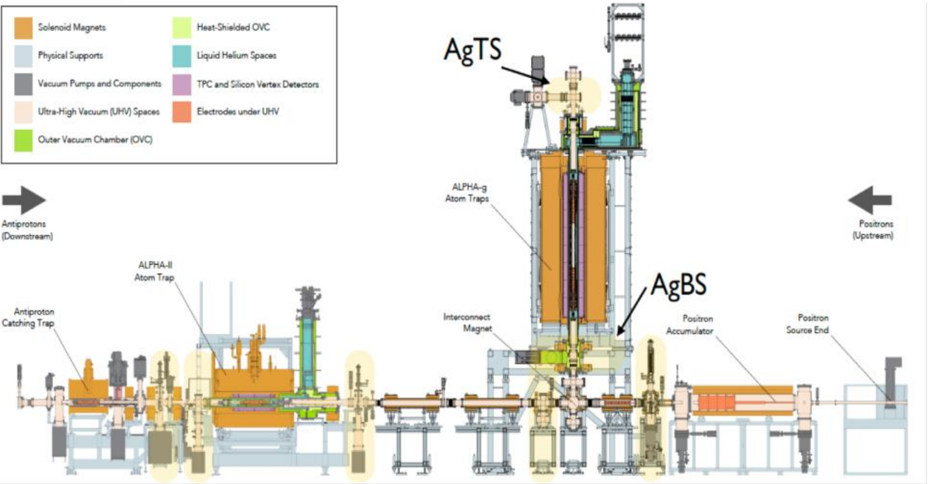
←Limit on scalar and tensor interaction

(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

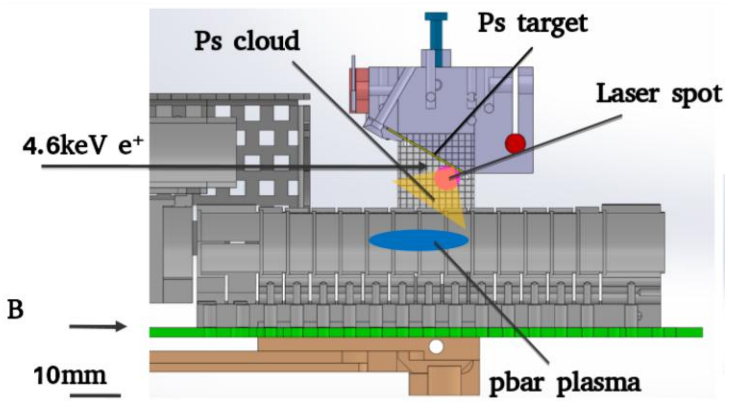
2023 : Rule out Repulsive antigravity by $\bar{H}$ with T <0.5K (**Nature 621, 716-722 (2023)**)

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

$\mathbf{WEP_{ff}}$ test approaches

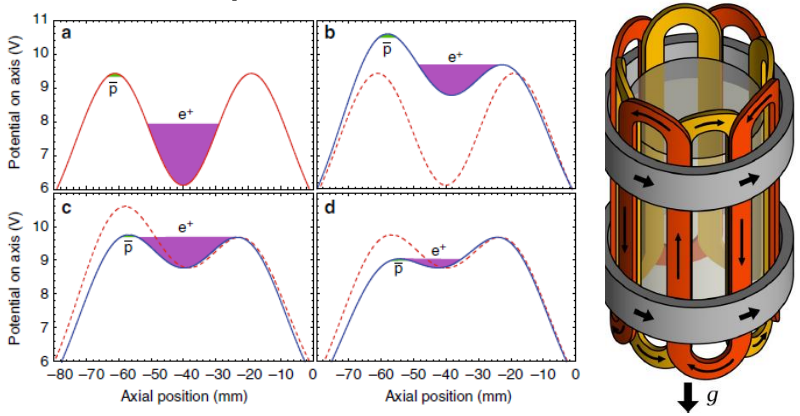
AEGIS

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



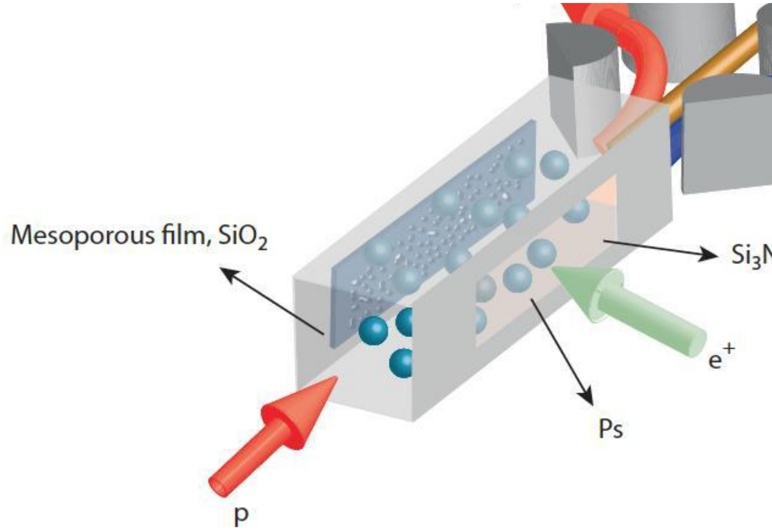
ALPHA-g

- 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

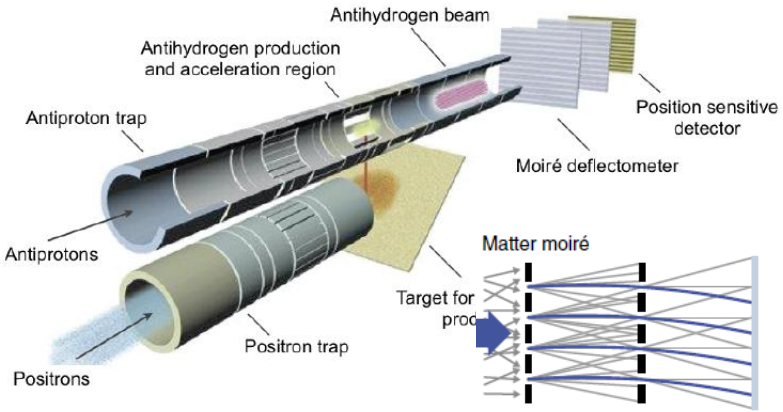
AEGIS

- **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

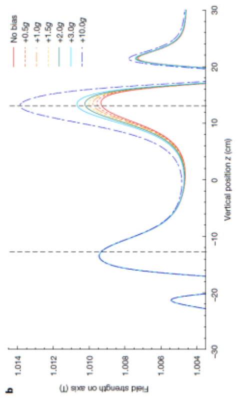
- Aim : ~100mK (v~40m/s)

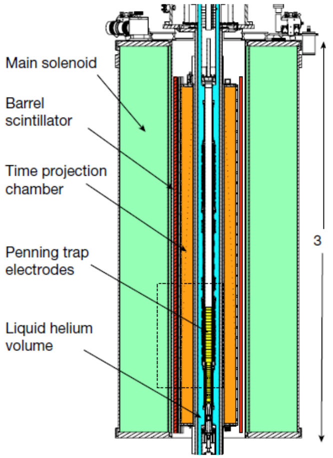
\- 1% precision with 1000# $\bar{H}$.



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

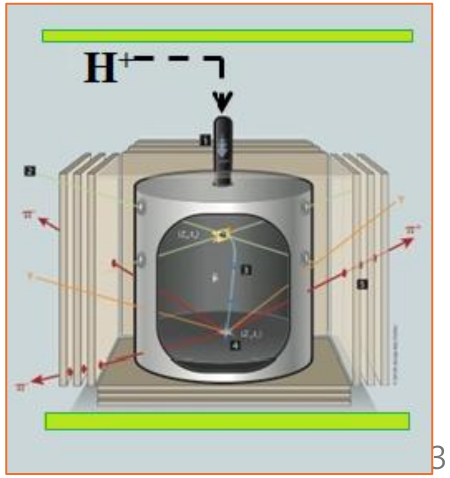




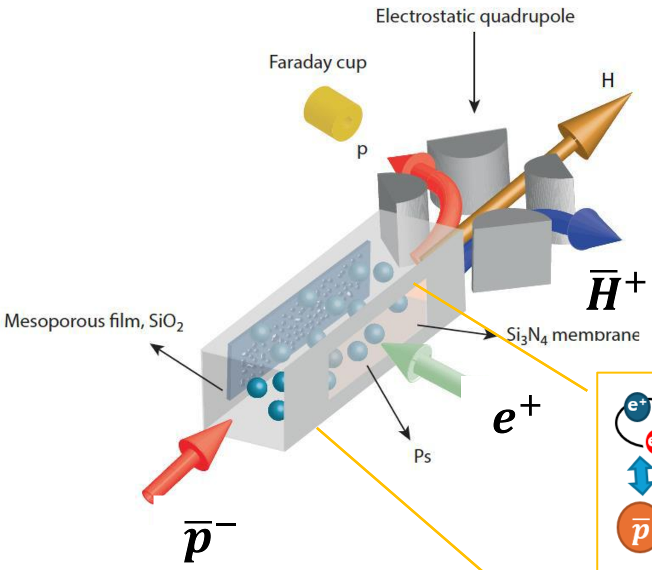
GBAR

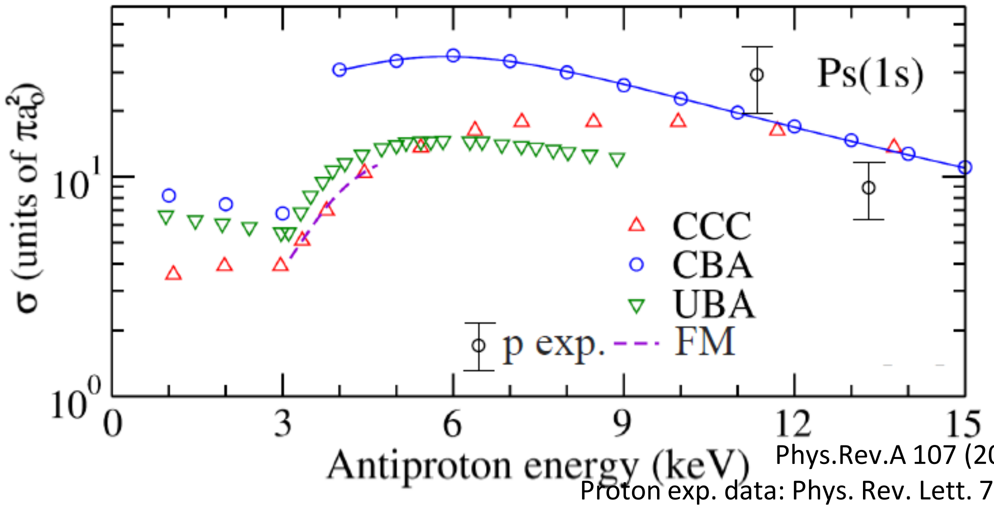
- Trapping and cooling $\bar{H}^+$ at paul trap.
- **Ultra-cold $\bar{H}^+$** by Sympathetic cooling by Be ion (10uK)
- Classical Freefall test (z=0.25m)
- Aim : 10uK (v~0.4m/s)

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

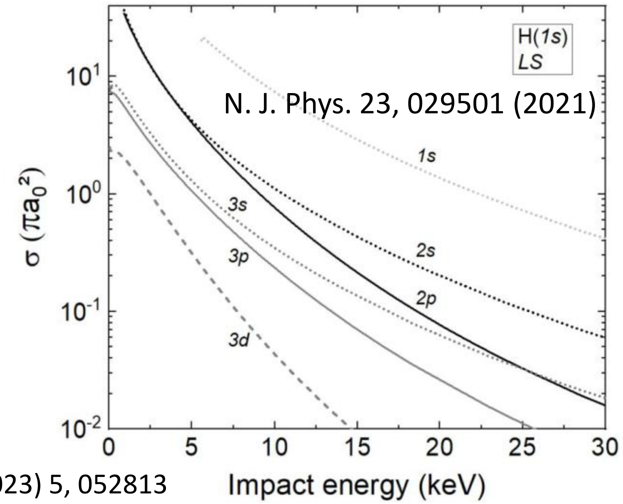


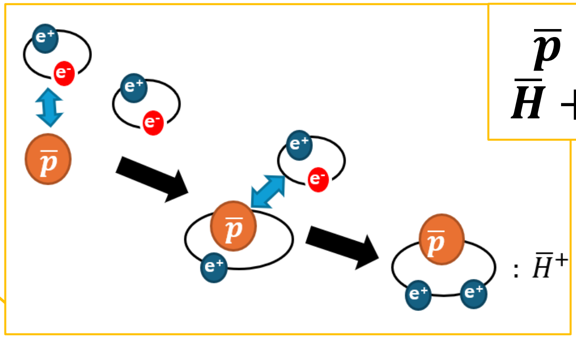
GBAR : Anti-anion generation





Phys.Rev.A 107 (2023) 5, 052813
Proton exp. data: Phys. Rev. Lett. 78, 2728 (1997)

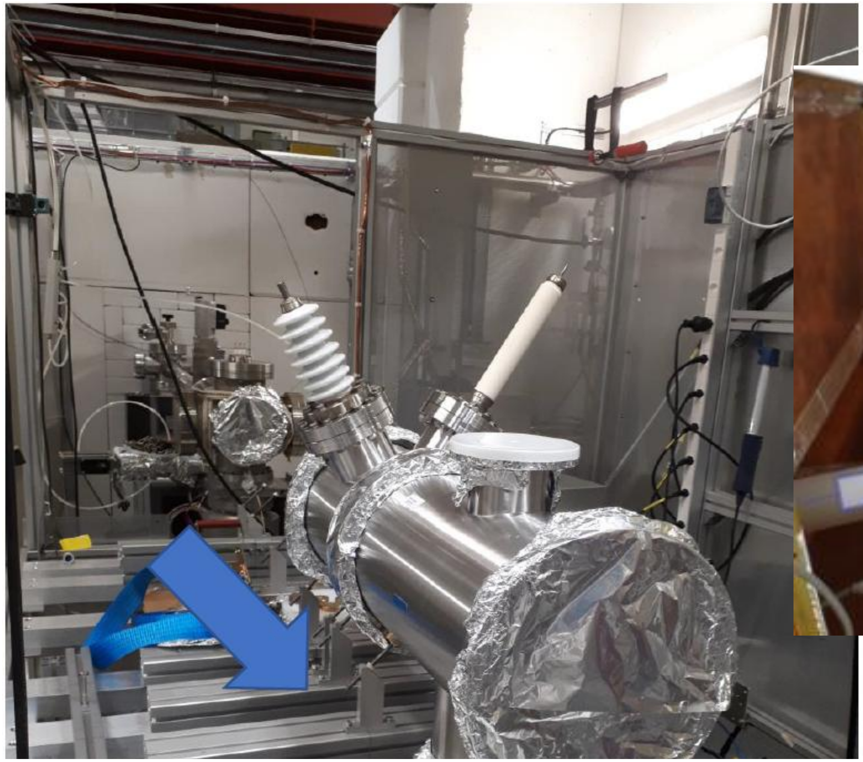


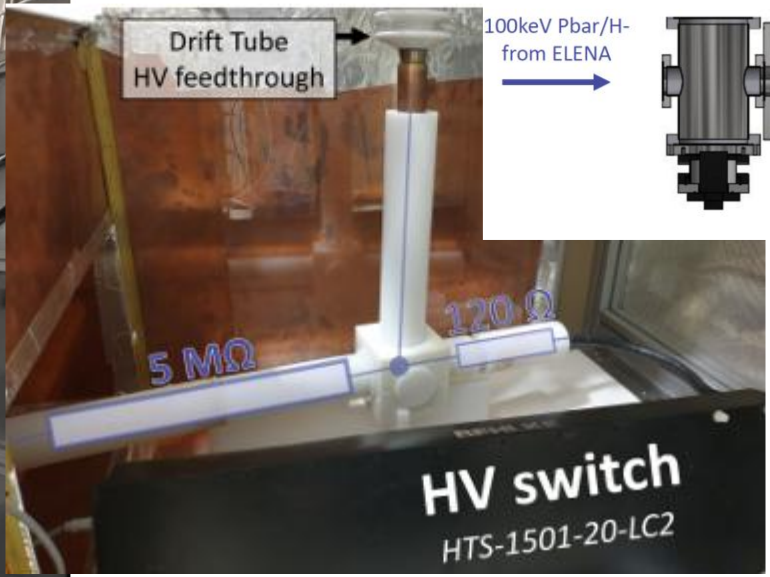


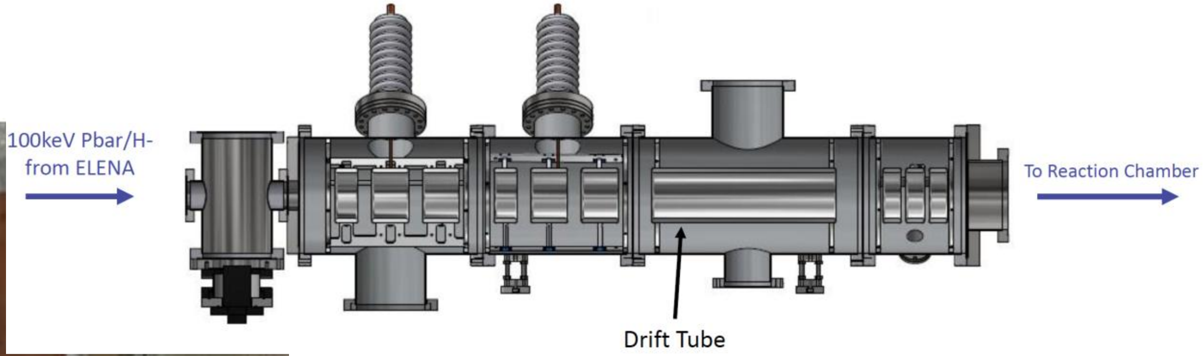
$\bar{p} + Ps \rightarrow \bar{H} + e^-$: 1st milestone
$\bar{H} + Ps \rightarrow \bar{H}^+ + e^-$: 2nd milestone

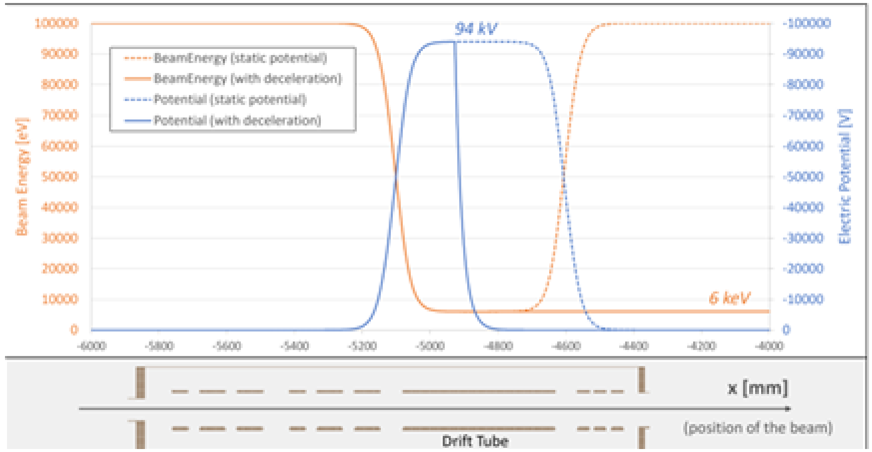
- Double charge exchange process between $\bar{p}$ beam and dense $o - Ps$ cloud required
- Cavity for $o - Ps$ designed to maximize the interaction 1x1.5x20mm^3 (limited positron spatial density)
- Dense $o - Ps$ (3x10^{11}cm^{-3} of o-Ps cloud) and intense pbar beam (5x10^6) through dense positronium in cavity are required to produce anti-anion (~0.5#)
- Also, laser excitation for o-Ps has been prepared.

GBAR Decelerator

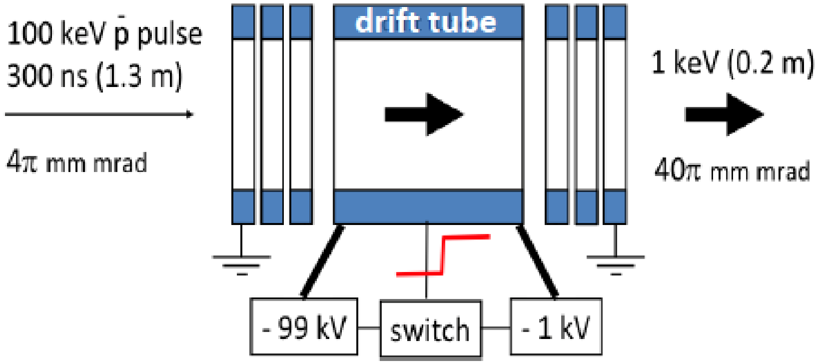








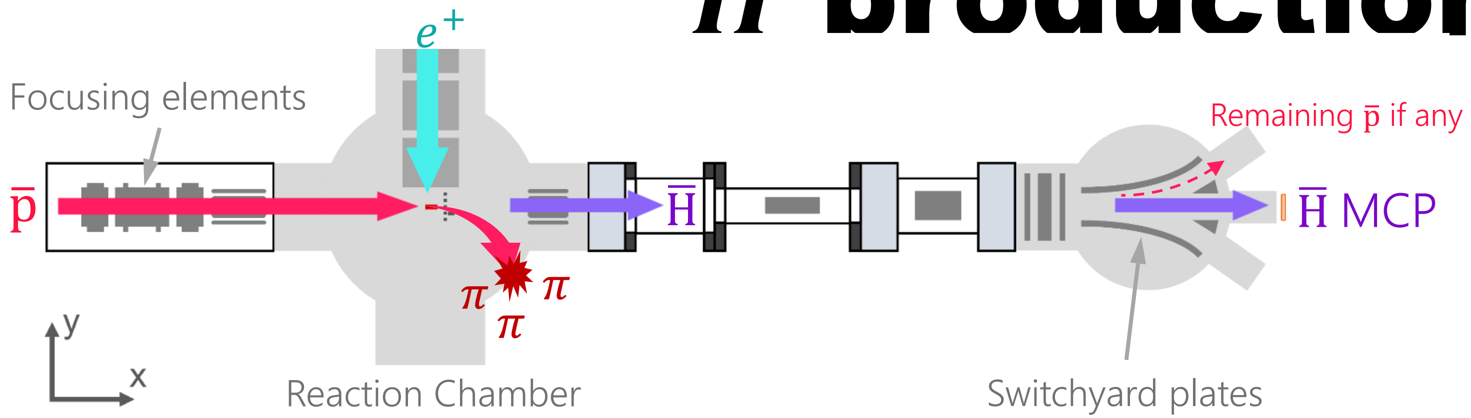
C. Roumegou, PhD thesis, Universite Paris-Saclay (2023)

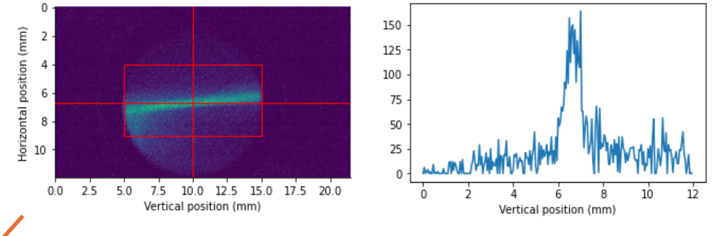


- GBAR decelerator

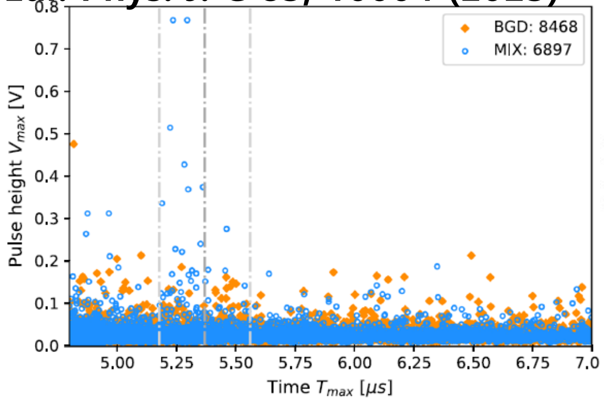
- Drift tube with –HV with fast-switching when pbar beam is in the tube
- Higher efficiency and mono-energy expected compared with Degrading foil
- With 100keV→1keV deceleration, emittance is increased about 10 times
- Almost 100% efficiency is shown down to 3keV KE (preliminary)

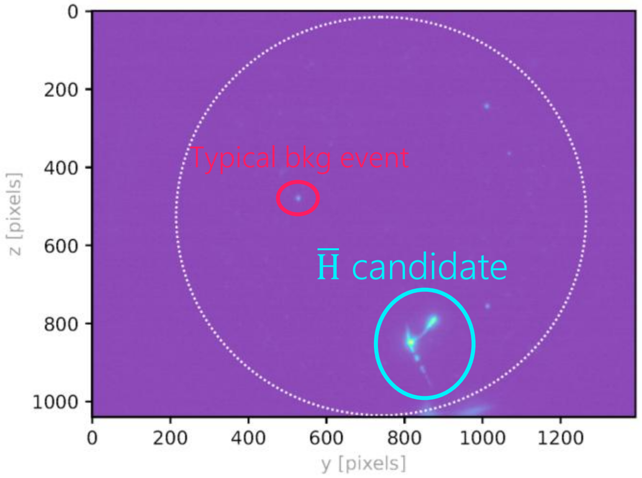
$\bar{H}$ production

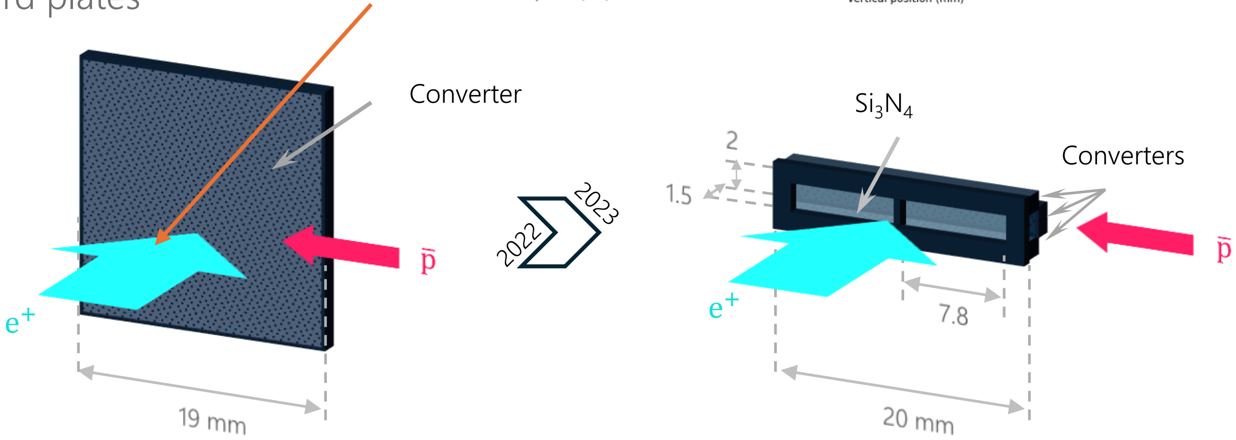


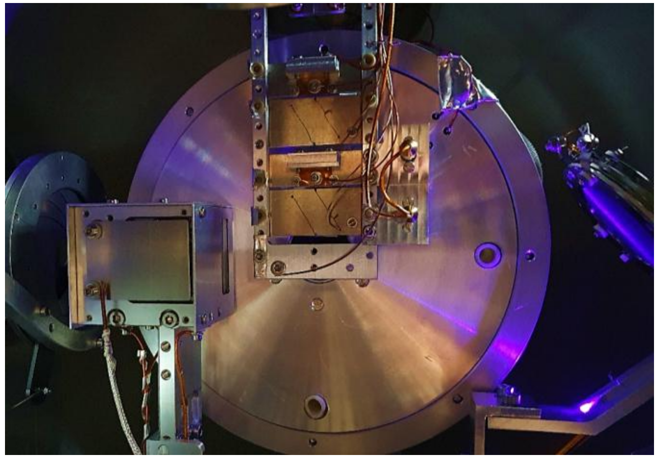


Eur. Phys. J. C 83, 10004 (2023)



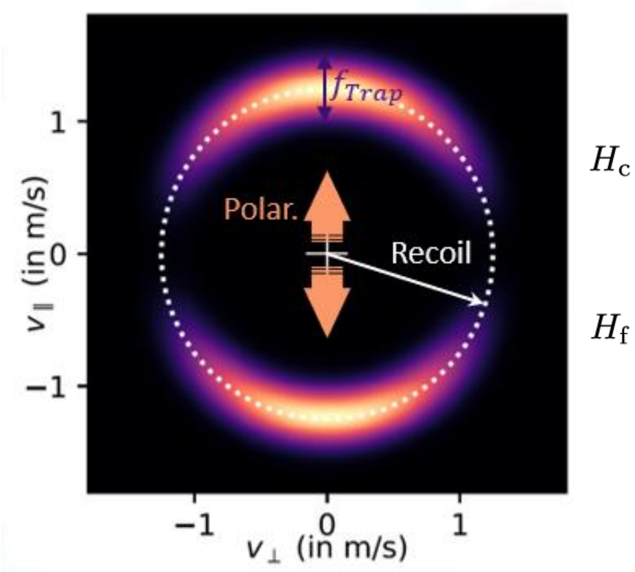


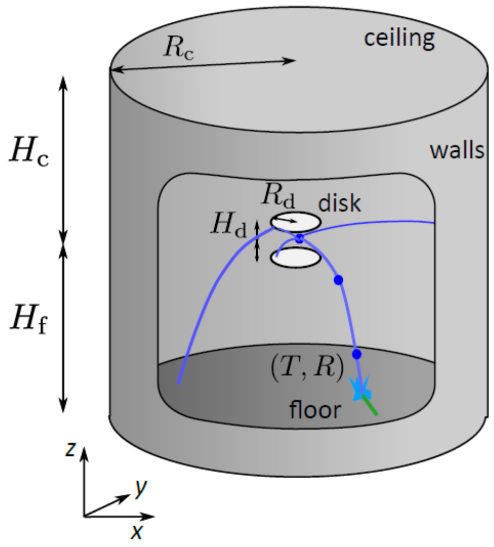


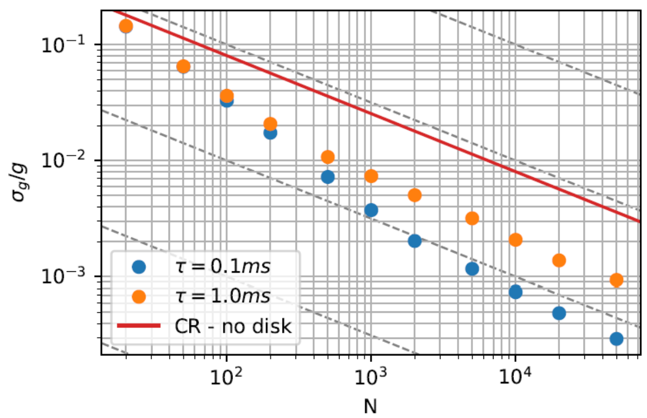


- Produced antihydrogen is detected above 3σ (which is **1st milestone**) at 2022
- About 6.8x10^6 o-Ps (5x10^7 e$^+$) and 3x10^6 $\bar{p}$ in flat target
- (First) production of $\bar{H}$ by charge exchange between o-Ps and antiproton **beam**
- Antihydrogen detection rate increased by 30 times (2023) compared to 2022

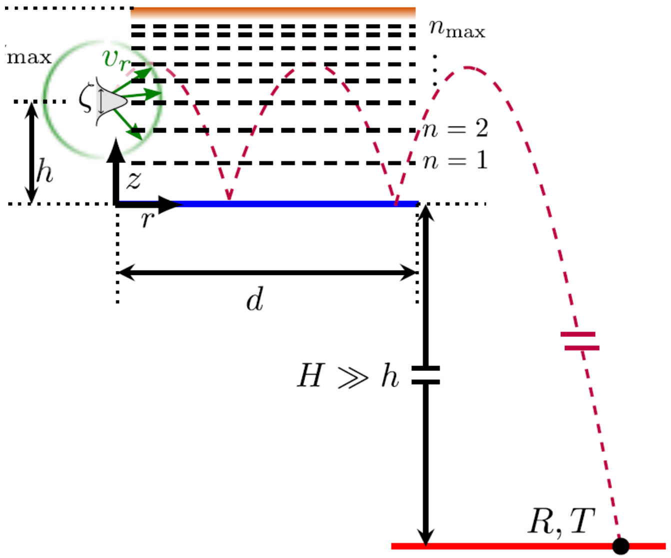
GBAR : Quantum reflection and levitation







O. Rousselle et al, Phys. Rev. A **105**, 022821 (2022)



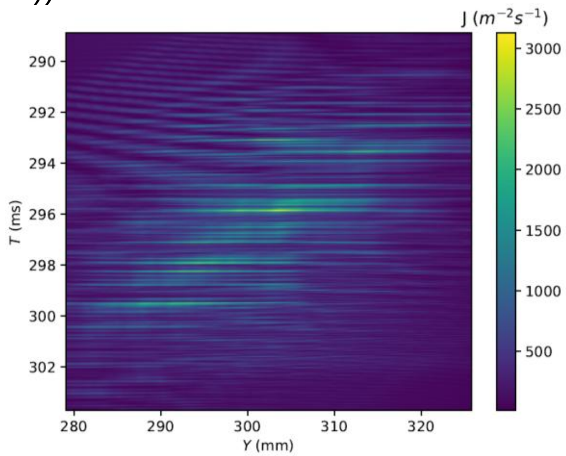
1. Polarization and Shaping with 0.1% uncertainty for 10,000 event (O.Rousselle et al, Eur. Phys. J. D **76**, 209 (2022))

- Polarization and shaping give constrains to the time structure
- Time width of photo-detachment laser by limited intensity gives uncertainty.
- Optimization for best condition is ongoing.

2. Quantum bouncing by Casimir-Polder potential vs Gravitational potential 10^{-5} precision

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

- Momentum selection reduces systematic uncertainty
- Gravitational Quantum states with pattern measurement makes possible to reach higher precision



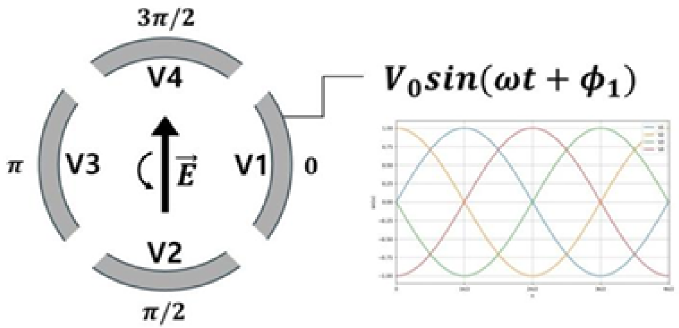
O. Rousselle *et al.*,
Eur. Phys. J. D **76**, 209 (2022)

Antiproton Beam Processing

from B.C.Lee

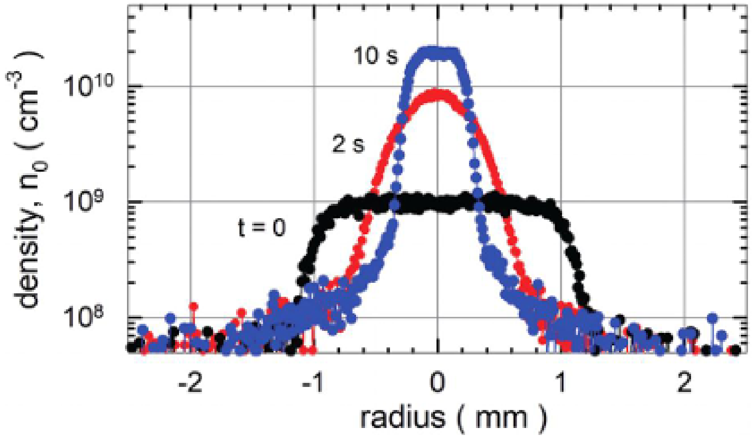
Rotating Wall Compression

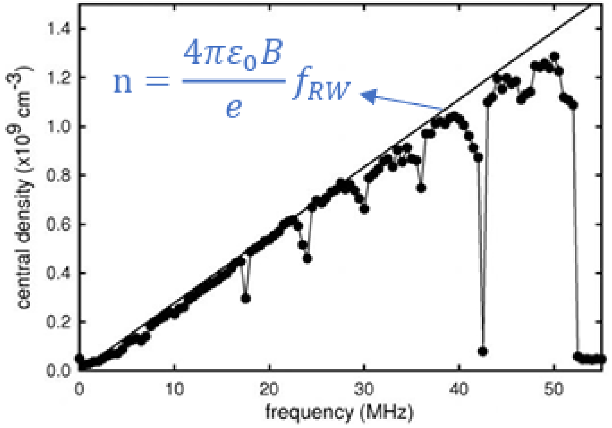
- The canonical angular momentum of the plasma: $P_\theta \sim -\frac{|e|B}{2} < r^2 > N$
- Rotating electric field → torque: $\tau = \frac{dP_\theta}{dt} \sim \frac{d<r^2>}{dt}$



electron: Strong Drive (Surko, https://doi.org/10.1063/1.5131273)

- $f_E = \frac{en}{4\pi\varepsilon_0 B}$ Plasma frequency; by ExB drift (source of E: space charge potential of the plasma)
- $f_E < f_{RW}$ 'spin-up' the plasma, compression, until it reaches $f_E \approx f_{RW}$
- $n \approx \frac{4\pi\varepsilon_0 B}{e} f_{RW}$

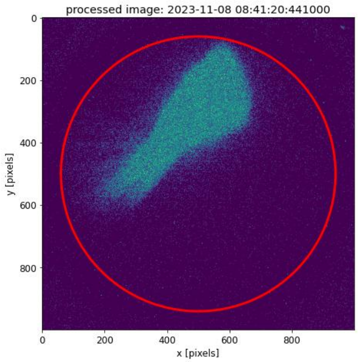




$f_{RW} > f_E$, strong drive regime of RW compression, B =0.04T, Surko, https://doi.org/10.1063/1.5131273

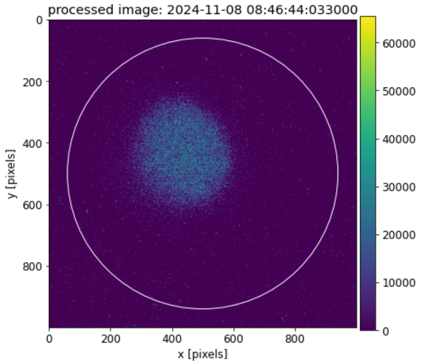
Antiproton beam line performance

Antiproton Trap extraction beam



2023 instllation

Beam Intensity	$(2.8 \pm 0.5) \times 10^6$
Extraction efficiency (/ELENA)	$(36 \pm 6)\%$
Beam size (σ_x)	4.26mm
Beam size (σ_y)	4.22mm
Bunch length (FWHM)	24ns

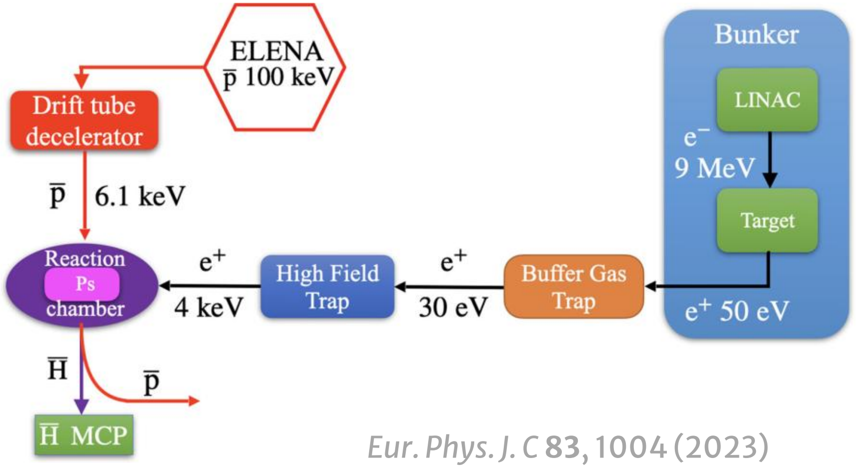


2024 comissioning

Beam Intensity	$(4.9 \pm 0.4) \times 10^6$
Extraction efficiency (/ELENA)	$(43 \pm 4)\%$
Beam size (σ_x)	2.71mm
Beam size (σ_y)	2.99mm
Bunch length (FWHM)	80ns

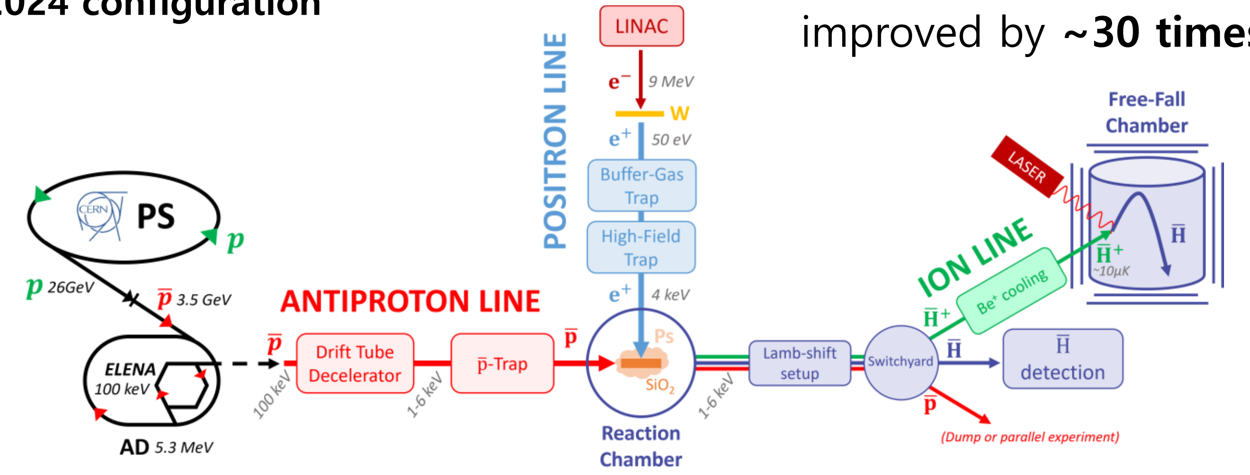
Antihydrogen ($\bar{\mathrm{H}}$) production rate

2022 configuration



Eur. Phys. J. C **83**, 1004 (2023)

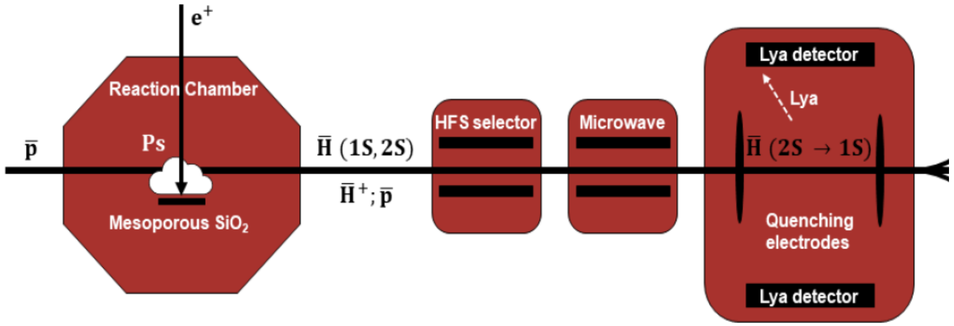
2024 configuration



$\bar{\mathrm{H}}$ detection rate improved by **~30 times**

CERN-SPSC-2025-005

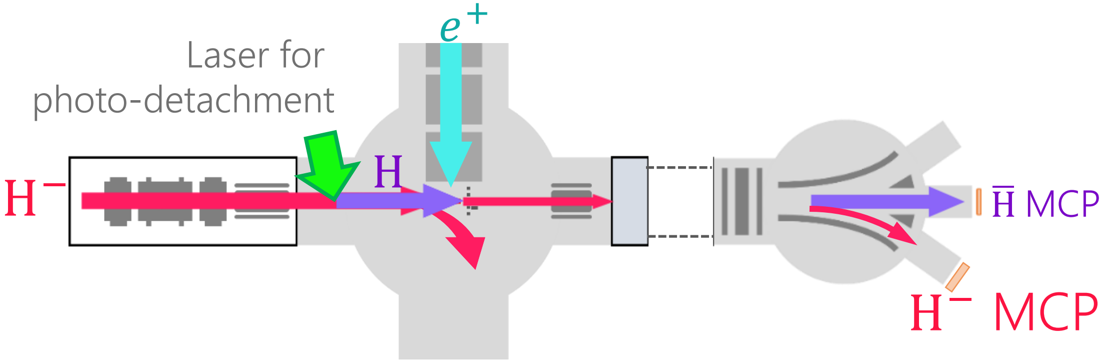
coming soon measurements

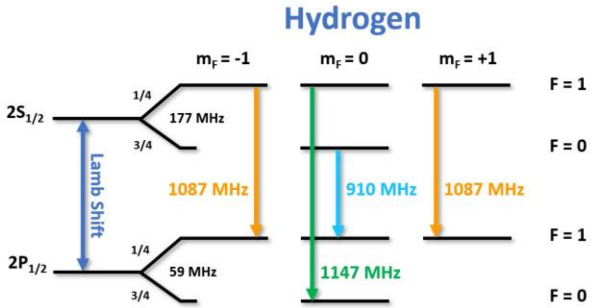


MW transitions
(HFS selector & MW TL)

P. Crivelli et al., Phys. Rev. D **94**, 052008 (2016)

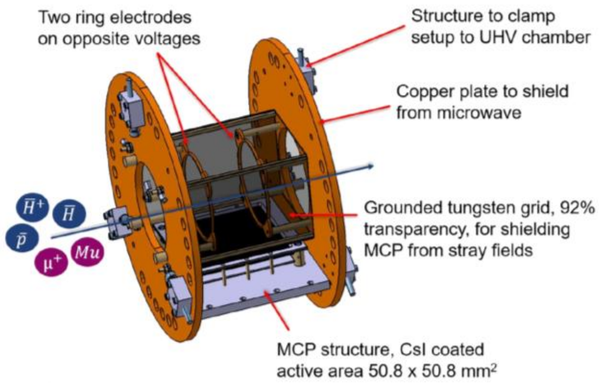
$H + Ps \rightarrow H^- + e^+$





Commissioned with H(2S) in GBAR

Ly-α photons detector



H(1S) + Ps(1S), assuming:

10^6 H at 6 keV + 3.10^7 oPs in present cavity

0.1 to 1.5 H^- depending on cross sections

- $\bar{H}$ Lamb-shift measurement (in flight) has been prepared
- H^-cross section measurement as counter part of $\bar{H}^+$ prepared