GBAR experiment

: Classical freefall experiment of antihydrogen at rest in terrestrial gravitational field

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on behalf of the GBAR collaboration

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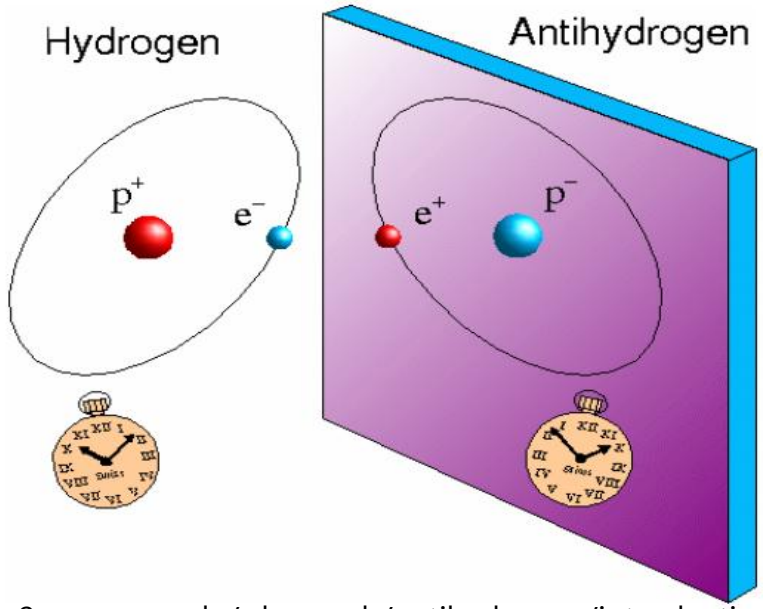
Antimatter



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

Dirac equation (1928)

$$(i\hbar\gamma^{\mu}\partial_{\mu} - mc)\psi = 0$$

❖ Antiparticle

- Paul Dirac predicted the existence of antiparticle in1931 and positron was discovered in 1932
- Antiparticle as a counterpart of ordinary particle for charge conjugation (charge, magnetic moment)
- With CPT symmetry (transformation), other quantities (mass, lifetime) are expected to be same

❖ Matter and Antimatter asymmetry

- 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) $\gg 10^{-18}$(expect))

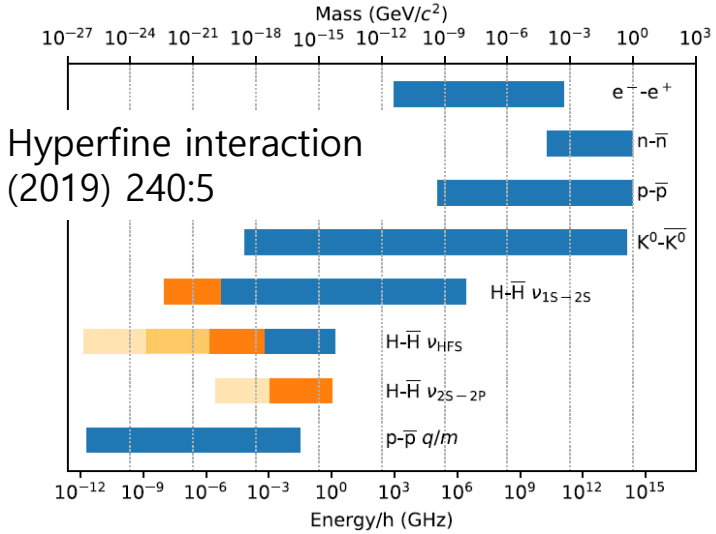
- Model to understand : Baryogenesis, Leptogenesis, etc..

Antimatter : CPT test

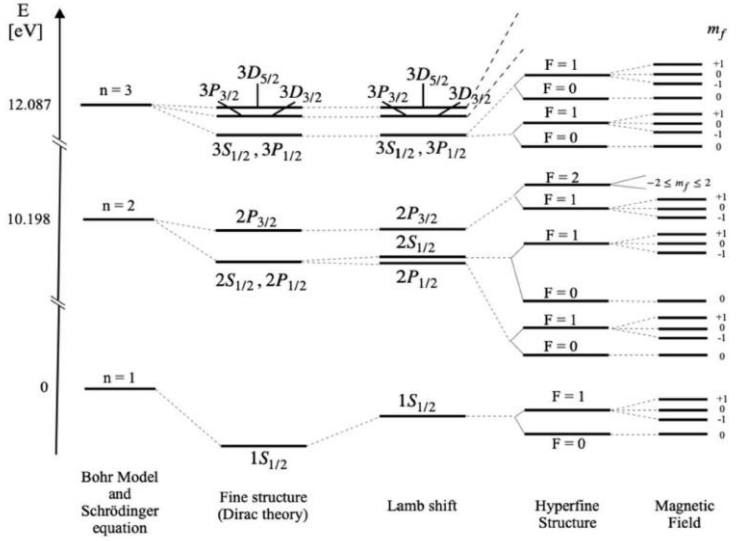
Charge conjugation (C), Parity : space reflection (P), and Time reversal (T)

CPT theorem presents CPT invariance (in Lorentz invariance, Locality, Unitarity)

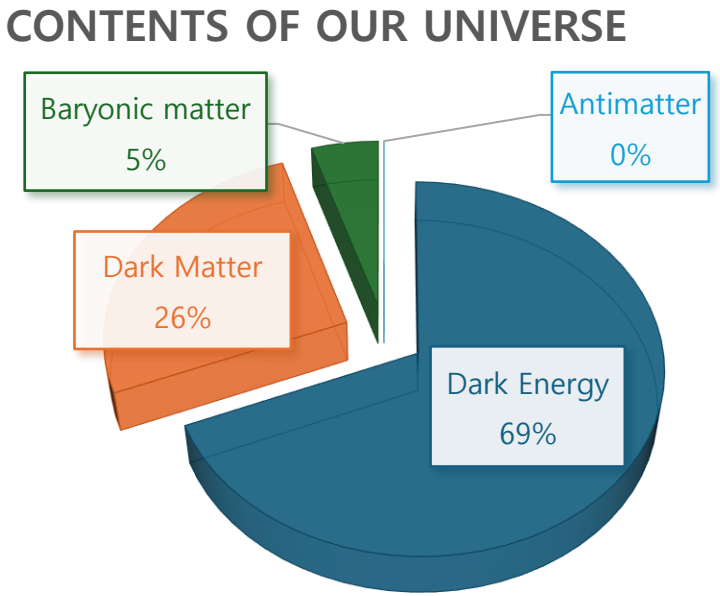
- mass, charge, lifetime and energy level have been compared
- Precise mass comparison by kaon $\Delta m < 4 \times 10^{-19}$ (pdg 2019)
- CPT test by μ^+ & μ^- magnetic moment
- neutrino oscillation, interaction..
- Many CPT test has been performed between matter and antimatter especially by p & $\bar{p}$ and H & $\overline{H}$
- Various parameters would be efficient to different effects

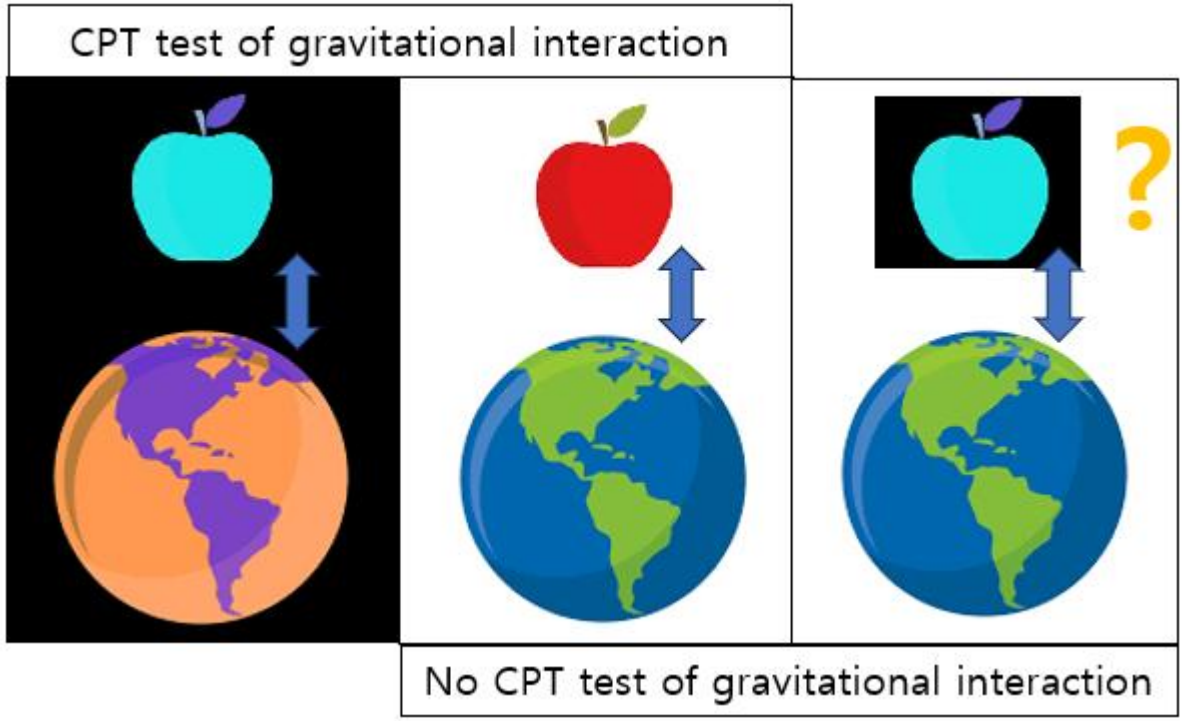


Hyperfine interaction (2019) 240:5



Antimatter : WEP





❖ Dark matter and Dark energy

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

❖ For known 6% contents which is mainly baryonic matters and radiation, we don't know why there's almost no antimatter

❖ Check fundamental interaction between matter & antimatter

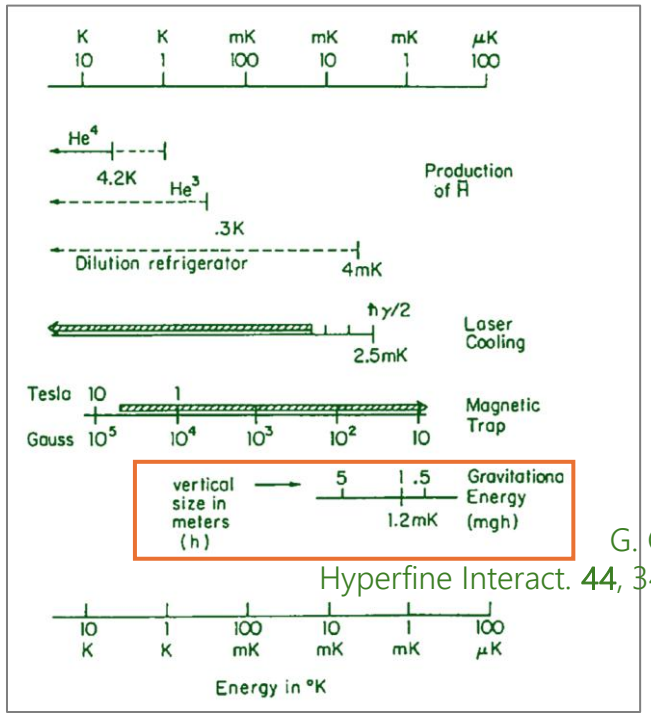
❖ Weak Equivalence Principle(WEP) : Universality of freefall

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

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

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

WEP test



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

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

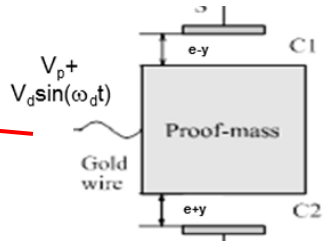
Eötvös ratio(for matter) $\eta(Ti;Pt) = \Delta(m_g/m_i)/(m_g/m_i)_{Be/Ti}$

$=-1.5\pm2.3(stat)\pm1.5(syst))\times10^{-15}$ (MICROSCOPE mission)

- Effect of different excited state is studied (*Nature Communications* **volume 8**, Article number: 15529 (2017))
- Quantum state of gravitational bounding using ultra-cold neutron has been studied (qBounce experiment)
- With absent of enough antimatter, cold temperature for single anti-matter is required to sense gravitational interaction with earth

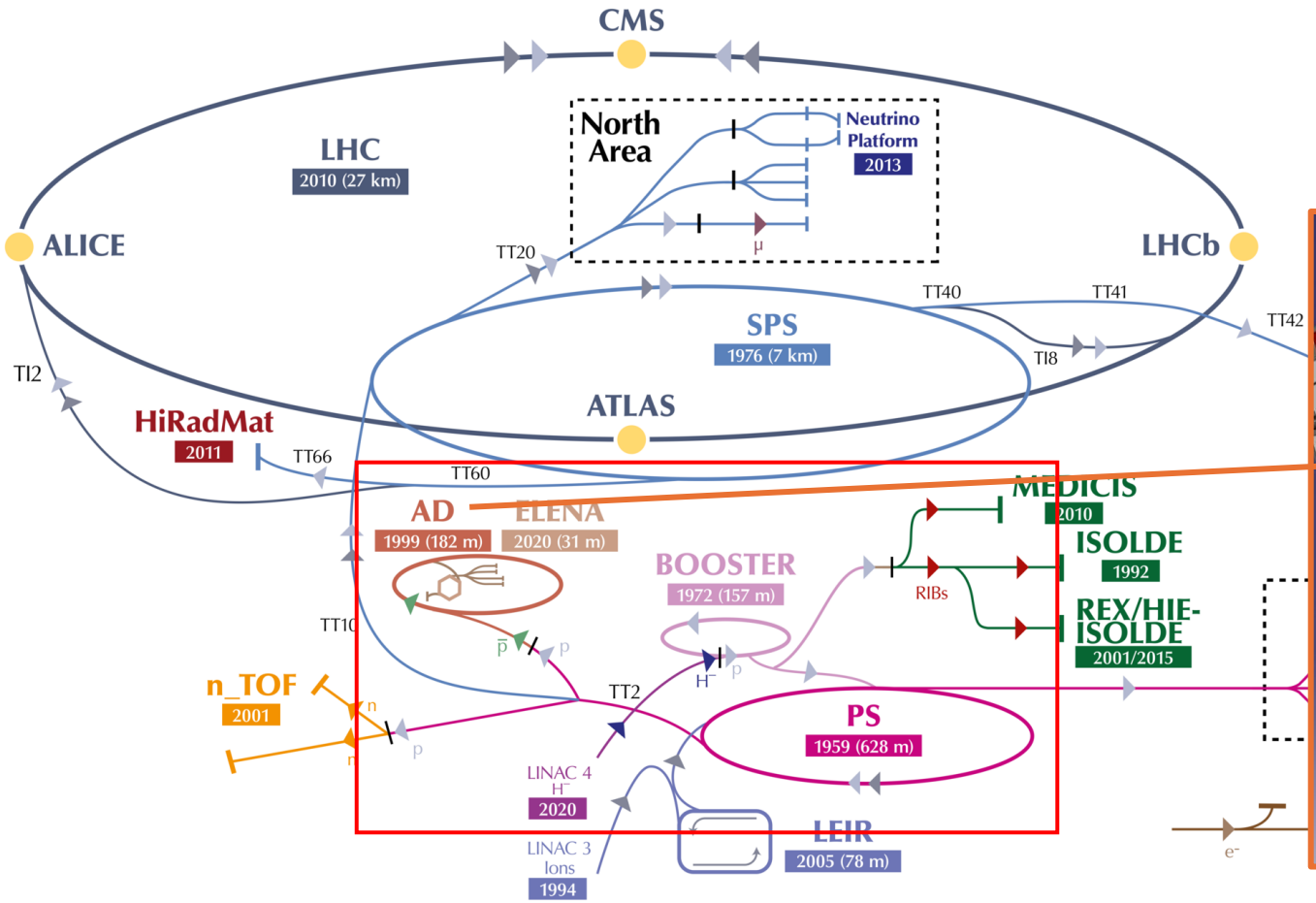
Relative strengths	Gravity	Weak (electroweak)	Electromag. (electroweak)	Strong (fundamental)	Strong (effective)
2 quarks *up* at 10^{-18} m	10^{-41}	0.8	1	25	—
2 quarks *up* at 3×10^{-17} m	10^{-41}	10^{-4}	1	60	—
2 protons in the nucleus	10^{-36}	10^{-7}	1	—	20

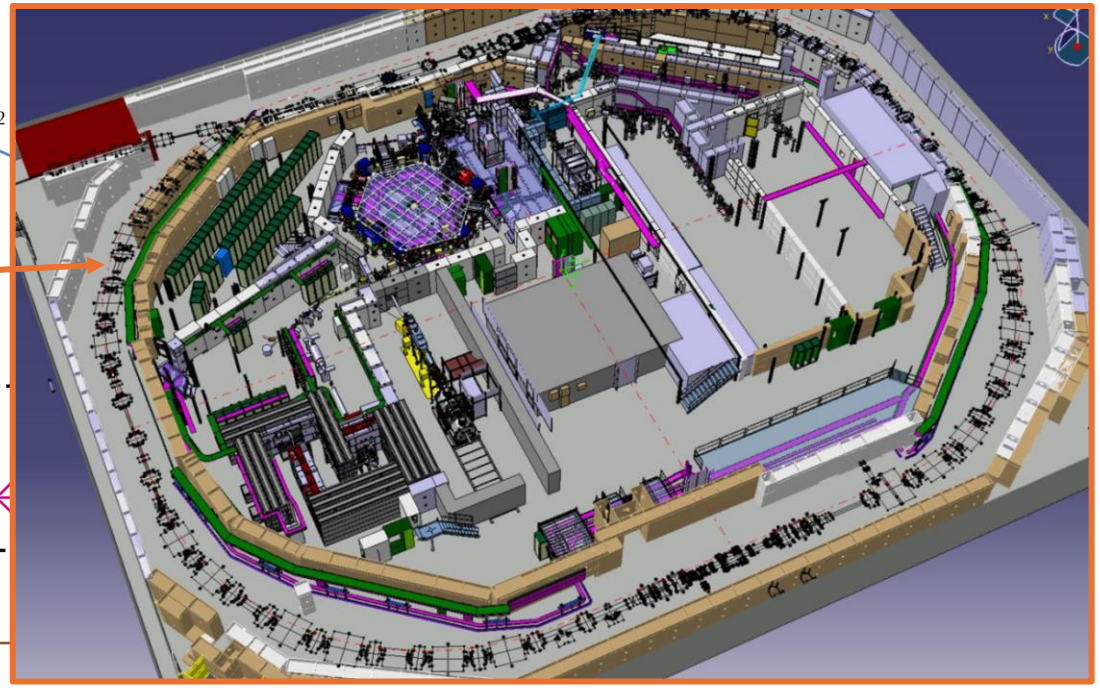
https://ftae.ugr.es/index.php/pages/particles



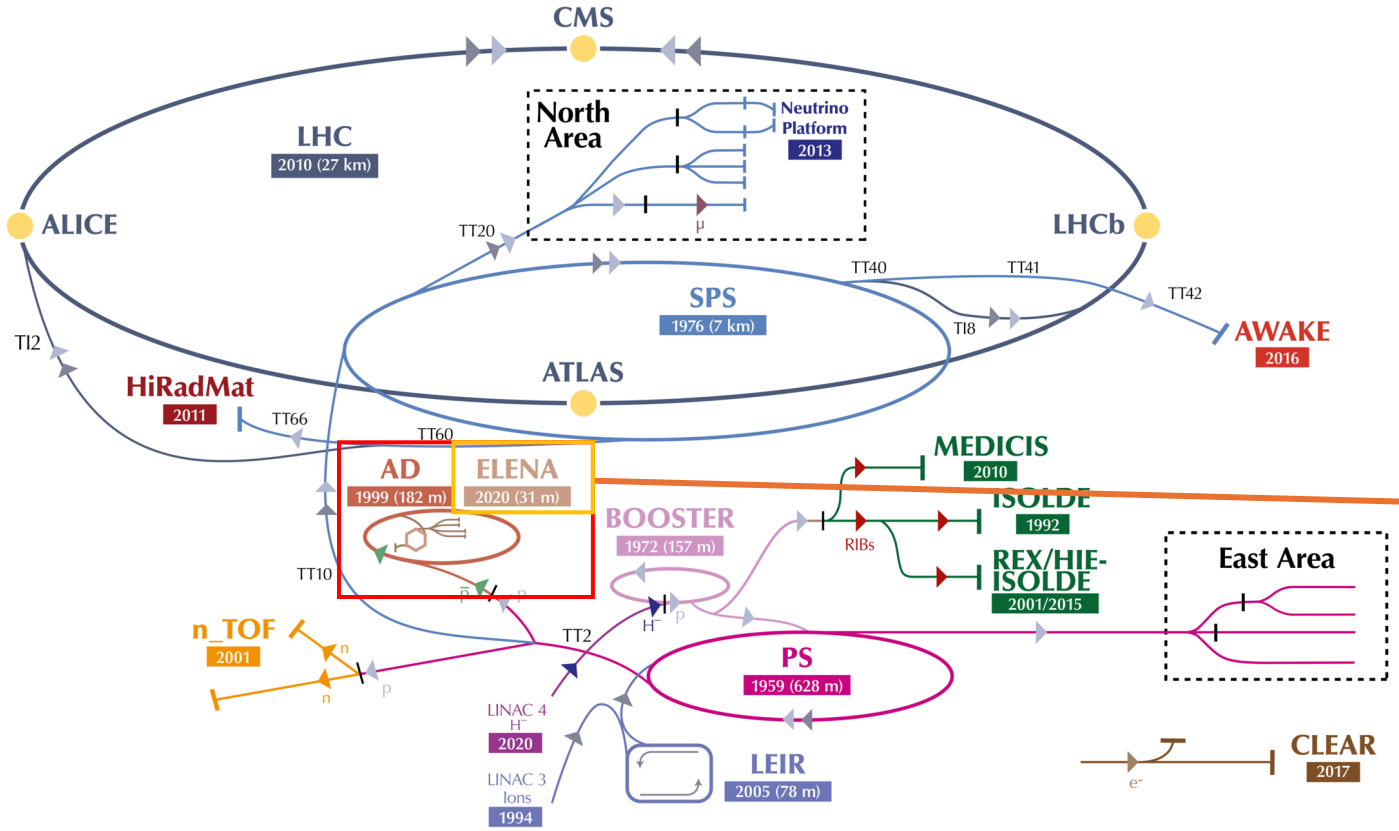
AD at CERN accelerator complex

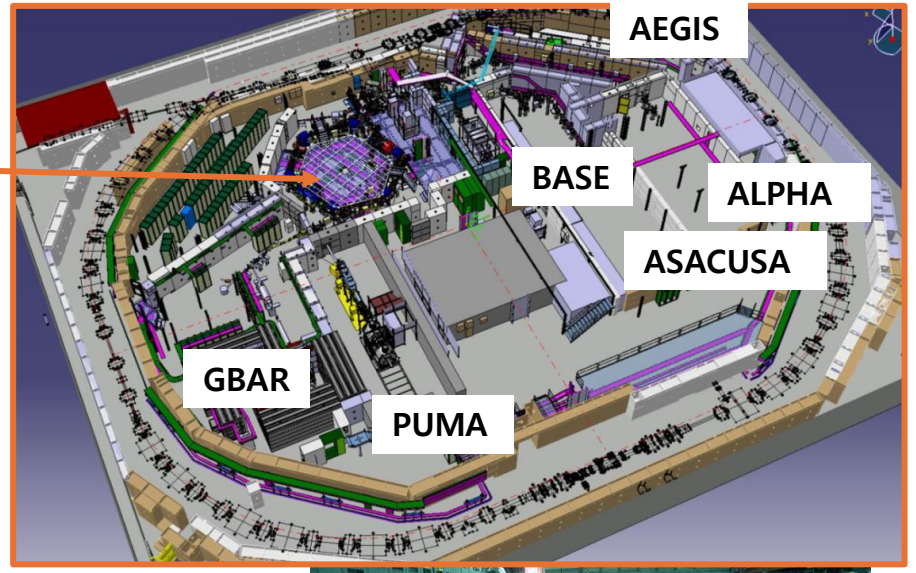
$p\ (26GeV/c) + N(iridium) \rightarrow \bar{p} + X\ldots$
Collecting $\bar{p}$ (p~3.5GeV/c)
Deceleration to 0.1GeV/c with cooling in Antiproton Decelerator (AD)
and providing low energy $\bar{p}$ beam ~ $4x10^7$ $\bar{p}$





Antimatter factory





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

- 1982 ~ 1996) LEAR (AA + AC)
- 2000 ~ now) Antimatter Factory (AD + ELENA : $\bar{p}$ with 100keV(KE))

: Stable intense low KE antiproton beam has been provided to 4 of

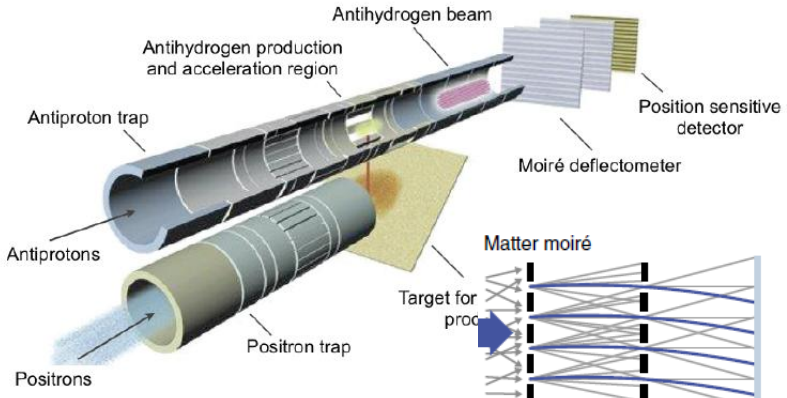
- 6 experiments (AEGIS, ALPHA, ASACUSA, BASE, GBAR, PUMA) with additional decelerations

WEP test at Antimatter factory

WEP test approaches

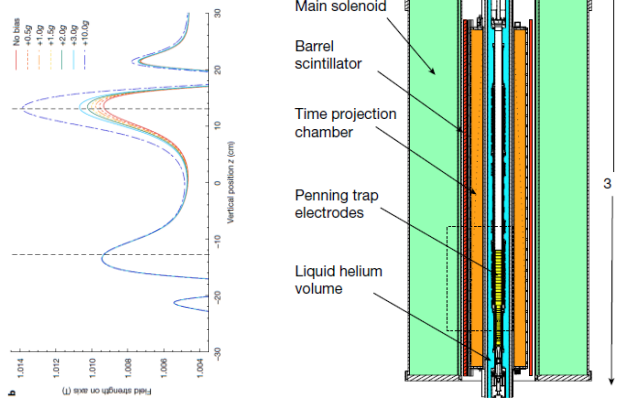
AEGIS

- $\bar{p} + Ps^*(Rydberg) \rightarrow \bar{H}^* + e^-$
- Pulsed Antihydrogen beam
- **Cold $\bar{H}$ beam** by cold antiproton E (100mK)
- Moire deflector(~interferometry).
- Aim : ~100mK (v~40m/s)



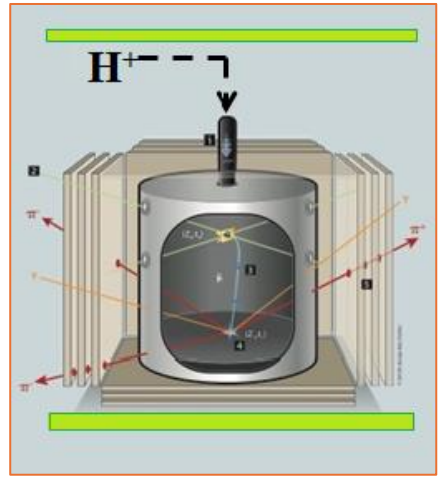
ALPHA-g

- $\bar{p} + e^+ + e^+ \rightarrow \bar{H} + e^+$
- Reaction in trap
- **Cold $\bar{H}$** trapping by penning-Ioffe trap (0.5K)
- Aim (1%) : sub-50mK (v~28m/s) temperature by laser cooling

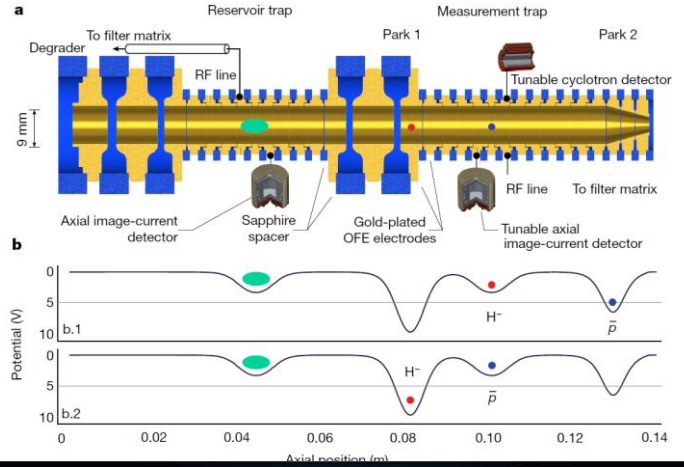


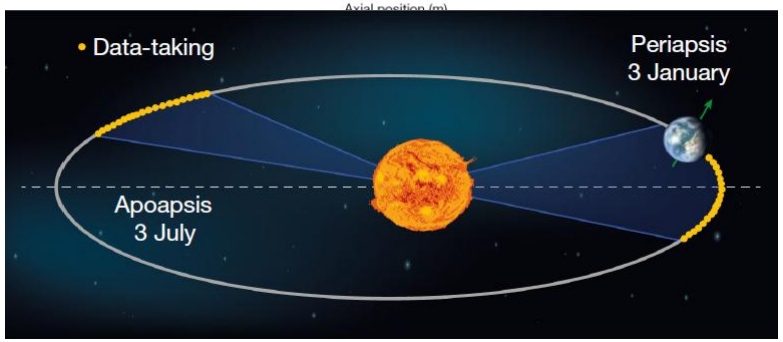
GBAR

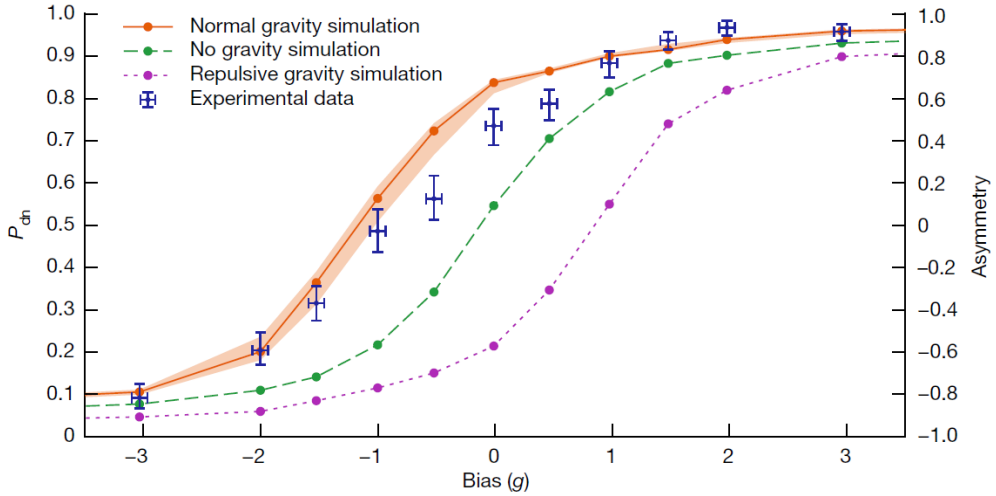
- $\bar{p} + Ps^{(*)} \rightarrow \bar{H} + e^-$
  $\bar{H} + Ps^{(*)} \rightarrow \bar{H}^+ + e^-$
- Trapping and cooling $\bar{H}^+$ at Paul trap.
- **Ultra-cold $\bar{H}^+$** by Sympathetic cooling by Be ion (10uK)
- Classical Freefall test (z=0.25m)
- Aim : 10uK (v~0.4m/s)

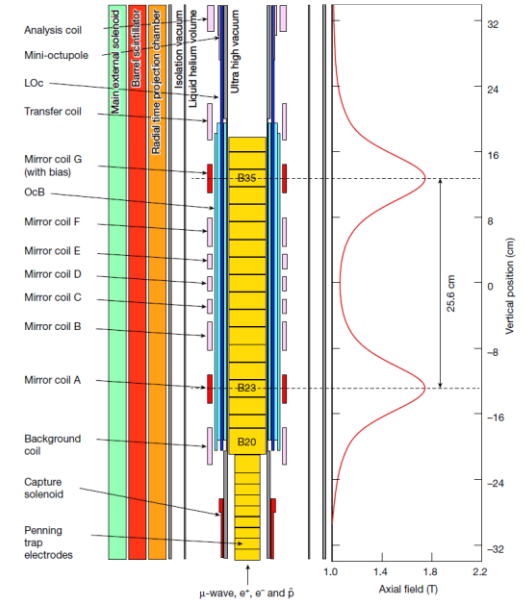


Anti-Hydrogen WEP test









- **Base experiment (penning trap 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

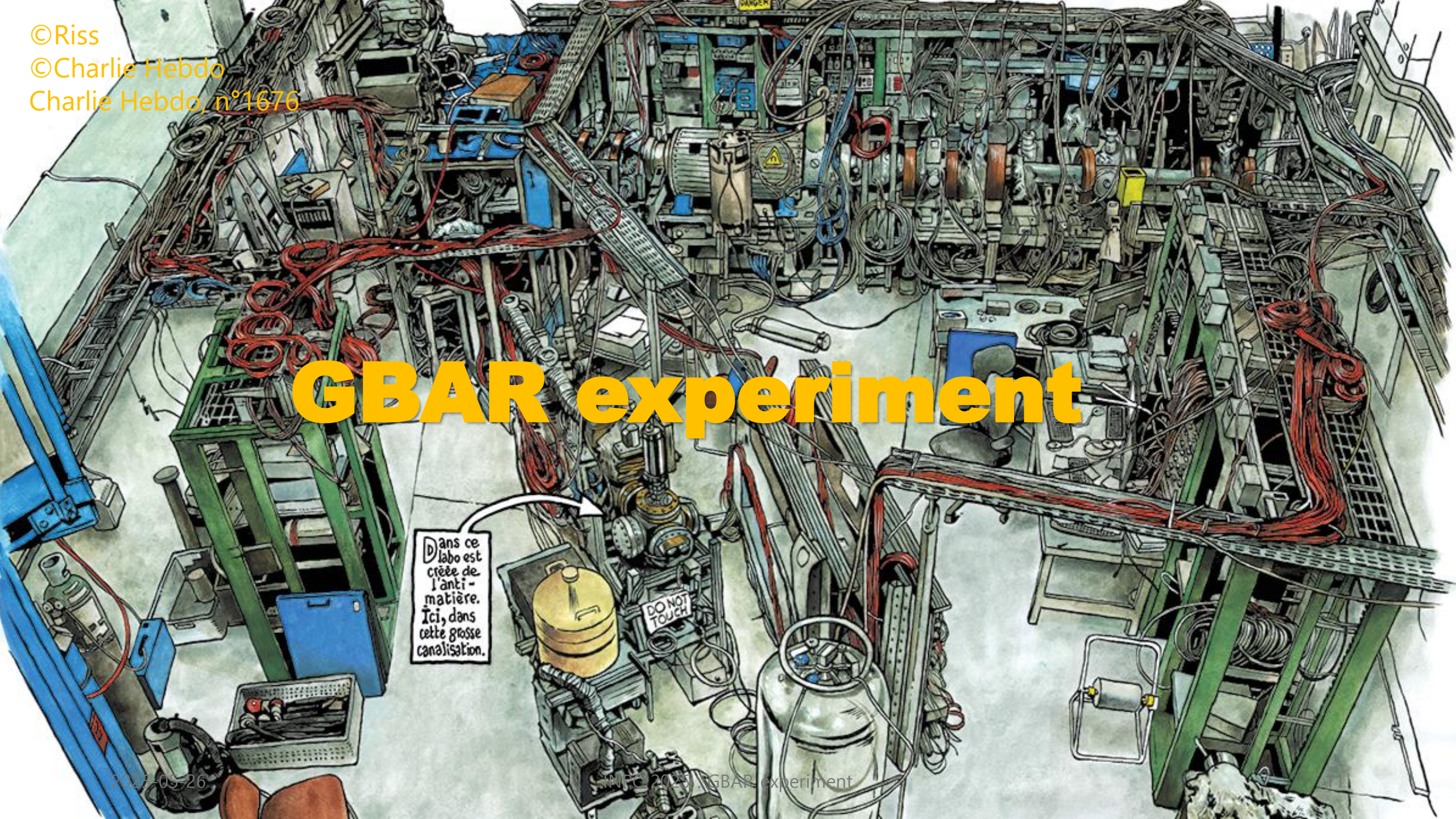
(Hughes R. J. & Holzscheiter M. H, PRL 66, 854 (1991))

- **ALPHA-g experiment**

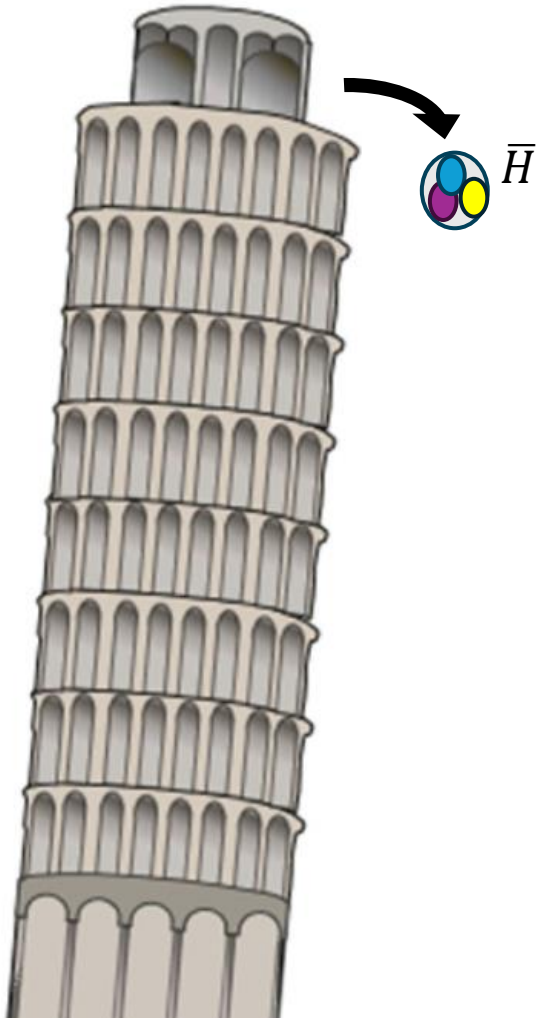
- Free-fall test in the magnet with changing magnetic potential

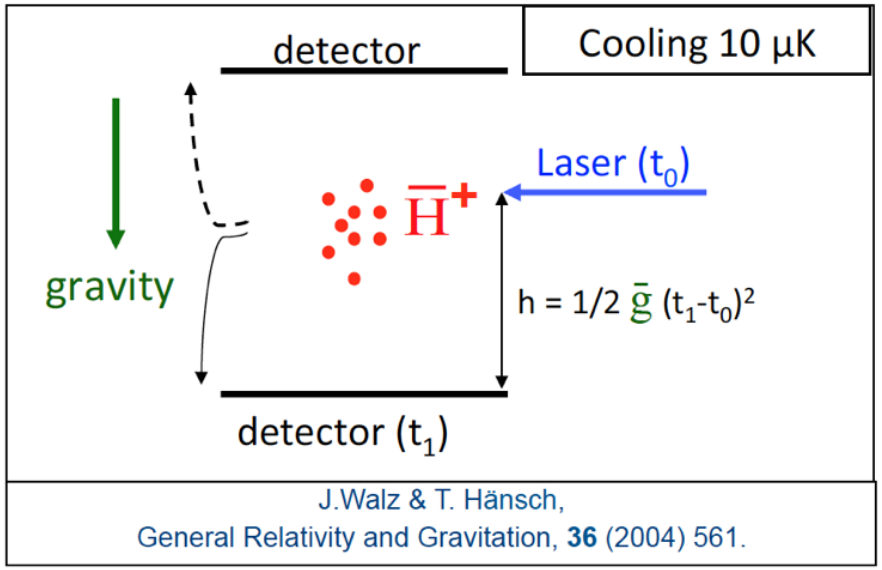
- 2023 : Rule out Repulsive antigravity by $\bar{H}$ with T <0.5K (**Nature 621, 716-722 (2023)**)

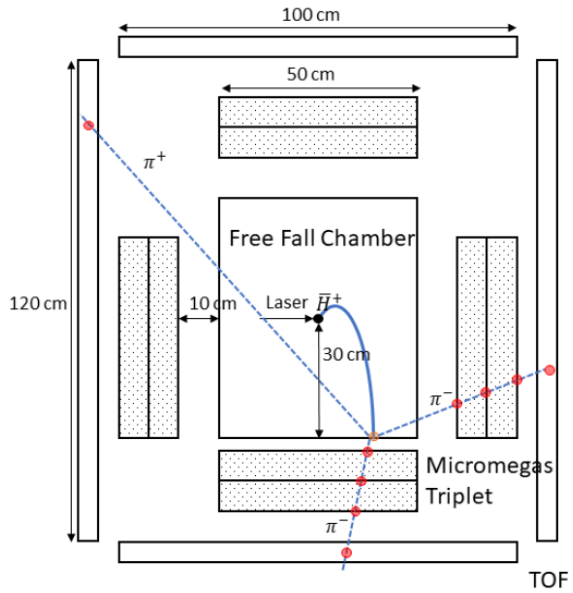
$$a_{\bar{g}} = (0.75 \pm 0.13 \pm 0.16) \times g$$


©Riss
©Charlie Hebdo
Charlie Hebdo, n°1676
GBAR experiment
Dans ce labo est créée de l'anti-matière. Ici, dans cette grosse canalisation.
DO NOT TOUCH

GBAR experiment







GBAR : Gravitational Behaviour of Antimatter at Rest

- Classical freefall test of antimatter using ultra-cold $\bar{H}$ (10uK)
- Time of flight (ΔT) measurement (Basic detection)

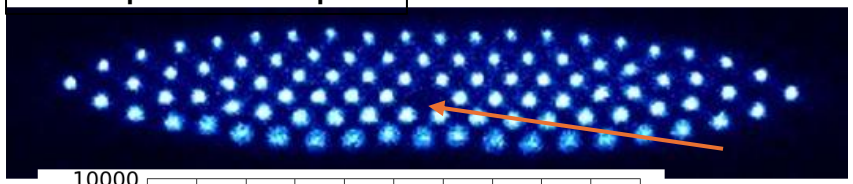
$$\bar{g} = \frac{2H}{\Delta T^2}$$

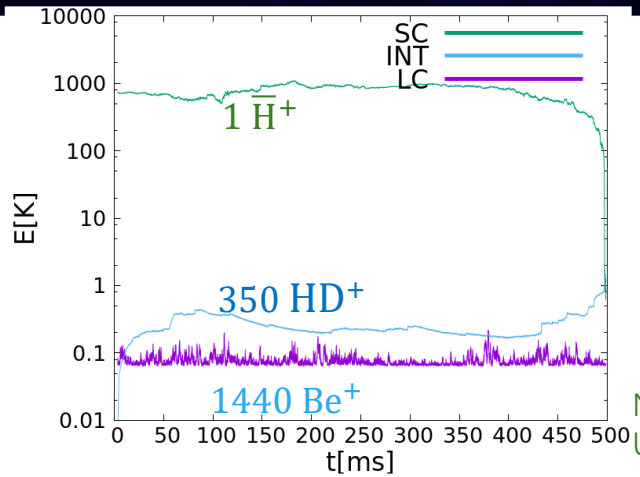
ex) H=10cm → ΔT = 143ms (for g)

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

GBAR : Ultra-cold anti-atom

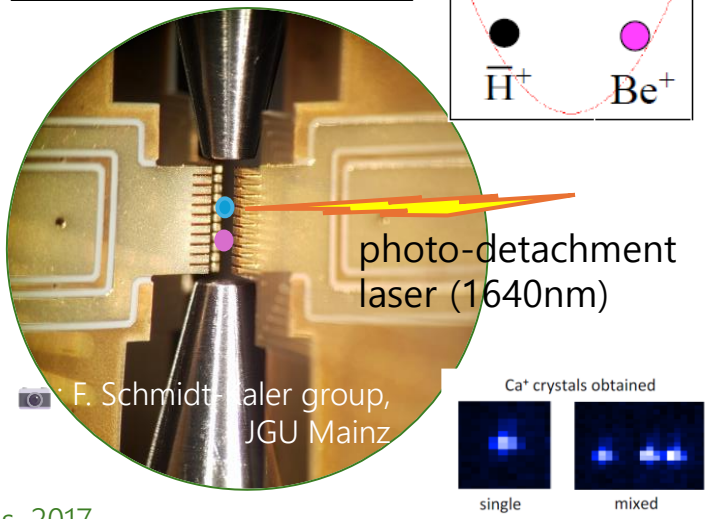
Capture trap

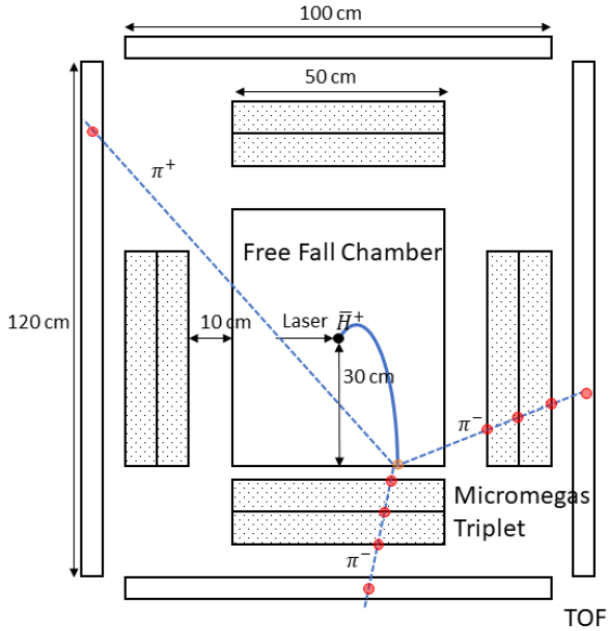




N. Sillitoe, PhD thesis, 2017
Uni. Pierre et Marie Curie - Paris VI

Precision trap





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

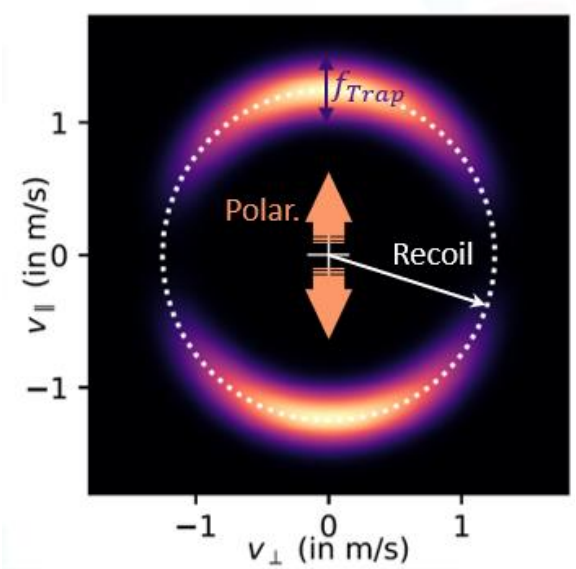
Sympathetic Doppler cooling by cooled Be^+/HD^+ ions (>1,000 laser(313nm), T~100mK limited by rf heating)

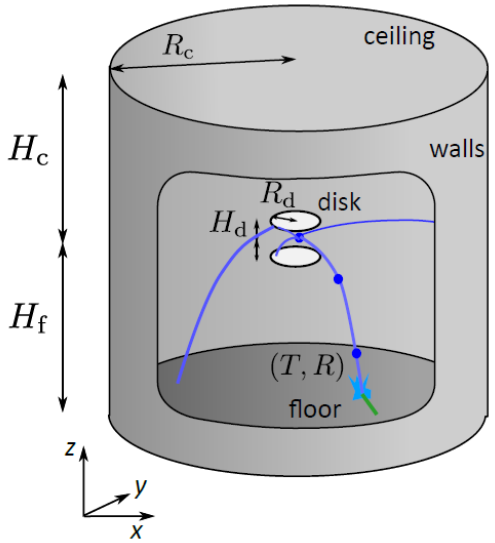
2. Precision trap : ion as a quantum harmonic oscillator, Raman sideband cooling for $Be^+/\bar{H}$ ion pair to T~10uK. (W. Schnitzler et. al, Physical Review Letters 102, 070501 (2009).)

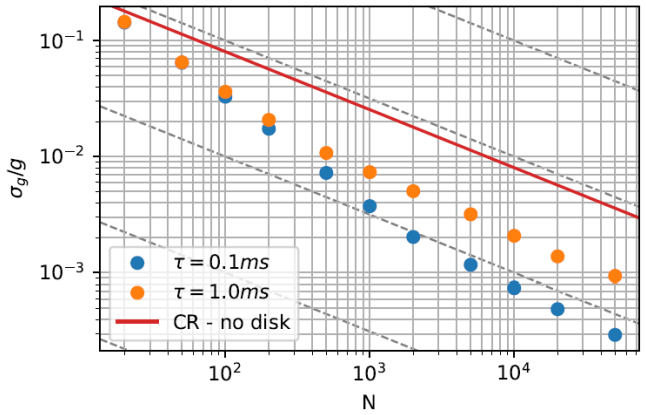
3. Photo detachment finally produces ultra-cold and-atom and then the atom free-falls

4. Secondary particle's trajectory (Micromegas) and timing (Scintillator) are measured for reconstruction.

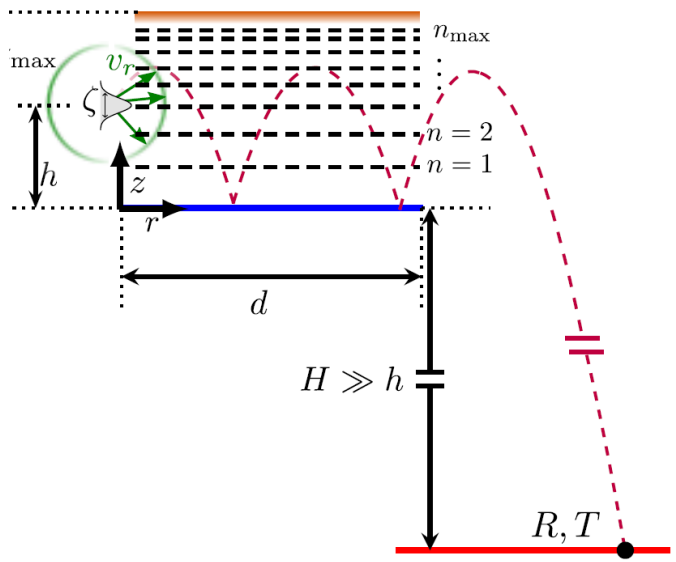
GBAR : Quantum reflection and levitation







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



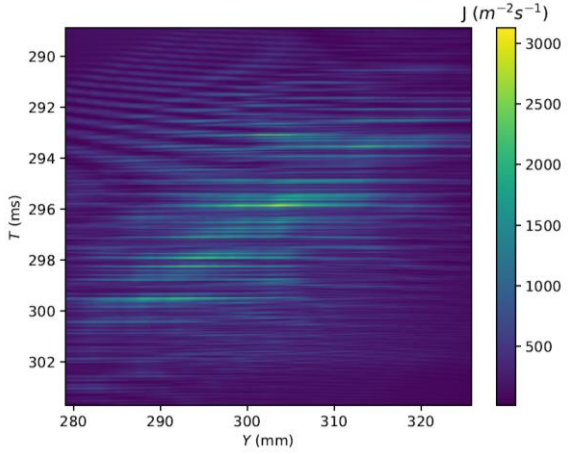
1. Polarization and Shaping with 0.1% uncertainty for 10,000 event (O.Rousselle et al, Eur. Phys. J. D **76**, 209 (2022))

- 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

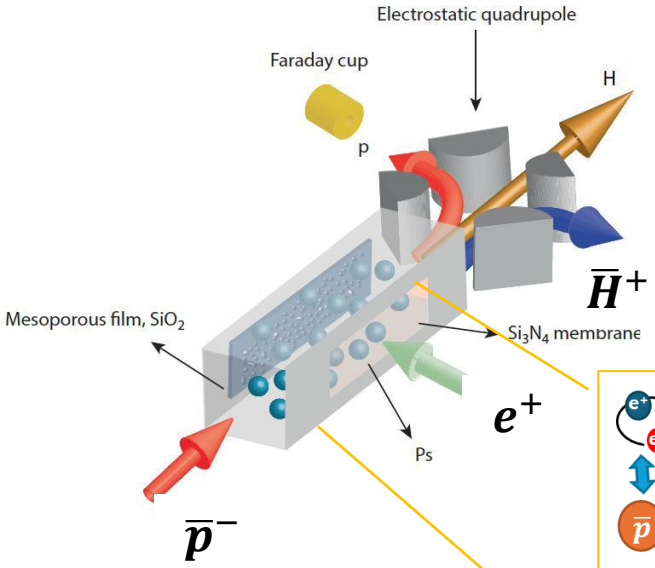
(G. Dufour et al., Eur. Phys. J. C (2014) 74: 2731)

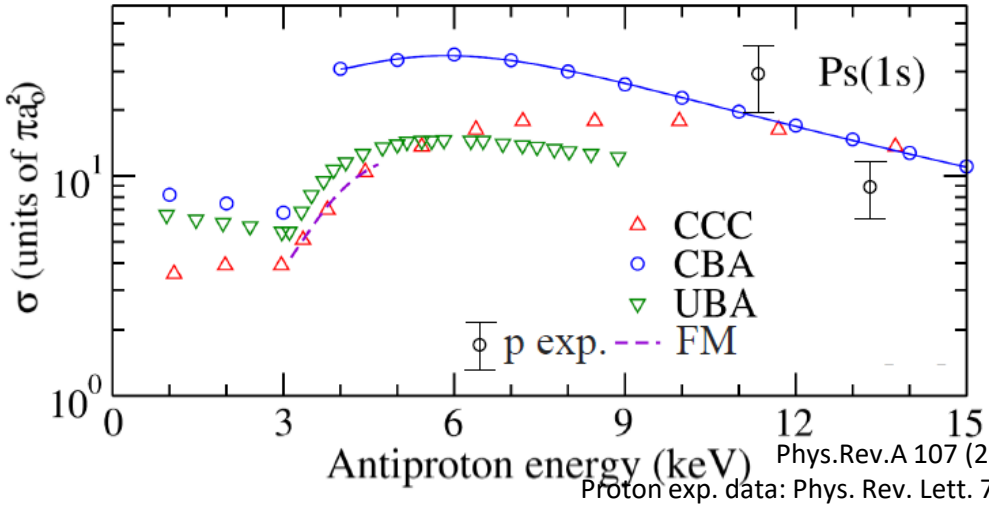
- Momentum selection reduces systematic uncertainty
- Gravitational Quantum states with pattern measurement makes possible to reach higher precision



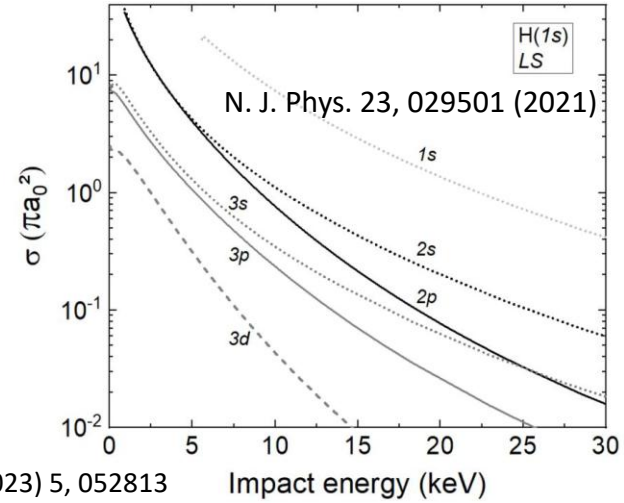
O. Rousselle *et al.*, Eur. Phys. J. D **76**, 209 (2022)

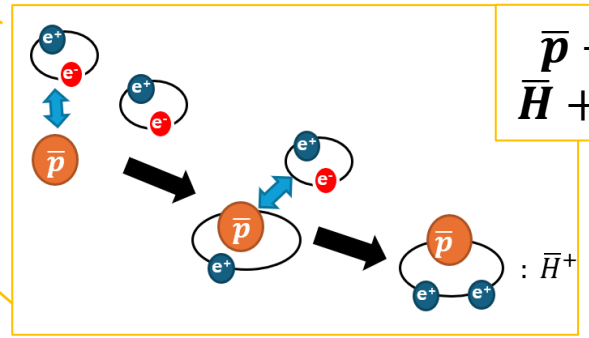
GBAR : Anti-anion generation





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



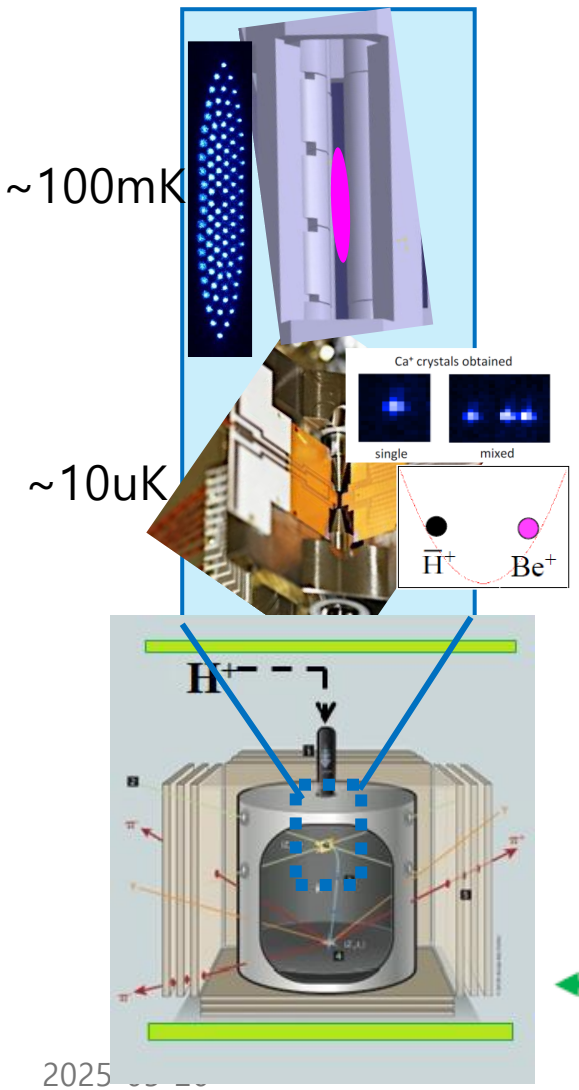


$\bar{p} + Ps \rightarrow \bar{H} + e^-$: 1st milestone

$\bar{H} + Ps \rightarrow \bar{H}^+ + e^-$: 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.

Experiment Scheme



3.5→0.1GeV/c

AD

5.3MeV

ELENA

now 1x10⁷

100keV (0.5x10⁷ $\bar{p}$ /110s)

decelerator

Anti-proton beam line

$\overline{P}$ trap

10eV~10keV

Laser Ps*

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

4kV

$\overline{H}$

$\overline{p}$

$\overline{H}^+$ ion

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

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

Antiproton beam line
- High efficiency
- Good phase-space
- Possible accumulation

Positron beam line
- High intensity
- High accumulation rate
- Narrow spot at target

High field trap

Ne remoderator

buncher

BG trap

e^+ target

Linac

Positron beam line

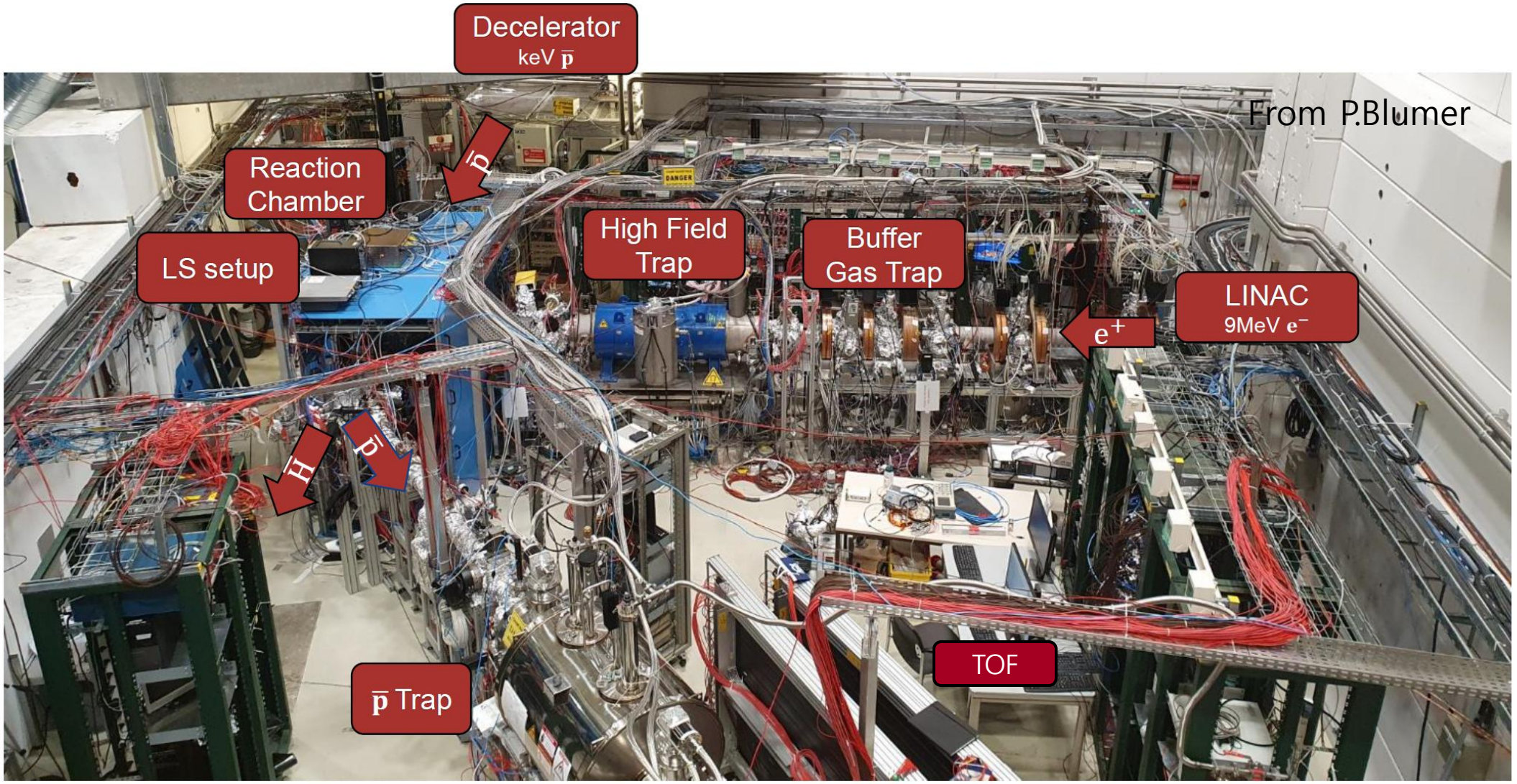
10^{10} e^+/bunch

1MeV→3eV → 50eV

$3x10^8 e^+/s$

e^- 10MeV

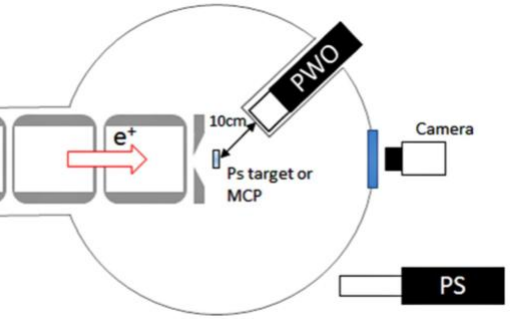
Experiment setup (2022)

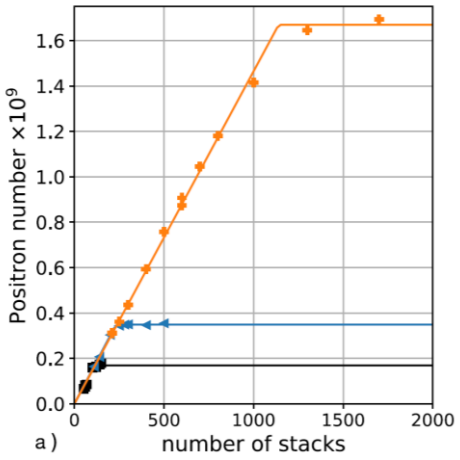


Positron beam line

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





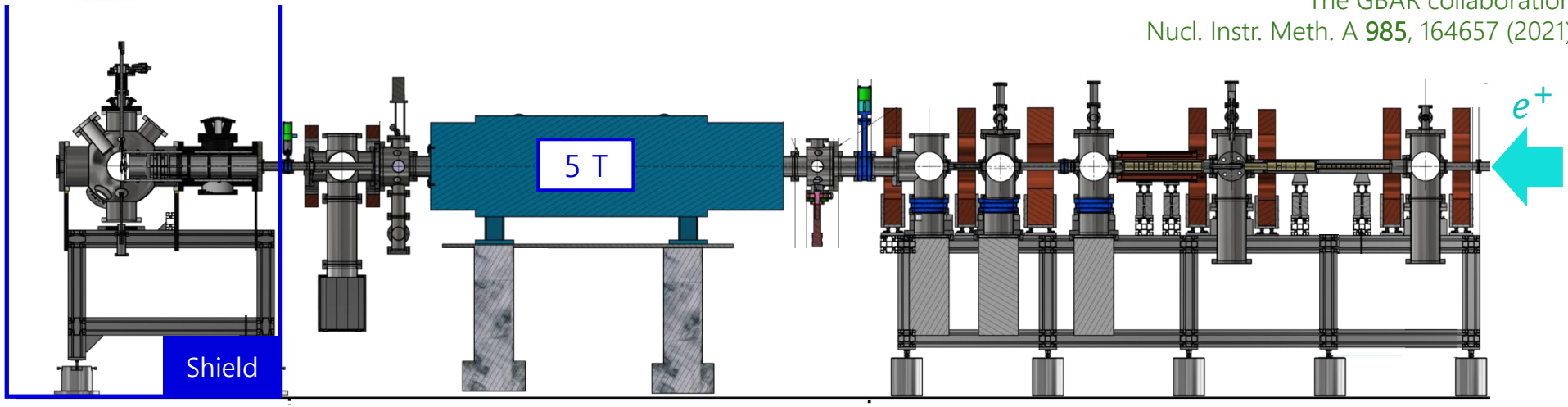
The GBAR collaboration,
Nucl. Instr. Meth. A **1040**, 167263 (2022)

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)

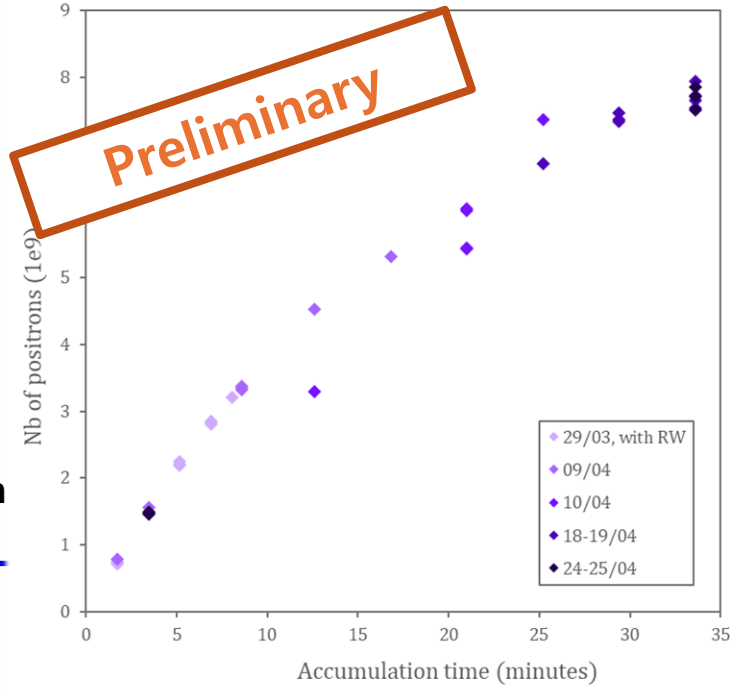
RC

HFT

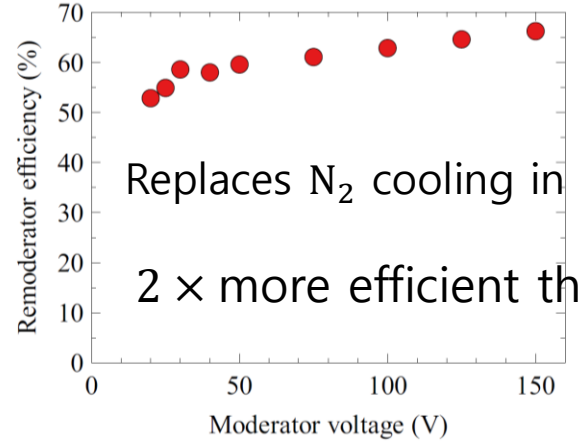
BGT

LINAC

Positron beam line

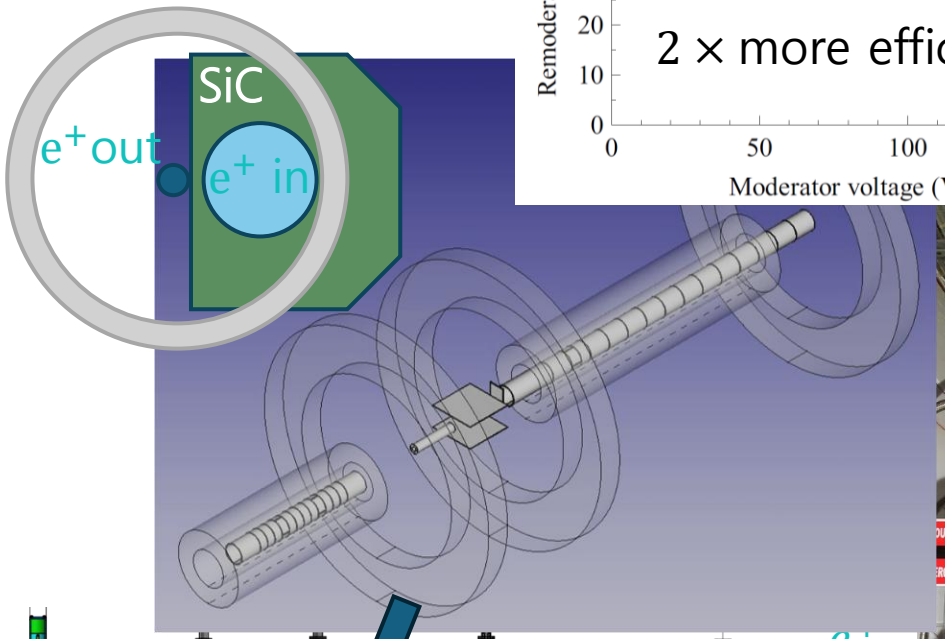


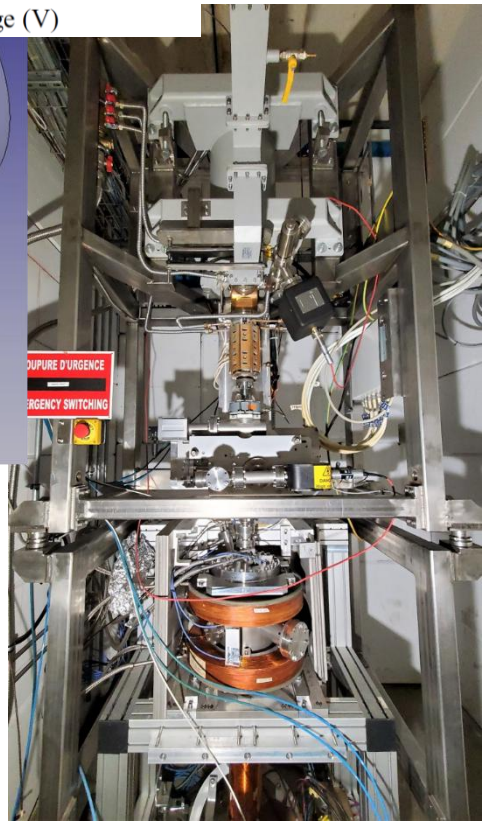
6x10⁸ e⁺/2min

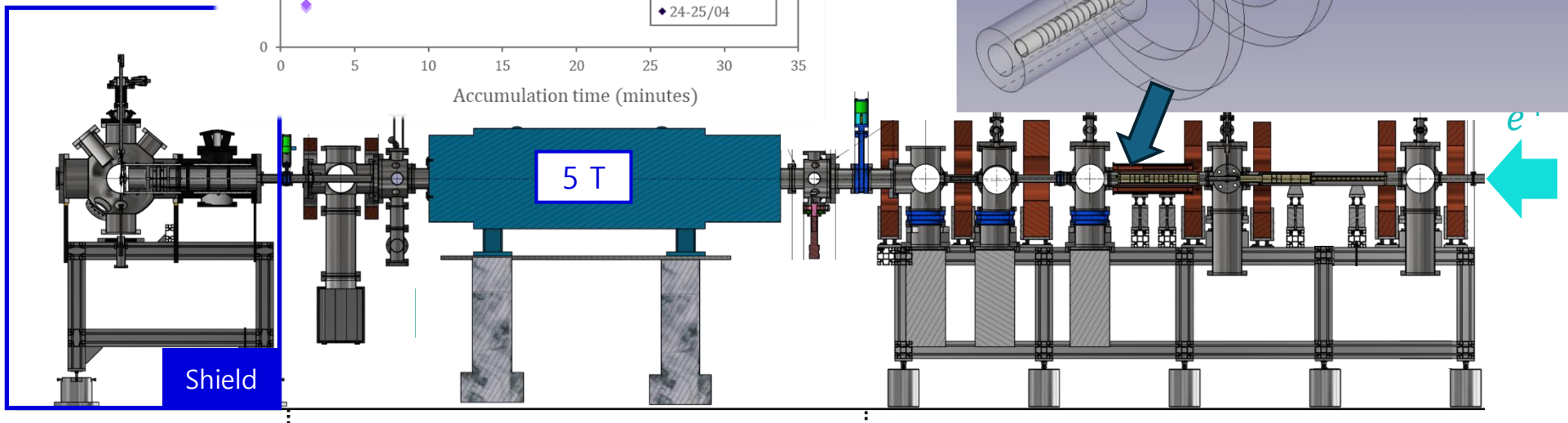


Replaces N_2 cooling in BGT. CO_2 kept.

2 × more efficient than former BGT

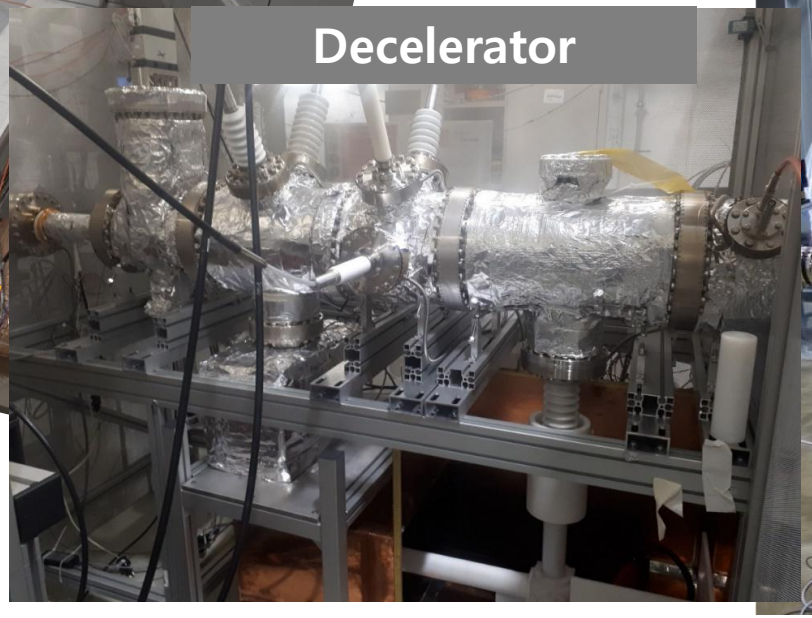


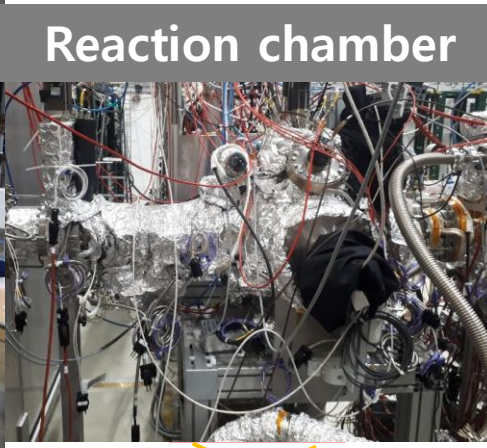


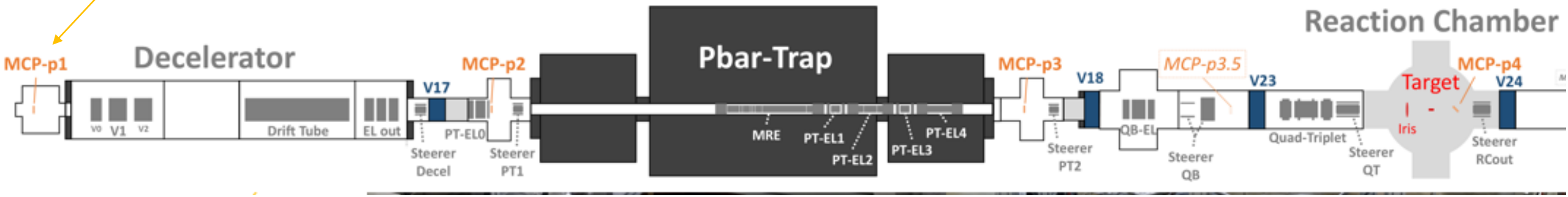


RC HFT BGT LINAC

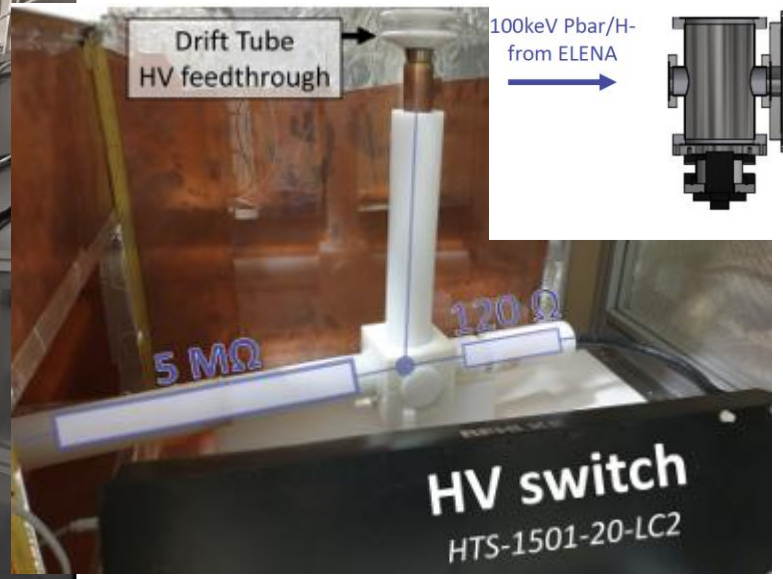
Antiproton beam line

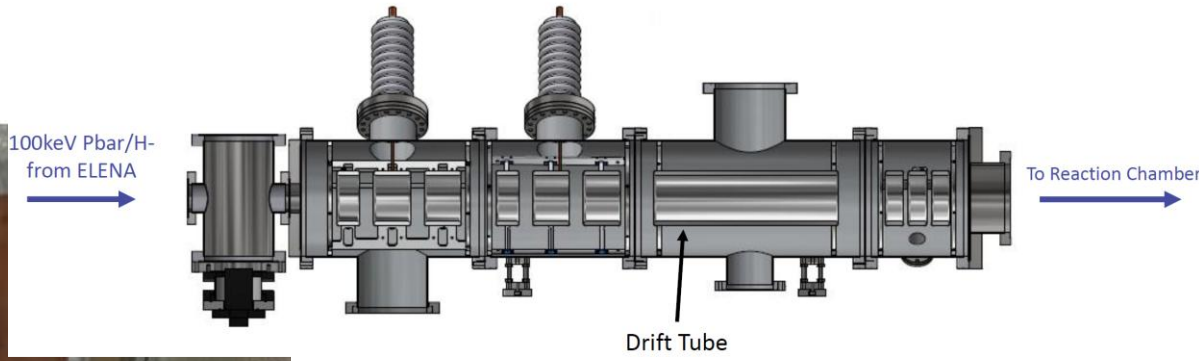


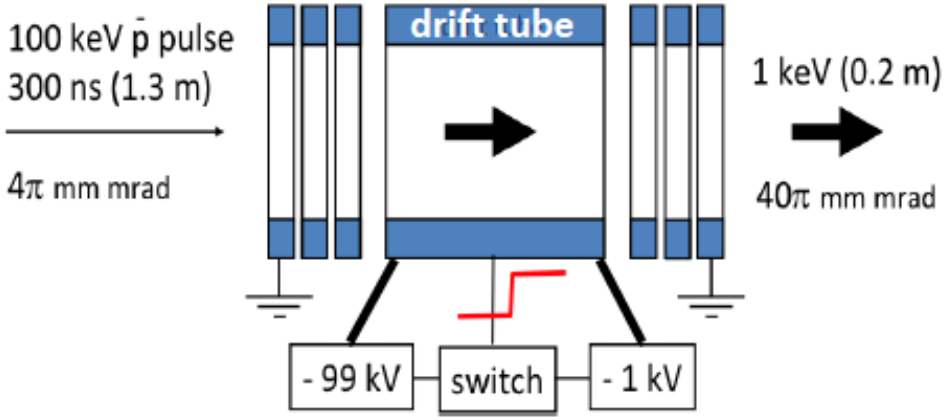




GBAR Decelerator

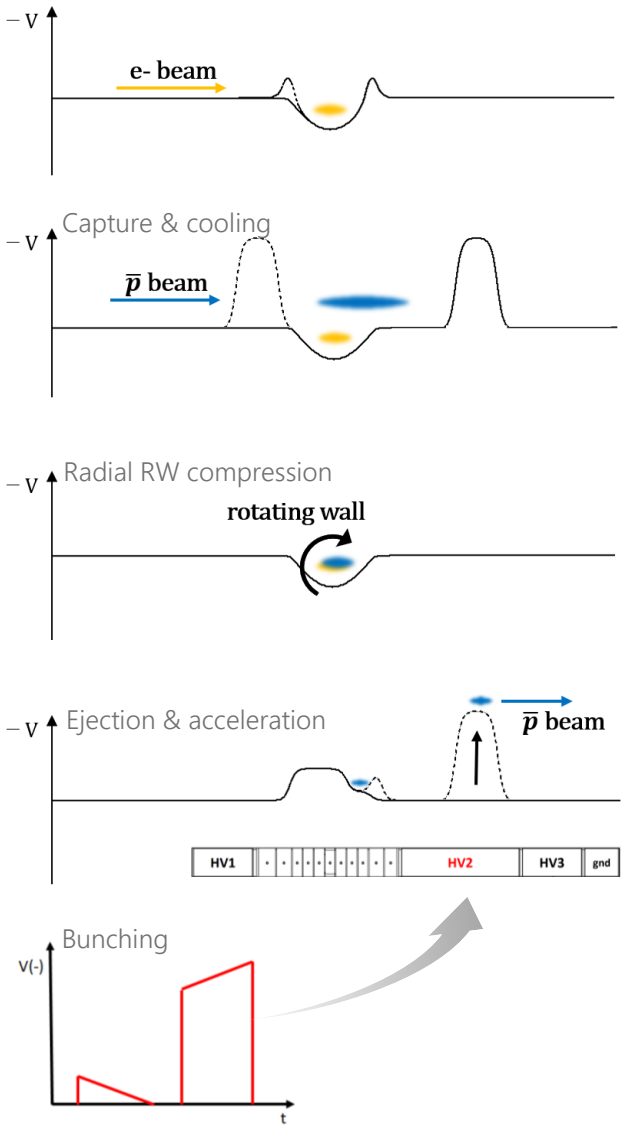


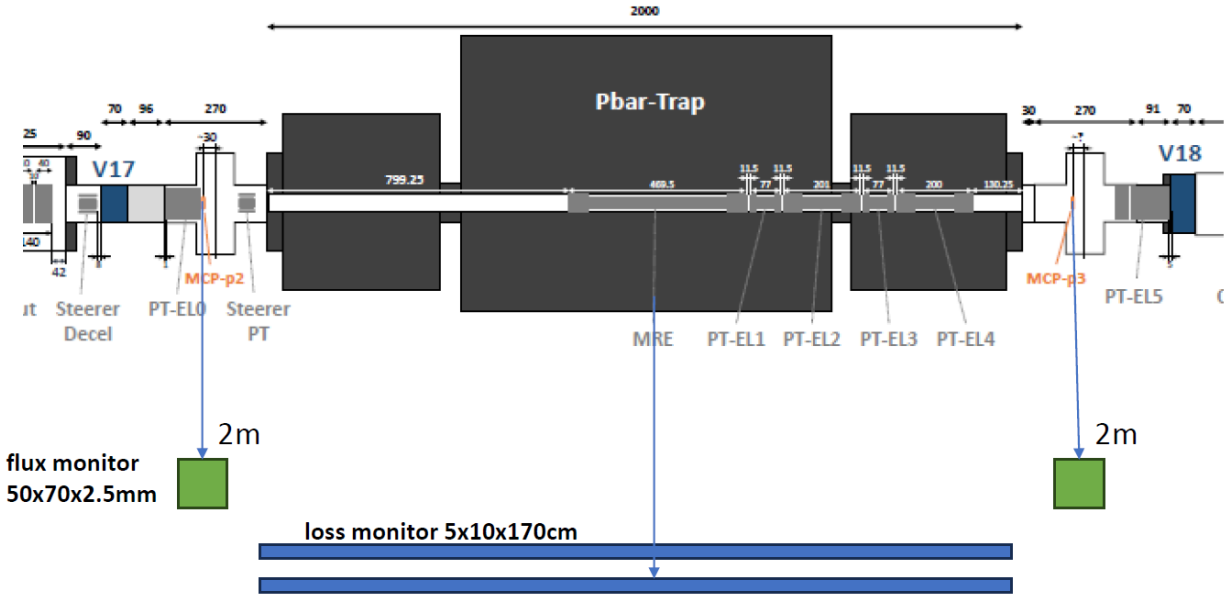




- GBAR decelerator
- Drift tube with –HV with fast-switching when pbar beam is in the tube
- Higher efficiency and mono-energy expected compared with Degrading foil
- With 100keV→1keV deceleration, emittance is increased about 10 times

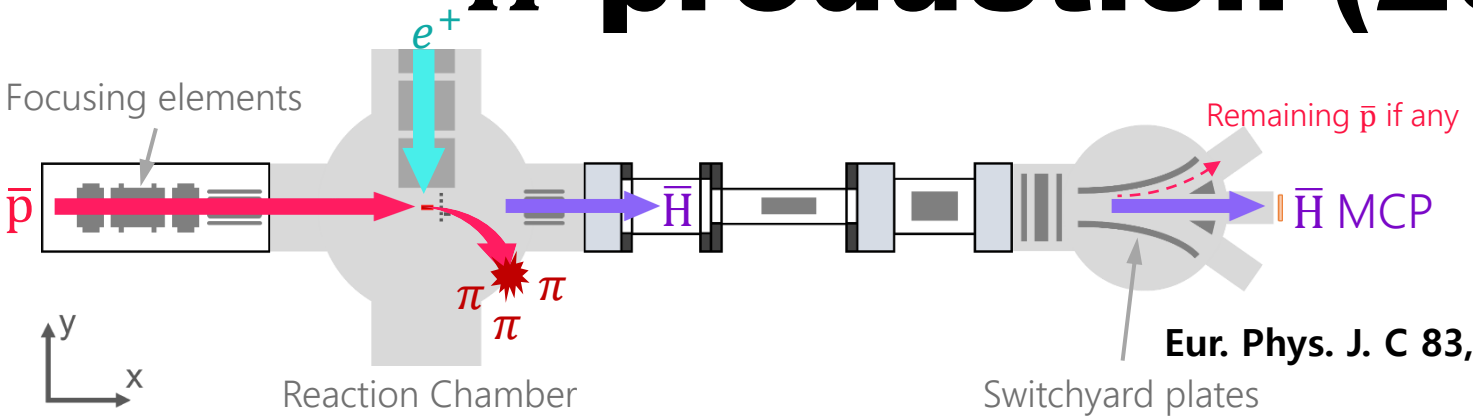
Antiproton trap

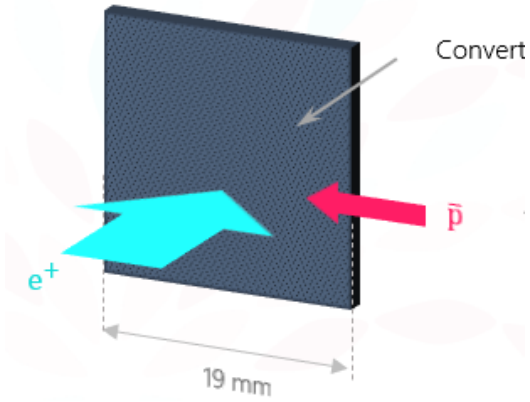




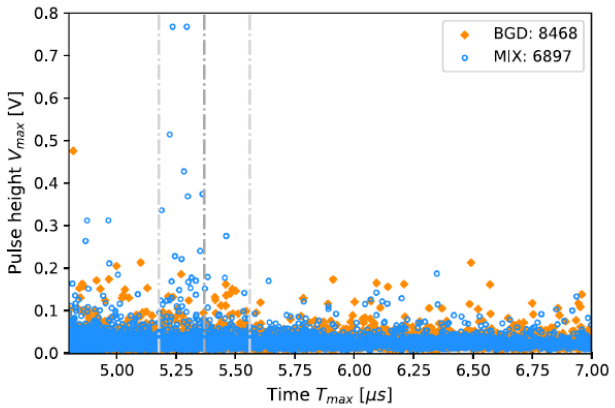
- Penning-Malmberg trap (5T; 7T max) for antiproton beam reprocessing
- Function : Trapping, cooling, compression, acceleration, bunching and accumulation
- Goal : Producing antiproton beam with good beam parameters (higher intensity with accumulation, good phase-space & time spread for double charge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

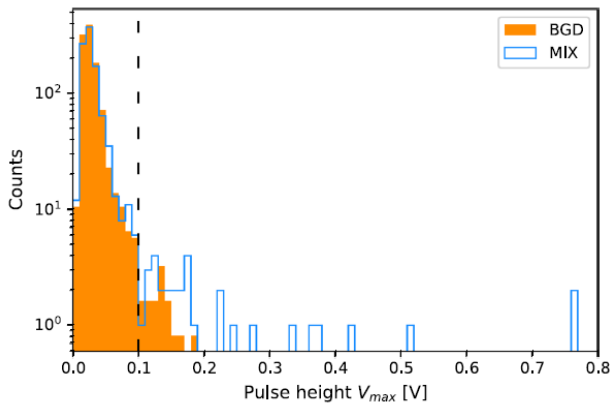
$\bar{H}$ production (2022)

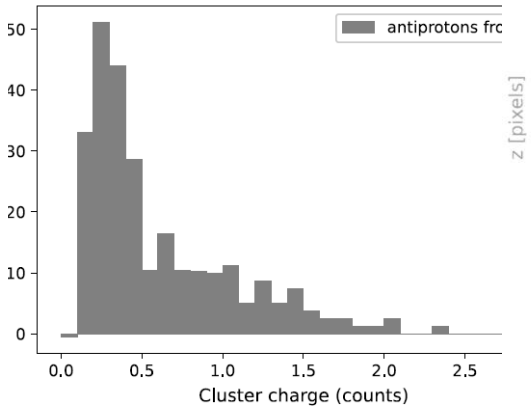


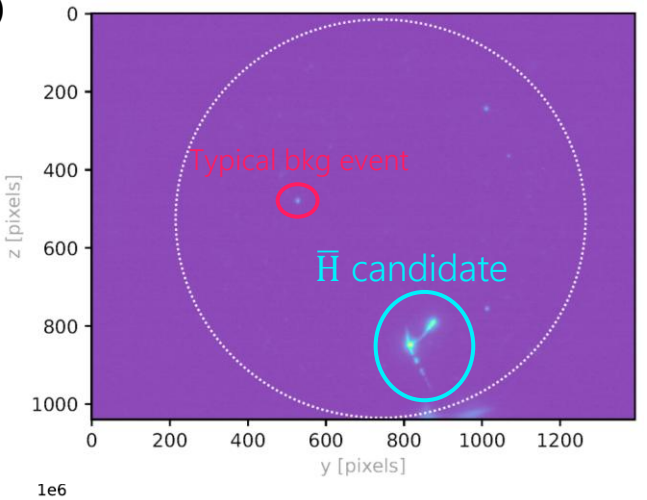


Eur. Phys. J. C 83, 10004 (2023)



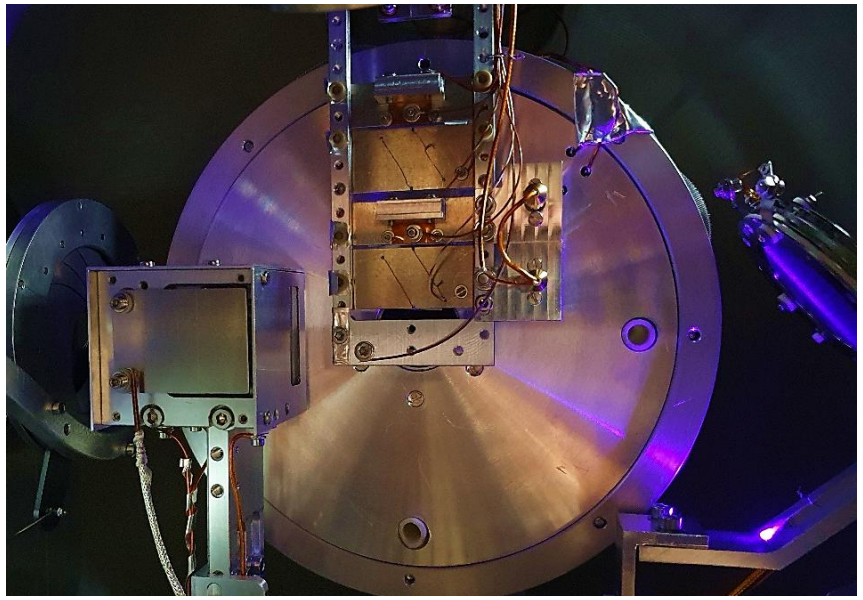


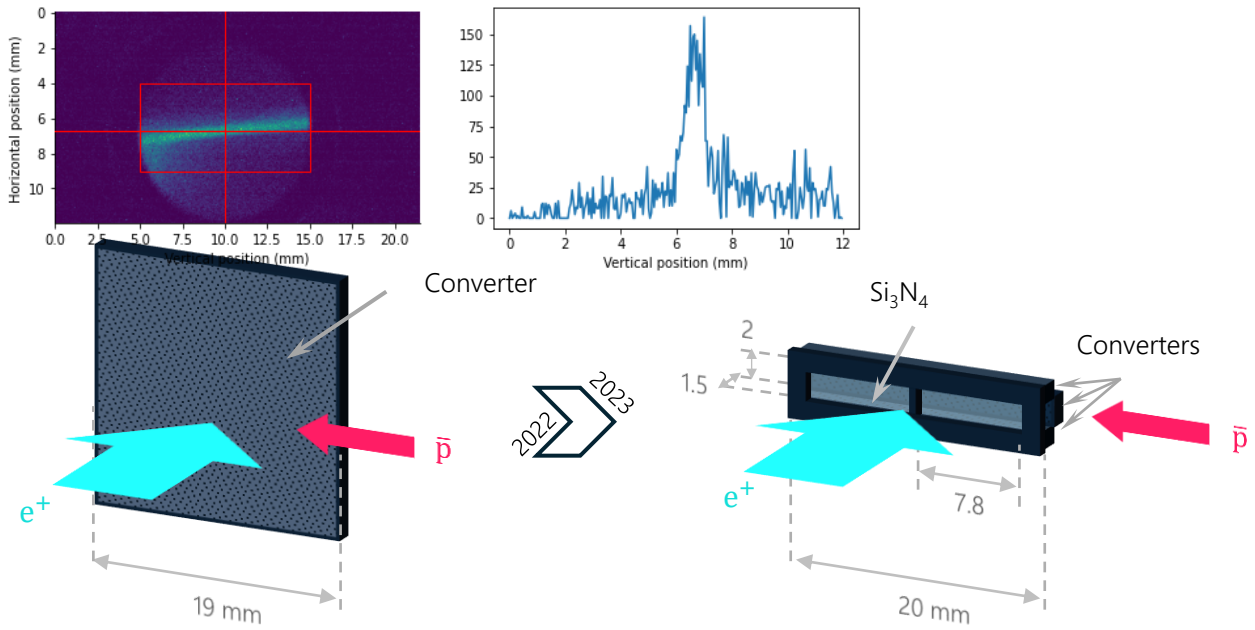




- Produced antihydrogen is detected above 3σ (which is **1st milestone**)
- About 6.8x10^6 o-Ps (5x10^7 e$^+$) and 3x10^6 $\bar{p}$
- (First) production of $\bar{H}$ by charge exchange between o-Ps and antiproton **beam**
- higher intensity with **better emittance** by pbar trap required $\bar{H}^+$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

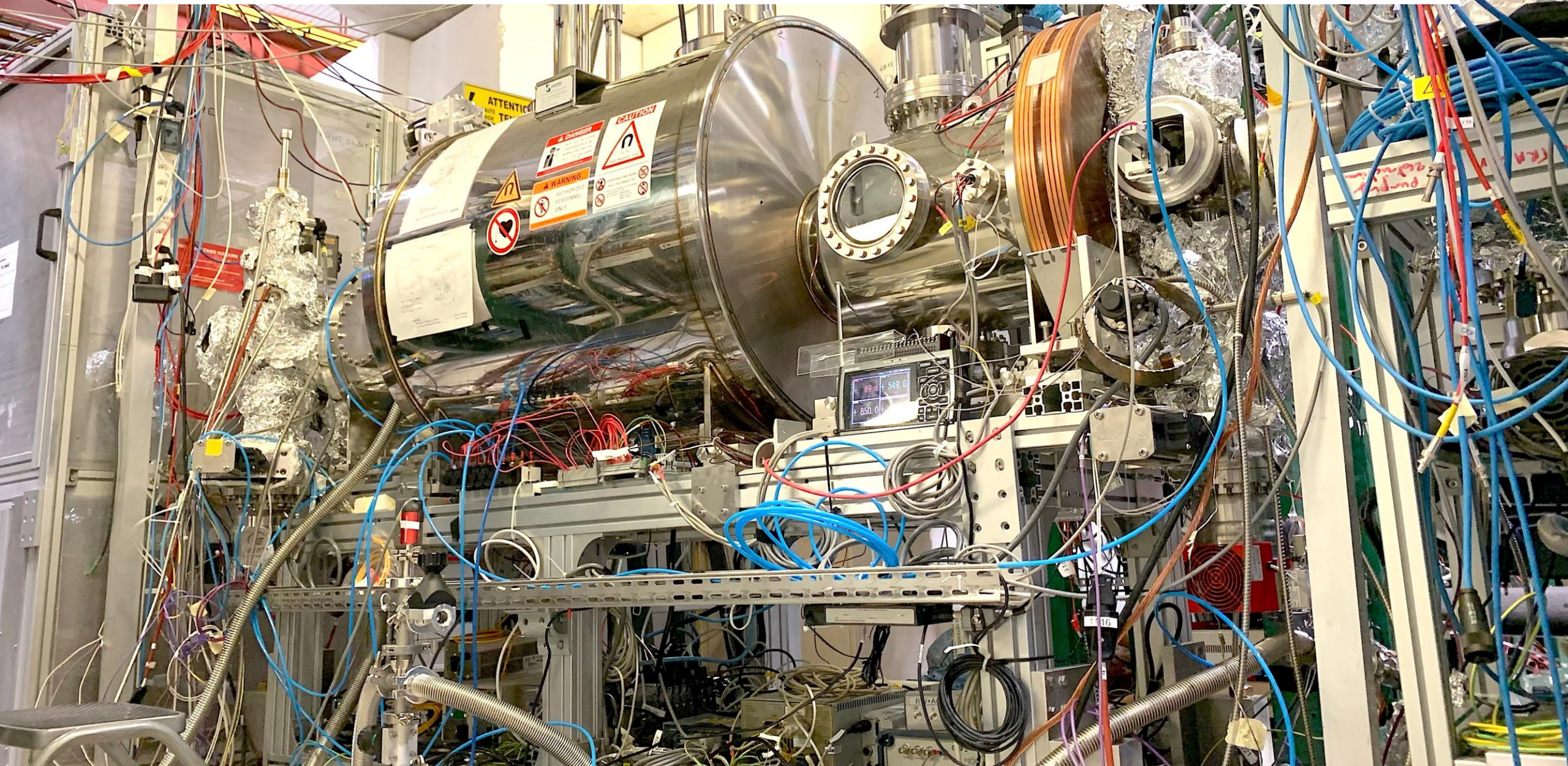
$\bar{H}$ production





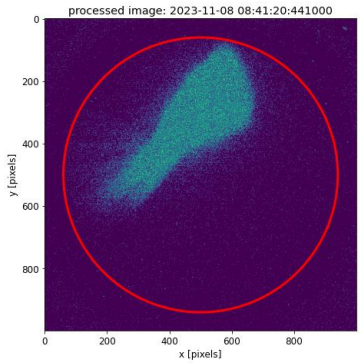
- For the proper next step, the target changed to cavity to foreseen double charge reaction
- The positron beam optics and guiding is adequate for proper squeezed beam

Antiproton trap installation (2023)



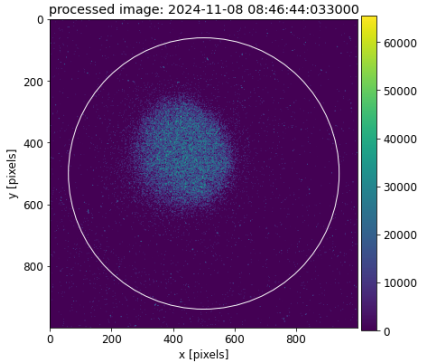
Antiproton beam line performance

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

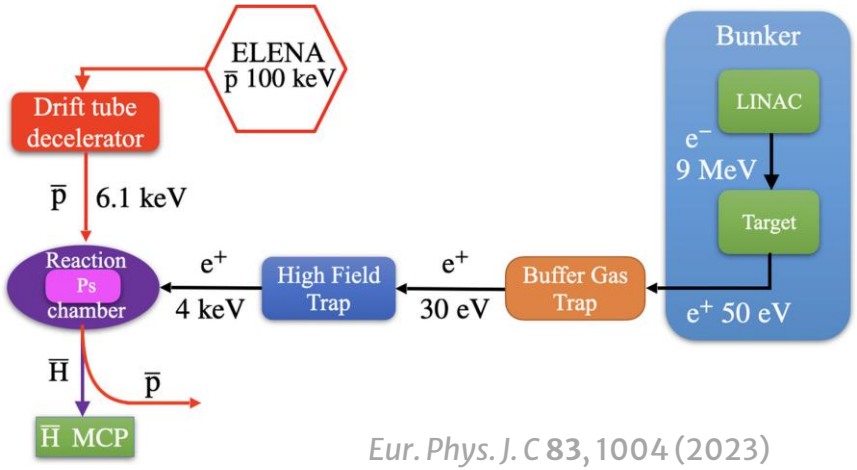


2024 comissioning

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

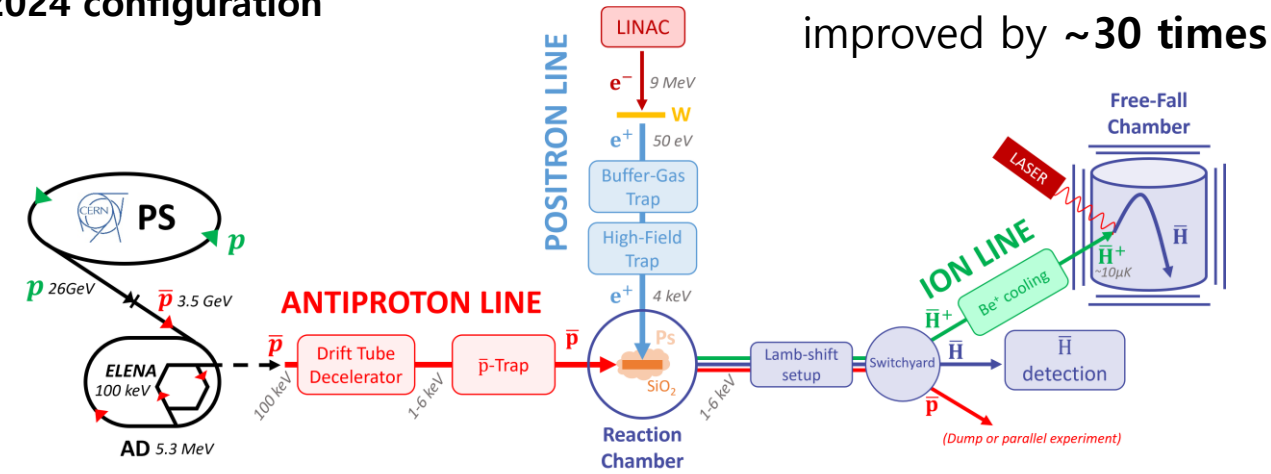
Antihydrogen ($\bar{H}$) production rate

2022 configuration



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

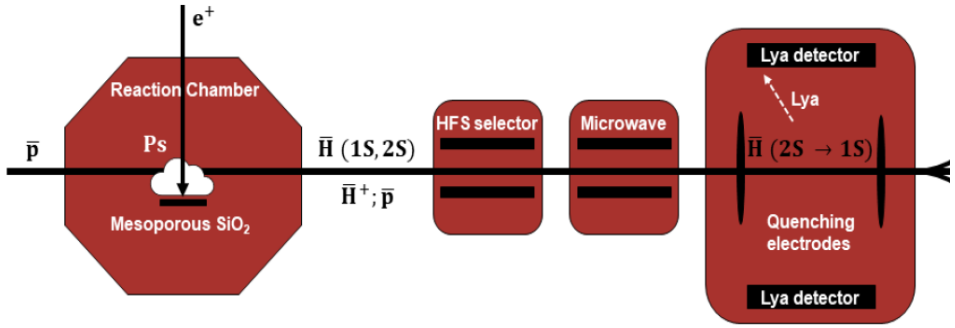
2024 configuration



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

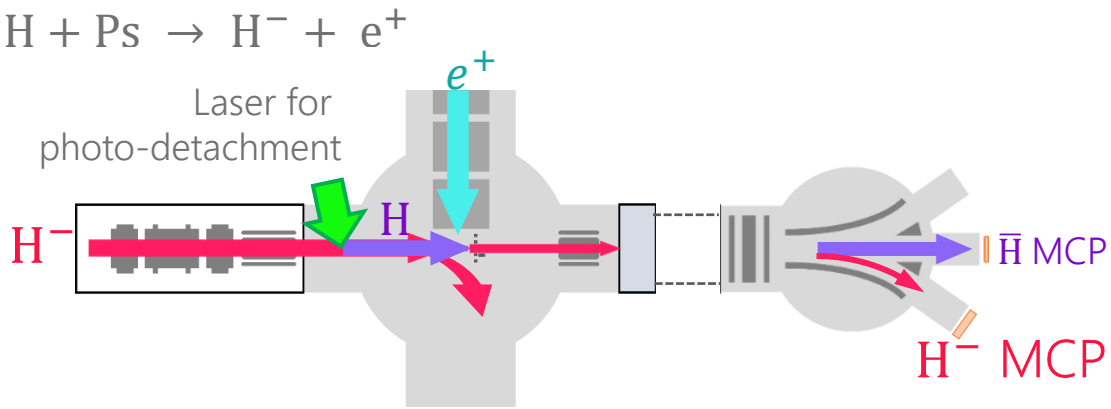
CERN-SPSC-2025-005

coming soon measurements

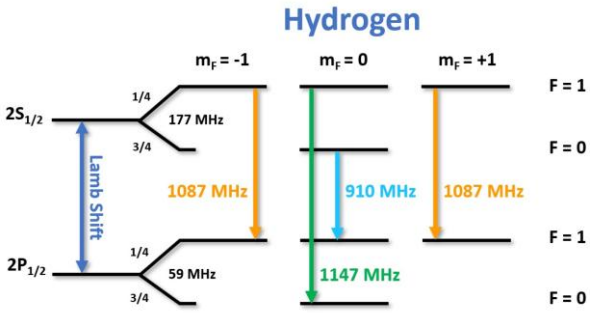


MW transitions
(HFS selector & MW TL)

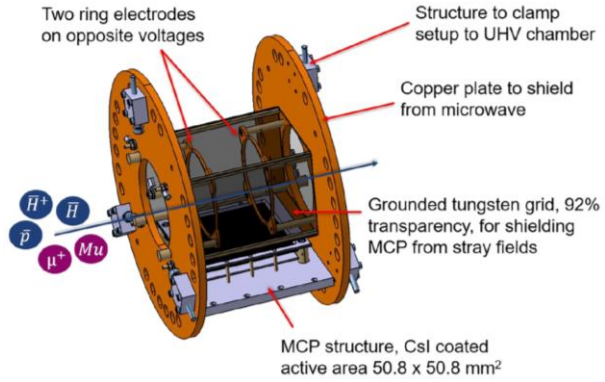
P. Crivelli et al., Phys. Rev. D **94**, 052008 (2016)



Ly-α photons detector



Commissioned with H(2S) in GBAR



$H(1S) + Ps(1S)$, 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

Summary

- Matter and Antimatter asymmetry is one of mystery and

exploring the antimatter physics is meaningful topic.

- The GBAR experiment aims to measure the gravitational acceleration of antihydrogen below 1% to 10^{-5}.
- For the most challenging experiment, few milestones should be reached.
- Getting close to the production of $\overline{H}^{+}$
- H^{-} cross-section measurement and Lamb-shift measurement has been prepared

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

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))

Antiproton trap operation

Preliminary

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