FKPPN-GBAR

Gravitational Behaviour of Antihydrogen at Rest

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Motivation

❖ **Matter and Antimatter asymmetry**

- Different with expectation by BIGBANG and Standard Model,

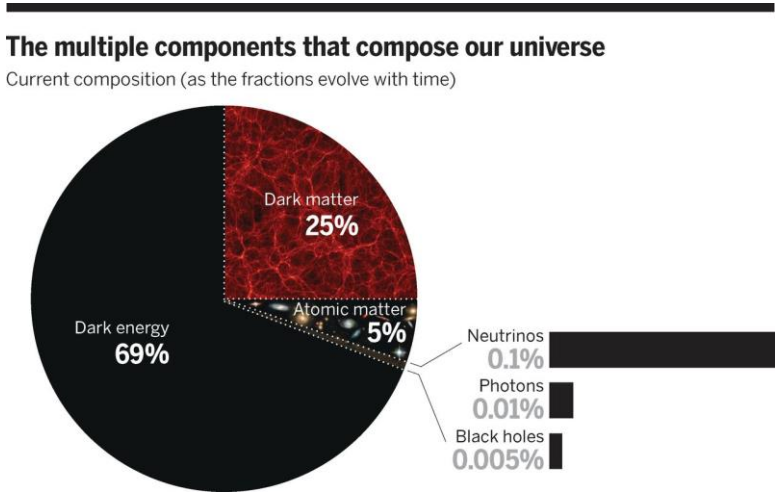
Matter domain in observable Hubble volume : $n_B \gg n_{\bar{B}}$

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

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

❖ Dark matter and Dark energy

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



❖ Antimatter's fundamental properties are not fully measured

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

➔ CPT and WEP test with antimatter by precision test

Motivation

Check fundamental interaction between matter & antimatter

- Weak Equivalence Principle(WEP) :

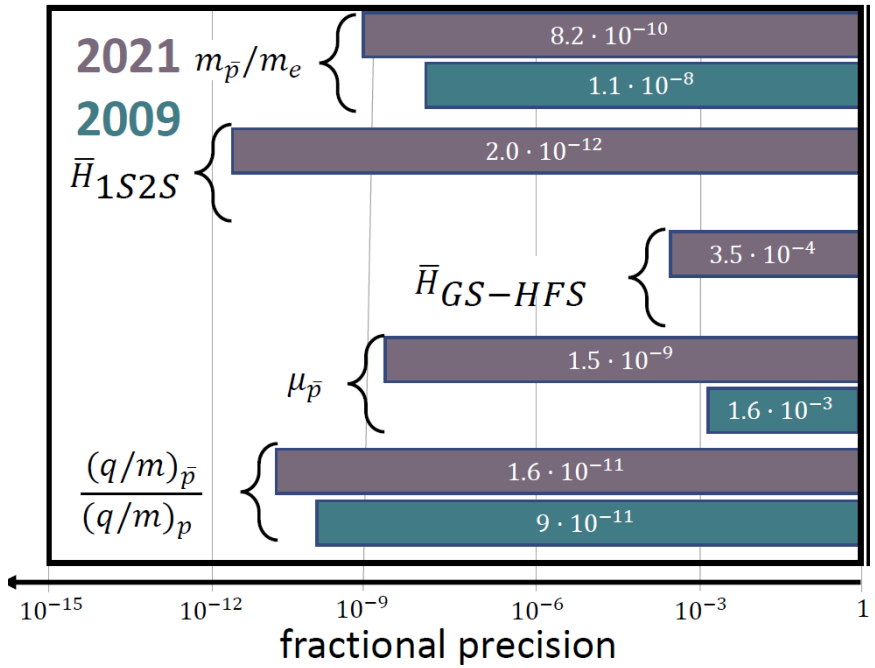
$$m_I = m_G \ (F = m_I a = -G m_G m'_G / r^2)$$

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

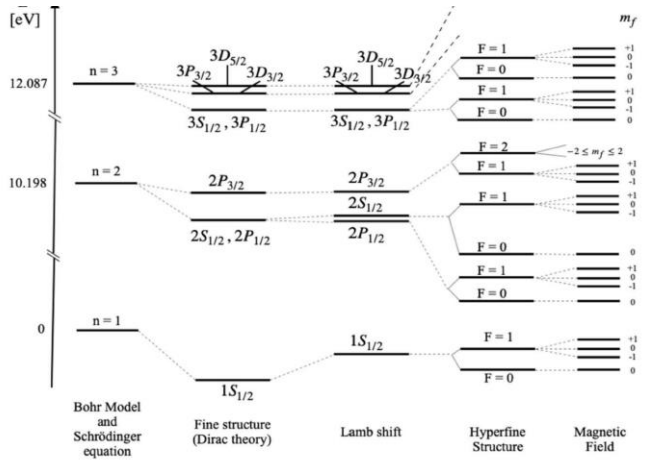
$$m_G = m_I = \overline{m_I} = ? \overline{m_G}$$

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

From Stefan Ulmer's slide (ADUC)

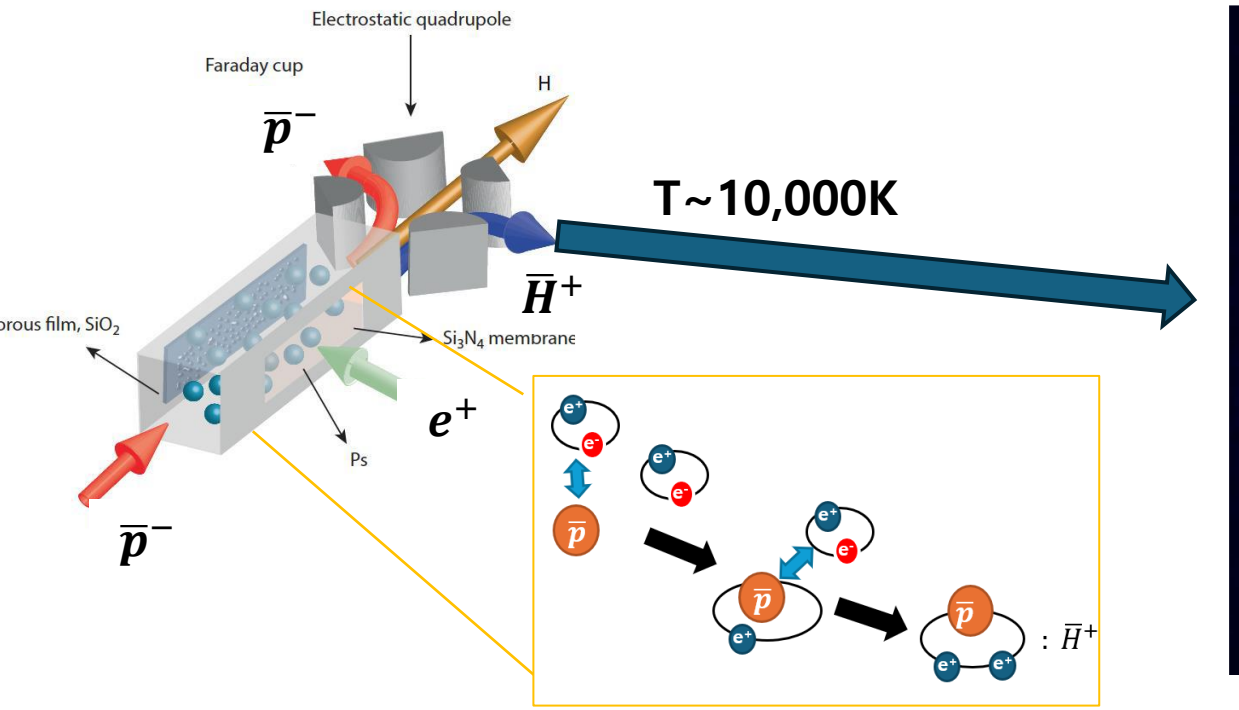


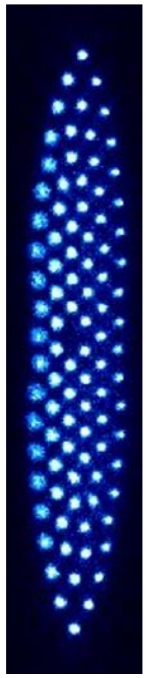
- Many CPT test has been performed between matter and antimatter especially by proton & antiproton and hydrogen and antihydrogen



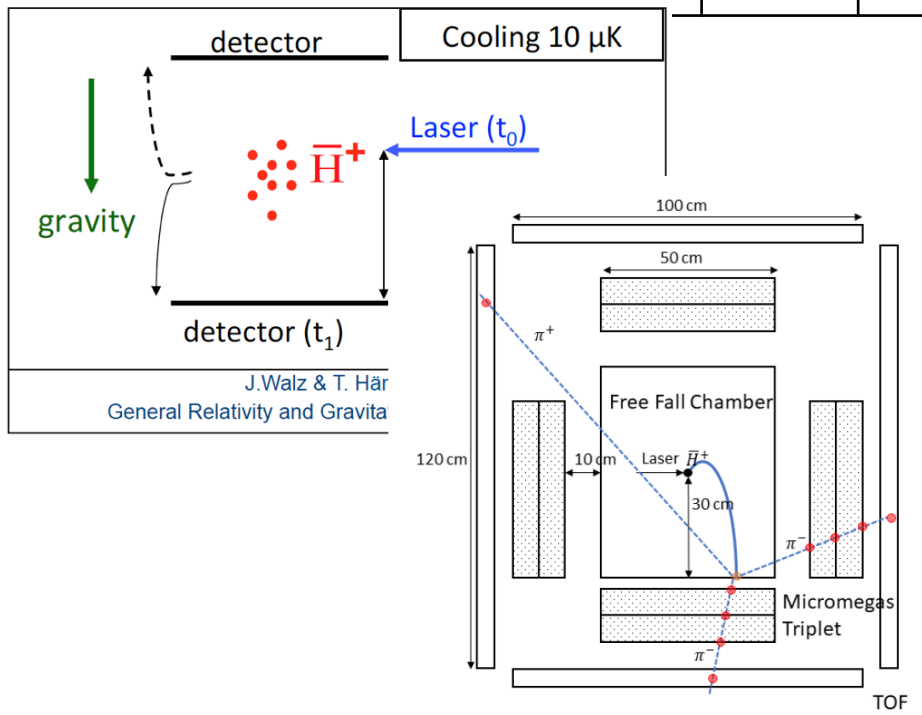
GBAR experiment

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





T~mK
→uK



- Double charge exchange process between anti-proton beam and dense positronium cloud (<1x1.5x10mm^3 cavity)

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

with

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

- Cooling anti-hydrogen ion down to **10uK** range (ultra-cold) with Be^+ to get extremely slow velocity : 3rd **milestone**
- After dropping one of e^+ (by photo-detachment laser), let the ultra-cold anti-hydrogen **freefall**.
- Direct measurement of the gravitational acceleration of anti-hydrogen (WEP_{ff}) below 1%
- $\bar{H}^+$ is required to get ultra-cold $\bar{H}$ (1500#) which can go below **10^{-5}** precision for WEP_{ff} (only ultracold anti-hydrogen can reach)

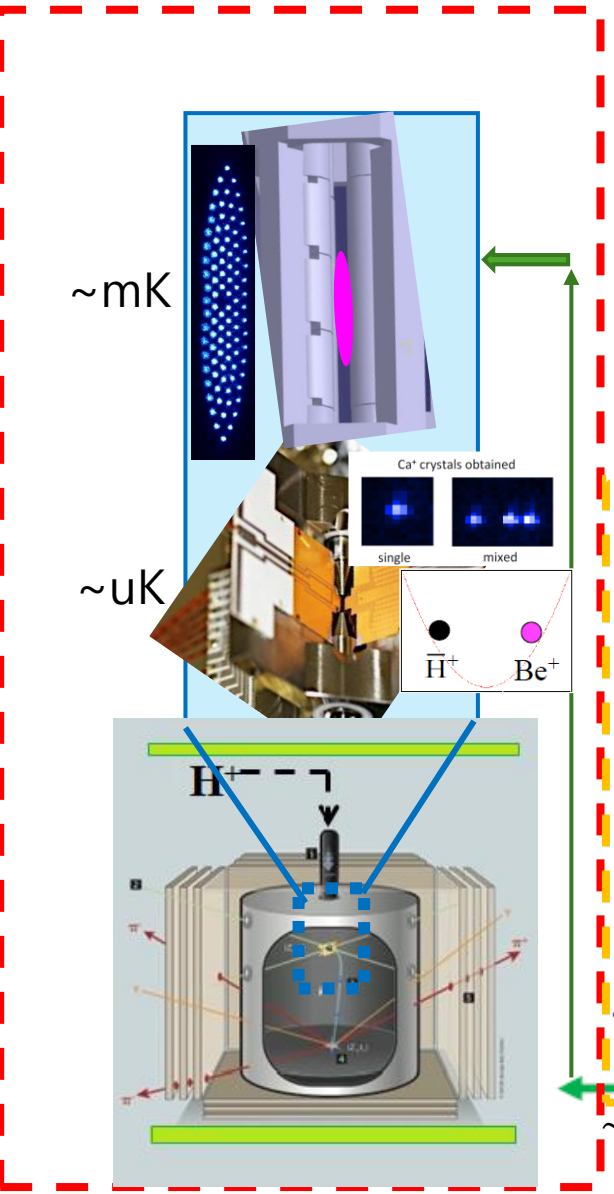
GBAR affiliation

members in FKPPN 2024

IJCLAB (French)
- **David Lunney**
- **Sarah Geffroy**

IBS (Korean)
- **Bongho Kim**
- **Kwanhyung Park**
- **Byunchan Lee (SNU)**

Experiment Scheme

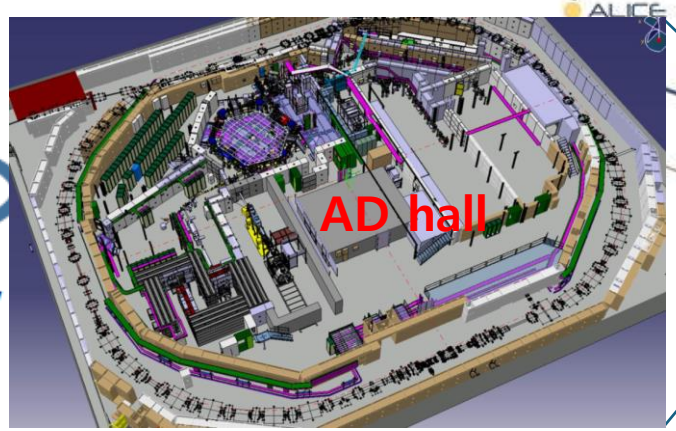


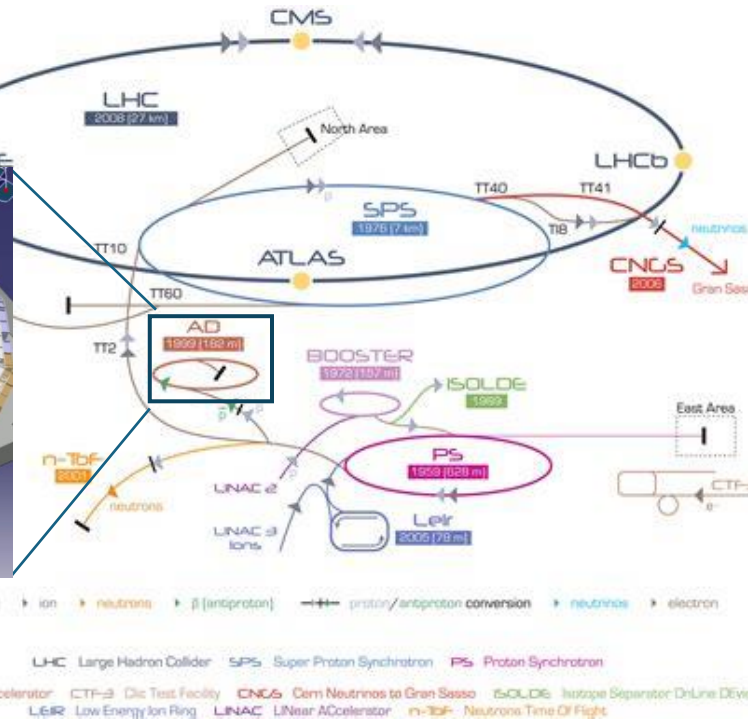
3.5→0.1GeV/c

AD

5.3MeV

ELENA





100keV (0.5×10^7 $\bar{p}$ /110s)

deceleration

Anti-proton beam line

$\bar{P}$ trap

10eV~10keV

Laser Ps*

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

4kV

High field trap

buncher

BG trap

Ne remoderator

e^+ target

Linac

Positron beam line

10^{10} e^+/bunch

1MeV→3eV → 50eV

e^- 10MeV

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

$\bar{H}$

$\bar{p}$

$\bar{H}^+$ ion

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

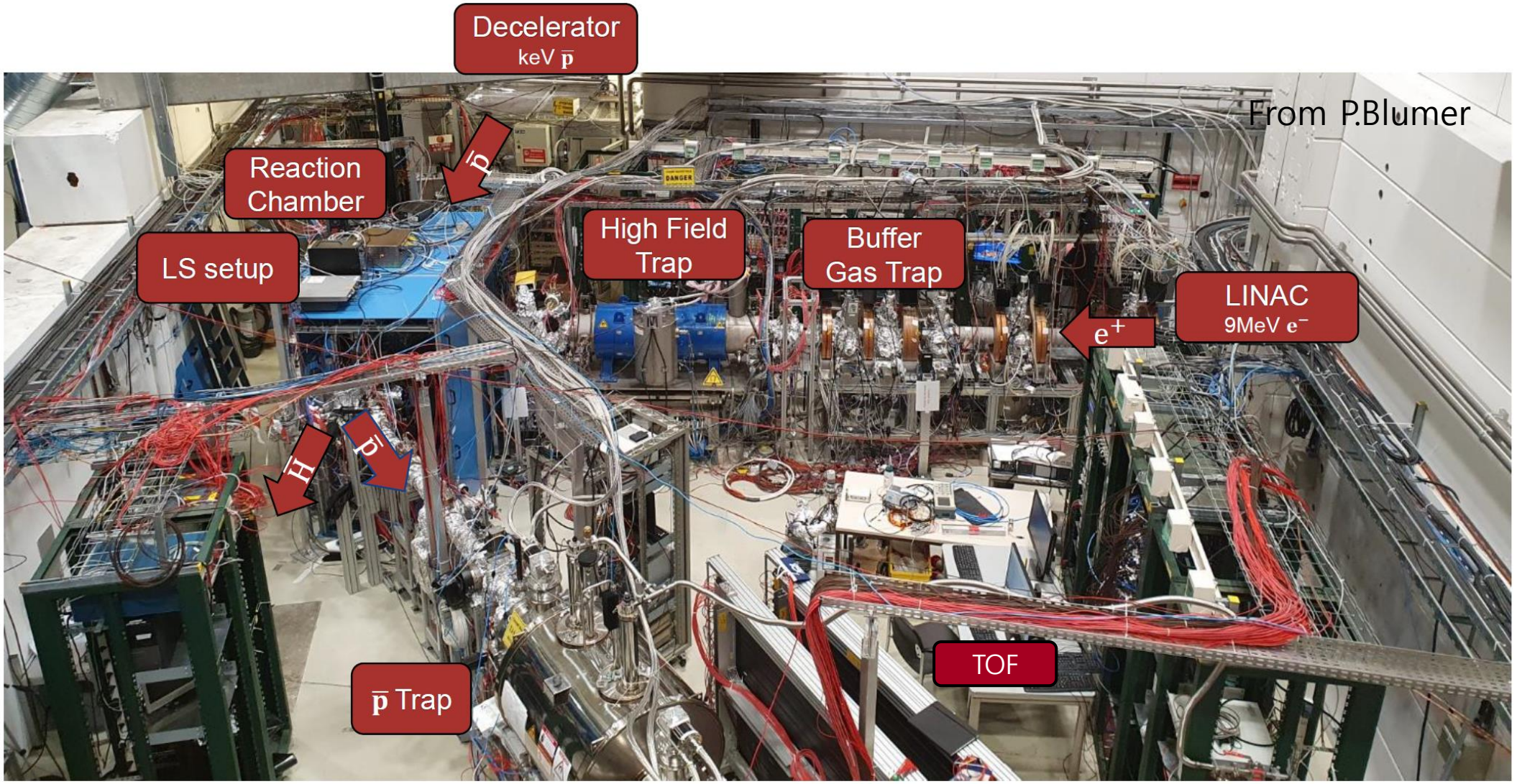
Recycler #($\bar{p}$) x10

Lyman-α

: Currently developed

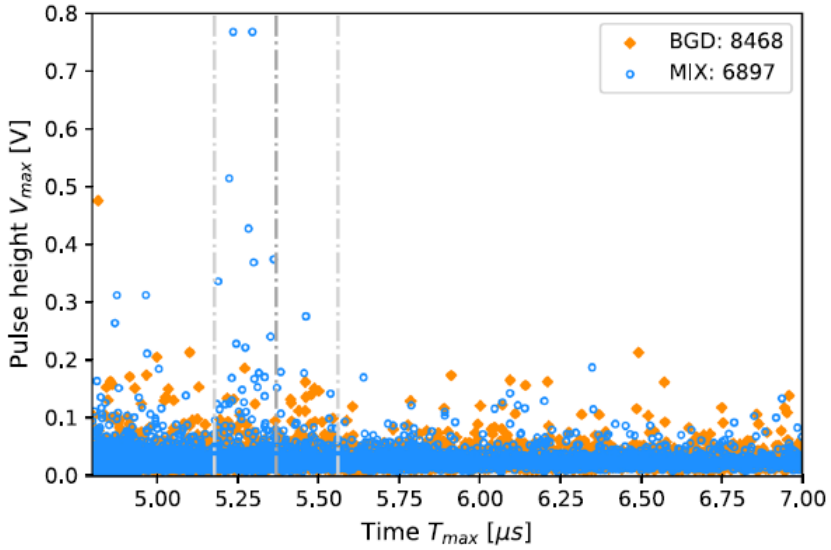
: related with FKPPN

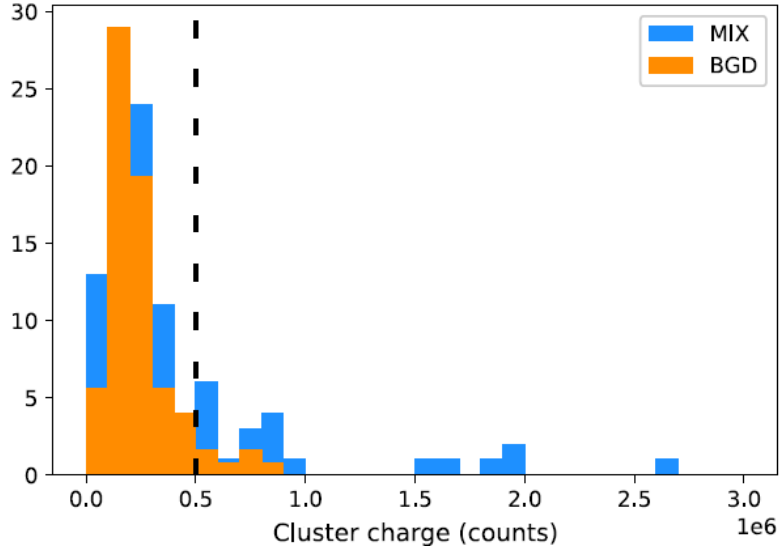
Experiment setup (2022)

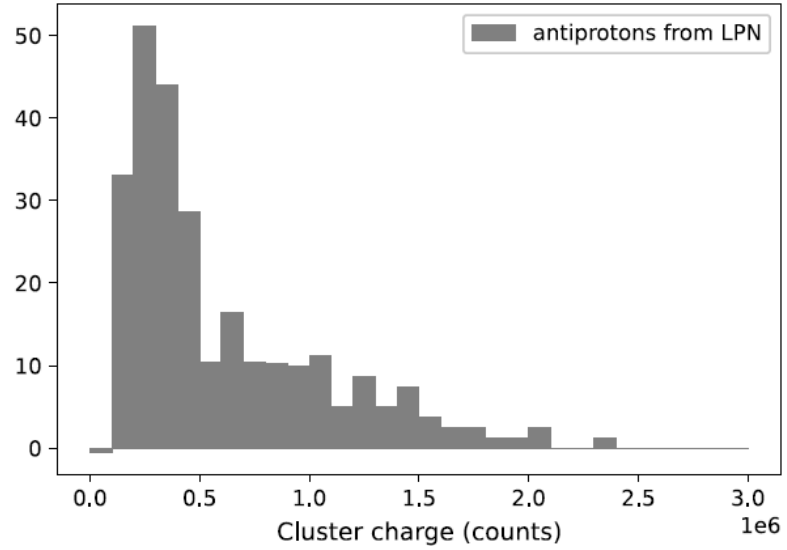


$\bar{H}$ production (2022)

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

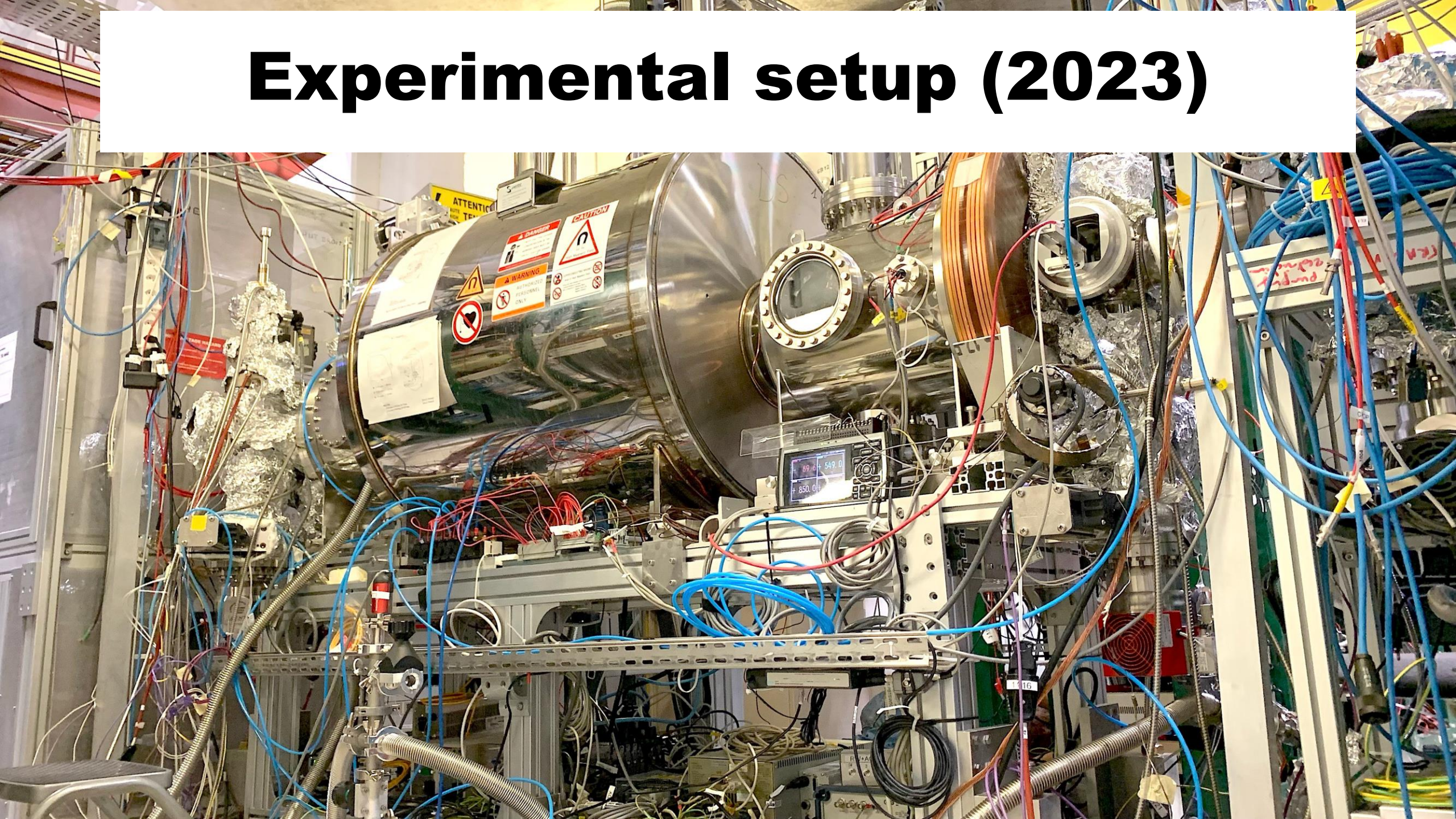






- Antihydrogen above 3σ is detected (which is **1st milestone**)
- (First) production of antihydrogen by charge exchange between o-Ps and antiproton **beam**
- $I_{e^+} \times 50, I_{\bar{p}} \times 2$ with **better emittance** required $\bar{H}^+$ production (**2nd milestone**)

Experimental setup (2023)



Antiproton beam line development

- Decelerator : French group
- Antiproton trap : Korean group
- Recycler and recycling : Started from French group and has been collaborated.
- What's done and planed : Reproduce antiproton beam from ELENA to well tuned beam for antihydrogen ion production

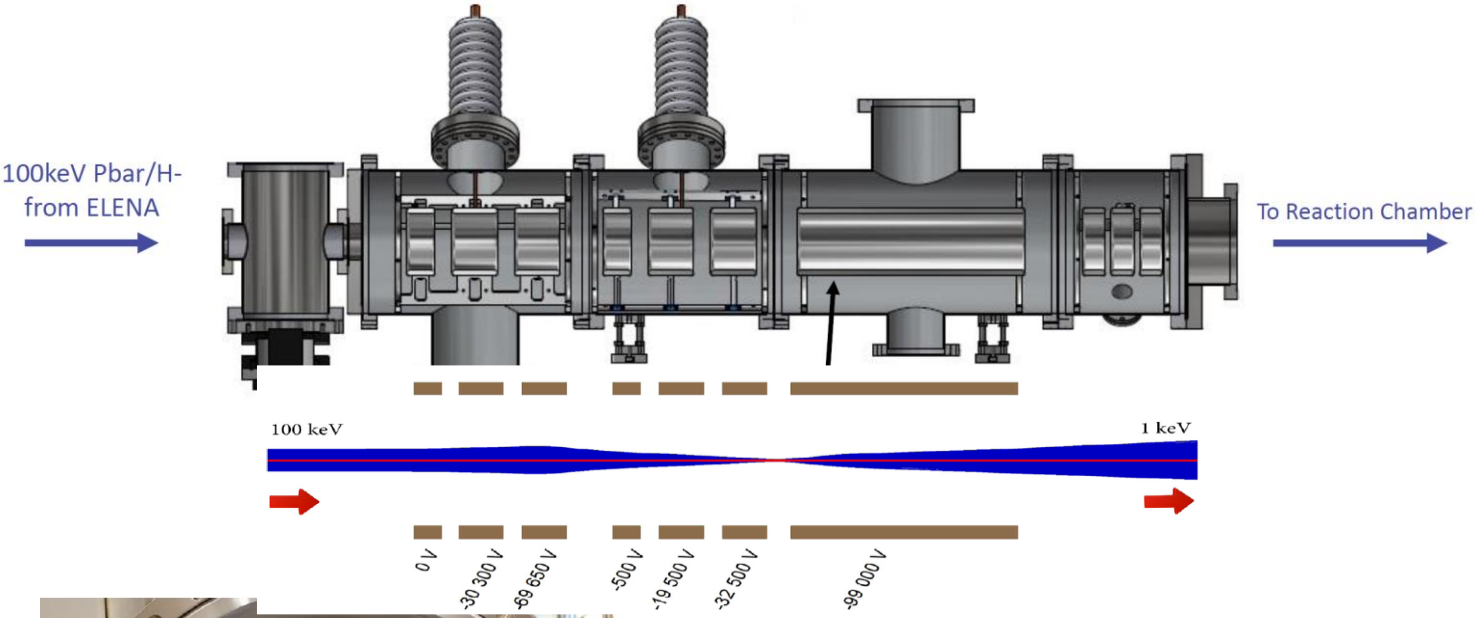
➔

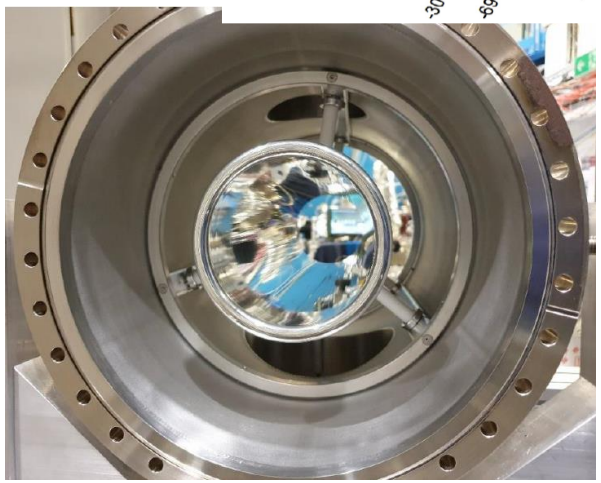
Decelerator			+ antiproton trap			
Energy	T width	Efficiency	σ_r(at RC)	ΔE	T width	Efficiency
<10keV	<100ns	~100%	<1mm	~10eV	56ns	~90%

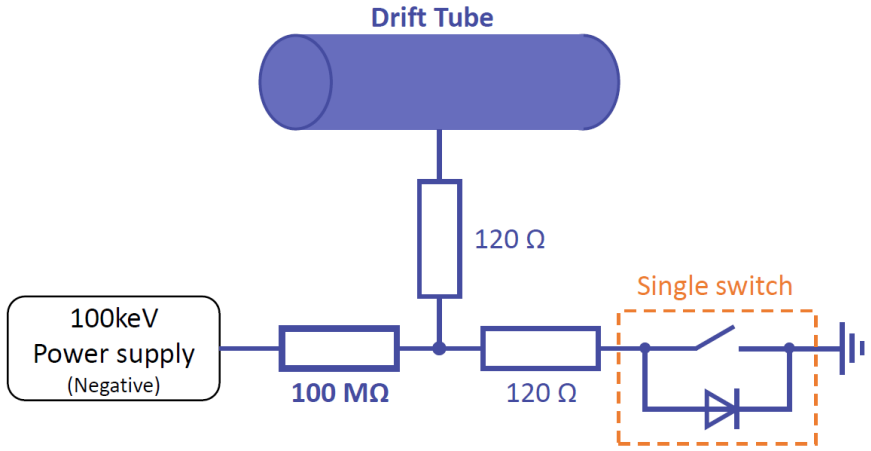
- Current charge exchange process is limited by poor beam phase-space and limited intensity
- Future plan : increasing antiproton intensity to > x5 by recycler

Decelerator

From C.Roumegou's slide and A.Husson's paper







- Nominal ELENA beam's parameters

intensity :5 x 10^6 #/pulse (~2min)

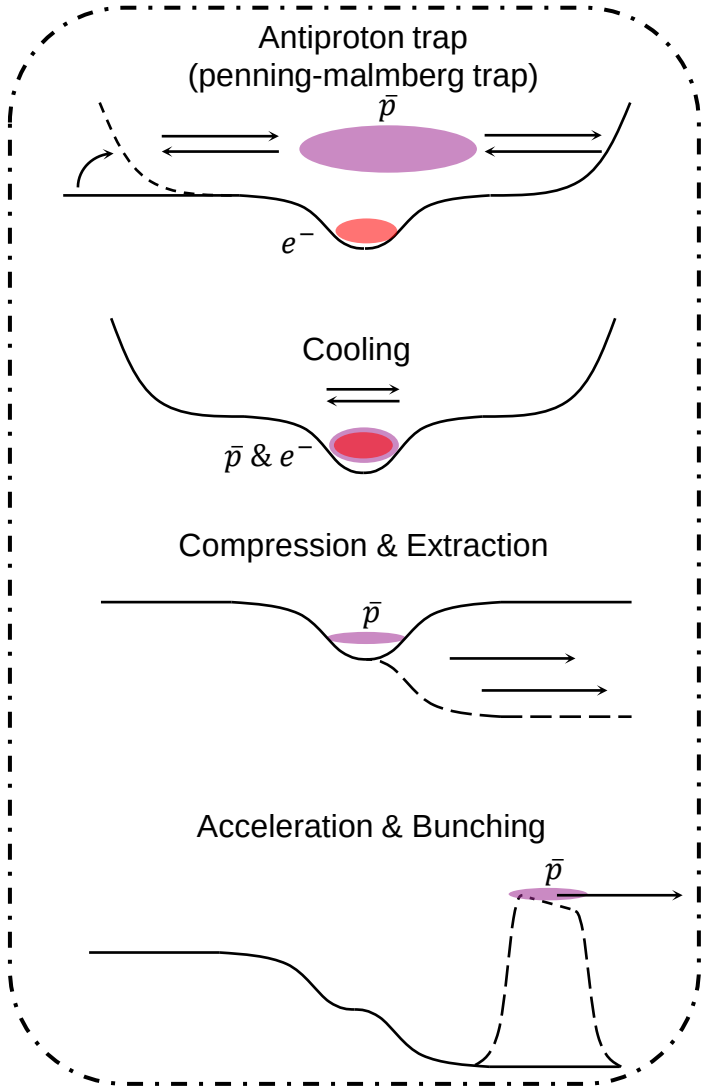
bunch length : 75ns

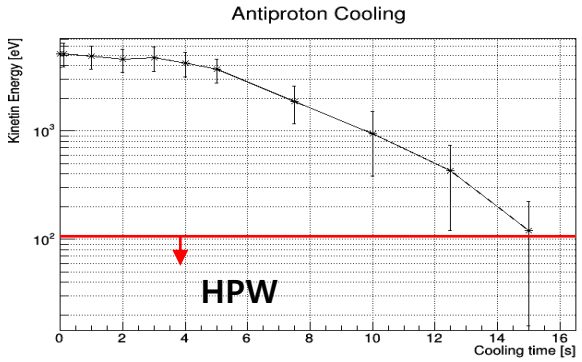
- Deceleration of 100keV antiproton beam (σ_t<100ns) to below 10keV by switching pulsed drift tube.

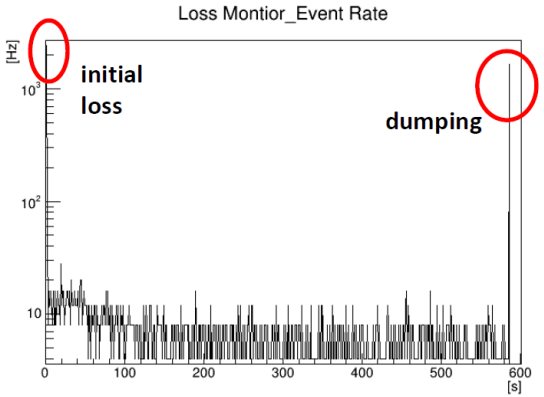
: Switching drift tube from high voltage to 0V while particles are inside

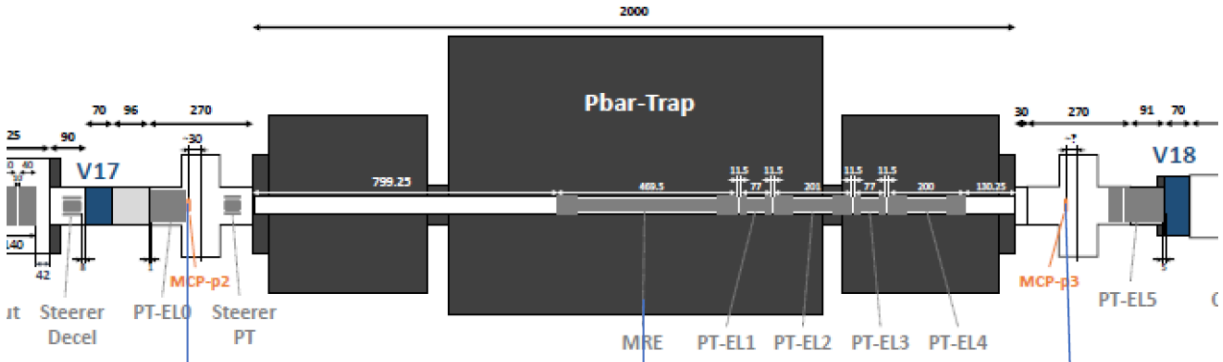
- Has been operated with stable condition
- Aim to decelerate the antiproton beam almost 100% efficiency. (95% in σ_t =300ns)

Antiproton trap

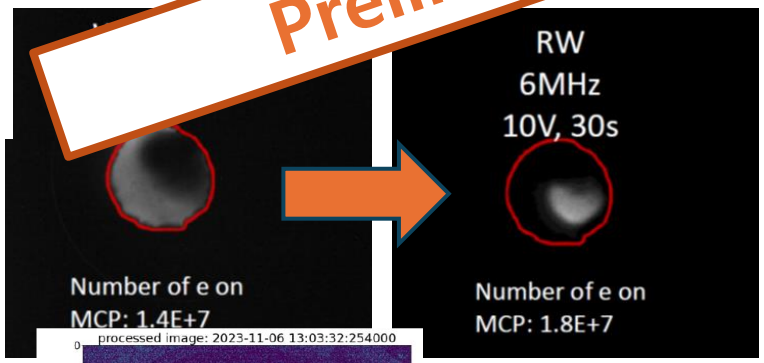


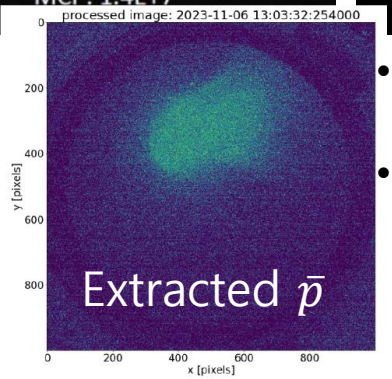






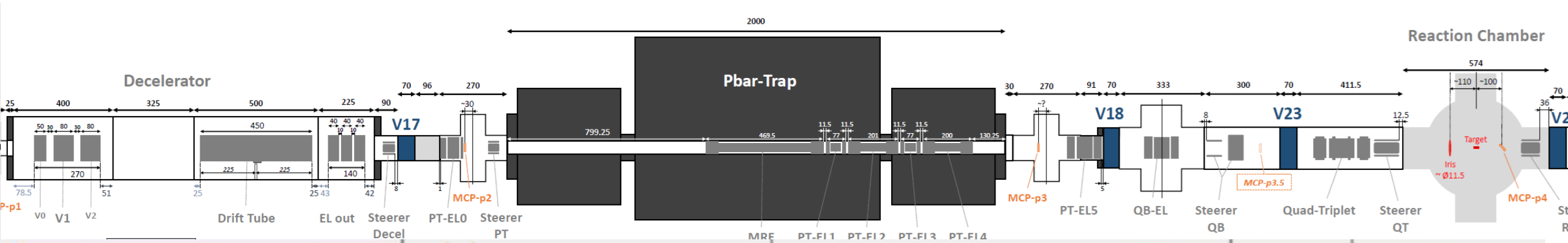
Preliminary

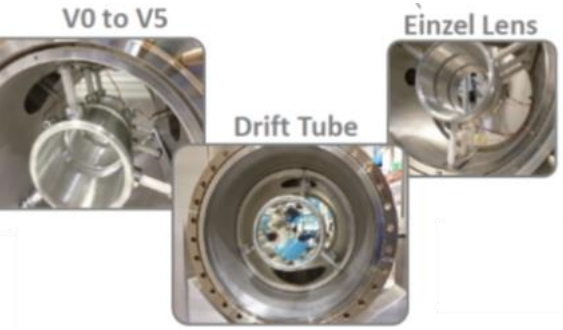


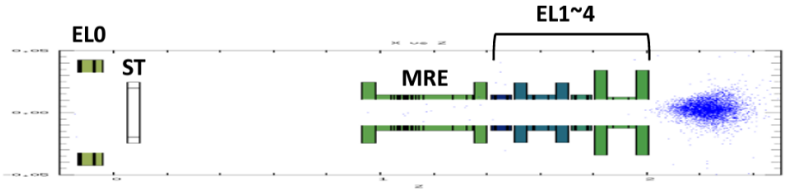


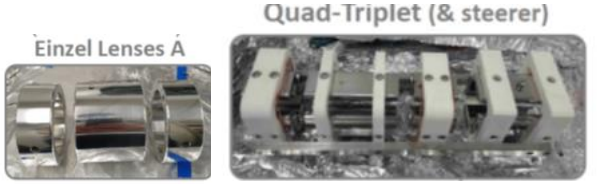
- Antiproton trap was installed to final position in Sep. 2023
- Full operation has been checked and 35% efficiency has been shown during 2023 (1.8×10^6/110s)

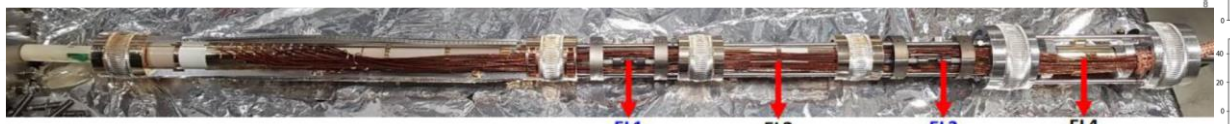
Beam guiding w&w/o pbar trap

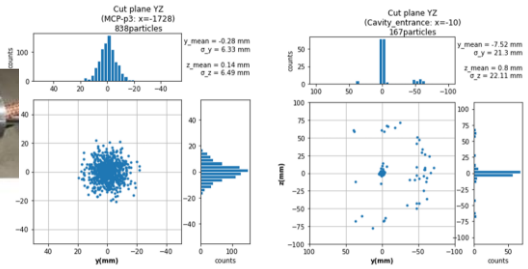






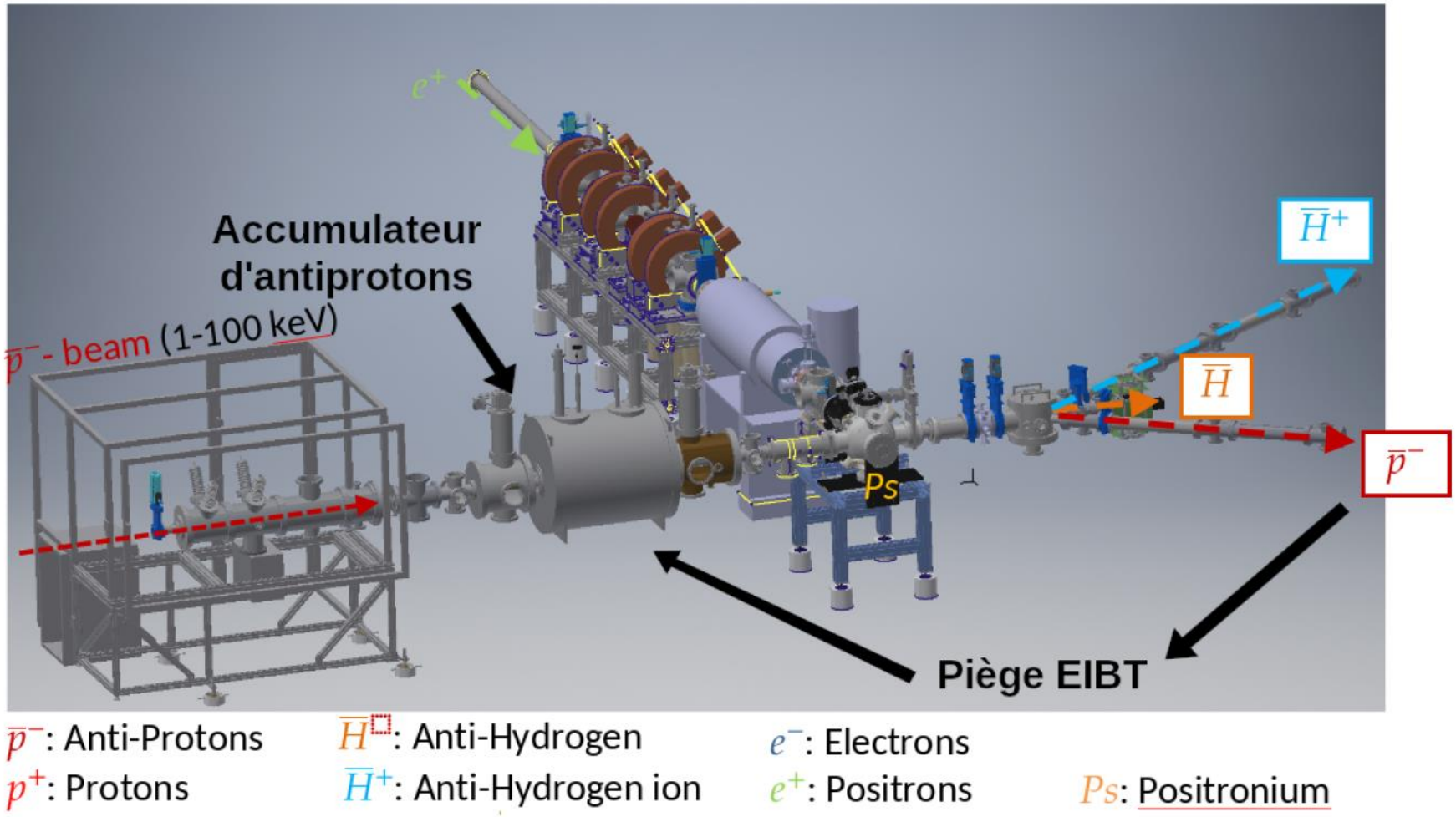






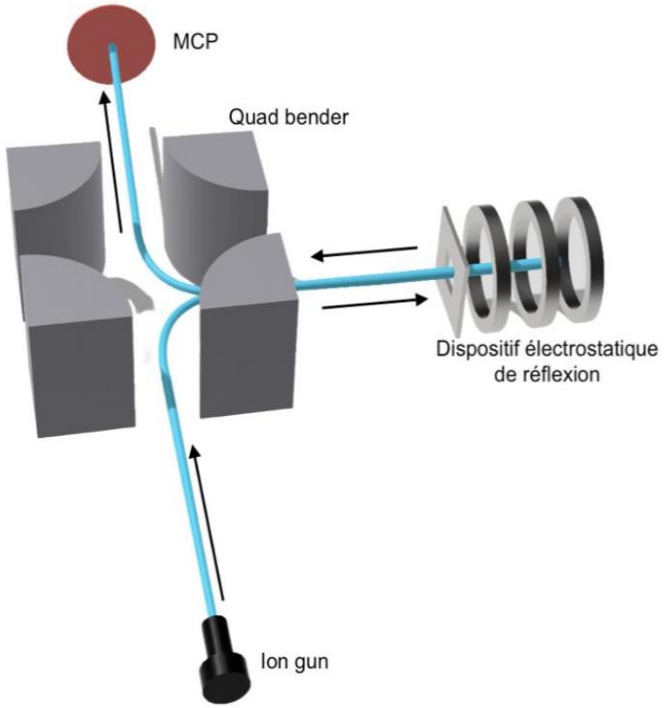
- General beam guiding simulation (French)
- Beam generation and local(trap) guiding simulation (Korean)

Antiproton beam with addition of recycler



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

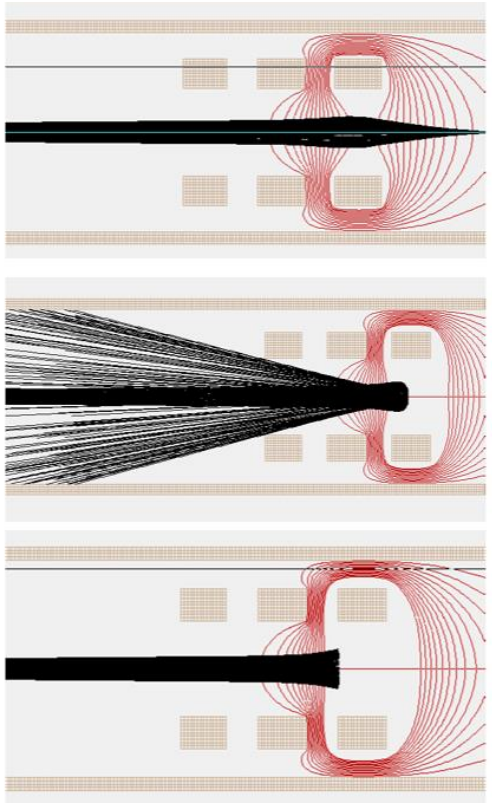
Recycler preparation



Simulating, designing, and experimenting an electrostatic device for reflecting ion packets.

Use of SIMION software and experimental set-up in Orsay.

From Sarah Geffroy



Voltage = 750 V
Beam is focused but not reflected

Voltage = 1000 V
Beam is not focused but reflected

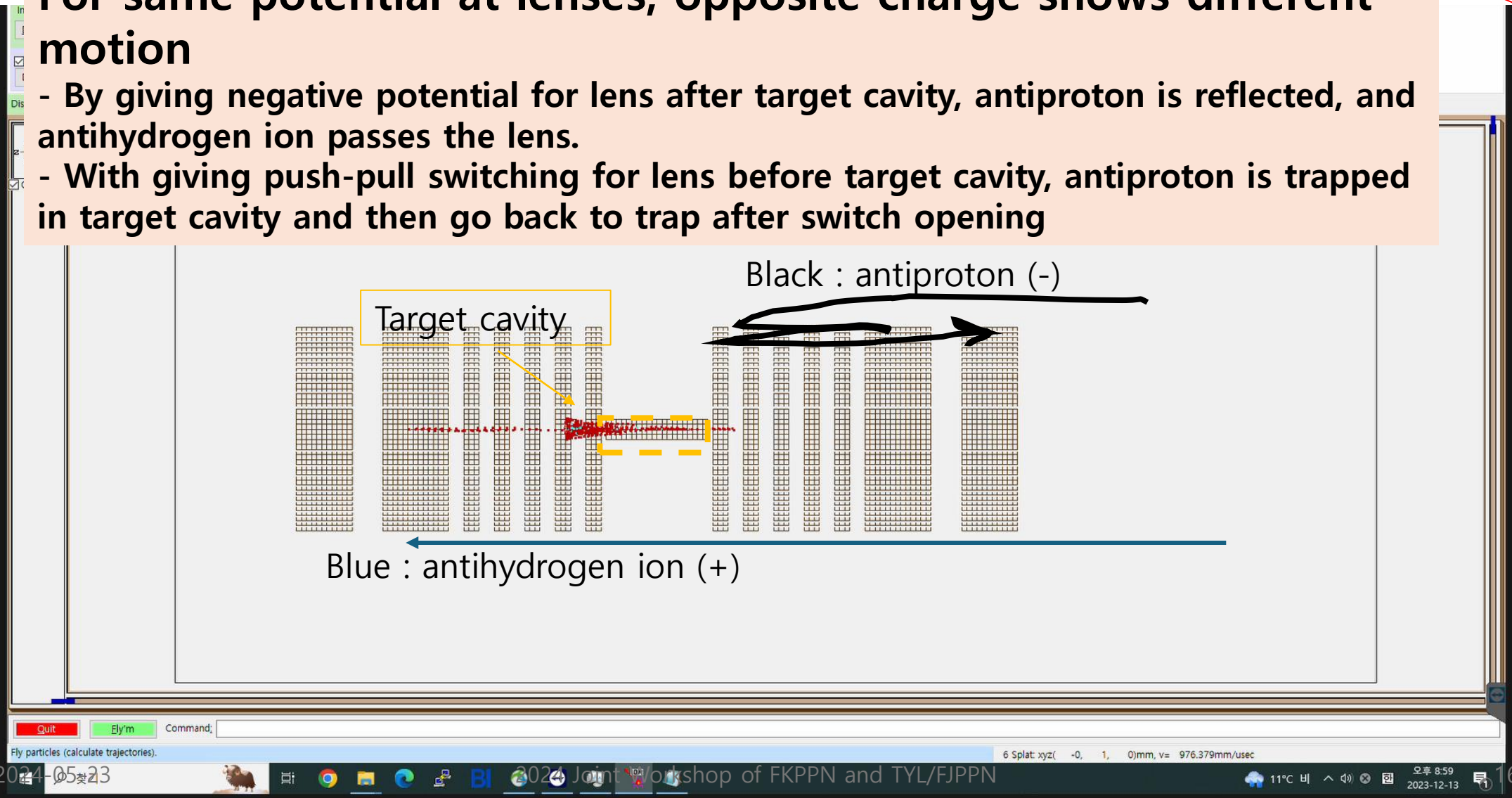
Voltage = 1150 V
Beam is focused and reflected

Charge filtering trap

new idea!

For same potential at lenses, opposite charge shows different motion

- By giving negative potential for lens after target cavity, antiproton is reflected, and antihydrogen ion passes the lens.
- With giving push-pull switching for lens before target cavity, antiproton is trapped in target cavity and then go back to trap after switch opening

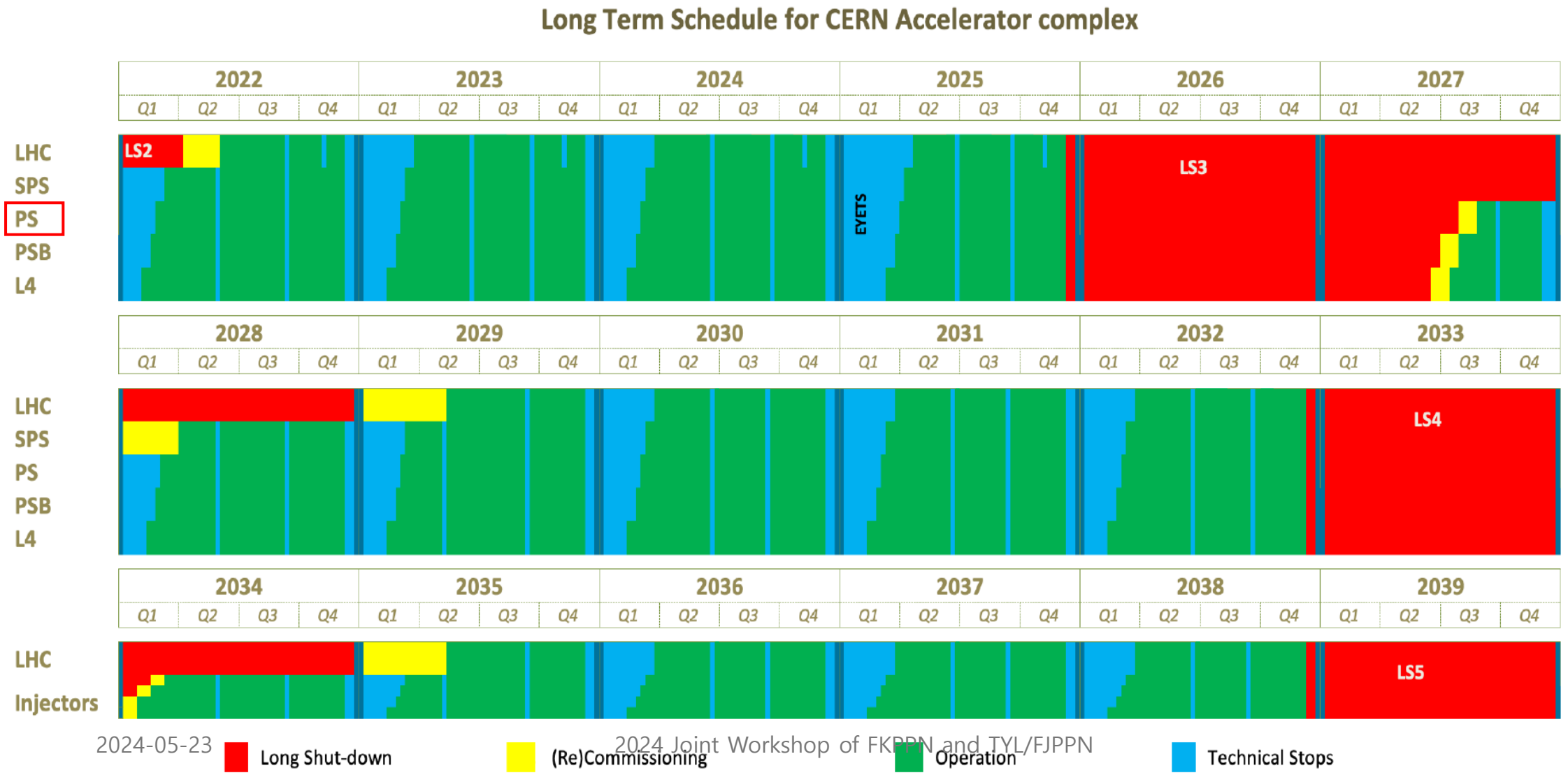


Conclusion

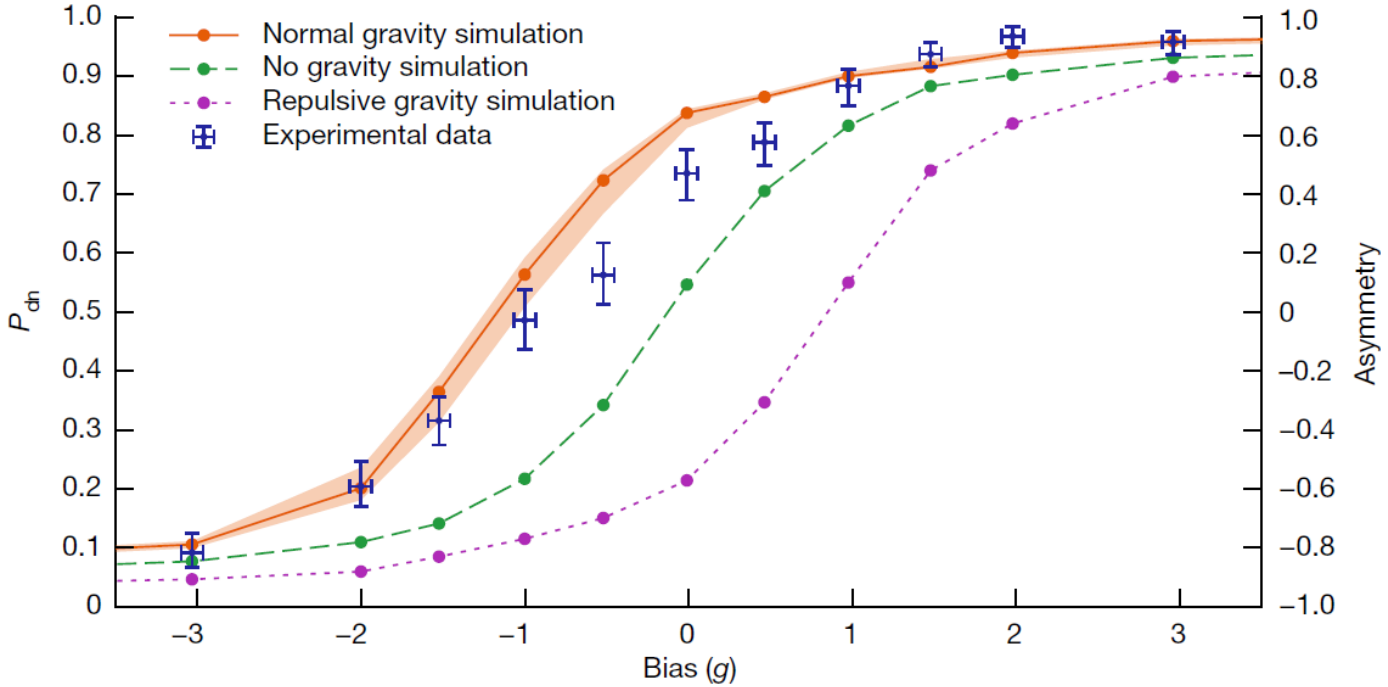
- GBAR experiment aims to measure the antimatter gravitational acceleration below 1% precision and go beyond
- Succeeded to produce antihydrogen by antiproton beam and positronium collision (1st milestone of GBAR experiment)
- For this, more antiproton intensity by recycling method is necessary as a solution to increase >x5 of antiproton intensity
- French and Korean team had worked for decelerator and have worked for whole antiproton beam line with addition of recycler at the GBAR experiment

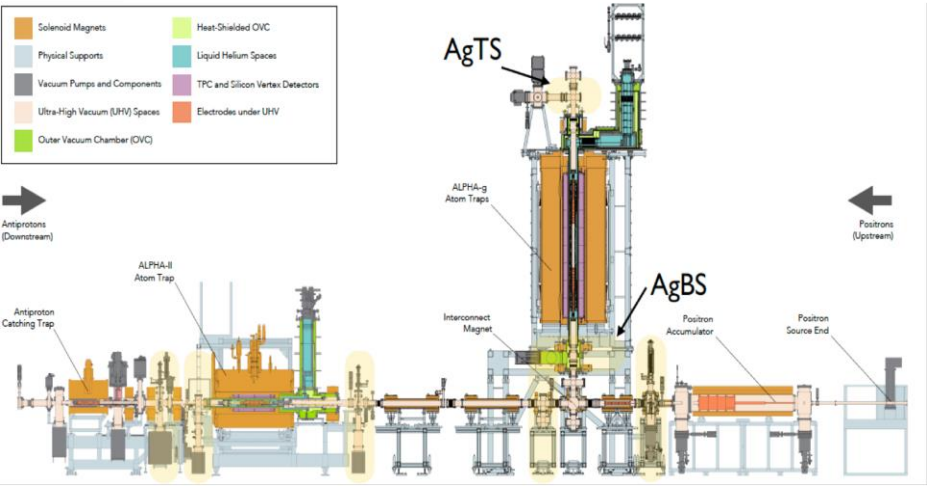
Back up

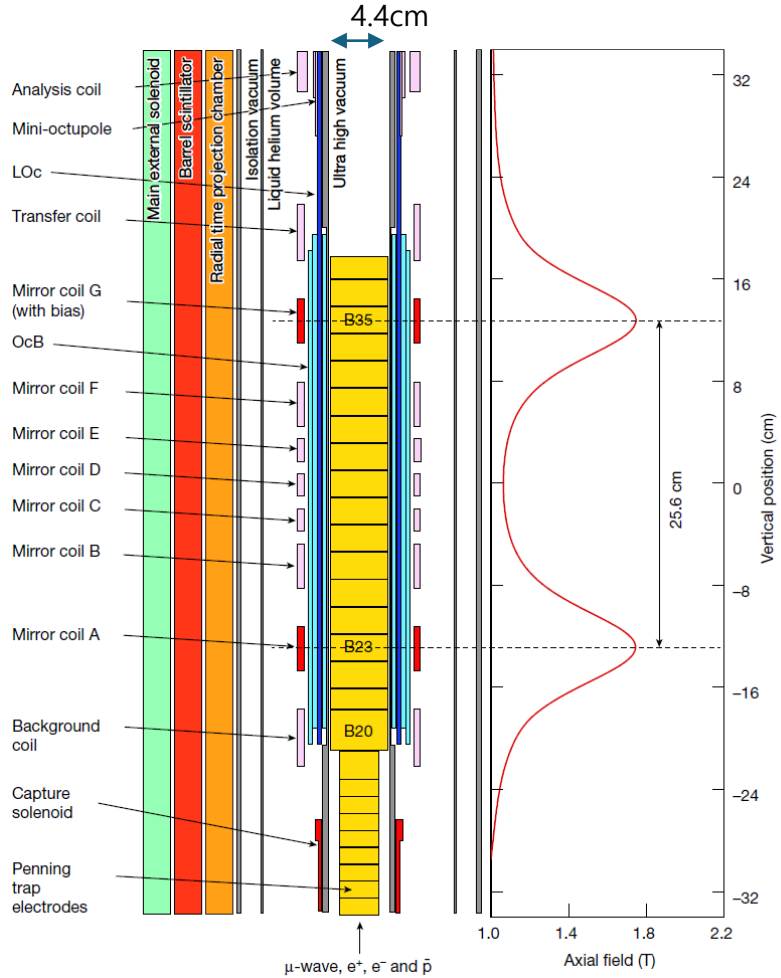
Current status and plan



Anti-Hydrogen WEP test







- **ALPHA-g experiment**

2013 : proof-of-principle experiment

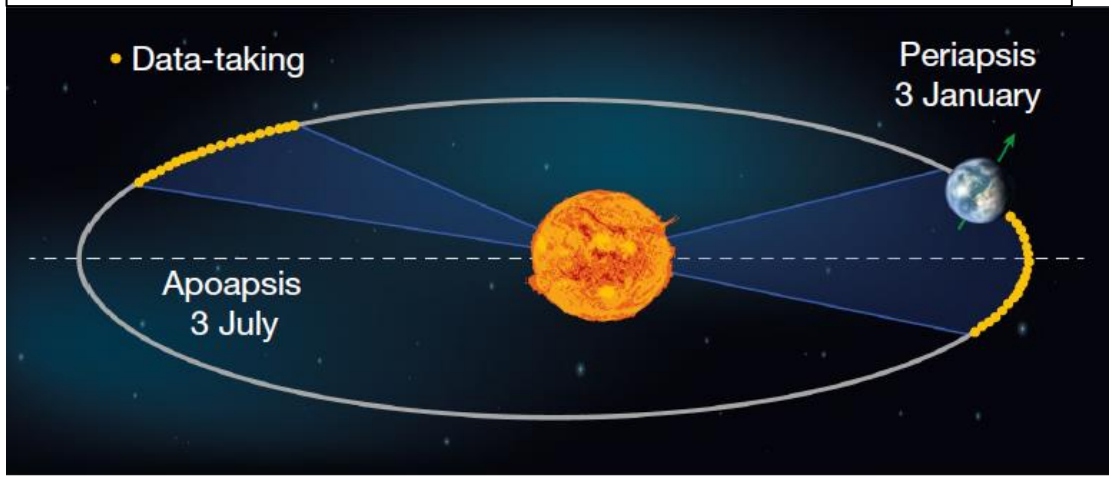
2018 : Alpha-g magnet constructed

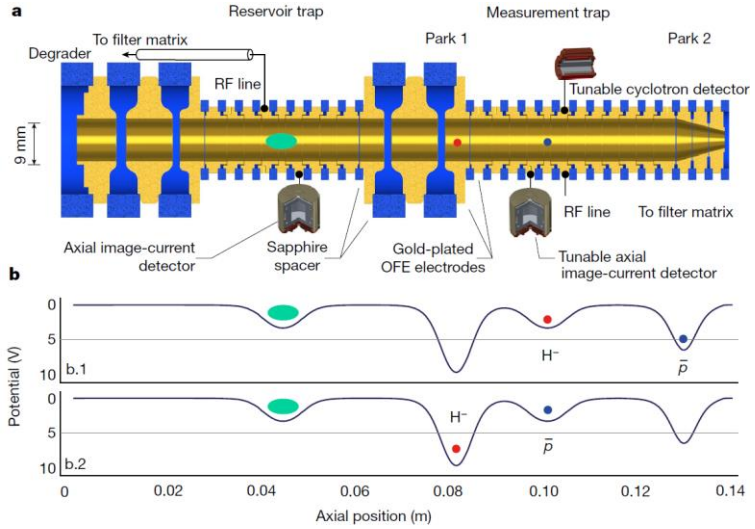
2023 : Rule out Repulsive antigravity by $\bar{H}$ with T <0.5K (**Nature 621, 716-722 (2023)**)

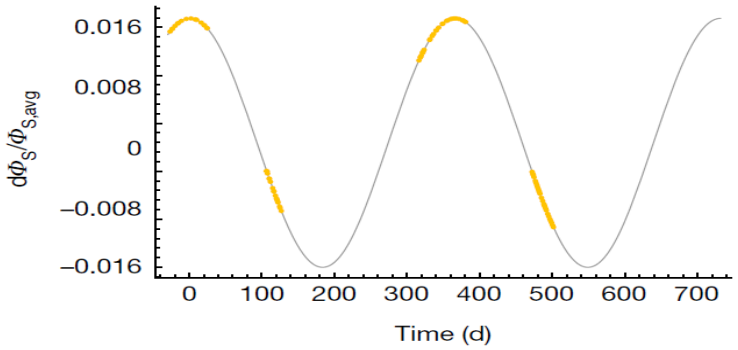
$$a_{\bar{g}} = (0.75 \pm 0.13 \pm 0.16) \times g$$

Antiproton WEP test

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







- **Base experiment**

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

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

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