FKPPN-GBAR
:Gravitational Behaviour of Antihydrogen at Rest

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Outline

- Introduction & motivation.

- GBAR experimental concept.

- GBAR experimental apparatus.
  - Positron beam line.
  - Antiproton beam line.

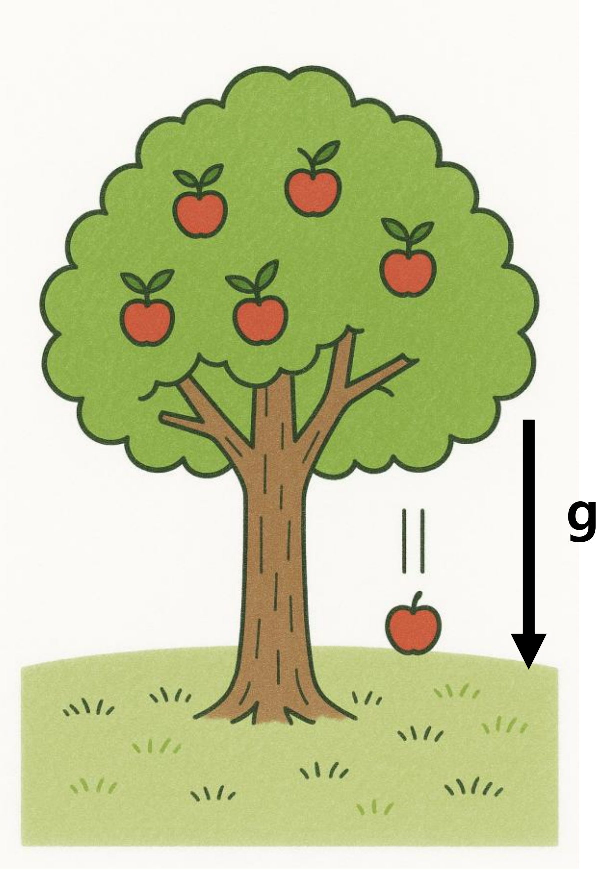
- $\overline{H}$ production 2022 & 2024.

- Future improvements
- GBAR affiliation
- Summary

Introduction & motivation

The GBAR experiment

- **G**ravitational **B**ehaviour of **A**ntihydrogen at **R**est

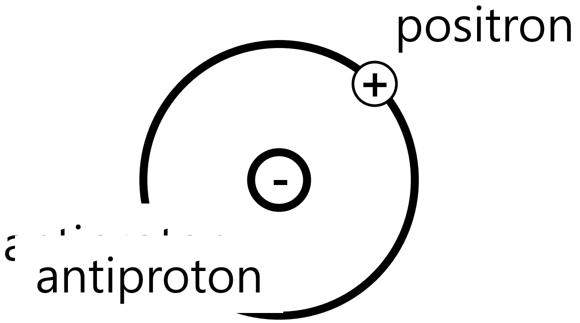


$\mathbf{g} = 9.8m/s^2$

Antimatter apple?

$\bar{g} = ?$

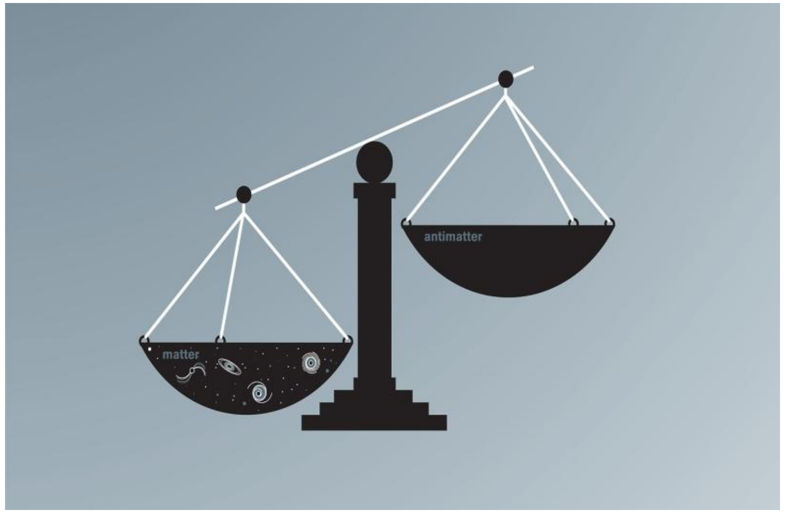
Antihydrogen

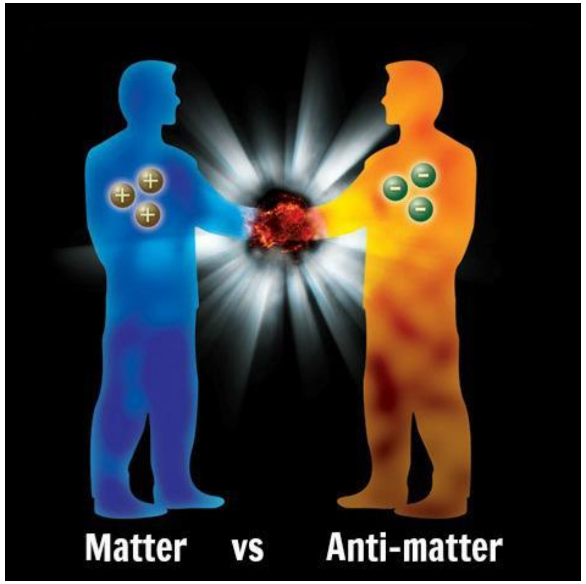


$\bar{g} = ?$

Antimatter and CPT Symmetry

- Antimatter is the mirror image of matter. It was predicted by Dirac in 1928 and experimentally confirmed with the discovery of the positron in 1932.
- The observable universe is composed almost entirely of matter, but antimatter is extremely rare.
- This asymmetry motivates experimental tests of fundamental symmetries such as CPT.



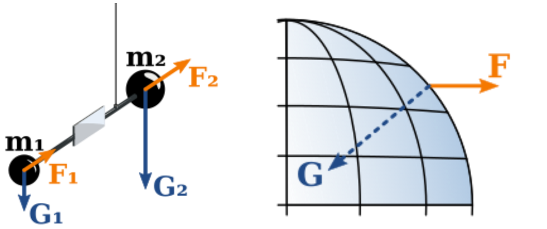


Weak Equivalence Principle (WEP)

- The WEP states that all objects fall at the same rate in a gravitational field, regardless of their composition.
- WEP has been confirmed for normal matter at extremely high precision.
- $m_I = m_G$
- Universality of free-fall: All bodies fall with the same acceleration in an identical gravitational field, regardless of their composition

Torsion balance of Eötvös experiment

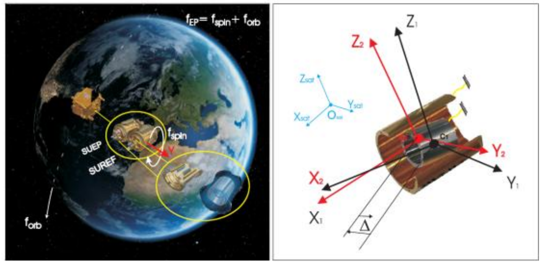
$$\eta_{AB} = 2\left|\frac{(m_G/m_I)_A - (m_G/m_I)_B}{(m_G/m_I)_A + (m_G/m_I)_B}\right| < 10^{-9}$$

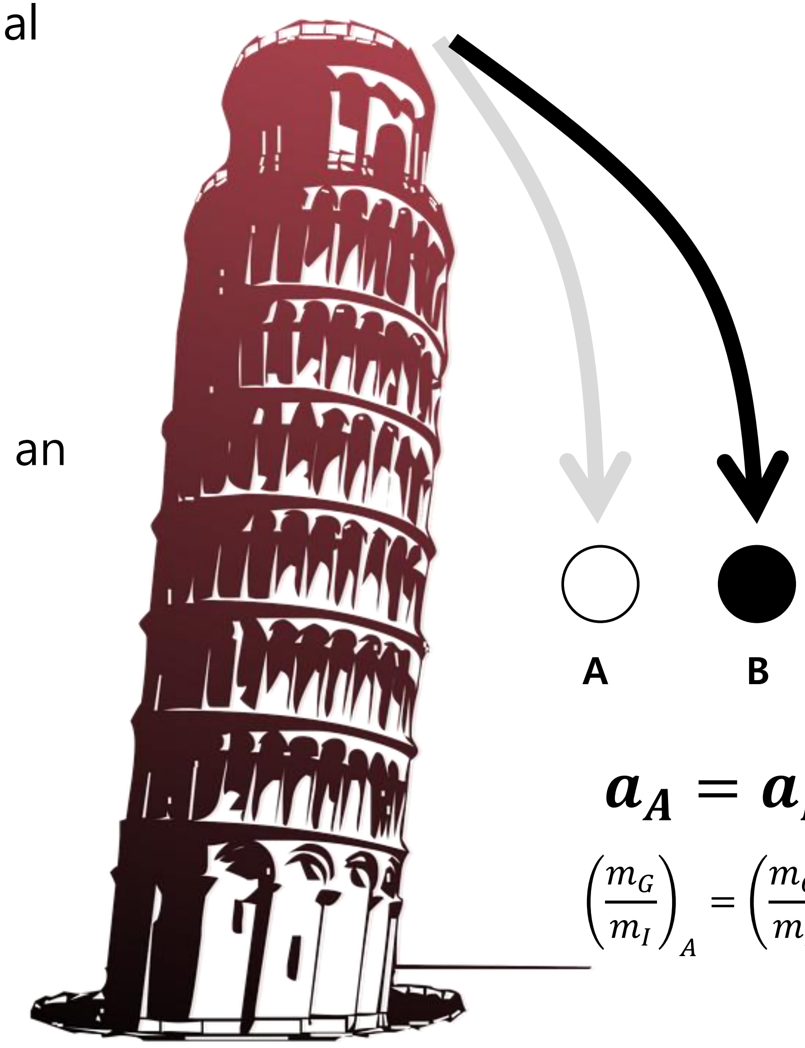


MICROSCOPE: Two accelerometers in a satellite

$$\eta(Ti, Pt) < 10^{-15}$$

Phys. Rev. Lett. 129, 121102 (2022)





$$a_A = a_B$$

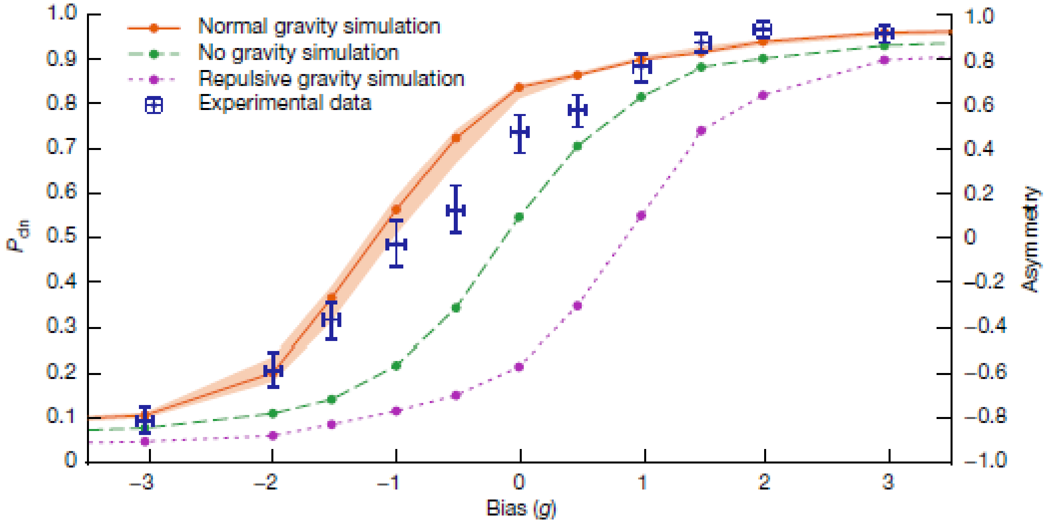
$$\left(\frac{m_G}{m_I}\right)_A = \left(\frac{m_G}{m_I}\right)_B$$

Weak Equivalence Principle (WEP)

- **WEP test for the antimatter?**

- There is still no high-precision experimental evidence for antimatter.

- On-going experiment with antihydrogen atom: ALPHA-g, AEgIS, **GBAR**



ALPHA-g apparatus

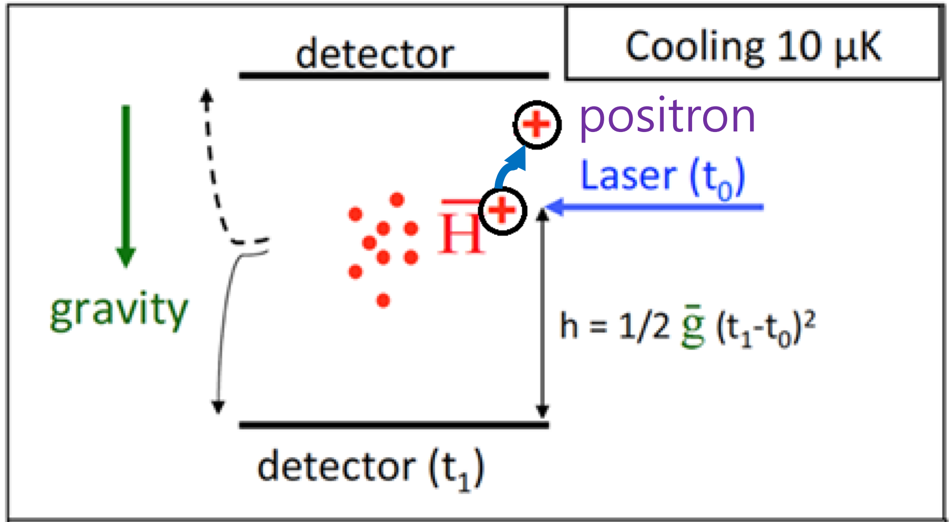
ALPHA-g: $\boldsymbol{a_{\bar{g}} = (0.75 \pm 0.13(stat, sys) \pm 0.16(simulation))g}$

Anderson et al., Nature 621, 716–722 (2023)

GBAR experimental concept

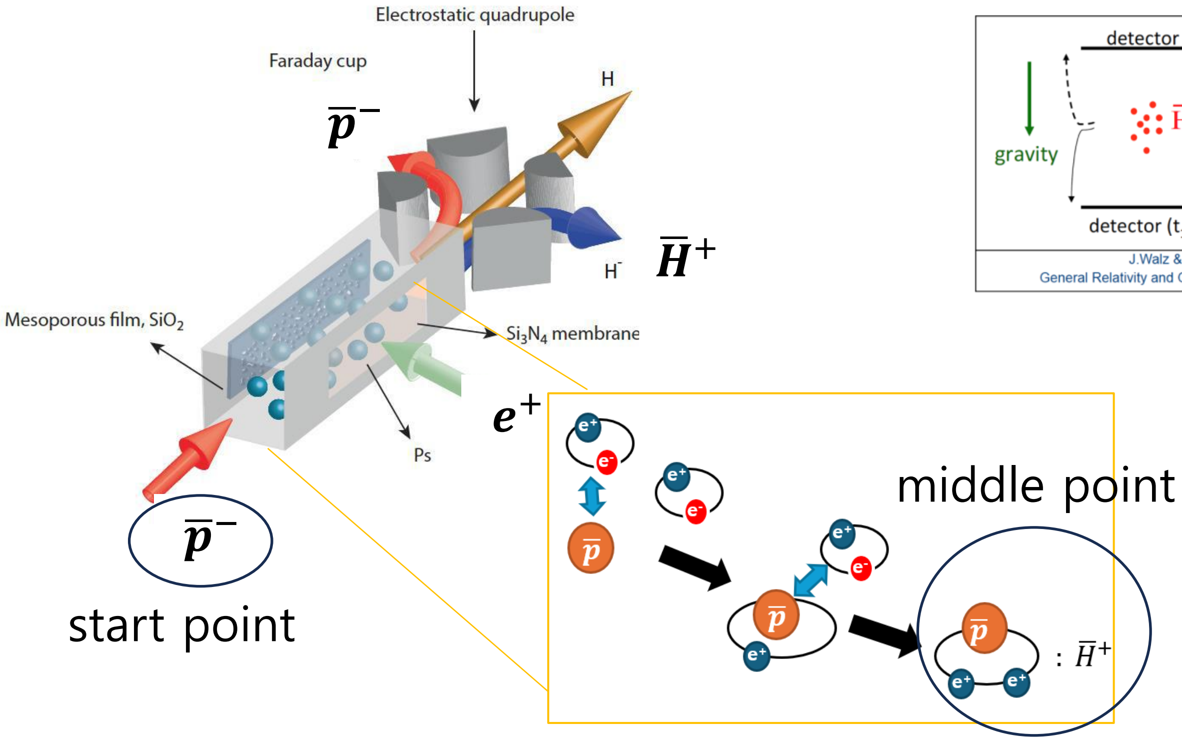
GBAR experiment concept

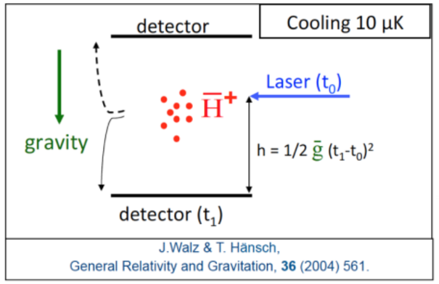
- GBAR aims to measure the free fall of ultracold antihydrogen atoms and determine the gravitational acceleration “g-bar” with a precision better than 1%(Phase 1) – High precision.
- This involves producing antihydrogen ions, sympathetic cooling them, and converting them to neutral antihydrogen for free-fall measurement.
- Ultra-cold antihydrogen(10uK : initial velocity<1m/s)
- Photo-detachment of positron
- $\bar{g} = \frac{2h}{(\Delta t)^2}$

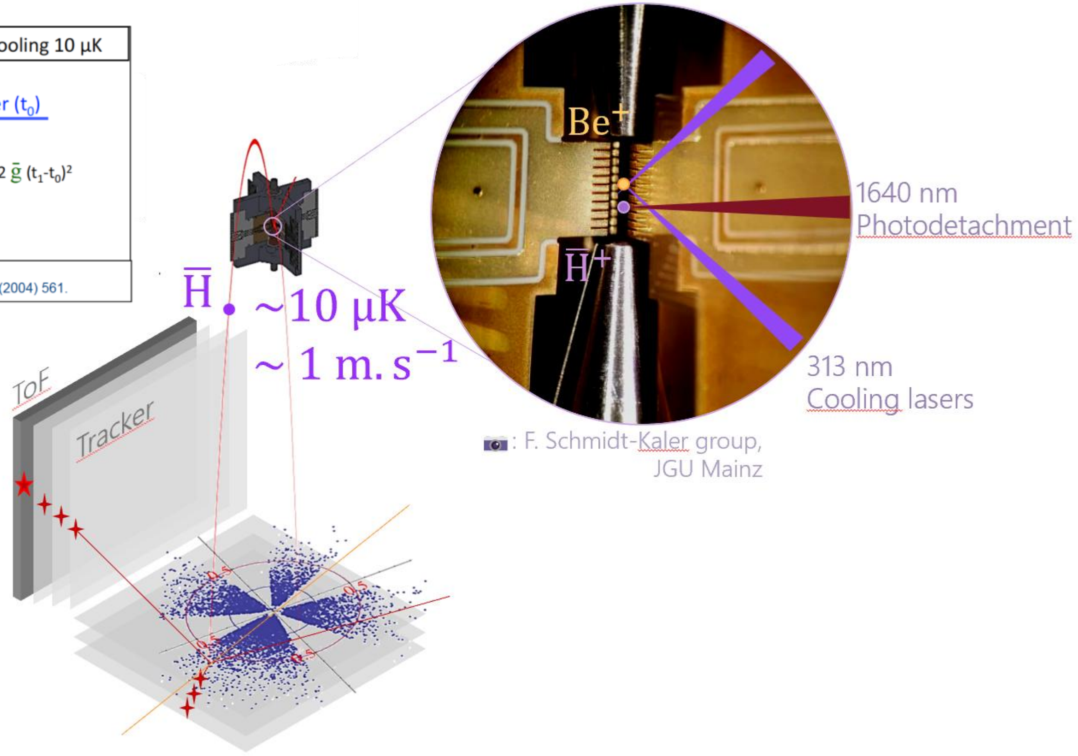


J.Walz & T. Hänsch,
General Relativity and Gravitation, **36** (2004) 561.

GBAR experiment concept







- Double charge exchange process between anti-proton beam and dense positronium cloud (1x1x20mm^3 cavity)

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

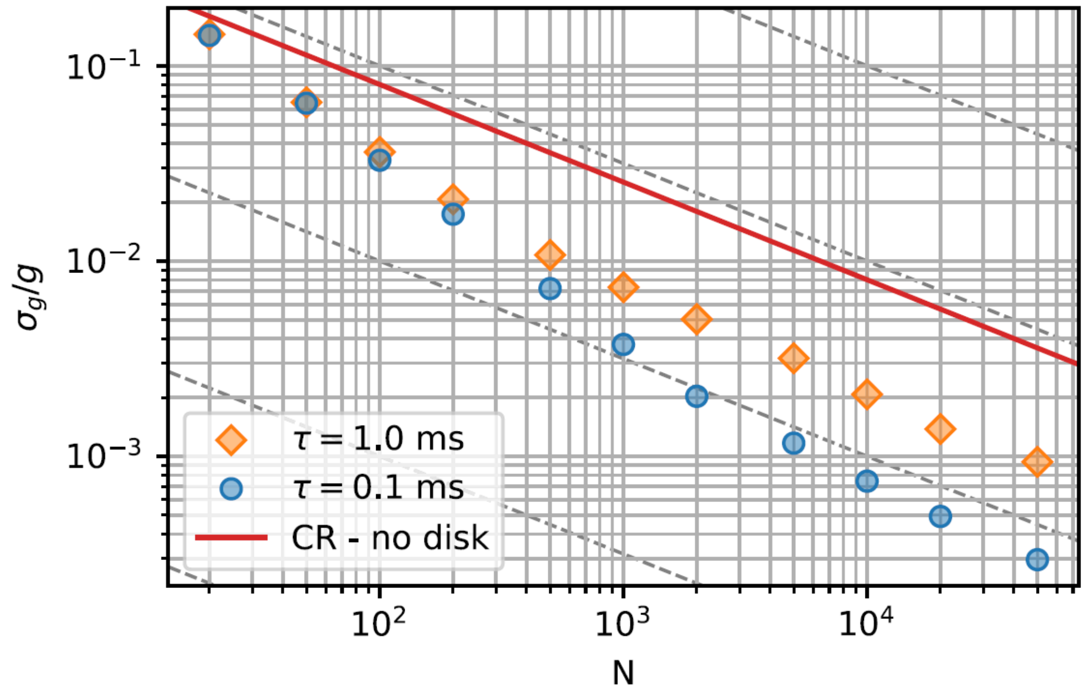
with

- 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**

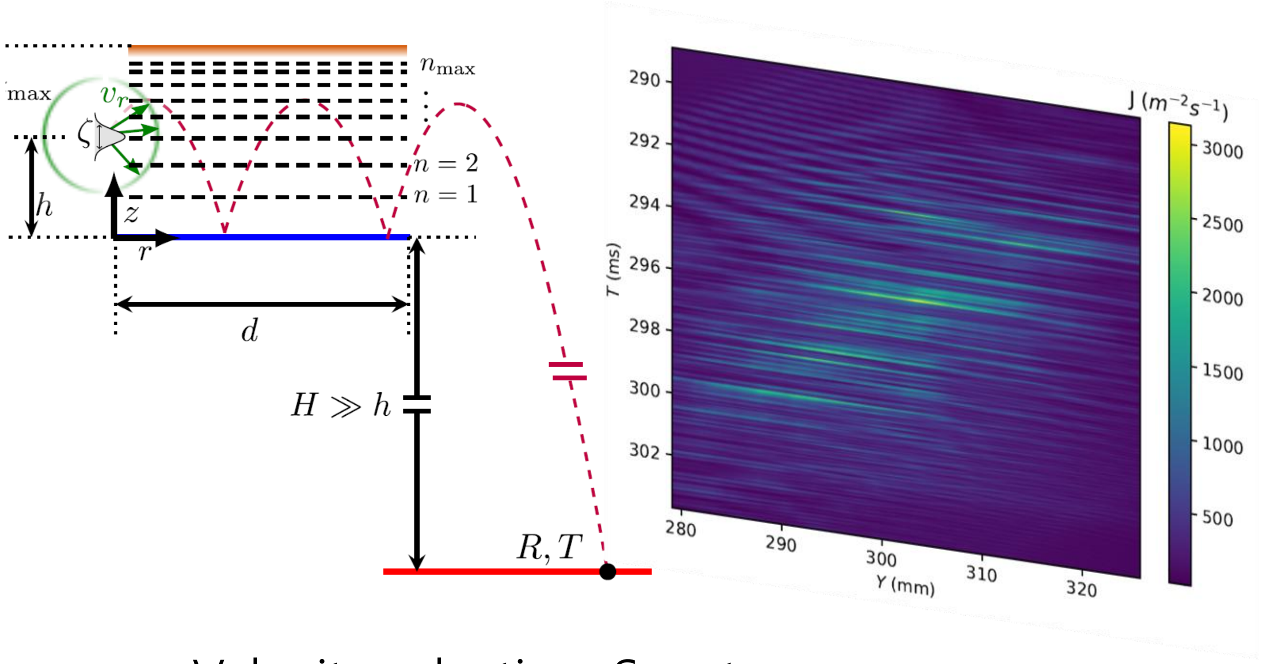
GBAR experiment concept

- Phase 1: 1 % precision on $\bar{g}$ with 500 $\bar{\mathrm{H}}$



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

- Phase 2: Gravitational Quantum States

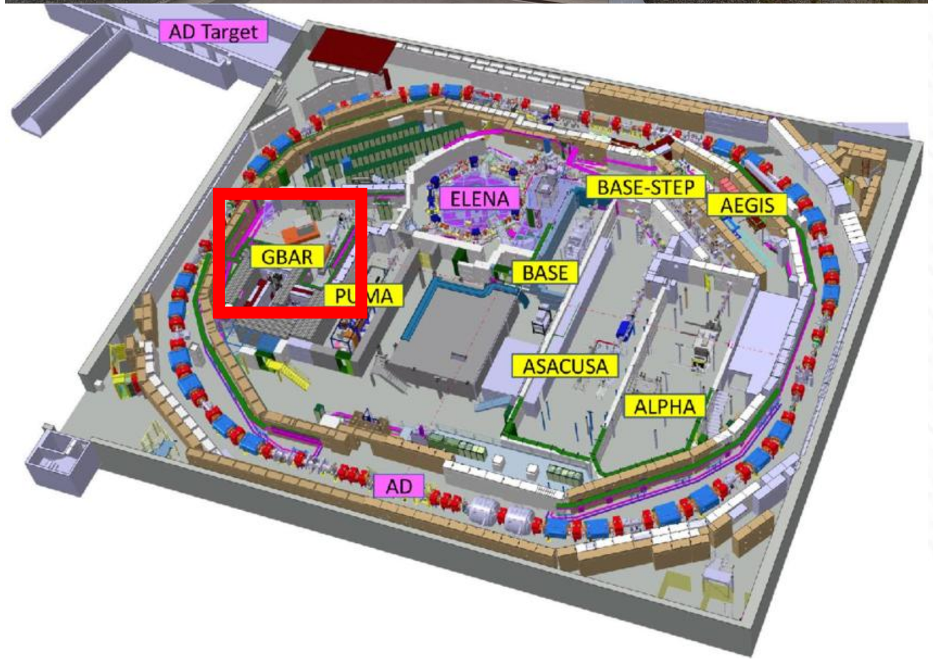


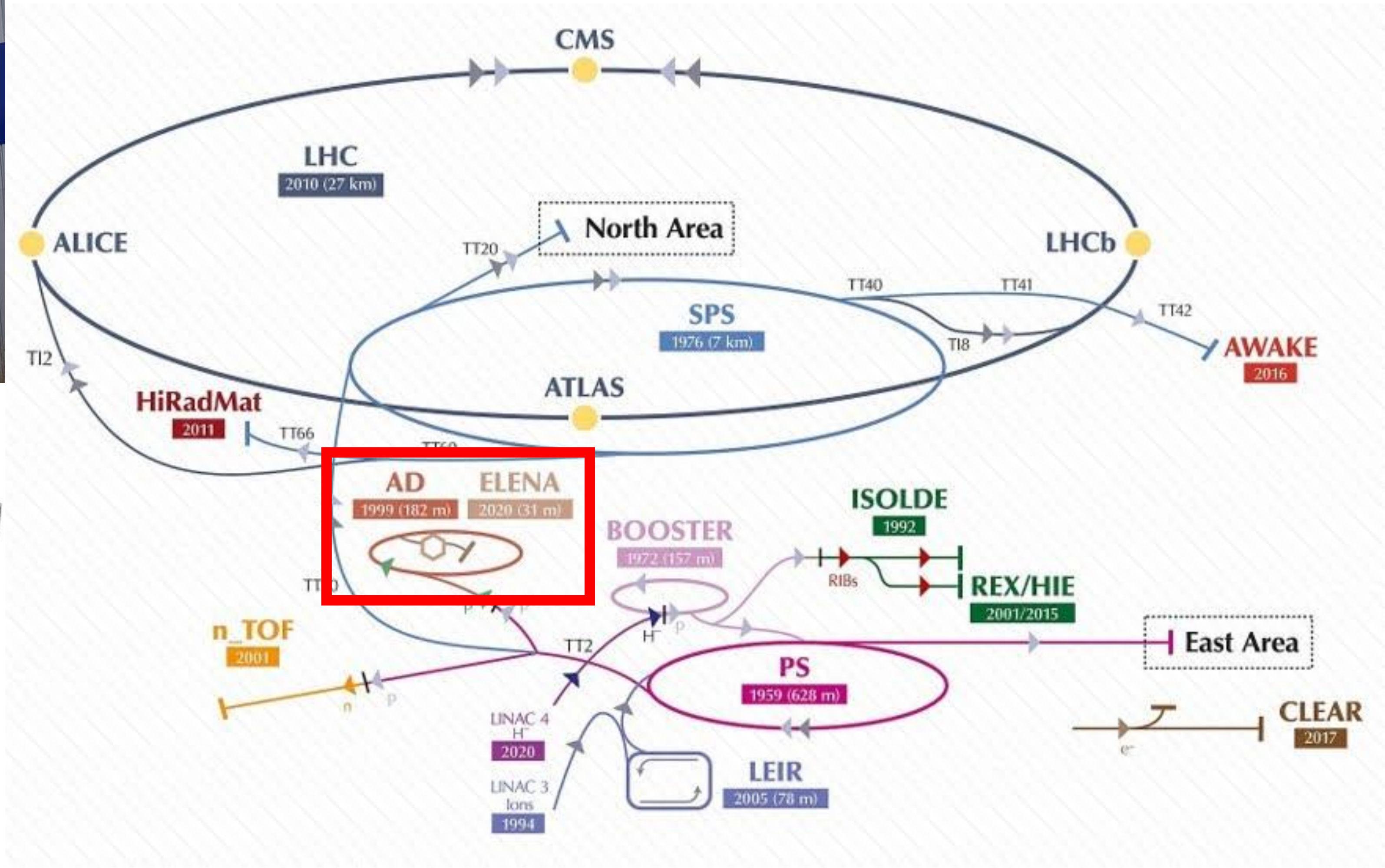
Velocity selection, Spectroscopy
Interferometry: at least 10^{-5} precision

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

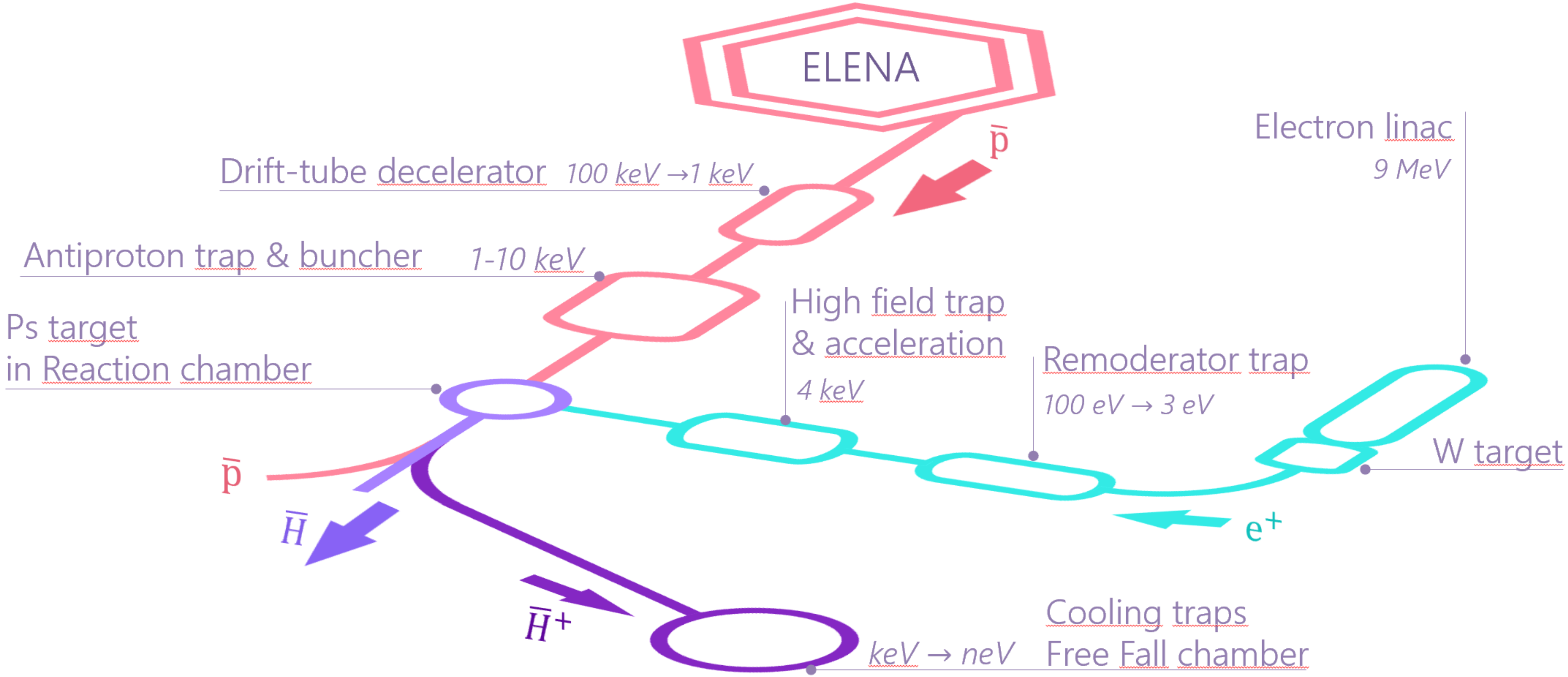
GBAR experimental apparatus

Experiment scheme

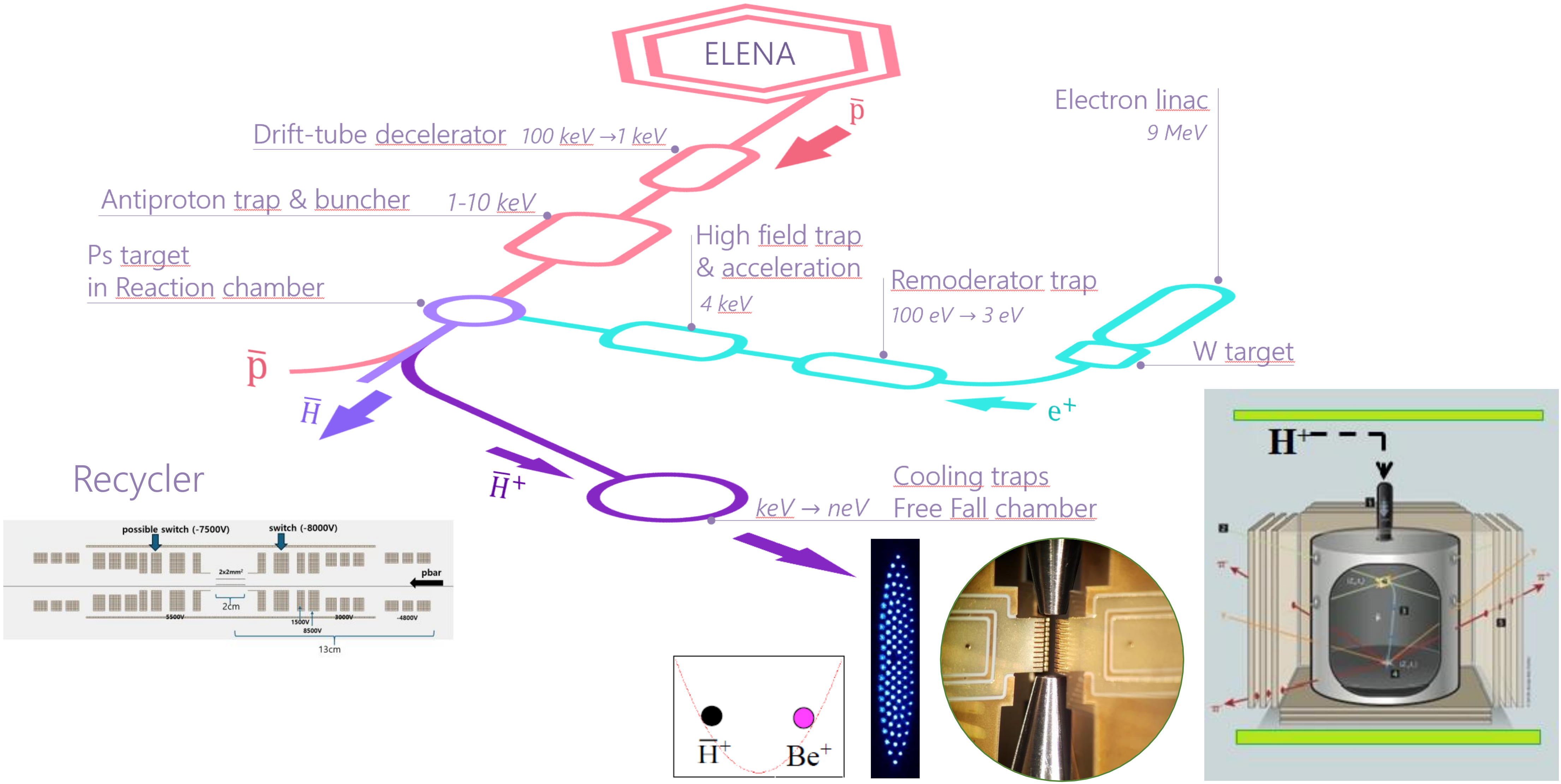




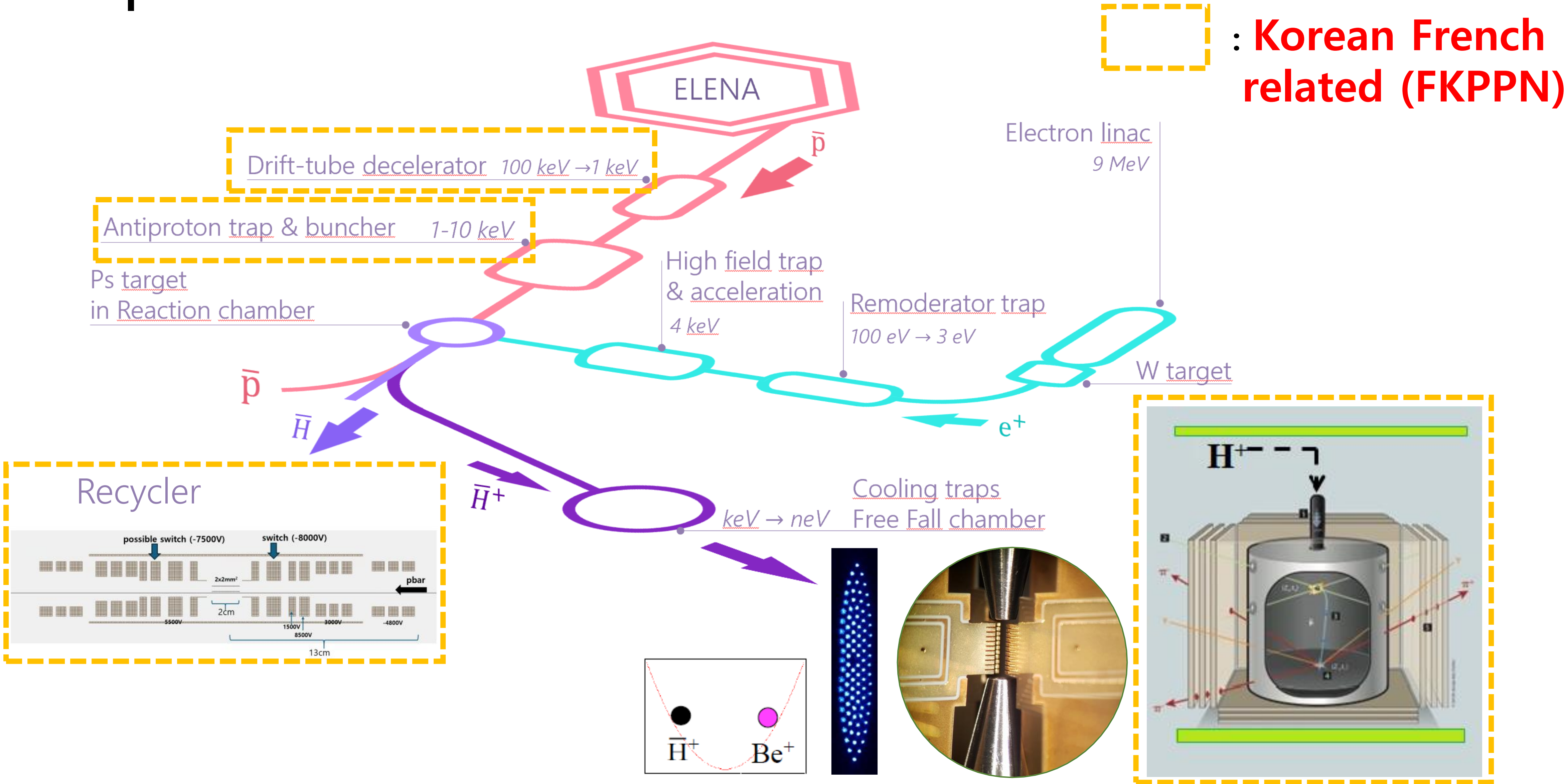
Experiment scheme



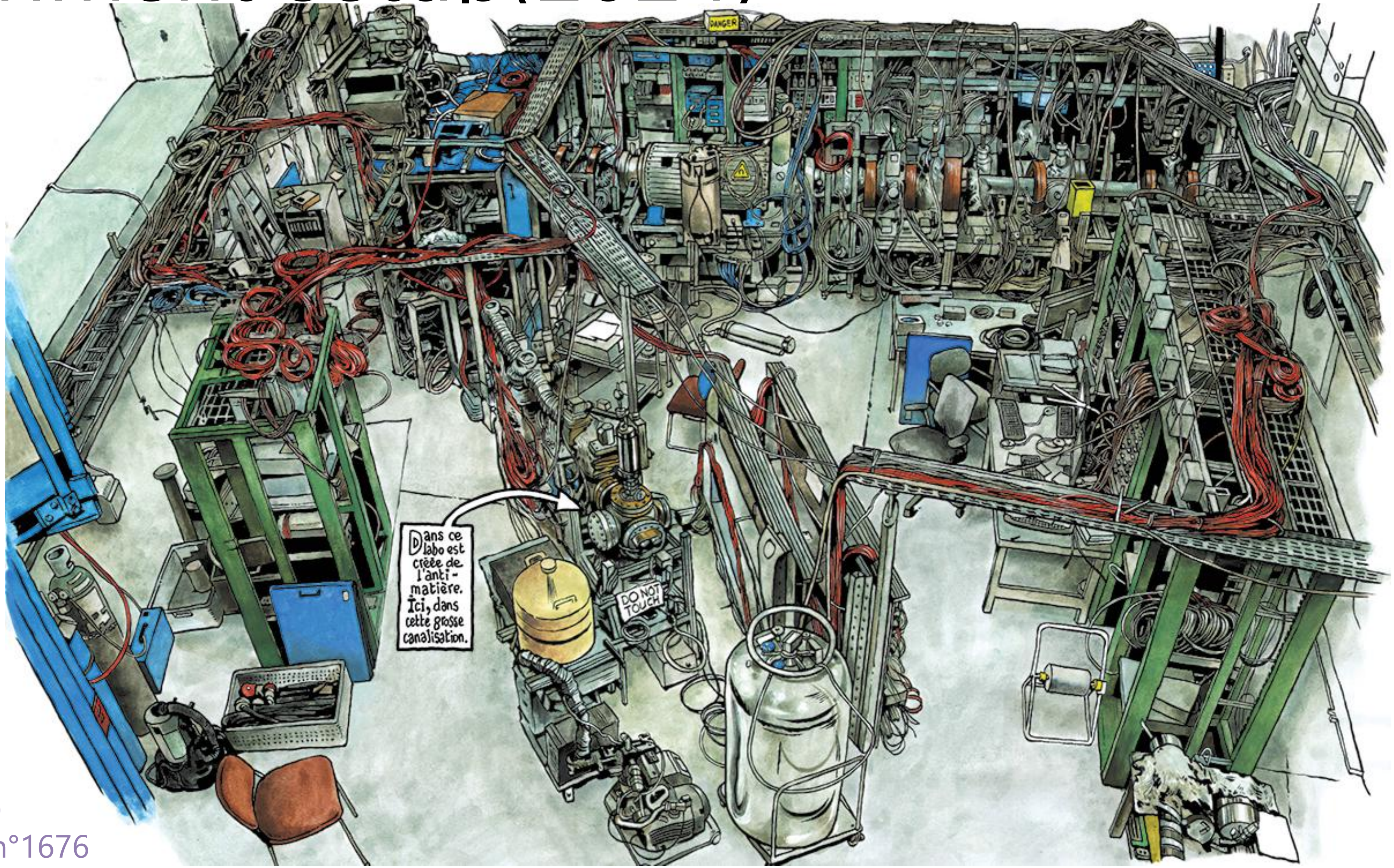
Experiment scheme



Experiment scheme

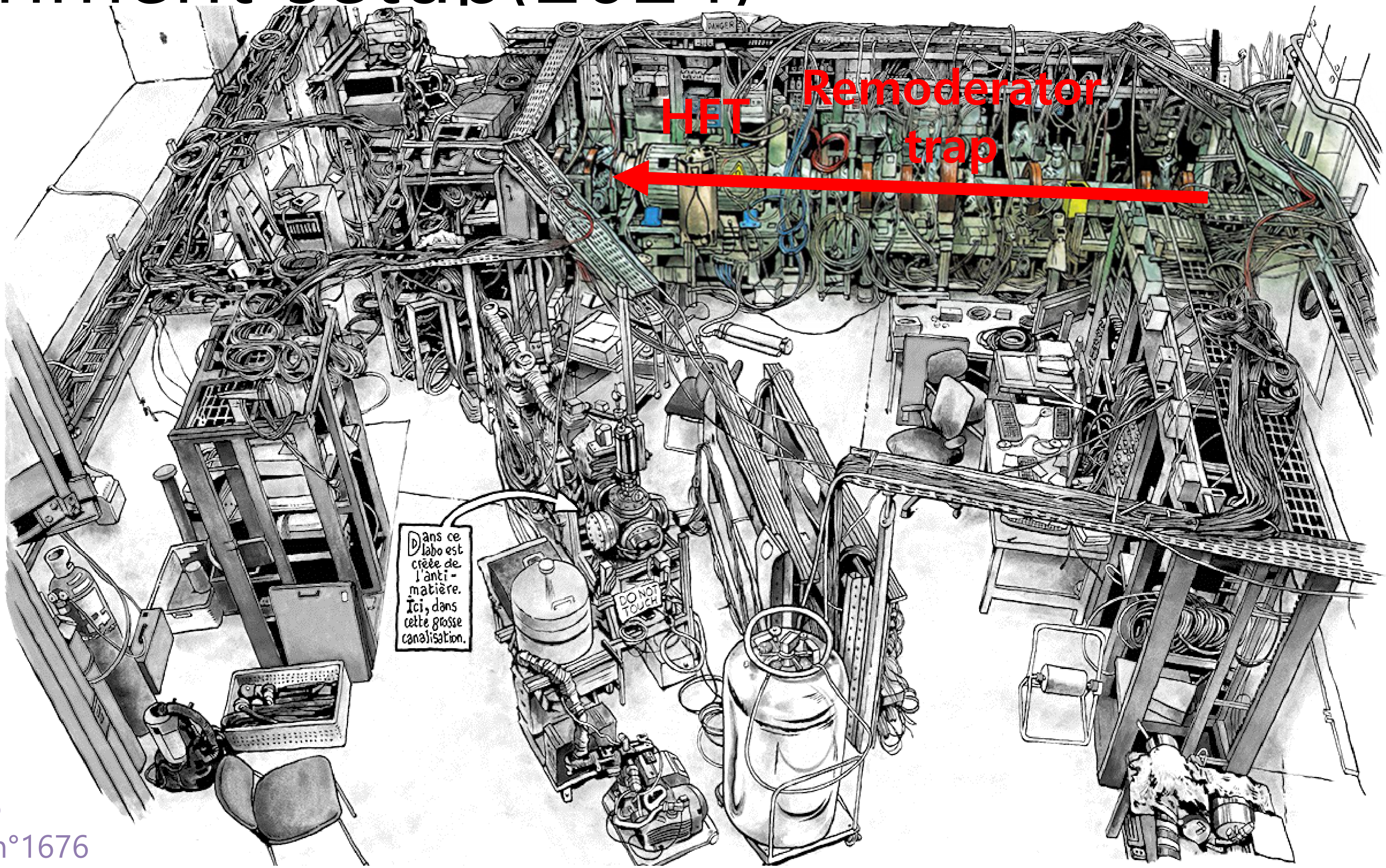


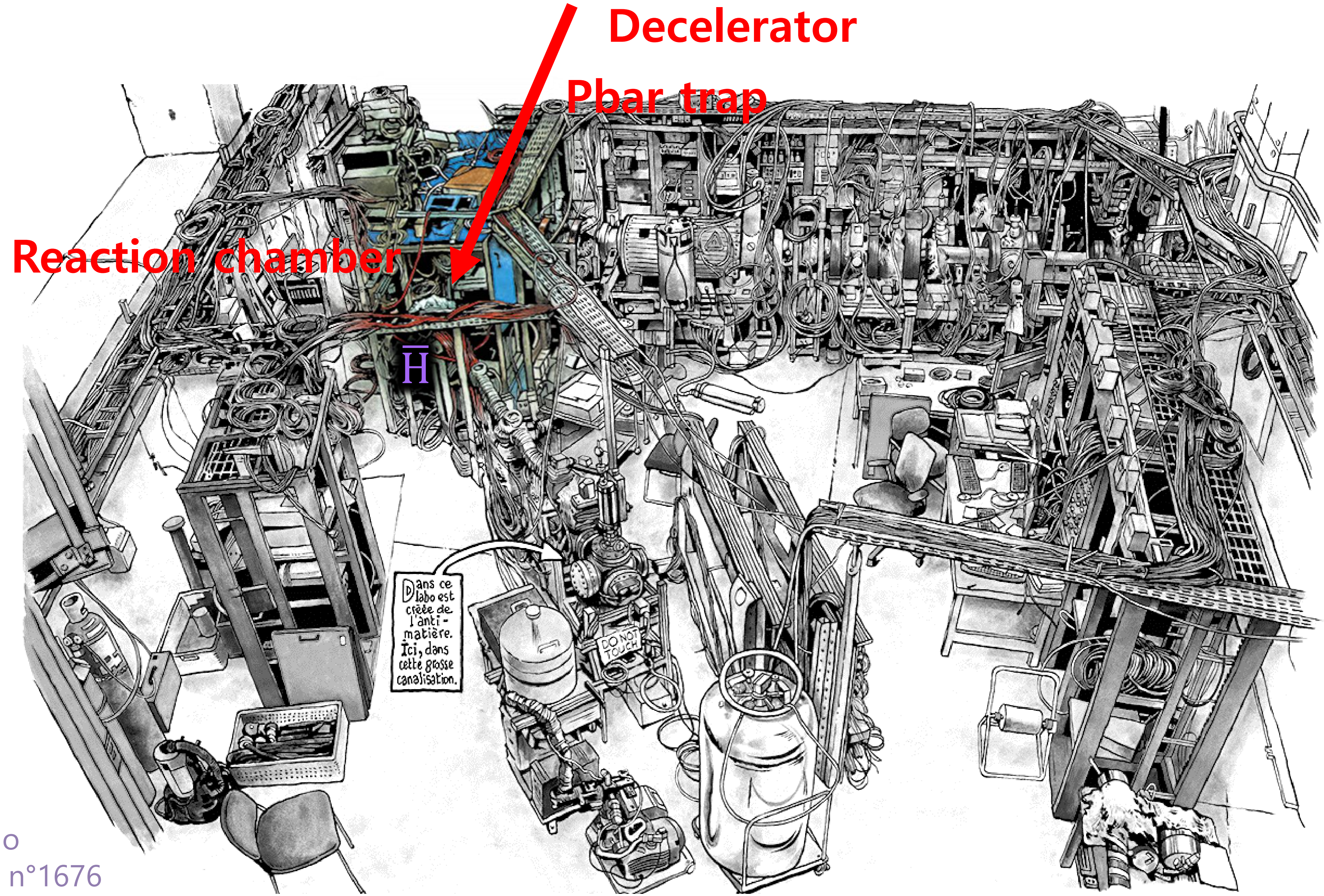
Experiment setup(2024)



Charlie Hebdo, n°1676

Experiment setup(2024)





Charlie Hebdo, n°1676

GBAR experimental apparatus

Positron beam line

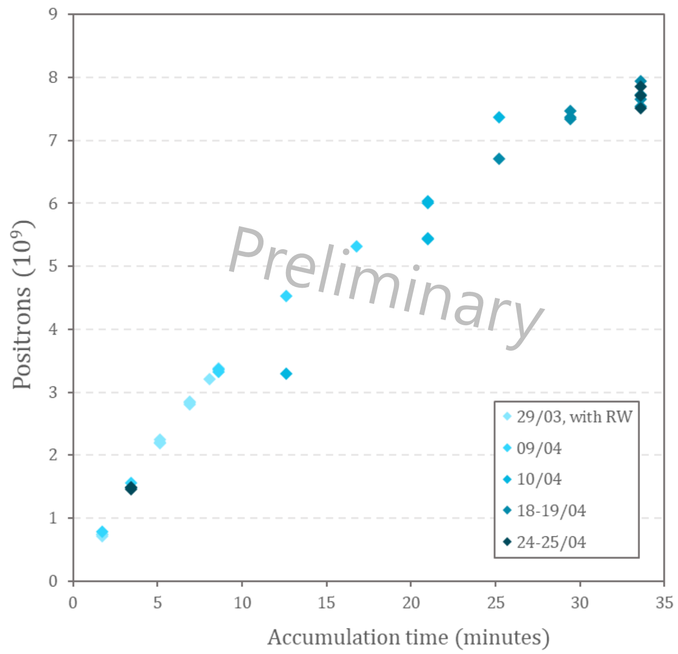
Positron beam line

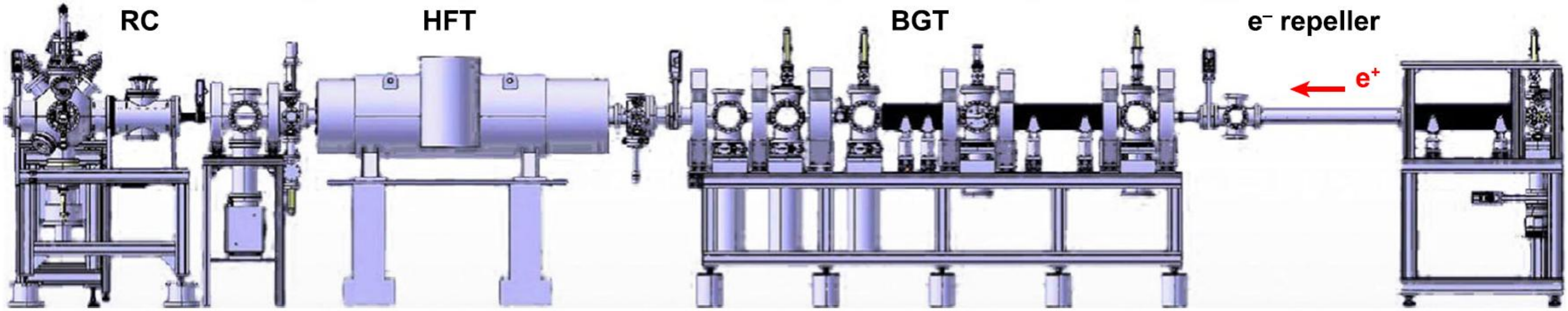
- **LINAC** → Impinges electrons on a W target + moderator

  → $3 \times 10^7 e^+/s$

e^+ accumulation

- $6 \times 10^8 e^+$ per AD/ELENA cycle(~2min)
- Record accumulation of more than $7 \times 10^9 e^+$ in 30min

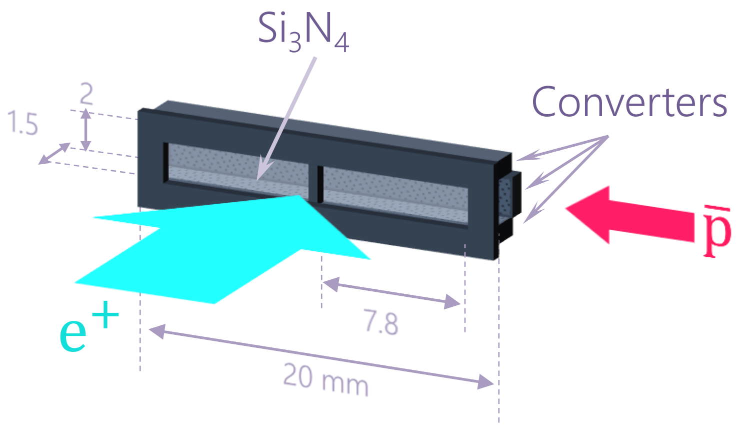


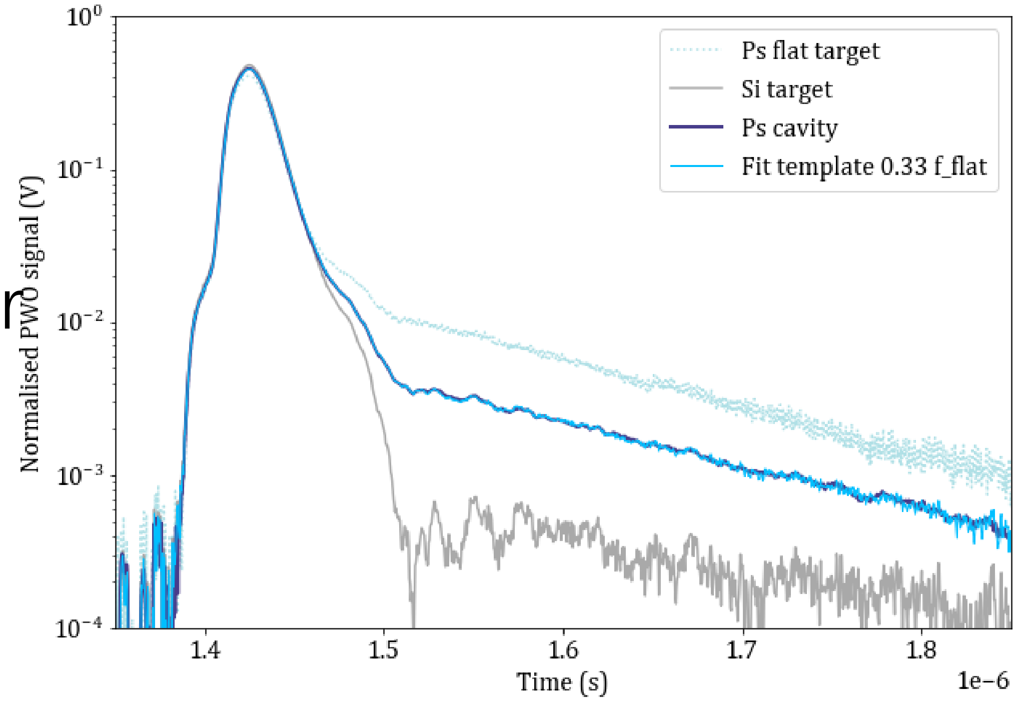


Positron beam line

- Confinement of more than 5×10^6 oPs in a tubular target(2mm x 1.5mm x 20mm) out of 7×10^7 e^+ on target area.

- Re-designed Ps cavity (2023) for higher positron acceptance and better e^+ to Ps conversion efficiency





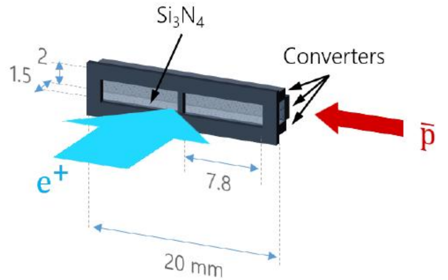
GBAR experimental apparatus

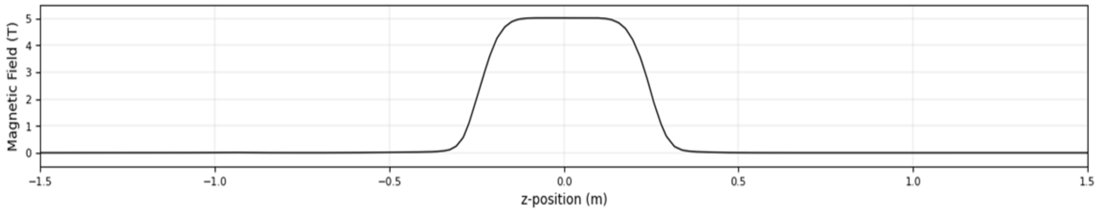
Antiproton beam line

Antiproton beam line

$\bar{\mathrm{p}} + \mathrm{Ps} \rightarrow \bar{\mathrm{H}} + \mathrm{e}^-$

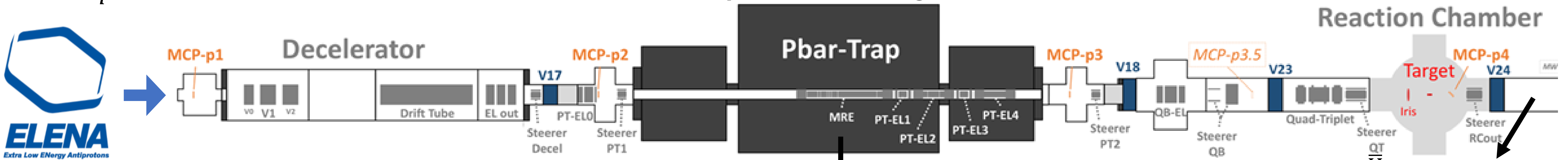
$\bar{\mathrm{H}} + \mathrm{Ps} \rightarrow \bar{\mathrm{H}}^+ + \mathrm{e}^-$





Penning-Malmberg Trap with a 5T Magnet

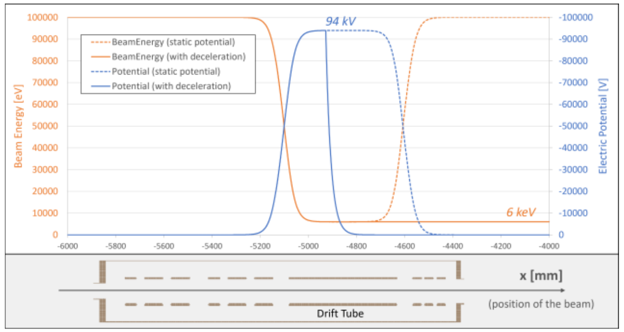
100keV $\bar{p}$

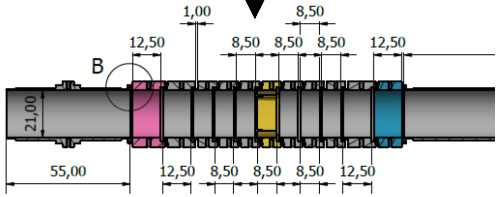


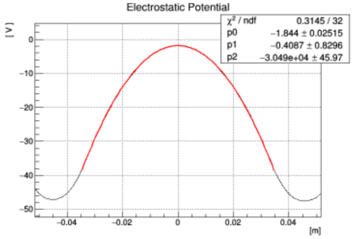
$\bar{\mathrm{H}}$
candidate

Dirft tube Decelerator

$\bar{p}$: 100keV → 1-10 keV

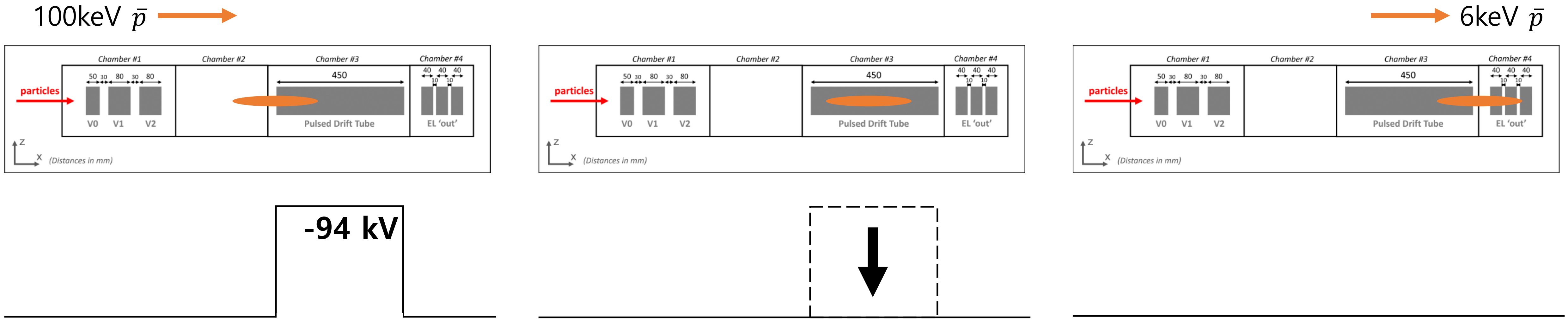






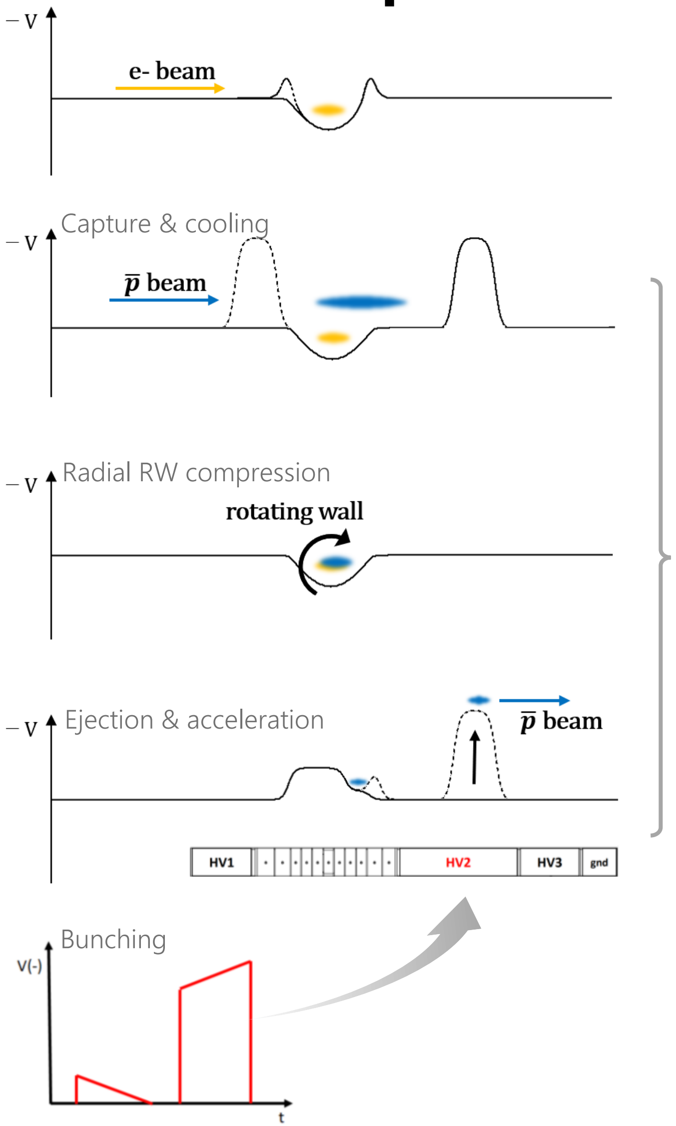
C. Roumegou, PhD thesis, Universite Paris-Saclay (2023)

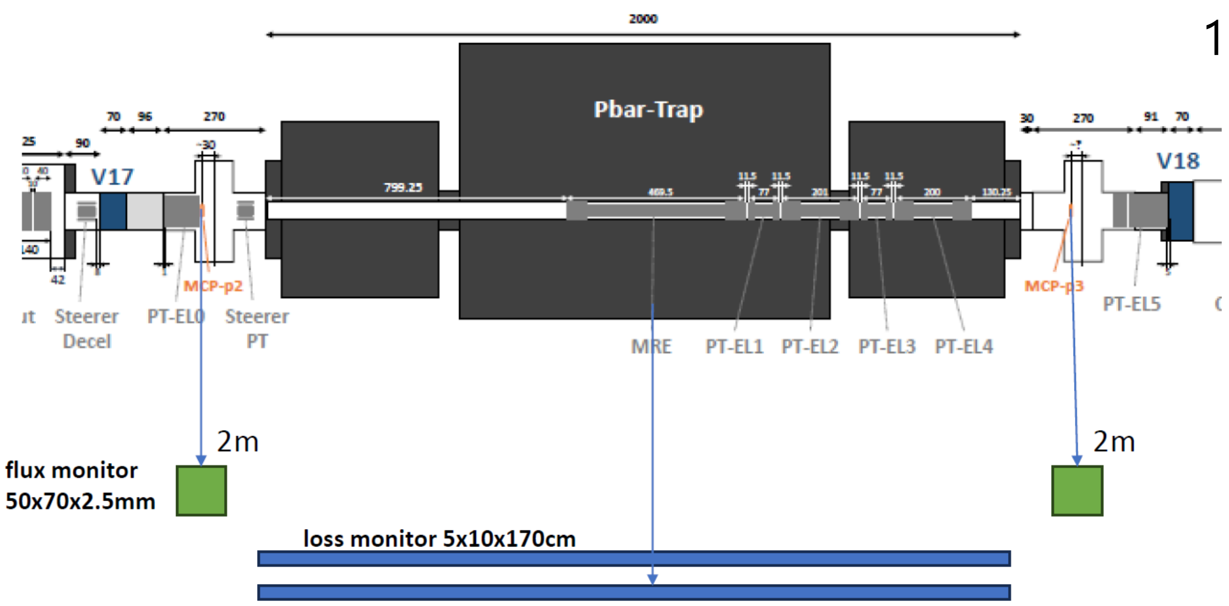
Decelerator



- GBAR decelerator – Prof. David Lunney developed.
- 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



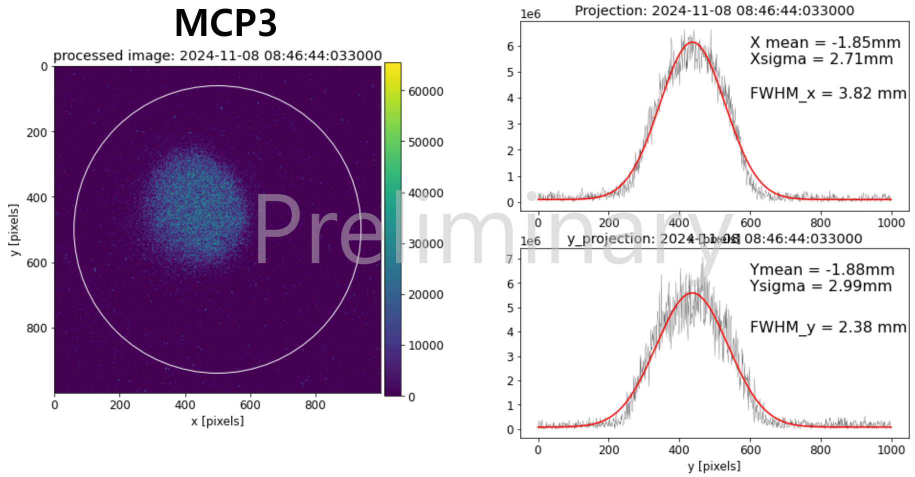


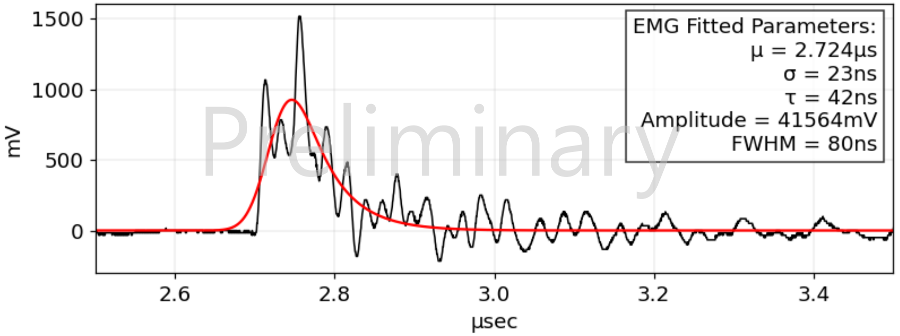
- Penning-malmberg trap (5T; 7T max) for antiproton beam reprocessing
- Function : Trapping, cooling, compression, acceleration, bunching and accumulation
- Goal : Producing antiproton beam with good beam parameters (higher intensity with accumulation, good phase-space & time spread for double charge reaction, small energy spread, etc)

Antiproton trap

- 6keV Beam Parameters at MCP3 (2024)

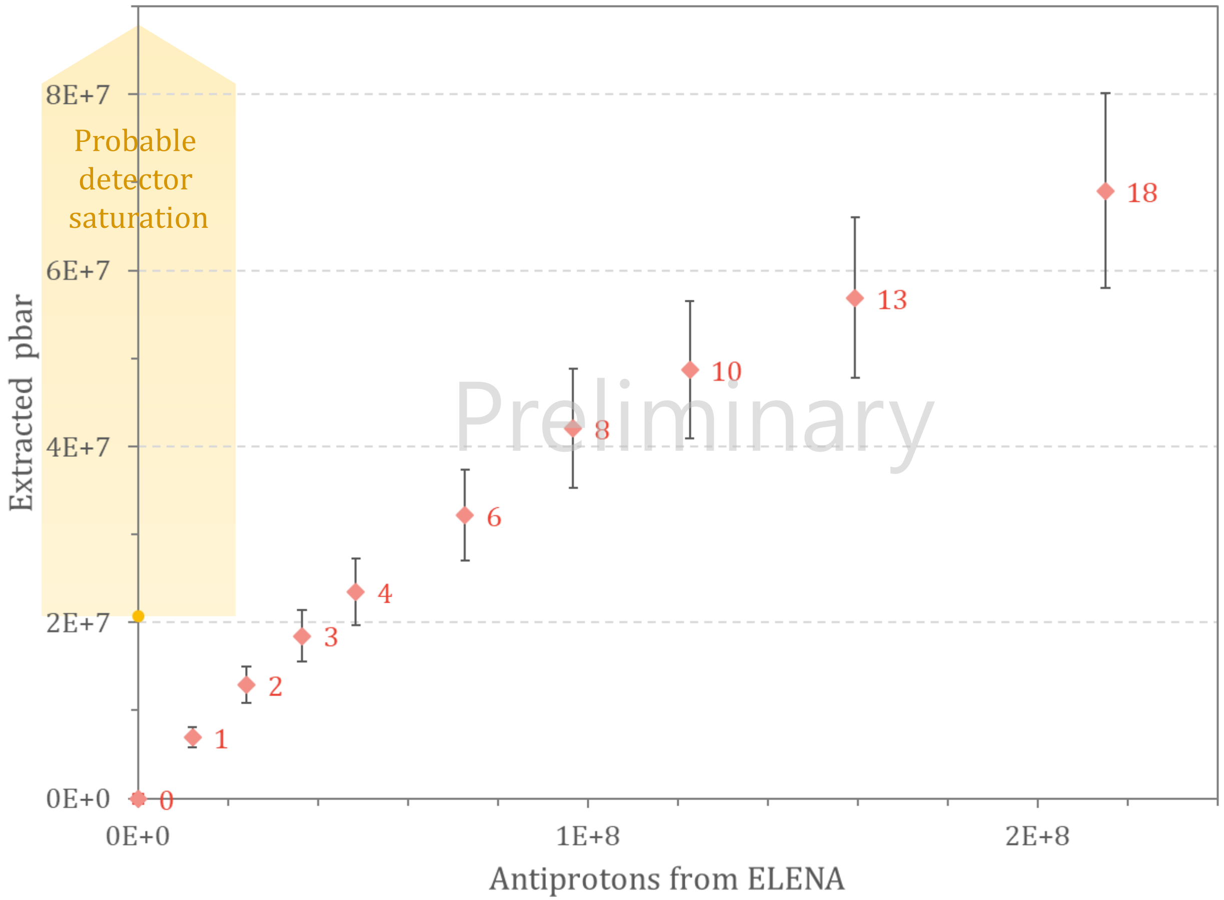
- Beam Intensity : 4.9x10^6(Num of pbar)
- Extraction efficiency(/ELENA) : 43%
- Beam size(σ_x) : 2.71mm
- Beam size(σ_y) : 2.99mm
- Bunch length(FWHM) : 80ns



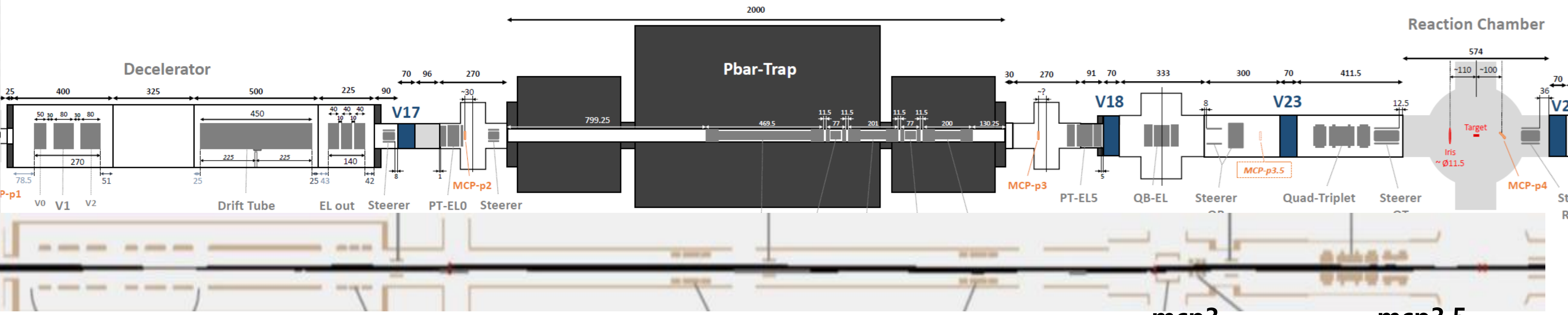


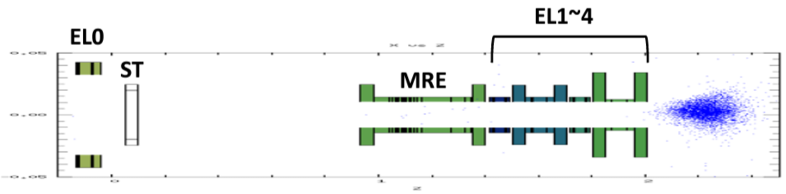
Antiproton trap

- Accumulation and extraction of up to $7x10^7$ pbar



Antiproton beam line guiding

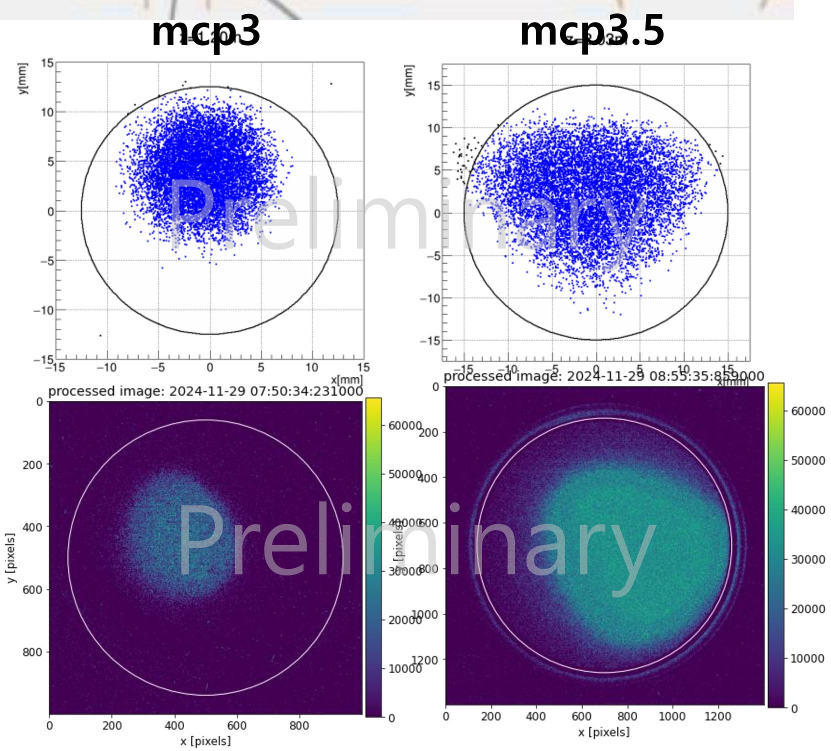




- General beam guiding simulation (French)
- Beam generation and local(after trap) guiding simulation (Korean)

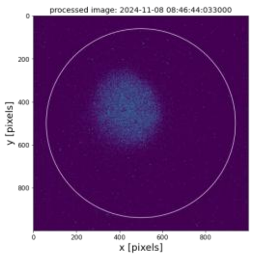
WARP

DATA

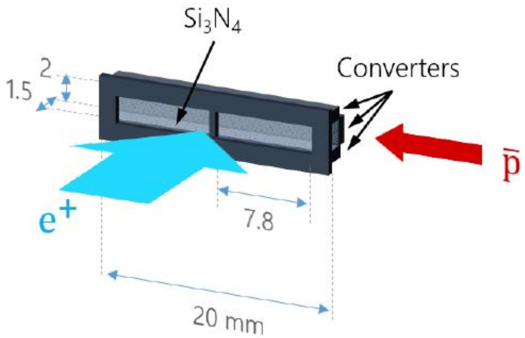


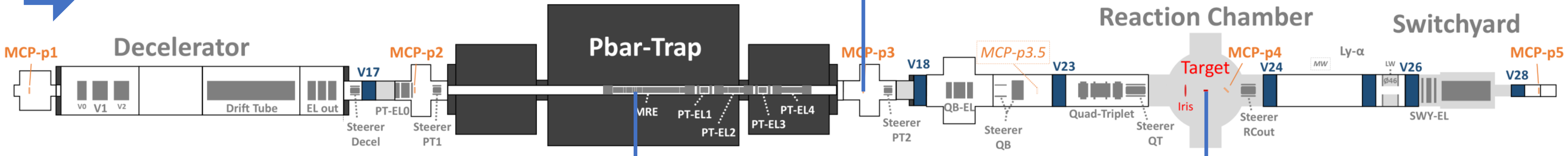
Antiproton beam line guiding

ELENA
$(10\sim12)\times10^6\bar{p}$
per 2min



Extraction 4 or 6keV $\bar{p}$
43%/ELENA(~5 x $10^6\bar{p}$)





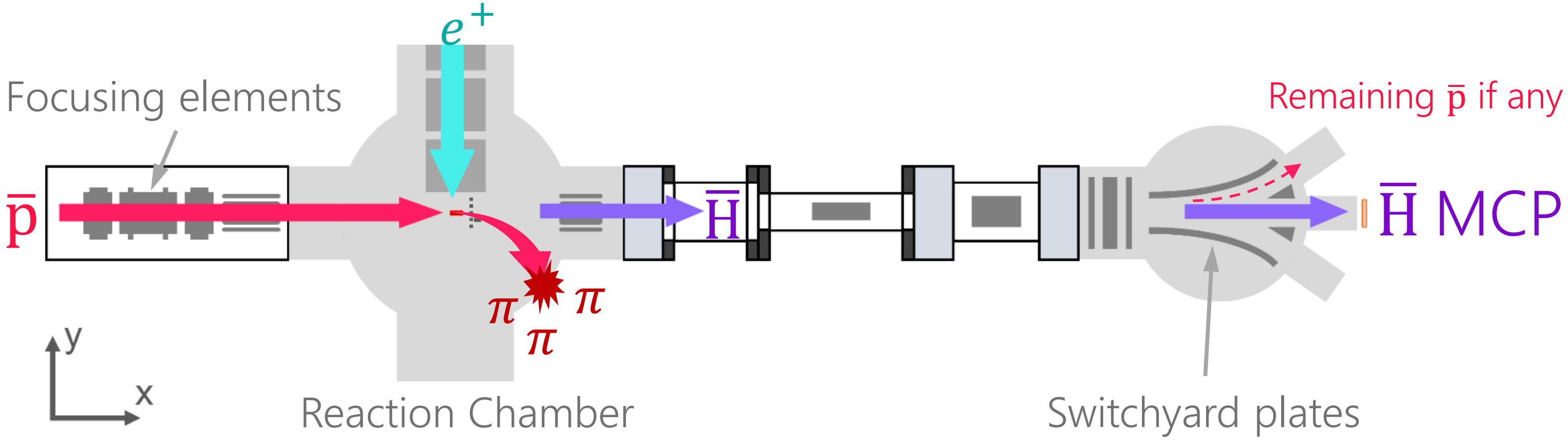
Trapping cold $\bar{p}$
55%/ELENA ($\sim6\times10^6\bar{p}$)

Through the cavity target
6keV: $\mathbf{1\times10^6}\boldsymbol{\bar{p}}$ per ELENA pulse
4keV: $\mathbf{5\times10^5}\boldsymbol{\bar{p}}$ per ELENA pulse

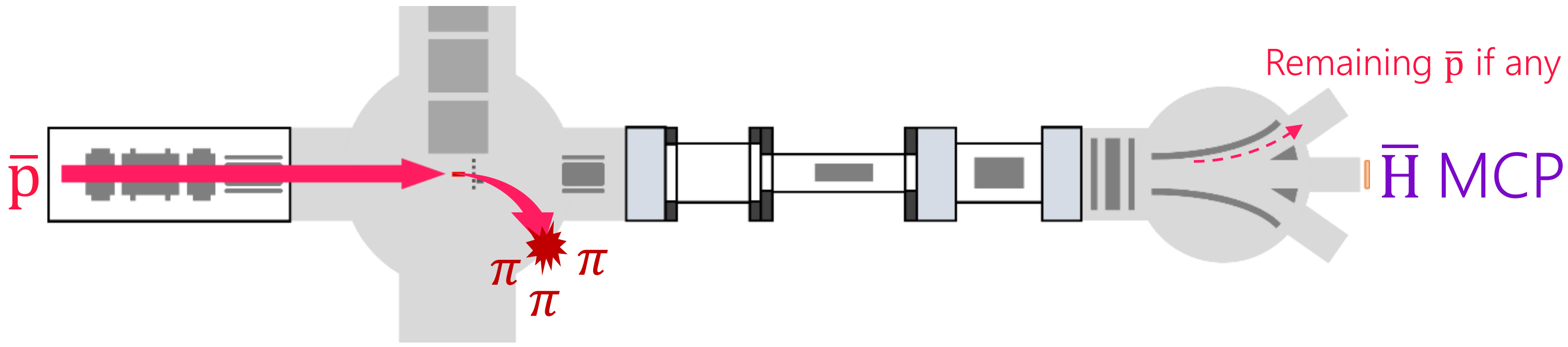
$\overline{H}$ production 2022 & 2024

$\bar{H}$ production

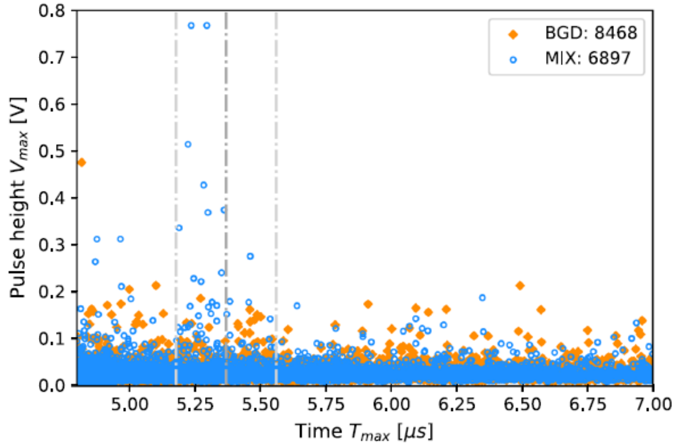
« Mixing » runs: $\bar{\mathrm{p}} + \mathrm{Ps(1S)} \rightarrow \bar{\mathrm{H}} + \mathrm{e}^{-}$

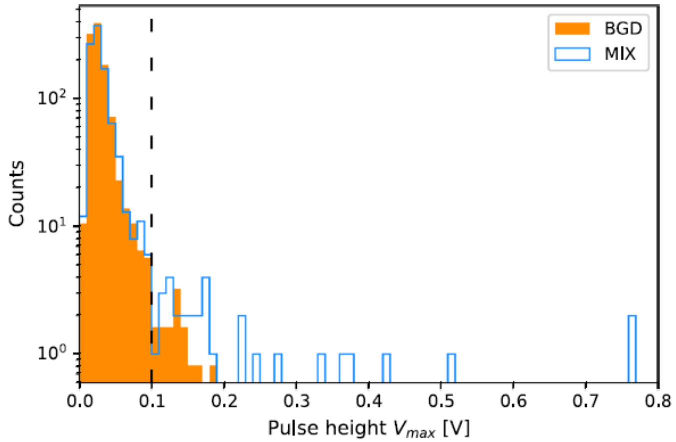


Background runs

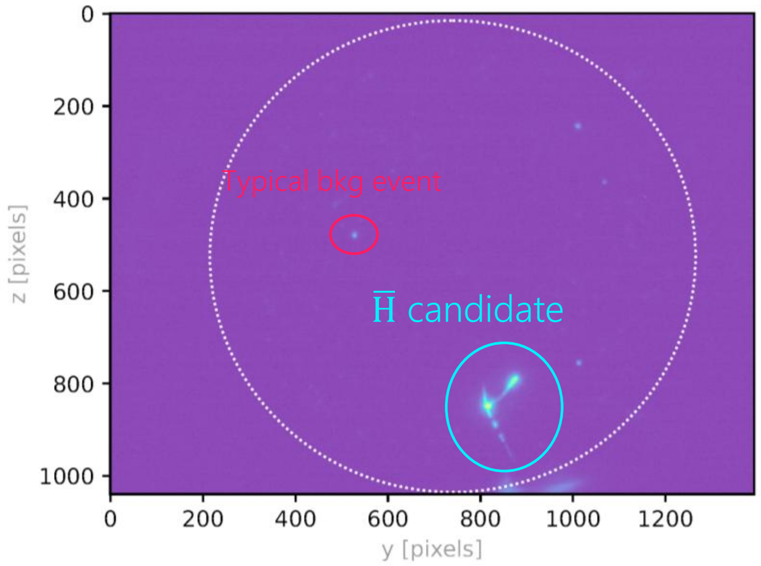


$\bar{H}$ production (2022)

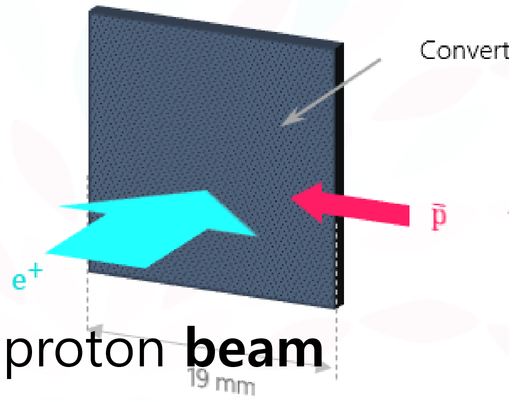




Eur. Phys. J. C 83, 10004 (2023)

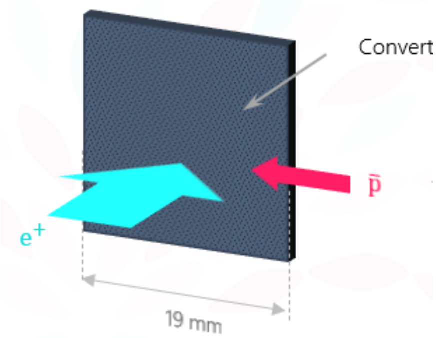


- Produced antihydrogen is detected above 3σ (which is **1st milestone**)
- About 6.8x10^6 oPs (5x10^7 e$^+$) and 3x10^6 $\bar{p}$/ELENA pulse(~2min)
- 17~20$\bar{\mathrm{H}}$ for 7000 shots of 'Mixing' ~0.003$\bar{\mathrm{H}}$/ELENA pulse(~2min)
- (First) production of antihydrogen by charge exchange between o-Ps and antiproton **beam**
- higher intensity with **better emittance** by antiproton trap required $\bar{H}^+$ **production** (**2nd milestone**)

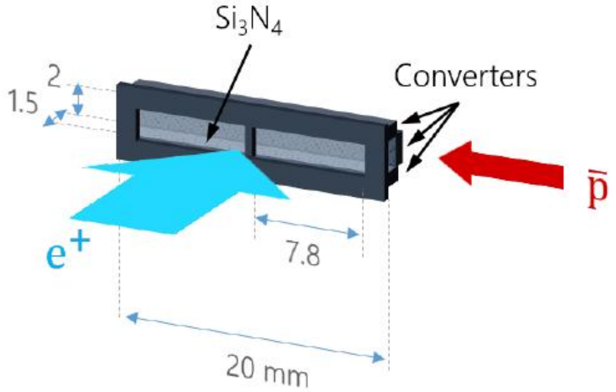


$\bar{H}$ production (2024)

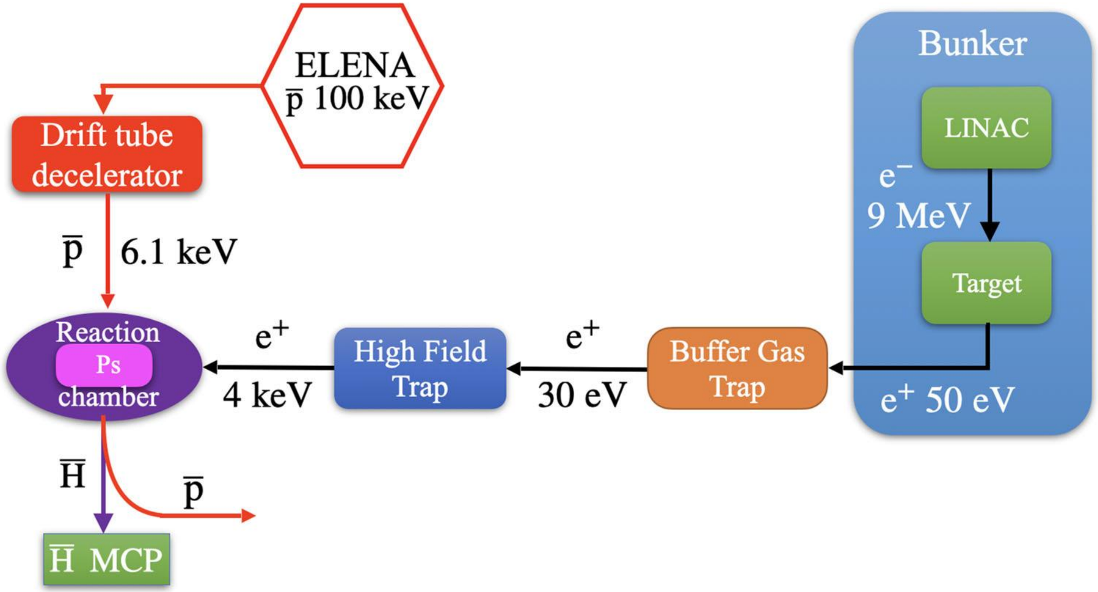
2022 Target



2024 Target

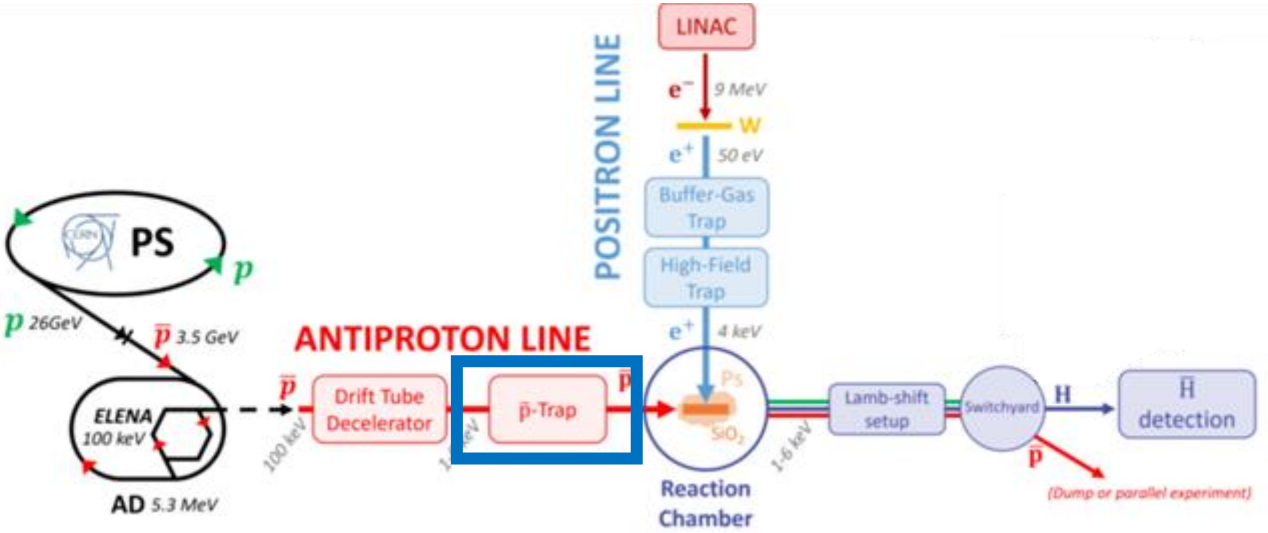


2022 configuration



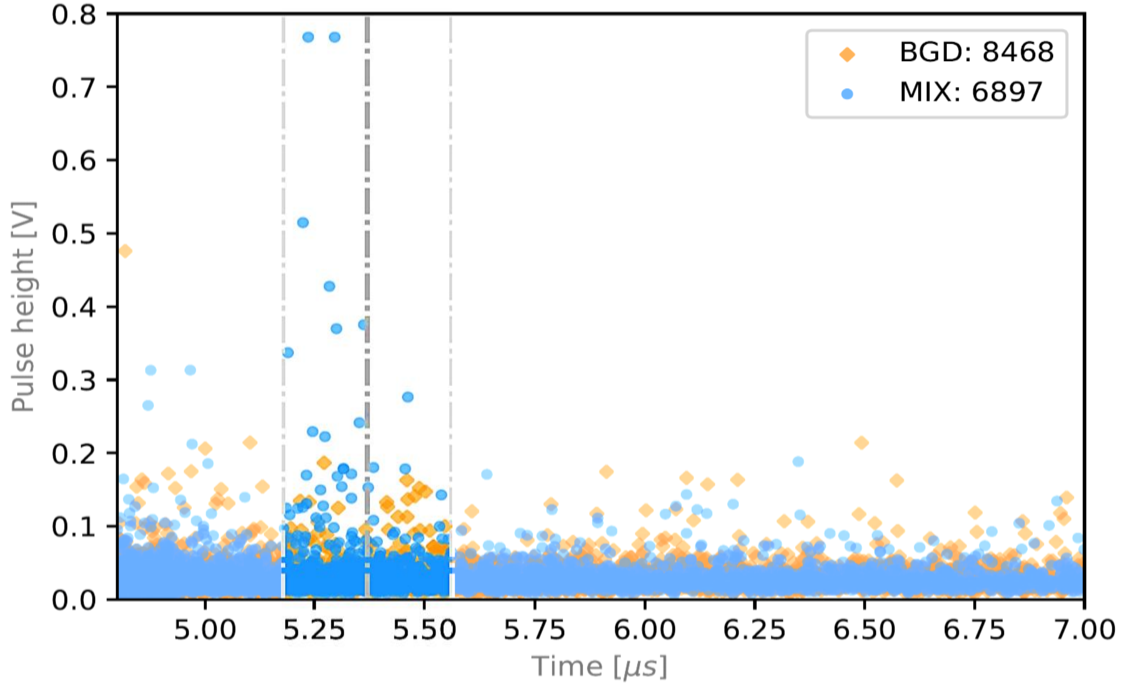
Eur. Phys. J. C 83, 1004 (2023)

2024 configuration

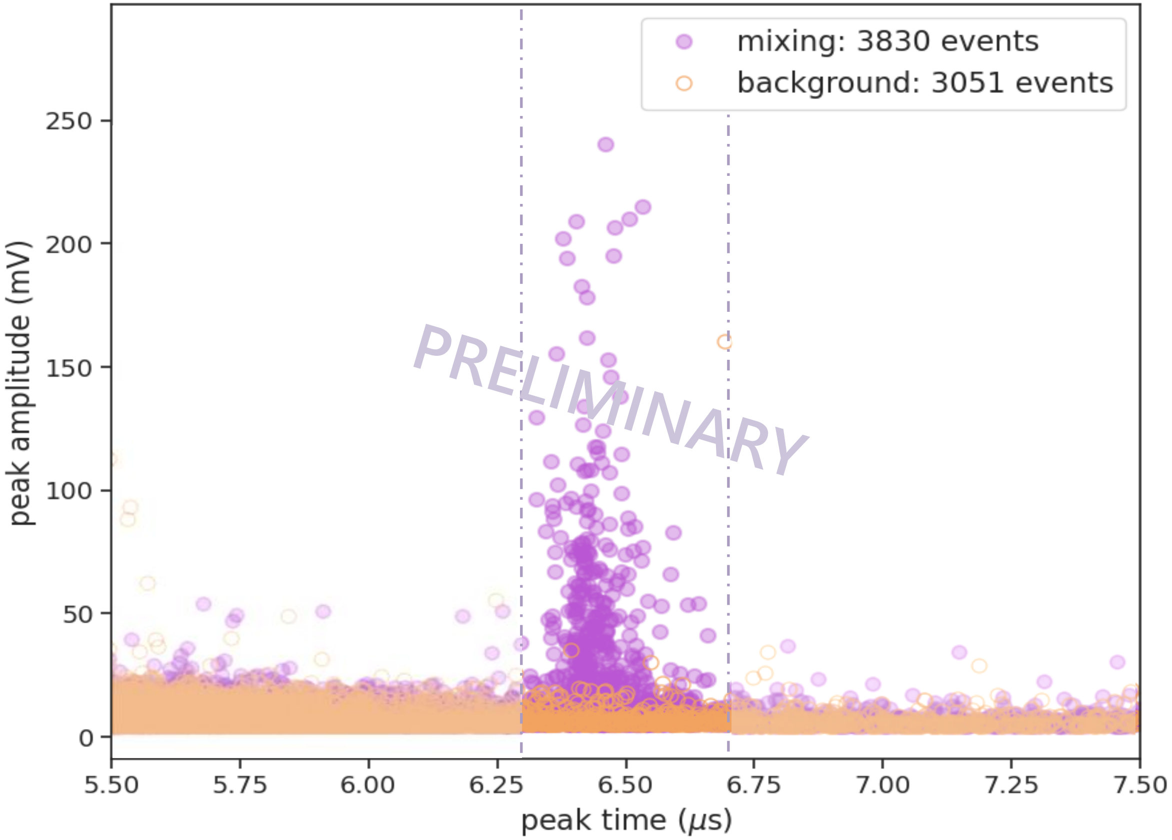


$\bar{H}$ production (2024)

- Antihydrogen production rate increased roughly by factor 30(preliminary)



P. Adrich et al. (The GBAR collaboration),
Eur. Phys. J. C **83**, 1004 (2023)



Future improvements
GBAR affiliation
Summary

Future improvements

- Positron transport efficiency between HFT and Ps target.
- Continue antiproton trap developments
- SPHINX(Study of Positronium Hydrogen Interactions - Negative hydrogen production Cross Sections) project
- Recycler

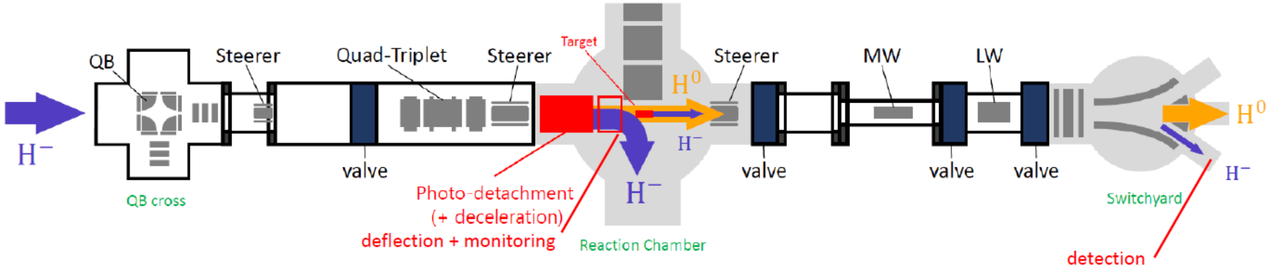
SPHINX project

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

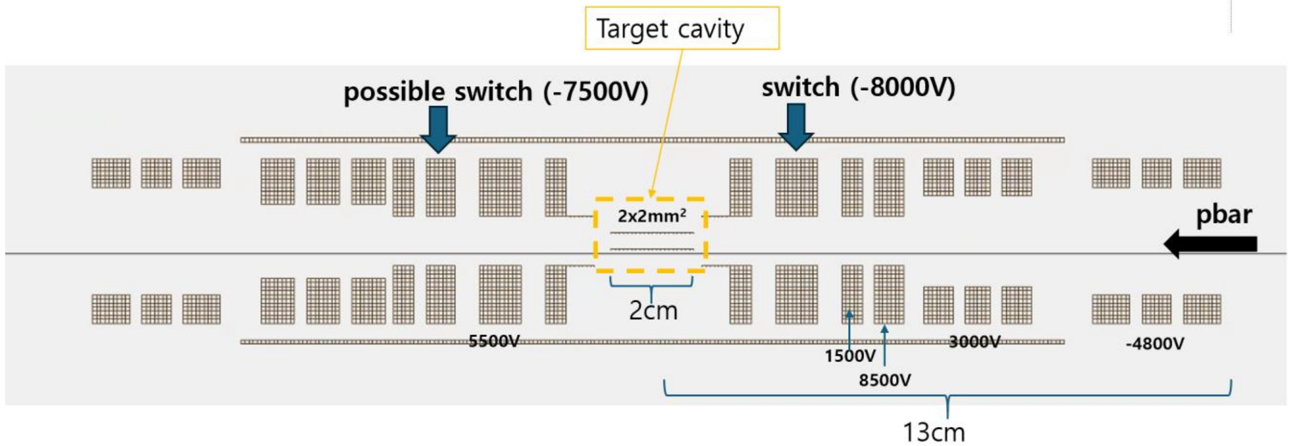
$$\Downarrow$$

$$\mathrm{H} + \mathrm{Ps} \rightarrow \mathrm{H}^{-} + \mathrm{e}^{+}$$

Idea: photodetached H^- beam from ELENA just before the interaction region to make pure H(1S) beam
Early form of the project first presented at the collaboration meeting in 2019



Charge filtering trap 2025

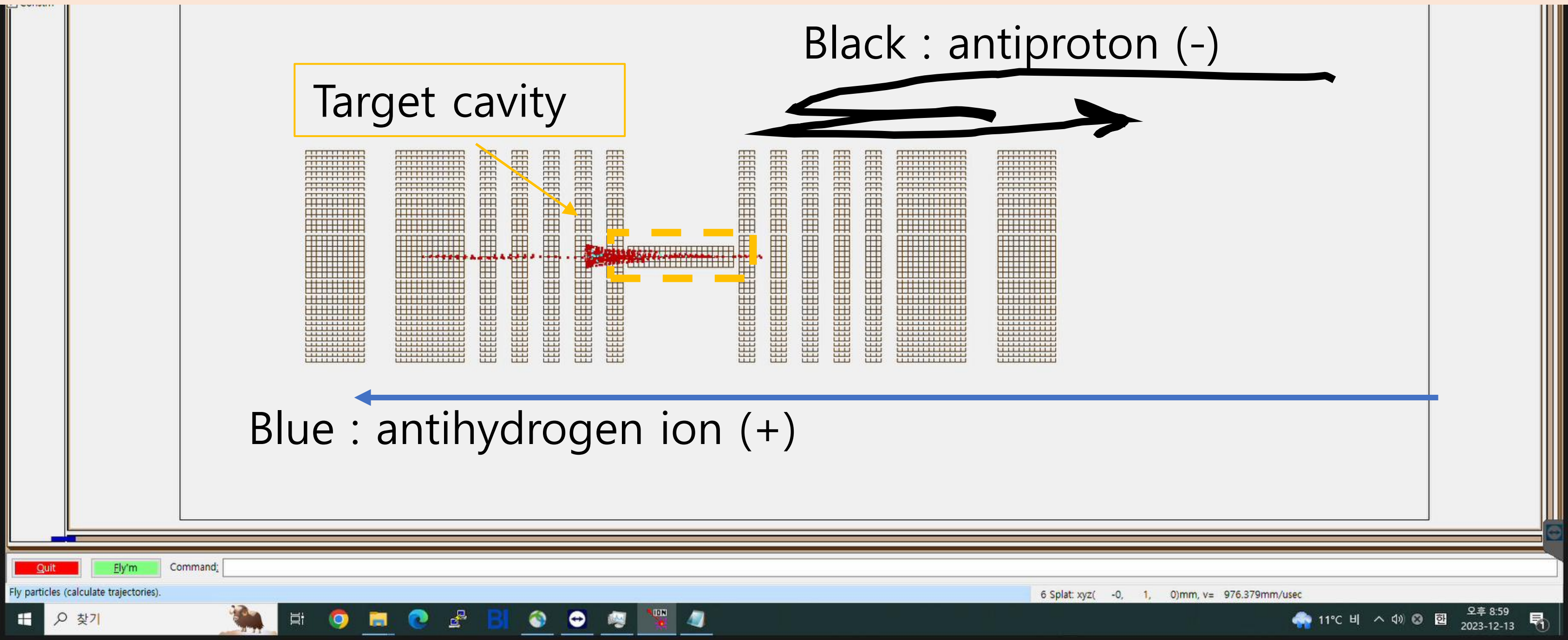


Charge filtering trap (2023)

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



GBAR affiliation

Related in FKPPN 2024

IJCLAB (French)
- David Lunney
- Sarah Geffroy

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

SNU (Korean)
- DongHwan Won
- Sunkee Kim

Summary

- The GBAR experiment aims to measure the gravitational acceleration of antihydrogen with a precision better than 1%.
- The first milestone has been achieved: successful production of antihydrogen via the reaction between antiprotons and positronium.
- French and Korean team has contributed significantly to whole antiproton beam line.
  - Development of the decelerator
  - The **antiproton trap -** antiproton beam reprocessing
  - The design of the recycler.
- All components are being continuously upgraded to support high-efficiency antihydrogen production & the second milestone.

Thank You!

Q&A