2024 Status report of the GBAR experiment

Pauline Comini
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on behalf of the GBAR Collaboration

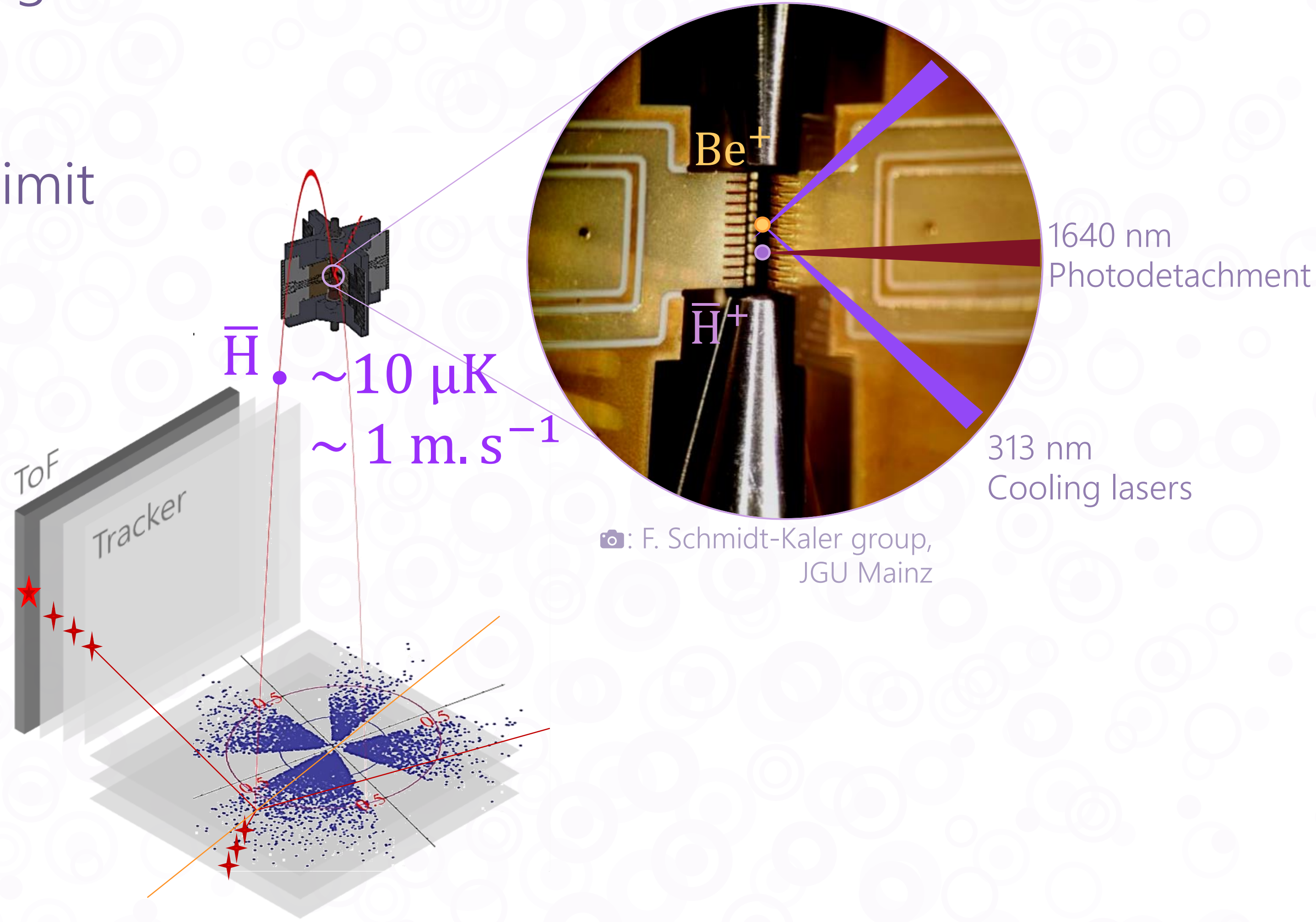
The GBAR experiment

Gravitational Behaviour of Antihydrogen at Rest

- Sympathetic cooling
  to go below H Doppler cooling limit

- Applied to $\overline{\mathrm{H}}^+$
  J. Walz & T. W. Hänsch,
  Gen. Relat. Grav. **36**, 561 (2004).

- Classical free fall
  after photodetachment
  near threshold

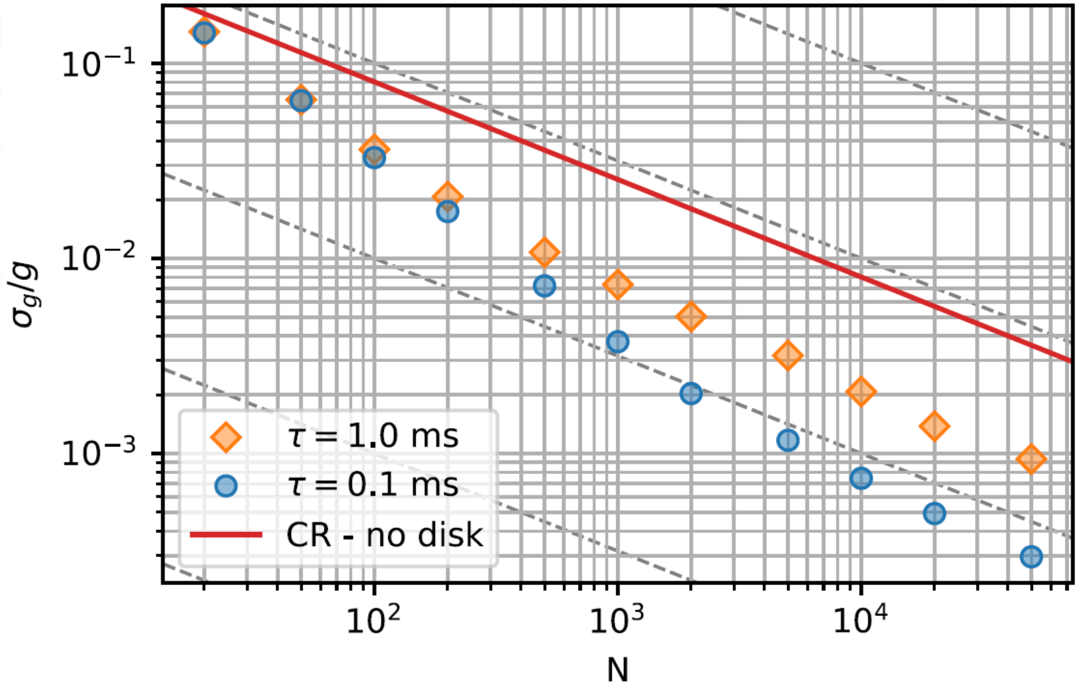


📷: F. Schmidt-Kaler group,
JGU Mainz

The GBAR experiment

Gravitational Behaviour of Antihydrogen at Rest

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

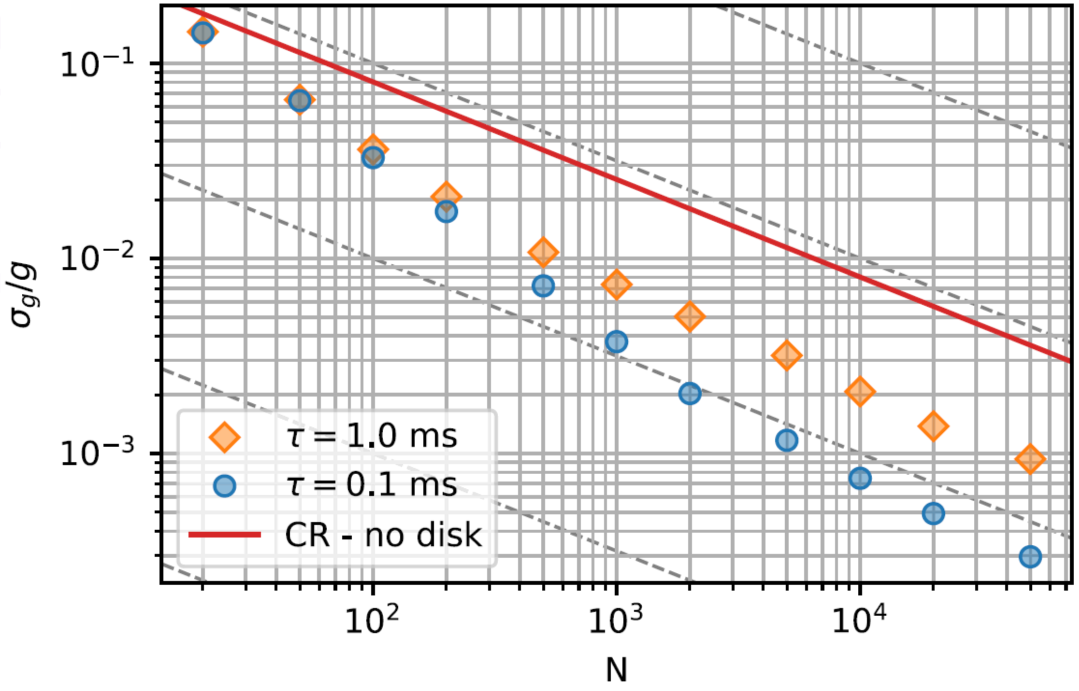


O. Rousselle *et al.*,
Phys. Rev. A **105**, 022821 (2022)

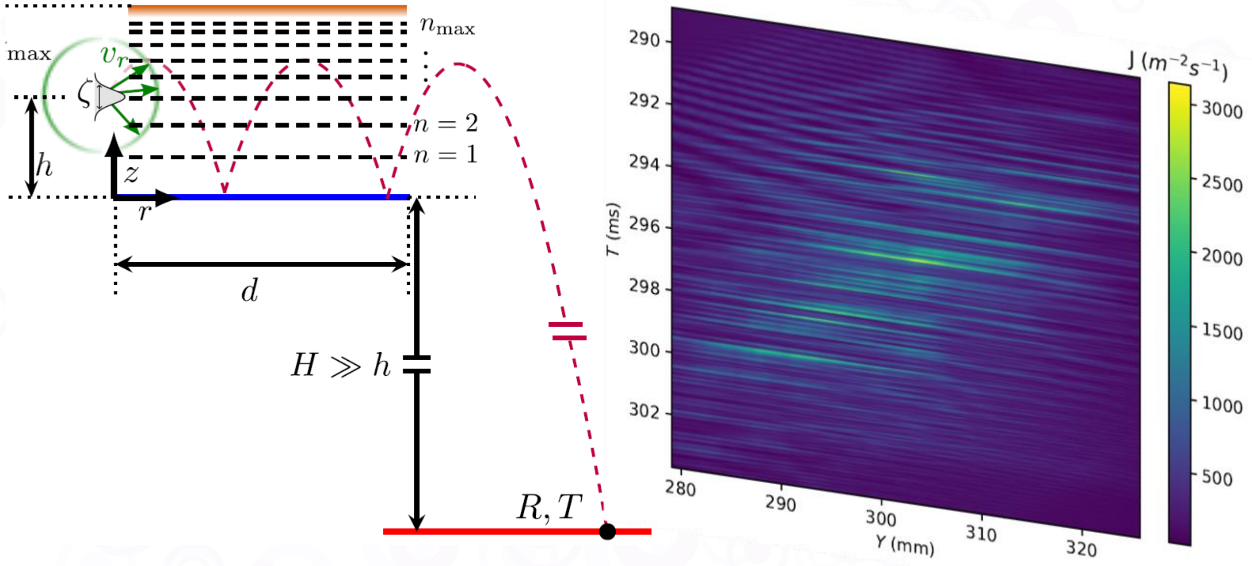
The GBAR experiment

Gravitational Behaviour of Antihydrogen at Rest

- Phase 1: 1 % precision on $\bar{g}$ with 500 $\bar{H}$
- Phase 2: Gravitational Quantum States



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



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

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

The GBAR experiment

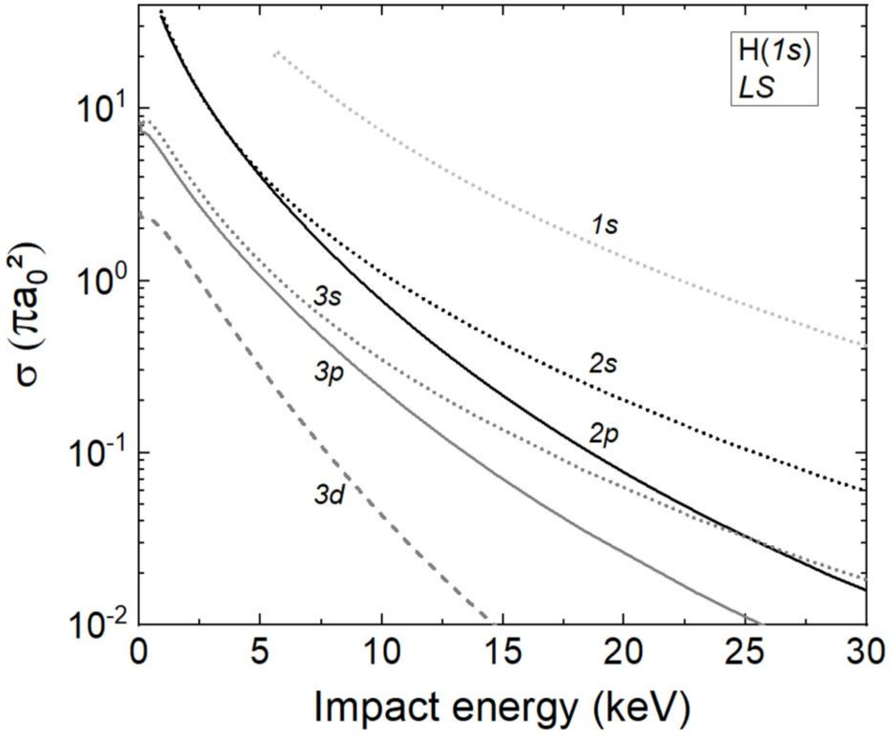
The positive antihydrogen ion, $\bar{\mathrm{H}}^+$

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

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

P. Pérez & A. Rosowsky,
Nucl. Inst. Meth. A **532**, 523 (2004)

$\bar{\mathrm{H}}(1S) + \mathrm{Ps}^* \rightarrow \bar{\mathrm{H}}^+ + \mathrm{e}^-$



P. Comini *et al.*,
N. J. Phys. **23**, 029501 (2021)

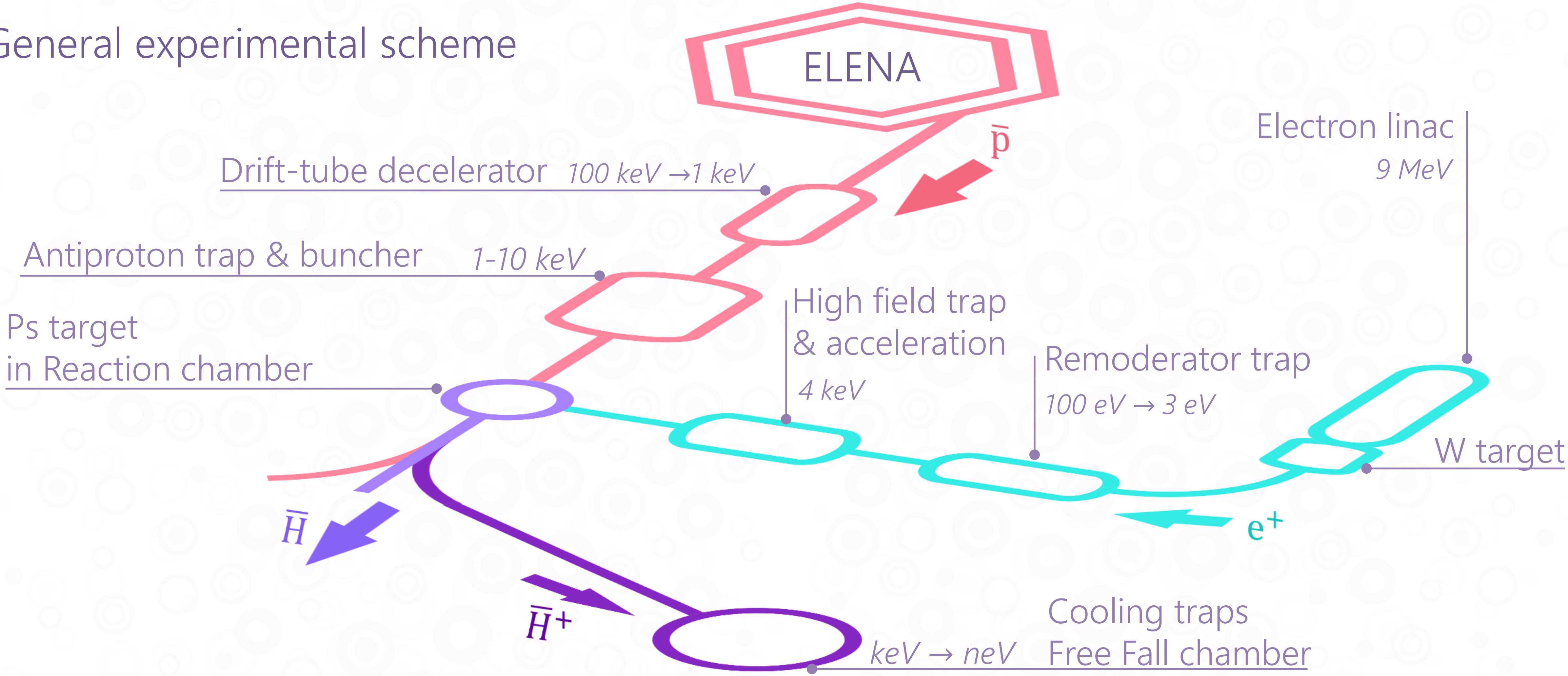
Typical values:

5.10^{11} cm^{-3} oPs density
\+
5.10^{6} $\bar{\mathrm{p}}$ at 6 keV

$\rightarrow 0.5\ \bar{\mathrm{H}}^+$

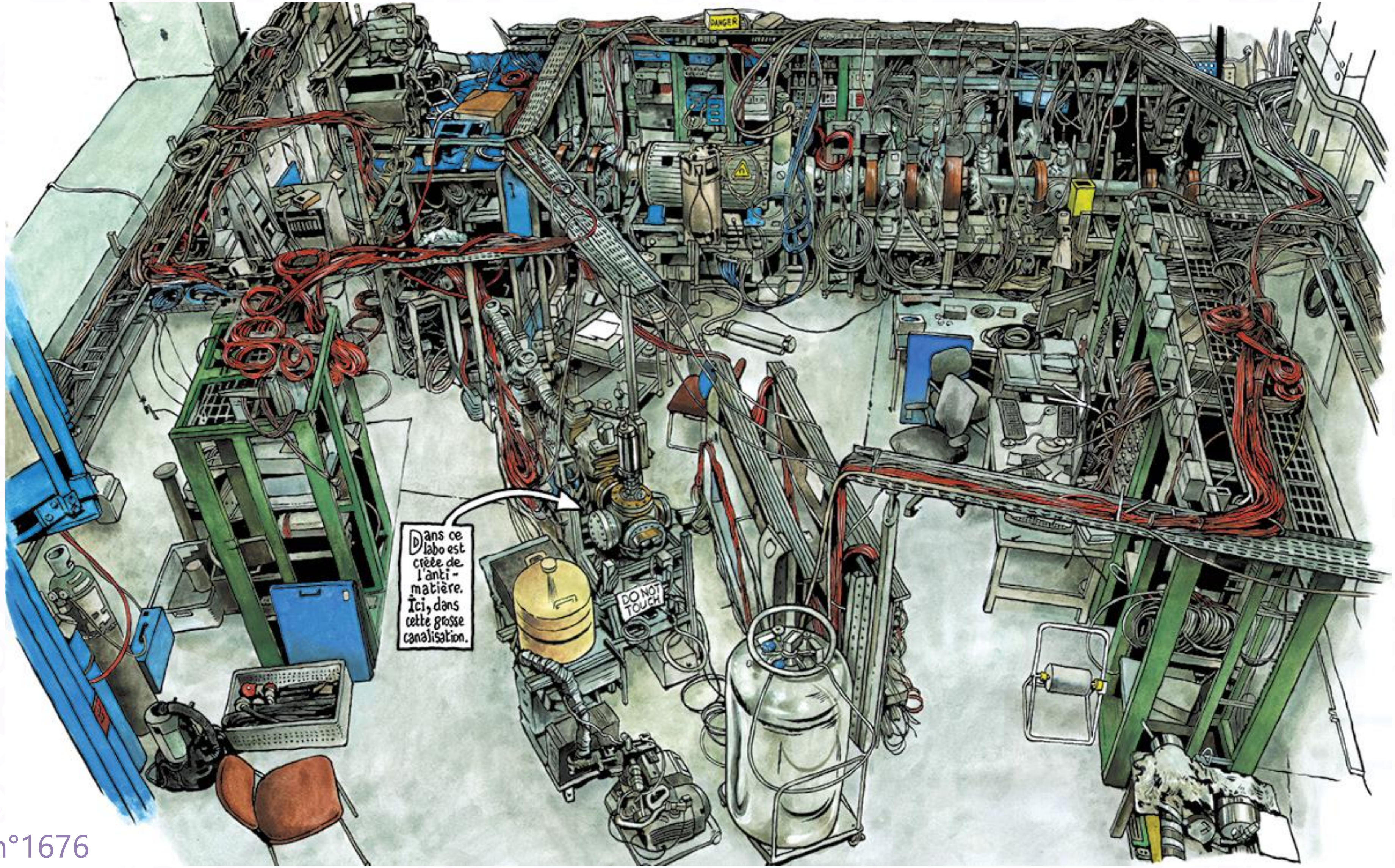
The GBAR experiment

General experimental scheme



The GBAR experiment

In 2024



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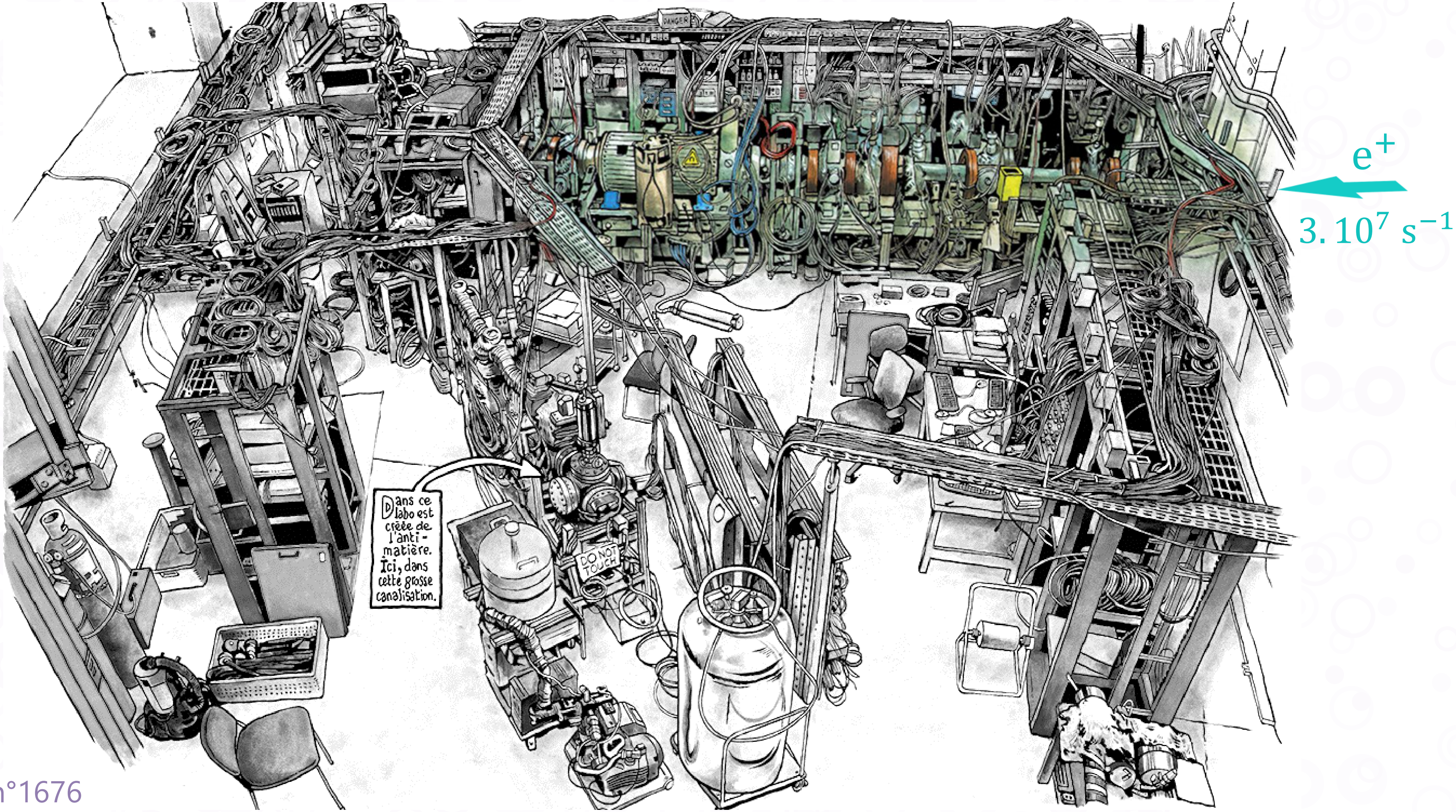
Charlie Hebdo, n°1676

The GBAR experiment

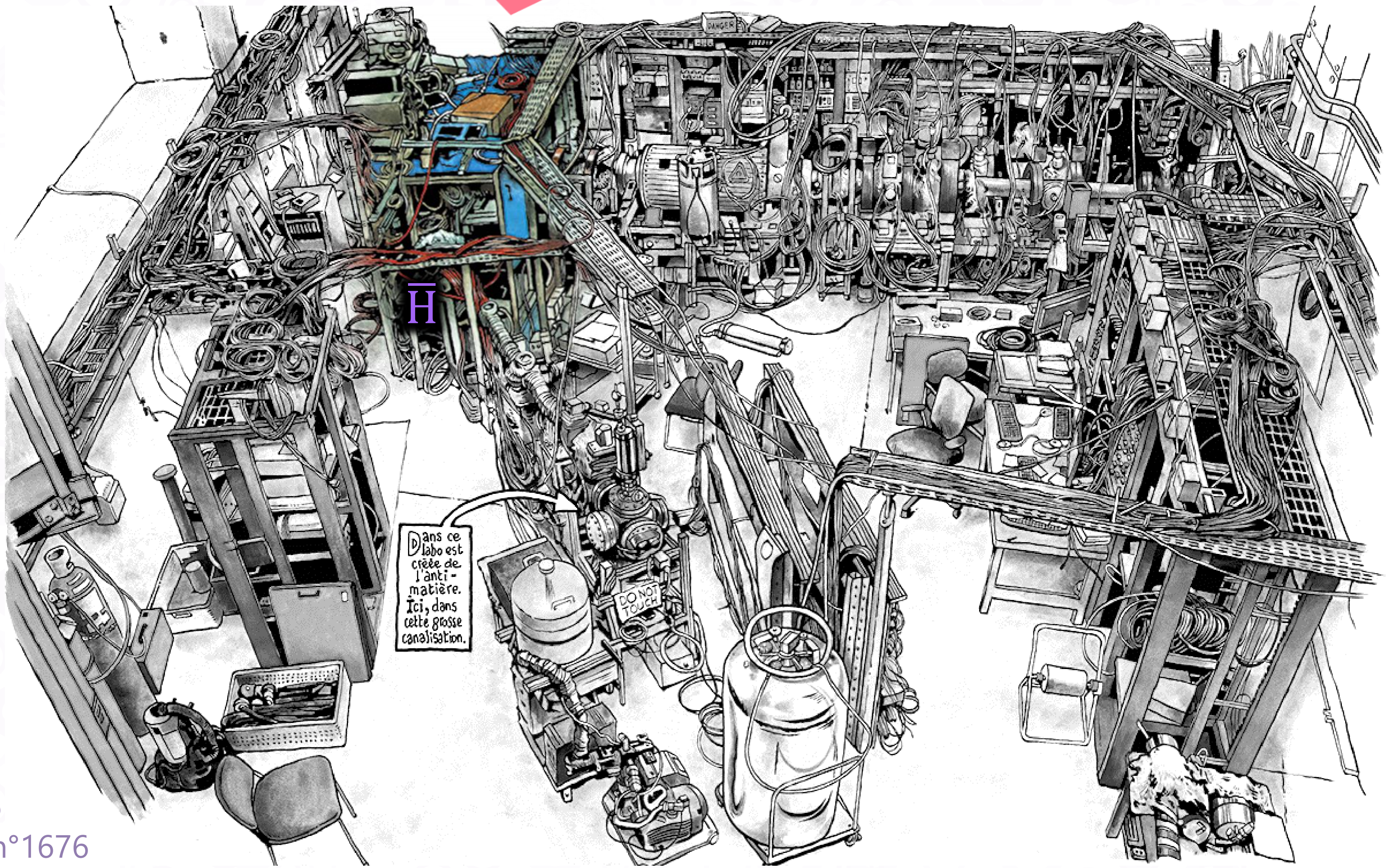
In 2024



The GBAR experiment

In 2024

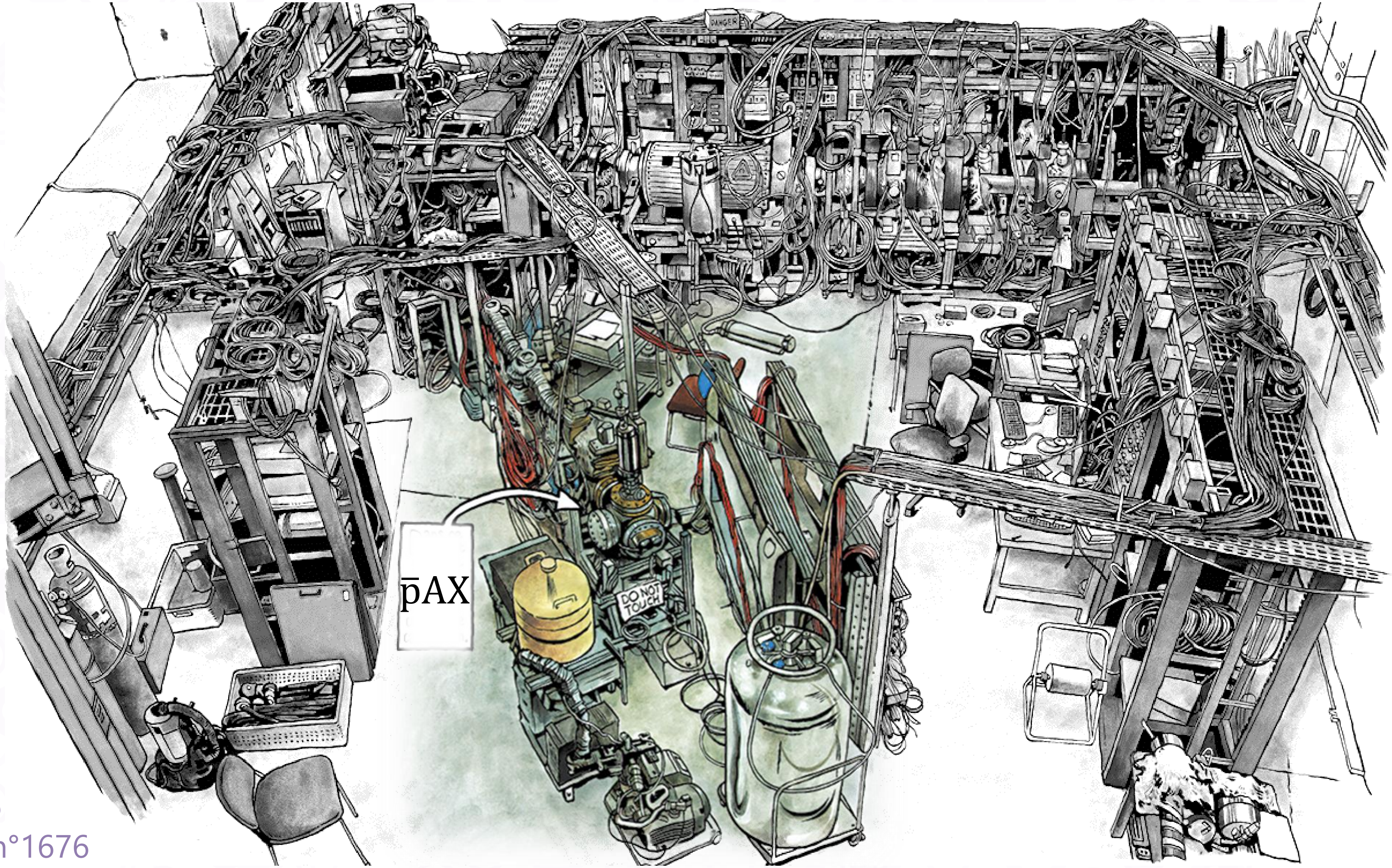
10^7 $\bar{p}$ from ELENA



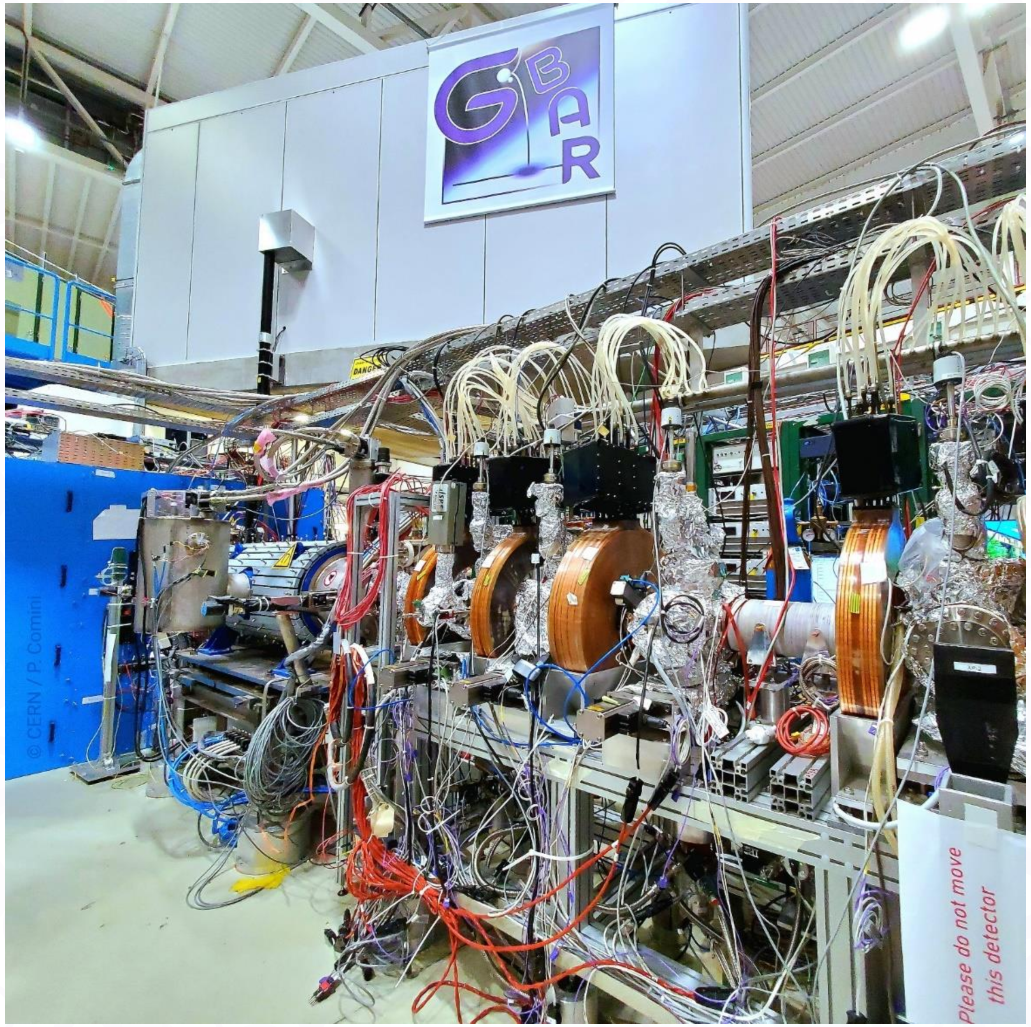
Charlie Hebdo, n°1676

The GBAR experiment

In 2024



Report on 2024 activities: positrons

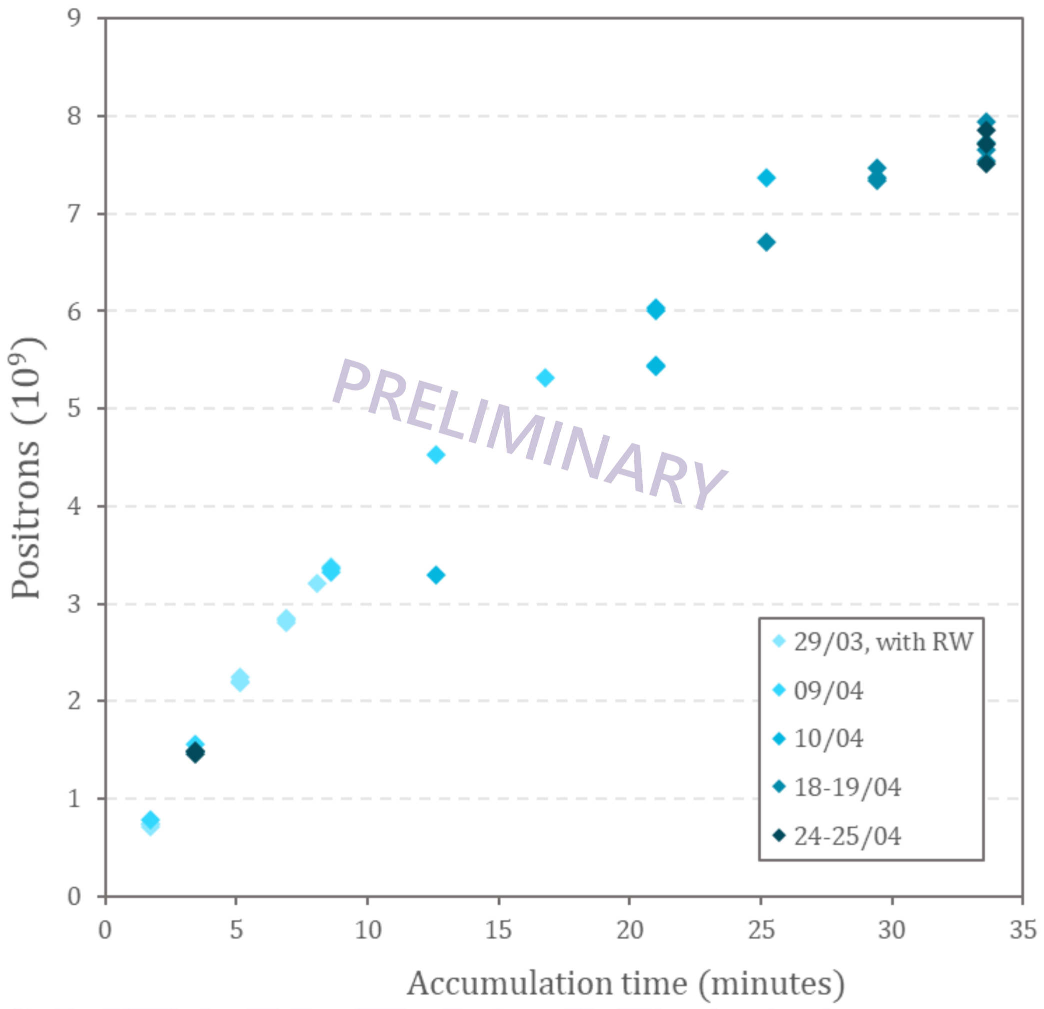


Report on 2024 activities: positrons

Record accumulation

of more than $7.10^9\ e^+$

in 30 minutes



Previously:

- Highest number: $4.\ 10^9\ e^+$ in 4.5 h by ATRAP

D.W. Fitzakerley *et al.*, J. Phys. B: At. Mol. Opt. Phys. **49**, 064001 (2016)

Report on 2024 activities: positrons

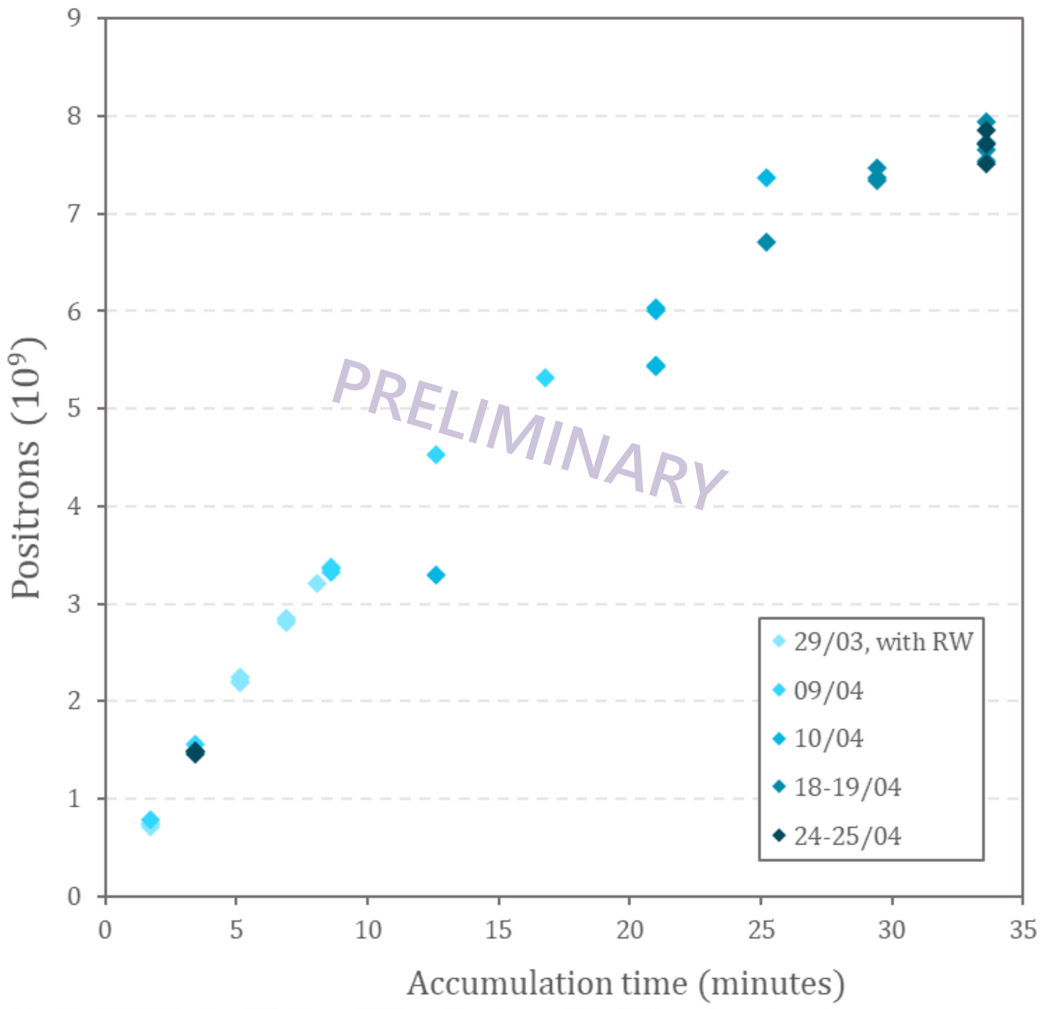
Record accumulation of more than 7.10^9 e^+

Per AD cycle: 6.10^8 e^+

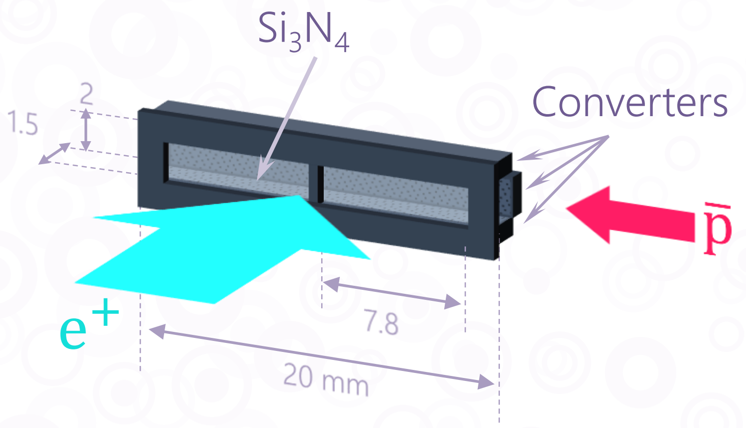
Thanks to:

- Replacement of the BGT (2023) by SiC remoderation of the pulsed beam + CO_2 cooling
  2x more efficient

- Reoptimisation of the trapping sequences
  Gain x2
  Loss minimisation during accumulation



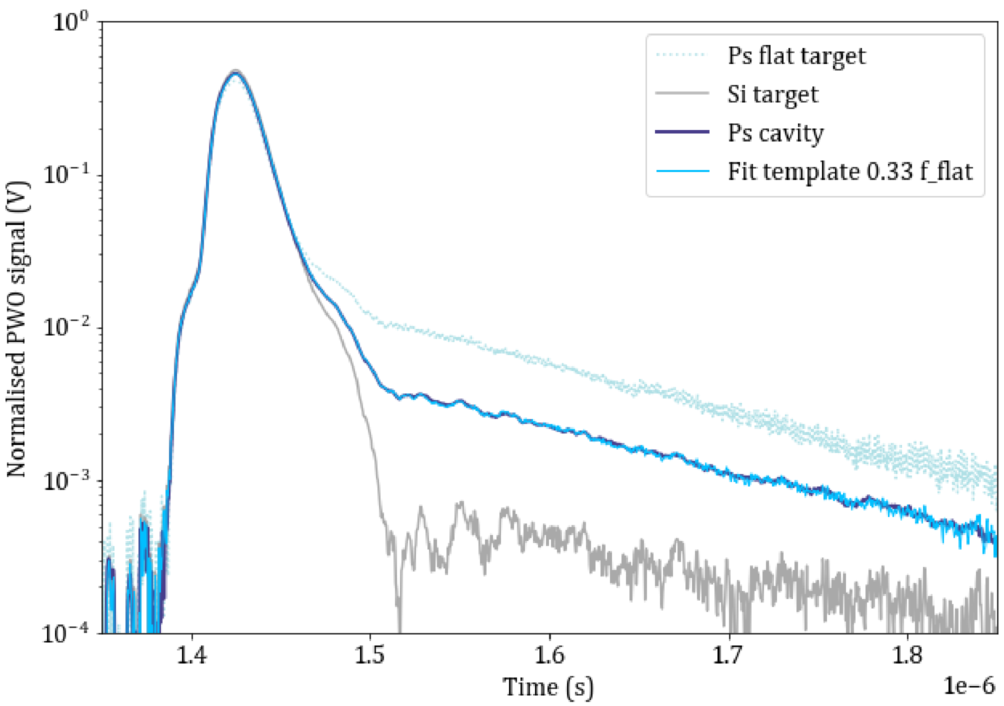
Report on 2024 activities: positrons



Confinement of

more than 5.10^6 oPs

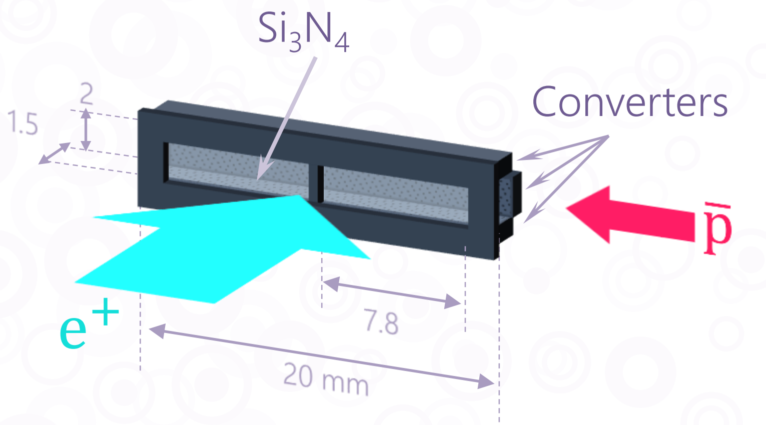
in a tubular target



Report on 2024 activities: positrons

Confinement of more than $\mathbf{5.10^6}$ **oPs** in a tubular target

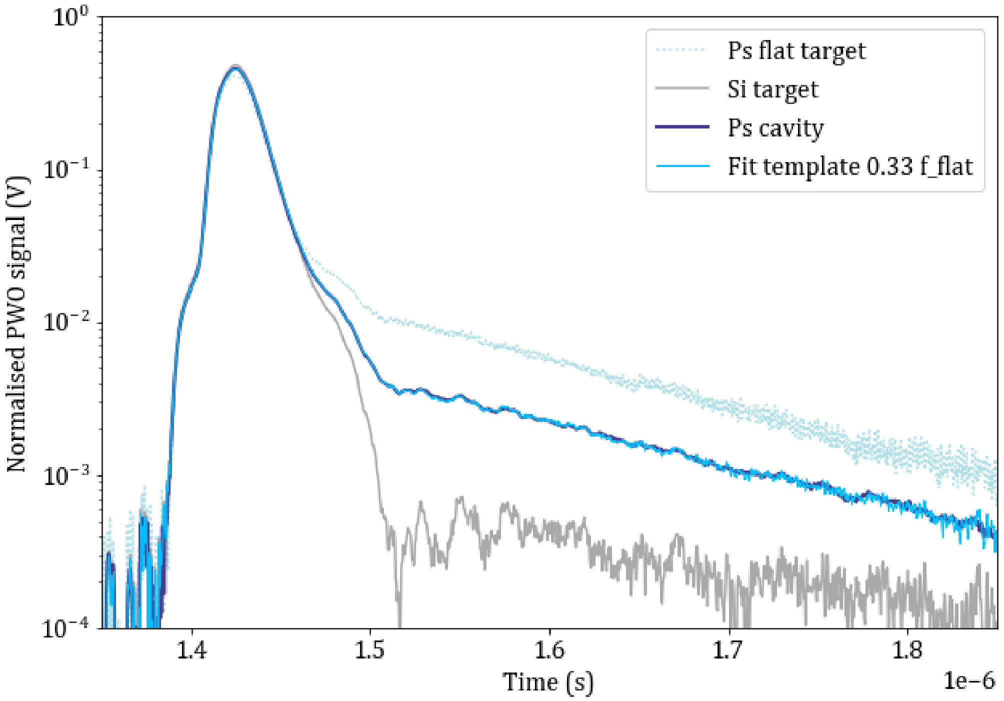
Out of $\mathbf{7.10^7}$ $\mathbf{e^+}$ on target area.



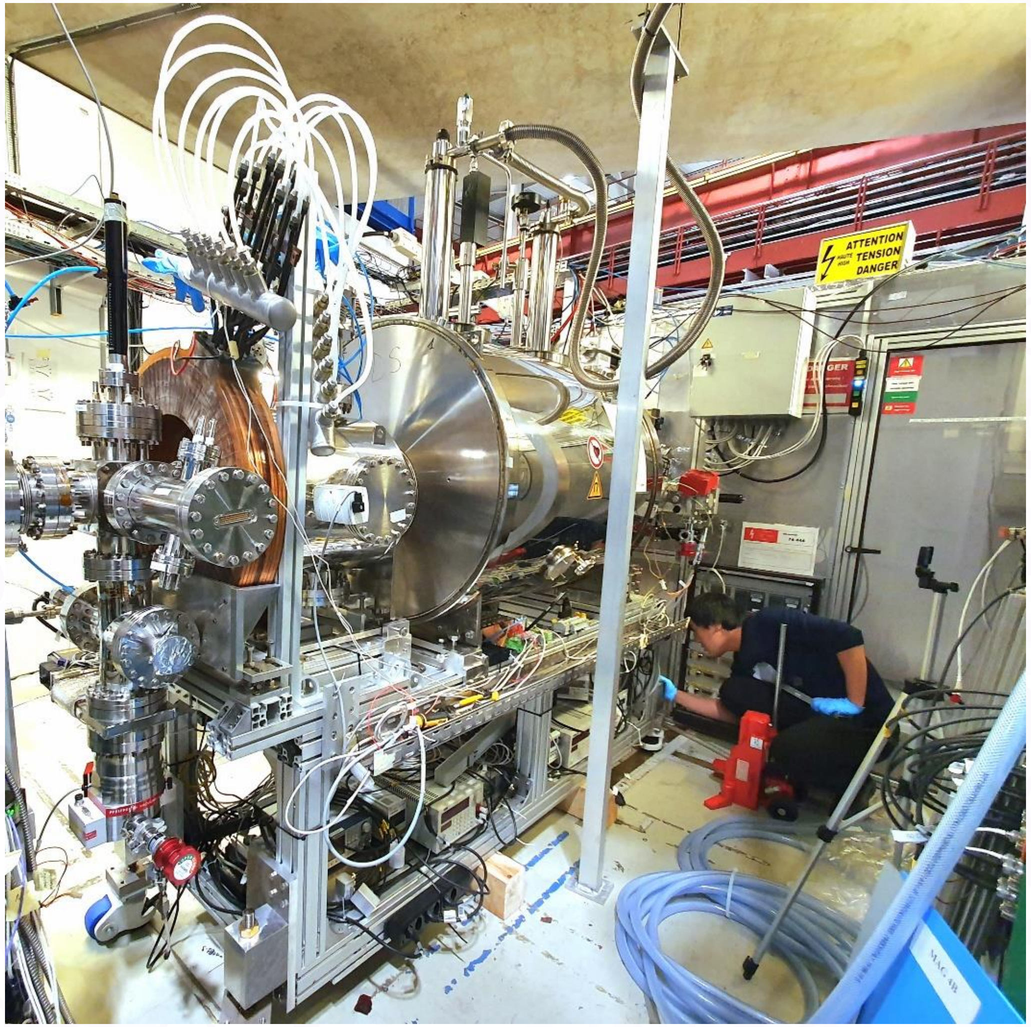
Thanks to:

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

- Transport optimisation on Ps signal



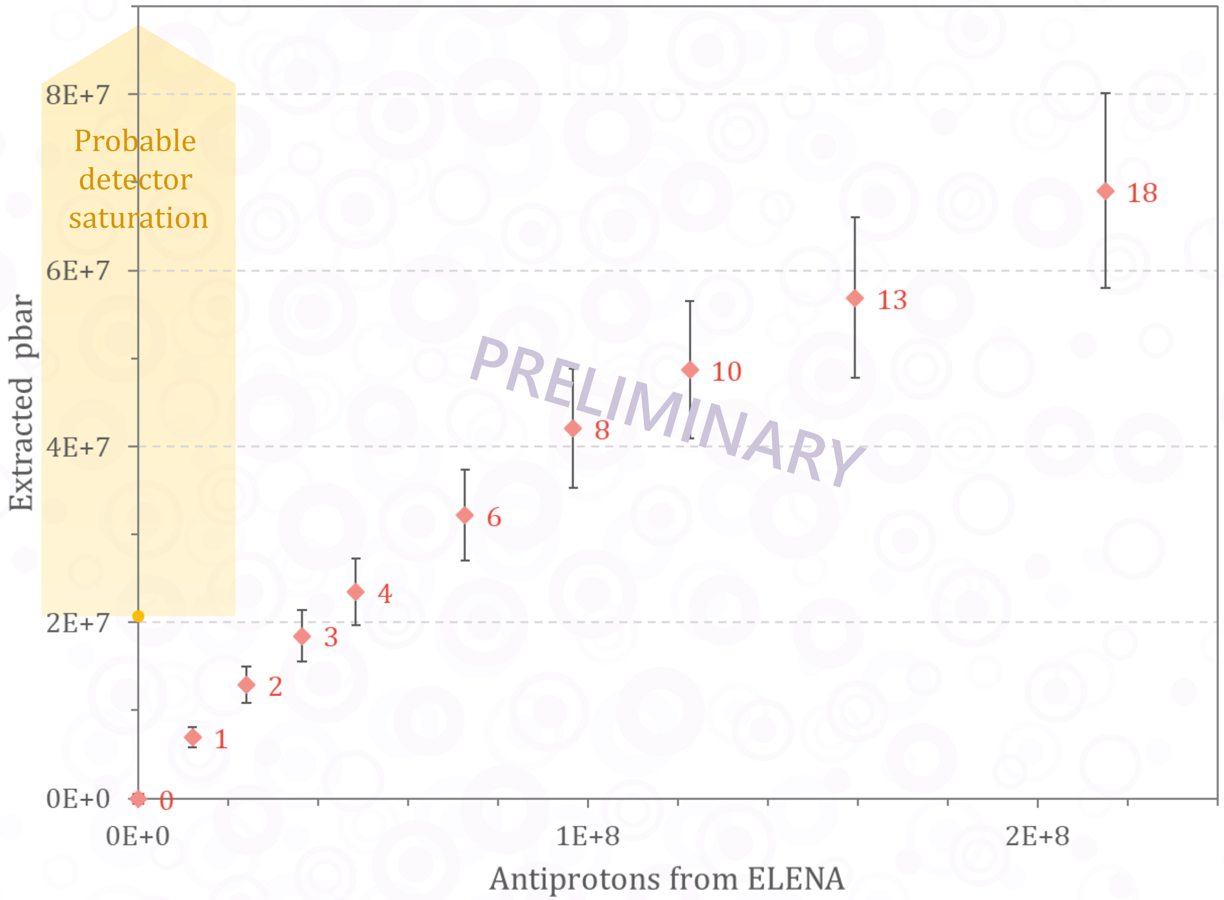
Report on 2024 activities: antiprotons



Report on 2024 activities: antiprotons

Accumulation and extraction

of up to $7.10^7\ \bar{p}$



Report on 2024 activities: antiprotons

Efficient trapping and accumulation of up to $7.10^7\ \bar{p}$

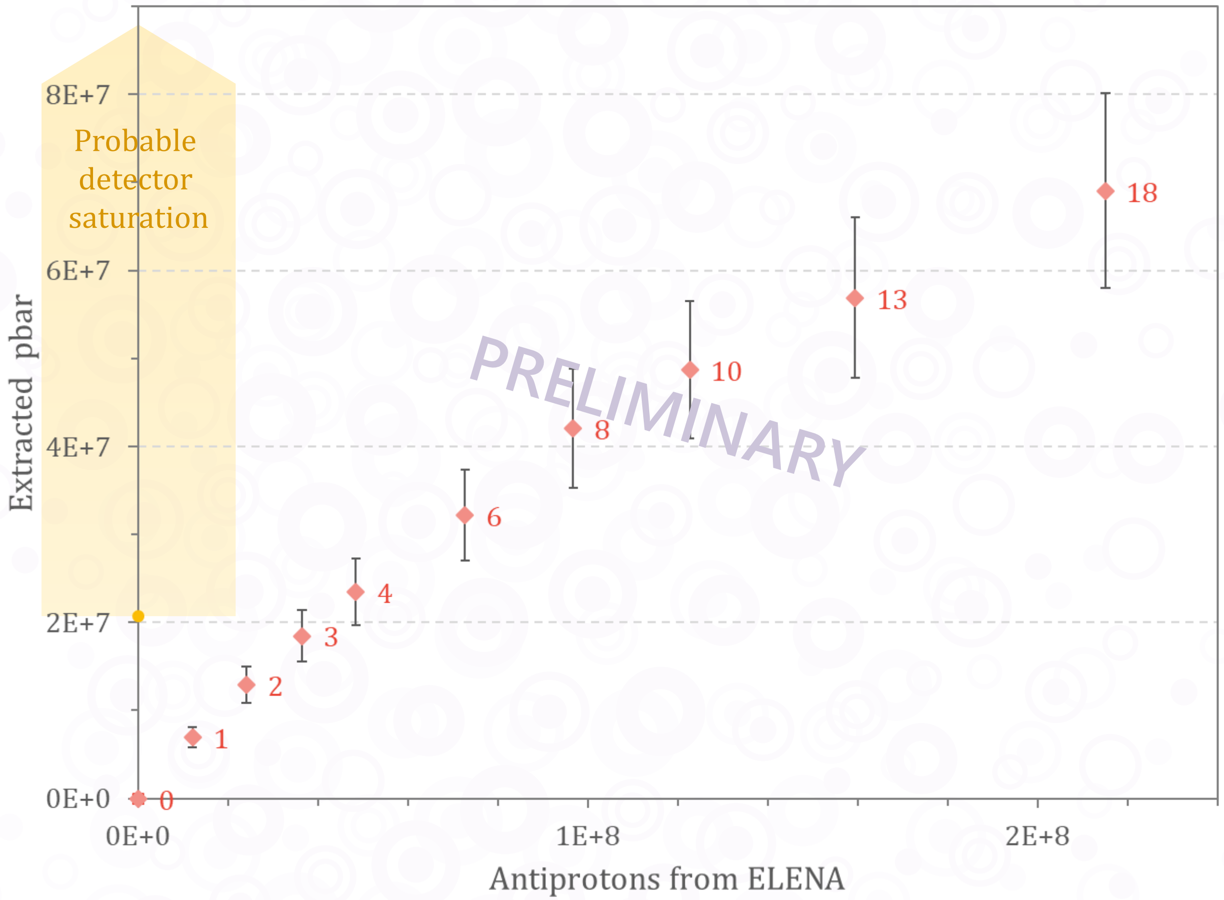
Per AD cycle: $6.10^6\ \bar{p}$ (55 % efficiency)

Thanks to:

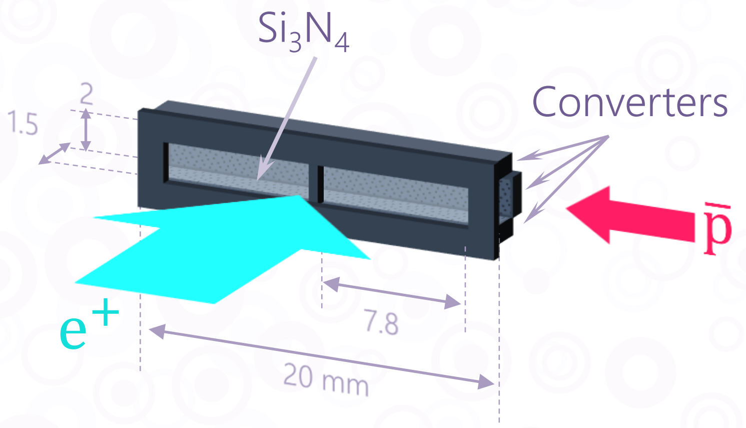
- Improvement of
  trap alignment and connections
  Increased lifetime (> 1h)

- Modified trapping potentials

Also: successful buncher operation
Bunch length reduced by ~1.5 at target



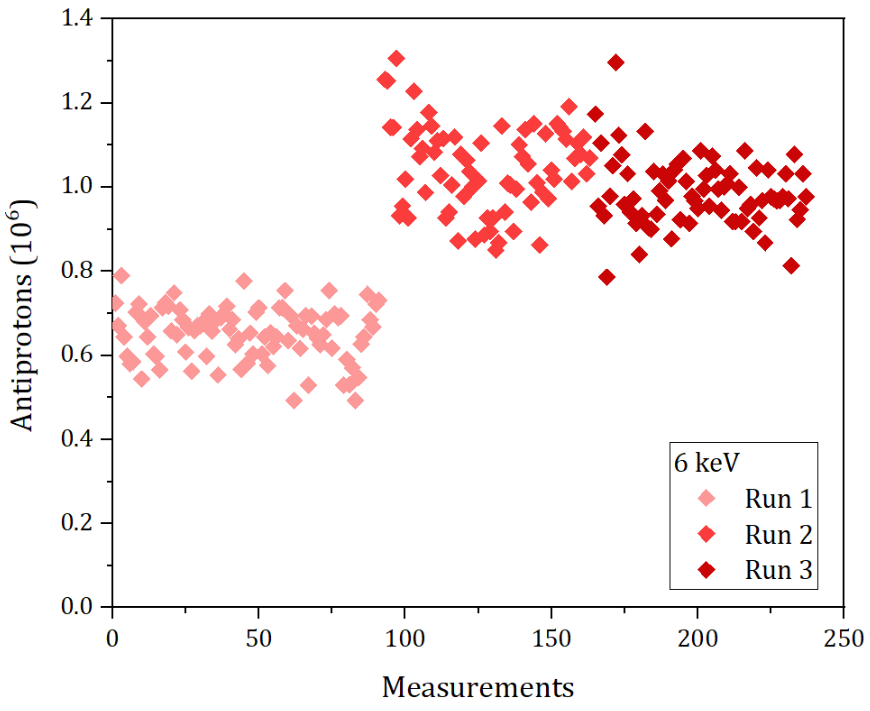
Report on 2024 activities: antiprotons



1.10^6 $\bar{p}$ transmitted

through the Ps cavity target

and to the end of the beamline

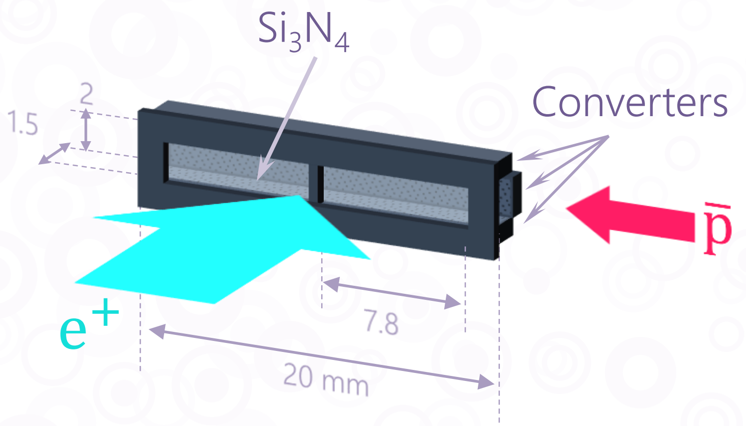


Report on 2024 activities: antiprotons

Transmission of $1.10^6\ \bar{p}$ through the Ps cavity target

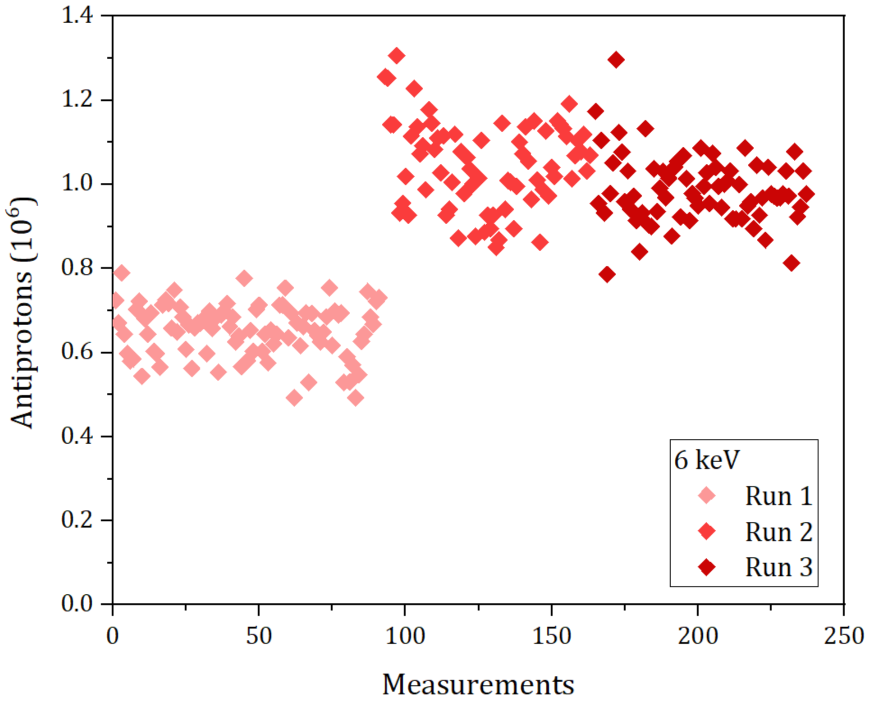
Best value at 6 keV: $2.10^6\ \bar{p}$

But less control over losses: not used.



Thanks to:

- Review of all possible charge-up (2023)
- Beam quality from the trap + new lens
- Automatic optimisation runs at night

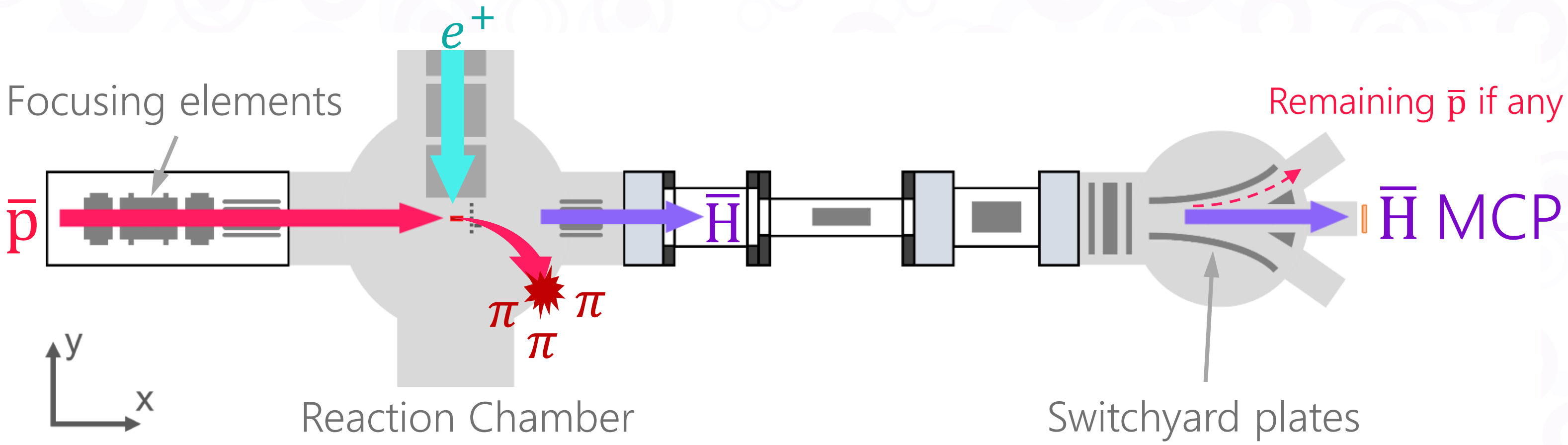


At 4 keV: $\sim 5.10^5\ \bar{p}$

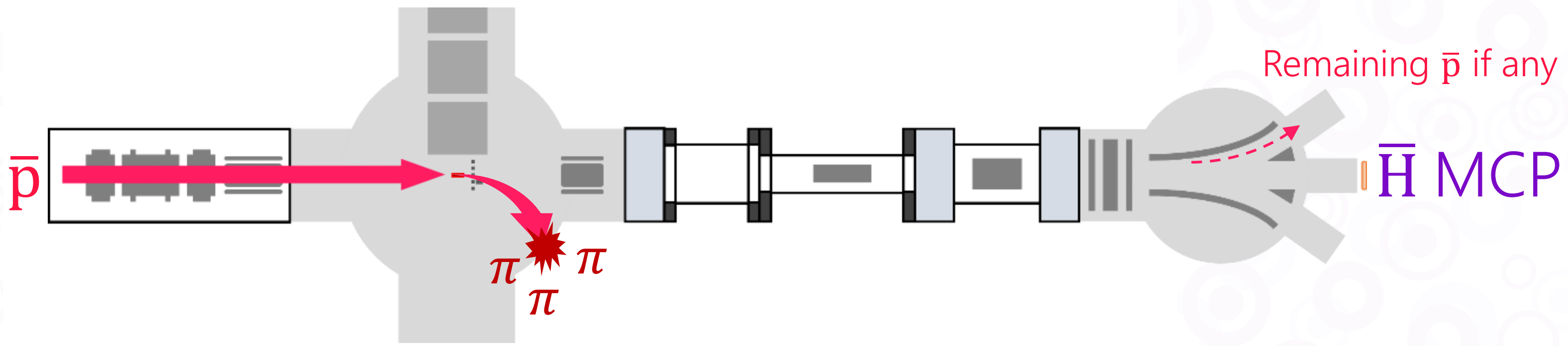
Report on 2024 activities: antihydrogen

Report on 2024 activities: antihydrogen

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



Background runs

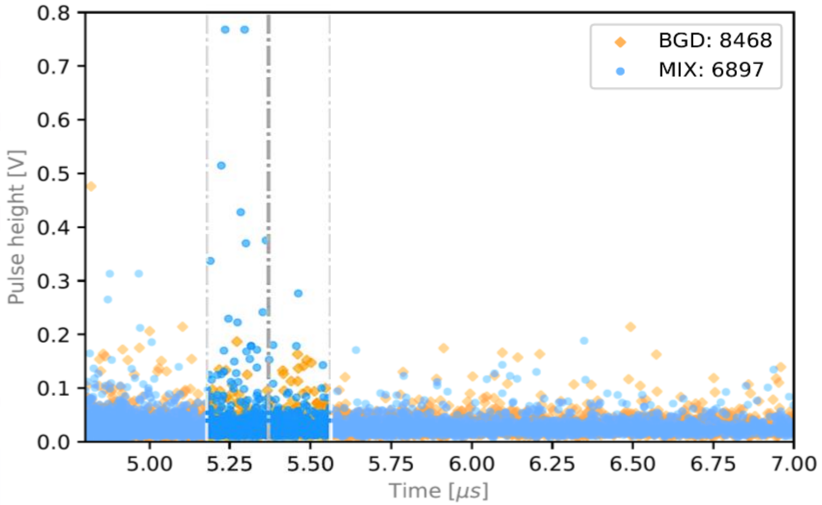


Report on 2024 activities: antihydrogen

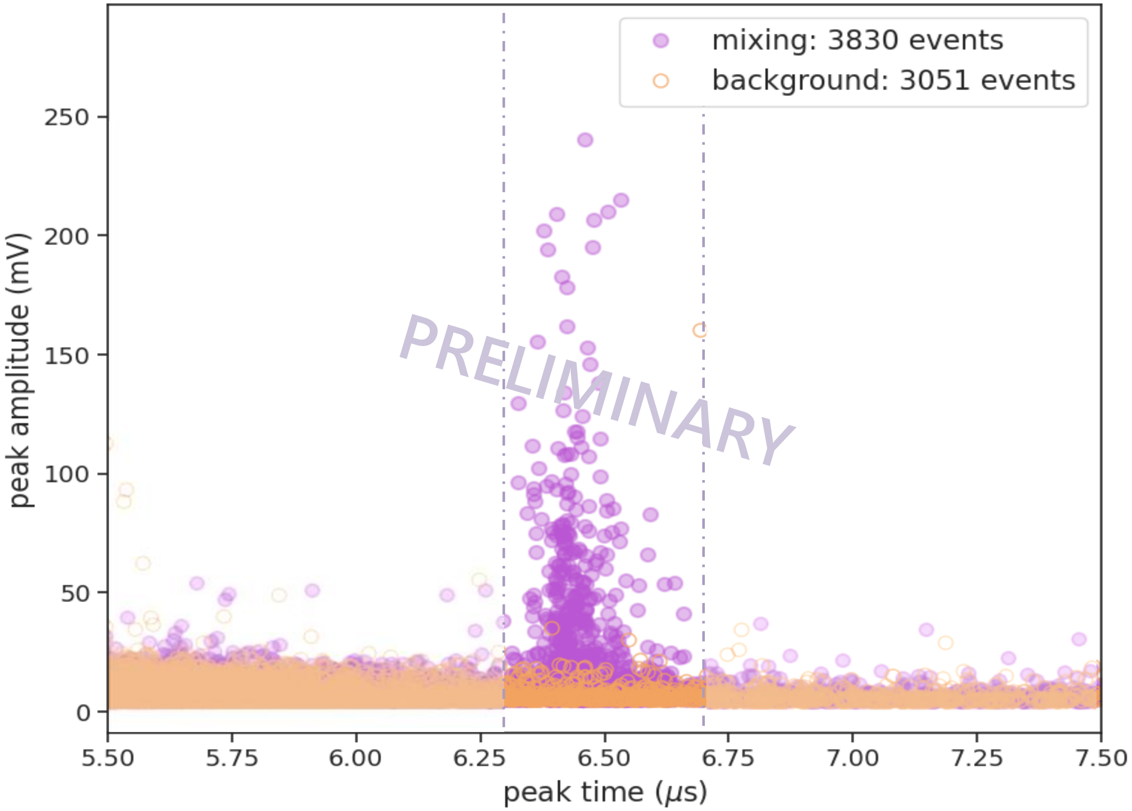
Antihydrogen detection rate

increased by ~30

compared to 2022



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

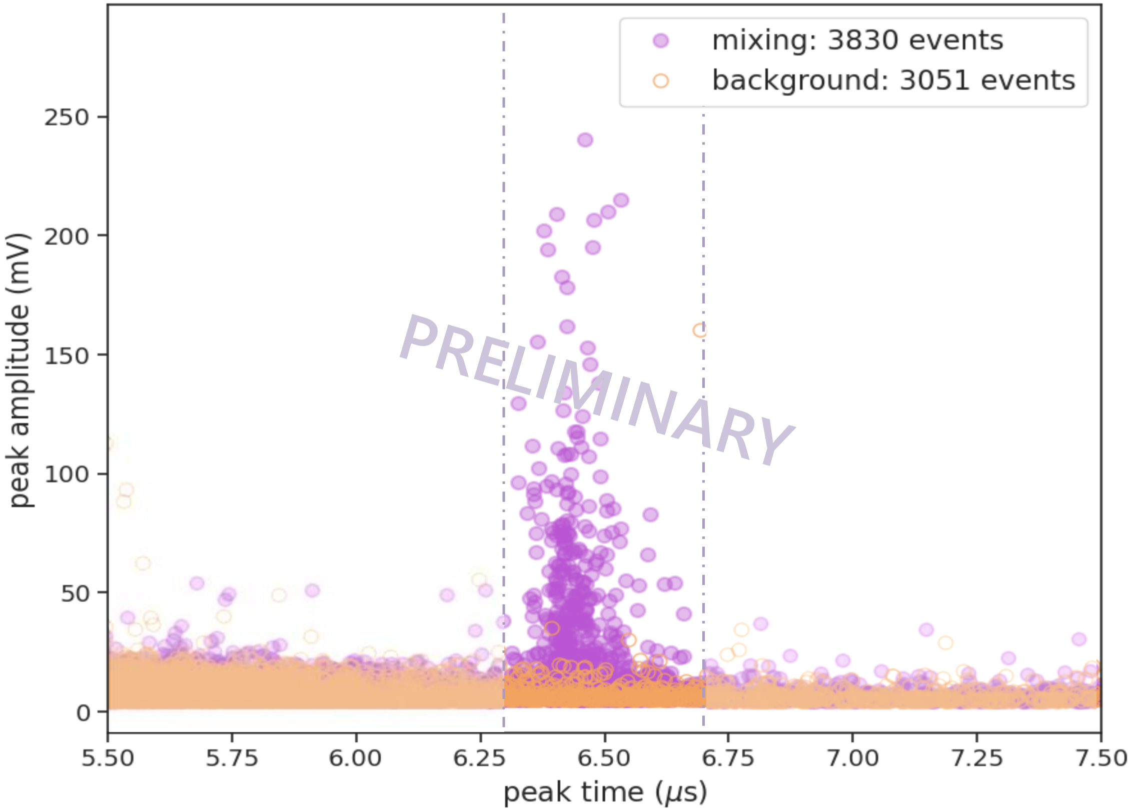


Report on 2024 activities: antihydrogen

Antihydrogen detection rate increased by ~30
At 6 keV: ~0.1 / shot

In summary:

- ELENA increased intensity!
- Trapping & bunching of $\bar{p}$
- Transport optimisations
- Increased Ps density by the cavity
  Main gain



Report on 2024 activities: antihydrogen

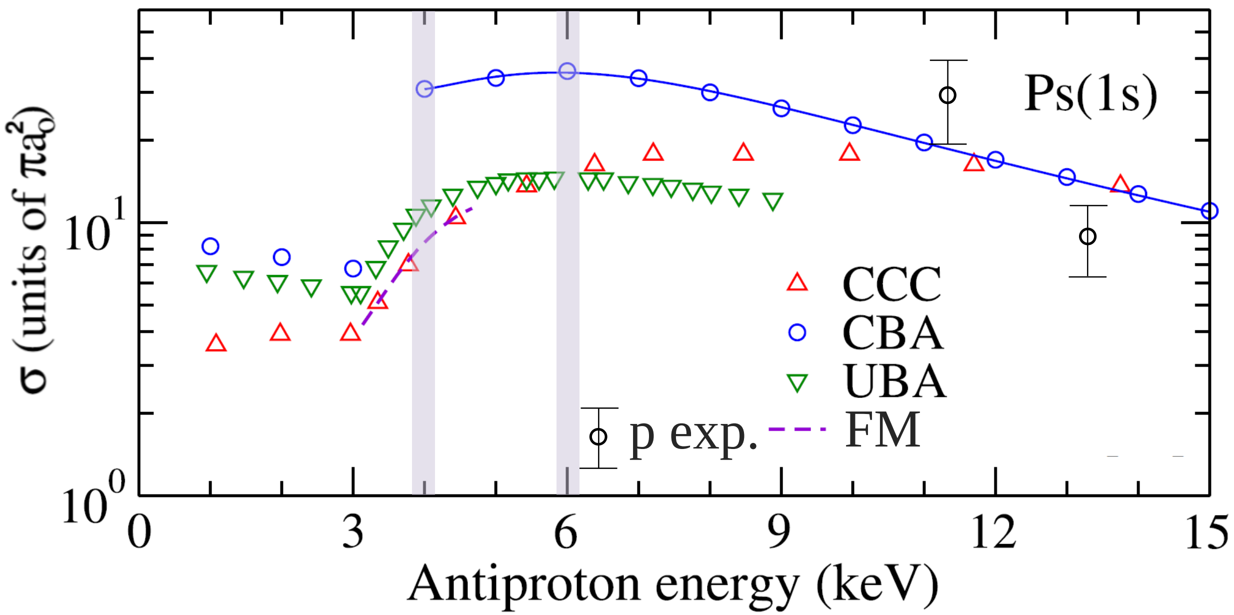
Ongoing analysis to provide cross section values for $\bar{p} + Ps(1S) \rightarrow \bar{H} + e^-$

At 4 and 6 keV

Compared to 2022:

- Better mastery of systematics
  e.g. detector acceptance for neutrals investigated with H^- beam

- Better statistics



Adapted from:
K. Lévêque-Simon & P.-A. Hervieux, Phys. Rev. A **107**, 052813 (2023)

p exp.: J. P. Merrison *et al.*, Phys. Rev. Lett., **78**, 2728 (1997)

Report on 2024 activities: antihydrogen

Lamb-shift measurement

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

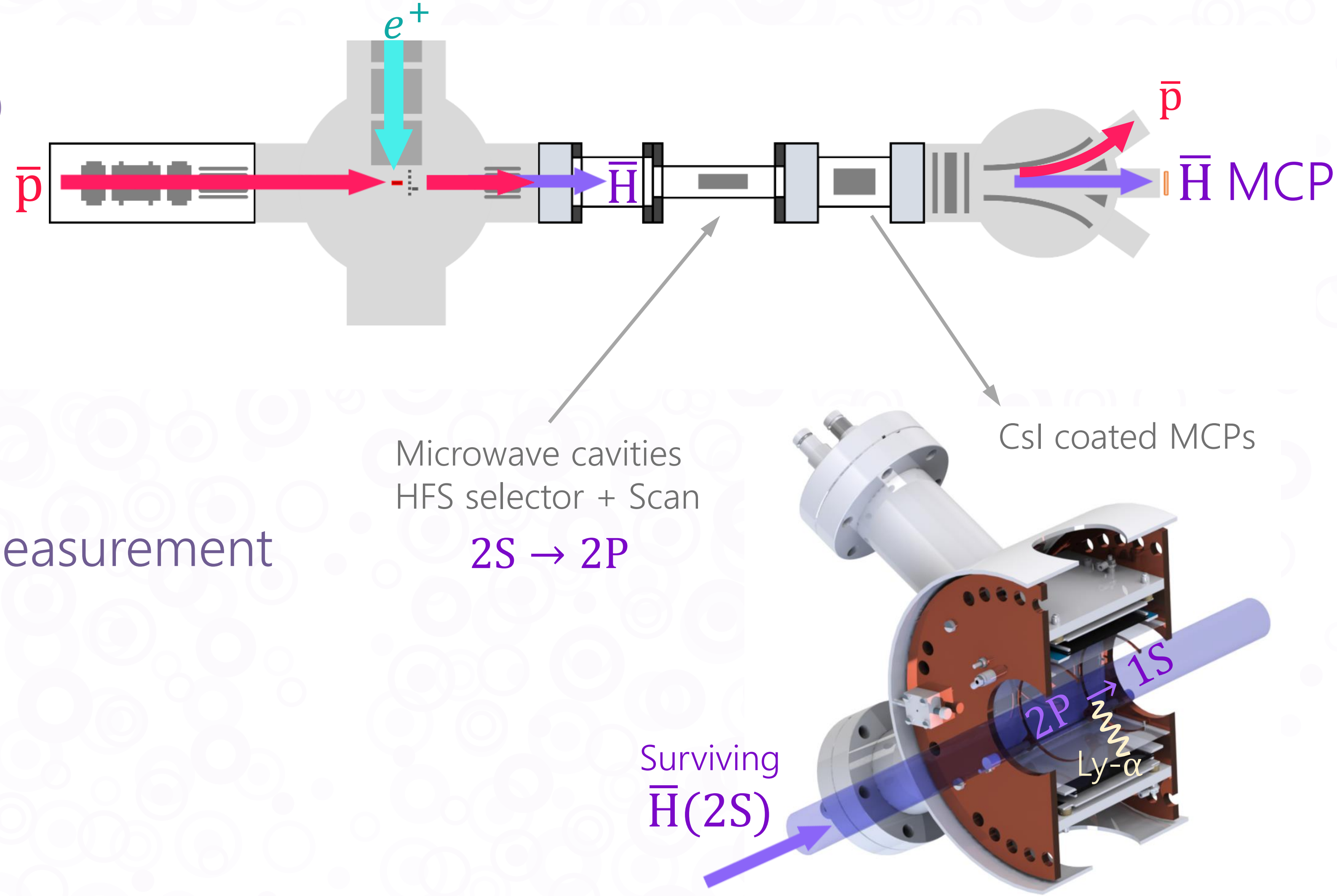
$\bar{p} + Ps(1S) \rightarrow \bar{H}^* + e^-$

At 6 keV, $> 10\ \%\ \bar{H}(2S)$

Complementary to ALPHA's measurement

M. Ahmadi *et al.*, Nature **578**, 375 (2020)

- Direct
- No B field



Report on 2024 activities: antihydrogen

Lamb-shift measurement

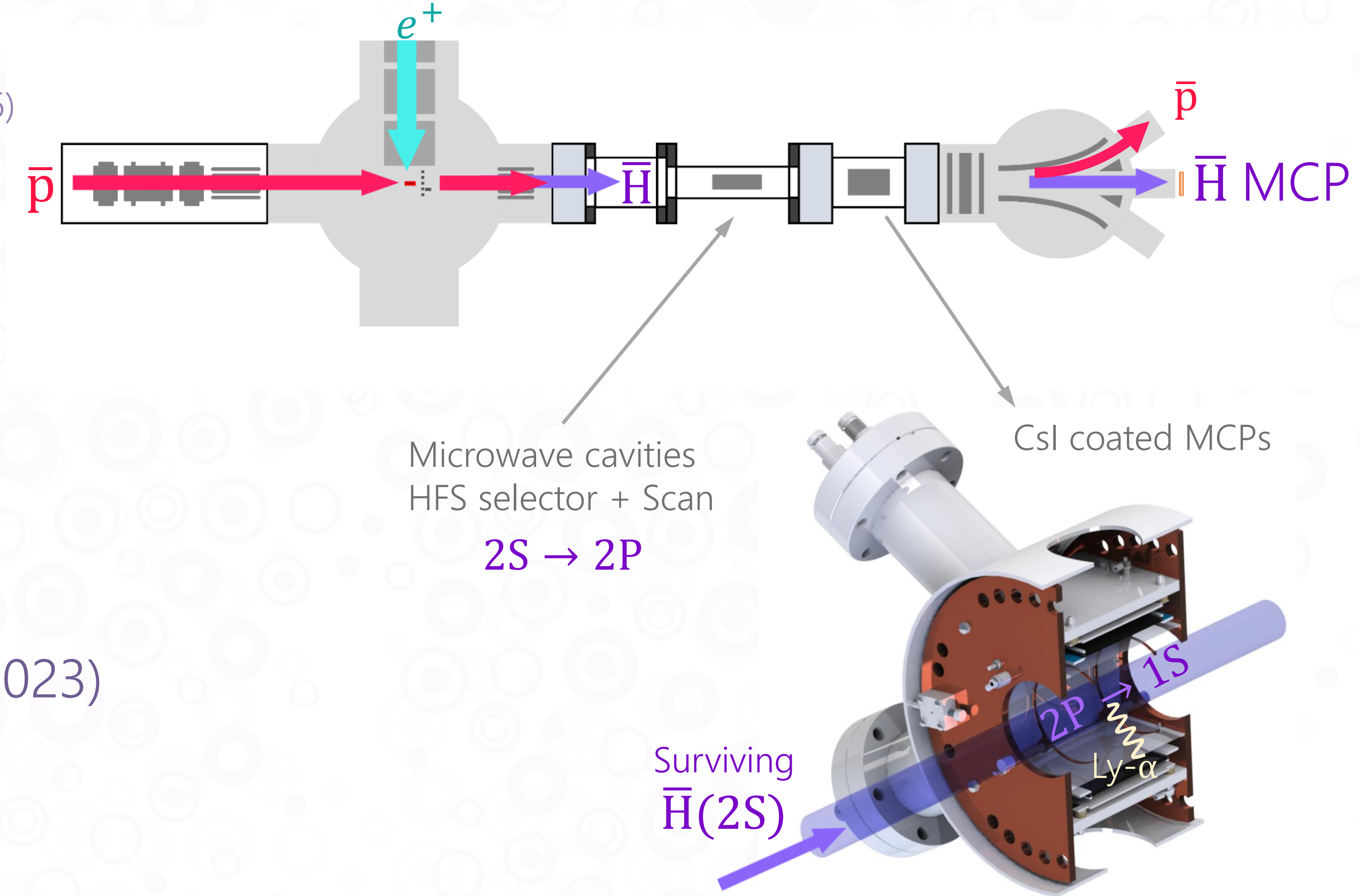
P. Crivelli *et al.*, Phys. Rev. D 94, 052008 (2016)

Tested in $\bar{\mathrm{H}}$ production mode

Background reduction in Ly-α detectors in 2024

Thanks to:

- New MW cavities design (2023)
- Improved $\bar{\mathrm{p}}$ beam quality



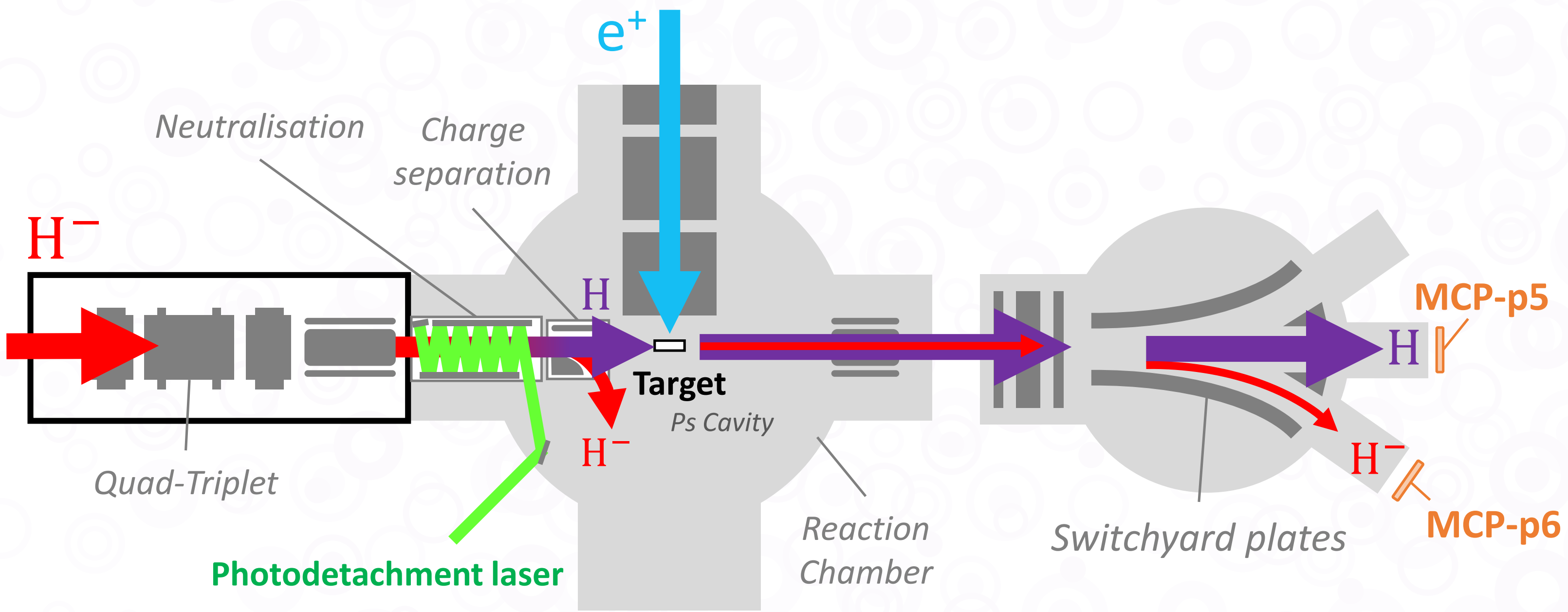
Also: commissioning with H^{-} beam + carbon foil

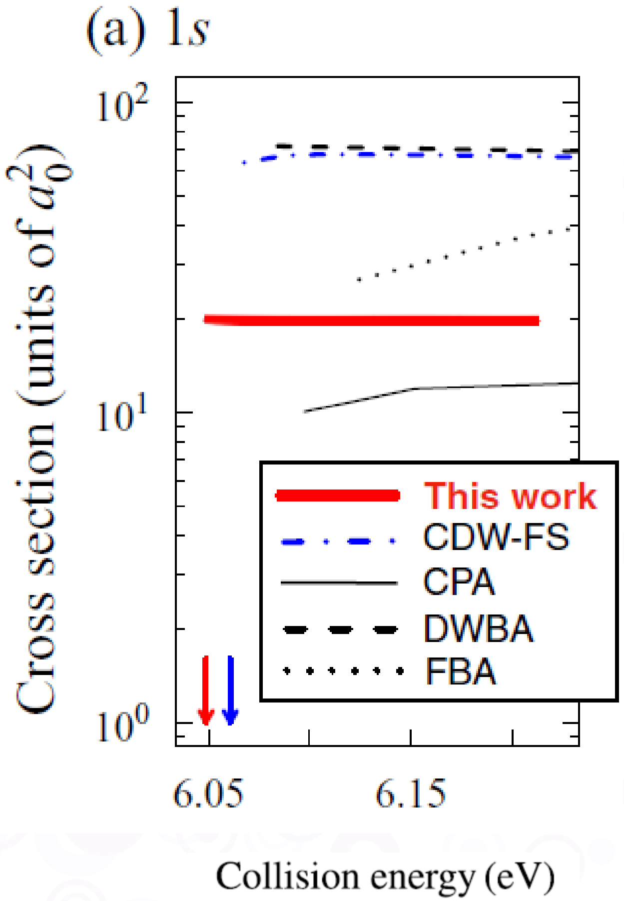
Report on 2024 activities: hydrogen anion

Cross section measurement for $\bar{H} + Ps \rightarrow \bar{H}^+ + e^-$

Actually for: $H + Ps \rightarrow H^- + e^+$

Idea: use H^- beam from ELENA for physics



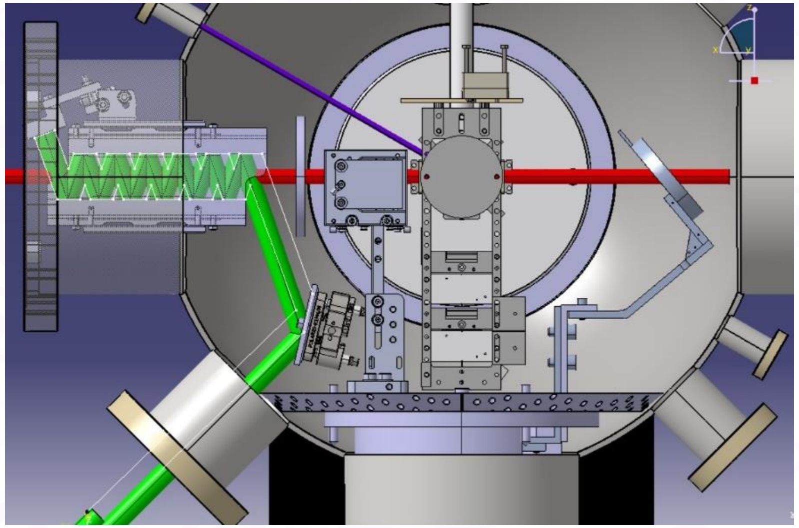


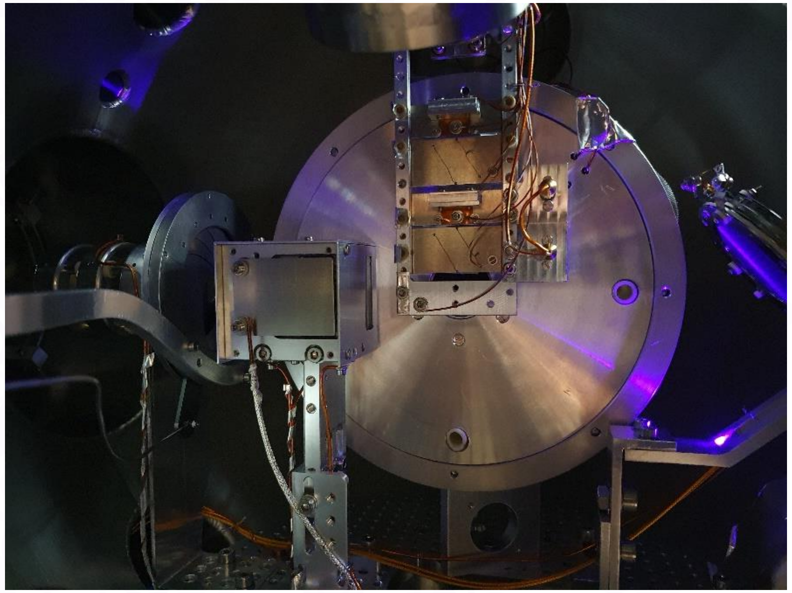
Adapted from:
Yamashita *et al.*,
Phys Rev A **105**, 052812 (2022)

Report on 2024 activities: hydrogen anion

Cross section measurement for $\mathrm{H} + \mathrm{Ps} \rightarrow \mathrm{H}^- + e^+$

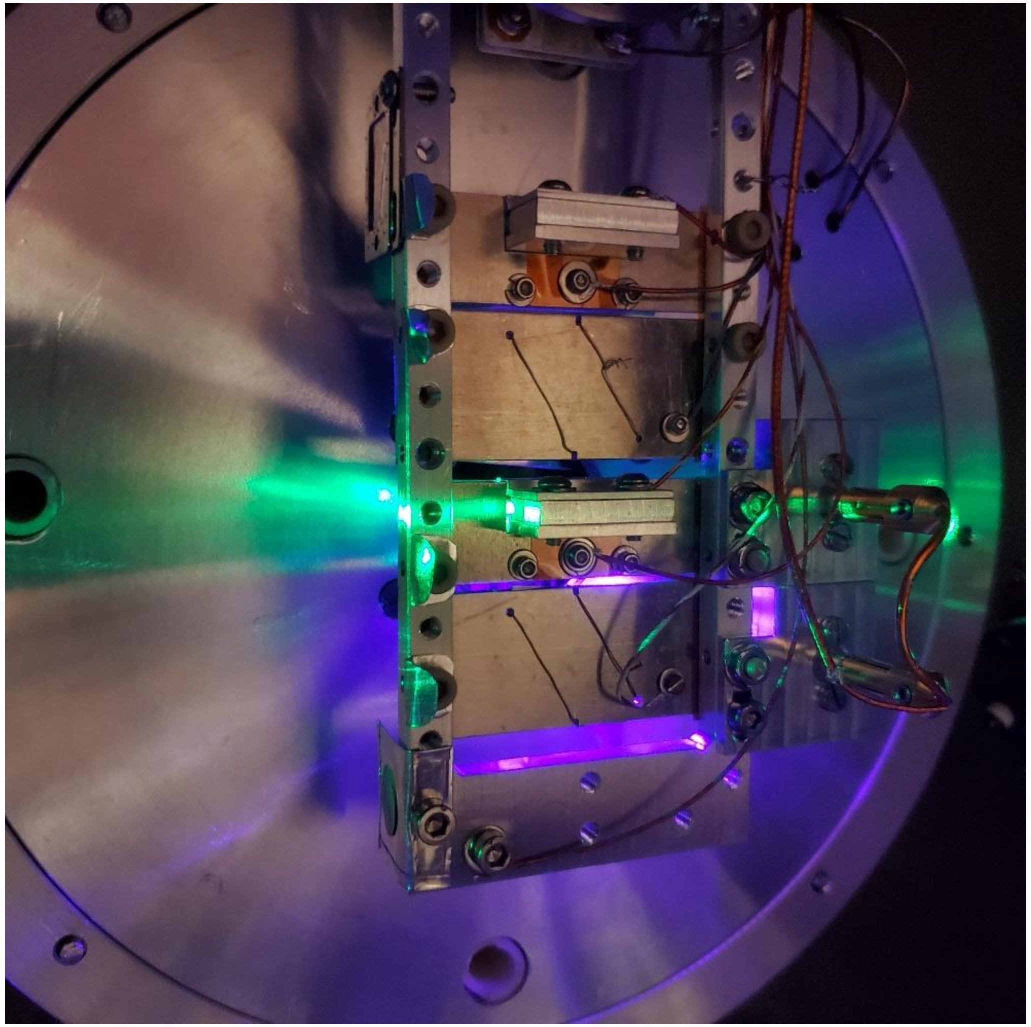
- Opto-mechanical design finisalised in 2024
- Parts already integrated to GBAR
- Short test beam with H^- in December
  Confirmed changes required in $\bar{\mathrm{p}}$ beam:
  $\bar{\mathrm{p}}$ trap temporary replaced by transfer line





Many thanks to the ELENA team for the H^-
and to BASE for good compromise!

Plans for 2025



Plans for 2025: improvements

Linac

- Sparks in klystron
  Limited operation at 150 Hz from November

  Update: water leak found in the insulating oil tank. Repaired. Klystron stability to be monitored.

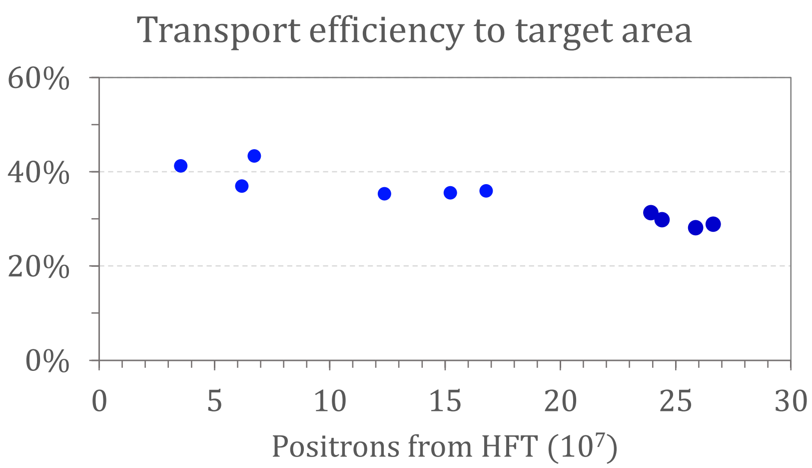
- Modifications of the W target / moderator

Plans for 2025: improvements

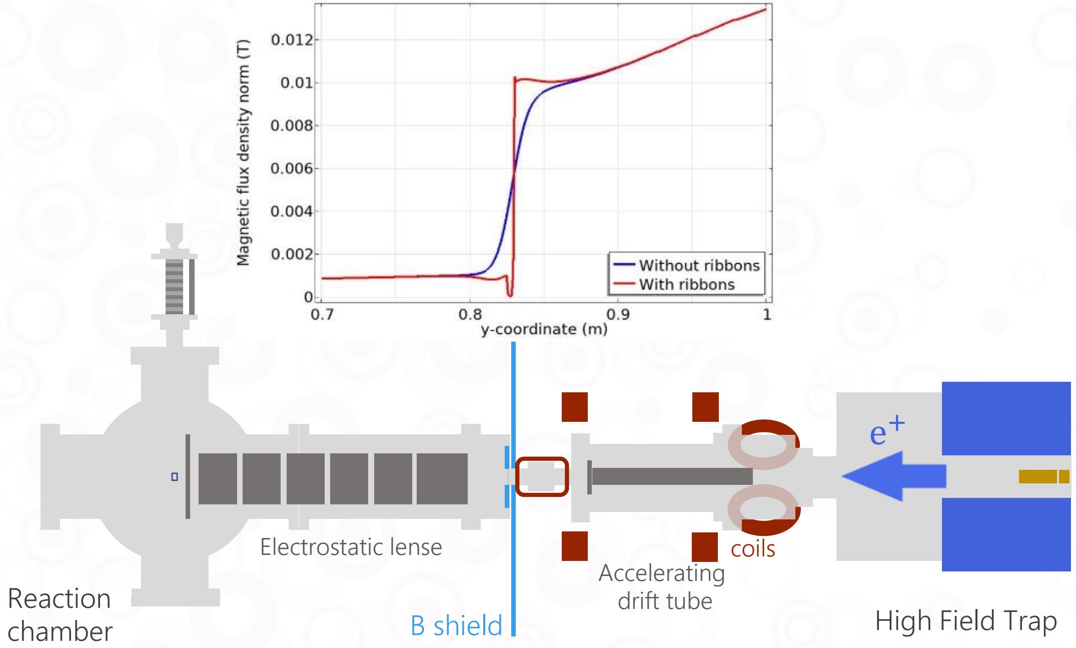
Toward better e^+ & $\bar{p}$ beam quality

1. Positron transport efficiency between HFT and Ps target

Main bottleneck
Conversely:
where factors can be gained for $\bar{H}^+$



- Improve magnetic field transition
  Solution ready to be implemented
- Further work on plasma compression



Plans for 2025: improvements

Toward better e^+ & $\bar{p}$ beam quality

1. Positron transport efficiency between HFT and Ps target

Main bottleneck
Conversely:
where factors can be gained for $\bar{H}^+$

- Improve magnetic field transition
  Solution ready to be implemented
- Further work on plasma compression

2. Continue $\bar{p}$ trap developments

Trap moved out of beamline
for H^- cross section experiment

- Electron plasma studies

Back in $\bar{p}$ beamline in 2nd half of 2025

- Optimisation of potentials
  trapping and compression
- Optimise extraction
  improve time structure

Plans for 2025: physics

March → June | July → November

$\bar{\mathrm{H}}$ production:

possibility for cross section measurements above 8 keV

then optimisation at 6 keV

1. Cross section for $\mathrm{H} + \mathrm{Ps} \rightarrow \mathrm{H}^{-} + e^{+}$

Objective: precision better than 50 %

- End of installation this month
- Commissioning & 1st data taking

Request:

- H^{-} beam position (& intensity) stability

2. Lamb-shift experiment

Objective: first Ly-α detection

- CsI coating renewal
- Further background reduction

With goal of first line profile in 2026

Summary

2024 Highlights:

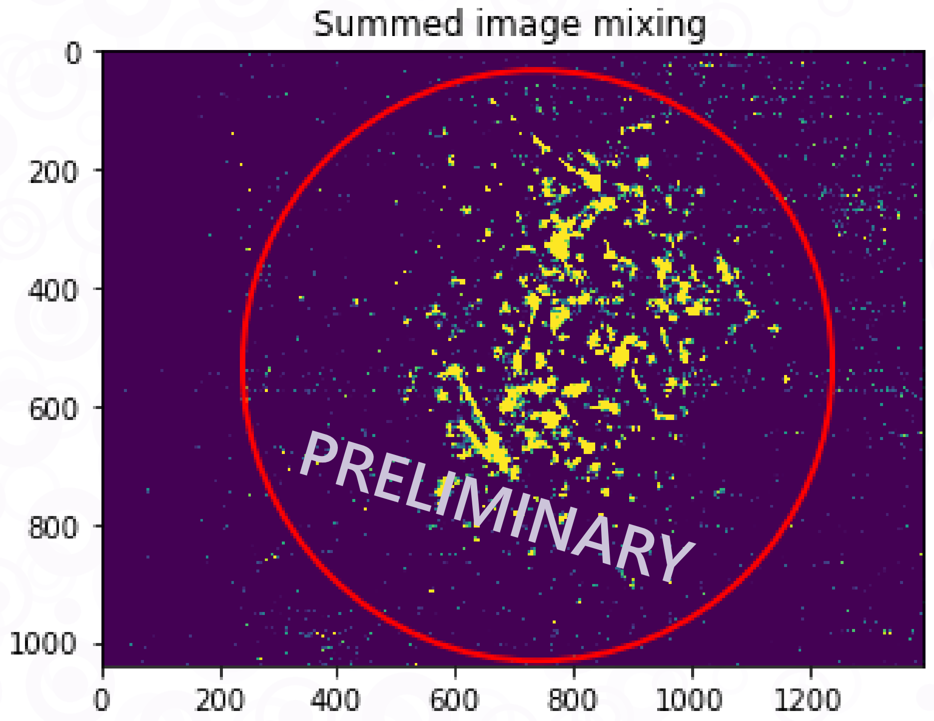
GBAR improved its $\bar{\text{H}}$ detection rate by ~30

- Over 5. 10^6 oPs
- 10^6 $\bar{\text{p}}$ through the Ps cavity

Cross section measurement at 4 and 6 keV (analysis ongoing)

Record antiparticle accumulation

- 7.10^9 positrons in 30 minutes - *World record*
- 7.10^7 $\bar{\text{p}}$ - *« personal best »*



Antihydrogen beam spot

Many thanks to…

the GBAR collaborators

P. Adrich[1], I. Belosevic[2], P. Blumer[3], M. Chung[4], P. Cladé[5], P. Comini[2], P. Crivelli[3], P. Debu[2], A. Douillet[5,6], D. Drapier[5], S. Geffroy[7], S. Guellati[5], P. Guichard[8], P.-A. Hervieux[8], L. Hilico[5,6], P. Indelicato[5], S. Jonsell[9], J-P. Karr[5,6], B. Kim[10], S. Kim[11], E-S. Kim[12], L. Koller[3], N. Kuroda[13], B. Lee[11], L. Liszkay[2], D. Lunney[7], G. Manfredi[8], B. Mansoulié[2], M. Matusiak[1], V. Nesvizhevsky[14], F. Nez[5], B. Ohayon[3], K. Park[11], N. Paul[5], E. Perez[15], P. Pérez[2], J. B. de Queiroz[15], C. Regenfus[3], A. A. Rodríguez Miranda[15], E. Rosin[15], C. Roumegou[7], J-Y. Roussé[2], M. Salman[5,6], F. Schmidt-Kaler[16], K. Szymczyk[1], T. Tanaka[13], B. Tuchming[2], D.-P. van der Werf[17] D. Won[11], S. Wronka[1], P. Yzombard[5],

and AD/ELENA team & F. Butin

Back-up slides

Back-up: Activities outside CERN

$\bar{H}^+$ sympathetic cooling

- Simulation of stripping in Be^+ Coulomb crystal
  No limitation
- Testbench for re-cooling of ions launched at different KE
  Using Be^+/ Sr^+ as $\bar{H}^+$/ Be^+ proxi

$\bar{H}^+/H^-$ photodetachment

- Toward a new calculation of photodetachment threshold
  Aiming at sub-μeV precision
- Project to measure the threshold at 1 μeV
  and provide the adapted laser for GBAR

Atomic processes in the GBAR Ps target and antihydrogen beam

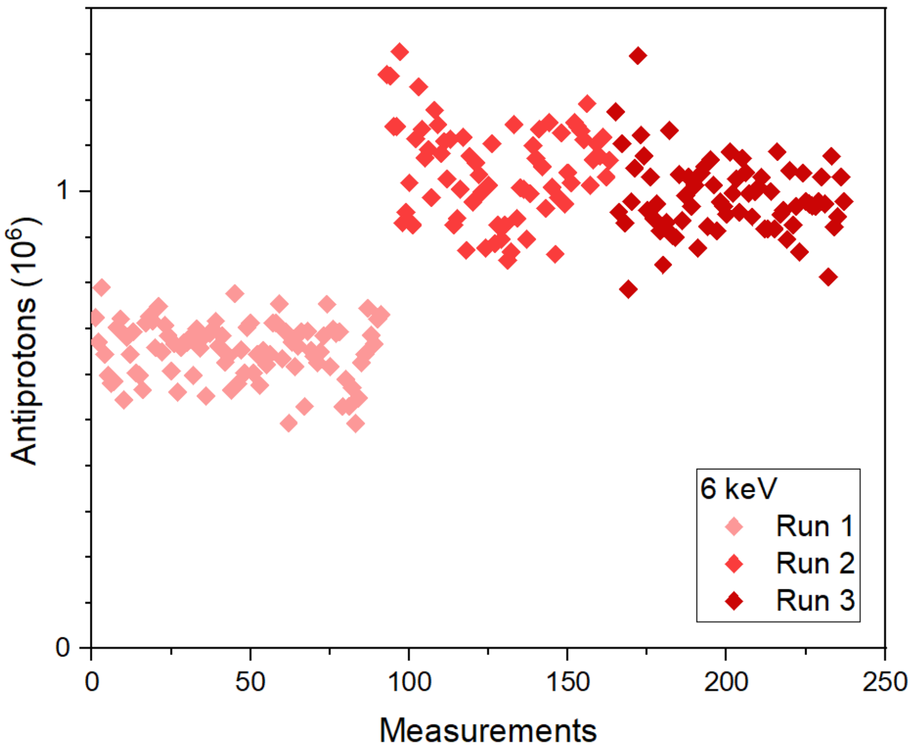
- Cross sections calculations

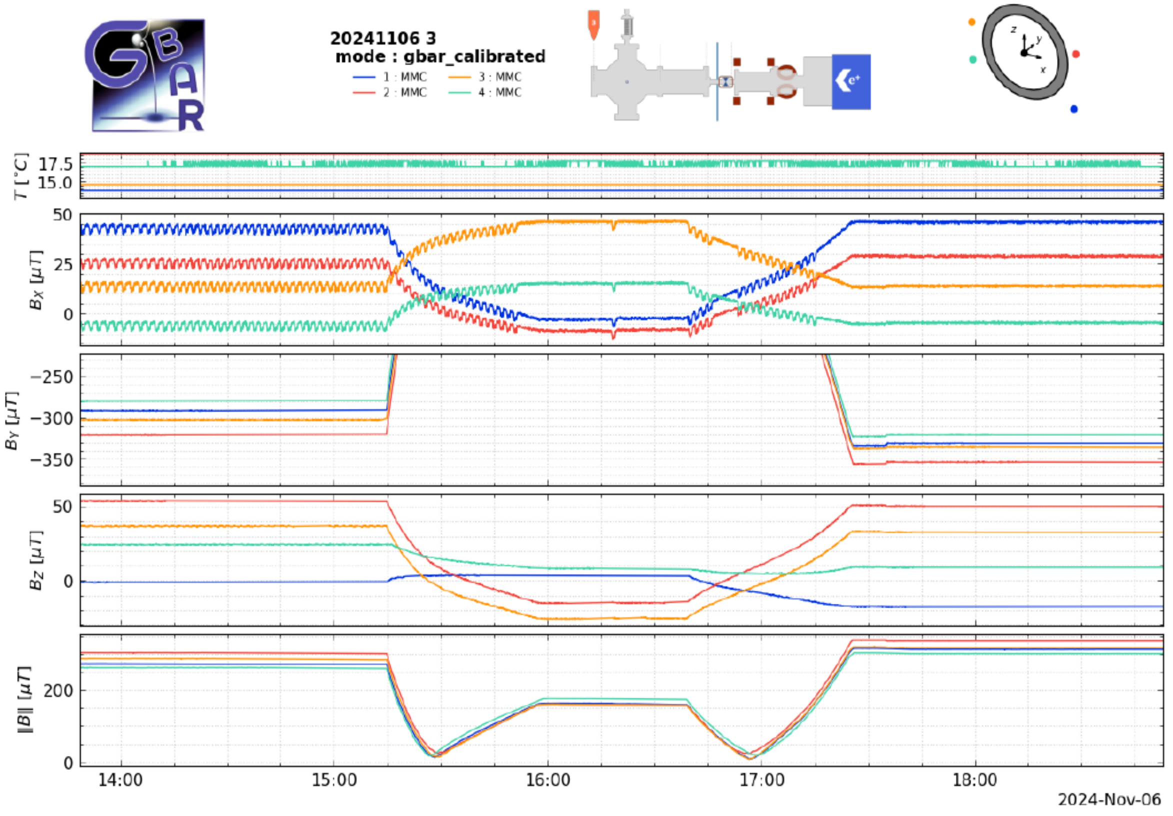
Back-up: Magnetic field monitoring

Low energy beams in GBAR sensitive to magnetic field changes

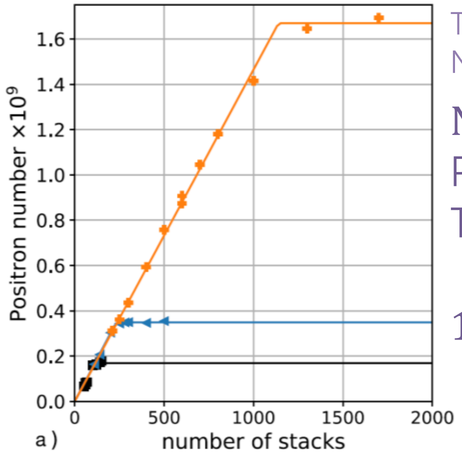
- Magnets ON/OFF & ramps – antiprotons & positrons
- AD field – H^-

Understand the origin of sudden alignment changes: deploiement of magnetic sensor array





Back-up: Previous achievements



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

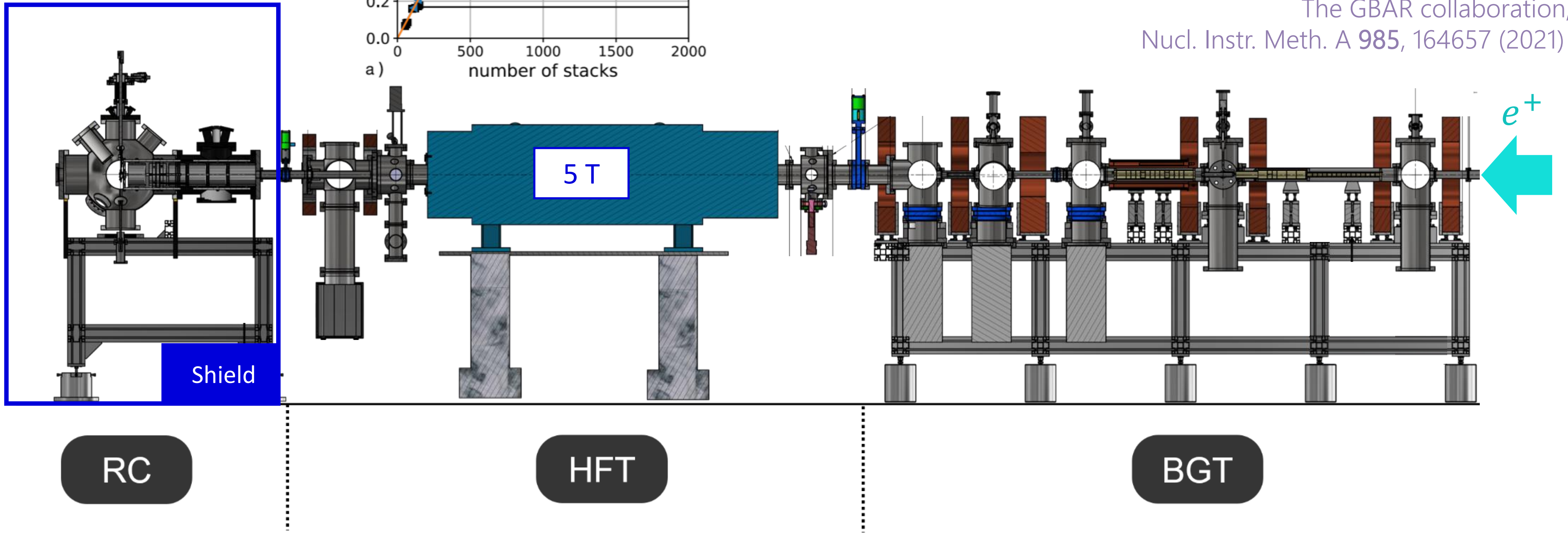
N_2/CO_2« Surko » trap
Pulsed operation
Transfer to HFT every 1 s

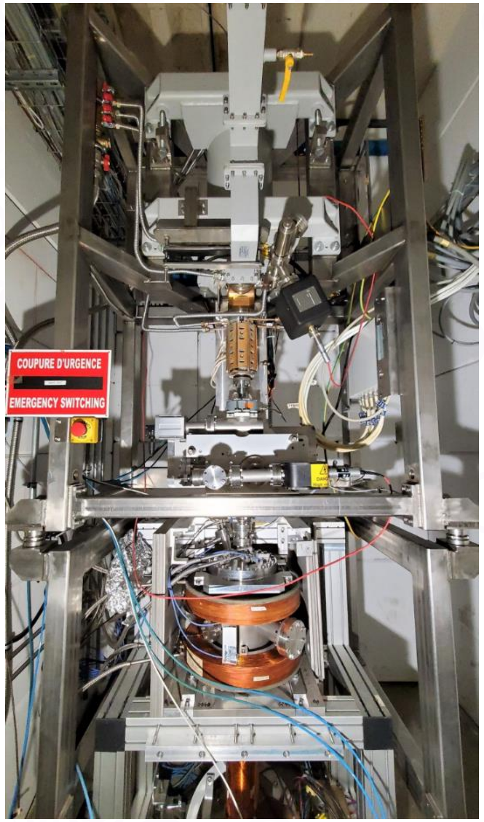
$1.4\ 10^9$ in 1100 s in 2021

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)





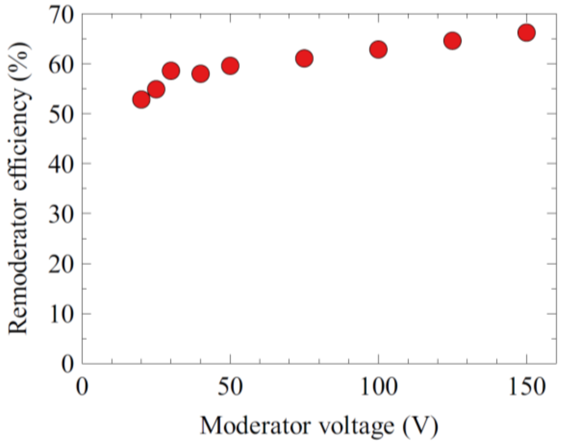
LINAC

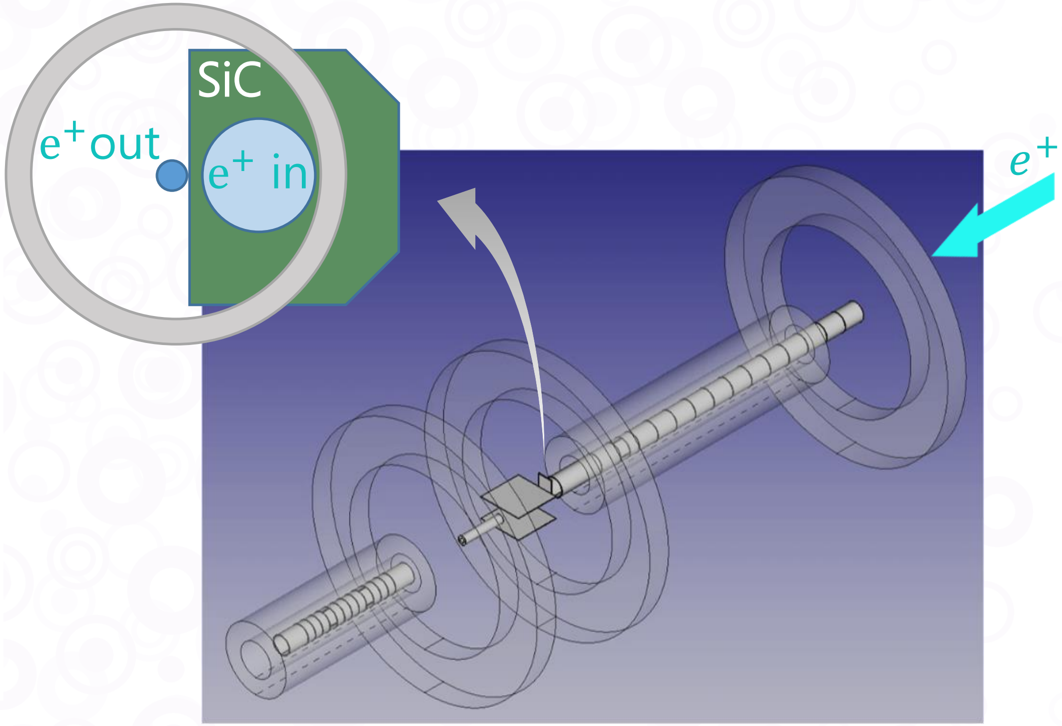
Back-up: SiC remoderator

Potential:
~60 % primary remoderation efficiency

Early study:
A. M. M. Leite *et al.*,
J. Phys.: Conf. Ser. **791**, 012005 (2017)

Reproduced at CERN (2021)





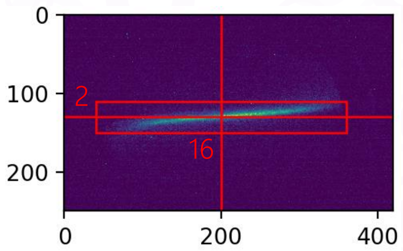
Similar to:
K. Michishio *et al.*, New J. Phys. **24**, 123039 (2022)

In reflection:
capture possible thanks to pulsed beam
+ positrons at source bunched

Replaces N_2 cooling in BGT. Factor 2 gain in 2023.

Back-up: Ps number

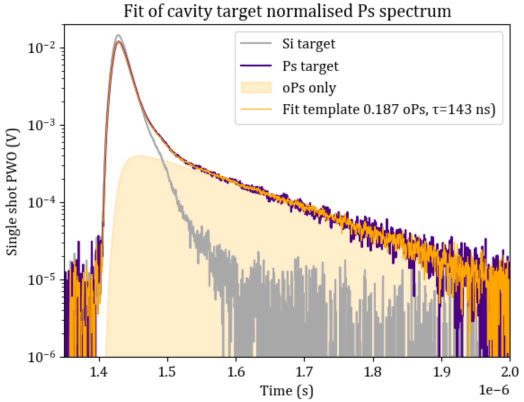
Principle example with low positron number



79 % in window

Cross check

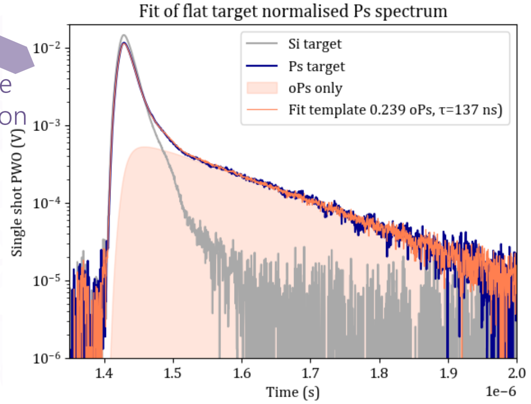
template generation



19 % ≈ 77 % Ps reference → 2.10^6 oPs

Charge measurement → 10^7 e^+

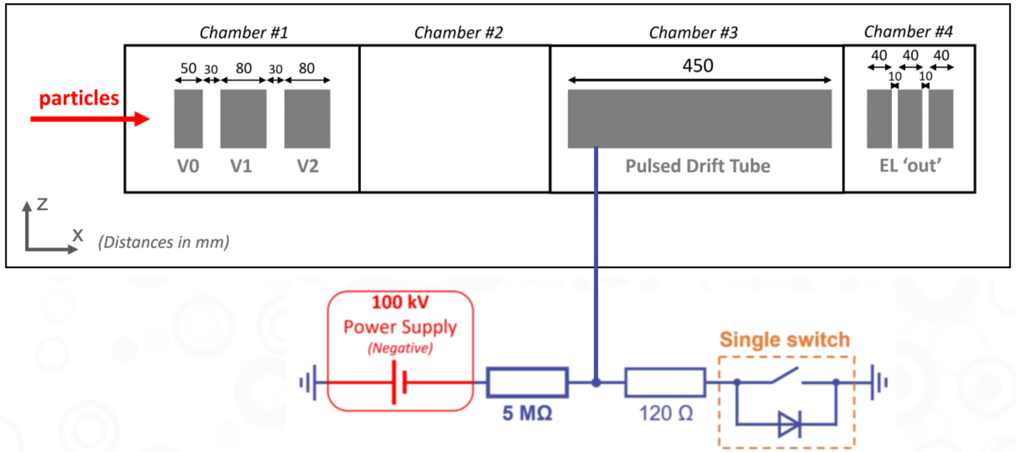
template generation

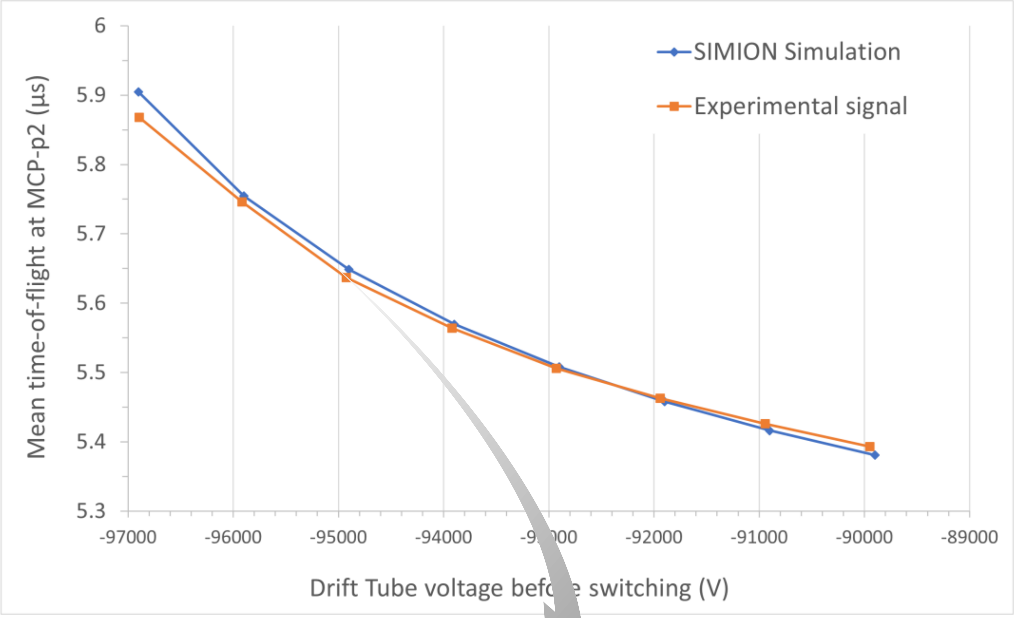


24 %

Ps reference
+ cross check with independent PALS measurement: 27 %

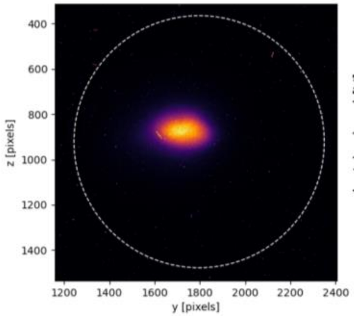
Back-up: Decelerator

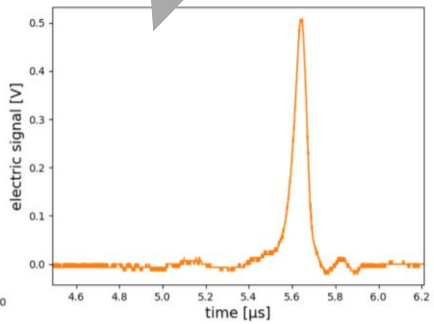




100 % deceleration efficiency to 3-10 keV

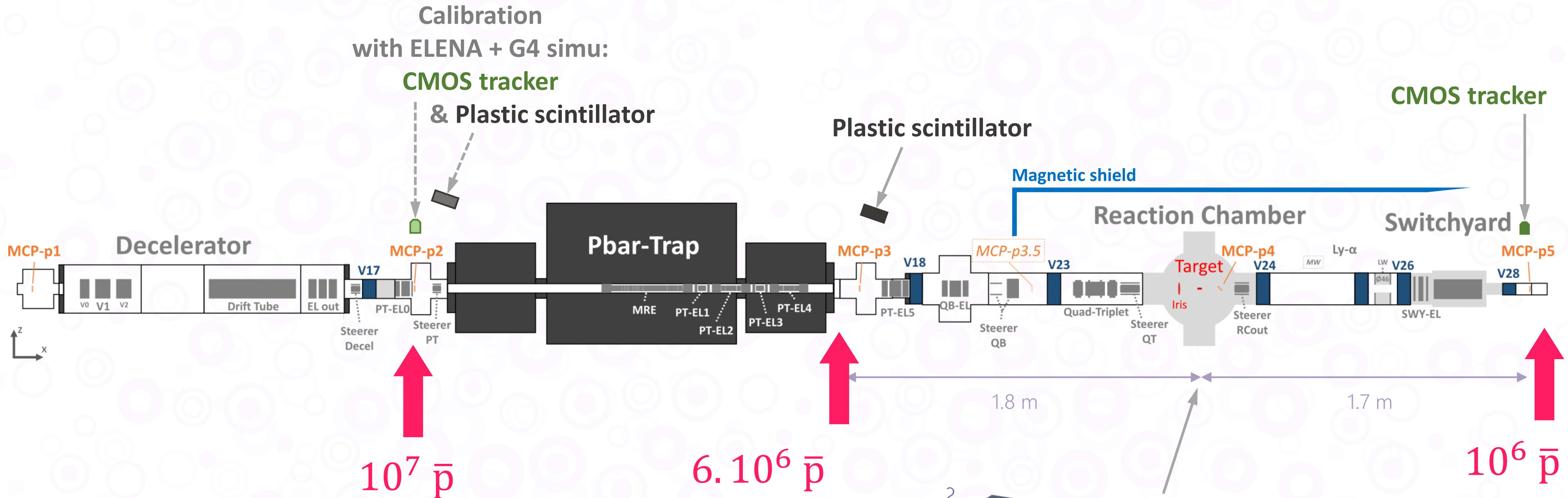
Example at 5 keV:

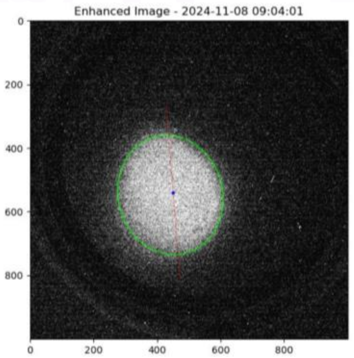


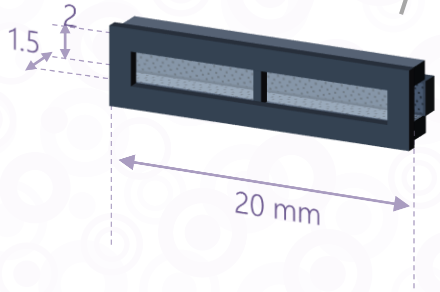


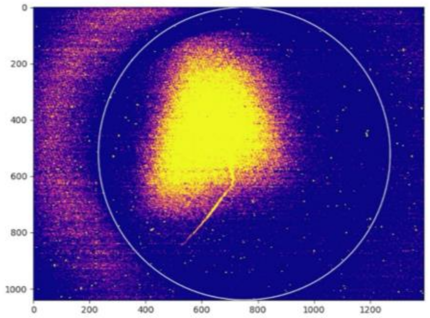
Highly stable operation

Back-up: Antiproton beamline









Back-up