Status report of the GBAR experiment

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on behalf of the GBAR collaboration

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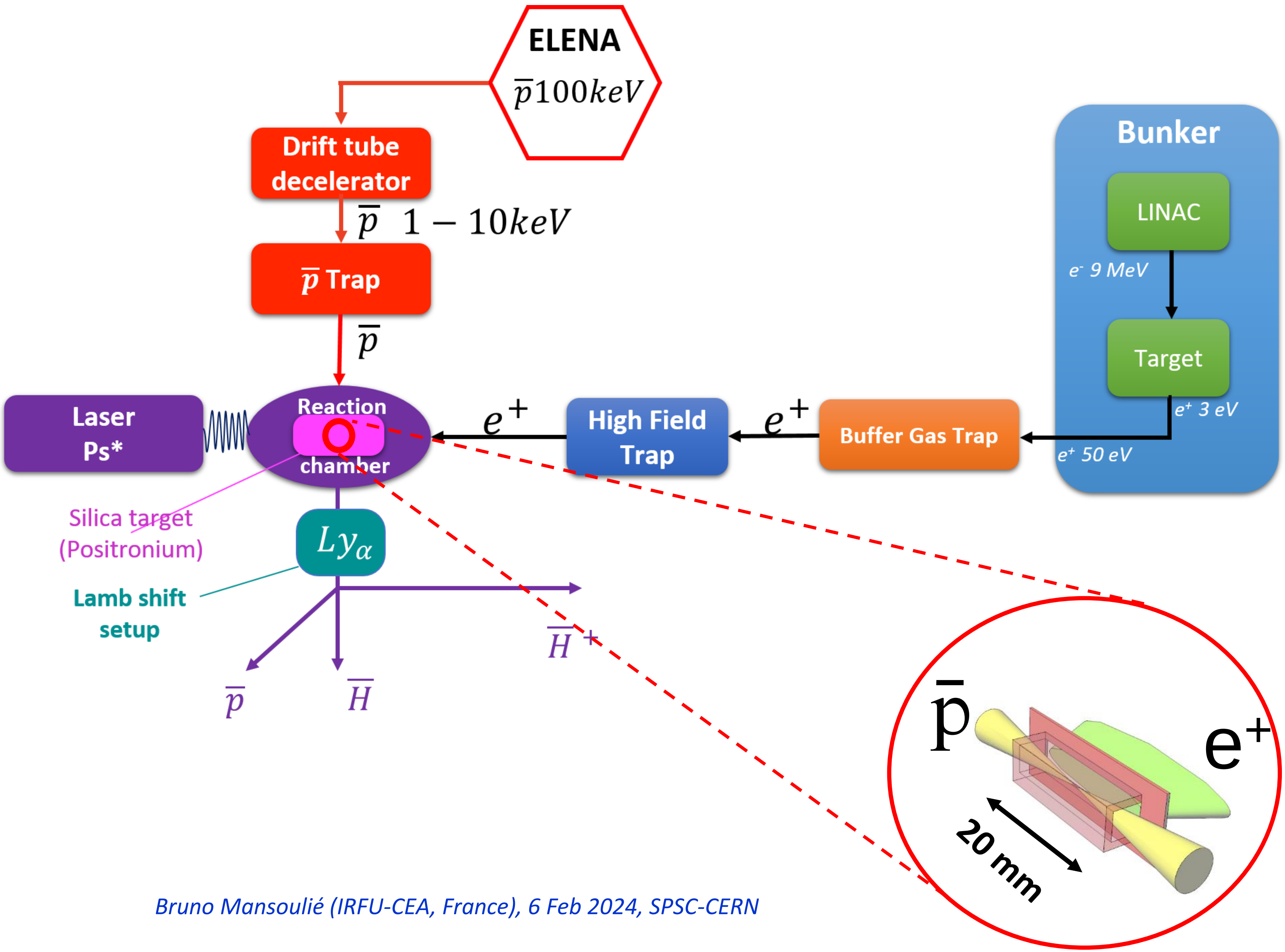
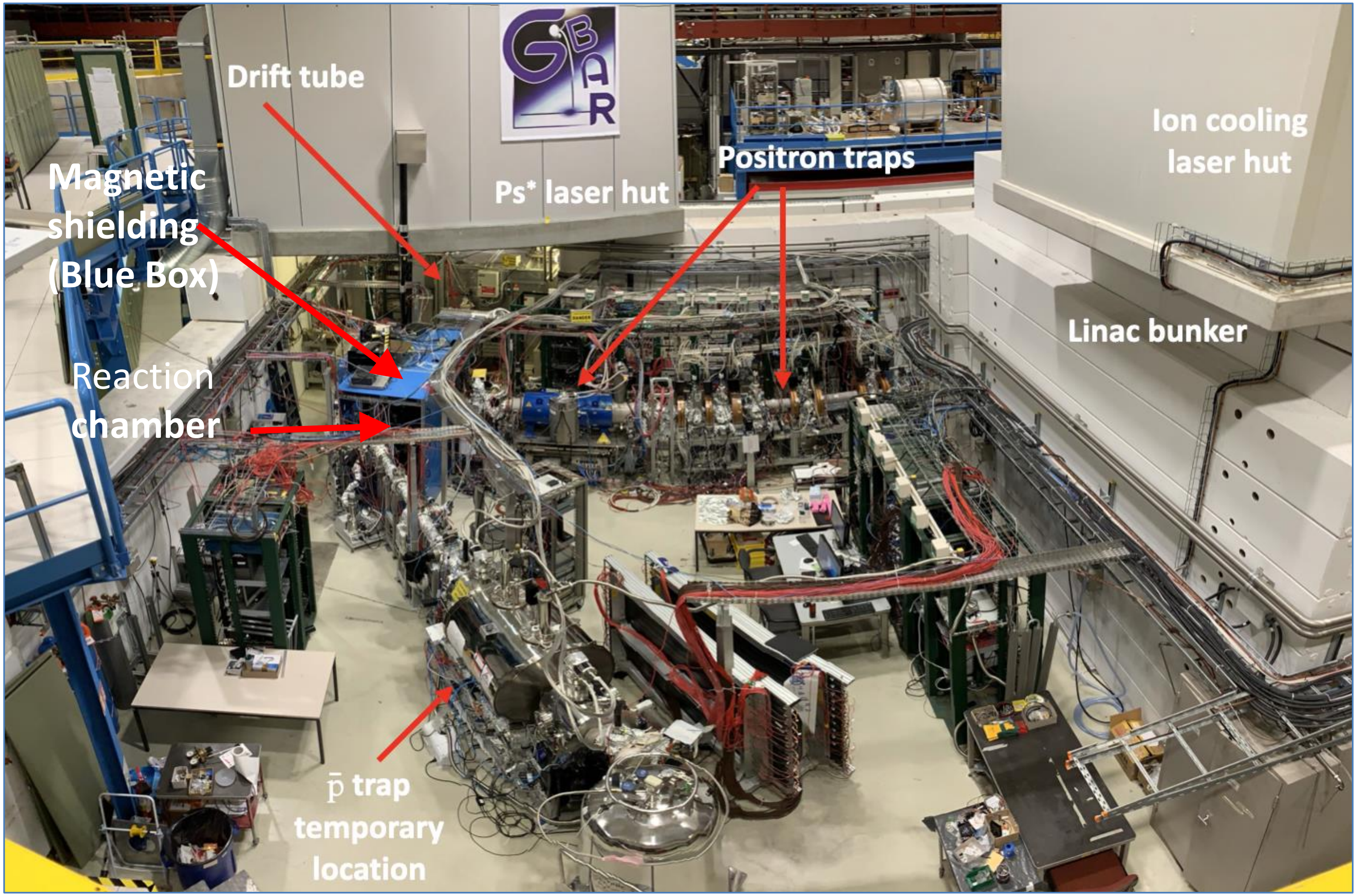
Introduction

- GBAR: measure the effect of Earth's gravity on an antihydrogen ($\bar{H}$) atom
- Principle:
  - Produce a $\bar{H}^+$ ion (antimatter eq. of H^-), trap it, cool it down to velocity ~m/s
  - Photodetach the outer e^+ $\Rightarrow$ very low velocity $\bar{H}$ $\Rightarrow$ observe free fall
- Method to produce the $\bar{H}^+$ ion :
  - e^- linac (9 MeV) on target produces e^+ $\Rightarrow$ trapped, cooled, stacked
  - e^+ bunch from trap, shot onto a converter (nanoporous SiO_2) makes positronium (Ps) cloud (in a small cavity 2x2x20 mm)
  - $\bar{p}$ from ELENA (100 keV) : decelerated (few keV), trapped, cooled
  - $\bar{p}$ from trap shot into the Ps cloud $\Rightarrow$ 2 reactions successively:
    - $\bar{p} + Ps \rightarrow \bar{H} + e-$ (1)
    - $\bar{H} + Ps \rightarrow \bar{H}^+ + e^-$ (2)

GBAR present configuration



GBAR area (before Sep 2023)



Article on antihydrogen production

- *Adrich et al. Production of antihydrogen atoms by 6 keV antiprotons through a positronium cloud. Eur. Phys. J. C 83, 1004 (2023).*

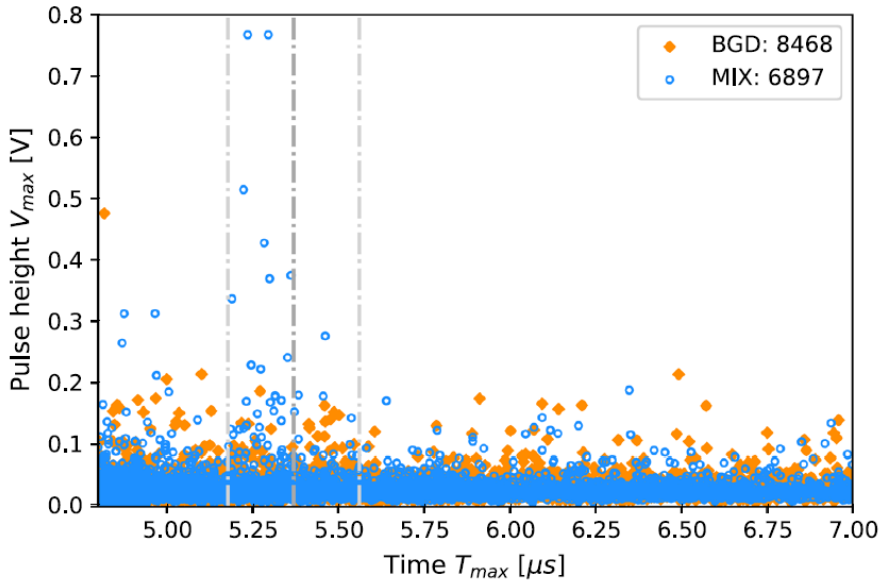
- **First simultaneous operation of positron line and antiproton line, without $\bar{p}$ trap.**
  - **e^+ beam: 3.9 10^7 , 7.4 ns (rms) , on flat SiO_2 converter to Ps (ε = 18%)**
  - **$\bar{p}$ beam: 3.1 10^6, 96ns (rms), onto Ø ~5 mm Ps cloud**

- **7000 "mixing" spills , 8500 "background" spills (without e^+)**

- **In $\bar{H}$ time-window, 32 events for mixing**
  15 for background

3.1 σ evidence for $\bar{H}$ production
(reaction (1))

- **In rough agreement with expected yield**



Positron production and trapping

- Electron LINAC: new (second-hand) klystron, used at 200 Hz (nominal 300 Hz)
- Primary e^+ moderator replaced beginning 2023 => increased yield

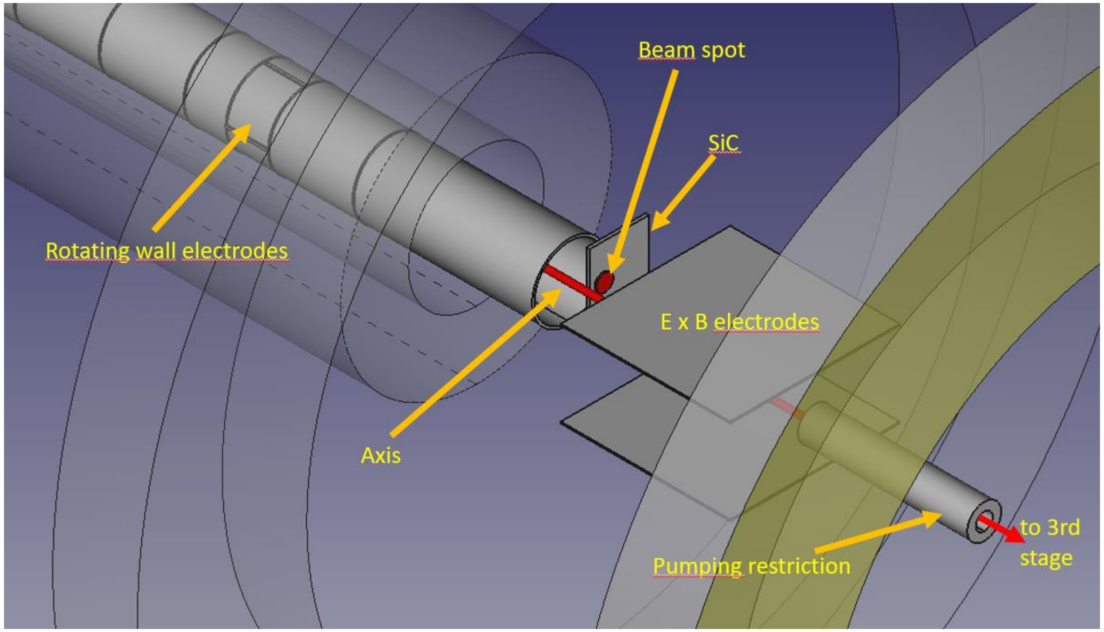
- New first stage trapping system

N_2 gas $\Rightarrow$ SiC remoderator

50-150 eV incident e^+'s → SiC

re-emitted at ~ 3 eV and trapped

SiC off-axis

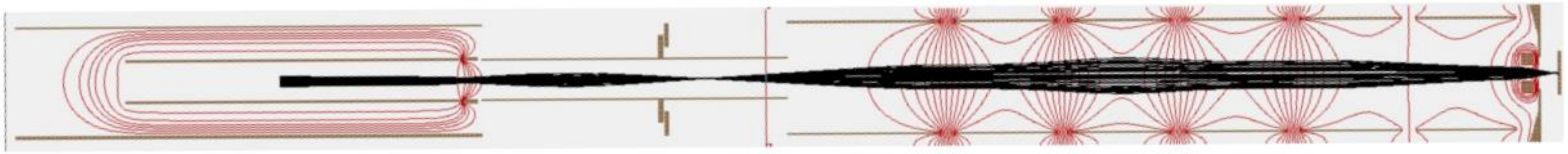


- Total trapped in High Field Trap: 6 10^8 e^+ between two $\bar{p}$ bunches (x 4 w.r.t. 2022)

1 – 1.2 10^9 e^+ in 3 min *(then saturates)*

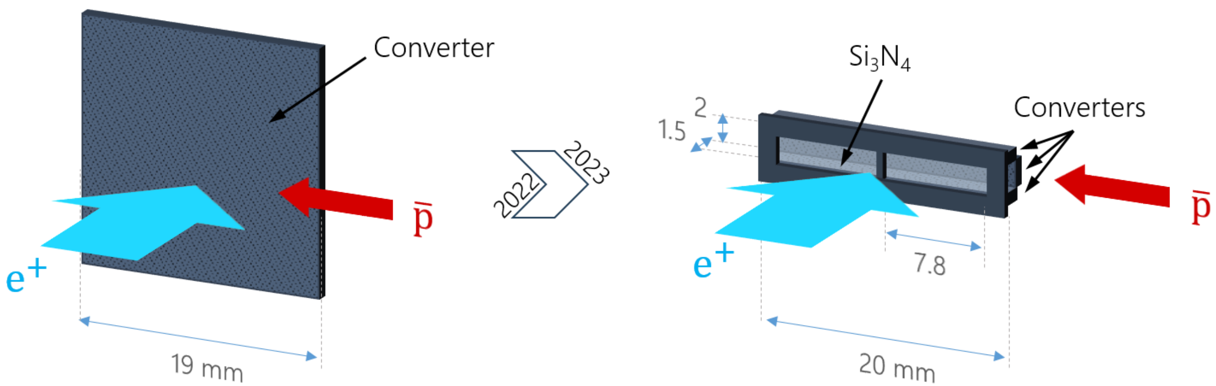
Positronium production

- **Transport from High Field Trap to Reaction Chamber (Ps converter target)**



  - **High magnetic field → low field : acceleration (4.3 keV) / non-adiabatic**
  - **Trajectories strongly depend on bunch diameter, and beamline details…**
  - **Presently low efficiency for 6 10^8 e^+ ⇒ needs strong effort**

- **e^+ to Ps converter (nanoporous SiO_2)**
  - **2022 run: flat target**
  - **2023: new Ps cavity**

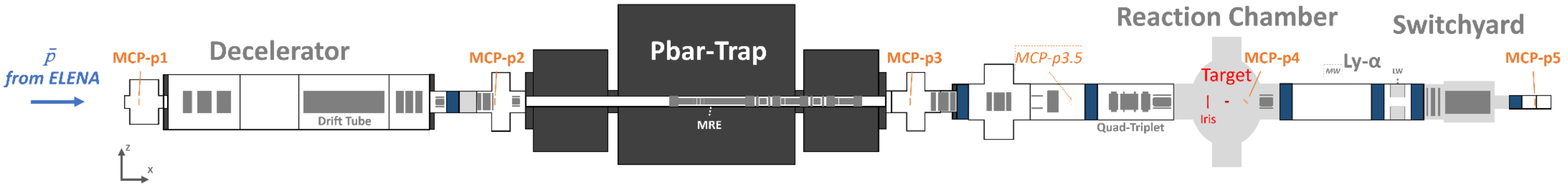


  - **Measured e^+ → Ps conversion efficiency: ~20%**
  - **Increases Ps cloud density by X 5 - 10 w.r.t. flat target**

Antiproton beam line

- In 2022 and beginning of 2023: antiproton trap in test position at the end of the ion line (after reaction chamber and switchyard)

  In Sept 2023: pbar-trap moved to nominal position



- Very good $\bar{p}$ beam from ELENA, typ. 7 10^6 $\bar{p}$ /shot (2 min), 40 ns (rms), stable

  emittances x 2 from design (2.9 μ, 2.1 μ resp.) $\Rightarrow$ mitigated by pbar-trap (?)

  Also H^- beam (Thanks +++ to the ELENA team!)

  15 s repetition rate: beam tuning, physics with H^- / H (see later)

  instabilities: intensity, position… (would need more work)

Antiproton line: decelerator

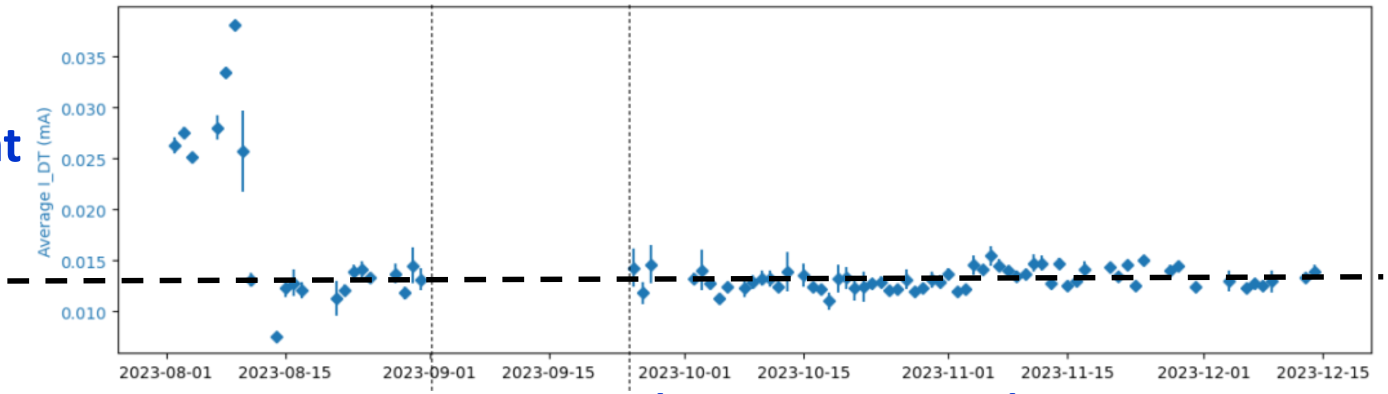
- **Beginning 2023: improved decelerator: remove unused electrodes, better Drift Tube support and connexion scheme, better DT polishing, remove ion pumps, etc.**

- **2023 operation:**
  - **High Voltage (90 to 99 kV) applied only for 3 sec before bunch**
  - **Reliable, low leakage current , limited by the HV-switch (not in vacuum)**

    ⇒ negligible voltage drop ⇒ decelerated energy is well-defined, stable

Leakage current

~13µA



Date (Aug – Dec 2023)

Antiproton trap

- **Preliminary tests in 2022 at the end of ion beam line (parasitic)**
- **Installed Sep 2023 in nominal position**
- **4 weeks commissioning**
  - **Electron accumulation**
  - **3 – 6 keV $\bar{p}$ trapped , up to 60% global efficiency (trapped/ELENA bunch)**
  - **e-cooling demonstrated: $\bar{p}$ trapped in harmonic potential < 140 eV in 10 s**
  - **Rotating wall compression observed qualitatively**
  - **Extraction and re-acceleration (by long electrode used as drift tube)**

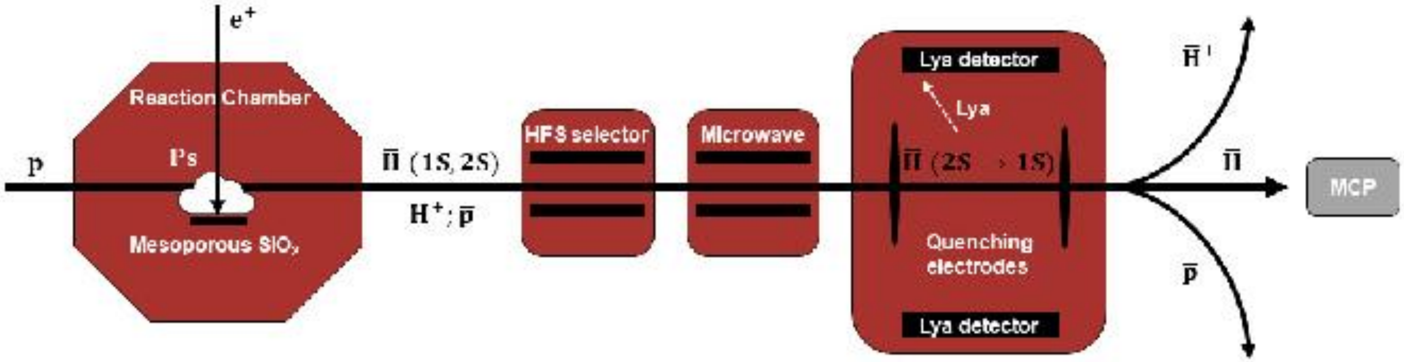
    Faulty electrode => use another (shorter) one => limited efficiency

    Demonstrated: acceleration, and longitudinal shortening by time-varying potential

  - **H^- bunch trapped, but e-cooling not possible**

Progress on Lamb shift experiment

- Antihydrogen beam allows to measure Lamb shift without magnetic field

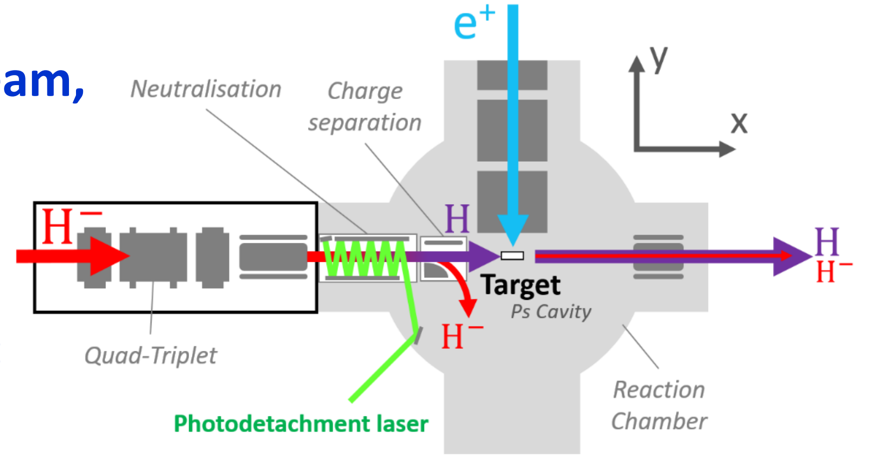


- $\bar{p}$ + Ps reaction produces ~ 15% $\bar{H}$ in 2S state
- 2S – 2P transition finely scanned by microwave section
- Remaining atoms quenched by E-field => detect Ly-alpha photons

- Setup tested at PSI with H and muonium atoms, and in 2021 GBAR : p + C-foil
- 2022 : number of $\bar{H}$ too low to see Ly-alpha photons
- 2023: studied background, redesigned electrodes, etc.
- 2024: Observe Ly-alpha photons. *First measurement would need ~1000 $\bar{H}$*

SPHINX project (with H^- beam)

- use H^- beam from ELENA, decelerated
- Photodetach outer electron => neutral H beam,
  impinging on Ps cloud
  remaining H^- 's deflected before target



- Measure the cross-section for H^- formation:
  $H + Ps \rightarrow H^- + e^+$
  Charge conjugate of GBAR "second reaction"
  $\bar{H} + Ps \rightarrow \bar{H}^+ + e^-$ never measured, critical for GBAR

- *Not possible to cool H^- in the pbar-trap $\Rightarrow$ use in passthru mode or remove it for this measurement (transfer line)*

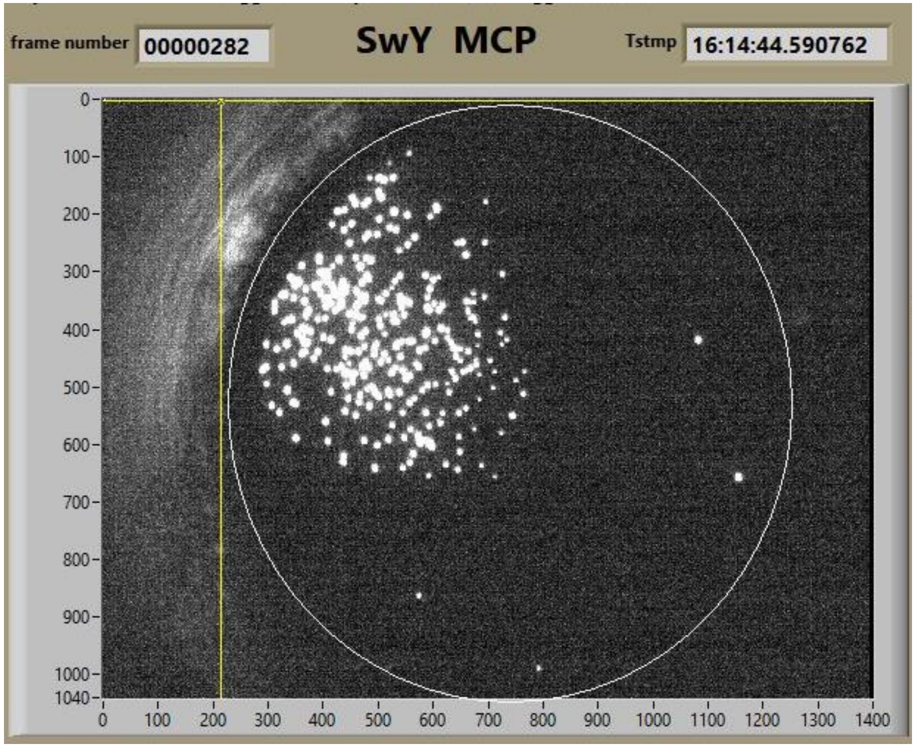
- Measurement needs multipass laser interaction with the H^- beam
  - Designing/building the setup
  - Studying mirrors

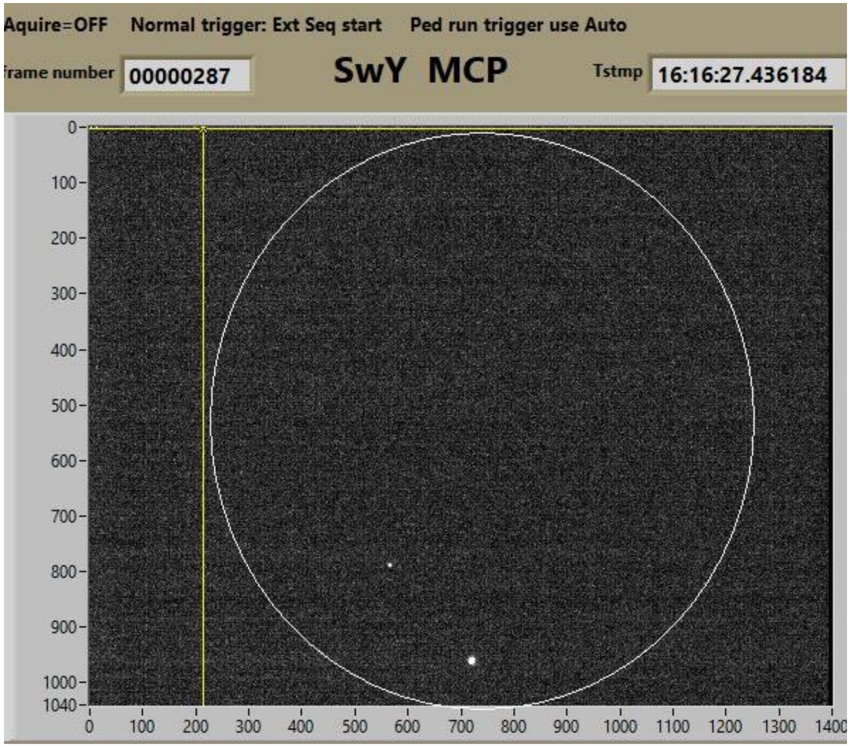
SPHINX: first tests

- **First tests with single pass laser**

Same H^- beam

with laser **without laser**





Outlook

- **2023**
  - **Publication : evidence of $\overline{\mathrm{H}}$ production**
  - **Positrons: SiC remoderator, new Ps cavity**
  - **Antiprotons: pbar-trap installed and tested**

    H^- : photodetachment tested

- **2024**
  - **Antiprotons on Ps: run, increase $\overline{\mathrm{H}}$ production by factor > 10**
    - **Measure the cross-section of the "first reaction" $\bar{p}$ + Ps -> $\overline{\mathrm{H}}$ + e-**
      - **at different energies [3-10 keV] (?)**
    - **Lamb-shift: observe Ly-α photons, control background**
  - **H^- : multipass photodetachment. Measure "second reaction" H + Ps -> H^- + e^+**

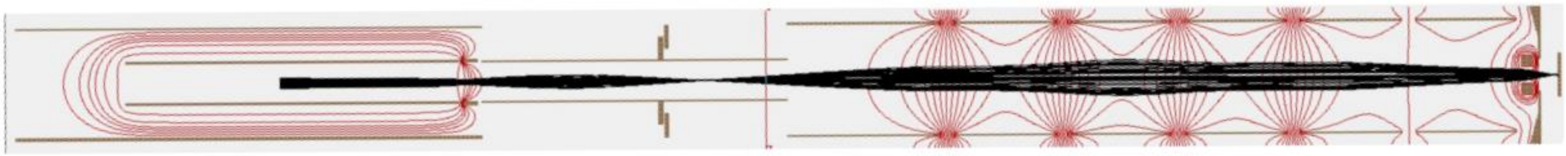
- **2025**
  - **Measure Lamb shift of $\overline{\mathrm{H}}$**
  - **Observe $\overline{\mathrm{H}}^+$ production**

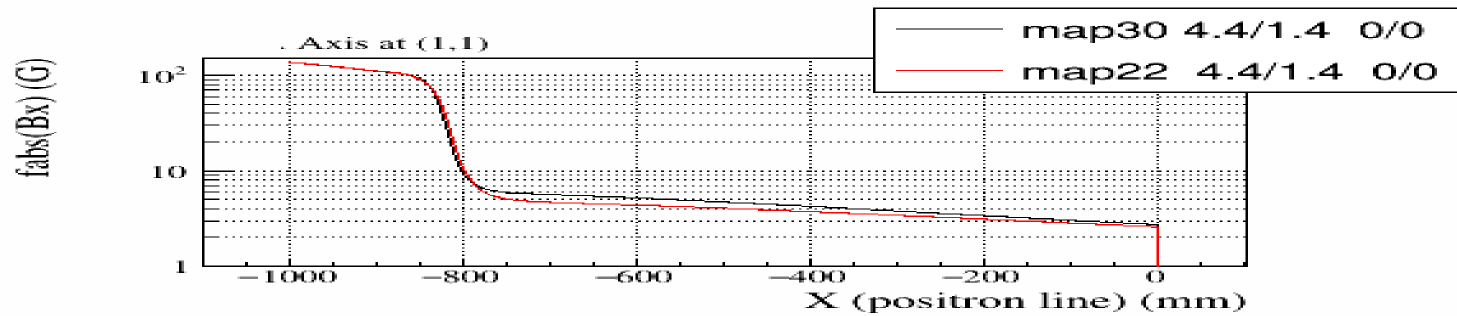
Additional slides

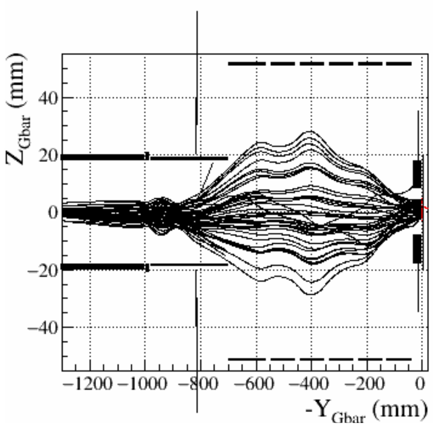
GBAR Plans

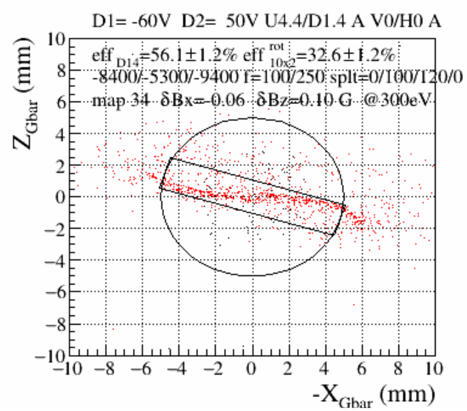
1. Before LS3
   1. Measure $\overline{\mathrm{p}} + \mathrm{Ps} \rightarrow \overline{\mathrm{H}} + \mathrm{e}^-$ cross section
   2. Measure Lamb shift
   3. Measure $\mathrm{H} + \mathrm{Ps} \rightarrow \mathrm{H}^- + \mathrm{e}^+$ cross section using laser neutralised H^- beam from ELENA
   4. First detection of $\overline{\mathrm{H}}^+$
2. During LS3
   1. Improve e^+ performances
   2. Improve $\overline{\mathrm{p}}$ beam line performances using H^- beam from ELENA if available & cross section measurements
   3. Install apparatus for $\overline{\mathrm{H}}^+$ capture/cooling/photo-detachment & gravity experiments
3. After LS3
   1. Routine production of $\overline{\mathrm{H}}^+$
   2. Gravity experiments (classical free fall & quantum interferences)
   3. Improve Lamb shift measurement precision
   4. $\overline{\mathrm{H}}_2$???

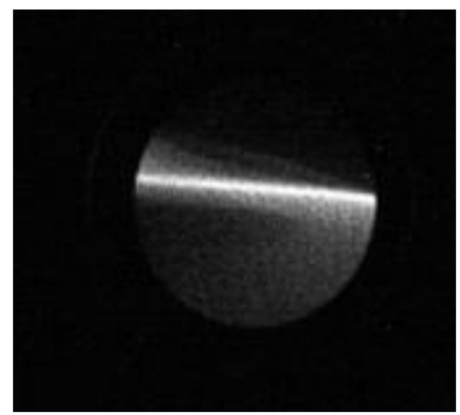
Positron transfer to Ps target





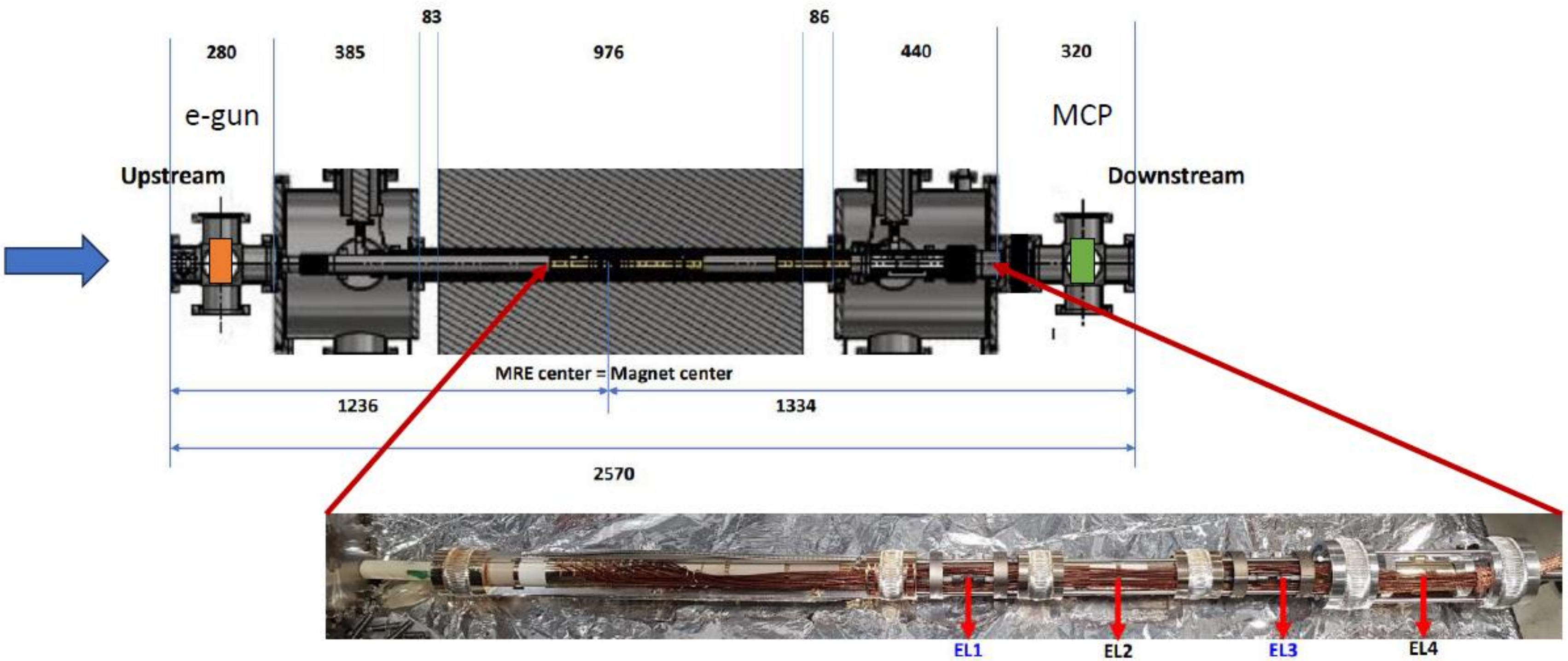




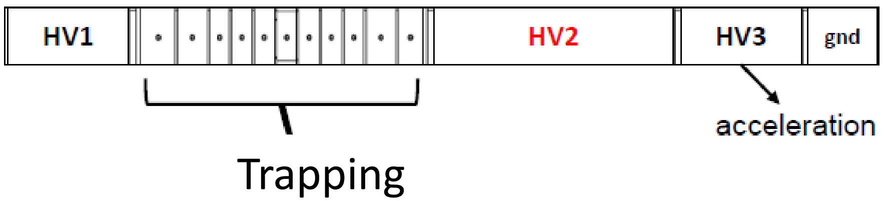


Antiproton trap

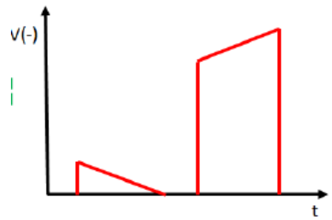
- Trap Dimension
- unit: mm



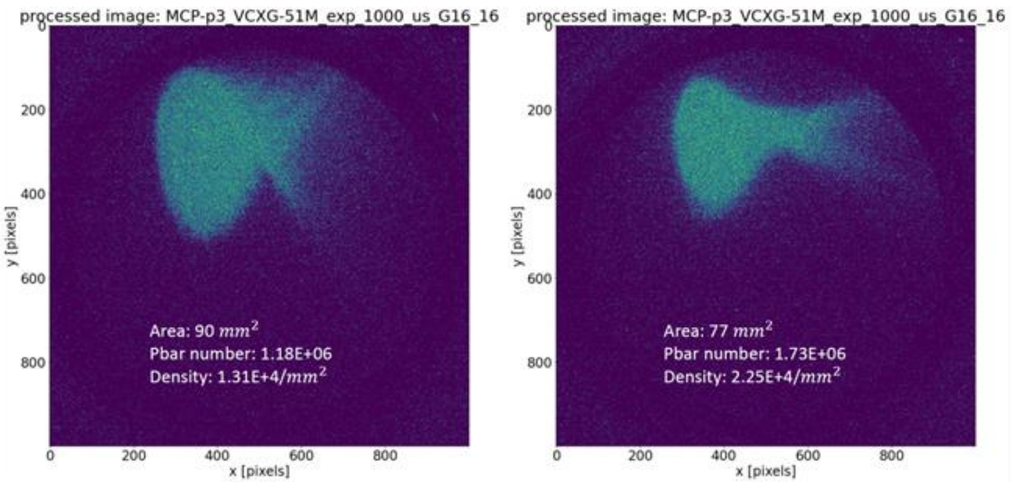
Antiproton trap



- **Buncher/accelerator**

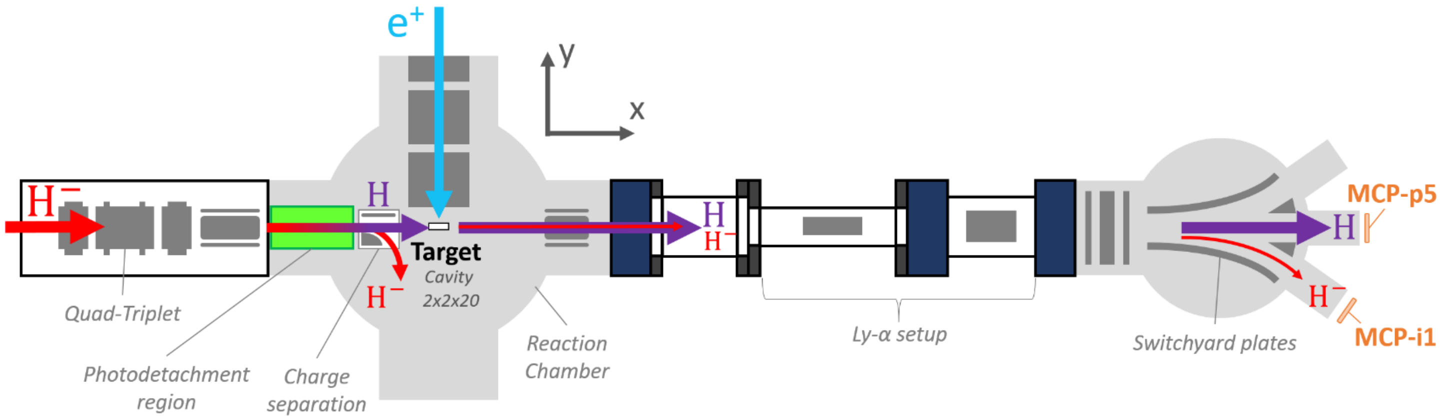


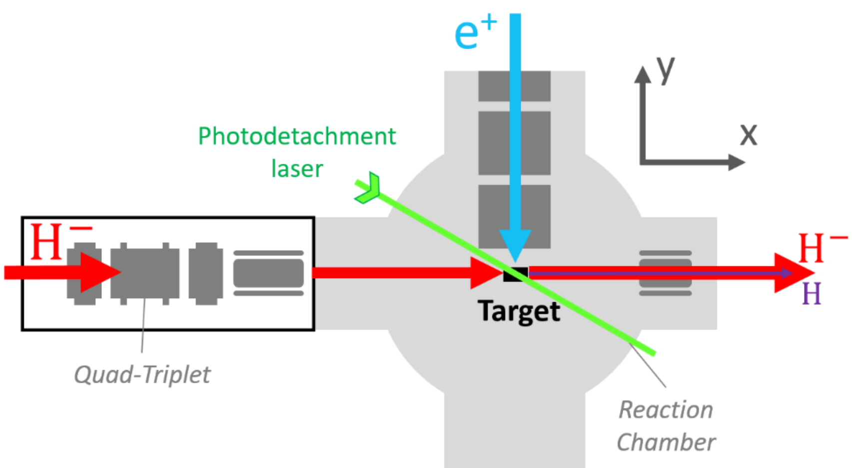
Antiproton Buncher System



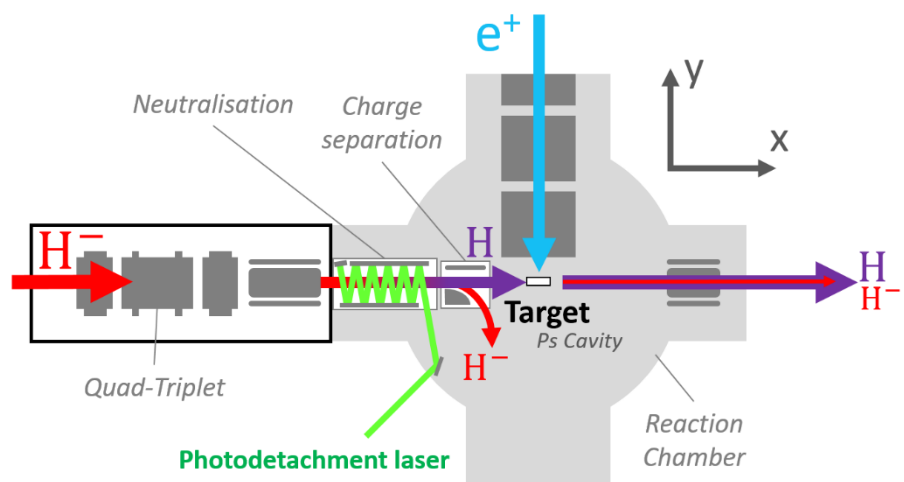
- **RW compression seen; beam profile, position, etc. needs more work.**

Sphinx





2023



2024