GBAR status report 2023

GBAR / Irfu

P. Debu, P. Comini, L. Liszkay, B. Mansoulié, P. Pérez, J-Y. Roussé, Y. Sacquin, B. Tuchming, B. Vallage

Outline

- Installation and first tests — *P. Pérez*
- 2022 run & improvements for 2023-2024 — *L. Liszkay*
- Future — *P. Comini*

16 institutes, 59 members

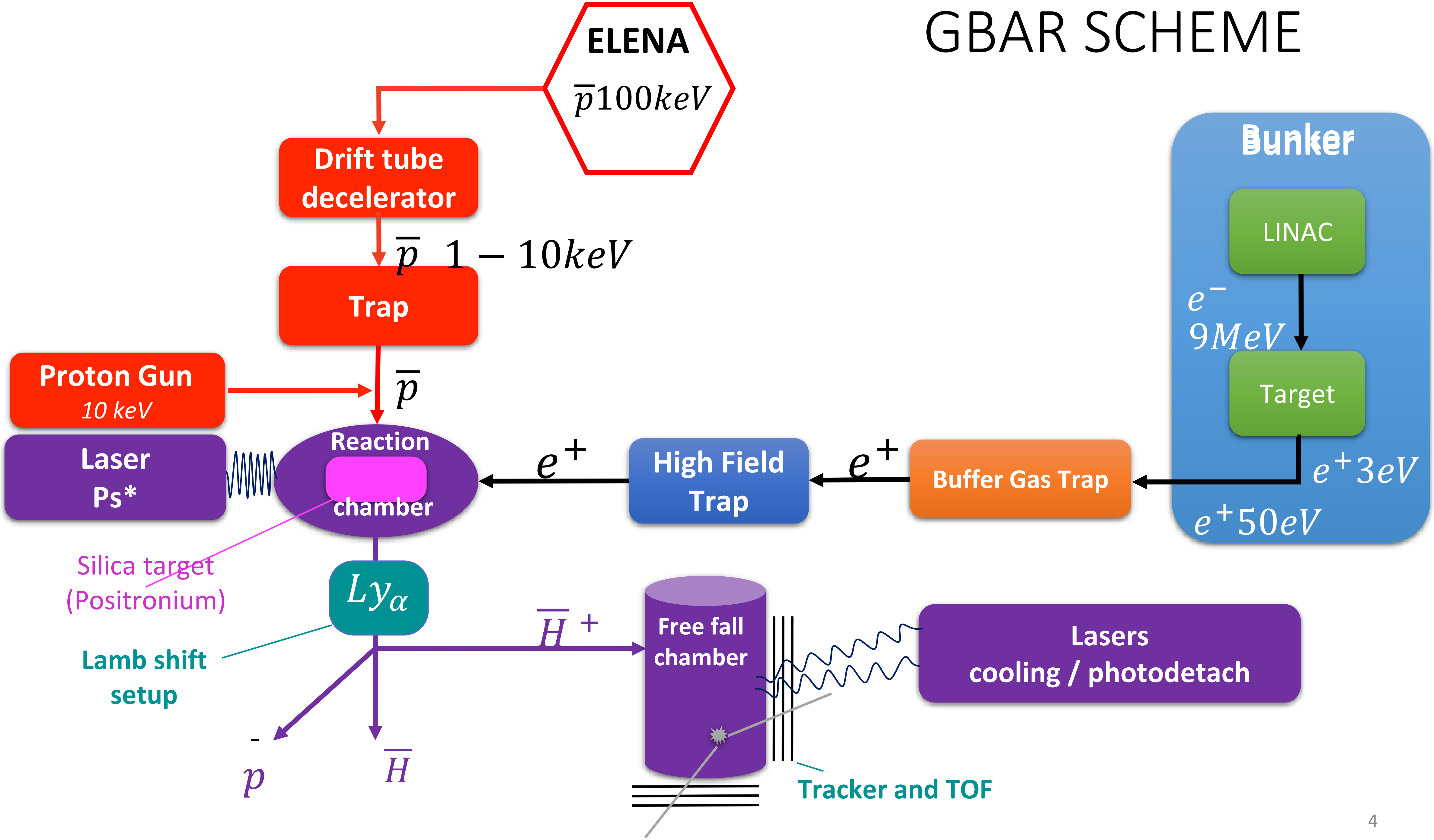
France, Germany , Japan , Poland, Republic of Korea, Switzerland, United Kingdom Me

Physics goals

- Produce antihydrogen atoms $\overline{\mathrm{p}} + \mathrm{Ps} \rightarrow \overline{\mathrm{H}} + \mathrm{e}^{-}$

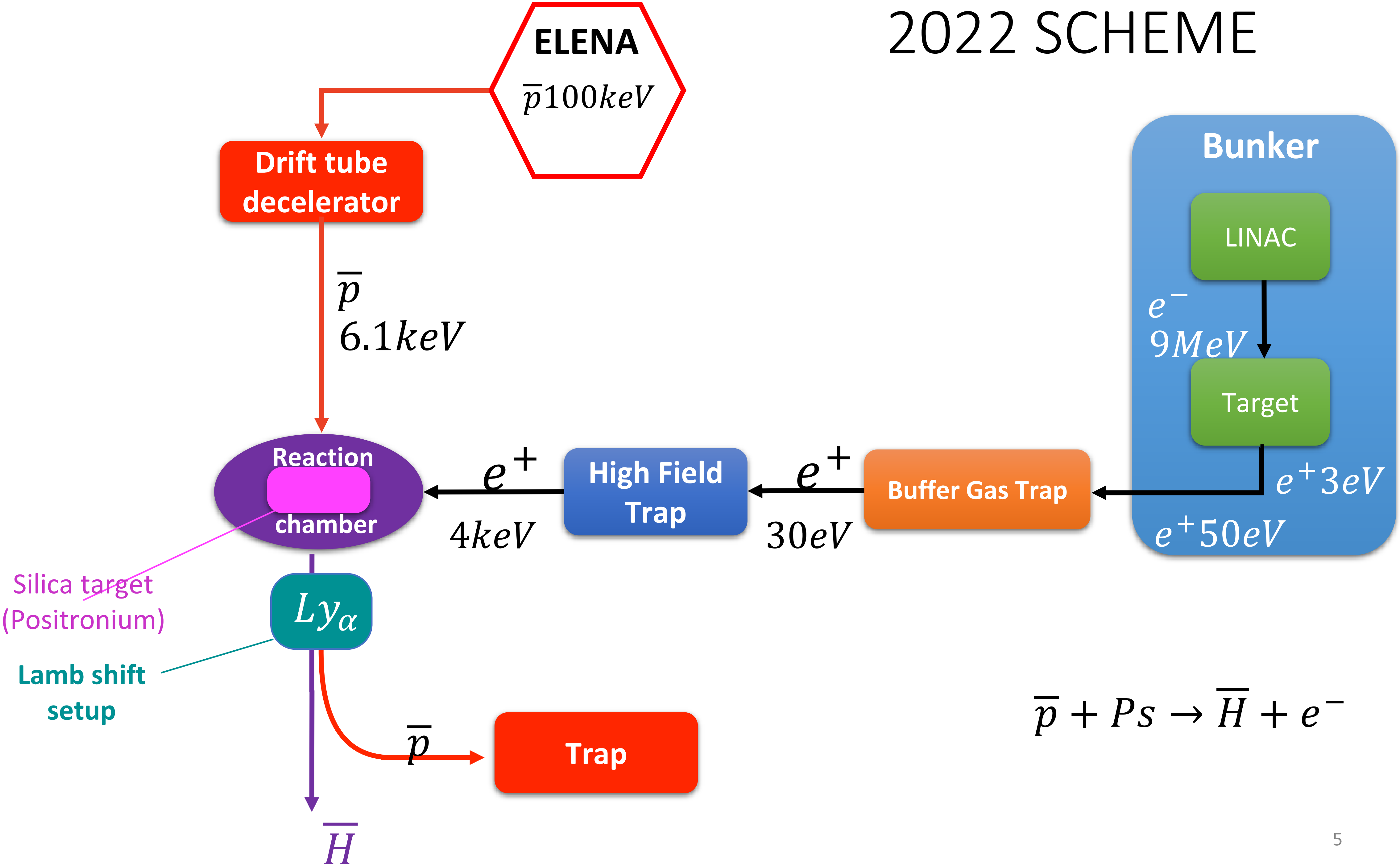
  ions $\overline{\mathrm{H}} + \mathrm{Ps} \rightarrow \overline{\mathrm{H}}^{+} + \mathrm{e}^{-}$
- Cool $\overline{\mathrm{H}}^{+}$ to 10 μK and photo detach —> ultra cold $\overline{\mathrm{H}}$
- Measure $\overline{\mathrm{H}}$ free fall
- Measure $\overline{\mathrm{H}}$ Lambshift —> radius of antiproton

GBAR SCHEME

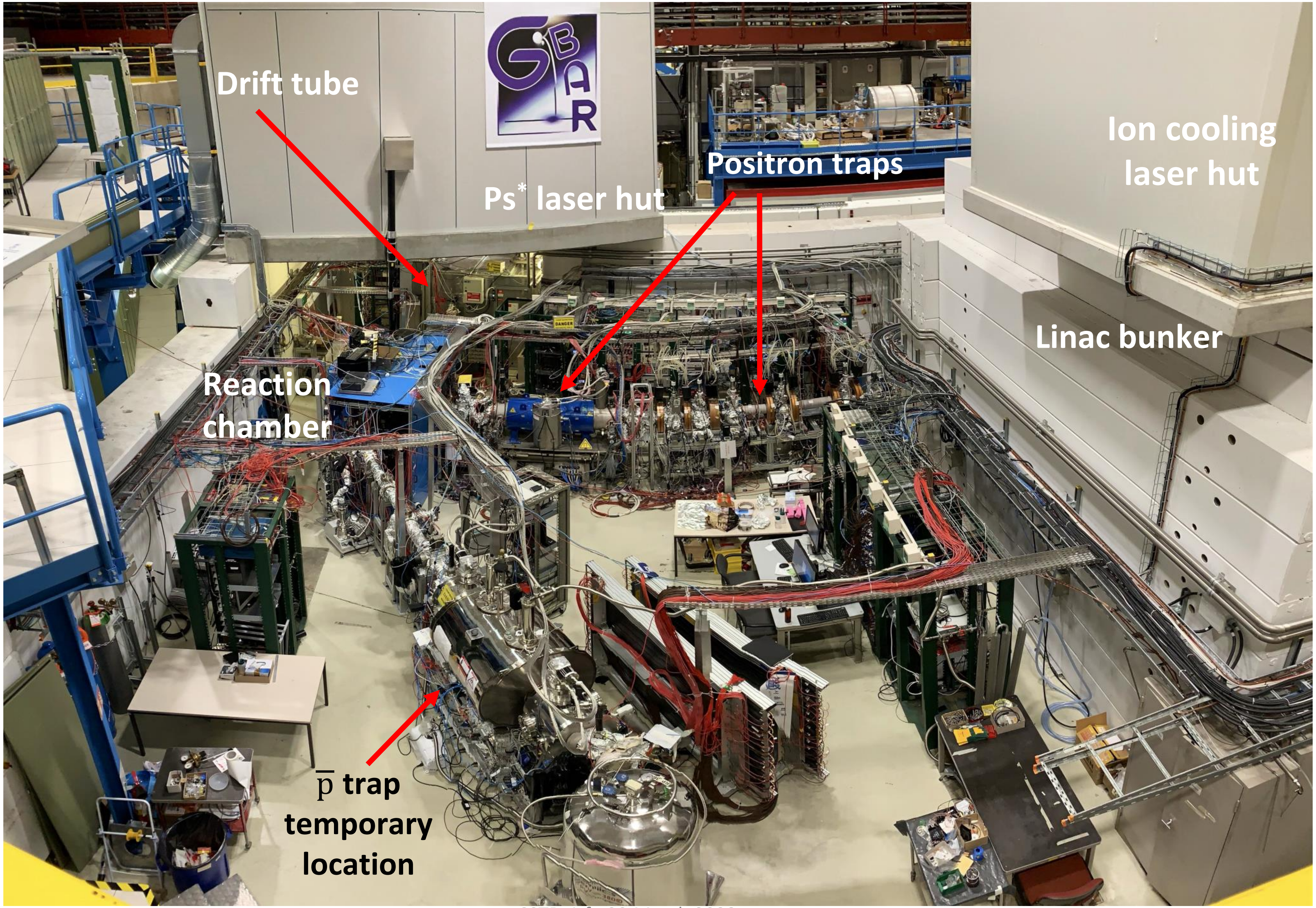


ELENA
$\overline{p}100keV$
Drift tube decelerator
$\overline{p}\ \ 1-10keV$
Trap
Proton Gun
10 keV
$\overline{p}$
Laser
Ps*
Reaction
chamber
Silica target
(Positronium)
Ly_α
Lamb shift setup
$\overline{H}^+$
Free fall chamber
Lasers
cooling / photodetach
Tracker and TOF
$\overline{p}$
$\overline{H}$
e^+
High Field Trap
e^+
Buffer Gas Trap
Bunker
LINAC
e^-
$9MeV$
Target
e^+3eV
e^+50eV

2022 SCHEME

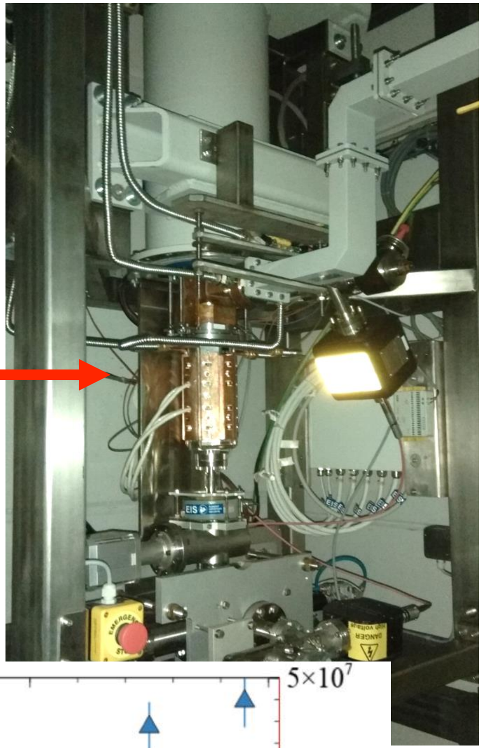


$$\overline{p} + Ps \rightarrow \overline{H} + e^-$$



Drift tube
Ps* laser hut
Positron traps
Ion cooling laser hut
Linac bunker
Reaction chamber
p̄ trap temporary location

Positron production



9 MeV, 300 mA, 2.85µs, 1-300 Hz

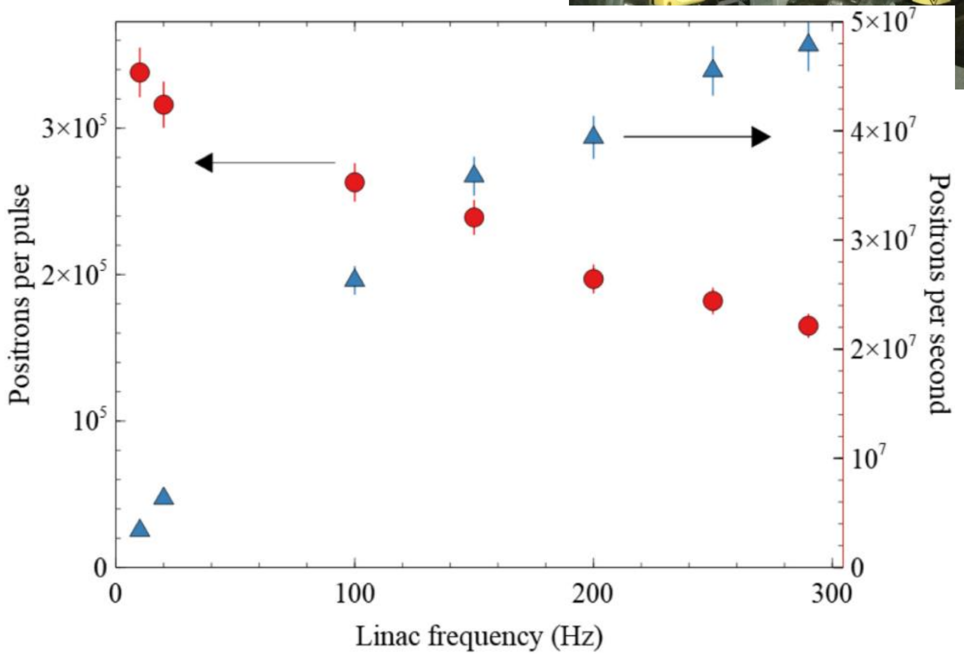
1mm W target water cooled + W mesh moderator

Linac accelerating cavity exchanged Feb 2022

- Higher current acceptance without RF power reflection
- Same Energy and Beam Current at lower RF level
- Lower stress for RF elements
- 7.3 MW —> 5.5 MW, can use other klystron types

Exchange of klystron Oct. 2022

3 x 10^7 e^+ / s   in 2022



M. Charlton et al., NIM, A 985 (2021) 164657

Positron trapping

BGT Buffer Gaz Trap 50 mT

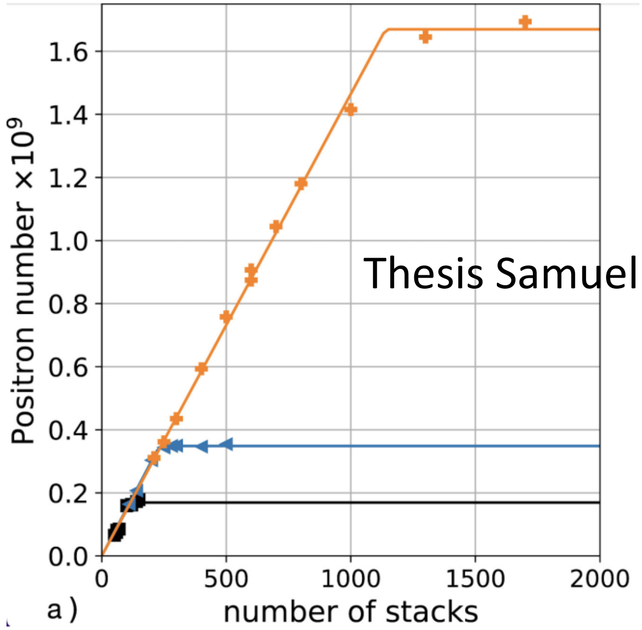
N_2 (capture) + CO_2 (cooling)

10^{-5} mbar 10^{-7} mbar

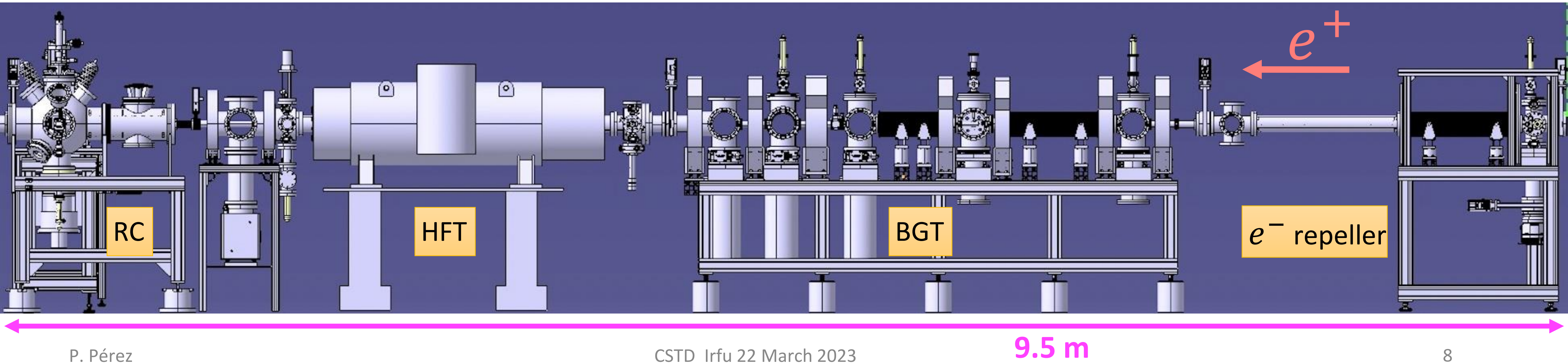
HFT High Field Trap 5 T < 10^{-10} mbar

routine operation —> 1.5×10^8 e^+/ 110 s

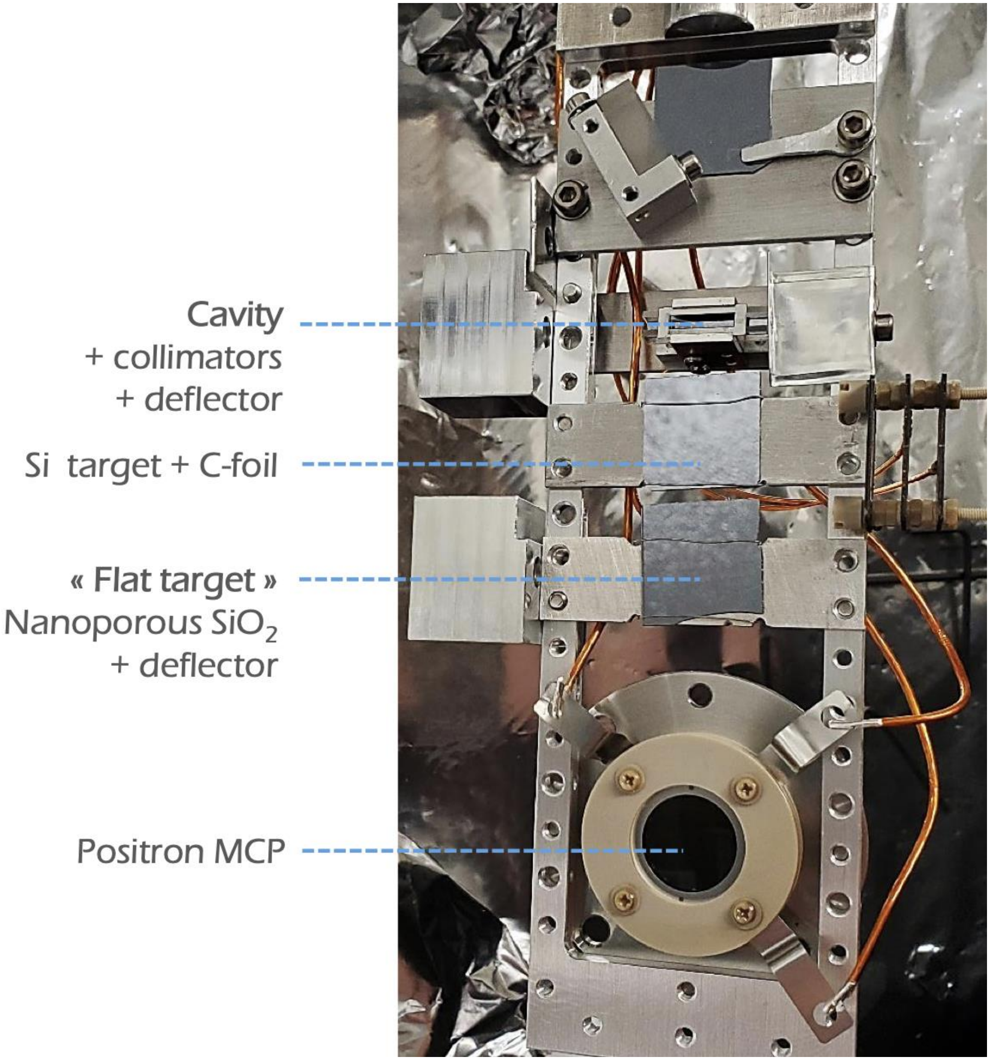
World record
1.4×10^9 / 1000 s

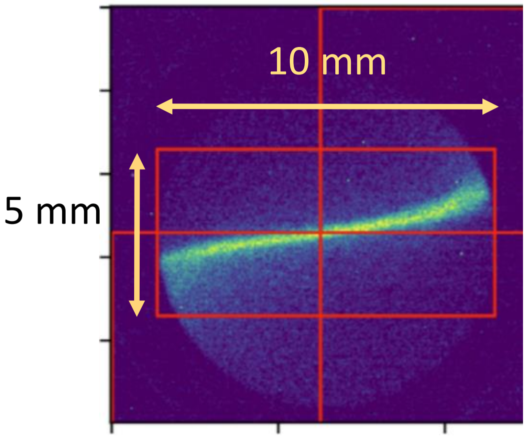


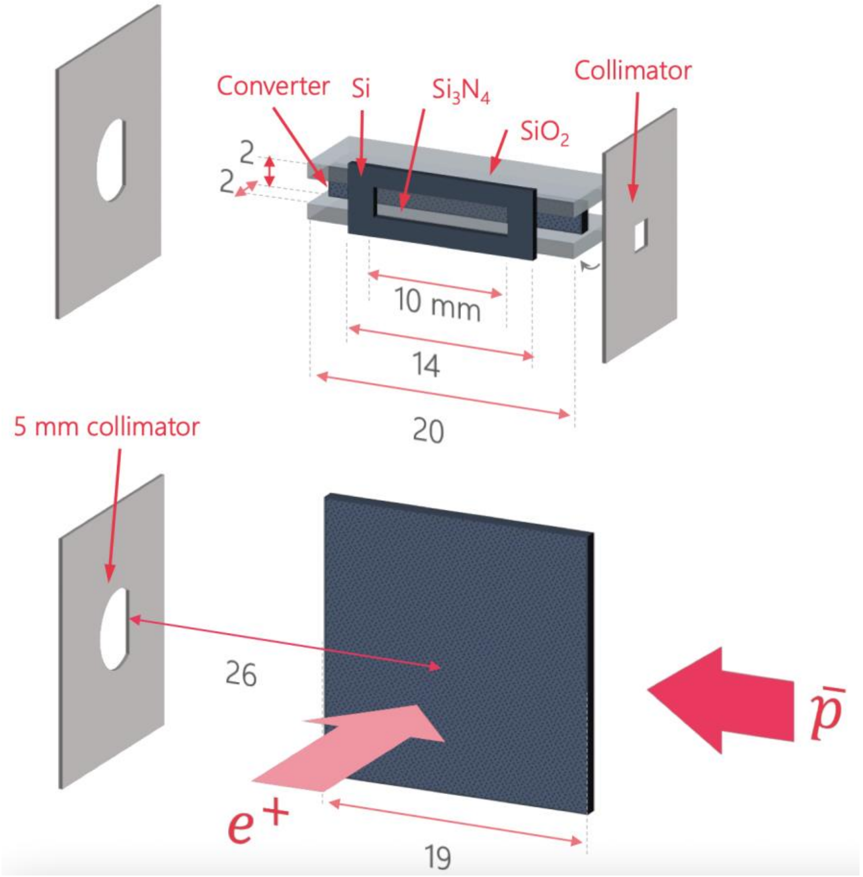
P. Blumer et al., [NIM A 1040, 167263 (2022)]



Focusing beams to targets

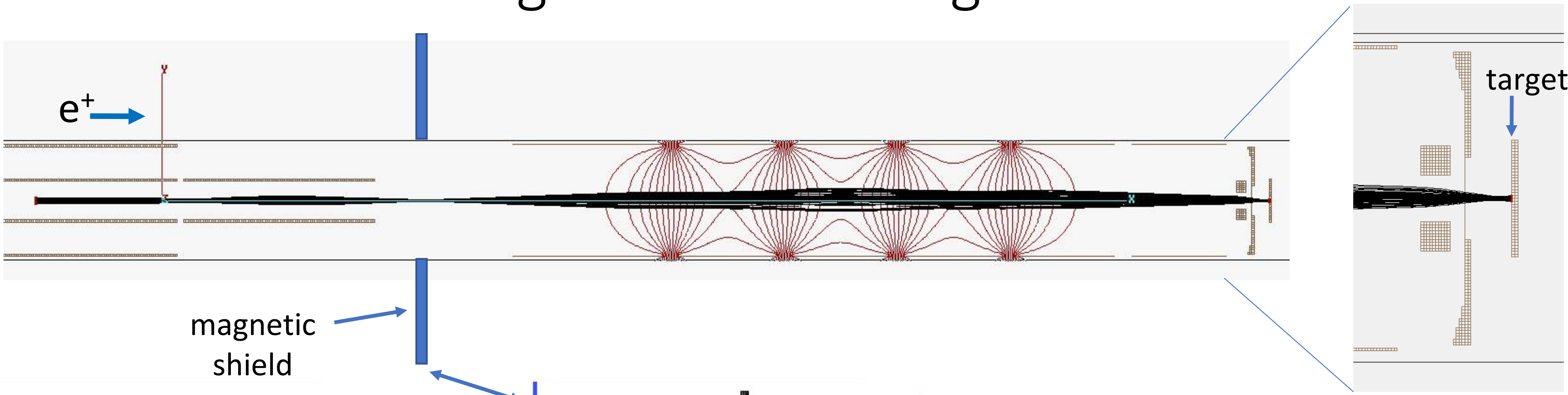


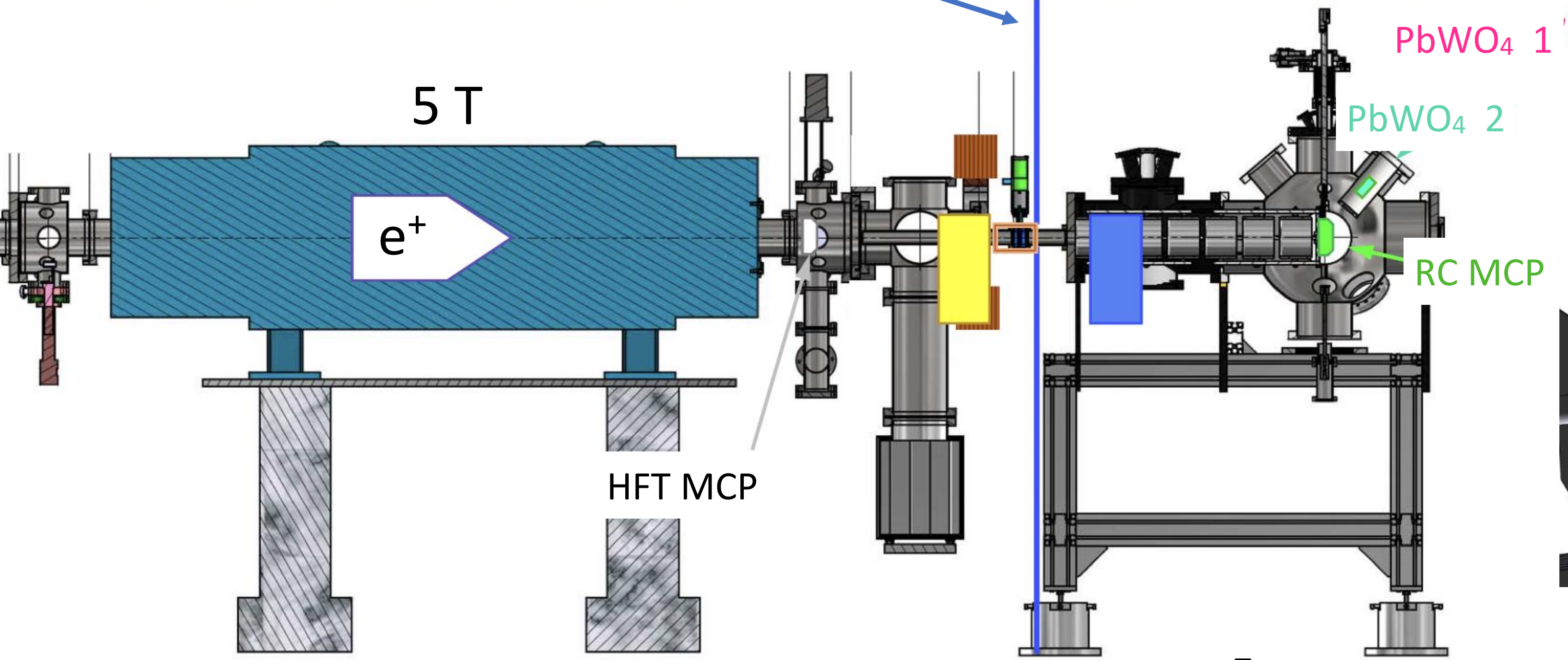




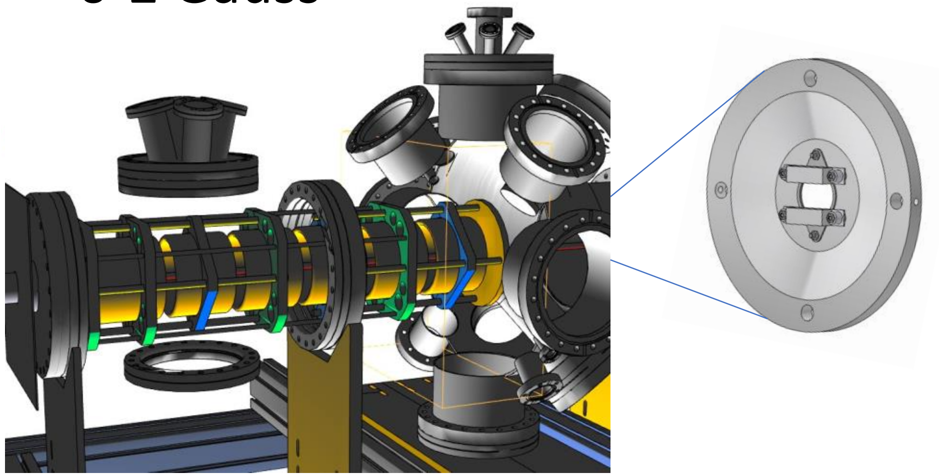
But:
$\bar{p}$ beam transmission through cavity only few percent
—> used flat target in 2022

Focusing e^+ beam to target





0-2 Gauss

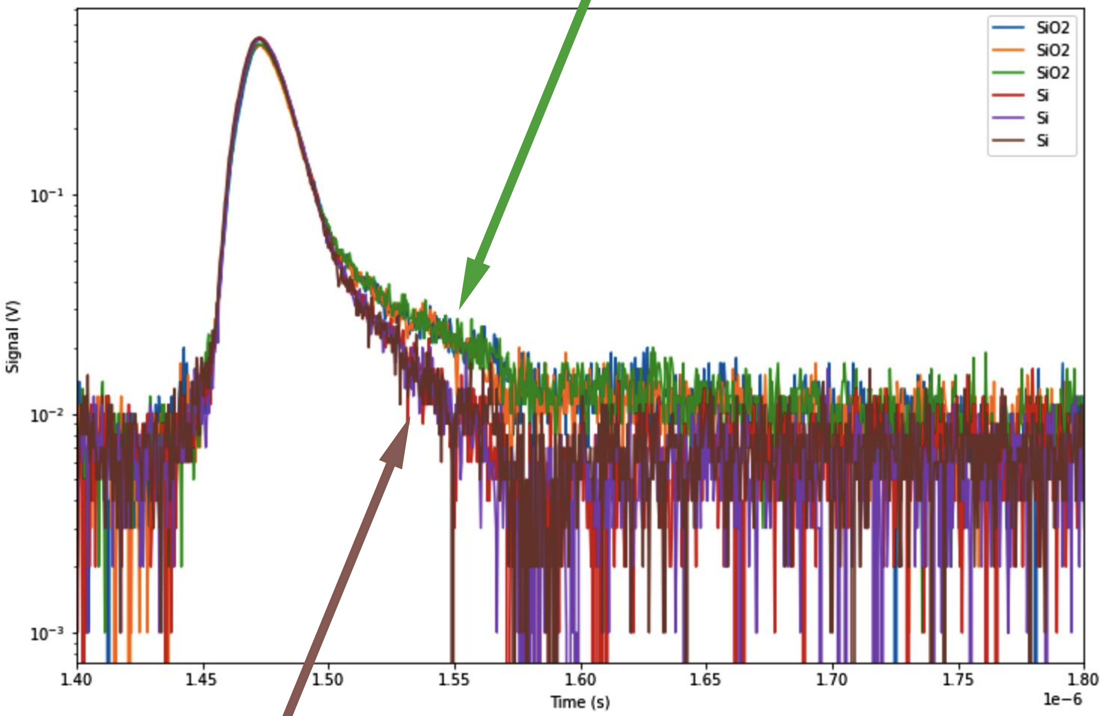


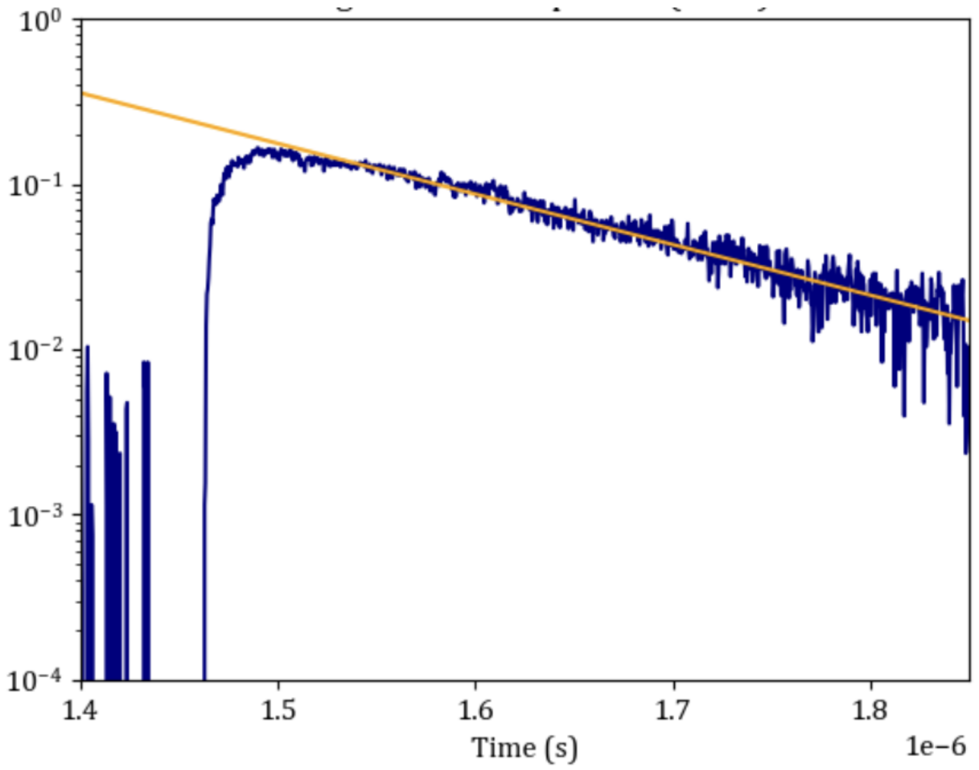
$1.5 \times 10^8\ e^+ \longrightarrow 5.3 \times 10^7\ e^+$ on target plane $\longrightarrow \sim 1 \pm 0.3 \times 10^7$ oPs

$e^+ \rightarrow Ps$ conversion

SiO2 target —> oPs

142 ns long lifetime component



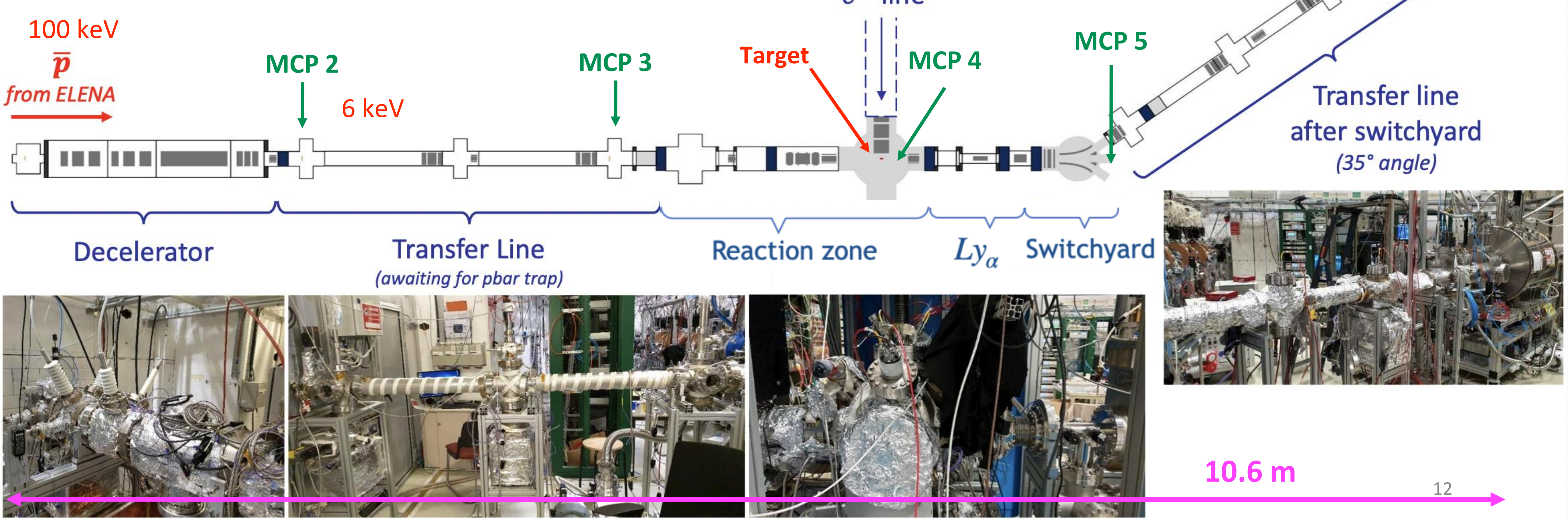


Si target

oPs conversion eff $\gtrsim$ 18% (expected 20%)

Antiproton beam line in 2022

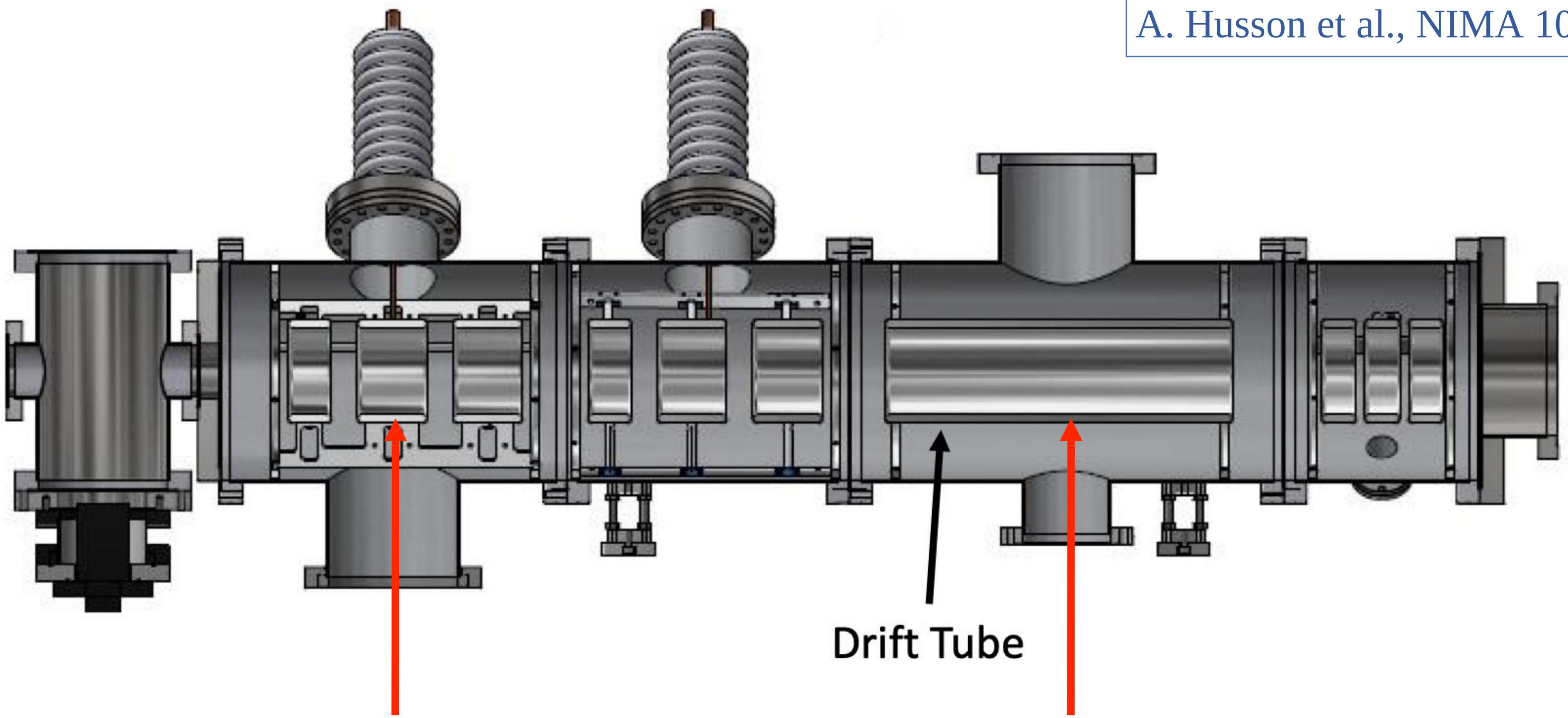
Tuning of 40-55 optical elements thanks to H^- beam from ELENA (15 s lapse time wrt 110 s for $\overline{\mathrm{p}}$)
ELENA ejection time jitter 4 ns
bunch length 40 ns (σ) with bunch rotation (75 ns in proposal)
—> ensures containment of decelerated pulse in drift tube
Sensitive to emittance: 2.9 and 2.1 µm (RMS) (1.2 and 0.75 µm in proposal)
Flux under study



$\bar{p}$ deceleration

A. Husson et al., NIMA 1002 (2021) 165245

100keV Pbar/H-
from ELENA



To Reaction Chamber

Bunch length
after deceleration
89 ns (σ)

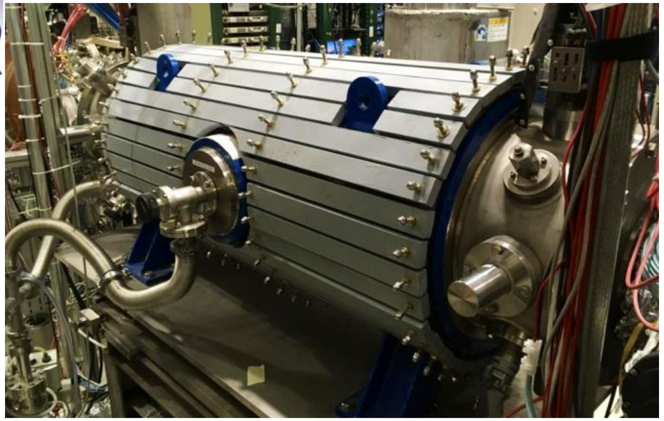
60 kV

ramped up to 94 kV 3 s before $\overline{p}$ bunch
switched to 0 in 30 ns while bunch is in the tube

50-150 V drop due to 10-30 µA leakage —> 6.05-6.15 keV

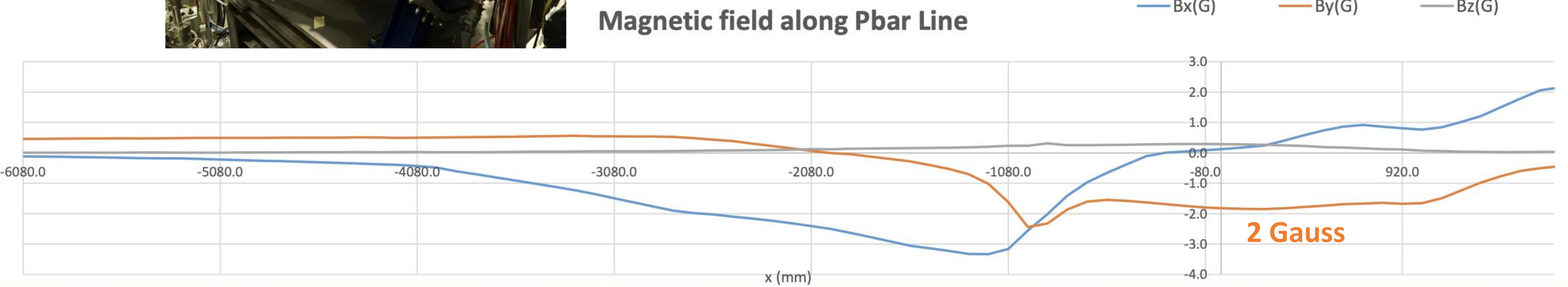
$\bar{p}$ beam steering

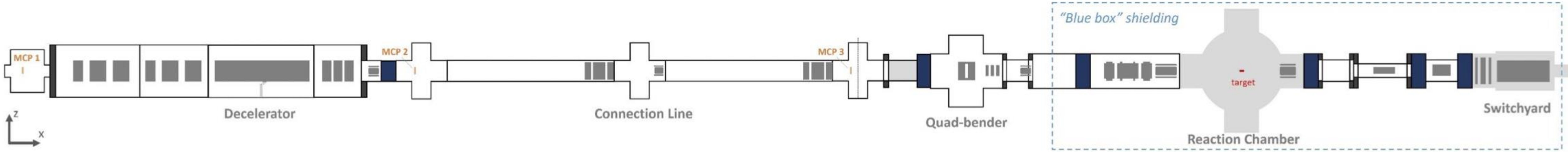
Additional flux return



along beam direction

vertical





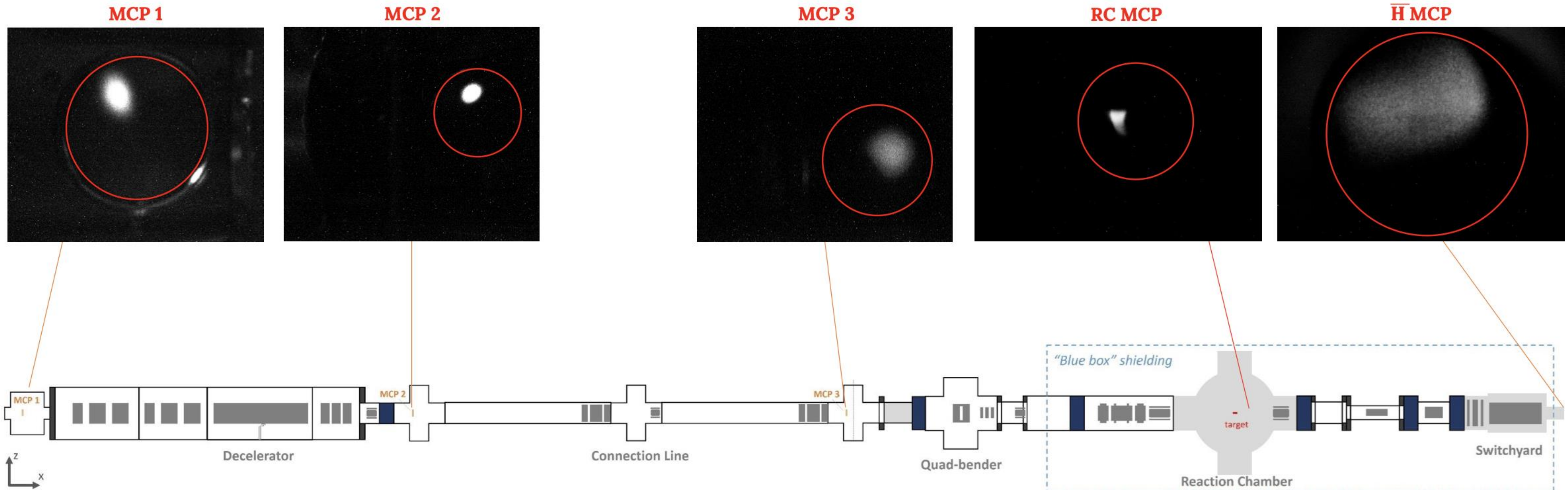
7.77 m

2 Gauss zone

$\overline{p}$ transport at 10 keV

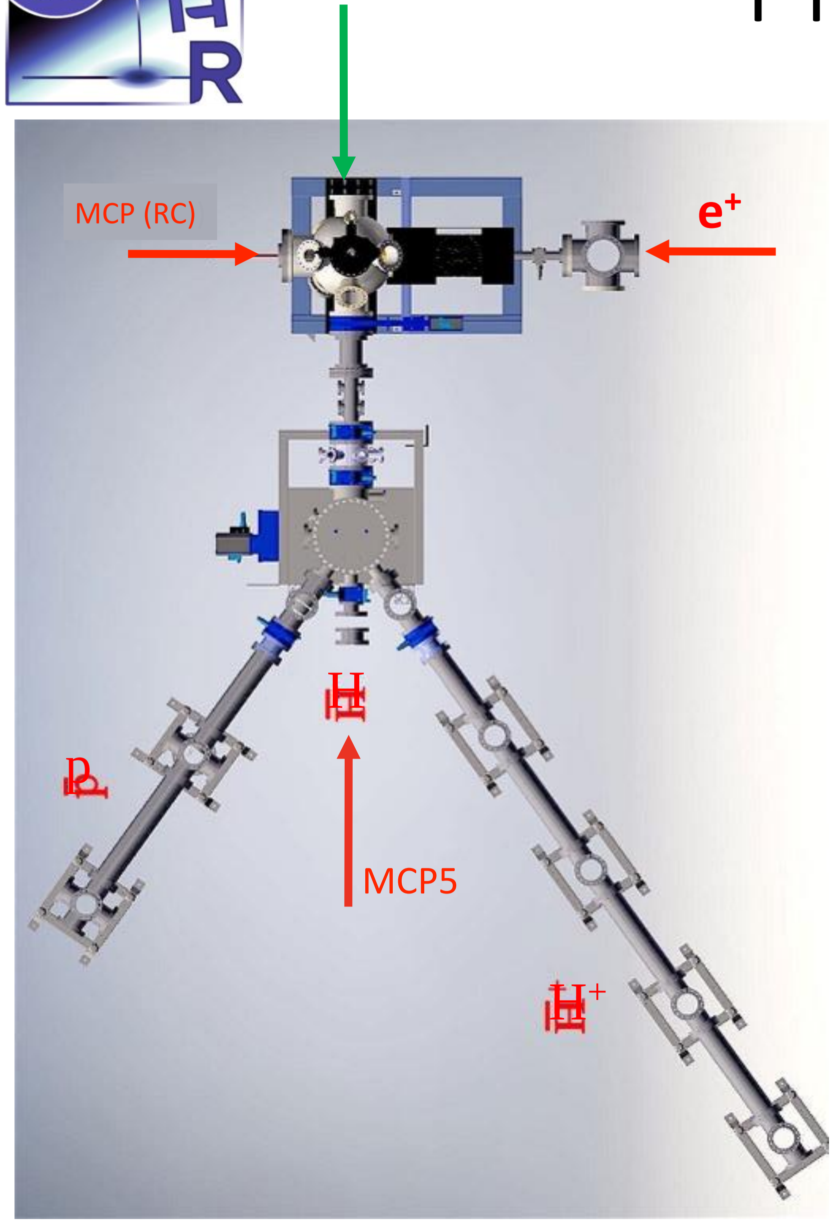
<u>Adjustment of voltages on optical elements</u>

- using MCP signals and images
- signals from scintillators along beam line
- guidance from beam transport simulation

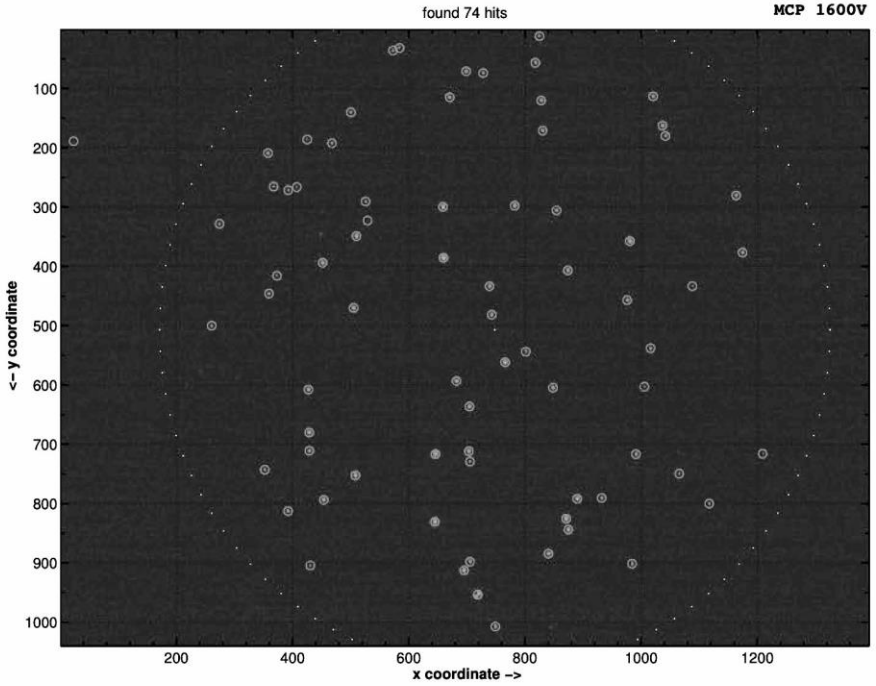


Proton beam

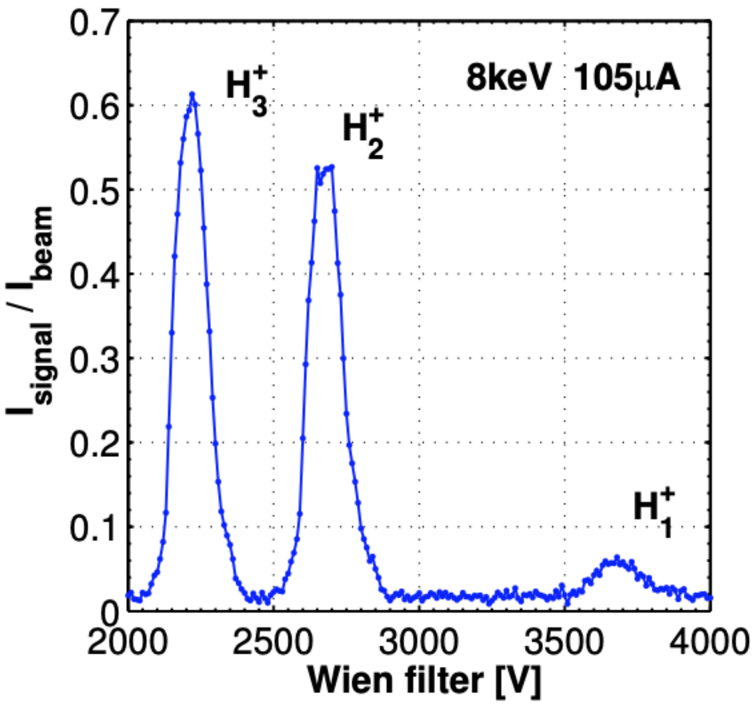
P gun



Interaction of p with residual gas
—> H of same energy
—> detected in MCP 5

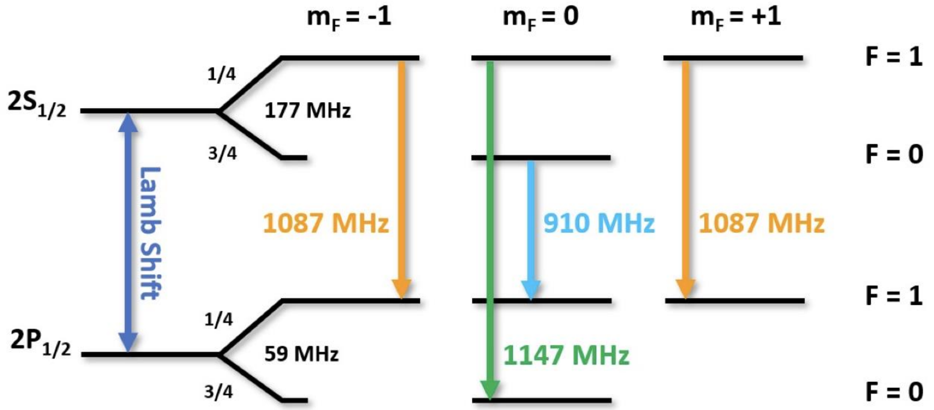


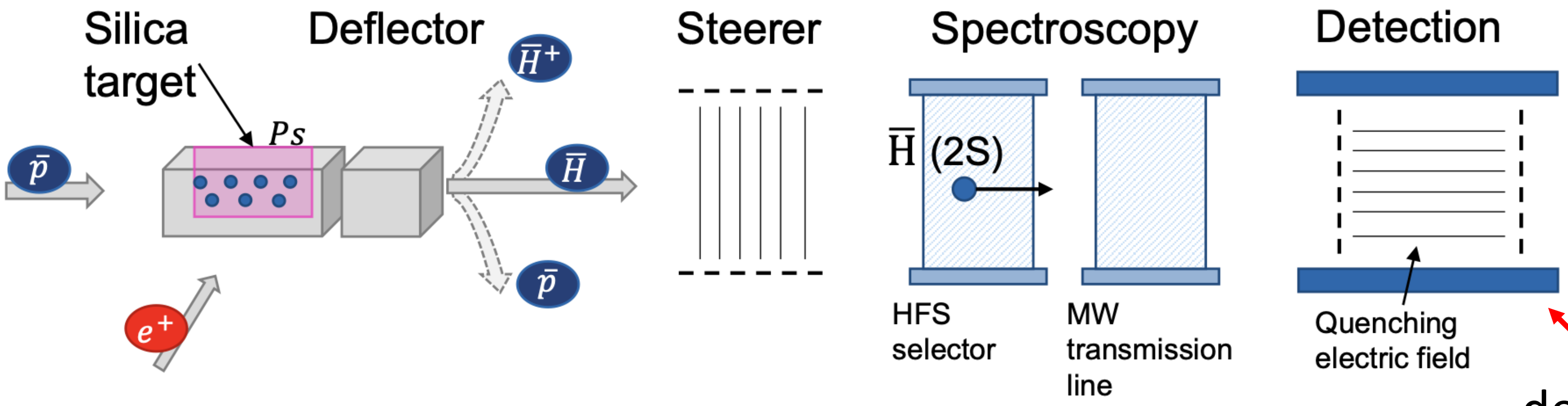
4-8 keV
5µA protons
100 ns

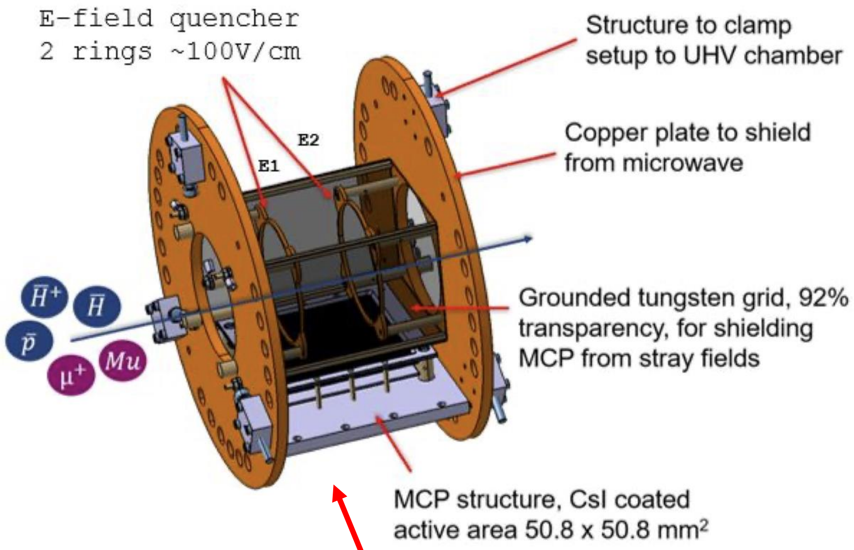


Hydrogen beam

10% of $Hin2Sstate$ (0.12 s lifetime) ⇒ study of Lambshift measurement systematics



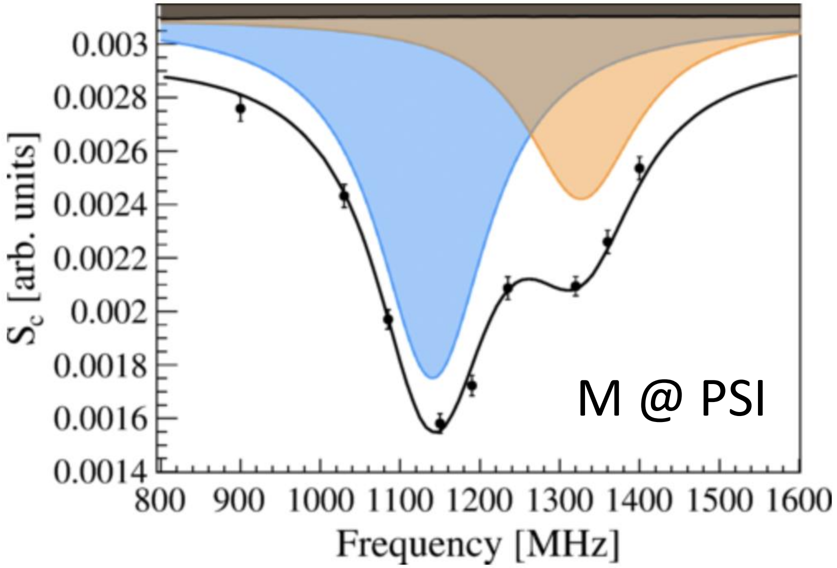


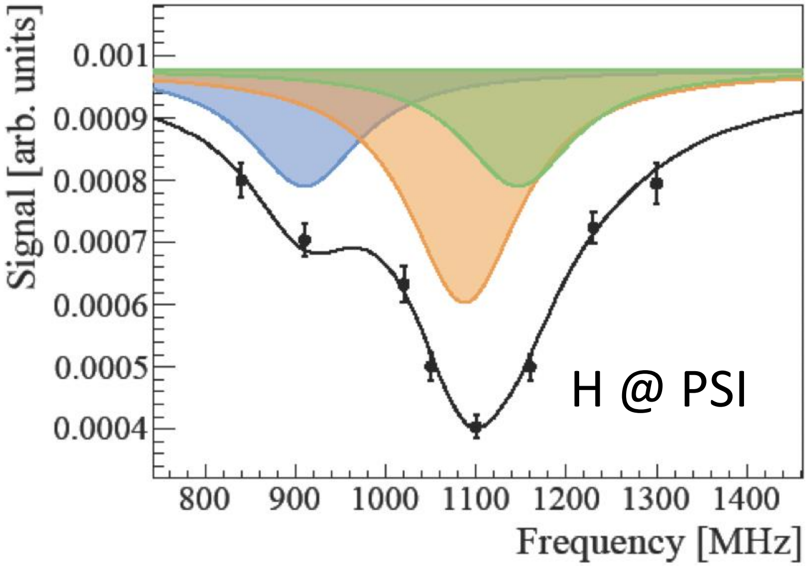


detect 121.5 nm γs with MCPs

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

Lamb shift





B. Ohayon et al., Phys. Rev. Lett. 128, 011802 (2022)

Measure quenched fraction as a function of microwave frequency

<u>At PSI with H</u>

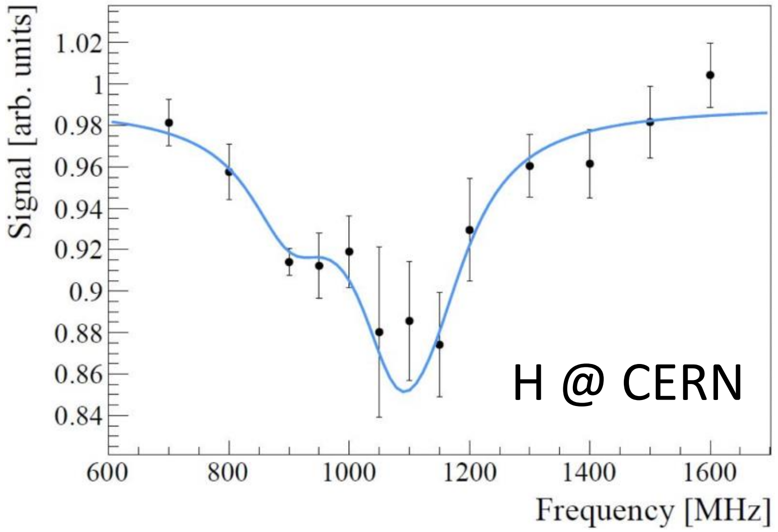
—> resonance 1087.4 ± 4.8 MHz (meas.)   1088 MHz (th.)

—> Lamb shift 1057.4 ± 4.8 MHz (meas.)   1057.8341 ± 0.0002 MHz (th.)

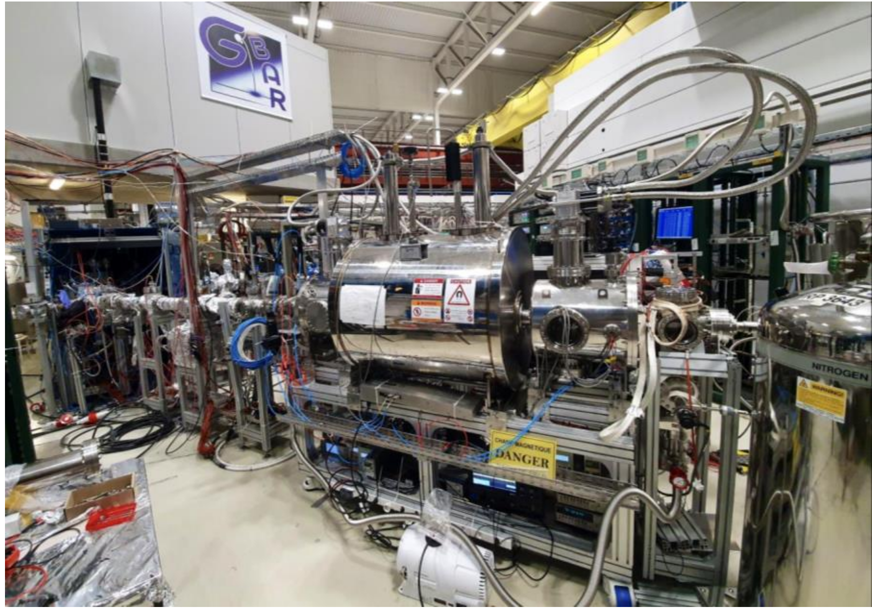
<u>At CERN with H</u>

—> resonance 1080.1 ± 13.5 MHz (meas.)   Syst. 100 kHz

—> Lamb shift 1050.5 ± 13.5 MHz (meas.)



Antiproton trap



100 ℓ LHe / 2 months

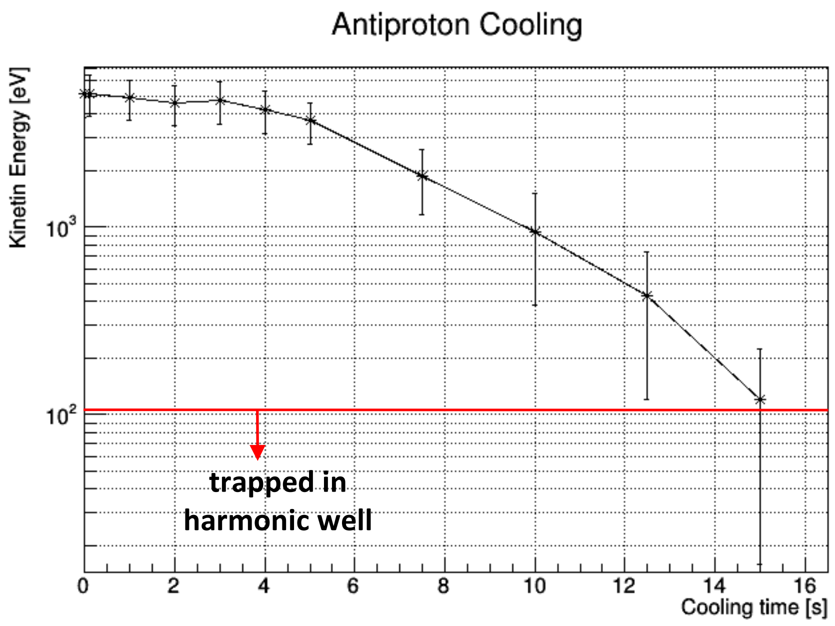
Expected improvements

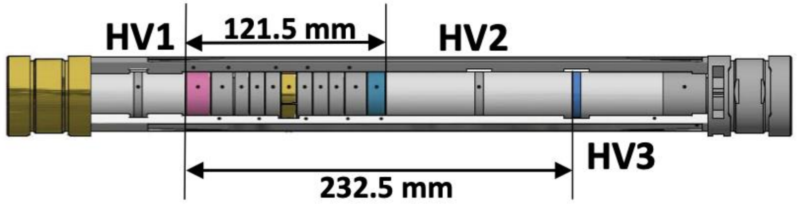
Flexibility (accumulation, extraction)

Beam divergence

Extraction energy and energy spread

Buncher for extraction





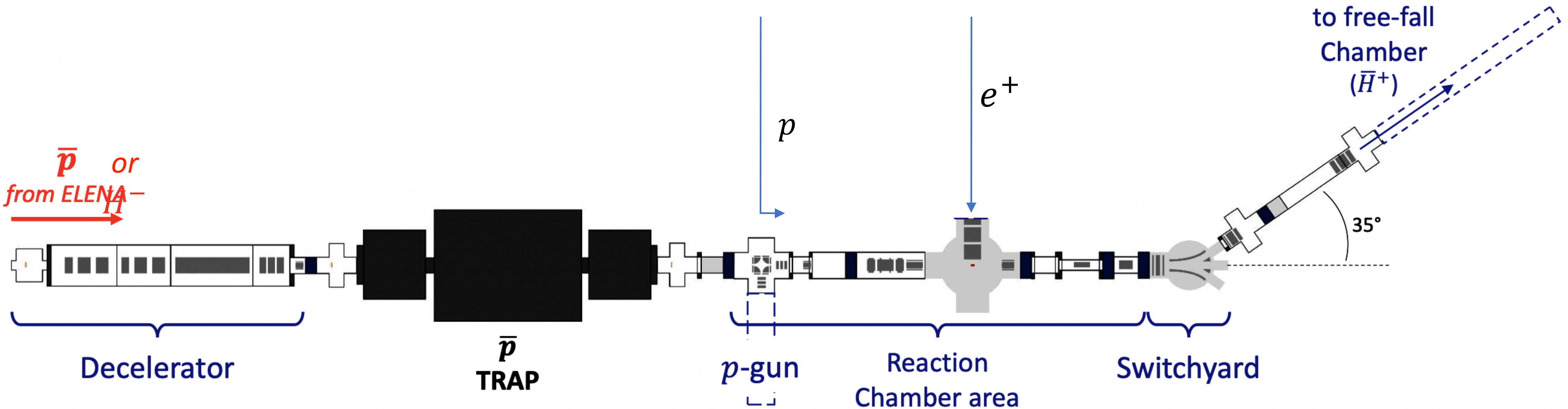
Now in temporary location

With $\approx 2 \times 10^5 \overline{p}$ incident:

40-70% trapping efficiency (dep. well length)

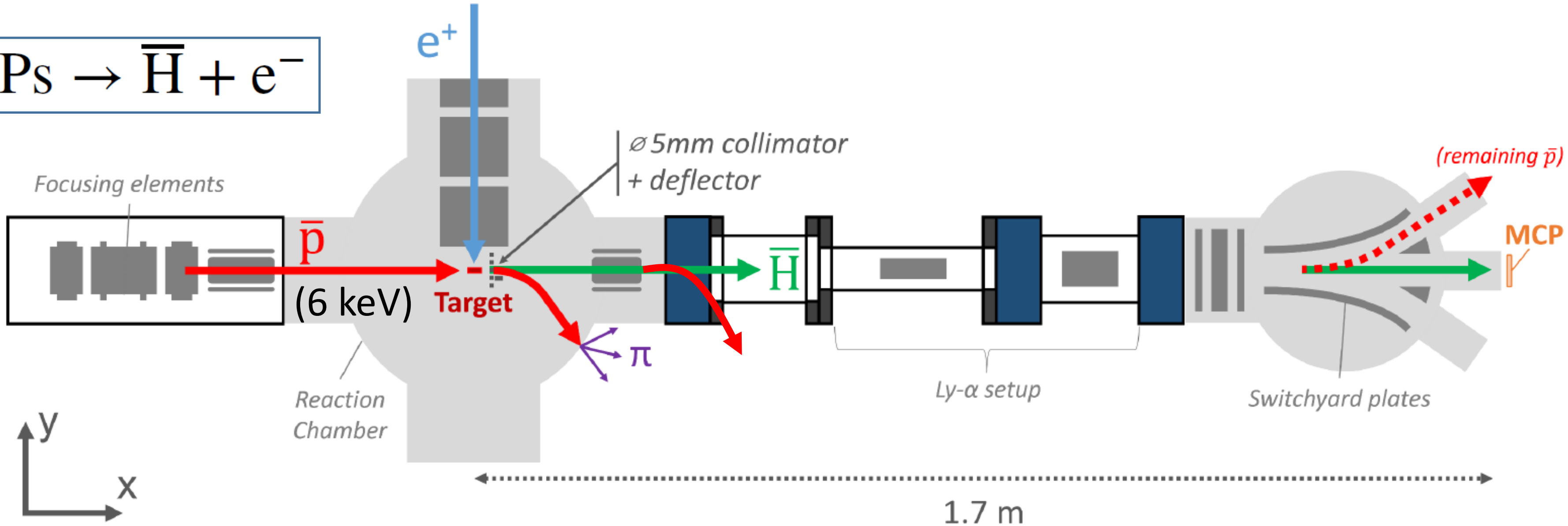
Cooling time with $10^5 \overline{p} + 10^7 e^-$ at 5T: 15 s from 6 keV to 100 eV

Antiproton beam line (planned 2023)

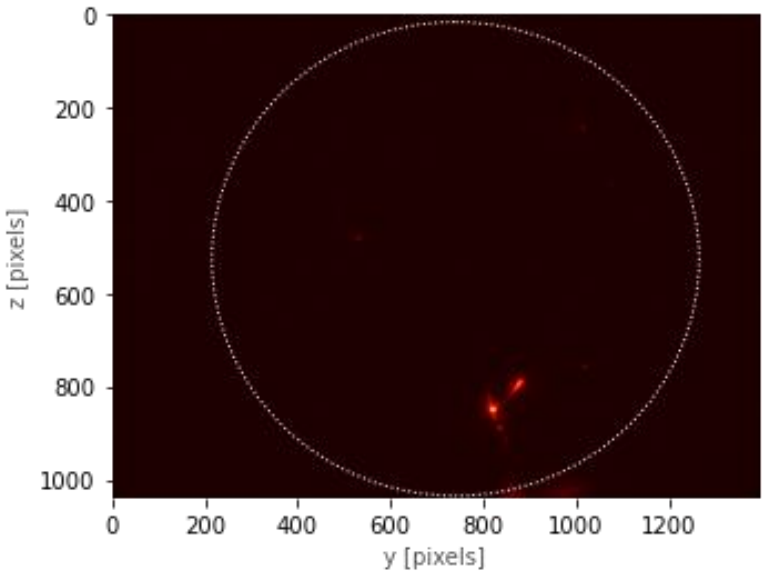


Antihydrogen production scheme in 2022

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

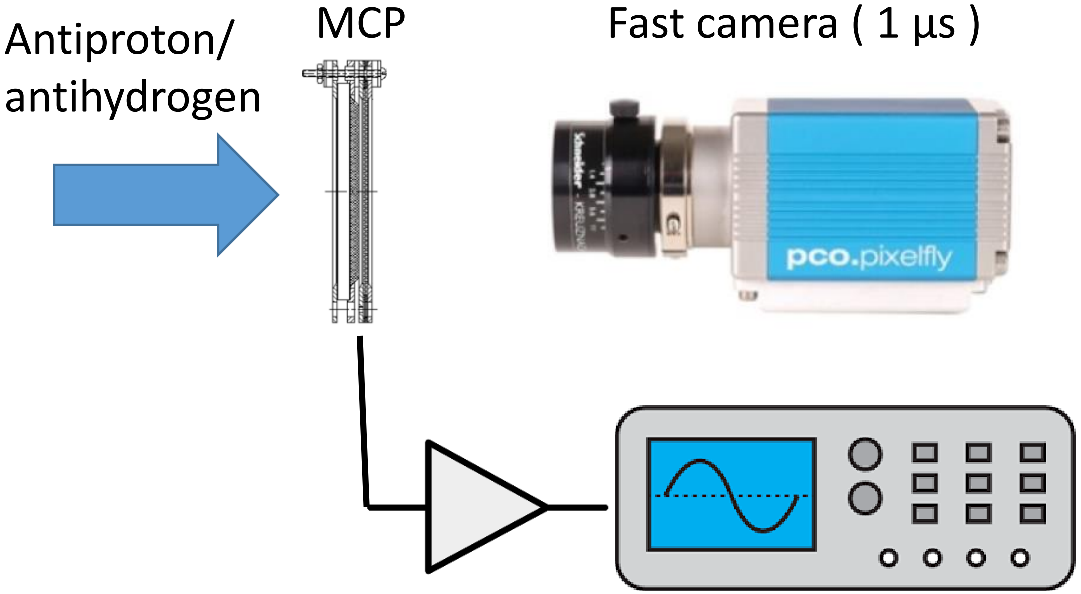


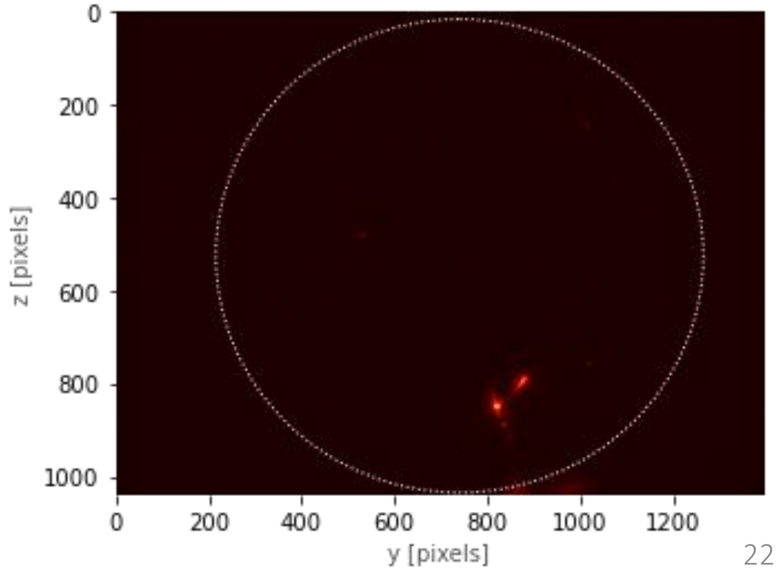
- Positronium cloud produced at flat nanoporous SiO_2 target (19x19 mm)
- $\bar{p}$ pass in front of target and pass through a collimator/deflector (Ø 5mm)
- static electric fields used to deflect charged particles
- Neutral particles (antihydrogen) on straight trajectory
- Background ($\pi^{\pm}$, γ) from $\bar{p}$ annihilation, mostly earlier
- Background from o-Ps annihilation is negligible



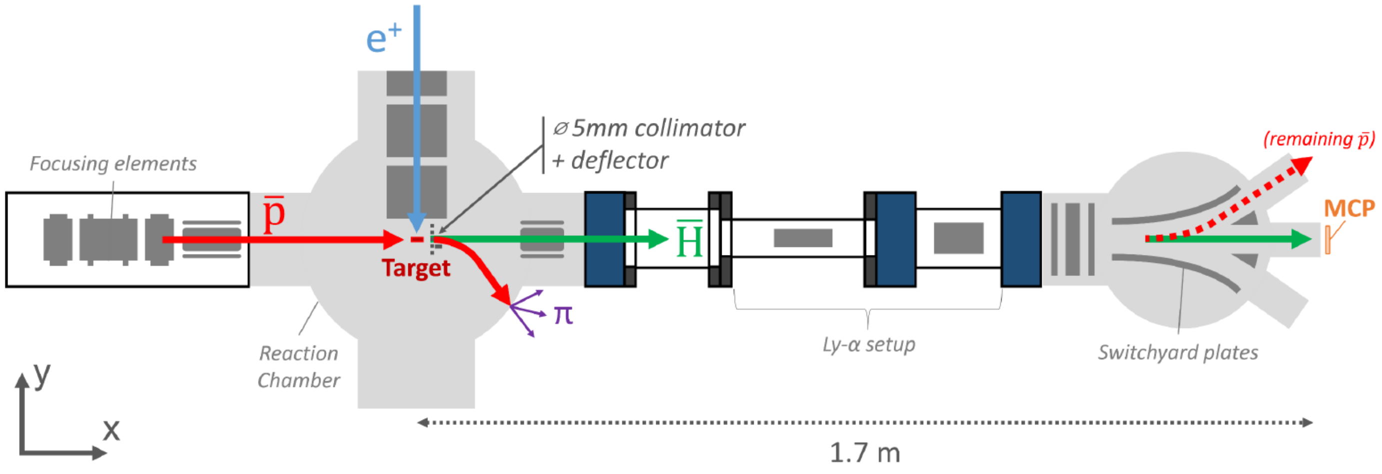
Detectors (2022)

- Main detector: multichannel plate (MCP) with fast phosphor and fast camera
  - Analysis are based mostly on the electrical signal
  - Image analysis is difficult but gives complementary information
- Further MCPs with phosphor screen are used in beam diagnostics
- Detection of annihilation products by fast scintillation detectors ($PbWO_4$, plastic) and CsI detectors (positron beam) is used for beam diagnostics
- Faraday cups (or MCPs used as Faraday cups) with charge sensitive amplifiers are used to calibrate e^+ pulse intensity
- Micromegas trackers are available but can not be used yet (high background from antiproton annihilation) – will be used for free fall measurements or others when the bgd. is low

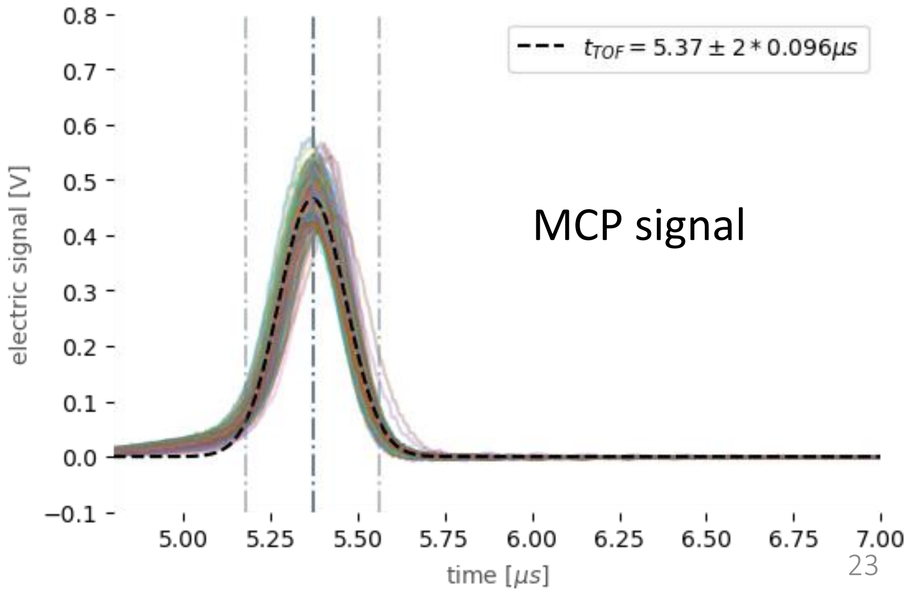




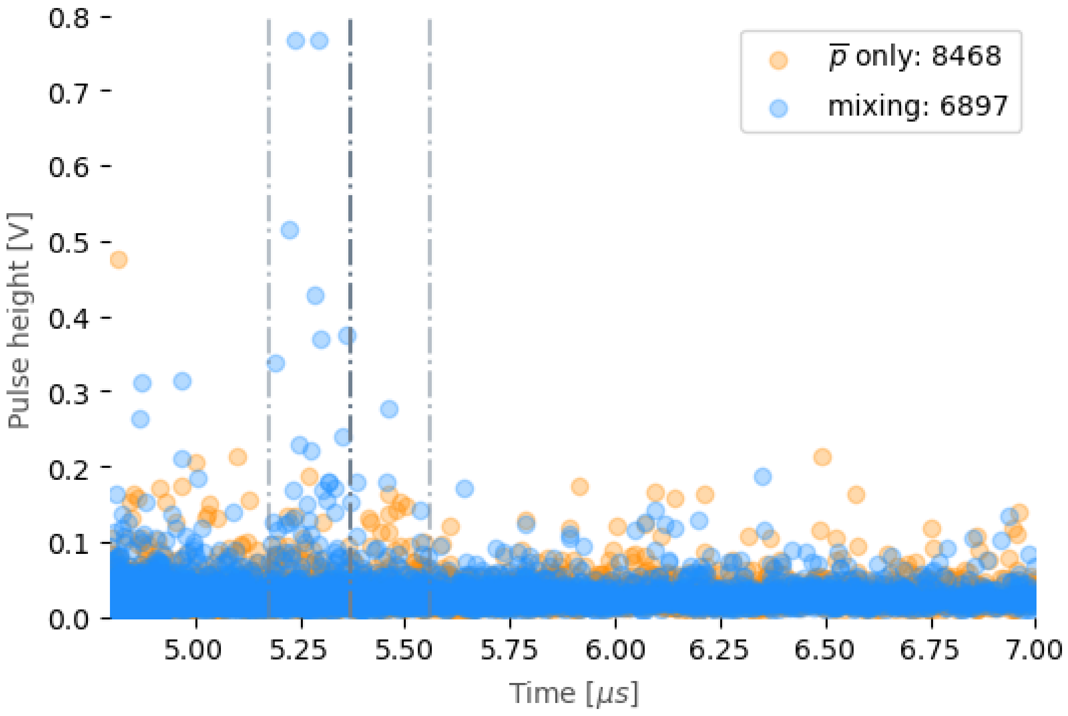
Time of arrival of antihydrogen

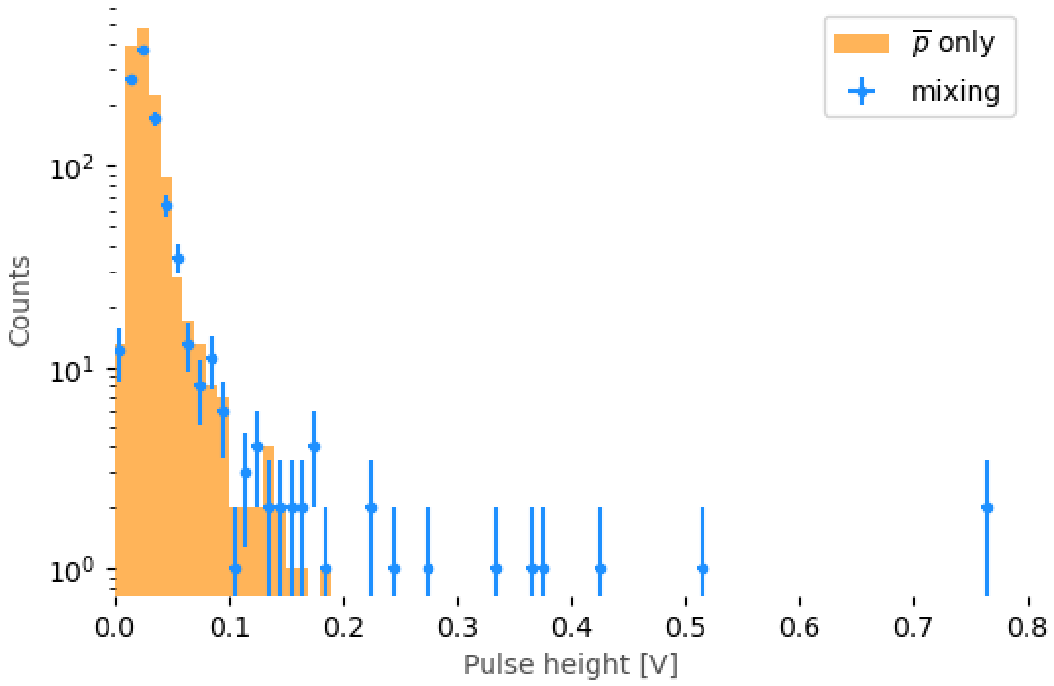


- Time of arrival on MCP is measured by the direct antiproton beam
- Measured expected time-of-flight:
  - $t_{\mathrm{TOF}} = 5.37$ $\sigma = 0.096\ \mu\mathrm{s}$
  - Detection window: ±2 σ
- This time window is used in antihydrogen detection (MCP electrical signal, camera trigger)



Antihydrogen production campaign – Analysis of electrical signal





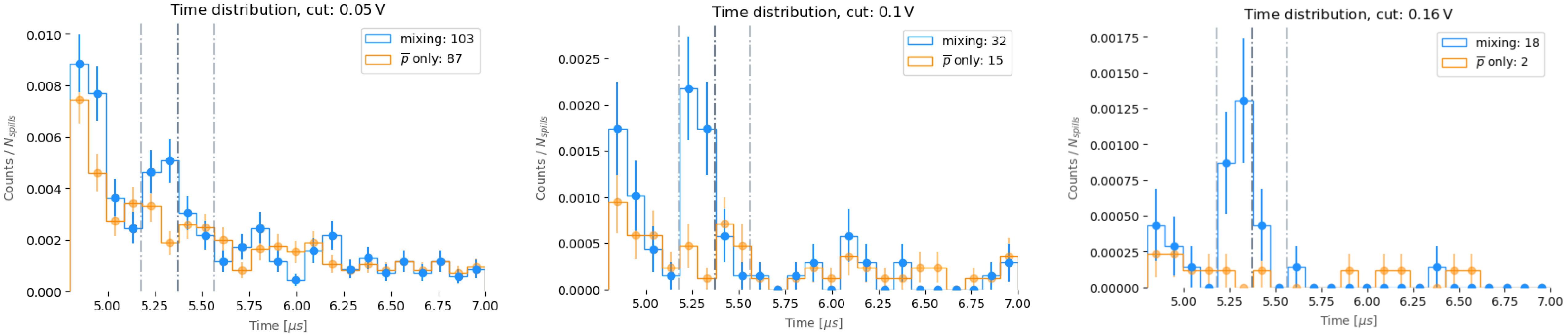
- $\overline{\mathrm{p}}$ only: 8468 spills
  - main background due to charged pions from $\overline{\mathrm{p}}$ annihilations upstream
  - Ps background negligible
- Mixing: 6897 spills
  - Both antiprotons and ortho-positronium

- Expected production rate at 6keV

$1.1 \pm 0.4\ \overline{\mathrm{H}}$ per 100 spills

- $\mathrm{N_{Ps}} = (9 \pm 3) \times 10^6 \mathrm{Ps}$
- $\mathrm{N_{\overline{p}}} = (2.2 \pm 0.6) \times 10^6 \overline{\mathrm{p}}$

Preliminary results from 2022



- Antihydrogen signal
  with > 3σ confidence level
- Final analysis ongoing
- Results consistent with cross-section and estimated geometrical acceptance

2 talks at Moriond (March 2023)

Comparison between proposal and performance in 2022

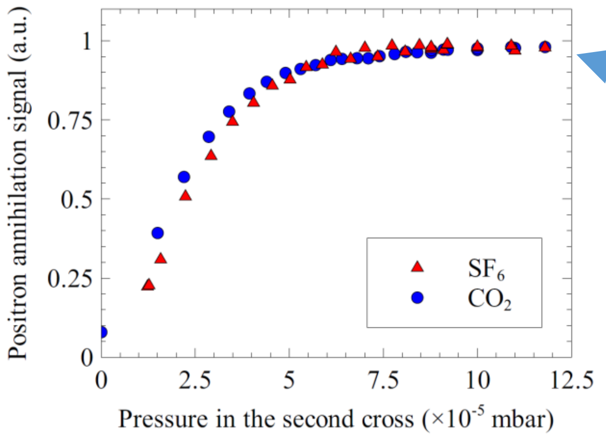
Item	Proposal	2022
Positrons		
Slow positron rate	$2.8x10^8$ e^+/s	$3x10^7$ e^+/s
Positron storage	$2.1x10^{10}$ e^+/110 s	$1.7x10^8$ e^+/110s
Ps number in interaction	7.4 x 10^9 e^+/110 s	$9x10^6$ o-Ps/110 s
Ps density	$7.4x10^{11}$ e^+/cm^2 (cavity)	$3.6x10^6$ e^+/cm^2 (flat target)
Antiprotons		
from ELENA	$6x10^6$ /110 s	$7x10^6$ /110 s
on target	$4.8x10^6$ /110 s	$3x10^6$ /110 s
Antihydrogen		
Antihydrogen	$3.9x10^2$ /110 s	0.01 /110 s
Antihydrogen ion		
Antihydrogen ion	0.32 / 110 s	Not detected

Improvements in 2023

Improvement	Expected gain	Time, responsible
	Positron line	
Use (improved) cavity instead of flat target	x 5 more positronium in interaction	May 2023, IRFU
Use SiC in buffer gas trap	x 3 more positrons trapped	April 2023, IRFU
Run linac at full power (300 Hz)	x 1.3 more positrons	March 2023, NCBJ, IRFU
Improve positron transport between the high field trap and the target	X1.5 more positrons on target	June 2023, IRFU
Paint electrodes in the high field trap with colloidal graphite	Better plasma stability, better transport to conversion target	April 2023, IRFU
	Antiproton line	
Better tuning,		2023
Install antiproton trap in final position	Commissioning (gain later)	To be decided Korean group, IRFU, IJCLab
Commission Lyman-α setup		ETHZ group

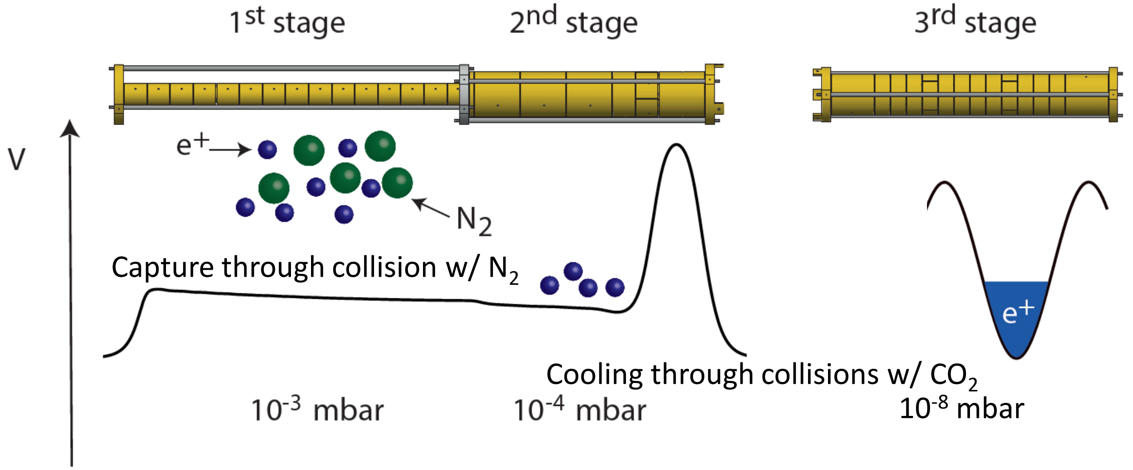
Novel SiC remoderator-based buffer gas trapping scheme

- High quality SiC single crystal remoderator replaces the nitrogen gas in the first stage
- Approximately three times higher trapping efficiency (defined as trapped e^+/e^+ flux from the source)
- Might be higher with well adapted hardware
- Commissioning in 2023:
  - New electrode stack
  - Solution to transfer trapped e+ to third stage (SiC blocks the way)

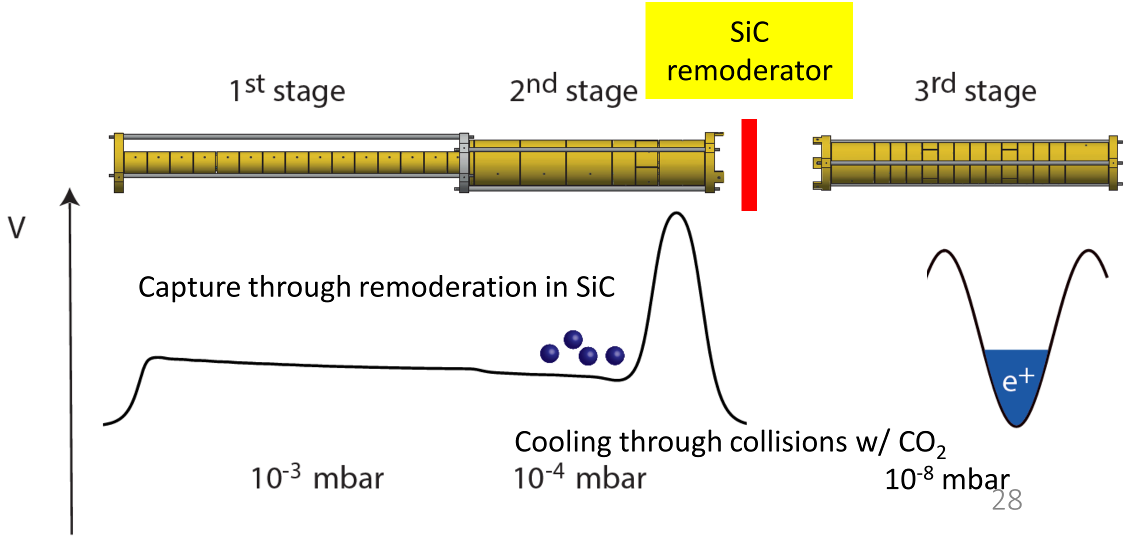


~40 % trapping efficiency

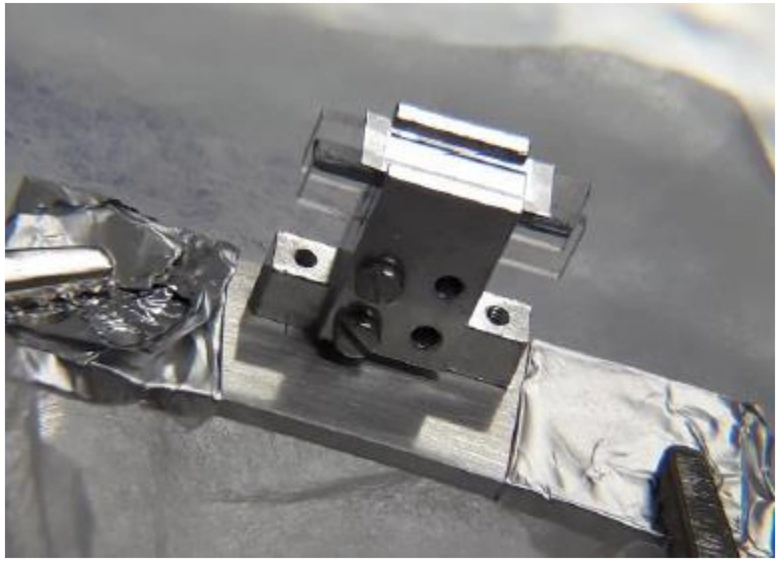
Old buffer gas scheme (nitrogen gas in the 1st stage)



New SiC remoderator-based buffer gas scheme)



Improved target cavity

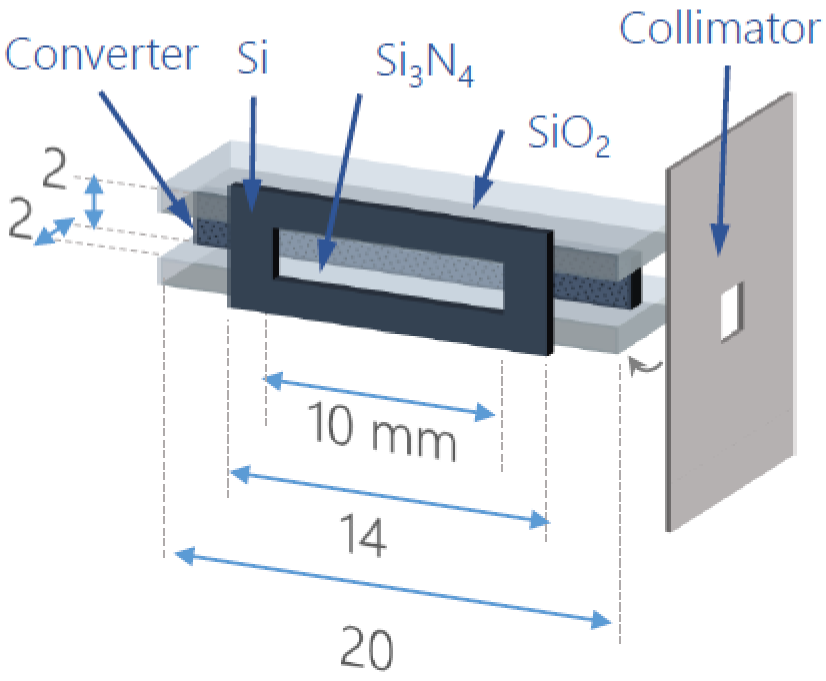


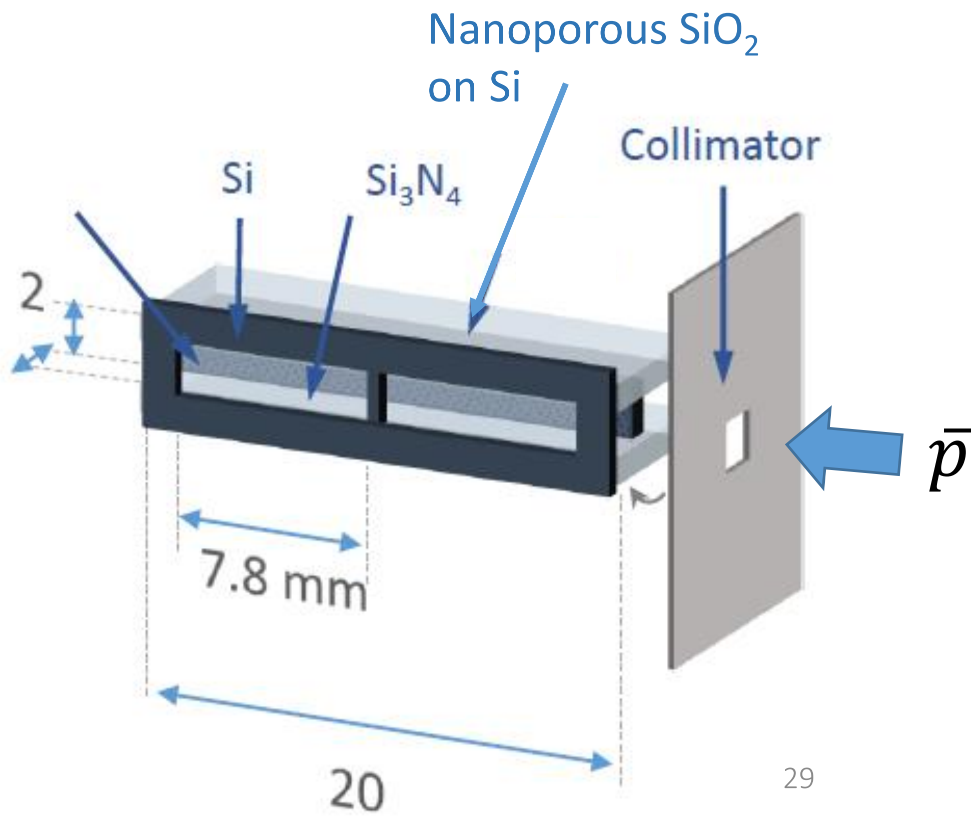
Present construction:

- Two sides are made of fused silica (laser window)
- 2x10 mm^2 entry window (30 nm Si_3N_4)
- 2022: only flat target was used

Improved cavity:

- Longer entry window
- Three walls are made of nanoporous silica on Si (no laser window)





Improvement of the high field trap and the e⁺ transport between the high field trap and the reaction chamber

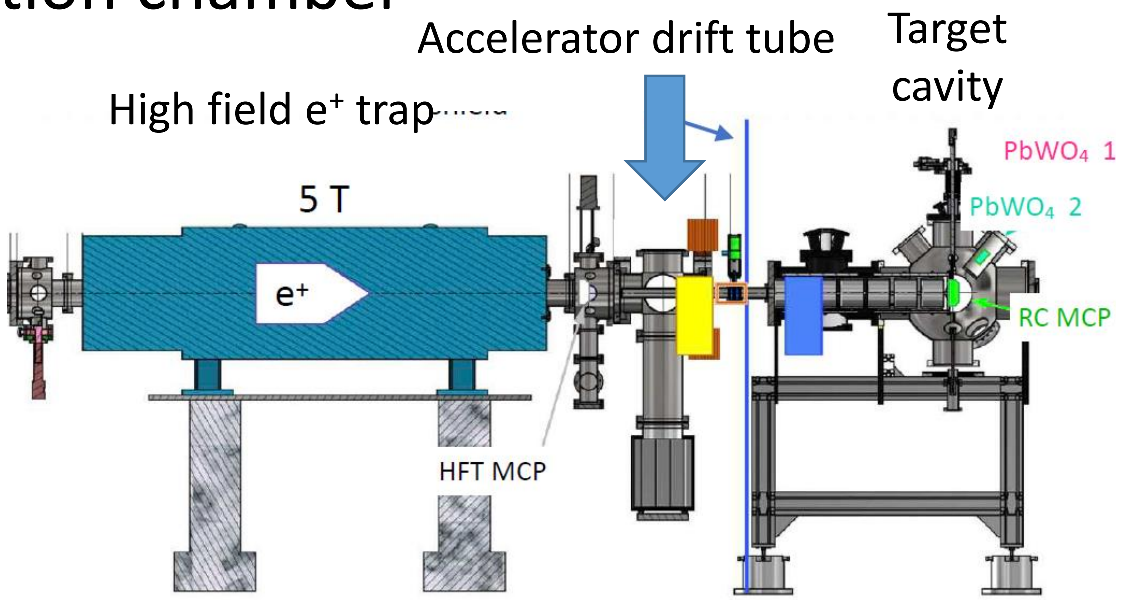
- Problem:
    - Trapping more positrons in the HFT, with the same plasma density
    - focusing the positron pulse on the target cavity (transport from 5 T to ~zero field)

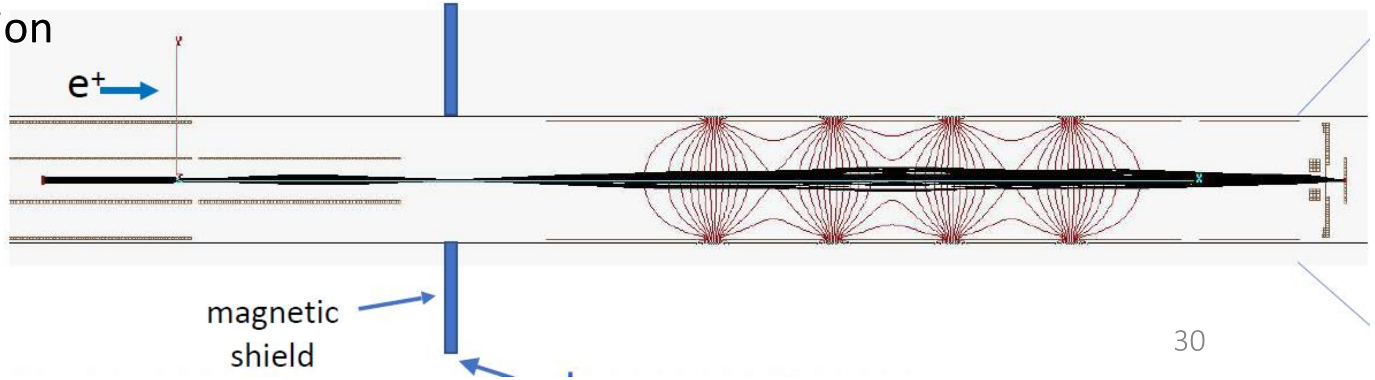
2023

- Improved transition to the low-field zone
- Accelerator drift tube extended (longer pulse possible)
- Improvements in the high field trap (colloidal graphite paint)

2024 or later

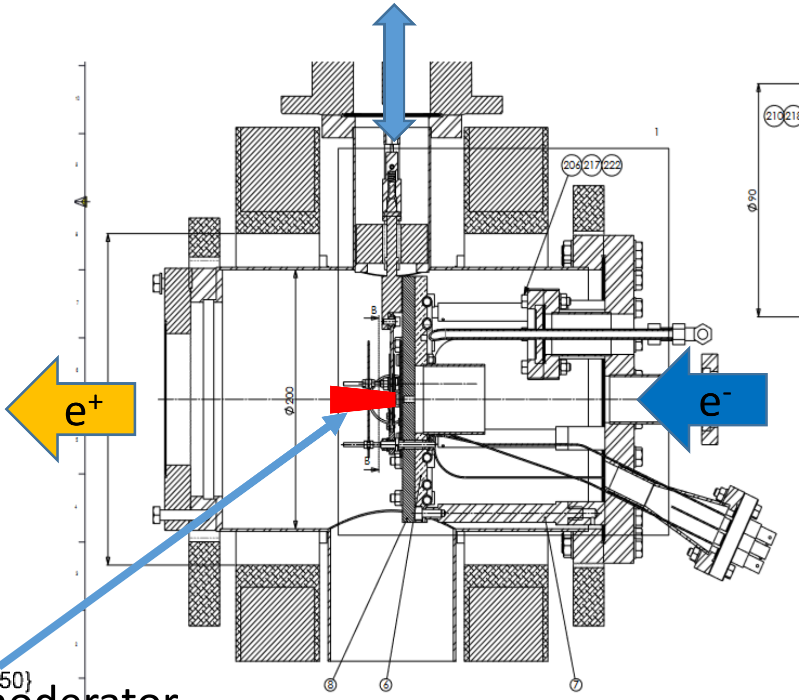
- redesign of the transport optics, based on simulation (simulation is being improved)



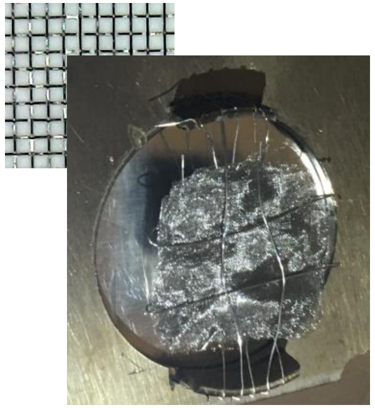


Improvement of the primary moderator (2024)

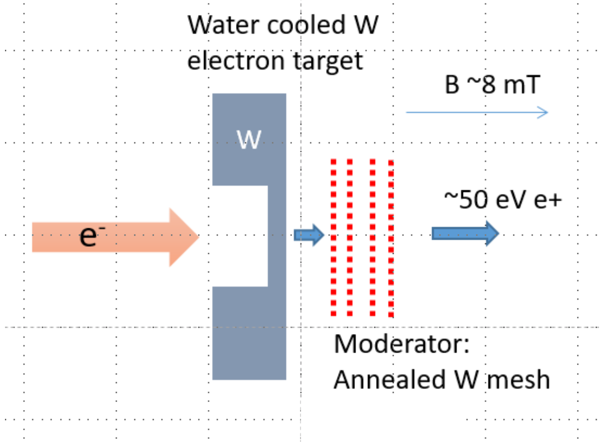
- At present:
  - flat moderator 20x20 mm^2, with 18 layers of 20 μm thick tungsten mesh (150 wires/inch)
  - Annealed at ~2400°C by Joule heating in ultra high vacuum
- The SiC-based buffer gas scheme allows larger beam spot with broader energy distribution ➔ possibility to enlarge primary moderator
- Planned improvement in 2024:
  - Truncated cone added in front of the present moderator
  - Expected gain: 1.5-2x (or more if more cones)
- Changes needed:
  - Modified moderator holder
  - Possibility to anneal 5-10 times more moderator mesh
  - Possible modification in the transport line (larger beam spot)

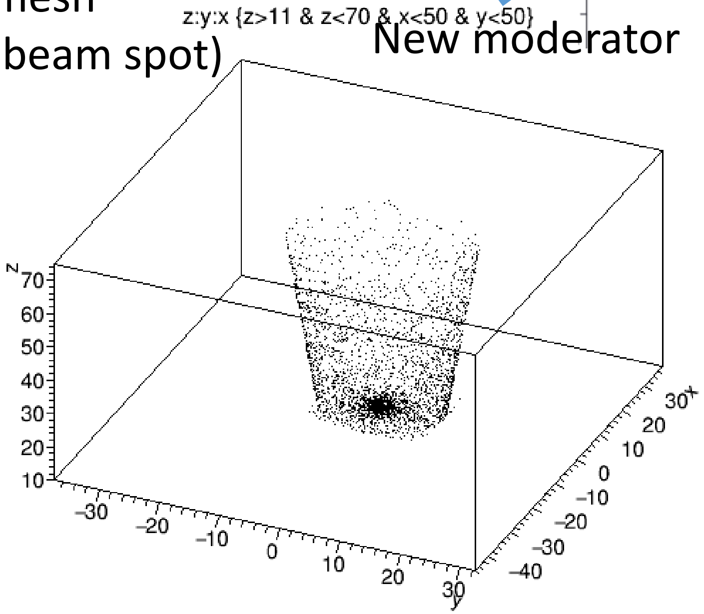


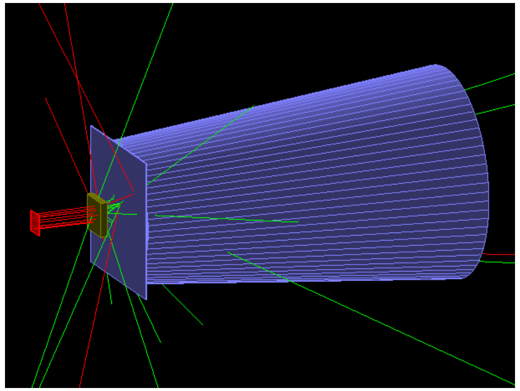
New moderator



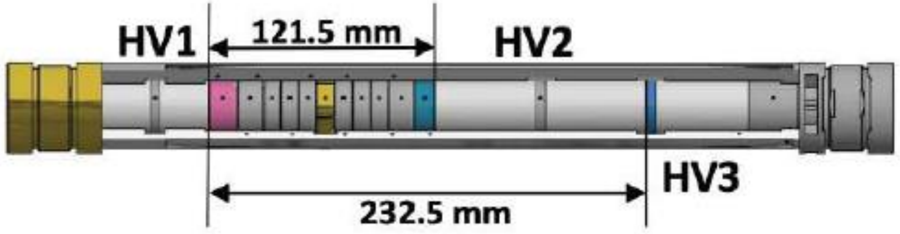
Present moderator





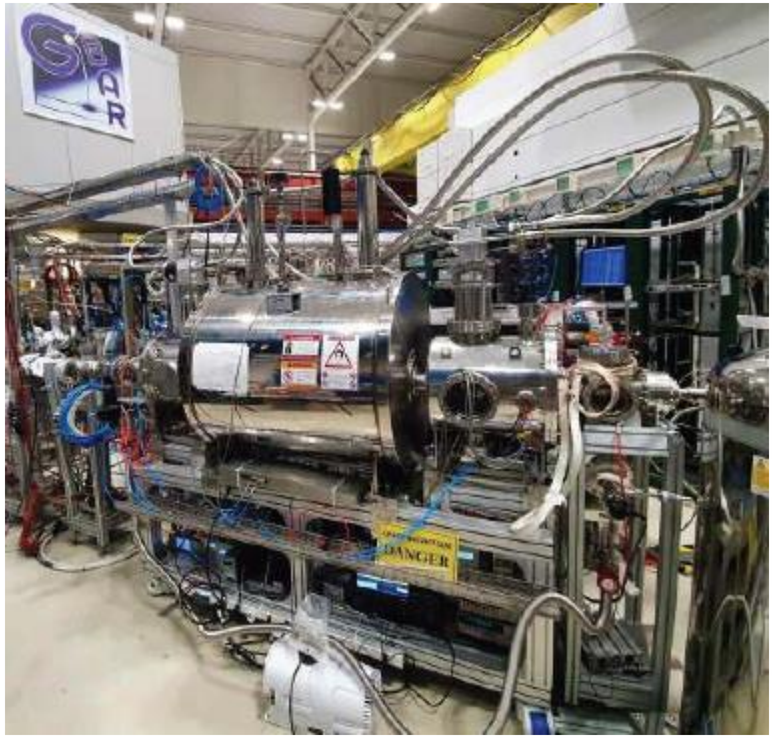


Improvement of antiproton transport

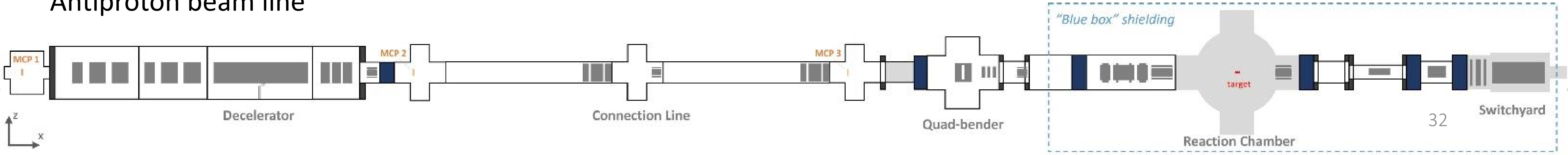


- Aim: focusing on smaller spot (cavity)
- Improvements of the incoming beam (ELENA) at present, emittance is about 2.5 x design value
- Many parameters to tune, charging effect
- Substantial improvement is expected after commissioning of the antiproton trap

Antiproton trap

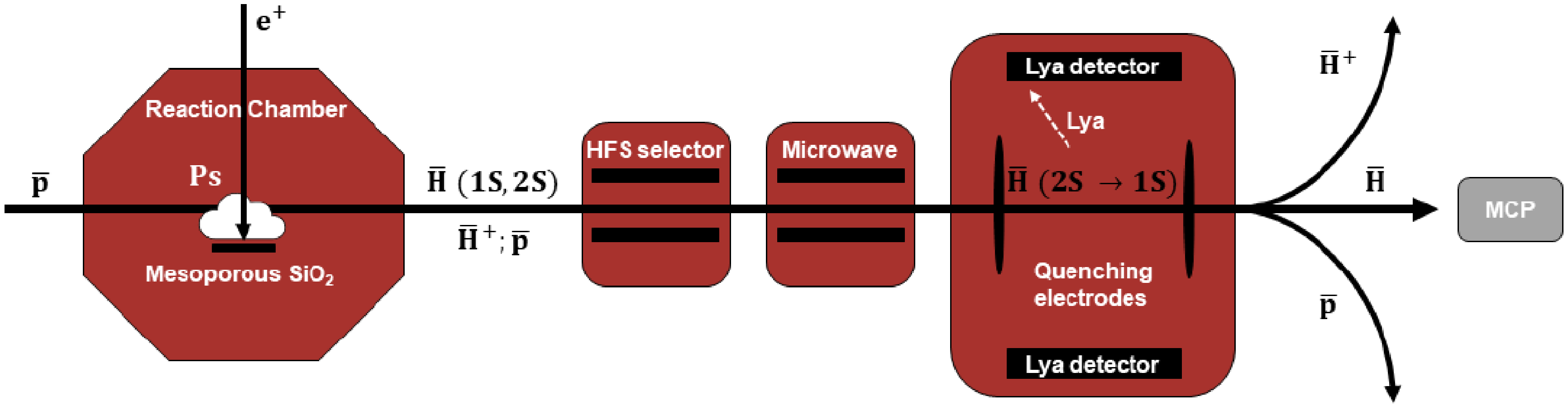


Antiproton beam line

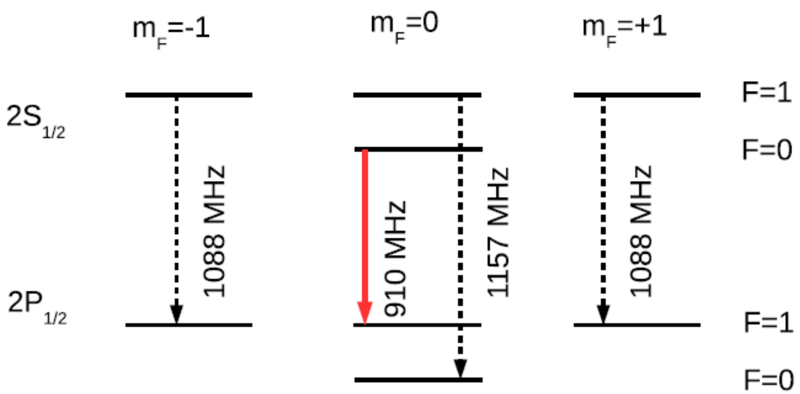


Antihydrogen Lamb shift measurement

(responsible: ETHZ group, leader: Paolo Crivelli)



- Towards determination of the antiproton charge radius – test of CPT symmetry
- At 6 keV 16 % of produced antihydrogen is in 2S state
- At the end of 2023 detection of 2S states
- First measurement in 2024



Milestones

2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028
pbar	LS2		pbar	pbar	pbar	pbar	pbar	LS3		pbar

- End of 2023
  - 1 antihydrogen / antiproton pulse
  - background measurement for 2S antihydrogen production (towards Lamb shift measurement)
  - cross section measurement (first reaction)
  - Antiproton trap: commissioning
- End of 2024
  - 10 antihydrogen/antiproton pulse
  - First Lamb shift measurement
- End of 2025
  - Detection of first antihydrogen ions

Human resources

DPhP

- Pauline Comini (~50 % on ANR SPHINX), Pascal Debu, Laszlo Liszkay (chef de groupe), Bruno Mansoulié, Patrice Pérez (spokesperson), Boris Tuchming, Bertrand Vallage (until summer 2023)
- Yves Sacquin (conseiller scientifique)
- 3 persons permanently at CERN (Patrice Pérez, Pauline Comini, Bruno Mansoulié)
- ~5 FTE (2023)
- Thesis works (Barbara Latacz 2019, Samuel Niang 2020; both have CERN contract now, on other projects)

DIS

- Jean-Yves Roussé (chef de projet IRFU)
- Slow control (Paul Lotrus, student)
- Cabling (very limited availability)

DEDIP

- Draftsman (Daniel Desforge until his retirement)
- Antenne Saclay (~1 FTE/year) – VERY IMPORTANT CONTRIBUTION

Urgent need

- Draftsman
- DAQ, software integration
- Electrician (reg.)

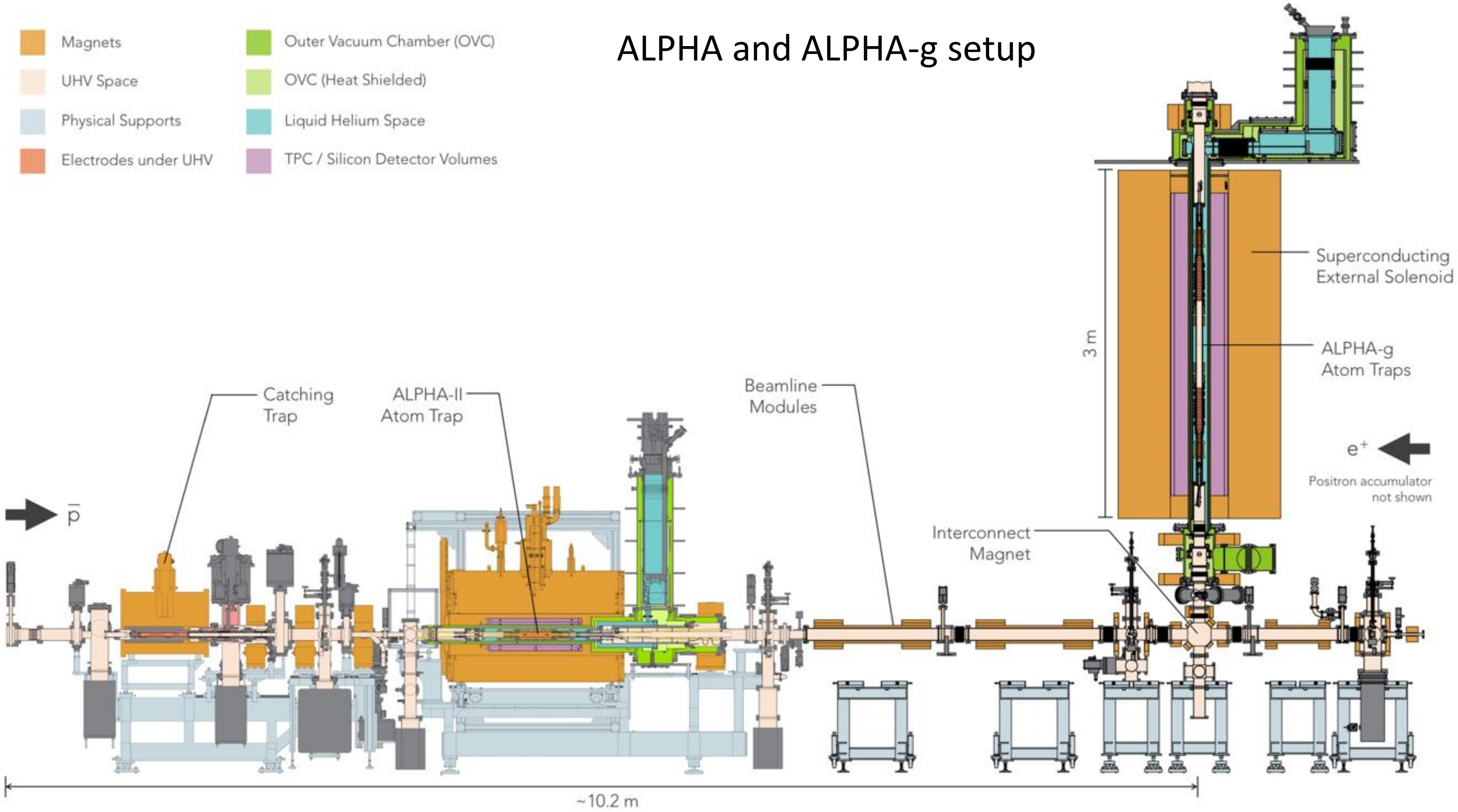
Budget

- The present budget is based on the assumption that the experiment is fully commisioned in 2022 and only maintenance costs are needed later
- Experience shows that the performance of the instrumentation can be increased step-by-step (while the present achievements are very competitive in international comparison)
- Improvements require investments into new instrumentation – we ask for support for investment
- Sufficient travel funds are needed to finance work in Geneva for those based in Saclay

Competition: ALPHA-g experiment

- well developped experiment at AD with proven technology to trap antihydrogen atoms
- Results in antihydrogen spectroscopy etc.
- First limit for ratio between gravitational and inertial mass of antihydrogen -65 < F < 75 (95 % confidence level)

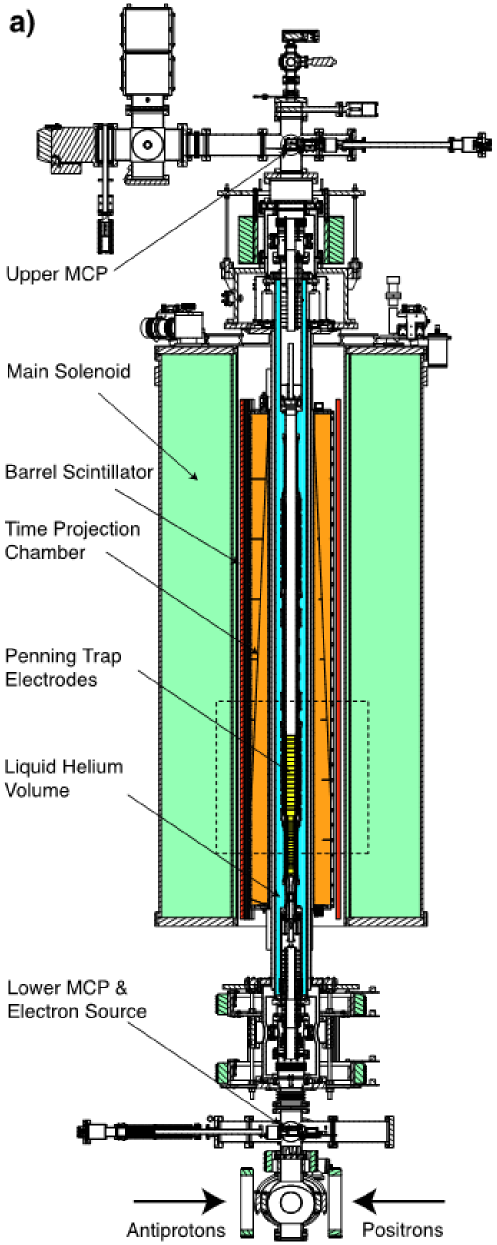
ALPHA and ALPHA-g setup

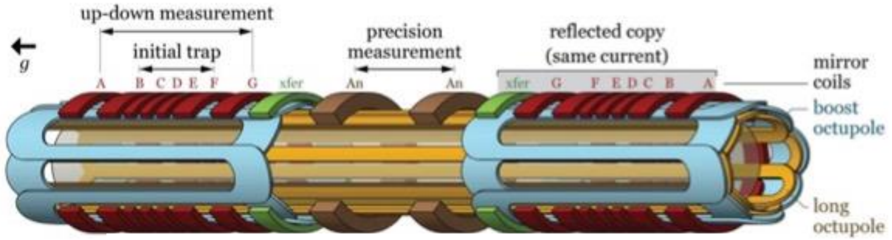


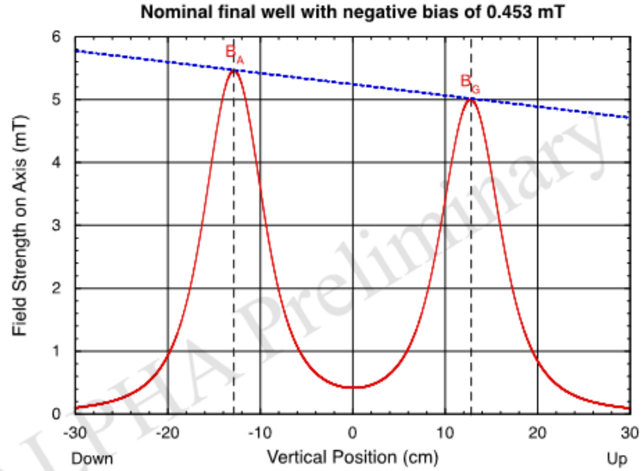
Competition: ALPHA-g: 2022 results

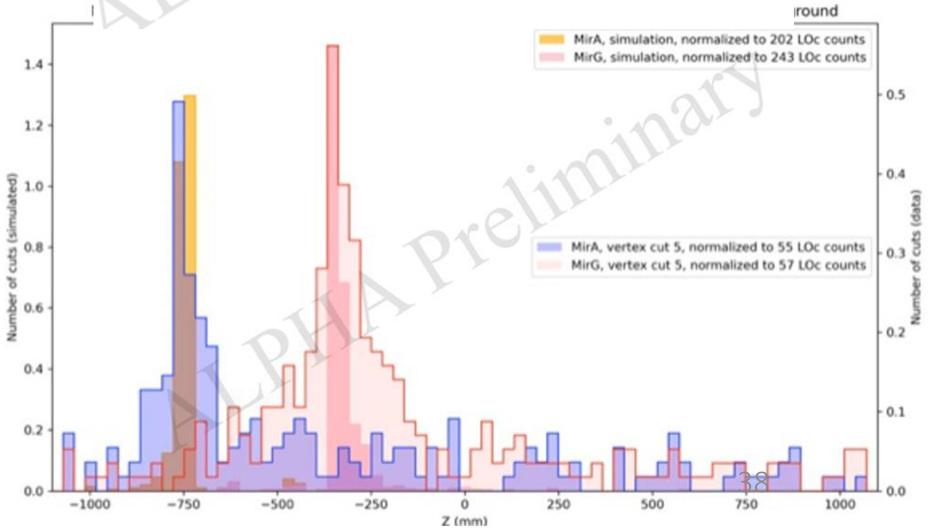
- Accumulate antihydrogen
- With a « magnetic bias » ramp down magnetic field
- Detect up/down annihilations
- Repeat for different bias

- “The first ALPHA-g trap is fully commissioned and capable of systematic investigations of the effect of gravity on antimatter.” (SPSC meeting)
- No information on the results
- Challenge: control and measurement of the magnetic field at the mirror coils







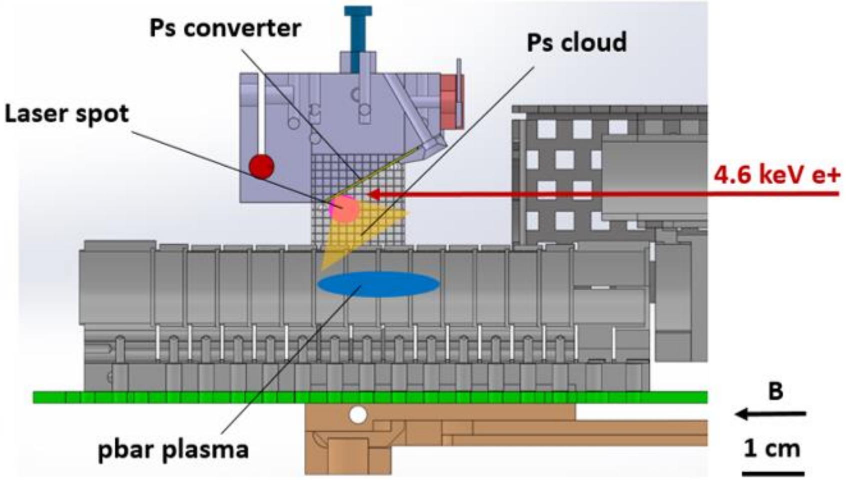


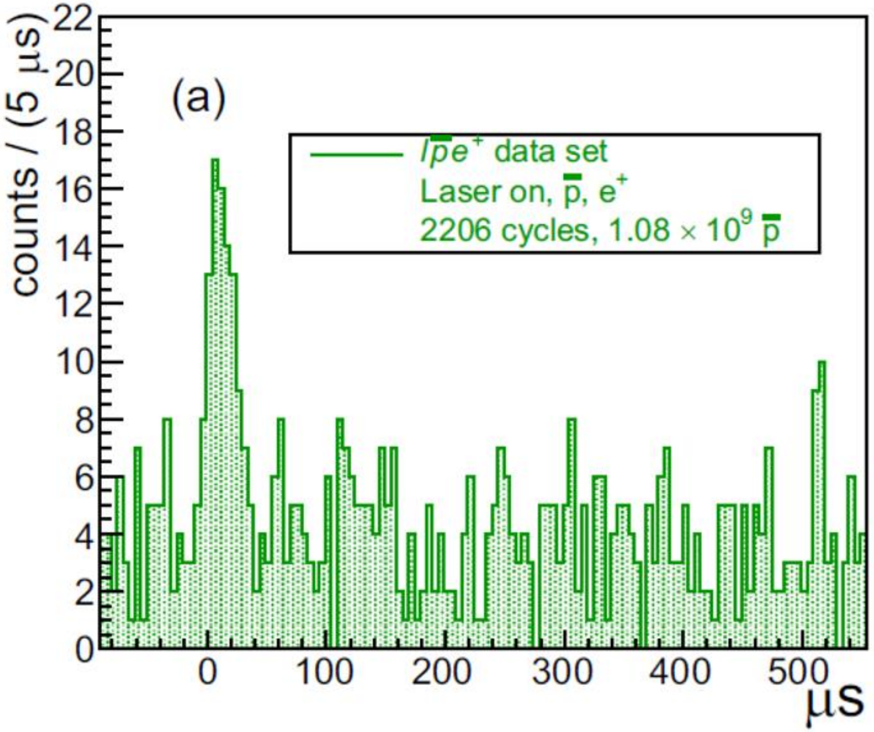
Competition: AEgIS experiment

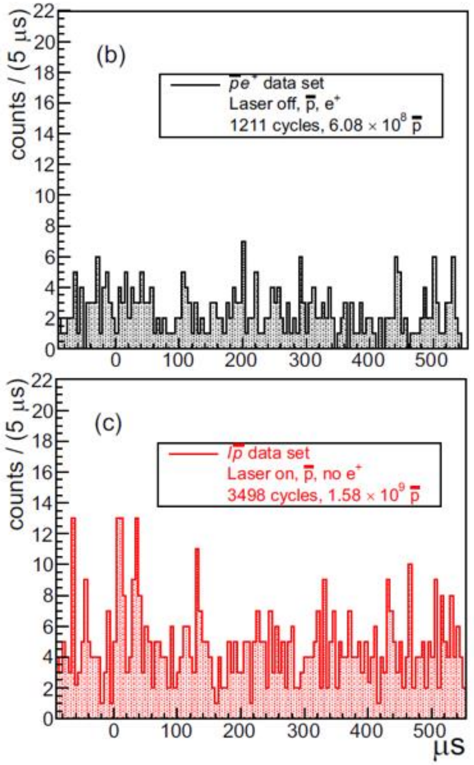
- Proposal: 100,000 pbar at 100 mK for 1 % precision
- Results in Rydberg positronium production, pulsed antihydrogen production in an antiproton plasma
- No new results in antiproton cooling
- No significant new results in 2022 (mostly development work)

https://doi.org/10.1038/s42005-020-00494-z OPEN

Pulsed production of antihydrogen





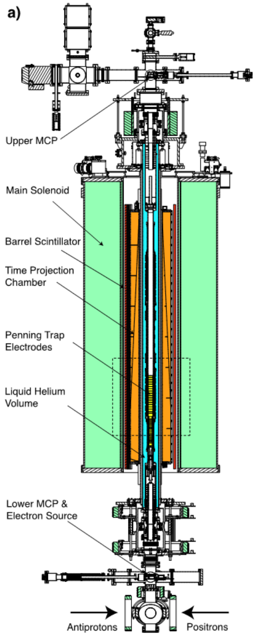


Key finding: 0.05 $\bar{H}^*$ produced every 2 mins (with $1.0 \cdot 10^6$ antiprotons)

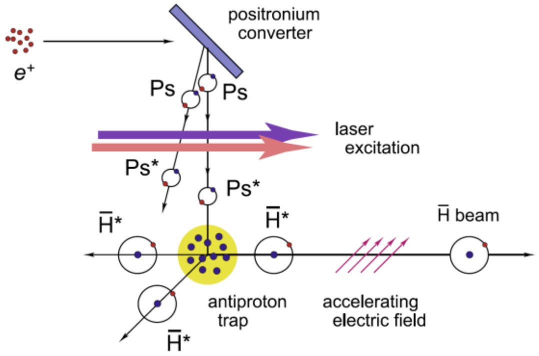
Competition

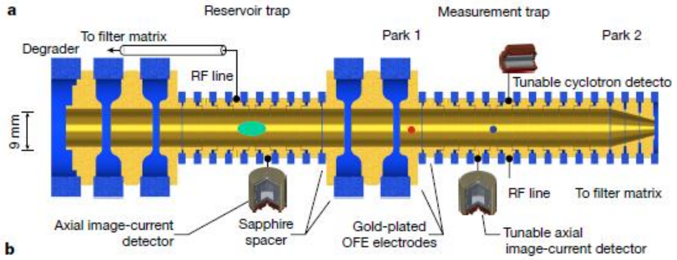
- Existing measurements:
  - ALPHA limits (Nature Comm. 4,1785 (2013)) $-65 < F < 75$ (95 % confidence level)
  - BASE, indirect measurement (Nature 601,53 (2022)) (cyclotron frequency comparison)
    « we constrain the differential WEPcc-violating coefficient to less than 0.030”
- The expected precision of ALPHA-g, AEgIS and GBAR is 1 %
- GBAR has the potential to increase the precision by orders of magnitude (gravitational quantum states)
- Trapped, ultracold antihydrogen ion gives opportunity for further experiments

ALPHA



AEgIS





BASE

ANR SPHINX – 4 years

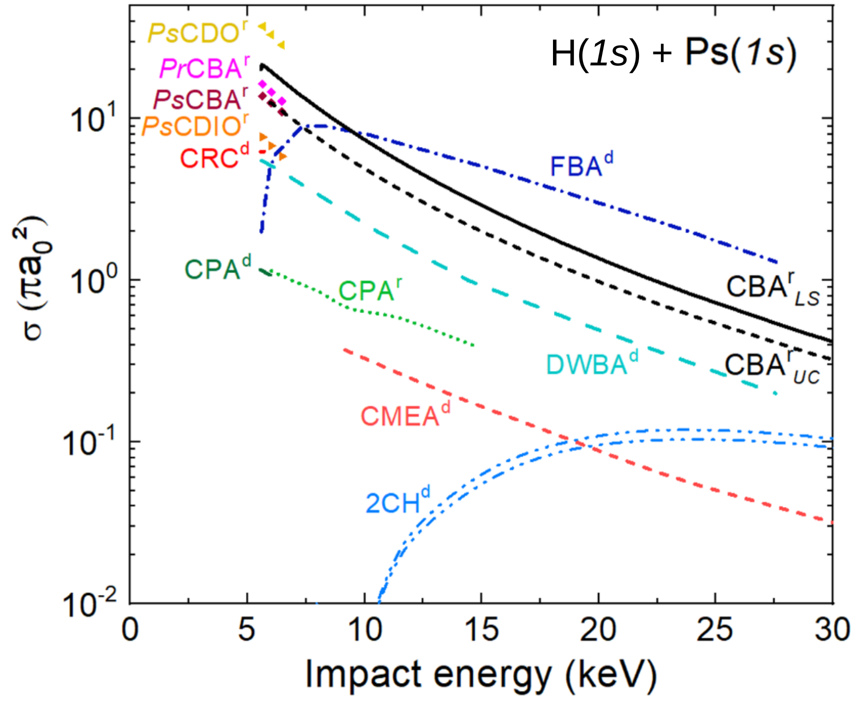
- **Objectives**

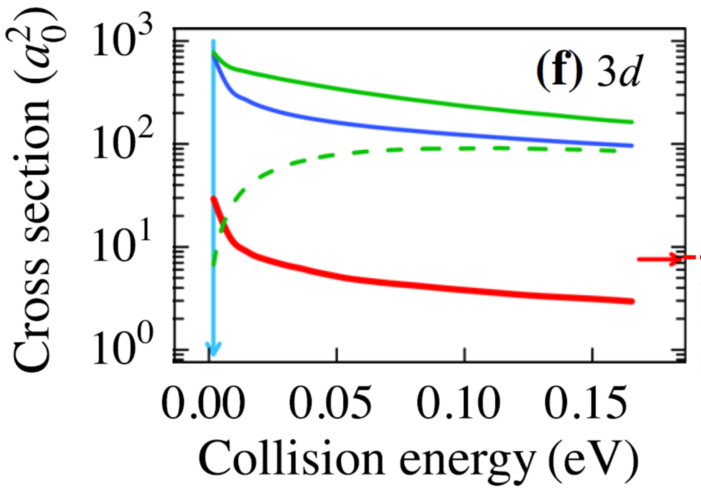
  $\overline{\mathrm{H}} + \mathrm{Ps} \rightarrow \overline{\mathrm{H}}^{+} + \mathrm{e}^{-}$

  Confront theoretical cross section calculations to experimental values > validation of theoretical calculations

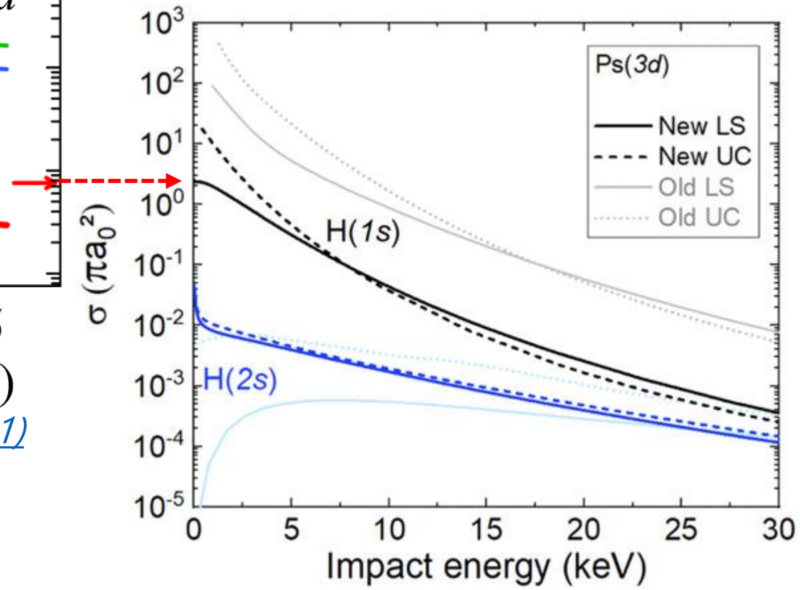
  Provide better estimations of antihydrogen ion production in GBAR and motivate the choice of a Ps excited state

  Outside the scope of GBAR: application of the validated cross sections to Ps formation in the ISM





[Few-Body Syst 62, 81 (2021)]



[NJP 23, 029501 (2021)]

Disagreement between models even in simplest case

Cross sections with excited Ps much lower than expected

ANR SPHINX – 4 years

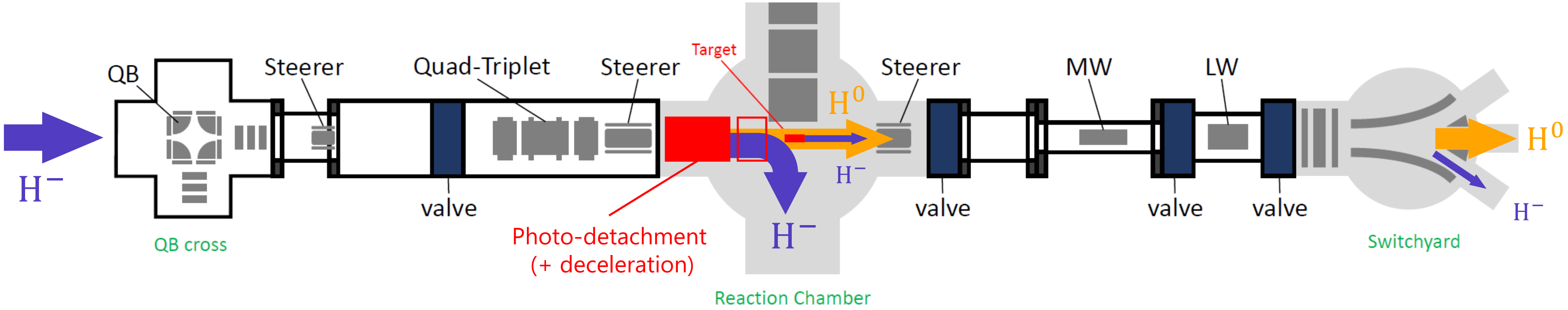
- **Principle**

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

  ELENA provides every 15 s a pulsed beam of $\mathrm{H^-}$ in between antiproton pulses > Easy to neutralise

  Set-up integration without disturbance to GBAR but requires positron resources:

  - SPHINX can run before antiproton beamtime (~1 month) ✓✓
  - during "antiproton only" studies in GBAR (typically 8h / day) ✓
  - just after antiproton ejection (then takes ~10% of positrons) ✓



- **Planning**

  2023: Neutral beam formation and characterisation, first data for $\mathrm{H(1s) + Ps(1s)}$

  2024: Continue $\mathrm{H(1s) + Ps(1s)}$, Beam deceleration down to 1 keV before the target, Measurement for $\mathrm{H(1s) + Ps(3d)}$

  2025: Continue $\mathrm{H(1s) + Ps(3d)}$

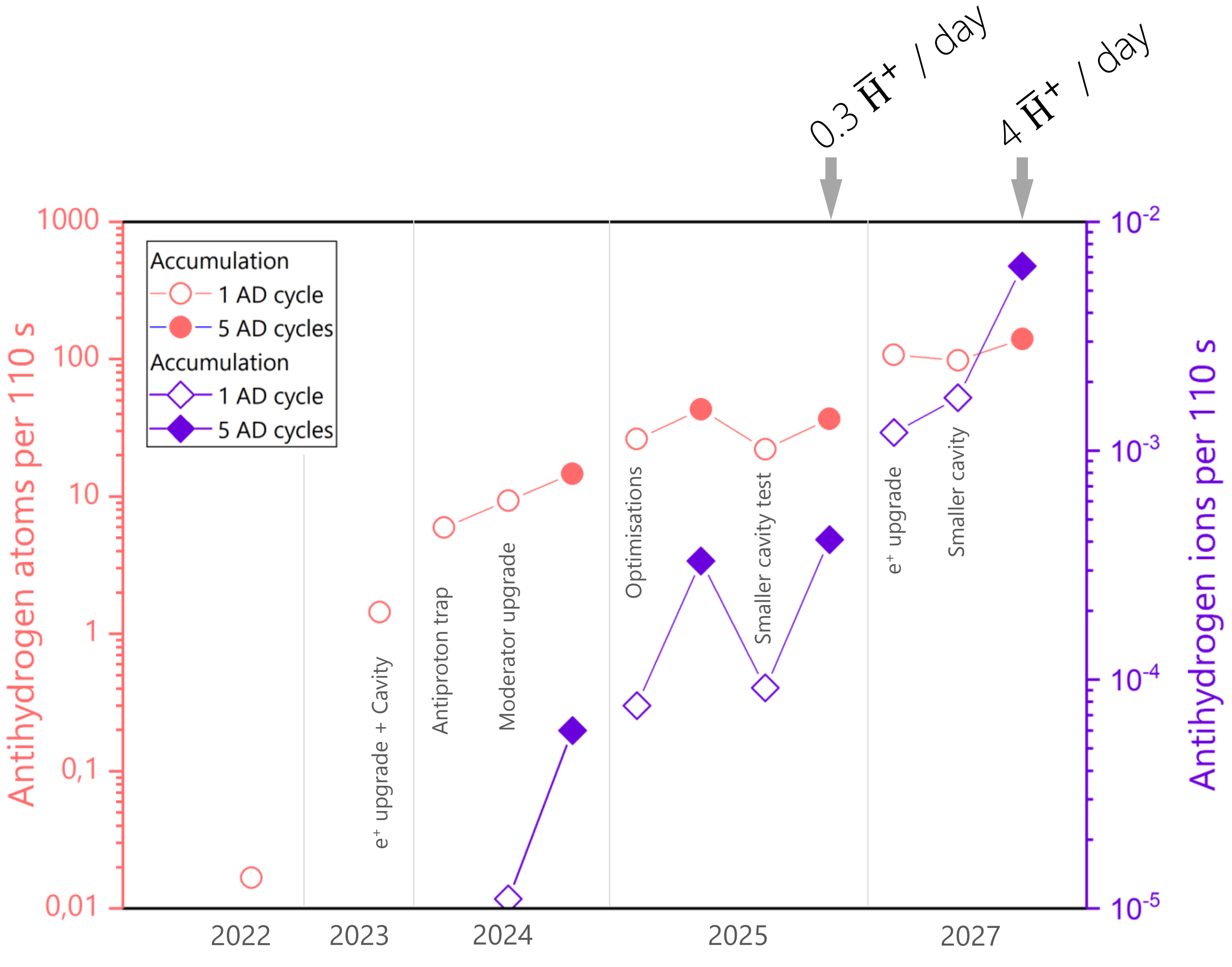
  2026: LS3, no $\mathrm{H^-}$, but still proton gun & carbon foil > possibility to test $\mathrm{H(2s) + Ps(1s)}$

Antihydrogen atoms & ions yield in the future

- **Foreseen evolution on the positron part**
  - Before LS3:
    - o Ps cavity and converter exchange
    - o Linac at 300 Hz > x1.3
    - o SiC scheme > x3
    - o W mesh moderator improvement > x1.5
    - o Longer accumulation time
    - o Transport optimisation
  - LS3
    - o Moderator upgrade > x2
    - o SiC in HFT > x1.5
    - o Smaller cavity

- **Foreseen evolution on the antiproton part**
  - In addition to continuous improvements from ELENA:
    - o Cooled antiproton
    - o Longer accumulation time / recycling

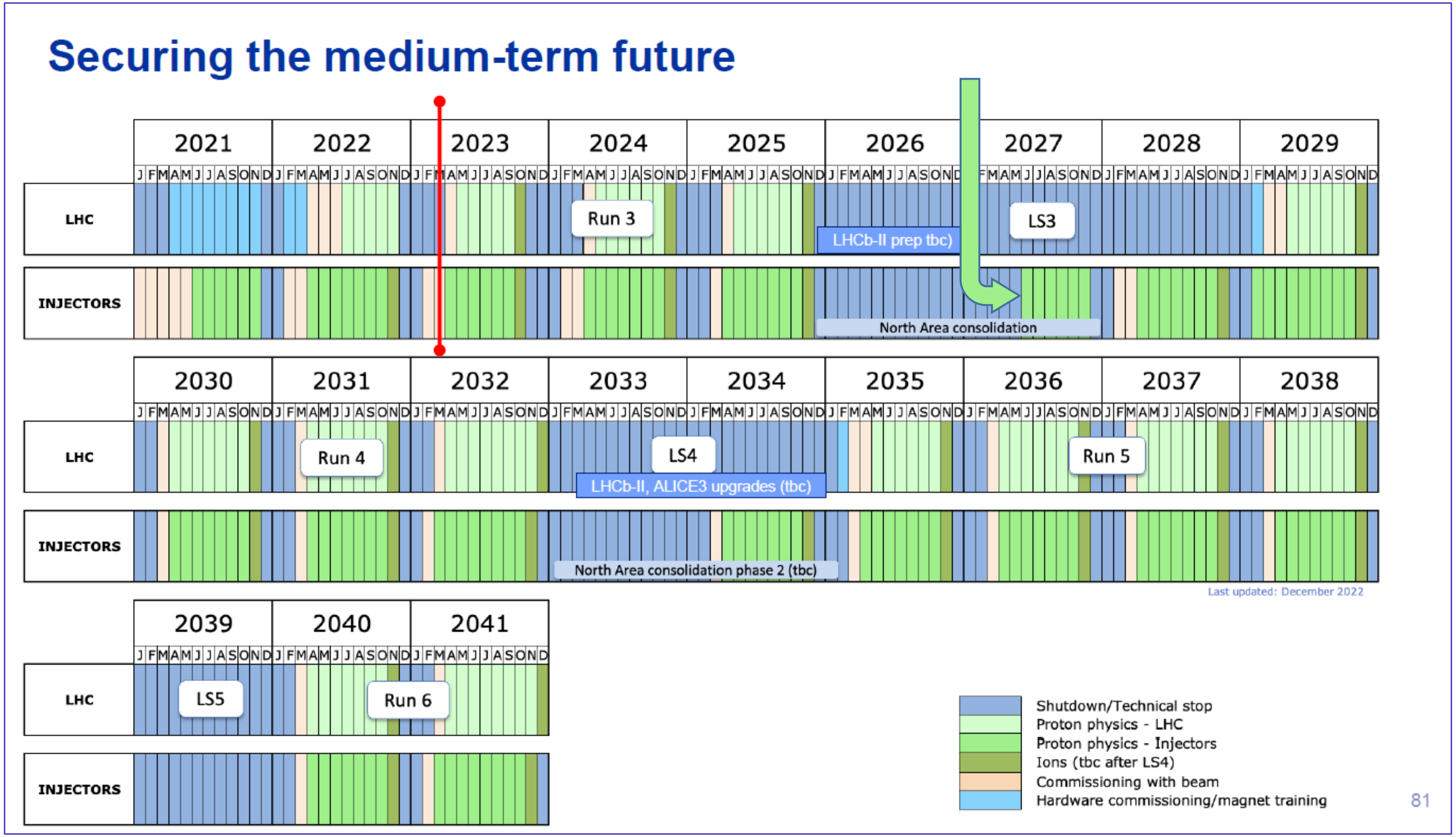
- **2025: 1st detection of $\bar{H}^+$**



Further improvements depending on SPHINX outcome:
- Ps excitation, 3D or n=2.
- If no Ps excitation: hot Ge Ps converter > x4

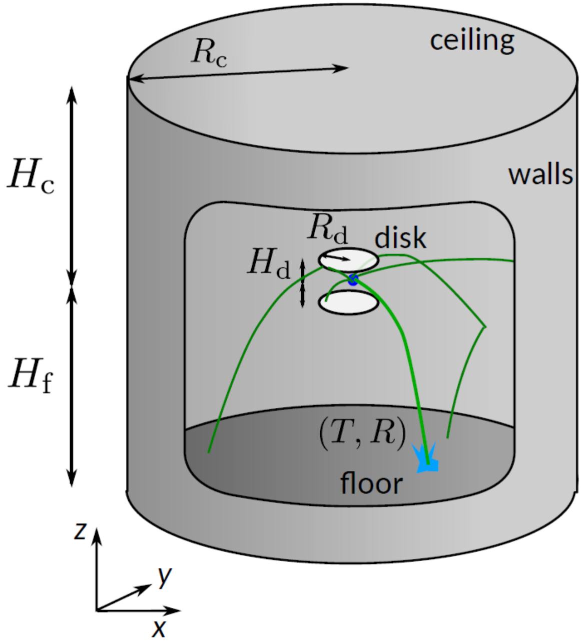
Plans for after LS3

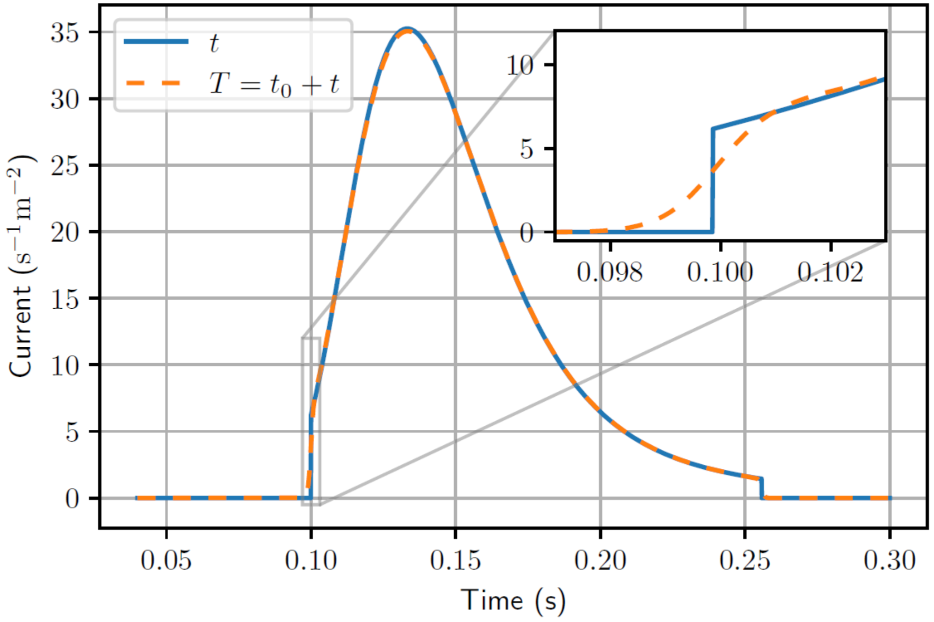
- CERN planning (from the Summary of the LHC "Chamonix" Workshop in Feb. 2023)

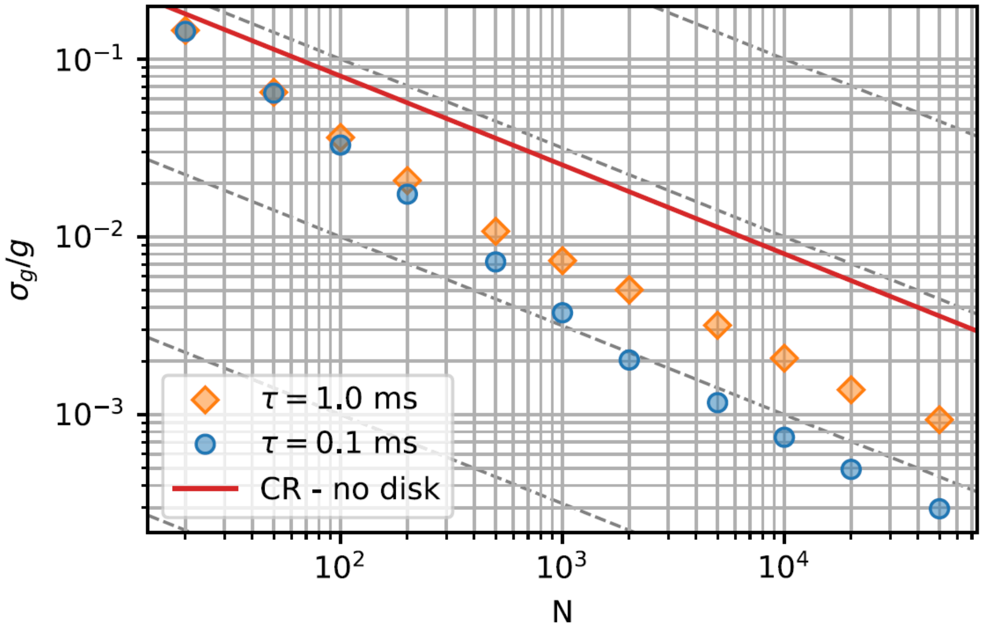


Plans for after LS3: free fall

- **Main project: precision measurement of the gravitational acceleration of antimatter on Earth**
  - 2027-2028: below 10 % $\bar{g}$ measurement with >30 detected cold antiatoms [PRA **105**, 022821 (2022)](#)







Hardware design adapted accordingly

Plans for after LS3: free fall

- **Main project: precision measurement of the gravitational acceleration of antimatter on Earth**
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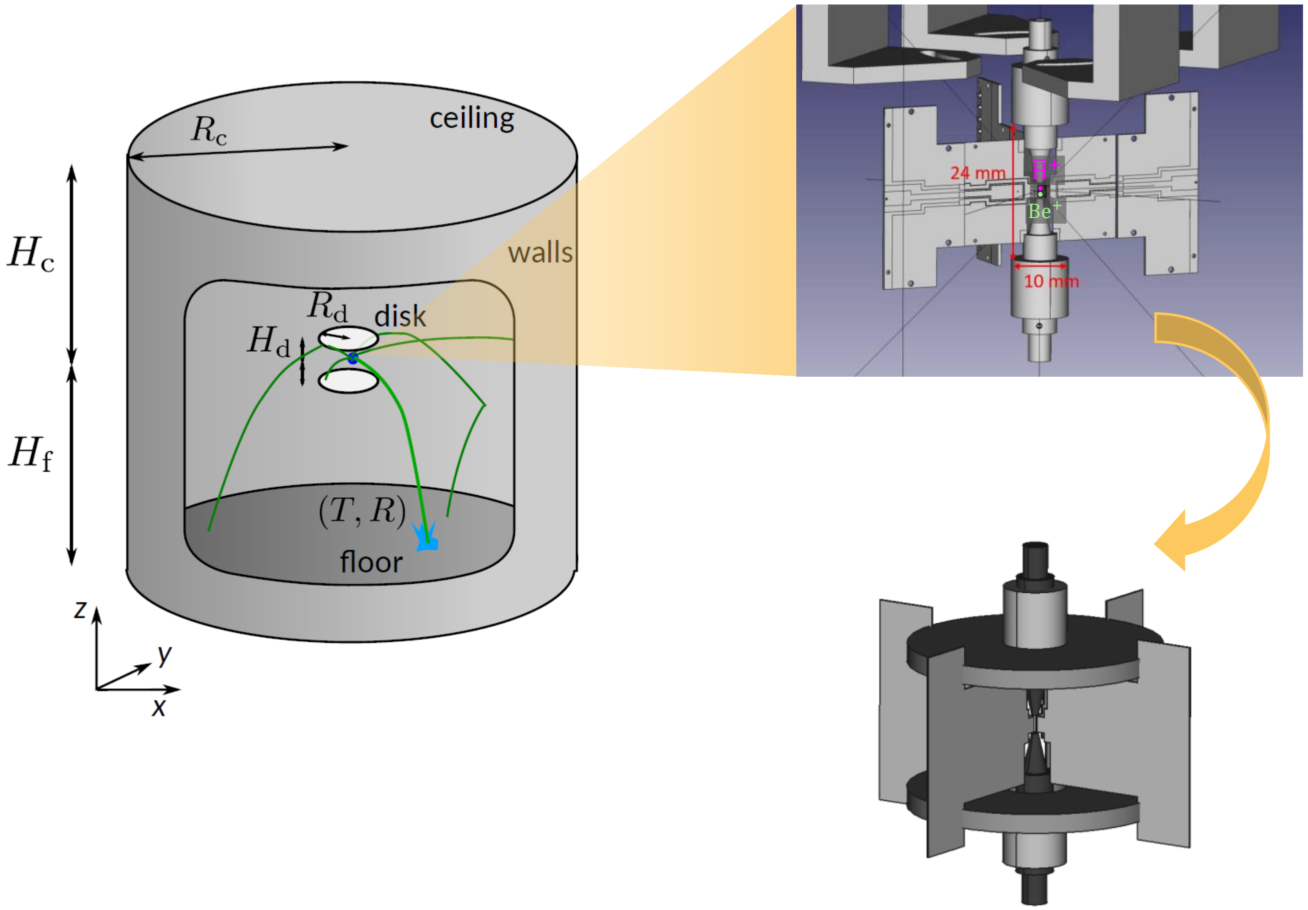
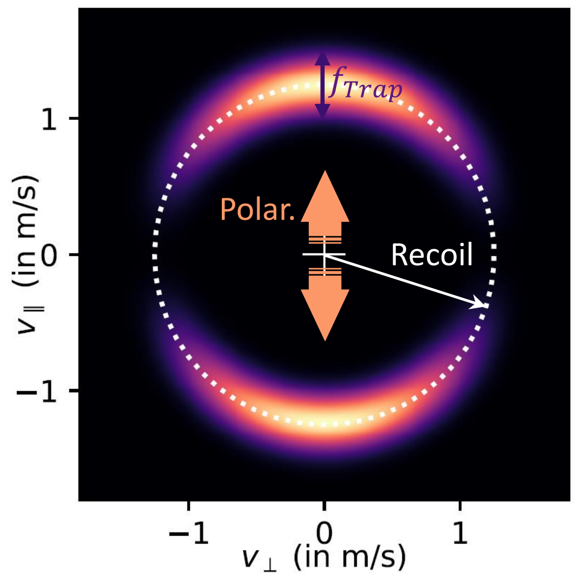


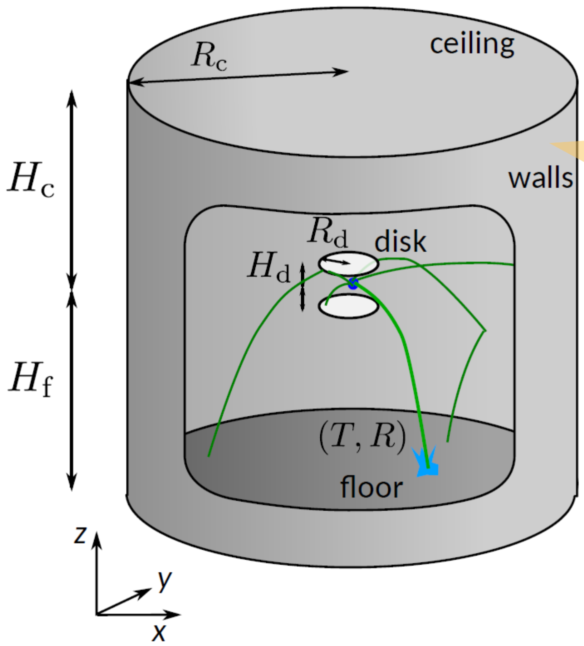


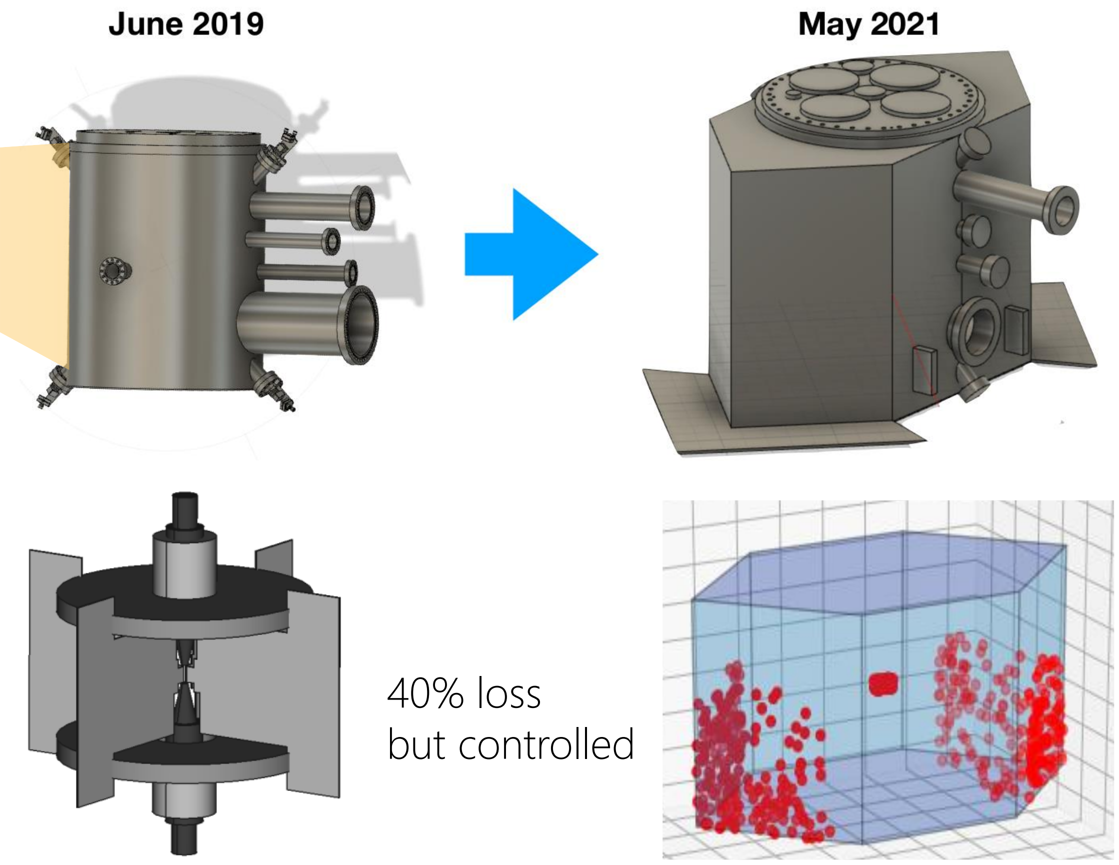
Horizontal polarisation to avoid obstacles

Photodetachment laser study and provision:
ANR PhotoPlus

Plans for after LS3: free fall

- **Main project: precision measurement of the gravitational acceleration of antimatter on Earth**
  - 2027-2028: below 10 % $\bar{g}$ measurement with >30 detected cold antiatoms *PRA **105**, 022821 (2022)*

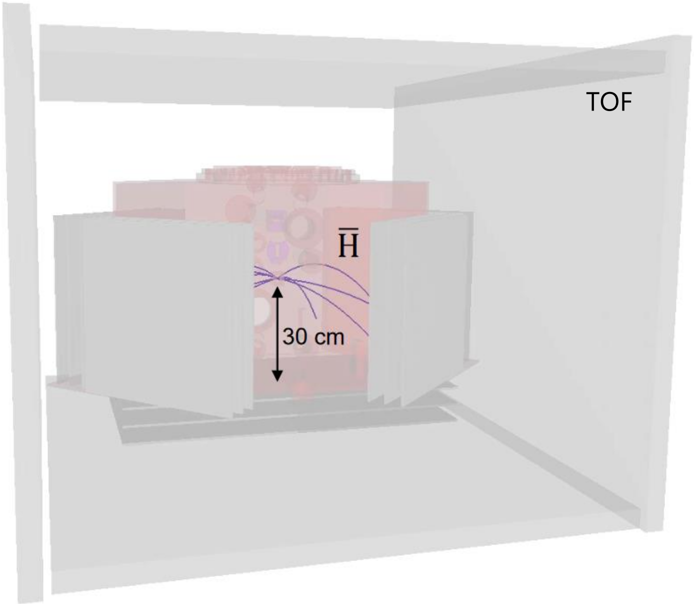




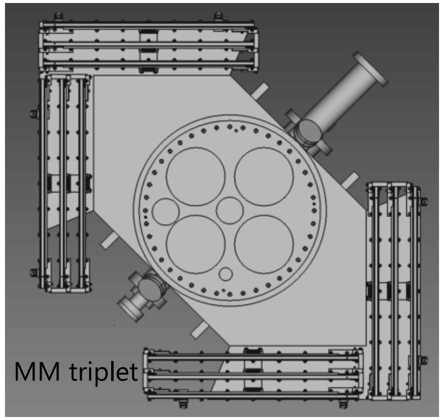
40% loss
but controlled

Plans for after LS3: free fall

- **Main project: precision measurement of the gravitational acceleration of antimatter on Earth**
  - 2027-2028: below 10 % $\bar{g}$ measurement with >30 detected cold antiatoms *PRA **105**, 022821 (2022)*

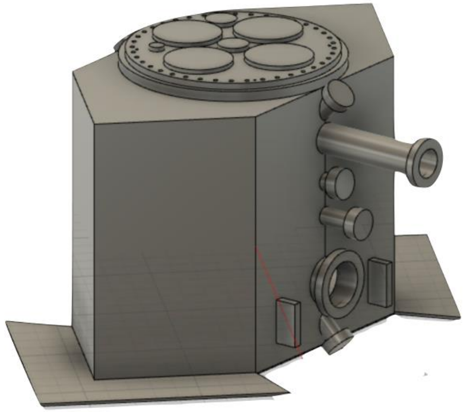


G4 geometry
Simulation of detector acceptance
& vertex reconstruction precision



MM trackers on the side
> Improved vertex reconstruction

May 2021



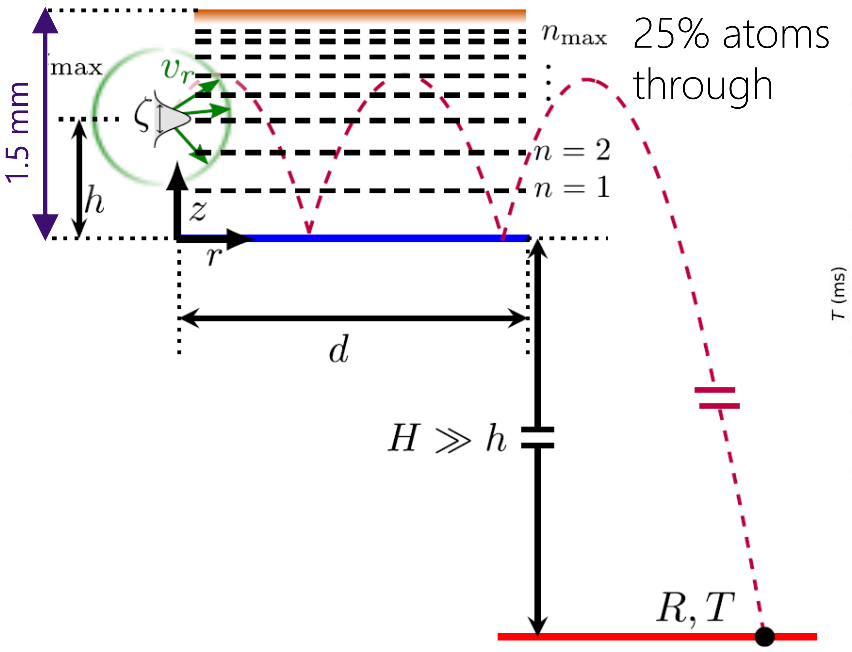
Event reconstruction ✓
Mechanical study ✓
Vacuum study ✓
…
> Ready for fabrication

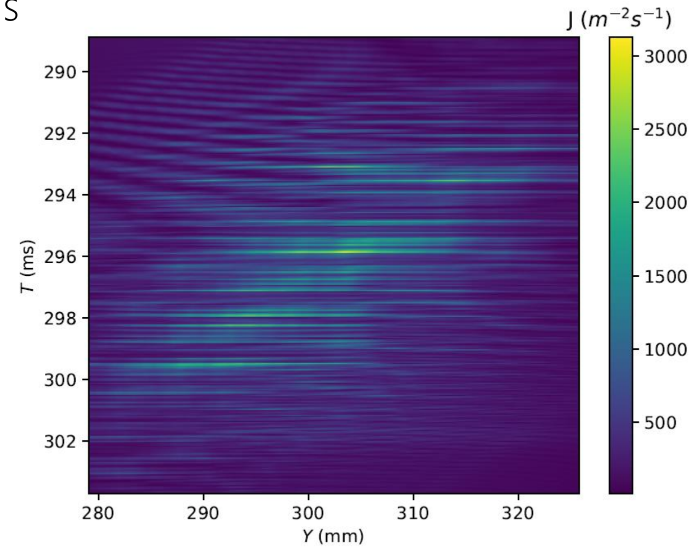
Simulation on $\bar{g}$ determination precision now includes
simulated precision on vertex reconstruction
in addition to photo-detachment details

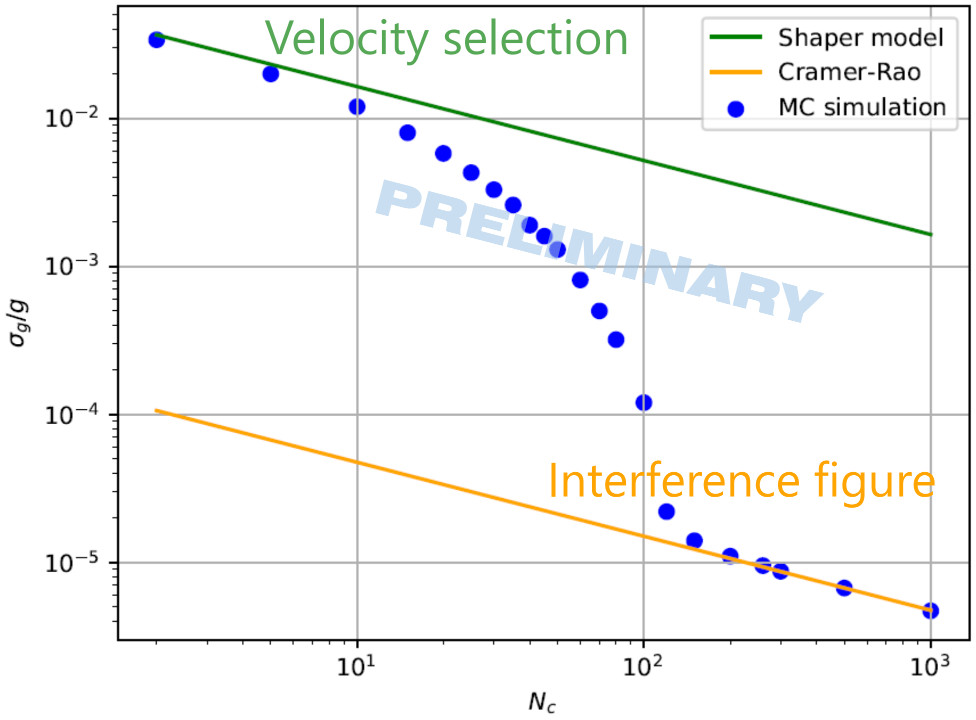
Enter the reflection of antihydrogen on mirror surface and gravitational quantum states…

GBAR plans for after LS3: free fall

- **Main project: precision measurement of the gravitational acceleration of antimatter on Earth**
  - 2027-2028: below 10 % ḡ measurement with >30 detected cold antiatoms *PRA **105**, 022821 (2022)*
  - Then: at least 1 % precision with QGS* interferometry (>10 detected events)
  - With potential for sub 10^{-5} precision *EPJD **76**, 209 (2022)*







+ GBAR collaborators involved in "mirror" measurement with Hydrogen (in GRASIAN collaboration)

*QGS: originally demonstrated with neutrons *Nature **415**, 297 (2002)*

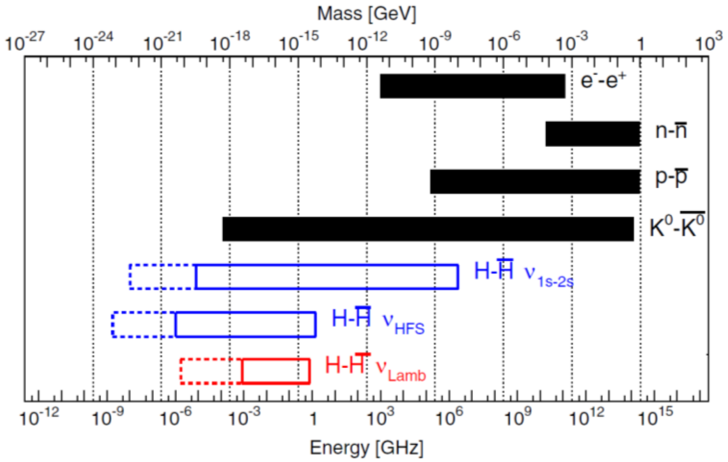
GBAR plans for after LS3: antihydrogen production, spectroscopy, GQS

- **Continuity of ongoing side-projects**
  - Lamb shift precision measurement and antiproton charge radius [PRD **94**, 052008 (2016)](#) >

Based on production of 2 $\bar{H}(2S)$ per cycle:

> 10^{-4} precision on Lamb-shift, 10 % on antiproton radius already in 2025

*(3.10^{-6} in Hydrogen, 1 % on proton radius [Science **365**, 1007 (2019)](#))*



  - Cross sections measurements ($\bar{\mathrm{H}}$, $\bar{\mathrm{H}}^+$) at low energies
  - X-ray spectroscopy of antiprotonic atoms [PRL **126**, 173001 (2021)](#)

- **Other projects under discussion and ideas**
  - Further in-flight antihydrogen spectroscopy (n=2 fine structure)
  - First production of $\bar{\mathrm{H}}_2^-$

Intra-beam collisions between $\bar{H}$-$\bar{H}$ or $\bar{p}$-$\bar{H}^+$

Competition looking to make $\bar{H}$-$\bar{H}$ in trap

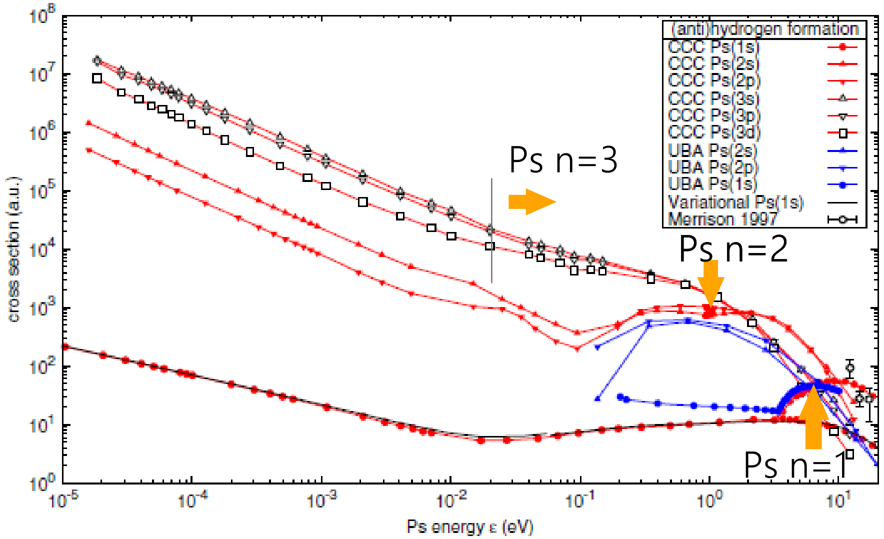
Motivation: Antihydrogen molecular ion spectroscopy [PRA **98**, 010101(R) (2018)](#)

  - Further investigation of the QGS, like spectroscopy, for another way to measure $\bar{g}$
  - Ultracold antihydrogen in optical trap ([Hyp. Int. **214**, 60 (2020)](#)) / atom chip trap, for single anti-atom spectroscopy

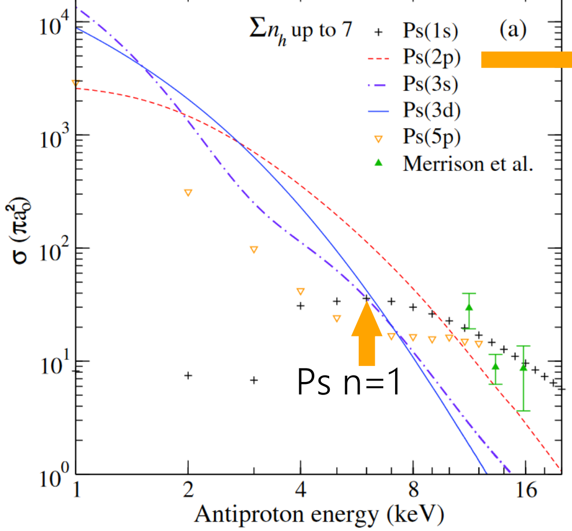
Back-up slides

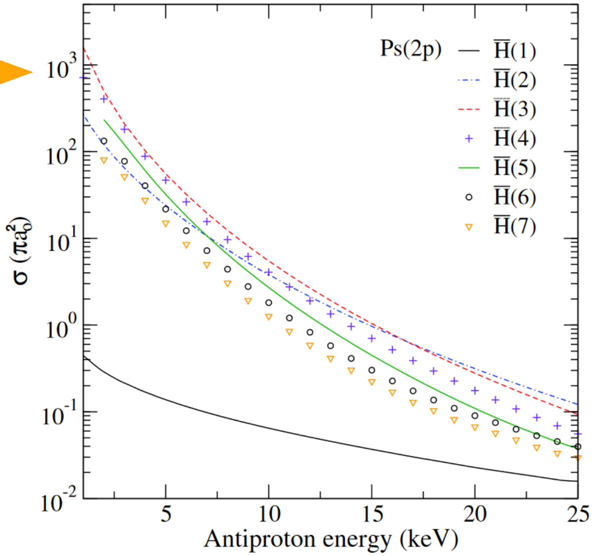
Back-up: Cross sections with excited Ps

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



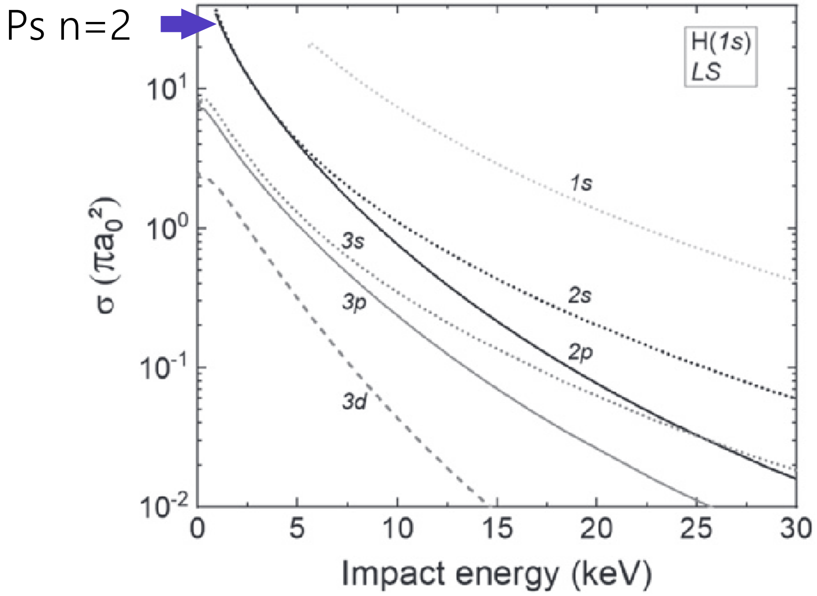
*PRL **114**, 183201 (2015)*

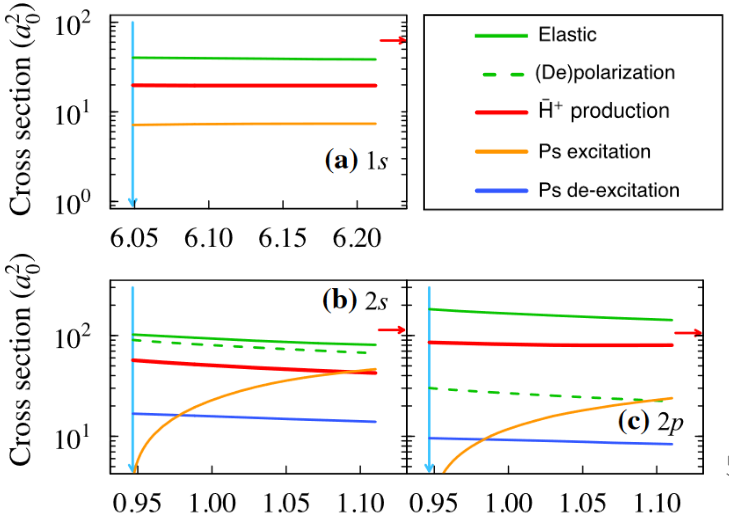




K. Lévêque-Simon, Thèse (2020)

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





Back-up: Sub-Doppler cooling

- **Main project: precision measurement of the gravitational acceleration of antimatter on Earth**
  - 2027-2028: below 10 % ḡ measurement with >30 detected cold antiatoms *PRA **105**, 022821 (2022)*

- **Capture trap**
  Experimental & numerical simulation
  of the kinetic energy transfer
  of a charged projectile in a cold ion cloud
  (ANR ESPRIT)

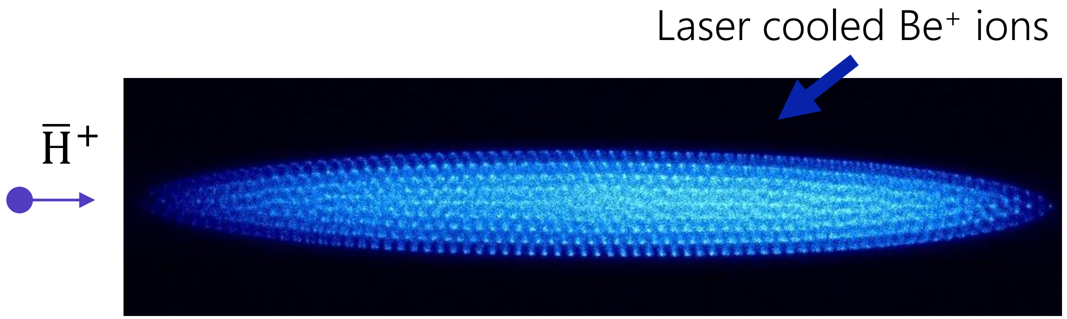
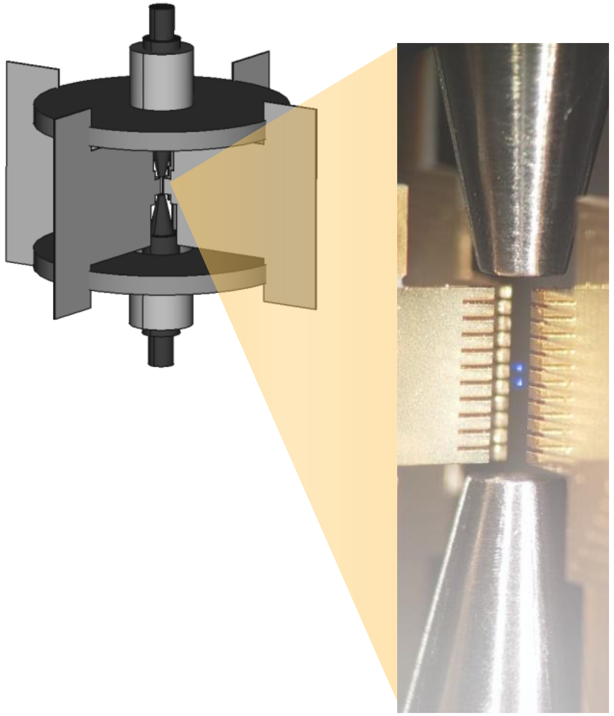
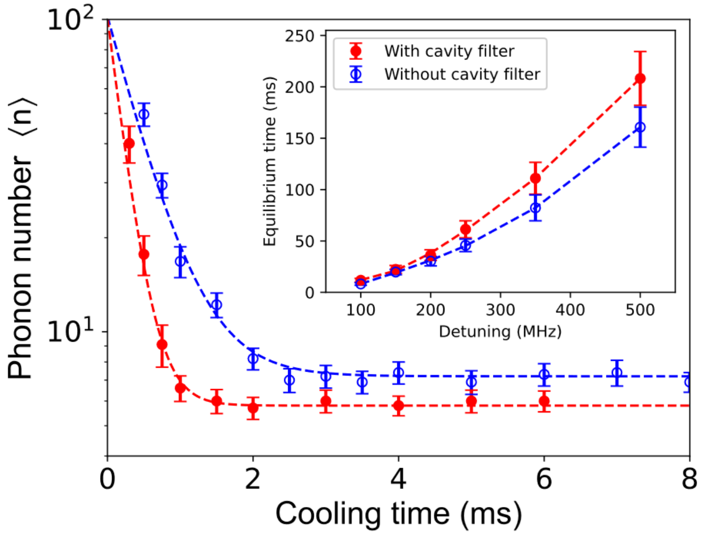


Image LKB Paris



Composite image JGU Mainz

- **Precision trap**
  Development of a faster and simpler
  sub-Doppler cooling technique:
  Polarisation Gradient Cooling



*NJP **24**, 043028 (2022)*

Demonstration on Ca^+,
to be done on Be^+

Back-up: Physics possibilities

- Taking advantage of GBAR specificities