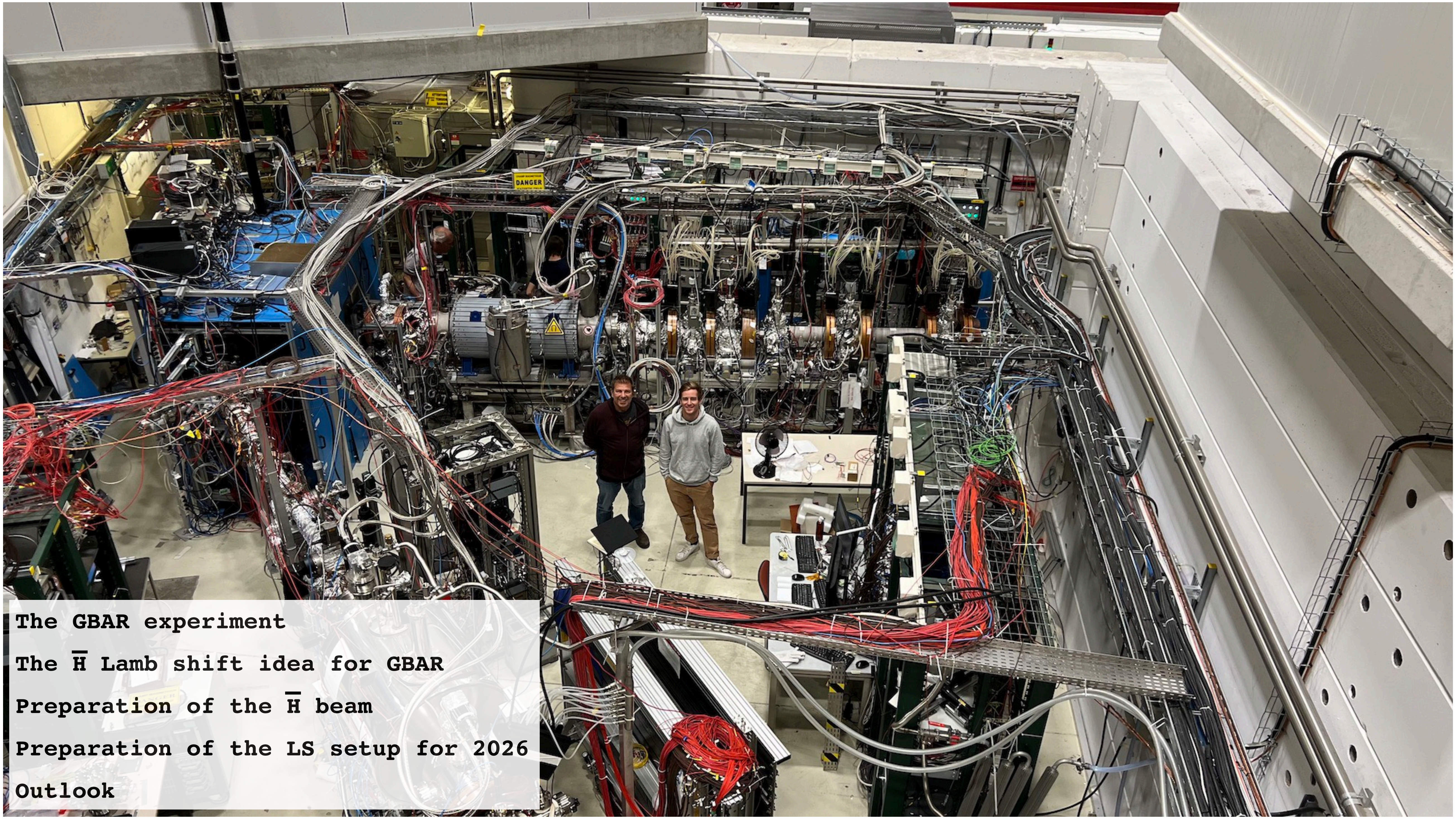
Towards a measurement of the $2S_{1/2}$-$2P_{1/2}$ Lamb shift for antihydrogen atoms at GBAR/Cern



The GBAR experiment

The $\bar{H}$ Lamb shift idea for GBAR

Preparation of the $\bar{H}$ beam

Preparation of the LS setup for 2026

Outlook

C.Regenfus - on behalf of the GBAR collaboration

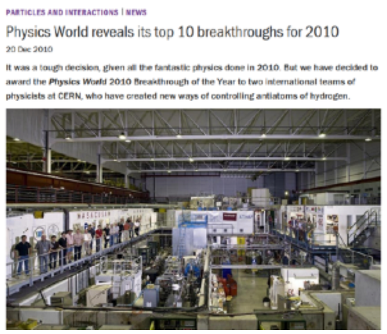
Precision physics in the antimatter sector at low energy AD/ELENA CERN

Baryon asymmetry – GR – SM-Extensions – Lorentz and CPT violations

Coefficients to be determined experimentally

- Advanced charged plasma control techniques
- Advanced magnetic trapping
- High power UV-laser technology
- Non-destructive quantum-transition spectroscopy
- Ultra-low-noise trapping techniques
- Sympathetic cooling and quantum-logic spectroscopy

Start of antihydrogen physics



PARTICLES AND INTERACTIONS | NEWS

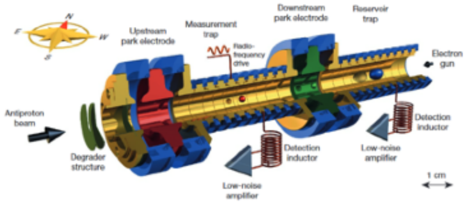
Physics World reveals its top 10 breakthroughs for 2010

20 Dec 2010

It was a tough decision, given all the fantastic physics done in 2010. But we have decided to award the *Physics World* 2010 Breakthrough of the Year to two international teams of physicists at CERN, who have created new ways of controlling antiatoms of hydrogen.

physicsworld TOP 10 BREAKTHROUGH 2010

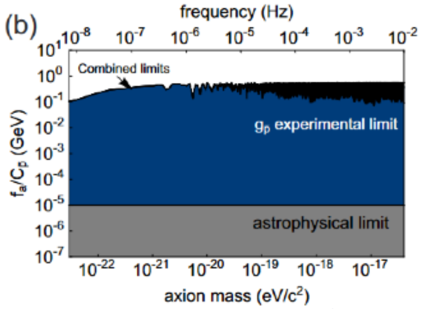
ALPHA
ASACUSA

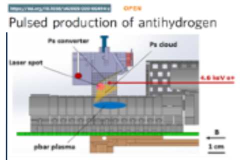


69 p.p.t. proton/antiproton q/m comparison

It is all about cooling

antimatter/dark matter coupling



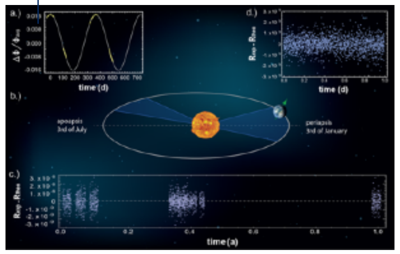


First Hbar production in GBAR

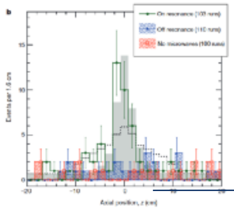
Increased Hbar production

2002 2010 2011 2012 2013 2014 2015 2017 2018 2019 2020 2021 2022 2023 2024

Observation of the effect of gravity on the motion of antimatter

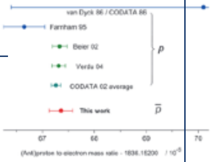


WEP test with clocks



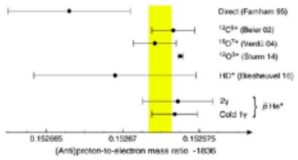
Resonant quantum transitions in Hbar

$m_{\bar{p}}/m_e$ at 1.5 ppb

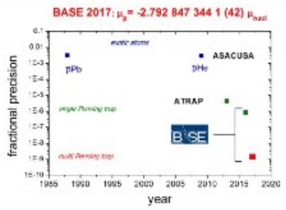


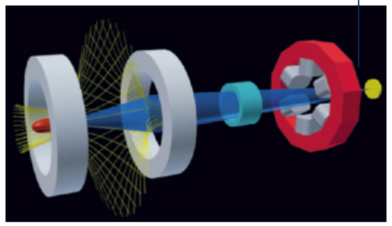
trapped antihydrogren

$m_{\bar{p}}/m_e$ at 0.8ppb



1.5ppb pbar moment





Production of a beam of antihydrogen atoms

ALPHA
BASE

physicsworld TOP 10 BREAKTHROUGH 2022

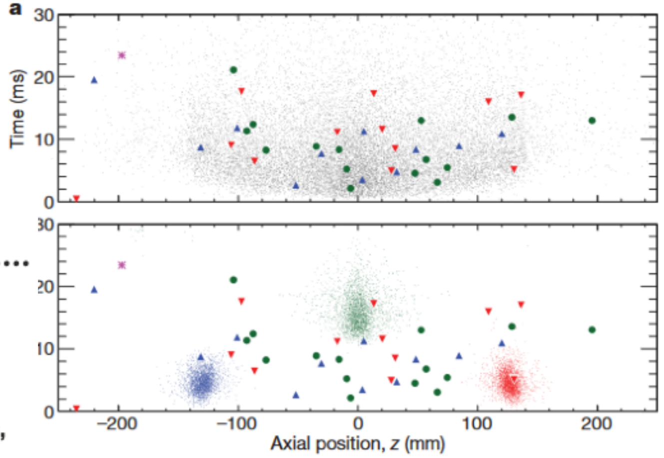
laser-cooled antihydrogren and sympathetically cooled protons

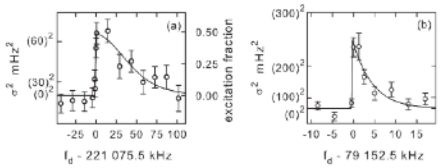
ATHENA 2002

letters to nature

Production and detection of cold antihydrogen atoms

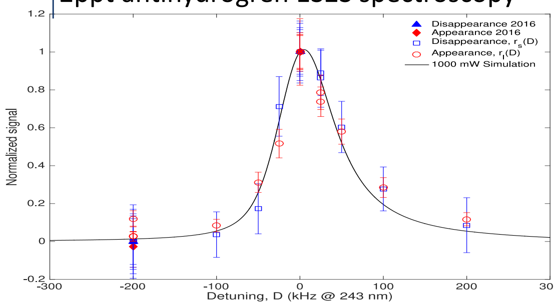
M. Amoretti*, C. Amsler†, G. Bonomi‡§, A. Bouchta‡, P. Bowe‖, C. Carraro*, C. L. Cesar¶, M. Charlton#, M. J. T. Collier#, M. Doser‡, V. Filippini☆, K. S. Fine‡, A. Fontana☆**, M. C. Fujiwara††, R. Funakoshi††, P. Genova☆**, J. S. Hangst‖, R. S. Hayano†† M. H. Holzscheiter‡, L. V. Jørgensen#, V. Lagomarsino*‡‡, R. Landua‡, D. Lindelöf†, E. Lodi Rizzini§☆, M. Macrì*, N. Madsen†, G. Manuzio*‡‡, M. Marchesotti☆, P. Montagna☆**, H. Pruys†, C. Regenfus†, P. Riedler‡, J. Rochet†#, A. Rotondi☆**, G. Rouleau‡#, G. Testera*, A. Variola*, T. L. Watson# & D. P. van der Werf#

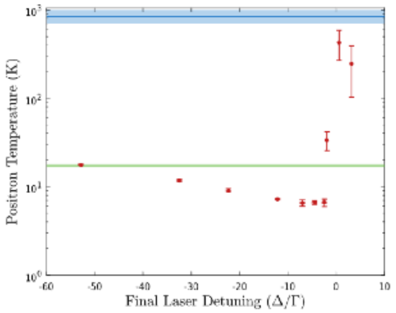




5ppm pbar moment

2ppt antihydrogren 1S2S spectroscopy





Laser cooled positrons

Latest achievement 3/26: transport of antiprotons in trap on a truck

Slide taken/modified from Stefan Ulmer

GBAR – the quest for the $\bar{H}^+$ ion

- **Direct test of WEP with antimatter (Gravitation, free fall)**
- **Precision physics with antihydrogen (Lamb Shift: CPT, $\bar{p}$ R_{chg} …)**

Collaboration ~50 physicists

ETH zürich
東京大学 THE UNIVERSITY OF TOKYO
Laboratoire Kastler Brossel Physique quantique et applications
IPCMS Institut de Physique et Chimie des Matériaux de Strasbourg
Stockholm University
JG|U JOHANNES GUTENBERG UNIVERSITÄT MAINZ
ill NEUTRONS FOR SCIENCE
cea irfu
Narodowe Centrum Badań Jądrowych National Centre for Nuclear Research ŚWIERK
RIKEN
서울대학교 SEOUL NATIONAL UNIVERSITY
KOREA UNIVERSITY
IJCLab Irène Joliot-Curie Laboratoire de Physique des 2 Infinis
Swansea University Prifysgol Abertawe
ibs 기초과학연구원 Institute for Basic Science
POSTECH POHANG UNIVERSITY OF SCIENCE AND TECHNOLOGY

Precision ion trap (2D)

Sympathetic Be+ cooling

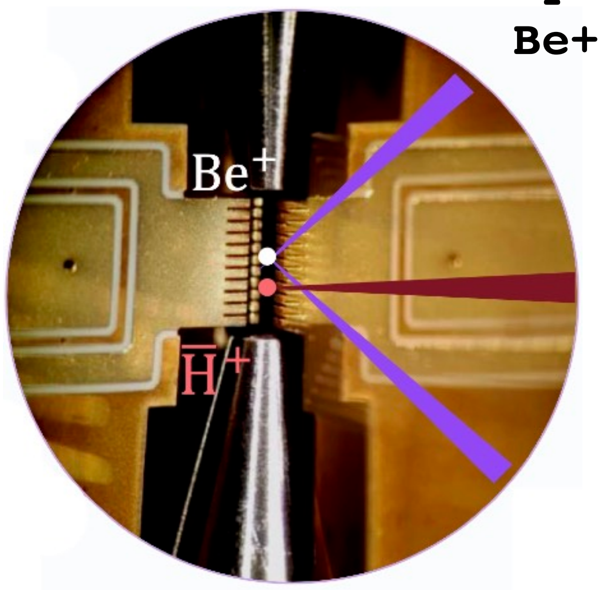
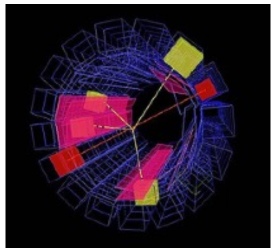


photo detachment (near threshold)



- **ATHENA 2002, 50k low-energy $\bar{H}$ atoms produced in a nested Penning trap**
- **Neutral $\bar{H}$ atoms difficult to manipulate – DCL ~2mK**
- **$\bar{H}^+$ (2 positrons bound to an p) would be much easier to manipulate**
- **Analog to the H^- ion E_{bind} = 0.75eV (no excited states)**
- **Sympathetic cooling with suitable ions possible, eg Be^+ ~10μK ~1neV ~1m/s**
- **Production challenging**

Walz, Hänsch, Gen.Rel.Grav. 36, 3, 561 (2004)

GBAR at ELENA/AD - creation of anti-ions

In-flight (keV) $\overline{\mathrm{H}}^+$ ion production in a 2-step charge exchange reaction on Positronium (Ps) atoms with an intense source of positrons

P. Pérez et al., NIMA 532, 523 (2004)

1st reaction no thresh.

2nd reaction thresh. ~6keV
$\overline{\mathrm{H}}$ needs to be in ground state

$$\boxed{\begin{array}{l} \overline{\mathrm{p}} + \mathrm{Ps} \rightarrow \overline{\mathrm{H}} + \mathrm{e}^- \\ \overline{\mathrm{H}} + \mathrm{Ps} \rightarrow \enclose{circle}{\overline{\mathrm{H}}^+} + \mathrm{e}^- \end{array}}$$

Be$^+$ cooling

σ ~10^{-15} cm^2

similar $\mathcal{O}$?

2nd reaction is presently explored at GBAR with H atoms impinging on a Ps target.

Cross sections for charge exchange reactions tiny

Second cross section not well known

Measurement with H presently ongoing in GBAR

$\overline{\mathrm{H}}^+$ number scales with the square of available e$^+$

Lots of neutral antihydrogen atoms available as beam!

GBAR - experimental principle - nanoporous Ps targets

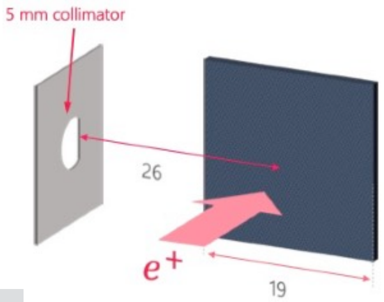
2022: Beam divergence too large for cavity use

- spatial overlap not well defined
- reduced particle densities

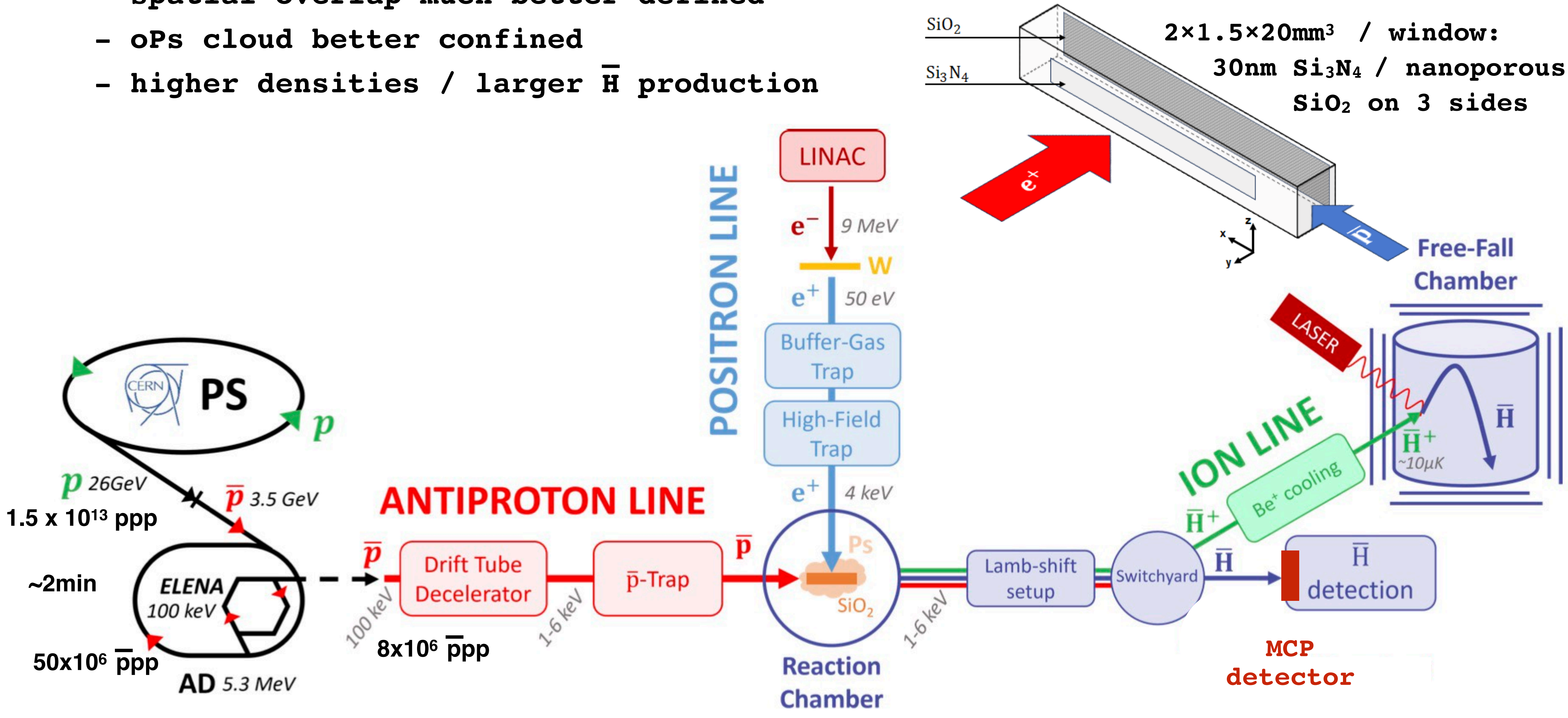
2024: Thanks to $\bar{p}$-trap cooled antiprotons

- spatial overlap much better defined
- oPs cloud better confined
- higher densities / larger $\bar{H}$ production

2022 Flat Ps target



2024 Cavity Ps target



2×1.5×20mm^3 / window: 30nm Si_3N_4 / nanoporous SiO_2 on 3 sides

1.5 x 10^{13} ppp

~2min

50x10^6 $\bar{p}$pp

8x10^6 $\bar{p}$pp

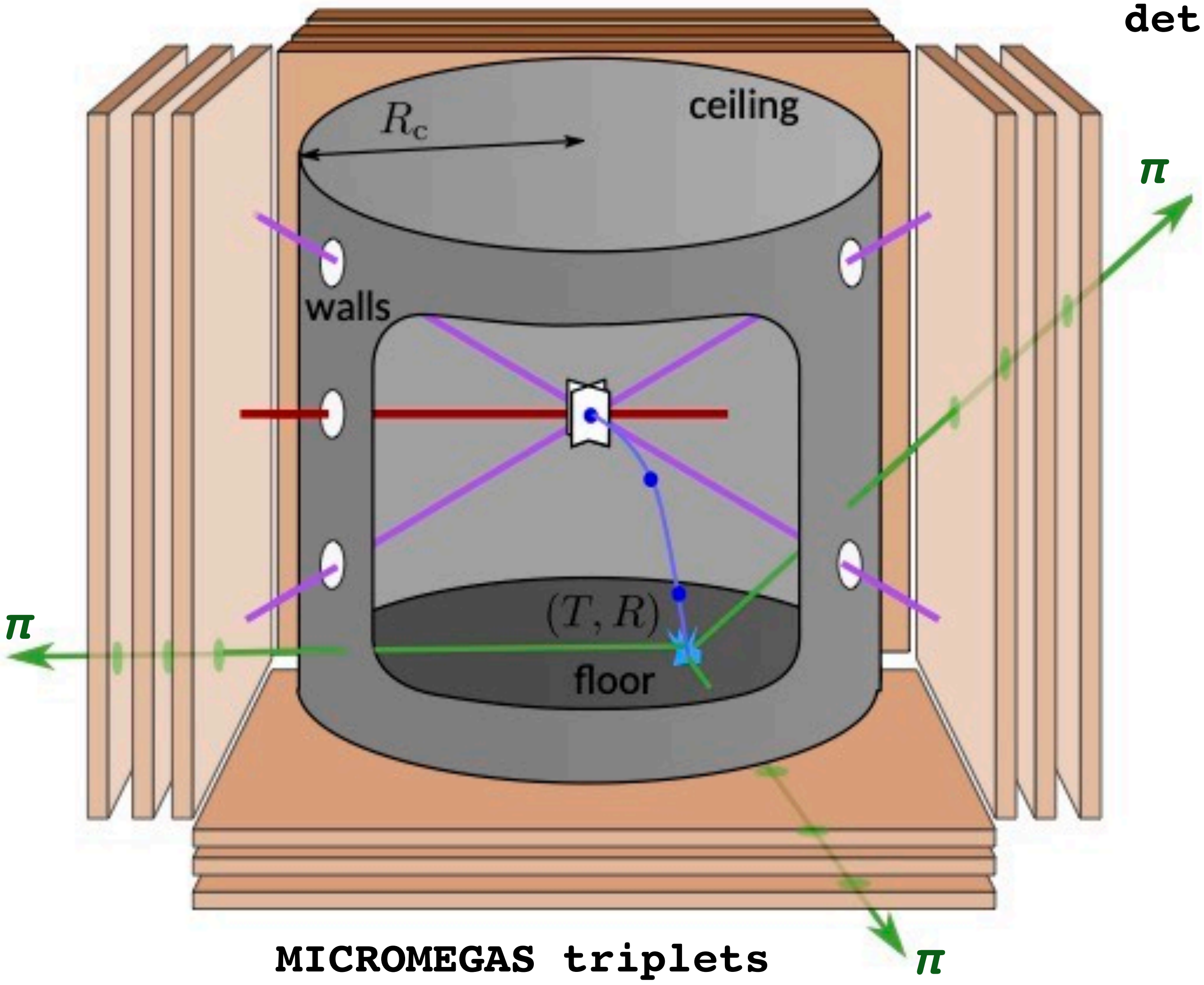
MCP detector

Particle numbers are there - transport between traps and reaction zones is presently the limiting factor

Free fall measurement - principle

Classical free fall after photo detachment near threshold:

1% precision on $\bar{g}$ with 500 $\overline{\mathrm{H}}^{+}$



1640nm photo detachment

MICROMEGAS triplets, large area trackers

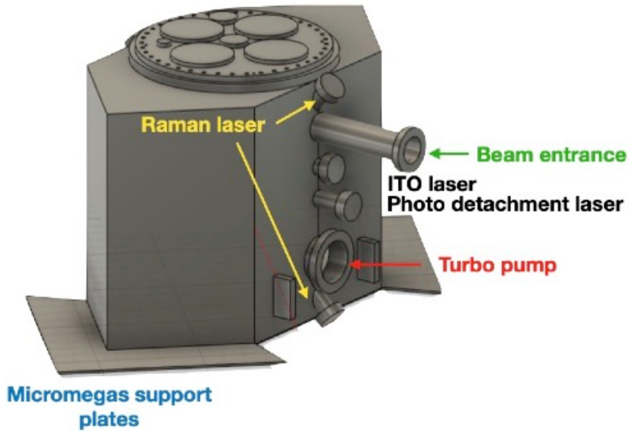
Cooling and detachment lasers

Sympathetic Be+ cooling 313nm

MICROMEGAS triplets

ETHzürich

Latest design study



Measurements

- **ALPHA-g (vertical trap releases):**
  $\bar{g}/g$ = (0.75 ±~20%)   Nature 621, 716-722 (2023)

- **BASE (extracted from gravitational redshift arguments):**
  $\Delta\bar{g}/\bar{g}$ = 3%   Nature 601, 53-57 (2022)

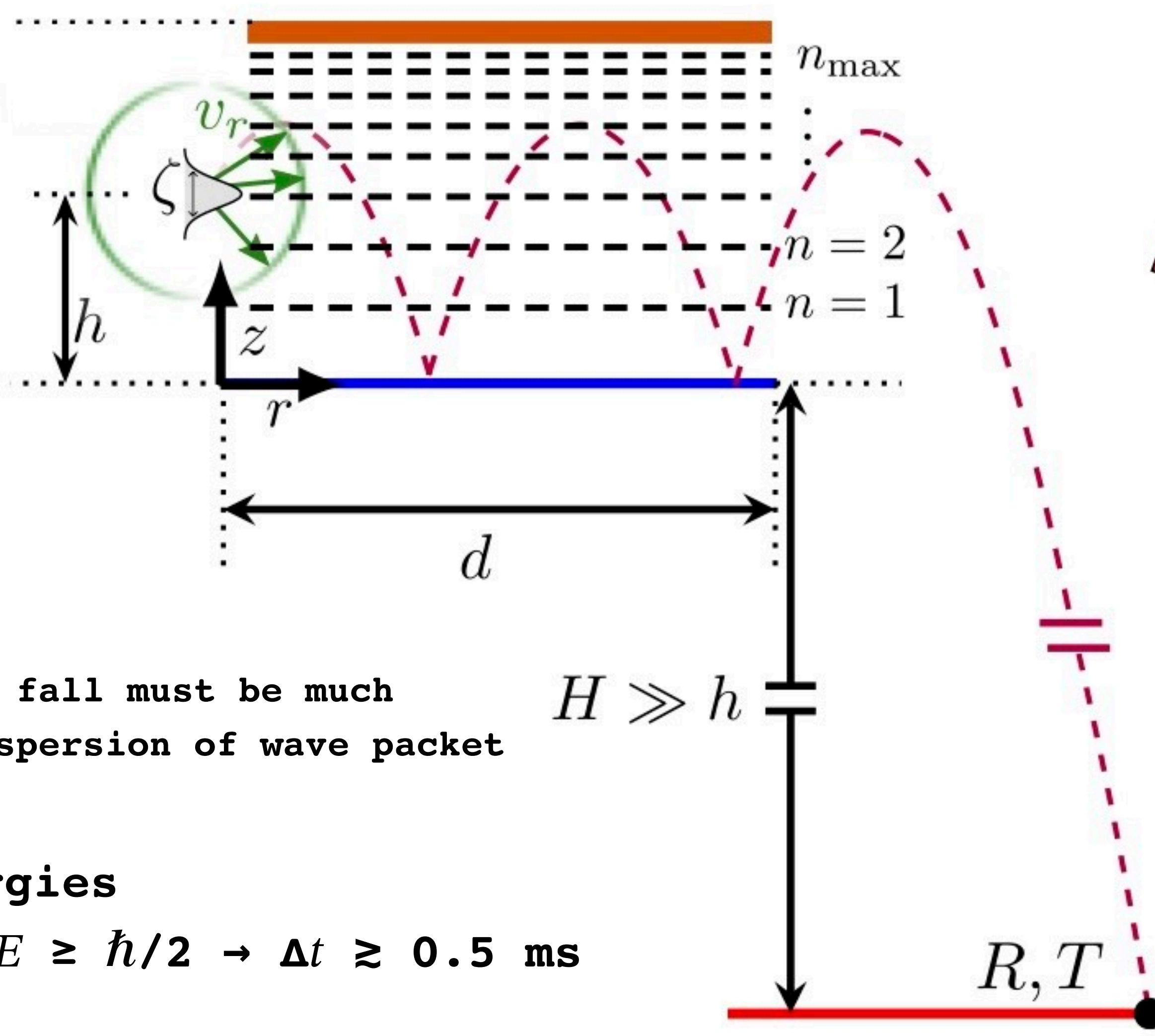
Long term outlook - Gravitational quantum states of Antihydrogen

2002: First demonstration of GQS with ultra cold neutrons V. Nesvizhevsky et al., Quantum states of neutrons in the Earth's gravitational field, Nature 415, 297–299 (2002)

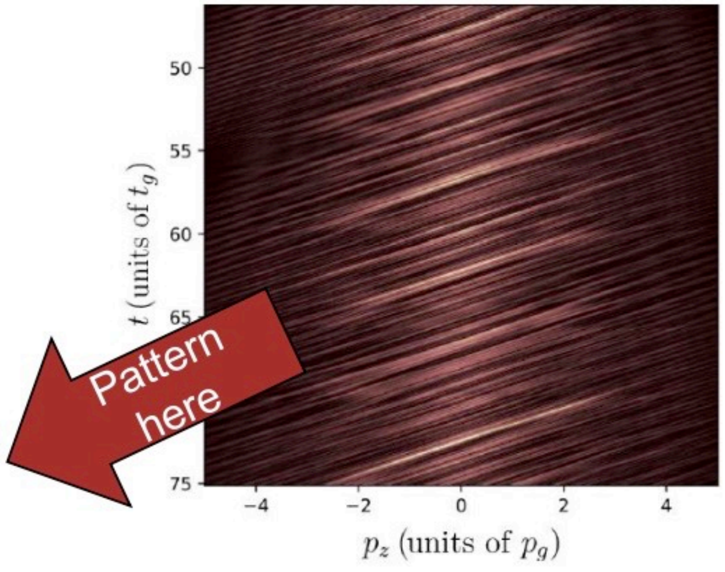
Parabolas: classical motion with rebounds above polished surface
Dashed horizontal lines: paths through different quantum states interfering in the detection pattern

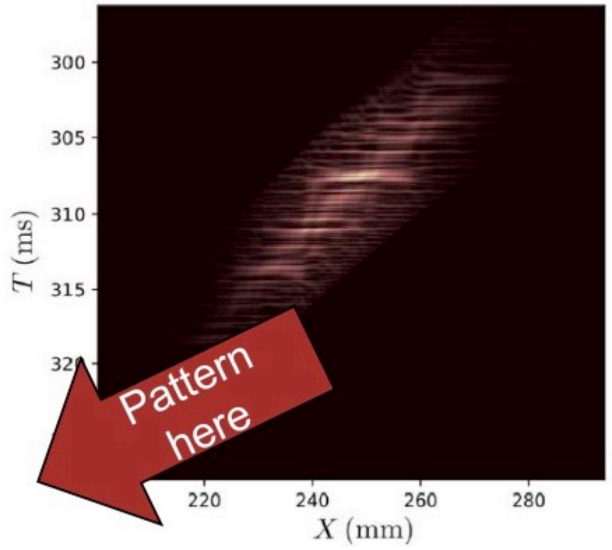
$v_r = 1\,\mathrm{m\,s^{-1}}$

$\Delta v = 0.1\,\mathrm{m\,s^{-1}}$



Height of free fall must be much larger than dispersion of wave packet





Expected precision

$$\frac{\Delta\bar{g}}{\bar{g}} \sim 10^{-5}$$

Eigenenergies

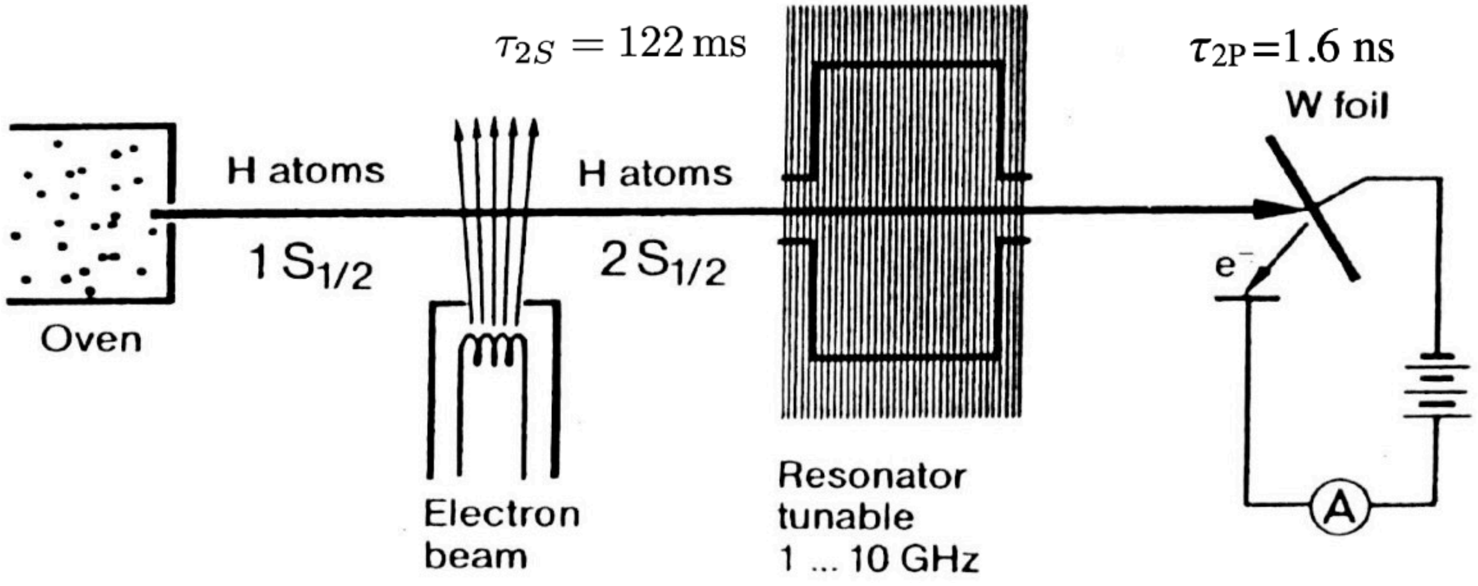
~peV $\Delta t \Delta E \geq \hbar/2 \rightarrow \Delta t \geq 0.5$ ms

Crépin et al., Phys. Rev. A 99, 042119 (2019)
J. Guyomard et al., arXiv:2505.04771 (2025)

GRASIAN: cold H and D beams for a first demonstration of gravitational quantum states of atoms Eur. Phys.J.D (2024)78:132 ETH zürich **participation**

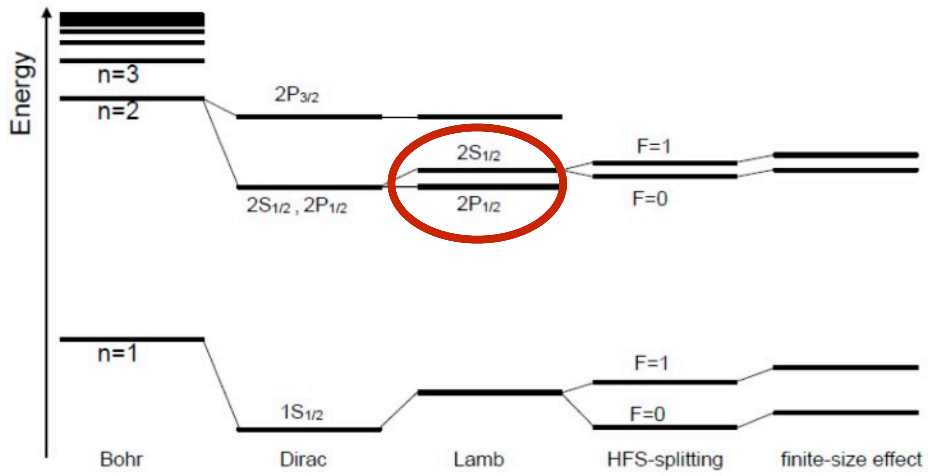
The $2S_{1/2}$->$2P_{1/2}$ Lamb Shift @ a Hydrogen beam
- the birth of QED -

Measuring surviving 2S states in the H beam



Lamb, W. E., and R. C. Retherford, "Fine structure of the hydrogen atom by a microwave method," Phys. Rev. 72, 241 (1947).

Upward shift of S state



QED: energy difference between the $2S_{1/2}$ and $2P_{1/2}$ states:

- quantum fluct. (self E) + 1086 MHz
- vacuum polarization – 27 MHz
- reduced mass and finite charge size 1 MHz

Best theoretical and experimental values for the $2S_{1/2}$– $2P_{1/2}$ energy difference:

1057.833 (4) MHz Eides, Grotch, Shelyuto, Physics Reports, 342, 63–261 2001
1057.845 (3) MHz Lundeen and Pipkin, Phys. Rev. Lett. 46, 232 1981

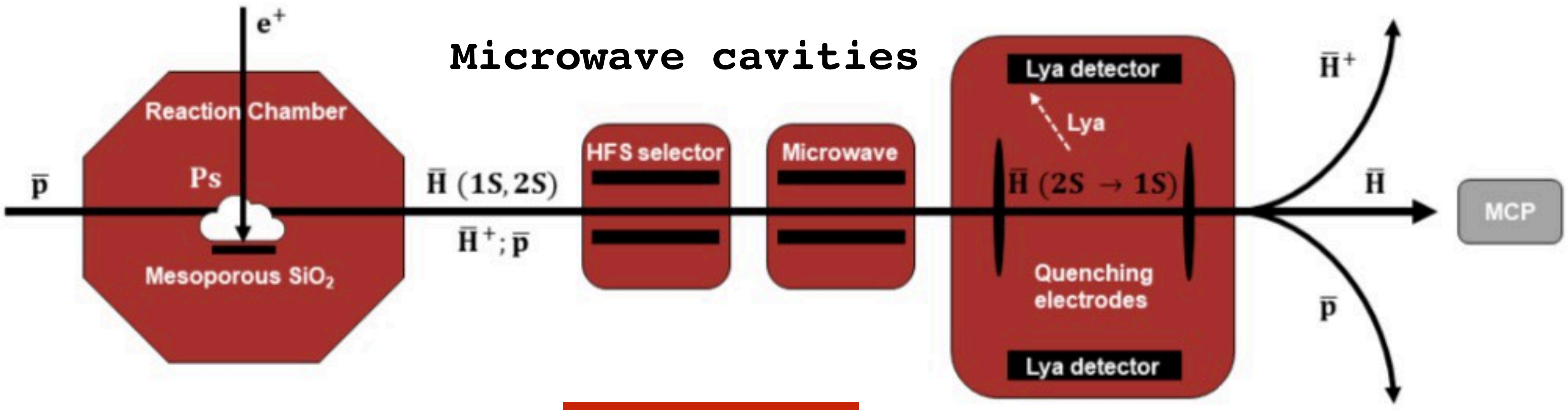
Nobel Prizes:
Willis Lamb, 1955 Nobel Prize in Physics "Discoveries concerning the structure of the hydrogen spectrum."
Richard Feynman, Julian Schwinger and Sin-Itiro Tomonaga, 1965 Nobel Prize in Physics "fundamental work in QED, with deep-ploughing consequences for the physics of fundamental particles."

$\bar{H}$ $2S_{1/2}$->$2P_{1/2}$ Lamb Shift measurement in GBAR - symbiotic to $\bar{H}^+$ production

Measuring surviving 2S states in the $\bar{H}$ beam

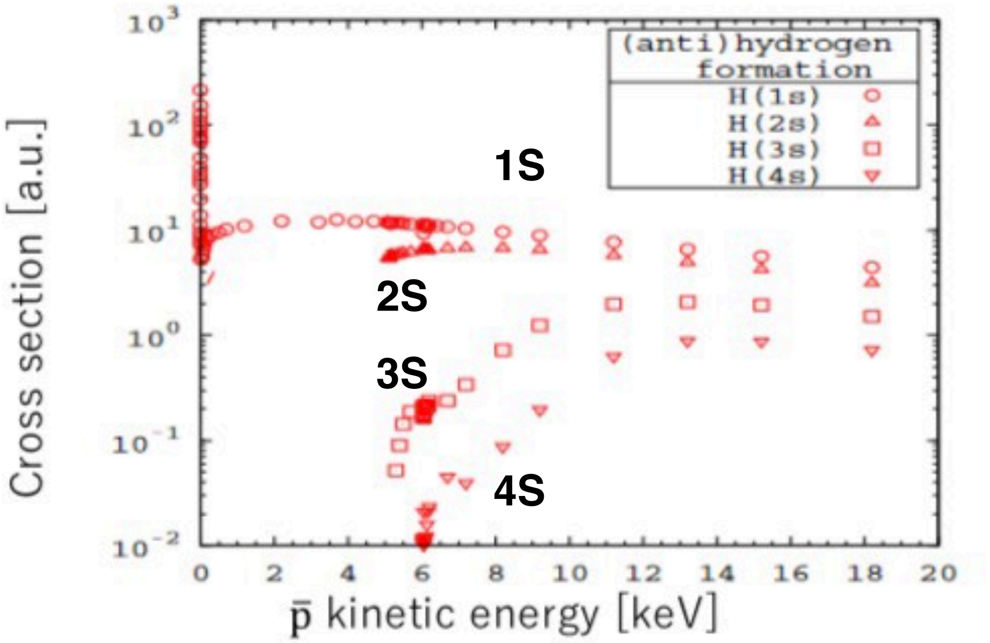
direct CPT test

P. Crivelli, D. Cooke, M. Heiss, Phys. Rev. D 94, 052008 (2016)



Microwave cavities

B-field ~0

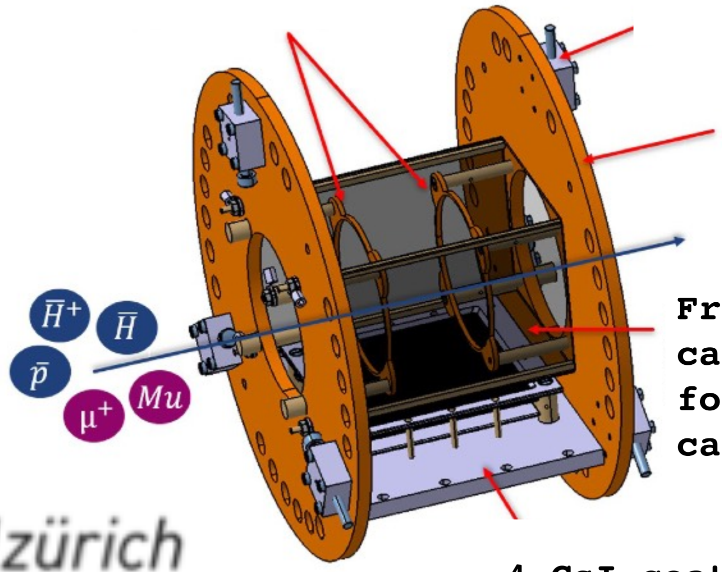


Rawlings et al. PRA 93, 012709 (2016)

At 6 keV

$$\frac{\sigma 2S}{\sigma tot} = 16\%$$

Lya detector - CsI-coated MCPs



E-field quencher
2 rings ~500V/cm

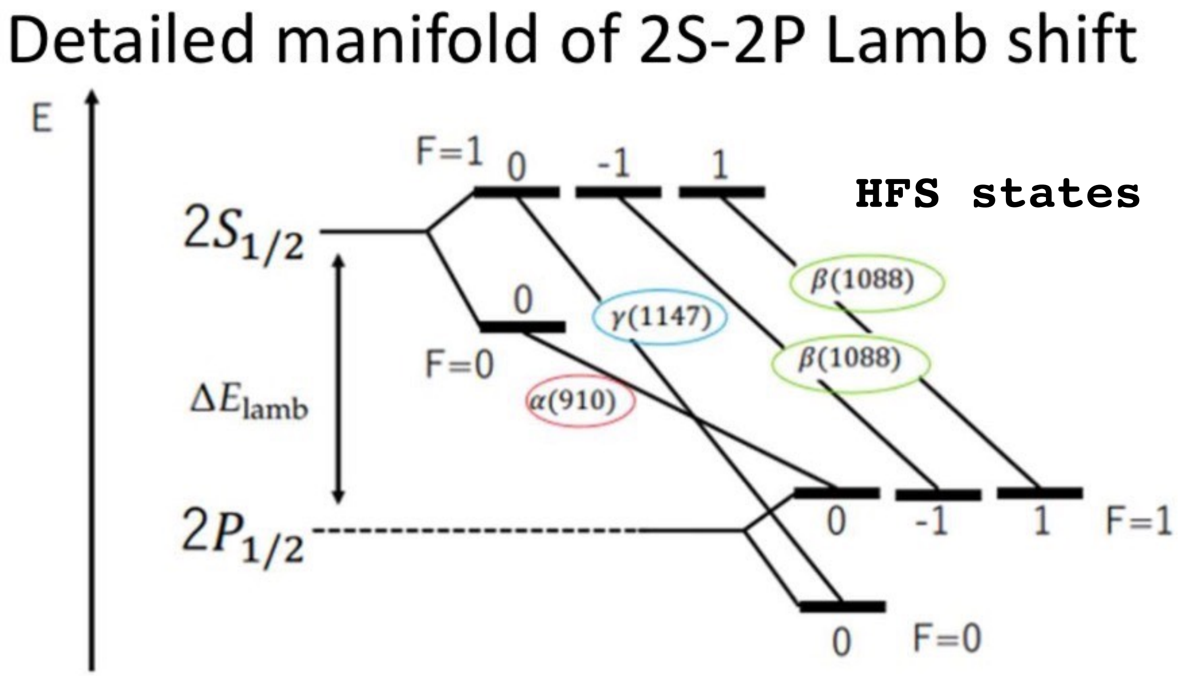
Grids (for shielding and repulsing electrons)

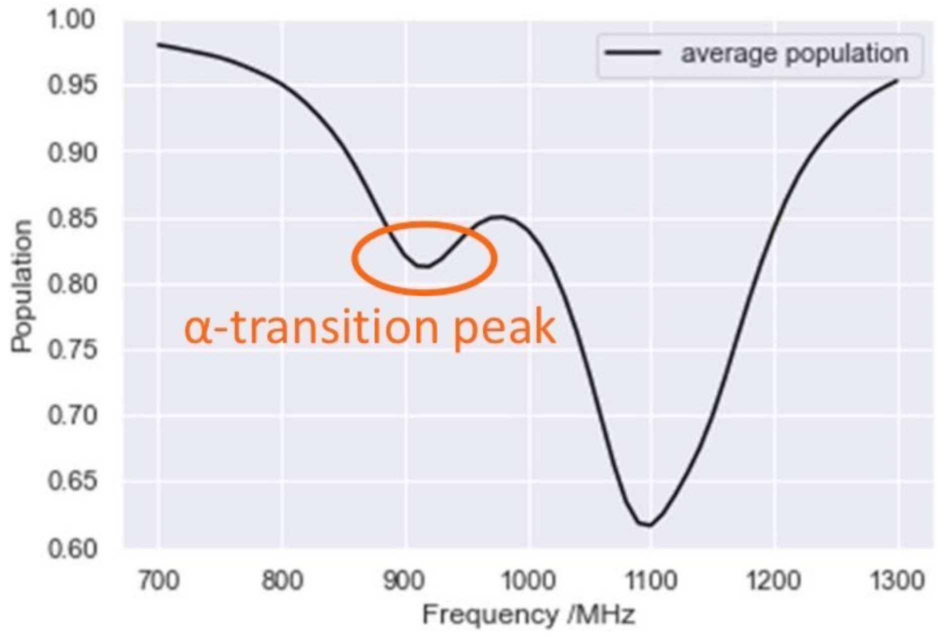
beam

Front side of MCPs can be polarised for photo electron capture

4 CsI coated large area square MCPs

$2S_{1/2}$->$2P_{1/2}$ Lamb shift for the H atom





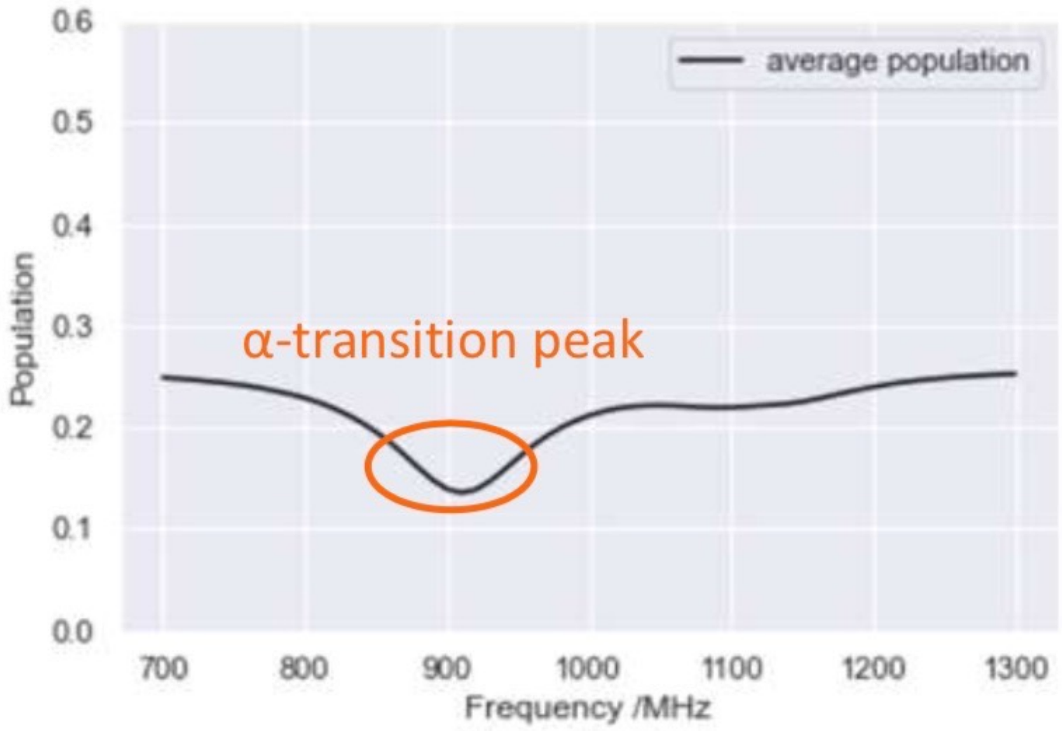
100 ppm spectroscopy (100kHz) is needed to measure the (anti)-proton charge radius to 10%

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

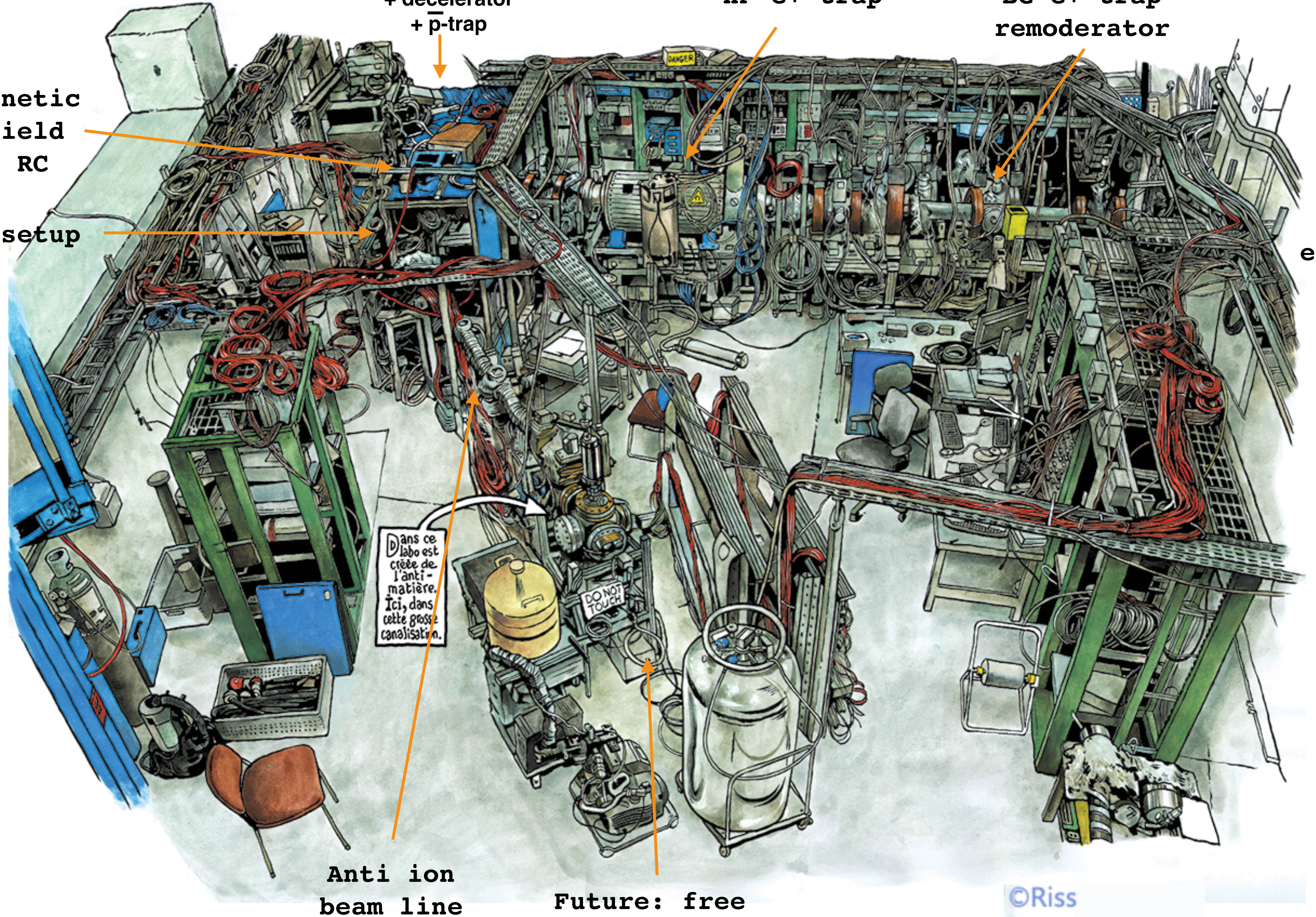
- **Nominally ~1058 MHz (nat. line width ~100Mhz)**
- **First measurement by fitting the full spectrum**
- **Higher energy lines can be quenched away in a HFS selector (1100MHz, ~10W)**
- **This kills about 5/6 of 2S states**
- **Measurement of the single 910MHz Line usually used for highest accuracy**

advanced technique - needs large number of events

Lundeen and Pipkin 1970-1994



Experimental setup - GBAR overview



$\bar{p}$ from ELENA
+ decelerator
+ $\bar{p}$-trap

HF e+ trap

BG e+ trap
remoderator

Magnetic
shield
+ RC

LS setup

e+ from
LINAC

Anti ion
beam line

Future: free
fall chamber

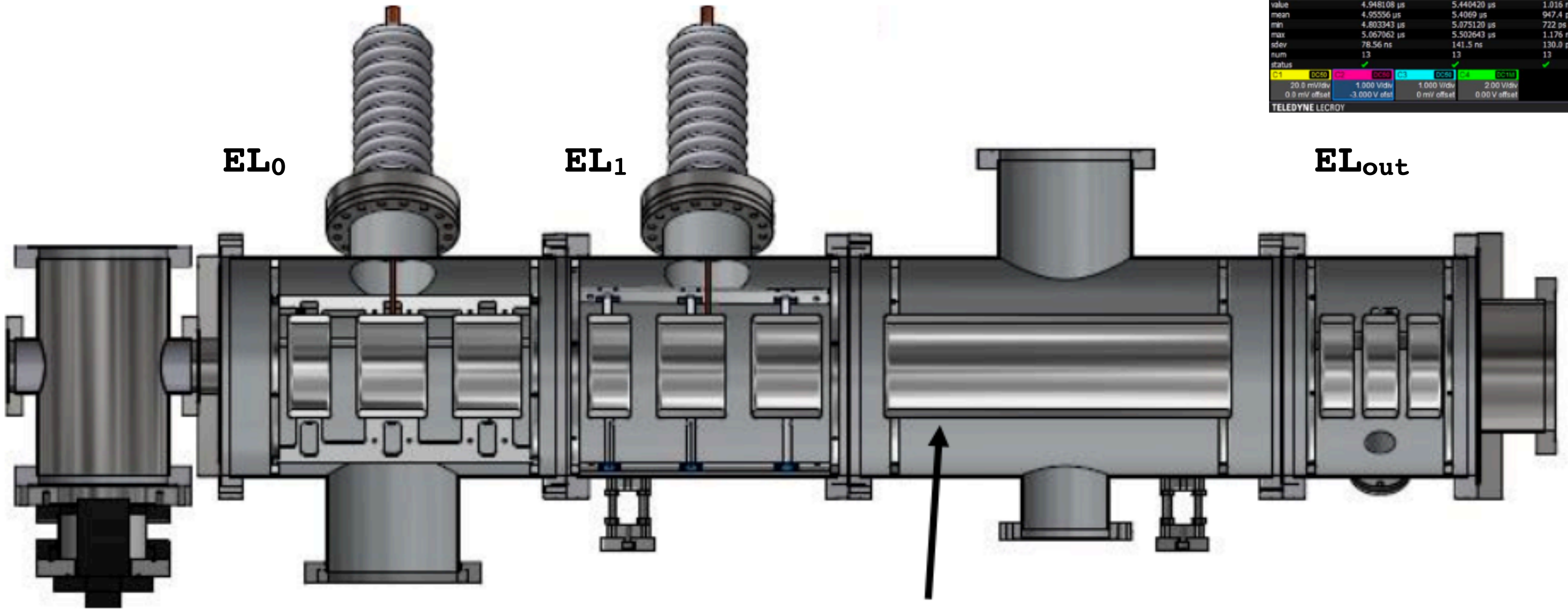
©Riss
©Charlie Hebdo

The HV decelerator

ELENA parameters
Emittance 2..3mm*mrad
~8e6 antiprotons per bunch (2min)
Bunch length (bunch rotation) ~40ns(σ) = 15cm
100keV dp/p ~200eV
Extraction time jitter <5ns(σ)

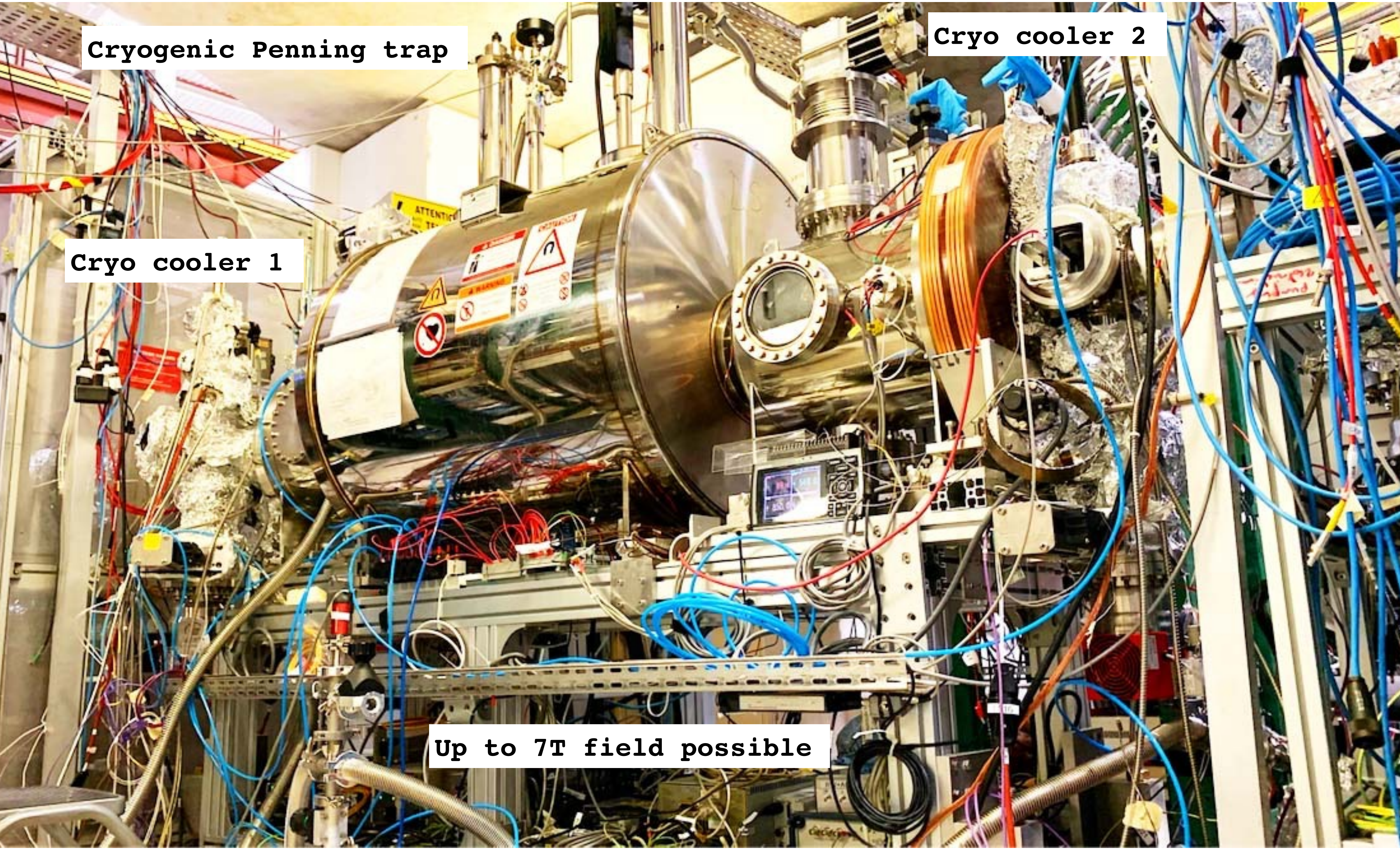
signal example

Measure	P1:delay(C1)	P2:delay(C2)	P3:delay(C3)	P4:width(C1)	P5:widn(C2)	P6:- - -
value	4.948108 µs	5.440420 µs	1.016 ns	59.236 ns	---	
mean	4.95556 µs	5.4069 µs	947.4 ps	32.41 ns	324.840 ns	
min	4.803343 µs	5.075120 µs	722 ps	9.000 ns	324.840 ns	
max	5.067062 µs	5.502643 µs	1.176 ns	59.236 ns	324.840 ns	
sdev	78.56 ns	141.5 ns	130.0 ps	14.16 ns	---	
num	13	13	13	141	1	
status	✓	✓	✓	✗	✗	



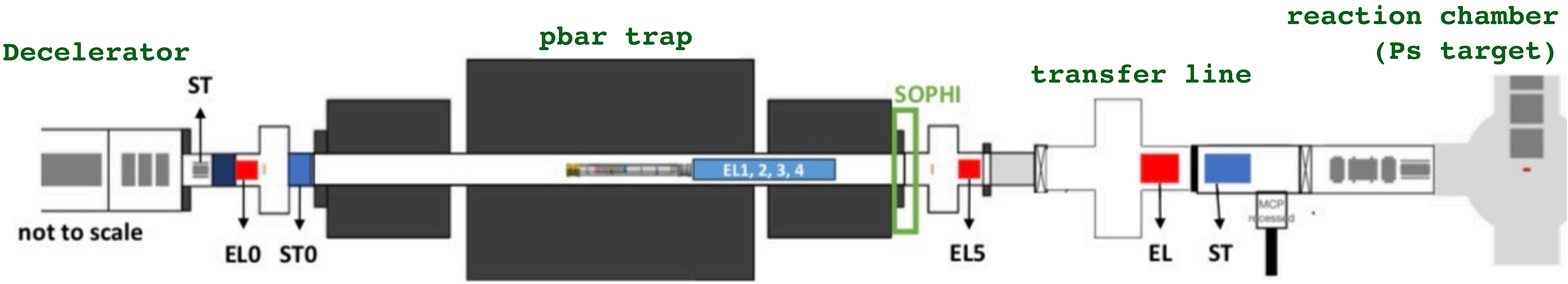
- typically 8M $\bar{p}$ with 100keV from ELENA every 2min
- practically 100% efficient - reducing only longitudinal momentum
- typical emittance 2…3mm*mrad - increasing by a factor ~4 at output
- Deceleration by a pulsed drift tube: switch HV → 0 while particles are inside
  ex: switch from 94kV to 0kV will decelerate the beam from 100keV to 6keV

Antiproton trap - installed autumn 2023

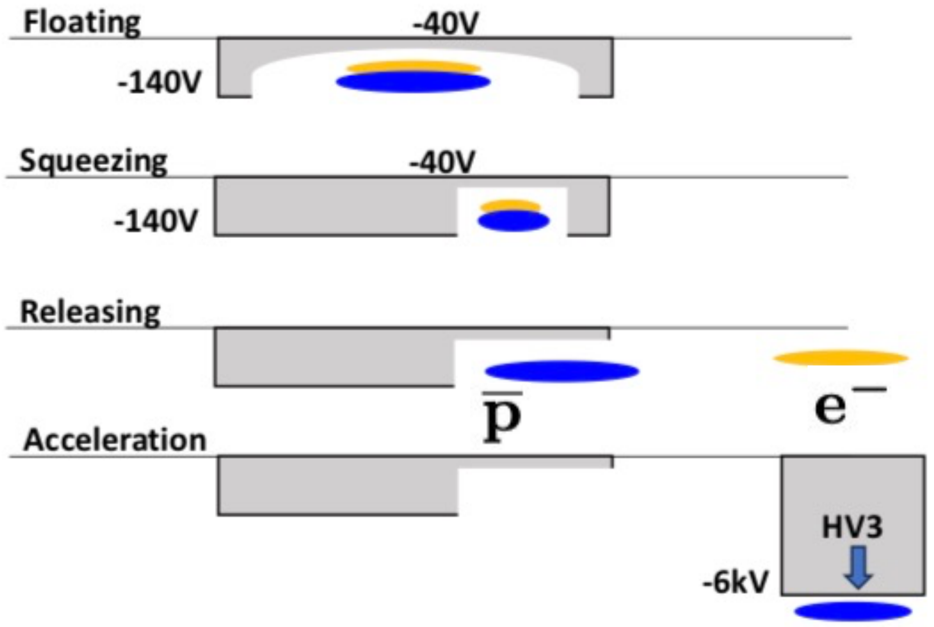


$\bar{p}$ multi-ring penning trap (5T)

Electron cooling of $\bar{p}$ (incl rotating wall)



Cooling principle



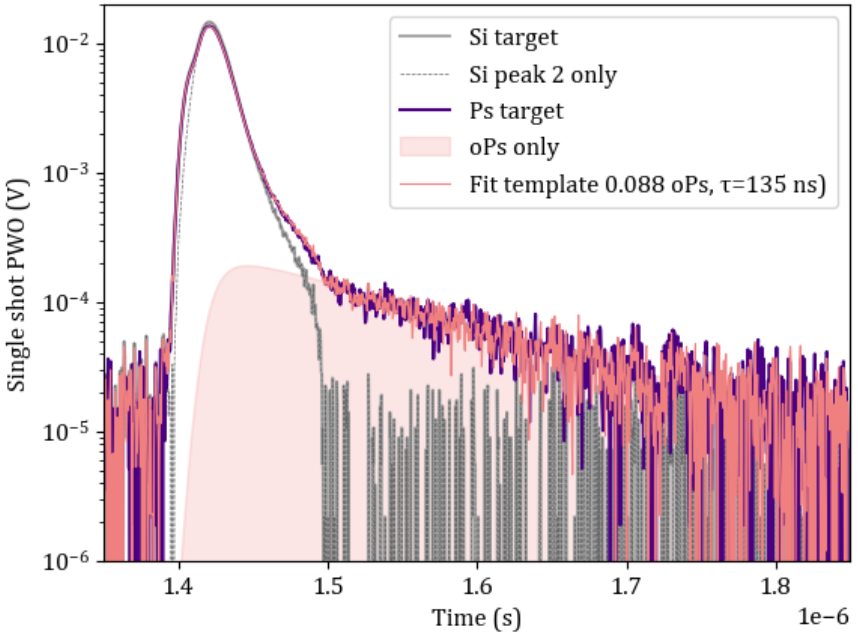
- Successfully commissioned on a fast pace
- Allows to capture and cool ps (by electrons)
- Trapping efficiency is >80% (extracted/injected)
- Antiproton life time >4000s
- Cooled $\bar{p}$ can be extracted, however beam divergence increases during extraction from high field region
- Electron kick out system under study
- Optimisations ongoing (capture, extraction, HV pulsing system, B field strength)

$\bar{H}$ production setup:
~5×10^6 $\bar{p}$ routinely extracted – 10^6 $\bar{p}$ reach the cavity

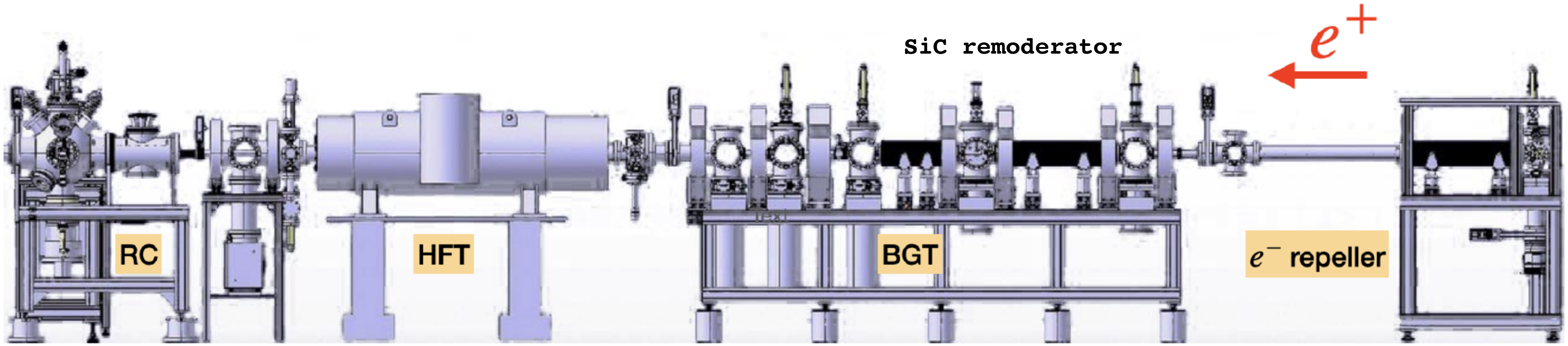
LINAC – e^+ beam line – oPs production

- LINAC: 9 MeV e- water-cooled tungsten target
- > 7×10^9 e^+ accumulated in HFT in about 30 minutes
- > 6×10^8 e^+ std collected in 2min
- main challenge: transport -> target
- space-charge effects – plasma size
- SIMION / COMSOL (magn. field maps) simulations ongoing
- target cavity (2×1.5×20mm3 with 30 nm Si3N4 window)
- 3 inner walls are laid out with nanoporous silica

SSPALS analysis from PWO xtal



$\bar{H}$ production setup:
From 3×10^8 e^+ ejected 6×10^6 oPs produced
in the cavity (SSPALS monitoring)

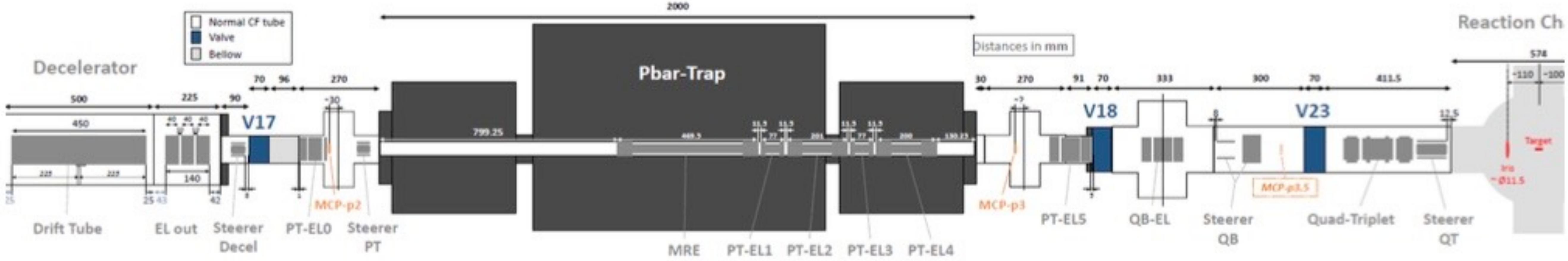


HFT: 5T Penning trap, stacking of e+ pulses from BGT (125ms), Plasma compression by rotating wall, ejection @ 500eV + acceleration to 4 keV

Pbar beam line – SIMION simulations + steering

SIMION: ion optics simulations calculating ion trajectories by applied E-fields

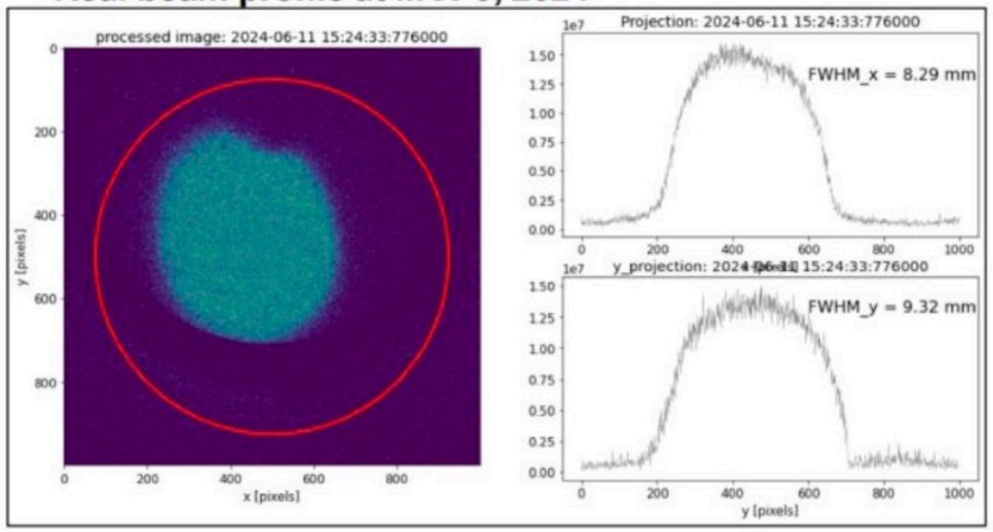
Principal problem: extraction from cold particles outside the high magnetic field regions

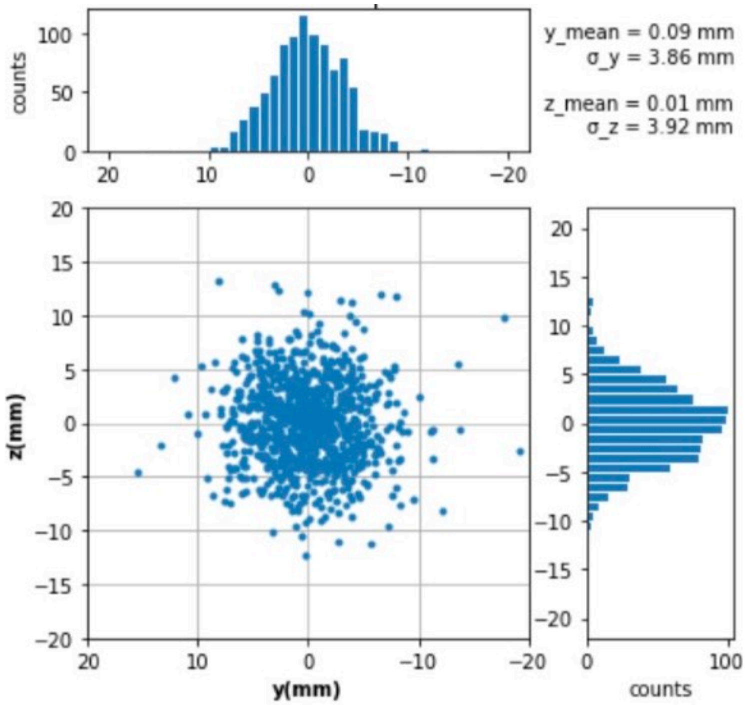


Particle simulators

- **Beam from ELENA with known emittance generated at the entrance of the GBAR $\bar{p}$ line**
- **WARP simulation extracted particles generated at the exit of the $\bar{p}$ trap (crucial)**

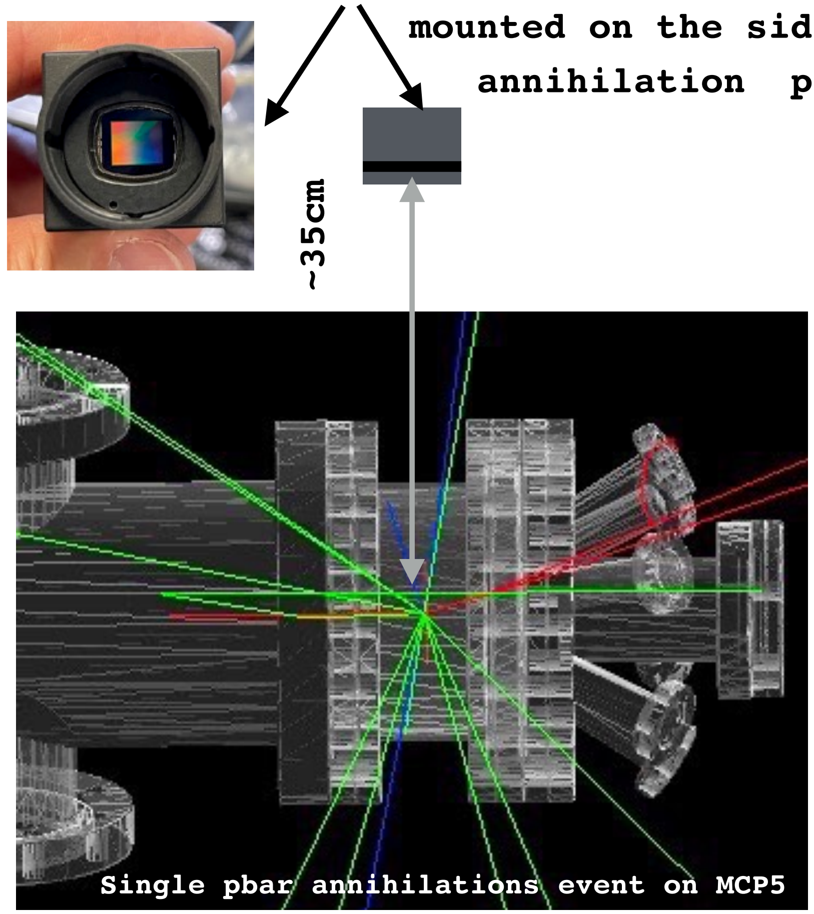
Real beam profile at MCP3, 2024





$\bar{p}$ numbers from particle tracks in a CMOS sensor

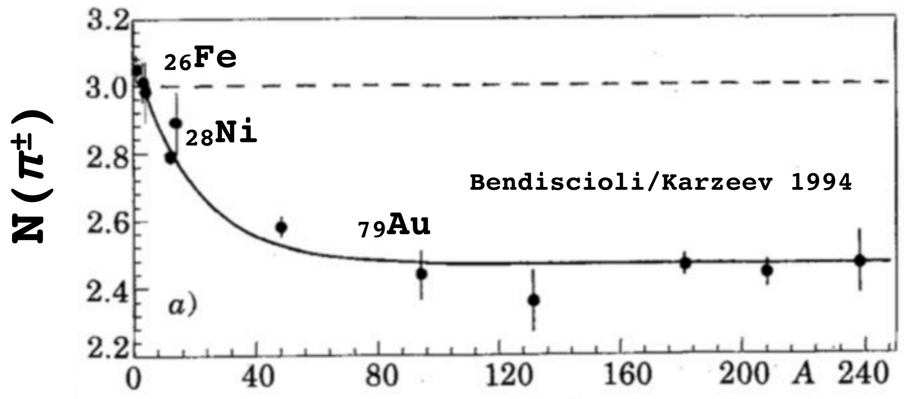
Baumer VCXG-51M CMOS camera without lens mounted on the side of annihilation point



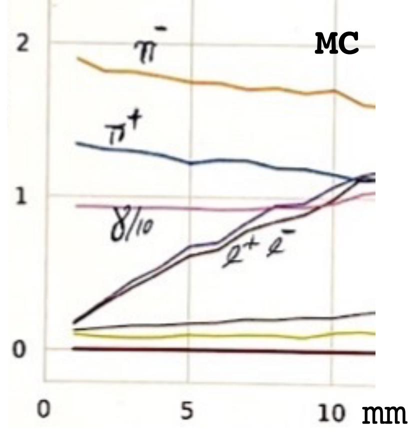
$\bar{p}$ number determination

- High granular (5M pixel), highly efficient tracking detector
- Small depletion volume, low Z - insensitive to γ rays
- 10^7 annihilating pbars yield typ. 500 hits (area ~0.5cm²)

2.5 … 3 pion tracks / pbar



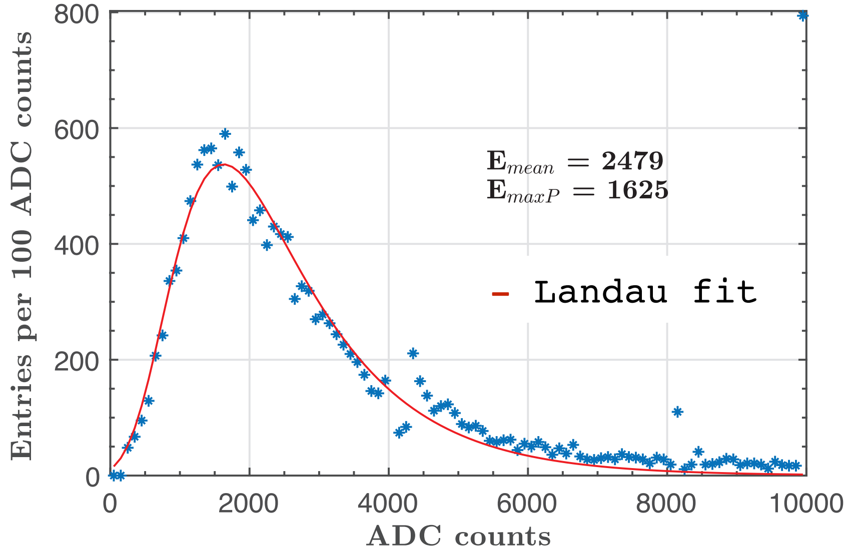
absorption - pair prod. in stainless steel



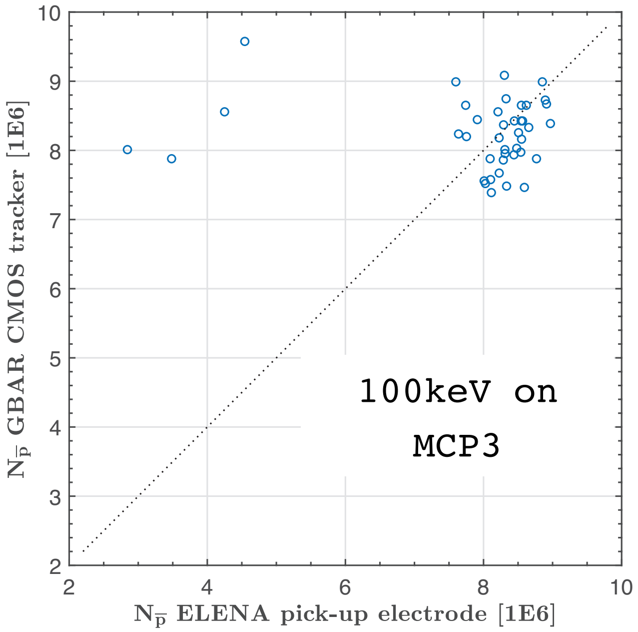
~10% error on $\bar{p}$ number from combined reference measurements and extensive GEANT4 simulations

Results:

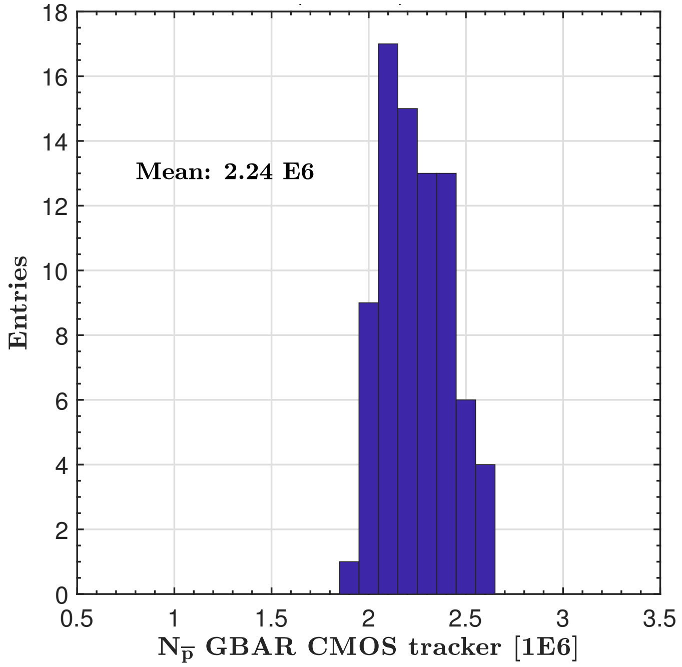
Energy deposit in CMOS



Comparison with ELENA

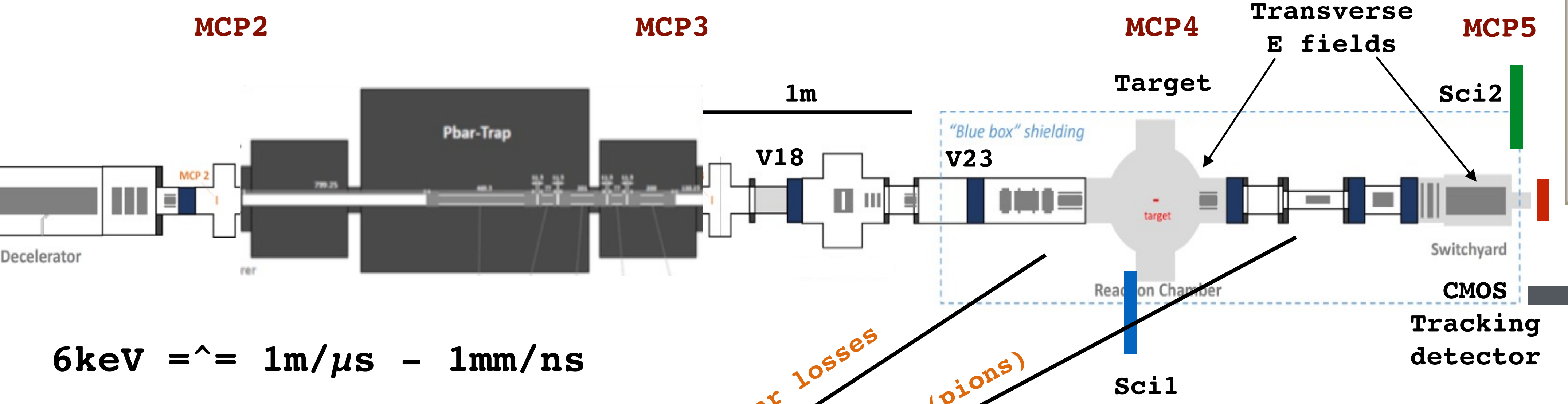


6keV $\bar{p}$ on MCP5 (Passthrough)

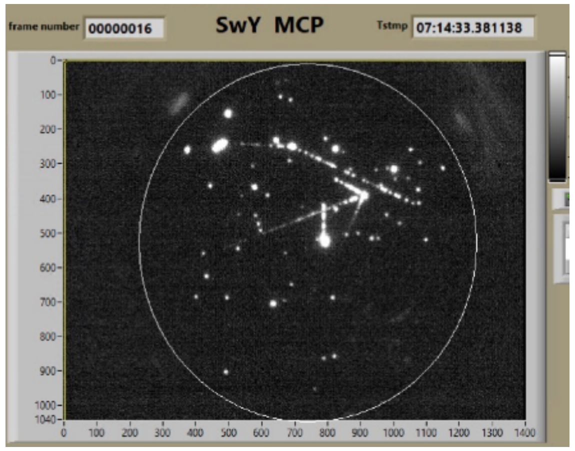


$\bar{H}$ production/detection – pion BG tomography

MCPs: Main imaging particle detectors
read out electric signal and image



example for mixed p and pion signals

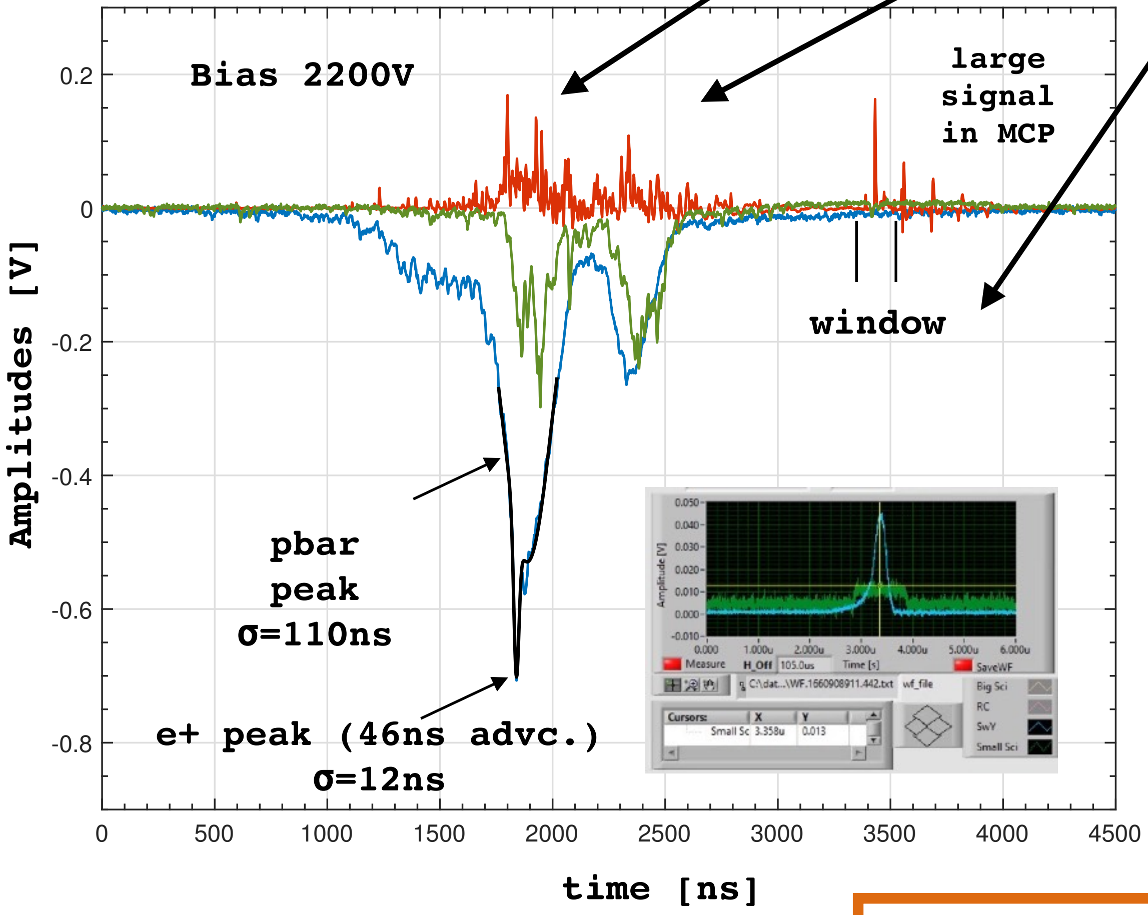


6keV =^= 1m/μs - 1mm/ns

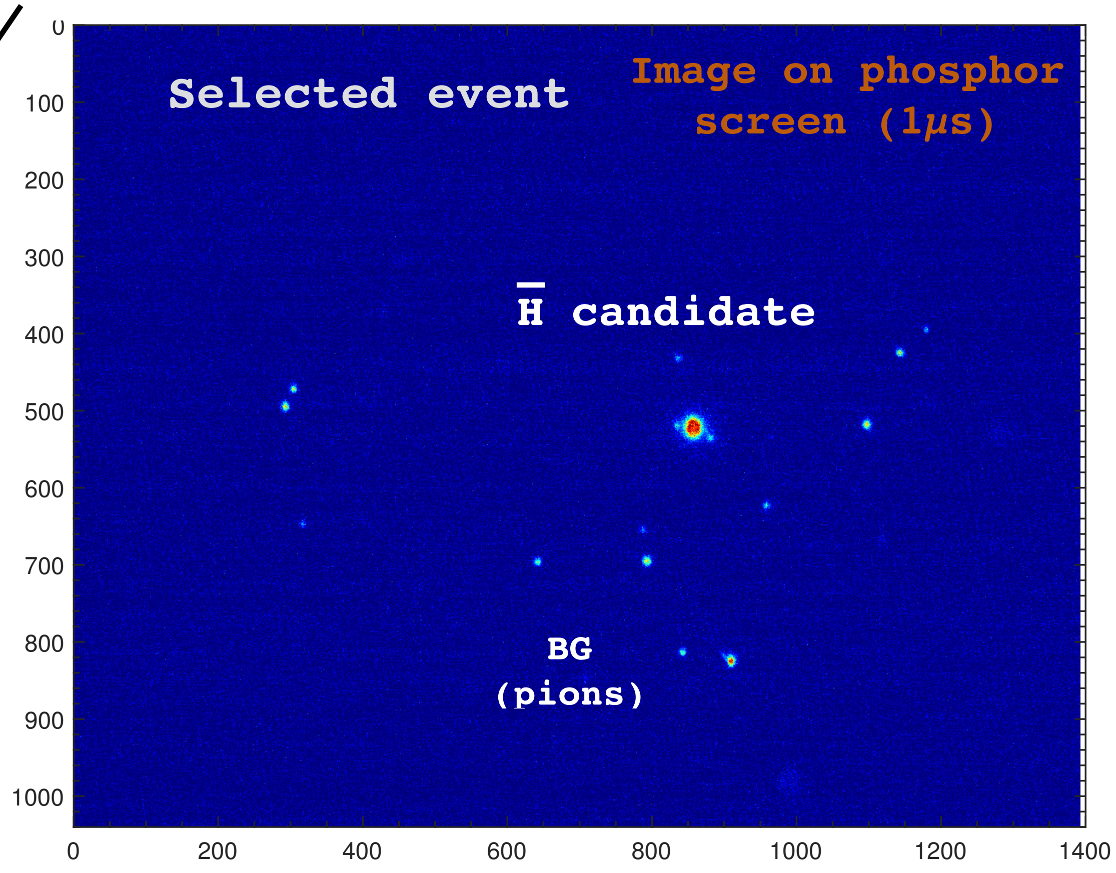
pbar losses

BG (pions)

MCP electric signal + scintillators



Signal time window rather well separated from BG

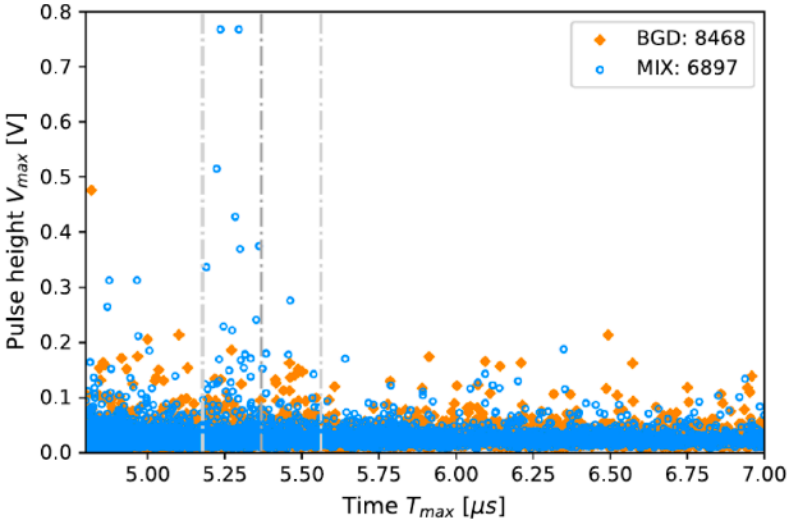


Lyα photon can be detected in coincidence with Hbar

$\bar{H}$ production factor 26 improvement towards 2022

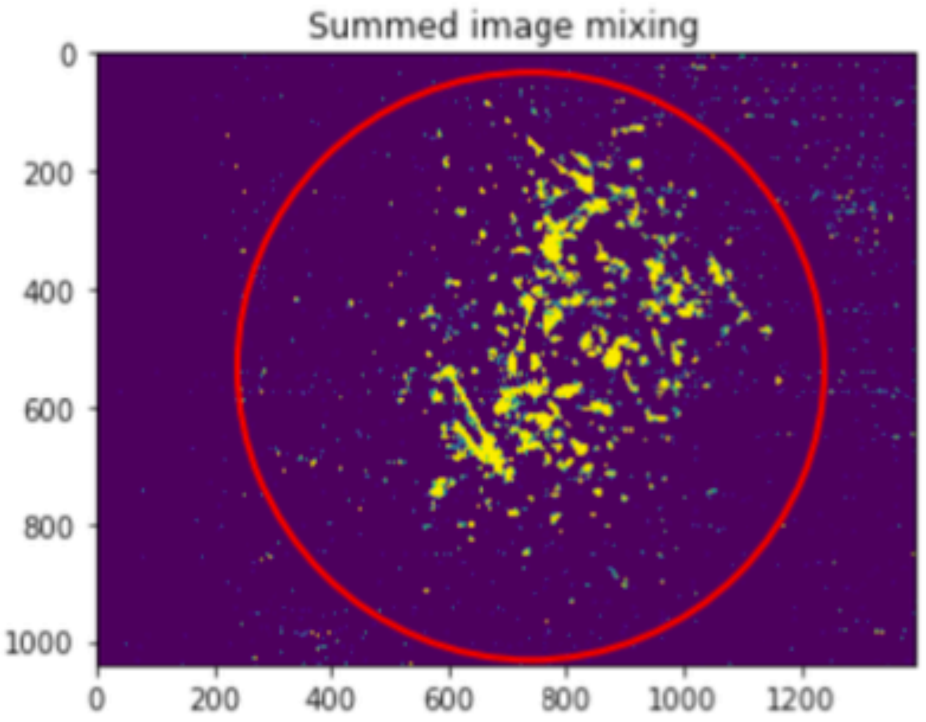
Data sets: $\bar{p}$ with e^+ present (= mixing) $\bar{p}$ without e^+ (= background)

GBAR 2022



19.8±6 detected Hbar candidates
→ ~0.003 per spill

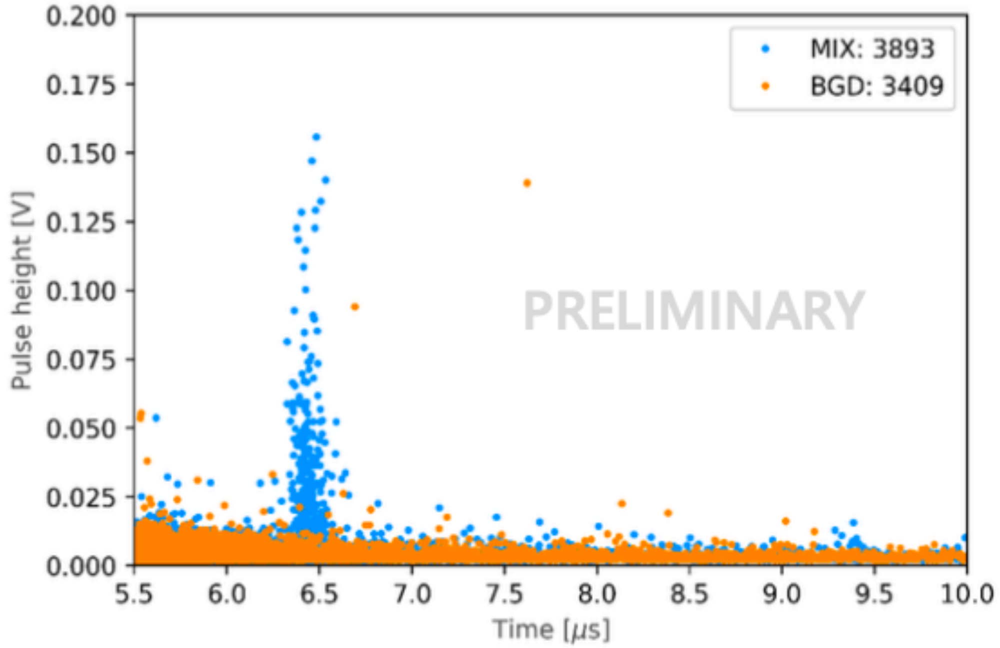
GBAR 2022 data:
Hbar production…,
P.Adrich et al. Eur.
Phys. J. C. 83, 1004
(2023)



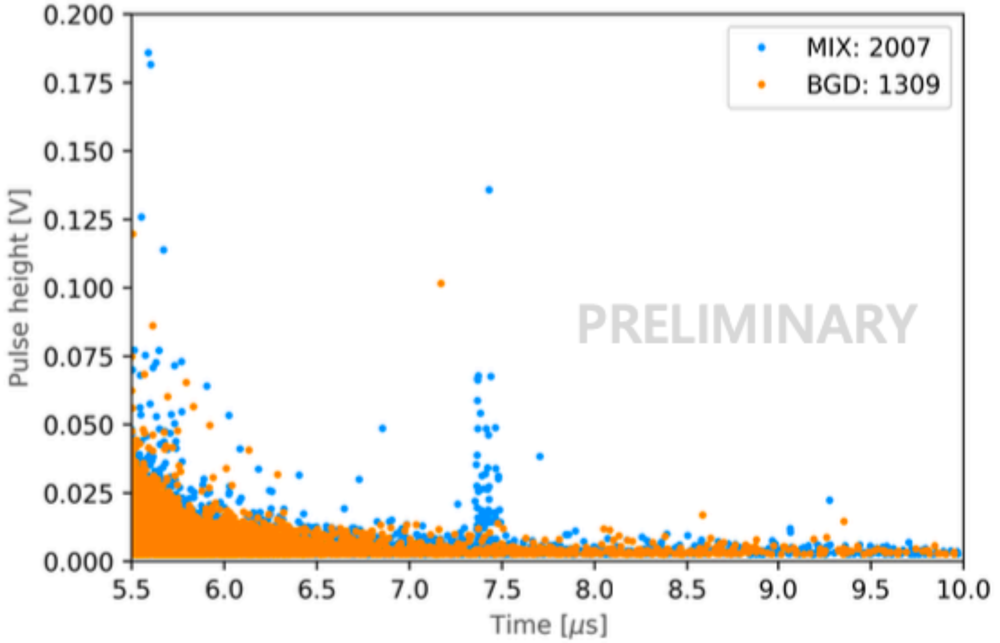
GBAR 2024

322±36 detected Hbar candidates → ~0.08 per spill

6 keV: 322 ± 36
antihydrogen candidates



4 keV: 69 ± 17 antihydrogen
candidates

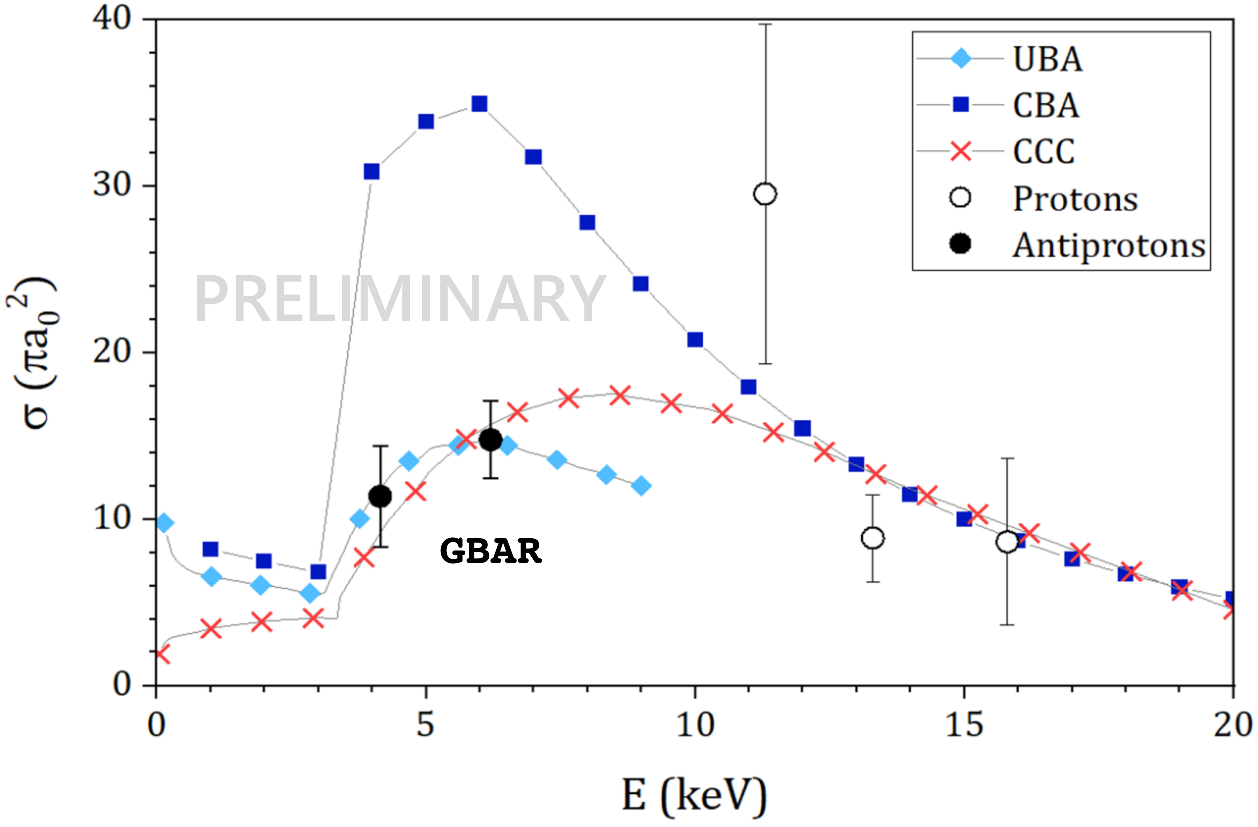


Antihydrogen production – cross section

Latest results were presented at ICPEAC and POSMOL in summer 2025 (also PSI2025) – to be published soon

- **Latest HW upgrades promising**
- **$\overline{\mathrm{H}}$ number significantly increased**
- **Cross section can be derived**
- **More precise determination as for the proton experiment in 1997**
- **Further rate improvements possible**
- **Next big milestone will be to see a Lya photon from $\overline{\mathrm{H}}$ atoms**

GBAR 2025



Theory:
UBA(Univ. Born Approx.): J. Mitroy, PRA 52, 2859 (1995)
CBA(Coulomb-Born Approx.): K. Lévêque-Simon et al. PRA 107, 052813 (2023)
CCC(Convergent Close Coupling): A. S. Kadyrov et al., PRL 114, 183201 (2015)

Proton experiment (1997):
J. P. Merrison et al., Phys. Rev. Lett., 78, 2728 (1997)

Preparation of the Lamb shift detection system for 2026: p,H$^-$ beams, C-foil, MW chamber and Lyα detector

- Metastable 2S states produced by collisions with Ps(or C-foil)
- Induce 2S-2P transitions by MW or Stark mixing (survival experiment)
- Detect Lyα photons from rapid 2P decays

H- beam from ELENA can be used for testing

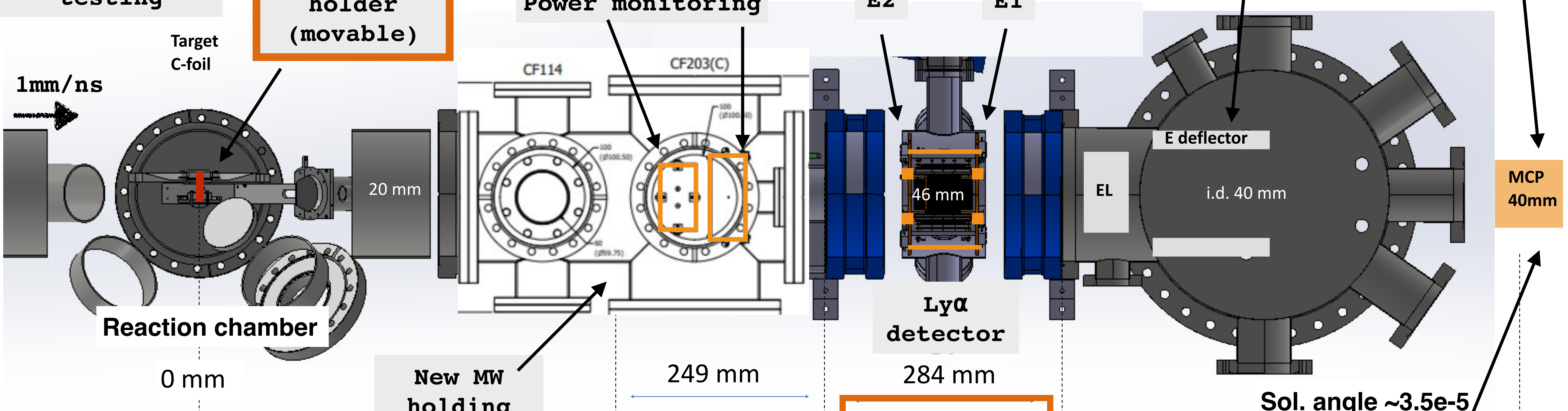
C-foil on target holder (movable)

HFS and MW scanner (2 frequencies 30mm bore) Power monitoring

E-field quencher (2 rings) ~500V/cm

SwY field (deflect charged part.)

MCP5
Detect particles (neutrals, charged)

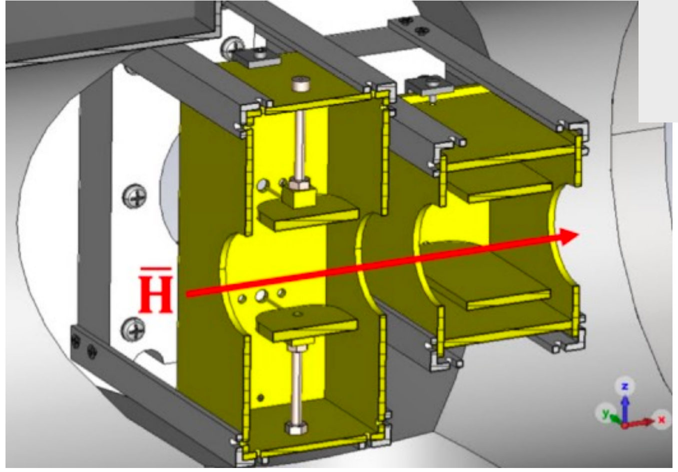


Lyα detector

New MW holding vessel (2023)

Total Eff. ~ 16%

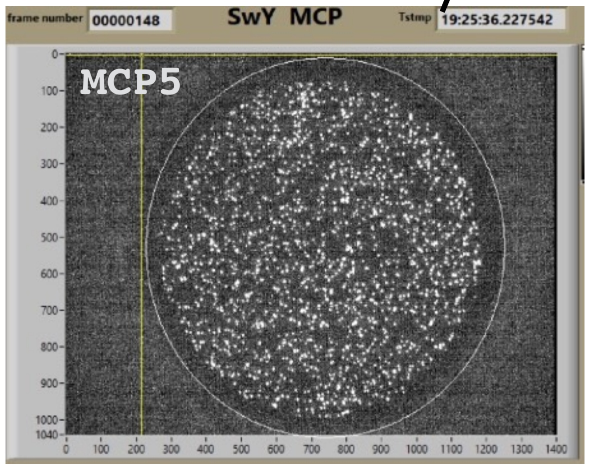
Sol. angle ~3.5e-5



3x MW 10W power amplifier

6keV speed: 1µs/m

>500 neutrals from C-foil


frame number 00000148 SwY MCP Tstmp 19:25:36.227542

Lyα detector system – CsI coated MCPs

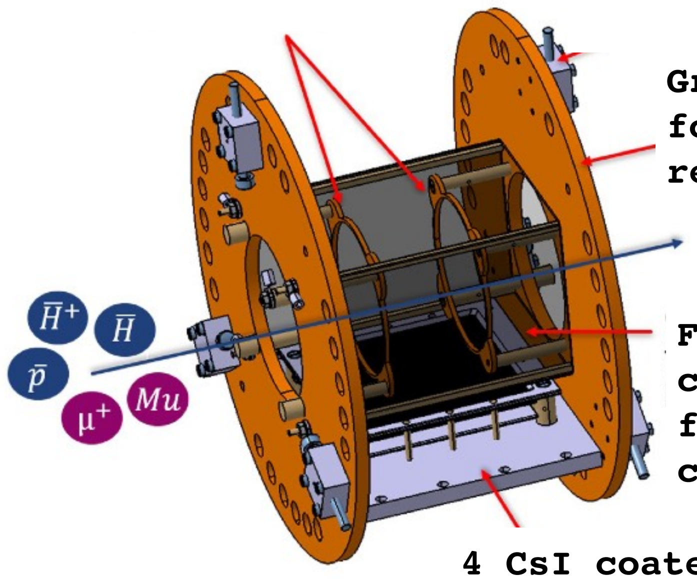
- Good QE can be achieved
- Fast response of detection system
- Signal gating possible

4 CsI coated Microchannel plates (MCP) detect LyA photons

- Detection efficiency: $\varepsilon_{\mathrm{LyA}} \times \varepsilon_{\mathrm{Geo/Qnch}} = 16\%$
- $\varepsilon_{\mathrm{LyA}} = \varepsilon_{\mathrm{MCP}} \times \varepsilon_{\mathrm{QE}} = 40\%$ Measurement ETH

$\varepsilon_{\mathrm{Geo/Qnch}} = 40\%$ SIMION/Geant 4 simulation
validated with H and M results at PSI

Total Eff. ~16%



E-field quencher
2 rings ~500V/cm

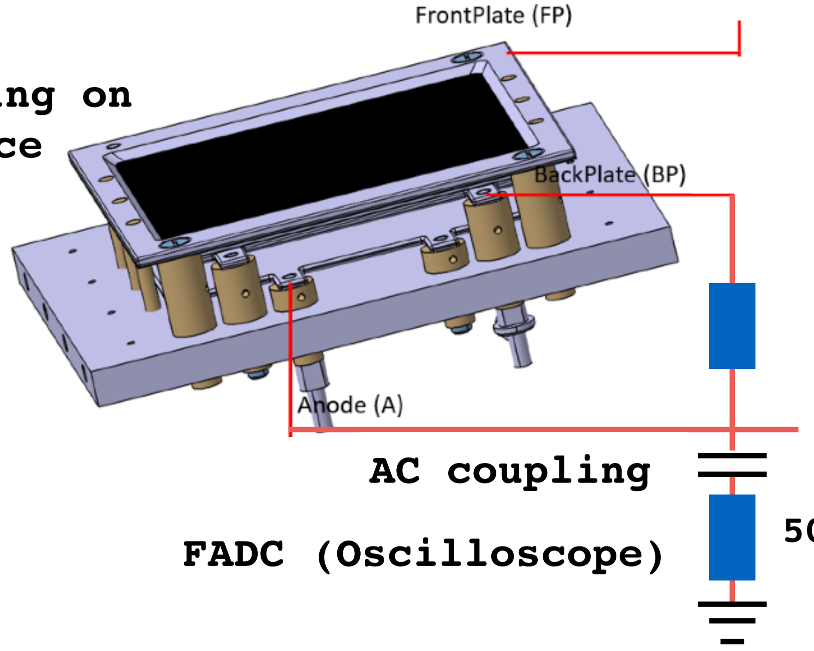
Grids (92% transp. for shiel-ding and repulsing electrons)

Beam

Front side of MCPs can be polarised for photo electron capture

4 CsI coated large area square MCPs (50 x 50 mm²)

MCP unit (4x)



CsI coating on surface

Front bias
+50V

Main bias
-2200V

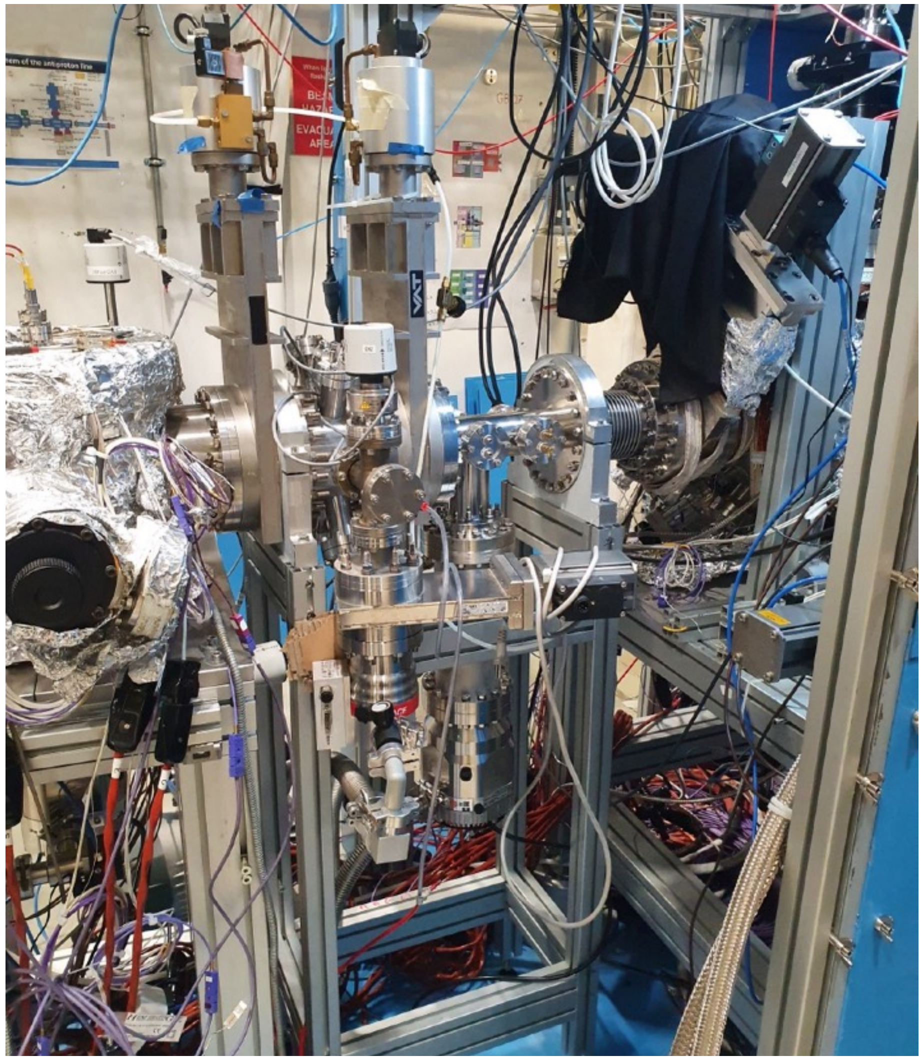
AC coupling

50Ω

FADC (Oscilloscope)

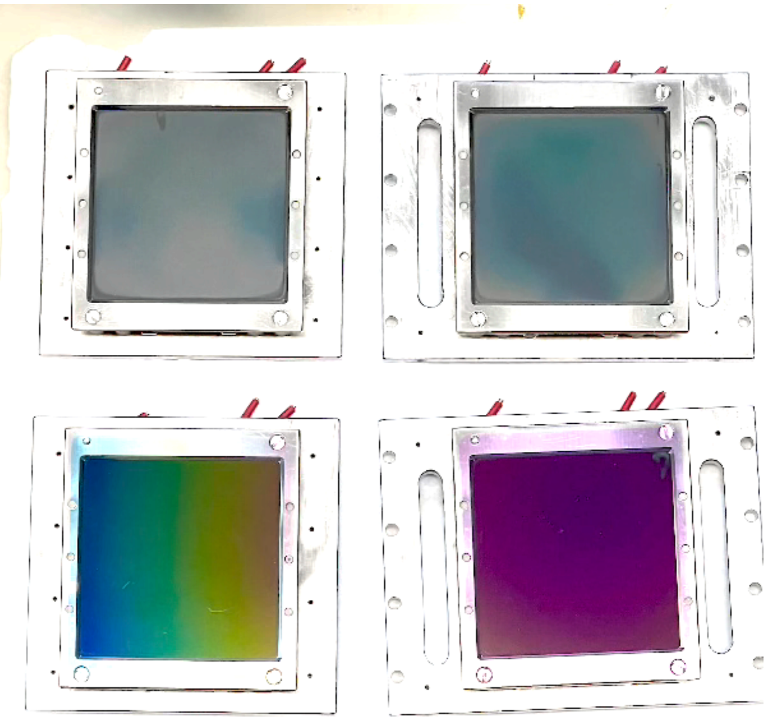
Signal

Placement in GBAR

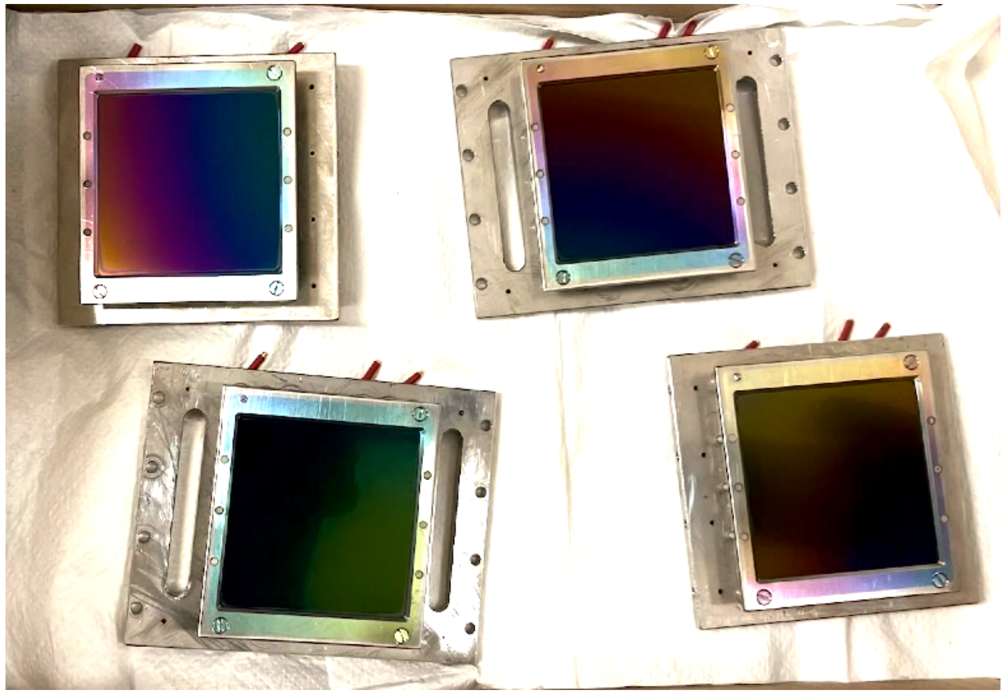


Recent refurbishment of CsI coated MCPs in CERN surface WS

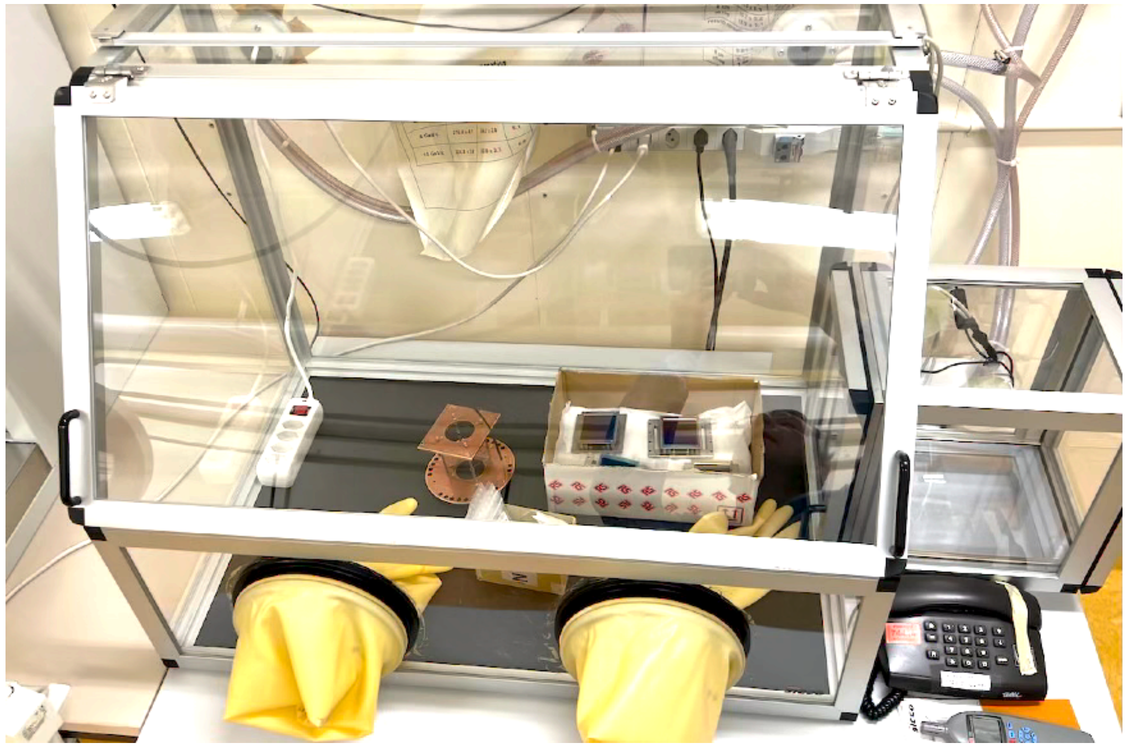
- **CsI coatings are ageing**



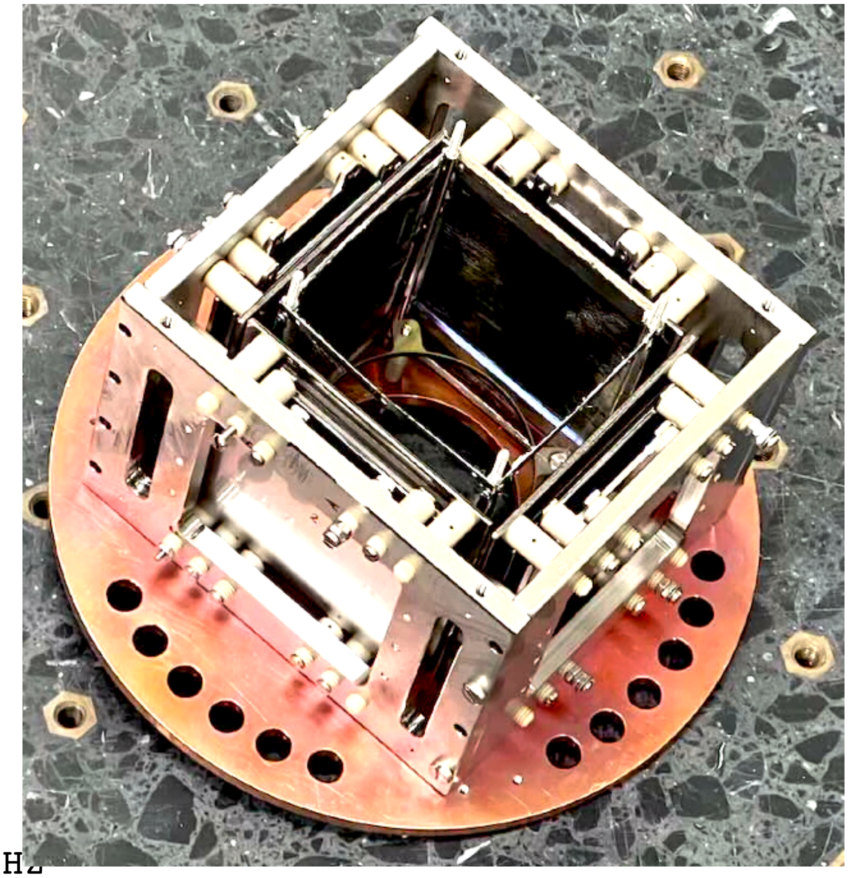
- **4 freshly coated MCPs (March 2026)**



- **minimal exposure to air during mounting process**



- **final assembly**



Recent installation of ~250nm UV LEDs for determination of PH spectra

VISHAY

VLMU35CR40-275-120, VLMU35CR41-275-120

www.vishay.com

Vishay Semiconductors

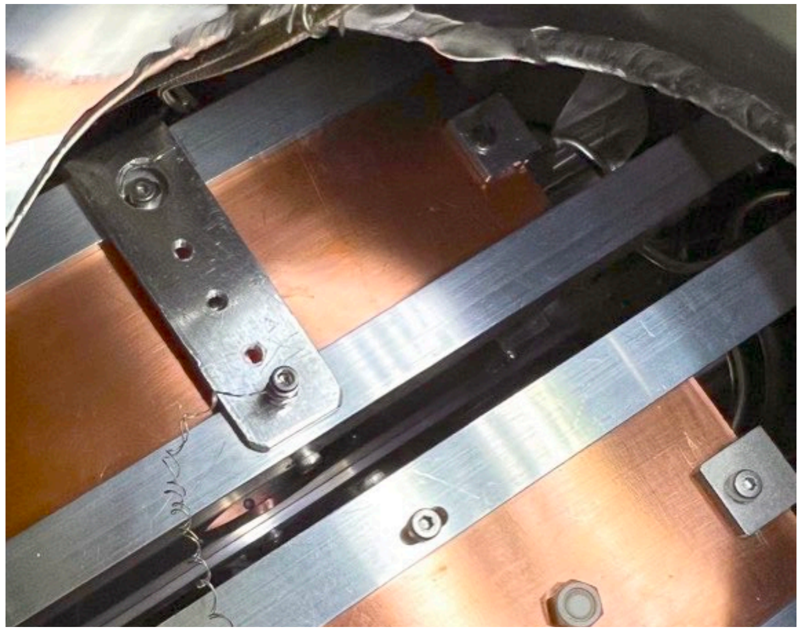
UVC Emitting Diode in SMD Package

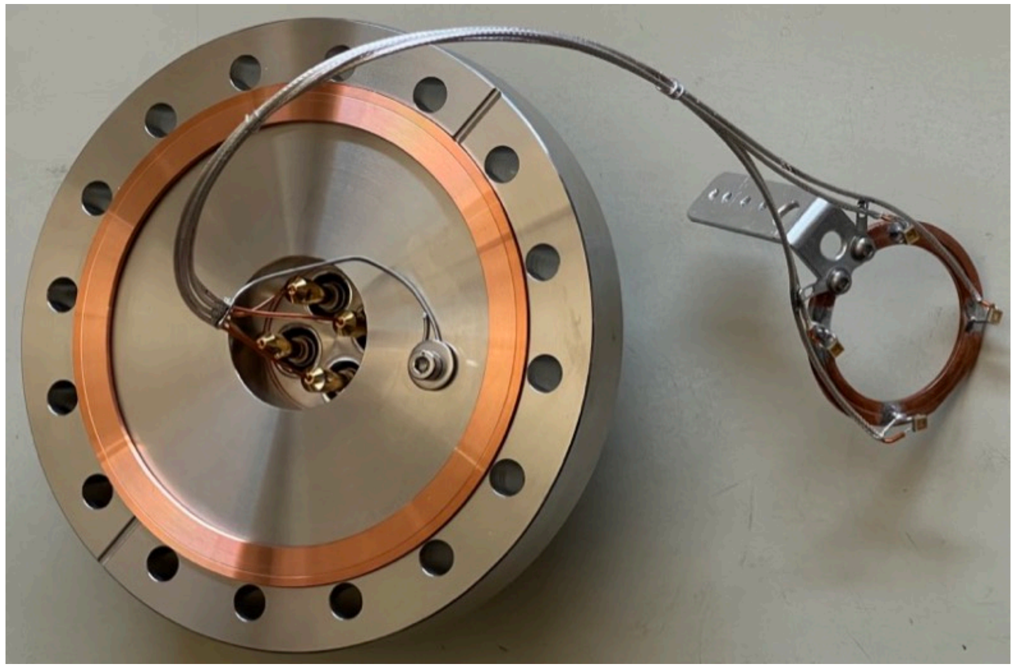
FEATURES

- Ceramic SMT package with quartz window
- Dimension (L x W x H) in mm: 3.45 x 3.45 x 1.7
- DC forward current: up to 300 mA
- Radiant power (typ.): 37 mW at 250 mA and 30 mW at 190 mA
- Leads / terminations finish: gold plated (Au)
- Reflow soldering method
- MSL 3 according to J-STD-020
- Material categorization: for definitions of

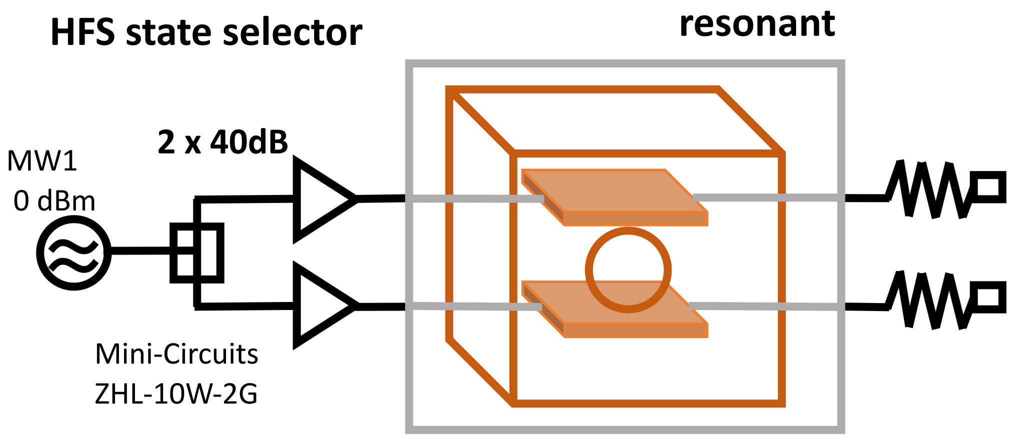
Fig. 4 - Relative Radiant Power vs. Wavelength

- Producing quite a bit of heat (if driven strongly)
- 4 LEDs mounted on heat dissipating copper ring
- Piggyback on the MW scanning cavity (exit orifice)
- prob. no direct line of sight onto MCPs

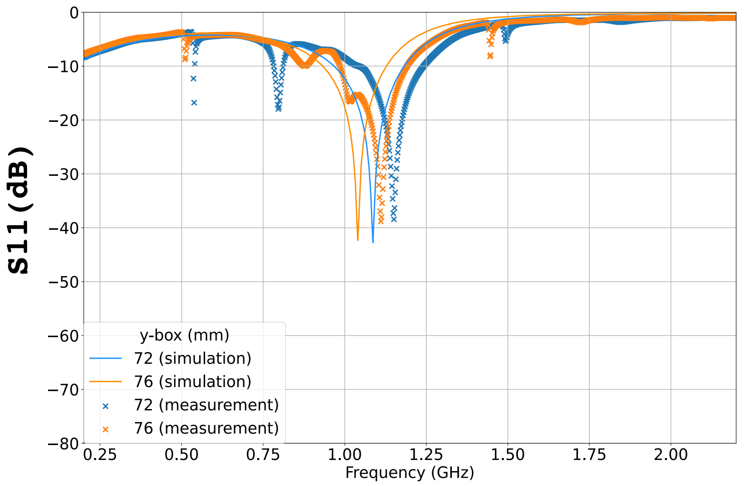




MW cavities design and calibration

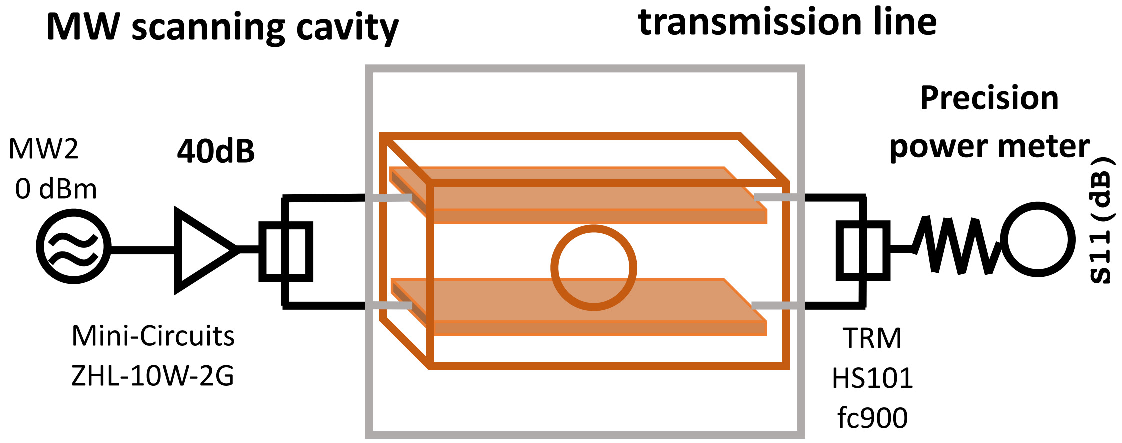


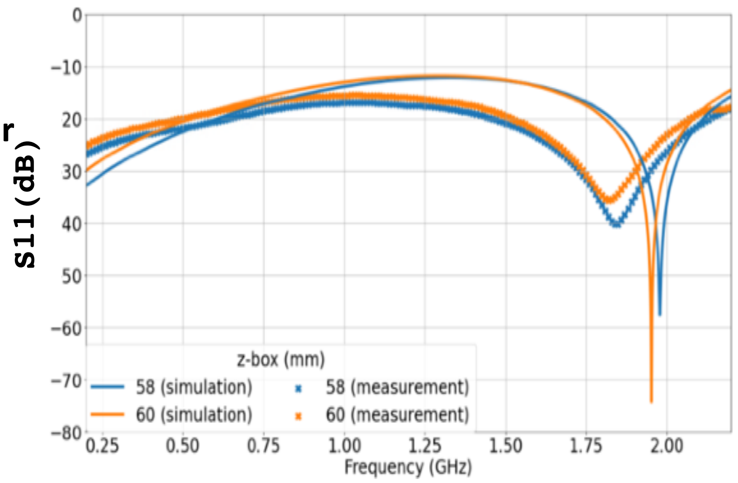
Simulations and measurements



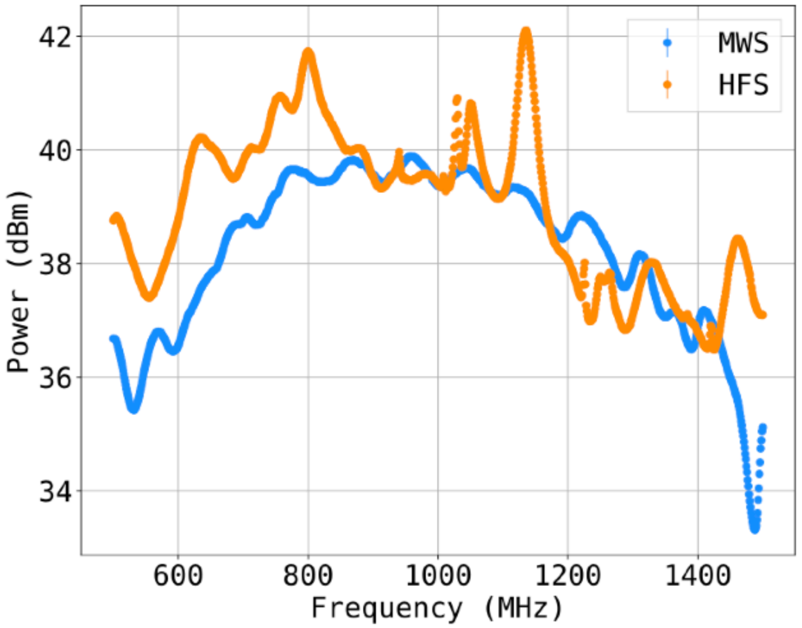
Power Meter + attenuators
Both require low loss and reflections

- **Need to know absolute average power to 10% (AC stark < 100kHz)**
- **Need to know frequency dependency to 0.5% (statistics of** few **10^4 /point)**





Typical calibration response



Measurments:
S11: Reflection (in1 to VNA out, out1 50Ω grounded ; in2/out2 50Ω grounded)
S12: Transmission (in1 to VNA out, out1 to VNA in, in2/out2 50Ω grounded)

More information can be found:

EXA-LEAP2024, Towards Lamb shift spectroscopy of Hbar atoms

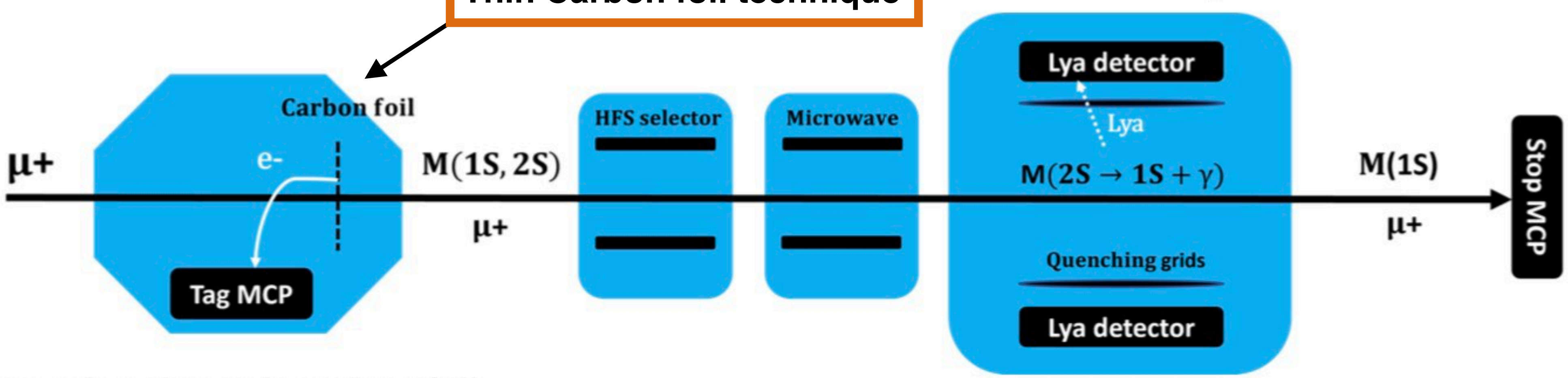
ICPEAC2025, Background measurement for the H Lamb shift spectroscopy at the GBAR experiment

by *T.A.Tanaka*, *P.Blumer*, *G.Janka*, *B.Ohayon*, *C.Regenfus*, *T.Higuchi and K.S.Tanaka*, *P.Crivelli and N.Kuroda* and GBAR collaboration

Early commissioning of the Lyα detector and MW system with Muonium & Hydrogen (2020-2021) at PSI

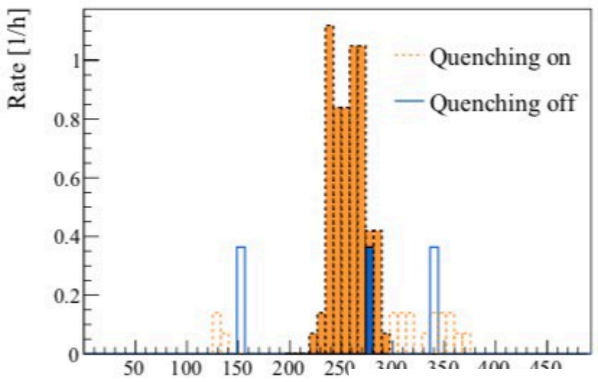
Thin Carbon foil technique

Coincidence measurement !



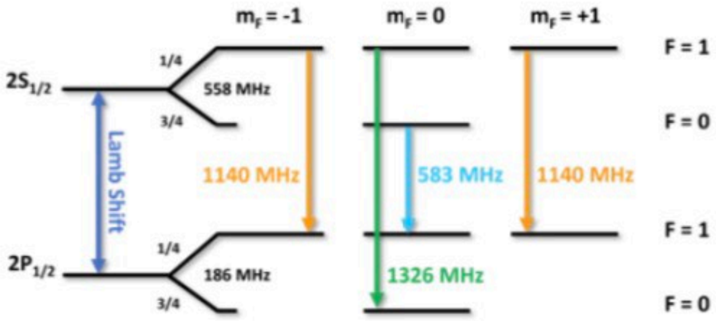
Formation through carbon foil

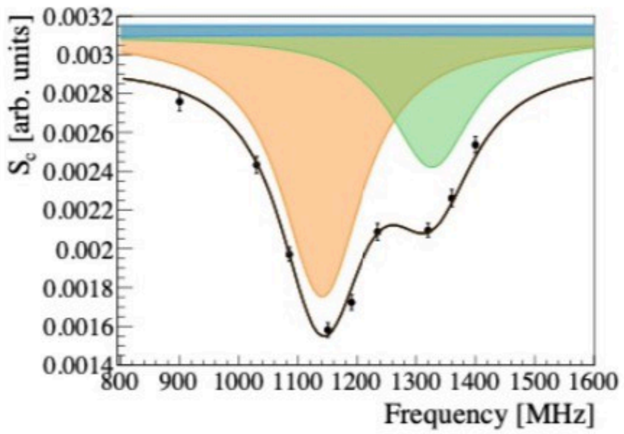
Detection of 2S states



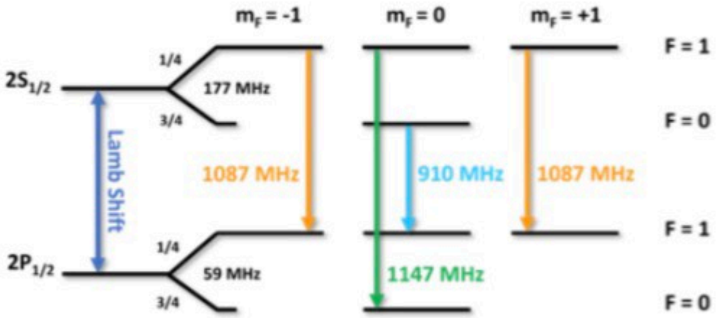
Very low BG

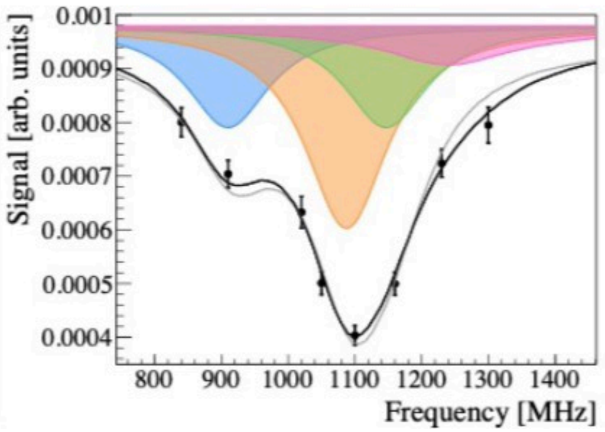
Muonium





Hydrogen





Results published in EPJC 80, 804 (2020) , Physical Review Letter 128, 011802 (2022) , Nature Comm. 7273 13 (2022)

p,H- beams on carbon foils to produce 2S H for tests

Designed from experience at PSI (ETH)

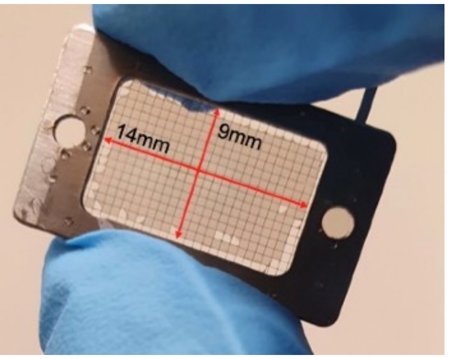
Cu mesh: 45 LPI -> 88% transm.

Carbon foil: ~ 2.0 µg/cm2

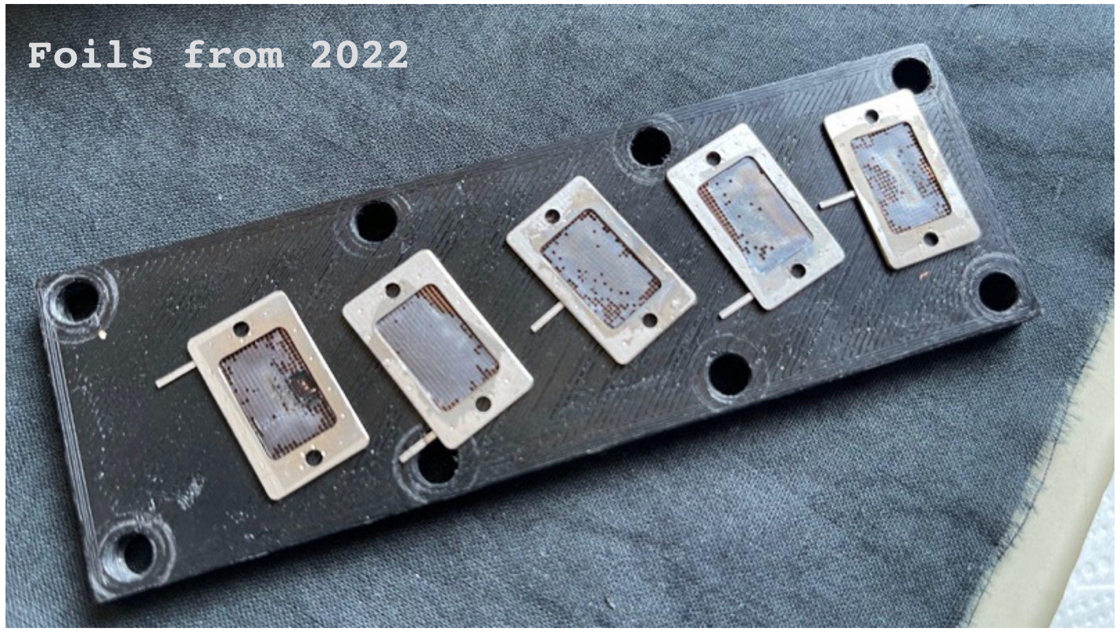
~80% neutrals ~20% charged

~10% 2S ?? (also 3S ……)

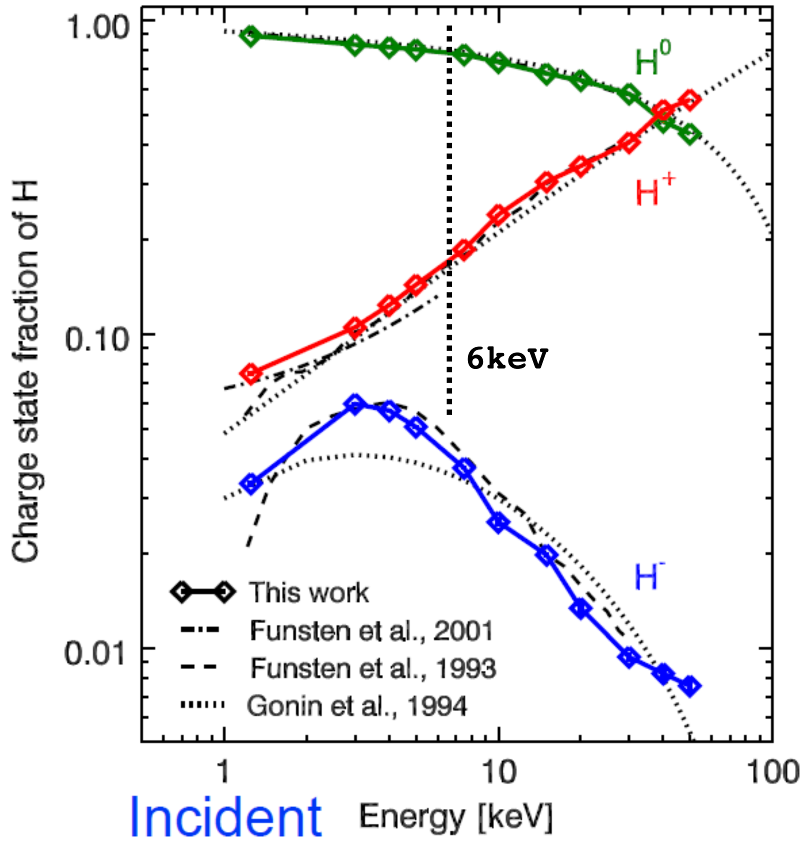
Good option to test LS setup



C-Foil



Graphenea



F. Allegrini et al., «Charge state of ~1 to 50 keV ions after passing through graphene and ultrathin carbon foils» , Opt. Eng. 53(2), 024101 (4 February 2014)

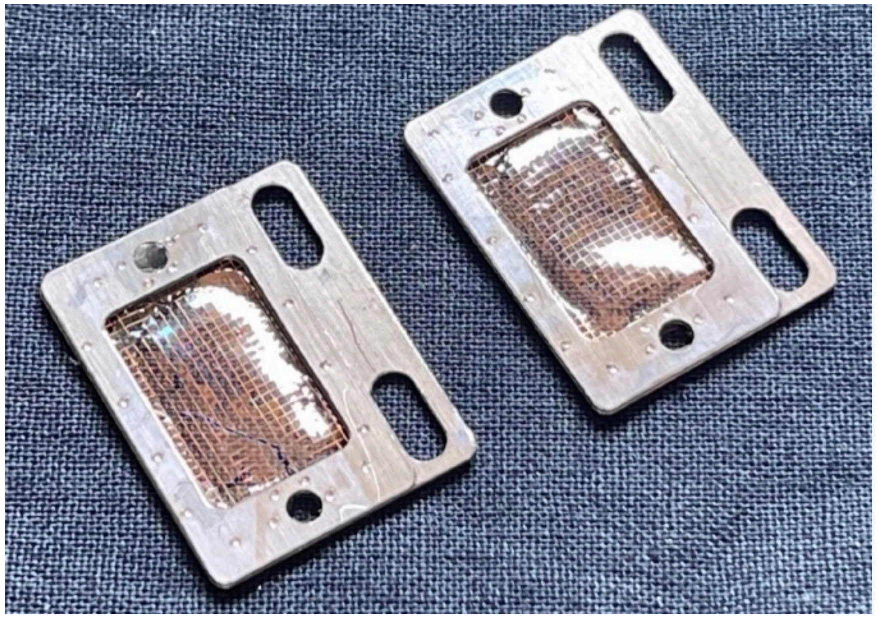
An E-field allows to induce 2S->2P Stark mixing to destroy the 2S states (2P mean life ~1ns)

ACF Home About

The Arizona Carbon Foil Co.

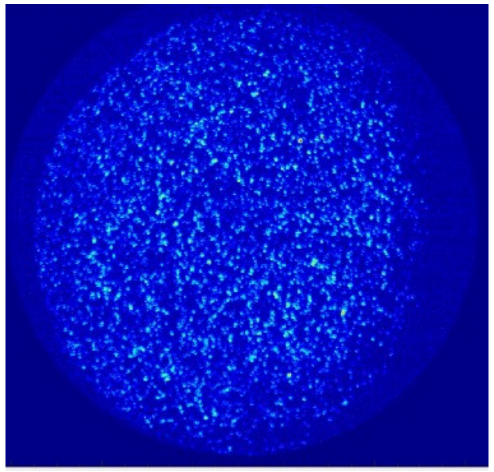
The Arizona Carbon Foil Co., Inc.

Result after 225C baking



Test runs with H^- or p (MW Off/On)

All 4 channels summed up; MW on: HFS 1162 (resonance), MW scanner 900MHz, all 10W, Quenching 4kV

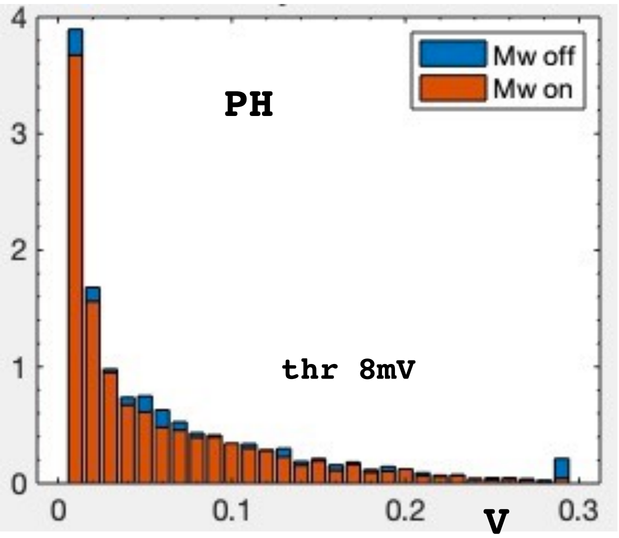


protons 2021

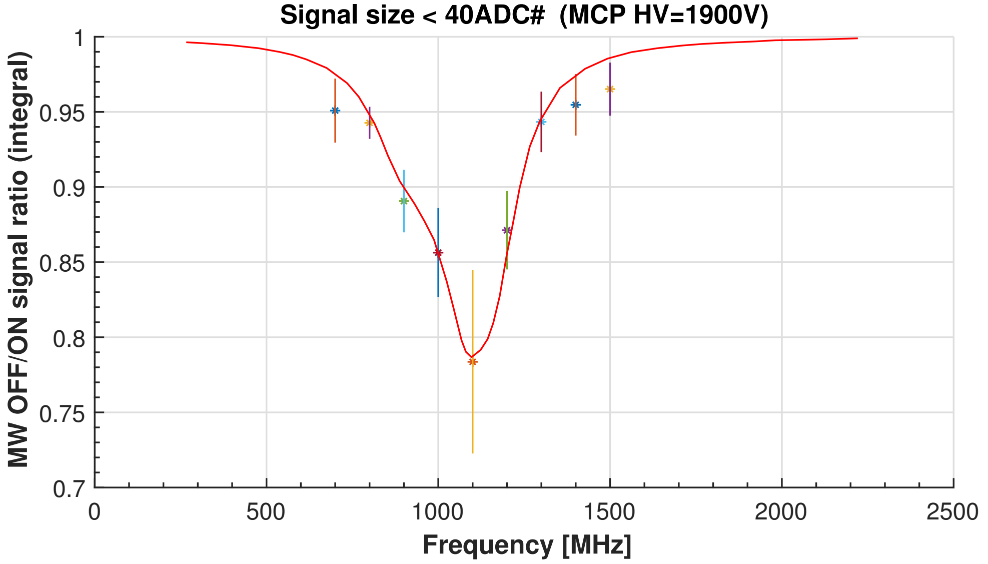
<< Signals from H atoms on the downstream MCP

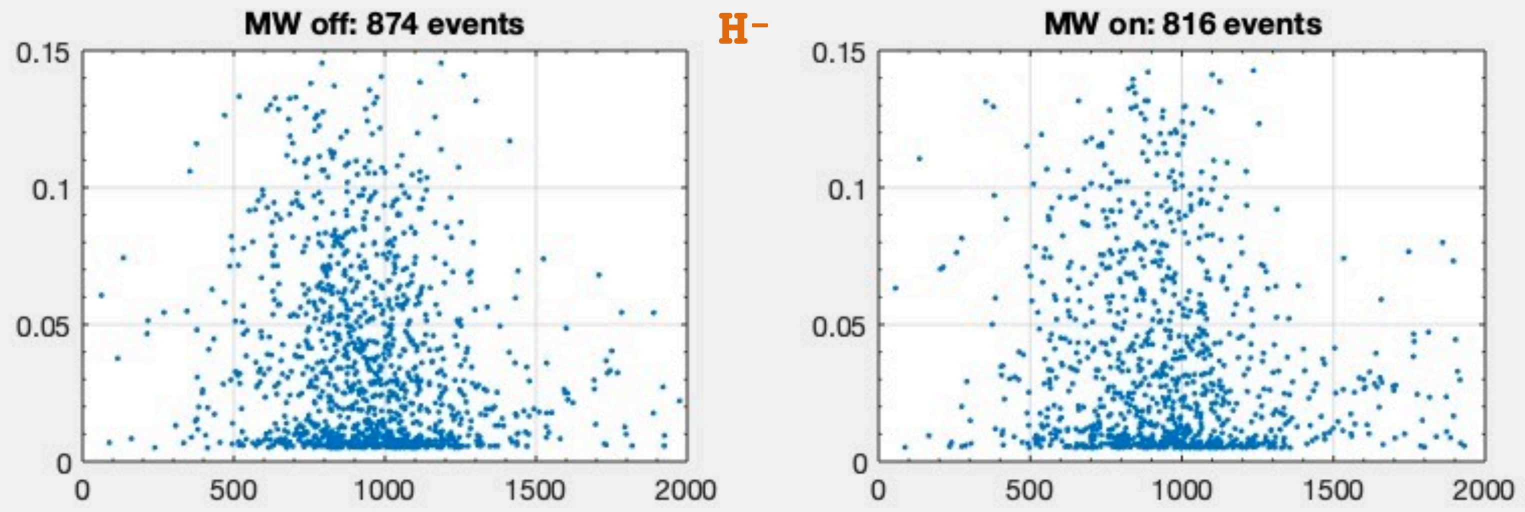
PH spectra differ at small signal sizes

PH spectra MW on/off

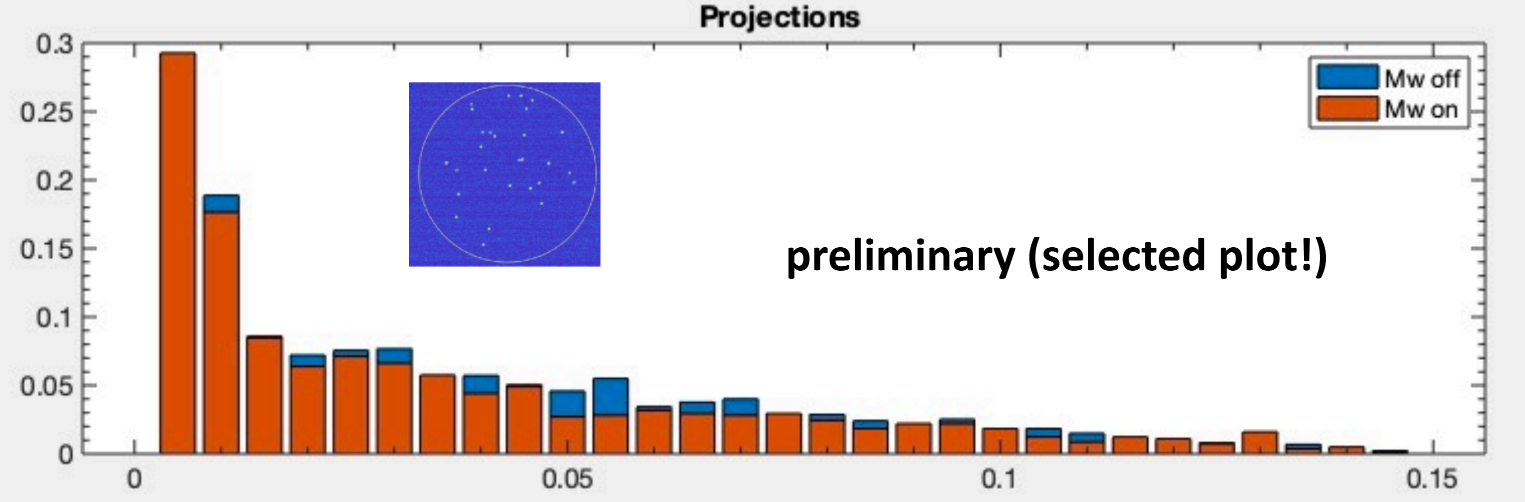


3000 events per frequency point

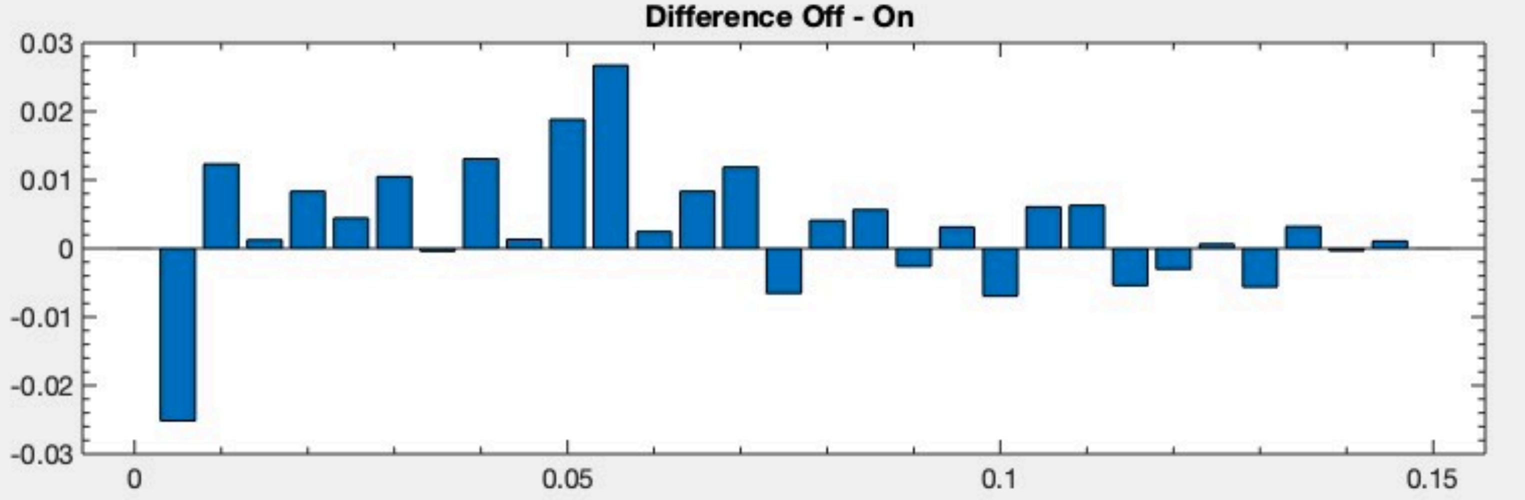




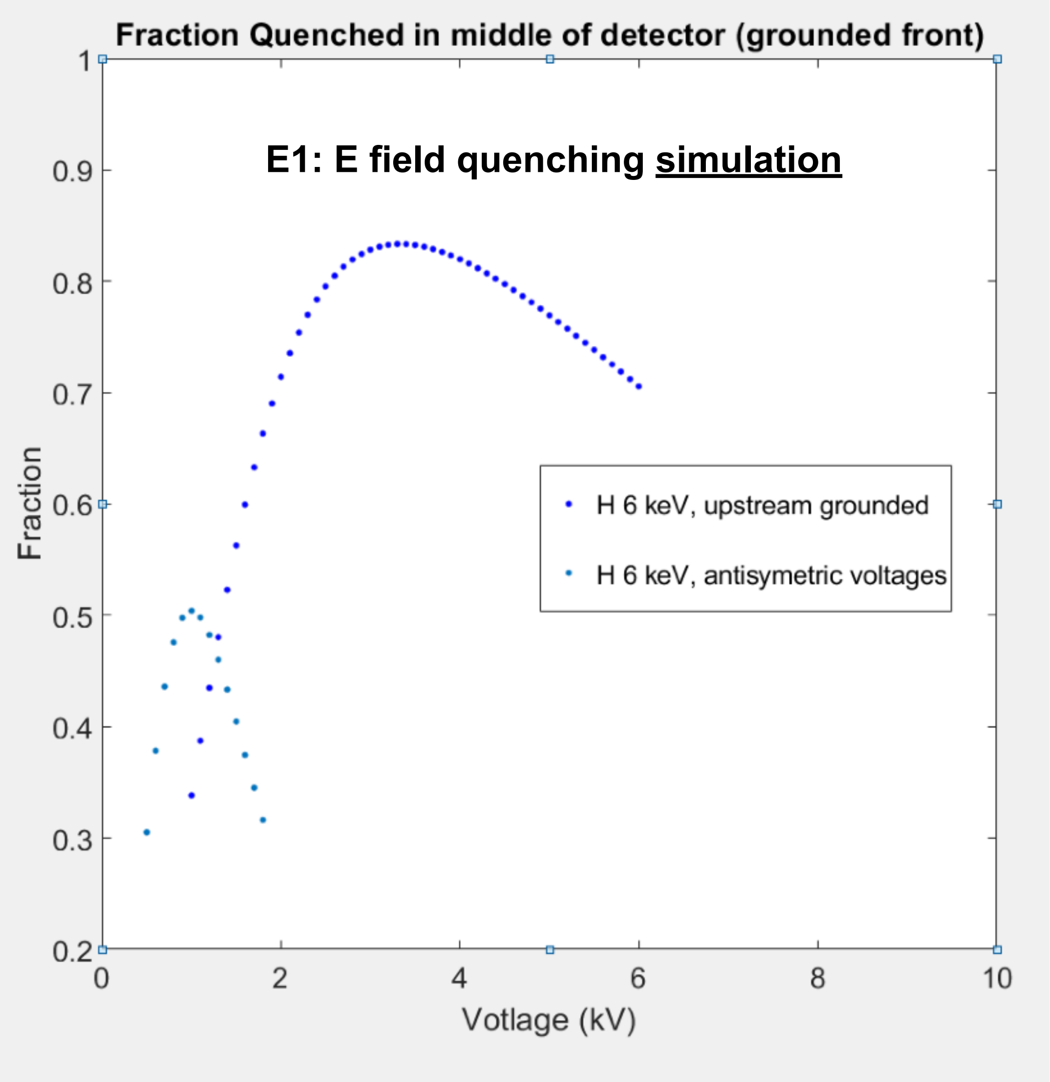
BG from scattered protons and electrons into the MCPs



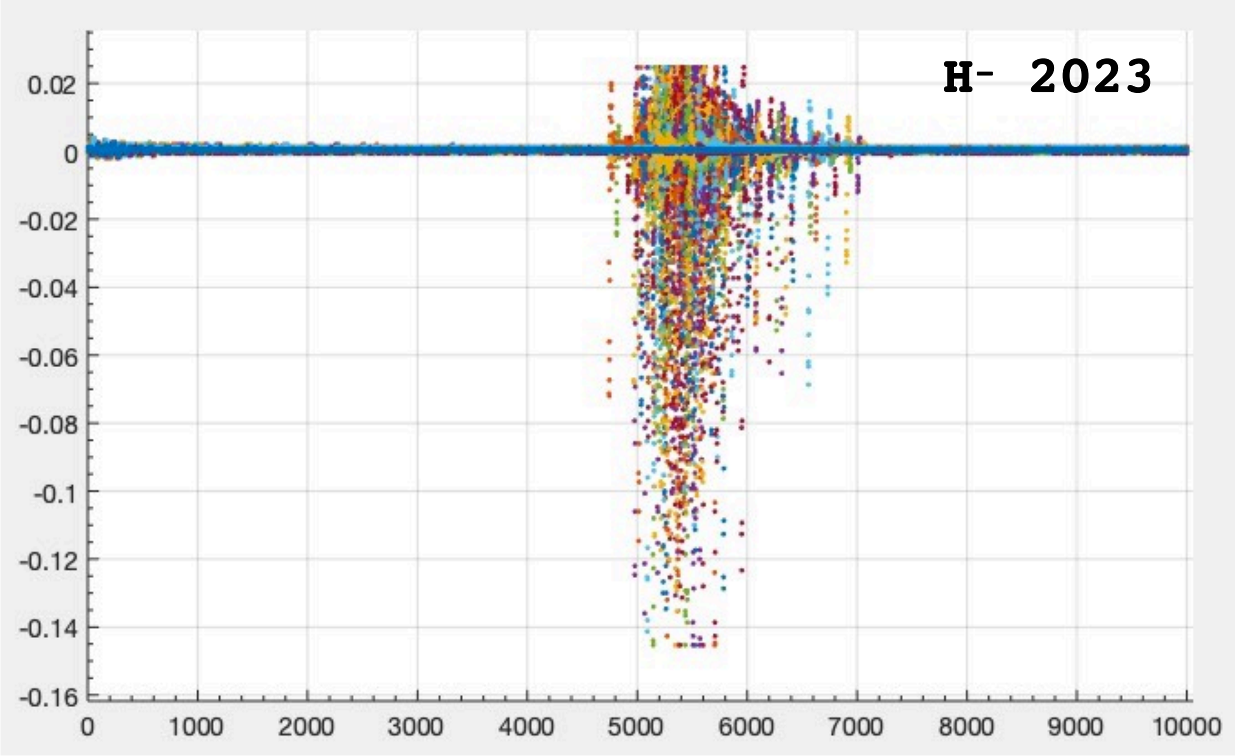
preliminary (selected plot!)



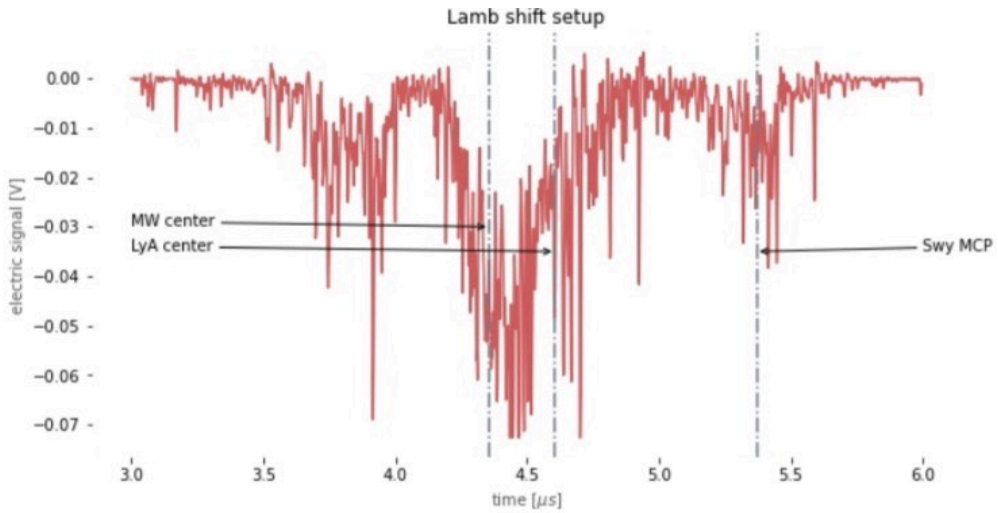
BG signals in LyA detectors – Quenching



- Q can reach 80%:
- Quenching settings +4kV on E1 (downstream)
- 0V on E2 upstream
- Quenching field influences charged BG



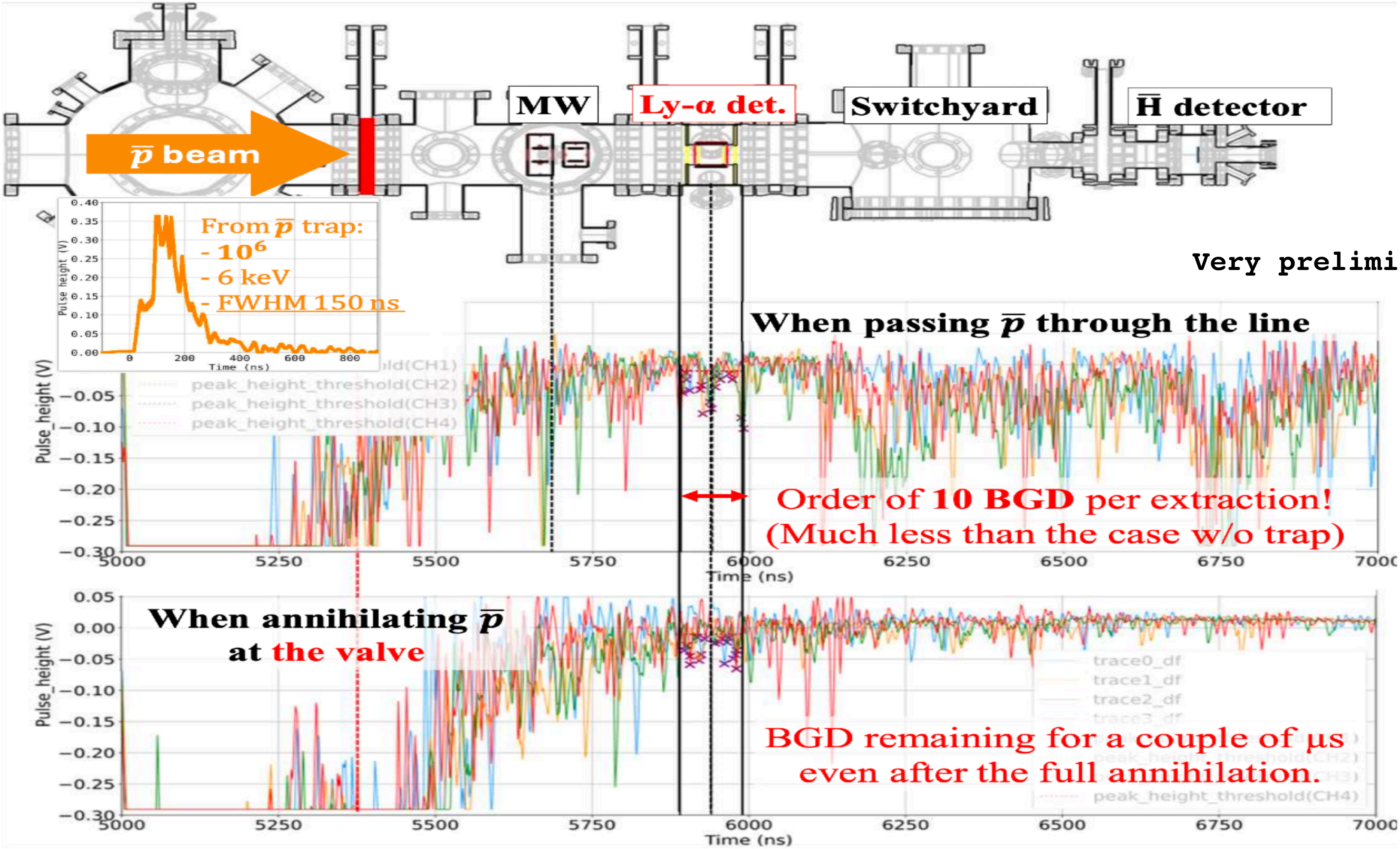
First tests with pbars show beam condition is crucial



- Here no background from pions
- mostly from scattered particles in the Lyα detectors , about P=50% per MCP
- Strongly dependent on beam steering
- Very good vacuum required
- Adjustable Iris diaphragm will be used

Background studies (also at early stage) - this will be main activity in 2026

BG is subject to many parameters will be optimised together with maximal Hbar production



From $\bar{p}$ trap:
- 10^6
- 6 keV
- FWHM 150 ns

Very preliminary

When passing $\bar{p}$ through the line

Order of **10 BGD** per extraction!
(Much less than the case w/o trap)

When annihilating $\bar{p}$ at the valve

BGD remaining for a couple of µs even after the full annihilation.

- **BG is created from pions and also from stray charges in the vacuum vessel**
- **Of great advantage is the speed of the MCPs (speed of H ~1µs/m)**
- **New are the polarisable grids in front of the MCPs**

Outlook

- A $\bar{H}$ LS measurement in GBAR requires the entire setup to work well
- $\bar{H}$ rate was largely increased, further improvements in reach
- Preliminary estimation of the first cross-section achieved
- Improved particle transports (e^+) are crucial for the future
- Lyα system - in the starting blocks to be employed this summer
- We look forward to see the first LyA photon from $\bar{H}$ atoms
- It is planned to increase substantially $\bar{H}$ rates in the future