Results of ELENA-based test experiments in GBAR and future plans of GBAR

ADUC and ELENA meeting

Dr. Andree Welker on behalf of the GBAR collaboration

10.12.2019
Overview

ELENA

- Antiproton “beam time” July-Nov. 2018
- H(-) beam “tests“

GBAR and future plans

- Current status and future plans
GBAR schematic

Gravitational Behaviour of Antihydrogen at Rest

Proton Gun
10 keV

Decelarator

Trap

ELENA
\( \bar{p} \) 100 keV

RC-MCP

Laser
Ps*

Reaction chamber

Silica target
(positronium)

\( \bar{p} \rightarrow H \)

\( H \rightarrow H^+ \)

High Field Trap

Buffer Gas Trap

Free fall chamber

Lasers cooling / photodetach

Bunker

LINAC
\( e^- 10 \text{ MeV} \)

Target
\( e^- 3 \text{ eV} \)

\( e^+ 50 \text{ eV} \)

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Location

AD/ELENA

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Location

GBAR

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SEM/BPM

LNE50 SEM1/SEM2/SEM3
LNE50 SEM1

First 100 keV antiproton beam profile with SEM1: 30.10.2018

M. Hori, J. Fullerton, D. Gamba
First 100 keV antiproton beam profile with SEM1: **30.10.2018**

M. Hori, J. Fullerton, D. Gamba
LNE50 SEM1

First 100 keV antiproton beam profile with SEM1: 30.10.2018

GBAR RC-MCP

GBAR’s Ps target holder

M. Hori, J. Fullerton, D. Gamba
LNE50 SEM1

First 100 keV antiproton beam profile with SEM1: 30.10.2018

But to see the beam in GBAR, we have to be 2 cm away from SEM1’s centre!
LNE50 SEM1

First 100 keV antiproton beam profile with SEM1: 30.10.2018

First SEM

Second SEM

Third SEM

Not taken at the same time, lag of SEM-PCB

To see the beam in GBAR, we have to be 2 cm away from SEM1’s centre!
LNE50 SEM1

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LNE50 SEM1

First 100 keV antiproton beam profile with SEM1: **30.10.2018**

First SEM  
Second SEM  
Third SEM

Not taken at the same time, lag of SEM-PCB

To see the beam in GBAR, we have to be 2 cm away from SEM1’s centre!

During beginning of 2020 GBAR’s and LNE50’s alignment will be checked!
LNE50 SEM3

• H⁻ source partially available since Sep. 2019.
• Only one SEM until today at a time.
• Only manual FPGA data extraction available before.
• First attempt, no baseline substraction.

GBAR’s 8keV p-beam

M. Mclean
LNE50 SEM3

- Only one SEM until today at a time.
- Only manual FPGA data extraction available before.
- First attempt, no baseline subtraction.

GBAR’s 8keV p-beam

What do we see? Broken wires?

M. Mclean
Current observation:

• Only three SEM PCB’s available.

• Were tested on SEM1/2/3. (Two PCBs per SEM needed)

• We have seen different beam profiles and only SEM1 seems working >95%.

• As same mezzanine-z boards are used, as well as the same H/V boards in each SEM!

→ Hints towards inner vacuum issue?

See M. Mclean’s talk for further information.
LNE50 SEM3

Status 25.02.2019 @ GBAR
Wires seemed to be OK.

Broken wire removed by J. Cenede

Only one broken wire

Weak points?
LNE50 SEM3

Tests with SEM3: 26.11.2019

• $H^-$ source pulsed and half ELENA ring turn (No RFQ).

• No FESA class at the time.

• Only one SEM at a time.

• New readout system. (Thanks to M. Mclean)
LNE50 SEM3

Second image of SEM3: 28.11.2019

H⁻ @ 100keV
Images of SEM3: 2018-2019

30.10.2018

$\bar{p}$

28.11.2019

$H^-$

M. Mclean, M. Hori, B. Lefort, D. Gamba, B. Mansoulie
„Beam time“ summary pbars (2018)

- Beam bunch was too long at the beginning 1µs → 400ns (solved)
- Beam energy spread was 1keV → 100eV (will be solved in 2020?)
- Beam ELENA ejection trigger with a jitter of >100ns and sometimes 8µs off (solved)
- Some issues for setting quadrupole elements symmetric (solved)
- During beam time, deflector stopped deflecting every ~15min (PS issues, solved)
- $H^-$ (short moment delivered) and $\bar{p}$ seem to have same shape/trajectory/shape (need to be checked)
- $\bar{p}$ beam tuned (understanding ELENA/transfer line), one pulse every ~2-4min with partially working SEMs at the end of the beam time (very last days 2018)

Thank you from GBAR, for the hard work to the entire ELENA team for beams and monitors!
Why alignment matters! Decelerator Drift Tube

Feasability:

- $b_s = 5 \text{ mm}$  
  Beam Size
- $E = 100 \text{ keV}$  
  Beam energy
- $\Delta E_T = 1 \text{ keV}$  
  Transversal energy spread
- $b_d = 0 \text{ mm}$  
  Beam displaced by
- $b_l = 230 \text{ ns}$  
  Beam bunch length

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Why alignment matters! Decelerator Drift Tube

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First drift tube decelerated pbars at ELENA/GBAR 2018.
Why alignment matters! Decelerator Drift Tube

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- $b_l = 400 \text{ ns}$ : Beam bunch length

First drift tube decelerated pbars at ELENA/GBAR 2018.
The GBAR zone 2017
The GBAR zone mid 2019

Thank you to the survey team.

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\( e^- \) - gun

\( e^+ \) trap

\( p^- \) - beam (1-100 keV)

\( p^+ \) - beam (1-10 keV)

\( e^- \) - gun

\( p^- \) trap

\( p^+ \): Protons

\( p^- \): Anti-Protons

\( \bar{H} \): Anti-Hydrogen

\( \bar{H}^+ \): Anti-Hydrogen ion

\( e^- \): Electrons

\( e^+ \): Positrons

\( Ps \): Positronium

GBAR – zone 2020

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AD hall status:

• Actively compensated superconducting solenoid placed between ASACUSA/GBAR.

• LN2 & LHe filled

• Energized to 7T & 5T

• Axis measurement is ongoing

• Field mapping to be done (early 2020)

Thanks to the magnetic field mapping team!
GBAR’s iron cage

GBAR open iron cage, will be closed mid 2020: 

Goal <1 G

5T trap
9 MeV electron LINAC and positron source

Status:
• We delayed commissioning the LINAC at full power (300 Hz) until early 2020 (not to hinder work with positron trap)
• The LINAC is now working reliably at 200 Hz (about $4 \times 10^7$ e$^+$/s max.)
• Shielding is installed around the target.
• Positron production and trapping, shown at SLOPOS15: $3.8 \times 10^8$ accumulated in 560s
  o Continuously improving

Thanks to RP team for the shielding simulation!
Other setups at GBAR in preparation

Tested during beam time 2018

ToF planes
170 cm × 10 cm × 5 cm

80 ps resolution allows to distinguish up-down particles

9.2 mJ 410 nm pulsed laser at RC entrance

Multiplexed micromegas working
50 cm × 50 cm

Currently, tested ETH/Zurich

Free Fall Chamber
Final design under discussion
Status LASER

Around the free fall chamber: laser implantation

1st laser room

2nd laser room will be on the linac bunker and host the Be ionisation & cooling lasers, $\bar{\text{H}}^+$ photodetachment laser

- Concrete floor installed
- Walls, tables, electricity and air condition: finalized for April 2020
- Fall 2020: Access control and laser installation
- Laser transport to the free fall chamber: mostly by optical fibres
- Additional optical bench at the closest of the chambre

Thank you to EN-EL. (F. Butin)
Summary

• First drift tube decelerated pbars in Oct. 2018 at GBAR.

• Work restarted with $H^-$ from ELENA – looking forward to more in 2020.

• GBAR is in its schedule:

  • First hydrogen measurements expected in mid 2020.
  • First ly-alpha measurements.
  • LASER systems for Ps excitation almost ready to use.
  • LASER system for detachment of positron and Free Fall Chamber will be ready mid/end 2020.
Thank you on behalf of the collaboration.

GBAR collaboration

First beam time

16.10.2018 first drift tube decelerated $\bar{p}^-$ at ELENA/GBAR
100 keV $\rightarrow$ 8 keV with a 400ns bunch
Decelerator Drift Tube

Feasability:

- $b_s = 5 \text{ mm}$  Beam Size
- $E = 100 \text{ keV}$  Beam energy
- $\Delta E_T = 1 \text{ keV}$  Transversal energy spread
- $b_d = 5 \text{ mm}$  Beam displaced by
- $b_l = 400 \text{ ns}$  Beam bunch length
Decelerator Drift Tube

Feasibility:

- $b_s = 5\,\text{mm}$ Beam Size
- $E = 100\,\text{keV}$ Beam energy
- $\Delta E_T = 1\,\text{keV}$ Transversal energy spread
- $b_d = 0\,\text{mm}$ Beam displaced by
- $b_l = 230\,\text{ns}$ Beam bunch length

50 ns late switching

Correct switching
**GBAR**

**Gravitational Behaviour of Antihydrogen at Rest**

**Principle:**
- $\bar{H}^+ = \bar{p}^- + e^+ + e^+
- Sympathetic cooling with Be$^+ \to 10 \, \mu K$
- Photodetachment of e$^+$
- Time of flight ($h = 10 \, \text{cm} \to \Delta t = 0.14 \, \text{s}$)

**Can measure all four systems at GBAR.**

**Beam production:**
- instead of 3-body process with 2e$^+$
- use Ps = e$^+$e$^-$, twice
- excite Ps (n=3)
From the p-gun to the end of the HbarPlus beam line:

8keV beam

Using the SIMION simulated values → reality and simulation agree!

![Diagram with FCs and p-gun](image)

No magnetic field here!

Currently (~66%) transmission, great starting ground!

The chopper can deliver now 100 ns bunches up to continues beam!
GBAR’s protongun

Scanned Wien filter steerers for a 4 keV beam, containing 50µA:

2.5 µA of protons with changing the plasma electrode, we will reach the necessary 5 µA and beyond.
First chopped beam

We have seen our first chopped beam in the RC:

Best tune measurement

Best tune simulated

Simulation and measurement match

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First beam time

**16.10.2018** first drift tube decelerated $\bar{p}^{-}$ at ELENA/GBAR

$100 \text{ keV} \rightarrow 8 \text{ keV}$ with a 400ns bunch

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**Diagrams**

- **Diagram 1:** Overview of the experimental setup showing the drift tube, quadrupole, lenses, and reaction chamber.
- **Diagram 2:** Graph showing the deceleration of $\bar{p}^{-}$ from 100 keV to 8 keV with a 400 ns bunch.

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**Graphs**

- **Graph 1:** Time of Flight (μs) vs. Count, showing the decay of $\bar{p}^{-}$ with MCPs at different energies.
- **Graph 2:** Switching time with 5kV on EL, demonstrating the stability and precision of the deceleration process.

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**Labelled Areas**

- **From ELENA**
- **6455 mm**
- **McP (100 keV)**
- **McP (8 keV)**
- **Switching time**
- **PbWO$_4$**
- **PbWO$_4$**
- **MCP**

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**Note:**

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Antiproton Trap Status

Temperature:

• 4K at the bore pipe
• 19K at MRE

Pressure:

• 2.4x10^-9 mbar in room temperature area.

Will be shipped to CERN beginning 2020
9 MeV electron linac and positron source

Status:
- We delayed commissioning the linac at full power (300 Hz) until early 2020 (not to hinder work with positron trap)
- The linac worked reliably at 200 Hz (about $4 \times 10^7$ e$^+$s max.)

Plans for 2020:
- New moderator (thinner mesh, more layers, improved position)
- Long time test (24h/24) of linac at full power

Thanks to RP team!
High field trap

Positrons are precooled in a three stage buffer gas trap (CO2/N2)

1. Accumulation of 50 stacks in a first well (blue).
2. Lowering the bottom of the well, then 240 stacks are added (orange).
3. We lower again, for 420 stacks (green).
4. We lower to reach a maximum of 560 stacks in a linear regime (red).
Trapping efficiency

Short term improvement:
• Buffer Gas Trap efficiency: 0.05 \(\rightarrow\) 0.15
• High Field Trap efficiency: 0.45 \(\rightarrow\) 1
• Positrons per LINAC pulse: 1.544(64) \(\rightarrow\) 10^5
• LINAC frequency 200 Hz \(\rightarrow\) 300 Hz
• Positrons per second in the HFT: 6.76(64)x10^5 \(\rightarrow\) 6.7x10^6
• In 100 seconds: 6.76(64) x10^7 \(\rightarrow\) 6.7x10^8

Final:
• 1x10^{10} e^+ in 200 s

\(\rightarrow\) 0.1 x \(\overline{H}^+ / H^-\) and 10 x \(\overline{H} / H\) per 200s
Positronium production target and reaction chamber

Status:
• We work with flat target at the moment
• Target cavity has been designed and built but not yet tested
• Positron extraction from the magnetic field and focusing on the positronium converter target is being tested
• Laser system to excite Ps has been built but not yet tested
• A new magnetic shield has been built

Plans for 2020:
• Commissioning of optics & cavity
• Laser excitation of Ps
• Tests with protons
Lamb shift measurement in GBAR

Experiment at GBAR:
• Antihydrogen production via charge exchange ($\bar{p} + \text{Ps} \rightarrow \bar{H} + e^-$)
• With 6keV antiprotons and positronium in ground state roughly 20 H(2S) expected per cycle: improvement by more than an order of magnitude using positronium in excited states (e.g. 2P) and slower antiprotons (< 1 keV)
• The HFS selector removes unwanted hyperfine states
• With the MW cavity the Lamb shift frequency can be scanned
• A static electrical field quenches the remaining 2S atoms, which emit Ly-$\alpha$ (121nm) photons
• Ly-$\alpha$ photons detected with CsI-coated MCPs (det efficiency + acceptance = 18%)

\[ \begin{array}{ll}
\text{Without HFS} & \text{With HFS} \\
\text{Lyman alpha rate (a.u.)} & \text{Lyman alpha rate (a.u.)} \\
\text{frequency (GHz)} & \text{frequency (GHz)} \\
0.7 & 0.7 \\
0.9 & 0.9 \\
1.1 & 1.1 \\
1.3 & 1.3 \\
\end{array} \]

\[ \Delta E = \frac{1}{12} \alpha^4 m_e^3 r_p^2 \rightarrow 10\% \text{ on } \bar{p} \text{ radius} \]

Authors: P. Crivelli, G. Janka, S. Procureur
Status:
- Thermal hydrogen beam has been set up at ETHZ to test the setup
- 1S-2S excitation through electron bombardment and two photon pulsed laser excitation
- MW cavity and Ly-a detector are operational
- Ly-a signal and MW transitions detected, Lamb shift measurement ongoing

Outlook:
- Muonium Lamb shift measurement (conditions closer to GBAR exp., i.e keV energies) (middle Dec. 2019)
- Installation and tests with HFS selector (early 2020)
- Installation at GBAR in June 2020 to measure Lamb shift of hydrogen with GBAR scheme
**Status of Micromegas trackers**

**Tracker:**

- Multiplexed, resistive, 2D bulk Micromegas (50x50 cm^2 active area)

- New multiplexing layout (17 → 12)

**Status:**

- Prototype detectors tested during beamtime 2018 → new multiplexing layout (17→12)
- R&D on resistive strip film: improvement in homogeneity achieved
- Development of an algorithm for multiple hits reconstruction in multiplexed micromegas
  

**Outlook:**

- Full Micromegas tracker being produced, ready to be characterized at CERN in Spring 2020

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Authors: P. Crivelli, G. Janka, S. Procureur

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Status LASER
Ps excitation laser, Be cooling laser, photodetachment laser

Laser for Ps n=3 excitation:
• Remote control, frequency stabilisation and pointing stabilisation implemented
• 9.2 mJ of 410 nm pulsed laser at the entrance of the reaction chamber
• Work on Ps excitation to resume in March 2020

Be cooling lasers:
• Doppler cooling lasers moved to JGU, Mainz
• Optical fibres for 313 nm bought

Plans for 2020:
• Sympathetic cooling of protons at JGU
• Test ion transfer between capture and precision traps
• Study possible use of optical fibres to align the 313 nm lasers inside the free fall chamber
• Development of the photodetachment laser

Authors: P. Comini
Dr. Andree Welker for GBAR, ADUC and ELENA meeting, CERN, 10.12.2019
Status LASER

Around the free fall chamber: detector implantation and chamber design

Authors: P. Comini

To be finalized beginning of 2020:
- Chamber design and ion traps’ integration
- Support design and detector integration

Free fall chamber at CERN: expected 2\textsuperscript{nd} semester of 2020

Nearby cleanroom to be installed