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Toward a pulsed antihydrogen beam for WEP tests in AEgIS

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Abstract. The AE$\overline{\text{g}}$IS collaboration at CERN's AD produces antihydrogen atoms in the form of a pulsed, isotropic source with a precisely defined formation time. AE$\overline{\text{g}}$IS has recently undergone major upgrades to fully benefit from the increased number of colder antiprotons provided by the new ELENA decelerator and to move toward forming a horizontal beam to directly investigate the influence of gravity on the $\overline{\text{H}}$ atoms, thereby probing the Weak Equivalence Principle for antimatter. This contribution gives an overview of these upgrades as well as subsequent results from the first beam times with ELENA.

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1 Introduction

The AE$\overline{\mathrm{g}}$IS (Antimatter Experiment: Gravity, Interferometry, Spectroscopy) collaboration at CERN's Antiproton Decelerator (AD) complex aims at probing the Weak Equivalence Principle (WEP) via a direct measurement of the gravitational acceleration of antimatter by means of a horizontal beam of antihydrogen atoms.

AE$\overline{\mathrm{g}}$IS forms Rydberg antihydrogen inside a Penning-Malmberg trap via a charge exchange reaction between cold antiprotons and positronium atoms laser-excited to Rydberg states:

$$Ps^* + \bar{p} \rightarrow \bar{H}^* + e^- . \tag{1}$$

The long-term aim is a measurement of the influence of gravity on these $\overline{\mathrm{H}}$ atoms, whose production time is known with a precision of a few hundred nanoseconds by forming a horizontal beam that traverses a known distance through a deflectometer to a position-sensitive detector, registering their vertical displacement [1].

During the AD run in 2018, individual $\overline{\mathrm{H}}$ atoms were successfully produced in the AE$\overline{\mathrm{g}}$IS apparatus in an isotropic, pulsed scheme [2]. This concluded the initial phase of the experiment, having demonstrated the feasibility of the approach for $\overline{\mathrm{H}}$ production with a well-defined formation time. AE$\overline{\mathrm{g}}$IS is now entering the subsequent stage: improving conditions to increase the rate of cold $\overline{\mathrm{H}}$ production, enabling efficient beam formation and gravity measurements.

With the installation of an additional decelerator, ELENA (Extra Low ENergy Antiproton ring), in the AD complex, the antiprotons directly available to the experiments have a strongly reduced energy of 100 keV, significantly improving the possible capture efficiency. Furthermore, ELENA enables 24 hour $\overline{\mathrm{p}}$ provision. AE$\overline{\mathrm{g}}$IS has taken the occasion of reconstructing the entire $\overline{\mathrm{p}}$ entrance region to connect to ELENA as well as to improve operation for the first beam time in fall of 2021 to also upgrade several further components essential to fully profit from ELENA and move toward beam formation.

2 AE$\overline{\mathrm{g}}$IS Phase 2

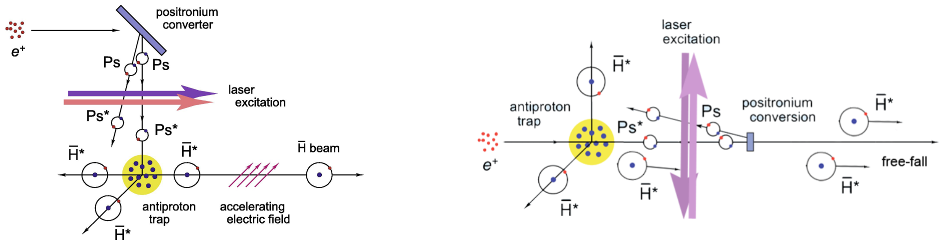

Figure 1: Schematics of antihydrogen production in AE$\overline{\mathrm{g}}$IS. Left: orthogonal scheme used for AE$\overline{\mathrm{g}}$IS Phase 1. Right: collinear scheme used for AE$\overline{\mathrm{g}}$IS Phase 2.

To reduce solid angle and ionization losses of Ps, the AE$\overline{\mathrm{g}}$IS $\overline{\mathrm{H}}$ production has been completely re-organized. For Phase 1, antihydrogen was produced by inserting Ps atoms through a hole in the top of the trap confining the antiproton plasma, as shown in fig. 1, left. Since the Ps atoms are excited to Rydberg states to increase their lifetime and benefit from the scaling of the charge exchange cross section [3], they experienced dynamical field ionization as they moved orthogonally in the magnetic field to reach the trap. The resulting losses limited the excitation to $n_{Ps} = 17$. To mitigate this effect for Phase 2, $\overline{\mathrm{H}}$ production has been transformed into the collinear setup depicted on the right side of fig. 1, with Ps produced on-axis.

2.1 Hardware upgrades

The adaptation to a collinear scheme has the added benefit of eliminating the need for an opening in the top of the $\overline{\mathrm{H}}$ production trap. Consequently, a brand new Penning-Malmberg trap without azimuthal asymmetries and with larger electrode radii has been constructed to prevent expansion and heating of the plasma (fig. 2, left photo). In addition to an improved monitoring for Ps excitation, the new trap incorporates further upgrades: 1. a set of cryogenic actuators to enable accurate alignment of the trap with respect to the magnetic axis and movement of the $\overline{\mathrm{H}}$ ionization grid at operating conditions, and 2. a novel e^+ to Ps conversion target installed on-axis on another such actuator and allowing for a deeper implantation of e^+ into the target to produce lower velocity Ps. The target consists of a $5{\times}5{\times}1\,\mathrm{mm}^3$ Si nanostructure on a 3D-printed Ti holder with included temperature control (fig. 2, central left image). Minimizing the dimensions of the whole structure is a requirement of the collinear $\overline{\mathrm{H}}$ production to limit solid angle losses as the $\overline{\mathrm{H}}$ beam travels axially outwards past the target.
Further hardware upgrades to the AE$\bar{\mathrm{g}}$IS apparatus include an entirely new laser system and transfer line for a more efficient Ps excitation, modifications to the central scintillating fiber tracking detector to allow for a larger sensitive area, and a new degrader setup. Thanks to the lower $\overline{\mathrm{p}}$ energies from ELENA, much thinner degrader foils are needed to achieve the final reduction to a trappable energy ($< 10\,\mathrm{keV}$). AE$\bar{\mathrm{g}}$IS Phase 2 is using Mylar and Parylene N foils with thicknesses of several hundreds of nanometers. The first degradation step is accomplished by the combination of a 1400 nm foil with a four-fold segmented, 10 nm aluminium layer and a coating-free central cross, which can thus simultaneously act as a rough beam position monitor, plus an additional, fully Al-coated, 100 nm foil that can also be used as a Faraday Cup. The signals of both can be obtained directly and via cryogenic amplifiers mounted on a circular PCB (fig. 2, central right photo). To perform the final degradation fine tuning, additional foils with thicknesses between 100 nm and 500 nm have been installed on an actuator-controlled ladder (fig. 2, right image).

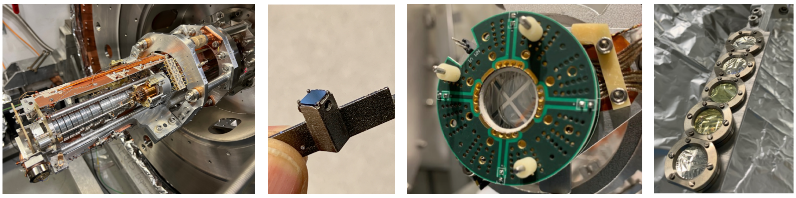

Figure 2: Photographs of upgraded hardware components in AE$\bar{\mathrm{g}}$IS. Left: $\overline{\mathrm{H}}$ production trap. Central left: positronium target on holder structure. Central right: main degrader with segmented Al coating. Right: Foil ladder for degradation fine tuning.

2.2 The new control system

One of the most central upgrades of AE$\bar{\mathrm{g}}$IS concerns the implementation of a completely new experimental control system, necessary for a full automation of the control and synchronization of all involved hardware as well as the data taking procedures and to render the experiment maintainable and adaptable in the long term.
The electronics of the new control system are based on Sinara hardware [4], which is designed for dedicated control and nanosecond synchronization using the ARTIQ control software [5]. The main control carrier is an Artix-7 FPGA, which, in the case of AE$\bar{\mathrm{g}}$IS, controls digital I/O units, fast 16-bit DAC modules, and custom-designed 1 MHz 200-fold high-voltage amplifiers for each DAC channel. Several such complete units have been commissioned and calibrated to precisely control the trap electrode potentials as well as to synchronize all involved sub-systems of the experiment.

From the software point of view, AE$\bar{g}$IS Phase 2 is being controlled by a newly constructed LabVIEW^{TM} control system, which manages the communication between all integral parts of the experiment, enables 24-hour automatized operation, and feeds the defined run routines to the hardware controllers. The LabVIEW^{TM} system is based on the division of the code into dedicated, autonomous components, which are monitored and synchronized by a distributed system of guardian processes. This approach provides the system with strong stability and facilitates a highly efficient use of beam time.

3 First beam times with ELENA

AE$\bar{g}$IS used the first ELENA $\bar{p}$ runs for in-depth tests of large parts of the upgraded hard- and software with a particular focus on the stability and operation of the control system.
In summary, the accurate timing control of the new system was verified, making full use of the precise triggering and coordinating the involved sub-systems accordingly, and close to no round-the-clock beam time was lost thanks to the full automation and stable operation. As shown in fig. 3, AE$\bar{g}$IS has furthermore successfully demonstrated antiproton degradation, capture and manipulation with the new system, paving the way for an improved antihydrogen production in the subsequent runs.

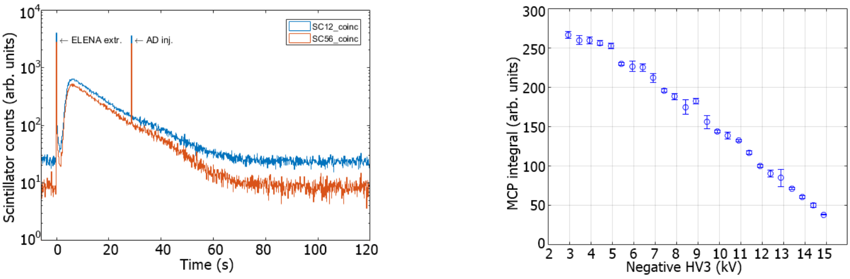

Figure 3: First results of $\bar{p}$ beam time with ELENA in AE$\bar{g}$IS. Left: $\bar{p}$ capture and annihilation on rest gas, monitored via two sets of external scintillators. Right: Amount of $\bar{p}$ passing the barrier of an HV electrode after energy degradation, as observed on a downstream MCP.

4 Conclusions

Having demonstrated the successful operation of a majority of the required hardware and software upgrades, AE$\bar{g}$IS is moving toward its main goal of efficiently producing cold antihydrogen and forming a horizontal $\bar{H}$ beam.
Once formed, the beam will traverse the grids of a deflectometer and its gravity-induced displacement will be measured on a time- and position-sensitive detector, while the pulsed production scheme yields precise knowledge of the passage time. Combining the data for both parameters, it is then possible to draw direct conclusions on the gravitational acceleration. Such a measurement will be a first step toward probing the WEP for antimatter.

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