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The AEgIS Experiment: Progress and Future Outlook

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The AEgIS experiment at CERN is pioneering measurements of gravity, spectroscopy, and interferometry using pulsed antimatter atomic sources. This work provides an overview of the AEgIS experimental setup and highlights recent advancements in antihydrogen production, positronium laser cooling, and the creation of antiprotonic atoms. Key technological developments, including the overhaul of the control system and its impact on precision experiments, are reviewed. Future perspectives for AEgIS before CERN Long Shutdown 3 and beyond are summarized.

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1. Introduction

Antimatter-based experiments open new frontiers in Physics by enabling precise tests of fundamental symmetries, such as the Charge-Time-Parity (CPT) symmetry and the Weak Equivalence Principle (WEP) [1], both cornerstones of our modern view of quantum field theory and gravitational interaction, respectively.

The AEgIS experiment at CERN is uniquely positioned to explore these, aiming at experimentally probing antimatter gravity with free-falling antihydrogen ($\bar{\mathrm{H}}$) in the absence of external fields, performing high-resolution spectroscopy of positronium (Ps) and antiprotonic atoms, and (in the future) atom-interferometric studies with antihydrogen and other antimatter systems [2–4]. This article provides an overview of the AEgIS setup and summarizes recent results and future prospects, with a particular focus on the key technological innovation (the re-design of its control system) that enabled them.

2. Overview of the AEgIS Experiment

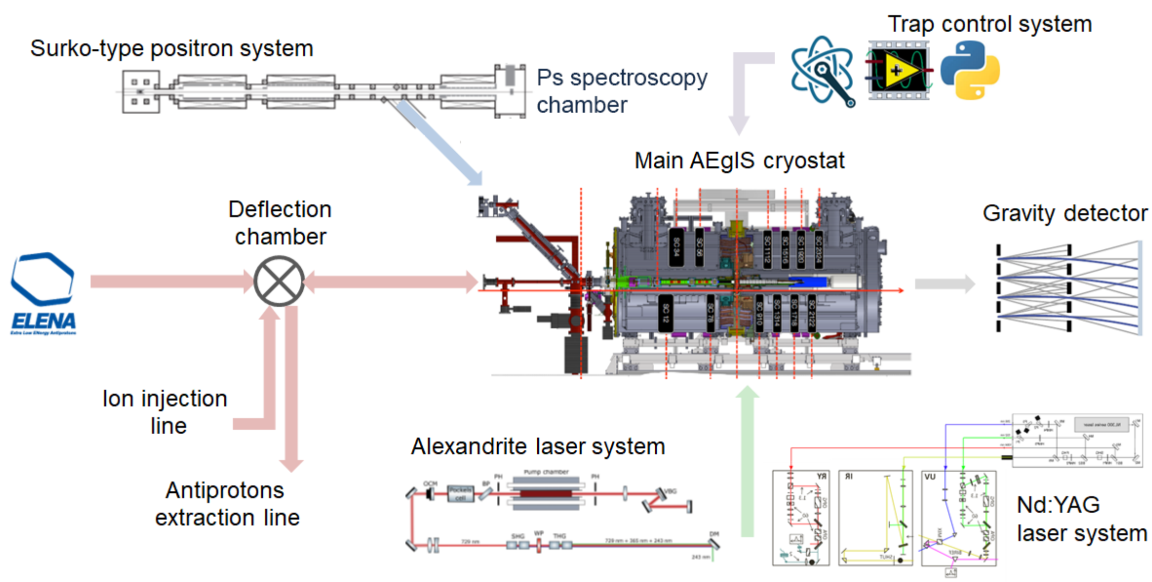

Figure 1: Overview of the AEgIS experimental setup as of 2024. The key components include the main cryostat, positron system, laser system, and detection arrays, as well as the control system for coordinating operations.

The AE$\bar{\mathrm{g}}$IS experimental complex, shown in Fig. 1 as of 2024, is composed of the following subsystems. The central element of the experiment is its main cryostat, housing two superconducting magnets at 5 T and 1 T, necessary for charged (anti-)particles radial confinement, and two sets of Malmberg-Penning traps [5] to provide axial confinement to the (anti-)particles. These are used for, respectively, cooling antiprotons to cryogenic temperatures after capture from the AD/ELENA decelerators, and manipulating them as well as positrons and other ionic species, to form antihydrogen, positronium and antiprotonic atoms. These traps are controlled by a complex electronics and control system, based on the Sinara/ARTIQ environment orchestrated by a LabVIEW control system with a high degree of automatism.

Positrons are obtained by a Surko-trap based system [6] with magnetic accumulation. Positronium atoms are typically formed by implanting keV bunches of positrons onto suitable positron-positronium converters.

Produced Ps atoms can be further excited to their Rydberg levels to enhance the antihydrogen formation cross-section, using a two-step laser excitation scheme with two laser pulses produced by a Nd:YAG laser system. Another alexandrite-based laser system has been recently developed to laser cool positronium [7].

The antihydrogen production region, shown in Fig. 3, combines the antiproton and Rydberg positronium clouds. A charge-exchange process between antiprotons and Rydberg Ps is used to form Rydberg antihydrogen atoms, which can be used for subsequent measurements. Detection of the resulting antihydrogen relies on either its annihilation products, and is performed by either the *Fast Annihilation Cryogenic Tracker* (FACT) or the *External Scintillation Detector Array* (ESDA), or by photo-/field-ionization and imaging of the released $\bar{p}$ or $\bar{e}^+$ on a micro-channel plate detector (see [8]). These detectors combined provide nanosecond-resolution timing information and mm vertexing resolution along the trap axis direction.

In addition to its main cryostat setup, AEḡIS also includes facilities for dedicated positronium and antiprotonic atom research. A deflection chamber has recently been added to the entrance of the cryostat, enabling ion injection in the main experiment traps as well as extracting cold antiprotons to deliver them in modular experimental setups installed after the deflection chamber. Two ion sources are currently under commissioning. Similarly, a dedicated room-temperature Ps spectroscopy setup is installed at the end of the positron system, allowing positronium-laser studies as well as the development of new techniques.

3. Recent Progress and Results

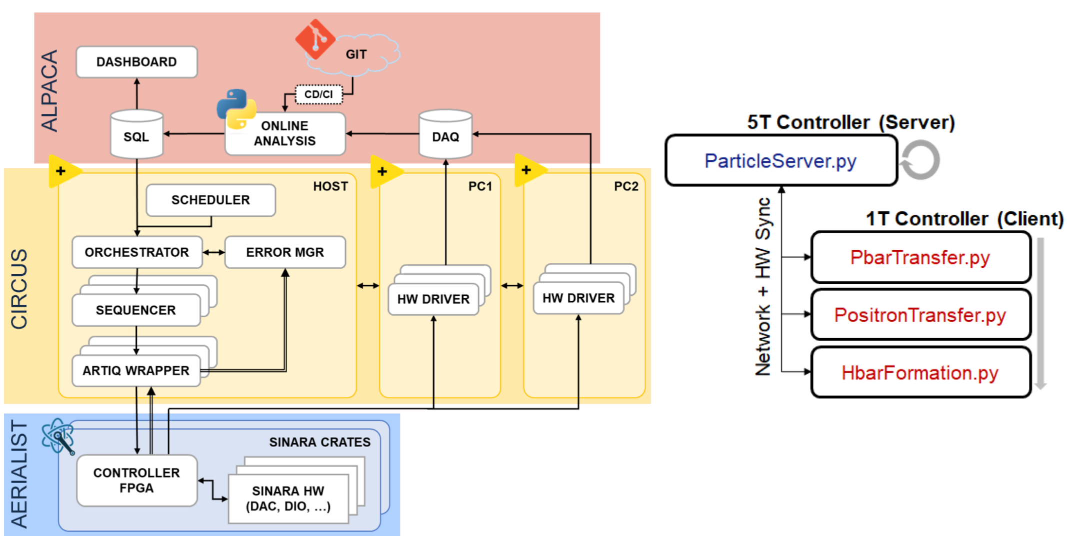

Figure 2: Architecture of the AEgIS control system

3.1 Technological Innovations: Autonomous Control System

The AEḡIS control system has undergone a complete overhaul. It is now based on three layers: hardware, slow control and feedback/monitoring (see Fig. 2, left panel, for an illustration). The hardware layer consists of two independent trap control electronic systems, realized with standard ARTIQ/Sinara ecosystem components for quantum experiments [9] complemented with some custom electronic devices, named *AERIALIST*. The slow control layer consists of a distributed LabVIEW control system named *CIRCUS*, described in the details in

[10, 11]) supporting distributed and concurrent asynchronous operations of multiple devices with nanosecond synchronization capabilities and a modular microservices architecture, without imposing strict constraints to the underlying Python/ARTIQ programming model of the Sinara controllers. The feedback/monitoring level consists of a automatic online analysis tool named *ALPACA*, supporting advanced automation functionalities like Bayesian optimization of experimental parameters and a dashboard.

The architecture was realized to enable asynchronous master-slave operation model between two (or more) trap controllers. For example, antihydrogen production can be run on one of the two controllers acting as a master/client, while constant accumulation of antiprotons runs in parallel on the other one, acting as server/slave (see Fig. 2 right panel).

This architecture supports an unprecedented level of modularity in handling complex procedures involving electrons, antiprotons, positrons, ions, lasers etc. An example ARTIQ/Python program to load antiprotons from AD/ELENA, sympathetically cool them with electrons, and extract them to either count them with the ESDA or image them with a micro-channel plate detector, can be compacted in just a few lines of code, hiding most of the complexity to the user into well-established asynchronous subroutines:

```
from AEgIS_imports import *
from AegisExperiment import _AegisExpOfficial

class PbarElectronCooling(_AegisExpOfficial):
    def build(self):
        self.Build1T()

    def closure(self):
        self.Send_Msg_Blocking("5TC1", "reset", timeout = 60)

    def experiment(self):
        self.Move_CryoMotor("Target", "All OUT") # Positronium converter moving

        self.Send_Msg_Blocking("5TC1", "prepare_trap,ctrap", timeout = 120)
        self.Send_Msg_Blocking("5TC1", "prepare_trap,ptrap", timeout = 120)
        self.Send_Msg_Blocking("5TC1", "wait_injection", timeout = 21600)

        self.Pbar_EnableCatching()
        self.Send_Msg_Blocking("5TC1", "load_electrons", timeout = 300)
        self.Send_Msg_Blocking("5TC1", "load_antiprotons", timeout = 300)
        self.Pbar_InhibitCatching()

        self.Send_Msg_Blocking("5TC1", "reshape_cooling2dump", timeout = 15)
        self.Send_Msg_Blocking("5TC1", "dump," + self.Pbar_DumpType, timeout = 60)
```

The system's features include advanced exception handling and automatic recovery, real-time feedback loops for data quality checks and Bayesian optimization for automated experimental tuning. These advancements ensure stability and scalability for future AE$\bar{g}$IS upgrades.

3.2 Antihydrogen Production

Phase 1 of AEgIS successfully demonstrated antihydrogen formation with a source intensity of 0.05 atoms per cycle [12]. To achieve a proof-of-concept inertial measurement with $\bar{\mathrm{H}}$, significant improvements in

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production efficiency were necessary, to 1 atoms per cycle or above [13]. Several actions were undertaken since then. First, the transition from the non-collinear interaction scheme of AEgIS-1 to the collinear geometry of AEgIS-2, as shown in Fig. 3, to mitigate Ps losses due to the motional Stark effect, enhance laser excitation efficiency, and allow a better overlap between antiproton and positronium clouds. Second, make effective use of the reduction in antiproton energy thanks to the new ELENA decelerator, aiming at factor of 10 increased cold $\bar{p}$ availability.

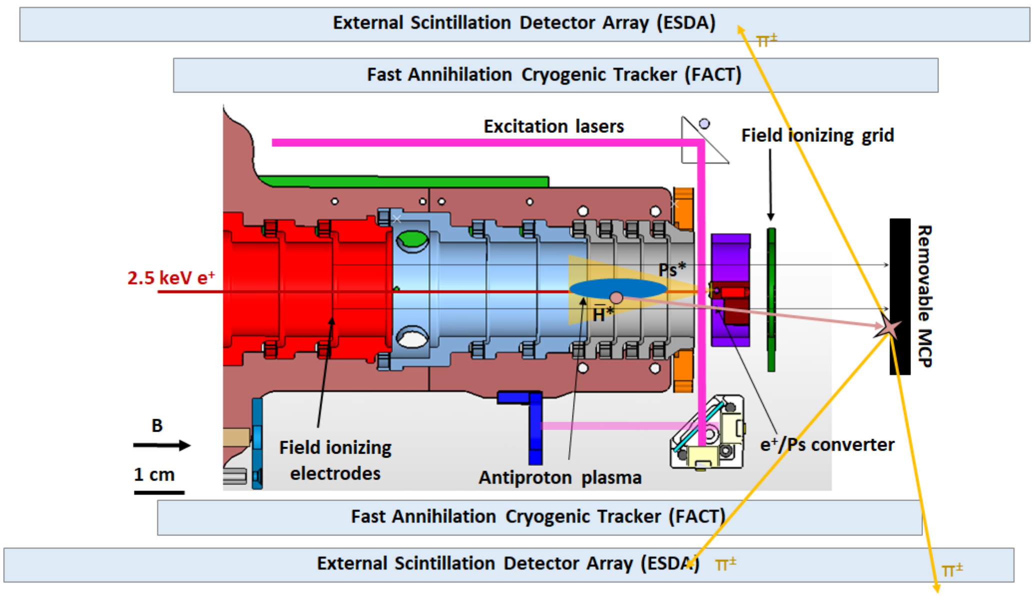

Figure 3: Updated scheme for antihydrogen production in AEgIS Phase 2.

An in-flight, or ballistic, production scheme of antihydrogen, employing synchronized clouds of antiprotons and positrons, and resulting in a boosted antihydrogen beam with controllable velocity, is currently under development. This technique may offer significant advantages for future beam implementations, allowing fine control of the produced antihydrogen velocity by acting on the mutual synchronization between the clouds.

3.3 Positronium Advances

The production of colder positronium with higher principal quantum number n_{Ps} is crucial to increasing the charge-exchange cross-section for antihydrogen formation, scaling as $\sigma \propto n_{Ps}^4$ [14]. Lowering its temperature can not only enhance the interaction probabilities, but also improve the Ps beam collimation and cloud density at the interaction point with antiprotons. Recent advancements along the realization of colder Ps sources include:

- The development of optimized nanochanneled silica positron-Ps converters in a reflection geometry, producing ≈ 30% of fully-thermalized Ps with a temperature of 300 K [15];
- The development of nanochanneled silica positron-Ps converters in a transmission geometry, achieving transmission yields of 9–16 % [16, 17];
- Efficient laser cooling of Ps, reducing produced Ps cloud temperatures from reflection targets from 380 K to 170 K, as described in [18].

The cooling methodology, based on Doppler laser cooling, represents a potential breakthrough, particularly as it allows further reducing the temperature to 10 K or better by prolonging the cooling laser duration and/or adopting cryogenic positronium converters to start from lower temperatures, and it can be adapted for operation in magnetic fields [19].

3.4 Antiprotonic Atoms and Ion Sources

Several methodologies are actively being studied at AE$\bar{g}$IS to produce antiprotonic atoms and study them.

In one methodology, recently developed and commissioned, antiprotonic atoms are produced by injecting low pressure gas into the Malmberg-Penning traps, used to shape a nested Penning trap potential profile, where negative antiprotons as well as the positively charged highly charged ions (HCIs) resulting from antiprotonic atoms' annihilation can be simultaneously trapped. These HCIs can be subsequently analyzed using time-of-flight spectroscopy.

In another methodology, anions from an external source are loaded into the Malmberg-Penning traps and co-trapped with antiprotons. The anions are then turned back into neutral atoms by means of pulsed laser photo-detaching of the extra electron, allowing them to interact with the co-trapped antiprotons. Antiprotonic atoms are thus formed with the precise knowledge of their formation instant, allowing for further spectroscopy schemes with pulsed lasers. A anion source based on electron dissociative attachment in a Paul trap is being commissioned at AE$\bar{g}$IS, and will be deployed for experiments during the 2025 Physics run.

These methods will enable new type of investigations of e.g. antiprotonic atoms' lifetimes, energy levels, produced exotic nuclei masses, highly charged ions spectroscopy, and opening new experimental pathways in precision Nuclear Physics in particle traps.

4. Conclusions and Outlook

AE$\bar{g}$IS is progressing toward its long-term goals of spectroscopy, interferometry and gravity measurements with antimatter. The recent advancements in ns-pulsed antihydrogen production, positronium cooling, and antiprotonic atoms formation, as well as the full renewal of the experiment control system, lay the groundwork for the main goals of its Phase 2 and beyond. Future short-term plans include increasing antihydrogen production rates by 2 to 3 orders of magnitude and demonstrate a velocity-tunable $\bar{\mathrm{H}}$ beam, to enable the first antihydrogen gravity experiments in the absence of external magnetic fields (expected at the $10G$ level in the initial realizations of the experiment); developing enhanced positronium laser cooling by introducing cryogenic Ps targets and extending the cooling laser duration; expanding applications of antiprotonic atoms in fundamental physics by demonstrating controlled formation from anions. On a longer term plan, AE$\bar{g}$IS aims at further developing its $\bar{\mathrm{H}}$ ns-pulsed beam, e.g. by introducing Ps transmission targets and Ps laser cooling in its $\bar{\mathrm{H}}$ production scheme, and develop the first generation of atom interferometers employing antimatter, as well as exploring new avenues: searching for a Dark Matter candidate in antiprotonic-^{3}He annihilations [20], and supporting the ongoing AD/ELENA team effort in evaluating the possibility to deliver a cold antideuteron beam to the experiments, by exploring antideuterium formation via charge exchange with positronium and antideuteronic atoms [21].

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