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# Development of nuclear emulsions operating in vacuum for the AEgIS experiment

**The AEgIS collaboration**

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ABSTRACT: For the first time the AEgIS (Antihydrogen Experiment: Gravity, Interferometry, Spectroscopy) experiment will measure the Earth's local gravitational acceleration $g$ on antimatter through the evaluation of the vertical displacement of an antihydrogen horizontal beam. This will be a model independent test of the Weak Equivalence Principle at the base of the general relativity. The initial goal of a $g$ measurement with a relative uncertainty of 1% will be achieved with less than 1000 detected antihydrogens, provided that their vertical position could be determined with a precision of a few micrometers. An emulsion based detector is very suitable for this purpose featuring an intrinsic sub-micrometric spatial resolution. Nevertheless, the AEgIS experiment requires unprecedented operational conditions for this type of detector, namely vacuum environment and very low temperature. An intense R&D activity is presently going on to optimize the detector for the AEgIS experimental requirements with rather encouraging results.

KEYWORDS: Particle tracking detectors; Particle identification methods

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## Contents



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## 1 Introduction

In the last decade cold antihydrogen atoms were created and trapped for a time long enough to allow for their study [1, 2]. This paved the way for the AEgIS experiment at the CERN Antiproton Decelerator (AD) that was proposed to directly measure the Earth's local gravitational acceleration $g$ on antihydrogen [3]. Several theoretical arguments suggest that the gravitational interaction of matter and antimatter should be identical [4, 5]. Nevertheless, the gravity acceleration has never been measured on antimatter. One of the first goal of AEgIS is then to test the Weak Equivalence Principle, observing the vertical displacement of an horizontal $\overline{H}$ beam in the gravitational field by measuring the annihilation point of the $\overline{H}$ atoms at the end of their trajectory. The fundamental steps for performing the experiment require the production of cold (100 mK) antihydrogen based on the charge exchange reaction between cold antiprotons and positronium in the Rydberg state. The produced Rydberg antihydrogen atoms have then to be accelerated by means of an inhomogeneous electric field to form a beam. Finally, $g$ can be determined through a two-grating moiré deflectometer coupled with a position-sensitive detector. In particular, this detector has to feature a position resolution of a few micrometers in order to obtain the precision of $\Delta g/g$ of 1%, initial purpose of AEgIS, with less than 1000 detected antihydrogen atoms. An emulsion based detector [6], with its intrinsic spatial resolution at the sub-micrometric level, has then been chosen to measure the arrival point of the antihydrogen atoms after a given flight path. However, emulsions have never been used in vacuum and at very low temperature (77 K) as required by the AEgIS experiment. For this reason, an intense R&D programme has started to study the mechanical stress of the emulsion detector in this new conditions, its background and its sensitivity [7]. First tests in the AEgIS beam line at CERN were carried out in December 2012, when emulsion detectors were exposed to a $\sim$100 keV antiproton beam [8].

## 2 Overview of the AEgIS experiment

The AEgIS experiment needs to produce cold antihydrogen atoms ($\sim$100 mK). They will be formed through the charge exchange reaction $Ps^* + \overline{p} \rightarrow \overline{H}^* + e^-$ [9] between cold antiprotons and positronium. In particular, antiprotons coming from AD are captured and trapped in a 5 T

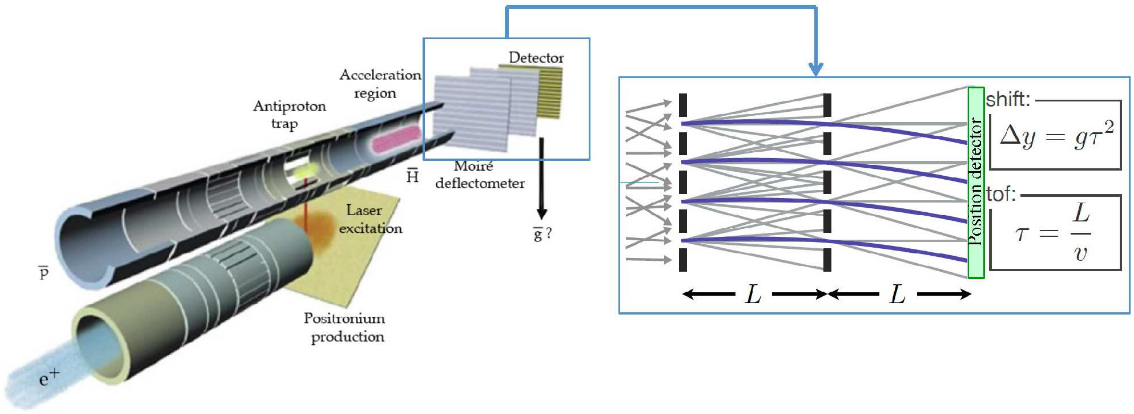


**Figure 1**. Left: sketch of the AEgIS apparatus. Right: the gravity measurement module.

magnet (4 K) where a cloud of $\sim 10^8$ electrons is used for their cooling, while positrons from a $^{22}$Na source are accelerated towards a nano-porous target to form the positronium, successively excited to a Rydberg state ($Ps^*$) by two laser beams. After the charged exchange reaction in the $\bar{p}$-trap in a 1 T field, $\bar{H}$-atoms, in the Rydberg state too, will have an average speed of 50 m/s, according to the Maxwell-Boltzmann distribution. An electric field is then applied along the beam axis to accelerate the $\bar{H}$-atoms to a velocity of about 400 m/s. A moiré deflectometer, consisting of two gratings at a given distance L, is then used to select the propagation directions of the originally diverging antiatom beam. Downstream the gratings the atoms are distributed in a shadow image forming a set of fringes which are eventually shifted in the Earth's gravitational field by $\Delta y = g\tau^2$, where $\tau$ is the time of flight between the two gratings. The position sensitive detector will measure the shift of the antihydrogens detecting the position of their annihilation taking place in a thin silicon foil placed in front of the detector to separate the high vacuum region of the apparatus to the ordinary vacuum region. An associated time of flight detector has to provide the time information corresponding to each annihilation event in order to fit the $g$ value from the above mentioned relation $\Delta y = g\tau^2$. A sketch of the AEgIS apparatus is shown in figure 1, where an enlarged display of the gravity measurement module is also reported.

## 3 Emulsion based position detector

Emulsion films went through many successful achievements as particle detectors leading physicists to fundamental discoveries [6]. They consist of silver bromide crystals (AgBr) uniformly distributed in a gel where a latent track is formed after being crossed by an ionising particle. The latent track become visible at the optical microscope after a chemical development process producing a sequence of silver grains along the particle track allowing for its full three-dimensional reconstruction even for very thin emulsion layers. The recent development of fast automated scanning systems for the track analysis [6] has overcome the problem of the time consuming manual scanning procedure, that represented the main limiting factor in the use of such a detector fostering a rebirth of their application in particle and nuclear physics. Their excellent intrinsic spatial resolution of about 0.050 $\mu$m can be exploited in the AEgIS experiment to reach the required 1%

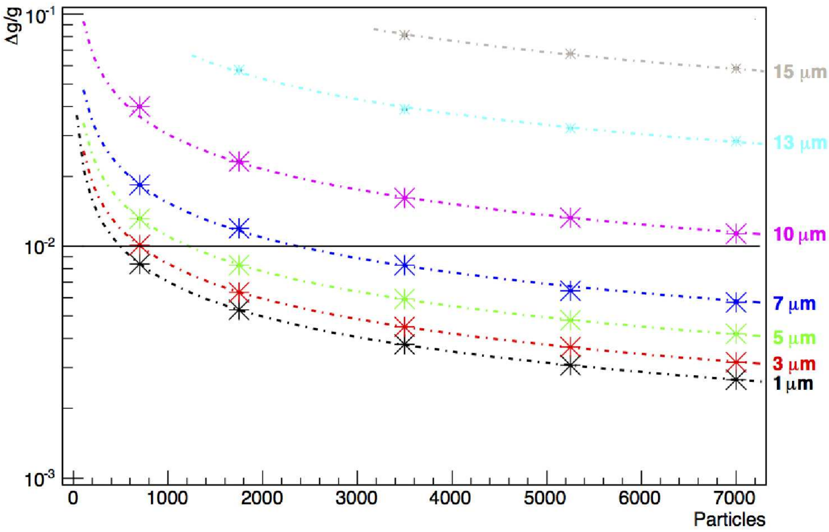


**Figure 2**. Simulated relative precision on the $g$ measurement as a function of the number of the detected annihilations for various detector vertex resolutions. The solid line indicates the $\Delta g/g = 1\%$.

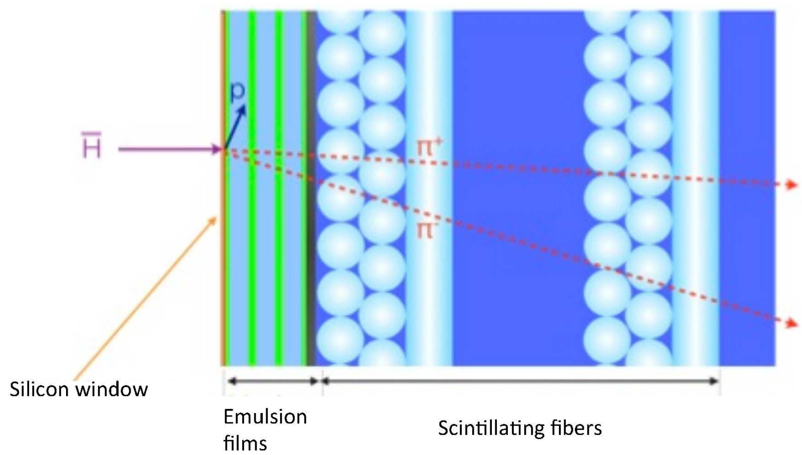


**Figure 3**. Schematic of the position sensitive detector in AEgIS.

precision on $\Delta g/g$, as results from Monte Carlo simulation studies performed to evaluate the relative precision on $g$ as a function of the detector resolution. An unbinned maximum likelihood was used to evaluate $\Delta g/g$ as a function of the number of detected annihilations for various vertex resolutions [8]. The simulation results are reported in figure 2 where it can be seen that reconstructing the annihilation vertex of the antihydrogen atom at a level of a few micrometers can assure the required precision on the $g$ measurement.

On this basis the proposed position detector for AEgIS is depicted in figure 3: a thin foil of silicon, where the annihilation events will take place, is needed to separate the high vacuum region of the experiment from the ordinary vacuum region where the emulsion detector will be located. Two planes of scintillating fibers will then be placed behind the emulsions to measure the time of flight for every annihilation event. The detector, and in particular the emulsions, will have to operate

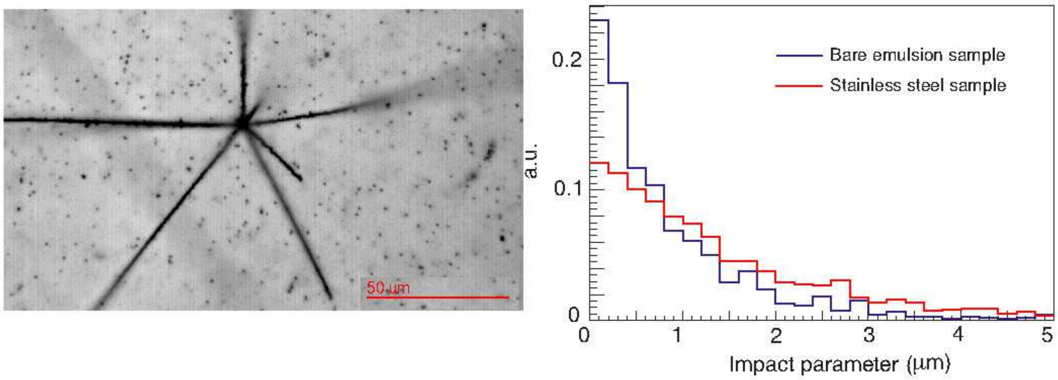


**Figure 4**. Left: microscope view of an antiproton annihilation. Right: impact parameter distribution of interaction products.

in vacuum and at temperatures between 77 K and room temperature. To cope with these unusual environmental conditions one needs to: i) improve the sensitivity of the detector developing a new emulsion gel; ii) study the performances of the emulsion detector in vacuum; iii) study the performances of the emulsion detector as a function of the temperature; iv) develop a new algorithm for a fast $4\pi$ steradian track reconstruction. Following several tests performed at the Laboratory for High Energy Physics (LHEP) of the University of Bern, principally devoted to assess the emulsion stability in vacuum [7], the emulsion detector commissioning in vacuum was performed in December 2012 at the AD at CERN with a $\sim$100 keV antiproton beam. The emulsions were installed in the AEgIS beam line in a six-way cross mounted at the foreseen position of the deflectometer. After the exposures, the emulsion foils were developed in a dark room at CERN, and then analised with the automatic microscope facility of the University of Bern. One of the thousands of antiproton annihilations successfully reconstructed is shown in figure 4. In the same figure the impact parameter distribution for the annihilation events is also reported for those taking place directly in the emulsions and for those taking place in a 20 $\mu$m thick stainless steel foil (simulating the window needed to separate in the final experiment the deflectometer from the emulsion detector) covering the emulsions. A resolution of $\sim$1 $\mu$m was achieved, confirming the feasibility and the advantages of the employment of the emulsion detector in AEgIS [8].

The multiplicity distributions of minimum and heavily ionizing particles in antiproton annihilations were also studied for different materials. First results are providing interesting indications for the discrimination among nuclear models embedded in the GEANT4 simulation package [10] and will be the subject of a forthcoming publication.

The study of the influence of the temperature on the background and sensitivity of the emulsions is presently underway at LHEP. A test facility has been set up for irradiating the films with a $\beta$-ray source in such a way that the sensitivity will be measured in vacuum and at different temperature. The apparatus is shown in figure 5. In parallel, a software development has been initiated by members of the LHEP for the automatic track scanning of the emulsion plates [11]. In fact, the microscope scanning facility of LHEP (figure 6) is well equipped and tuned for the research activity on neutrino oscillation experiment characterized by a forward boosted event topology.

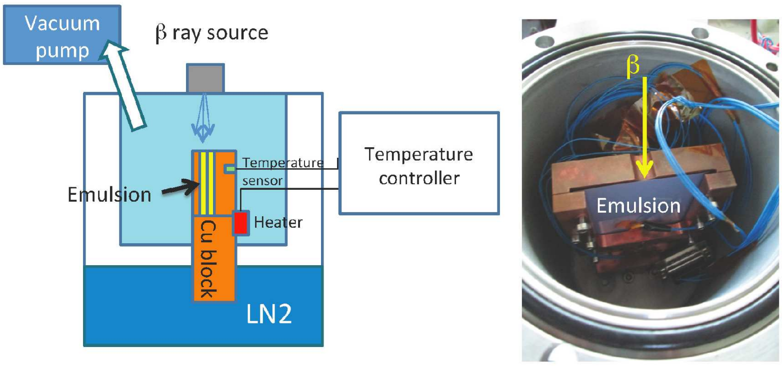


**Figure 5**. Apparatus for testing the emulsion characteristics as a function of the temperature.

**Figure 6**. Emulsion scanning facility at LHEP (University of Bern).

However, this topology substantially differs from that of the antihydrogen annihilation events to be detected in AEgIS. In the latter case a track reconstruction algorithm over a $4\pi$ solid angle is needed implying about a factor 100 larger data processing without loosing the present processing speed of about 10 $cm^2$ emulsion surface per hour. To meet these requirements, a new track reconstruction based on the GPU (Graphic Processing Unit) technology combined with a multithread programming has been developed and the processing of 3D emulsion detector data is now about 60 times faster. As a consequence 15 $cm^2$ emulsion surface can be scanned per hour by GPUs with an excellent tracking performance [11].

## 4 Conclusions

The AEgIS experiment aims at measuring for the first time the Earth's local gravity acceleration on antimatter, namely on antihydrogen atoms produced at the AD accelerator at CERN. The initial goal is to determine $g$ with a relative precision of 1%. The results of the tests performed in December 2012 at the AD at CERN with an antiproton beam demonstrated that emulsion detectors can be successfully used to measure the annihilation vertices of antihydrogen atoms in vacuum with very high precision (1–2 $\mu$m), hence allowing to reach the above-mentioned goal with less than 1000 antihydrogen reconstructed annihilation events. The emulsion behavior at low temperature remains to be assessed and tests are presently under way to optimize the performances of the detector.


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