2 Test of the equivalence principle with antihydrogen

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(AEgIS Collaboration)

The main goal of the AEgIS experiment (CERN/AD6) is to test the Weak Equivalence Principle (WEP) using antihydrogen ($\bar{H}$). This principle of the universality of free fall has been tested with high precision for matter, but not with antimatter, due to major technical difficulties related to stray electric and magnetic fields. In contrast, the electrically neutral $\bar{H}$ atom is an ideal probe to test the WEP, and the antiproton decelerator (AD) at CERN is a worldwide unique antihydrogen factory. In AEgIS the gravitational deflection of $\bar{H}$ atoms launched horizontally and traversing a moiré deflectometer will be measured with
4 an initial precision of 1% on $|\Delta g|/g$, using a position sensitive annihilation detector. Details on the experiment can be found in ref. [1, 2].

The number of antihydrogen annihilations required to achieve a given precision decreases dramatically with increasing tracking resolution. In the proposal [1] a resolution of some 10 μm was to be achieved with a silicon strip annihilation detector. In 2012 we tested the use of emulsion films to achieve a resolution of the order of 1 μm [3, 4], and completed the construction of the annihilation detector (FACT) used to characterize the antihydrogen cloud prior to its acceleration into an $\bar{H}$ beam. Most of the AEgIS apparatus (apart from the gravity section) was commissioned in 2012, including the antiproton capture trap and the positron line. A photograph of the apparatus is shown in Fig. 2.1.

[1] G. Drobychev *et al.*, http://doc.cern.ch/archive/electronic/cern/preprints/spsc/public/spsc-2007-017.pdf.

[2] A. Kellerbauer *et al.*, Nucl. Instr. and Meth. **B 266** (2008) 351.

[3] C. Amsler *et al.*, J. of Instrumentation **8** (2013) P02015.

[4] M. Kimura *et al.*, 13th Vienna Conference on Instrumentation, (2013).

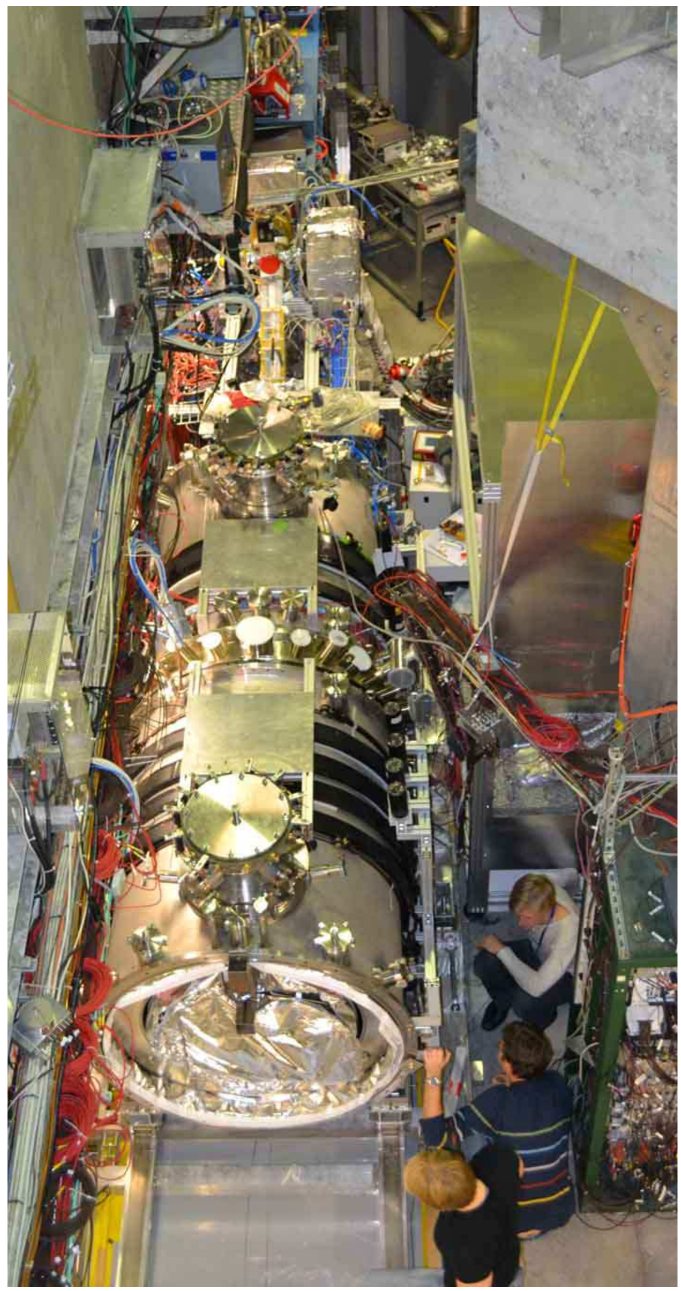

Fig. 2.1 – The AEgIS apparatus in the AD-hall at CERN in December 2012.

2.1 Nuclear emulsions

Nuclear emulsions [1] are photographic films with extremely high spatial resolution. A track produced by

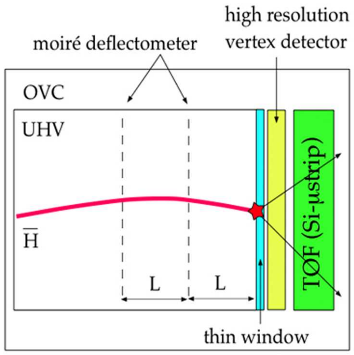

FIG. 2.2 – Schematics of the AEgIS detectors. The vertex detector is based on nuclear emulsions. The time-of-flight detector (TOF) measures the velocities of the $\bar{H}$ atoms.

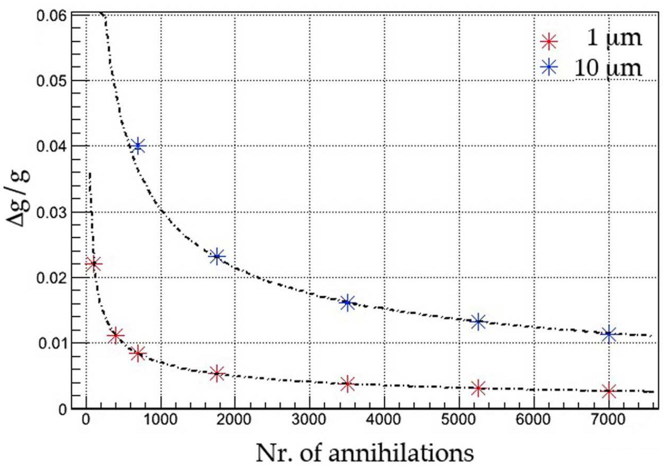

FIG. 2.3 – $\Delta g/g$ vs. number of particles for vertex resolutions of 1 μm and 10 μm.

a charged particle is detected as a sequence of silver grains, where about 36 Ag grains per 100 μm are created by a minimum ionizing particle. The intrinsic spatial resolution is around 50 nm. For AEgIS we developed nuclear emulsions which can be used in ordinary vacuum (OVC, 10^{-5} – 10^{-7} mbar). Figure 2.2 shows the setup envisaged for the g-measurement. The expected performance is shown in Fig. 2.3.

A sketch of the setup used for test exposures with stopping antiprotons in 2012 is shown in Fig. 2.4. The emulsion detector consisted of 5 sandwiches made of emulsion films (OPERA type). A thin foil will be needed in the g-measurement as a window to separate the $\bar{H}$ beam line at UHV pressure from the OVC section containing the emulsion detector. Thus for the tests half of the emulsion surface was covered by a 20 μm (SUS) stainless steel foil.

In December 2012 we also carried out measurements with a series of thin foils of varying compositions (Al, Si, Ti, Cu, Ag, Au, Pb) to determine the relative contributions from protons, nuclear fragments and pions as a function of atomic number. Figure 2.5 shows annihilation vertices on the bare emulsion surfaces and tracks behind a 5 μm thick silver foil. Tracks emerging from the annihilation vertex are clearly observed. Tracks from nuclear fragments, protons, and pions were reconstructed and the distance of closest approach between pairs of tracks was calculated. With *e.g.* a 20 μm steel window a vertex resolution of ~ 1 μm can be achieved.

Products from annihilating antiprotons (or $\bar{H}$ atoms) are emitted isotropically, in contrast to the τ-decay products measured in OPERA. The scanning efficiency must be improved for tracks traversing at large angles. We are also investigating the emulsions with higher sensitivity which were developed at Nagoya University and coated onto glass substrates in Bern. Glass is well suited for highest position resolutions thanks to its superior mechanical stability compared to plastic.

A proof of principle of the deflectometer to be used AEgIS was also performed in 2012 with emulsion films irradiated with antiprotons passing through a small moiré deflectometer shown in Fig. 2.6. The device contained several pairs of gratings with different spacings,

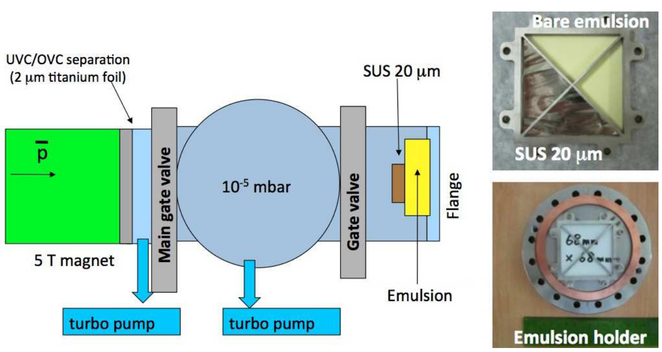

FIG. 2.4 –
Test setup with a picture of the vacuum flange holding the emulsion stack attached by a crossed bar frame.

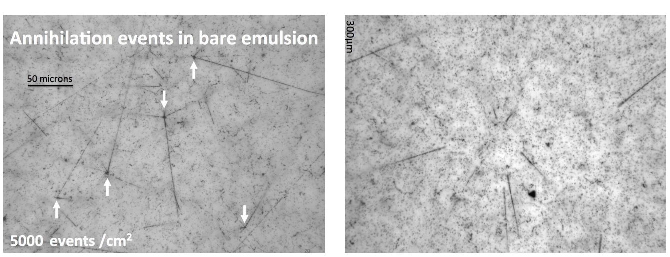

FIG. 2.5 – Typical antiproton annihilation vertices in the bare emulsion (left) and tracks observed behind a thin silver foil in which the antiprotons annihilate (right).

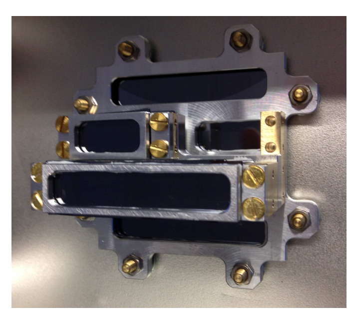

FIG. 2.6 – The miniature moiré deflectometer.

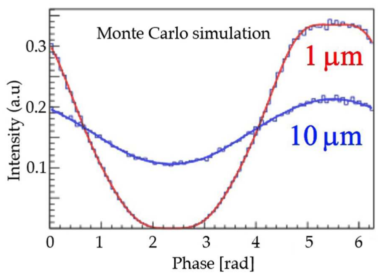

FIG. 2.7 – Simulated distributions of reconstructed vertices with position resolutions of 1 and 10 μm.

as well as gratings in direct contact with the films. Figure 2.7 shows as an example the simulated interference pattern at the emulsion layer, generated by a pair of gratings (12 μm slit, 40 μm pitch, separated by L = 25 mm). The antiproton data is being analyzed and preliminary results are quite encouraging.

[1] G. de Lellis, A. Ereditato, K. Niwa, *Nuclear Emulsions*, C. W. Fabjan and H. Schopper eds., Springer Materials, Landolt-Börnstein Database (http://www.springermaterials.com), Springer-Verlag, Heidelberg, (2011).

2.2 Fast Annihilation Cryogenic Tracking detector

The FACT detector [1] will determine the position of the annihilation vertex along the beam axis, which will enable measurements of antihydrogen production, temperature and beam creation. Charged pions from annihilations are traced back to determine the r, z - coordinates of the annihilation vertex. Simulations predict a vertex resolution of $\sigma = 2.1$ mm which satisfies our requirements. The detector (Fig. 2.8) must identify each of the $\sim$1000 annihilations in the 1 ms interval of pulsed $\bar{H}$ production, operate at 4 K inside a 1 T field, and produce less than 10 W of heat.

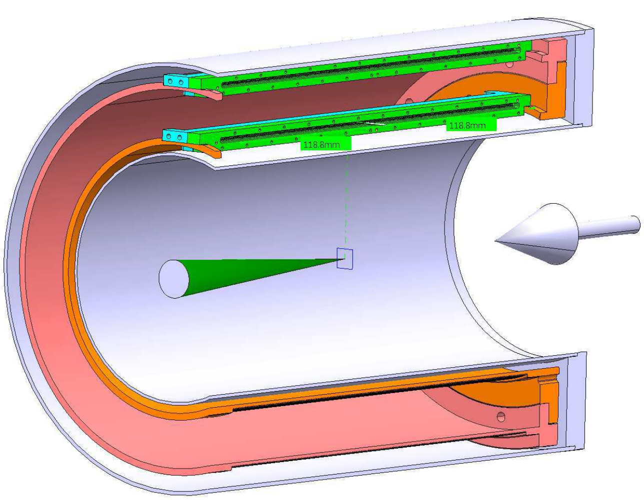

FIG. 2.8 – Support structure of the FACT detector. The beam axis is indicated by the arrow and the green cone illustrates the $\bar{H}$ beam enveloppe.

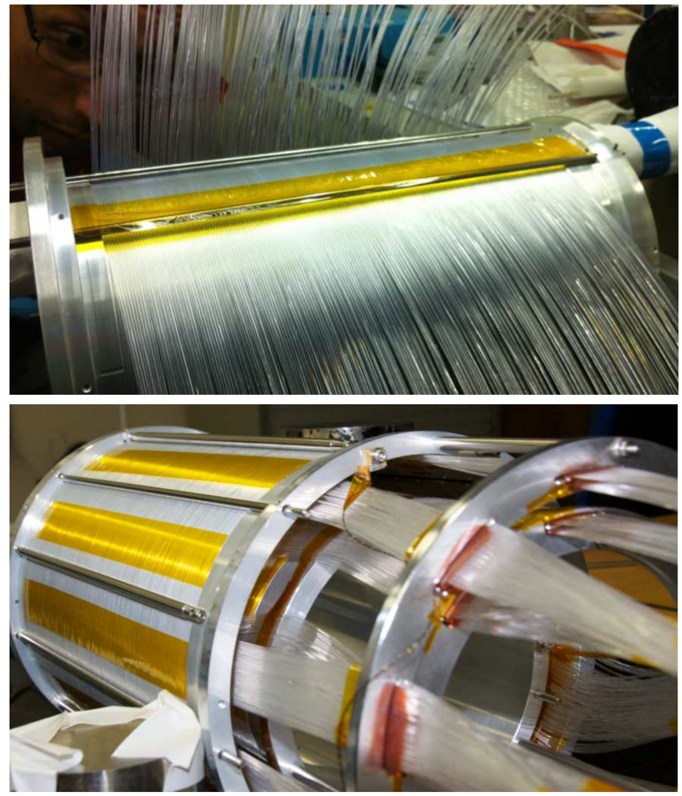

FIG. 2.9 – Scintillating fibers before (top) and after (bottom) being mounted on the support structure. Groups of 25 fibers emerging from the support structure are guided by a ring with rectangular slots.

The detector consists of two concentric cylindrical layers of scintillating fibers at radial distances of 70 mm and 98 mm from the beam axis. Each layer consists of 400 scintillating fibers (1 mm diameter Kuraray SCSF-78M) separated by 0.6 mm, located in U-shaped grooves, with alternate fibers displaced radially by 0.8 mm. Figure 2.9 shows the fibers before and after being mounted on the support structure.

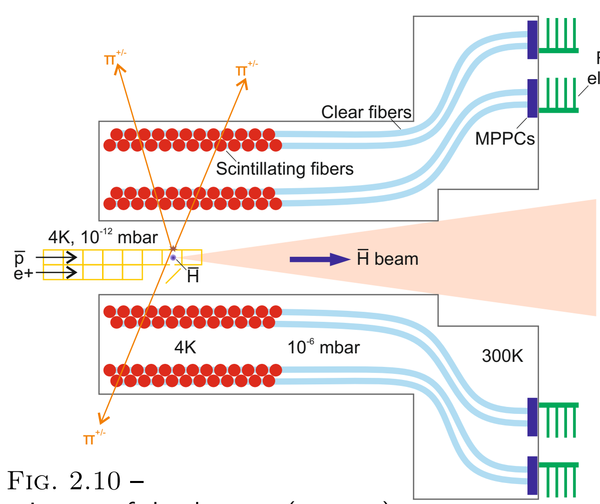

FIG. 2.10 –
Layout of the detector (see text).

Fig. 2.11 – Clear fibers connected to the MPPCs.

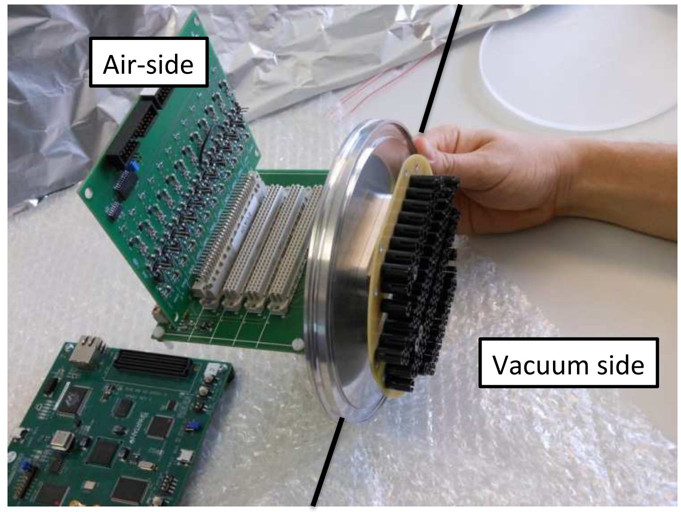

Fig. 2.12 – Air and vacuum side electronics for the FACT detector. On the bottom a Xilinx Spartan-6 FPGA development board.

The scintillating light is transported from the cryogenic region to the room temperature readout electronics by means of 2 m long clear fibers (Fig. 2.10). Particular attention was given to the routing of the clear fibers to ensure that the bending radius always exceeds 50 mm to avoid light losses. A plastic connector developed by the T2K collaboration is used to couple the clear fibers to Hamamatsu Multi-Pixel Photon Counters (MPPC) consisting of 100 Geiger mode Avalanche Photo Diodes (APDs). To minimise the heat load to the cryogenic region only the MPPCs are placed inside the vacuum vessel. A photograph of an assembled vacuum feedthrough is shown in Fig. 2.11.

Figure 2.12 shows a photograph of the readout electronics, designed to continuously detect the light from the scintillating fibers for the duration of the 100 ms period during which $\bar{H}$ is produced. The signals from 96 MPPCs on the vacuum side are routed via the backplane PCB to one of four analogue boards. The signals are amplified and connected to fast discriminators which are read directly by a Field Programmable Gate Array (FPGA). The readout is supervised by a Xilinx Spartan-6 FPGA development board. The complete readout system consists of 9 vacuum feedthroughs, 18 backplane PCBs, 67 analogue boards and 16 Spartan-6 development boards.

Cosmic ray tests of the plastic scintillating fibers at 4 K have been performed to study the light yield, the decay time and the lifetime of the fibers at cryogenic temperatures. The apparatus to perform this measurement consisted of 3 layers of 1 mm diameter scintillating fibers arranged in loops at the bottom of a liquid helium cryostat. The event rate decreased $\approx 10\%$ from room to liquid helium temperature. Examination of the fibers under a microscope after many cycles to 4 K revealed no sign of mechanical damage.

The FACT detector was installed in the AEgIS apparatus in 2012 and is currently undergoing commissioning with cosmic-rays. FACT will be used to study $\bar{H}$ formation, when the low energy antiproton physics programme resumes at CERN in 2014.

[1] J. Storey *et al.*, 13th Vienna Conference on Instrumentation, Vienna (2013).