2 Test of the equivalence principle with antihydrogen

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in collaboration with:
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(AEgIS Collaboration)

The AEgIS experiment [1] will measure for the first time the gravitational acceleration of antimatter $\bar{g}$ using a beam of antihydrogen ($\bar{H}$) atoms. Previous attempts to measure $\bar{g}$ with positrons and antiprotons failed due to stray electric or magnetic fields. From attempts to unify gravity with the other forces the possibility that $\bar{g} \neq g = 9.81$ m s^{-2} cannot be excluded [2]. Many arguments have been put forward to rule out any difference between g and $\bar{g}$, and correspondingly many rebuttals have been published [3]. The validity of the weak equivalence principle (WEP) for antimatter thus rests on experimental evidence.

The goal of AEgIS is to measure $\bar{g}$ with an initial precision of 1%. First we need to produce $\bar{H}$-atoms at ~100 mK. A promising technique [4] uses the interaction between the antiproton and the highly excited Rydberg state positronium (Ps*) in which the bound positron is captured by the antiproton and an electron is released ($\mathrm{Ps}^* + \bar{\mathrm{p}} \rightarrow \overline{\mathrm{H}}^* + \mathrm{e}^-$). Figure 2.1 shows a sketch of the apparatus. The process begins with the production of positronium (Ps) by accelerating 10^8 positrons from a Surko type accumulator onto a nanoporous material. The ortho-Ps emitted from the target is then brought to the Rydberg state Ps* by two-step laser excitation. Some of the Ps* atoms diffuse across a Penning trap in which 10^5 antiprotons from the CERN antiproton decelerator (AD) have been stored, producing $\bar{H}$ through the charge exchange reaction. An electric field is then applied along the beam axis to accelerate the $\bar{H}$-atoms to ~400 m/s. This

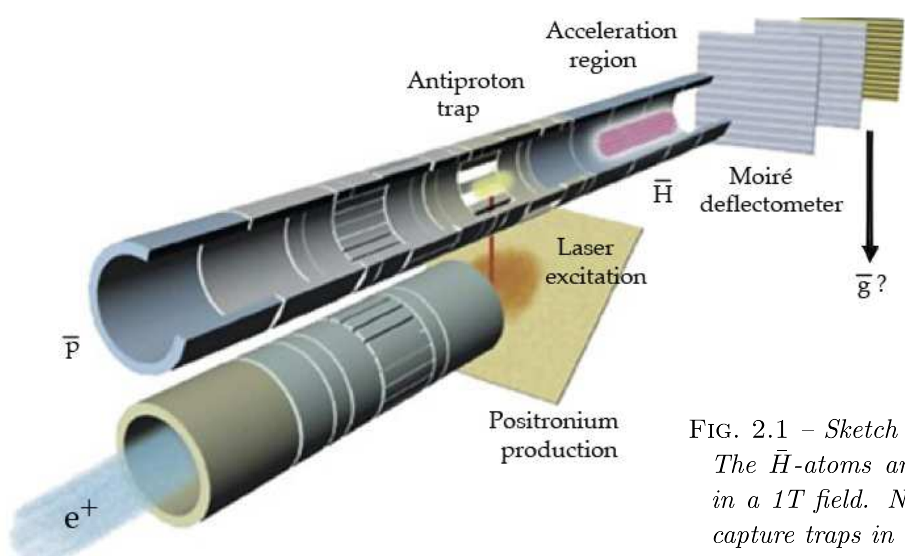

Fig. 2.1 – *Sketch of the AEGIS apparatus. The $\bar{H}$-atoms are produced in the $\bar{p}$-trap in a 1T field. Not shown are $\bar{p}$- and e^+-capture traps in the 5T magnet at the entrance of the apparatus.*

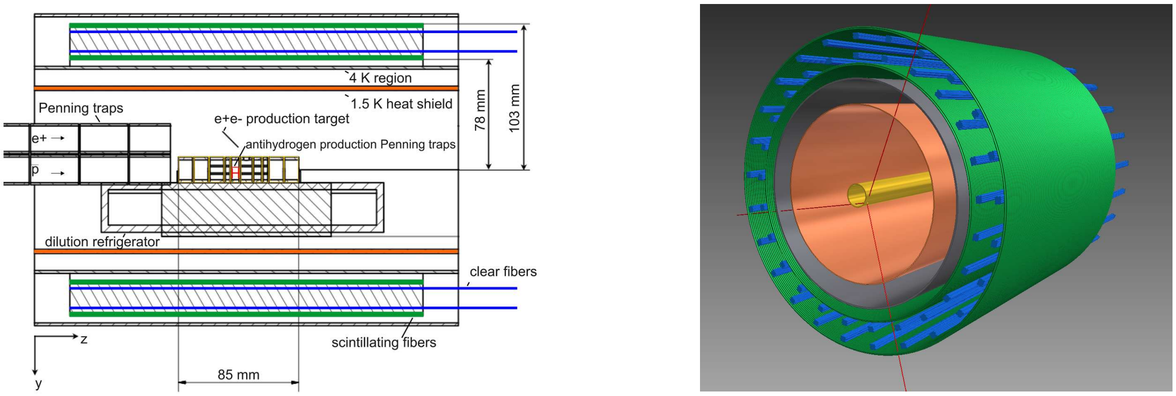

FIG. 2.2 – *Conceptual design of the Fast Annihilation Tracking (FACT) detector (see text).*

technique has already been demonstrated by members of the AEgIS collaboration with hydrogen atoms [5]. A Moiré deflectometer consisting of two gratings and a position sensitive annihilation detector is used to measure the deflection of the $\bar{H}$ beam in the gravitational field. The downward (or upward!) shift of the Moiré intensity pattern at the detector due to gravity needs to be combined with time of flight and be measured with a vertical precision of $\sigma \simeq 10$ μm. The Zürich group is designing and building (i) the annihilation detector and its readout to characterize the $\bar{p}/\bar{H}$ cloud in the Penning trap and (ii) the position sensitive detector to measure the Moiré pattern.

The AEgIS apparatus, less the Moiré deflectometer, will be installed for the AD runs in 2012. Objectives are to produce $\bar{H}$-atoms, measure their temperature and demonstrate the production of the $\bar{H}$-beam by means of Stark acceleration. The goal of our group is to commission the Fast Annihilation Cryogenic Tracking (FACT) detector designed and constructed in 2011/2012.

Depending on temperature, a large fraction of the $\bar{H}$-atoms annihilate by hitting the confinement walls within $\sim\mu$s. The detector must therefore be very fast, but only needs to be active for 1 ms every 100 s between AD pulses. The operating conditions are challenging as the detector occupies a cylindrical volume around the trap with an inner radius of 78 mm and outer radius of 103 mm in a 1T magnetic field, and must operate at 4K. A further complication is the strong 511 keV γ background produced by positrons hitting the positronium target. This occurs a few μs before the first $\bar{H}$ annihilations.

We have opted for a scintillating fiber detector with silicon photomuliplier readout. The FACT detector consists of four layers of 1 mm diameter scintillating fibers[1] coupled to clear fibers of the same diameter which direct the optical signal from the cryogenic region onto arrays of 1 mm diameter silicon photomultipliers (MPPC)[2]. Each layer consists of 200 scintillating fiber loops aligned orthogonal to the beam axis. A sketch is shown in Fig. 2.2. A vertex resolution along the longitudinal axis of 2.5 mm is expected from simulations, which is sufficient for our requirements.

The readout electronics for the 800 fibers must be fast enough to measure the speed (temperature) of the $\bar{H}$-atoms. The output of the MPPCs is sampled continuously. The principle is shown in Fig. 2.3 for a single channel. The MPPC is connected to a linear amplifier and a fast discriminator feeding the FPGA. The latter controls the MPPC voltage and threshold levels, samples the output of the comparators with a time resolution of $\sim$10 ns, and transfers the data to the DAQ system through a USB connection. A single FPGA manages several channels (upper part of Fig. 2.3). The FPGA can be programmed to perform a fast and

[1] Kuraray SCSF-78M multi-clad scintillating fibers [6].
[2] Hamamatsu silicon photomultipliers MPPC S10362-11-100C [7].

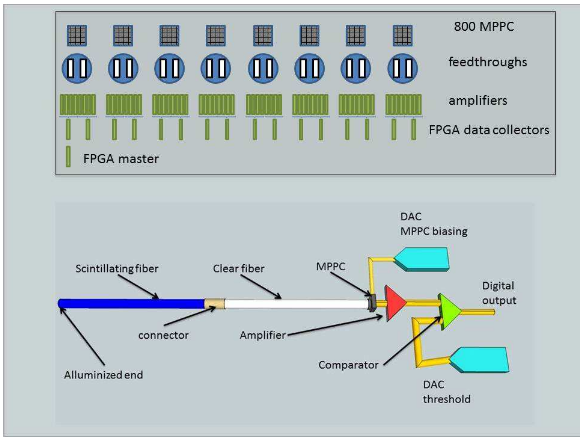

FIG. 2.3 – *Electronics layout for the fiber readout (see text) and readout for one scintillating fiber.*

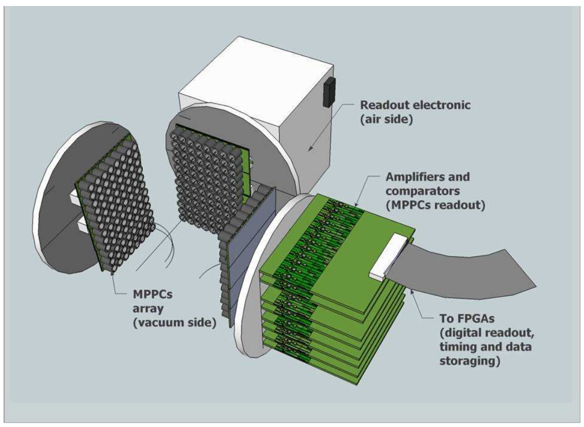

FIG. 2.4 – *MPPCs inside the vacuum region connected by feedthroughs to the readout electronics.*

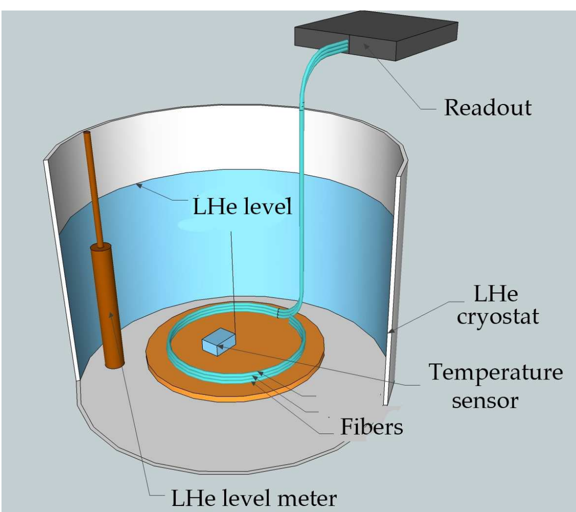

FIG. 2.5 – *Equipment used to measure the performance of scintillating fibers at cryogenic temperatures.*

smart real time readout of all channels. The MPPCs are located inside and the readout electronics outside the AEgIS apparatus (Fig. 2.4).

The scintillating fibers must operate at 4K. Since no data exist we have tested the performance of scintillating fibers with cosmic rays at cryogenic temperatures. The test apparatus consisted of 3 layers of 1 mm diameter Kuraray scintillating fibers arranged in loops at the bottom of a liquid helium cryostat (Fig. 2.5). The light from the scintillating fibers was detected by 3 MPPCs, the outputs of which were amplified and digitized by a LeCroy Wavepro 7100 10 GS/s oscilloscope. The oscilloscope was triggered when the signal of two of the three fibers exceeded 4 photoelectrons and we counted events with a coincidence observed in the third fiber, corresponding to the passage of a cosmic ray through the three fiber layers. The cryostat was filled with liquid helium immersing the fibers for 4 hours during which the detection efficiency was monitored, followed by warm-up to ambient temperature. The rate of events as a function of temperature is shown in Fig. 2.6. We observed a small ($\sim$15%) decrease in light yield from room to liquid helium temperature.

We are also investigating (in collaboration with the Albert Einstein Center in Bern) the possibility to use photographic emulsions of the OPERA type to reconstruct more accurately the interference pattern in the gravitation experiment. We would measure the annihilation points of $\bar{H}$- atoms on the vacuum exit window behind the Moiré de-

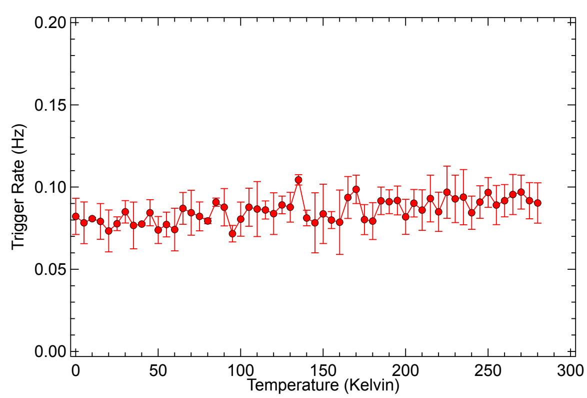

FIG. 2.6 – *Trigger rate of a scintillating fiber from cosmic rays as a function of temperature (see text).*

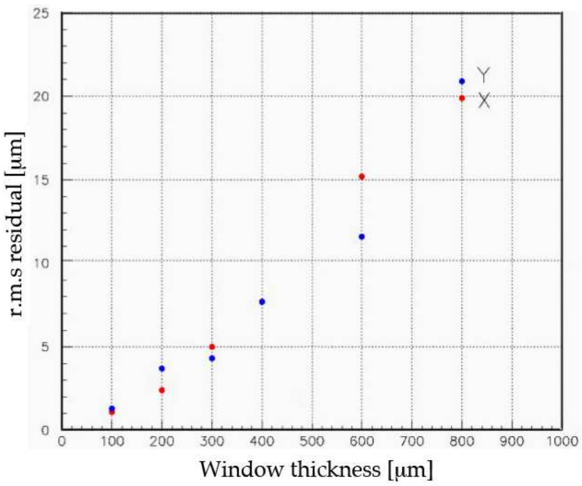

FIG. 2.7 – *R.m.s. position resolution on annihilation tracks as a function of thickness for a titanium vacuum window in which the $\bar{H}$-atoms annihilate.*

flectometer, using two or more annihilation pions. The emulsion stack would be placed immediately behind a very thin window separating the UHV vacuum from normal vacuum. The time-of-flight and the approximate track positions would be determined by a silicon or scintillating fiber detector located outside the vacuum enclosure and stored for offline analysis. The emulsions would then be removed periodically and processed in Bern. Figure 2.7 shows the expected vertical resolution on the annihilation point due to multiple scattering as a function of window thickness (neglecting distortions and alignment errors). The Monte Carlo simulation indicates that r.m.s position resolutions of 3 μm could be achieved on the annihilation vertex, much better than the required 10 μm, thus allowing a more accurate measurement of $\bar{g}$.

However, technical issues such as the performance of emulsions in vacuum (in particular dehydration) need to be investigated first. Also the background rate in the AD hall due to muons from the antiproton production target and from annihilation pions in the AEgIS apparatus need to be measured to assess the frequency at which emulsions would need to be changed. In 2012 we will commission the FACT detector and perform several test with photographic emulsions to plan for the first measurement of $\bar{g}$ after the 2013 maintenance of the CERN accelerators.

[1] Proposal: http://doc.cern.ch/archive/electronic/cern/preprints/spsc/public/spsc-2007-017.pdf

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