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Antimatter annihilation detection in AE$\bar{g}$IS

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AE$\bar{g}$IS (Antimatter Experiment: Gravity, Interferometry, Spectroscopy) is an antimatter experiment based at CERN, whose primary goal is to carry out the first direct measurement of the Earth's gravitational acceleration on antimatter. A precise measurement of antimatter gravity would be the first precision test of the Weak Equivalence Principle for antimatter. The principle of the experiment is based on the formation of antihydrogen through a charge exchange reaction between laser excited (Rydberg) positronium and ultra-cold antiprotons. The antihydrogen atoms will be accelerated by an inhomogeneous electric field (Stark acceleration) to form a pulsed cold beam. The free fall of the antihydrogen due to Earth's gravity will be measured using a moiré deflectometer and a hybrid position detector. This detector is foreseen to consist of an active silicon part, where the annihilation of antihydrogen takes place, followed by an emulsion part coupled to a fiber time-of-flight detector. This overview presents the current results from the R&D efforts for the construction of the silicon position detector. Low energy antiproton annihilations in silicon were studied in detail using different silicon sensor technologies. A first comparison between experimental data and Monte Carlo simulations for low energy antiproton annihilation is also reported, suggesting areas where the improvement of simulation models is possible. The outcome of these tests defined the basis for the final design parameters of the silicon position detector. This detector will consist of a 50 μm thick silicon strip sensor bonded to an application specific integrated circuit (ASIC) with self-triggering readout capabilities and a timing resolution in the order of μs.

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1. The AEḡIS experiment

AEḡIS is an antimatter experiment at the Antiproton Decelerator (AD) that aims at carrying out the first precise measurement of the local gravitational acceleration for antimatter, i.e. for antihydgrogen [1]. Such a measurement would test the universality of free fall, which has been tested to a precision of 1 in 10^{12} for matter, but never precisely for antimatter. In the first phase of the experiment, the gravity measurement will be attempted by producing a cold, pulsed antihydrogen beam and measuring its vertical shift after a free fall of about 1 m in the horizontal direction. Higher precision gravity and/or accurate spectroscopic measurements, such as Rydberg spectroscopy are foreseen for the later stage of the experiment.

The antihydrogen production scheme in AEḡIS is based on a charge exchange reaction between ultra-cold antiprotons and Rydberg state positronium [2]. A scheme of the apparatus is given in fig. 1. The 5.3 MeV antiprotons that are supplied by the AD are slowed down with several degraders, then trapped into the catching traps inside the 5 T magnet and cooled down by means of electrons. The positrons are supplied from a ^{22}Na source and are guided into the main apparatus via their own transfer line. Both particles (antiprotons and positrons) will be transferred, through the central region into the 1 T magnet, where the mixing trap is placed and where the charge exchange reaction will occur. Prior to this reaction, the positrons will be converted into positronium using a nanoporous material [3] and the positronium will be subsequently laser excited to Rydberg states (n=20-30) [4].

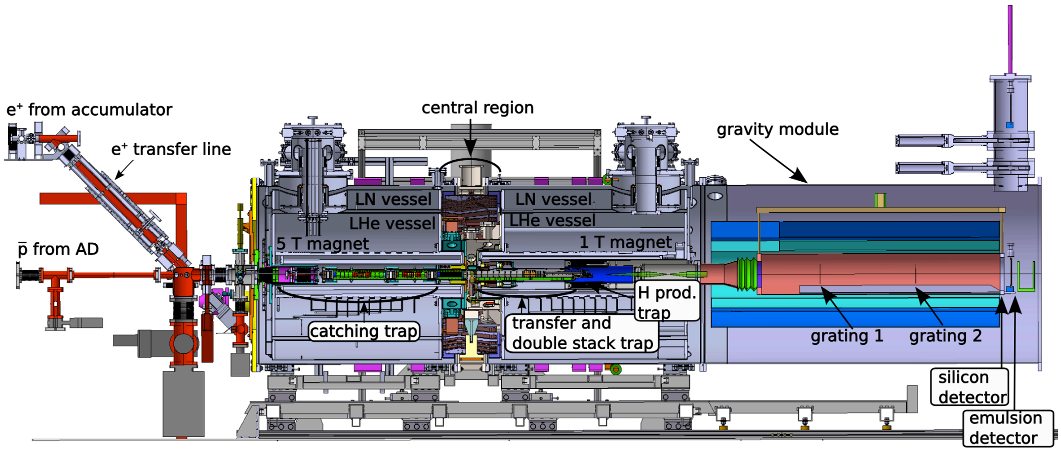

Figure 1: A schematic cross-sectional view of the AEḡIS apparatus at CERN, showing its different parts. Positrons from the accumulator (not shown) are transferred to the 5 T magnet with their own transfer line. The 5 T and 1 T magnet are connected through the central region and house the catching traps, the transfer traps and the antihydrogen production ultra cold trap. The gravity module will be attached downstream the 1 T magnet and encloses the moiré deflectometer and the hybrid position detector.

The produced antihydrogen atoms will be in Rydberg states and they can be accelerated into a horizontal beam by applying an inhomogeneous electric field (Stark acceleration) [5]. The expected free fall of the ultra-cold antihydrogen over a horizontal path of $\sim$1 m is in the order of tens of

μm. This vertical shift is proportional to the gravitational acceleration for antihydrogen and will be measured through the shift of a shadow pattern produced by the antihydrogen atoms that pass through a set of gratings, i.e. moiré deflectometer [6, 7], as shown in fig. 2. A specially designed position detector, consisting of a silicon and emulsion part according to the current design, will detect the antihydrogen annihilations and give the required position and timing information to determine $\bar{g}$.

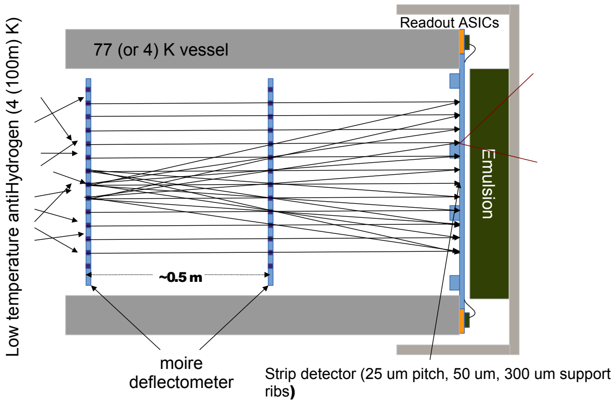

Figure 2: Schematic overview of the propagation of the antihydrogen beam throuhg the two-grating moiré deflectometer, before being detected by the position sensitive detector.

2. Development of a silicon position detector

The position detector in AEḡIS is an ensemble of three different detector technologies: silicon detector, emulsion detector [8, 9] and fibre detector. The silicon detector is the front-most layer where the antihydrogen atoms annihilate after passing through the gratings of the moiré deflectometer. Its role is to provide an on-line measurement of each antihydrogen annihilation, including an information on the annihilation position ($\sim$ 10 μm) and the arrival time. According to the current mechanical design of the AEḡIS apparatus, this detector will act a separation membrane between the ultra-high vacuum (10^{12} mbar) and the secondary vacuum (10^{6} mbar), and will operate in cryogenic conditions at 77 K or 4 K. The active area covered by the detector will be about 10×7 cm^2. In this configuration, the silicon detector serves both as an annihilation and detection medium.

When the antihydrogen atoms arrive on the detector surface, the antiproton annihilates with a nucleon of the silicon atom, producing mesons (mostly pions). The mesons interact with the remaining nucleus and cause its fragmentation, where a variety of charged nuclear fragments of different energies penetrate into the detector and are detected [10]. In order to minimize the scattering for the pions and protons emerging from the antiproton annihilation in the silicon, to be detected by the emulsion detector, the maximum allowed thickness for the silicon detector is 50 μm. Given the expected velocity distribution of the antihydrogen atoms (few hundred m/s) and the distance that they will travel before annihilating on the detector (1 m), the necessary time resolution is in the order of μs.

The development of the silicon position detector included several beam test periods with different detector technologies in order to study the annihilation of low energy antiprotons in silicon, to define the design specifications and to make estimations on the position resolution of the annihilation point. The results from the beam test campaigns elaborated here have been published [11, 12, 13] and what follows is a summary.

3. Low energy antiproton annihilations in silicon detectors: measurements and results

3.1 MAPS detector

The design process of the silicon position detector started with studying the signature of low energy antiproton annihilations in different sensor technologies. No detailed study on this topic was found in literature and a systematic investigation was performed by exploiting several silicon detectors. During the beam test campaigns, each of these detectors was placed at approximately the same position in a six-way cross attached at the end of the AE$\bar{g}$IS apparatus. A detailed description of the set-up is given in [11]. The first measurements were expected to be mainly used for the estimation of the energy deposited in the detector due to an annihilation. For this reason, a Monolithic Active Pixel Sensor (MAPS) with wide dynamic range was chosen. After the successful observation of the on-sensor antiproton annihilations in silicon, the clusters produced from the annihilation events were studied in terms of energy and topology (fig. 3 and fig. 4), showing that an annihilation can deposit as much as 40 MeV in the MAPS. The small geometrical acceptance of the MAPS due to its small thickness (14 μm) resulted in small clusters that consisted mainly of one or two pixels. Tracks from the annihilation products were observed in very few events ($\sim$ 20 in total). The results were compared with two GEANT4 [14] simulation models, FRITIOF Precompound (FTFP) [15] and CHiral Invariant Phase Space (CHIPS) [16], showing that agreement for both models at energies $<$ 5 MeV is generally poor, and that FTFP provides a better description of data points for energies $>$ 5 MeV. The results also provided directions for improvements and tuning of these models. The measurements and the detailed results are presented and extensively elaborated in [11].

3.2 3D silicon pixel detector

In the next step of the study of low energy antiproton annihilations, measurements were carried out with a 3D silicon pixel detector, originally developed for the ATLAS experiment at CERN. While the analysis from the data taken with MAPS provided an indication of the deposited energy due to an antiproton annihilation, the data obtained with the 3D detector were more suitable for a thorough investigation on the topology of the clusters as well as the tracks produced by the annihilation prongs. A sample event is given in fig. 5. The linear fitting of the tracks and the calculation of the errors on their interception point allowed to determine the position resolution on the annihilation point that can be achieved which the 3D detector, which was found to be $\sim$20-30 μm.

A comparison of the results for the two pixel detectors (MAPS and 3D) was performed, indicating the advantages for each of them when used for our specific application, i.e. detection of low

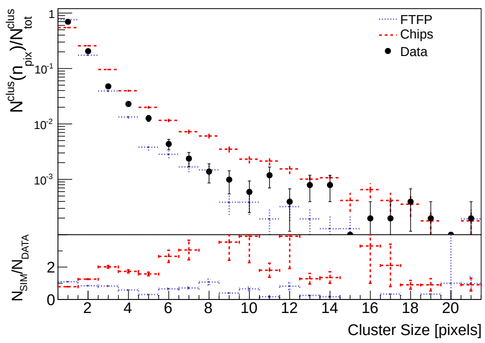

Figure 3: Cluster size distribution for data obtained with MAPS and the two studied simulation models. Most clusters have 1 or 2 pixels, but some clusters consist of as many as 20 pixels [11].

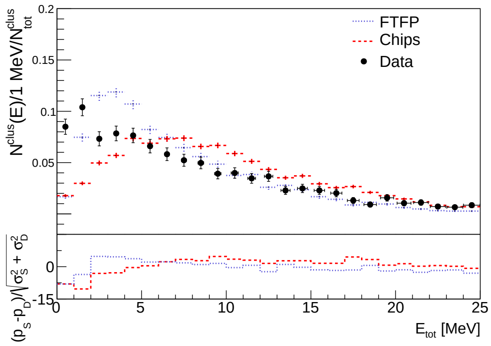

Figure 4: Distribution of the total cluster energy for the antiproton annihilatin in MAPS compared to the two simulation models, FTFP and CHIPS, excluding the one-pixel clusters [11].

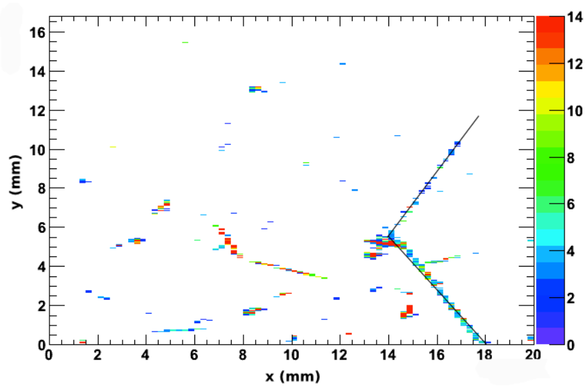

Figure 5: Sample hitmap of the 3D sensor with two fitted proton tracks coming from an antiproton annihilation, used to reconstruct the annihilation point [12].

energy antiproton annihilations. Fig. 6 and 7 show the results for the cluster size and the deposited cluster energy in both MAPS and 3D detectors. Also shown are the respective simulation results in GEANT4. The small thickness and the relatively low granularity of the MAPS detector resulted in smaller clusters when compared to the typical annihilation event of the 3D detector, where more and longer tracks were observed, as a result of the thicker active volume.

Despite the smaller cluster size observed in the MAPS detector, the overall deposited energy due to an annihilation was found to be higher in the MAPS than in the 3D. This effect is caused by the low dynamic range of the 3D detector, which led to saturation of ∼35 % of all hit pixels. A simulation for the deposited energy in the 3D detector without taking into consideration the saturation was also performed, as shown in fig. 7. Despite the greater thickness of the 3D, these simulations indicated a lower energy deposition from an antiproton annihilation in the 3D when compared to MAPS. This effect is assumed to happen due to the much thicker passivation layer of the 3D detector (∼3 μm) compared to the MAPS (only 100 nm), which prevents the heavy ions emerging from the annihilation to penetrate the active volume of the detector. The results for the 3D detector and the comparison were fully reported in [12].

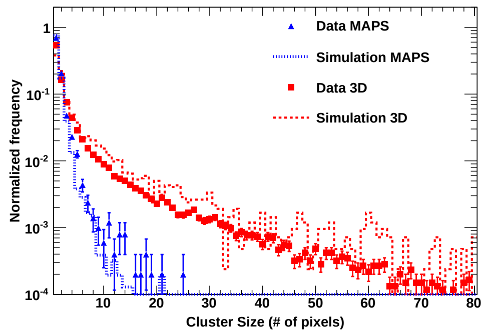

Figure 6: Cluster size distribution for the MAPS and 3D pixel sensors for data and the respective simulation results in GEANT4. All distributions are normalized to unit integral [12].

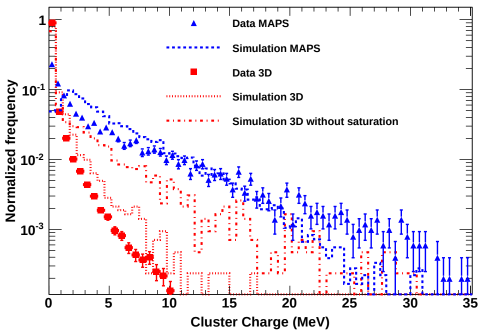

Figure 7: Cluster energy distribution for the MAPS and 3D pixel sensors for data and the respective simulation results in GEANT4. All distributions are normalized to unit integral [12].

3.3 Silicon microstrip detector

Another geometry that was investigated in the scope of the design process of the silicon position detector in AEḡIS was the silicon strip sensor. The main advantages of the planar strip sensors specific to our application are the possibility of having a thin sensitive volume that would minimize the scattering of the pions and protons to be detected by the downstream emulsion detector and the possibility to operate the detector in cryogenic conditions. The measurements were performed with planar strip sensors on standard 300 μm thick, MCz n-type wafers with p^+ strip implants. Two different sensors with 50 μm and 80 μm strip pitch and 1 cm strip length, read out with Alibava R/O system with two Beetle chips were exploited. The dynamic range spans from 20 keV (5 noise RMS) up to 800 keV per strip. Annihilations of low energy antiprotons were detected at different bias voltages in order to asses the impact of the active volume thickness on the cluster size and the total cluster energy. Fig. 8 shows the two extreme cases where the applied bias voltage is equal to the built-in potential of the sensor (0.6 V) and, in the second case, above the full depletion voltage (150 V, over-depleted sensor). By increasing the depletion voltage the sensors become sensitive to long-range particles (pions and high energy protons), which results in an increase of the cluster size. Therefore, a better spatial localization of the antiproton annihilation is achieved at lower bias voltages, through detection of highly ionizing fragments only. For the same reason, the total cluster energy is higher at low depletion, with most clusters having a total energy lower than 600 keV, as presented in fig. 9. In general, most of the annihilation events deposit energy >200 keV, up to saturation. The overall analyses and results are presented in [13].

4. Conclusions and further work

The work summarized here was performed in order to define the design parameters of the silicon position detector for the AEḡIS experiment. The emphasis in the research was on recognising

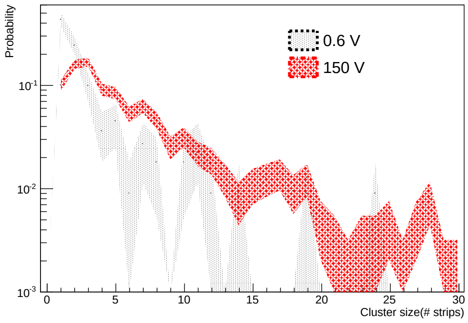

Figure 8: Cluster size distribution for the planar strip sensor for two extreme cases of the applied bias voltages: 0.6 V ($\sim$ built in potential) and 150 V (overdepleated sensor), normalized to unit total integral [13].

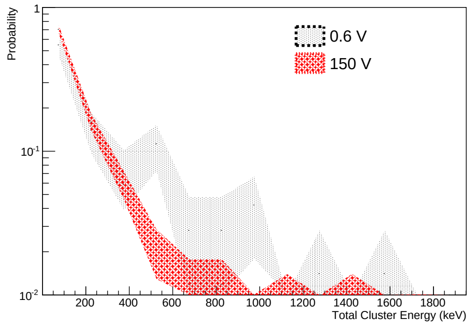

Figure 9: Deposited energy distribution of the clusters obtained in the planar strip sensor for two extreme cases of the applied bias voltages: 0.6 V and 150 V, normalized to unit integral [13].

and studying the signal from a low energy antiproton annihilation event in different silicon sensor technologies, originally designed to detect minimum ionizing particles (planar strip and 3D pixel sensors) or slow charged hadrons (planar monolithic pixel sensor). The annihilation events were characterized by the size of the produced clusters and the deposited energy. The presented test-beam data, together with the mechanical constraints imposed by the design of the AEḡIS apparatus allowed to define the specifications for the final AEḡIS silicon position detector that is currently being produced, i.e. the most suitable technology to be implemented, the required dynamic range and the geometry. The silicon detector that is currently being produced will consist of a planar strip sensor with a thickness constraint of 50 μm and will be read out with daisy-chained readout made of ten ASICs (256 channels each), manufactured by SINTEF and IDE AS (Norway), respectvely. The strip pitch will be 25 μm and the reconstruction of the annihilation position will rely mostly on the detection of highly ionising annihilation products. Moreover, the relatively small thickness reduces the sensitivity to sidewise travelling products, enhancing the resolution. The chip interface is to be derived from the VATAGP7.1 readout chip [17] which allows for sparse readout i.e. only the strips with a hit are read, thus reducing the dead time of the detector. Moreover, as the antihydrogen arrival time is one of the quantities to be measured, the ASIC will have self-triggering readout capabilities. Other characteristics specific to the chip design will include extended dynamic range (up to 1 pC of charge per channel), cryogenic operation, which reliability will be ensured by the possibility to force specific bias voltages to critical elements of the chip (pre-amplifier, shaper, etc) and low power dissipation (in the order of 1mW per readout channel). The chip will be manufactured in CMOS 0.35 μm technology.

Further work has the potential of improving the efficiency and resolution of the AEḡIS silicon annihilation detector by means of new reconstruction algorithms. While, ideally, simulation tools would be the benchmark for such algorithms, this R&D has pointed out some limits of the simulation models, where more work is required. A strong potential for future upgrades of the silicon position detector is seen in the pixel detector technology and measurements with a 300 μm thick silicon pixel sensor bump bonded to the Timepix3 [18] readout chip are undergoing. The main goal of this ongoing work is to investigate different algorithms for the reconstruction of the annihilation point and to study their accuracy. One of the main ideas is to track the prongs back to the annihilation point and fit the tracks with weighted fitting algorithms.

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