6 Production and Spectroscopy of Antihydrogen

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(ATHENA Collaboration)

The goal of the ATHENA (AnTiHydrogEN Apparatus [1]) experiment is to produce antihydrogen atoms at low energies, to capture them in a magnetic trap and to compare by 2 photon laser excitation the 1S - 2S energy difference of antihydrogen with the one for hydrogen, in view of testing CPT invariance at the level of about 1 part in 10^{15}.

In a first phase of the experiment (2000 - 2001) we will study the formation rate of antihydrogen atoms as function of temperatures and densities of the antiproton and positron plasmas. No attempt to capture antihydrogen will be done. A first test run is foreseen for July 2000. In the second phase of the experiment (2002 - 2004) the neutral antihydrogen will be captured in a magnetic trap for precision spectroscopic measurements. The experimental setup for the first phase consists of two main parts:
a) The apparatus to collect antiprotons and positrons and bring them in close contact to produce antihydrogen. This part is briefly described in the Sec. 6.1.
b) The annihilation detector that will monitor the number of produced antihydrogen atoms. Our institute has the main responsibility for the design and construction of this detector. The detector elements and electronics are described in more detail in Sec. 6.2.

6.1 Production of antihydrogen

The apparatus to produce antihydrogen is presently being assembled in the AD hall at CERN. It consists of a superconducting solenoid (3 T) with a cold bore to house the antiproton capture trap, the positron storage trap, and the recombination trap.

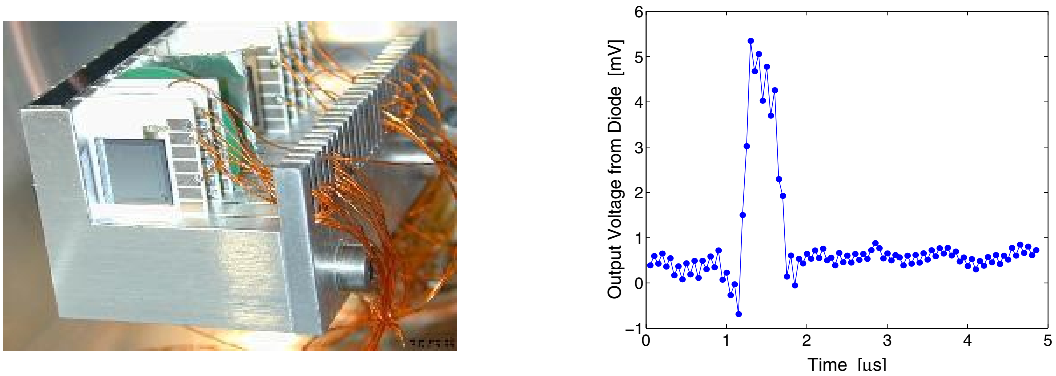


Figure 6.1: *Left: Beam telescope consisting of 6 silicon diodes. The 6 micron thick diodes have an active area of 1 cm*^{2}*; right: Signal amplitude produced by a bunch of slow antiprotons (100 MeV/c) going through one of the Si diodes. Note the small noise level, which was not obtained in a clean laboratory environment, but in a noisy accelerator hall!*

Antiprotons were extracted from the Antiproton Decelerator (AD) for the first time in November 1999. We designed a telescope to monitor the beam, consisting of ultra thin

(6 μm) silicon diodes obtained from SINTEF, Norway (fig. 6.1). The small signal from a bunch of antiprotons (extracted within 200 ns) could be identified unambiguously by the diodes. Multiple scattering in these thin diodes is negligible, making them ideal to be used as beam counter in the apparatus. Unfortunately, the beam was still too divergent to be transported to the antiproton trap.

The configuration of the electromagnetic field in the antiproton trap is similar to the one for a Penning trap. The antiprotons are confined in the radial direction by the magnetic field of the solenoid and in the axial (z) direction by an electric quadrupole field produced by cylindrical electrodes. The positrons from a strong ^{22}Na source will be accumulated in a similar Penning trap. From these traps the particles will be transported by electrical fields to the recombination trap, which consists of a series of coaxial cylindrical electrodes with alternating electric fields (fig. 6.2).

The loading, storage in a Penning trap and dumping of an electron plasma was studied in a test setup, called MINERVA (see ref. [2] for details). The signal amplifiers of the pickup electrodes (Faraday cups) were built in the electronics workshop of our institute. Several voltage dividing and switching schemes were studied. The setup was controlled by a PC running a LabView DAQ program. The results of these tests are now used for ATHENA, where currently the antiproton trap is tested with electrons.

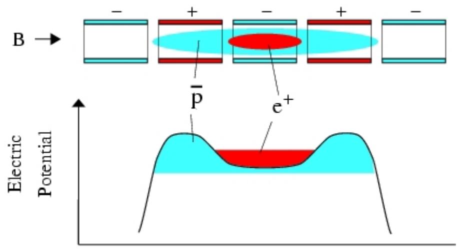


Figure 6.2: *The recombination trap is a nested Penning trap which brings the antiprotons and positrons in close contact for a time sufficiently long to allow the formation of antihydrogen.*

6.2 Annihilation detector

Once antiprotons and positrons have been recombined, the confinement by electric forces ceases, causing the antihydrogen atoms to escape, to hit the trap wall and to annihilate. The unambiguous proof of antihydrogen formation will be obtained by detecting antiproton annihilation products in time coincidence with the two back-to-back 511 keV photons from e^+e^- annihilation.

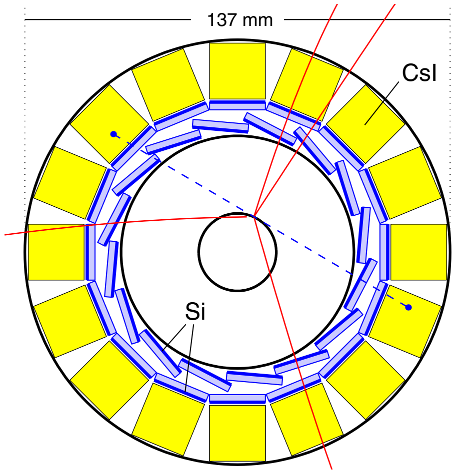


Figure 6.3: *Front view of the ATHENA annihilation detector showing a Monte Carlo simulation of an antihydrogen atom annihilating into pions (solid lines) and into two back-to-back 511 keV photons (dashed lines). The pions are detected in the two layers of silicon microstrip detectors and the 511 keV photons in the CsI crystals. The two fired crystals and the reconstructed annihilation vertex should lie on a straight line, an important requirement to reduce background.*

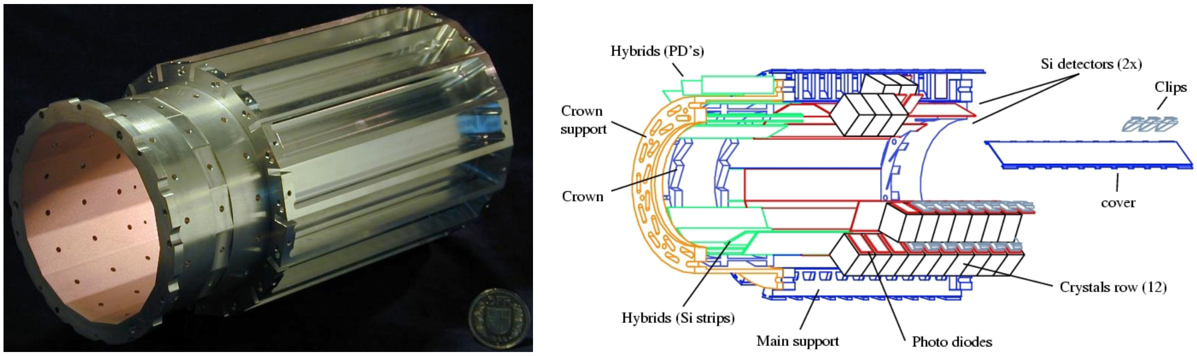


Figure 6.4: *Left: Aluminium support structure of the annihilation detector; right: Cut-away view of the annihilation detector.*

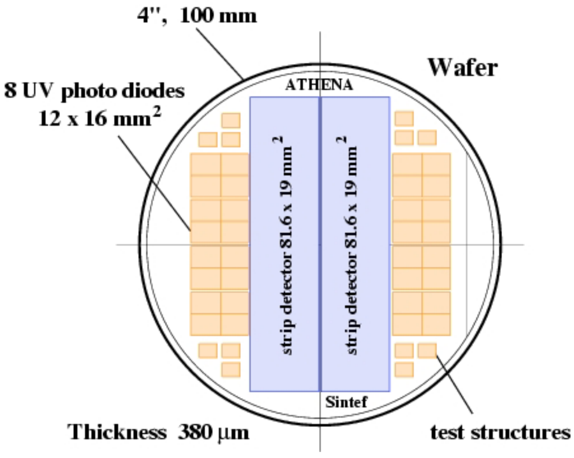
The detector (figs. 6.3 and 6.4) consists of two parts: Two cylindrical layers of 16 silicon microstrip modules each detect the charged pions stemming from an antiproton annihilation on the wall of the recombination trap or with a rest gas atom. The second part, a cylindrical array of 192 pure CsI crystals, will detect the 511 keV photons from e^+e^- annihilation.

The mechanical structure holding the silicon microstrip modules and the CsI crystals (fig. 6.4) was machined from one block of aluminium in the mechanics workshop of our institute. The inner wall of the support structure had to be as thin as possible to minimize multiple scattering and γ conversions. After premachining the inner part of the aluminium block, the final precise shape of the inner surface was achieved by electroerosion at Helefil, France.

Since the recombination trap works at very low temperature (< 1 K) the surrounding annihilation detector cannot operate at room temperature. In 1998 (see the previous annual report) we demonstrated that the silicon microstrips and the amplifiers work at liquid nitrogen temperatures (77 K). The detection of the 511 keV photons with pure CsI crystals at 77 K was also demonstrated with photomultipliers [3]. In 1999 the next step from the prototype to the complete detector design was made. Details are given in the following subsections.

6.2.1 Silicon microstrip detector

The silicon wafers (fig. 6.5) containing the microstrip detector modules were produced by SINTEF, Norway. The wafers also included especially designed UV-sensitive photodiodes to be used for the readout of the CsI crystals (next subsection).



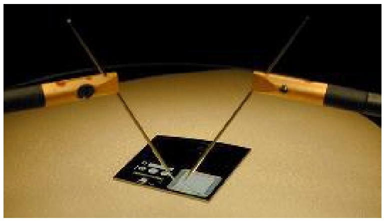


Figure 6.5: *Top: Static tests on the probe station; left: Silicon wafer layout of 2 double sided strip detectors and 8 photo diodes with extremely thin entrance windows (UV-sensitivity).*

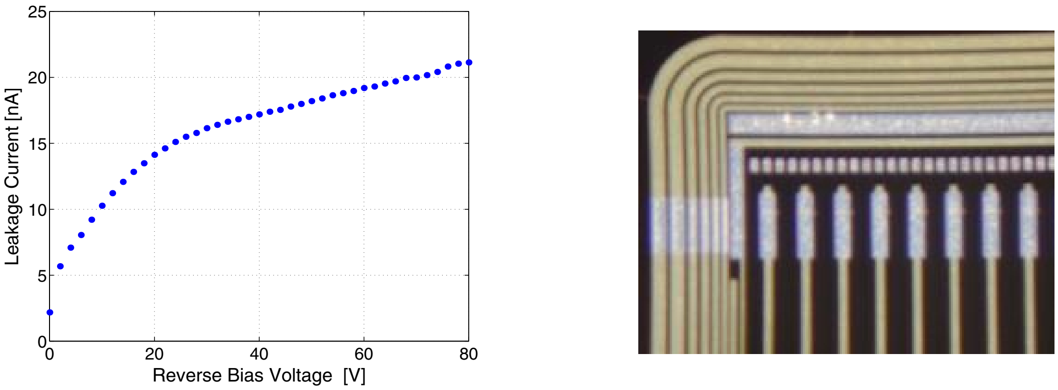


Figure 6.6: *Left: I- V curve of a strip detector measured on a probe station; right: Detail of the front side of the microstrip detector showing the multiple guard ring structure and the bond pads at the end of each readout strip.*

Each strip detector has an active area of $18.1 \times 80.2\,\mathrm{mm}^2$ and a thickness of $380\,\mu$m. The front side is divided into 384 strips with a pitch of $47\,\mu$m (measurement of the azimuthal angle ϕ), but every third strip only is connected to the readout electronics. The charge collected by the floating strips induces a signal on the readout strips by capacitive coupling. A multiple guard ring structure around the strips (fig. 6.6) ensures low leakage current and a good stability against breakdown. The back side contains 64 pads with a pitch of 1.25 mm. The pads are perpendicular to the strips (measurement of the z coordinate along the detector axis).

Static tests of the silicon microstrip detectors and photodiodes were done using our newly acquired probe station and standard laboratory equipment controlled by a Macintosh computer running a LabView DAQ program (see ref. [4] for details). The performances (leakage current, breakdown stability, functionality of guard rings and depletion voltages) exceeded in general our design expectations.

6.2.2 CsI Crystals

The positron annihilation detector consists of 16 rows of 12 CsI crystals. The crystal dimensions are $13 \times 17.5 \times 17.5\,\mathrm{mm}^3$ giving a total length of 16 cm in z direction. Tests with crystals from various suppliers using different polishing and wrapping methods were done at Pavia [5]. The crystals were directly coupled to Hamamatsu S3590 photodiodes (quantum efficiency 37 %) without grease. From these tests CHRISMATEC was chosen as supplier and 220 crystals were delivered.

For optimum light output we designed a special photodiode optimized for the 350 nm UV light from pure CsI crystals at 77 K. The quantum efficiency is expected to exceed 90 %. To reduce costs the photodiodes were produced on the same wafers as the microstrip detector (see fig. 6.5). Results from test diodes obtained from SINTEF are very promising. For 511 keV photons a resolution of 9.4 % was obtained (fig. 6.7). The light output of the crystals produces 28,000 photoelectrons/MeV in the photodiode. This number was obtained from the position of the 511 keV peak in the spectrum and from an absolute calibration of the photodiode using the 22 keV photons from a ^{109}Cd source. It is in agreement with a first estimate obtained from measurements with photomultipliers [3]. As expected, the light output increases with decreasing temperature down to 120 K (fig. 6.7). However, below 120 K it decreases again and at 77 K the light yield is only 55 % of the maximum yield at 120 K. This behaviour is not understood yet. Measurements with Hamamatsu photodiodes and

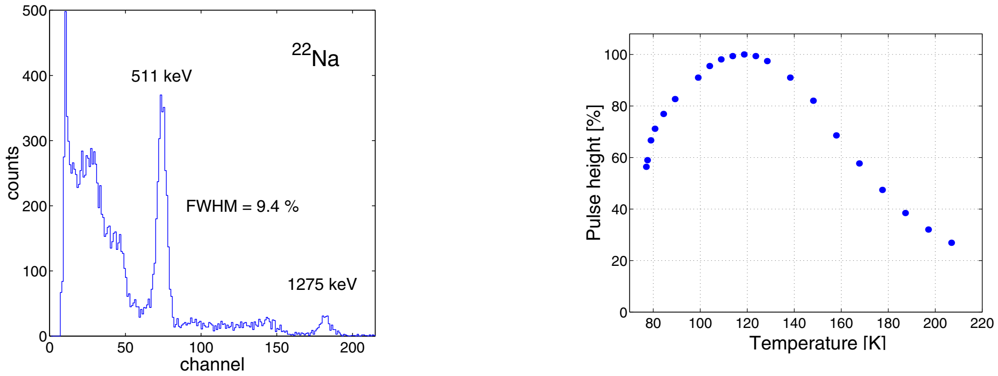


Figure 6.7: *Left: Spectrum of a* ^{22}*Na source measured at 120 K; right: Pulse height of 511 keV* γ*'s as function of crystal temperature.*

photomultipliers show that the light yield does not decrease significantly ($\leq 10\%$) between 120 K and 77 K.

6.2.3 Electronics

To increase the solid angle for detection, two silicon strip modules are connected. The total active length is then 160.4 mm. The backplanes of the modules are glued to a silicon structure which holds at the same time the transmission lines for the 128 pads. A prototype of this fragile structure was successfully cooled down to 77 K without any noticeable deformation. The two modules are connected to the VIKING type (VA2_TA) readout chips [6] mounted with passive electronics on a small ceramic hybrid (see fig. 6.8).

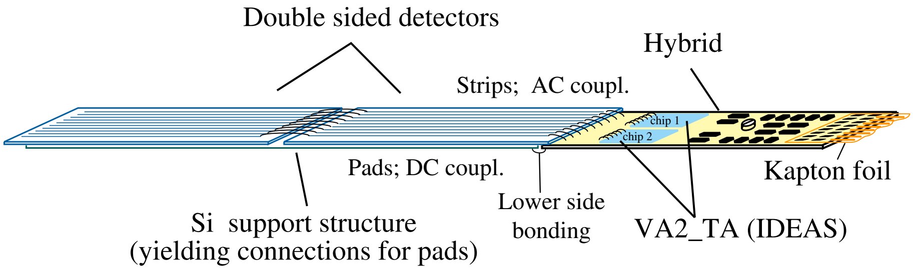


Figure 6.8: *A microstrip module consists of two connected detectors with 128 readout strips (total length 160 mm) and 128 pads.*

A similar readout system is used for the photodiodes. Photodiodes are segmented into four sections covering a total active area of $12\times16\,\mathrm{mm}^2$. The 48 readout lines of a crystal row are connected to one VA2_TA chip on a PCB hybrid.

The self-triggering VA2_TA chip is multiplexing its 128 channels into one analog output line. The two VA2_TA chips on the hybrid of each microstrip module are connected to the outside electronics through only 33 lines which provide e.g. the symmetric analog output of the 256 channels, a symmetric trigger output, bias, digital and analog control signals and supply voltages. Custom designed capton cables connect the 48 hybrids (2×16 for the 2 silicon layers and 16 for the crystals) with the patch panel (fig. 6.9). This circular PCB board works as a passive fan-in for common signals and collects analog signals to the corresponding cable bundles. The patch panel is connected to the outside electronics through 250 coaxial cables

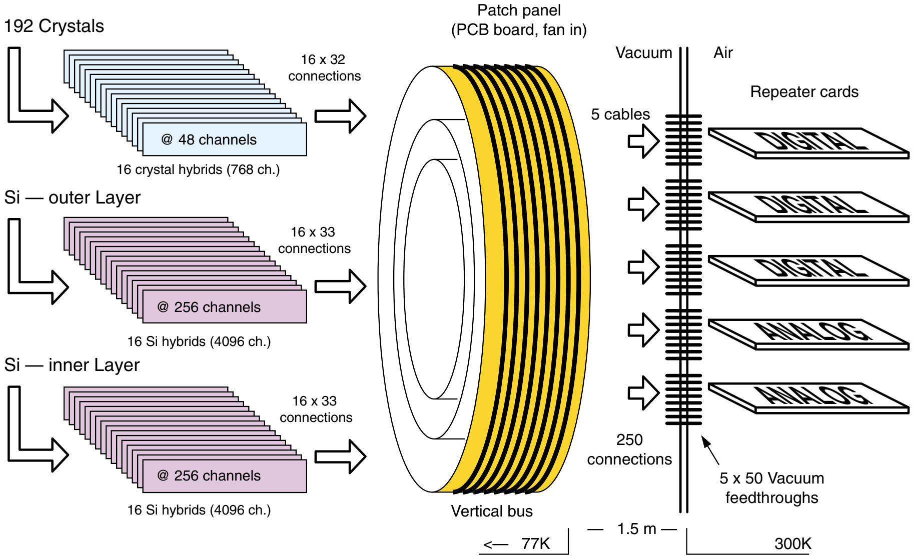


Figure 6.9: *Block diagram of the readout electronics.*

and five vacuum feedthrough connectors (50 pin D-Sub type). We designed this complex system of electronics and cables in vacuum at 77 K by using our previous experience with the similar but much simpler Crystal Barrel silicon microstrip vertex detector [7].

Beyond the vacuum flange the signals are processed by two analog repeater cards which were designed and assembled with the help of the electronics workshop of our institute. The digital repeater cards were designed at Pavia. The analog signals from the repeater cards are digitized by 36 VME FADC modules. The readout system is controlled through a fast VME-PCI link by a PC running a LabView DAQ program. We developed this system for the silicon microstrip beam telescope used in the CMS pixel test experiment (see last year's annual report).

The detector will be assembled and mounted in the ATHENA magnet in spring 2000. A first run with antiprotons and positrons is foreseen next summer.

References

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