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# DESIGN AND PERFORMANCE OF A MAGNETIC SPECTROMETER FOR ANTIMATTER SEARCH IN SPACE

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For the AMS Collaboration

## *Abstract*

The conceptual design of the spectrometer and the scientific goals of the AMS experiment, will be presented here as well as the measured performances for minimum ionising particles using ground level cosmic-rays and reconstructed events from space. The first results of a test done with relativistic carbon ions at GSI (Darmstadt) will be also given. A preliminary version of the AMS apparatus flew on June 1998 on shuttle mission STS-91. In 2002 the complete system will be installed on the space station Alpha and it will take data for three years.

## I. INTRODUCTION

The main scientific goal of the AMS (Alpha Mission Spectrometer) experiment, that will be installed in the International Space Station Alpha (ISSA) at the end of year 2002, is the search for antinuclei with a sensitivity of 4 to 5 orders of magnitude better than the previous experiments. The detection of antimatter would be a discovery of fundamental importance in cosmology [1] [2]. The Big Bang theory predicts that at the beginning of the universe, equal amounts of matter and antimatter should have been created. The non-observation of antimatter has led the theorist to elaborate on a mechanism of evolution that starting from an initial barion-antibarion symmetry evolves into a completely non-symmetric situation with the absence of antimatter aggregates. Such a mechanism should include the three Sakharov conditions [3] that are: non-thermal equilibrium during universe expansion, CP violation, and barionic number non-conservation. The third condition has never been observed, the second has been observed only for the $K^0_S$-$K^0_L$ system. Since the three conditions are not yet fully verified, the symmetric model (equal amounts of matter and antimatter and existence of anti-galaxies), is not completely ruled out. According to some authors [4] the present limits on antinuclei non observation are not jet significant for extragalactic antimatter in a symmetric universe and the measurement of the antihelium on helium ratio should be pushed below $10^{-6}$ - $10^{-7}$. AMS has been designed in order to reach an $\overline{He}/He$ ratio of about $10^{-9}$.

As an additional goal the precise measurement of the antiproton to proton ratio below 3 GeV and positron fraction up to 100 GeV will be included in order to find traces of WIMP signals for dark matter searches. Another goal will be a measurement of the isotopic composition of Helium, Hydrogen and Beryllium below 3 GeV which is needed in order to study the propagation of cosmic rays. Another item that will be studied is the gamma ray spectrum from 300 MeV to 300 GeV. For an extensive review of the physical goals of AMS on the space station see ref. [5]. A precursor flight of the AMS experiment has flown from the 2nd to the 12th of June 1998 on the shuttle mission STS-91; data analysis for this flight is currently ongoing. The AMS apparatus on the STS-91 shuttle mission is a prototype instrument that has less acceptance and limited particle identification capabilities compared to the final Space station design. The aim of this shuttle flight was mainly a verification of the detector performance on the space environment including operation in vacuum, verification of vibration resistance during takeoff and data communication during flight. Even if all the scientific goals of the AMS experiment can be achieved only with the AMS apparatus with its full instrumentation, acceptance and data taking time; the prototype apparatus which has flown on the shuttle can still give some interesting preliminary data. The AMS apparatus which has flown on the shuttle has 1/3 of the total acceptance, of the final AMS detector configuration and its operating time is about 1/100 the operating time that it will have on the space station, and it can identify single charged particles only below 3 GeV. Nevertheless we expect to have collected more than $10^6$ Helium nuclei from which it is possible to give upper limits to the existence of antihelium comparable if not better than the current upper limit of 3.1 x $10^{-6}$ [6].

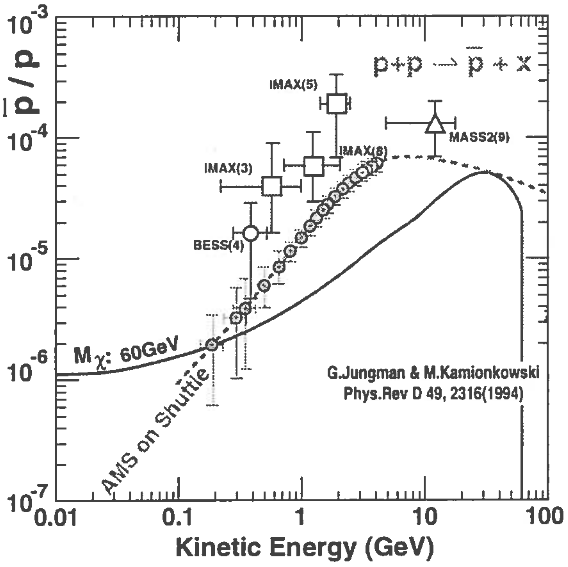

Figure 1: Antiproton/proton flux ratio calculated according to the Leaky Box Model for the AMS STS-91 flight compared with data from previous experiments and expected flux ratio for neutralino annihilation with mass 60 $GeV/c^2$

Furthermore if neutralino is a relevant dark matter constituent, its annihilation should visibly modify the antiproton to proton flux ratio below a few GeV; a region where the instrument that has flown on the STS-91 mission is sensitive. The expected event statistic (about 600 event) is sufficient to positively detect this effect. Fig. 1 shows the expected $\overline{p}/p$ flux ratio from neutralino annihilation where the neutralino mass is 60 $GeV/c^2$; the graph also shows the previous measurements from other experiments and the expected AMS measurements according to the Standard Leaky Box model predictions.

The apparatus which flew on the shuttle mission included (fig. 2 ):

1. A cylindrical permanent magnet equipped with 6 planes of silicon microstrip detectors with space resolution of about 10 $\mu$m in the direction of bending. The intensity of the magnetic field is about 0.15 T and the resulting maximum detectable rigidity is 500 GV/c. The front-end electronics of the silicon detectors have a wide dynamic range and can determine the absolute value of the charge up to oxygen ions.
2. An anticoincidence veto system providing the rejection for particles scattered by the wall of the magnet.
3. A time of flight system based on 4 planes of scintillators having about 100 ps time resolution giving the trigger to the electronics, measuring the velocity of low energy particles, rejecting upward moving particles and giving an additional measurement of the particle charge.
4. Four layer of aerogel Cerenkov detector to provide additional measurement of charge and to identify antiprotons below 3 GeV.

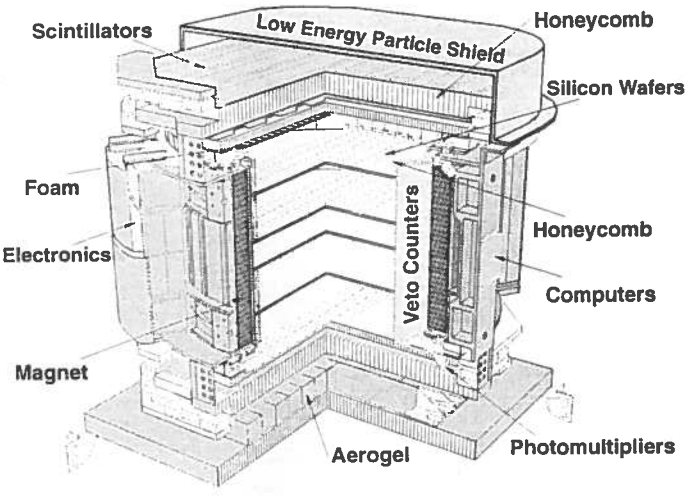

Figure 2: The AMS apparatus for the Shuttle flight STS-91

In this paper an overview of the silicon spectrometer design and performance will be presented. In section II the basic parameter of the permanent magnet and of the tracker will be given, in section III a more detailed description of the silicon ladder, which is the basic construction element of the tracker, will be presented. Section IV describes the tracker readout electronics and the power supply system. The performances of the tracker on an ion beam test will be shown in section V and the preflight and inflight data taking performances will be reported on section VI. Section VII will present some conclusions and perspectives.

## II. THE MAGNETIC SPECTROMETER

The magnetic spectrometer of the AMS apparatus is composed of a cylindrical permanent magnet and 6 planes of double sided silicon microstrip detectors.

The permanent magnet which has flown with the STS-91 Shuttle flight has been assembled in China at the Institute of Electrical Engineering of the Chinese Academy of Science and the Chinese Academy of Launch Vehicle Technology in Beijing. It is made of 6000 high grade NdFeB blocks from vacuumschmeslze (Germany). It is cylindrical it is 800 mm high, has an inner diameter of 1115 mm and an outer diameter of 1299 mm, its weight is 1900 kg. This magnet generates a parallel magnetic field inside the cylinder having an intensity of 1.5 kG. Since the fringe field may disturb the shuttle navigation instrumetation and may interact with the earth magnetic field creating a torque that can affect the shuttle orbit, it was verified that the field was below 3 Gauss at the distance of 260 cm from the cylinder central axis as requested by NASA for safety.

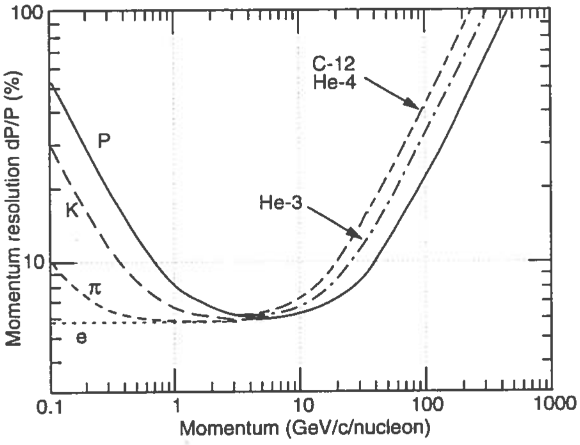

Figure 3: Expected momentum resolution of the AMS spectrometer

The tracker detector is made of 6 Silicon detector planes; 4 are located inside the inner volume of the permanent magnet, one is over the top and one is below the bottom. The spatial resolution of the tracker is about 10 $\mu$m in the bending direction and 30 $\mu$m in the non-bending direction. It has a total of 58368 readout channels and a total area of 2.4 $m^2$. It is the largest silicon microstrip tracker ever built. The basic structure elements of the tracker planes are the ladders; each ladder is built assembling silicon detectors, front-end hybrid and carbon fiber support structure. The ladders are assembled on the 6 ultralight honeycomb plates using a three-dimentional precision metrology machine obtaining an alignment accuracy better than 10 $\mu$m. During flight the stability of the alignment was controlled by a laser monitoring system. The ladder elements and its front-end electronics will be described in the next section. The total amount of matter traversed from a vertical particle in the tracker is 3.6 x $10^{-2}$ radiation lengths.

The overall performance of the spectrometer in terms of momentum resolution is shown in fig. 3, the best momentum resolution is about 7% around 10 GV/c and the maximum detectable rigidity is 500 GV/c.

## III. THE SILICON LADDERS AND THE FRONT-END ELECTRONICS

The tracker is built from silicon sensors manufactured by CSEM (Neuchatel) having 70 x 40 $mm^2$ area and 300 $\mu$m thickness. The sensors are segmented into strips on both sides. On the p-side the strip pitch is 55$\mu$m and on the n-side it is 52$\mu$m; the p-side is segmented into about 1270 strips (along the 70 mm side) and the n-side into 767 strips (along the 40 mm side). The strips on both sides are directed orthogonally. Each sensor also has a guard ring, its polarization being achieved by connecting the guard rings on both sides to a biasing potential. The guard ring on the p-side is connected to each strip by $10G\Omega$ resistors, while that of the n-side is connected to each strip by a $40M\Omega$ resistor. When biased, a sensor draws an average current of ca. 400 nA, 2 $\mu$A maximum.

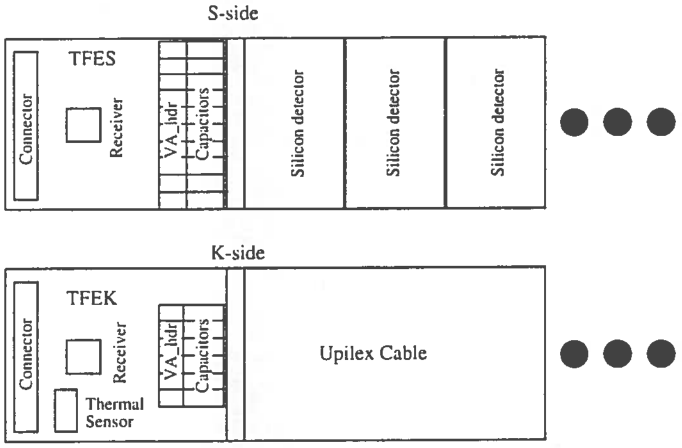

Figure 4: Ladder scheme (S and K side), only 3 detectors per ladder are shown.

Silicon sensors are assembled to form a ladder (fig. 4) . A ladder is a row of detectors with strips bonded on the long (70 mm) side. Depending on the structure of the tracker, a ladder can be composed of 7 (280 mm long ladder) to 15 (600 mm long ladder) sensors. The n-side of a ladder will be glued onto a Upilex [7] cable which connects the n-side strips to the front end electronics. The n-side is sometimes referred as the K-side while the p-side is called the S-side. Due to problems in keeping a constant resistivity during silicon detectors manufacturing, the sensors have been grouped into two categories: high resistivity (depletion voltage below 50 V) and low resistivity (depletion voltage above 50 V). The two types of detectors have been assembled into different ladders and their biasing potential is set to $+48.8V$ for high resistivity detector ladders and $+93.8V$ for low resistivity detector ladders. This biasing potential was applied on the K (n) side. The ladders are wrapped on copper plated kapton for shielding.

The readout of the ladder is accomplished by several 64 channel high dynamic range (0 to 100 MIPs) readout chips called $VA\_hdr$. The chips are glued and bonded on a hybrid substrate. This front-end hybrid card is called the TFE (Tracker Front End). There are 10 chips reading the S-side (p-side) connected with one channel every two strips (readout pitch of 110$\mu$m) and 6 chips for the K-side of each ladder. The readout pitch on the K-side is 208$\mu$m (one channel every 4 strips). With this chosen number of readout channels (384 per ladder) in the K-side it is not possible to read all the strips individually. For this reason every readout channel is connected to $d/2$ strips where d is the number of detectors on one ladder. In this way we introduce an ambiguity on the non-bending coordinate to be resolved during track reconstruction with the help of the time-of-flight system and the Cherenkov counters. The $VA\_hdr$ chip includes a low noise CMOS charge preamplifier, a CR-RC semi-gaussian shaper, a sample-and-hold and an analog multiplexer. The readout of the S-side of a ladder proceeds along two independent output lines, one for each 5 $VA\_hdr$ chip. On the K-side only one output line (for 6 chips) is implemented. The $VA\_hdr$ is connected to the silicon strips through a decoupling capacitor chip that is not able to withstand the applied bias voltage; all the front-end and readout circuits for the K side have to be referred to a voltage close to the biasing potential. On a TFE we also have the receiver circuit (54AC14) for the digital signal, a digital thermal sensor and several filters.

The front-end electronics requires $\pm 2V$ and a reference ground. The power consumption of a $VA\_hdr$ chip depends on the prebias current. We measured a power consumption of $0.77mW/ch$ which correspond to a total power consumption of $45mW/chip$. The reference ground voltage for the S (p) side will be 0 V while for the K (n) side it will be +50 V or +95 V. The biasing voltages for the detectors will be referred to the same ground reference. For the p-side (dVp) the bias voltage will range from -2 to -7V. For the n-side it will have the fixed value of -1.2V (dVn) in addition to the reference +50 V or +95 V. For the STS-91 flight a total of 57 ladders were assembled in the 6 planes of the tracker, for the space station a total of 172 ladders is foreseen.

## IV. THE AMS TRACKER READOUT AND POWER SUPPLY SYSTEM

The Tracker readout and power supply system for the AMS apparatus is integrated inside two electronic crates placed around the magnet structure. One crate is for the ladders with detectors having 50 V bias and the other for the ladders having 95 V bias. The crates are VME 6U having 19 slots with a customized backplane. Each crate has its own power supply named PSB (Power Supply Box). Each PSB takes its input power from the +120 Volts main power line of the shuttle and it gives as output a fused +120 V line and a 5.2 Volts line for digital electronics. Those two lines go through the backplane of the crates and reach the cards via the standard card connectors. The cards in each tracker crates are arranged as follows:

- 12 TDR (Tracker Data Reduction) cards.
- 6 Power supply cards
- 1 JDQT card

The readout of the tracker is accomplished by the TDR cards (12 per crate 8 ground-referred and 4 bias-referred). The TDR card digitized the output of the TFE and makes pedestal subtraction, common noise subtraction and zero suppression compression. A TDR card contains: 8 analog receivers, 8 ADCs for data digitalization and 4 DSPs (2 active and 2 redundant). The cards having input and power referred to the bias voltage (TDRKs) are divided into two halves (galvanically separated) and have optocoupler output circuits in the connection to dataway because they are connected to the JDQT that is not referred to bias. A TDRS (readout card for the S-side) is connected to 4 ladders sides receiving the output of 8 output lines. A TDRK is connected to 8, bias-referred ladder sides and also receives the output of 8 lines.

The JDQT controller formats the data from the various TDR and sends the output to the event builder computer. This card also acts as main controller for the power supply control circuit.

The power supply system of the tracker takes input power from the PSB (both 120V and 5.2V). It is composed of 6 cards per crate, the cards are arranged as follows:

1. 1 TBS (tracker bias supply) provides the bias for the detectors (dVn, dVp) and the reference ground for the electronics in the non-bending side (K or n side). Power output is negligible and power dissipation is about 5 W.
2. 4 TPSFEs (tracker power supply - front end) provide power for the front end circuits. Each card will power 8 front-end circuits (full ladders K and S side). It takes the bias voltage from the TBS giving ±2 volts and a ground return for both the S-side and the K-side. It has 6.4 W of output power, (assuming 55% efficiency), 11.6 W input power and 5.2 W internal dissipation.
3. 1 TPSR (tracker power supply - readout) provides power for the readout electronics; each card will power the 12 TDR cards, 8 referred to ground (TDRS) and 4 referred to bias (TDRK). It takes the bias voltage from the TBS. The output voltages will be $\pm 6V$ (unregulated) and ground return. The output power for this card is 39W, assuming an efficiency of 76%; the input power will be 51 W with an internal dissipation of about 12 W.

The power supply cards are connected to the TDR through the custom backplane bus and not directly to the front-end electronics since cables are foreseen only between the front-end and the TDRs. A more accurate description of the AMS power supply system is given in ref. [8].

## V. THE PROTOTYPE TEST AT GSI

In order to measure the effectiveness of ion identification using the AMS spectrometer, two prototypes of the silicon ladder to be used in the AMS tracker, has been tested with $^{12}C$ ions and their spallation products, having a kinetic energy of 1.5 GeV/Nucleon. The test has been performed at the GSI laboratory in Darmstadt (Germany). The experimental setup was composed of 2 pairs of scintillation counters (S1,S2, S3,S4), two boxes each containing three 2 x 2 $cm^2$ single side silicon detectors to measure the ionization and to define the track (D1, D2, D3, D4, D5, D6) and a box containing 2 prototype ladders (L1,L2) each having two AMS silicon sensors. The setup is shown in fig. 5. The trigger was obtained as a coincidence from all scintillation counters. During the analysis, as a further constraint, we requested a valid signal on all silicon detectors. The pulse height in each scintillator was used to make a pre-identification of ion charges. In each scintillator we selected a narrow pulse height range for each different charge. In order to further reduce the contamination we also requested the coincidence in the same range for all scintillators. We collected a total of 70100 events of which 38711 survived the cuts done during analysis on scintillator pulse height.

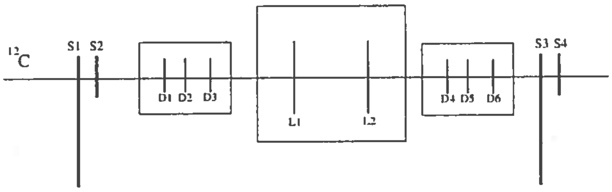

Figure 5: Beam test setup at GSI

When an ion transverses a silicon ladder the charge is induced in several adjacent strips (cluster). To calculate the position of the hit and the total collected charge, we consider a valid cluster when there is a strip having a signal more than 5 times the RMS noise above the pedestal. We consider the neighbouring strips belonging to the cluster if their signal is above 1 RMS noise over the pedestal. Using sets of pre-identified ion triggers from scintillators we observed the pulse height and the number of hitted strips in each cluster for each ladder S-side (cluster size). The average cluster size ranges from 2.9 strips for protons to 8.8 for Carbon.

By summing the total pulse height in a cluster we calculated the total collected charge (in ADC counts) in the ladders for each ion type, the results are displayed in fig. 6 where in the x axis we put the expected charge deposit of the ion in

MIPs, the straight line is a fit between the data points. Using the collected charge distributions we have also measured the proton contamination on the Helium signal. This measurement is important for the determination of antiproton background on the antihelium signal. With two ladders we measured a value of 1.9 x $10^{-4}$, an extrapolation to 4 (out of 6) silicon planes gives 1.0 x $10^{-6}$.

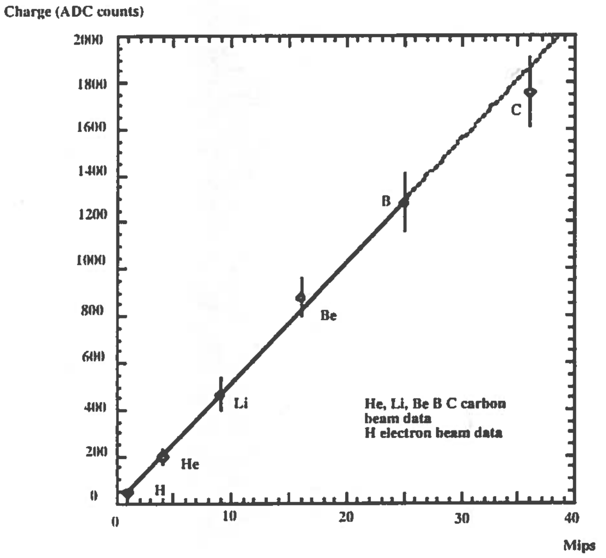

Figure 6: Collected charge in ADC counts versus expected energy deposit in MIPs

## VI. PREFLIGHT AND INFLIGHT DATA TAKING

The integration of the AMS apparatus was performed at ETH Zurich starting from march 1997 when the permanent magnet arrived from Beijing and continued there until January 1998 when the apparatus was shipped to Kennedy space center. At Kennedy we took data until a few days before the flight. During this period we monitored all noise parameters, namely common mode noise, and signal to noise ratio; that were stable at the level of 10%. Figure 7 shows the typical noise distribution for all channels in the n and p side of a 50 V biased ladder, for reference the mean value of a MIP signal is 40 ADC counts.

Figure 8 shows a muon event on ground seen with the online monitoring program. From the view of the non-bending coordinate it is possible to see how the position of the hits on scintillator detectors help to solve the ambiguities in track reconstruction due to multiple strip readout.

During the 10 days (2nd -12th June 1998) the Shuttle Discovery completed 152 orbits at ±$52^0$ degrees of latitude at about 370 km of altitude. In this mission the AMS apparatus collected 100 million cosmic ray events at a rate varying from 100 to 700 Hz depending on latitude. A small sample (below 10%) was sent to ground to monitor the status of data taking, and all data were recorded on hard disks on board.

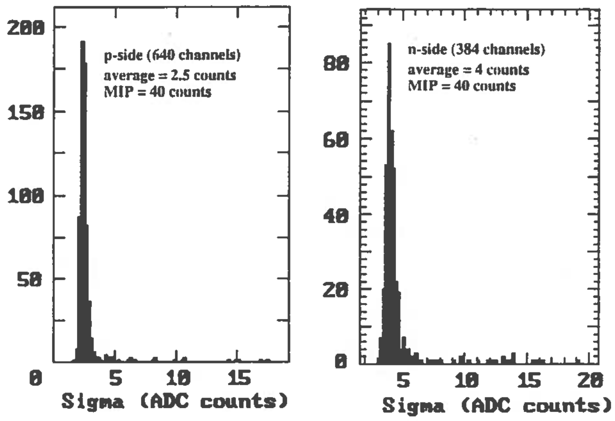

Figure 7: Typical noise distribution for one ladder after common mode noise subtraction

During the mission we monitored ladder temperature, RMS noise, common mode noise and leakage current for the tracker. Fig. 9 shows the average RMS noise for all the 50 V biased S-side ladders ( Crate 32 ) and for all the 95 V biased S-side ladders (Crate 72) versus data acquisition time. One time unit corresponds to one run ( one run about 15 minutes). Average RMS noise on all ladders ranges from 2.2 to 2.6 in 50V biased ladders and from 2.45 to 2.85 in the 95 volts biased ladders. This noise evolution depends: on the thermal history of the flight, on the noise level of the the DC-DC converter in the power supply ( we observed that in the first few hour of operation the DC-DC converters are noisier ) and on the presence of the KU band antenna that was turned off during the latest hours of operation. Globally the overall noise variation is within ±10%.

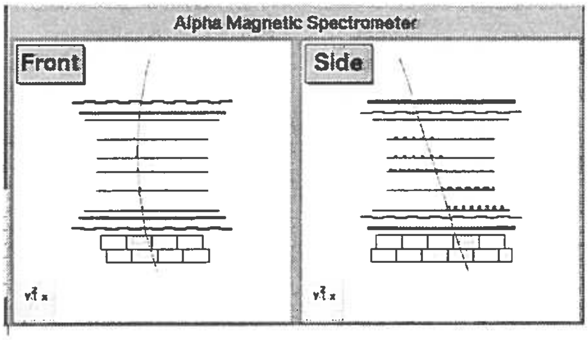

Figure 8: Ground muon seen with the online event display

A typical candidate antiproton event having 700 MeV/c of momentum is shown in fig 10.

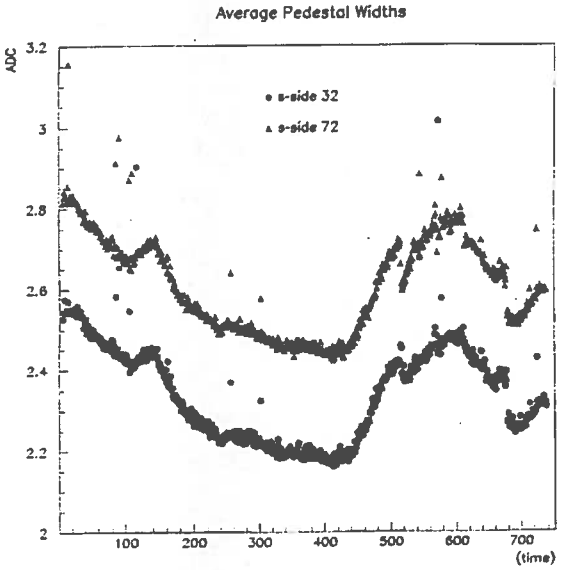

Figure 9: average RMS noise in ADC counts versus mission elapsed time for 95 volts biased ladders (crate 75) and for 50 volts biased ladders (crate 32)

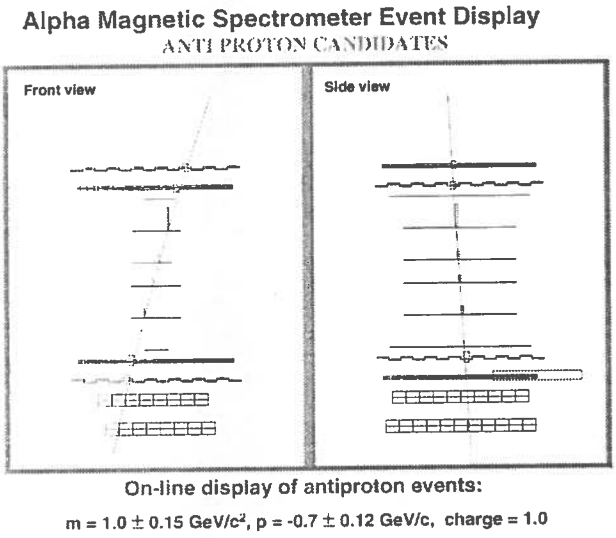

Figure 10: Antiproton candidate seen with the online event display

Fig. 11 shows the $p/Z$ versus $dE/dx$ in a double logarithmic plot; this plot is done only with information coming from the tracker during online monitoring, using a subset of data and without correction for gain non-uniformity in front-end preamplifier and for different track incident angles. Nevertheless it is possible to see the various bands corresponding to light particles ( electrons and secondary muons and pions coming from reentrant albedo or, during MIR docking, interaction with interleaved material) protons, helium and heavier ions.

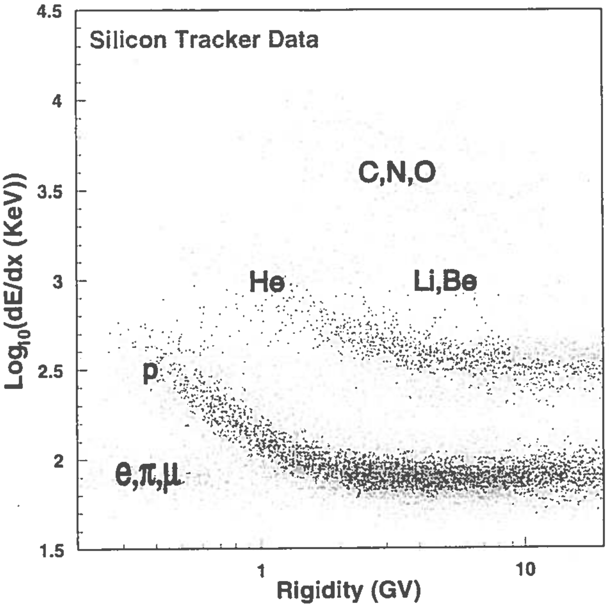

Figure 11: Double-Log plot of dE/dx versus rigidity measured with the AMS spectrometer

## VII. CONCLUSIONS

The largest silicon tracker ever built completed successfully its ten days precursor flight on the space shuttle. Analysis of the 100 million events collected is currently going on. We expect to measure the antiproton spectrum below 3 GeV with good statistics and accuracy, we also expect to set an upper limit to antihelium and heavier antinuclei comparable if not better than the present limits. The flight of the complete AMS apparatus on the International Space Station will further enhance those limits and will provide a more extensive study of cosmic ray components including gamma rays. In the space station flight the tracker will be completed and the overall tracker area will be $5.4m^2$ for a total of $0.6m^2sr$ of acceptance and 164000 readout channels.

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