PROCEEDINGS OF SCIENCE

The AMS-02 Silicon Tracker after 500 days in space

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The *Alpha Magnetic Spectrometer* (AMS) space experiment is devoted to direct measurements of galactic cosmic rays (CRs) in the rigidity range GV – TV. Prime goals of the AMS project are the direct search of anti-nuclei and the indirect search of dark matter particles. The final version of the experiment, AMS-02, is operating in the *International Space Station* (ISS) since May 2011. The AMS-02 tracking device, tout court Tracker, consists of nine planes of micro-strip silicon sensors giving a total active area of 6.4 m^2. The Tracker is composed by 2264 double-sided silicon sensors ($72\times41\,\mathrm{mm}^2$ area, 300 μm thick) assembled in 192 read-out units, for a total of nearly 200,000 read-out channels. In this proceeding, we review the Tracker performances and status after the first 500 days of data taking in space.

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1. Introduction

The main physics objectives of the AMS project are (1) to search for primordial antimatter particles such as antihelium, (2) to search for dark matter particle signals through their annihilation products $e^{\pm}$, $\overline{p}$ or γ-rays, and (3) to search for exotic particles such as strangelets, (4) to provide high accuracy measurements of CR spectra and chemical composition up to Z=26. A first version of the experiment, AMS-01, operated successfully in a 10-day shuttle mission (STS-91) in June 1998 [1]. The AMS-01 mission provided results on CR protons, helium, electrons, positrons, antiprotons, antihelium search, light nuclei and light isotopes [1, 2, 3, 4]. The second generation detector AMS-02, is a large acceptance detector that has been launched with the Space Shuttle STS-134 flight on May 16th 2011 and installed on board the ISS on May 19th 2011.

The AMS-02 tracker provides positions measurements of the impinging particles in a 0.14 T magnetic field, allowing the determination of their rigidity and sign of the charge. Multiple measurements of the specific energy loss of the charged particle, in addition, allow the determination of the magnitude of the particle charge.

AMS-02 is currently downlinking data at a rate of $\sim$ 50 million triggers per day (with an average bandwidth of $\sim$ 10 Mbps) and will be active during all the ISS lifetime.

2. The spectrometer

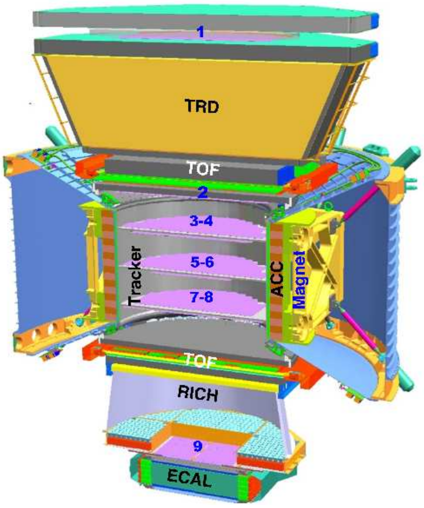

Figure 1: Schematic view of the AMS-02 spectrometer.

The AMS-02 detector is a state of the art particle physics detector, designed to work in space, that has been optimised to cope with rare signals and large backgrounds. As shown in Fig.1, it consists of:

- A 20-layer Transition Radiation Detector (TRD) to discriminate electrons and positrons from protons with a rejection factor of $10^4 - 10^3$ from 1.5 to 300 GeV;
- Four layers of plastic scintillators that provide precision Time-Of-Flight (TOF) measurements with a precision of $\sim$ 160 ps ($\delta\beta/\beta \sim 4\%$) and dE/dx loss measurements;

- A permanent magnet providing an almost uniform field of 0.14 T;
- Nine layers of silicon Tracker with a total active area of 6.4 m^2, which provide a proton rigidity measurement (R=pc/Ze, the particle momentum divided by the particle charge) with a resolution of 25% at 500 GV [5] and charge discrimination of nuclei up to Z=26 (Fe) [6];
- Plastic scintillator anti-coincidence counters (ACC), acting as Veto, which allow to reject particles entering the magnet bore laterally;
- A Ring Imaging Cherenkov (RICH) detector, which permits the measurement of the particles velocity with 0.1% resolution and provides charge measurement with discrimination power above Z=26;
- A 3D imaging sampling calorimeter (ECAL) made of 16.7 X_0 of lead and scintillating fibers, which allows accurate energy measurement for γ rays, electrons and positrons, with a rejection factor, to the large hadrons background, at the level of 10^4 in the range between 1.5 GeV and 1 TeV;

The programmed observation time ($\gtrsim 10$ yr), the large geometrical acceptance ($\sim 0.5\,m^2\,sr$), the wide rigidity range, ~ 0.2 GV – 2 TV (4 TV) for Z=1 (Z=2) particles, and the excellent identification capabilities of AMS-02 represent a significant improvement for the flux determinations of the rare CR components and the antimatter search.
The AMS-02 spectrometer operates on the ISS at an altitude of 400 km, free from backgrounds due to the interactions between cosmic rays and the atmosphere. The power consumption of the whole detector is $\sim$ 2 kW, continuously provided by solar panels of the ISS.

3. The AMS-02 Silicon Tracker

The AMS-01 Silicon Tracker [1] was the first application in space of the high-precision silicon technology developed for position measurements in accelerator experiments. The high modularity, low voltage bias levels needed (O(100V)), and gas-free operation of a solid-state device are well suited for operation in space. The major challenges are to maintain the required mechanical precision and low-noise performance in the large-scale application in space. The AMS-01 test flight in 1998, with its silicon tracking device, demonstrated the robustness of the AMS Tracker design.
The Tracker is composed of 2264 double-sided silicon micro-strip sensors with an area of $72\times41\ mm^2$ and thickness of 300 μm. These sensors are arranged into 192 independent units, the *ladders*, assembled in nine almost circular layers ($\sim$ 1 m diameter) as schematically shown in Fig.1. Seven layers are placed inside the magnet bore on four support planes, while two external layers are installed on both sides of the spectrometer, above the TRD system and between RICH and ECAL respectively, to maximize the level arm ($\sim$ 3 m) and allow a Maximum Detectable Rigidity (MDR) of $\sim$ 2 TV ($\sim$ 4 TV) for Z=1 (Z=2) particles.
The device has been designed to survive and operate in a wide temperature range between -20° and 40° C. All the support planes are made of an aluminum honeycomb structure enclosed within thin carbon fiber skins. The total thickness of one internal plane including two silicon layers and one

support plane is about 1%X_0 and has been specifically optimised to minimize the material budget inside the tracking path.

On the opposite sides of each silicon sensor, p-type (junction) and n^+-type (ohmic) strips are implanted, on a n-type substrate, along orthogonal directions with implantation (readout) pitches of 27.5 (110) μm and 104 (208) μm, respectively. The junction side provides a measurement of the bending coordinate (Y) in the spectrometer. Running along the ladder the p-type strips are brought to the ladder end, where a front-end hybrid provides the bias voltage and holds the readout chips. The ohmic side strips, providing the measurement of the non-bending coordinate (X), are routed to the ladder end by means of a kapton cable which distributes signals of alternating sensors to the same readout channel. The ladder design and its components are sketched in Fig. 2.

A detailed description of the ladders, as well as results for the position resolution can be found in [5]. Fig. 3 shows the on-ground measured [9] Tracker position resolution as a function of projected impact angle.

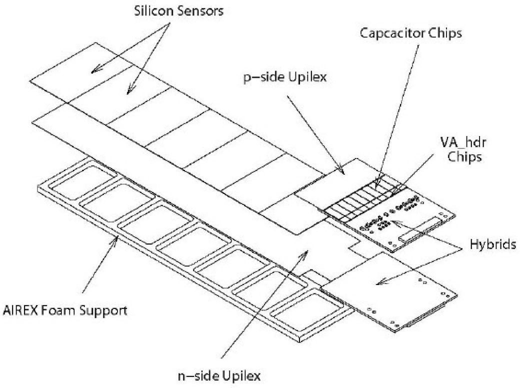

Figure 2: The components of a AMS-02 silicon tracker ladder.

The 640(384) readout strips from the p(n) sides of each ladder are AC-coupled to a 64 channel low-noise, high dynamic range readout chip `VA_hdr9a` via 700 pF capacitors. Each channel has a leakage current at the level of nA resulting in a total of few μA per ladder. The analog signals of each hybrid pair, for p and n side, are transferred to a Tracker Data Reduction (TDR) board which is equipped with three 12-bit ADCs, Field Programmable Gate Arrays (FPGAs) and Digital Signal Processors (DSPs) for data reduction. The ADC information on the readout strips include a pedestal, a common noise, a single-strip noise and an eventual signal. The mean and root mean square (RMS) of the pedestal are determined in a calibration run at the beginning of each scientific run. A valid signal is defined by a threshold applied to the signal-to-noise ratio for each readout strip after pedestal and common noise subtraction. The noise refers to the RMS value obtained in the calibration run.

Due to the limited bandwidth, signals collected by all subdetectors have to be processed on board. Tracker analog signals of the front-end electronics are processed by TDR boards that digitize them, apply calibration data, subtract pedestal and the common noise, search for clusters, and perform online *zero-suppression*.

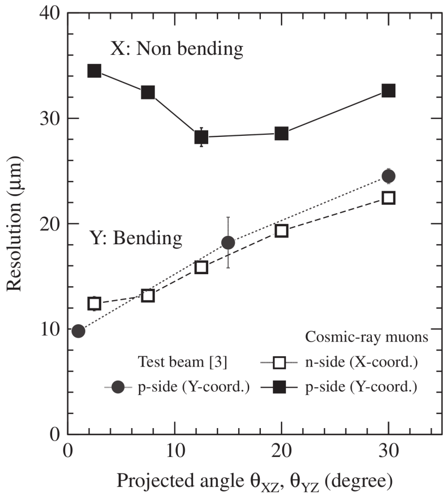

Figure 3: The position resolution in the X (n-side strips, non-bending) and Y (p-side strips, bending) coordinates as a function of the projected angle, θ_{xz} and θ_{yz}, measured with cosmic-ray muon data on ground. Proton test beam results [5] are also shown.

4. Tracker Status and Operation in Space

Since its activation on May 19th 2011, the AMS-02 detector is working nominally onboard the ISS and no crucial issues were noticed. The Tracker performance and its functionality are continuously monitored at the *Payload Operation Control Center* (POCC) located at CERN (Geneva, CH).
Calibration runs are performed every 46 minutes, when the ISS passes above the equator, measuring pedestal and noise level of each channel and assigning a status bit to each in order to avoid the use of noisy or dead strips in the science data analysis.

4.1 Tracker cooling

Detector operation in space requires an active cooling system to either remove the heat produced, mainly, by the front-end electronics, and also to keep the tracker temperature stable. The Tracker Thermal Control System (TTCS) has the aim to keep the temperature of the inner tracker under control. It consist of a pumped CO_2 loop designed to maximize the exchange of the heat, coming from the Tracker electronics, taking advantage of the latency heat needed for the evaporation of the fluid. The fluid loop is connected to a pair of condensers where, by means of a radiator facing the deep space, the gaseous CO_2 is liquified. A schematic of the whole system is presented in Fig.4.
Temperatures are measured at different points of the detector by Dallas sensors. Thanks to such a cooling system the temperatures of the various parts of the detector show a remarkably stable temperature (oscillations within $\sim 1^\circ$ C), as shown in Fig.5.

The temperature stability is needed to achieve and reflects immediately into the performances stability of the tracking device. The Tracker calibration response, in terms of pedestal values and noise levels, has been found to be, in facts, very stable in time. The stability of such a kind of

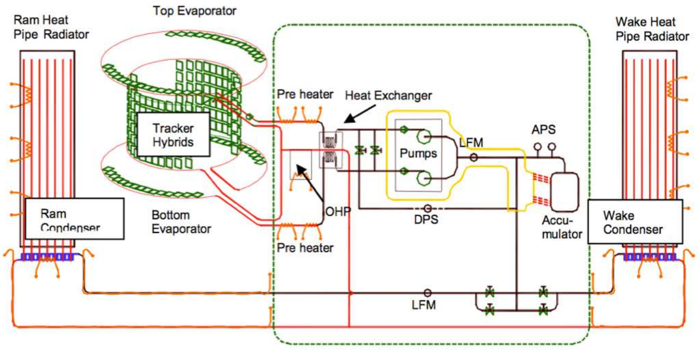

Figure 4: Schematic view of the Tracker Thermal Control System (TTCS). A pumped CO_2 loop is used to keep the Tracker temperature stable removing the heat mainly produced by the front-end electronics.

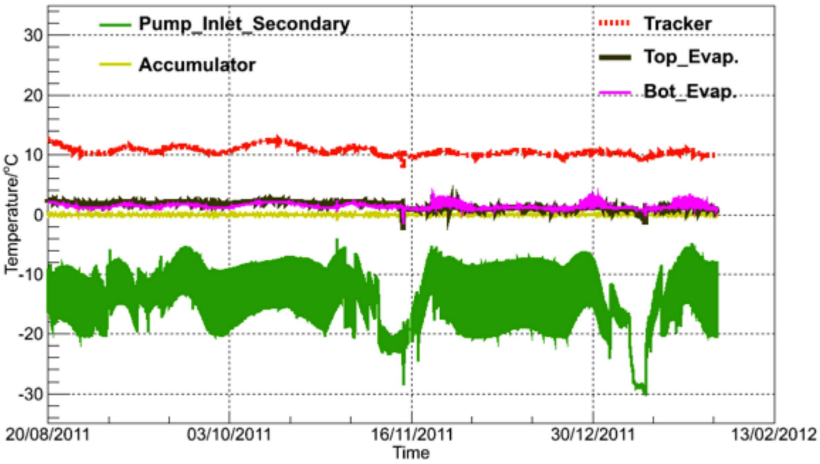

Figure 5: Temperatures of the Tracker (red, dotted line) and of the various parts of the TTCS system (green, yellow, black and violet filled lines) as a function of time for a period of about six months of continuous operations in space. Even with a $\sim 10^\circ$ C temperature variation of the CO_2 injected into the pump (green filled line), the temperature of the Tracker is kept stable within $\sim 1^\circ$ C.

basic operational parameters, guarantees the stability in terms of tracking efficiency and position measurement performance.

4.2 Alignment and time stability

In Figure 6, the time dependence of the external tracker planes positions is shown in the two uppermost panels: it is clearly related to the temperature gradient across the AMS mechanical structure (third panel). The time dependence of the β angle between the vector to sun position and the orbital plane is also reported as a reference of the environmental conditions.
Two independent dynamic procedures of alignment have been developed in order to take into account thermal movements and correct for time dependencies. The alignment was based on the minimization of the proton and helium track residuals in the external planes, and independent cross

checks were performed using the energy measurement in the ECAL. The stability in the bending coordinate (Y) at the first layer after the alignment is reported in Fig.7, no time dependent structure are visible and a dispersion at the $\sim 3\ \mu$m level is reached. In Fig.8, the E/R distribution for positron and electrons are consistent with a 0 μm shift after applying either of the two alignment procedures, *PG* and *CIEMAT*, the expected discrepancy for a $\sim 25\ \mu$m relative shift between the external layers is shown as a reference.

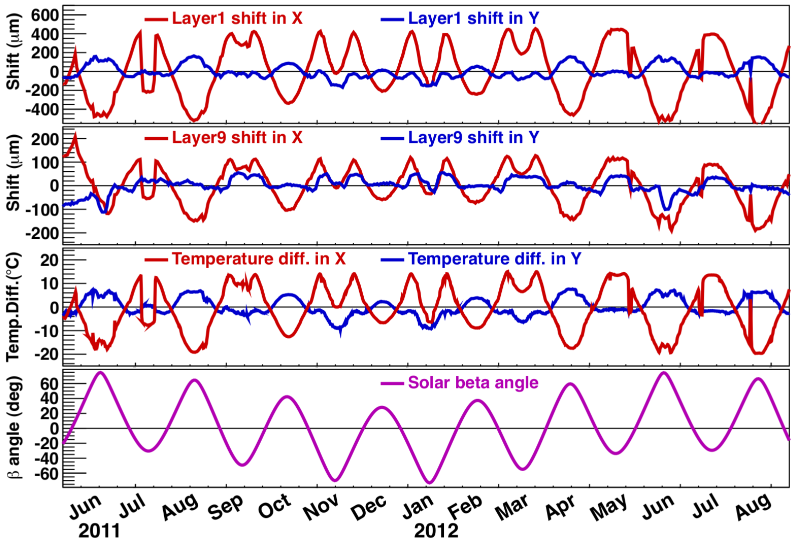

Figure 6: First (second) panel: shifts of the L1 (L9), with respect to nominal position in the bending (Y) and not bending (X) coordinates, as a function of time. Third panel: temperature differences between opposite sides of the main AMS structure, as a function of time. Fourth panel: angle (β) between the vector from the sun and the orbital plane, as a function of time.

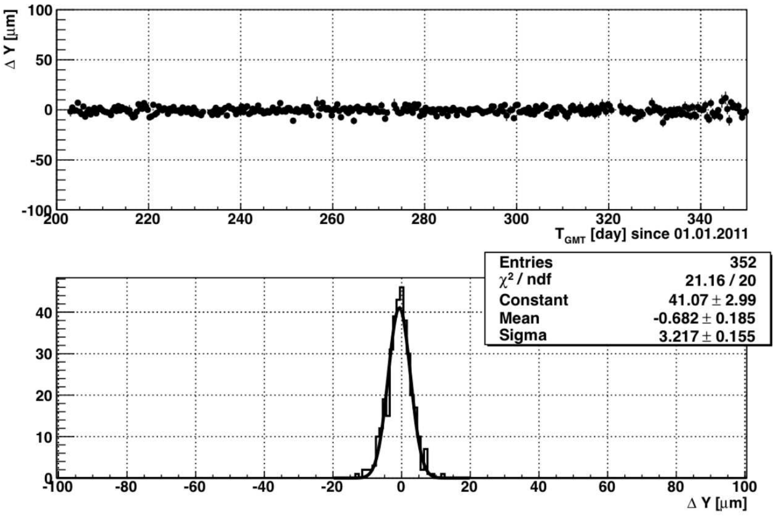

Figure 7: Layer 1 Y coordinate stability as a function of time after alignment (top). No time dependence is observed at the $\sim 3\ \mu$m level, as derived from a gaussian fit to the stability distribution (bottom panel).

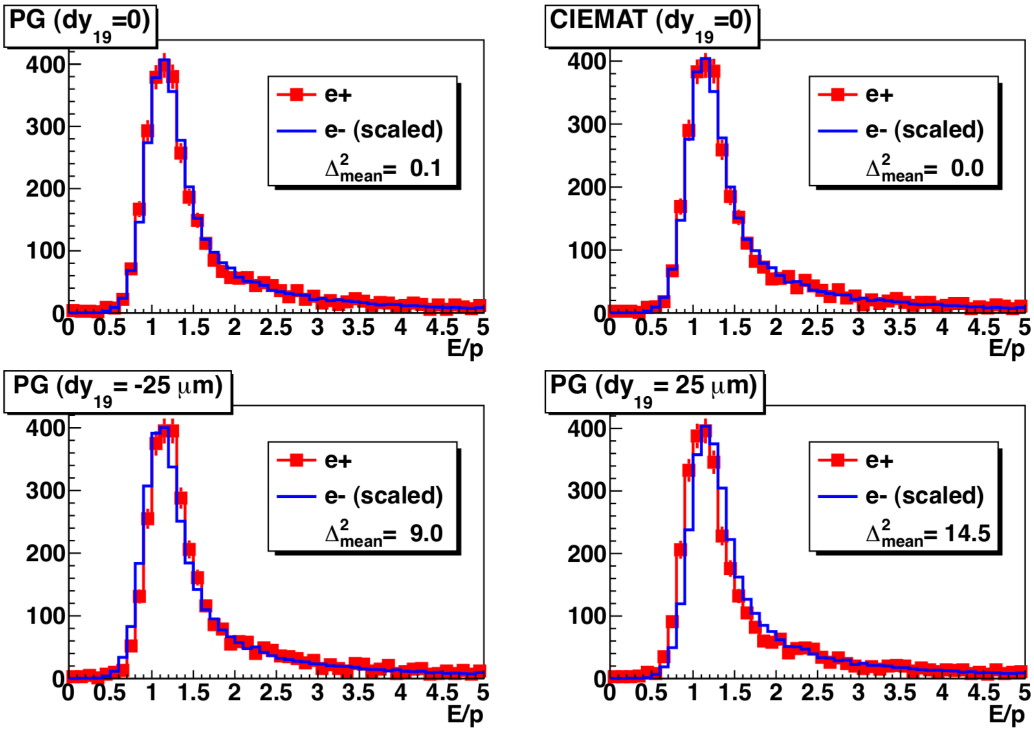

Figure 8: Check of the alignment with positrons and electrons using the ECAL energy over rigidity ratio. The two independent developed alignment (*PG* and *CIEMAT*) show the same result, i.e. the E/R value is the same for positive and negative particles (top left and right). Changing the Y alignment of the two external layers, by a ± 25 μm shift, the E/R distributions for positive and negative particles significantly diversify (bottom left and right).

4.3 Single Event Effect and operational issues

In the space environment the estimated total dose for a detector like AMS is at the level of $\sim$ 1 krad per year. This doesn't constitute at all a problem in terms of radiation damage for the silicon detectors. The only issues, related to radiation, are coming from the SEE (Single Event Effect). In fact, the ionization energy loss experienced by the charged particles passing through the readout electronics may create conductive paths inside the boards or corrupt some of the DSP memories. For the first type of issue a passive solution has been chosen: to avoid short circuits all the power supplies are current protected. To cope with the DSP memory corruptions, instead, an active solution was implemented. The DSP memory is protected with a Cyclic Redundant Check (CRC) that is monitored every 23 minutes. As predicted on ground before the launch and then confirmed once in space, the AMS electronics is experiencing a rate of $\sim$ 1 board failure per day. Most of the times, however, the corruption affects unused memory areas, with no resulting effect on the data taking. As shown in Fig.9 (left) the DSP memory corruption is equally distributed over all the various detectors, i.e. there are no *weak* nodes, and (right) the failure rate is constant as function of time, i.e. there's no degradation of the DSP memories.

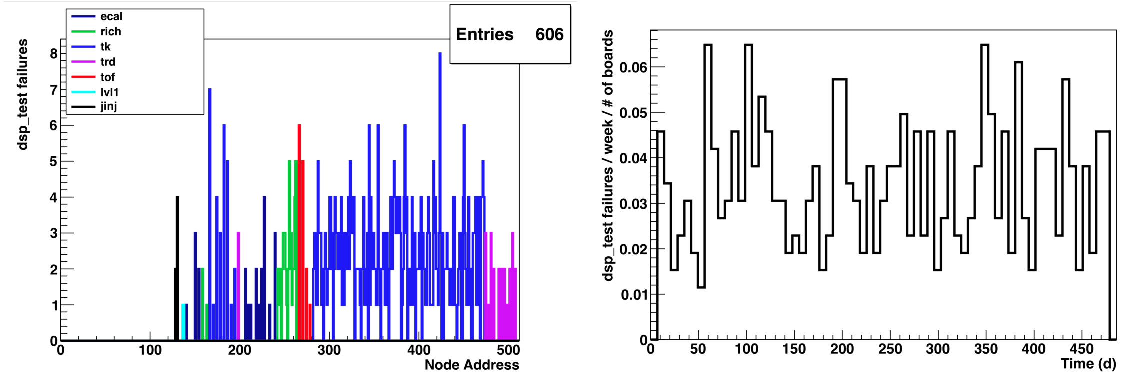

Figure 9: Left: distribution of the DSP memory failures, after 500 days of operation in space, as function of the microprocessor address in the DAQ chain. The corruptions are equally distributed all over the various detectors. No *weak* nodes have been found. Right: failure rate as a function of time. After almost 2 years in space no degradation is observed.

5. Conclusions

AMS-02 is collecting data since 2011, May 19th, at a steady rate of $\sim$50 million triggers per day. All the sub-detectors and the data acquisition system are working nominally. The Tracker is exhibiting the expected behaviour with high stability of pedestal and noise levels. Furthermore, it has been observed a high ladder uniformity in terms of efficiency response to CR particles.

The Tracker can reach a rigidity resolution of $\sim$10 % at 10 GV and has a MDR of about 2 TV (4 TV) for Z=1 (Z=2) particles.

After more than 500 days in space, no major problems affected the tracker operation, with less of 1% of degraded channels, over the whole data taking period.

6. Acknowledgements

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