

## Alignment of the AMS-02 silicon Tracker

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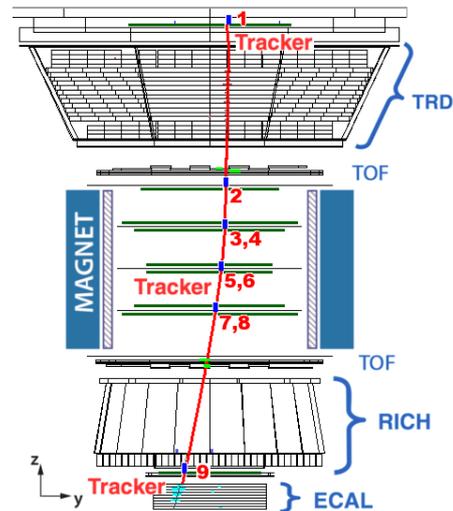
**Abstract:** The AMS-02 was installed on the International Space Station (ISS) in May 2011 and has since then been successfully collecting data. One of its main sub-detectors, the silicon tracker, determines the rigidity, charge sign and absolute charge of cosmic rays by up to nine layers, which give the maximum lever arm of 3 m. For the best performance of the tracker the relative position of nine layers has to be known with a precision better than  $10 \mu\text{m}$  at any moment. In this contribution the procedure and the evaluation of the accuracy of the alignment are discussed.

**Keywords:** Silicon Tracker, Cosmic Ray Detector, Alignment

### 1 Introduction

AMS-02 is a magnetic spectrometer designed to measure energy spectra of cosmic-ray charged particles, ions, antiparticles and gamma-rays in GeV-TeV region to understand Dark Matter, matter anti-matter asymmetry, and the origin of Cosmic rays, as well as to explore new physics phenomena. AMS-02 is taking data on the International Space Station (ISS) since May/2011. As shown in Figure 1, the detector consists of nine layers of precision silicon tracker inside and outside the field of a permanent magnet, a transition radiation detector (TRD), four planes of time of flight counters (TOF), an array of anti-coincidence counters (ACC) surrounding the inner tracker, a ring imaging Cerenkov detector (RICH), and an electromagnetic calorimeter (ECAL). More details on the various sub-detectors can be found in [1].

In order to maximize the statistical potential for up to 20 years, a permanent magnet of 0.14 Tesla is used [2]. The deflection of incoming particles by the magnetic field is measured by the silicon tracker with a position resolution of  $10 \mu\text{m}$  for single charged particles [4]. Seven layers placed inside the magnet bore and two layers placed on top and bottom of the spectrometer give the maximum lever arm of 3 m and enable us to achieve the Maximum Detectable Rigidity (MDR) of about 2 TV. Due to temperature variations along the ISS orbit, displacements of the outer layers of up to a few hundred microns were observed at a time scale of tens of minutes. For the best performance of the rigidity measurement and charge sign determination, the relative position of nine layers has to be known with a precision better than 10 microns at any moment. In this contribution the procedure and the evaluation of the accuracy of the alignment are discussed.



**Fig. 1:** Schematic view of AMS-02 detector in the bending ( $y$ - $z$  plane) with a cosmic-ray proton track in space. Tracker layers (1-9) are also shown.

### 2 The Silicon Tracker

The tracker system is composed of 2284 double-sided silicon micro-strip sensors, with dimensions  $72 \times 41 \text{ mm}^2$ , assembled in basic functional elements called ladders. Each ladder is composed of 9 to 15 sensors, for a total of 192 ladders, and an active area of  $6.75 \text{ m}^2$ . Each face of a sensor is implanted with metallic strips running in orthogonal directions, providing the three dimensional measurement

of the particle's position. The junction side (or p-side) is composed of  $p^+$  doped strips, for an implantation (readout) pitch of  $27.5 \mu\text{m}$  ( $110 \mu\text{m}$ ); the opposite ohmic side (the n-side) has an implantation (readout) pitch of  $104 \mu\text{m}$  ( $208 \mu\text{m}$ ). The coordinate in the p (n)-side corresponds to the  $y$  ( $x$ )-coordinate in the AMS master reference system<sup>1</sup>.

Positions of the planes of the inner tracker are held stable by a special carbon fiber structure [2]. It is monitored by using 20 IR laser beams which penetrate through all planes of the inner tracker and provide micron-level accuracy position measurements [3]. Details of the tracker design, construction and the performance can be found in [4].

There are two types of tracker alignment; one is a static alignment of all the 2284 sensors and the other is a dynamic alignment of outer layers. The static alignment has been made both on ground and in space, while the dynamic alignment is needed only in space, which is due to the thermal deformation of AMS support structure.

### 3 Static Alignment of sensors

The mechanical positioning precision of the tracker assembly of about  $100 \mu\text{m}$  is much worse than the track position measurement which has the intrinsic resolution of  $\sim 10$  ( $30$ )  $\mu\text{m}$  in the  $y$  ( $x$ )-coordinate. An accurate knowledge of the ladder and sensor geometry with a precision of a few  $\mu\text{m}$  is required to maximize the tracker performance. The fitting residuals of tracks passing each sensor include the intrinsic resolution of the sensors, the multiple scattering error, and the mechanical precision of the assembly. The first two make the residual width wider and the third one shifts the residual mean. From the structure of the residual mean, the displacement ( $\delta x$  and  $\delta y$ ) for each sensor can be estimated.

In order to determine the static alignment following steps for the static alignment of sensors have been carried out:

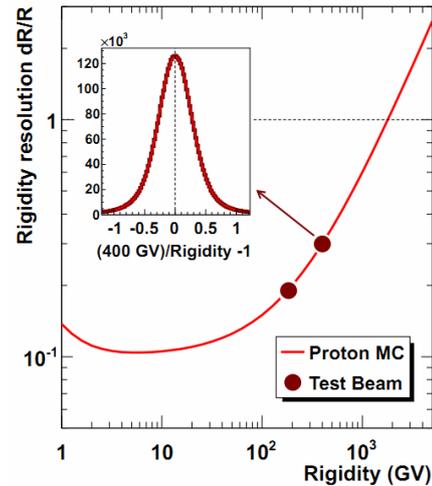
1. Initial alignment using cosmic-ray muons on the ground
2. Alignment with 400 GeV/c test beam and calibration of measured momentum
3. Check and small correction of the alignment with protons on ISS

#### 3.1 Initial Alignment with muons on ground

The initial alignment was determined in the pre-integration phase of the AMS spectrometer from September 2007 to June 2008, when all the detector subsystems were integrated. 90 million of cosmic-ray muon events were taken without magnetic field in a stable condition. The estimation of the alignment parameters is iteratively made so as to improve the predicted track position by applying the alignment parameters estimated in the previous iteration.

#### 3.2 Alignment with test beam

The complete AMS detector was tested at the SPS at CERN. These tests show that the detector functions as designed. In the beam tests, AMS was exposed to secondary beams of positrons and electrons in the momentum range from 10 to 290 GeV/c and the primary 400 GeV/c proton beam. The tracker alignment was done with the primary proton beam. The position and orientation of AMS with respect to the beam line was changed in 896 different combinations,



**Fig. 2:** Relative momentum resolution of protons estimated with MC simulation as well as the measured one with 400 GeV/c proton beam at CERN SPS.

where 416 positions are for the acceptance of both layer 1 and 9, 360 positions are for the acceptance of either layer 1 or 9, and 120 positions are for the acceptance of inner tracker only. The alignment of sensors was made by tracks of the fixed momentum. After the alignment, momentum resolution was estimated as 30 %, which agreed well with the expected performance obtained with the MC simulation as shown in Figure 2.

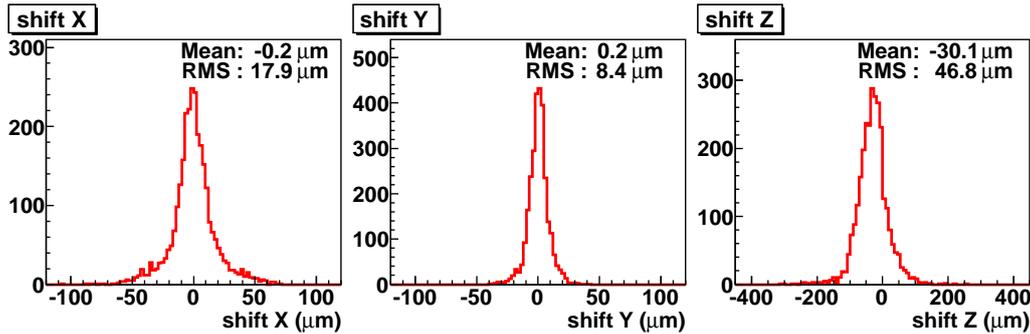
#### 3.3 Check and small correction of the alignment on ISS

Silicon sensors are glued to a foam support and foam is connected to a carbon fiber skin of the plane support structure with small aluminum fixation frames. Although it is designed to minimize the thermal deformation, non negligible shift of sensor position was expected. So the same sensor alignment procedure as done on the ground was performed and the relative shifts of sensors with respect to the test beam alignment was evaluated. Figure 3 show the relative shifts of sensors between test beam and ISS data. The shift in  $z$ -coordinate is defined with respect to the support frame. The mean shift of  $30 \mu\text{m}$  in  $z$ -coordinate can be interpreted as out-gassing of the foam support in space. The same effect was also observed in AMS-01 precursor flight [5].

### 4 Dynamic Alignment of outer layers

The variation of temperature of AMS support structure was more than  $\pm 10^\circ\text{C}$  so the relative position of outer layer suffered from the thermal movement both in long term and short term. The long term variation, shown in Figure 4, is mainly caused by the change of solar beta angle which is defined as the angle between the orbit plane and the vector from the sun. In case the ISS orbit it changes by  $\pm 80$  degrees and has a cycle of about two months. The short term thermal variation is caused by the

1. The AMS master reference system is defined with an  $x$ -axis along the main component of the magnetic field, a  $z$ -axis normal to the tracker planes pointing upward, and a  $y$ -axis to complete a right handed system.



**Fig. 3:** Relative shifts of sensors between test beam and ISS data. The shift in  $z$ -coordinate is defined with respect to the support frame. The shift of  $30 \mu\text{m}$  in  $z$ -coordinate can be interpreted as out-gassing of the foam support in space.

temperature cycle in one orbit which is about 90 minutes. We have developed two statistically independent alignment procedures to correct the effect of these thermal movements at a given moment in time. A first one uses a time sliding window to estimate the required correction. The second method folds several consecutive orbits to build a model of the layers movements due to the thermal variation at a give time, and this is used to compute the correction. Both methods have similar performances and are almost statistically independent, allowing the combination of both to reduce the statistical uncertainty of the correction. We firstly describe the second procedude which does not make any assumption about the long term dependence of position and orientation of the layers with time.

#### 4.1 Sliding window fit method

The first step consists in a fit to the difference between the inner tracker reconstructed track extrapolated to the outer layers and the measured hit position on these, for events in a time window around the moment in time being considered. The parameters being fit are the corrections to the position and orientation of the layer, and the first derivatives with time of these. Given a hit position  $\mathbf{x}_{hit}$  at one of the outer layers, the corrected position  $\tilde{\mathbf{x}}_{hit}$  is assumed to be

$$\tilde{\mathbf{x}}_{hit} = \mathbf{x}_{hit} + \delta\mathbf{x}(t) + \mathbf{M}(t) \cdot \mathbf{x}_{hit} \quad (1)$$

where  $\delta\mathbf{x}(t)$  is a time dependent translation of the nominal position of the center of the layer, and  $\mathbf{M}(t)$  is a rotation matrix around the nominal center of the layer, also depending on time. Since due to mechanical constraints the rotation has to be small, it is linearized by expanding it up to first order in the rotation angles. Furthermore, the time dependence within the time window used for the fit is kept up to first order in time. With this the correction is given by twelve linear parameters, six for the correction parameters and other six for their time derivatives. These are obtained for each layer by searching the parameters minimizing the following goodness of fit

$$gof = \sum_i (\mathbf{x}_{track}^i - \tilde{\mathbf{x}}_{hit}^i)^2 \cdot w^i \quad (2)$$

where  $i$  runs on all the events with hit associated to a track in the layer associated within a fixed time window,  $\mathbf{x}_{track}^i$  is the extrapolation of the track reconstructed using the inner tracker only to the  $Z$  position of  $\tilde{\mathbf{x}}_{hit}^i$ , and  $w^i$  is a weight that takes into account the expected error in the track extrapolation in a event by event basis. Since this error is dominated by multiple scattering, the error is estimated

using measurements on the velocity with the TOF and RICH to avoid biasing the estimate of the parameters.

##### 4.1.1 Refinement

The layers position and orientation precision obtained before depends on the time window used for the fit. It has to be large enough to guarantee that it is below the intrinsic hit position resolution of the layers. Given the available statistics it is achieved with a window of  $\pm 10$  minutes for any position in AMS-02 orbit. This is close to the time scale of movements of the layers, thus the fit parameters are underestimated close to extrema of the movement. To improved this, a simple procedure that adds an effective inertia to the parameters evolution is used. Given the set of layer correction parameters at a given time  $\mathbf{p}(t)$ , they can be extrapolated to other time using their time derivatives  $\mathbf{p}'(t)$ . Therefore it is possible to build a new estimate for time  $\tau$  that enforces consistency in time as

$$\tilde{\mathbf{p}}(\tau) = \frac{1}{W} \int_{\tau-W/2}^{\tau+W/2} \mathbf{p}(t) + \mathbf{p}'(t) \cdot (\tau - t) dt \quad (3)$$

The width of the window  $W$  is optimized by minimizing the systematic error, which is computed as explained in next section.

##### 4.1.2 Error estimation

The statistical error of the described method is computed in a event by event basis using bootstrapping. However this estimate does not account for the contribution of any residual uncorrected movement with a time scale smaller that the time window used in the layer position and orientation correction determination. An estimate to this error can be obtained by noticing that if we take non overlapping time windows of fixed time width  $T$ , the distribution of the ratio of the average of the distance between the corrected hit position and the track extrapolation along an given axis and its variance for each time window, should be distributed as a Gaussian with mean zero and sigma 1 as far as the number of events in the window is large enough. If there is a bounded residual movement, the width of that distribution tends to one as the size of the window width used increases, and tends to an effective error estimate added in quadrature to unity as the window width decreases. Therefore we can estimate this error by computing the second moment of the distribution of the ratio referred before as a function of the time window width. The extrapolation of this to a window width of zero provides the estimate of the residual misalignment of the outer layers. Following this

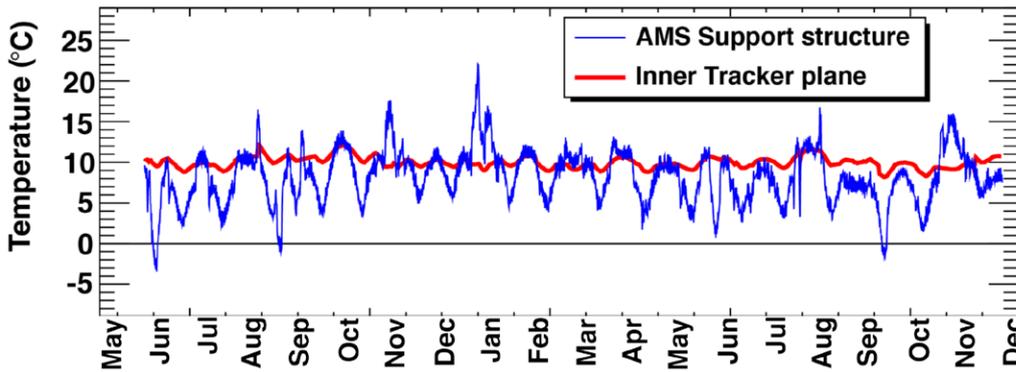


Fig. 4: Long term temperature variation with time of (blue) AMS-02 support structure and (red) inner track plane.

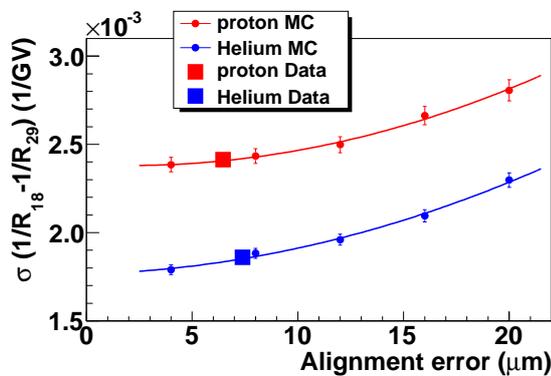


Fig. 5: Comparison of  $1/R_{18} - 1/R_{29}$  between ISS data and MC, where  $R_{18}$  and  $R_{29}$  are defined as measured rigidity with layers from 1 to 8 and from 2 to 9, respectively.  $\sigma(1/R_{18} - 1/R_{29})$  is the Gaussian sigma of the distribution.

procedure we obtain that these amount to  $5.5 \mu\text{m}$  statistical and  $2.0 \mu\text{m}$  systematic for tracker layer 1, whereas they are  $6.0 \mu\text{m}$  statistical error and  $2.5 \mu\text{m}$  systematic for tracker layer 9.

#### 4.1.3 Comparison with MC

The alignment errors, i.e. the residual misalignment, of the outer layers have been evaluated by comparing the distribution of  $1/R_{18} - 1/R_{29}$  between ISS data and MC, where  $R_{18}$  and  $R_{29}$  are defined as measured rigidity with layers from 1 to 8 and from 2 to 9, respectively. Figure 5 shows the Gaussian sigma of the distribution,  $\sigma(1/R_{18} - 1/R_{29})$  as a function of different alignment error assumed in MC. We estimated the alignment error from  $\sigma(1/R_{18} - 1/R_{29})$  obtained in ISS data as  $7 \mu\text{m}$ , which is consistent with the total error estimated in Section 4.1.2.

#### 4.2 Orbit folding fit method

As above mentioned, a second independent correction estimate method has been developed. Its purpose was to provide a statistically accurated estimated of the corrections without weighting the data. It makes use of the fact that the period of the fast thermal variation is one orbit, and assumes that the orbit to orbit variation is negligible compared with the correction. Therefore the time dependent functions of Equation 1 can be approximated by

$$\delta\mathbf{x}(t) = \frac{1}{2N} \sum_{i=1}^N \delta\mathbf{x}(t+i \times \Delta) + \delta\mathbf{x}(t-i \times \Delta)$$

$$\mathbf{M}(t) = \frac{1}{2N} \sum_{i=1}^N \mathbf{M}(t+i \times \Delta) + \mathbf{M}(t-i \times \Delta)$$

with  $\Delta$  the orbit time, and  $N$  a small enough number. The algorithm proceeds by combining the data of  $2N$  orbits, and by obtaining the layers position and orientation parameters by fitting the layers hits residuals and their dependence with the track inclination. The number of orbits folded is fixed by minimizing the combination of the systematic and statistical error, resulting in a total of 6 orbits. The uncertainty on the obtained corrections, estimated as explained in Sec. 4.1.2 are  $3.5 \mu\text{m}$  statistic error and  $4 \mu\text{m}$  systematic error for the tracker layer 1, and  $3.5 \mu\text{m}$  and  $6 \mu\text{m}$  respectively for the layer 9. In addition to this, the obtained corrections agree with the ones obtained with the procedure in Sec. 4.1 within the quoted errors. Moreover, the marginal overlap of the data used to compute the corrections with both methods allows to statistically combine them, resulting in a total statistic error of  $3.0 \mu\text{m}$  and  $3.5 \mu\text{m}$  for layers 1 and 9 respectively, and a systematic error of  $2.0 \mu\text{m}$  and  $2.5 \mu\text{m}$  respectively.

## 5 Conclusion

We made two types of tracker alignment, static alignment of sensors and dynamic alignment of outer layers. Additionally, the outer layers were aligned using two independent methods. The outer layer alignment procedure allows to reduce the outer layer movement due to thermal variations to a systematic error of about  $2.5 \mu\text{m}$ , with an additional statistic error of about  $3.5 \mu\text{m}$ . This allows AMS-02 tracker to reach a MDR of about 2TV for single charged particles.

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