33RD INTERNATIONAL COSMIC RAY CONFERENCE, RIO DE JANEIRO 2013
THE ASTROPARTICLE PHYSICS CONFERENCE

Operations and Alignment of the AMS-02 Transition Radiation Detector

M. HEIL[1] AND K. ANDEEN[1] WITH A. BACHLECHNER[2], A. BARTOLONI[4], U. BECKER[3], B. BEISCHER[2], B. BORGIA[4], C.H. CHUNG[2], W. DE BOER[1], H. GAST[2], I. GEBAUER[1], T. KIRN[2], A. KOUNINE[3], K. LÜBELSMEYER[2], N. NIKONOV[1], A. OBERMEIER[2], A. PUTZE[2], S. SCHAEL[2], A. SCHULZ VON DRATZIG[2], G. SCHWERING[2], T. SIEDENBURG[2], F, SPADA[4], W. SUN[3], V. VAGELLI[1], Z. WENG[3], S. ZEISSLER[1], V. ZHUKOV[2], N. ZIMMERMANN[2], FOR THE AMS COLLABORATION.

[1] *Institut für experimentelle Kernphysik, Karlsruhe Institute of Technology, KIT, Karlsruhe*
[2] *I. Physikalisches Institut B, RWTH Aachen University, Aachen*
[3] *Massachusetts Institute of Technology, MIT, Cambridge, Massachusetts*
[4] *Istituto Nazionale di Fisica Nucleare (INFN), Sezione di Roma*

karen.andeen@cern.ch

Abstract: The Transition Radiation Detector (TRD) is a sub-detector of the Alpha Magnetic Spectrometer (AMS-02), a cutting-edge cosmic ray detector that has been operating on the International Space Station since May 2011 and is expected to be taking data for at least 15 years. The aim of AMS-02 is to search for dark matter and the origin of high energy cosmic rays; therefore, resolving positrons from their proton background is a crucial aspect of many analyses using AMS-02 since positrons are an important key for investigations of dark matter, while protons dominate cosmic radiation. The TRD was developed specifically for the purpose of positron identification. The constantly changing conditions on the ISS create a unique operating environment for the sub-detectors comprising AMS-02, including the TRD. To ensure a high purity positron spectrum can be achieved in the complex conditions in space all subsystems are constantly monitored online, gas refills have been fine-tuned and are carried out on a monthly basis, and a new alignment method has been developed. The details of the operations, monitoring and alignment of the TRD aboard the ISS will be discussed.

Keywords: AMS-02, transition radiation, alignment

1 Introduction

The Alpha Magnetic Spectrometer (AMS-02), a general-purpose high-energy particle physics detector, was successfully launched on board the STS-134 mission on May 16, 2011, and deployed on the International Space Station (ISS) three days later. The detector has been steadily collecting data at a rate of 1.4×10^9 events per month since its activation. The goal of AMS-02 is to conduct a long-duration mission of fundamental physics research in space: specifically, to study cosmic rays in the GeV to TeV energy range and to perform searches for dark matter. To accomplish these goals, AMS-02 is comprised of a permanent magnet and several specialized detector systems, including nine planes of precision silicon tracker, the transition radiation detector (TRD), four planes of time of flight (TOF) counters, an array of anti-coincidence counters surrounding the inner tracker, a ring imaging Cherenkov (RICH) detector, and an electromagnetic calorimeter (ECAL). The focus of this paper is the operation and alignment of the TRD, highlighted in Figure 1.

AMS-02 has lately published its first results: a precision measurement of the cosmic ray positron fraction [1]. One of the most critical aspects of the positron fraction measurement is the separation of positrons from protons. High energy protons and positrons which have the same energy (and charge) are indistinguishable using the Tracker, TOF and RICH sub detectors. The ECAL can separate these particles; however, the discrimination power of the ECAL becomes insufficient when the proton flux is more than three orders of magnitude greater than the positron flux. At that point, the presence of the TRD becomes crucial to provide the needed reduction of the proton background. Here the operational details of the TRD will be discussed.

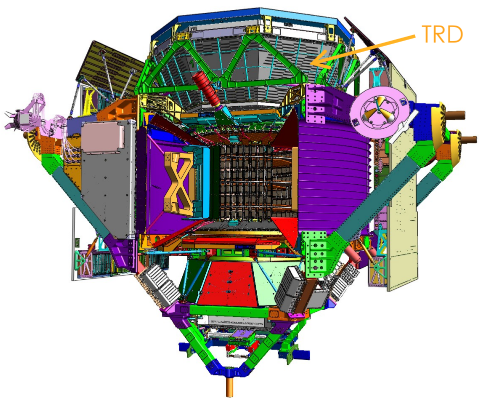

Fig. 1: A schematic of the Alpha Magnetic Spectrometer (AMS-02), highlighting the position of the transition radiation detector (TRD), which is shown in grey.

2 The AMS-02 Transition Radiation Detector

Transition radiation consists of soft x-rays which are emitted when charged particles traverse a boundary between two media with different dielectric constants. Transition radiation is emitted collinear to the primary particle's trajectory, and the amount of radiation emitted is proportional to the particle's Lorentz factor and thus inversely proportional to that same particle's rest mass. At energies up to $\sim$300 GeV, light-weight particles such as electrons and positrons have a much higher probability of emitting transition radiation photons than heavy particles such as protons. The TRD is sensitive to both the signal of

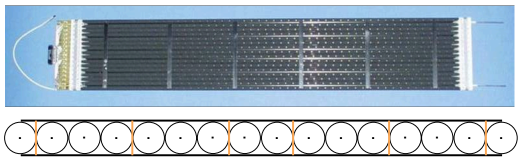

Fig. 2: Above, the photo shows a 0.6 m space-qualification TRD module of 16 proportional tubes with width-wise stiffeners every 10 cm. Below is a schematic of the edge-on view of the tubes, where the length-wise stiffeners are depicted in orange between the tubes.

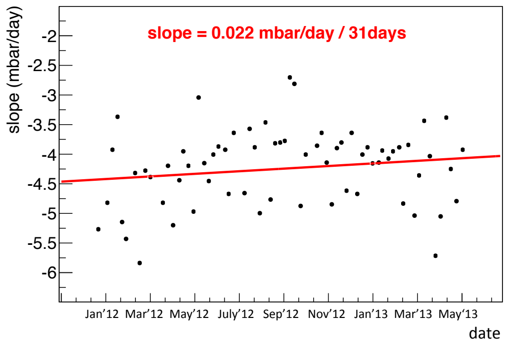

Fig. 3: Leak Rate vs Time for the TRD.

direct ionization from the primary particle and the signal from the transition radiation. Using the transition radiation contributions, the TRD is able to clearly separate protons from positrons and electrons up to many hundreds of GeV. These signals are quantified as a TRD likelihood estimator, which is used as an input parameter for physics analysis [6]. Furthermore, the direct ionization signal can be used to independently identify heavier nuclei up to iron [7].

The AMS-02 TRD is located near the top of the detector (below the first layer of the tracker), as shown in Figure 1. The TRD is 80 cm high and spans 200 cm at its top plane and 150 cm at its bottom plane: an inverted octagonal pyramid shape was used for the TRD to optimize its angle of incidence against its mass and size. The detector has a skeleton made of aluminum honeycomb walls and carbon fiber skins and bulkheads. The skeleton is populated with 5248 proportional tubes of diameter 6 mm made from 72 μm thick double-layered kapton-aluminium foil which functions as the cathode of the proportional tubes. A 30 μm thick gold-plated tungsten wire, fixed in polycarbonate end pieces and tensioned to 1 N, is used as the anode, which is then surrounded in a gas mixture of approximately 90:10 ratio of xenon (Xe) to carbon dioxide (CO_2). When a passing charged particle ionizes the active gas in a tube, a voltage proportional to the number of ionized gas atoms is produced on the output of the wire (which is why they are called "proportional" tubes). The constant of proportionality is known as the "gas gain". [2] In the TRD, xenon is used to detect the ionization signal of crossing charged particles in addition to the low energy photons of the transition radiation, while carbon dioxide acts as a quenching gas for charge multiplication, ensuring that the gas returns to its initial state for the next measurement. Each straw tube was individually tested for gas tightness [5].

The proportional tubes are grouped into sets of 16 to form 328 flat modules which range in length from 0.8 m to 2.0 m due to the pyramid shape of the TRD. Each module has carbon fiber stiffeners for lengthwise and widthwise stabilization, as shown in Figure 2. Since the probability of emitting transition radiation increases with the number of boundaries crossed, the modules are arranged into 20 vertical layers with 22 mm of fleece radiator interleaved between each layer. The fleece radiator is composed of 10 μm polypropylene/polyethylene fibers with a density of 0.06 g/cm^3 (LRP 375 BK). The proportional tubes in the four highest and lowest layers of the TRD are mounted parallel to the x-axis of the AMS-02 coordinate system (the non-bending plane of the magnetic field), while the straw tubes in the middle layers are parallel to the y-axis (the bending-plane of the magnetic field), to allow for a three-dimensional reconstruction of the particle path.

The analog pulse height is read out and is used to separate signals in the tubes due to pure ionization losses (protons and heavier nuclei) from signals containing both ionization and transition radiation photons (positrons, electrons). Digitization of the tube output signals is performed on 82 front-end boards attached to the TRD skeleton, each of which serves four TRD modules. The data reduction and low/high voltage supply units are situated in separate crates next to the TRD. In total the front-end-readout consumes 20 W of electrical power (AMS-02 uses $\sim$1500 W in total) [4]. 120 V DC power is supplied from the ISS via a power distribution box.

2.1 Gas System

In the vacuum of space, gas continuously diffuses out of the pressurized proportional tubes and, since carbon dioxide molecules are smaller than those of xenon, carbon dioxide can traverse the wall of the tubes more easily than the xenon; thus, the diffusion is due almost entirely to carbon dioxide. Furthermore, there have been two small increases in the leak-rate in the TRD since launch. Together, these constitute a leak rate of $\sim$4.5 mbar/day, shown in Figure 3: 1.0 mbar/day of carbon dioxide (from diffusion and the leaks) and 3.5 mbar/day of xenon (from the leaks). This change in composition and gas pressure contributes to a rise in the gas gain and, therefore, the most probable value (MPV) of the energy deposited. To produce an accurate most probable energy deposition measurement, it is necessary to keep the gas mixture as stable as possible over time. Thus, the AMS-02 TRD became the first detector in space to have a dynamic gas system. [3]

At the time of the launch, the gas system (schematic shown in Figure 4) was equipped with a 49 kg xenon tank and a 5 kg carbon dioxide tank, which together can supply $\sim$30 years of steady TRD operations in space at the current rate of use. These tanks are housed in a supply box, which is also where the Xe/CO_2 mixture is prepared in a 1 L mixing vessel. The supply box leads to a circulation box, which contains circulation pumps and a gas composition analyzer. The circulation box then leads to the manifolds, which distribute the gas mixture to the proportional tubes of the TRD.

The total volume of the proportional tubes in the TRD is 230 L, which are divided into ten separable gas groups. Each gas group is connected to a separate manifold which is equipped with a shut-off valve in order to isolate its gas group in case one of the connected tubes develops a leak. Nine of the gas groups contain four, and one group contains five, gas circuits connected in parallel. Each of the 41 gas

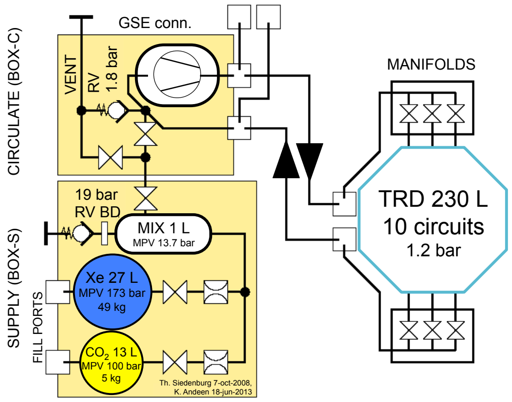

Fig. 4: TRD Gas schematic (not to scale).

circuits consists of eight straw modules connected in series. To preserve the best detector performance and acceptance in case one of the manifolds needs to be closed, the gas circuits within each gas group are maximally spread over the entire volume. At all points of the gas system the valves have a two-fold redundancy.

2.2 Online Monitoring

The TRD includes a network of pressure and temperature sensors to monitor the status of the detector and the gas supply system which are read out regularly. Additionally, high energy particles hitting the electronic boards can lead to bit flips in the electronics or trip off the high voltage chains. In the high-radiation environment of space, these events are relatively common; thus, the status of the detector electronics as well as the high voltage values of each channel are also read out regularly.

System information is transferred to the ground and continuously monitored at the Payload Operations Control Center (POCC) at CERN using monitoring programs that have been specifically designed for this task. In the POCC a number of actions can be taken to correct errors; however, depending on the seriousness of any problem found, predefined commands may be automatically sent to try to recover operations. This is a necessity since communication to the detector is dependent on satellite positioning; thus, transmission delays anywhere from seconds to hours may occur before data indicating a problem arrives in the POCC to be viewed by the person on shift.

2.3 Typical TRD Operations

The TRD is, in general, operated at a high voltage between 1300 and 1500 V with a pressure in the straw tubes $\sim$1 bar. These values were selected in order to have a stable detection of ionization signals while still preserving a wide ADC range for the detection of transition radiation photons and the ionization signal of ions up to boron without saturation. To ensure the optimal performance of the TRD, the detector has been tuned on the ground using beam tests and with muons from cosmic rays [3, 4, 5].

A number of factors affect the gas amplification of the particle signal in the TRD, and therefore the MPV of deposited ionization energy. The continuous loss of gas in space discussed in Section 2.1 causes pressure and composition ratio changes of the gas in the TRD. Temperature gradients throughout the detector affect both the gas gain (by causing fluctuations in the local gas density) and physical positioning of the proportional tubes, which results in systematic errors in physics analyses. In order to reduce the changes in the temperature of the detector, it is wrapped in multi-layer insulation, which reduce the “daily” temperature changes (between the day and night part of each 90 minute orbit) to $\sim$1° C. However, the orientation of the ISS and the position of the ISS radiators and solar arrays also cause the temperatures to vary. These fluctuations are limited by thermostat-controlled heaters on the TRD skeleton which are always enabled and are configured to turn on at 10°C and off at 20°C. In the event of a sudden change in position of the radiators, solar arrays, or the station itself (due to a shuttle docking, or a reboost, for example), the temperature can change within a few hours’ time. This not only affects the gas amplification but, in the event that the temperature drops below $\sim$10°, the TRD circulation pumps approach their lower operational limit. In this case, a number of actions are available: the TRD vessel heaters may be turned on and NASA may be requested to move the radiators or solar panels of the ISS to a more favorable position for AMS-02. In a very extreme case the TRD pumps may be turned on. This generates heat while benignly driving the TRD gas in a trapped volume. However, due to the movement of gas in the detector, running the pump also affects the data quality of the TRD (and thus the AMS-02 detector overall), so this action is taken only in very extreme cases when all other options are not sufficient to return the temperature to nominal operational limits.

Aside from these extreme temperature situations, the gas pressure will decrease over time due to diffusion and leaks in the system (see 2.1). This decrease causes an increase in gas gain (i.e. signal amplitudes) and therefore the MPV of the energy deposition in the TRD. There are two types of adjustments that can be made to account for this increased MPV: fine-tuning in the form of high voltage adjustments (a decrease in high voltage will will decrease the signal amplitudes), and coarse steps in the form of gas refills (which increase the pressure and modify the gas composition). Gas refills are performed in two stages: first a mixing step, where the carbon dioxide and xenon are released from the supply vessels and mixed in the proper proportions in the mixing vessel (usually a 10:3 ratio of xenon to carbon dioxide is required in the 1 L mixing vessel to keep the 90:10 ratio in the 230 L TRD), and then an injection step, where the gas is injected from the mixing vessel through the manifolds and into the TRD in many short puffs. These two steps are repeated twice during each gas refill, over the course of two days. While the daily high voltage adjustment produces a $\sim$5 minute interruption to data-taking, the 2$\times$ $\sim$3 hours of gas injections of the gas refill strongly interrupt data taking. Thus, to minimize the impact on data taking, high voltage adjustments of around -3 V are executed daily, while gas refills are monthly operations; this combination preserves stable signal amplitudes and keeps the TRD within its optimal operating limits of $\sim$900 and $\sim$1000 mbar.

2.4 Gain Calibration

In order to perform adjustments to correct for environmental influences on the TRD, as discussed in 2.3, a fast, *in-situ* calibration is necessary. Clean, single-track protons are used for this task for two reasons: they are abundant, dominating the cosmic ray flux ($\sim$89%) at the average proton energy observed by AMS-02 (8 GeV); and they have a low probability of emitting transition radiation,

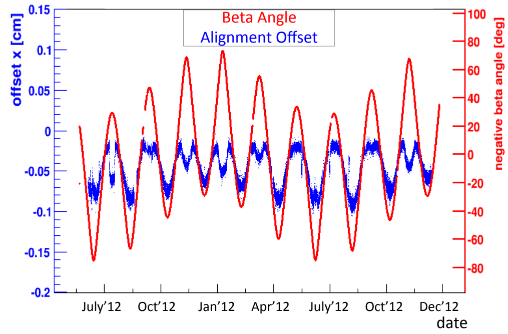

Fig. 5: Correlation of beta angle (red) and alignment offset (blue) of TRD module 150 .

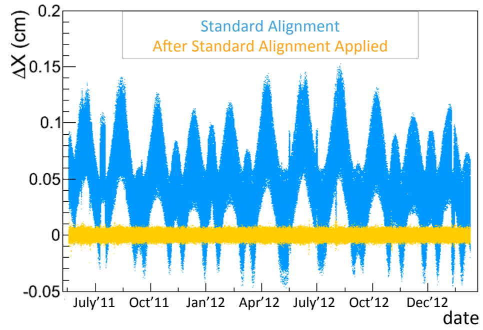

Fig. 6: Offset of the positions of TRD layers 5-16 with respect to the tracker extrapolation into the TRD as a function of time before (blue) and after (orange) applying standard alignment corrections.

which allows the calibration to use only the ionization signal. Protons are selected using information from the other detector systems. Since the energy deposited by a proton due to ionization is well-understood, it can be fitted and used as an indicator for the change in the gas amplification. After the calibration is applied the detector response is stable for all tubes within 2%. More details can be found elsewhere in these proceedings [6].

2.5 Alignment

As the ISS is in constant motion in space with respect to the sun and the earth, and due to frequent repositioning of radiators and solar arrays aboard the ISS, the amount of sunlight incident on the detector varies greatly with time. In the short-term, the temperature varies based on the 90 minute day/night orbital cycle. The orbital temperature change can cause movement of the TRD tubes relative to the inner tracker of $\sim$100 μm, as seen in the high-frequency variation in Figure 5. In the long-term, the position of the tubes is correlated to the β-angle, the angle between the orbital plane of the ISS and the sun vector, which is an indicator of the fraction of time the ISS is exposed to sunlight throughout one orbit (with $\beta = 0°$ having the smallest and $\beta = \pm 90°$ having the largest amount of sunlight per orbit). The β-angle has a 60 day cycle which causes a movement of up to 1 mm of the straw tubes; a correlation between the β-angle and the tube position can be clearly seen in the low-frequency oscillation of Figure 5. Combined, these short- and long-term temperature changes cause relative movement of the TRD modules with respect to the Tracker, which results in the need for alignment corrections.

A standard alignment method is therefore present in the official AMS software. This method extrapolates the tracker track (the best known estimation of the particle track) to each TRD tube, where the track position is compared to the default position of the tube wire. A single time-dependent offset in the horizontal direction is then calculated for each of the 328 modules. The alignment correction is calculated as often as the data allows, which can vary from 40 minutes to 8 hours, depending on the hit frequency of each module. The alignment can then be accessed in the software to correctly calculate the path of each particle through the gas volume. The effect of applying the alignment correction is shown in Figure 6, where the difference in position with respect to the tracker extrapolation is shown for all TRD modules as a function of time both before and after the correction has been applied. The residual misalignment is reduced to the level of 20 μm for two years over all modules, allowing for a precise determination of the path lengths inside the TRD straws.

An improvement to the standard alignment package is under development with the inclusion of "missing signal data," which occur either when a particle does not deposit energy in a layer of the TRD due to the incomplete volumetric filling the layer (there is a 68% chance that a particle will pass between two tubes in one of the 20 traversed layers) or statistical fluctuations of the ionization signal down to low amplitudes (which are removed by a noise cut in standard data cleaning). Since the gap between two tubes ranges from 200-500 μm, while the inner diameter of the tubes themselves is 6 mm, the inclusion of "missing signals" can add precise points to the calculation of the alignment parameters. The comparison of this improved analysis to the standard alignment is still in progress, however initial results indicate that this is a promising method.

3 Conclusions

AMS-02 has been running on the space station for two years and plans to continue operations for another $\sim$15 years. AMS-02 with its TRD provides a significant improvement over previous space-based detectors. After two years of experience the procedures for operation and alignment are well established, while we continue to investigate possible improvements. With future operation that is consistent with our current experience, we expect there to be sufficient gas stored on board to continue operating the TRD for the lifetime of the ISS.

References

[1] M. Aguilar, et al (the AMS-02 Collaboration), PRL 110, 141102 (2013)
[2] M.W. Charles, Gas gain measurements in proportional counters. J. Phys. E: Sci. Instrum. 5 95 doi:10.1088/0022-3735/5/1/031 .
[3] M. Heil, PhD Thesis, Karlsruhe Inst. of Tech. (2013).
[4] Th. Kirn, Nucl. Instrum. Methods Phys. Res., Sect. A.706,43 (2013).
[5] T. Siedenburg et al., Nucl.Phys.B(Proc.Suppl.).150(2006), 30-33.
[6] H. Gast for the AMS Collaboration, these proceedings.
[7] W. Sun and X. Weng for the AMS Collaboration, these proceedings.