# The Performance of the Transition Radiation Detector of the AMS-02 experiment

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on behalf of AMS02-TRD Collaboration

***Abstract*—The Alpha Magnetic Spectrometer (AMS-02) is an experiment which will be mounted on the International Space Station (ISS) in 2006 to measure primary cosmic ray spectra in space and to perform an indirect search of dark matter component of universe. A key element is a Transition Radiation Detector (TRD) to distinguish an $e^+$ or $p^-$ signal reducing the $p^+$ or $e^-$ background by a rejection factor $10^3 - 10^2$ in an energy range from 10-300 GeV. This will be used in conjunction with an electromagnetic calorimeter to provide overall $p^+$ rejection of $10^6$ at 90% $e^+$ efficiency.**

**The detector consists of 20 layers of 6 mm diameter straw tubes alternating with 20 mm layers of polyethylene/polypropylene fleece radiator. The tubes are filled with a 80%:20% mixture of $Xe : CO_2$ at 1.0 bar absolute from a recirculating gas system designed to operate $>3$ years in space.**

**A TRD protype has been calibrated and its performance measured in test beams with $p^+$, $e^-$, $\mu^-$, $\pi^-$ in the momentum range from 3 to 250 GeV/c and compared with Monte-Carlo predictions. It achieves rejection factors from 2000-140 for protons in a momentum range of 15-250 GeV/c. The design and construction of the detector is presented and results from test beam runs are discussed.**

***Index Terms*—AMS, TRD, transition radiation detector, proton rejection.**

## I. Introduction

The Alpha Magnetic Spectrometer is an experiment which will be mounted on the International Space Station (ISS) to measure primary cosmic ray spectra in space [1]. A main physics goal of AMS-02 is the search for dark matter. One way of doing this is to search for an enhancement in the positron spectrum as a function of energy. Since the ratio of fluxes of $p^+$ to $e^+$ in orbit is on the order of $10^4$, AMS-02 must be able to avoid confusing protons with positrons to a level better than $10^6$. Its uppermost element is a Transition Radiation Detector (TRD) (see Fig. 1). Transition radiation (TR) consists of soft X-rays which are emitted when charged particles traverse the boundary between two media with different dielectric constants. In the momentum range of 10-300 GeV/c, light particles such as electrons and positrons have much higher probability of emitting TR photons than heavy particles such as protons and antiprotons. At a single boundary, the probability of emission is still very small, on the order of $10^{-2}$, but this is enhanced by using a fleece as a radiator. This, in turn is divided into twenty 20 mm thick layers, with layers of 6 mm diameter straw tubes, filled with an 80%:20% $Xe : CO_2$ gas mixture, in between to detect the photons. In this way a rejection factor of $10^3 - 10^2$ for $p^+$ and $e^-$ can be achieved against $e^+$ and $p^-$ in the abovementioned momentum range. Combining the TRD rejection power with that of an electromagnetic calorimeter (ECAL in Fig. 1) located at the bottom of AMS-02 increases the $p^+$ rejection to the order of $10^6$ at 90% $e^+$ efficiency, in this energy range.

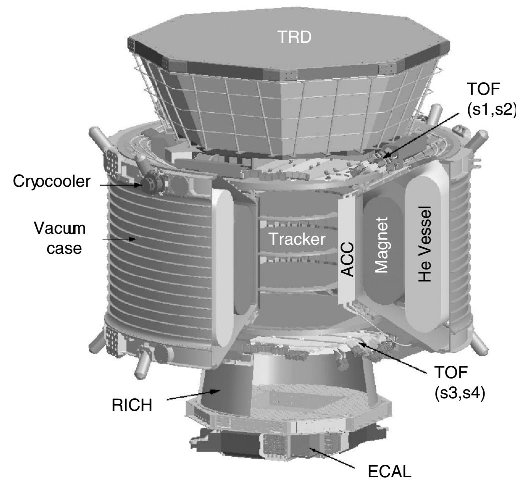


Fig. 1: The TRD in AMS-02

## II. Mechanical Structure

The TRD detector is described in [2]–[5]. It is supported by a conical octagon structure (width from 1.5 m at bottom to 2.2 m at top) built of a carbon fiber and aluminum honeycomb sandwich material for the sidewalls, with slots machined with a precision of 100 $\mu$m, the top and bottom covers. The dimensions are verified on a precision measuring machine. The octagon is supported from the magnet vacuum case and the Universal Support Structure (USS) which holds AMS-02 in the shuttle and on the ISS by an aluminum M-structure. Detailed finite element calculations have been performed to verify that the large TRD octagon structure and support satisfies all dimensional and safety requirements. The straw tubes are

Manuscript received Nov 14,2003.

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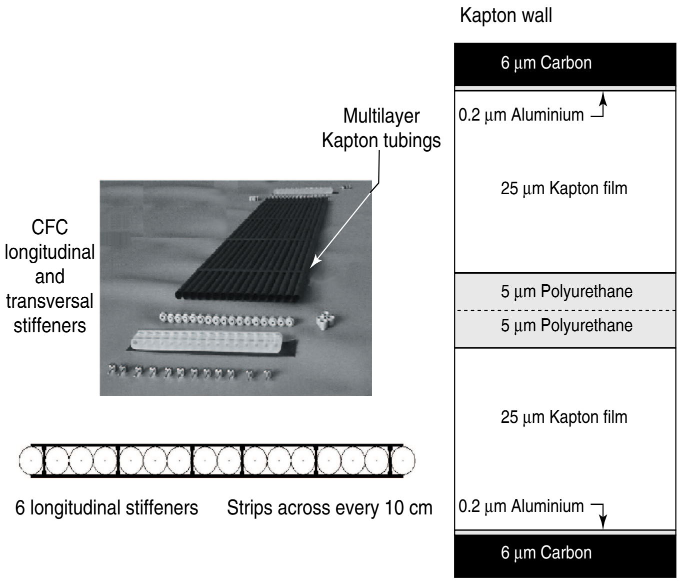


Fig. 2: Straw Tube Module: 16 6 mm tubes with 30 $\mu$m W-Au wire

built as modules of 16 tubes with 6mm diameter. The 20 layers, each with 20 mm fleece, of modules are arranged in the conical octagon structure. The top and bottom 4 layers are oriented parallel to the AMS-02 x axis, which is the direction of the field in the magnet. The middle 12 layers are oriented along the perpendicular y direction. Thus the tubes provide tracking both in the bending and non-bending directions of the magnet as well as particle identification.
The length of the straw modules varies from 0.8 m to 2.0 m. In all, there are 328 modules, for a total of 5248 straws. The wall material of the straws is a 72 $\mu$m Kapton foil, whose structure is shown in Fig. 2. The anode wires are 30 $\mu$m gold plated tungsten. The wires are held in the polycarbonate end pieces by crimping in Cu-Te blocks. The radiator is a fleece of 10 $\mu$m polyethylene/polypropylene fibers.

## III. Electronics and DAQ System

The Data Acquisition (DAQ) system of the TRD is divided in two parts: The front end electronics, constituted of 5248 channels, which are mounted on the walls of the detector, and the first level of data acquisition which is hosted in two identical crates. The digitization of the signals from the straw tubes is done in the front end electronics. The crates hold the power supplies, the boards which collect and compress the data and the control of the whole TRD DAQ system. A more detailed description of electronics and DAQ system can be found in [2].

## IV. Module Production

Each straw is pretested and accepted only with a He leakrate below $10^{-5}$ l mbar/s/m. Straw module production continues with gluing of 16 straws with their stiffeners. Then the endpieces are glued to the straws. After curing the glue, the wires are inserted, tensioned, and crimped into the CuTe blocks in a special machine. The wire tension is measured, then a preview test of the signal noise spectrum is made with HV and an $\mathrm{Ar/CO_2}$ gas mixture. After these tests are passed, the final glue potting of the endpieces is done and the HV boards are mounted. This is followed by a serial test of gas tightness, dark current and corona, and the gas gain is measured as a function of high voltage with an $Fe^{55}$ source and the $\mathrm{Ar/CO_2}$ gas mixture. An X-ray measurement of the wire position is made on a subsample of the modules, as well as a long term test in vacuum of the gas gain.

## V. Gas System

The TRD contains $\mathrm{Xe/CO_2}$ mixed 4:1 in volume. The gas has to be stored, mixed, and distributed through the TRD modules. The gas system to do this is divided into three parts. Box S stores the Xe and $CO_2$ in separate vessels, which will contain 46 kg of Xe and 4 kg of $CO_2$, 50 kg in total. The gases are transferred in controlled amounts (by measuring partial pressures) to a mixing vessel, from which the mixture is released to box C. Box C contains redundant pumps to circulate gas through the TRD to ensure uniform gas properties. It also contains a $CO_2$ analyzer and monitor tubes for measuring gas gain with an $Fe^{55}$ source. Gas tightness is crucial for the operation of the TRD detector in space. The 300 flight modules produced so far all show a leak rate below $10^{-4}$ l mbar/s/m, which is sufficient for operating the TRD up to 10 years. Nevertheless, the volume of the TRD is divided into 41 separate gas circuits, each consisting of eight modules connected in series. Pressure sensors and valves located in the so-called manifolds can detect leaks and isolate a leaky segment.

## VI. Monitoring and Control

The monitoring and control crate for the gas system contains two redundant Universal Slow Control Modules (USCMs) which contain the monitor program which tests the status of the gas system against preset conditions and executes commands, which are stored in the form of decision tables. The USCMs are connected to the main Monitor and Control Computer of AMS via CAN-Bus, and to the gas system control electronics via a dedicated control bus. The gas control electronics consists of separate redundant Box S, Box C, and manifold control cards in the crate, and cards mounted on the manifolds for the pressure sensors. The cards monitor pressures, temperatures, gas composition and gain, and control the opening and closing of the valves for safety and gas mixing operations.

## VII. Gas gain control

To achieve the requested performance the gas gain,G, has to be controlled carefully. This has dictated severe constrains to our detector. The effect of mechanical wire displacement is for example extremely important. A 100 $\mu$m wire displacement off the center causes a change in the gas amplification by 1.5%.

The percentage of the two gas $Xe/CO_2$ is higly determining the amplification:

$$\frac{dG}{Gdf} = \frac{8\%}{1\% CO_2} \quad (1)$$

where $f$ is the $CO_2$ percentage in the gas mixture. A variation of only 1% in $CO_2$ content implies a 8% variation on gas gain

The gas density, $\rho$, also, has to be carefully controlled:

$$\frac{dG}{Gd\rho} = \frac{-5.5\%}{1\% \rho} \quad (2)$$

a variation of 1% in the density implies a 5% variation in gas gain. The same variation is caused by a temperature gradient of 2.7K assuming a constant gas volume.

Another important element is the control of applied voltage U:

$$\frac{dG}{GdU} = \frac{1\%}{1V} \quad (3)$$

a variation of 1V in the applied voltage U implies a 1% variation in gas gain. In the design and realization of this detector these effects have been taken in account.

## VIII. Verification of TRD Performance

To verify the performance, a 20 layer prototype was built with two 16 tube modules staggered side by side in each layer. This was used for a beam test at CERN. In 16 layers the tubes ran horizontally, and in 4 layers the tubes ran vertically. Aside from length, the tubes and radiator were identical to those of the flight TRD. They were filled with an $80\% : 20\%$ $Xe : CO_2$ gas mixture at at 2 mbar above atmospheric pressure. Runs were taken at 15 different beam energies at test beams at CERN. Over 3 million events were recorded: $p^+$ at 15-250 GeV, $e^-$, $\mu^-$ and $\pi^-$ at 20-100 GeV. Particles were identified by Cerenkov counters and by penetration of an iron beam dump at the end of the beam line. A glance at energy spectra of protons, pions and electrons, as in Fig.3, clearly shows the effect of transition radiation and the dependence of TR on the Lorentz factor $\gamma$.

## IX. Calibration

A tube by tube intercalibration with protons and muons was done to equalize the signals from each tube to a standard value. This was done to correct for differences in the electronics and mechanical construction of the different tubes. For each run, a Landau fit was done to each tube's energy deposit spectrum to determine its most probable value, and these were used to prepare intercalibration tables of the tubes, run by run, and then summed for all runs, using overlapping tubes. The intercalibrations are accurate to the 1% level. Pressure and temperature were monitored for gas density corrections between runs. At the standard density of $4.46 \times 10^{-3}$ $g/cm^3$ with HV at 1470 V for a gas gain of 5000 an increase of density of $1\%$ leads to a decrease of gas amplification of $5.5\%$. $Fe^{55}$ spectra were taken between runs on the first and last layers to calibrate the energy deposition by photons to the ADC scale. $9.09 \pm 0.05$ eV of photon energy corresponded to one 12 bit ADC bin. Neglecting variation of $CO_2$ and voltage, including intercalibration, gas density and energy (obtained with $Fe^{55}$) effects the correction is accurate to $2\%$.

The calibrations were done for both protons and for muons, with good agreement.

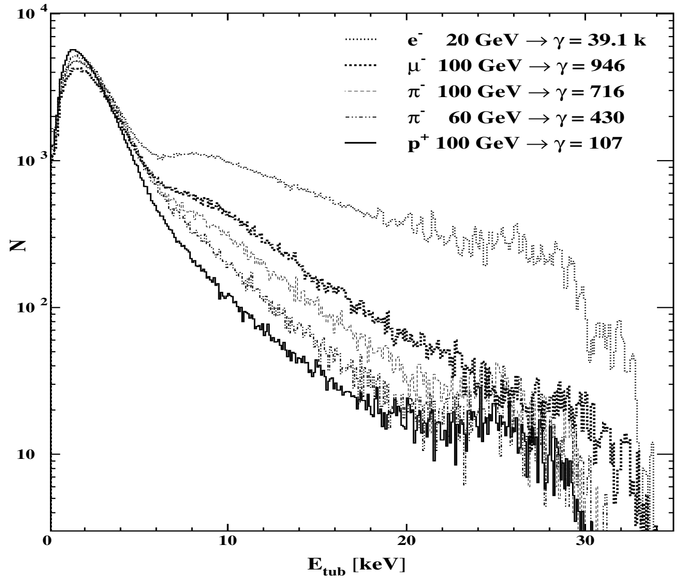


Fig. 3: Energy spectra recorded with particles at various Lorentz factors [4]

## X. Radiator Test

The polyethylene/polypropylene fleece material LRP 375BK from Freudenberg Vliesstoffe KG to be used as radiator has to be washed with $CH_2Cl_2$ to satisfy NASA outgassing limit of $10^{-12}$ $g/s/cm^2$ . The fiber sheets of radiator have a density of $0.06$ $g/cm^3$ and are 5mm thick. The energy deposition spectra from single track electron events were used to compare the performance before and after cleaning, and also to compare it with a polyacryl fleece (Separet 405/Freudenberg Vliesstoffe) with acceptable outgassing properties, but whose behavior as radiator was unknown. The AMS radiator was unaffected by cleaning and was slightly better than the Separet 405.

## XI. Event Selection

Secondary particles produced before or in the TRD are eliminated by requiring clean single track events, which made up $50\% - 80\%$ of the data, depending on the beam setup.

## XII. Proton rejection vs. Beam Energy

Electron and proton energy depositions in one tube are shown in Fig.4a. This effect of transition radiation is enhanced averaging the energy deposition of the 20 layers of the detector. The electron and proton signal is clearly separated (Fig.4b). For preselected single track events, Fig.5 shows the energy spectra for all tubes on the reconstructed track with the transition radiation component clearly visible in the electron spectrum above 6 KeV.

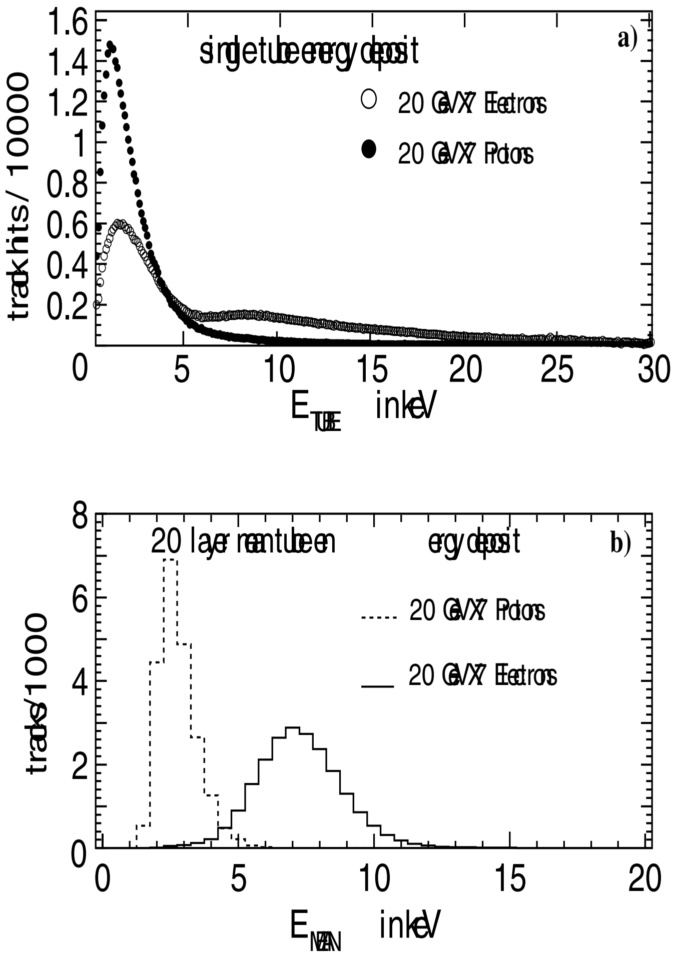


Fig. 4: Energy deposition of electrons and protons in a single tube (a) and in 20 layers (b)

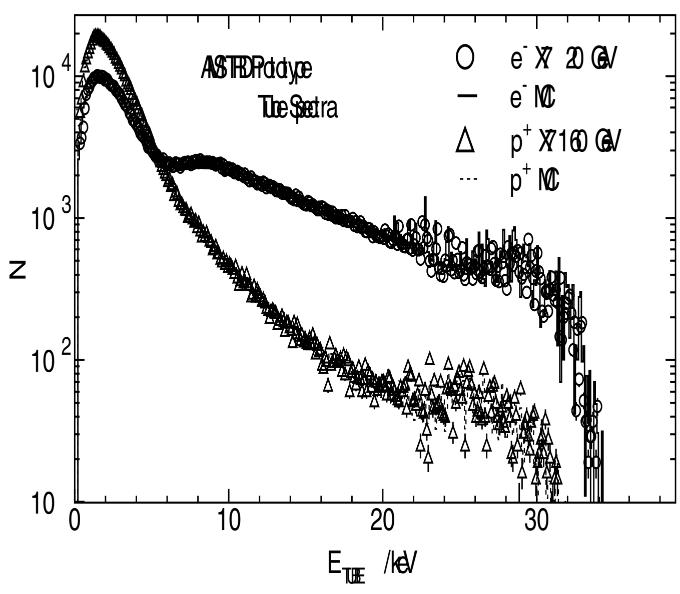


Fig. 5: Energy Deposit Distributions for $p^+$ and $e^-$

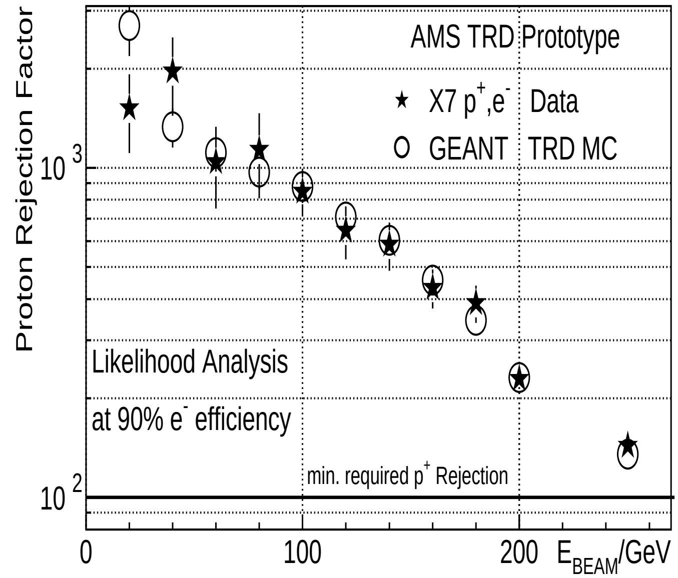


Fig. 6: Proton Rejection vs. Energy

Proton rejection is defined as the ratio of the number of incident protons to those selected when the total number of electron events are not reduced below typically 90% by applying the same cuts. To measure proton rejection, two methods were used: cluster counting and maximum likelihood. In cluster counting, there must be at least a minimum number of hits (typically 5 or 6) on the track with an energy deposit greater than an energy cut (5 to 10 keV) for a particle to be classed as an electron. In the maximum likelihood method, the energy deposit distributions for protons and electrons, shown in Fig. 5, are normalized and used as the probability distributions for each hit, $P^i_{e,p}(E_i)$. A combined probability, $W_{e,p}$, is calculated and used to determine the likelihood ratio $L_e$ for N hits on the track:

$$W_{e,p} = \prod_{i=1}^{N} P^i_{e,p}(E_i); L_e = \frac{W_e}{W_e + W_p} \tag{4}$$

The proton rejection factor is determined as the inverse proton selection efficiency with a likelihood cut set for an electron efficiency of 90%. Fig.6 shows the proton rejection as a function of beam energy. In the cluster method, at least 6 hits with an energy deposit of at least 6.5 keV are required. The cluster method gives a proton rejection factor higher than 100 up to 200 GeV.

## XIII. Comparison Monte Carlo - Data

The beamtest results were compared with a GEANT 3.21 simulation with improvements in the $\frac{dE}{dx}$ simulation for thin gas layers and inclusion of transition radiation as implemented by the HERA-B collaboration. After tuning the simulation to the AMS TRD fleece, the Monte-Carlo simulation reproduces the proton energy spectra over the full range of beam energies, and the proton rejection factors agree well with the values from the measured data (Fig. 6).

## XIV. SPACE QUALIFICATION

There are stringent requirements on the TRD due to its operation on the ISS. TRD modules and structures have undergone an extensive program of space qualification tests to verify, among other things, leak tightness and thermal performance in space, mechanical stability both on launch and on orbit, power consumption and electromagnetic interference.

## XV. CONCLUSIONS

A TRD protype, built with 20 layers of straw tubes, has been calibrated and its performance measured in test beams with $p^+$, $e^-$, $\mu^-$ , $\pi^-$ in the energy range from 3 to 250 GeV/c and compared with Monte-Carlo predictions. The rejection factors achieved is in the range of 2000-140 for protons in an energy range of 15-250 GeV/c. This requirement is fundamental to reach the precision in positron spectroscopy over the dominating proton background to observe the positrons originated from neutralino annihilation.


## ACKNOWLEDGMENT

I would like to thank all my colleagues and technical staff in the collaboration for all their efforts, in particulary J.Burger (MIT) and Th. Siedenburg (Aachen).


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