The AMS-02 Transition Radiation Detector to Search for Dark Matter in Space

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***Abstract*— The Alpha Magnetic Spectrometer (AMS) is a high energy physics experiment to be installed on the International Space Station (ISS) to measure the primary cosmic rays spectrum in space. A Transition Radiation Detector (TRD) will provide a proton rejection factor of $10^2 - 10^3$ to search for SUSY neutralino dark matter annihilation in cosmic rays in the energy range of 10-300 GeV. The TRD consists of 20 layers of straw proportional tubes interleaved with a fleece radiator; the tubes will be filled with a 80:20 Xe:CO_2 mixture at $\sim$ 1.2 bar to detect the transition photons. To satisfy all the requirements for the expected detector's performances, it is necessary to performe careful checks of the gas parameters and the gas gain. Several tests showed that the detector can fulfill all the stringent requirements for operation on the ISS, assuring the required rejection factor in the energy range of interest.**

***Index Terms*— Transition radiation detector, straw tubes, gas gain, dark matter, proton rejection.**

I. Introduction

The Alpha Magnetic Spectrometer (AMS) [1] will be located on the International Space Station (ISS) at a mean altitude of 400 km.

Fig. 1. Location of AMS-02 on the ISS.

It will perform primary cosmic rays spectroscopy for energies up to TeV to search for antimatter and dark matter in space during a 3 years mission. For these goals, AMS will use all the state of the art technologies of the modern particle physics, allowing crossed checks among its subdetectors. The AMS detector has an acceptance of 0.45 m^2sr with payload limited to 6.7 tons and power to 2.5 kW. It is built around a superconducting magnet with a bending power of 0.86 Tm^2 and eight planes of a silicon tracker. Around the tracker it hosts AntiCoincidence scintillation Counters (ACC), while above and below the tracker it has two planes of scintillator for trigger and Time Of Flight measurements (TOF). Finally, particle identification is enhanced by a Ring Imaging Čerenkov Counter (RICH), a Transition Radiation Detector (TRD) and an Electromagnetic CALorimeter (ECAL).

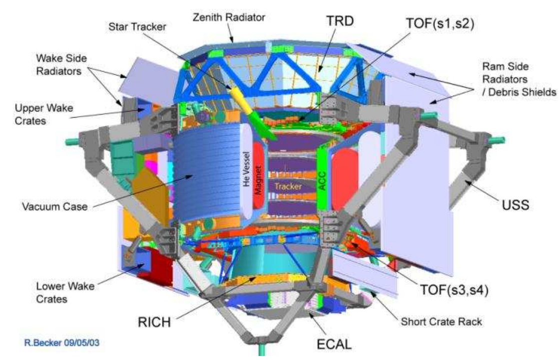

Fig. 2. The AMS detector.

In particular the TRD, together with the Electromagnetic CALorimeter (ECAL), is of fundamental importance to search for SUSY dark matter. Annihilation of neutralino, major candidate as SUSY dark matter constituent, could produce an excess of positrons in the energy range between 10 GeV and 300 GeV; to search for neutralino annihilation signatures a proton rejection factor of 10^6 is required. The TRD will provide a proton rejection factor of the order of 10^2-10^3 while the missing factor will be provided by the ECAL [2].

II. Transition Radiation Detector

Transition radiation (TR) is a soft X rays emission, peaking around 5 keV, generated when a charged particle traverse the boundary between two materials having different dielectric constants. Since the intensity of TR is proportional to the Lorentz factor γ, the detection of TR allows an efficient separation of light and heavy particles. If the Lorentz factor is greater than a threshold of 500, the TR photons are emitted collinear to the primary particle, so it's necessary to distinguish primary protons from positrons recording both the ionizzation signals from the primary particle and the TR emitted. The probability of TR emission at a single surface is of the order of 10^{-2} so a fleece radiator is necessary to enhance this factor [3], [4], [5].

A. TRD Structure

The AMS-02 TRD consists of 20 layers of straw proportional tubes, interleaved with 20 mm thick radiator material, placed into an octagonal support structure. The support structure has aluminum honeycomb walls covered by 2 mm of carbon fiber and is machined with a precision of 100 μm to avoid wires displacement or straw walls deformation; it is covered by a Multi-Layers Insulation (MLI) to guarantee thermal stability. The radiator material (LRP 375 BK) consists of polyethylene/polypropylene fibers with a mean diameter of $\sim$10 μm and a density of 0.06 gcm^{-3}; the LRP 375 BK material satisfies weight constrains and TR yield requirements [6]. The straw tubes are arranged into 328 modules of 16 straws each; the tubes have an inner diameter of 6 mm and lenght between 0.8 m and 2.2 m with 72 mm thick kapton/aluminum walls. A W/Au wire with diameter of 30 μm tensioned with 100 g is centrally located in each tube.

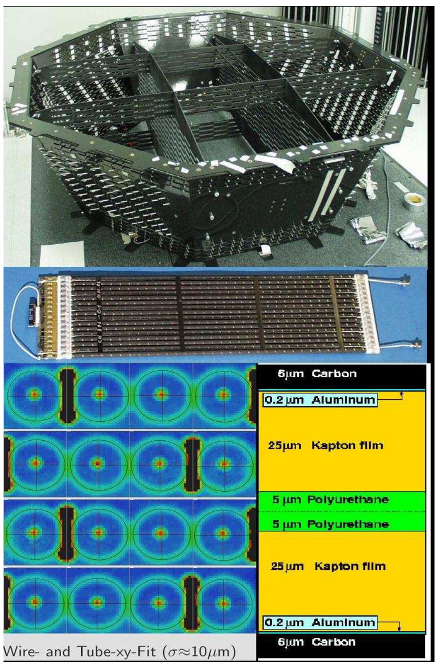

Fig. 3. Support structure, TRD module, wire allignment accuracy and straw wall composition.

The modules are arranged in 41 TRD segments and will be filled with a Xe/CO_2 (80:20) mixture at $\sim$1250 mbar to detect the TR photons generated inside the radiator material [7], [8], [9].

B. Front End Electronics and DAQ

The front end electroics consist of 82 units (UFE) corresponding to a total of 5248 channels powered by 20 W; they digitize the signal produced in the straw tubes. Dedicated boards (UTE) are used to distribute the high voltage to the tubes and collect straws signals. Two crates with 28 V DC connection each host the whole TRD DAQ system (UCrate) and power supplies (UPD); in particular the Ucrate contains the UDR board dedicated to the reduction of the data coming from the UFEs [7], [10].

III. TRD Gas System

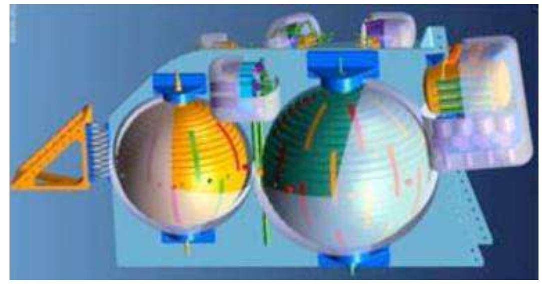

Fig. 4. TRD gas system project.

A. Gas System Structure

The gas system stores sufficient gas for the whole duration of the AMS-02 mission, transfers fresh mixture to the TRD every day, circulates the gas through the detector and monitors the gas content continuously. It consists of a supply module (Box S), a circulation module (Box C) and distribution modules (Manifold) [11].

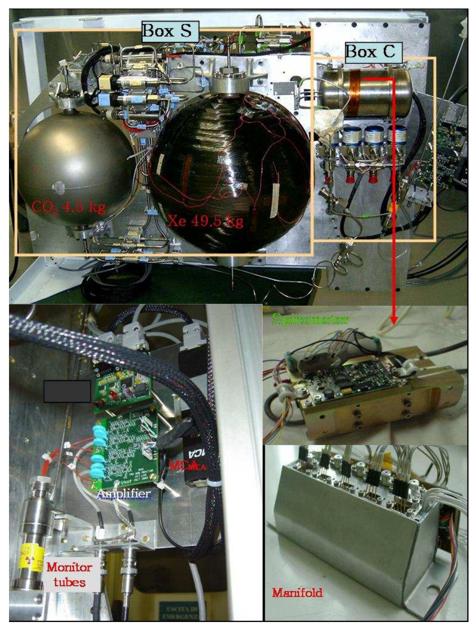

Fig. 5. TRD gas system with the monitor tubes, the spirometer and a manifold.

Box S contains two carbon fibers over-wrapped stainless steel gas tanks to store 49.5 kg of Xenon at 107 bar and 4.5 kg of CO_2 at 65 bar. High pressure valves allow gas transfer to a mixing vessel with a volume of $\sim$1 l where the Xe:CO_2 (80:20) mixture is obtained to 1% accuracy. Heaters are used for uniform and safe gas transport.

Box C contains diaphragm pumps to circulate the mixture through the system. Four calibration tubes coated with ^{55}Fe monitors the gas gain and mixture quality and a spirometer allows to calculate the CO_2 fraction in the mixture from transit time measurements of an ultrasonic pulse.

Manifolds constitute the gas inlet and outlet to each TRD segment; they are supplied with differential pressure sensors to reveal pressure drops and they allow to isolate leaking segments. The gas flow in the detector will be 1 l/h per gas circuit.

All the main components are double redundant to assure safety and functionality in space.

B. Gas System Electronics

The system is controlled via the electronics crate (UGcrate) that contains the double redundant control board (USCM) and dedicated boards to control Box S (UGBS), Box C (UGBC) and Manifolds (UGFV); it also contains one board to supply the high voltage to the monitor tubes located in Box C (UHVG). The electronic control includes a main DAQ computer (JMDC) that communicates via CAN bus with the USCM and then with each board that controls the electromechanical devices. A Power Distribution Box (PDB) provides 28 V DC from the 120 V DC supplied by the space station [12].

IV. Requirements and Performances

A. Gas Thightness

The gas thightness depends on the gas diffusion through the straw walls and from the leak rate through the modules end-pieces. The straw modules are terminated with polycarbonate endpieces and Cu-Te crimp connectors to the electronic boards; AW 134 glue is used for potting.

A TRD longterm test has demonstrated that gas thightness is unchanged over a period longer than 2 years. The CO_2 leak rate is about $7.7 \cdot 10^{-5}$ l mbar s^{-1} corresponding to a safety factor of $\sim$7.

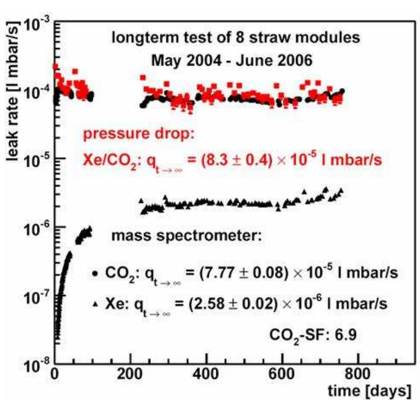

Fig. 6. Leak rate measurements results from the logterm test.

B. Gas Gain

The TRD will operate at a gain of $\sim$3000. Since the gas gain is strongly dependent on high voltage and gas density, it's necessary to correct for variation in gas gain due to variations of these two parameters. For example a 3°C temperature change causes a 1% gas density variation, which implies a gas gain variation of about 5%. So to obtain the required proton rejection power, a stringent control over the gas parameters is necessary.

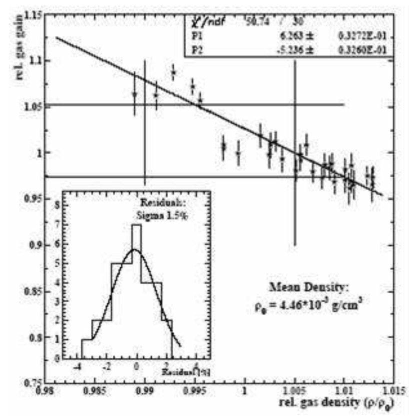

Fig. 7. Relative gas gain as a function of gas density.

C. Thermal Stability

Because of the dependance of the gas gain on the gas density, it is necessary to keep pressure and temperature stable during the operation in space. In particular the temperature gradient has to be $\Delta T < 1$ K; the temperature variation during the orbit ranges from T = +35°C to -15°C. Multilayer insulation and heaters allow to keep the thermal stability, while 200 Dallas temperature sensors in the whole TRD monitor the temperature.

D. Gas Quality Check

The mixture quality is of fundamental importance to obtain the expected gas gain. To control the accuracy of the gas ratio the TRD uses two techniques: a spirometer and monitor tubes. In particular the monitor tubes are used to analyze the gas gain variation measuring ^{55}Fe spectra. We performed a test on the engineering model of the gas system using a premixed 80:20 Xe:CO_2 mixture. The gas was flushed into an open system, thus increasing impurities on the cathode or in the mixture composition. Despite the high background due to the test conditions, the result shows that is possible to perform a good fit of the spectra using an exponential function for the background and two gaussian to describe the photopeak and the escape peak. The test has also shown that is possible to control the whole apparatus successfully using the gas system electronics and slow control software.

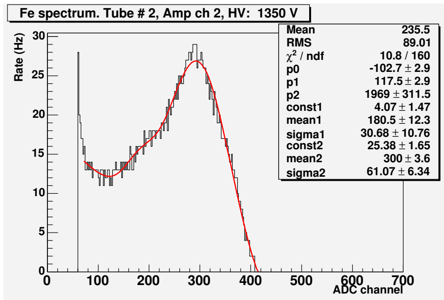

Fig. 8. ^{55}Fe spectrum at an applied voltage of 1350 V.

E. Data Preparation for Proton Rejection Analysis

Prior to the proton rejection analysis, it is necessary to correct the raw data, channel by channel, because of interfering effects like pedestal position and common baseline shift of all detector channels, referred to as common mode. Also, it is necessary to correct for the permanent gas amplification differences due to the finite mechanical accuracy, like wire displacement and shape deformation.

The first step of the data preparation is the pedestal subtraction: the pedestal position and widths are calculated from each data sample.

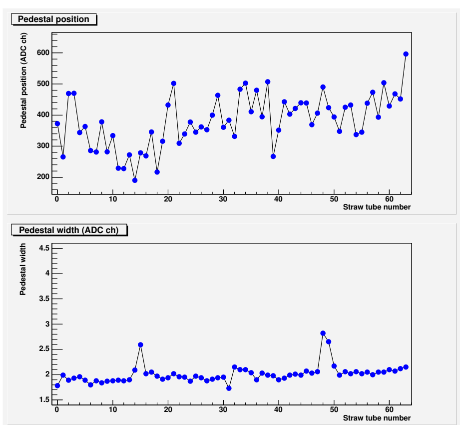

Fig. 9. Pedestal positions and widths for the 64 channels of a 4-module prototype.

The second step is the event selection. A straight line fit is performed for each event; the selection of events with a single track in the detector requires the definition of several cut parameters.

Then it's necessary to correct the data for tube to tube differences in the average signal heights by intercalibration channel by channel. The correction factors are defined for each tube as:

$$CP_i = \frac{\overline{MPV}}{MPV_i}$$

where MPV is the most probable valus obtained from a Landau fit of a single tube spectrum.

The last step is the detector's energy calibration. The calibration is performed using random triggered ^{55}Fe measurements. The photopeak is derived from a correlation between one of the Fermi function parameter and the σ of the Gaussian distribution.

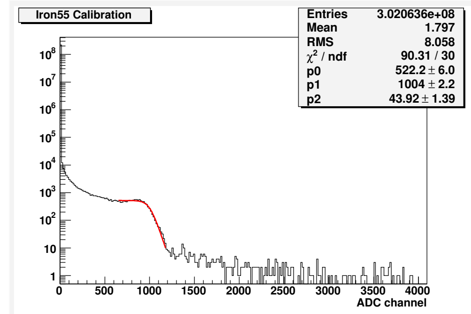

Fig. 10. Random triggered ^{55}Fe signals with Fermi function parametrization.

A cosmic test performing using a 4-layer prototype (64 channels) shows good agreement between the results and the expected value for MIP crossing ∼3 mm of Ar/CO_2 (82:18) mixture at known density.

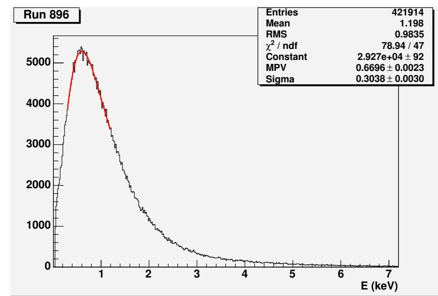

Fig. 11. Energy deposit at 1400 V, 1028 mbar, 22.7 ◦C.

F. Proton Rejection

Proton rejection is defined as the ratio of the number of incident photons to those selected, keeping the total number of electron events above 90% applying the same cut. To determine whether a track belongs to a proton or a positron, we use a likelihood method.

The probability density functions $P^i_{e,p}(E_i)$ are calculated for each hit on track; in doing this, we use as probability distributio the energy spectra of electron and protons normalized to an integral of one. Then the combined probabilities of the event are built as:

$$W_{e,p} = \sqrt[N]{\prod_{i=1}^{N} P^i_{e,p}(E_i)}$$

where N denotes the number of hits on the track. The likelihood function is defined as

$$L_e = \frac{W_e}{W_e + W_p}$$

The likelihood distribution for electrons and protons shows that low -ln(L_e) values are an indication of electron-like events.

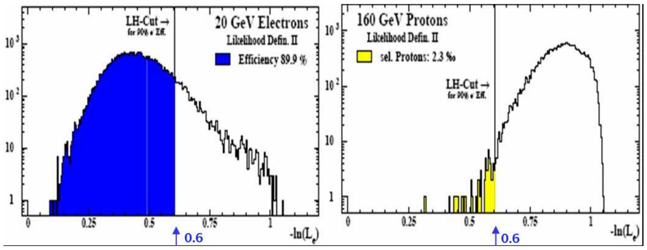

Fig. 12. Likelihood distribution for 20 GeV electrons and 160 GeV protons from a 20-layer prototype beam test data.

Proton rejection is calculated as the inverted percentage of proton events selected as electron-like to the total number of proton events in the sample, applying the same cut. Assuming that events with L $<$ 0.6 from light particles, a proton rejection factor $> 10^2$ is reached up to 250 GeV with 90% electron efficiency [13].

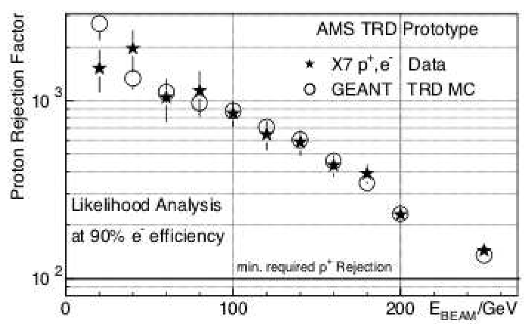

Fig. 13. Proton rejection from MC and beam test of a 20-layer prototype.

V. Conclusion

Tests performed show that it is possible to fulfill the requirements for a successful mission in space and to achieve the expected performances. The 20-layer TRD, equipped with fleece radiator and straw proportional tubes filled with a Xe:CO_2 mixture, will provide a proton rejection factor of $10^2 - 10^3$ to performe precise positron spectroscopy in the energy range of interest, thus increasing the probability to detect positrons originated from neutralino annihilation.
Flight TRD octagon has been assembled and is currently under test. AMS-02 is scheduled for flight in 2009.

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