Performance of the AMS02 Electromagnetic Calorimeter in space

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Abstract.
The Alpha Magnetic Spectrometer (AMS-02) is a general purpose high energy particle detector which was successfully deployed on the International Space Station (ISS) on May 19, 2011 to conduct a long duration mission of fundamental physics research in space. After one year of operation, AMS-02 has collected more than 17 billions of events. The main scientific goals of the experiment are the searches for antimatter and dark matter, the high precision measurement of charged cosmic ray spectra and fluxes and the study of gamma rays, in the GeV to TeV energy range. In AMS-02, the Electromagnetic Calorimeter (ECAL) is required to measure e+, e− and gamma spectra and to discriminate electromagnetic showers from hadronic cascades. To fulfill these requirements the ECAL is based on a lead/scintillating fiber sandwich, providing a 3D imaging reconstruction of the showers. AMS-02 has been tested during Summer 2010 in a test beam at CERN, using 10 to 250 GeV electron and positron beams and proton beam at 400 GeV. After a summary of the AMS02 performance in space, results on the measurements of ECAL parameters and performance will be reviewed.

1. Introduction
AMS-02 is a general purpose particle detector capable of identifying and measuring simultaneously all cosmic ray particle species: photons, electrons, protons and nuclei as well as all corresponding anti-particles. This feature becomes very important to distinguish signals from new phenomena and background processes, given a significant uncertainty in the background calculations related to the modeling of the standard processes and subsequent propagation.

AMS will measure spectra for nuclei in the energy range from 0.5 GeV/nucl to 2 TeV/nucl with 1% accuracy over the 11-year solar cycle. The scientific goals of AMS are to reach a sensitivity of antimatter search of 10^{-10} (ratio of anti-helium to helium), an e+/p rejection of 1/10^6 and to measure the composition and spectra of charged particles with an accuracy of 1%.

Looking at the recent measurements of e^+/(e^+ + e^-) by AMS-01, HEAT, PAMELA and Fermi [1] which indicate a large deviation of this ratio with respect to the model expectations (that include only secondary species produced in the cosmic ray collisions), AMS-02 detector is expected to extend the energy domain and the statistics allowing to perform more precise measurements and provide more informations to understand the nature of this deviation. Undoubtedly, the calorimeter will play a leading role in this challenging search.
2. The AMS Detector
AMS-02 is a general purpose detector to study primordial cosmic ray particles in the energy range from 0.5 to 2000 GeV. In order to ensure that technologies used in the detector construction work reliably in space, a scaled down detector (AMS-01) was built and flown in 1998 on board the STS-91 mission for 10 days [2]. Layout of the AMS-02 detector is presented in Figure 1. It consists of six complementary sub-detectors, providing measurements of the energy, the mass and the charge leading to an unambiguous identification of the cosmic rays.

It consists of: a Transition Radiation Detector participating to the e/p rejection and the charge measurement via dE/dx; four planes of Time of Flight counters, the key detector for the trigger and measuring the timing, the velocity and the charge via dE/dx; a Permanent Magnet important to determine the sign of the charge combined with a precision silicon Tracker consisting of 9 layers, out of which 7 are in the magnetic field (Inner tracker). This combined detector, provides the rigidity and the charge via dE/dx measurements and participates to the e/p rejection by comparing the rigidity with the energy measured in the calorimeter; an array of Veto Counters included in the trigger system, surrounding the Tracker; a Ring Image Cerenkov detector providing the charge and the velocity measurements and the Electromagnetic Calorimeter which contributes to the trigger, the e^+, e^−, γ identification and the energy as well as the charge via dE/dx measurements. The maximal AMS acceptance given by the TRD and the inner Tracker, amounts to 0.5 m².str.

![Figure 1. AMS layout with the different sub detectors](image)

3. AMS Operation on ISS
AMS was successfully installed on the International Space Station on May 19, 2011 and since that date the detector is collecting data at an average rate of 10 Mega bits per seconds as presented at ICRC2011 [3]. Particle rates over one ISS orbit vary between 200 Hz near the equator to about 2000 Hz near the Earth magnetic poles. Data acquisition efficiency is on average 85% (it reaches 96% near the equator and 65% near the poles) resulting in an average event acquisition rate of 700 Hz. Over 17 billion events have been collected during the first year of operations in space. Over its lifetime of approximately 20 years AMS will collect 300 billions
of triggers. Typical Positron and Boron events are displayed in Figures 2 and 3 illustrating the complementary responses of the sub-detectors; the different charges of both candidate can be observed qualitatively through the amplitudes of the signals in the detectors.

![Figure 2. Positron candidate of 464 GeV](image1)

![Figure 3. Boron candidate, seen at the minimum ionizing in the calorimeter](image2)

The status of all AMS subsystems is constantly monitored in the AMS Payload Operations and Control Center, POCC, located at CERN. Dynamically changing running parameters (data downlink bandwidth, distribution of available electrical power, rotation of ISS solar panels and radiators near AMS,) are followed by shifters, who are also in permanent contact with the NASA ground staff on voice loops. Commands are sent to AMS from POCC in response to changing conditions, as necessary. All AMS subsystems are fully operational with the performance expected from ground measurements, including the gas leak rate of the TRD which is found to be identical to the one measured on the ground. Variations of ambient conditions (temperature in first place) are studied and will be accounted for with proper calibrations and alignments. Therefore, calibration work for all detector systems is going on now in order to maximize the accuracy of the measurements.

4. The Electromagnetic Calorimeter of AMS

The role of the calorimeter is threefold:

- Measure precisely the energy of the electromagnetic particles on a wide energy range from 0.5 GeV to 1 TeV: the largest depth in radiation length \( x_0 \) is mandatory.

- Identify photons, electrons, positrons, thus be able to reject protons. Since the expected secondary positron flux is \( 1000 \) to \( 10000 \) lower than those of protons, a rejection factor of \( 10^5 \) is needed. This is achieved with a high granularity in the longitudinal and lateral views. In addition, the ratio between the interaction length \( \lambda_I \) and \( x_0 \) has to be at least 22.

- Trigger on the non converted photons. Since 75% of the photons are not converted in the TRD, a standalone Ecal trigger is needed, at the first level of the trigger to accept the gamma events. In addition such redundant trigger is mandatory to increase the electron efficiency at high energy that could generate high multiplicity hits in the Veto counters with the backsplash.
On top of that physics requirements, one had to cope with space constraints and environment and in particular with the limitation on weight, on power consumption and on number of channels.

4.1. 3D imaging Calorimeter

The 3D imaging electromagnetic calorimeter (ECAL), consists of 9 modules (called superlayer) made of a sandwich of grooved lead foils and of layers of scintillating fibers glued together [4], [5], representing an active area of 648x648 mm$^2$ and a thickness of 166.5 mm. The ECAL acceptance amounts to 0.06 m$^2$.str. / Each superlayer is 18.5 mm thick and made of 11 grooved (1 mm thick) lead foils interleaved with 10 layers of 1 mm diameter scintillating fibers. In each superlayer, the fibers run in one direction only and are alternatively read at one end. Each anode covers an active area of 9x9 mm$^2$, corresponding to 35 fibers, defined as a cell as illustrated in Figure 4. In total the ECAL is subdivided into 1296 cells (324 PMTs). Thus the calorimeter consists of 18 longitudinal independent samplings leading to a segmentation in the longitudinal view (vertical axis) of 0.95 radiation length and in each lateral view (X and Y) of 0.5 Moliere radius ($R_M$).

![Figure 4](image)

**Figure 4.** One of the 9 superlayers of the calorimeter with the fibers lightened on the back, with the footprint of the PMT superimposed.

Two calorimeters, the engineering Model (IM: 2001-2005) and the flight model (FM 2005 to 2010) have been built and extensively tested from 2001 to 2010, passing successfully the functional and flight qualification tests (thermal, vibration, electromagnetic interference and radiation hardness). The ECAL performance of the flight model have been measured in different beam tests at CERN: both for an ECAL standalone mode (2007) and with the complete AMS detector (2010).

4.2. Light Collection and readout system

The light collection system, detailed in Figure 5, consists of four 30 mm wrapped long light guides, the PMT and the front-end electronics inserted into a polycarbonate support tube, this latter being inserted itself into a magnetic shielding iron tube. The front-end electronics was implemented in a dedicated ASIC chip [6] in BiCMOS 0.8 microns technology with very low power consumption (21 mW in total). The signals in the 9 channels of the chip (2x4 anodes + 1 dynode) are shaped to give a peaking time around 2.2 $\mu$ sec. and are hold until they are read.

![Figure 5](image)
via a multiplexing circuit and sent sequentially to a serial 12 bits ADC (AD7476A, also used by other sub-detectors). The High Voltage dividers are implemented on two 26 × 26 mm² boards. The 3 boards (Front end and HV dividers) are assembled together and mounted behind each PMT. The HV dividers and the rear of the PMT are completely potted to avoid corona effect while the Front-End board is only coated to save weight.

About 8 photoelectrons per cell are expected for a minimum ionizing particle while 48000 photoelectrons are produced in one cell by the electromagnetic showering of a 1 TeV electron. In addition the signal-to-noise MIP (minimum ionizing particle) ratio should be greater than 10, leading to a total dynamic range of 60000. To insure this, for each anode, the front end electronics is designed with two gains (high and low) with a ratio high to low of 33.33 on average as illustrated in Figure 6. Figure 7 shows the gain distribution map as measured on the ISS, during one run. The gain dispersion is of the order of 1% , as expected. The pedestal values in space and on ground are fully consistent, the rms-noise both on the high and low gains are of the order of 0.4 ADC counts leading to a signal-to-noise ratio for the MIP of 30 (with the present High Voltage settings). The saturation has been also measured for each anode on both gains and the saturation is reached on the low gain for electromagnetic shower of 1 TeV; Thus, there is some room to reach 2 TeV by simply decreasing the High Voltage supplies by 50 volts, the signal-to-noise for the MIP becoming 15.

The EDR (Ecal Reduction Board) receives the digitized signals from 27 PMTs (3 EIB) over Low Voltage Differential Signal (LVDS) lines. The data reduction, thought the DSP of the EDR, computes pedestals and its rms for each channel, every 2 runs (i.e 42 minutes, at the equator) then subtracts pedestals, suppresses zeros and sends the results throughout the backplane to the central Data Acquisition chain [5]. The EDR also acts as a bridge for the Front End power supply (+3.5, -2.5 VDC) and for the control of EIBs using single ended TTL (5 V) signaling. The 12 EDR boards are distributed into 2 crates. Each EDR is fully redundant. Each half of the EDR is protected by a solid state circuit breaker (SSF).

The electronics was designed following stringent requirements on mechanical and thermal stability, power consumption, radiation hardness and double redundancy. The full system has successfully gone through the space qualification tests [6]. After one year of data taking on the ISS, all the front end boards are operating, as well as all EDRs or EIBs. In total, since 2005, 2 PMTs have been lost. Less than 0.2 % of the anodes are noisy time to time, nominal
behavior being recovered when performing HV power cycles. In term of gain, rms-noise, pedestal, saturation, noise, the electronics behaves nominally, the environment in term of noise being better in space with respect to the ground.

4.3. Trigger data
The ECAL is included in the global trigger for detecting $\gamma$ and to identify electrons. The constraints are the following: the decision of the fast ECAL trigger should be given within 180 ns, the additional trigger rate should be less than 50 Hz (compared to the maximal value of 2 kHz) and the power consumption below 10 Watts. During the 2002 test beam, it was demonstrated that the last dynode signal after amplification can be used in a fast standalone trigger for photons with energies above 2 GeV. The analog signal has to be amplified by a factor 10, in order to get a signal amplitude of 25 mV for an energy deposition of 100 MeV. Thus, the signal of the last dynode of the PMT is read out and simultaneously sent to a low gain electronic channel in the chip for redundancy purpose and amplified (by a factor of 10) and sent to a comparator for the analog gamma-trigger.

The trigger decision is build into 2 steps: a fast decision, available within 180 ns, given by the count of PMTs above threshold in the 6 central superlayers of the calorimeter; a level 1 trigger decision, well before 1 $\mu$s, obtained with a fast reconstruction of the particle direction [5].

In order to be able to trigger on gamma of 1 GeV, thresholds as low as 20 mV have been set corresponding to a signal of 2 mV before amplification. To this end EMI and grounding issues have been carefully studied. Performance of the analog part are detailed in [6]. Results concerning the comparison of the events with or without trigger, for a threshold of 33 mV, are illustrated in Figure 8 and 9. The efficiency has been measured for each threshold and is close to 100 % for 98.7 % of the trigger channels (2 channels exhibit some inefficiency since 2007 and one trigger channel has been lost since the launch). The rising time is of the level of 5 % of the threshold, as expected. The random trigger rate has been also measured and be found to be less than 0.1 % on ground and seems to a factor 10 lower in space [6].
4.4. Slow Control

The calorimeter must be able to stand extreme temperatures without irreversible damages, the reference temperatures being -30 °C and + 50°C; thus the temperature variations have been and are the main concerns. Each part of the detector readout has been tested under vacuum individually in the laboratories. In addition, at ESTEC in Holland, thermal vacuum tests (TVT) have been performed with the complete assembly detector in Spring 2010. The TVT took 20 days, and were very useful to verify the performance of the complete detector under vacuum and in a wide range of the temperatures close to those of those on the space station.

40 thermal sensors are used to measure the temperatures of the calorimeter (6 on each face), the crates and on the HV power supplies and the mechanical structure (4 sensors per corner). Due to the position of the ISS with respect to the sun and its orientation, temperatures may vary over a large range, typical variations as a function of time for the nine first months of operation are shown in Figure 10. The temperature dependence of the pedestals, the pulse heights, the saturations and gains have been carefully measured since the beginning of data taking. Relative dependence with a sensitivity as low as $10^{-5}$ have been measured. Examples are given in Figure 11. Everything is behaving similarly in space and on the Earth.

5. Energy reconstruction

5.1. Corrections at the pixel level: Equalization and attenuation

The first set of corrections is meant to equalize the response of each anode, to correct from the light attenuation. The equalization is performed using the minimum ionizing particle (MIP) signal obtained in each cell from a scan along the X and Y axis in the middle of the calorimeter. Each distribution is fitted by a Landau function convoluted by a Gaussian function plus an exponential background. The MIPs are distributed with an average of 15 ADC counts and a sigma of 2.3 ADC counts. MIP measurements have been measured on the ground (test beam and during the commissioning at Kennedy Space Center) and in space. An anti correlated variation
of the MIP with the temperature is observed, as illustrated in Figure 12, and a global correction is applied run per run.

The signal is attenuated along the fibers and needs to be corrected depending upon the original position along the fibers. For each layer, attenuation curves have been fitted simultaneously by the following function $f \times e^{-x/\lambda_{\text{fast}}} + (1 - f) \times e^{-x/\lambda_{\text{slow}}}$ letting free an individual amplitude per cell; an example of the fit is given in Figure 13[7]: Test beam, cosmics data and ISS data agree well as depicted in Figure ?? . The correction is applied such that there is no correction in the center of the calorimeter.

$$\Delta \text{MIP/MIP} = -2.5 \times 10^{-3} \text{ per } ^\circ\text{C}$$

![Figure 12. Variation of the MIP pulse height, averaged over all the channels, with temperature](image)

5.2. Global corrections: Impact and Rear leakage corrections

To take account of the light loss at the edges of the light collection guides, a standalone method correction was developed. The signal loss is maximal for particle with normal incidence impinging between two pixels, i.e a dead zone and is then of the order of 10 %. This impact correction relies on the fraction of energy deposited in the central cell (S1) of the electromagnetic shower relative to the one deposited in the neighbouring ones (S3). Thus, the ratio S1/S3 is estimated ones per layer and summed over all layers in each direction (X or Y). The dependence of the deposited energy as a function of this variable is nicely linear; it was checked with test beam date that the amplitude of the correction does not depend on the energy [7]. The effect of the correction is illustrated in Figure 14 where the deposited energy before and after impact correction are compared as a function of the impact position as measured with the center of gravity.

The last correction will correct for the energy rear leakage. The relative leakage energy is approximated by a linear function of the fraction of energy measured in the latest layers of the calorimeter. This linear relation scales with energy, as observed with test beam data. Therefore this dependence was accounted for, using the energy divided by the longitudinal barycenter which is roughly proportional to the incident energy, Figure 15 shows the principle of the correction. The rear leakage has been also estimated by fitting the longitudinal profile of the shower, well parametrized by a Gamma function; Both methods give similar performance, the latter one including all the layers.

![Figure 13. MIP signal attenuation along the fiber average over one layer, for three different periods. The attenuation on the total length is about 30 %, for 16 layers and about 38 % for 2 layers](image)
5.3. Performance on the Ground (test beam)

During test beams in 2007, the properties of the calorimeter have been extensively measured, such as the total radiation length $X_0$, by extracting first the position of the maximum of the longitudinal profile, then fitting the linear dependence of the maximum with the logarithm of the energy. Thus, $X_0$ has been measured to be $1.05(0.02)$ layer unit. Therefore, the calorimeter consists of 17.1 radiation lengths ([5],[7]). Thus, the expected rear leakage for 1 TeV electrons is on average, 16 % and the maximum of the shower is expected to be in layer 11. The critical energy has been also deduced from the radiation length measurement and the fit according to equation 1 propagating all the relevant uncertainties. The measurements are compared to the expectation (Rossi formula $E_c = \frac{610\text{MeV}}{Z^{1.24}}$ [8]). A critical energy of $7.6 \pm 0.2$ MeV is obtained. Finally, since the Moliere radius is directly linked to the critical energy according to [8], typical values of $R_M = 2.5 - 2.6X_0$ have been also derived.

$$z_{max} = X_0 \times \ln\left(\frac{E_{beam}}{E_c}\right) + X_0 \times C_e \quad C_e = -0.5$$ (1)

In 2010, the AMS detector was fully assembled and the performance in term of linearity and energy resolution, with less energy points are similar to what was previously measured [5], despite the $\sim 0.65$ expected radiation length in front of the calorimeter. Results on the energy resolution and the linearity are shown respectively in Figures 16 and 17. The resolution was fitted to be

$$\frac{\sigma_E}{E} = 10.4\% \div 1.4\%$$

while the linearity is kept within 1%. Using the same complete set of corrections, the linearity and the resolution are not degraded when the incidence angle of the beam is 15 degrees.

6. Charge Measurement

The ionizing energy loss is well described by the Bethe Bloch equation which shows that in a given material, for a given velocity, the energy loss is proportional to the square of charge of the
Figure 16. The linearity is better than 1%, after applying all the corrections. After having applied topological cuts related to the starting point of the shower, specific selection cuts more based on the electromagnetic shower properties are applied. Global variables both in the longitudinal and lateral views are build. Figure 21 shows two typical discriminant variables, in the Y view (lateral) the fraction of energy deposited in 1.5 Molière radius and also

crossing particle. So the charge of the particle can be discriminated by the response of ECAL. Identification of the nuclei has been performed with the ECAL for the first time by analyzing the ISS data by measuring their deposited energy in ECAL. The non-interacting particles in ECAL are selected by requiring a low hit multiplicity layer by layer, thanks to the low noise level in the calorimeter. The deposited energy in the layer should be concentrated in one cell (i.e representing at least of 99 %). Doing so, it is possible to identify the starting point of the shower (called hereafter apex) and determine the path length of the nucleus remaining at the minimum ionizing. The layers selected at the MIP, i.e before the apex, only contribute to the charge measurement of the nuclei. The energy loss dependence on the rigidity is shown in Figure 18. The total deposited energy of the same charge follows a Gaussian-like distribution from proton to oxygen nuclei as depicted in Figure 19. The charge determined this way is consistent with what is measured by the other specific charge-measuring sub-detectors and will be included in the AMS global charge estimator.

7. Electron Identification

As introduced previously, the imaging calorimeter of AMS has been designed to precisely reconstruct the longitudinal and lateral profiles of interactions and to measure the deposited energy. The longitudinal and lateral segmentation of the calorimeter, combined with the measurement of the particle energy loss, allows a very high identification power for electromagnetic showers. In particular, the high longitudinal granularity allows to reconstruct the apex position and then reject most of the proton (∼80 %) starting an hadronic shower after the three first layers. Figure 20 exemplifies the different hadronic showers pattern of interacting proton, preselected with the TRD and the tracker; The probability of interaction for proton as a function of the calorimeter depths is shown in Figure 20; it turns out that, on average, 53 % of the protons crosses the calorimeter without developing a shower, leading to an interaction length of 28 layers (25.75 cm, or 26.6 $X\text{_{0}}$). The calorimeter depth is then equivalent to 0.64 $\lambda\text{_{int}}$.

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Figure 17. Energy resolution as measured in 2010, on electron and positron beams. The resolution is better than 2% for energies greater than 80 GeV.
Figure 18. $dE/dx$ measurement in the calorimeter as a function of the Rigidity measured in the Tracker, for Hydrogen to Oxygen nuclei

Figure 19. Charge measurement in the calorimeter (Log($dE/dx$)) for the Lithium to the Oxygen Nuclei

Figure 20. The typical interacting proton patterns in the calorimeter (right). Fraction of protons developing a shower as a function of the calorimeter depth(left)

the chi square of the longitudinal fit, for 400 GeV protons and 180 GeV electrons. The separation is clear and the method based on simple cuts allow to achieve a proton rejection factor ranging from 50 to 100 with an efficiency of 80-90 %. This is not enough to reach the rejection goal even after having included the TRD and the tracker, maintaining an overall efficiency of 90 %.

A multi variate analysis, based on the TMVA package [9] has been then proposed exploring the different techniques (Boost Decision Tree, neural network, Likelihood,..). One of the main issue is the selection of the training samples (background and signal) to avoid any overtraining or any bias that could be introduced due to the lack of statistics or a wrong simulation model for example. In what follows, trainings were performed on data only. For what concerns ISS data subsample data are selected using the TRD and the tracker, while for test beam data both electron and proton beams have been used. In total, 56 discriminant variables have been
combined including global variables but also the fraction of the deposit energy and the width of the shower in each of the 18 layers. Analysis based on boosted decision trees has been studied, handling the correlations between the variables. The boosted decision trees have been trained in several energy bands between 2 GeV and 1 TeV. This leads to a large improvement of the analysis sensitivity, with respect to cut based analysis, reaching a rejection factor greater than 4000 for an efficiency of 90%. The signal over background ratio is dramatically increased compared to the original cut based methods, as shown in Figure 22. Combined with the other detectors (TRD and Energy and momentum from the tracker matching) an overall rejection factor of $10^6$ is achieved, from 2 GeV to 100 GeV. Analyses probing higher energies are ongoing.

Figure 21. Distribution of two discriminant variables based on the lateral (top) and longitudinal (bottom) electromagnetic shower properties obtained with 2010 test beam data

Figure 22. Ecal Boost Decision Tree output variable as obtained with ISS data.

8. Conclusions
The AMS experiment on the ISS has collected cosmic rays for more than one year. Throughout this period, the imaging calorimeter of the apparatus has been performing nominally. In particular, all functional parameters (pedestals, noise, signal, gain, attenuation) are nominal and temperature variations well monitored. The physics performance are consistent with the expectations and the test beam results. During this first year of operation in space, no failures nor loss/degradation of performance have been observed and the calorimeter proved to be able to fulfill the requirements needed to achieve the scientific goals of AMS.

9. References
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