Performance of the AMS-02 Electromagnetic Calorimeter in Space

G.Gallucci (for the AMS-02 ECAL group)
INFN - Sezione di Pisa, Largo Bruno Pontecorvo 3, 56127 Pisa, Italy
E-mail: giovanni.gallucci@pi.infn.it

Abstract. AMS-02 (Alpha Magnetic Spectrometer) is an high energy particle detector developed to operate on the International Space Station. AMS-02 was installed on ISS on May 2011 and is expected to operate for 10-20 years collecting about 160-320 billions of events. The main goals of the experiment are the detection of primordial antimatter and dark matter by studying spectra and flux of different cosmic ray components (protons, electrons, nuclei, positrons, antiprotons, gamma rays, etc) in the high energy range (1-2000 GeV). Identification of electrons, positrons and photons is provided by the Electromagnetic Calorimeter (ECAL), a fine grained lead-scintillating fibers sampling calorimeter that allows for a precise three-dimensional imaging of the longitudinal and lateral shower development. It provides an excellent reconstruction of electromagnetic shower energy and a highly efficient rejection of the hadronic background. Thanks to the 3D shower reconstruction capability, ECAL allows a stand-alone determination of the incoming particle direction, with unprecedented angular resolution. As a result, ECAL is able to identify high energy photons coming from galactic or extragalactic sources.

1. The AMS-02 Experiment
The AMS-02 is a TeV precision multipurpose spectrometer designed to operate in space, outside the International Space Station (ISS). Its launch and subsequent installation on the ISS took place successfully on May 2011. The main goals of AMS are the precise measurements of cosmic ray composition and flux (protons, electrons, ions, strange matter, etc...), the indirect search of Dark Matter (positron fraction, anti-proton fraction, etc...) and search and study of primordial anti-matter (anti-helium, etc...). Moreover, it could study the diffused gamma rays in the GeV to TeV range.

2. The AMS-02 Detectors
The layout of AMS-02 detector consists of a Transition Radiation Detector (TRD), a Time of Flight (TOF), a Magnetic spectrometer, an Anti-Coincidence scintillator counter system (ACC), a Ring Image Cherenkov (RICH) and an electromagnetic calorimeter (ECAL) as shown in figure 1:

- The TRD is composed by 5248 proportional tubes of 6mm diameter and maximum length of 2 m filled with Xe and CO2 (90:10 mixture). The tubes are organized in 16-tube modules and mounted in 20 layers. Between two layers there is a 20 mm thick polypropylene/polyethylene radiator. The TRD is used to distinguish between electrons and protons up to few hundred GeVs and to independently identify nuclei using $dE/dx$ [1].
• The **TOF** consists of four planes of plastic scintillators. Each plane contains eight or ten paddles and each paddle is readout by two or three phototubes on each end. It is used for charged particle triggers, timing information, beta and dE/dx measurements[2].

• The Magnetic spectrometer is composed by a silicon tracker (**TRK**) and a permanent magnet of 0.14 Tesla. The TRK is made by 192 ladders, each containing double-sided silicon sensors, mounted on 9 layers. Seven layers are in inside the magnet volume and constitute the inner tracker. One layer is located on top of TRD and the last one is located between the RICH and the ECAL. The TRK provides the rigidity, the charge and the charge sign of particles [3].

• The **ACC** is made by 16 curved scintillator planes 0.8 m long surrounding the inner tracker inside the magnet. They are used as veto to reject events entering the detector through the sides and, in general, to detect unwanted particles that enter or leave the inner tracker volume transversely [4].

• The **RICH** consists of two dielectric radiators with different refractive index and different beta thresholds. The Cherenkov light is detected by 10880 photosensors of 8.5x8.5 mm2. It is used to measure velocity of cosmic rays [5].

• The **ECAL** is shown in the next section.

![Figure 1. Sketch of the AMS-02 detector with the different sub detectors.](image_url)

3. **The Electromagnetic calorimeter: ECAL**
The calorimeter has been designed to precisely reconstruct the longitudinal and the lateral profiles of electromagnetic showers and to measure the deposited energy. For these characteristics it is used to provides energy and axis direction of electromagnetic showers as well as reject the protons using the different shape of hadronic showers.
3.1. Structure and light collection
ECAL is a lead-scintillating fiber sandwich with an active area of 648x648 mm$^2$ and a thickness of 166mm for a weight of $\sim$ 500 Kg [6]. The calorimeter consists of 9 modules (called superlayers) with a thickness of 18.5 mm (figure 2a). Each superlayer is composed by grooved lead foils alternate with 1mm scintillating fiber layer glued to the foils by mean of optical epoxy. The resulting ECAL volume is 58% of lead, 33% of fibers ($\sim$ 50000) and the remaining part of optical glue. The fibers run only in one direction so, in order to obtain a 3D image, the 9 modules are stacked with fibers alternatively parallel to x-axis (five superlayers) and y-axis (4 superlayers). Each superlayer is readout by 36 four-anode photomultipliers (PMTs), only at one edge. In order to avoid dead zones the PMTs are place alternatively on the two opposite ends. The entire calorimeter is readout by 324 PMTs, 1296 anodes. Each anode covers an active area equal to 9x9 mm$^2$ corresponding to 35 fibers called cell (figure 2b). Each cell correspond to $\sim$1 radiation length and half Moliere radius. Thus the calorimeter consists of 18 longitudinal independent samplings and 72 lateral samplings. The entire structure corresponds to 17 radiation lengths but only 0.7 nuclear interaction lengths. To maximize light yield and reduce crosstalk between cells, scintillating light is collected by individual light guides wrapped in an aluminum foil with chromium and quartz coating (figure 3). Furthermore for each PMT, the light guides and the front end electronics are shielded from residual magnetic field by a 1mm thick soft iron square tube(figure 4). In order to have a good linearity in a large energy range (from few MeVs up to about 60 GeVs), each anode signal is split into two different channels and digitized. The first channel (High Gain) is amplified and is sensitive to Minimum Ionizing Particles (MIP) that release around 7 MeV/cell. The second one (Low Gain) is not amplified and is used for high energy measurement. The gain ratio between the two is about 33. Also the signal of the last dynode of each PMT is readout to ensure a redundant measurement of energy deposition and to provide input to the trigger logic.

3.2. ECAL trigger
ECAL is involved in the trigger for electromagnetic particles and provides a standalone trigger for photons. When a high energy-deposit is recorded in the innermost layers of the calorimeter, a fast signal is generated and processed by the trigger board which can enable the event acquisition. Also the incident particle direction is evaluated by taking, for x and y sides, the average position of the fired PMTs. A cut at 20 degrees is applied to select particles inside AMS-02 geometrical acceptance and reject charged particles entering by side. The efficiency for photons is about 20% at 1 GeV and reaches about 99The one-orbit average ECAL trigger rate is about 115 Hz (approximately 10% of total AMS-02 rate).

4. ECAL calibration and performances at Test Beam
ECAL was tested at CERN on H4 and H8 beam lines, alone and after the integration with rest of apparatus. It was exposed to electrons and positrons beams with energy in the range 6-250 GeV and to primary proton beam line of 400 GeV. Using test beam data, equalization and calibrations procedures have been created and verified and the calorimeter performance has been measured.

4.1. Light attenuation
In order to measure light attenuation along fibers we used the MIP peak (figure 5). The light attenuation is parametrized using two different attenuation constants, $\lambda_s$ and $\lambda_f$ fast and slow respectively:

$$A(x) = f e^{-\lambda_f x} + (1 - f) e^{-\lambda_s x}$$

(1)
Figure 2. a) ECAL Structure. b) One of the 9 superlayers of the calorimeter with the footprint of the PMT and single cell superimposed.

Figure 3. Scheme of the PMT light collection system.

Figure 4. Light guides and polycarbonate support.

with $A$ the attenuation factor and $x$ the distance travelled by the light along the fiber. Typical value are $f = 0.17$, $\lambda_f = 110mm$ and $\lambda_s = 2605mm$ with a spread shown in figure 5.

4.2. Equalization

Equalization is done adjusting each High Voltage so that the cell response to MIP is the same. Because of intrinsic fluctuation of the four different anodes of each PMT and the fact that 84 PMT pairs are fed by the same HV lines, an offline correction is needed. Only HG channels are equalized but HG-LG ratio is constantly evaluated.
4.3. Radiation length

Using the different electron and positron beams, we measured the $X_0$ of calorimeter. Figure 6a shows the energy longitudinal distribution for 10 and 180 GeV. The distribution is well parametrized from a Rossi function $R$. Figure 6b shows the distribution of the max as function of the energy beam and we obtained:

$$X_0 = 0.98 \pm 0.02 \text{ cm}$$

as expected from the project.

The total thickness of ECAL, corresponding to $17.0 X_0$, still contains $\sim 75\%$ of energy of 1 TeV electrons.

4.4. Anode Efficiency and rear leakage

We observed that anode efficiency in not uniform, in particular it decreases at the cell border with respect to the centre. Farther there is a small dead space at the edge of each cell. This effect appears to be linearly dependent on the ratio between the sum of the maximum energy deposited in each layer (S1) and the sum of (S1) plus the content of the two cells adjacent to the maximum in each layer (S3). This ratio, called S1/S3, tends to 0.5 for particles hitting ECAL between two cells, corresponding to maximal energy loss ($\sim 10\%$), and to 1 for particles hitting ECAL in the cell centre, corresponding to minimal energy loss. Figure 7 shows the ECAL energy response before and after correction.

A second correction is applied to take into account of the energy leakage after the 17 radiation lengths of ECAL. This loss is proportional to the energy deposited in the last part of the shower. We used the energy fraction of the last two layers of ECAL ($\sim 2 X_0$) and computed the following formula:

$$\frac{E_{\text{true}}}{E_{\text{dep}}} = \alpha (E_{\text{dep}}) + \beta \frac{E_{LS}}{E_{\text{dep}}} + \gamma \left( \frac{E_{LS}}{E_{\text{dep}}} \right)^2$$

with $E_{\text{dep}}$ the deposited energy corrected for anode efficiency, $E_{LS}$ the deposited energy in the last two layers. $\alpha$, $\beta$ and $\gamma$ has been measured at test beam. $\alpha$ has a slightly energy dependence and it has been corrected using an iterative process.
4.5. **Energy resolution and linearity**

Using the different energy beams we measured the linearity and the energy resolution of ECAL. The linearity is within 1% in the range 6-250 GeV (figure 8), energy resolution is well...
parametrized by (figure 9):

$$\frac{\sigma(E)}{E} = \frac{(10.4 \pm 0.2)\%}{\sqrt{E(\text{GeV})}} \oplus (1.4 \pm 0.1)\%$$  \hspace{1cm} (4)

\textbf{Figure 8.} The energy linearity is held within 1%.

\textbf{Figure 9.} ECAL energy resolution from Test Beam.

4.6. Angular resolution
The high granularity of calorimeter allows a good reconstruction of shower axis and, consequently, a good angular resolution. Shower directions, in x and y side, are determined by fitting the axis positions in each layer. Three different methods has been developed to do it:
(i) the Centre Of Gravity (COG), evaluated from the energy weighted centres of the cells belonging to the shower:

\[ y_{\text{COG}}(x_{\text{COG}}) = \frac{\sum y_i(x_i)E_i}{\sum E_i} \quad (5) \]

where \( E_i \) is the energy deposited in the i-th cell and \( y_i(x_i) \) is its position;

(ii) the Neighbour Cells (NC) method, which uses the ratio of the energy deposited in the cells adjacent to the most energetic one as a function of the impinging position;

(iii) the Lateral Fit method, in which the energy distribution of the cells in the layer is fitted using the following parametrization:

\[ f(x) = \frac{2(x - x_C)R^2}{((x - x_C)^2 + R^2)^2} \quad (6) \]

where the lateral width \( R \) and the axis position \( x_C \) are the output of the fit.

Figure 10 summarizes angular resolution for the three methods.

![Figure 10. Angular resolution as a function of Test Beam momentum for the three analysis methods.](image)

5. ECAL performances on flight
The launch was a very stressing test for apparatus. Otherwise the hard environment conditions in the space needed for a continuously monitoring of calorimeter response and performance. After three years of data taking no major problems have happened and only 1 PMT is dead and 1 PMT is noisy. No fiber aging has been observed.
5.1. Equalization and light attenuation

Using cosmic ray MIPs it is possible to perform the same tests and measurement done on ground. Figure 11 shows the light attenuation measured in two different periods compared to the on-ground one. The thermal environment in space is severe: Sun light as well as the position of the solar panels onboard the ISS can affect the thermal configuration of the instrument producing temperature changes of several degrees. A dependence between the PMT gain and temperature was observed in flight data. The gain is anti-correlated with temperature and change $\sim 1\%$ for 4 degrees (figure refMIPTemp). An offline correction has been developed and implemented.

![Figure 11. Attenuation length measured in two different data taking periods (June and September 2011) compared to the test beam one.](image)

5.2. Energy scale

Energy scale has been checked using MIP peak as well as the ratio between the reconstructed energy and the pulse measured by the tracker. Figure 13 shows that energy scale is stable at 1%.

6. Proton rejection

As mentioned before, high granularity of calorimeter provides a good 3D reconstruction of the shower development. It allows the identification of electromagnetic particles with respect of protons using the different shapes of showers. Several approaches have been studied and developed to achieve the necessary separation between electrons and protons: cut based methods and multivariate analysis. The best method for ECAL has been a Boosted Decision Tree (BDT). To avoid any bias the training samples (background and signal) were selected from ISS data using the TRD and the tracker. Figure 14 shows the distribution of the BDT for electrons (and positrons) and hadrons. Adding the match between the reconstructed energy and the pulse measured by the tracker, we obtained a proton rejection more than $10^4$ until 300 GeV and still $10^3$ at 1 TeV (figure 15).
7. Photon study
The material before ECAL is only 0.6 $X_0$ so we expected $\sim$60% of photons interact directly in the calorimeter. Applying the selection cuts summarized in table 1 to the ECAL standalone trigger data we selected a photon sample. Backtracking electromagnetic shower axis and correcting for exposition time we obtained a picture of photon sky in which we could recognize known photon sources (figure 16). The two black holes in figure 16 are blind regions due to the ISS orbits. Reversing the procedure we used know positions of photon sources to measure the angular resolution of ECAL obtaining expected values.

8. Conclusions
The AMS-02 electromagnetic calorimeter design has been described, as well as its performance with Test Beam and flight data. After 3 years of data taking, ECAL is performing according to expectations. Energy resolution and electromagnetic shower identification already achieved
**Figure 14.** BDT variable distribution for electrons and positrons (blue distribution), as well as for protons (red distribution) for all energies.

**Figure 15.** Proton rejection as function of proton momentum. ECAL BDT plus a 0.75 cut on $E/p$ ratio are applied.

**Table 1.** Selection cuts to obtain photon sample.

| Detector | Cut                                                                 |
|----------|----------------------------------------------------------------------|
| TRD      | No tracks reconstructed                                               |
| Tracker  | No tracks reconstructed, no hits correlated with shower axis          |
| TOF      | Limits on hits numbers. Time difference between Upper and Lower TOF   |
| ACC      | Limits on the number of hits                                          |
| RICH     | Limits on the number of hits                                          |
| ECAL     | Shower axis within ECAL fiducial volume                               |
|          | Extrapolation of shower inside active upper TOF area                  |
|          | Electromagnetic shower shape                                          |
Figure 16. Photon sky obtained using ECAL reconstructed photons. Inside the red circles there are known photon sources (Vela, Galactic Center, etc...). Black holes are blind regions due to the ISS orbits.

relevant scientific results on electron/positron measurement [7]. Otherwise angular and energy resolution allow to search for substructures in the diffused gamma flux from center of galaxy or other possible dark matter candidate sources.

9. References
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