The AMS-02 time of flight (TOF) system: construction and overall performances in space

V. BINDI[1], E. CHOUMILOV[2], A. CONTIN[3,4], N. MASI[3,4], A. OLIVA[5], F. PALMONARI[3,4], L. QUADRANI[3,4], Q. YAN[6].

[1] *University of Hawaii, Physics and Astronomy Department, 2505 Correa Road, WAT 432; Honolulu, Hawaii 96822, USA*
[2] *Massachusetts Institute of Technology, MIT, Cambridge, Massachusetts 02139, USA*
[3] *Università di Bologna, I-40126 Bologna, Italy*
[4] *INFN-Sezione di Bologna, I-40126 Bologna, Italy*
[5] *Centro de Investigaciones Energeticas, Medioambientales y Tecnologicas, CIEMAT, E-28040 Madrid, Spain*
[6] *Institute of High Energy Physics, IHEP, Chinese Academy of Sciences, Beijing, 100039, China.*

lucio.quadrani@bo.infn.it

Abstract: AMS-02 is a magnetic spectrometer designed to measure the energy spectra of the cosmic rays and gammas in the GeV to TeV energy region. AMS-02 has been installed on the International Space Station on May 2011 where it will operate for the next 15 years.
The TOF system of AMS-02 consists of four layers of plastic scintillator counters, it provides the fast trigger to the experiment, a high precision measurement of the cosmic rays velocity to distinguish up-going to down-going particles and the measurement of the particle charge in order to separate chemical elements with high accuracy.
The main characteristic of the TOF system is the redundancy of components to operate in the space environment without any human intervention. The design, construction, and in-space overall performances of the TOF apparatus are presented.

Keywords: Cosmic rays, AMS-02, TOF, scintillator counters.

1 Introduction

The Alpha Magnetic Spetrometer (AMS-02)[1] on the International Space Station (ISS) measures the cosmic rays with high precision up to the TeV energy scale, with the aim of searching dark matter and anti-matter.

The Time Of Flight (TOF)[2, 3] detector provides the fast trigger to the experiment and measures the velocity and the charge of the cosmic rays. It has been designed and built at the INFN laboratories in Bologna (Italy) and consists of four layers of scintillator counters. The long term operation reliability of the TOF system is assured by the redundancy of the components.

After more than two years of data taking the performances in space show a velocity resolution better than 4% and a charge resolution that allows to distinguish cosmic rays with charge up to Z=30.

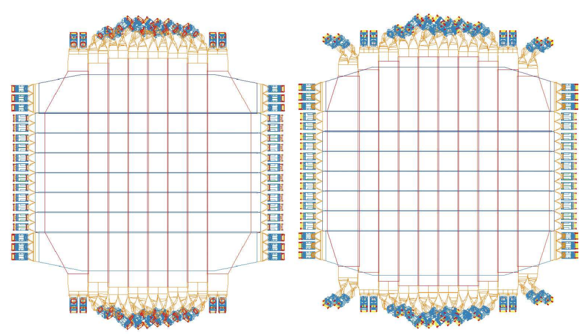

Fig. 1: Time Of Flight detector: upper TOF (to the left) and lower TOF (to the right).

2 The TOF system

The TOF system (fig. 1) is composed by 4 layers of scintillator counters, two above and two below the AMS magnet. The four layers have respectively 8,8,10,8 paddles of different lengths (between 117 and 134 cm), longitudinally overlapping by 0.5 cm to avoid geometrical inefficiencies. Each counter (fig. 2) is made of a 1 cm thick scintillator paddle[1], optically coupled at both ends with photomultiplier tubes (PMTs). The external counters have a trapezoidal shape in order to maximize the acceptance.

The PMTs fine-mesh R5946 Hamamatsu[2] have been chosen for their capability of working in high magnetic fields, while keeping good timing characteristics.

Each counter is equipped with two or three PMTs at both sides, for redundancy. Due to weight and power limitations the PMTs are powered in pairs. To increase the fault tolerance of each side of the counter, the PMTs on the same side are powered by different HV channels.

The anode signals from the PMTs on each side of the counter are passively summed to be used at the trigger level and to measure the time and the charge of the cosmic rays. The third last dynode of each PMT is read-out independently, through electronics cards mounted inside the TOF detector, and it is used to measure the charge of particles with Z>4.

The anode signals are compared with three thresholds:

- low (LT) for the time measurement;
- high (HT) for the Z=1 trigger selection;

1. The scintillator material is Eljen Technology type EJ-200.
2. PMT datasheet at www.bo.infn.it/ams/R5946.pdf

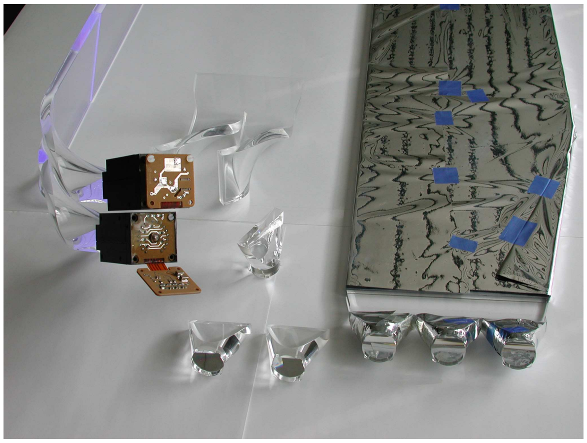

Fig. 2: TOF counter components: scintillator, light guides and photomultipliers.

- super high (SHT) for the Z>1 trigger selection.

The PMTs are coupled to the scintillator through plexiglass light guides, tilted or twisted in order to minimize the angle between the magnetic field direction and the photomultiplier axis.

The 144 photomultipliers of the TOF detector are powered by 4 SHV power supply, with a voltage between 1700V and 2250V. The gain of the photomultipliers is about 10^6 at 2000V.

All the TOF counters have been characterized in a cosmic rays telescope, measuring the following parameters:

- attenuation lengths at both ends;
- light velocity in the scintillator;
- number of photons produced at counter center;
- time resolution.

The TOF counters have been tested in a vacuum chamber and then they have been assembled in two planes: lower and upper TOF. The lower and the upper TOF have been space qualified (through thermal vacuum and vibration tests at SERMS laboratories in Terni), in order to verify the requirements by NASA for payloads using the space shuttle and to check its functioning in space conditions. The thermal vacuum test consisted in several thermal cycles in a vacuum chamber, reproducing the temperature range and the pressure of AMS when operated on the ISS. The vibration test consisted in dynamic mechanical tests on vibrating tables, simulating the shuttle during take-off.

The lower and upper TOF were integrated with the other AMS detectors in a clean room at CERN. The electronics has been installed in two radiators and all cable connections were checked and tested.

The TOF electronics consists of:

- the doubly redundant SHV (scintillator high voltage) brick to supply the high voltage to the TOF photomultipliers;
- the SFEC (scintillator front end charge) board located inside the cover of the TOF detector, to measure the charge from the dynode signals;
- the doubly redundant SFET2 (scintillator front end time) board to measure the charge and the time from anode signals;
- the doubly redundant SPT2 (scintillator pre-trigger) board to produce local fast triggers;
- the doubly redundant SDR2 (scintillator data reduction) board for the data acquisition;
- the doubly redundant TSPD (tracker and scintillator power distributor) to supply the low voltage to the TOF and ACC electronics.

The SFET2, SPT2 and SDR2 boards are placed in four electronics crates (S-crates). Each crate is doubly redundant and serves two sides of different TOF layers.

The system has been designed for maximum redundancy to ensure the fast trigger to AMS even in presence of power supply, photomultiplier or front-end electronics faults: each counter is 4-fold redundant in PMTs, each HV channel is doubly redundant and each fast trigger signal is doubly redundant.

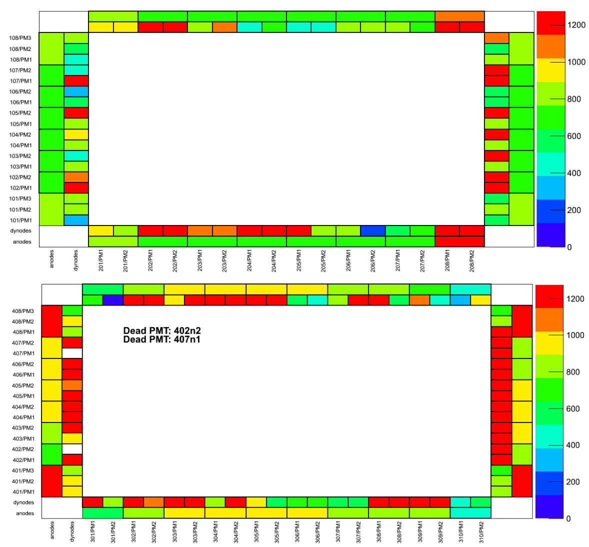

Fig. 3: The upper TOF and the lower TOF occupancy plots. On March 3^{rd} 2013, two PMT signals (402n2, 407n1) were lost because of one high voltage channel failure.

3 In-space performances

Since May 2011, AMS-02 is acquiring data at an average trigger rate of 800Hz, with a peak of 2kHz in the South Atlantic Anomaly and at the geomagnetic Poles. The mean event size is about 2KB.

After the installation on the Space Station, several tests were performed to verify the TOF detector status: calibration curves, threshold settings and trigger efficiency were checked for each counter. No major problems were found.

During the first two years of operation, the TOF detector worked properly. In fig. 3 the TOF occupancy is shown: since in space only 2 PMTs (402n2 and 407n1) of the 144 were lost on March 3^{rd} 2013 because of one high voltage channel failure.

In order to determine the TOF performaces, precise time-dependent calibrations of the TOF detector are performed regularly using cosmic rays[4].

3.1 Trigger performance

There are two kinds of triggers for charged particles generated by TOF anode signals: one for Z=1 particles and one for ions.

The normal trigger configuration in space requires a hit on three TOF layers out of four.

In fig. 4 it is shown the trigger efficiency curve for one TOF counter: the efficiency has been measured at different PMT high voltages, close to the nominal one (up to ±250V). The PMT efficiency at the nominal high voltage is about 100%. In fig 5 are shown the trigger efficiencies for all counters of the four TOF layers. The TOF counter effiency is computed using the OR of the two sides. The efficiencies are of the order of 99% for all, with the exception of two external counters.

In view of possible long-term changes in the PMTs and the scintillators response, it is foreseen to repeat the check of the trigger efficiencies every two to three years, and to optimize the TOF settings.

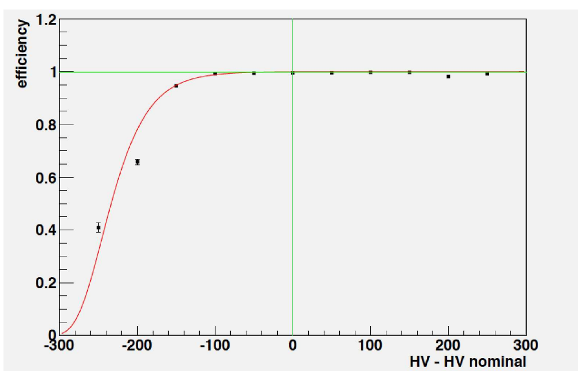

Fig. 4: Trigger efficiency curve for one TOF counter. The efficiency has been measured at different PMT high voltages (around the nominal value).

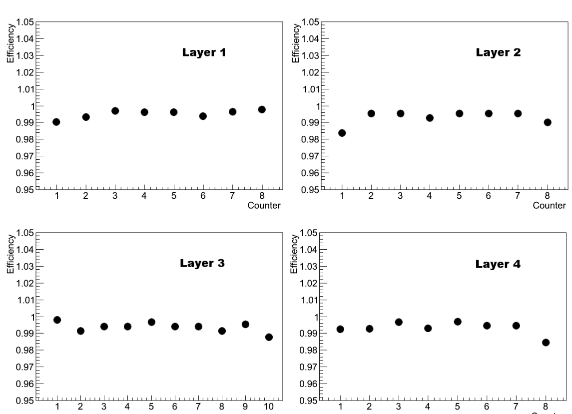

Fig. 5: TOF counters trigger efficiencies.

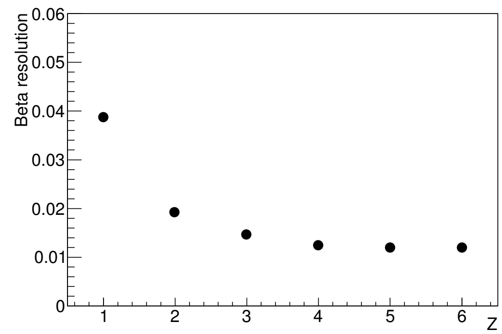

Fig. 6: TOF beta resolution decreases with Z.

3.2 The measurement of the velocity

The cosmic rays velocity $\beta = \frac{\Delta s}{c\Delta t}$ is measured by TOF using the particle time of flight Δt between the upper and lower planes and the trajectory length Δs given by the tracker. The time measurement is performed using the PMT anode signals and it is corrected during the calibration, mainly by:

- the slewing effect;
- the delay introduced by the cables;
- the delay due to the propagation inside the counters.

As shown in fig 6, the resolution in the measurement of the velocity decreases with Z and it is about 4% for protons, 2% for He, 1.2% for C. In fig. 7 it is shown the velocity resolution for charge Z=6; it corresponds to a time resolution σ_{time}=48ps, compatible with the electronics resolution.

This precise measurement of the velocity allows to distinguish upward-going to downward-going particles at level of 10^{-9}.

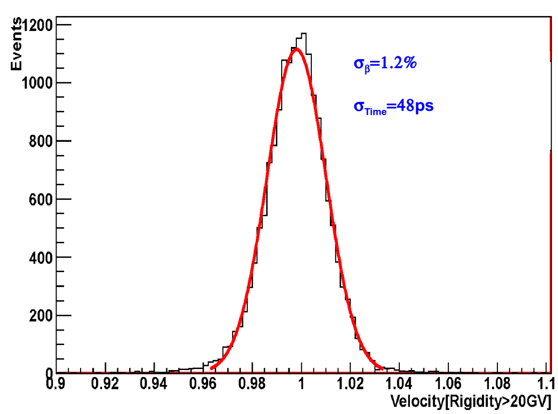

Fig. 7: TOF beta resolution for C (Z=6).

Measuring simultaneously the particle momentum and its velocity, it is possible to identify the mass of the particle, using the relation: $pc = m\beta\gamma$.

The TOF velocity resolution allows to distinguish positron from proton in the rigidity range R$\simeq$(0.5 ÷ 2)GV and protons from ions up to R$\simeq$3.5GV (fig. 8).

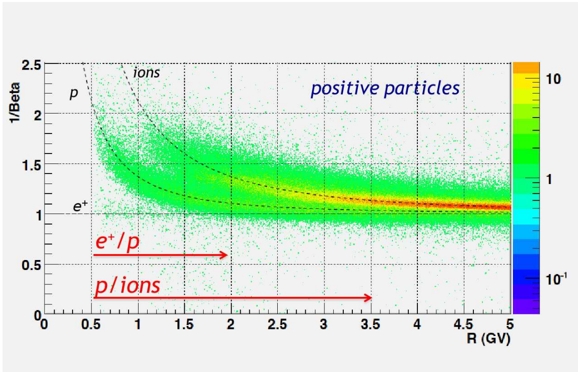

Fig. 8: TOF particle ID using β measurement. Selecting positive particles, it is possible to distinguish positrons, protons and ions.

3.3 The measurement of the charge

The measurement of the charge from the PMT anode and dynode signals allows to determine the cosmic rays charge with high precision up to heavy nuclei.

The anode signals are used to distinguish the particles with charge up to Z=4; when anode signal starts to saturate, the dynode signals are used to enlarge the dynamical range for particles with higher Z[5].

The energy deposited (dE/dx) in the TOF counters by the passage of cosmic rays particles is proportional to Z^2. The measurement of the energy loss is corrected by several effects:

- the light attenuation inside the counters;
- the saturation of the light yield in the scintillator material, according to the Birk's law[6];
- the β dependence: $dE/dX = f(\beta)Z^2$.

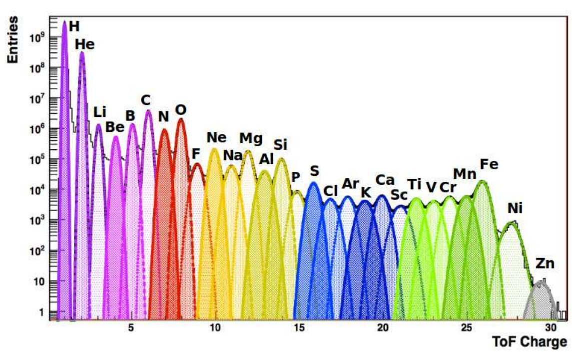

Fig. 9: The TOF charge measurement of the cosmic rays.

Thanks to its charge resolution, the TOF detector is able to distinguish all the different species of cosmic rays (fig. 9) up to the Zn (Z=30).

4 Conclusions

The TOF system and its electronics have been built according to the specifications required by NASA for payloads operating on the ISS.

Since May 2011, the TOF detector is operating in the space station without major problems. All the counters are working properly, providing a trigger efficiency around 99%.

The particle velocity resolution is 4% for protons and 1.2% for Z≥6, corresponding to a time of flight resolution from 160ps to 48ps, allowing to distinguish upward to downward going particles at level of 10^{-9}.

The TOF detector, using the anode and the dynode signals, is capable of measuring the charge of the cosmic rays up to Z=30.

References

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