The ToF and Trigger systems of the PAMELA Experiment: performances of the flight model

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Abstract—**A Time of Flight scintillator system has been developed for the Pamela satellite-borne cosmic ray experiment.**

The main scientific goal of Pamela experiment is the measurement of the fluxes of antiprotons and positrons in cosmic rays over the large energy ranges of respectively 80 MeV-190 GeV and 50 MeV-270 GeV.

The installation of the apparatus on board the Russian satellite Resurs DK1 has been completed at the beginning of 2006 and on the 15th of June 2006 the instrument was launched. The TOF system provides the fast trigger to the experiment, the rejection of albedo particles and the possibility to distinguish electrons from anti-protons up to about 1.5 GeV.

The performances of the ToF and Trigger flight model systems, measured using cosmic rays and light ions in a test beam at GSI, are described.

Index Terms— **Cosmic rays, satellite applications, scintillation counters, time measurement.**

I. INTRODUCTION

THE PAMELA experiment [1] is a space-borne apparatus devoted to the study of cosmic rays, with an emphasis on antiparticles and search for antimatter. Especially, the instrument will measure the spectra of cosmic rays (protons, electrons, corresponding antiparticles and light nuclei) over an energy range and with a statistics unreachable by balloon-borne experiments. The core of the instrument is a permanent magnet spectrometer equipped with a double-sided, micro strip Si tracker. Under the spectrometer lies a sampling electromagnetic calorimeter, composed of W absorber plates and single-sided, macro strip Si detector planes. A Time-of-Flight (ToF) system made of three double-layers of plastic scintillator strips, is employed for particle identification at low energies. At the bottom, a neutron detector made of ^{3}He counters enveloped in polyethylene moderator is placed. A series of plastic scintillator counters for anticoincidence and shower tail catching complete the apparatus.

The instrument was launched, by means of a Russian Soyuz-TM rocket, on the 15th of June 2006 from the cosmodrome of Baykonur, in the former Soviet Republic of Kazakhstan. It is carried as a "piggy-back" on board of the Russian Resurs-DK1 satellite for Earth observation. The satellite flies on a quasi-polar (inclination 70.4°), elliptical orbit (altitude 300-600 km), and the expected mission length is of 3 years.

The ToF system of PAMELA is composed of several layers of plastic scintillators read out by Photo-Multiplier Tubes (PMTs). The ToF must fulfil the following goals:

- provide a fast signal for triggering data acquisition in the whole instrument.
- measure the flight time of particles crossing its planes; once this information is integrated with the measurement of the trajectory length through the instrument, their velocity β can be derived. This feature enable also the rejection of albedo particles.
- determine the absolute value of charge Z of incident particles through the multiple measurement of the specific energy loss dE/dx in the scintillator counters.

Additionally, segmentation of each detector layer in strips can provide a rough tracking of particles, thus helping the magnetic spectrometer to reconstruct their trajectory outside the magnet volume.

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II. DETECTOR DESCRIPTION

A. *PMT and scintillator*

A space-borne experiment such as PAMELA requires for the ToF detector a scintillator material which has to be light, resistant, easy to shape and with good timing properties. In order to meet all these requirements, the obvious choice are plastic scintillators. For the ToF of PAMELA, the choice has been the BC-404 manufactured by BICRON [2].

The light produced by the scintillators is viewed by mod. R5900 PMTs, manufactured by Hamamatsu Photonics. The R5900 is a metal package head-on PMT, with a square section of 30 mm × 30 mm. This PMT suits very well our needs, for its small size, weight (25.5 g) and power consumption. Although not specifically designed for space-borne applications, it has undergone several environmental tests by NASA and it has been already successfully employed in a space-borne experiment.

B. *ToF layout*

The ToF system, as shown in Fig. 1, is divided in six layers, arranged in three planes, each plane composed of two layers. The first plane, S1, is placed on top of the instrument; the second plane, S2, is placed between the TRD and the spectrometer, just above the top anticounter; the last plane, S3, is placed between the spectrometer and the calorimeter, just below the magnet.

The strips of layers Si1 (i=1,3) are oriented along the y-axis (non-bending view) of the instrument, while the strips Si2 are oriented along the x-axis (bending view). For the layers of S2, the opposite applies. The distance between the S1 and S3 planes is 77.3 cm. In Table 1 the main geometrical parameters are summarized.

TABLE I
Geometrical parameters of the ToF system.

Plane	n. of strips	strips dim. (mm × mm)	thickness (mm)	section area (mm^2)
S11	8	330 × 51	7	357
S12	6	408 × 55	7	385
S21	2	180 × 75	5	375
S22	2	150 × 90	5	450
S31	3	150 × 60	7	420
S32	3	180 × 50	7	350

C. *Mechanics*

Both ends of each scintillator paddle are glued to a one-piece adiabatic UV-transparent Plexiglas light guide. The gluing is obtained with an optical cement, mod. BC-600 manufactured by BICRON, which has a refractive index of 1.56, therefore well matching that of our scintillator material, and ensures a transmission factor above 95% for wavelengths of more than 400 nm. Each light guide is in turn mechanically coupled to a PMT by means of optical pads, mod. BC-634A manufactured by BICRON, which have a refractive index of 1.41 (at a wavelength of 425 nm), and ensure a transmission factor above 90% for wavelengths of more than 400 nm. The pads are 25.7 mm × 25.7 mm wide and 3 mm thick in the case of S1 and S2, 6 mm for S3. Scintillators and light-guides are wrapped in a 25 mm thin Mylar foil. The S3 plane is housed directly in the base plate of PAMELA and kept in place by a set of steel frames. The other two planes will be enclosed in light-proof boxes. The external shell of these boxes is 300 mm thick Al2024, while between the box and the scintillator a single piece of polyethylene, shaped to fill all empty space, is placed.

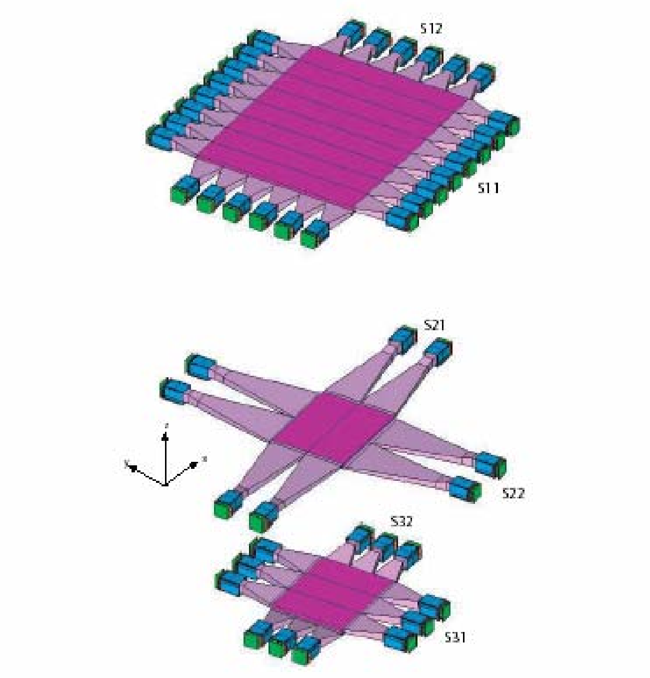

Fig. 1. A schematic overview of the Time of Flight system. The distance between the S1 and S3 planes is 77.3 cm.

D. *Trigger electronics*

The electronic of the ToF system [3] is composed of nine 6U-VME boards. Six Front-End (FE) boards perform the time and charge digitization of the 48 PMTs pulse of the PAMELA ToF. Data from these are collected by a DSP board through a serial link and, after digital processing, transferred to the main data acquisition system. Finally, the trigger board receives signals from the FE boards to generate the main trigger of PAMELA. In order to avoid critical failures of the system, redundancy has been applied to all components. The trigger and DSP boards have been produced in two identical copies, one "hot", the other "cold".

The PAMELA main trigger condition is defined by coincident energy deposits in the scintillator ToF layers. A total of 29 configurations have been implemented on the trigger board which can be selected from ground with dedicated commands to the CPU. The default ones used outside and inside radiation environments are:

- *(S11 or S12) and (S21 or S22) and (S31 or S32)* outside radiation belts and SAA;
- *(S21 or S22) and (S31 or S32)* inside radiation belts and SAA;

The system can switch from the first trigger configuration to the second one on the basis of the counting rate of the plane S1 measured by rate-meters present on the trigger board. It is also possible to mask noisy channels from ground.

Beside the 48 signals from ToF system for the main trigger, the trigger board receives also 8 signals from other subsystems able to generate auto trigger for particular events. To guarantee synchronization of the data acquisition the trigger board manages the busy lines coming from each of the PAMELA subsystem for a total of 20 busy lines. About 60 rate counters, dead-live time counters and the logic to generate calibration pulses sequence for different subsystem of the apparatus are also implemented on the board. The logic is distributed on 9 Actel 54SX32A FPGAs. A DSP (ADSP 2187L) is used to manage the data structure organization and to monitor the rate counters of the ToF channels and other subsystems.

III. QUALIFICATION TEST

Several qualification tests were performed on each element of the two systems in order to reach maximum reliability and best performances. Vibration and environmental tests were performed on different models of the system to evaluate its behaviour during the launch and the flight. Accurate selection of scintillator paddles, light guides and PMT was achieved analysing result of several measurements in different experimental setup.

The intrinsic time resolution and the charge distribution of each ToF paddle were measured using a small test facility made by an apparatus able to track cosmic muons. Each paddle was housed in a custom-made light-proof box, placed on top of a drift chamber (DC). The analog signals coming from the two tubes were splitted in two signals: one signal was sent to an ADC, the other one was discriminated and then injected at the input of a coincidence unit and then to the TDC. The whole apparatus was triggered by the coincidence of the discriminated PMT signals, accepted only if the DC signal was above a given threshold.

Evaluation of the timing resolution of the paddles is performed comparing the impact point reconstruction done by the scintillator with the one obtained by the DC. Since the DC can reconstruct the tracks of ionizing particles passing through its sensitive volume with a precision of 300 mm, we can assume that the contribution from the DC finite precision is negligible, therefore the width of the residual distribution gives us the intrinsic timing resolution of the paddle. In Table 2 we summarize the final results of these measurements for the different layers before and after the time-walk correction.

TABLE II

The average time resolution measured for different layers before the assembling of the system.

Paddle ID	**Before Correction (ps)**	**After Correction (ps)**
<S11 >	145	125
<S12 >	150	135
<S21 >	145	125
<S22 >	166	144
<S31 >	122	110
<S32 >	134	116

IV. FLIGHT MODEL

The measure of the performance of the ToF system and trigger in the real flight configuration was possible only during the final assembling phase of Pamela apparatus in Rome. Only there all the subsystems were integrated, cabled and supplied with 'flight' low and high voltage power supplies. In this conditions cosmic muons were acquired using the ToF scintillators and trigger board in order respectively to detect the particles passing through the apparatus and to trigger and to manage the data acquisition.

A. Time measurement with cosmic rays

In order to obtain a first evaluation of the time resolution of the single paddle we adopt a procedure similar to the one used for the qualification test. The position of the track along the paddle as measured from the tracker is compared to the one obtained from the difference of the TDC value associated to the two PMT's of the paddle. Assuming negligible the uncertain due to the tracker also in this case the distribution of the residuals give us the time resolution of the paddle. The result for a paddle of S2 is shown in Fig.2.

TABLE III

The average time resolution measured for different layers after the assembling of the system.

Paddle ID	**Time resolution (ps)**
<S11 >	200
<S12 >	210
<S21 >	175
<S22 >	180
<S31 >	185
<S32 >	180

In Table 3 results for all the paddles are summarized. In this analysis we didn't apply any correction to the data so the result obtained should be compared with the one shown in the first column of Table II. These preliminary results show a general worsening of the performances respect to the one obtained in the qualification test.

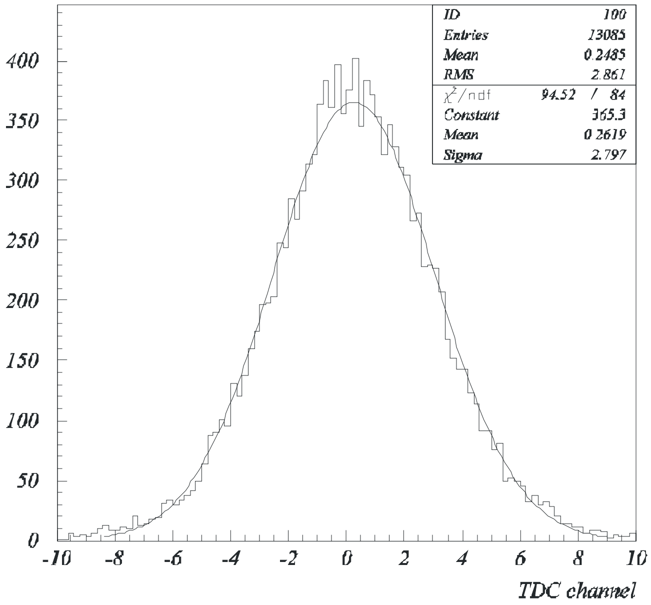

Fig. 2. Time resolution in unit of 50 ps for a S2 paddle

Respect to the values shown in Table 2 the time resolution measured is roughly 30% worse for the paddles of S1 and S3 and less than 10% worse for the paddles of S2.

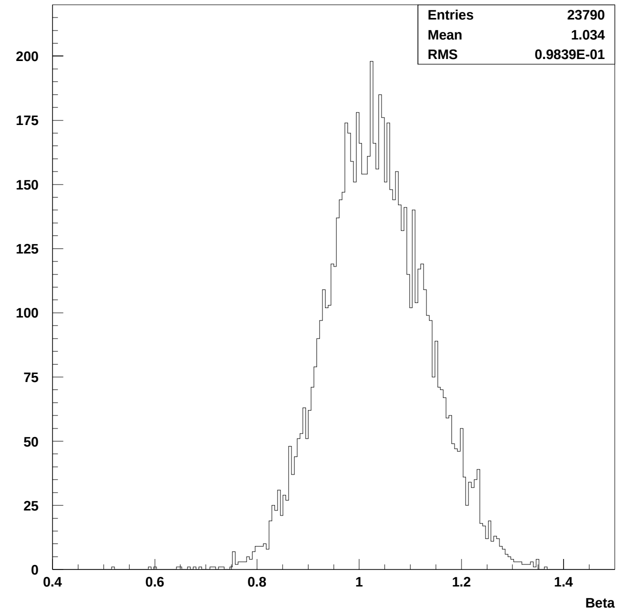

Fig. 3. Distribution of the velocity of particles (in units of speed of light, β) for relativistic muons.

In the Fig. 3 we show the preliminary distribution of the velocity of particles (in units of speed of light, β) measured by the ToF system on a small fraction of the sample of cosmic muons acquired in Rome. The distribution is the weighted mean of the 4 independent beta measurements between the layers S11-S31, S12-S32, S21-S31, S22-S32. Figure 4 shows the velocity of particles measured by the ToF system as a function of their rigidity as measured by the spectrometer. Most of the events are relativistic muons. A small proton component is visible at low rigidity (the solid line indicates the theoretical β for protons).

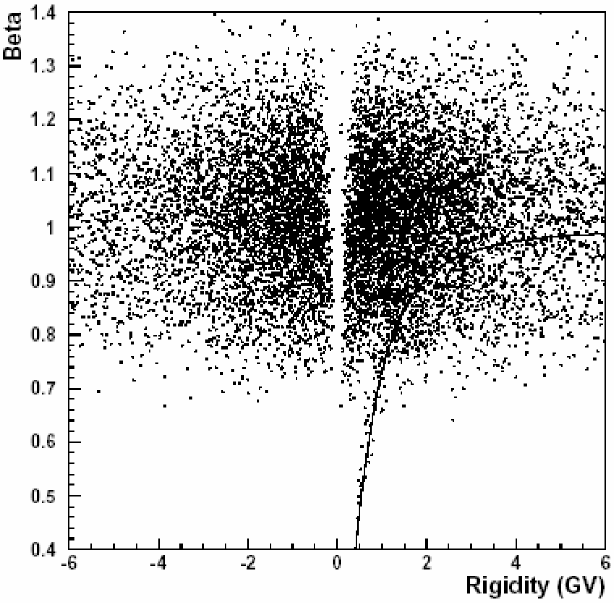

Fig. 4. Beta versus rigidity plot. The solid line shows the expected behavior for protons.

B. Time and Charge measurements with nuclei

The performances of the system in the determination of the absolute charge of the particles have been evaluated performing a beam test at the GSI facility in Darmstadt in February 2006. Due to several delays in the construction phase was not possible to calibrate the whole apparatus with light nuclei. Prototypes of the S1, S2 and S3 ToF paddles were exposed to ^{12}C and ^{50}Cr beams at several energies. The electronic read-out was performed using the spare electronics boards of the flight model. A silicon tracker was interleaved between S1 and S2 paddles to reconstruct the particle tracks. It comprises five 300 μm thick silicon sensors segmented into micro-strips on both sides. In the x-view, the implantation pitch is 25 μm and the read-out pitch is 50 μm. In the y-view, the read-out pitch is 67 μm with the strips orthogonal to those in the x-view.

For each beam set up a collection of events was acquired without any target between ions beam and the apparatus. The main goal of this subset of data was to measure the time resolution. In Fig. 5 we show the distribution of β measured using the scintillators S1 and S3 for a 1200 MeV/n ^{12}C beam. The theoretical value of β for these particles is 0.899. The measured sigma in the β distribution corresponds to a time resolution of about 62 ps. The observed improvement, respect to the result obtained with particles at minimum of ionizing energy, is reasonable since the timing resolution improves with the number of photons created in the scintillator.

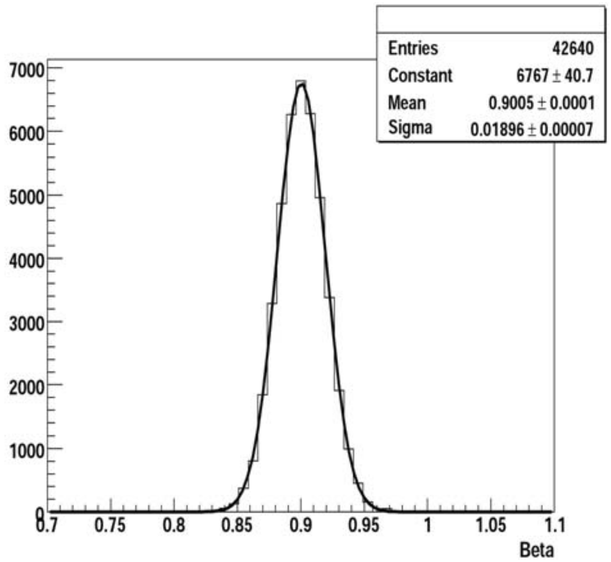

Fig. 5. Distribution of the velocity of particles (in units of speed of light, β) measured between the planes S1 and S3 for a 1200 MeV/n ^{12}C beam.

The table IV summarizes the results of the measurements of time resolution of the ToF system measured with different beams and for different combinations of paddles.

TABLE IV
The time resolution measured for two different combinations of layers for the three beam setup.

	S1-S2	S1-S3
^{12}C 200 MeV/n	61 ps	62 ps
^{12}C 1200 MeV/n	67 ps	62 ps
^{50}Cr 500 MeV/n	62 ps	68 ps

Targets of aluminium and polyethylene were used to generate a variety of fragmentation products to study the performances of the system in measuring the charge of the signals produced by different highly ionizing particles. In Fig. 6 we show the charge distribution (in unit of atomic number, Z) obtained in the case of a 1200 MeV/n ^{12}C beam. A 5 cm thick polyethylene target was used to increase the fragmentation probability. Energy deposits in the scintillators, converted by the ADC, permit to identify the secondary particles produced by fragmentation of the incident ^{12}C beam.

The plot shows the Z distribution measured in the S3 scintillator requiring that on both planes S1 and S2 the particle has the same Z within 2 sigma and cutting events in which a further fragmentation takes place between S2 and S3 planes. In this analysis we use only information coming from ToF. We hope to improve the separation between He and Li using the information from the tracker, to select events in which no more than one fragment at a time is present.

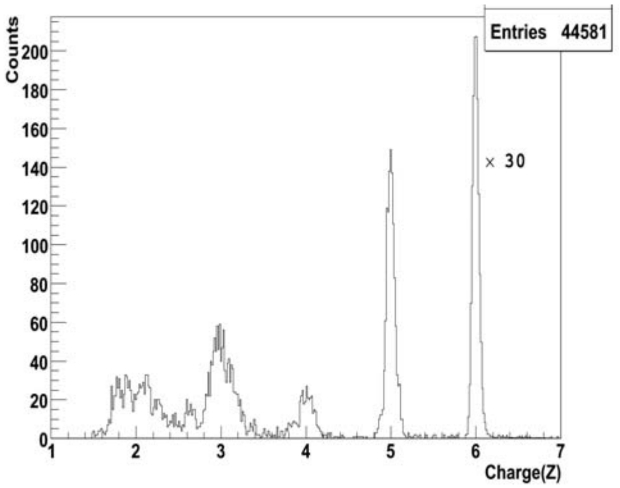

Fig. 6. Energy deposits in the S3 scintillator for a 1200 MeV/n ^{12}C beam.

V. CONCLUSION

The ToF detector and the trigger electronics for the satellite based PAMELA experiment have been constructed and characterized. The counters of ToF have an intrinsic time resolution of ~190 ps for minimum ionizing particles and ~65 ps for light nuclei. The measured charge resolution will allow to discriminate between different species of light nuclei and their isotopes in cosmic rays.

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