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THE TIME-OF-FLIGHT SYSTEM OF THE PAMELA EXPERIMENT

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ABSTRACT

The PAMELA satellite-borne experiment, scheduled to be launched in 2004, is designed to provide a better understanding of the antimatter component of cosmic rays. In the following we report on the features and performances of its scintillator telescope system which will provide the primary experimental trigger and time-of-flight particle identification.

1 Mission overview

The PAMELA experiment [1] is a satellite-borne apparatus devoted to the study of cosmic rays, with an emphasis on antiparticles and search for antinuclei. 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 (shown in Fig. 1) is a permanent magnet spectrometer [2] equipped with a double-sided, microstrip silicon tracker. Under the spectrometer lies a sampling electromagnetic calorimeter [3], composed of tungsten absorber plates and single-sided, macrostrip silicon detector planes. A Time-of-Flight (ToF) system made of three double-layer planes of plastic scintillator strips, and a Transition Radiation Detector [4] (TRD) made of 9 planes of proportional counters (*straw tubes*) interleaved with carbon fiber radiator, are employed for particle identification at low and high energies, respectively. 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 will be carried as a "piggy-back" on board of the Russian Resurs-DK1 satellite for Earth observation. The launch, by means of a Russian Soyuz rocket, is scheduled for the first half of 2004 from the cosmodrome of Baykonur, in the former Soviet Republic of Kazakhstan. The satellite will fly on a quasi-polar (inclination 70.4°), elliptical orbit (altitude 350–600 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 fulfill 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[1];
- determine the absolute value of charge z of incident particles through the multiple measurement of the specific energy loss $\mathrm{d}E/\mathrm{d}x$ 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

[1]Upward incoming particles, produced by the interaction of primary cosmic rays with the upper layer of the atmosphere.

their trajectory outside the magnet volume.

2 ToF layout

The ToF, as showed in Fig. 2, will be divided in 6 layers, arranged in three planes, each plane composed of two layers. The first plane is placed on top of the instrument, the second between the TRD and the spectrometer, and the last one just below the magnet. The overall geometry of the ToF layers is summarized in Tab. 1.

plane	no. of strips	strip 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

Table 1: *Summary of ToF planes geometry. The section area of each strip should be compared with the (effective) sensitive area of the PMT's photocathode, equal to 324 mm^2.*

2.1 Scintillator and PMT

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 these requirements, the obvious choice are plastic scintillators. The chosen material is the BC-404, manufactured by Bicron, whose scintillation emission has a maximum at a wavelength of 408 nm. It is characterized by a relatively large light output (68% of anthracene) and a short decay time (1.8 ns). This makes the material well suited for fast timing measurements.

The light produced by the paddles is viewed by mod. R5900 PMTs, manufactured by Hamamatsu Photonics. The R5900 is a metal package head-on PMT, with a square section of 30×30 mm^2. This PMT suits very well our needs, for its limited 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. The R5900 PMTs for the PAMELA ToF are selected with a Quantum Efficiency $> 21\%$. Redundant 900 V HV supplies are connected to each PMT through a regulator circuit capable of 800 V swing. This is used to trim the individual PMT gains and to compensate for differential aging of the PMTs and scintillators. Voltage is distributed within each PMT by a resistive voltage divider designed to accommodate the largest particle rates to be measured. Since the core of the PAMELA apparatus is a permanent magnet, it has been decided to shield all our PMTs with a 1 mm thick μ-metal[2] screen which extrudes from the PMT length of about 18 mm.

2.2 Mechanical structure

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 25.7×25.7 mm^2 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 μm thin mylar foil. The S3 plane will be 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 (as shown in Fig. 3 and 4). The external shell of these boxes is 300 μm thick Al2024[3], while between the box and the scintillators is placed a single piece of polyethylene shaped to fill all

[2] μ-metal is a nickel-iron alloy (77% nickel, 15% iron, plus copper and molybdenum) that is very efficient for screening magnetic fields. The name of the material refers to the fact that μ-metal has a high value of the magnetic permeability μ.

[3] A high strength, low weight aluminum alloy (95% Al, 4% Cu, 1% Mg), of limited weldability, also known as Avional and used in aircraft and aerospace applications.

empty space.

3 ToF electronics and trigger

The ToF and trigger electronics for PAMELA is a system made of nine boards in the 6U VME format. These are the six Front-End (FE) boards, the DSP board and the two identical trigger board (one “hot”, the other “cold”).

3.1 Front end

Each FE board, shown in Fig. 6, receives the analog signals coming from 8 PMTs. For each channel the input is split in two branches, corresponding to the time and charge sections. The first measures the arrival time of the signal with respect to the trigger pulse, and generates the signal for trigger formation. The other section measures the charge of the PMT signal.

3.1.1 Time section

For each PMT, the anode line is coupled to a fast discriminator. To minimize the time-walk effect, a double threshold discriminator has been chosen, mod. AD8611 manufactured by Analog Devices, which has a maximum propagation delay of 4 ns. Its two thresholds can be set by remote, each through a DAC, mod. AD7303 manufactured by Analog Devices. The discriminated signals are shaped, translated in the LVDS standard and sent to the trigger board. The discriminator is part of a more complex logic that controls a double-ramp Time-to-Amplitude-to-Time (TAT) converter. A low-loss, low-thermal drift, storage capacitor is charged with a high-stability constant current source during the time between the pulse edges of the FE discriminator signal and the trigger signal. The arrival time of the latter starts the discharging of the capacitor with a constant current which is about 200 times smaller than the previous. Hence, measuring the discharging time, a time expansion factor of 200 is obtained. A fast discharge is produced if the trigger is not generated within 150 ns from the signal edge. The logic needed to control the TAT converter is fully implemented in a low-power, rad-tolerant FPGA, mod. 54SX08A manufactured by Actel. Since each of these devices serves two channels, four of these FPGAs are mounted on the FE board.

3.1.2 Charge section

The amplitude of each PMT pulse is measured with a Charge-to-Time (CT) Converter. A charge amplifier collects the anode current from the PMT and provides an output signal which is proportional to the total current. A pulse stretcher operates by charging-up a capacitor at the peak value of the input waveform and then discharges it linearly. This signal has a length proportional to the maximum voltage reached on the capacitor and hence to the PMT charge. The charge amplifier and the pulse stretcher are implemented using a monolithic transistor array, mod. CA3127, manufactured by Intersil. The last stage of the CT converter is a discriminator that generates the digital pulse with a length equal to discharging time of the pulse stretcher.

3.1.3 Digital section

The output digital signals coming either from the time of charge sections, are sent to a 100 MHz multichannel, common start, Time-to-Digital Converter (TDC), fully implemented in a FPGA, mod. 54SX32A manufactured by Actel. The circuit (realized with a 12 bits Gray counter and 8 registers) has a 10 ns resolution over a time window of 40.95 μs, which means (taking into account the time expansion factor) a 50 ps resolution on a 200 ns range. The first edge of the trigger signal starts the counter: when a new signal edge arrives at one of the channel inputs, the hit control logic writes the current value of the free running counter in its own register. The registers are 12+4 bits long to encode the channel number. Since each TDC receives a signal for measuring the time and one for the charge from each channel, the board houses two converters. The readout and the initialization of the TDCs is performed by a dedicated 54SX32A FPGA which acts as an interface between the FE and the DSP boards. Upon request from the DSP board it acquires data from the two TDC and writes them in a 16 hits-deep FIFO. Data are then serialized and transmitted according the Data-Strobe protocol at 16 Mbit/s.

3.2 DSP board

The readout of all PAMELA data is performed through a Data-Strobe serial link, with a dedicated link for each subsystem. To readout the six FE boards of the ToF subsystem an interface DSP board has been developed which collects the data from all the boards and transmit it, through the serial link, to the main DAQ. On this board is mounted a DSP, mod. ADSP-2187L, manufactured by Analog Devices. The DSP collects the data and builds the data packet for the main DAQ. All the state machines needed to decode the macrocommands from the CPU of PAMELA and to control the interface with the DSP, are implemented on a 54SX32A FPGA. Another FPGA of the same kind controls the data flow with the FE boards. In order to increase the reliability of the system, two copies of this circuit are implemented on the same VME board: the "cold" version can be turned on if there is a failure of the "hot" one, thus preserving the full functionality of the board.

3.3 Trigger board

The trigger board is a complex digital board that generates the first level trigger for the apparatus and performs several more tasks. It receives the 48 signals from the ToF system for the main trigger and 8 signals from the other subsystems capable to generate self-trigger for particular events. To guarantee synchronization of the data acquisition the trigger board manages the 20 busy lines coming from each of the PAMELA subsystem. All the input and output lines are in the LVDS standard. 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 54SX32A FPGAs. Control masks select trigger types and allows the selection of failed (noisy or dead) ToF channels. The pattern of the channels fired for each trigger is generated for each event. 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.

4 Qualification tests

4.1 PMT qualification tests

Several qualification tests were performed in order to select a "good" sample of PMTs to be employed in the final model of the ToF. The gain was measured applying the method described in [5]. To test the linearity, the Double Pulse Method was employed (as described in [6]). Finally to measure the photocathode homogeneity, the PMT has been illuminated with LED light fed through an optical fiber, and moved with a stepper motor.

4.2 Counter qualification tests

The intrinsic time resolution and the charge distribution of each ToF paddle were measured in different experimental situations. Each paddle was housed in a custom-made light-proof box, placed on top of a drift chamber (DC). The whole apparatus was triggered by the coincidence of the signals coming from the two PMTs of the paddle. 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 μm, 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. Preliminary tests give the following results

S1	110 ps $<\Delta$T$<$ 120 ps
S2	140 ps $<\Delta$T$<$ 150 ps
S3	120 ps $<\Delta$T$<$ 140 ps

A typical time resolution plot is shown in Fig.7 before and after corrections for the time-walk effect.

4.3 Environmental tests

In order to estimate the PMT behavior during the flight of PAMELA gain measurements were performed at different temperatures (in the range $0 \div 50^\circ$ C). The gain was measured by modulating the light from a green LED, with a low yield when the single photoelectron peak has to be estimated. The data have been analyzed with three different methods for gain calculation but the result is the same in all three cases and does not show any strong dependence on temperature variations in the range of interest. Full paddles were also submitted to thermal test to characterize the whole apparatus. Data acquisitions of cosmic ray events have been made by keeping counters at fixed temperature in an insulated box.

Mechanical tests on the engineering models of the three ToF planes have been performed applying the expected random vibration spectrum of the satellite launch on a shaker machine. The qualification spectrum is about 3-fold bigger than the real one to ensure maximum reliability of the system. For all the planes the models withstood the qualification test without damages or worsening of the performances.

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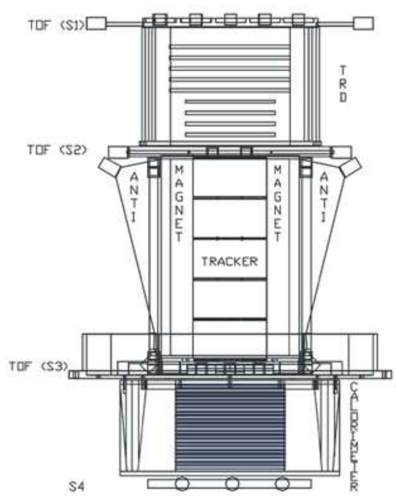

Figure 1: *Schematic drawing of the* PAMELA *apparatus.*

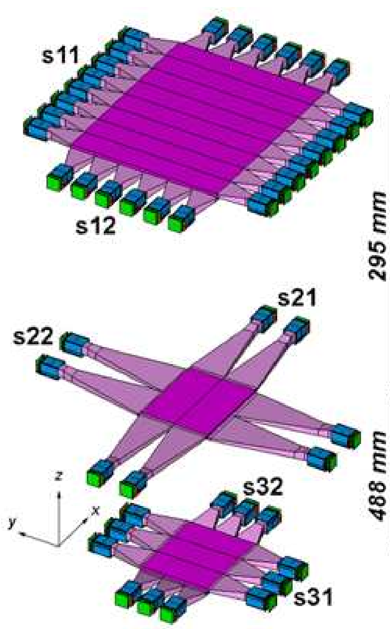

Figure 2: *Isometric view of the ToF planes.*

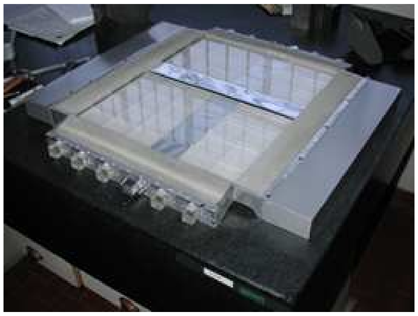

Figure 3: *Assembly of a prototype of the S1 plane.*

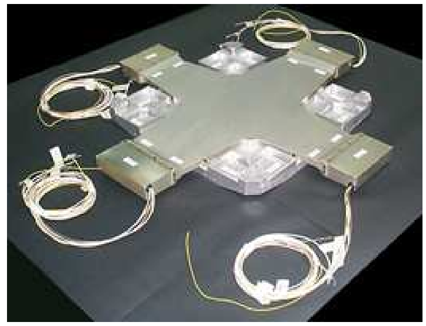

Figure 4: *The flight model of the S2 plane.*

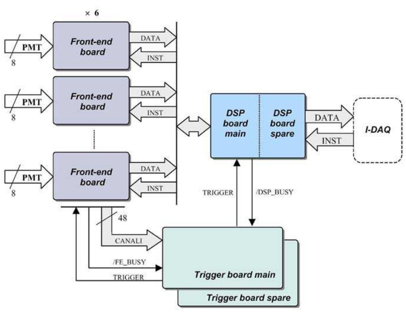

Figure 5: *General electronics layout.*

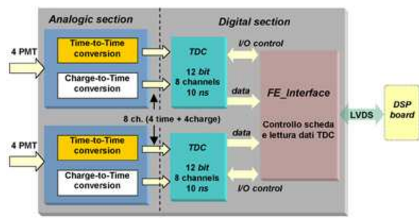

Figure 6: *Block diagram of a FE board.*

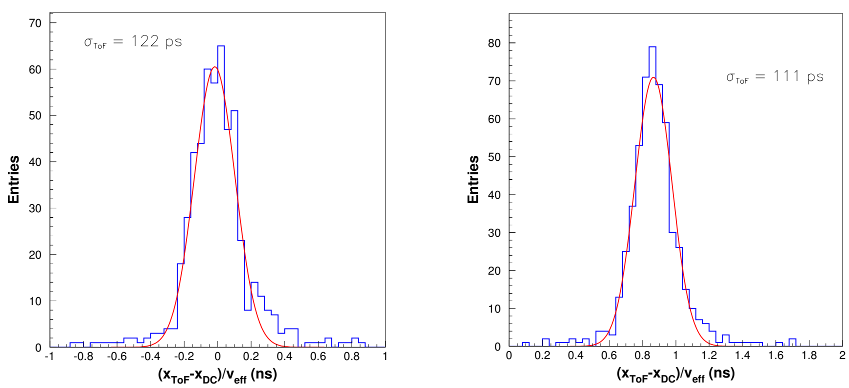

Figure 7: *Sample time resolution of a ToF paddle before (left) and after (right) time-walk correction.*