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First flight data from the PAMELA spectrometer

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ABSTRACT

PAMELA is a satellite-borne experiment designed to study charged particles in the cosmic radiation, optimized in particular for antimatter components search. The experiment is mounted on the Resurs DK1 satellite that was launched on June 15th 2006 from Baikonur cosmodrome and is now collecting data from a semi-polar elliptical orbit around the Earth. The core of the PAMELA apparatus is a magnetic spectrometer, designed to determine precisely the rigidity and the absolute charge of particles crossing the detector. The tracking system is composed of six planes of silicon microstrip detectors dipped in an almost uniform magnetic field generated by a permanent magnet made of an Nd–Fe–B alloy. Some preliminary analysis about the spectrometer's performances, made using data collected since July 2006 till June 2007, are here reviewed.

1. Introduction: the PAMELA experiment

The PAMELA [1] (Payload for Antimatter Matter Exploration and Light-nuclei Astrophysics) cosmic ray telescope is installed on board the Russian Resurs-DK1 Earth-observation satellite that has been launched into space with a Soyuz-U rocket on June 15th 2006 from the Baikonur cosmodrome in Kazakhstan.

The satellite performs an elliptical and semi-polar orbit, with an altitude varying between 350 and 600 km, and an inclination of 70°. The mission is foreseen to last for at least three years.

The main scientific objective is the precise measurement of the energy spectra for antiprotons $\bar{p}$ (range 80 MeV–190 GeV) and positrons e^+ (50 MeV–270 GeV) in cosmic rays, together with e^-, p, light nuclei and their isotopes, in order to search for evidence of dark-matter particle annihilations, to test cosmic ray propagation models and to search for direct evidence of antinuclei (in particular $\overline{He}$, with a sensitivity in the $\overline{He}/He$ ratio of $\sim 10^{-7}$).

Beside momentum measurement, particle identification is performed with the help of the other detectors included in the PAMELA apparatus (see Fig. 1): a three-plane time-of-flight system, an electromagnetic imaging silicon–tungsten calorimeter, an anticoincidence system around and on top of the magnet, a shower-tail catcher scintillator under the calorimeter (S4) and a ^{3}He neutron detector.

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2. The magnetic spectrometer

PAMELA scientific objectives require an extremely good momentum resolution. This can be achieved by having a micrometric spatial resolution and a reduced amount of material traversed by the particle into the tracking volume. The central component of PAMELA is a magnetic spectrometer [2], formed by a permanent magnet and a tracking system composed of six planes of silicon sensors, which satisfy both the requirements.

This device, designed and developed by the Florence group of the PAMELA collaboration, is used to determine the rigidity $R = pc/Ze$ and the charge of particles crossing the magnetic cavity. The detector design had to take into account the strong limits imposed by a satellite mission for mass, volume, power and the amount of data to be transmitted to ground.

The magnet is a tower 43.66 cm high, formed by five superposed identical modules with a central rectangular cavity (16.14 cm × 13.14 cm), with a total geometric factor of 21.6 cm^2 sr. Each module is composed of 12 Nd–Fe–B alloy elements with high residual magnetic induction (≈ 1.32 T), in such a way that the field inside the cavity has practically all the strength along the Y-axis and a good uniformity (average value $B \simeq 0.43$ T).

The rigidity measurement is done through the reconstruction of the trajectory based on the impact points on the tracking planes (housed in slits and located between each couple of modules, as well as at the top and at the bottom of the structure) and the resulting determination of the curvature due to the Lorentz force. Each plane of the tracking system (see Fig. 2) has three

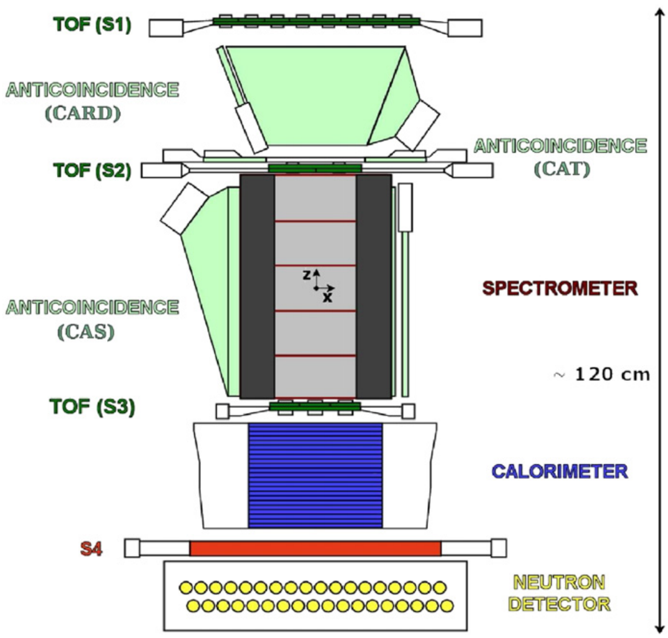

Fig. 1. Schematic drawing of the PAMELA detector. The detector has a mass of 470 kg and an average power consumption of 355 W. The magnetic field lines inside the spectrometer cavity are oriented along the *y* direction. The average value of the magnetic field is $\langle B\rangle = 0.43\,\mathrm{T}$.

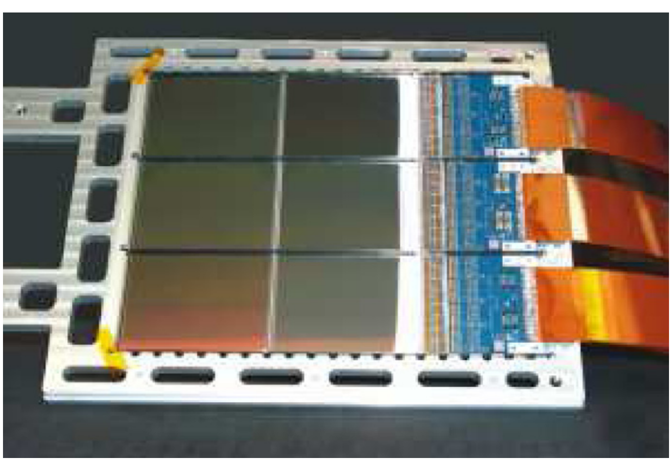

Fig. 2. A plane of the tracking system, composed of three *ladders* each made of two silicon sensors and the hybrid circuit.

independent sections (*ladders*), each composed of two double-sided n-type silicon sensors, $5.33 \times 7.00\,\mathrm{cm}^2$ wide and $300\,\mu\mathrm{m}$ thick, and a hybrid circuit. The implant pitch is $25.5\,\mu\mathrm{m}$ on the junction side (2035 strips) and $66.5\,\mu\mathrm{m}$ on the ohmic side (1024 strips).

The silicon microstrip sensors are double sided, and they can measure both the orthogonal coordinates of the charged particles which cross them. The junction side (or *X* view), which has better performances, is used to measure the impact-point *X* coordinate in the main bending plane *XZ*, orthogonal to the magnetic field. As front-end electronics, eight 128-channel VA1 chips are used for each ladder. The low noise and low power consumption which characterize these chips allow the detector to get a high spatial resolution and to comply with strict power requirements of the satellite.

3. Tracker performances: preliminary analysis

On June 21st 2006 PAMELA has been switched on for the first time. After a brief period of commissioning, during which several trigger and hardware configurations have been tested, PAMELA has been in a continuous data taking mode since July 11th. The in-flight calibration of PAMELA is currently underway, and the results show that the detectors are working as expected and fulfill the nominal requirements.

Some preliminary studies about the spectrometer's performances in orbit are here reviewed: significant improvement can be expected once the calibration is completed.

The thermal environment is fundamental to guarantee stability of operation for the magnetic spectrometer. Several temperature sensors are placed on the external walls of the magnetic tower: the registered temperatures increase from $\sim 21\,^{\circ}\mathrm{C}$, when the system is off, to $\sim 31\,^{\circ}\mathrm{C}$, when the system is on, with variations of less than $1\,^{\circ}\mathrm{C}$ at regime.

To obtain the best impact-point resolution (related to the signal/noise ratio which can be achieved in detecting the clusters of charge which are released by the ionizing particles when crossing the silicon sensors) the cluster signal has to be treated with proper algorithms. The distribution of the signal/noise ratio for clusters on one of the planes of the tracking system is shown in Fig. 3. The signal/noise ratio for a cluster is defined as the sum of the signal/noise ratios of the strips which collect the ionization charge. The mean values are consistent with those obtained during beam-test sessions, 56 for the *X* side and 26 for the *Y* side.

The most simple way to evaluate the impact-point coordinate is the cluster center of gravity algorithm. However, as is well known, the center-of-gravity is not the best estimator of the impact coordinate; in fact, due to discretization effect of the signal distribution, charge sharing among adjacent strips in silicon microstrip sensors is not linear. When charge collection is not linear, the best estimate of the impact coordinate is given by the η_2-algorithm [3] that use the variable defined as

$$\eta_n = \frac{\sum_n ps}{\sum_n s} \qquad (1)$$

(where p is the strip coordinate relative to the strip with the maximum signal, expressed in pitch units, s is the strip signal and the sum is over $n = 1, 2, \ldots$ strips around the cluster) with $n = 2$. The spatial resolution obtained by applying this algorithm has been studied during the past years by means of beam-test data

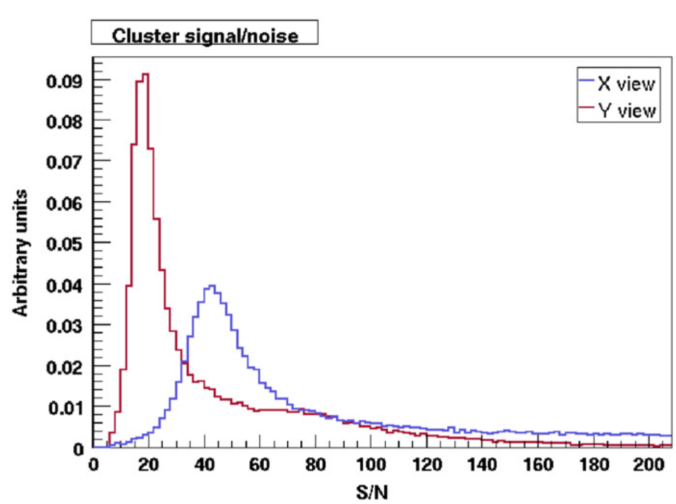

Fig. 3. Distribution of the signal/noise ratio for clusters on the *X* and *Y* sides of one plane. This sample contains also non-MIP cosmic rays (He, etc.).

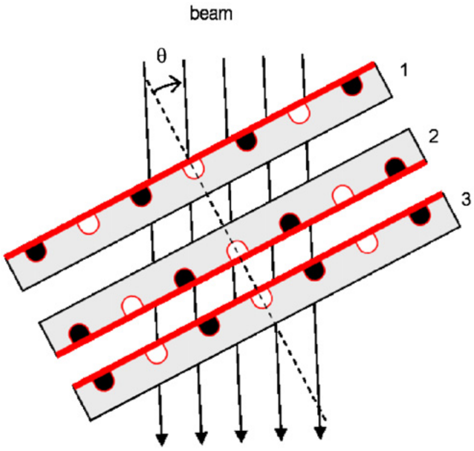

Fig. 4. Schematic view of the beam-test setup.

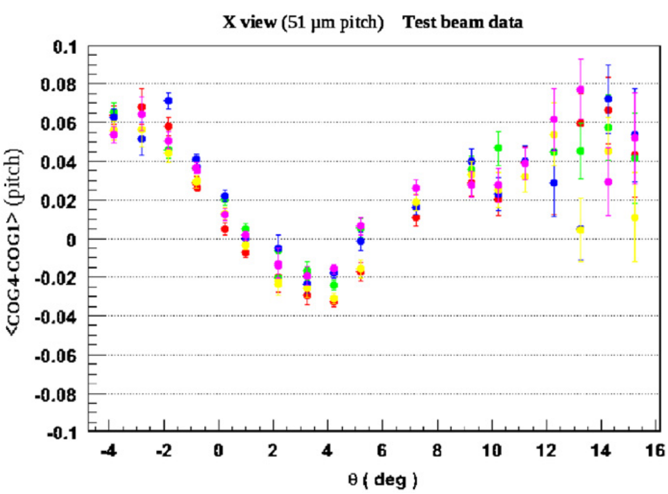

Fig. 5. Angular correction Δ, expressed in pitch units. Results are from beam-test data (CERN-SPS, 2006).

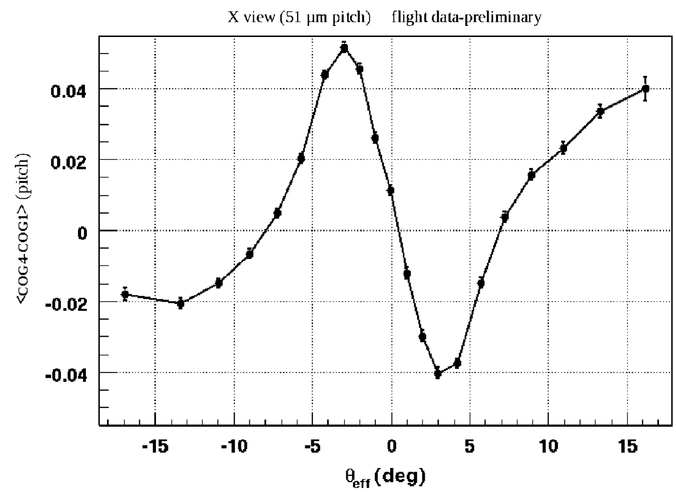

Fig. 6. Angular correction Δ, expressed in pitch units. Results are from flight data.

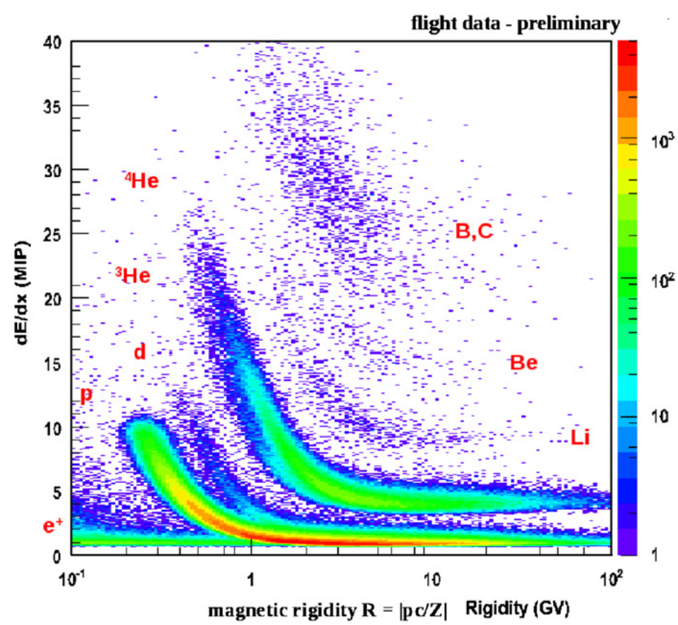

Fig. 7. Distribution of the mean rate of energy loss in the silicon sensors of the tracking system, as a function of the particle rigidity, for a sample of positively charged cosmic rays. Moving from bottom-left to top-right, the following particle species can be recognized: e^+, p and d, ^{3}He and ^{4}He, Li, Be, B and C.

and simulation [4]. In particular, the evaluated resolution (rms) on the X side, which is used to measure the coordinates along the bending direction, is $\sim 3\,\mu$m up to 5°; above 10°, simulation shows that better results are obtained by using more than two strips in the evaluation of the impact coordinate, since the deposited charge is collected by more strips. On the Y view, where the pitch is larger, a 2-strip algorithm gives the best result up to 20°.

However, if an asymmetry in the signal distribution is present (as in the case of the inclined tracks) a systematic shift is introduced in the coordinate evaluation, if the standard η_2-algorithm is applied. This angular effect on the position reconstruction with silicon microstrip detectors has been extensively studied by Ref. [5] by means of both an analytical model, based on signal theory, and statistical simulations.

In order to measure the angular effect, a dedicated beam test was performed in 2006 with protons of momentum 50–150 GeV/c, at the CERN-SPS facility. For this purpose, a small tracking system made of five planes was prepared. The detector was placed on a turntable, so that the beam angle relative to the x side of the sensors could be varied. Three of the five planes were placed at a closer distance, in order to minimize multiple scattering effect on the measured coordinates, and the middle plane was rotated of 180° around the y-axis (see Fig. 4). With this setup the spatial residual on the x side of the middle plane, evaluated as $\delta = x_2 - (x_1 + x_3)/2$, is equal to twice the coordinate shift, if any.

The colored markers on the plot of Fig. 5 show for each plane the correction, defined as $\Delta = \langle \eta_4 - \eta_1 \rangle$ (where η_4 and η_1 are defined by Eq. (1)), to eliminate the systematic shift. The same behavior we observe in the flight data (see Fig. 6). This analysis is in progress.

Besides rigidity and charge sign, the tracking system can be used also to determine the absolute value Z of the charge, by multiple measurements of the mean rate of energy loss in the silicon sensors. Fig. 7 shows the Z discrimination capability of the tracking system. The task of selecting charge of particles can be accomplished in PAMELA by the time-of-flight system and the calorimeter. Nonetheless, the spectrometer can contribute with a good charge resolution at least up to Be (above the Be the single-channel saturation of the electronic readout chips reduces the performances), and it is also able to perform isotopic discrimination for H and He at low rigidities.

4. Conclusion

Since June 2006 the PAMELA detector have been orbiting around the Earth and it has been continuously taking data. This paper presents some preliminary analysis of the data collected by the magnetic spectrometer; from these results we can conclude that most of the systematic effects present in the impact-point reconstruction are well understood and under control.

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