29th International Cosmic Ray Conference Pune (2005) **3**, 317–320

The magnetic spectrometer of the PAMELA experiment: on-ground test of the flight-model.

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The magnetic spectrometer of the PAMELA satellite experiment is composed of a microstrip silicon tracking system inserted inside the cavity of a permanent magnet. Providing that an accurate alignment of the tracking sensors is performed and adequate position-finding algorithms are applied, a spatial resolution of less than 3 μm can be achieved. The tracking system performances combined with the magnetic field of the permanent magnet will allow the measurement of the high-energy cosmic-ray particle spectrum. The detector has been intensively tested during the long integration phase with both particle beams and ground muons. Results on the spectrometer performances in the flight configuration will be presented.

1. Introduction

PAMELA (Payload for Antimatter Matter Exploration and Light-nuclei Astrophysics) [1] is a satellite-borne experiment that will be launched from the Baikonur cosmodrome in Kazakhstan on board the Russian Resurs-DK1 satellite within the end of 2005. The main scientific objective of the experiment is a precise measurement of the energy spectra of cosmic rays in a wide range with high statistics (data will be gathered for at least 3 years, with an expected trigger rate of about 12 Hz). In particular the experiment has been designed to provide an high-sensitivity identification capability for the antimatter components.

The main challenge of the experiment was the use of advanced detection techniques, developed for the high-energy physics, on board of a satellite. In particular, the main novelty is the installation of a magnetic spectrometer based on a microstrip silicon tracking system, which compared with traditional gas detectors provides a spatial resolution of more than one order of magnitude better. This allows a precise measurement of particle

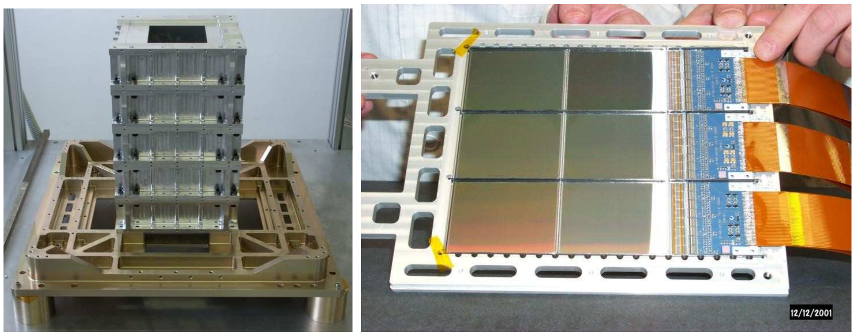

Figure 1. Left: view of the magnetic tower mounted on the base plate. Right: view of a tracker plane.

spectra up to several hundreds GeV. In order to achieve this goal, it is necessary to carefully study any possible systematic effect and to develop adequate calibration procedures. The characteristics and performances of the magnetic spectrometer have been studied since 1994 by the Florence group and the flight model of the detector has been completed in 2001. Several beam tests have been performed since than (the last one in 2003) and a large number of atmospheric-particle events has been gathered during the long integration phases in Italy and in Russia. Systematic check of the flight-model performances, based on these data sets, have been performed.

2. Description of the apparatus

The magnetic system of the spectrometer has been manufactured by using permanent magnet technology. The magnet is composed of five modules forming a tower 44.5 cm high (fig. 1-left). Each module has been built by assembling twelve magnetic blocks, made of a Nd-Fe-B alloy, in a configuration that provides a rather uniform magnetic field ($\sim$0.43 T) oriented along a preferential direction inside a cavity of dimensions $13.2\times16.2\ \mathrm{cm}^2$. The permanent-magnet dimensions define the geometrical factor ($\sim$20.5 cm^2) of the experiment. The field inside and outside the magnet has been 3D-mapped by an automatic positioning machine equipped with a triaxial Hall probe.

Six equidistant detector planes are inserted inside the magnetic cavity. Double sided silicon sensors provide two independent impact coordinates on each plane.

The basic detecting unit is the *ladder*, which is made of two sensors ($5.33\times7.00\ \mathrm{cm}^2$) assembled with a hybrid circuit that houses the front-end electronics. Each plane is composed by three ladders that are inserted inside an aluminum frame (fig. 1-right). In order to limit multiple scattering in dead layers, no additional supporting structure is present above or beneath the planes.

Silicon sensors (produced by Hamamatsu) consist of a n-type 300 μm bulk, with implanted strips on both sides in orthogonal directions and integrated decoupling capacitors. The strip pitch on the junction side is 25.5 μm and only one strip out of two is read out. On the ohmic side the pitch is 67 μm and p-stop strips are used to increase the interstrip resistance; on this side a double metal layer is used to bring the readout strips parallel to each other on the two sides, so that the readout electronics can be housed on the same substrate for both sides. The front-end electronic is based on VA1 chips [2], which are characterized by low noise (strictly related to the spatial resolution) and small power consumption.

The best spatial resolution is obtained in the junction side, which is used to measure the particle coordinate in the bending view. Beam-test results of ladder prototypes [3] have shown that a spatial resolution less than 3 μm can be achieved in the bending view.

The silicon planes and its readout electronic have been designed [4] in order to meet the requirements for a space environment: radiation hardness, system reliability and mechanical strength. Electronic components have been space qualified by means of radiation-hardness tests [5]. Vibration and thermal tests have proved that the detector structure is suitable to the PAMELA mission [4].

3. Track reconstruction

3.1 Determination of spatial coordinates

Raw signals (clusters) are converted to spatial coordinates, by means of the non-linear eta-algorithm [6, 7]. It is an empirical procedure developed to reduce the systematic error in the impact coordinate due to the discretization of the signal distribution [8], which significantly affects the position determination for a detector configuration typical of silicon microstrip sensors. The algorithm involves the integral of experimental distributions and requires previous calibration.

The calibration procedure and the spatial resolution of the PAMELA tracker sensors were investigated by means of a simulation [9] and the results were applied to analyze ground data. According to the simulation, a resolution of less than 3 μm can be achieved on the junction side for angles less than 5°; the resolution becomes poorer with increasing angles, up to about 8 μm at 20°, which is the maximum track inclination allowed by the PAMELA geometrical factor. On the ohmic side the resolution is less than 14 μm, with a minimum value of 8 μm at about 10°.

In order to take advantage of the intrinsic sensor resolution in track reconstruction, impact coordinates must be corrected for sensor misalignment relatively to the nominal mechanical positions. The alignment parameters of the sensors were first evaluated by means of beam particles. In this case the particle momentum (and as a consequence the track curvature) is known and the parameters can be determined by means of a spatial-residual minimization procedure. After the mechanical qualification of the PAMELA flight model, second order corrections to the alignment parameters have been performed by using ground muons. In-flight checks of the detector alignment are also foreseen by means of cosmic-ray electrons, for which an independent measurement of the energy is provided by the calorimeter.

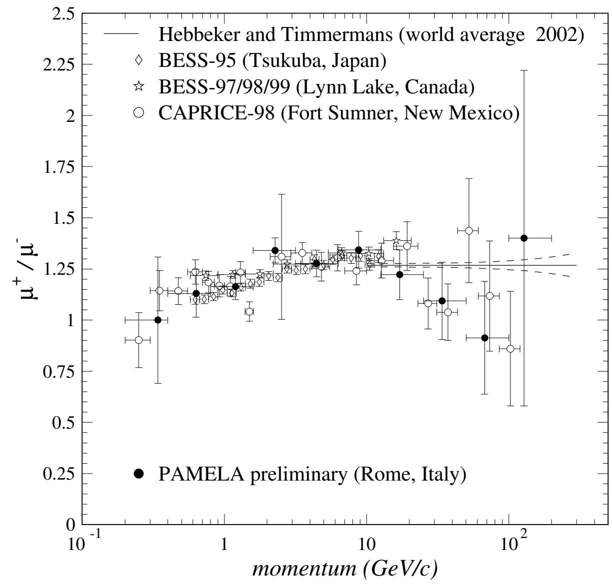

Figure 2. Preliminary result on the all-particle charge ratio measured by PAMELA during the ground test.

3.2 Track fitting

The Hough transform [10] has been adopted as track recognition method, which also provides the initial guess of track-candidate parameters. Hence track fitting is performed by means of an iterative procedure, based on the χ^2 minimization as a function of the track state-vector components, developed by Golden et al. [11].

The particle trajectory is calculated by stepwise integration of the equations of motion in a not-homogeneous magnetic field by means of the Runge-Kutta method. The magnetic-field components along the trajectory are evaluated by linear interpolation of the measured field map. The inner-map pitch (5 mm) ensures accurate determination of the trajectory in the whole tracking volume.

4. On-ground tests

The physically significant parameter resulting from the track fitting is the magnetic deflection η, defined as $\eta = 1/R$ where $R = pc/Ze$ is the particle magnetic rigidity. The deflection resolution is affected by multiple scattering at low energy and decreases for increasing energy up to a constant value σ_η^{he} , which is directly connected to the spatial resolution of the detectors. The performance of a spectrometer is generally expressed by means of the Maximum Detectable Rigidity ($MDR = 1/\sigma_\eta^{he}$), which is reached when the relative error in rigidity is 100%. Analysis of the beam-test data has shown that an MDR greater than 1 TeV can be achieved.

The last beam test of the flight model of the PAMELA spectrometer was carried out in 2003 at the CERN SPS. At this time PAMELA detectors were only partially integrated and both the power supply and the acquisition system were external. Nevertheless, the spectrometer was already in the final flight configuration and proton data could be used to perform first-order alignment of the silicon detectors (section 3.1).

Before delivering the apparatus to the Russian Space Agency, all the flight operative modes have been extensively tested with the fully assembled instrument. This provided a large sample of charged particles (mostly atmospheric muons) that could be used to check the performances of the detectors. In particular, an high-statistics clean sample of both positive and negative charged muons represents for the spectrometer a basic tool to check sistematics. Fig. 2 shows the all-particle charge ratio obtained from a subset of data, compared with some measurement of the muon charge ratio [12, 13, 14]. This result, even if preliminary, confirms the good performances expected from the spectrometer.

5. Conclusions

Studies of the magnetic spectrometer performances, by means of both particle beams and ground muons, have proved that the detector meets the requirements for the PAMELA mission. The analysis is still in progress and results will be presented during the conference time.

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