# The magnetic spectrometer of the PAMELA satellite experiment

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## Abstract

In this paper, we describe in detail the design and the construction of the magnetic spectrometer of the PAMELA experiment, that will be launched during 2003 to do a precise measurement of the energy spectra of the antimatter components in cosmic rays. This paper will mainly focus on the detailed description of the tracking system and on the solutions adopted to deal with the technical challenges that are required to build a very precise detector to be used in the hostile space environment.
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## 1. The PAMELA experiment

The PAMELA experiment [1,2] is devoted to the study of cosmic rays in the Earth's near orbit. It will be installed during 2003 on board of the Russian RESURS-DK1 satellite, to be launched from the Baikonour cosmodrome, in Kazakhstan. The main scientific objectives of the experiment are the precise measurements of the energy spectra of cosmic rays in a large energy range (from less than 100 MeV up to a few hundreds GeV), with high statistics (the average expected trigger rate is 12 Hz) and for a long period of time (at least 3 years). In particular, the experiment has been designed to identify with great sensitivity the antimatter components (mainly antiprotons and positrons). The central part of PAMELA is a magnetic spectrometer, consisting of a permanent magnet and silicon microstrip detectors, used to measure the rigidity, charge and charge sign of the cosmic rays; the system will be fully described in the following sections of this paper.

## 2. The permanent magnet

The magnetic system [3] of the spectrometer has been manufactured by using the permanent magnet technology, and it has been shaped in a

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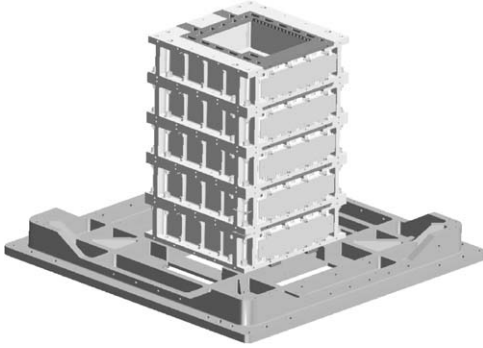E-mail address: adriani@fi.infn.it (O. Adriani).

Fig. 1. The magnet, consisting of five modules of an Nd–Fe–B alloy, assembled on the base plate.

tower structure, 44.5 cm high, obtained by assembling together five identical modules, as shown in Fig. 1. These modules form a rectangular cavity ($131 \times 161$ mm$^2$) which defines the geometrical factor (20.5 cm$^2$ sr) of the experiment. The magnet is made of an Nd–Fe–B alloy which has a residual magnetization of 1.3 T. The magnetic material has been assembled in such a way to give rise to an almost uniform magnetic field inside the cavity, with an average value of about 0.43 T. The field inside and outside the magnetic cavity has been precisely 3d-mapped by an automatic measuring machine, with a 5 mm step along the three axes. Six planes of silicon detectors are inserted inside the cavity, 8.9 cm apart each other, to allow a precise measurement of the momentum of the crossing particles.

## 3. The silicon tracker

Design and construction of this detector were particularly difficult, because several constraints, due mainly to the hostile space environment, had to be satisfied. Three problems have to be taken into account: (i) the radiation damage for electronics, (ii) the reliability of the system due to its inaccessibility during the flight and (iii) the mechanical strength. They can be explained in a bit more detail:

(i) The radiation level estimated for the orbit is about 1 krad/year and this is not dangerous for the detectors. Nevertheless, the presence of highly ionizing particles in cosmic rays can give rise to Single Event Effects (such as Upset and Latch-up) that are potentially dangerous for the readout electronics.

(ii) The reliability is a very critical issue for satellite experiments, because no human intervention is possible for the whole mission. Redundancies in all the boards are foreseen to overcome problems coming from failures of some component. In addition, the power consumption should be minimized, because of the stringent constraints imposed by the spacecraft: the total power for all PAMELA should be less than 350 W.

(iii) During the launch phase the rocket transmits to the apparatus a vibrational spectrum that could be dangerous for fragile devices such as silicon microstrip detectors. In fact, in order to build a detector as precise as possible in the reconstruction of the trajectories of the cosmic rays (a 3 μm spatial resolution in the bending view permits to extend the measurement of the rigidity up to about 740 GV/c) the amount of material along the particle trajectory, like supporting dead layers above or beneath the planes, should be minimized to reduce the effect of multiple scattering.

These conflicting requirements imposed a very careful design, supported by continuous tests during project and construction phases.

### 3.1. The silicon sensors

The basic spectrometer detection unit is a plane, $14 \times 16$ cm$^2$, inserted inside the magnetic cavity through a dedicated slit. Each plane is composed of six silicon sensors [4], each one $53.33 \times 70.00$ mm$^2$, 300 μm thick, produced by Hamamatsu. They are double sided, with implanted strips orthogonal to each other on the two sides. The implant strip pitch is 25 μm on the junction side, and 67 μm on the ohmic side, where $p$-stops are used to increase the interstrip resistance. The decoupling capacitors are integrated on the sensors on both sides, and a double metal layer is used on the ohmic side to bring the readout strips parallel to each other on the two sides. One

implanted strip out of two is connected to a preamplifier. The readout pitch is 50 μm, allowing a good matching with the readout chip pitch. The biasing mechanism is based on the punch-through effect on the junction side, which is used to measure the cosmic rays' deflection. On the ohmic side the bias is supplied through a polysilicon resistor ($\simeq 40$ MΩ). Two sensors are daisy chained in our detector and they are connected to an Aluminum Oxide double-sided hybrid circuit, that houses the VA1 [5] front-end chips; this basic structure is called ladder. A total of 1018 and 1024 strips are read out, respectively, on the junction and ohmic sides.

### 3.2. The mechanical structure

The project and the construction of the detector planes required a big R&D effort, because they should survive the vibration levels and shocks foreseen during the satellite launch phase. In particular, the whole apparatus will be subjected to a random vibration spectrum with an acceleration spectral power density of 7.4 g RMS (along $X$-, $Y$-, and $Z$-axis) on the interface between the PAMELA apparatus and the satellite, which corresponds to 11.1 g RMS in the positions of the planes. As a result of this R&D a planar structure with the highest possible first resonance frequency (above at least 300 Hz) is required [3]. In order to achieve this goal without insertion of additional material, a self supporting structure has been designed, stiff enough to survive all the foreseen shocks. The two sensors and the hybrid circuit that constitute the ladder are glued together head-to-head with epoxy glue Araldite AY103 and HY991 hardener. On the lateral side of each ladder we glued with the same epoxy two narrow stiffeners, 150 mm long, 5 mm high and 500 μm thick, made of carbon fibers with very high Young modulus (> 290 GPa), obtained with the pultrusion technique. Three ladders are then glued together to form a plane: four stiffeners are used in each plane (Fig. 2). The resulting detecting unit is inserted in a precisely machined aluminum frame, 7.95 mm thick, glued through the carbon fibre stiffeners; in two points the epoxy glue has been used, while in all the other points a silicone
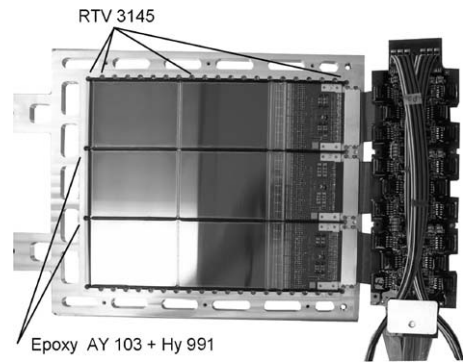


Fig. 2. One flight-model plane. On the right there are the ADC boards.
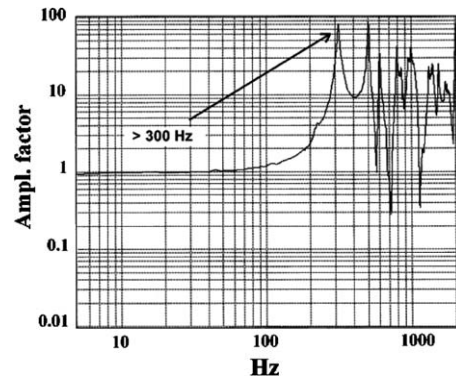


Fig. 3. The response acceleration spectrum measured for a flight-model plane.

glue (RTV3145) has been applied, to reduce the thermal stresses, due to the different thermal expansion coefficients of aluminum and silicon. Extensive vibration tests have been performed on many samples of this structure since it is very difficult to perform an analytical prediction of the resonance frequencies: in fact they depend mainly on the behaviour in the points of connections between the silicon plane and the aluminum frame. The first measured resonance frequency is about 340 Hz, as measured by an accelerometer placed in the centre of the plane during some vibration test sessions (see Fig. 3). The structure survived many repeated tests with a power spectral density up to two times greater (22.2 g RMS) than that expected during the launch phase.

### 3.3. The readout electronics

The choice of the electronics for the tracker design allows the best possible reconstruction of the impact point of the cosmic rays on the detection planes, hence maximizing the signal-to-noise ratio for Minimum Ionizing Particles. The front end chip (VA1) used to amplify the signals coming from the sensors has a particularly low equivalent noise charge: $230\ e^- + 13\ (e^-/pF) \cdot C_L$ for 1 μs shaping time, where $C_L$ is the total load capacitance, whose value is $\sim 20$ pF/channel for the junction side and $\sim 40$ pF/channel for the ohmic side. A total number of about 500 and 750 $e^-$, respectively, can be inferred. Since the power allocated for the tracker was limited to 100 W (45 W actually employable because of the inefficiencies of the various DC/DC converters and of the linear regulators) the VA1 with 1 mW/channel became the design choice for the readout electronics (with 288 VA1 chips, for a total of 36 864 channels). The hybrid circuits are connected to the electronics boards used to do the analog to digital conversion (ADC boards) by very short Kapton cables ($\simeq 5$ cm long), to reduce the noise pickup on the analog lines. The ADC boards are inserted on the lateral side of the magnet, and are connected to the DSP boards through LVDS serial lines. The DSP boards (power consumption: $\sim 5$ W) are based on 12 ADSP2187 processors, by Analog Devices: they are used to implement a very efficient compression algorithm which reduces to about 5% the data transmitted to the Earth, because of the limited (20 Gbyte/day) transmission bandwidth. We looked after the reliability of the system: all the power lines are protected against possible latch-ups, all the chips have been tested for total dose at 30 krad (about 10 times the dose expected in 3 years) and the modularity has been increased to reduce the effect of any possible failure.

### 4. Conclusions

The flight model of the PAMELA silicon tracker has already been completed, and it is now ready for the final integration on the satellite. The performances of the detectors have been measured in several beam tests: the signal-to-noise ratio for MIPs is greater than 50 on the $X$ bending view and about 25 on the $Y$ view, allowing a spatial resolution of about 3 μm [2] for $X$ coordinate. This resolution makes it possible to extend measurements of particles in cosmic rays up to 740 GV/c rigidity.

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