The Penetrating particle ANAlyzer (PAN) instrument

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Abstract— PAN is an instrument designed to precisely measure and monitor the flux, composition, and direction of highly penetrating particles (>100 MeV/nucleon) in deep space and interplanetary missions. The detector design is based on the well-known magnetic spectrometer detection principle, with novel layout and detection concept. In order to reach an energy resolution better than 10% for nuclei from H to Fe at 1 GeV/n, the spectrometer has been designed by dipole magnet sectors built from high field permanent magnet Halbach arrays, instrumented with high resolution silicon strip detectors. The particle charge will be determined by scintillating detectors and silicon strip detectors, with readout ASICs capable of large dynamic range. Silicon pixel detectors used in a low power setting will maintain the detection capabilities for high rate periods due to the strongest solar events. The fast scintillator system will be readout using SiPMs to determine the entering direction of the particle, provide timing information and perform high rate particle counts. The overall instrument will be limited to about 20 kg in mass and 20 W in power consumption. PAN will fill an observation gap of galactic cosmic rays in the GeV region, and provide precise information on the spectrum, composition and emission time of energetic particle originated from the Sun. The precise measurement and monitoring of the energetic particles are also a unique contribution to space weather studies.

Keywords — Cosmic rays; Space weather; Space radiation; Magnetic spectrometer; Silicon tracker

I. MEASUREMENT OF COSMIC RAYS IN DEEP SPACE

The flux of cosmic radiation is mainly composed by three components: particle trapped in the geomagnetic field, particles originating from the Sun (SEPs) and Galactic Cosmic Rays (GCRs), whose origin is of today still unknown. GCRs, which mainly consist of protons and helium nuclei, are the dominant component of cosmic rays with energies above 100 MeV. The understanding of their origin and propagation mechanisms requires the precise measurement of cosmic ray composition and flux intensity in a wide range of energies. However, while cosmic rays have been studied in great detail in Low Earth Orbit (LEO) by recent spectrometer missions like PAMELA and AMS-02, a precise measurement of the cosmic ray components in deep space between 100 MeV/n and 20 GeV/n is still missing. This highly penetrating component of cosmic rays represent a serious hazard for long term deep space travel, so a precise and long-term measurement of the spectra and composition of these particle are mandatory to study related health risks and develop adequate mitigations strategies. The Penetrating particle ANAlyzer (PAN) has been designed to measure the cosmic ray flux in deep space with unprecedented accuracy in terms of energy and charge resolution, and to distinguish positively and negatively charged particles to also provide precise information on the rare cosmic ray antimatter components. PAN will also monitor short and long-time variation in the fluxes to investigate the origin and properties of low energy cosmic rays as well as to provide important information for the scientific research in solar-terrestrial and space weather physics.

II. INSTRUMENT CONCEPT

PAN is particle detector based on a magnetic spectrometer with a novel layout conceived to optimize the detection for both high flux and low flux particles with limited mass budget (20 kg) and power consumption (20 W) for long time operations in deep space. It is designed to precisely measure the momentum, direction, charge and charge sign of GCRs and SEPs between 100 MeV/n and 20 GeV/n and to provide a measurement of the integral particle flux above 10 MeV/n. Figure 1 shows a conceptual drawing of the PAN instrument.

Figure 1. (a) Drawing of the baseline PAN instrument. (b) Exploded view showing the baffle, the TOF module coupled to the Pixel module, the tracker module and part of the magnet sector. (c) Exploded view of a tracker module showing the two StripX layers with the support frame, and the StripY layer.

PAN consists of a 44 cm long cylindrical magnetic spectrometer (MS) with 10 cm inner diameter segmented into 4 sectors, instrumented with 5 tracker modules and with a fast time-of-flight (TOF) detector coupled to a pixel detector at each end.

The dipole magnet sectors are built from Halbach arrays of high field NdFeB permanent magnets to produce an enclosed
and uniform magnetic field [1]. The chosen geometry allows to achieve a field uniformity of 5% around the nominal 0.2 T for a total weight of 8 kg.

Each tracker module is composed by two detectors (StripX) measuring the bending plane coordinate and one detector (StripY) measuring the non-bending coordinate. Fine pitch (25 µm) and thin (150 µm) silicon strip detectors will be used for the StripX detectors to minimize the amount of material budget crossed by the particles and consequently reduce Coulomb scattering effects to reach a position resolution of 2 µm using a floating strip charge sharing mechanism. Such resolution has not been yet achieved with 10 cm long strips, but is nowadays in reach. The total capacitance of each strip of 2-2.5 pF/cm is well suited for low noise readout ASICs. The large channel number (40'000) requires a power consumption of less than 0.2 mW/channel for a total maximum consumption of 8 W.

StripY sensors are instead designed with a larger pitch of 500 µm corresponding to a position resolution of 144 µm that provides an angular resolution of 0.12° that is above the requirements for PAN.

Plastic scintillator tiles with 3 mm thickness readout by four 3x3 mm² Silicon Photomultipliers per side provide the measurement of the particle time-of-flight (TOF) with a time resolution of 100 ps for a maximum nominal rate of 10 MHz to monitor the most intense solar particle bursts expected. SiPMs have never been operated in harsh space environment, and require a dedicated program of space qualification R&D. To improve the particle identification capabilities and suppress pileup effects, hybrid active silicon pixel detector based on the Timepix3 concept [2] will be equipped next to the TOF. Custom modifications to the digital data processing of the chip will be implemented to reduce the power consumption.

Differently from what applied in previous deep space missions, the classical \( \frac{dE}{dx} \) method for the measurement of the particle energy cannot be applied in the energy range investigated by PAN. An improved resolution is instead achieved by the measurement of the particle bending trajectory to infer its rigidity, hence its energy. Both the bending radius and bending angles are measured to increase the geometrical acceptance and improve the energy resolution of the spectrometer. The design of the spectrometer has been developed to maximize the energy resolution in a wide range: for high flux particles, event passing through the whole detector can be measured with the best energy resolution, while for low flux particles also event crossing less than 4 sectors can be analyzed to improve the statistical uncertainty of the measurement. With this approach the target requirement of a geometrical factor of 10 cm² sr with resolution of 20% (50%) for H (Fe) between 100 MeV/n and 20 GeV/n can be satisfied by events passing the 3 sectors. Even particles traversing only 1 segment can be used since the momentum can be measured by the bending angle method using the two StripX modules of each sector. Figure 2 shows the energy resolution as function of the energy achieved with the baseline PAN design.

The measurement of the particle charge \( Z \) is determined by the sampling of the particle \( \frac{dE}{dX} \), proportional to \( Z^2 \), in up to 17 layers of the detector. To achieve a large dynamic range to measure nuclei up to Fe (Z=26), PAN optimizes the readout of the TOF and StripY detectors for large \( Z \) measurements, and the Pixel and StripX detectors for low \( Z \) but high rate measurements. The readout ASICs will be designed to reach a dynamic range of 10⁵ while keeping the power consumption below the requirements set by the mission operation.

More details on the concepts, designs and possible technological breakthroughs for the PAN instrument will be discussed in this contribution.

III. Overview

From the technological point of view, the precise measurement of energetic particles in space is extremely challenging. The PAN instrument, based on a magnetic spectrometer with moderate mass and power consumption, has been designed to monitor with unprecedented precision cosmic rays in the 100 MeV/n – 20 GeV/n over a long period of time in solar and interplanetary missions. PAN will fill the actual observation gap of penetrating energetic particles in deep space, providing novel information and inputs to a cross- and multidisciplinary science program on cosmic ray physics, solar-terrestrial physics, circum-terrestrial and planetary space weather science and space travel.

REFERENCES