PROCEEDINGS OF SCIENCE

Penetrating particle ANalyzer (PAN)

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The Penetrating particle Analyzer (PAN) is a compact magnetic spectrometer with relatively low power budget allowing it to be used in deep space and interplanetary missions for cosmic rays, solar physics and space weather studies. It can precisely measure and monitor the flux, composition, and direction of highly penetrating particles in the range between 100 MeV/n and 10 GeV/n. The device consists of permanent magnet sections, silicon strip detectors, scintillating detectors and silicon pixel detectors. At the current stage of the R&D, the first smaller prototype, called Mini.PAN, was built. Mini.PAN is designed to demonstrate the capabilities and performance of the instrument concept. The key component of Mini.PAN is the fine-pitched and thin silicon strip detectors custom designed for measuring the bending of the charged particle in the spectrometer. These detectors are 150 μm thick layer with 25 μm readout to achieve a position resolution of a few μm and provide the optimal momentum resolution within the effective energy range.

In 2021 and 2022 several beam tests were performed at CERN with various types of particles and of different energies to demonstrate the quality and performance of different subdetectors as well as the integrated Mini.PAN. In this contribution the design of the demonstrator is described, and preliminary results from the beam tests are presented.

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1. Introduction

The Penetrating particle Analyzer (PAN) [1] is an innovative energetic particle detector designed for deep space applications. It aims to make groundbreaking measurements crucial for space sciences and interplanetary explorations. PAN is a lightweight instrument, weighing only 20 kg, with a low power consumption of 20 W, suitable for deployment on deep space and planetary missions like Lunar Orbital Platform-Gateway (LOP-G) [2], COMPASS [3] mission, and REMEC [4] mission.

PAN addresses the observational gap of energetic particles in deep space, aiming to provide precise measurements of flux, composition, and incoming direction of highly penetrating particles (100 MeV/n) over one full solar cycle.

The instrument consists of permanent magnet sections, silicon strip detectors (StripX and StripY), scintillating detectors (Time-of-Flight detector or ToF), and silicon pixel detectors (TimePix3 Quads).

PAN has several scientific objectives:

- Precise flux and composition measurements of Galactic Cosmic Rays (GCR).
- Monitoring the properties of GCRs over a full solar cycle.
- Measurement of Solar Energetic Particles (SEPs) during SEP events.
- Space environment monitoring outside Earth's magnetosphere.

PAN's innovative instrument concept enables groundbreaking measurements in cosmic ray physics, solar physics, space weather, and human space travel. Its precise measurements of GCRs and SEPs, along with continuous monitoring capabilities, enhance our understanding of the energetic particle environment in deep space. PAN has the potential to become a standard onboard instrument for deep space manned missions and provide crucial data for space weather forecasting and radiation protection strategies.

2. Mini.PAN – the demonstrator

PAN's modular structure is versatile, allowing for changes in the size of the spectrometer or the number of detectors inside the modules while maintaining the general concept and main functionality. To demonstrate the PAN technology, a prototype named Mini.PAN was constructed (see Fig. 1). Mini.PAN consists of two magnet sectors with smaller dimensions but incorporates the same instrumentation, including silicon strip detectors, plastic scintillators, and pixel detectors. The shorter length (5 cm) of the magnet sectors is compensated by a stronger magnetic field (0.4 T).

The current prototype (see Fig. 2) has a weight of approximately 10 kg and consumes around 14.5 W of power (excluding digital readout electronics). It is equipped with 6 StripX, 3 StripY, 2 pixel, and 2 Time-of-Flight (ToF) detectors. Two permanent magnet blocks are positioned between the outer tracking modules (2 StripX + 1 StripY). The design of Mini.PAN is symmetric, enabling the measurement of particles from either side. The complete dimensions of the prototype are 200 mm × 165 mm × 165 mm.

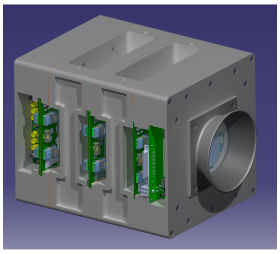

Figure 1: A render of Mini.PAN instrument.

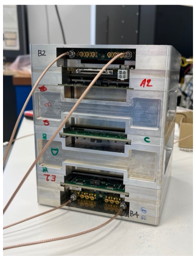

Figure 2: A real instrument produced by PAN collaboration.

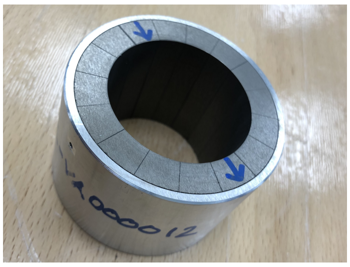

Figure 3: A top view of one of Mini.PAN magnets.

2.1 Magnets

The magnet sectors of Mini.PAN are made of 16-block Halbach arrays each. The inner diameter of each sector is 5 cm, the distance between the sectors is 12 mm, the weight of one magnet is 0.8 kg. The magnet blocks are made of high-grade NdFeB permanent magnets. The blocks are arranged in an Halbach array, which generates a dipolar magnetic field of 0.4 T inside the magnet bore with the main field component aligned along the Y coordinate (see Fig. 3). The incoming particles are bent in the XZ-plane, where the device measures the position with the highest accuracy.

The initial design, tests and field map measurements of the magnets were performed at the CERN Magnetic Measurements Lab by P. Thonet, C. Petrone, M. Liebsch, and G. Deferne.

2.2 Time-of-Flight detector

Two Time-of-Flight (ToF) modules are integrated at the ends of the Mini.PAN prototype. Each module comprises a plastic scintillator (EJ-230) measuring 65 mm × 65 mm × 6 mm, which is covered with 3M Vikuiti reflecting film. Around the perimeter of the scintillator, 12 Hamamatsu HPK-S13360 SiPMs are positioned: 4 of the 6050 type, 2 of the 6075 type, 2 of the 6025 type, and 4 of the 1325 type. The signals from the SiPM arrays are read and digitized by Citiroc and Triroc ASICs. Citiroc generates the trigger signal for the rest of the system and provides digital data for calculating the ionization energy of incoming particles. Additionally, the Triroc ASIC furnishes the required timing information for the functioning of the two modules as a Time-of-Flight detector. By combining the Citiroc and Triroc ASICs on the same front-end board, a comprehensive readout system is achieved, offering precise charge measurement, accurate timing, triggering capabilities, and coincidence detection. The front-end board is connected to a GPIO [5] board developed at the University of Geneva, which handles data management and transfer to a PC, as well as managing the output trigger signal and input busy signal from other subsystems.

2.3 Pixel detectors

Pixel detectors are positioned between the ToF modules and tracker modules on both sides of the Mini.PAN prototype. Each detector is equipped with a Timepix3 Quad sensor, with a thickness of 300 μm, a pixel pitch of 55 μm, and a total size of 28 mm × 28 mm, resulting in a total of 262,144 pixels. The Timepix3 ASIC enables simultaneous time of arrival (ToA) and time over threshold (ToT) measurements of the analog signal, as well as precise position measurements of incoming

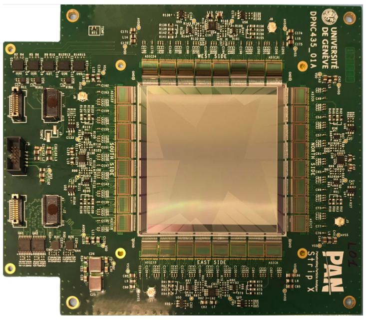

Figure 4: StripX detector.

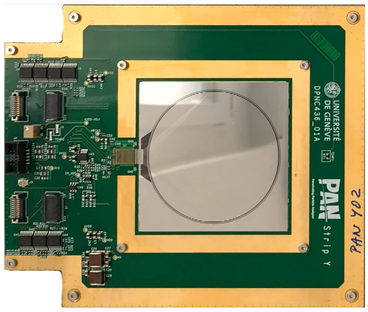

Figure 5: StripY detector.

particles. The data readout is performed using the Katherine [6] system, developed at the Czech Technical University in Prague.

2.4 Strip detectors

Mini.PAN is equipped with three tracker modules. Two modules are positioned between the magnet sectors and pixel detectors, while one module is located in the middle of Mini.PAN between the two magnet sectors. Each module consists of 2 StripX detectors and 1 StripY detector. The tracking detectors are arranged in the following configuration: YXX – Magnet – XYX – Magnet – XXY. This arrangement minimizes the material between two consecutive X-layers, which are used for measuring the momentum of incoming charged particles. In the middle module, the Y-layer is placed between the two X-layers to minimize the gap between magnets (12 mm). Every Y-layer provides an extra position measurement helping with the alignment of Mini.PAN.

The StripX (see Fig. 4) detector features a 150 μm silicon sensor with a 25 μm strip pitch, totaling 2048 strips. The signals from all the strips are readout using 32 IDEAS IDE1140 ASICs, which utilize the double metal layer on the sensor for analog signal routing. The active area of the sensor is 5 cm $\times$ 5 cm.

The StripY (see Fig. 5) detector is equipped with a 150 μm silicon sensor with 128 strips, resulting in a pitch width of 400 μm. The readout of all the strips is performed by a single IDEAS VATAGP7.2 ASIC. The active area of the sensor is a disk with a diameter of 5 cm. Both sensors are manufactured by Hamamatsu.

The analog signals from the sensors are digitized at the front-end boards and then transmitted in digital form to the UNIGE GPIO boards (one per tracking module) through custom-designed adapters. The GPIO boards handle the data flow to the PC and the delivery of trigger signals to the front-end boards. The VATAGP7.2 ASIC used for reading out the StripY sensor has the capability to generate a trigger signal when an incoming particle penetrates the sensor. By combining the triggers from the Triroc and VATAGP7.2 ASICs, the directions of the incoming particles passing through the Mini.PAN instrument can be distinguished.

3. Performance of Mini.PAN

The main objective of Mini.PAN R&D is to achieve the modeled and simulated performance in practice (see Fig. 6). Adapting and improving the existing technology is crucial to meet the

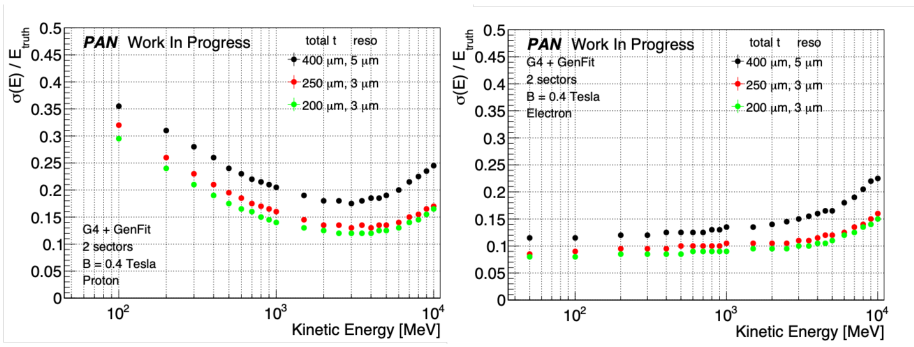

Figure 6: Geant4 simulation of the energy resolution of Mini.PAN for protons and electrons.

constraints defined by the PAN concept, especially regarding weight and power consumption limits.

The Timepix3 Quad pixel detectors used in Mini.PAN are known to operate at relatively high temperatures (75-85°C in air) and consume a fair amount of power (≈6 W) under nominal operating conditions. To minimize the analog readout part's power consumption, a power mode study [7] was conducted. The results depicted in Fig. 7 demonstrate that the readout can function at approximately 4 W of power without significant performance loss. This optimization also helps lower the chip temperatures to 50-60°C, and there was even a suggestion for a lower power mode at 2.4 W.

Ensuring the position resolution and charge separation requirements are vital steps in achieving the performance goals of Mini.PAN. The StripX detectors offer the finest pitch (25 μm) and, therefore, provide the best position resolution in horizontal dimension. Hence, a high quality of detector production is required. The manufacturing technology for the StripX detectors has been continuously improving during the R&D process. The first prototype of a StripX detector had approximately 1.5% of noisy channels, while the latest ones manufactured have 0-0.05% of noisy channels. The complete noise performance is shown in Fig. 8. Optimal gain and dynamic range of the analog readout are required to ensure the best possible charge separation for ions. Time-of-Flight (ToF) provides excellent charge separation. According to preliminary analysis results it is capable of separating up to $Z = 21$ (see Fig. 9), while StripX can separate up to $Z = 17$ (see Fig. 10).

High-quality StripX detectors, accurate spacepoint reconstruction by pixel detectors, and precise positioning of detectors inside the supporting structure are crucial factors for successfully aligning the device with incoming particles. The quality of the track-based alignment is critical

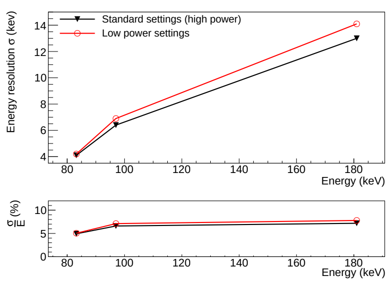

Figure 7: Energy resolution in the pixel detector for two power modes.

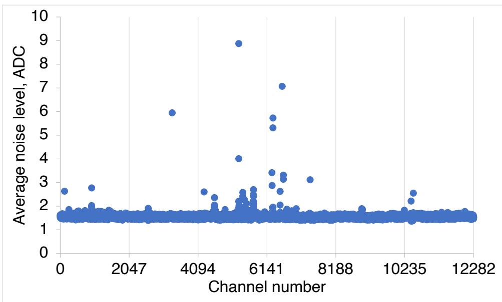

Figure 8: Noise levels across all channels of StripX detectors. Common noise is subtracted.

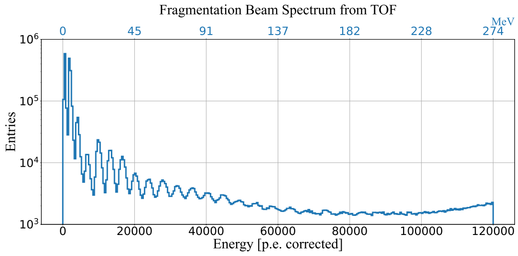

Figure 9: Energy spectrum of the fragmented ion beam (by ToF). Fragmented ions beam in November 2022 at SPS (CERN).

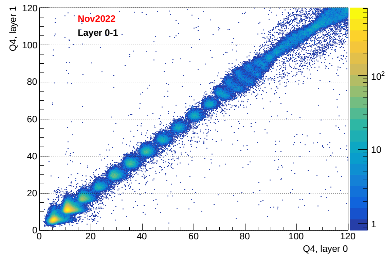

Figure 10: Correlation between square root of the sum of ADC values in 4-strip clusters (Q4) in StripX Layer 0 and 1. November 2022 (CERN).

for estimating the position resolution of Mini.PAN. Three beam tests were conducted at CERN in 2022-2023 to estimate the instrument's position resolution. The removal of magnets during these tests eliminated the effect of charged particle track bending. Data taking was synchronized between the strip and pixel detectors to ensure the most accurate trajectory reconstruction. Each detector has 6 alignment correction parameters that reflect their translations and rotations (the corrections are assumed to be smaller than 1-2% of the corresponding dimension of Mini.PAN). Alignment is performed iteratively using the gradient descent method to minimize the global χ^2 of reconstructed tracks in the XZ and YZ planes. The unbiased residuals per tracking layer after the alignment procedure are shown in Fig. 11. The residuals exhibit a double Gaussian shape due to the contribution of single strip clusters and particles passing between two consecutive strips. The core of the narrower Gaussian is considered for position resolution calculation. The Fig. 11 clearly illustrates that the residual width is smaller for the internal layers of Mini.PAN compared to the external ones, indicating lower track extrapolation errors in the internal layers.

The angular dependence of residual widths and the contribution from multiple Coulomb scattering (MCS) were also studied. The effects of MCS were estimated by considering the amount of material passed by particles inside the Mini.PAN spectrometer. It was observed that the MCS contribution for the internal layers of Mini.PAN varies between 0.3-0.4 μm for a 180 GeV/c positive pion beam and between 2.8-3.4 μm for a 15 GeV/c proton beam, depending on the incident angle

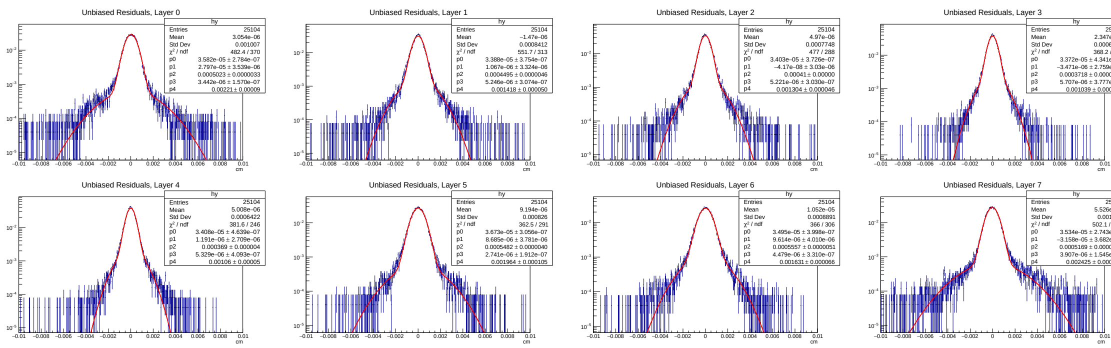

Figure 11: Unbiased residuals per tracking layer in Mini.PAN. Layers 0 and 7 are pixel detectors, Layers 1 – 6 are StripX detectors. 180 GeV/c π^+ beam, August 2022 (CERN).

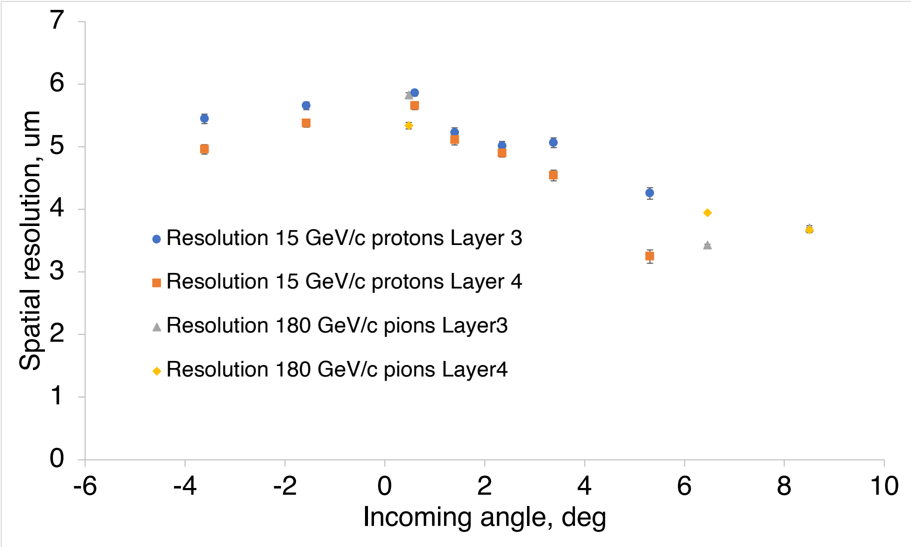

Figure 12: Spatial resolution depending on the incoming angle of the particles. Data from two beamtests is shown: August 2022 at SPS and April 2023 at PS (CERN).

of the particle with respect to Mini.PAN. The MCS contribution is subtracted from the core of the Gaussian in Layer 3 and 4 ($\sigma_{p.res.} = \sqrt{\sigma_1^2 - \sigma_{MCS}^2}$), and the obtained values are considered as estimations of the position resolution due to the smallest effects of track extrapolation errors in those layers. The dependency of the position resolution on the incident angle of particles is shown in Fig. 12.

Momentum resolution studies are still ongoing. The calculation of momentum resolution depends on the quality of alignment of curved tracks due to the effect of the magnetic field. An alignment algorithm for curved tracks is under development, which will be based on using the tools of Millepede II [8] and Genfit 2 [9] software packages.

4. Space qualification of the demonstrator

One important aspect of the Mini.PAN development has been the vibration and shock tests conducted on mechanical grade versions of the detectors, performed at the space qualification facility in Terni, Italy. The tracker testing has been completed successfully, while the pixel and time-of-flight (TOF) detector tests are scheduled to take place in August 2023. Another significant test that has been carried out is the magnet vibration test, which revealed a need for improvement in magnet fixation. As a result, a new iteration of the test is planned for August 2023. Additionally, thermal tests of the detector modules are scheduled for September 2023, and a possible thermal vacuum test may be conducted later in 2023.

5. Conclusions

The detector has reached completion, undergoing extensive testing over the past two years that has demonstrated its excellent performance, specifically in position resolution reaching 3.43 ±

0.02 μm and ion identification (up to $Z = 21$ by ToF and $Z = 17$ for StripX). The work on momentum resolution estimation is ongoing. The current success of the detector has led to additional beam tests being planned at CERN, and potentially TIFPA. Furthermore, vibration and thermal tests are scheduled for the second half of 2023 to ensure the detector's durability and stability. The proposed concept for different projects has gained traction, since it was adopted in several mission proposals: REMEC, COMPASS, and LOP-G [2–4]. These developments emphasize the continuous efforts to enhance the detector's functionality and expand its applications in scientific research.

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