PROCEEDINGS OF SCIENCE

Penetrating Particle Analyzer (PAN)

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Penetrating particle Analyzer (PAN) is a compact magnetic spectrometer with relatively low power budget designed to be used in deep space and interplanetary missions for cosmic rays, solar physics, space weather studies. It can precisely measure and monitor the flux, composition, and direction of highly penetrating particles in the range between 100 MeV/nucleon and 10 GeV/nucleon.
The device consists of permanent magnet sections, silicon strip detectors, scintillating detectors and silicon pixel detectors. At the current stage of the R&D, a first 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 have a thickness of 150 μm, with a readout pitch of 25 μm, designed 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.

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1. Introduction

The Penetrating Particle Analyzer (PAN) is a compact magnetic spectrometer conceived for interplanetary and deep-space missions [1]. Its main goal is the precise measurement and monitoring of flux, composition, and direction of highly penetrating particles ($>$ 100 MeV/n), to overcome several limitations for the measurements that previous instruments could perform.

For example, it only possible to extrapolate Low Earth Orbit (LEO) measurements (e.g. PAMELA, AMS-02) to deep-space, while measurements across and outside the heliosphere have only been performed in a different energy range, usually below 100 and 500 MeV/n (e.g. ACE and Voyager, respectively). PAN is designed to fill this gap, performing measurements over at least one solar cycle (11 years) needed for different science goals:

Cosmic ray physics measurements performed by PAN can help with the understanding of the origin of Galactic Cosmic Rays (GCR) and Antimatter searches

Solar physics measurements will be able to provide precise information on solar energetic particles

Space weather improvement of space weather models from the energetic particle perspective

Planetary science clearer picture of the radiation environment of a planet/moon, in particular as a potential future habitat

Deep space travel as an on-board instrument suitable for radiation monitoring

2. The PAN instrument

The PAN concept is driven by two core principles: firstly, it focuses on minimizing detector thickness, thereby reducing the material in the path of particles; secondly, it ensures high-rate capability, addressing the need for efficient particle detection and analysis.

A fundamental aspect of the PAN concept involves enhancing the geometrical acceptance and energy resolution compared to previous experiments, achieved through the instrument symmetry.

The 44-cm-long cylindrical magnetic spectrometer (figure 1a) presents Time-Of-Flight (TOF) and Pixel detectors at the two entrances and includes four sectors of Halbach permanent magnets, instrumented with five tracker modules (figure 1b). Each tracker module consists of three layers of detectors — two StripX and one StripY. Each magnet section is 10 cm long, 10 cm diameter, with a dipole magnetic field of ≈ 0.2 T.

PAN is able to measure particle trajectory, time of arrival, and time of flight using multiple detectors, enabling the discrimination of particle type and charge. The concept is characterized by robustness and modularity, incorporating high redundancy across all measurements to enhance entrance acceptance angles.

The modular design not only improves acceptance (given the symmetry from the two sides) but also potentially extends the instrument's lifetime, as instrumentation modules are mechanically independent from the magnets and can be easily exchanged. The power and mass budgets for the instrument are 20 W and 20 kg, respectively.

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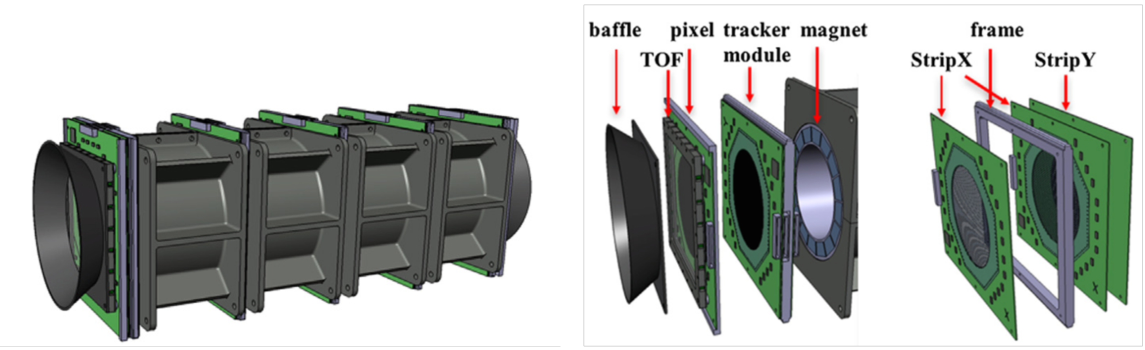


(a) 3D rendering of the PAN detector

(b) Exploded view of the detectors inside PAN

Figure 1: The Penetrating Particle Analyzer

3. The Mini.PAN demonstrator

The Mini.PAN detector is a smaller scale demonstrator for PAN technology. Exploiting the modular design of PAN, it is composed of two sectors with smaller dimensions with the same instrumentation.

It weighs approximately 10 kg and consumes around 14.5 W of power excluding digital readout electronics. Each magnet has an inner diameter of 5 cm and is 5-cm long, for a total weight of 0.8 kg. The magnets are a 16-block Halbach array and each block is made of high-grade NdFeB permanent magnets, for final magnetic field of $\approx$ 0.4 T.

Mini.PAN design is symmetric, enabling the measurement of particles from either side and uses the same instrumentation of PAN.

3.1 Time Of Flight

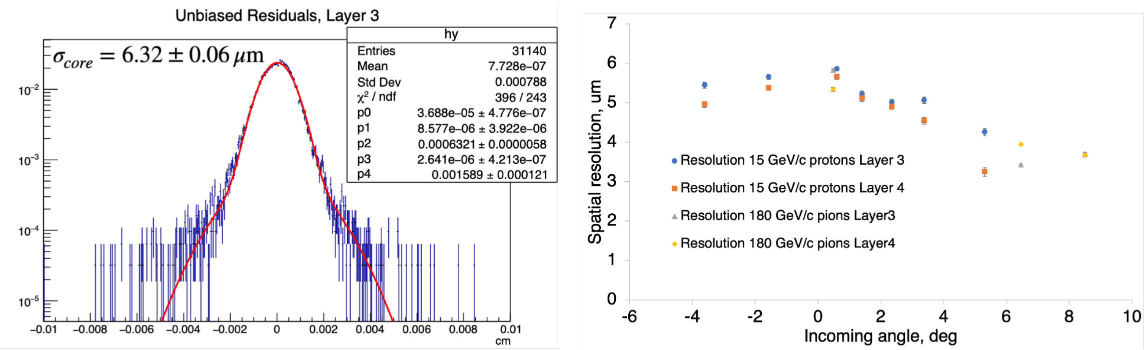
Positioned at the ends of Mini.PAN, the ToF detector is made of fast response scintillator with SiPM readout around the perimeter. The readout is performed with two ASICs: Triroc (used for time measurements, charge ID and trigger) and Citiroc (used for redundant charge ID and trigger).

3.2 Pixel

Positioned between TOF and TRACKER modules at the ends of Mini.PAN, it is equipped with Timepix3 quad detectors of 262'144 pixels, with pixel pitch 55 μm (2.8×2.8 cm^2 active area), and provides an accurate measurement of the particle position entering the magnetic spectrometer. Simultaneous time of arrival (ToA) and time over threshold (ToT) measurement can be performed by each pixel to help with particle identification. The sensor thickness is 300 μm and ToA binning is down to 1.56 ns. It is used in low power mode (4 W instead of 6 W) with no significant performance loss [2]. An even lower power mode (2.4 W) is currently under study, which is expected to give an appreciable loss mostly on the timing performance, while mantaining good tracking resolution.

3.3 Tracker module

The goal of the tracker modules is to achieve accurate position measurements, with the additional feature of triggering capabilities and particle identification. As the magnets generate a



(a) Unbiased residuals for one of the StripX detector **(b)** Spatial resolution as a function of the impact angle

Figure 2: Tracker performance

uniform magnetic field along the y-axis, the system requires precise measurements along the x-axis and more relaxed along the y-axis. Consequently, the configuration includes two detectors for precise measurements along the x-axis (StripX) and one detector for the y-axis (StripY). All the sensors are produced by Hamamatsu.

3.3.1 StripX

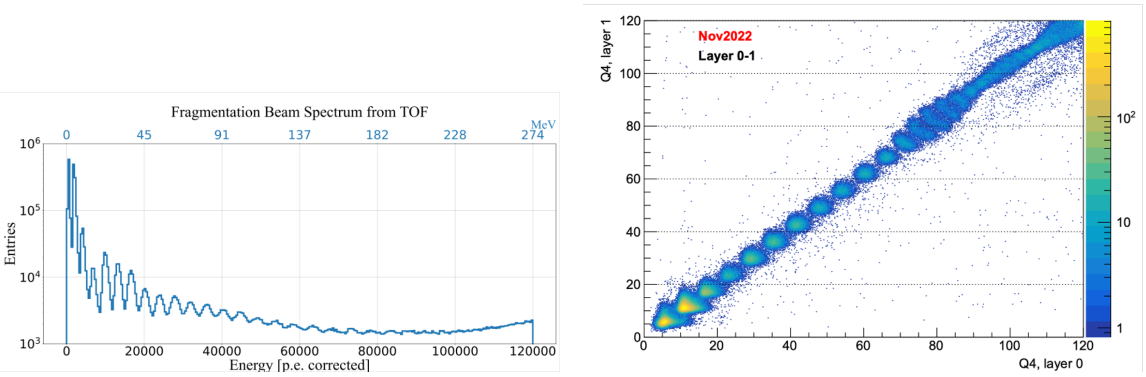
The detector is made of a 150 μm thick silicon strip detector with dimensions of $X \times X$ cm^2 and an active area of 5×5 cm^2. It has 2048 strips with a 25 μm pitch, all read out by 32 IDEAS IDE1140 ASICs. A double metal layer is used to route the signals off the sensor.

3.3.2 StripY

The detector is made of a 150 μm thick silicon strip detector. The silicon detector has dimensions of $X \times X$ cm^2, with a circular active area of 5 cm diameter to cover the circular acceptance of the magnets. It has 128 strips with a 400 μm pitch, read out by one IDEAS VATA GP 7.2 ASIC, which also provides trigger signal generation capabilities.

4. Performance

The Mini.PAN demonstrator has been tested at several beam tests at CERN in 2022 and 2023. Position resolution measurements have been performed with runs w/o magnets using 15 GeV/c positive hadrons. The tracks are reconstructed with combining data from both Strip-X and Pixels. Figure 2 shows an example of the computed spatial resolution values after the iterative alignement method (to minimize the global χ^2 of the reconstructed tracks in the XZ and YZ planes) and evaluation of Multiple Coulomb Scattering and track error extrapolation effects. Dedicated runs for different incident particle angles have been performed, and position resolution is estimated from the unbiased residuals distributions of the central layers, to reduce the track extrapolation errors (fig. 2b). Finally, figure 3 shows the reconstructed charge peaks for the ToF (3a) detector and the StripX tracker detector (3b). Momentum resolution is currently under study.



(a) Charge reconstructed by ToF **(b)** Charge correlation for two Strip X modules

Figure 3: Charge reconstruction performance

5. Conclusions

The Penetrating particle Analyzer (PAN) is a low power and compact magnetic spectrometer that can be used in deep space and interplanetary missions for cosmic rays, solar physics, space weather studies. The Mini.PAN demonstrator construction has reached completion and extensive testing over the past two years has demonstrated its excellent performance.

The demonstrator is able to achieve a position resolution under 6 μm (down to $3.43 \pm 0.02\mu$m for the central layers with incoming particles entering with an angle), using the information of both pixel and silicon strip tracker, and ion identification up to $Z = 21$ by its Time Of Flight detector and $Z = 17$ by StripX. The work on momentum resolution estimation is ongoing, with additional beam tests being planned at CERN, and potentially TIFPA (Trento Institute for Fundamental Physics and Applications) accelerator in Trento.

A series of vibration and thermal tests have been performed, with more scheduled for the second half of 2023. The Mini.PAN concept excellent performance has led to its adoption in several mission proposals like REMEC [3], Pix.PAN [4], and LOP-G [5] (Lunar Orbital Platform-Gateway).

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