PROCEEDINGS OF SCIENCE

A pixel based tracker for the HEPD-02 detector

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Tracking detectors serve as the foundational technology for a diverse array of instruments designed to measure particles in space, significantly enhancing our understanding of the Universe, as seen through projects like PAMELA, AMS-02, and Fermi. These experiments have relied on silicon microstrips as tracking detectors due to their established reliability, stability, and exceptional performance.
Looking ahead to the design of upcoming missions such as AMS-100 or ALADINO, which involve detectors spanning tens of square meters and requiring sub-micrometer spatial resolution, the scientific community seeks solutions to mitigate noise, streamline readout systems, and bolster track reconstruction capabilities. A near-optimal solution emerging as a standard in particle physics experiments at accelerators and adaptable for space applications is pixel detectors.
The HEPD-02 detector has proven to be an ideal benchmark for a novel approach based on Monolithic Active Pixel Sensors. While sharing the same scientific and technical requirements as previous experiments, HEPD-02 covers a smaller surface area. This contribution outlines the technical challenges tackled by the team that constructed the HEPD-02 tracker, along with the solutions implemented. Additionally, the detector's characterization with electrons and hadrons demonstrates the excellent performance of this new design.

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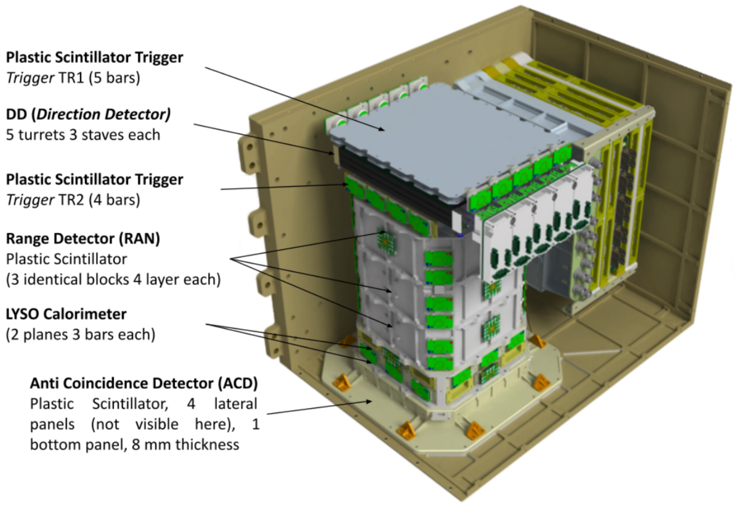


Figure 1: HEPD-02 detector structure

1. CSES mission

The China Seismo-Electromagnetic Satellite (CSES) space program is designed to investigate phenomena occurring in the higher layers of the ionosphere, with a focus on measuring electromagnetic fields and waves, plasma, particles, and their perturbations. The data collected by the scientific payloads of the satellite are used to study the interactions between the atmosphere, ionosphere, and magnetosphere, generated by natural sources or human activities [1].

The Italian Limadou collaboration realized the High Energy Particle Detector (HEPD-01) for the CSES-01 satellite, launched in February 2018, as well as the HEPD-02 and the Electric Field Detector (EFD-02) for the CSES-02 satellite, whose launch is scheduled for early 2024.

2. HEPD-02 detector

The design of the HEPD-02 detector, shown in Figure 1, builds upon the experience gained from the HEPD-01 detector, which is described in [1] and [2]. The HEPD-02 features some improvements aimed at addressing minor issues that emerged during its now 5-year-long operations and incorporates a fully redesigned tracking system. The scientific requirements for HEPD-02 are listed in Table 1.

The structure of the HEPD-02 detector can be divided into the following sub-detectors:

- A particle tracker, described in detail in the next section;
- Two trigger layers made of plastic scintillator bars;
- A range detector made of plastic scintillator tiles;
- A calorimeter made of LYSO bars;
- A containment system made of plastic scintillator.

Kin. energy range (e-)	3 MeV to 100 MeV
Kin. energy range (p)	30 to 200 MeV
Angular resolution	$\leq$ 10° for E_{kin} > 3 MeV (e-)
Energy resolution	$\leq$ 10% for E_{kin} > 5 MeV (e-)
PID efficiency	90%
Detectable flux	up to 10^7 $m^{-2}s^{-1}sr^{-1}$
Op. temperature	-10°C to 35°C
Op. pressure	$\leq 6.65\cdot10^{-3}$ Pa
Mass budget	50 kg
Power budget	45 W
Data budget	$\leq$ 100 Gb/day

Table 1: HEPD-02 system requirements.

The main differences between the HEPD-01 and HEPD-02 detectors, aside from the tracker, are the trigger system and the LYSO calorimeter. The HEPD-01 has only one trigger layer between the tracker and the range detector, whereas the HEPD-02 features two trigger layers: the first is located on top of the detector, before the tracker, and the second is positioned between the tracker and the range detector. The LYSO calorimeter of HEPD-01 consists of an array of 9 LYSO cubes, with a total volume of 15×15×4 cm^3. On the other hand, the HEPD-02 calorimeter is composed of two layers of LYSO bars and has a total volume of 15×15×5 cm^3.

At the time of writing, the HEPD-02 is qualified and tested, and it is ready for shipment to the satellite integration site.

3. HEPD-02 tracker

The HEPD-02 detector is the first experiment to use a pixel detector for tracking particles in space. While pixel detectors are now well-established for ground-based experiments, they were considered relatively new for space applications. They can be realized with hybrid or integrated readout technologies. The former technology is already in use for several applications since some decades. The latter, mostly known as Monolithic Active Pixel Sensors (MAPS), is currently at the forefront of research in the field, and its application is spreading due to the simplicity of integration and use, as well as their low thickness and low cost compared to other solutions, such as silicon microstrip detectors.

3.1 Design constraints

To successfully use MAPS in space, few solutions can be inherited from silicon microstrip detectors. In-pixel readout and relatively high power consumption made it necessary to design the tracker system from scratch. The most important critical points that were identified and addressed during the development are the following:

- Power consumption reduction
- Temperature control

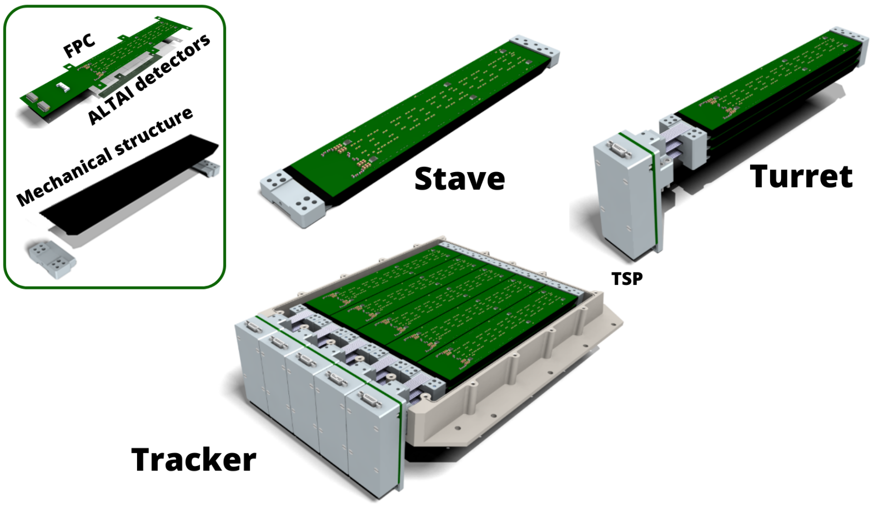


Figure 2: Exploded structure of HEPD-02 tracker.

- Mechanical stability
- Material budget minimisation.

3.2 HEPD-02 tracker structure

The HEPD-02 tracker is realized using the ALTAI detector, a branch of one of the most diffuse MAPS technologies currently available, the ALPIDE detector [3]. To fulfill the requirements for use in space, the power consumption has been reduced from the nominal 20 mW/cm^2 [3] (in the master/slave configuration used for ALICE ITS2 outer barrel) to less than 10 mW/cm^2 by using a control line driven by the 40 MHz clock for data readout, and distributing the clock only to the sections of the detector involved in the event. This solution was possible thanks to the low occupancy expected on the tracker during data-taking and the hold time of ALTAI pixel's front-end preamplifier.

Yet reduced from nominal value, power dissipation in silicon heats up the sensors, increasing the operating temperature, deteriorating the performance and accelerating the aging. To efficiently drain the heat towards the payload base plate, the mechanics of the modules have been designed to maximize thermal conductivity. The same structure that ensures thermal control also provides mechanical support, yet minimizing the thickness of materials crossed by particles.

The tracker structure is shown in Figure 2. It consists of five modules, named turrets. Turrets are composed of three sensitive layers called staves and a splitting board (TSP) that routes the power supply and the data lines to the dedicated boards.

Each stave hosts 10 ALTAI detectors, organized in two columns of five. Each column is composed of a master sensor and four slave sensors. The master collects all the data from the other four sensors on the line and sends it to the dedicated acquisition board (TDAQ). The sensors are glued and wire-bonded to a Flexible Printed Circuit (FPC) that distributes power and clock signals and collects the readout. A mechanical structure made of CFRP and aluminum provides temperature control and mechanical stability.

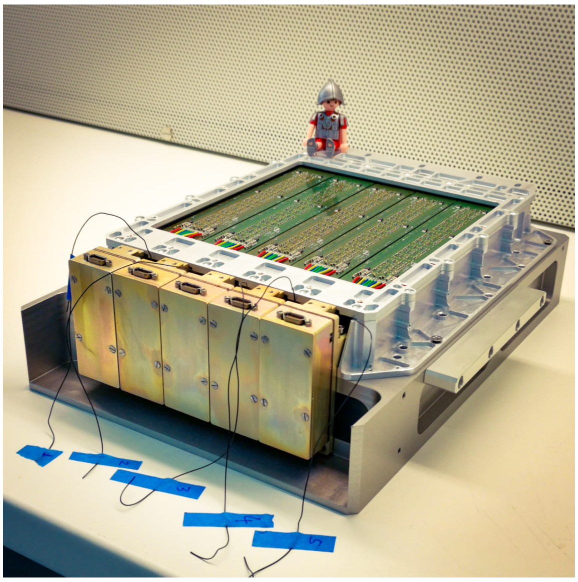


Figure 3: HEPD-02 tracker after a test of dry assembly.

Pressure [Pa]	$<6.66\times10^{-3}$
Hot temperature at fixture [°C]	50
Cold temperature at fixture [°C]	-30
Number of cycles	6.5
Temperature rate change [°C/min]	≥ 1

Table 2: Thermal vacuum test conditions.

A picture of the HEPD-02 tracker taken before the final assembly and integration on the HEPD-02 detector is shown in Figure 3.

3.3 Tracker qualification

The HEPD-02 tracker turrets have been qualified for use in space with a dedicated test campaign carried out on a prototype. The prototype underwent vibration tests, thermal vacuum tests, and thermal cycles. The conditions applied during the tests are the same as those foreseen for the qualification of the HEPD-02 qualification model (QM).

During the vibration test, sinusoidal profiles ranging from 0 Hz to 200 Hz at 12G and random profiles with an RMS of 11.3G were applied along all three axes. Resonance search within the 0 to 2 kHz range before and after each test showed the first resonance line at approximately 800 Hz, meeting requirements (no resonances below 100 Hz). The spectrum displayed no discrepancies before and after stress application, indicating preserved detection performance stability. The thermal vacuum test, with conditions detailed in Table 2, was successfully applied to the prototype. Performance monitoring during hot and cold phases showed behaviour consistent with expectations. The device functionalities and performance remained consistent with prior data. The Qualification Model (QM) of HEPD-02 was subbject to 26 thermal cycles with the conditions reported in Table 2 and no pressure requirements. Functional stability and performance remained nominal all along the test.

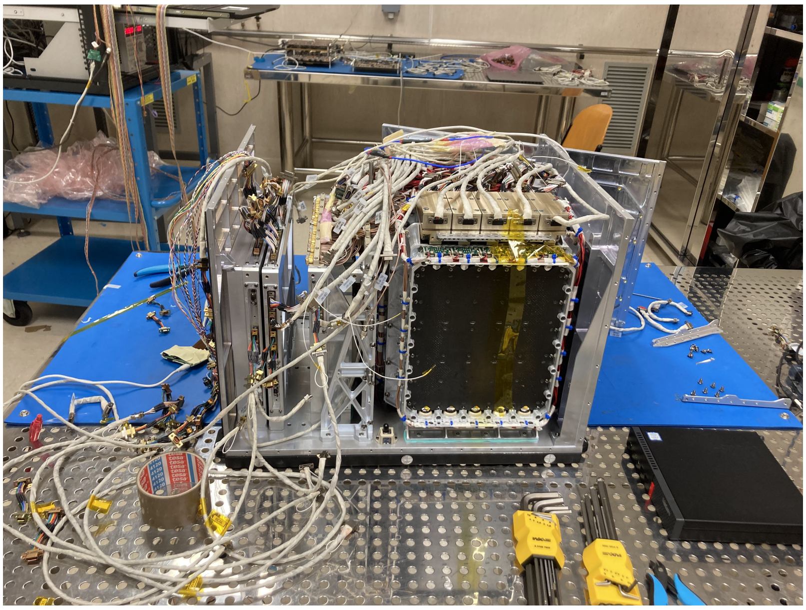


Figure 4: HEPD-02 detector during the integration. The only visible part of the tracker is the TSPs (the golden boxes on top of the detector on the right).

At the end of the test, the prototype reached a Technology Readiness Level of 7.

3.4 Integration

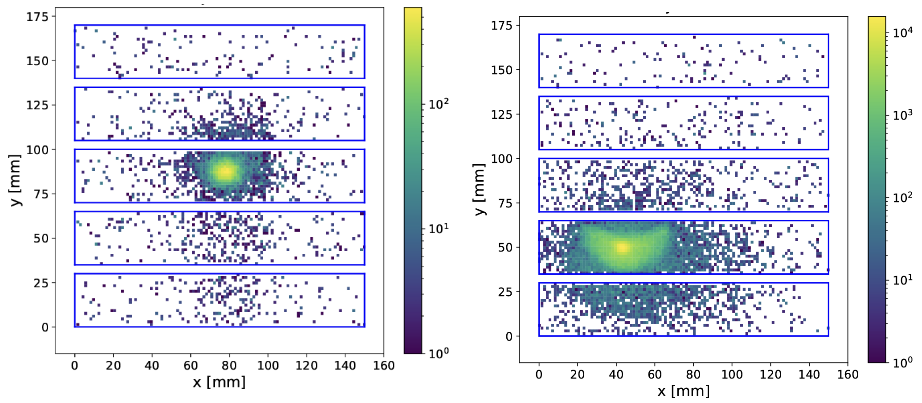
Within the HEPD-02 project, 46 fully functional staves were produced, and 11 turrets were assembled. The first one is considered an Engineering Model (EM) level, and 10 are Qualification/Flight Model levels. The five best-quality turrets were used for Flight Model (FM), and the other five were used for Qualification Model (QM). Staves have been integrated inside the INFN laboratories in Torino, while turrets were integrated inside the clean room of Trento Institute for Fundamental Physics and Applications (TIFPA).

Both the QM and FM trackers were built and integrated on the HEPD-02 at the beginning of September 2022 inside the clean room of the Tor Vergata University in Rome. Figure 4 shows the detector during the integration. The integration was completed in December 2022 for QM and in March 2023 for FM. The assembled detectors were then qualified for flight using the same test sequence described above, and their responses were characterized with cosmic muons and particle beams.

4. Tracker performance

Between June and July 2023, the HEPD-02 FM has undergone testing with different particles at various facilities to characterize its response across its entire operational range. The primary focus was on electrons and protons, but the collaboration also assessed its response to heavy nuclei and photons. The explored ranges are as follows:

- Electrons, 6-12 MeV, tested at the Medical Linac, S. Chiara Hospital, Trento (Italy);



(a) 450 MeV electrons. **(b)** 400 MeV/amu carbon ions.

Figure 5: Stacked view of test particles at beam facilities. Pixels were grouped to reduce the image size. Color scale used to indicate the number of times each pixel group was fired.

- Electrons, 30-450 MeV, tested at the Beam Test Facility (BTF), Laboratori Nazionali di Frascati, Frascati (Italy);
- Protons, 30-230 MeV, tested at the Trento Proton Therapy Center, Trento (Italy);
- Photons, (bremsstrahlung from 4-10 MeV electrons), tested at the Medical Linac, S. Chiara Hospital, Trento (Italy);
- Carbon ions, 115-400 MeV/amu, tested at the Centro Nazionale di Adroterapia Oncologica (CNAO), Pavia (Italy).

Ongoing data analysis targets the complete characterization of HEPD-02 before launch.

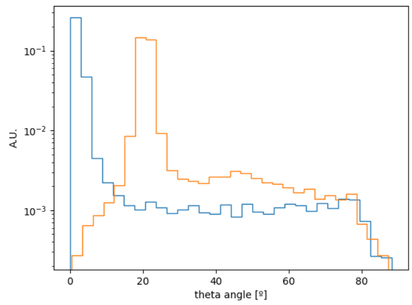
4.1 Beam quality monitor

Figure 5 shows the beam profile for different particles, namely electrons in Figure 5a, and carbon ions in Figure 5b. These plots were produced in real-time during the tests to monitor the beam position on the detector.

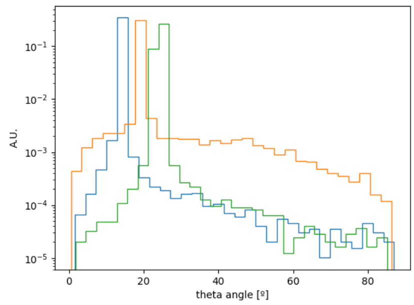
The beam diagnostics included a simplified tracking algorithm that provided an estimate of the angle between the beam and the detector. Figure 6 shows the distribution of the particles incoming directions. Although very preliminary, these results demonstrate the excellent tracking capabilities of the HEPD-02 tracker.

5. Conclusions

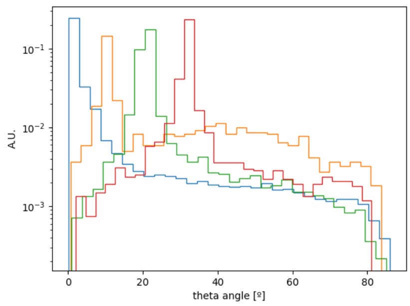
The HEPD-02 tracker is the first MAPS-based detector designed for space use. It is currently integrated into the HEPD-02 detector and has undergone full qualification. The beam tests concluded at the beginning of July 2023, and ongoing data analysis will provide the full characterization of the apparatus. The shipment to the satellite assembly site is scheduled for the end of 2023.



(a) 120 MeV electrons.



(b) 230 MeV protons.



(c) 400 MeV/amu carbon ions.

Figure 6: Each plot contains the distribution of angles reconstructed from fast tracking algorithm. It is possible to see that different angles are well separated for all the specied considered.

After the launch, foreseen for mid-2024, the HEPD-02 performance will be assessed in flight. If successful, th MAPS technology will be then fully qualified and available for use in any other space-based particle tracker.

References

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