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The innovative particle tracker for the HEPD space experiment onboard the CSES-02 satellite

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China Seismo-Electromagnetic Satellites are the most advanced initiative for the study of the ionosphere-lithosphere coupling from space. They are sensitive to any type of short- to long-lasting perturbations in the ionosphere, thanks to the variety of instruments that they host on board. Among them, the High-Energy Particle Detector is devoted to the observation of electrons and protons with energy thresholds of 3 MeV and 30 MeV respectively. The Limadou collaboration has designed an improved version of the HEPD for the second satellite of the CSES constellation, whose launch is scheduled for the end of 2022. The main upgrade pertains to the tracker, which will be made of Monolithic Active Pixel Sensors, never used so far in space. With respect to the standard hybrid silicon microstrip technology, MAPS are more precise, more robust, easier to control and readout, cheaper and less invasive. On the other hand, they are still relatively small-sized and power-demanding. We report on the process of spatialisation carried out by the HEPD-02 tracker team, which has adapted the operation mode of the ALPIDE sensor to realize a modular and compact particle detector, made of 5 turrets, each one containing 3 stacked sensitive planes. All of 150 ALPIDE sensors are controlled and readout with a Hybrid Integrated Circuit and supported by Carbon Fiber Reinforced Plastics staves, housed in an aluminium case. We describe in detail the HEPD-02 tracker project, demonstrating the advantages of using MAPS in space and manifesting the pioneering nature of the project for next-future larger size space missions.

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1. The High-Energy Particle Detectors onboard the CSES misssions

China Seismo-Electromagnetic Satellites (CSES) are state-of-the-art devices to explore the circumterrestrial medium at 500 km of altitude. The first one, CSES-01, is operative since February 2^{nd}, 2018, while CSES-02 will be launched at the end of 2022. Among the payloads, the High-Energy Particle Detector (HEPD) is designed to measure electrons in the energy range 3-100 MeV and light-nuclei in the energy range 30-200 MeV/z.

The HEPD concept is based on a sub-detector measuring tracks from particle trajectories (tracker), a trigger system made of thin plastic scintillators, a low-energy calorimeter made of plastic scintillator tiles to measure the range of light nuclei, a high-energy calorimeter made of scintillating LYSO crystals. To veto data acquisition of spurious signals and to have information about the containment of the signal inside the instrument, plastic scintillators surround the HEPD. A detailed description of sub-detectors and readout and control systems of the HEPD-01 operated onboard the CSES-01 satellite can be found in [1].

HEPD-02 will be an upgraded version of HEPD-01, yet following the same experimental approach of its predecessor. The readout and control systems have been updated and the design contains improvements in the size and the distribution of sensitive volumes [2]. The tracker constitutes the major novelty, providing for the first-ever use of monolithic active pixel sensors (MAPS) in space.

2. From hybrid microstrips to Monolithic Active Pixel Sensors

The most advanced particle trackers for space experiments all rely on micro-strip silicon sensors, readout with custom ASICs including amplification and shaping stages. This technology proved to be efficient, robust and fully compliant with space requirements. Both in its single- and the double-sided versions, microstrips allowed for important experiments like Pamela, AGILE, Fermi, AMS-02 and DAMPE [3–7]. They are still an important option for near future enterprises like HERD [8]. Nonetheless, microstrips have become a niche application for silicon foundries, with profound consequences on the pace of their development, the cost of their fabrication and the complexity of their implementation. With respect to the standard hybrid silicon microstrip technology, MAPS are more precise, more robust, easier to control and readout, cheaper and less invasive. On the other hand, they are still relatively small-sized and power-demanding. The last two limitations are still subject to improvement by MAPS developers and can be worked out on small-size projects like the tracker of HEPD.

The ALPIDE sensor When the conceptual design of HEPD-02 was issued, the only MAP sensor with technology readiness level adequate to be taken in consideration for use in space was ALPIDE [9]. It is a MAP sensor conceived, designed and developed for the ALICE Inner Tracker System upgrade at the LHC [10]. Fabricated by Tower Semiconductor LTD with a 180 nm CMOS process, ALPIDE features the largest size of the category (4.5 cm^2) and it can be thinned down to 50 or 100 μm. It is an optimal choice among MAPS for charged radiation available on the market, because of its (i) resolution (5 μm single hit for $Z = 1$ minimum ionizing particles, m.i.p.), (ii) cleanliness ($< 10^{-7}$ fake hit rate), (iii) low power consumption (< 19 mW/cm^2), (iv) speed (1.2 Gbps via serial output port, after zero-suppression) and (v) TID radiation hardness (2700 krad).

The authors carried out in parallel the space qualification of the ALPIDE sensor and the construction of the ALPIDE-based HEPD-02 tracker.

3. Space qualification of the ALPIDE-based technologies

The main threats for devices working in space are (i) mechanical stresses due to the launch; (ii) thermal stresses while settling the orbit or unforeseen situations; (iii) damages after prolonged exposure to cosmic radiation. For what concerns (iii), the ALPIDE technology already proved to be space-proof for what concerns the radiation tolerance. Both the levels of TID and NIEL radiation hardness are above the requirements for a 5-year lasting space mission at 500 km altitude in Sun-synchronous orbit like CSES. Concerning (ii), the space-compliance of materials and solutions of assembly (bonding, gluing, grounding) was also validated during summer 2019, with 6.5 thermal cycles in the temperature range $-30^{o}/+50^{o}$C, imposed to the engineering model of a stave. Concerning (i), the engineering model of a turret underwent qualification tests during summer 2020, withstanding vibrations up to frequencies as high as 100 Hz and as intense 12g sinusoidal accelerations. Random vibrations were also applied, with frequencies up to 2 kHz and acceleration RMS as large as 11.3g. Mechanical stresses were imposed along each axis and no damage was observed, neither degradation of performance. These tests followed prescriptions by ASI and CNSA and constituted the premise for the construction of the ALPIDE-based HEPD-02 tracker. A picture of a qualification HEPD-02 tracker turret just after vibration tests is reported in figure 1. More information can be found in [11].

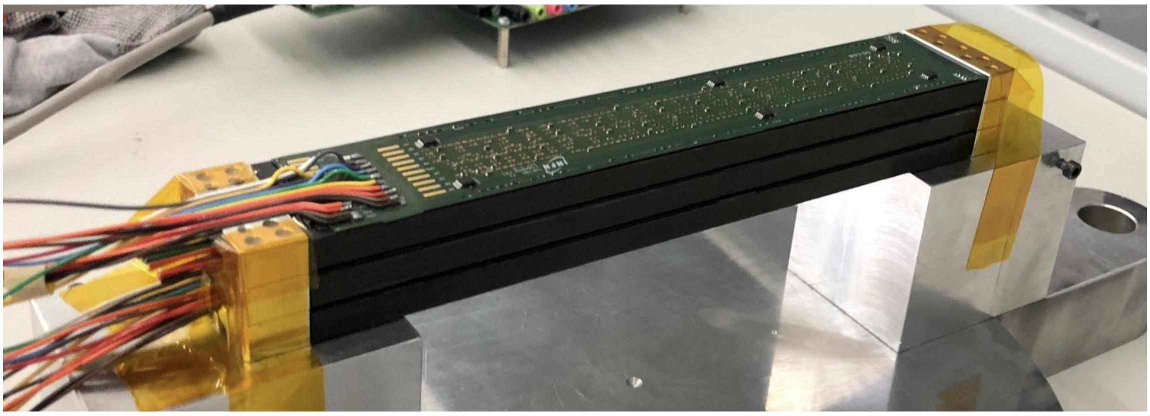

Figure 1: HEPD-02 tracker turret mounted on the fixture for vibration test for space qualification.

4. Design and construction of the HEPD-02 tracker

The design of the HEPD-02 tracker accounts for the segmentation of the new trigger system, which is made of two layers of thin plastic scintillators, positioned upstream and downstream the tracker. Figure 2 shows a breakdown of the HEPD-02 tracker.

Turrets. Just like the first trigger layer, the tracker is made of five independent modules, named “turrets”, each one featuring three sensitive layers, as distant as 8.5 mm from each other. Tracks

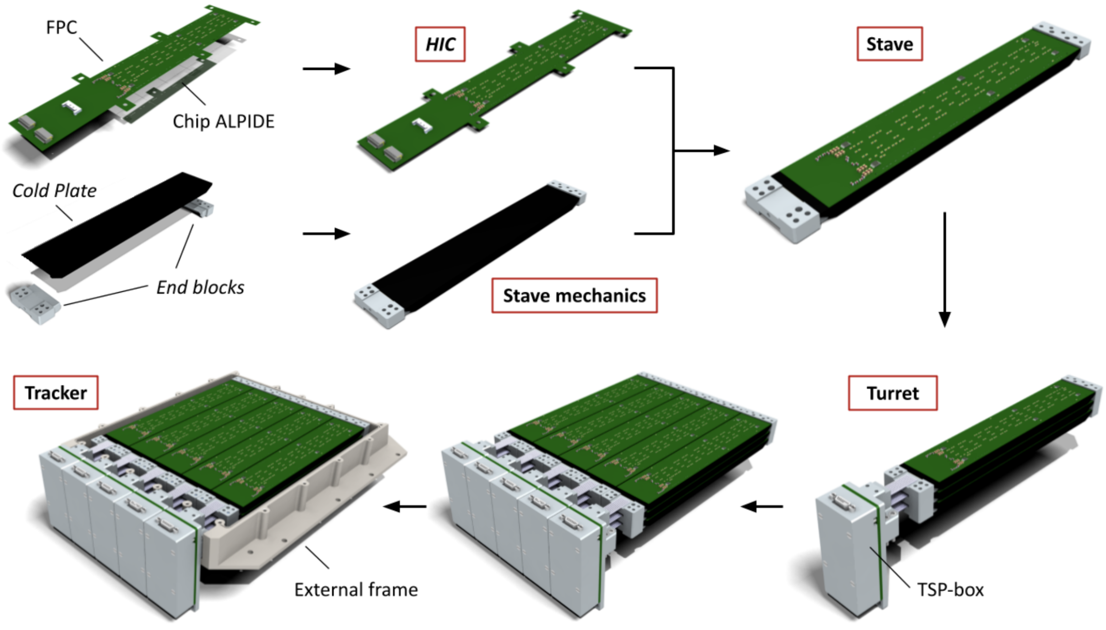

Figure 2: Rendering of the HEPD-02 tracker. See text for details.

will be reconstructed by fitting straight lines to position triplets, better than for HEPD-01 where just two measurements per event were available. Each turret is interfaced to the power supply system and the control/readout electronics with a Tracker SPlitter (TSP) board, providing suitable segmentation and redundancy. Control and readout are up to the TDAQ-board, which implements a "clock-on-demand" strategy that allows to reduce the average power consumption to 11 mW/cm^2 at 100 Hz trigger rate. Details can be found in [12].

Stave. Each turret layer is named "stave". Stiffness and thermal drain are provided by a carbon-fiber reinforced polymer U-shaped structure, secured to the external frame with aluminum end-blocks, suitably shaped to allow wire harness. The thermal gradient along the stave is expected to be less than 5^o C at 100 Hz trigger rate. Each stave hosts a Hybrid Integrated Circuit (HIC), the readout unit of the HEPD-02 tracker, containing 10 ALPIDE sensors organised in two rows (15×150 mm^2 each), where a master controls 4 slave chips, to limit the power consumption. Sensors are glued to a flexible PCB, with pad-over-logic wire bonds providing electrical connection.

With a total of 150 ALPIDE sensors, 80 Mpixel over 675 cm^2 of instrumented area and a sensitive area of 225 cm^2, the HEPD-02 provides three points of measurement with just 1.5% radiation lengths distributed in 17 mm depth. At the time of writing the HEPD-02 qualification model is under completion and the construction of the flight model about to start.

5. Performance of the HEPD-02 tracker

In-orbit self-calibration. Alignment and calibration are of great importance to fully exploit the potential of MAPS. With respect to hybrid silicon microstrips, the calibration procedure does not foresee the online calculation and subtraction of common noise. As for other MAPS, ALPIDE features a calibration injection circuit, allowing to measure the hit efficiency as a function of the injected threshold *on a pixel basis*. In such a way, hot pixels can be masked and thresholds finely adjusted, to maintain constantly good the performance of the instrument, which may change because of changes in the operation mode (e.g. bias voltage or pre-scaler mode in the trigger system) or variation of environmental conditions (e.g. the operating temperature) or due to aging effects (e.g. the cumulative dose of absorbed radiation). An example of online self-calibration is reported in fig. 3.

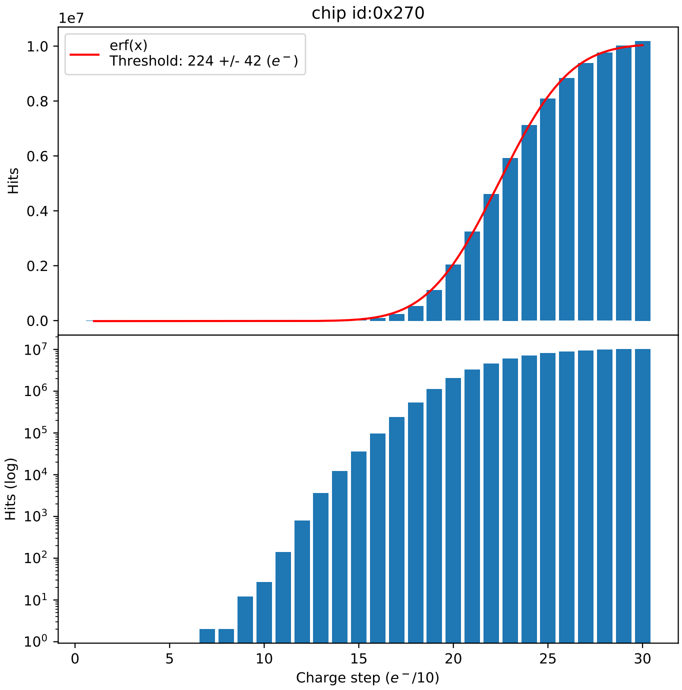

Figure 3: Result of the threshold scan performed on a stave (chip id:0x270). The amount of responsive pixels (hit) is reported as a function of the amount of charge injected for test. A fit to the error function provides the threshold value of $224 \pm 42e^-$ (at 50% hit pixels).

Online tracking. The standard way of measuring single particles in space experiments is to record data after trigger, send them to Earth and finally analyze them with sophisticated techniques of fine-calibration, feature selection and statistical interpretation. Hybrid microstrip particle trackers do not escape this logic: the single hit centroid, the trajectory connecting hits and the average energy release per track are estimated offline with complex software procedures. In this respect, MAPS are different: they output the hit pixel position, so that very simple FPGA-implemented algorithms can use (x, y, z) coordinates to calculate tracks *online*. An example from the HEPD-02 project is reported in fig. 4. The potential behind online tracking in space is not fully understood yet: as long as scientific missions on low-Earth orbits are considered, the need for online data-analysis could be not so urgent. But dealing with very large trigger rates from big and complex experiments orbiting

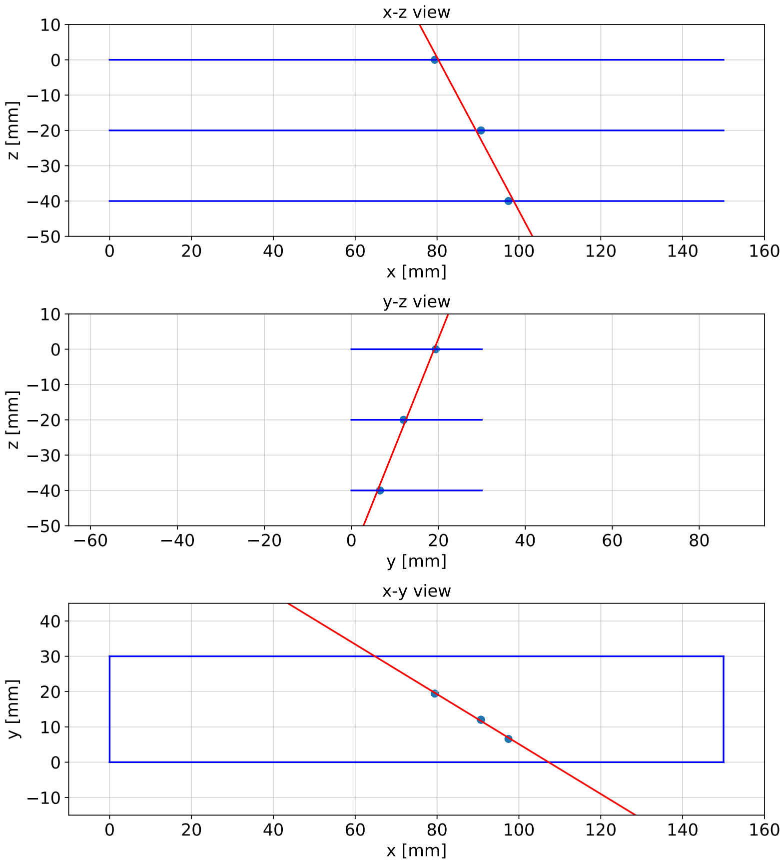

Figure 4: Event display obtained in laboratory with cosmic muons by using three qualification staves on a test mechanical support (vertical distance as large as 20 mm). No guides were used for alignment. Blue lines delimit the sensitive plane on each stave. Tracks are obtained with online 3D fitting to straight lines.

far away from the Earth demands for having artificial intelligence onboard, systematically resorting to hardware pre-processing.

Cluster size. ALPIDE features a binary threshold readout, providing boolean information whether a pixel has been hit or not. This is an important difference with respect to hybrid microstrips, because no direct measurement of the amount of energy deposited in silicon is available, preventing from tradiation application of dE/dx techniques for particle identification. Nonetheless, the electric field inside the ALPIDE epitaxial substrate is very weak (less than 120 V/mm), what allows to observe the diffusion of electrons up to few pixels away from the hit position. Such dependence of the cluster size (and shape) on the primary energy is unimportant for quasi-m.i.p. and it has been little explored by the ALICE collaboration. Nonetheless, for HEPD-02 light-nuclei with kinetic energy as low as 50 MeV/Z may generate in silicon up to 60 times the e-h pairs of a m.i.p. with clear impact on the cluster size. Characterisation and potential uses are reported in fig. 5 and 6.

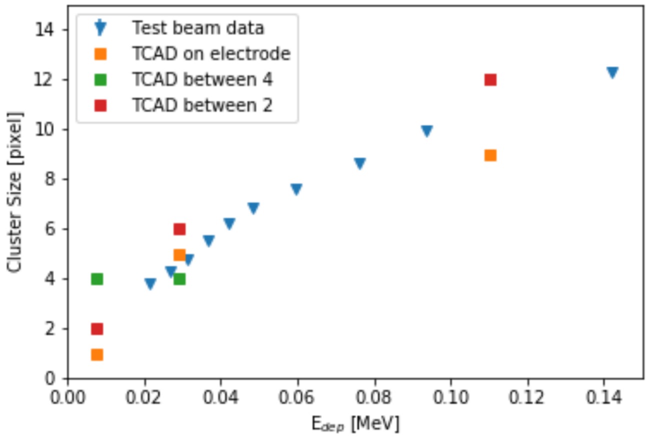

Figure 5: Comparison of cluster size from data and Monte Carlo simulations as a function of the energy deposited by 30-220 MeV protons. Data were collected at the APSS Proton therapy center in Trento, whereas simulations were performed with the Synopsys TCAD Sentaurus software. The cluster size from Monte Carlo changes according to the hit position inside the pixel.

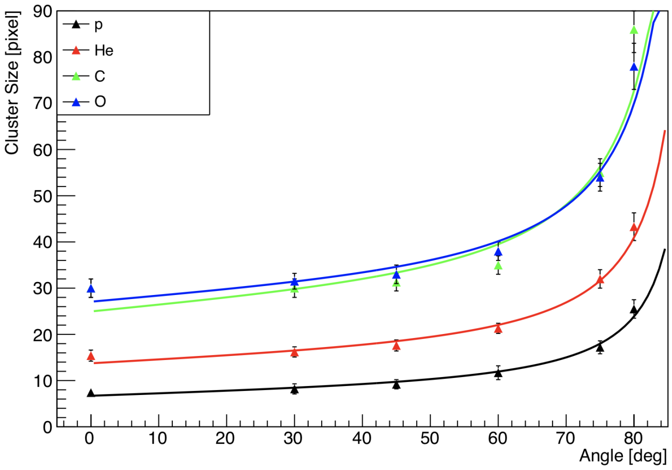

Figure 6: Cluster size versus primary particle charge and inclination angle. Data were taken at the cyclotron of INFN Catania. With the kinetic energy is fixed at 62 MeV/a.m.u., the energy deposit in silicon is proportional to z, where z is the charge of the nucleus. The dependence of the cluster size on z shows saturation after $z = 3$ because of diffusion times too long for collection. The dependence of the cluster size on track inclination follows expectations from geometry (solid lines).

6. Conclusions

The tracker of the High Energy Particle Detector, to be launched on board the second China Seismo Electromagnetic Satellite in mid 2022, will be made of ALPIDE Monolithic Active Pixel Sensors, a 3.0×1.5 cm^2 ASIC, fabricated with a 180 nm CMOS process. The use of Monolithic Active Pixel Sensors is unprecedented in space applications and demands for specific solutions to limit the power consumption and ensure robustness against the mechanical and thermal stresses that the module has to withstand during the launch and in operation. These solutions have been space-qualified in the last three years by the authors. The design of the HEPD-02 tracker has been optimised for the detection of electrons and protons in the 3-100 and 30-200 MeV range respectively, a scientific case that laboratory tests demonstrated is well in the reach of the ALPIDE technology. More generally, the results mark the passage from hybrid microstrip to monolithic pixel silicon sensors in space, paving the way for bigger and more complex scientific missions.

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