First space application of Monolithic Active Pixel Sensors for particle tracking: the High Energy Particle Detector onboard the CSES-02 satellite

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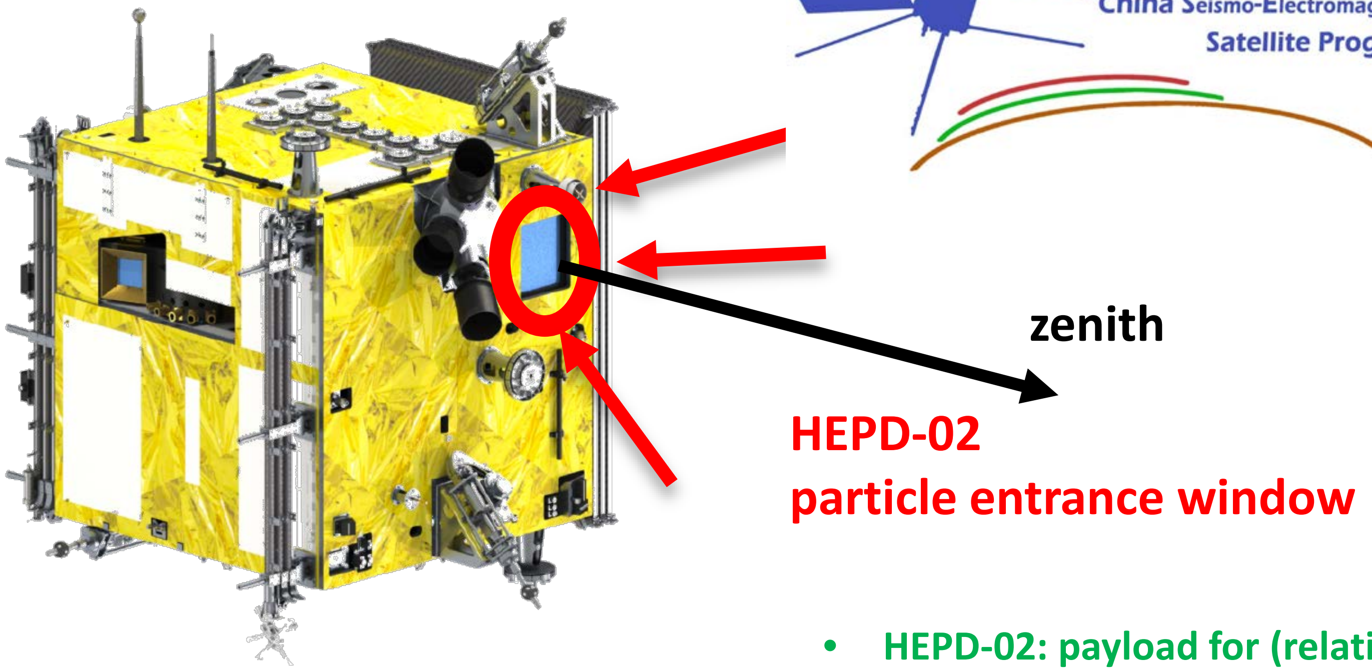
Summary

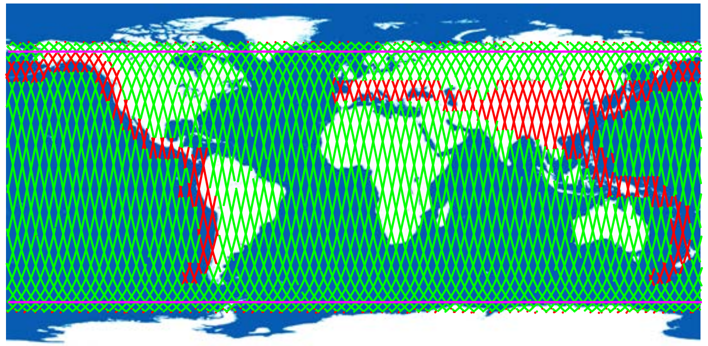
- The **CSES-02 satellite** and the **High-Energy Particle Detector (HEPD-02).**
- The **ALPIDE** Monolithic Active Pixel Sensor (MAPS) in **HEPD-02 tracker**.
- ALPIDE tracker design and space-application compliance.
- ALPIDE performances in HEPD-02.
- Control and read-out electronics for HEPD-02 tracker.

CSES-02 satellite

电磁监测卫星计划
China Seismo-Electromagnetic Satellite Program

- **CSES-02: China Seismo-Electromagnetic Satellite.**
- **Total Mass:** 900 kg
- **Orbit:** -65° to +65° latitude, 500 km, sun-synchronous.
    - Same as CSES-01 (launched in Feb 2018), with 180° phase difference.
    - Orbit maneuver capability.
    - Earth-oriented stabilization system.
- Design life cycle > 6 years.
- **Equipped with several payloads for electromagnetic and plasma measurements in the Van Allen belts.**

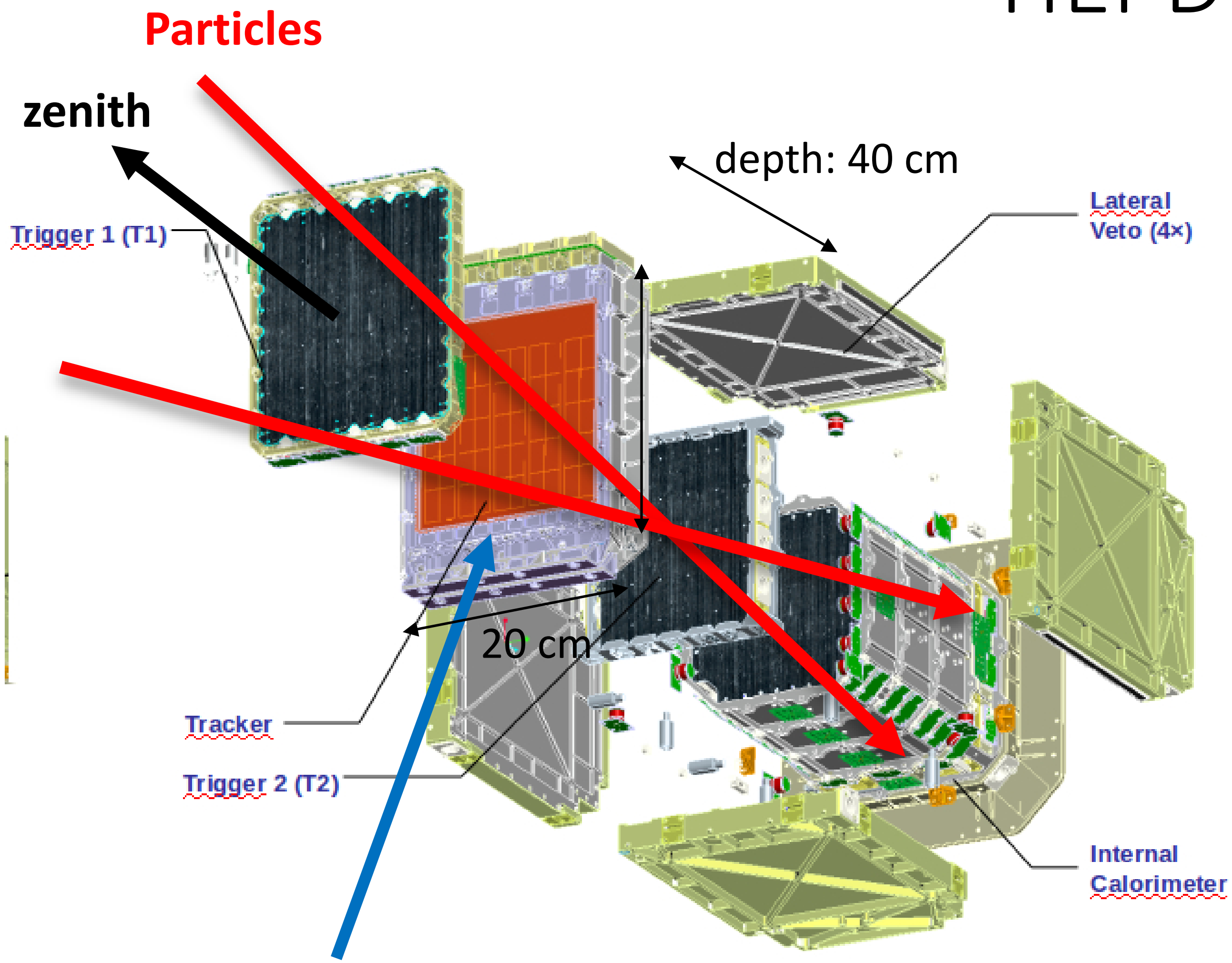




(Courtesy of DFH Satellite Co., Ltd.)

- **HEPD-02: payload for (relatively) High-Energy Particle Detection.**
  Main target: energy spectrum of electrons and protons in the Van Allen belts.
    - To be delivered for satellite integration within 2022.

HEPD-02



- The tracker (3 MAPS layers) follows the first thin layer of trigger scintillators.
- Amount of materials on top and inside the tracker has been minimized to reduce multiple scattering.

Kin. energy range (electron)	3 MeV to 100 MeV
Kin. energy range (proton)	30 MeV to 200 MeV
Angular resolution	≤10° for E_{kin} > 3 MeV electrons
Energy resolution	≤10% for E_{kin} > 5 MeV electrons
Particle selection efficiency	> 90%
Detectable flux	up to 10^7 $m^{-2}s^{-1}sr^{-1}$
Operating temperature	-10 °C to +35 °C
Operating pressure	≤ $6.65 \cdot 10^{-3}$ Pa ("vacuum")
Mass budget	50 kg
Power Budget	45 W
Data budget	≤ 100 Gb/day

From HEPD-01 to HEPD-02 tracker

HEPD-01 tracker (on-board of CSES-01 satellite) employs Si microstrip sensors (50 µm resolution).

- Technology developed for vertexing and momentum measurement.
- **Traditional technology for tracking particles in space.**
- **Well-known assembly designs for space compliance.**

Some disadvantages:

- custom-made technology;
- sensor and analog read-out circuit are separately manufactured and bonded together;
- possible multiple-track hits on the same strip.

HEPD-02 tracker will employ ALPIDE Monolithic Active Pixel Sensor (MAPS).

- **Binary pixel response.**
- **Sensor and read-out circuit on the same Si substrate (difference with respect to hybrid pixel sensors).**

Some advantages:

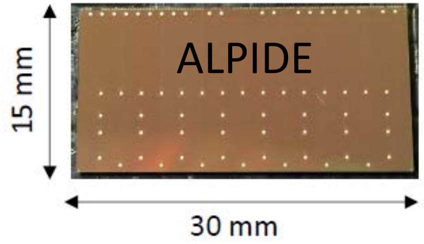
- compact assembly;
- low noise;
- spacial resolution (for Z=1 MIP): 5 µm.

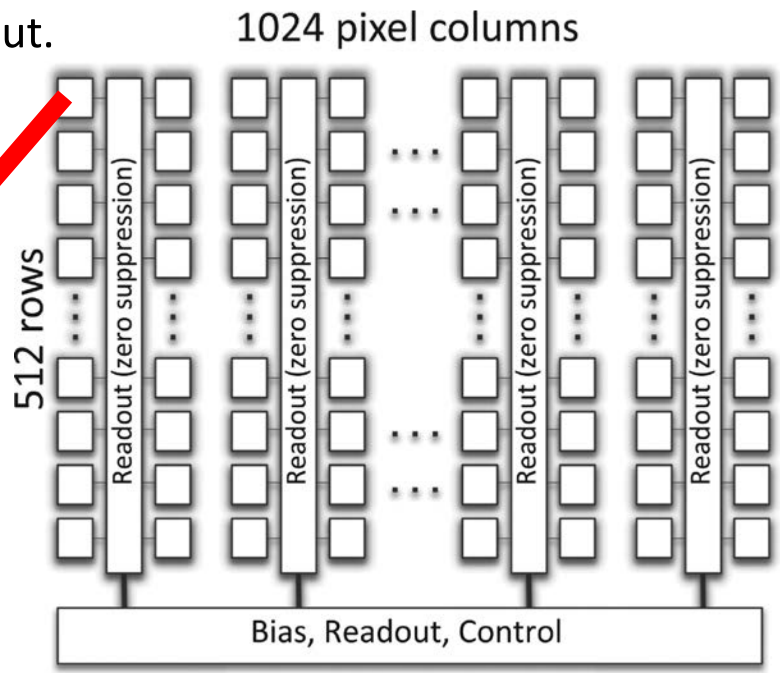
Several challenges:

- **relatively new technology**, not build for use in space;
- assembly must be **stiff for expected structural stresses**;
- assembly must sustain **repeated thermal cycles in vacuum;**
- **power consumption must reduced** to comply with budget;
- requires **characterization for use with low-energy protons and ions.**

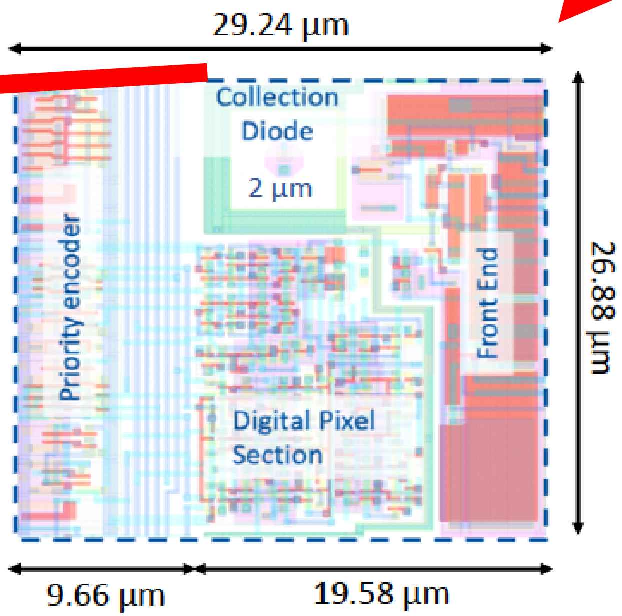
The ALPIDE MAPS in HEPD-02 tracker

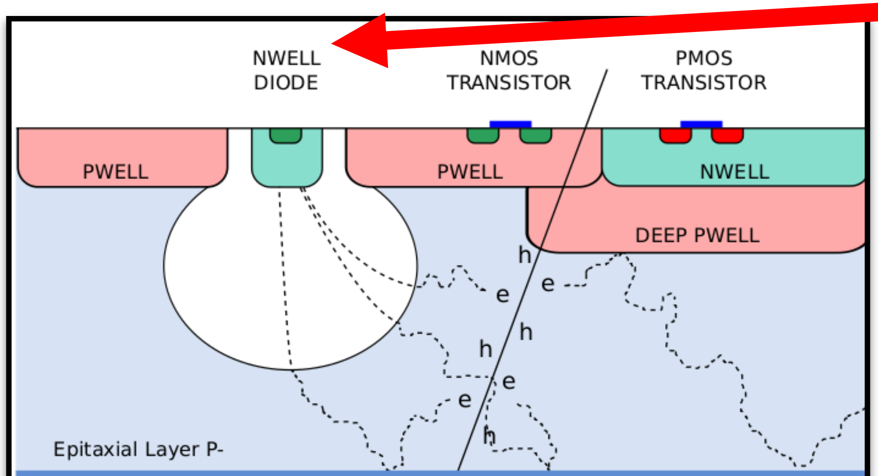
- ALPIDE MAPS was designed for ALICE Inner Tracker (ITS) upgrade at LHC accelerator (CERN).
- ALPIDE: **512 x 1024 pixels** in 15 x 30 mm^2.
  - Available thickness 100 or **50 µm.**
  - Back-bias up to -6 V.
  - Charge collection by **diffusion.**
  - **Low noise (~10 e / pixel).**
- Threshold readout circuit (binary output): 180 nm CMOS technology.
  - Deep p-well allows for **PMOS transistor implantation** on chip without reducing collection efficiency.
- Fully zero-suppressed digital output.





Pixel Layout





The ALICE collaboration, J. Phys. G: Nucl. Part. Phys. 41 (2014) 087002

Space compliance: main items

- Use of MAPS is **unprecedented in space,** thus the tracker design requires R&D for:
  - (1) adequate assembly **stiffness** to sustain structural stresses during launch, orbital maneuvers and demanding qualification tests required by Space Agencies (**> 10 G accelerations**);
  - (2) appropriate **thermal drain** by **pure conduction** toward external Al-alloy support frame ("vacuum" condition means absence of air convection);
  - (3) endurance over repeated **thermal cycling** and operation in vacuum between **-30°C and +50 °C** temperature of HEPD-02 mechanical frame;
  - (4) keeping the **power budget** within strict limits imposed by satellite application (**~13 W** available for the whole tracker).

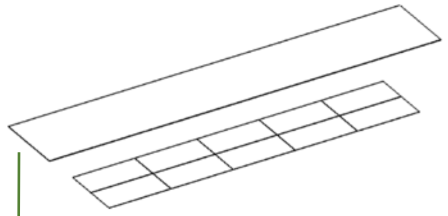
- (1) and (2) go against HEPD-02 scientific requirements of **low-density / low-thickness support materials** along the incoming particle direction:
  - to minimize multiple scattering;
  - to minimize the energy loss in passive layers.
- This is especially important for electrons in the lower part of the kinetic energy range of interest (down to 3 MeV).

- (4) goes against fast event processing and data transmission.

- The tracker design has therefore been driven to possibly find the **best achievable compromise between scientific and technological requirements.**

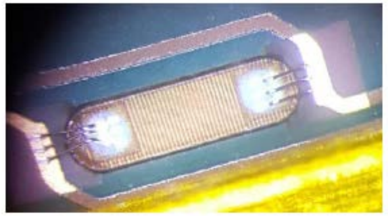
HEPD-02 tracker design: HIC and stave

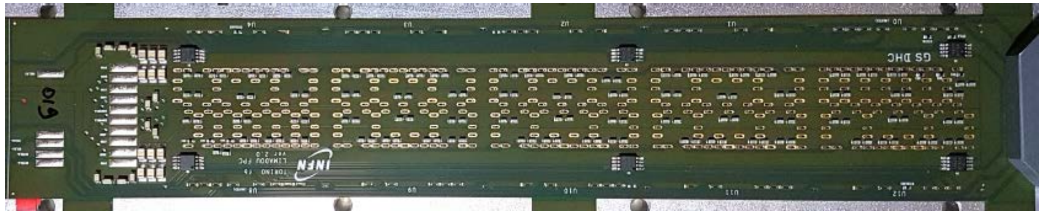
(I) HIC (Hybrid Integrated Circuit): FPC + 10 ALPIDE.



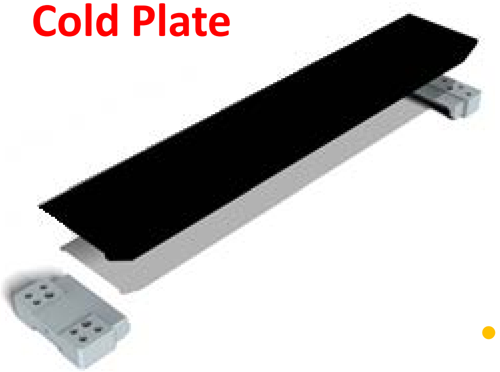
FPC (Flexible Printed Circuit): kapton + copper tracks for signal and power routing to chips.

FPC/ALPIDE glued and connected via triple-redundancy bondings.

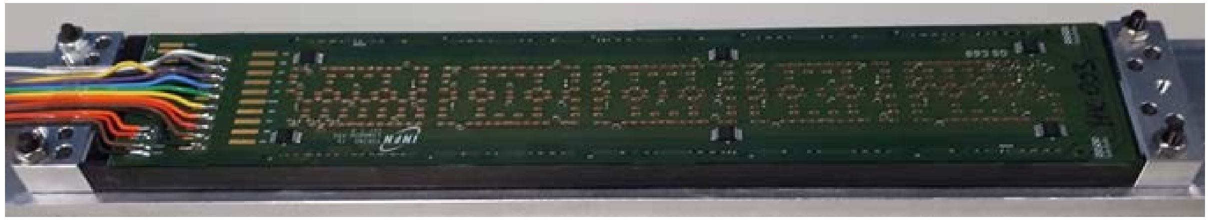




(II) End Blocks + Cold Plate



(III) Stave: HIC glued to Cold Plate.



- **End Blocks** (Al alloy) for fixing to support frame.
- **Cold Plate** (CFRP: carbon fibre + epoxy resin) with optimized structural/thermal design, glued to End Blocks via high-performance glue.

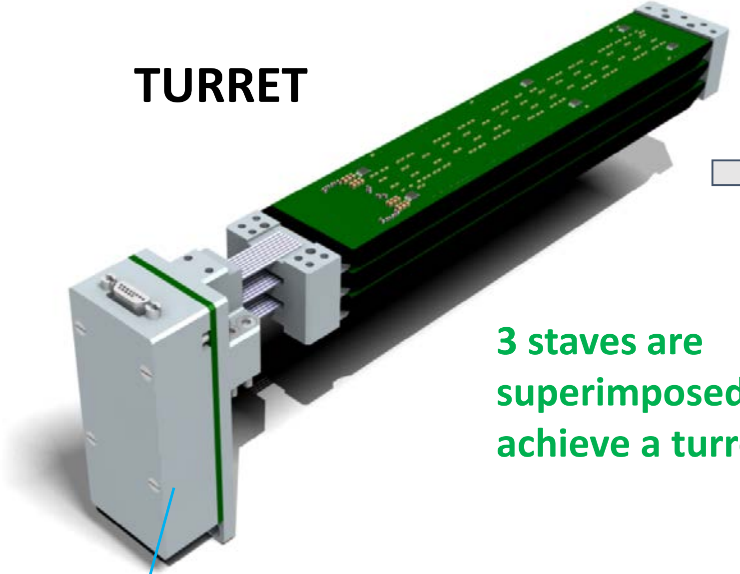
This assembly gives:

- **stiffness** against structural stresses;
- endurance over **thermal cycling**;
- **thermal drain** from ALPIDE chips toward support frame, with gradient along Cold Plate kept within 6° C, when all ALPIDE chips are fully active.

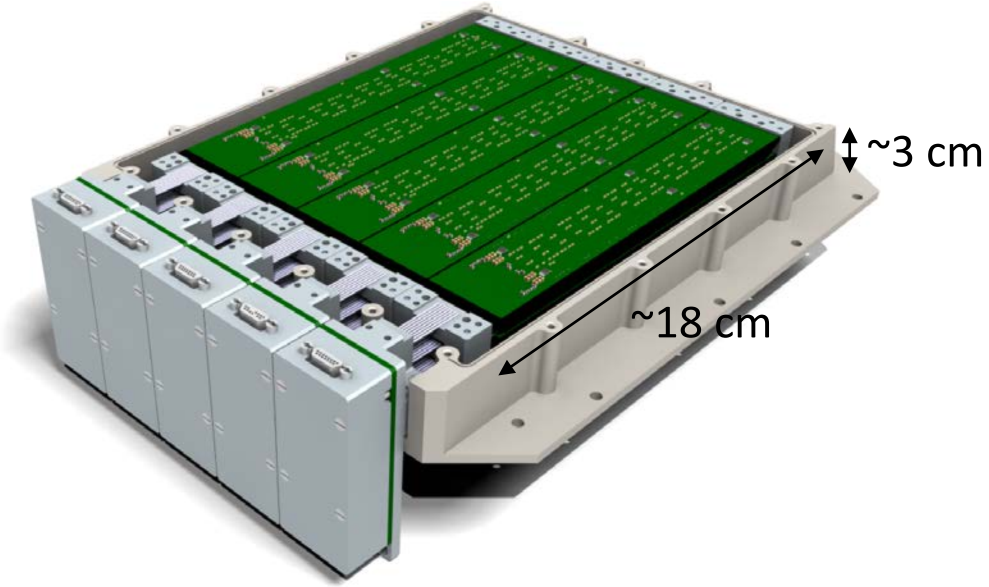
For more details see **poster by E. Serra:**
https://indico.cern.ch/event/981823/contributions/4295441/

HEPD-02 tracker design: turrets

TURRET



3 staves are superimposed to achieve a turret.

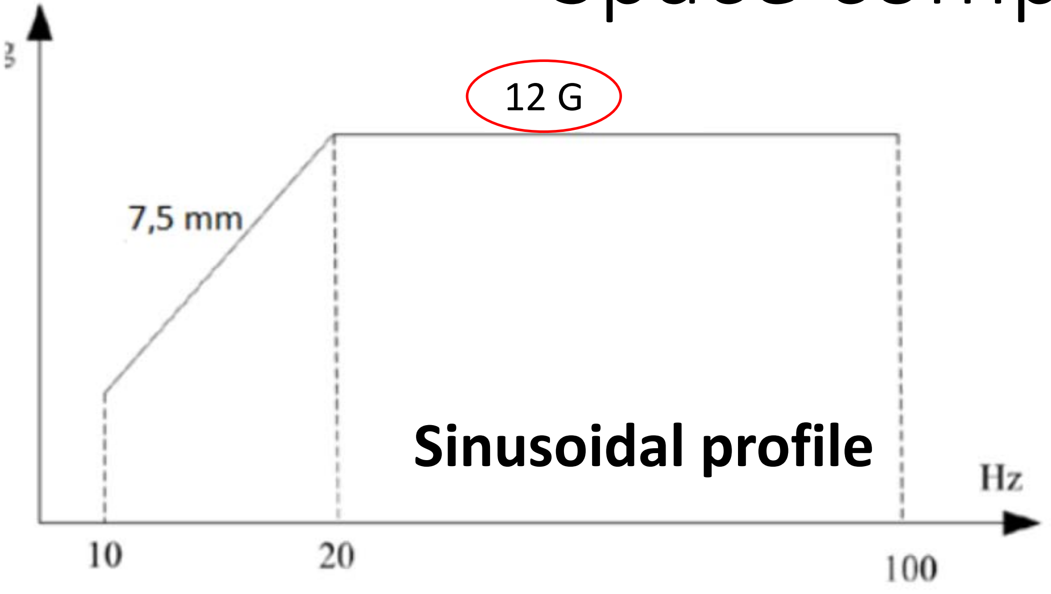


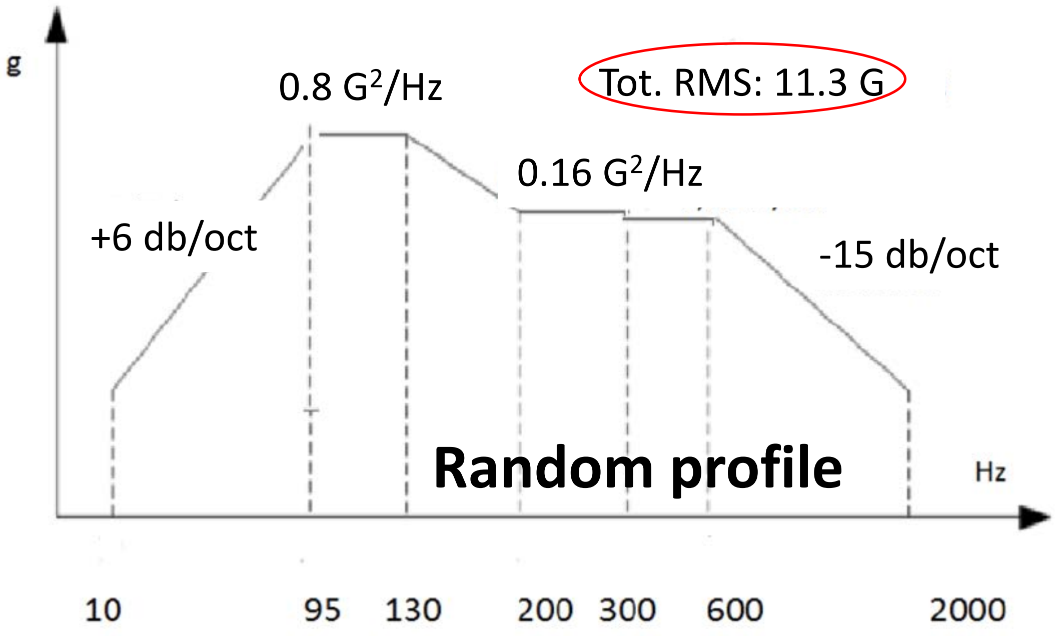
The whole tracker is formed by 5 turrets.
- 15 staves;
- 150 ALPIDE;
- ~ 80 Mpixel in 3 planes.

TSP (Tracker SPlitter) board for cabled interface with power and control/read-out electronics.
TSP connected to the staves via soldered wires (few cm length).

- The first set of staves have been assembled.
- A first prototype turret has been assembled.
- Space compliance verification tests are ongoing.
- First complete tracker to be assembled in few months, for integration in HEPD-02 qualification model.
- See also **poster by L. de Cilladi:** https://indico.cern.ch/event/981823/contributions/4295446/

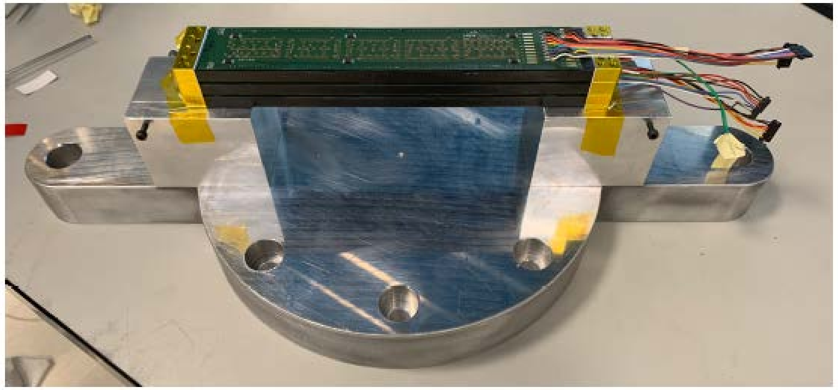
Space compliance: vibration tests





- **Vibration tests performed on a prototype turret** at SERMS, Terni (IT).
  - Stress profiles applied (on each axis) to take into account extreme vibration profiles, much worser than expected at launch (as required by Space Agencies).
  - Control accelerometers located on the turret (bottom Cold Plate) and on the fixture.

- **The test was successful:**
  - **verified first resonance mode >800 Hz (>> 100 Hz required);**
  - **no mechanical anomalies detected on the assembly (gluings, bondings, solderings etc.);**
  - **detector performances not affected.**

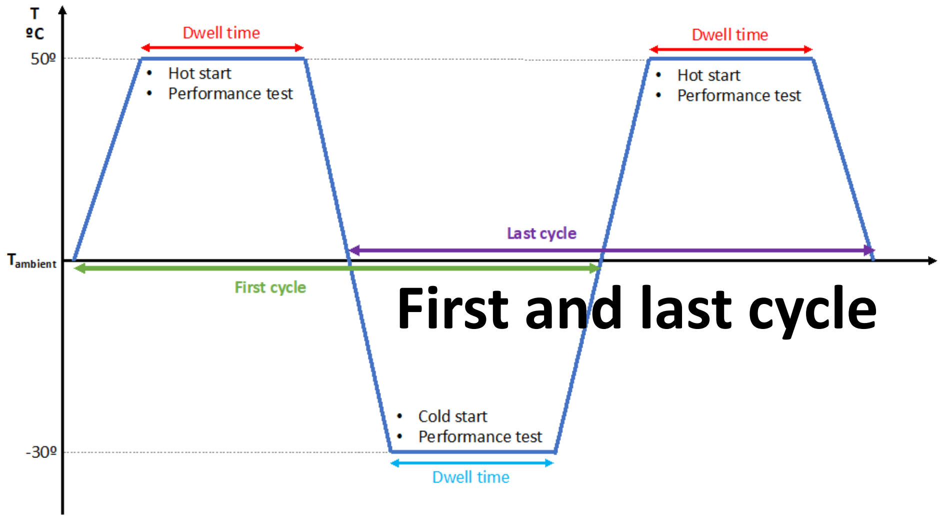


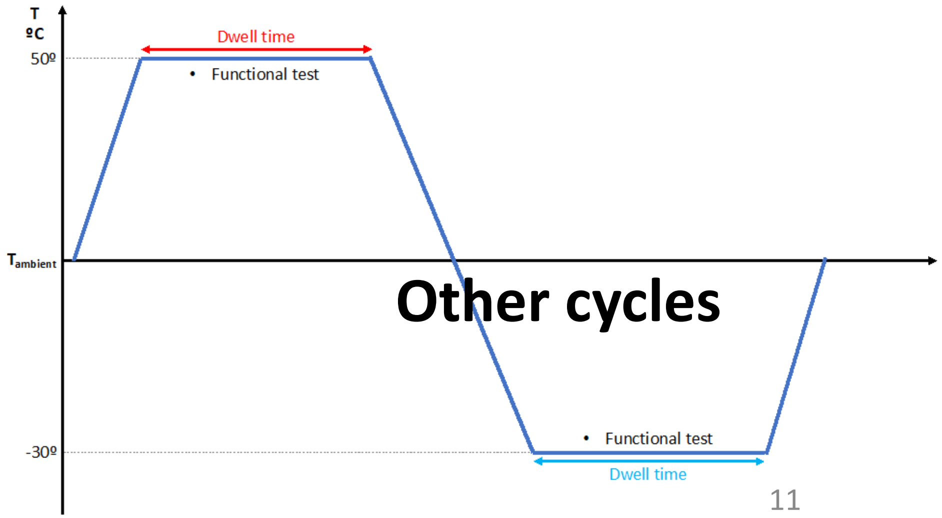
Space compliance: thermo-vacuum test

- **Thermo-vacuum cycle tests performed on a HIC.**
  - Test designed to apply thermal stresses in "vacuum", much worser than expected during the flight (as required by Space Agencies).
  - Detector performances monitored at low and high cycle temperatures (thermal dwell).

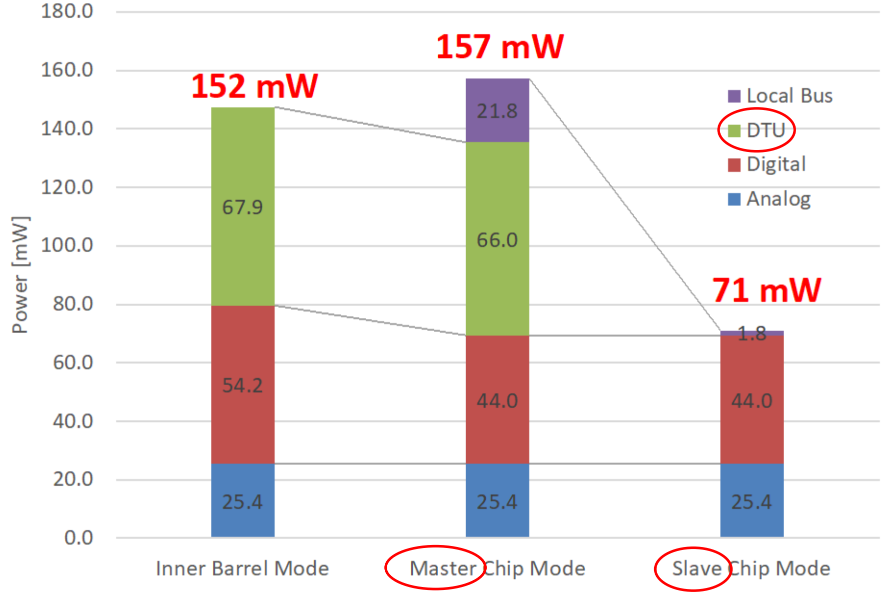
- **The test was successful for HIC:**
  - **no mechanical anomalies detected on the assembly (gluings, bondings etc.) after the cycles;**
  - **detector performances not affected both during and after the cycles.**

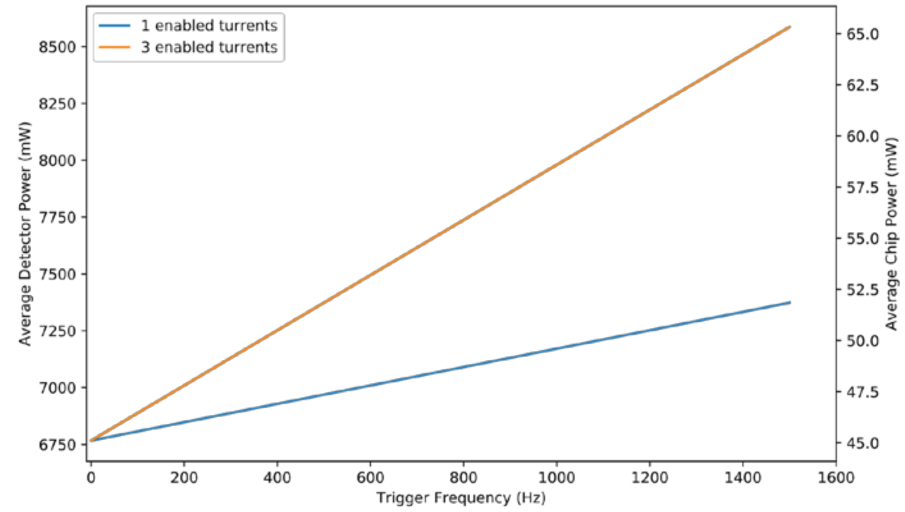
Parameter	Test conditions
Pressure [Pa]	$<6.66 \cdot 10^{-3}$
Hot temperature at fixture [°C]	**+50**
Cold temperature at fixture [°C]	**-30**
Number of cycles	6.5
Temperature rate of change [°C/min]	≥1
Dwell time [h]	≥2





Space compliance: power consumption mitigation

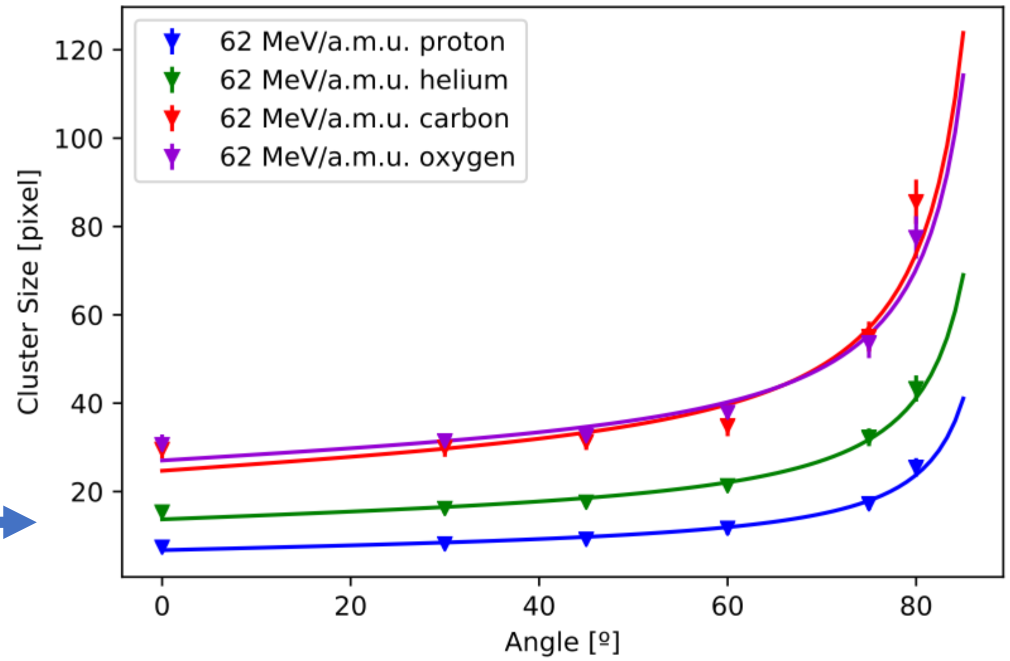


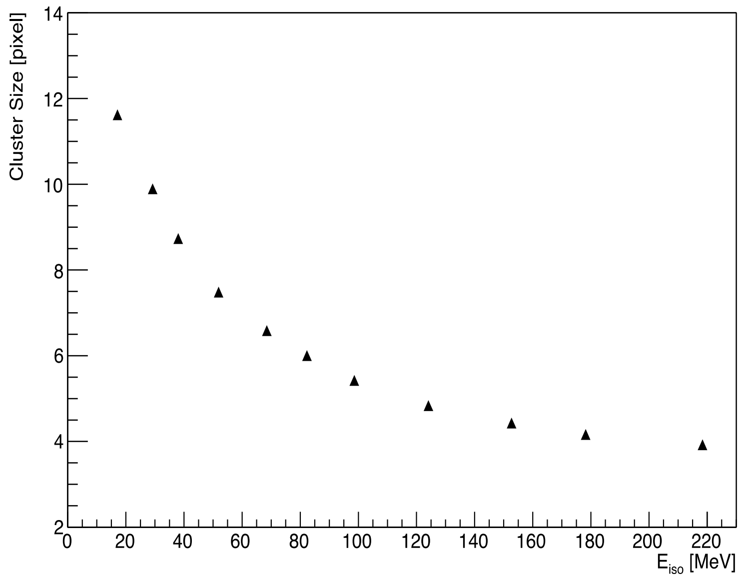


- Several changes of configuration implemented with respect to application in ALICE (CERN), to comply with strict power limitation on satellite (~13 W available for the whole tracker).
  - **Master-slave architecture** (1 master out of 5 chips) with sequential slave read-out through master.
  - Permanent switch-off of fast data transmission unit (DTU) and **read-out through serial slow-control line.**
    - Acceptable increase of dead time, given the relatively low trigger rate sustainable by the HEPD-02 system (up to few kHz).
  - **Clock gating**: ALPIDE clock normally off, set on with trigger:
    - **trigger: clock on (17 mW/cm^2);**
    - wait for signal digitization;
    - transmit data to control/read-out electronics;
    - **clock off (7 mW/cm^2): wait for new trigger.**

ALPIDE response to low-energy ions

- ALPIDE designed and widely characterized for Z=1 MIP detection, for application in ALICE at LHC (CERN).
  - Main observable: cluster size i.e. number of pixels with signal > threshold (binary output 1).
  - For Z=1 MIP, cluster size is ≤ 4 pixel.
- In view of HEPD-02 application, **ALPIDE response has been tested for low-energy ions with different incoming directions.**
  - Protons at Trento Proton Therapy Centre, Trento (Italy).
  - Nuclei at LNS, Catania (Italy).



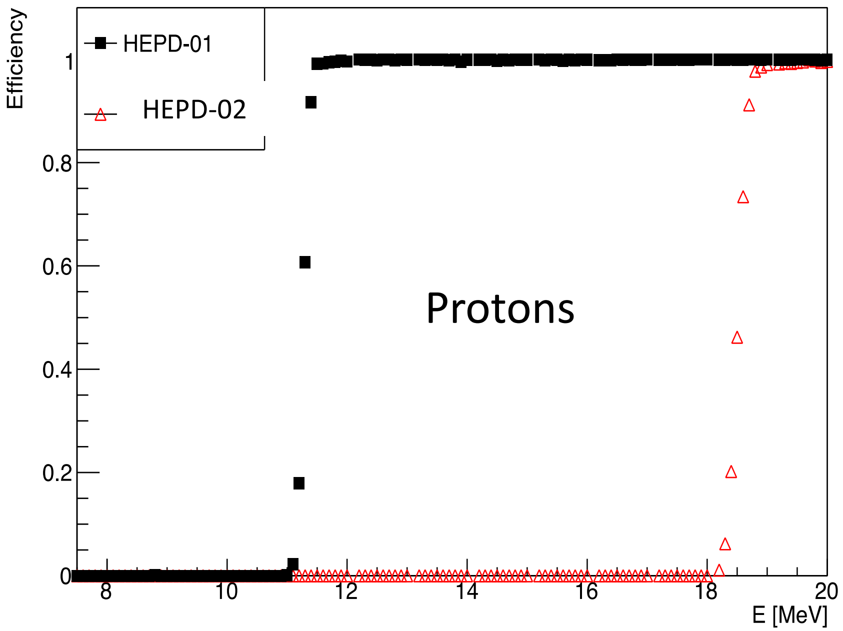


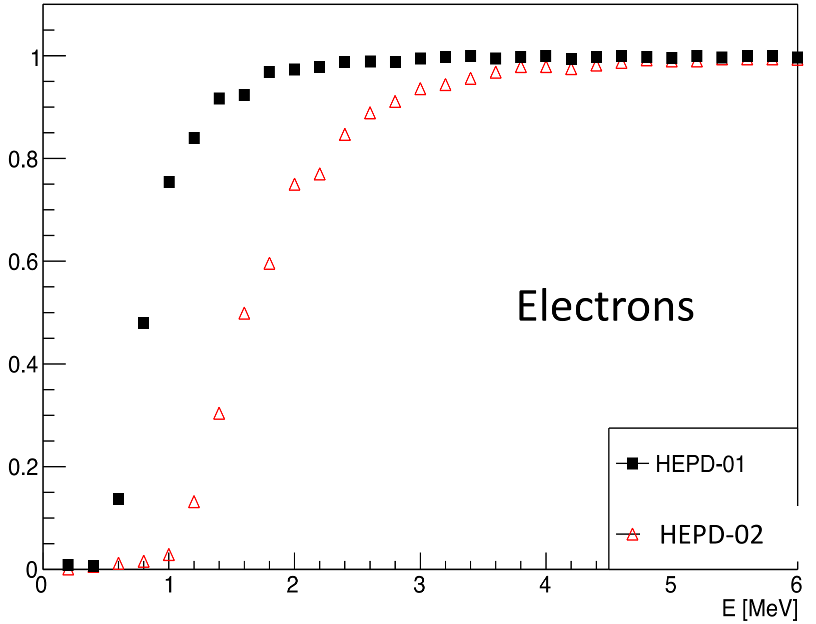
- Having a binary threshold readout, ALPIDE can not be used for measurement of deposited energy (dE/dx).
- **An interesting dependence of typical cluster size from kinetic energy** of the incident particle was measured for low-energy protons and nuclei.

Energy threshold for particle detection

Comparison between HEPD-01 microstrip tracker and HEPD-02 ALPIDE tracker:

- energy threshold for particle detection (i.e. for all planes, the signal is over the noise-rejection threshold set).





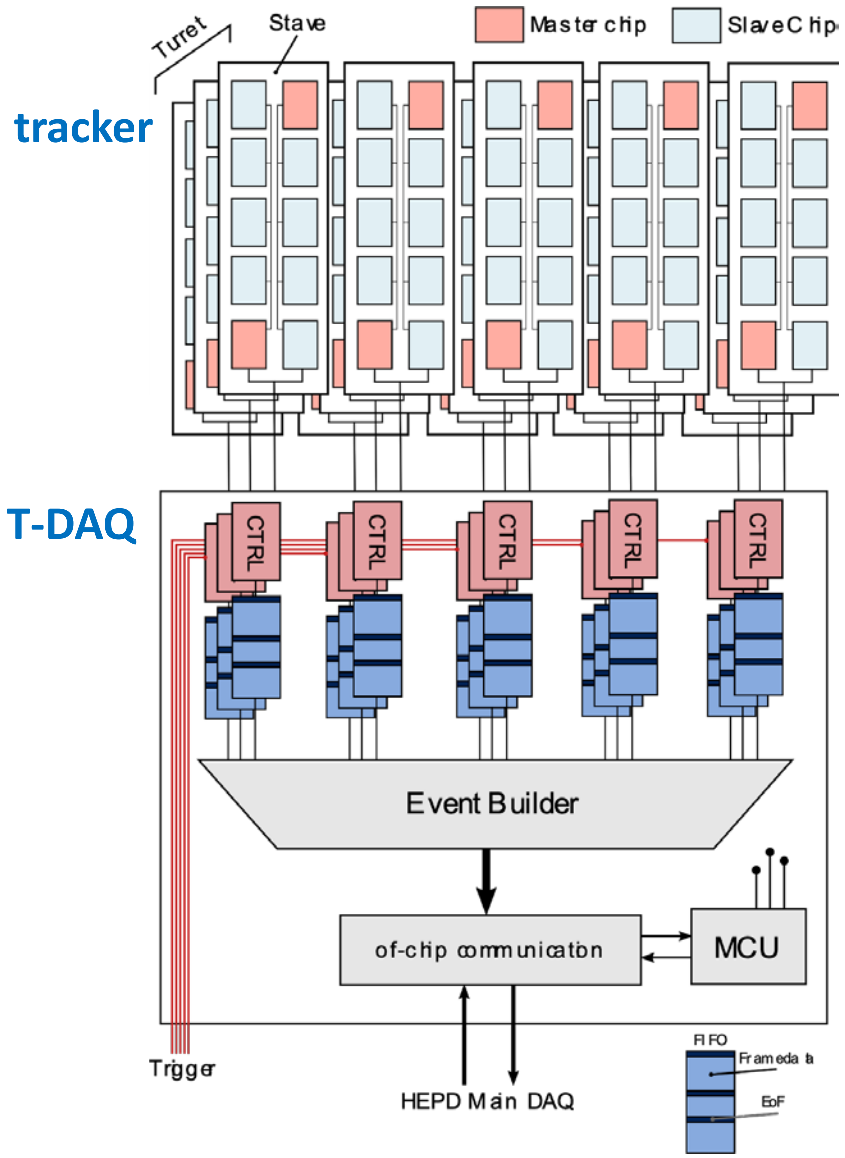
Detection threshold of HEPD-02 tracker is higher than HEPD-01 tracker (but still compatible with requirements) because:

- **number of detector planes has been increased from 2 to 3** to obtain redundancy of track sampling thus improving tracking quality;
- there is a major contribution to energy loss from **FPC copper tracks** and **CFRP Cold Plate**, while the **Si thickness has been reduced by 6 times** (from 300 µm microstrip sensor to 50 µm ALPIDE).

Stave element	Material	Thickn. [µm]	Rad. length X_0 [%]
FPC board	Kapton	135	0.048
FPC tracks	**Cu**	**36**	**0.251**
Glue	Araldite 2011	130	0.029
ALPIDE	Si	50	0.053
Cold plate	**Carbon fibre + epoxy resin**	**350**	**0.134**
TOTAL			0.515

Control and read-out electronics

- **Fully customized for HEPD-02 space application.**
  - Compactness: whole tracker control and read-out in a single board (T-DAQ).
  - Design driven by power consumption limits (3 W budget for T-DAQ).
  - Hot/cold redundancy (i.e. two identical copies of the circuit in the same board) to increase overall reliability during flight.
- Control logics and Microblaze soft processor implemented on Xilinx Artix 7 FPGA.
- 15 CTRL logic modules (one per stave) handle the full ALPIDE housekeeping and data acquisition through serial bidirectional line.
  - Tracker segmentation (and superposition of an independent trigger bar to each turret in HEPD-02 layout) allow to read-out a subset of the 5 turrets (or 2 planes only), if required to reduce power or dead time.
- The soft processor implements calibration and service procedures (switched-off most of time to save power).
  - Threshold calibration procedure identifies and excludes dead/noisy pixels.



Conclusions

- HEPD-02 ALPIDE tracker will be the **first ever use of MAPS in a space application.**
- HEPD-02 tracker design is a compromise between scientific target and demanding space compliance requirements.
- **Several space compliance tests successfully performed. More to come.**
- Basic ALPIDE performances in HEPD-02 studied. More studies to come.
- **Tracker modules (staves) currently undergoing production.**
- Integration in HEPD-02 flight model scheduled within 2022.