THE CMOS PIXEL SENSORS PARTICLE TRACKER FOR THE CSES-02 SPACE EXPERIMENT

Stefania Beolé
Università degli Studi di Torino & INFN

on behalf of the HEPD-02 tracker team
Università degli Studi and TIFPA, Trento (IT)
IFAC-CNR, Firenze (IT)
Università degli Studi and INFN, Torino (IT)

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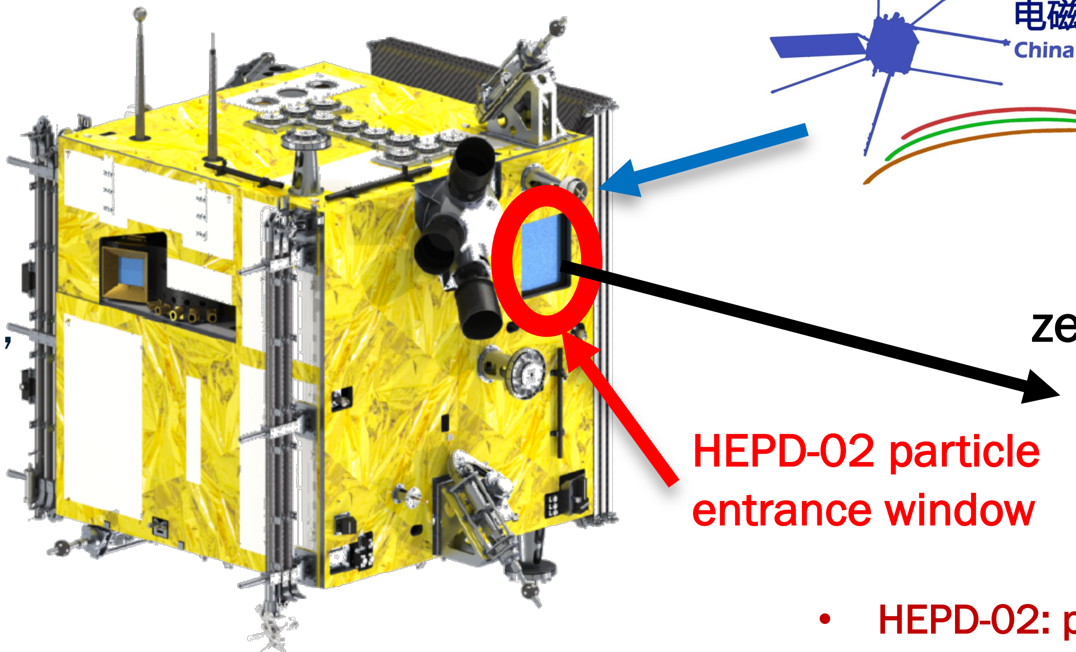
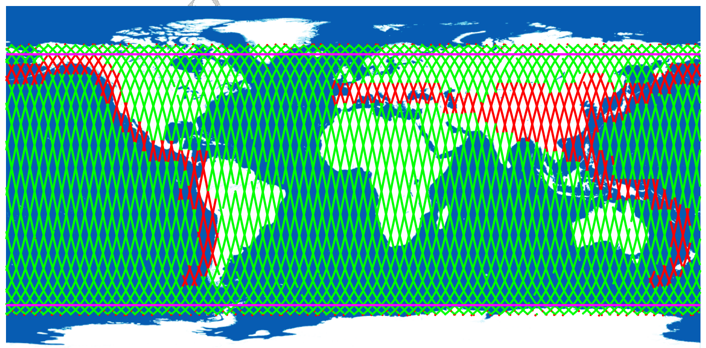
CSES-02 SATELLITE

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.**

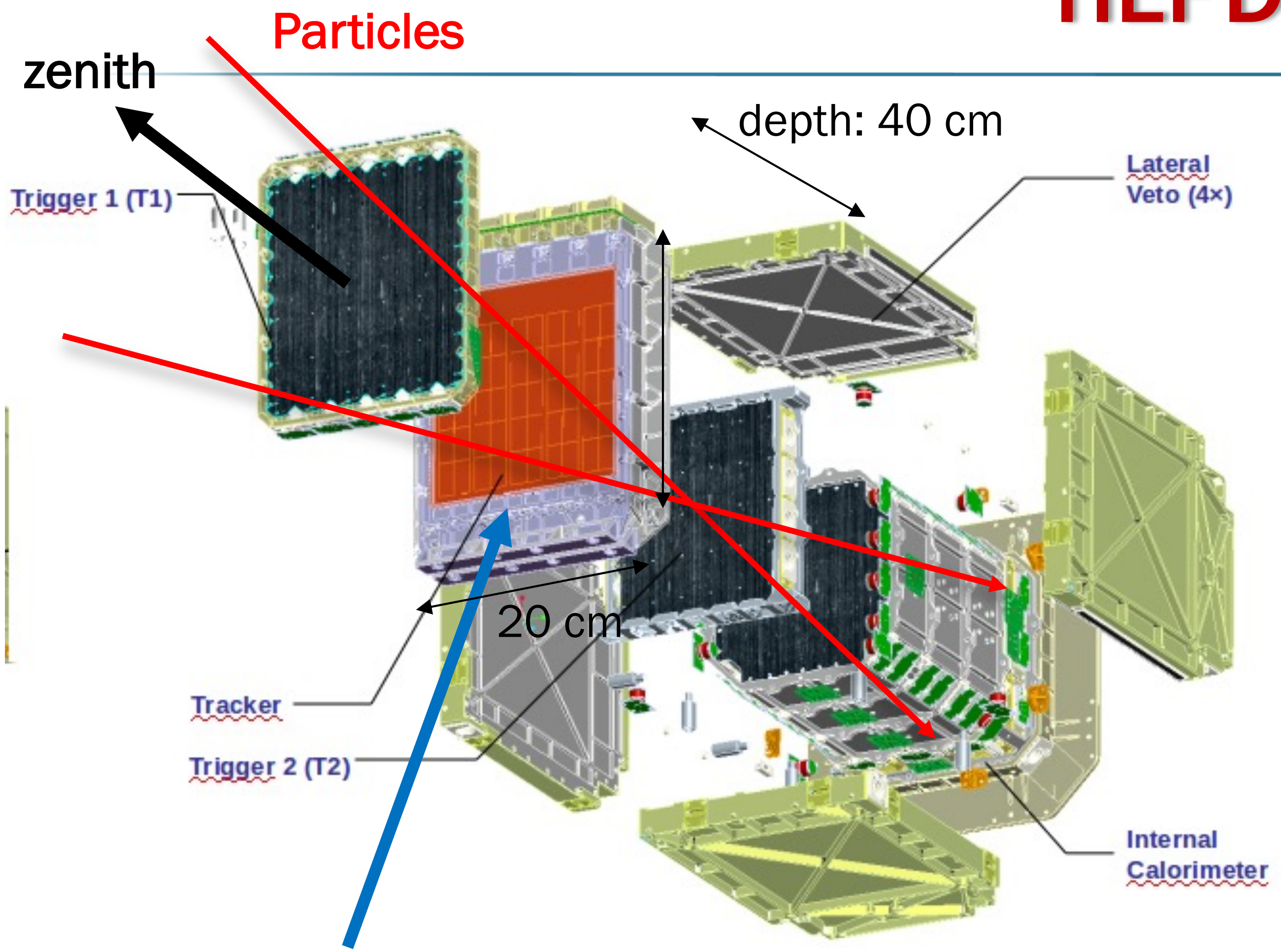




(Courtesy of DFH Satellite Co., Ltd.)

- **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:

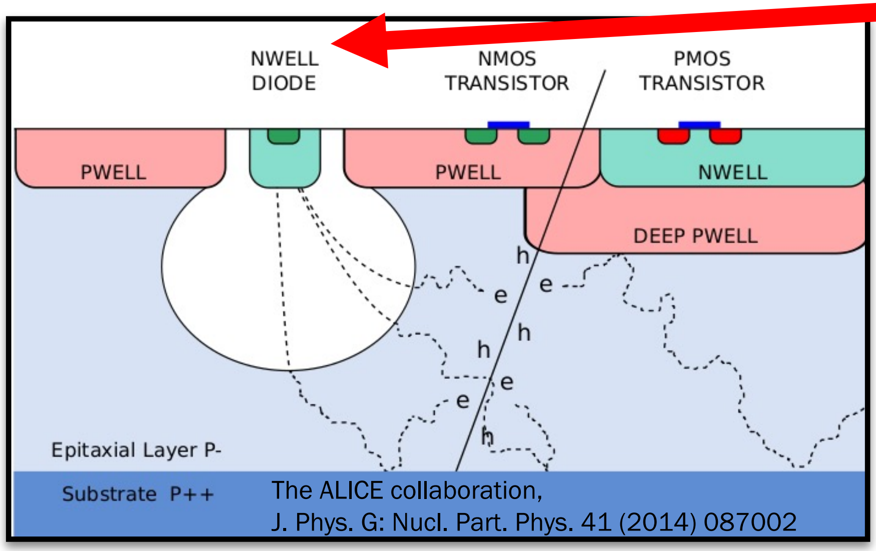
- compact assembly;
- low noise;
- position resolution (for Z=1 MIP): 5 μm.

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 be reduced** to comply with budget;

THE ALPIDE MAPS IN HEPD-02 TRACKER

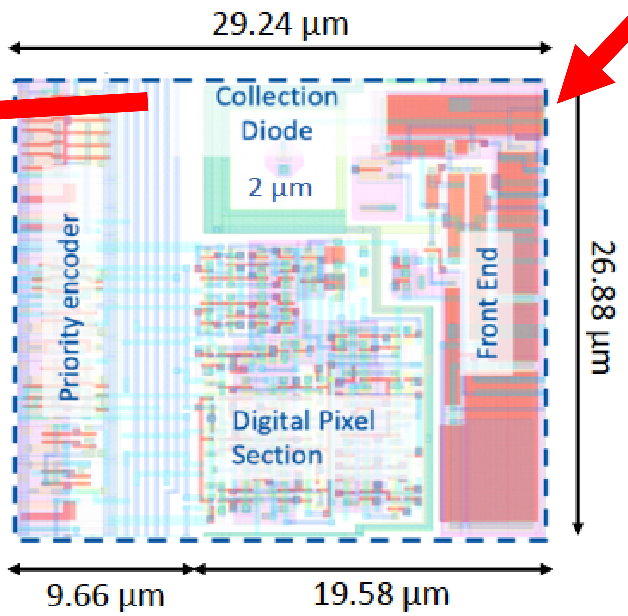
- ALPIDE MAPS was designed for ALICE Inner Tracker (ITS) upgrade at LHC (CERN).
- ALPIDE: **512 x 1024 pixels** in 15 x 30 mm^2.
  - Available thickness 100 or **50 μm.**
  - Back-bias up to -6 V.
  - Charge collection by **diffusion.**
  - **Low noise (<10 e$^-$ / pixel).**

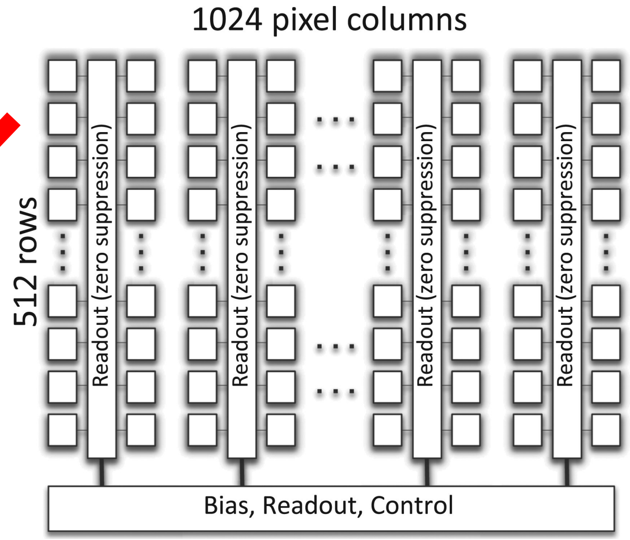


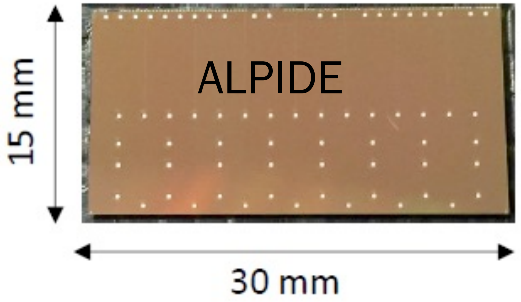
The ALICE collaboration, J. Phys. G: Nucl. Part. Phys. 41 (2014) 087002

- 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







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 maneuver 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.

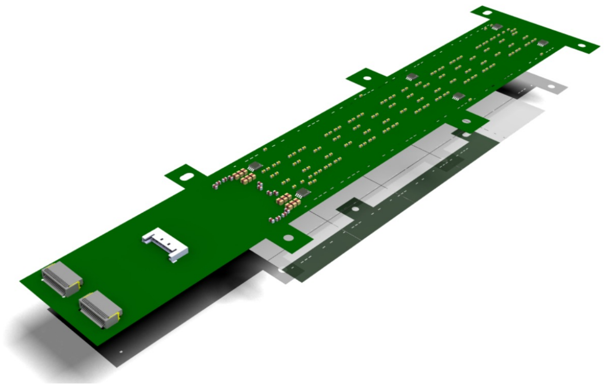
This is especially important for electrons in the lower part of the kinetic energy range of interest (down to 3 MeV).

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

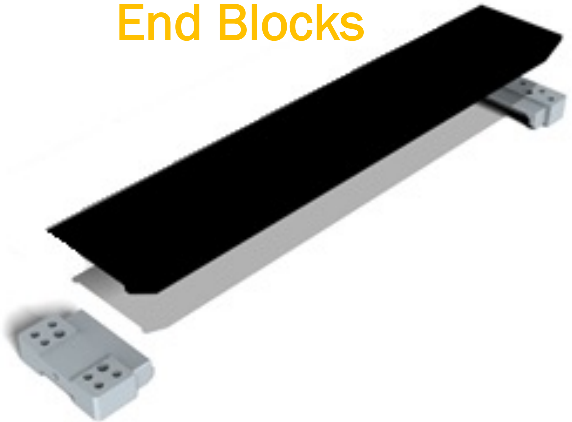
- The tracker design has therefore been driven to possibly find the best achievable compromise between scientific and technological requirements.

HEPD-02 TRACKER DESIGN: HIC AND STAVE

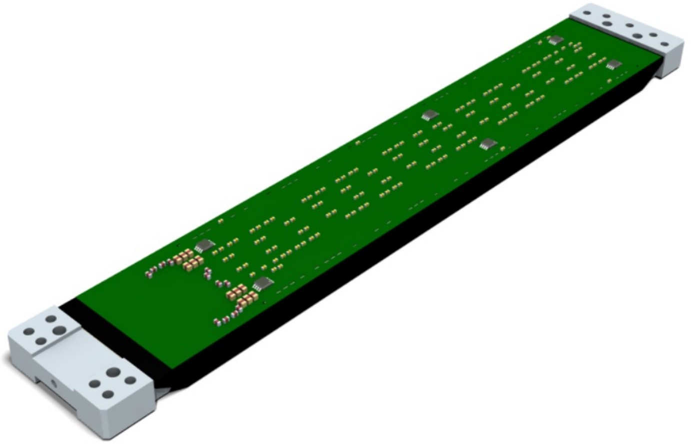
(I) HIC (Hybrid Integrated Circuit): FPC + 10 ALPIDE.



(II) Mechanical support: Cold Plate + End Blocks



(III) Stave: HIC glued to Cold Plate.



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

FPC is glued on top of 2 lines of ALPIDE chips to form the HIC

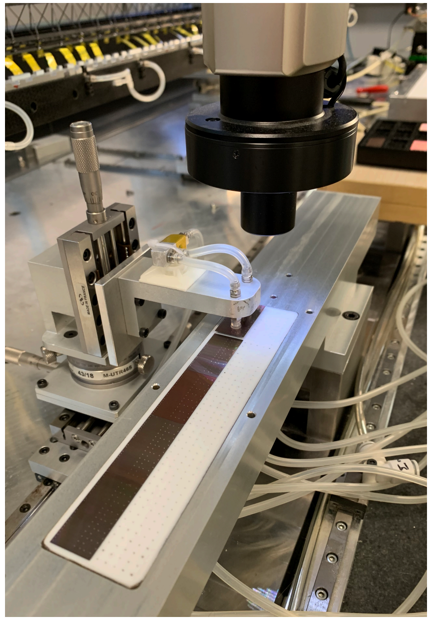
Chips are wire bonded to the pads through holes on the FPC

- 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.

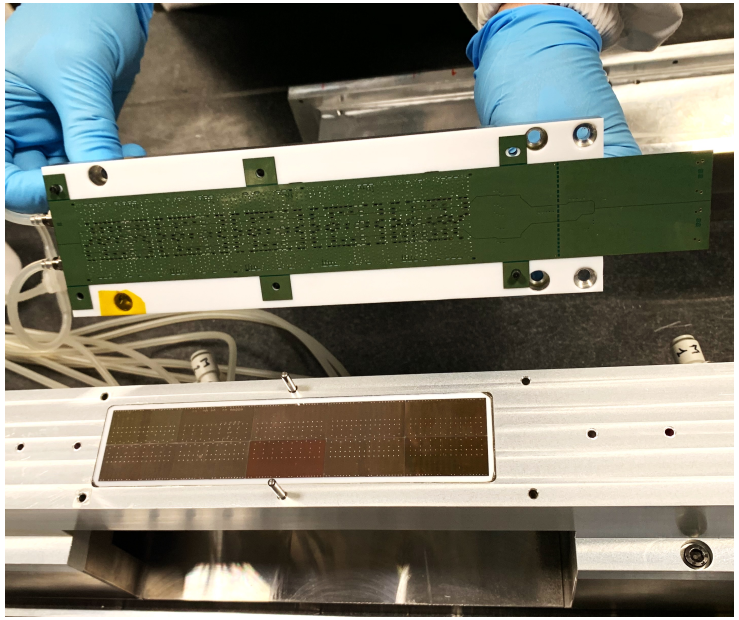
This assembly gives:

- 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.

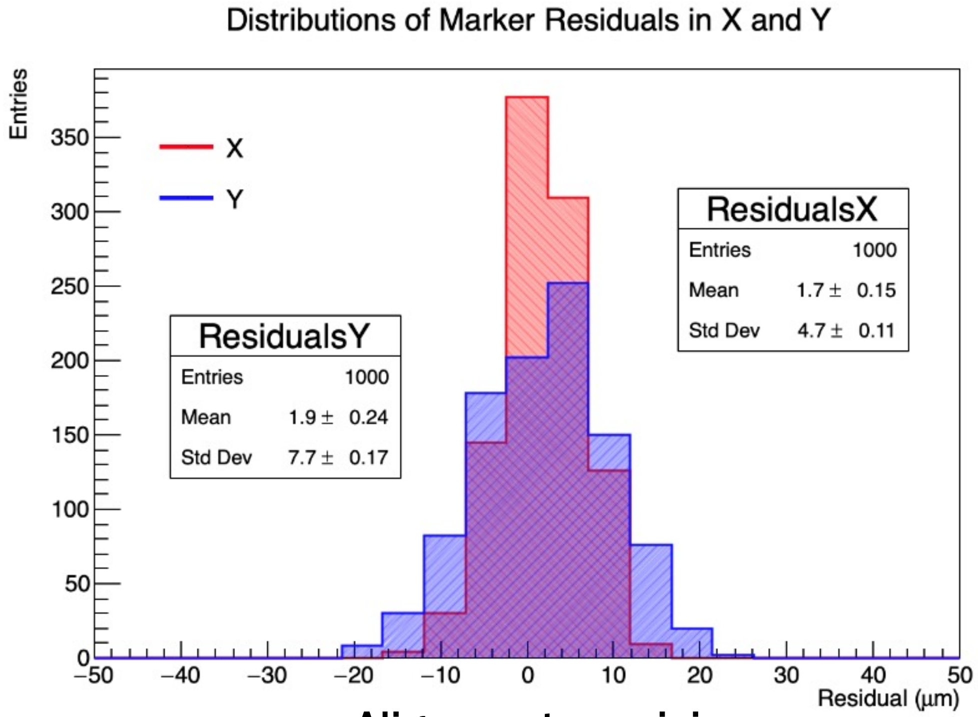
HEPD-02 TRACKER DESIGN: HIC ASSEMBLY



chip positioned using a CMM

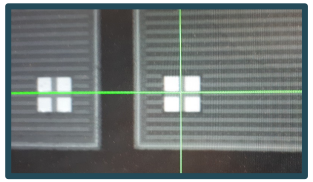


FPC glued on top of the aligned chips

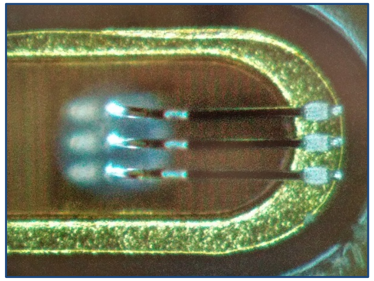


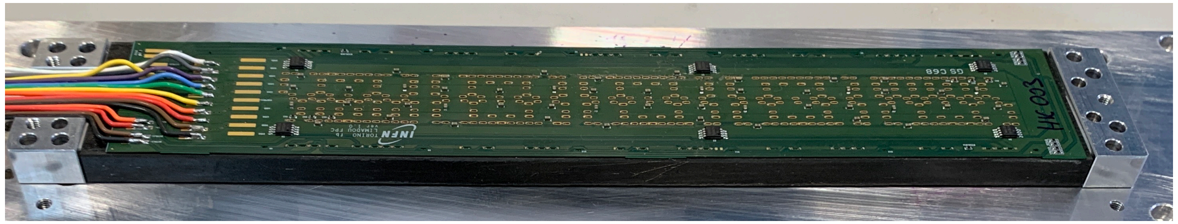
Alignment precision

reference: markers on the chip corners



triple-redundancy wire bonds

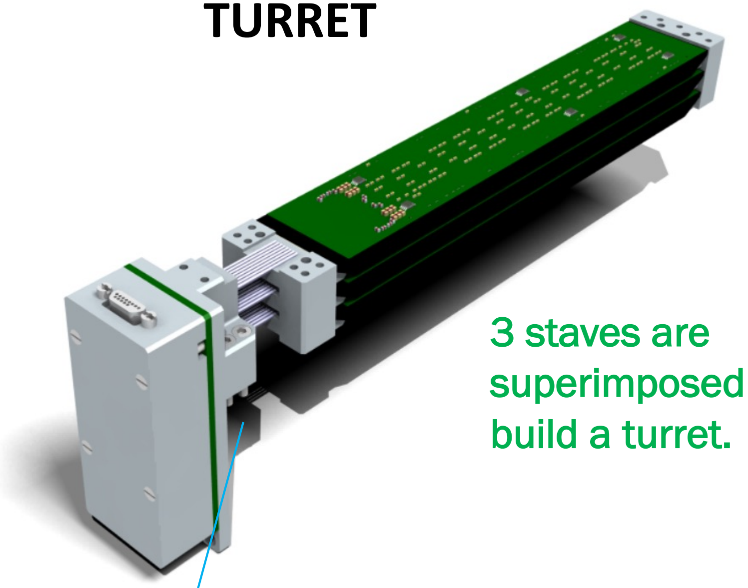




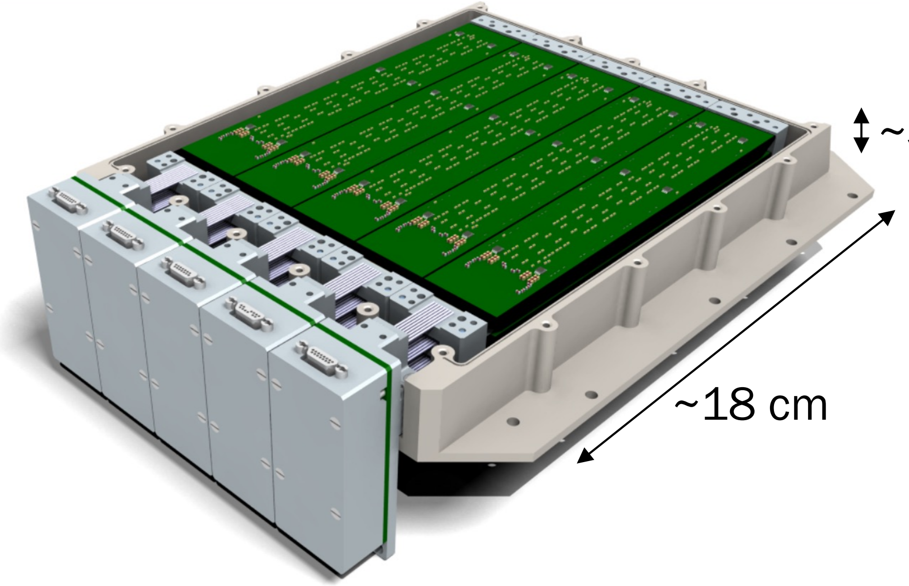
Assembled stave

HEPD-02 TRACKER DESIGN: TURRETS

TURRET



3 staves are superimposed to build a turret.



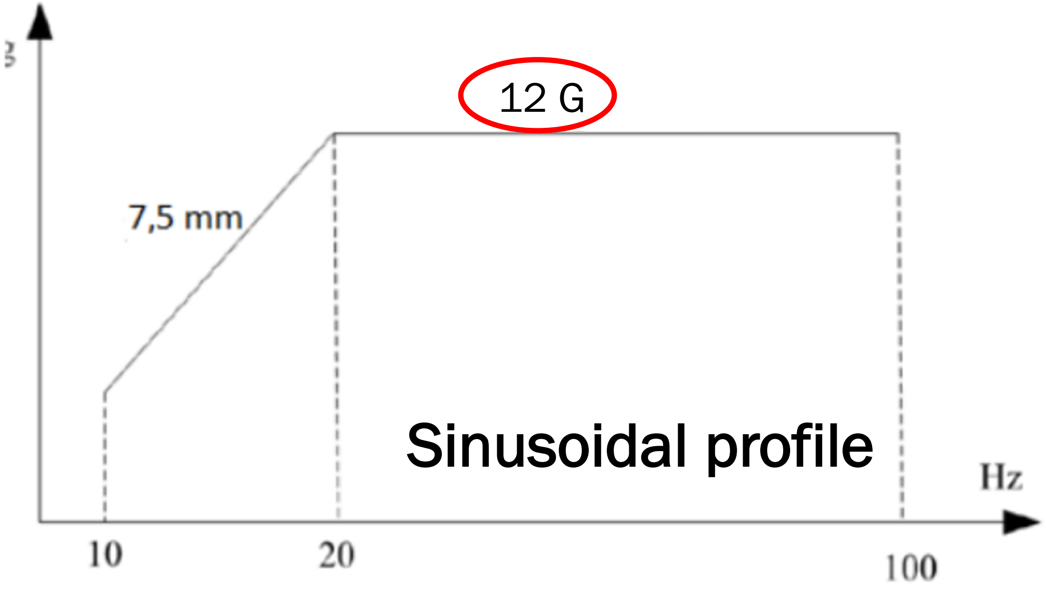
The whole tracker is formed by 5 turrets.

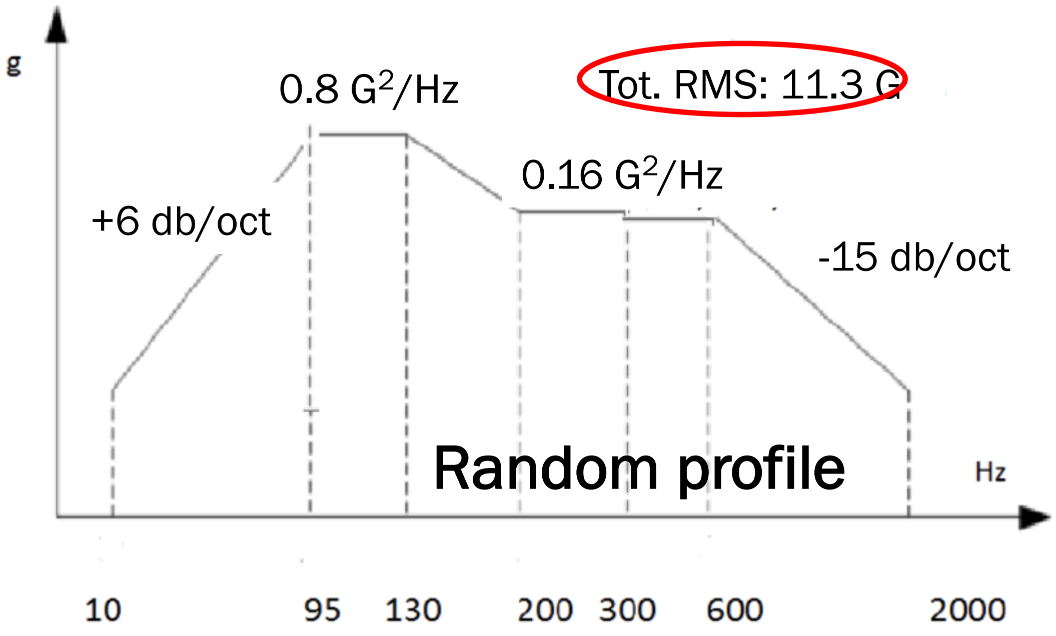
- 15 staves;
- 150 ALPIDE;
- ~ 80 Mpixel in 3 planes.

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 has 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.

SPACE COMPLIANCE: VIBRATION TESTS



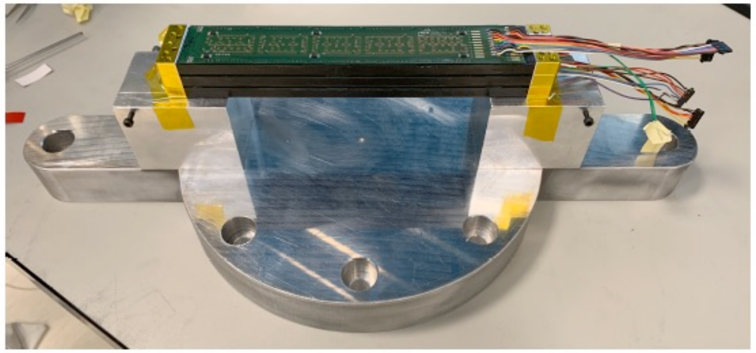


Vibration tests performed on a prototype turret at SERMS, Terni (IT).

- 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** (glues, bonds, solderings etc.);
- **detector performances not affected.**



SPACE COMPLIANCE: THERMO-VACUUM TEST

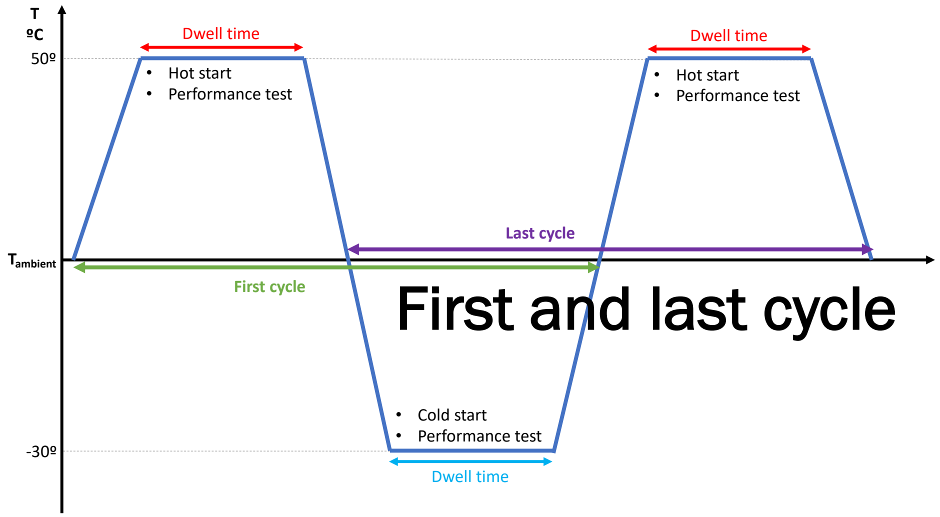
Thermo-vacuum cycle tests performed on a HIC.

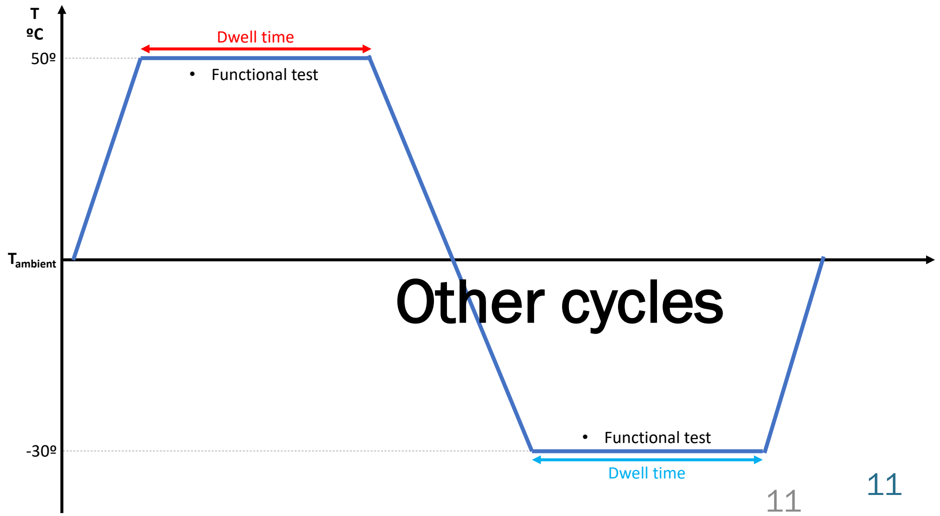
- Test designed to apply thermal stresses in "vacuum", much worse than expected during the flight (as required by Space Agencies).
- Detector performances monitored at low and high cycle temperatures (thermal dwell).

The test was successful for HIC:

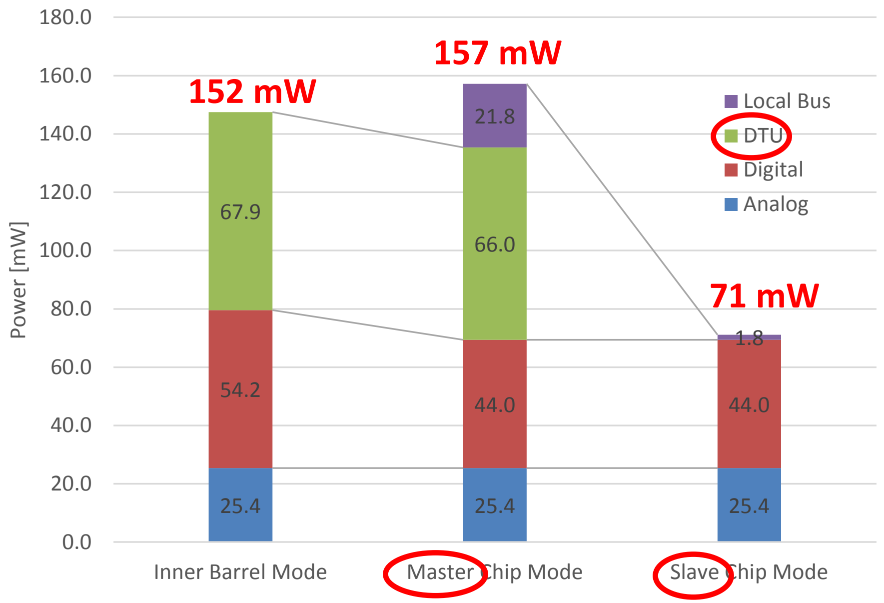
- **no mechanical anomalies** detected on the assembly (glues, wire bonds etc.) after the cycles;
- **detector performances not affected both during and after the cycles.**

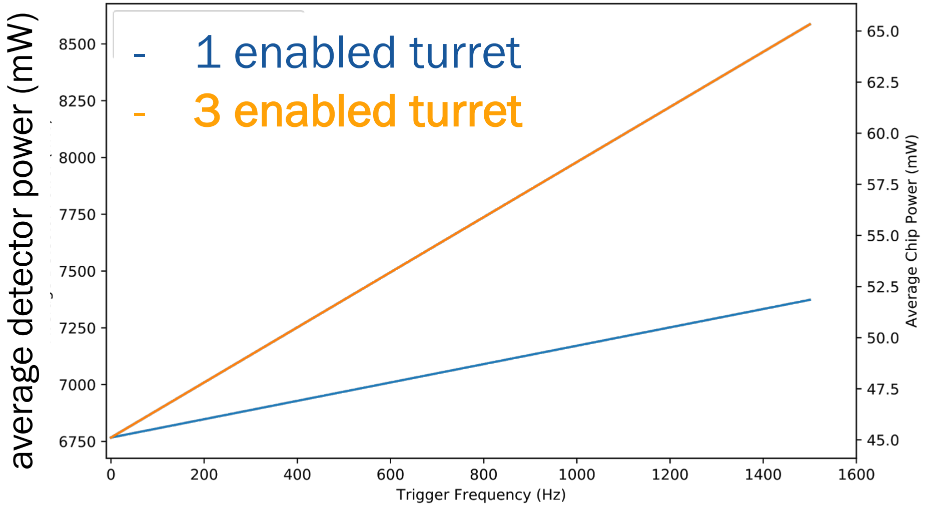
Parameter	Test conditions
Pressure [Pa]	$<6.66 \cdot 10^{-3}$
Hot temperature at fixture [°C]	+50
Cold temperature at fixture [°C]	-30
Number of cycles	6.5
Temperature rate of change [°C/min]	≥1
Dwell time [h]	≥2





SPACE COMPLIANCE: POWER CONSUMPTION MITIGATION





- Several changes of configuration implemented with respect to application in ALICE ITS, to comply with strict power limitation on satellite (~**13 W available for the whole tracker**).

- ALICE ITS OB 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/cm2);
  - wait for signal digitization;
  - transmit data to control/read-out electronics;
  - clock off (7 mW/cm2): wait for new trigger.

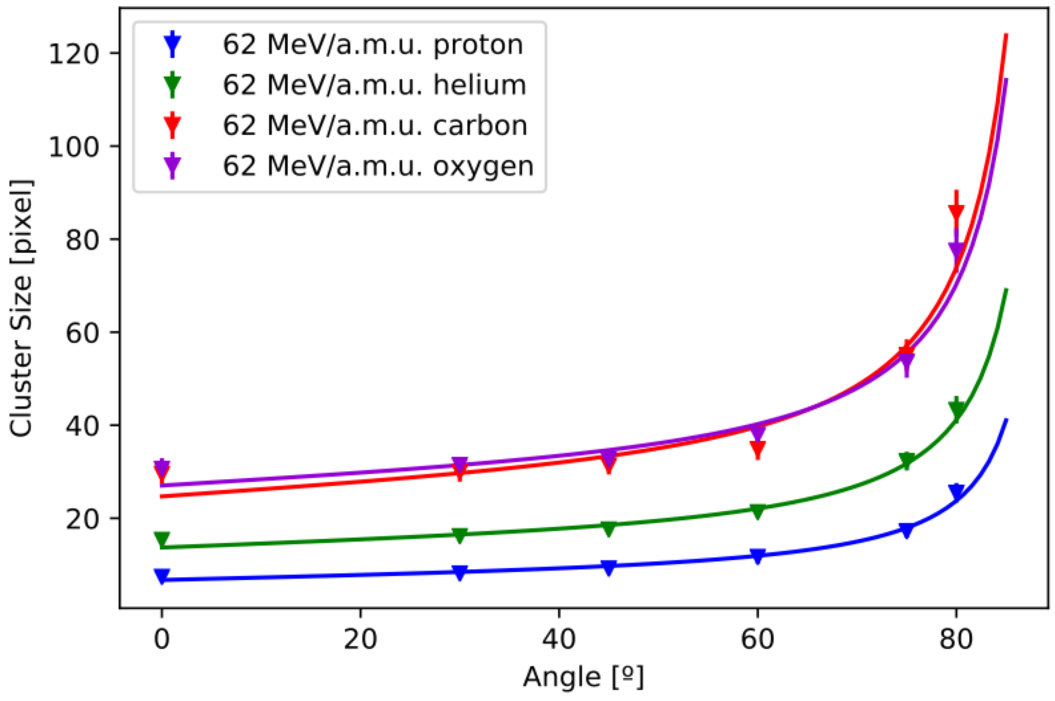
ALPIDE RESPONSE TO LOW-ENERGY IONS

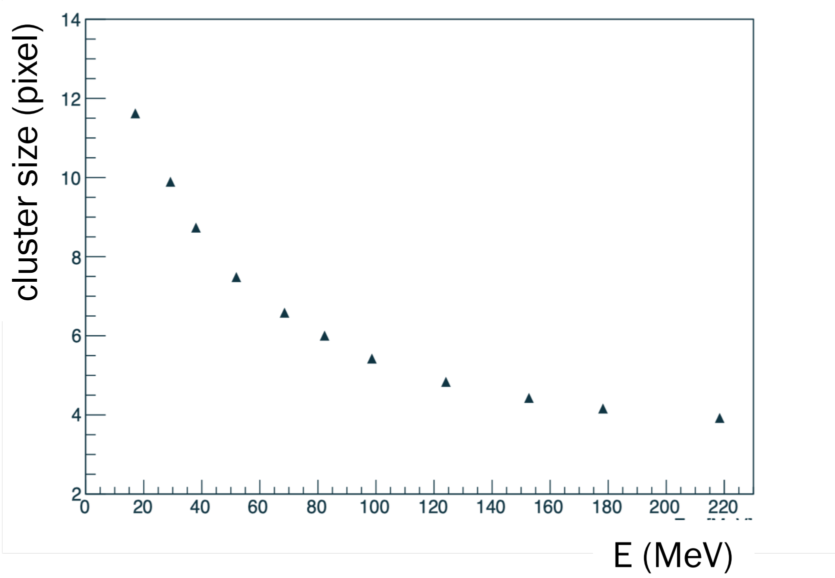
ALPIDE designed and widely characterized for Z=1 MIP detection, for in ALICE at LHC (CERN).

- 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).



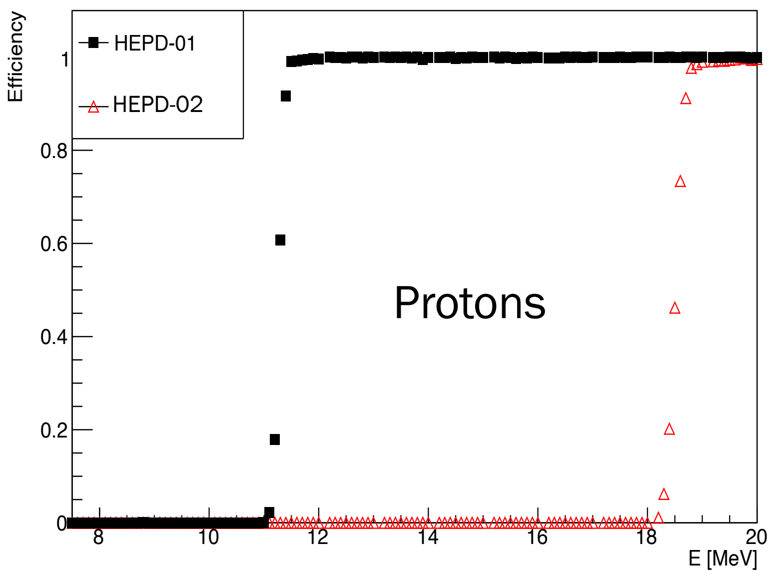


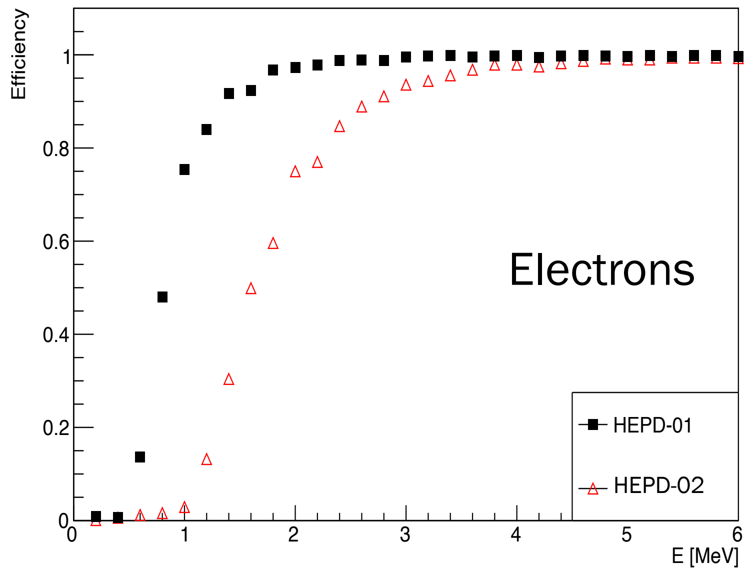
- Having a binary threshold readout, ALPIDE can not be used for measurement of deposited energy (dE/dx).
- A clear dependence of typical cluster size from kinetic energy of the incident particle was measured for low-energy protons and nuclei.

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	Thick [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

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 foreseen.
- **Tracker modules (staves) currently in production.**
- Integration in HEPD-02 flight model scheduled within 2022.

BACK UP SLIDES

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.

tracker

T-DAQ