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Development of a Carbon-fiber reinforced polymer-based mechanics for embedding ALPIDE pixel sensors in the High-Energy Particle Detector space module onboard the CSES-02 satellite

Silvia Coli[a,*], **Massimo Angeletti**[b], **Corrado Gargiulo**[b], **Roberto Iuppa**[c,d], **Enrico Serra**[c]

[a] *INFN-sezione di Torino*
Via Pietro Giuria 1, 10125 TORINO, Italy
[b] *CERN*
Esplanade des Particules 1, 1211 Meyrin, Switzerland
[c] *INFN-TIFPA*
Via Sommarive 14, 38123, Povo (Trento), Italy
[d] *University of Trento*
Via Sommarive 14, 38123, Povo (Trento), Italy

E-mail: silvia.coli@to.infn.it

The mission CSES (China Seismo-Electromagnetic Satellite) will put into orbit satellites to study perturbations in the ionosphere, possibly correlated with the occurrence of seismic events. CSES-02, the second satellite of the constellation, will be supplied with a High-Energy Particle Detector (HEPD), composed by a tracker, a trigger system and a calorimeter, designed for the detection of electrons (protons) in the 3-100 (30-200) MeV energy range. The tracker is based on the innovative monolithic pixel sensors ALPIDE, developed for the ALICE experiment, at CERN. The adaptation of the ALPIDE technology to the use in space environments, demanded for ad-hoc solutions for the mechanics, as supporting structures have to withstand structural and vibrational stresses in a wide energy range, maintaining their capability to dissipate the heat generated by ALPIDE operations. This work presents the HEPD-02 tracker, consisting of 150 pixel sensors, supported by Carbon Fiber Reinforced Plastic (CFRPs) and enclosed in an Aluminum frame, focusing on the limited impact that devised solutions have on the physics performance. We report results from an intense campaign of qualification tests, conducted according to the space register and constituting an important premise for using monolithic active pixel sensors in future space cosmic ray experiments.

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* Presenter

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1. The HEPD-02 tracker concept

The HEPD-02 Tracker was developed with a particular focus on the aspects of modularity and compactness. A single stave was expanded three times in the out-of-plane direction and five times in the in-plane direction to form the desired read-out pixel surface. To satisfy the alignment requirements for the pixel sensor in-plane and out-of-plane distribution, the pixel support CFRP staves were clamped by auxiliary metal blocks which set the tolerances in the final assembly.
Going into details, as shown in Fig.1, the stave is made as a hierarchical structure with a Hybrid Integrated Circuit (HIC) glued to the carbon fiber Cold Plate (CP) and clamped with the aluminum end blocks.
The fundamental building block of the tracker is the HIC, which consists of 10 fifty microns thick ALPIDE chips, distributed in 2 rows of 5 chips each and connected to a common Flexible Printed Circuit (FPC) through glue and bonding wires. On one side of the FPC, pads for the electrical connection are located.

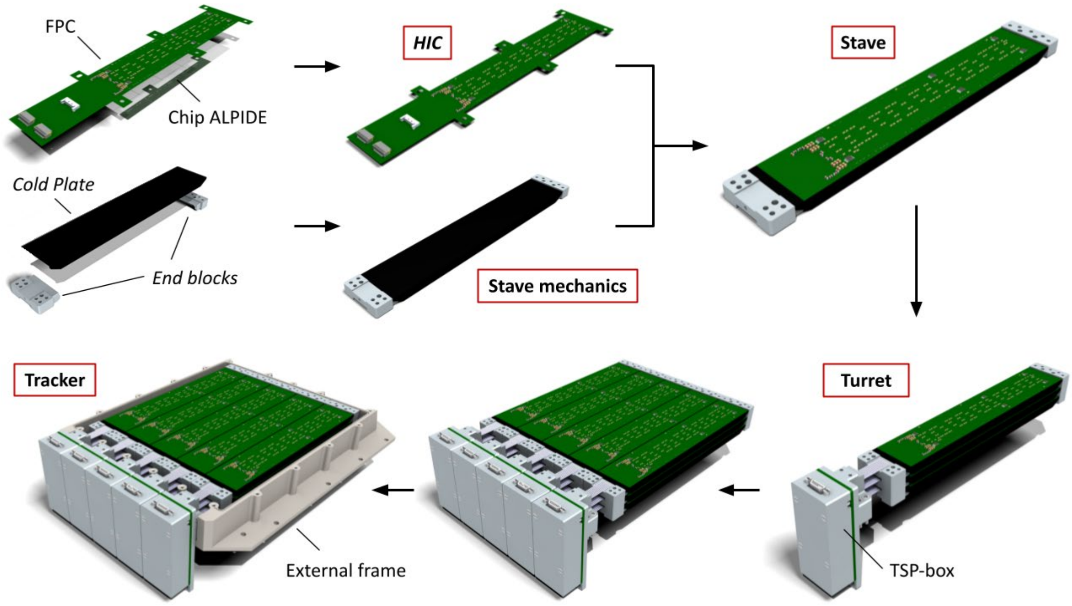


Fig. 1 Description of the HEPD Tracker particles.

In the experiment, the cooling system completely relies on the conductivity of the materials which stand between the chips and the thermal plate of the entire HEPD-02. For the end-blocks and external frame, in contact with thermal plate, aluminum has been adopted.
Since the tracker will be subject to structural and thermal stress, carbon fiber with high module and high thermal conductivity was chosen as the material for HIC mechanical support (the Cold Plate) with the purpose of minimizing the temperature gradients on the CP due to chip power dissipation (about 0.8 W/stave). At the same time, the tracker structure must have the lowest possible impact on the material budget, in order not to degrade the detector tracking performance. To deal with all these requirements, properly oriented plies made of unidirectional carbon fiber K13D2U with cyanate ester pre-preg resin EX1515 have been identified as the optimal material choice for the CP.

2. Cold Plate Design Layout and manufacturing process:

High thermal conductivity, high stiffness and low material budget are the requirements that drive the design for the support structures.
In order to enhance the structural strength and to optimize the thermal efficiency, a C-shape was chosen for the Cold Plate, consisting in a flat thin part and two lateral ribs; the flat part of the C-shape lies under the chip region (see Fig 2).

Fig. 2 Carbon Cold Plate (CP) and constituent materials

The Cold Plate is composed of different plies of carbon fibers K13D2U embedded with cyanate ester resin EX1515. Two layers of Fleece roll up both the top and bottom sides. On the flat part the carbon layout is [90;0;90] and on the lateral part 14 plies at 0° are stack together as shown in Fig. 3:

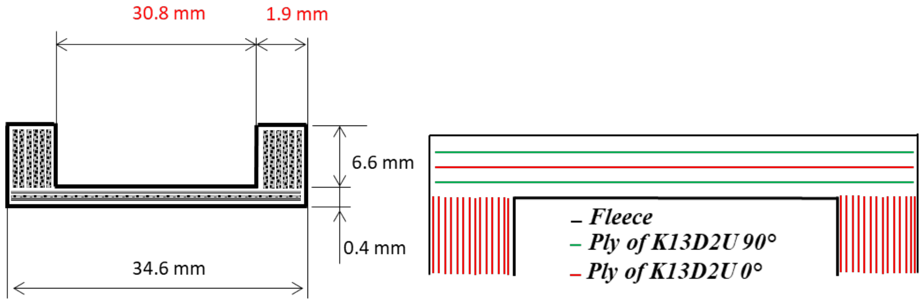


Fig. 3 CP pre-preg plies layout.

A dedicated mold was designed for the production of the part (Fig.4). It consists of four parts with two Teflon pins ensure the alignment of the different components. The lamination begins after all the plies were cut. The different carbon plies are laminated on the mold. The plies of fleece are applied to close the laminate. The different parts of the mold are then assembled. A non-porous release film is surrounded all the mold to avoid the excess of resin to be stacked to the bleeder or to the vacuum bag. A bleeder is used around the mold to protect the vacuum bag and ensure a good homogeneity of the vacuum inside the bag. The vacuum part is then placed into the autoclave where the polymerization cycle is applied.

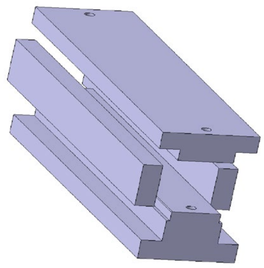


Fig. 4 Mold exploded view

3. Measures and test campaign

The Cold Plate mechanics production is based on a non-conventional use of carbon material. For this reason, the Cold Plate manufacturing and the characterization of the cold plates have been managed by the EP-DT department at CERN (Experimental Physics- Detector Technology) which has experience in serial productions of similar structures. An intense campaign of measurements and tests have been conducted on Cold Plates, stave and turret elements to assess thermal, thermo-elastic stiffness and planarity characteristics.

3.1. Cold Plate CTE measurements:

The Coefficient of Thermal Expansion (CTE) measurement has been performed inserting Cold plate specimens of side ribs and plate in a dilatometer while temperature increased till 70°C with a ramp of 0.5°/min. In Fig. 5 the specimens orientations and the test set up are presented.

Fig. 5 Set-up used for the specimens CTE measure

The results indicate a CTE always < 5 ppmC^{-1} for all the specimens.

3.2. Cold Plate thermal conductivity measurements:

For the test of the CP thermal conductivity measure, two custom-made setups were realized and employed to perform temperature measurements for the CP heated in a vacuum chamber (see Fig.6).

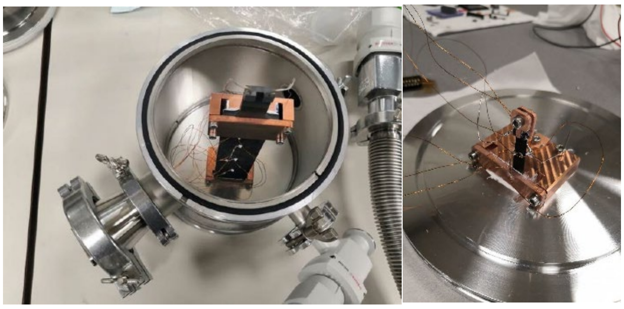


Fig. 6 Set-up used for the thermal conductivity measure

Detailed Finite Element (FEM) models of the test setups have been employed to assess and support the consistency of the thermal measurements. The global thermal conductivity of the cold plate along the longitudinal-direction, about 343-367 W/mK, was determined by means of the thermal measurements and was then confirmed by FEM analysis results. Analogously, the thermal conductivity along the transversal-direction, about 173-180 W/mK was determined starting from a direct measurement on a narrow slice and confirmed by FEM analyses. The thermal conductivity of the lateral ribs along the longitudinal-direction was analytically estimated under simplifying assumptions. The obtained values, about 464-516 W/mK, prove the major role in the ALPIDE heat dissipation of the ribs. The global conductivity in the CP longitudinal and transversal directions ensure a thermal gradient below 6°C along the CP as shown in Fig.7:

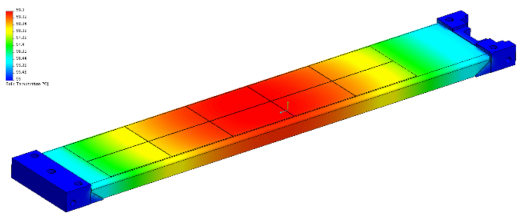


Fig. 7 Thermal analyses in case of power dissipation on CP both sides

3.3. Bending Test:

Each Cold Plate has been systematically undergone to a three-point bending test.

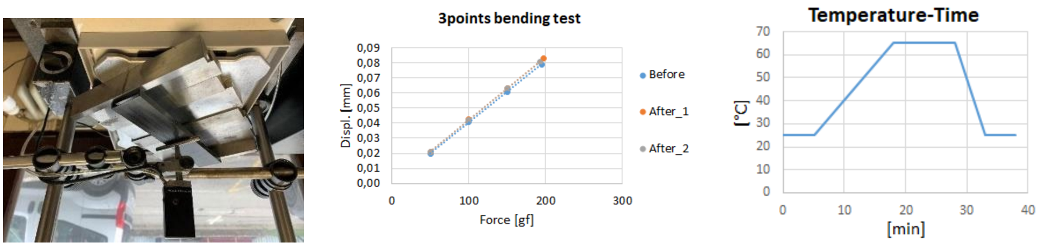


Fig. 8 Set-up used for the bending test with a linear behavior before and after thermal cycle

A bending test has been conducted also after a thermal cycle to verify the elastic properties changes, but the values confirm the same mechanical properties before and after thermal test, as shown in Fig.8.

3.4. Strain Test:

Mechanical staves (end blocks + Cold Plate) have been assembled for the strain test. The test aimed to determine the thermally induced strains in the glue layer between the cold plate and the end block by the differential expansion of both materials. It was performed in a laboratory furnace (heating rate 0.5 °C/min) with 3 temperature sensors attached to the back surface of the CP and a Digital image correlation system to observe the strain. Results are presented in the last picture of Fig. 9.

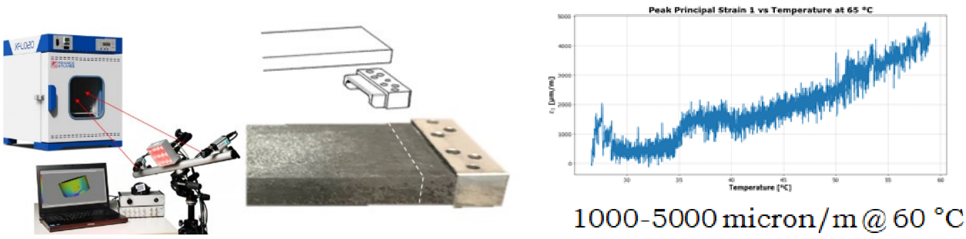
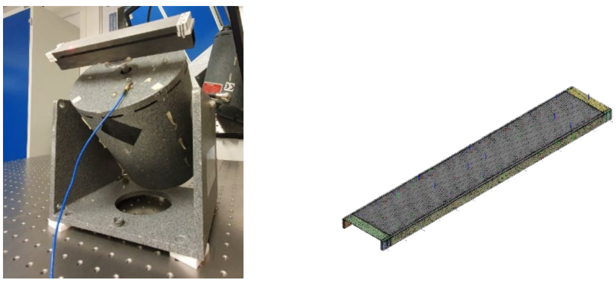


Fig. 9 Test set up and results for strain test with a ramp till 65°C.

3.5. Vibration Test:

The Cold Plate and the mechanical stave (Cold plate + end blocks), have been submitted to a vibration test. In Fig. 10 the vibration test set up used for the modal analysis test is shown. The Input power spectral density comes from an excitation source as a loudspeaker or a shaker.



	Frequency [Hz]	Mode Shape
1	803	Rotation
2	1038	Bending
3	1534	Bending
4	2201	Rotation
5	2567	Bending
6	2878	Bending
7	3091	Bending
8	3377	Bending
9	3590	Bending
10	3905	Bending

Fig. 10 Set up for vibration test

The test allows to evaluate the natural frequencies of the Cold Plate connected to the end blocks and to tune the FE Model to match Modal test results on free-free configuration. The results, in Fig. 11, show the first mode at about 800 Hz.

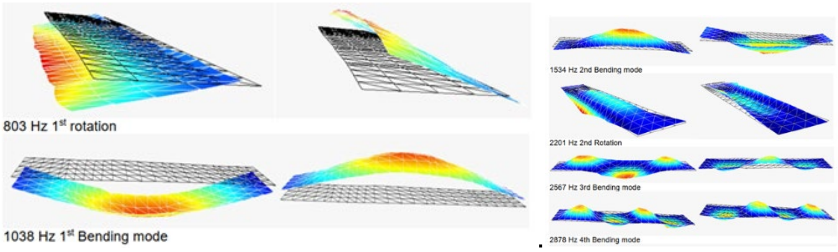


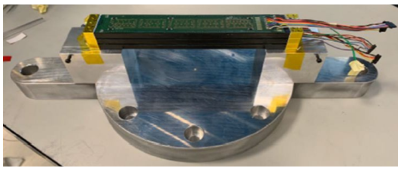
Fig. 11 Vibration test results

3.6. Vibrational Test on Engineering Model:

An Engineering Model (EM) version of a stave and a Turret have been submitted to a vibrational test in compliance with CSES environmental test requirements.

1.The tests consist of 4 steps, repeated for the 3 axes:
2.First resonance search Sine wave test
3.Random test
4.Second resonance search

The final results for resonance, presented in Fig. 12, confirm the values founded in the vibration test during CP characterization:



Axis	f_n [Hz] single STAVE	f_n^* [Hz] single TURRET
Z	832.8	842.5
Y	1092.0	1150.0
Z	1741.6	1634.6
X	1792.5	1625.2

Fig. 12 EM vibrational test results

No changes in results of resonance occurred between the first and the last measure, and no changes in the functional test, the vibrations did not damage the stave/turret mechanical structure, neither the HIC functionality and the model was validated.

3.7. Thermal cycle test:

Thermal cycles have been conducted with a stave positioned on an aluminum plate, reproducing two ways of the turret connections to the external frame: with the cursor system, shown in Fig. 13, or with fixed screws.

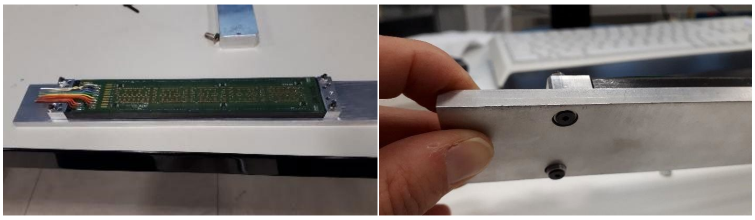


Fig. 13 Thermal cycle test set up with cursor system

The cursor system consists of 2 sockets with Teflon washers connected to the stave through the frame on one side and fixed screws on the other side. The cursors on one side can slide along a slot, allowing the external frame to move with respect to the staves. This system has been implemented to compensate the dilatations due to different CTE (aluminum of frame and carbon fiber of CP) for thermal gradients. Each thermal cycle has been performed in compliance with temperature and ramp qualification requirements.

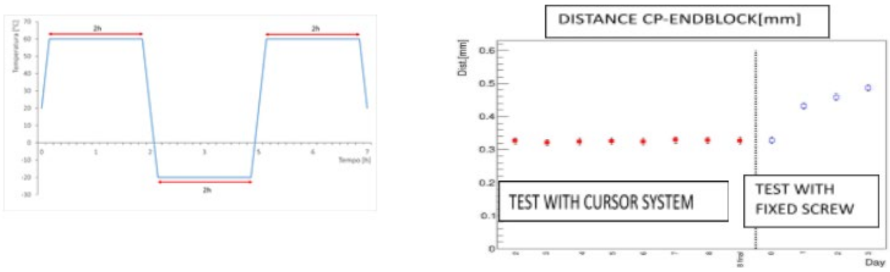


Fig. 14 Thermal cycle and test results

Test, conducted with the cursor system and without, shows variations in distances between CP and end blocks, measured after each thermal cycle, for the two connection systems. After 8 thermal cycles with the cursor system, the distances between CP and end blocks are always below 20 µm; after the first thermal cycles without the cursor system, differences grow up to 150 µm on one side as shown in Fig. 14.

4. Assembly

The assembly of the turret implies three main steps characterized by dedicated jigs and a Reference System replicated on each one of them. The three main steps are: the HIC assembly, the Stave Assembly and the Turret Assembly

The stringent requirement in chip positioning below 50 microns is driven by the need for a precise alignment between chip pads and FPC holes, to allow the wire bonding operation.

All the steps which require precision in components positioning below 100 µm are performed with the use of a Coordinate Measuring Machine (Mitutoyo Crista Apex 9206).

For the assembly, dedicated software programs with CMM have been developed to guide the operator during chip alignment and assembly procedure, avoiding human errors and helping in the numerous operations.

For the HIC assembly, the precision in positioning obtained on the actual production can be resumed in the distribution shown in Fig. 15.

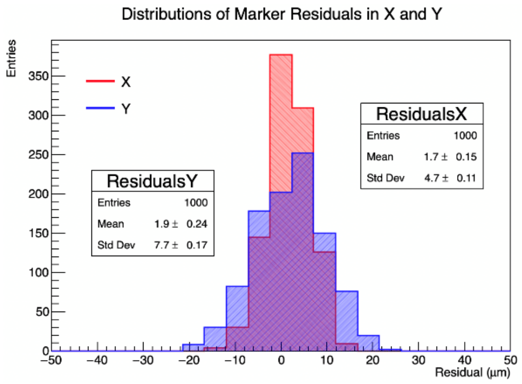


Fig. 15 Residuals distribution in HIC production

5. Conclusion

The HEPD-02 tracker is the results of optimized geometries and materials in order to withstand the elevate structural and vibrational stress in an extended range of temperature occurring during launch phase, complying with the scientific objectives. An intense campaign of test has been conducted according to the space standards.

References

[1] NIMA, Volume 824, 11 July 2016, Pages 434-438

[2] Rinella G.A. 2017 Nucl. Instrum. Methods Phys. Res. A 845 583

[3] Zherebchevsky V.I. et al 2018 J. Instrum. 13 T08003