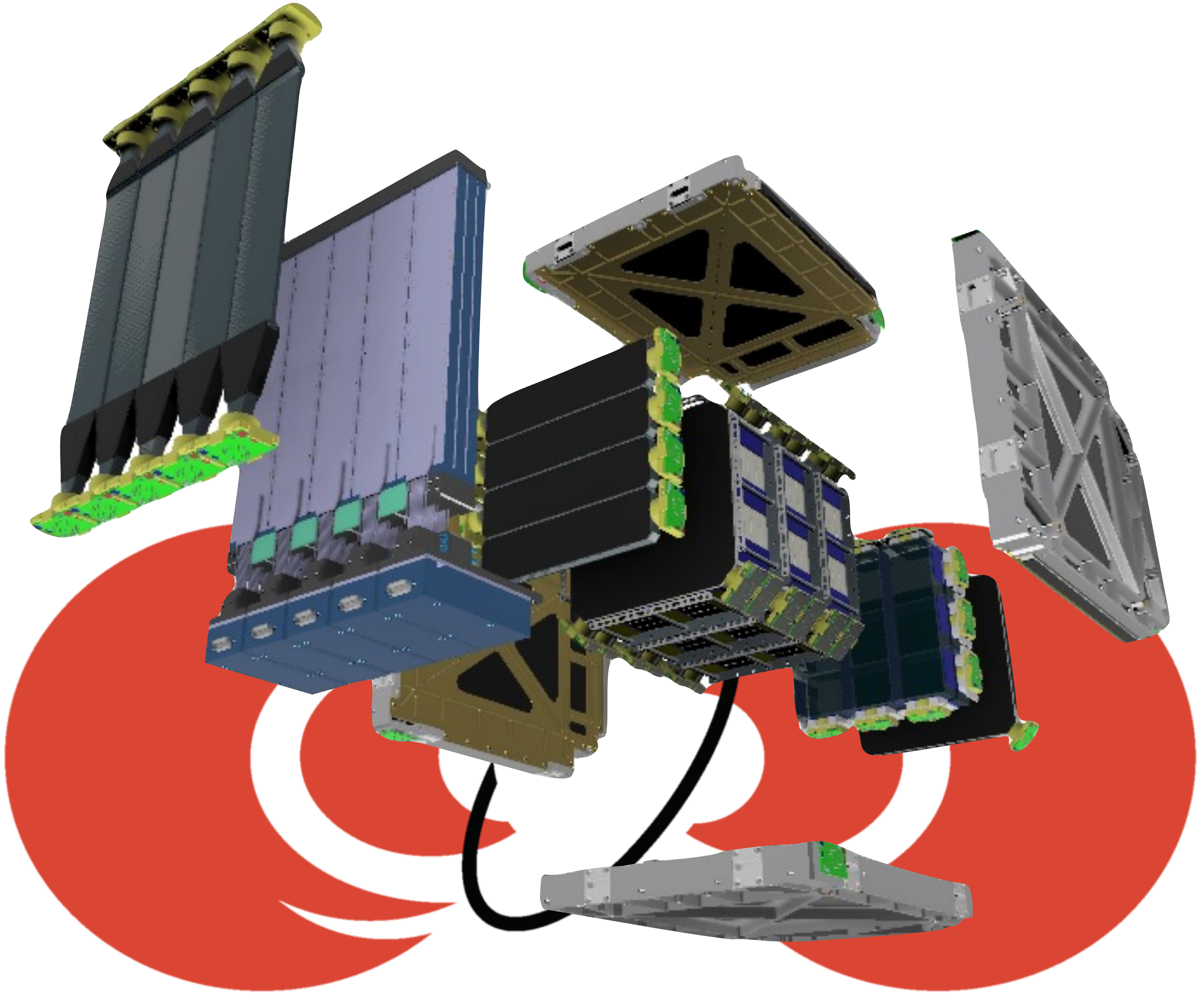
UNIVERSITÀ DI TORINO
INFN TORINO

The novel direction detector on board of the second China Seismo-Electromagnetic Satellite

Innovative Detectors & Data Handling Techniques

Umberto Savino
on behalf of the CSES-Limadou collaboration



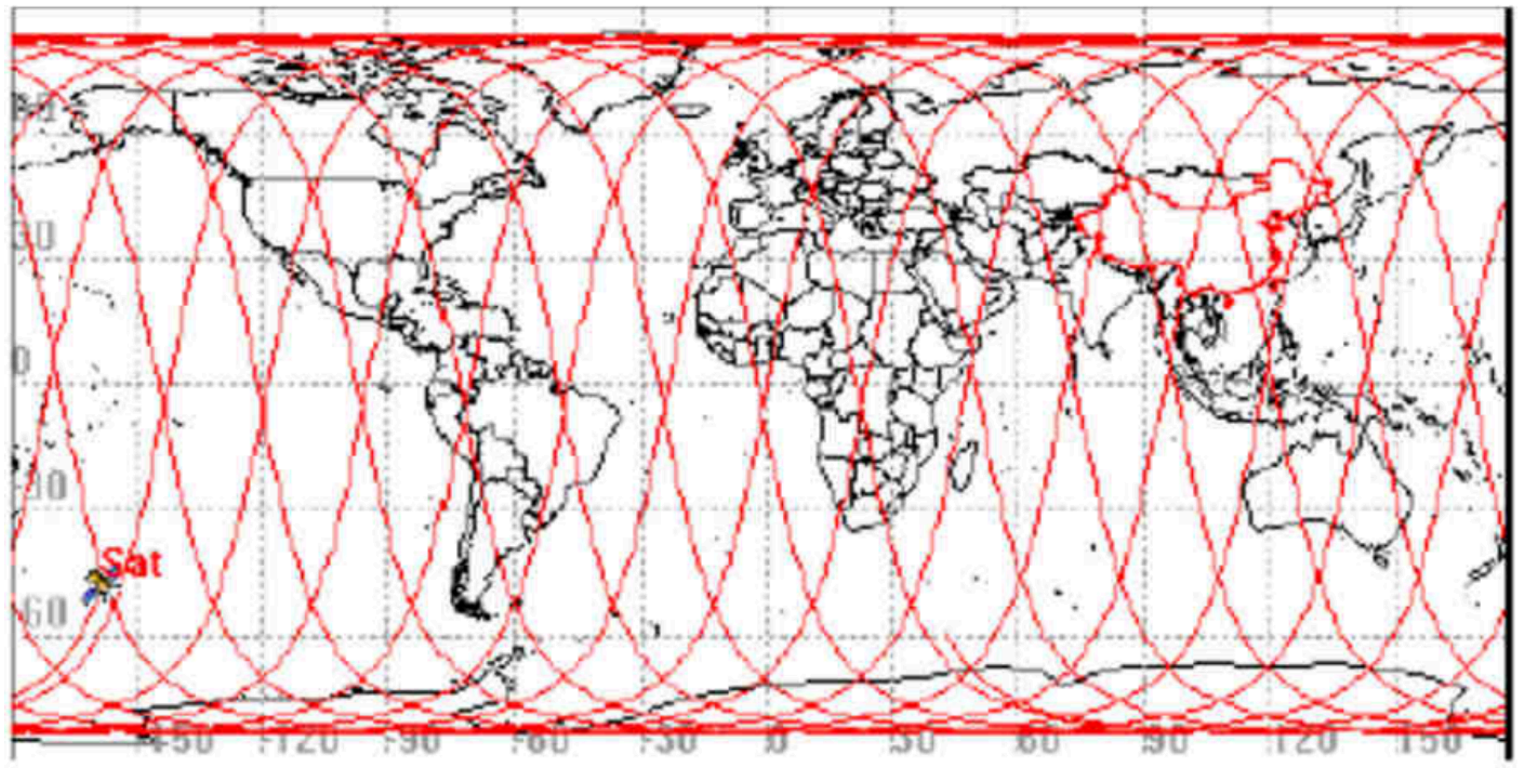
LIMADOU 利瑪竇

CRIS-MAC 2024
13th Cosmic Ray International Studies and Multi-messenger Astroparticle Conference
Trapani, Italy, June 17 – 21, 2024

CSES-02 scientific mission objectives

- Monitoring of the electromagnetic near-Earth space environment
- Analysis of the ionospheric and plasmaspheric fluctuations
- Measurements of iono-magnetospheric perturbations possibly due to seismo-electromagnetic phenomena
- Study of fluxes of high & low energy charged particles precipitating from the Inner Van Allen radiation belt
- Measurements of magnetospheric and solar activity
- Monitoring of the e.m. anthropic effects at low Earth orbit altitude
- Observations of e.m. transient phenomena caused by tropospheric activity

CSES-02 planned orbit
-82.6° to +82.6° latitude
500 km altitude
Sun-synchronous
180° phase difference wrt CSES-01
Operating temperature: -30 to +50°C
Operating pressure:6.65·10-3 Pa



CSES-02 main characteristics
Orbit maneuver capability
Full-time operational
Mass: 900 kg
Power: 900 W
Storage: 512 Gbyte
Life cycle: > 6 years

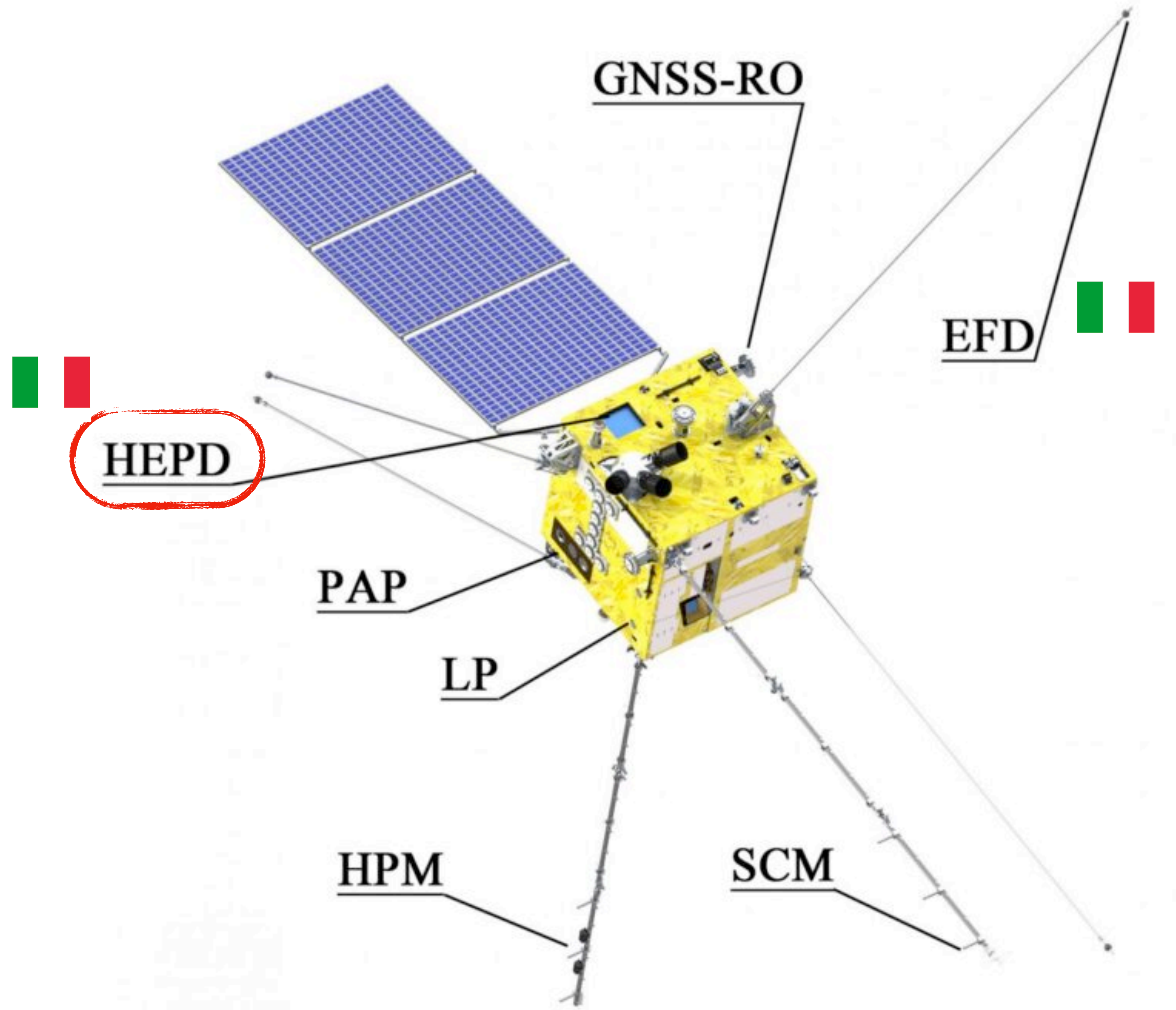
CSES-02 payload

The High Energy Particle Detector on board of CSES-02

First detector hosting monolithic active pixel sensors (MAPS)
for the tracking of charge particles in space

HEPD-02 main requirements

Data budget	100 Gb/day
Mass budget	50 kg
Power budget	45 W
Electron kinetic energy range	3 MeV ÷ 100 MeV
Proton kinetic energy range	30 MeV ÷ 200 MeV
Angular resolution	≤10° for e^- with E > 3 MeV
Energy resolution	≤10% for e^- with E > 5 MeV
Pointing	Zenith



https://cses.web.roma2.infn.it/?page_id=198

Scientific goals and main features

> measure the increase of the electron and proton fluxed due to short-time perturbations of the radiation belts

> detect different particle populations (solar, trapped, galactic, etc.) according to the satellite position and energy

> implements trigger configuration dedicated to gamma rays on a time basis of 5 milliseconds

High Energy Particle Detector (HEPD-02)

- front trigger plane (200×180 mm^2)
  5 plastic scintillator bars (2 mm thick)

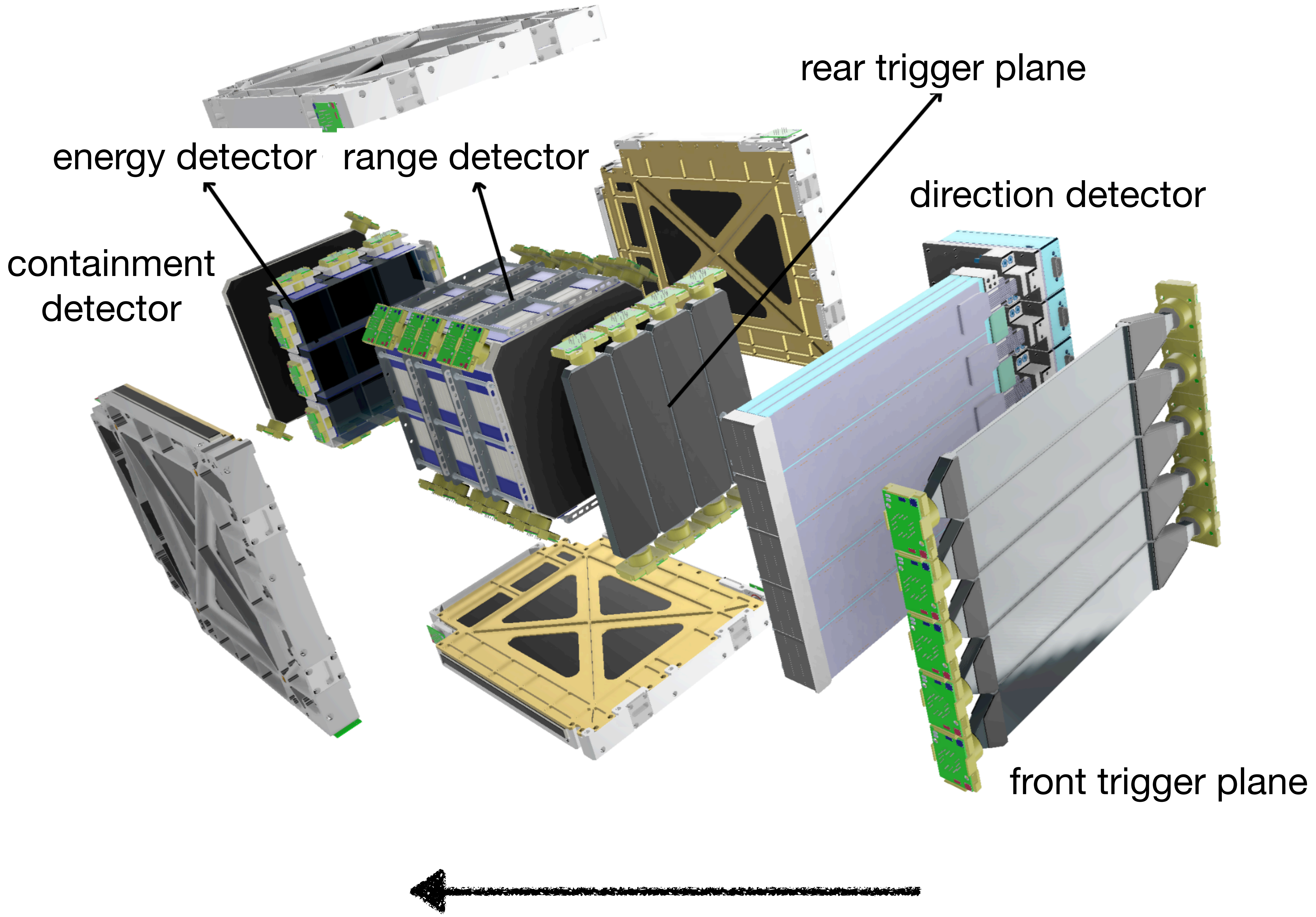
- direction detector (tracker)
  five standalone tracking modules

- rear trigger plane (150 x 150 mm^2)
  4 plastic scintillator bars (8 mm thick)

- range detector (150 x 150 x 10 mm^3)
  12 plastic scintillator planes

- energy detector (150 x 150 mm^2)
  2 crystal (LYSO) scintillator planes
  3 x 2 bars (25 mm thick each)

- containment detector
  plastic scintillator planes (8 mm thick)
  4 lateral and 1 bottom plane



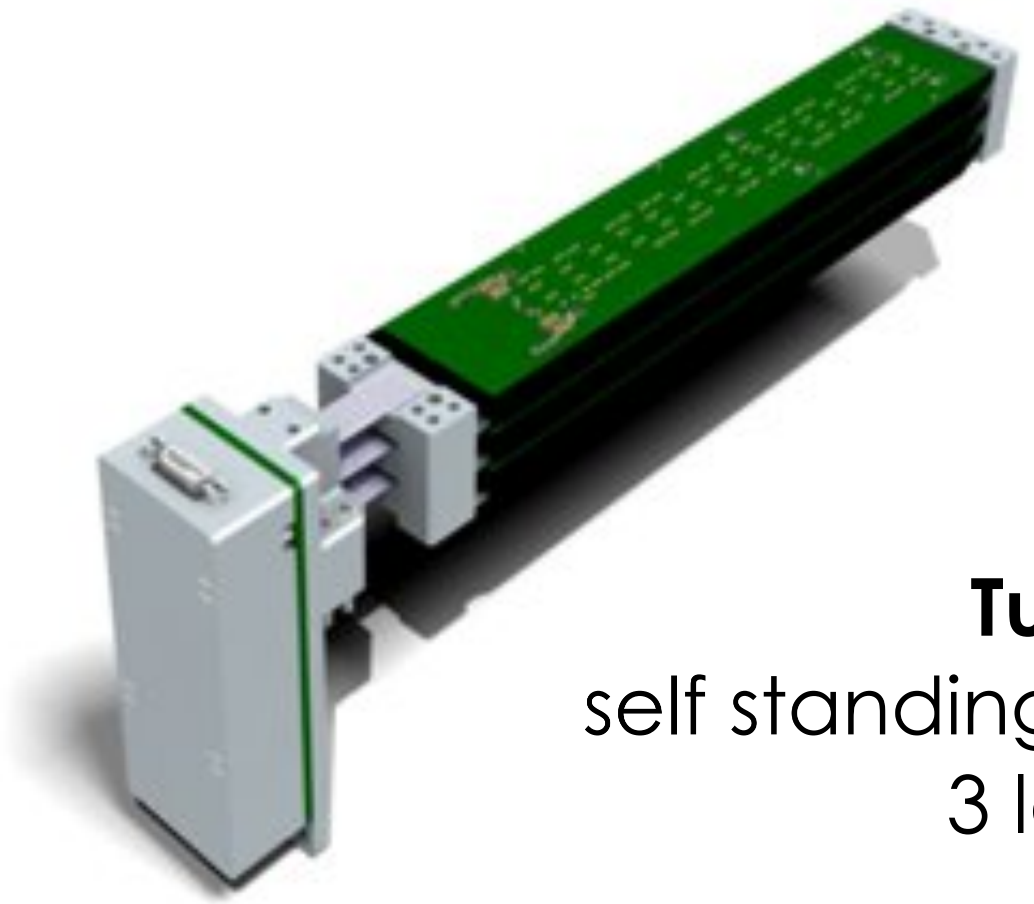
Direction detector

Modules composing the tracker

5 tracking units
top layer

TCP
power &
data transfer

5x



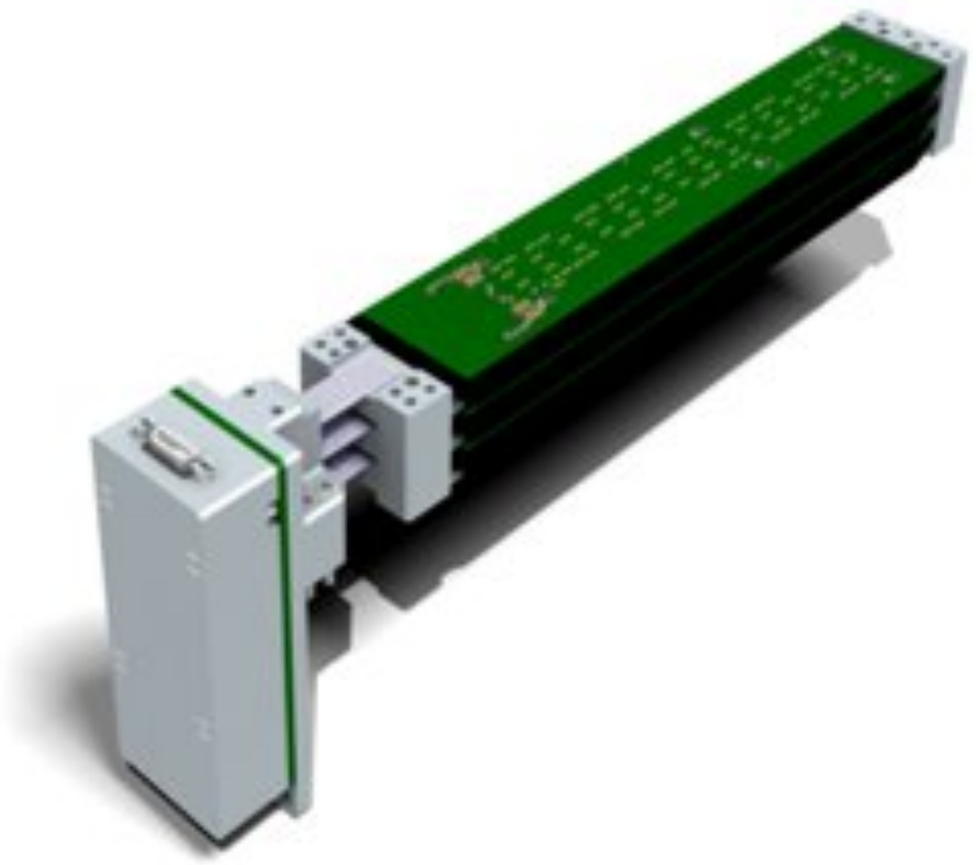
Turret
self standing tracking unit
3 layer

Qualification model (QM)
Flight model (FM)

5 turrets for QM
5 turrets for FM
+ spare turrets

Direction detector

Modules composing the tracker

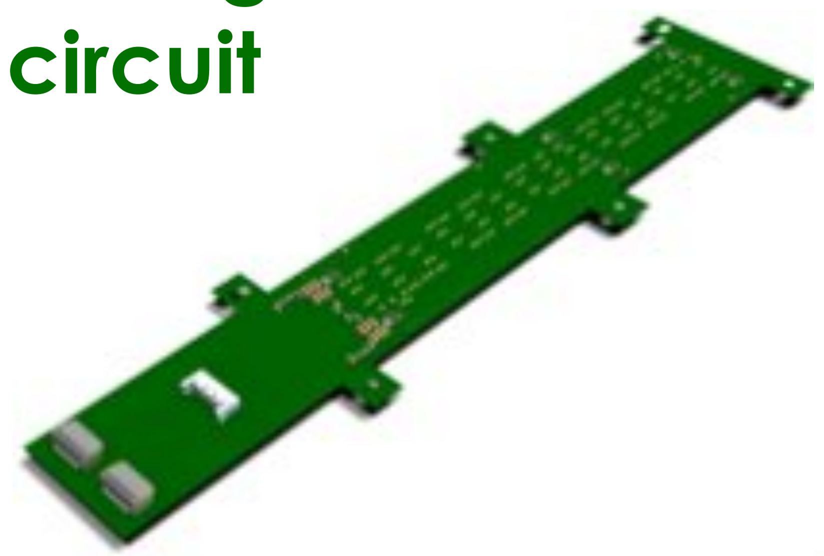


Turret

3x

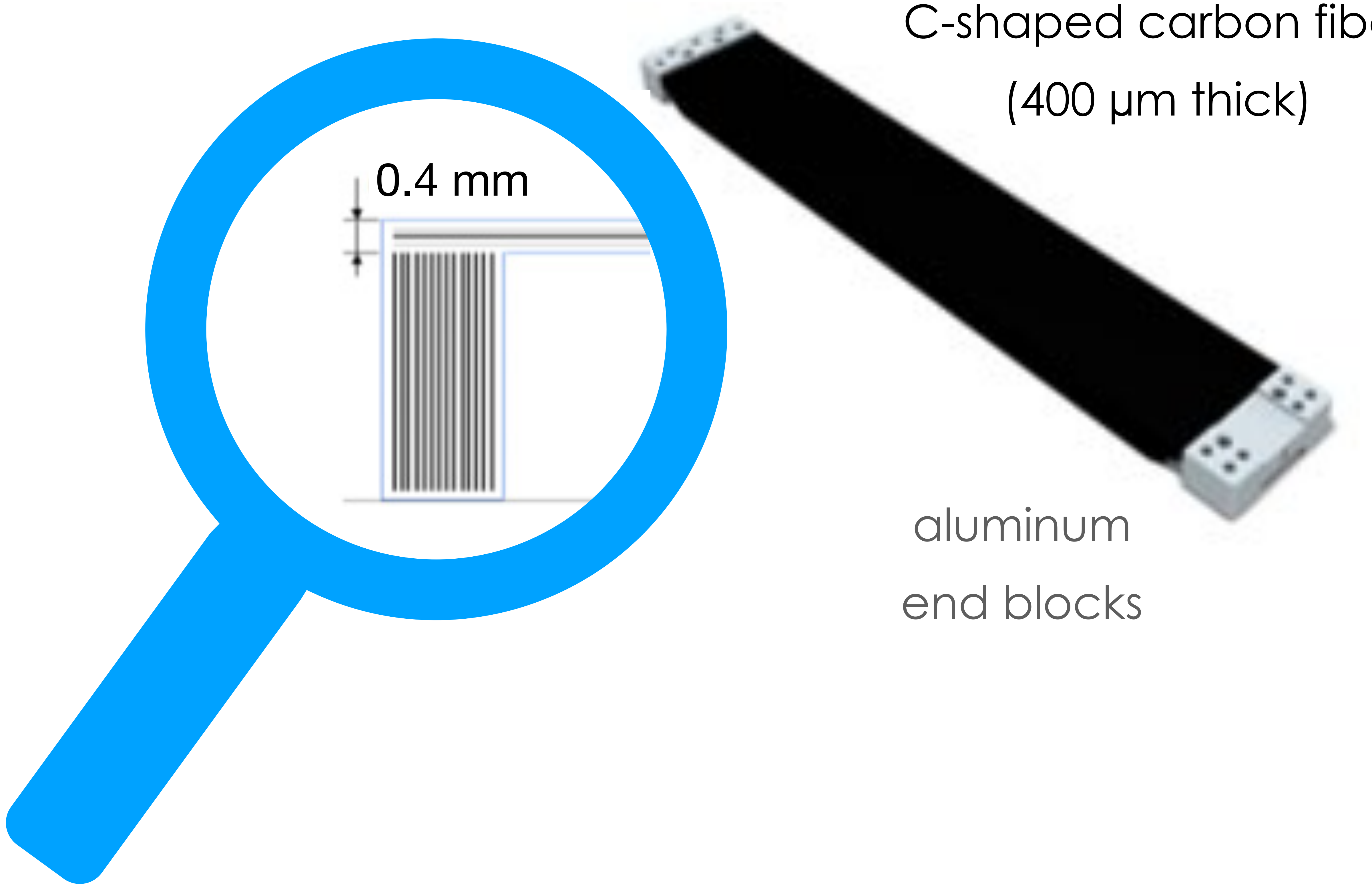
Stave

Hybrid integrated circuit



Cold plate
mechanical support

Mechanical support



TARGET: stiffness and thermal drain

Cooling is granted by material thermal conductivity

support has to be **stiff** enough to resist to 10G

the **material budget** has to be minimized

Material budget of STAVEs

STAVE element	material	thick [μm]	rad.length X_0 [%]
FPC board	capton	135	0.048
FPC tracks	Cu	36	0.251
glue	ARALDITE 2011	130	0.029
ALTAI	Si	50	0.053
cold plate	Carbon fiber + epoxy resin	350	0.134
Total:			0.515

- Thermo-mechanical design for ALPIDE pixel sensor chip in a high-energy particle detector space module
DOI: https://doi.org/10.1088/1748-0221/17/01/C01019
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DOI: 10.1088/1742-6596/2374/1/012049
- Experimental investigation of new ultra-lightweight support and cooling structures for the new Inner Tracking System of the ALICE Detector
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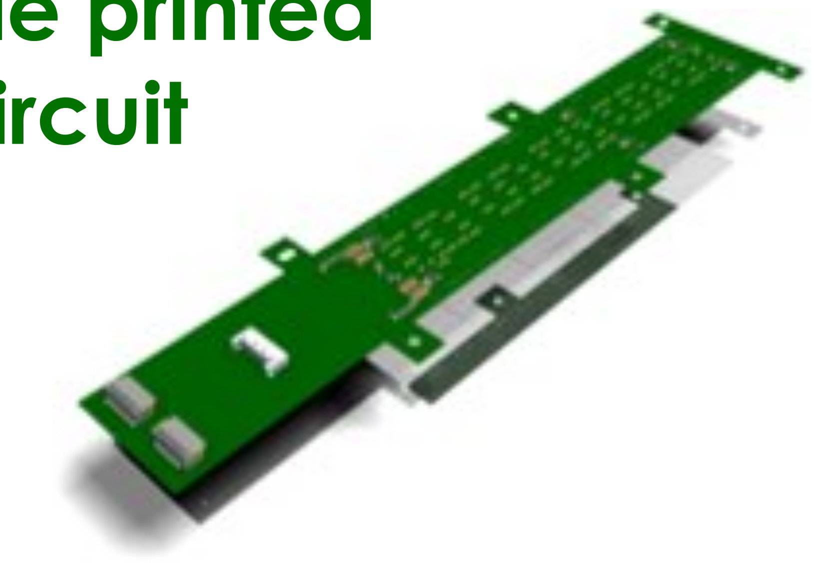
DD realization

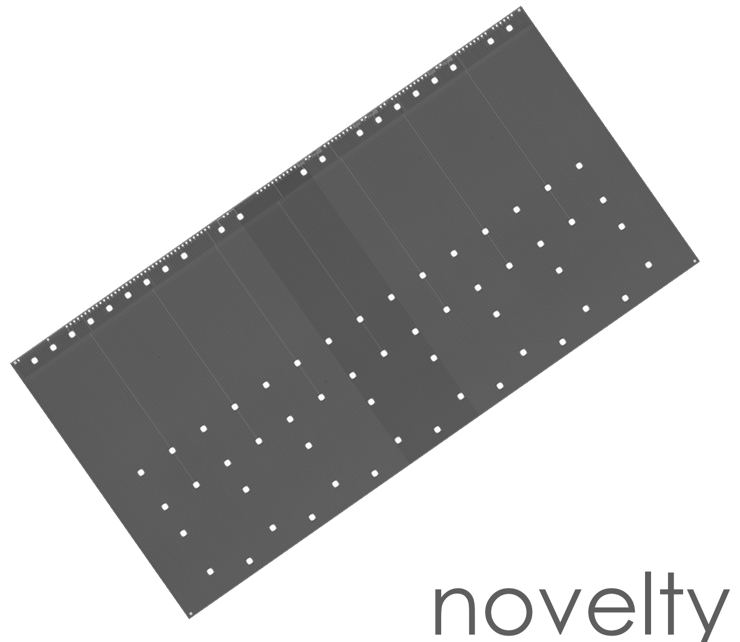
Modules composing the tracker

Flexible printed circuit

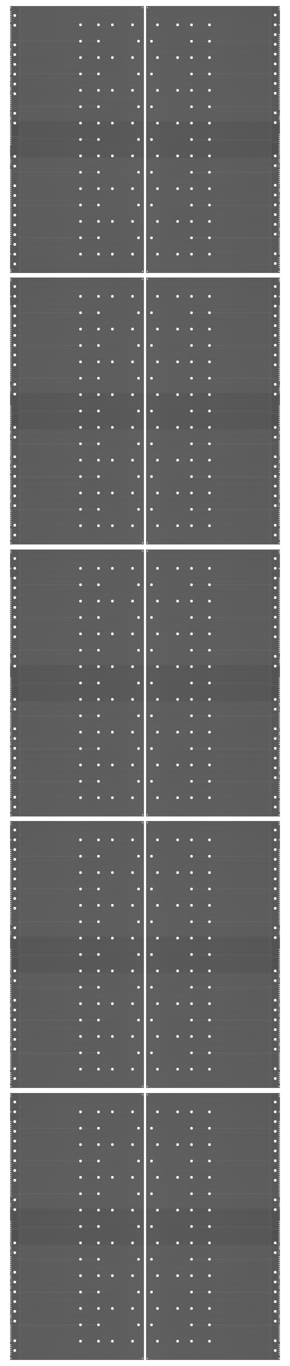


Hybrid integrated circuit

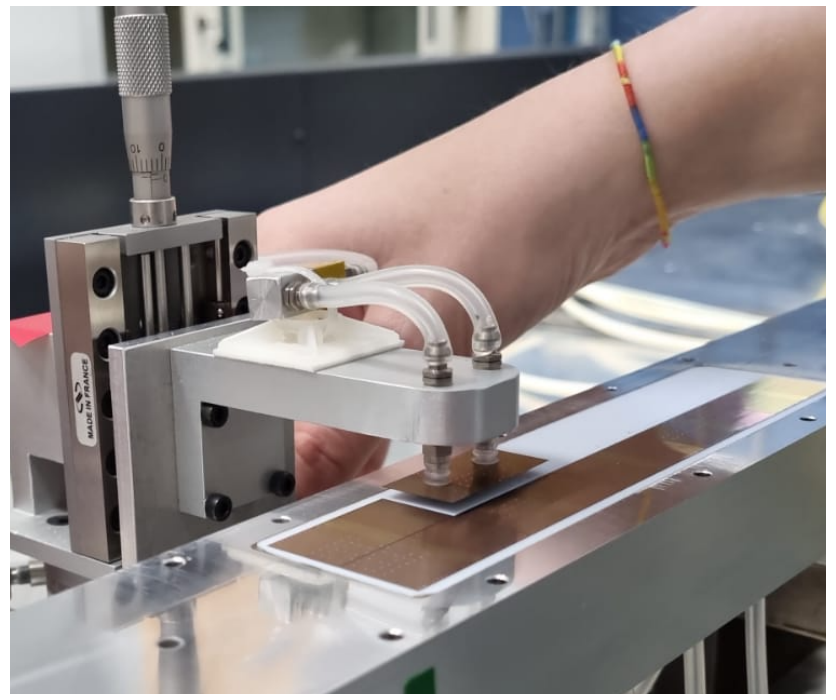
10x



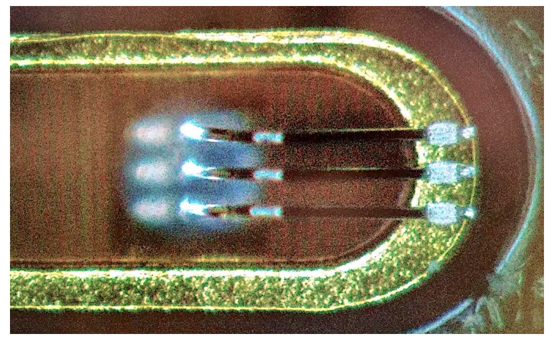
novelty
MAPS
'ALTAI'



ALTAI alignment with CMM



wire bond through the FPC



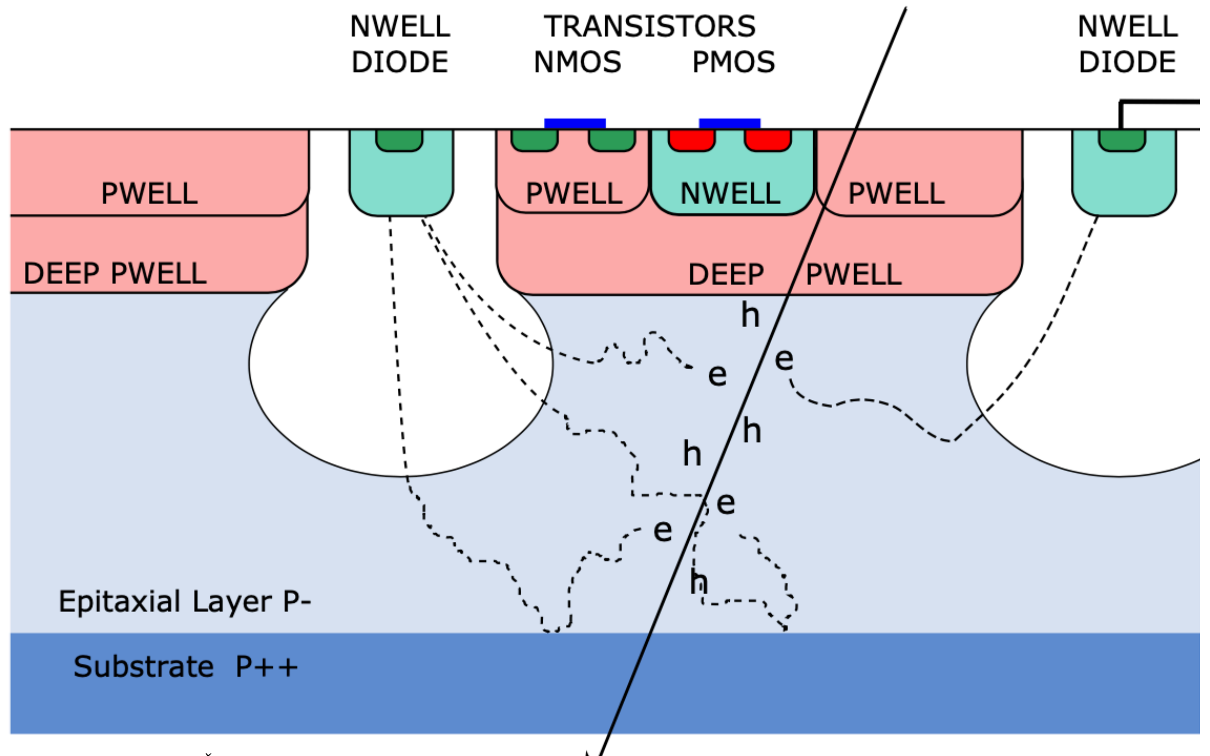
Monolithic active pixel sensors

ALTAI sensors - CMOS 180nm technology from Tower Jazz

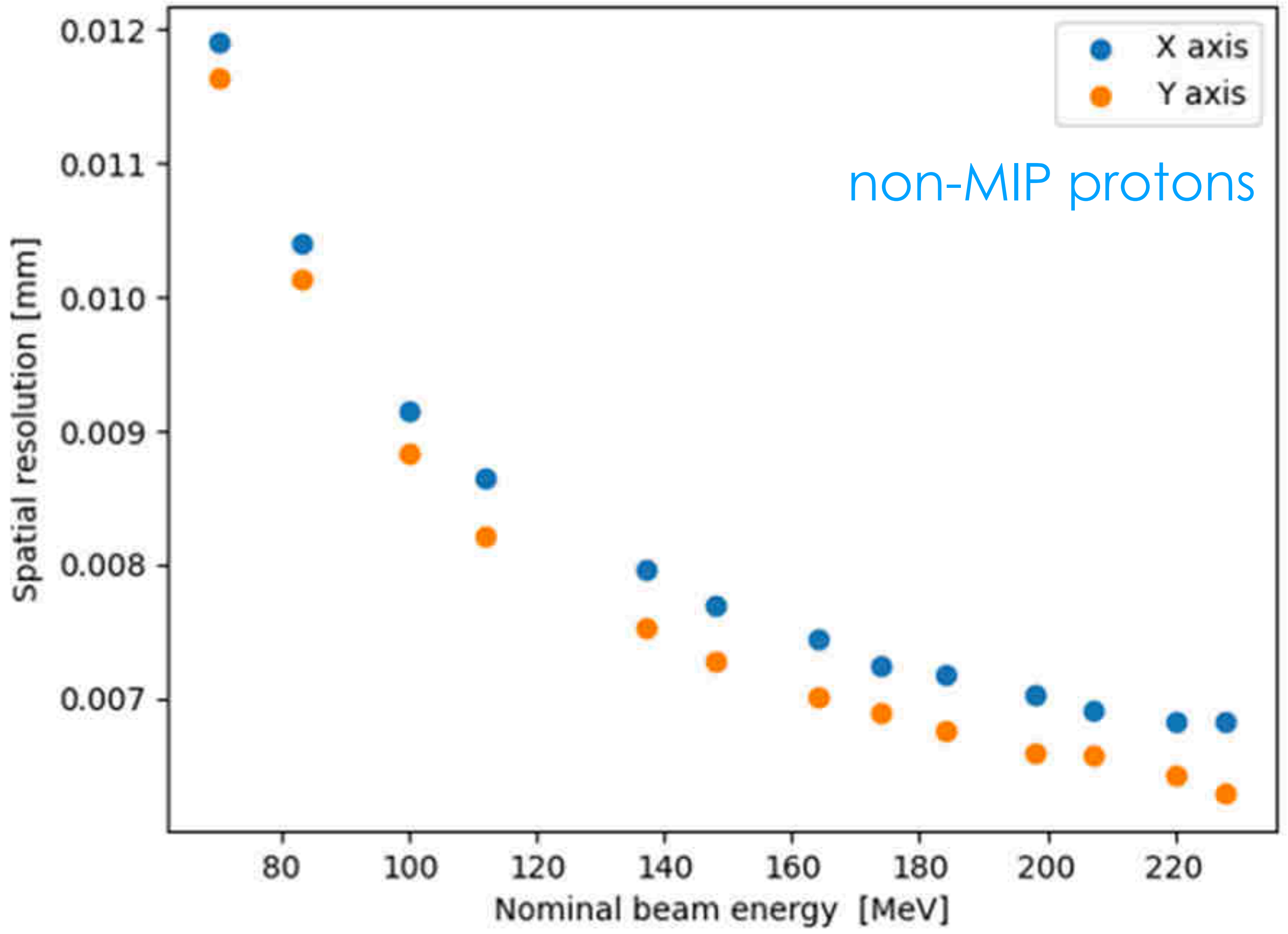
Parameter	Values
Detector size [mm^2]	15 x 30
Columns x rows	1024 x 512
Pixel size [µm x µm]	26.9 x 29.2
Detector thickness [µm]	50
Spatial resolution [µm]	5
Detection efficiency	>99%
Fake hit rate [evt^{-1} $pixel^{-1}$]	$<10^{-7}$
Integration time [µs]	~2
Power density [mW/cm^2]	<50

The sensor and readout circuitry are implanted in the same silicon

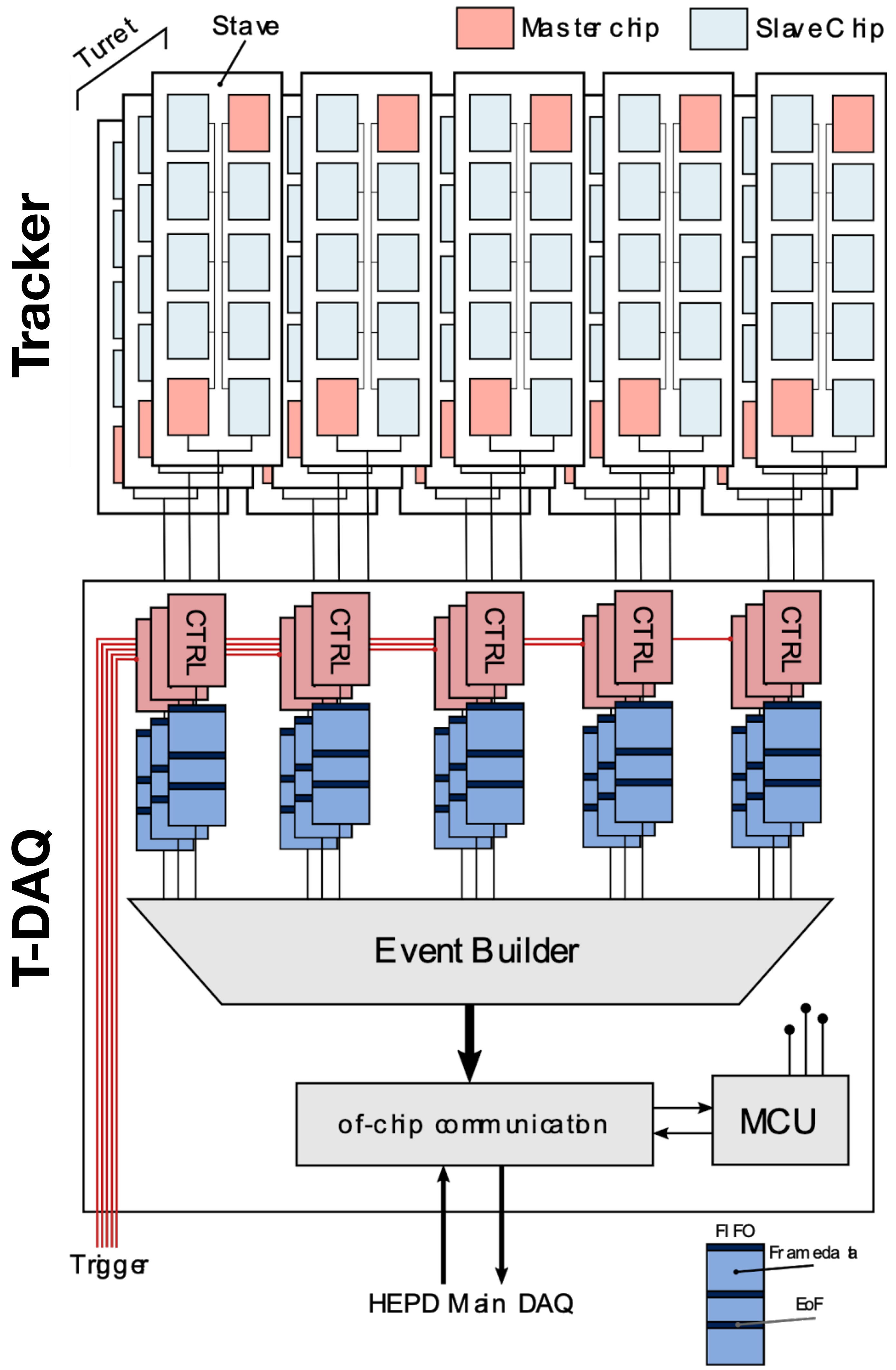
- low material budget
- charge collection by diffusion (bigger clusters → better spatial resolution)
- light output (zero suppression)
- cheaper that micro strips
- digital readout (limited charge information)



Courtesy of Miljenko Šuljić "Study of Monolithic Active Pixel Sensors for the Upgrade of the ALICE Inner Tracking System" - PhD thesis

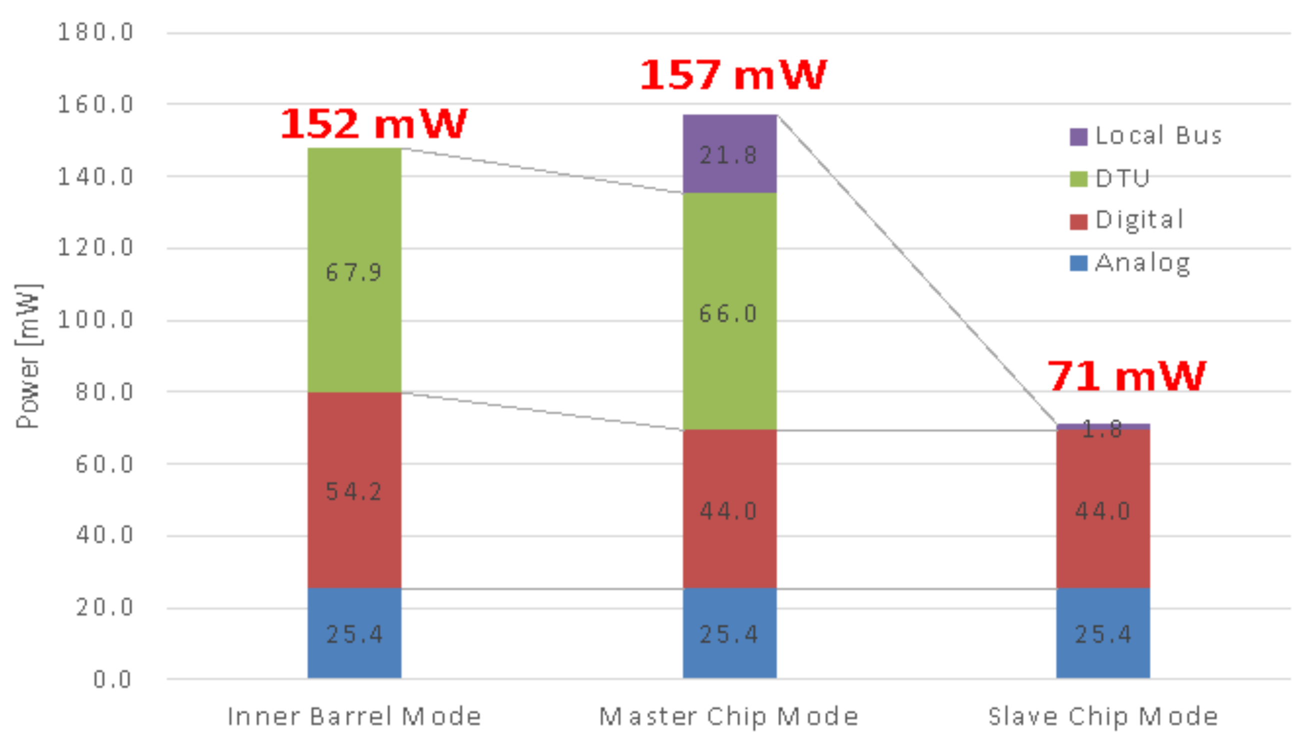


Power consumption mitigation



TARGET: power budget ~13 W

- **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:** ALTAI 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



Statistics from the production

- **CMM** to perform the **ALTAI alignment**
- **3 stages of functional test** (2 on HICs and 1 con STAVEs) + test on turrets and traders

Total production:

- 68 bonded HICs
- 41 STAVES

Production yeld

Quality TAG *	HIC assembly + bonding	HIC post Tab/Wings cut	Stave Assembly
GOLD	40%	44%	56%
SILVER	15%	15%	5%
BRONZE	12%	23%	10%
NOT OK	34%	19%	29%
Total:	68	48	41

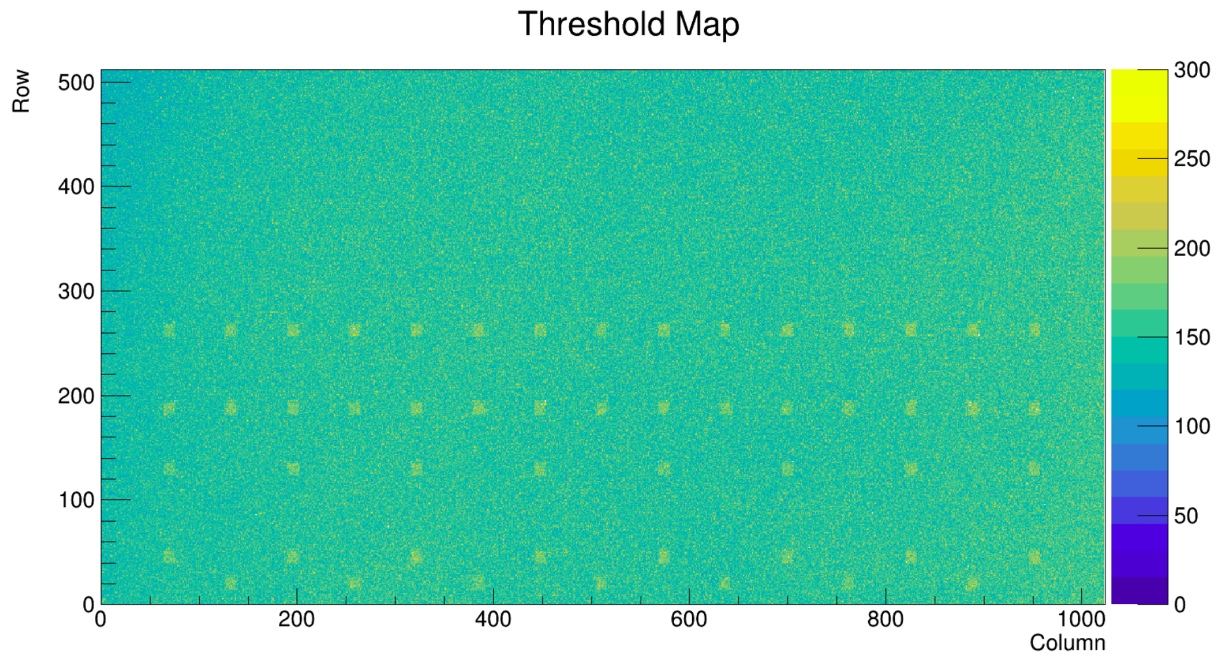
* quality categories based on functional performance

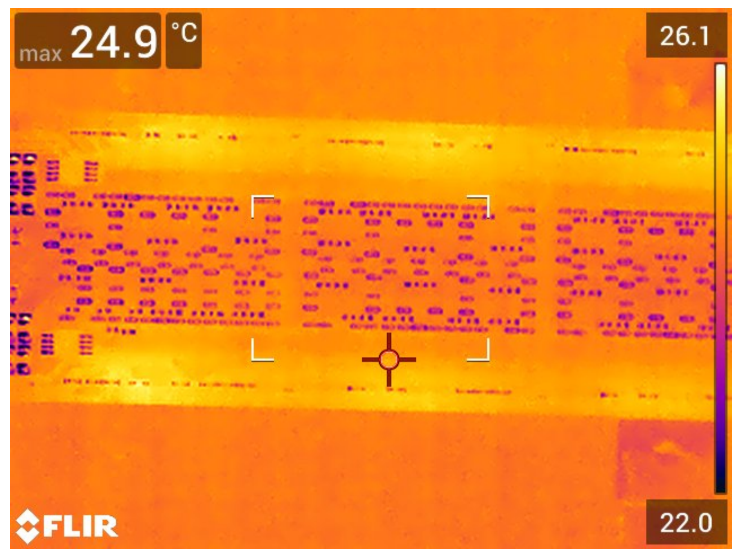
Test procedure to assess stave quality:

- check for hotspot with thermal camera
- chip scan → read/write procedure returning chip ID
- digital scan → readout digital check
- threshold scan → charge injection

Threshold tuning:

- scan of chip biases to tune the threshold level





Heat dissipation

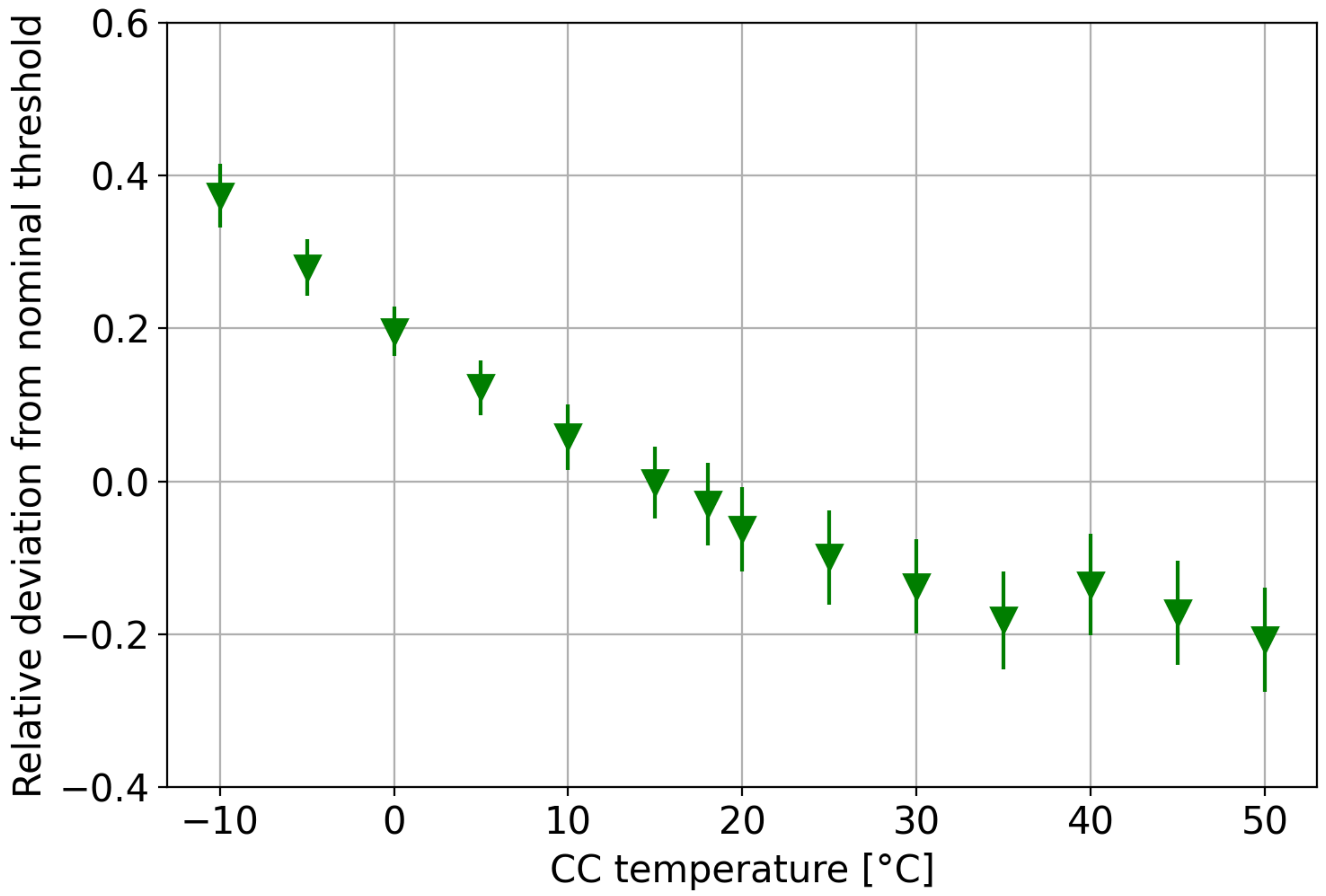
Space condition

- Vacuum environment of 6.65 10^{-3} Pa
- Repeated thermal cycles from -30 °C to +50 °C
- Cooling system on one side
- Temperature gradient of 6 °C

TARGET: thermal drain (0.8 W/STAVE)

Validation setup

- Climatic chamber
- Dallas sensors (DS18B20U) on board of FPC
- temperature variation from -10 °C to +50 °C

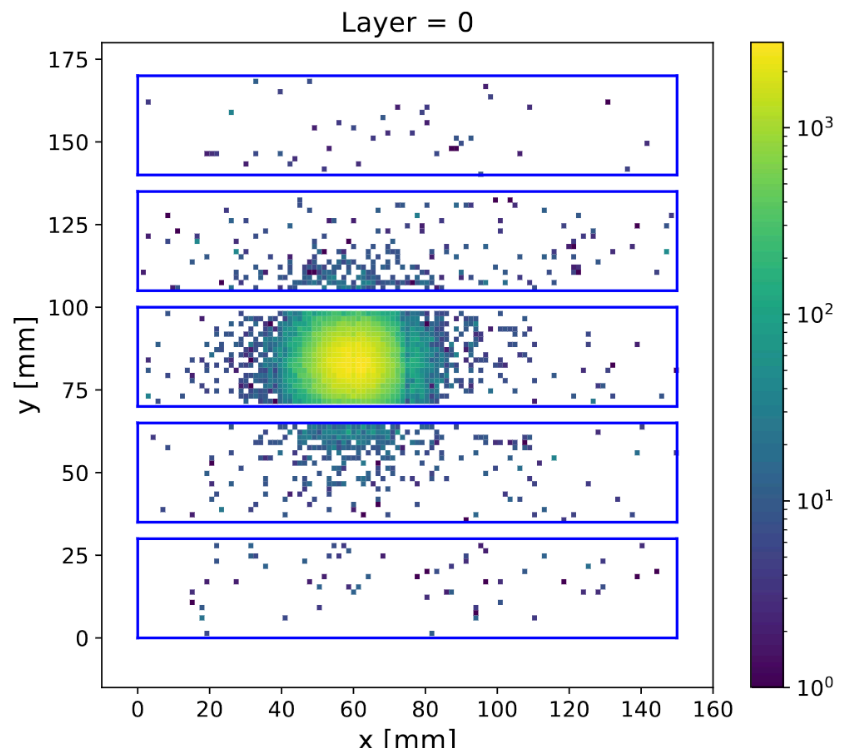


Result

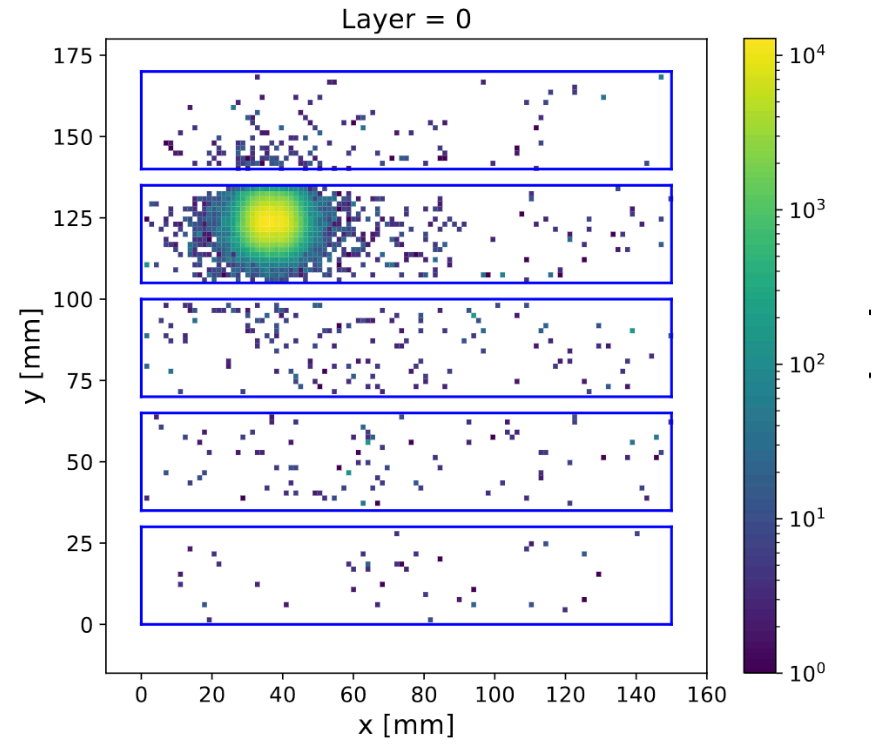
- Threshold variation of 1 e^-/°C in the characterization range
- Standard deviation of every-chip pixel threshold higher than threshold residuals

Test beam campaign

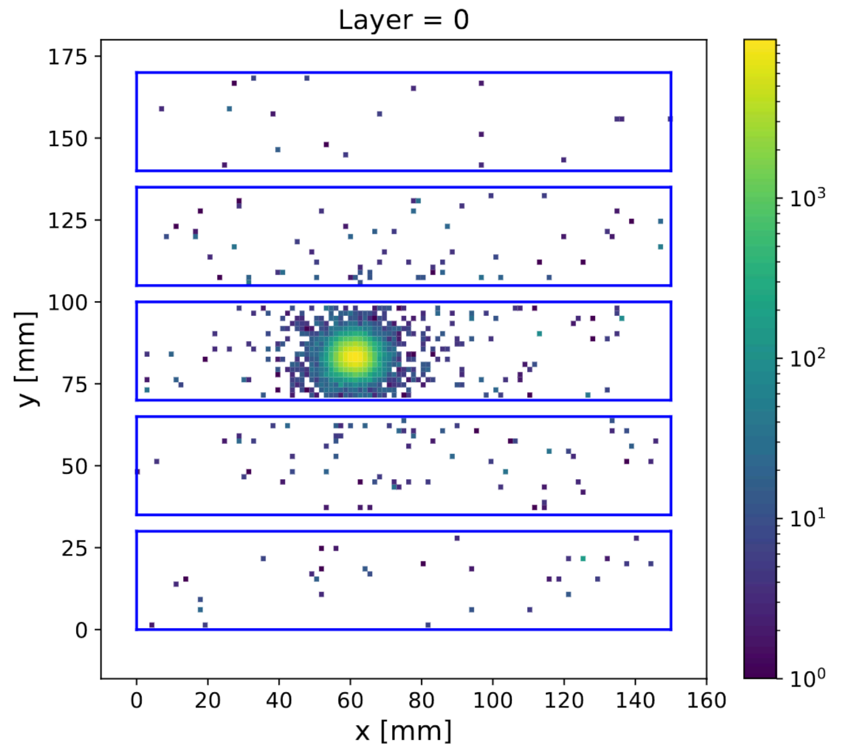
Protons - 70 MeV



Protons - 164 MeV



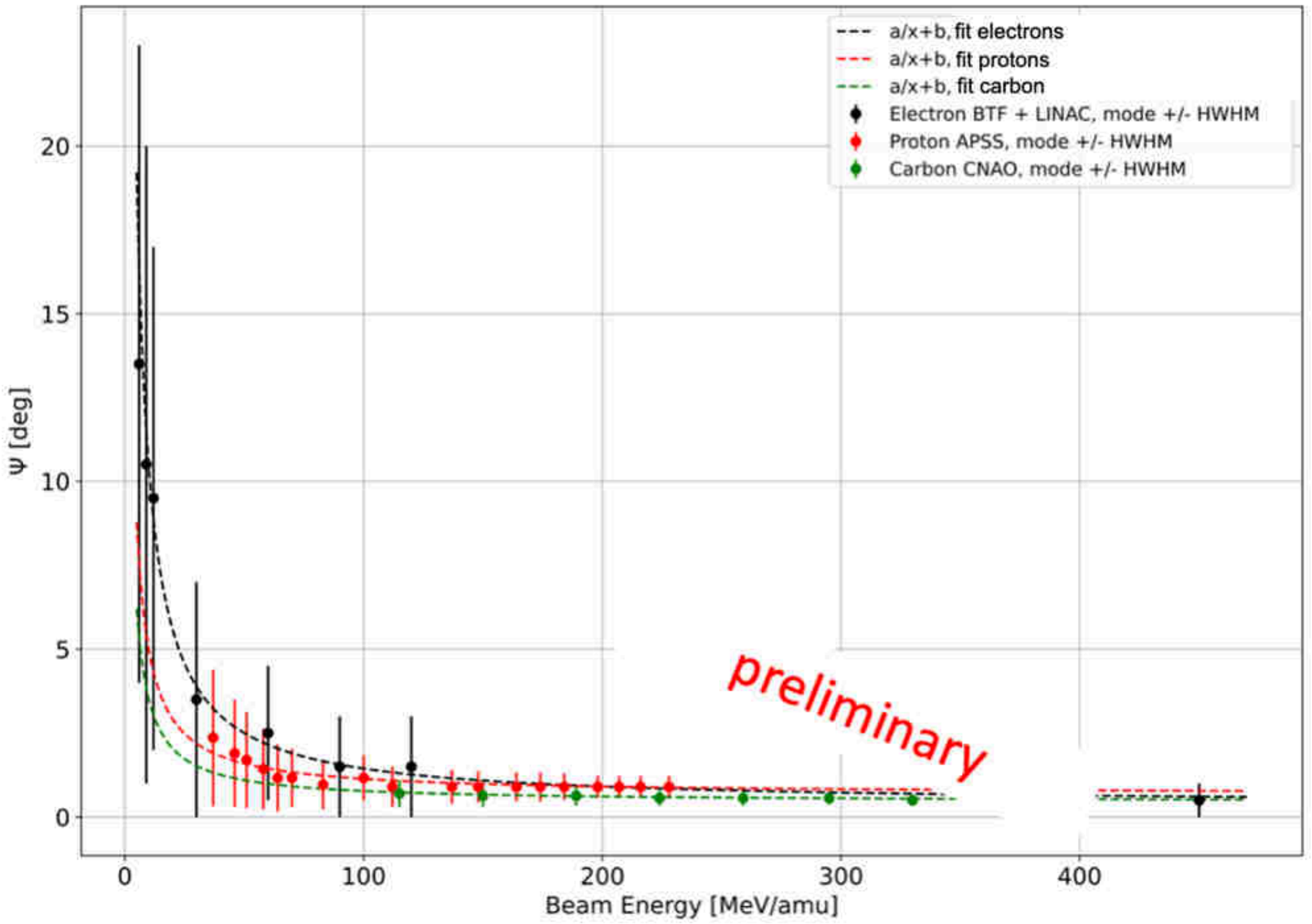
Protons - 228 MeV



Beam (particles/photons) energies

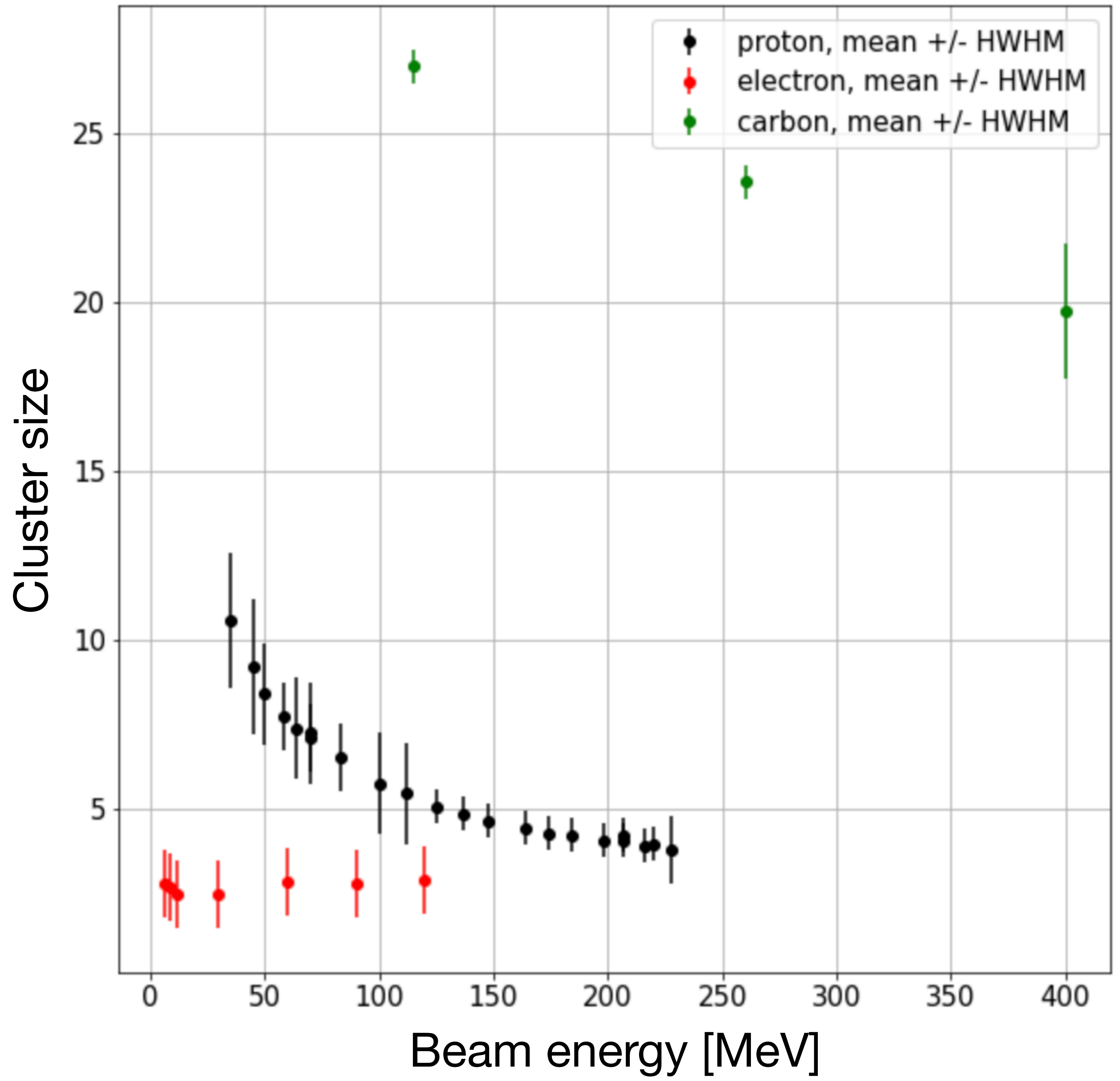
	energy range
electrons	6 -- 450 MeV
protons	10 -- 230 MeV
carbon	115 -- 400 MeV
photons	1 -- 10 MeV

Ψ is the angular difference between the reconstructed track and the true direction.



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.**

[PoS(ICRC2021)070]



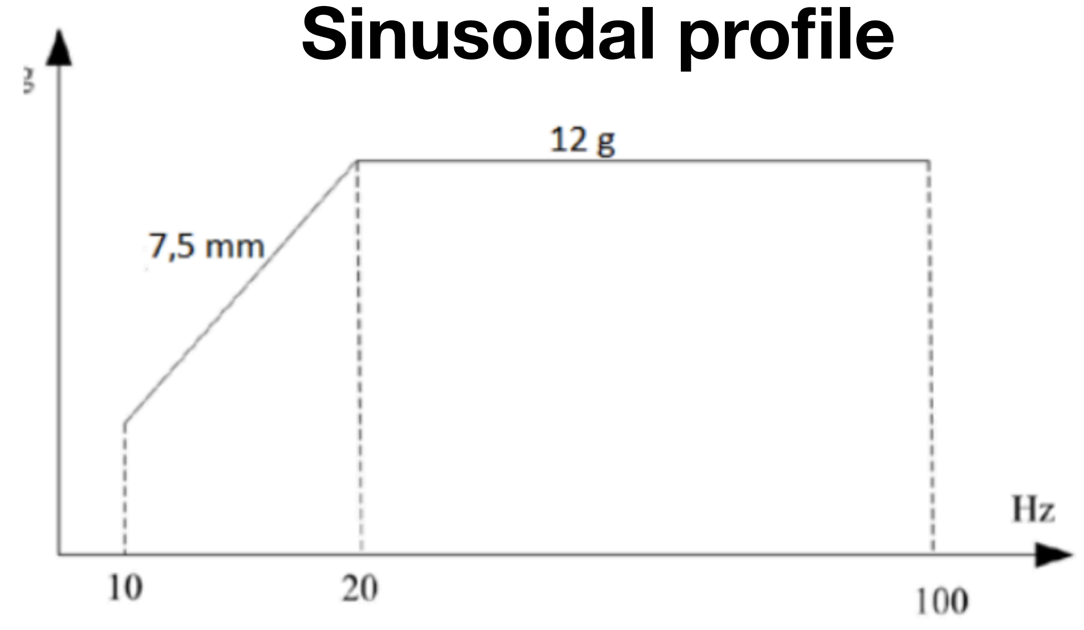
Qualification/acceptance tests

In compliance with CSES-02 satellite requirements

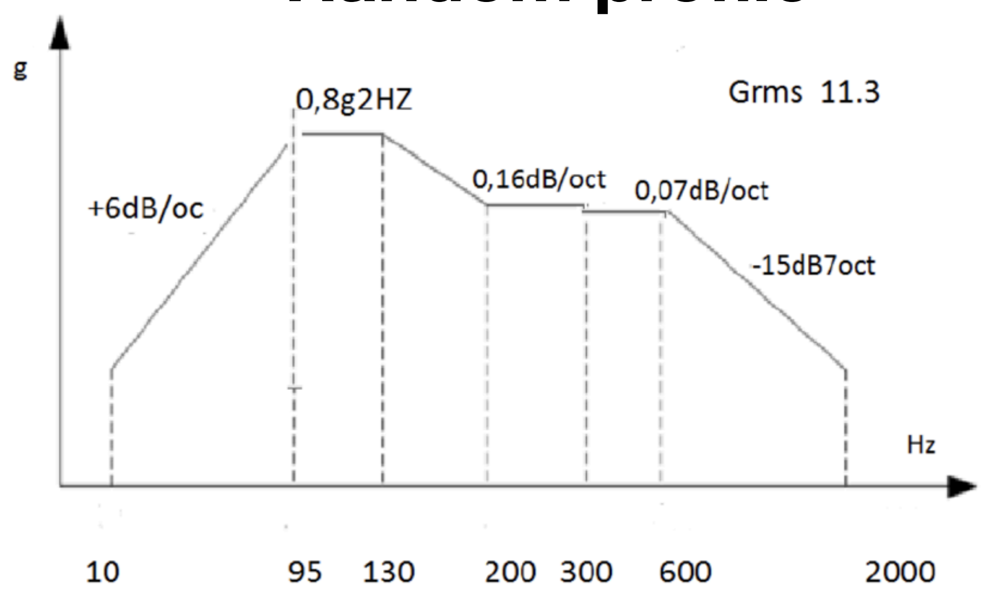
- **Vibrational test**
  - resonance search scan along the axis
  - apply Sine and Random vibration load levels
  - visual inspection and verification of the insulation resistance
- **Shock test** (only QM)
- **Thermo vacuum test**
  - temperature cycles from -30 to +50 °C
  - pressure to nominal value ≤ 6.65×10^{-3} Pa
  - QM: 25.5 Thermal cycles, 6.5 Thermal Vacuum
  - FM: 14.5 Thermal cycles, 3.5 Thermal Vacuum
  - anomaly monitoring and performance test

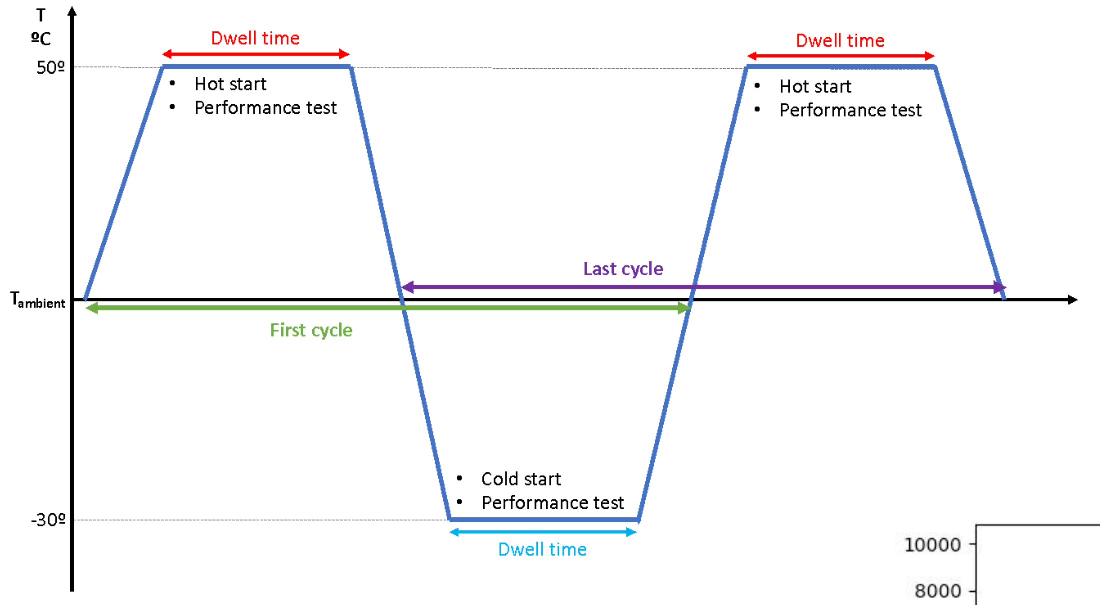
- **Test result: passed**

Sinusoidal profile



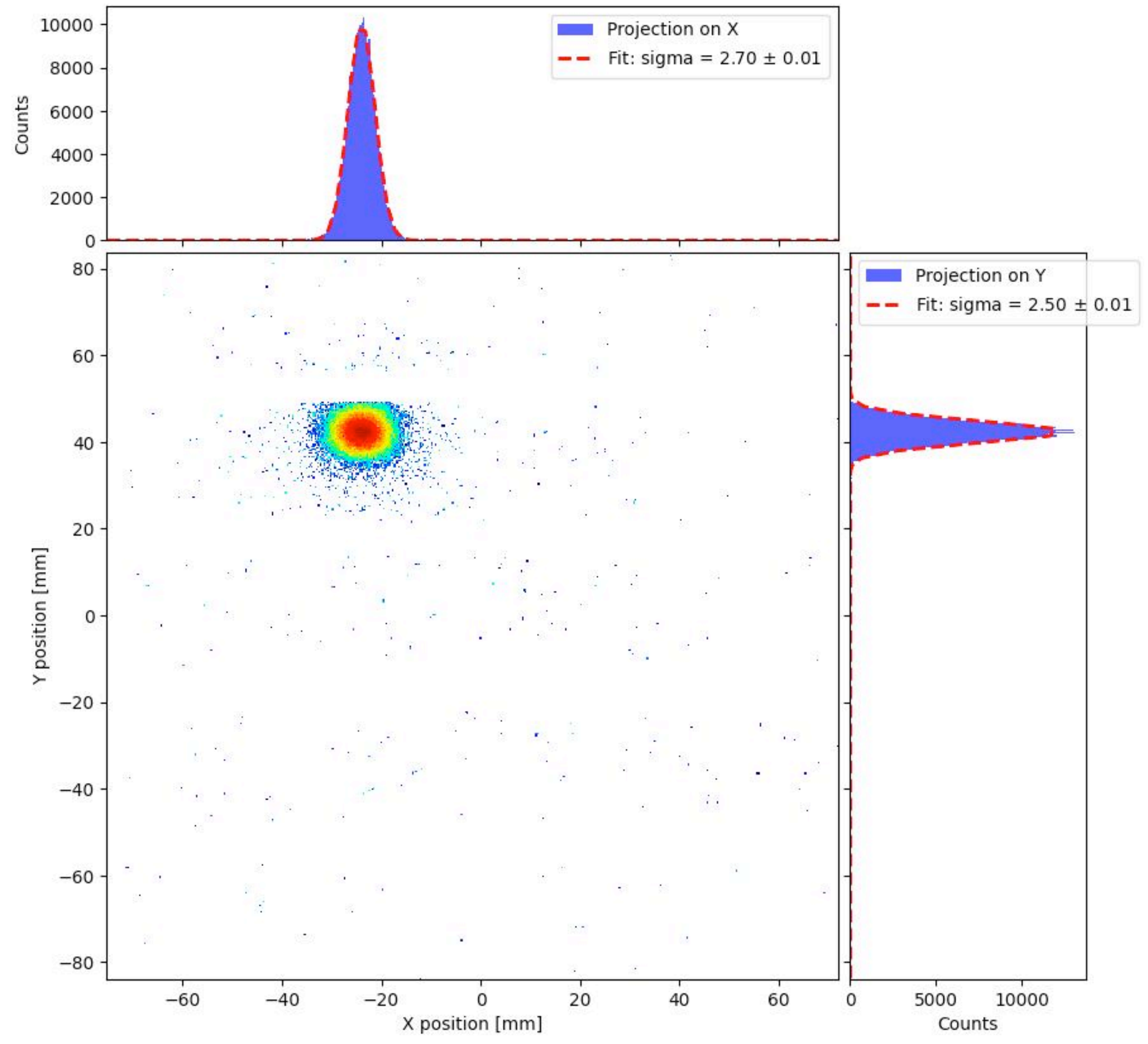
Random profile



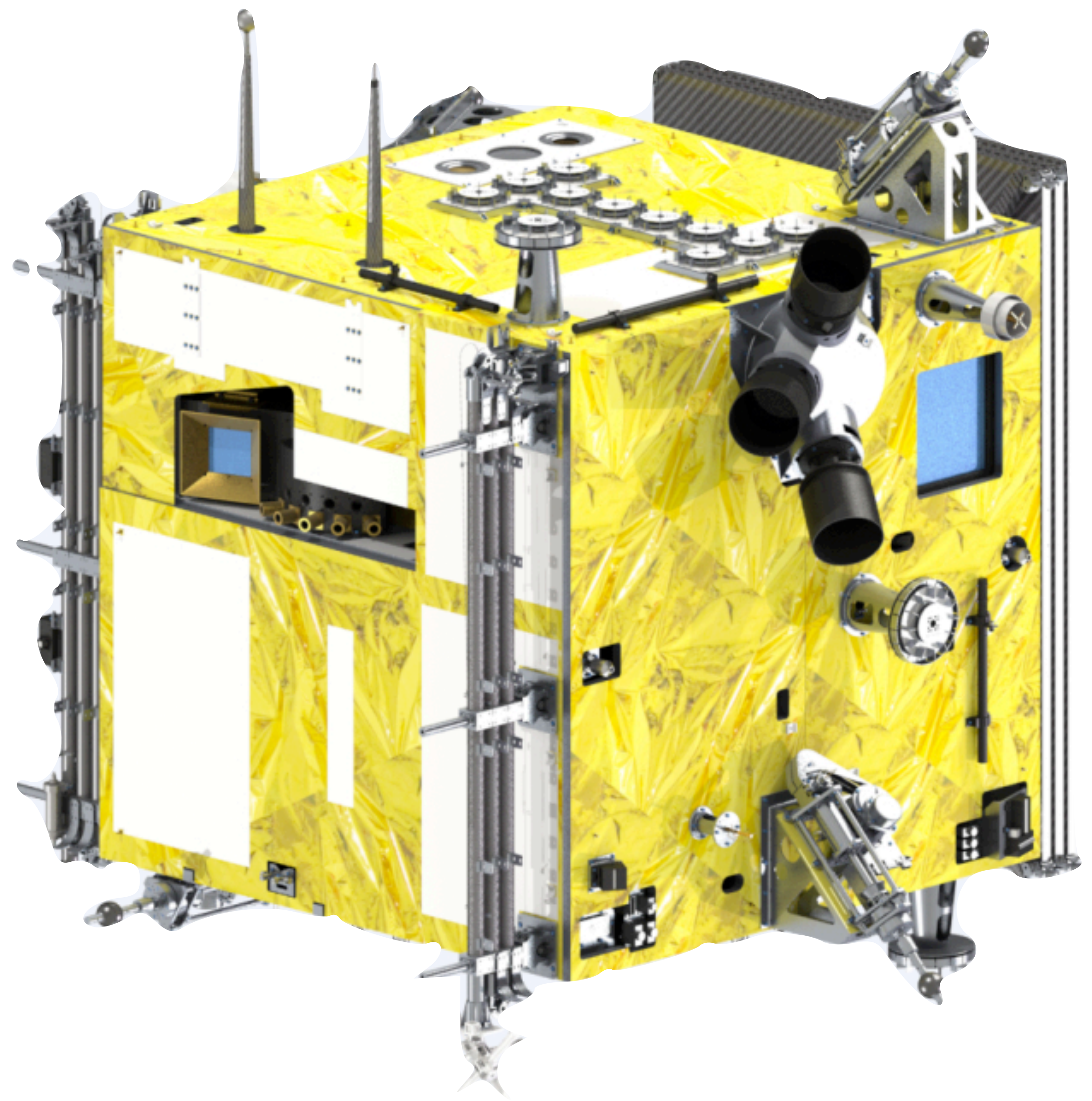


Thermal cycles

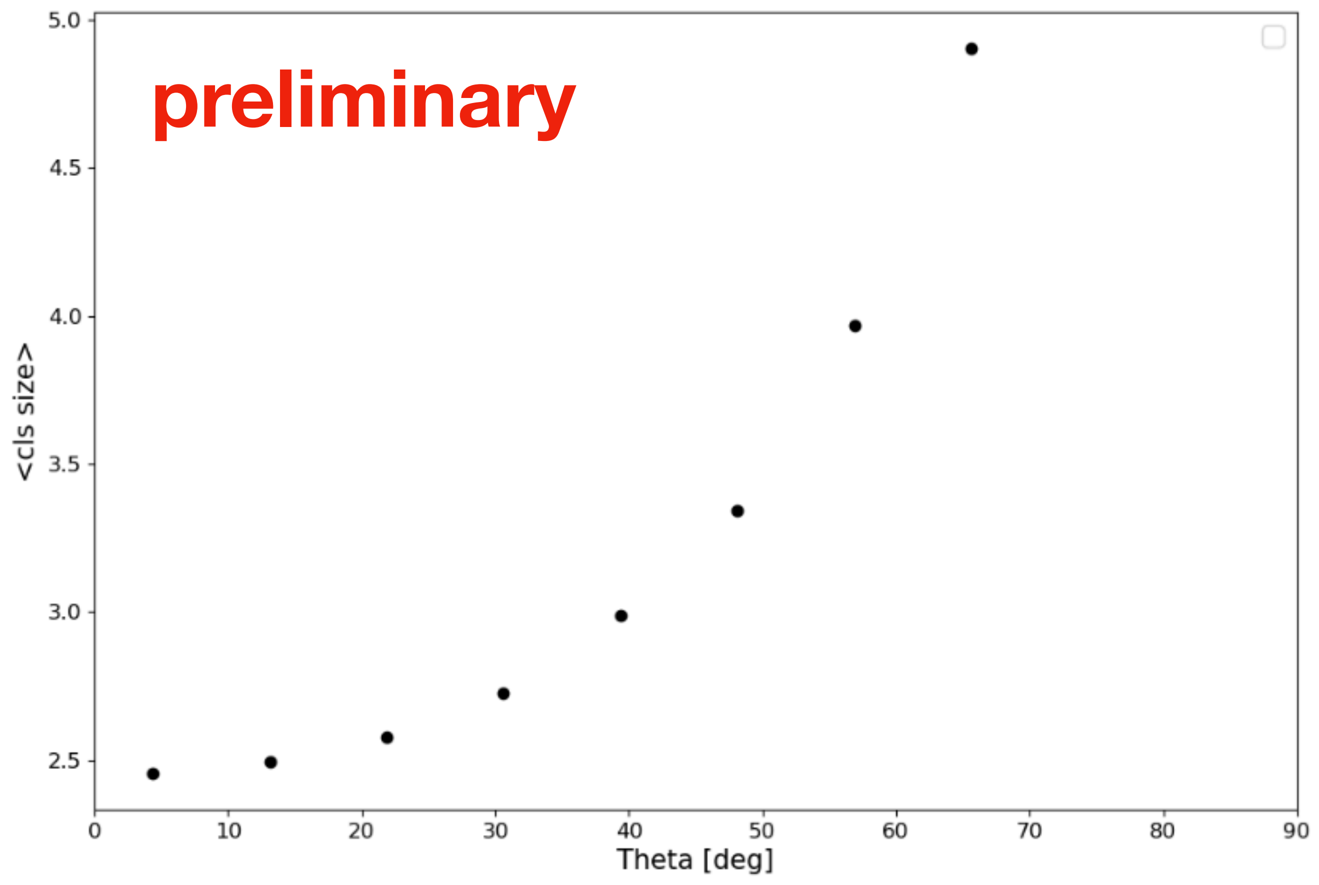
Beam spot
from a test beam
post qualification/acceptance tests
> no damage observed
> the beam profile reconstructed
and consistent to the nominal shape



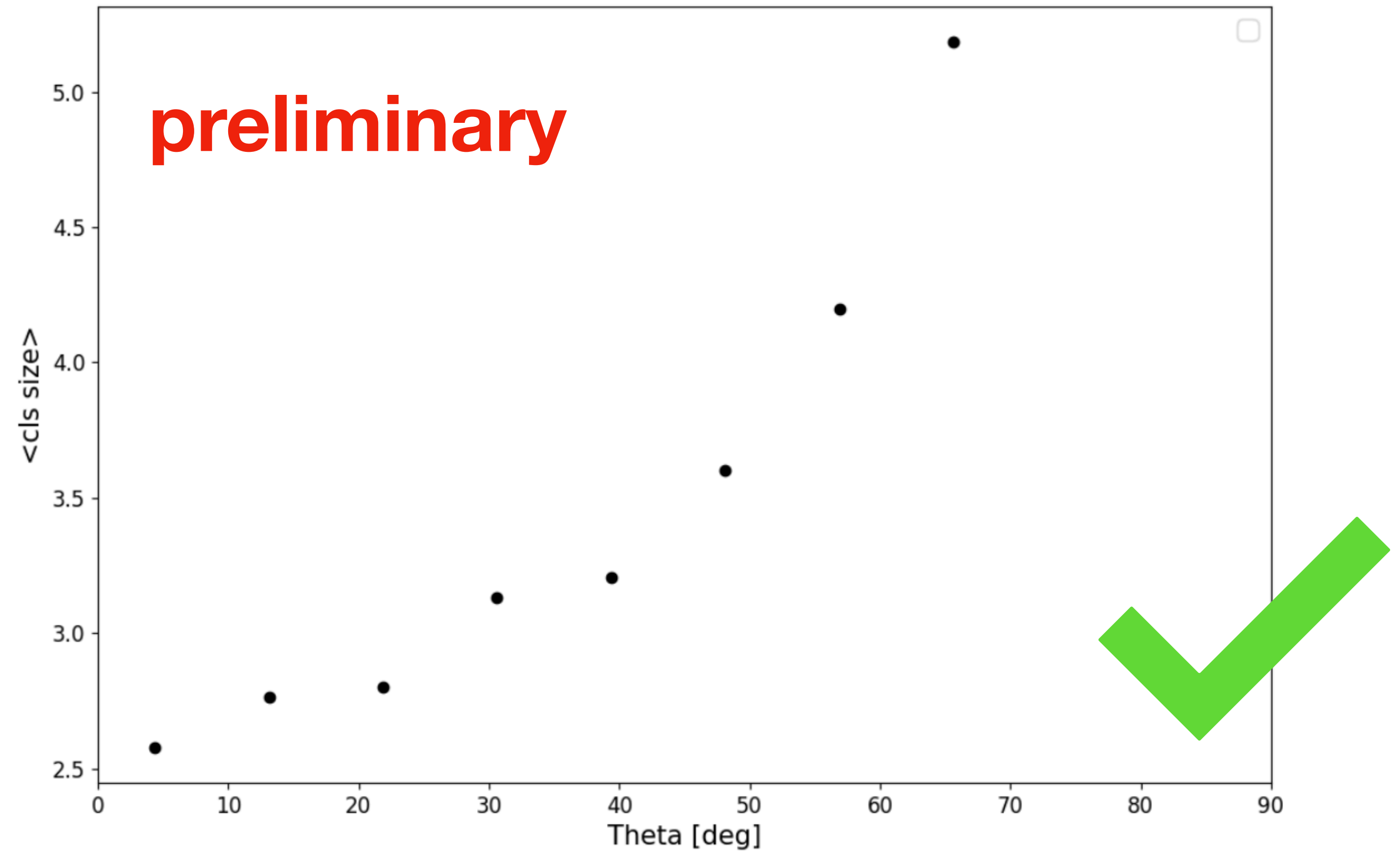
HEPD-02 integration in CSES-02



Cosmic rays data acquisition
before integration in CSES-02
statistics: about 117,000 events



Cosmic rays data acquisition
after integration in CSES-02
after vibrational tests
statistics: about 7,000 events



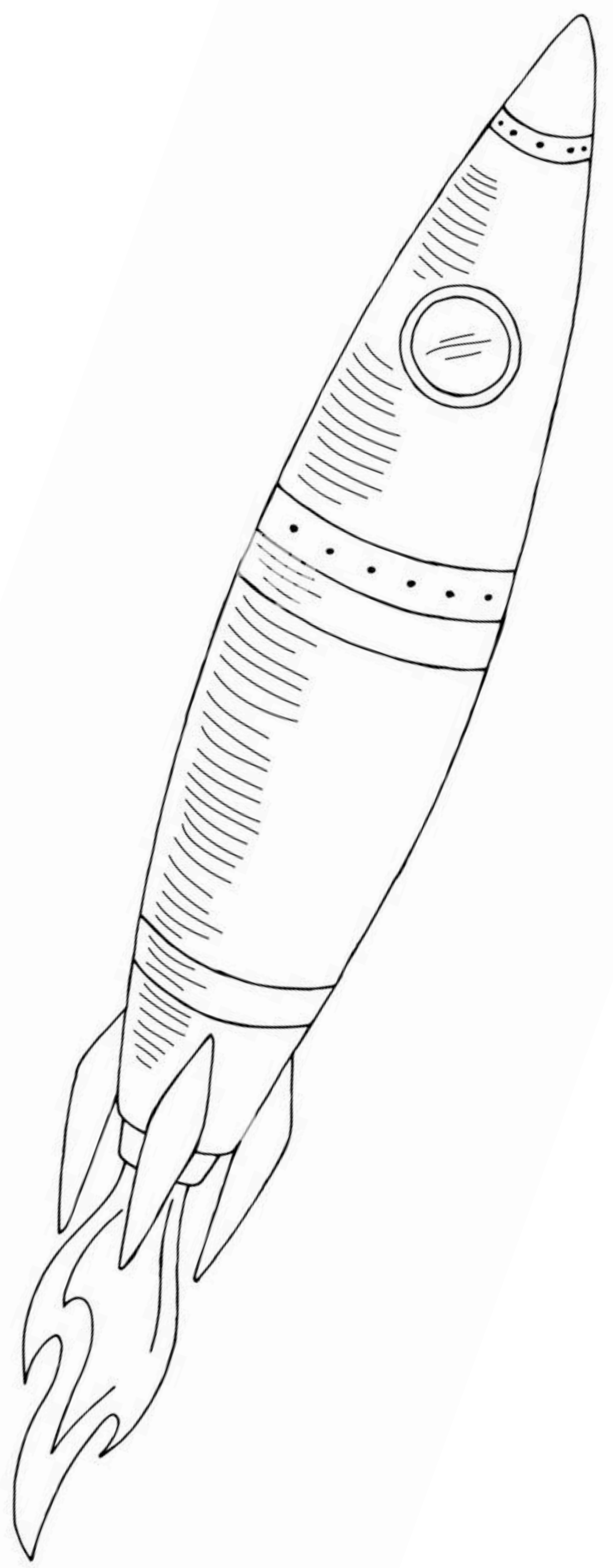
Conclusions

- HEPD-02 DD will be the first ever use of MAPS in a space application

- Two HEPD-02 payloads produced and qualified (QM and FM)
- Space compliance tests successfully performed on HEPD-02 payload

- Analysis on test beam data currently under publication
- HEPD-02 integrated on board of CSES-02 → satellite acceptance campaign ongoing

- Launch scheduled in December 12, 2024



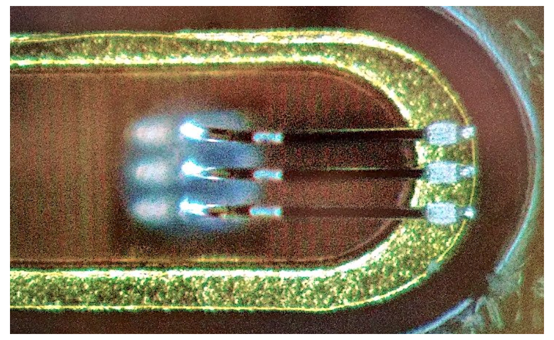

Thank you for your attention

SPARE SLIDES

1st requirement: precision

HIC assembly under CMM required to guarantee alignment precision for wire bondings

Space requirement:
- redundancy → 3 bonds per each pad

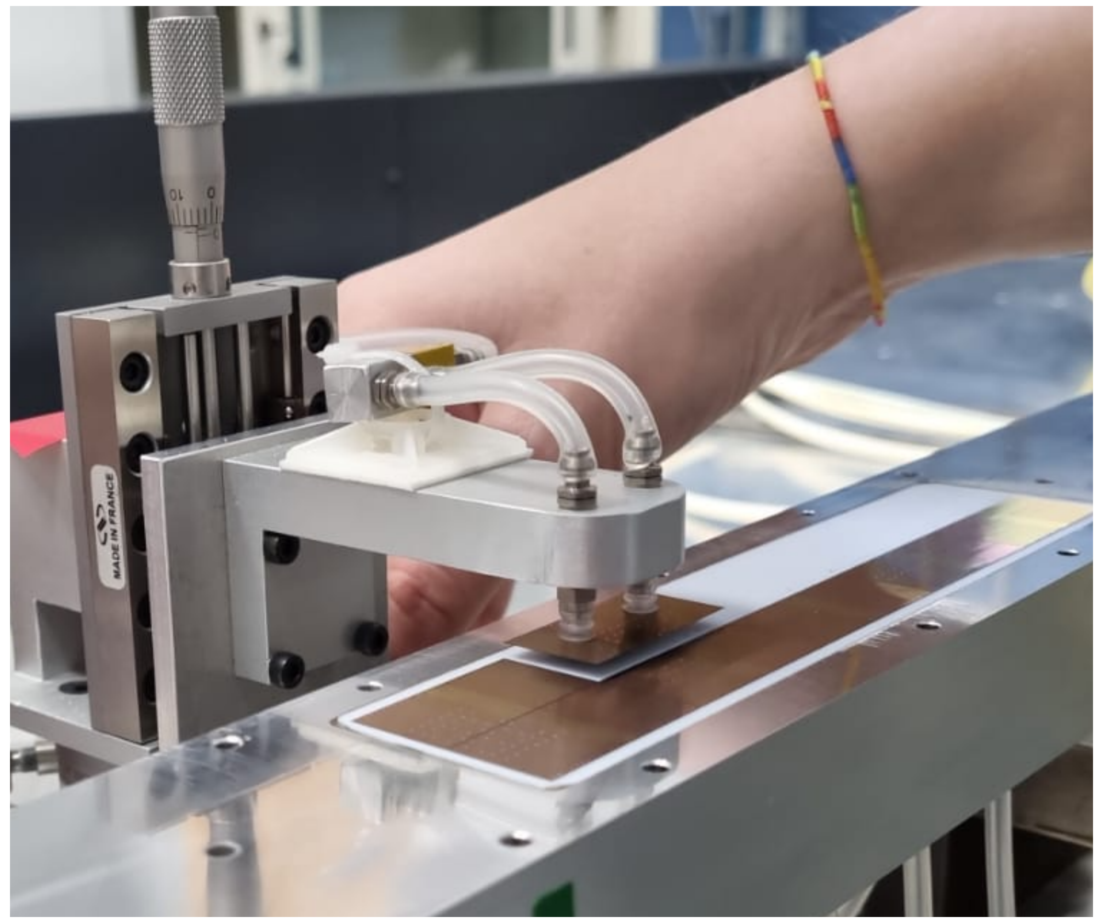


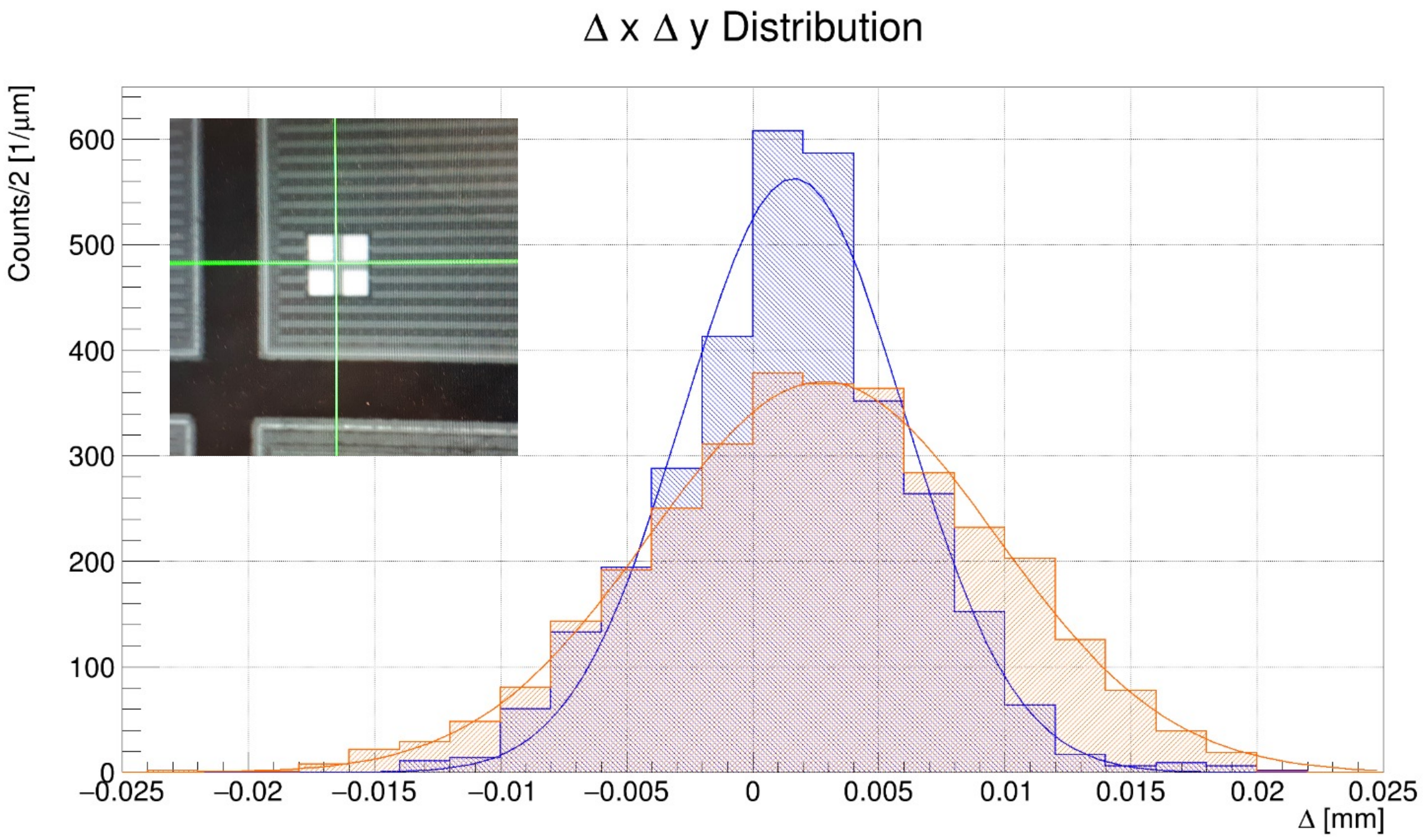
- Mitutoyo CMM measure the position of the ALTAI reference pads

CMM resolution: x = 7 μm | y = 7 μm | z = 20 μm

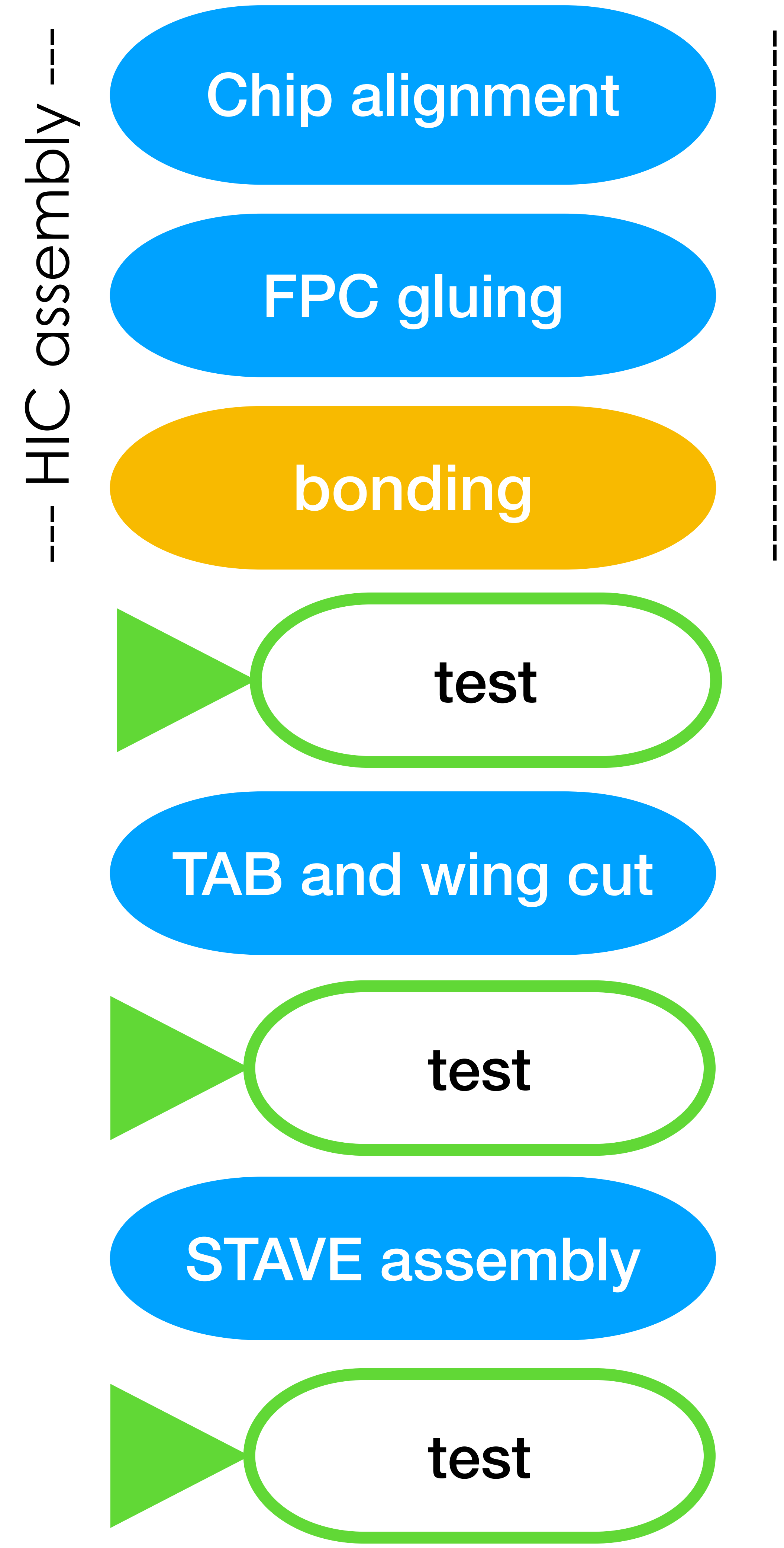
Resuduals wrt nominal positions

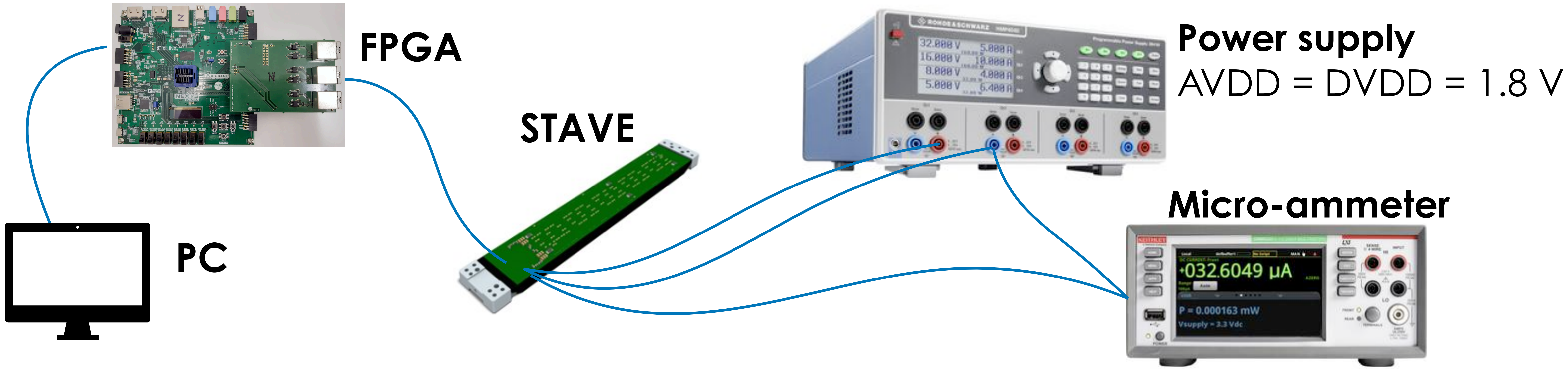
	mean [μm]	rms [μm]
Δx	1.9	11.7
Δy	0.2	12.4
Δz	-8,477	57





2nd requirement - power consumption





Test procedure to assess stave quality:

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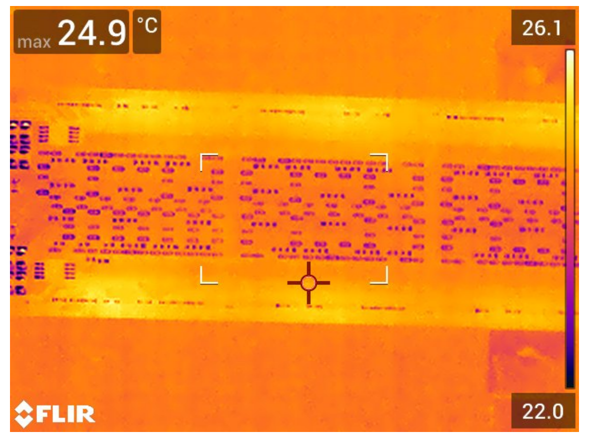
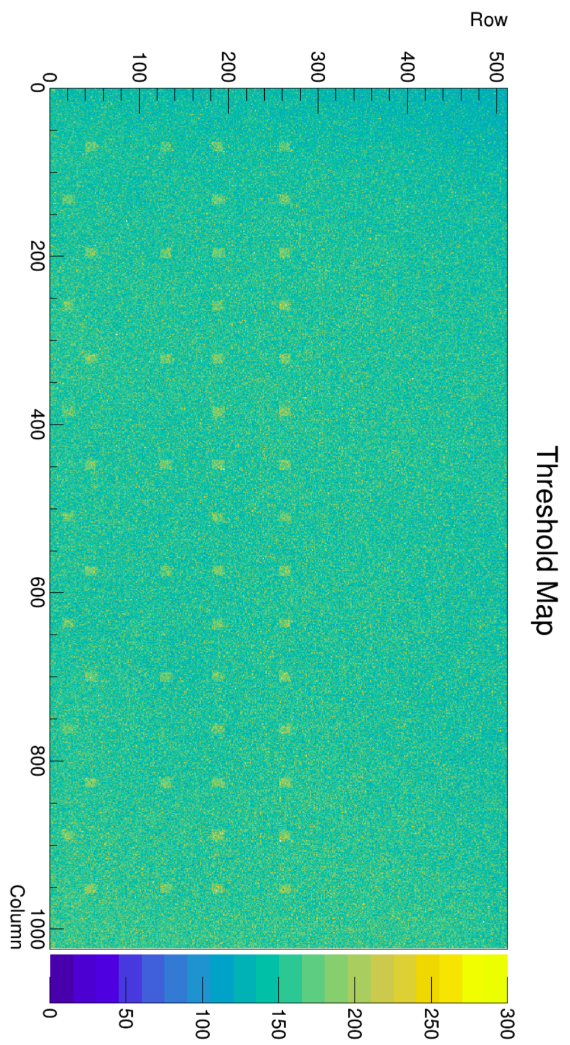
Threshold tuning:

- scan of chip biases to tune the threshold level





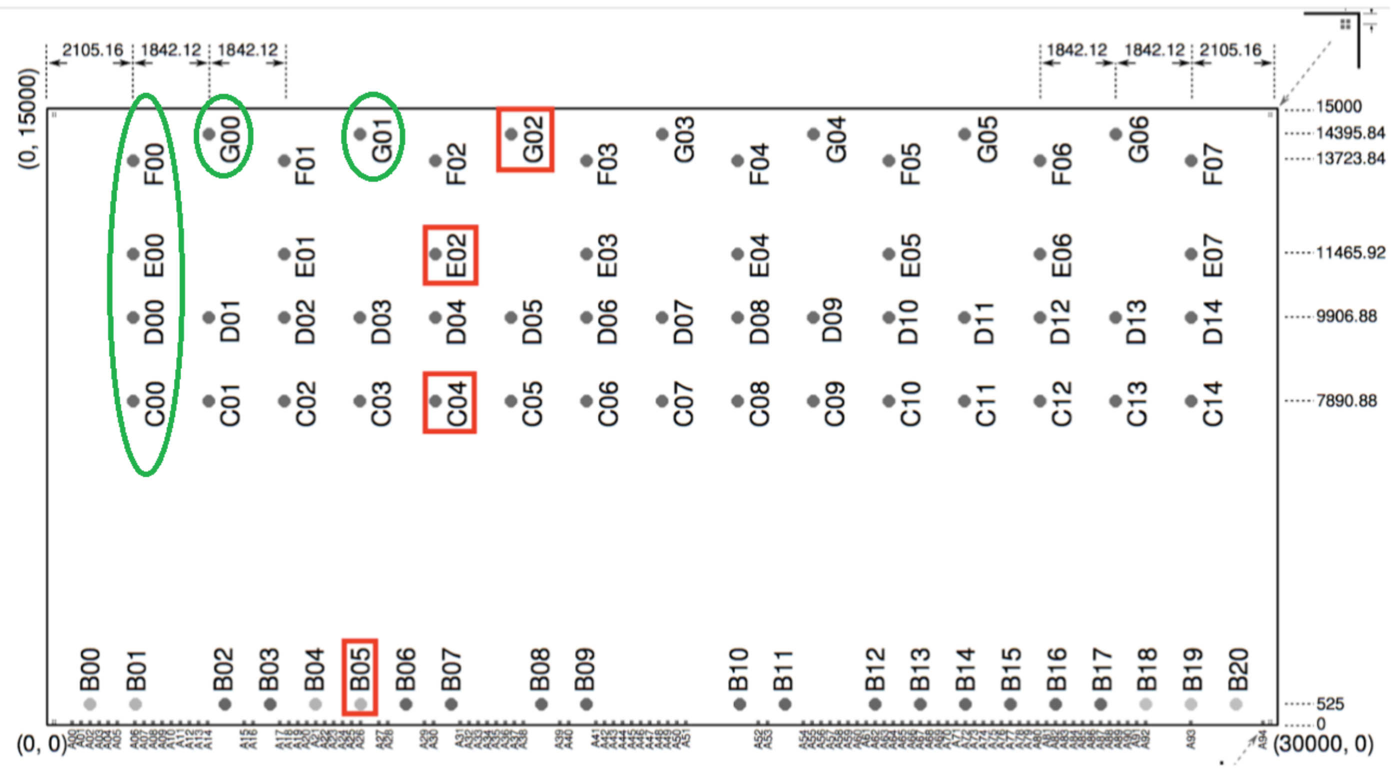
Staves power consumption

	BRONZE	SILVER	GOLD	GOLD spare
AVDD [mA]	124 ± 1	124 ± 2	125 ± 5	112 ± 2
DVDD [mA]	466 ± 6	460 ± 21	451 ± 11	421 ± 10

Wire bonding and gluing

- **Numbers:**
  - 74 pads/chip x 3 bonds/pad x 10 chips/STAVE → 2220 bonds/STAVE
- **Materials:**
  - ENEPIG (electroless nickel electroless palladium immersion gold) for FPC bonding pads
  - bonding wire in Al
  - ARALDITE 2011 - bi-component epoxy glue

- **Challenge:**
  - managing the uniformity of the glue and the planarity of chip-FPC to have automatic bonding
- **Space compliance**
  - space-compliance of materials and solutions of assembly (bonding, gluing, grounding) was validated during summer 2019, with 6.5 thermal cycles in the temperature range −30°/+50°C, imposed to the engineering model of a stave



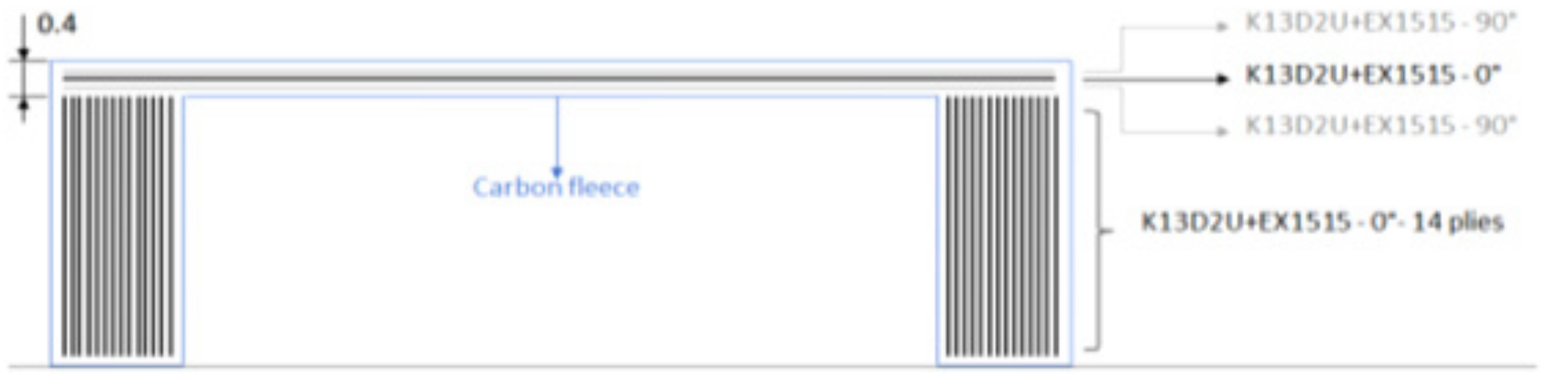
Pull test
Electrical test

Pull test results

sample	25 HICs
force mean	11.9 g
force std	1.9 g
liftoff	226

Carbon fibers

- **Support:** C-shaped carbon fiber cold plate 400 μm thick with lateral ribs + aluminum end blocks
  - Simulated (Finite Element Model) optimal lay-up configuration → oriented plies of unidirectional carbon fiber K13D2U with cyanate ester prepress resin EX1515
- **Cooling based on conductivity of material** standing between chips and the thermal plate
- Global thermal conductivity of CP:
  - longitudinal 343-367 W/m K
  - transversal 173-180 W/m K
- Vibrational tests on the turret assembly to comply with standards EN ISO:9100 for Aerospace, Space, and Defence.



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  S. Coli et al., 2021, 22nd International Workshop on Radiation Imaging Detectors
  DOI: https://doi.org/10.1088/1748-0221/17/01/C01019
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  E. Serra et al., 2022, Journal of Physics Conference Series, 2374, 012049, IOP Publishing
  DOI: 10.1088/1742-6596/2374/1/012049
- Experimental investigation of new ultra-lightweight support and cooling structures for the new Inner Tracking System of the ALICE Detector
  V.I. Zherebchevsky *et al* 2018 *JINST* **13** T08003
  DOI: 10.1088/1748-0221/13/08/T08003

Material budget of STAVEs

STAVE element	material	thick [μm]	rad.length X_0 [%]
FPC board	capton	135	0.048
FPC tracks	Cu	36	0.251
glue	ARALDITE 2011	130	0.029
ALTAI	Si	50	0.053
cold plate	Carbon fiber + epoxy resin	350	0.134
Total:			0.515

Control and readout electronics

- **Fully customized** for HEPD-02 space application.
  - **Compactness**: 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** 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 ALTAI 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.