LIMADOU 利瑪竇

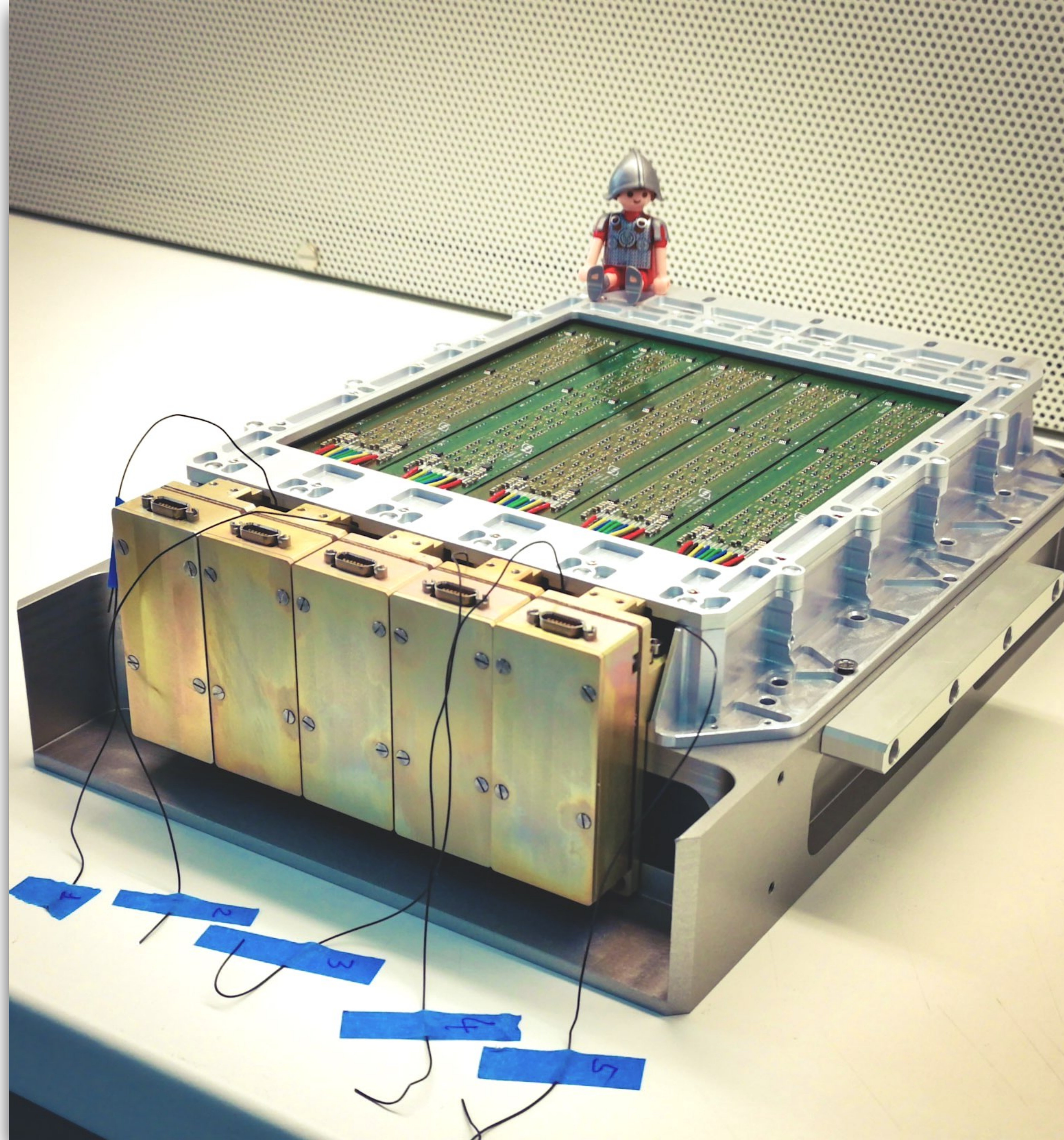
UNIVERSITÀ DI TORINO

Expected performance of the High Energy Particle Detector (HEPD-02) tracking system on board of the second China Seismo-Electromagnetic Satellite

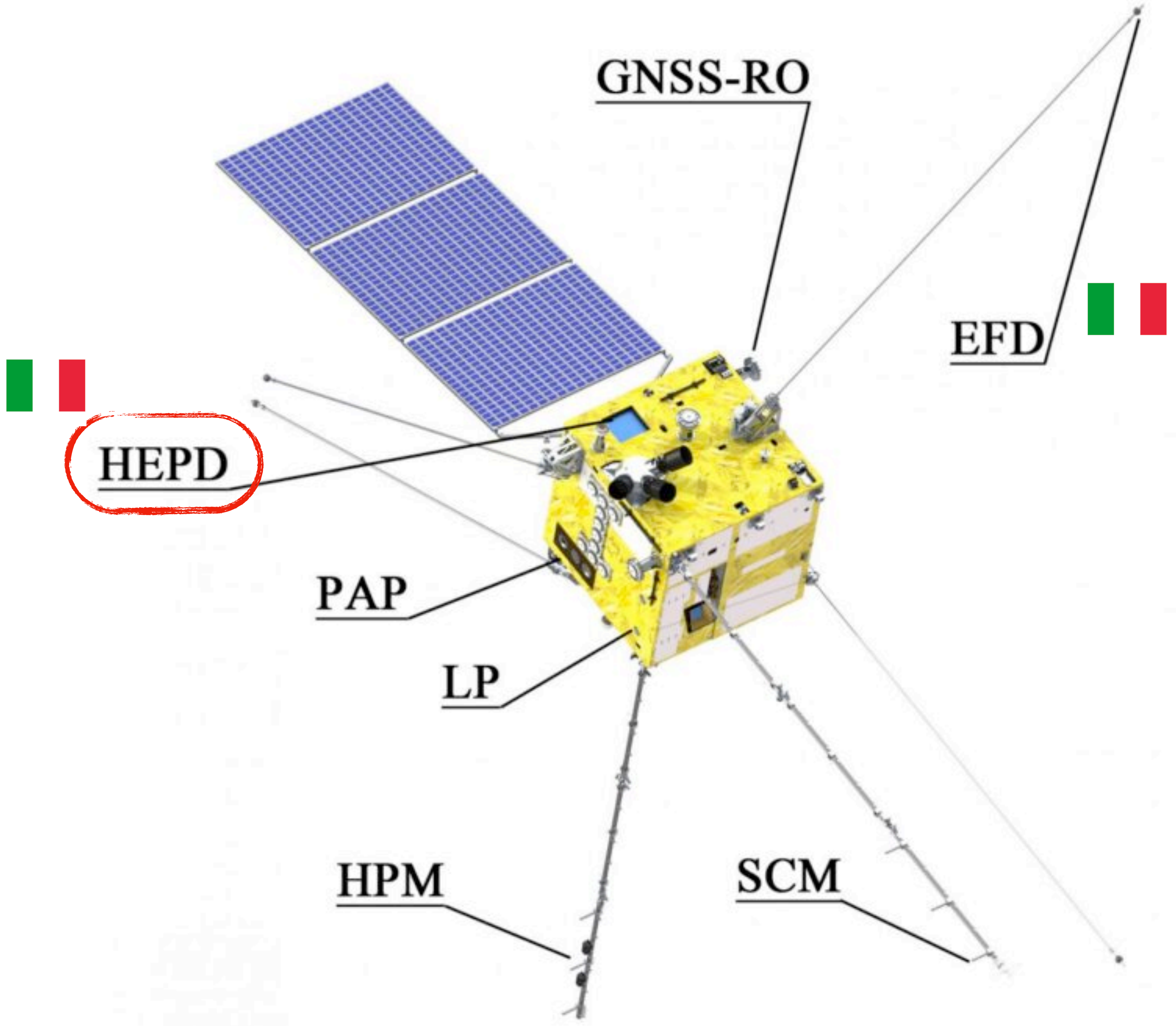
Applications in Planetary & Space Science

Umberto Savino for LIMADOU collaboration

INFN TORINO



Outline



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

CSES-02 scientific mission objectives ⇐

HEPD-02 design and characteristics ⇐

Space environment requirements ⇐

strength (light and stiff) ⇐

low power consumption ⇐

cooling in vacuum ⇐

MAPS in space - ALTAI chips ⇐

Ground test first results ⇐

assembly ⇐

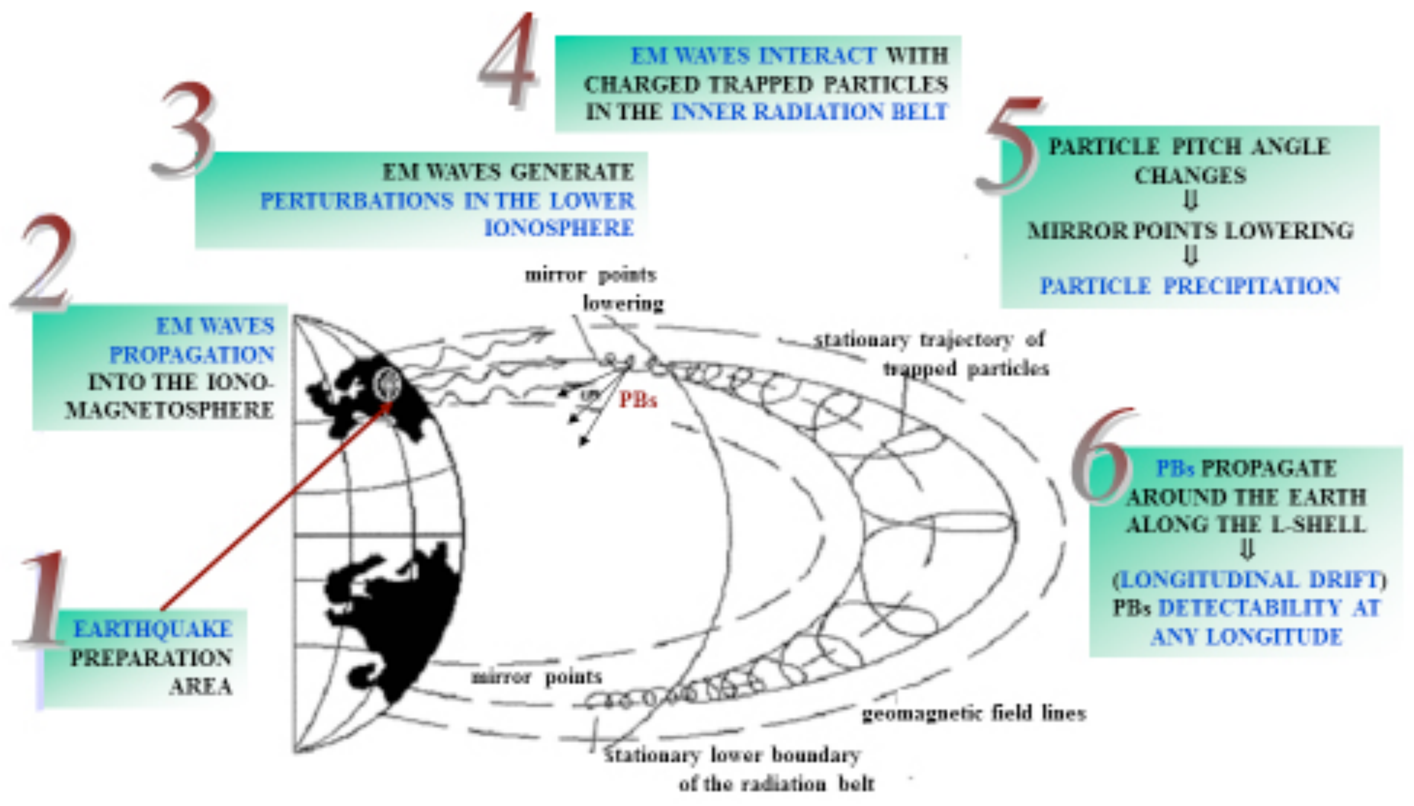
qualification/acceptance tests ⇐

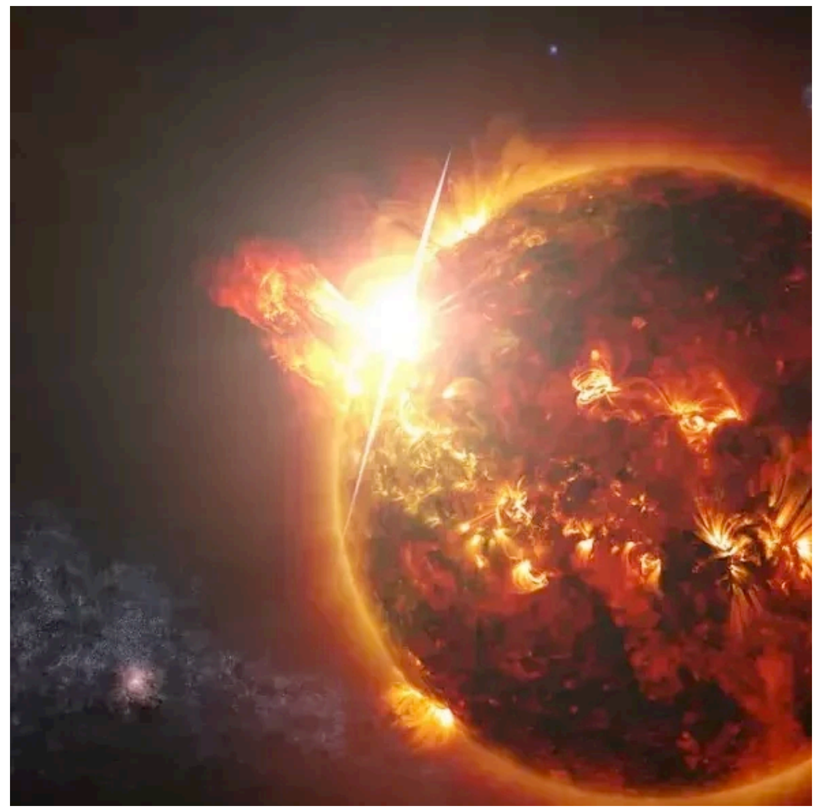
first results on particle detection ⇐

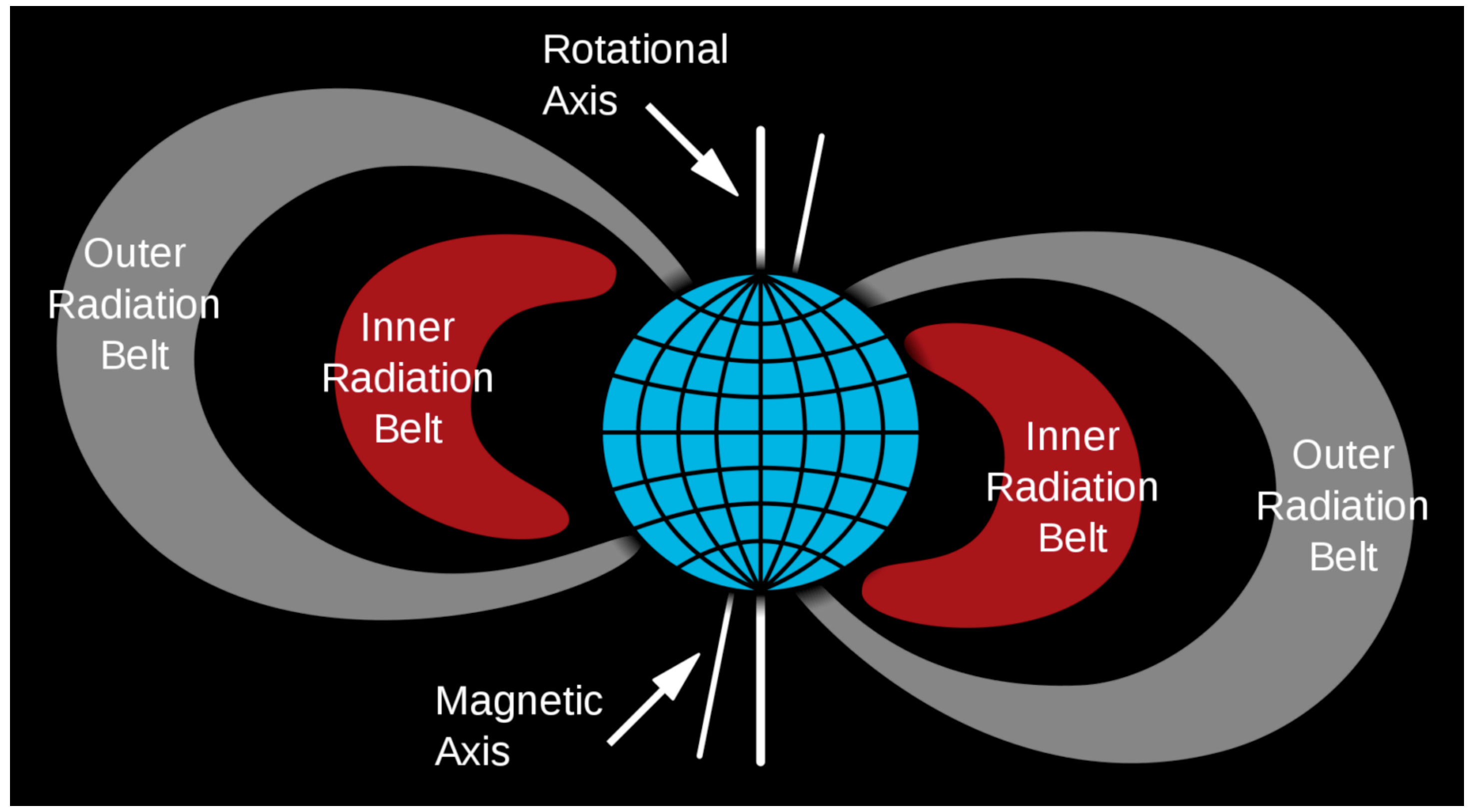
Next steps to the Space ⇐

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







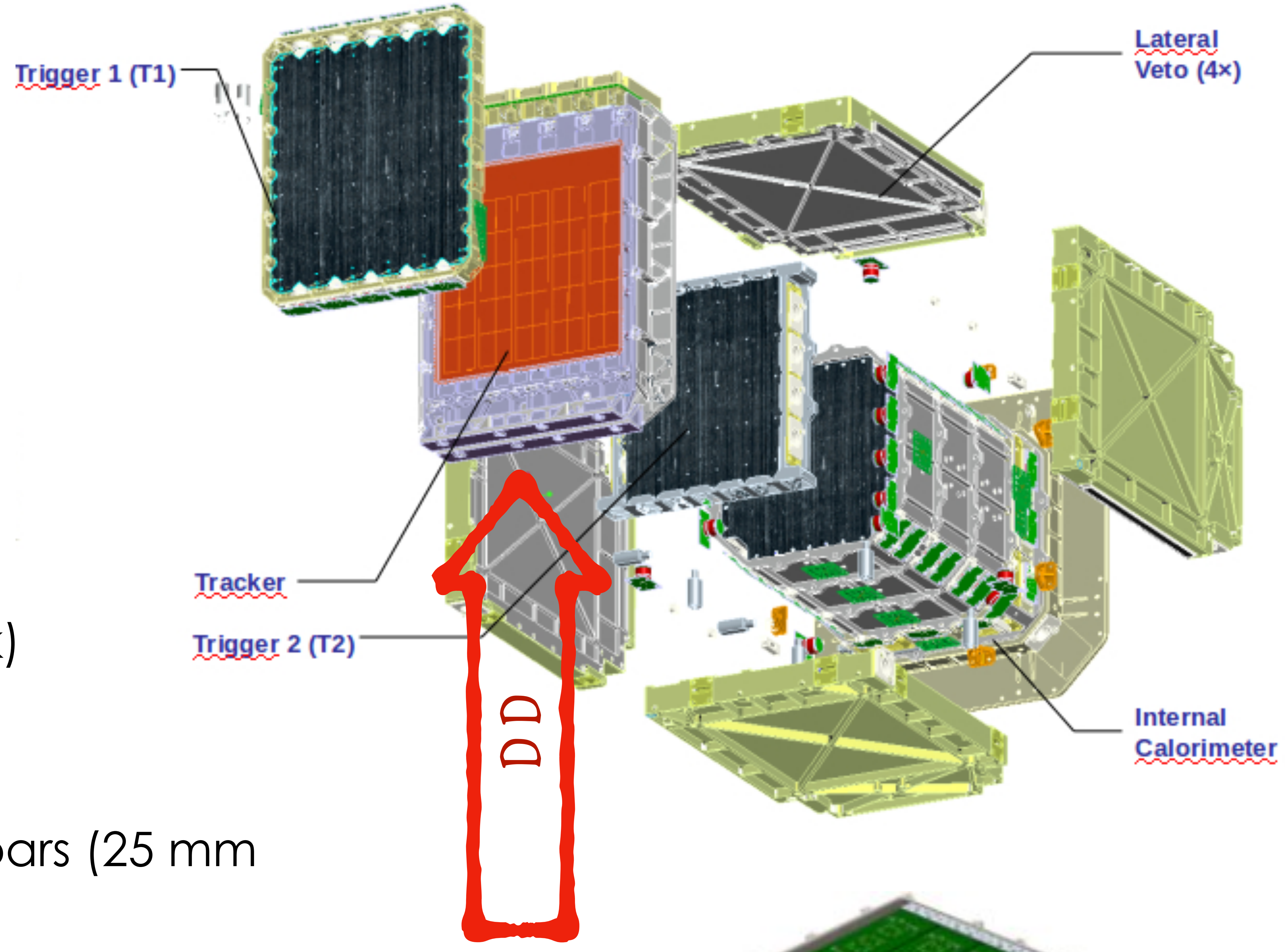
High Energy Particle Detector (HEPD-02)

HEPD-02 aim:

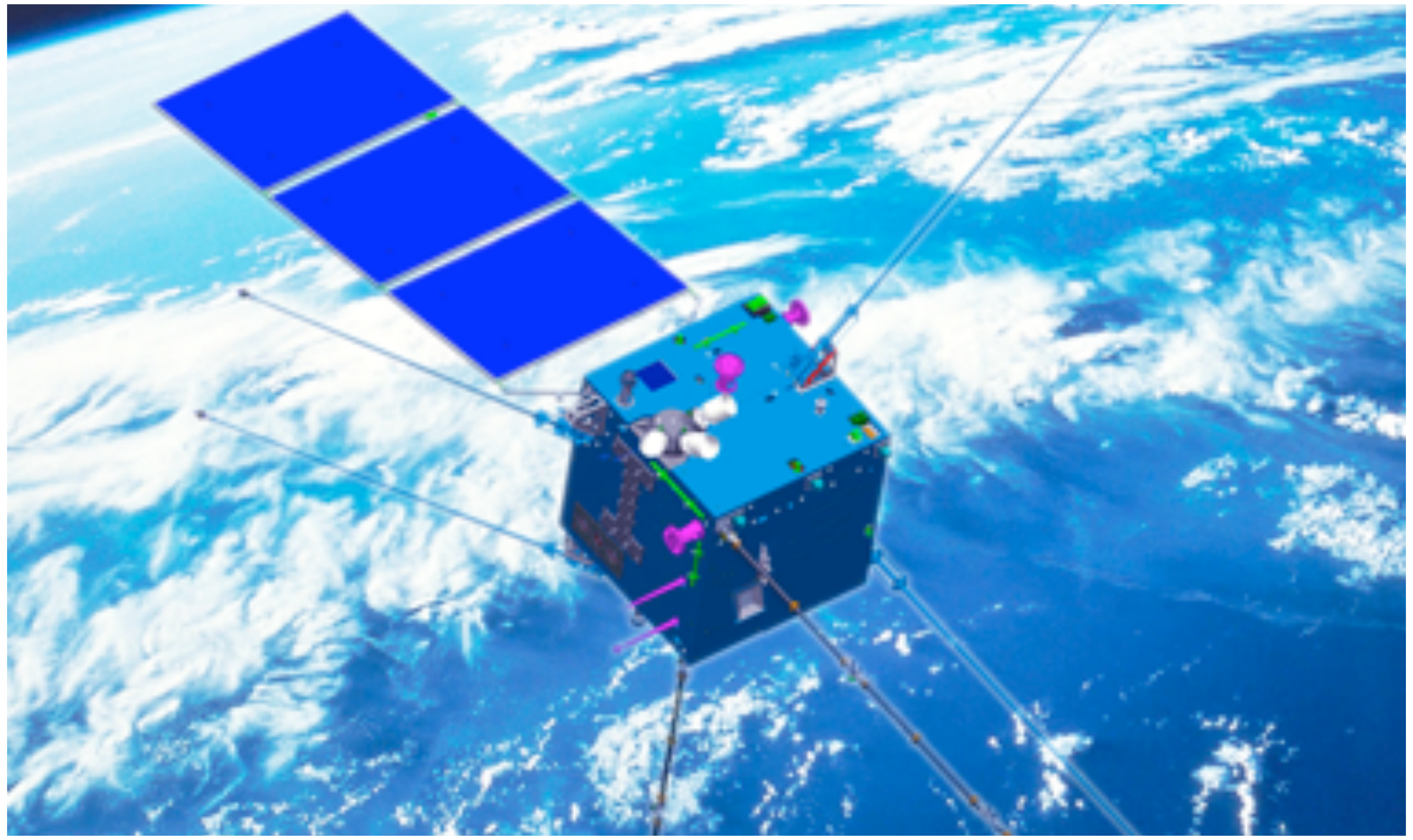
- detecting electrons (3MeV–100MeV)
- detecting protons (30MeV–200MeV)

Payload consists of:

- a particle tracker (DD) -- five standalone tracking modules
- a trigger system
  - TR1 (200×180 mm^2) -- 5 plastic scintillator bars (2 mm thick)
  - TR2 (150 x 150 mm^2) -- 4 plastic scintillator bars (8 mm thick)
- an energy detector (ED) composed of:
  - 12 plastic scintillator planes (150 x 150 x 10 mm^3);
  - 2 crystal (LYSO) scintillator planes (150 x 150 mm^2) -- 3 x 2 bars (25 mm thick each)
- a **containment detector CD** made of plastic scintillator planes (8 mm thick) -- 4 lateral and 1 bottom plane



Space environmental requirement



stiffness
> 10g accelerations

thermal drain
vacuum

power budget
(~13 W for DD)

Requirement:
minimization of
- multiple scattering
- energy loss

Requirement:
fasten
- event processing
- data transmission

HEPD-02 main requirements

Operating temperature	263 to 308 K
Operating pressure	$6.65 \cdot 10^{-3}$ Pa
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
Scientific data bus	RS-422
Data handling bus	CAN 2.0
Life cycle	> 6 years

Monolithic active pixel sensors

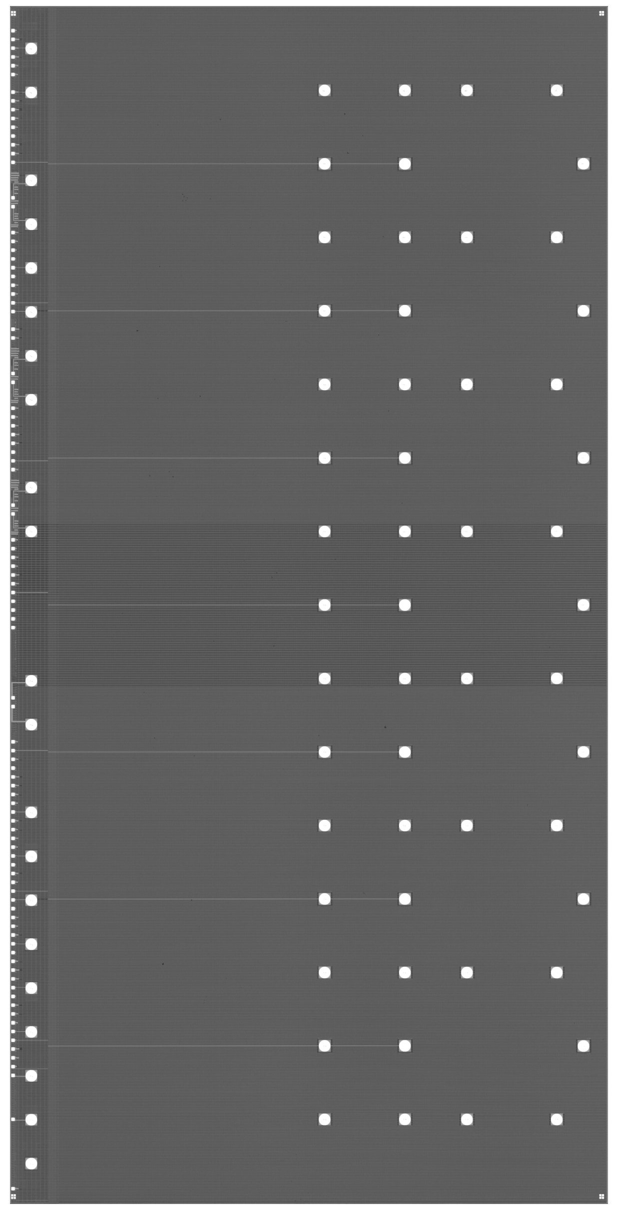
ALTAI sensors

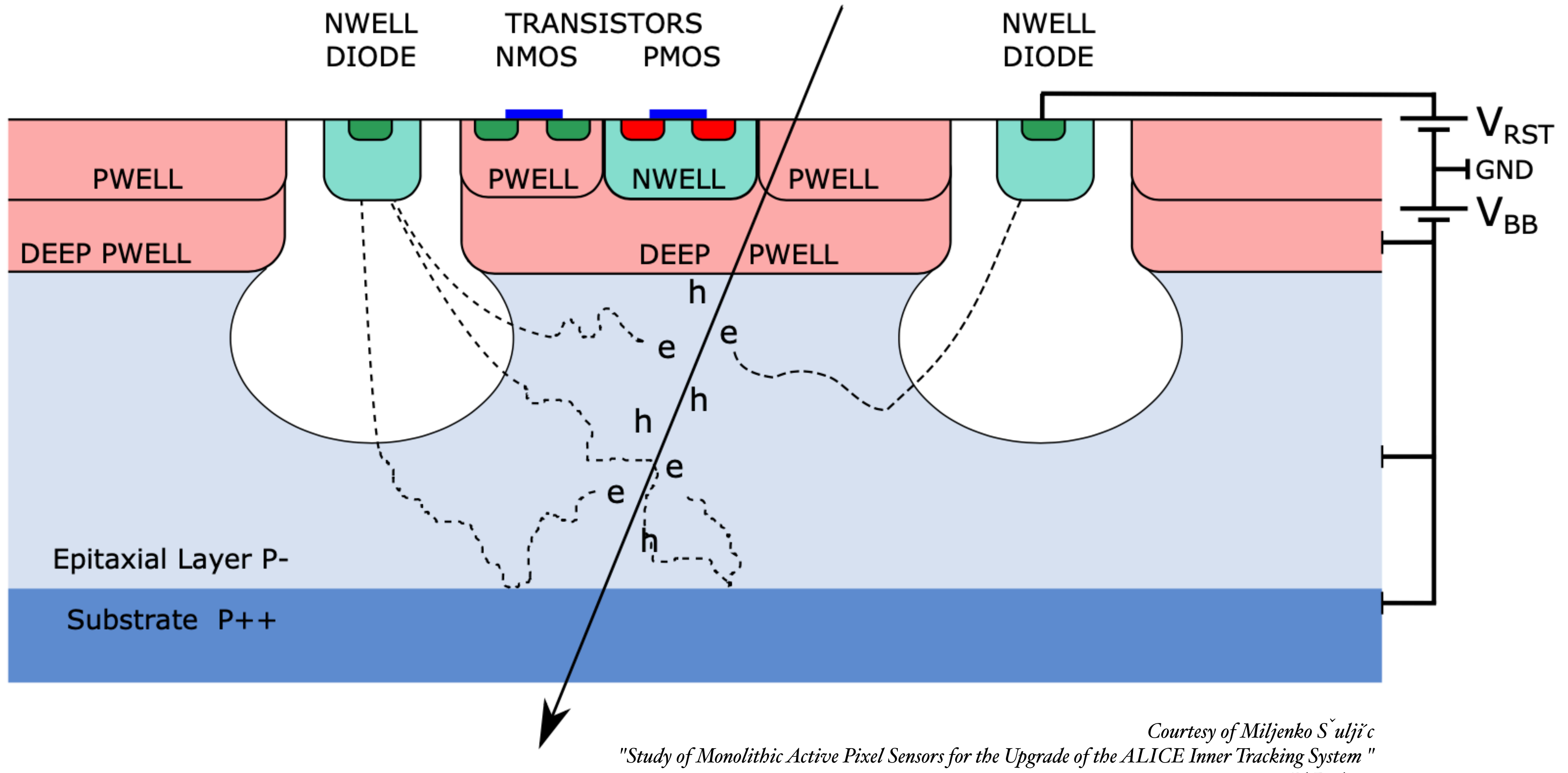
The sensor and readout circuitry are implanted in the same silicon

- Sparsified readout
- Pixel pitch: 26.88 x 29.24 μm^2
- Columns x rows: 1024 x 512
- Electrode diameter: 2 μm
- Producer: Tower Semiconductors

Parameter	Values
Detector size [mm^2]	15 x 30
Detector thickness [μm]	50 - 100
Spatial resolution [μm]	4
Detection efficiency	>99%
Fake hit rate [evt^{-1} $pixel^{-1}$]	$<10^{-7}$
Integration time [μs]	~2
Power density [mW/cm^2]	<50 *

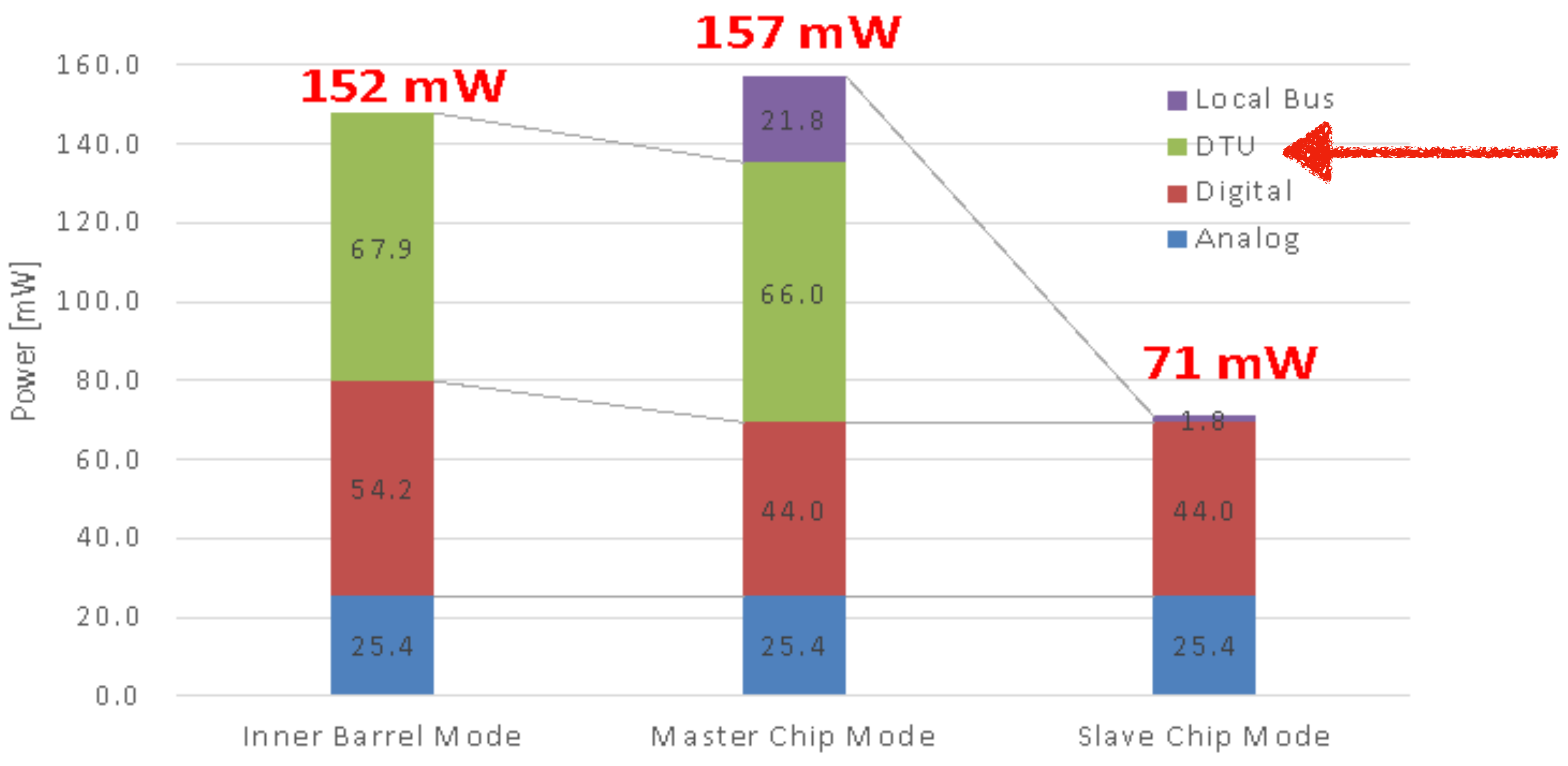
Advantages	Challanges
reduces systematic uncertainties on tracking	Tradeoff for mechanical supports
Ultra low material budget (50 μm chip thickness, 180 um FPC readout)	Limited power budget
Cheaper than standard microstrips	Heat dissipation
Monolithic ($<10^{-7}$ fake hits per trigger)	limited charge information (digital readout)

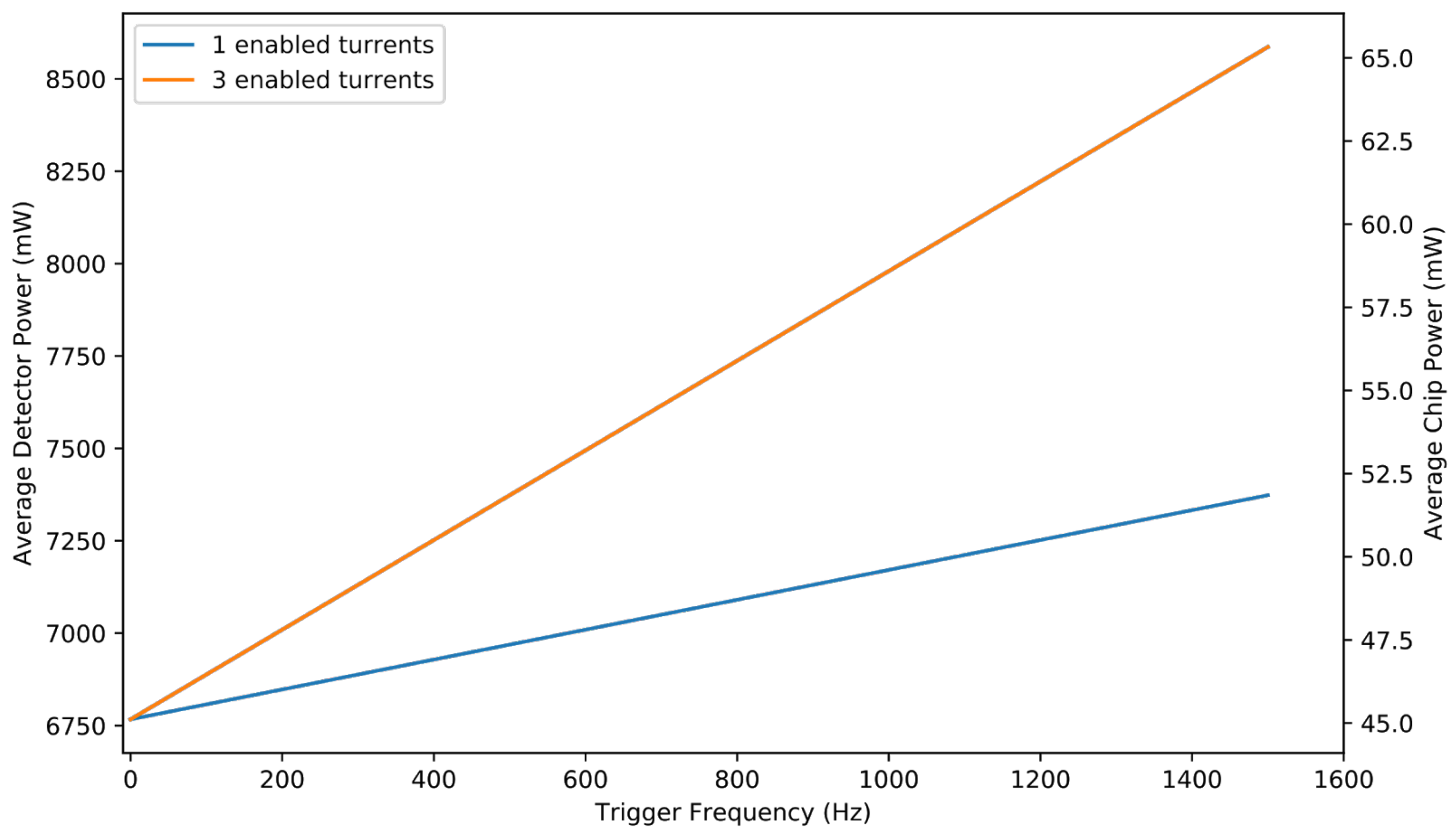




Courtesy of Miljenko S̆uljic̆ "Study of Monolithic Active Pixel Sensors for the Upgrade of the ALICE Inner Tracking System" - PhD thesis

Power consumption mitigation





- **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.

DD realization

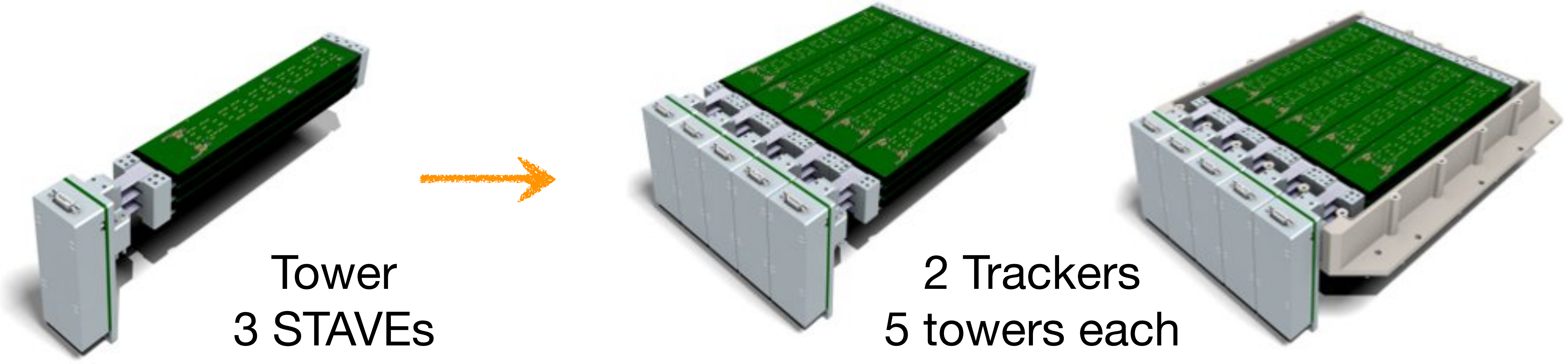
From ALTAI to tracker

- **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

10 ALTAI aligned glued on FPC



Qualification model (QM)
Flight model (FM)
+ spares modules

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

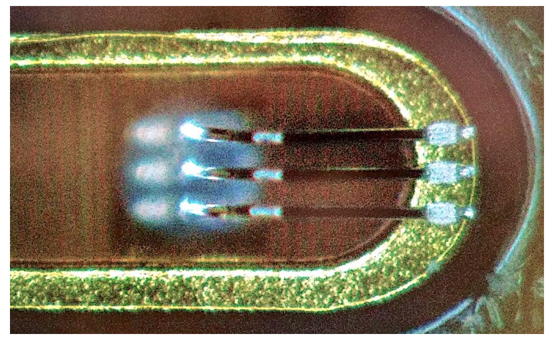
* quality categories based on functional performance

1st requirement: precision

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

Space requirement:

- redundancy → 3 bonds per each pad

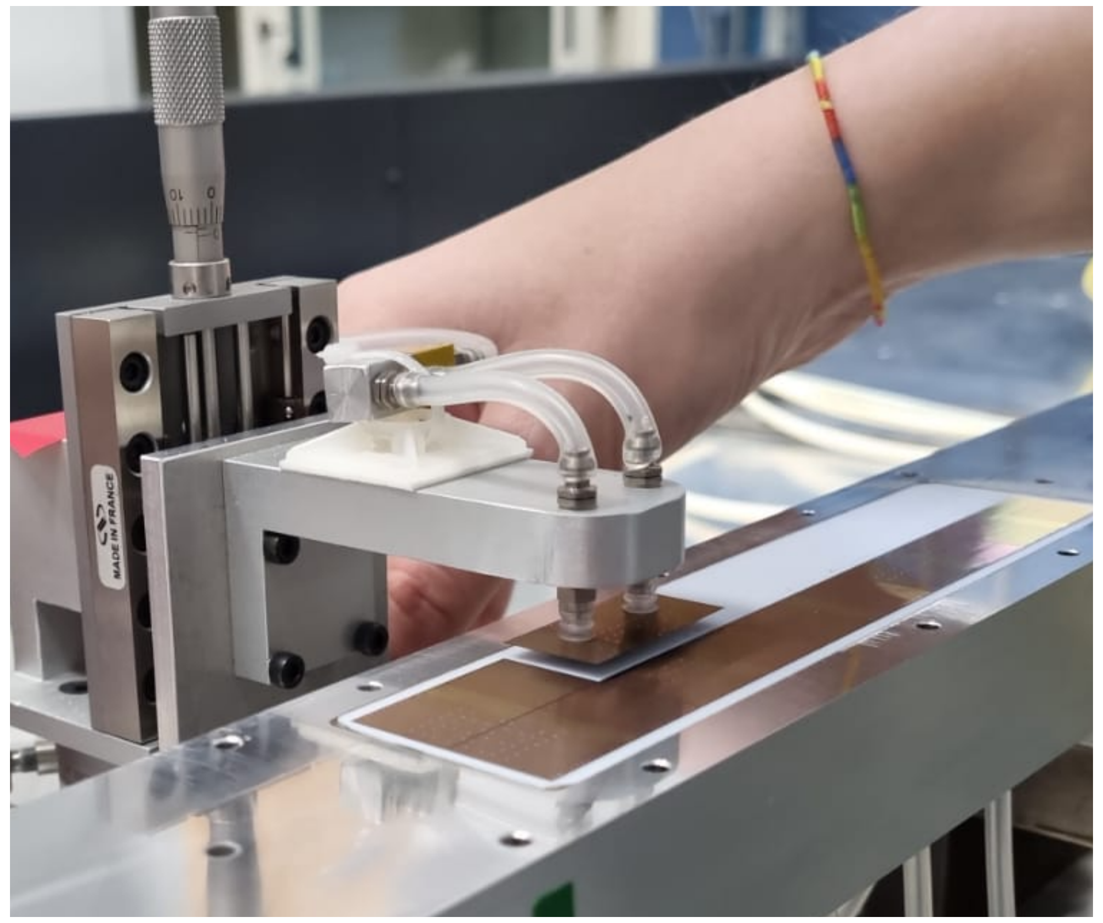


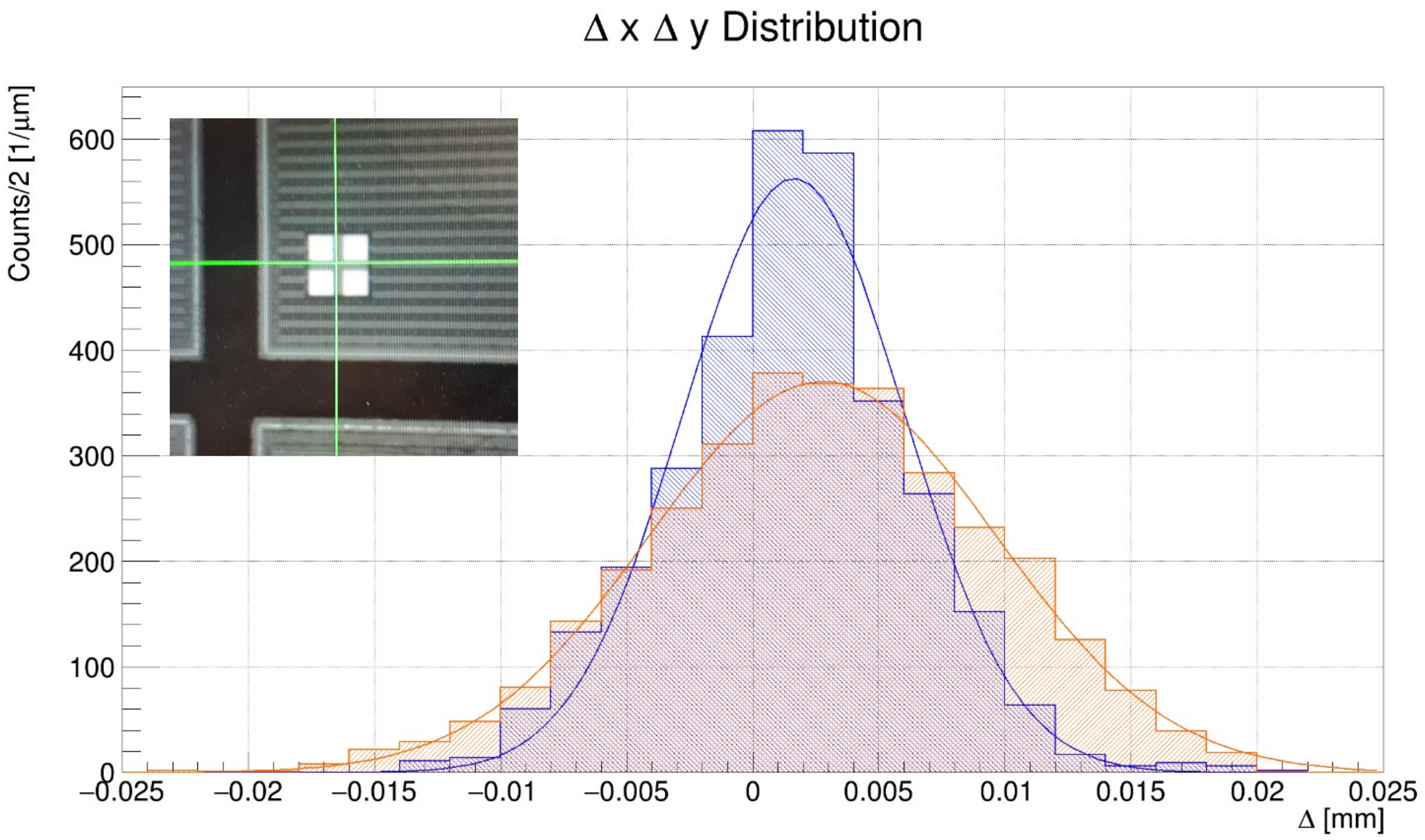
- Mitutoyo CMM measure the position of the ALTAI reference pads

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

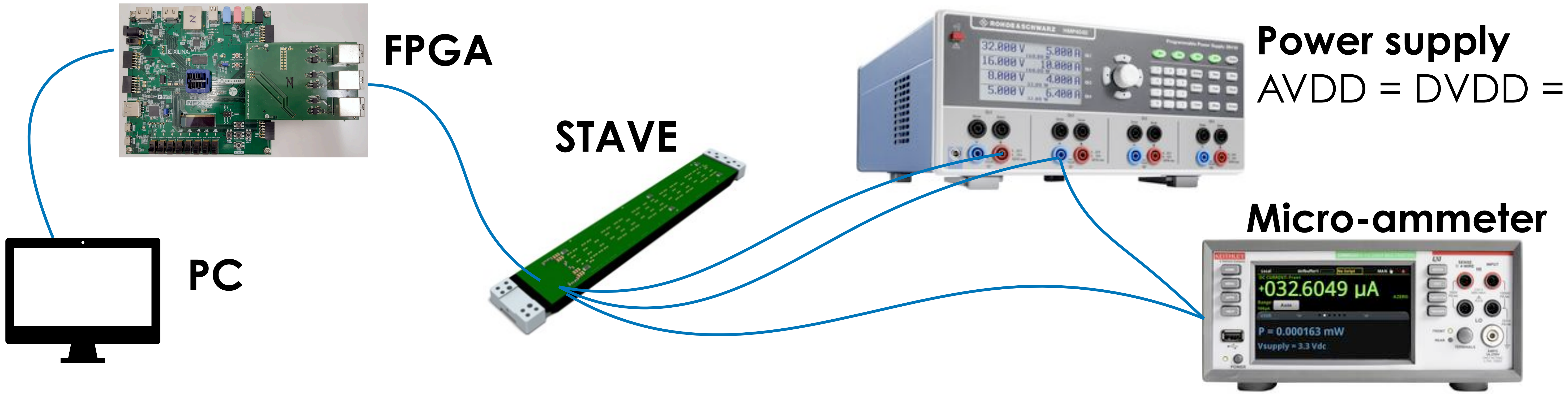




2nd requirement - power consumption

--- HIC assembly ---

- Chip alignment
- FPC gluing
- bonding
- test
- TAB and wing cut
- test
- STAVE assembly
- test

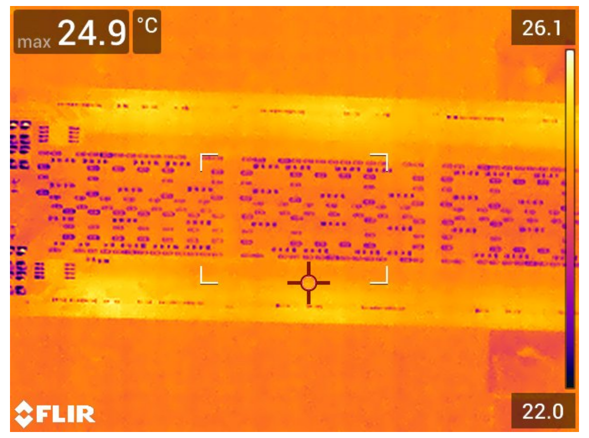


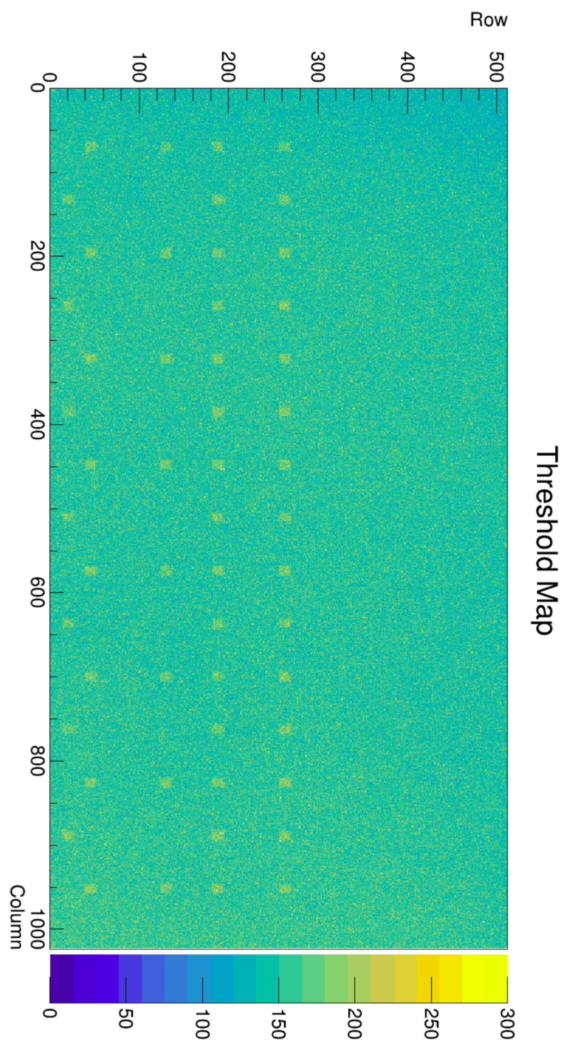
Test procedure to assess stave quality:

- check for hotspot with thermocam
- 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





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

3rd requirement - heat dissipation

Light and stiff supports

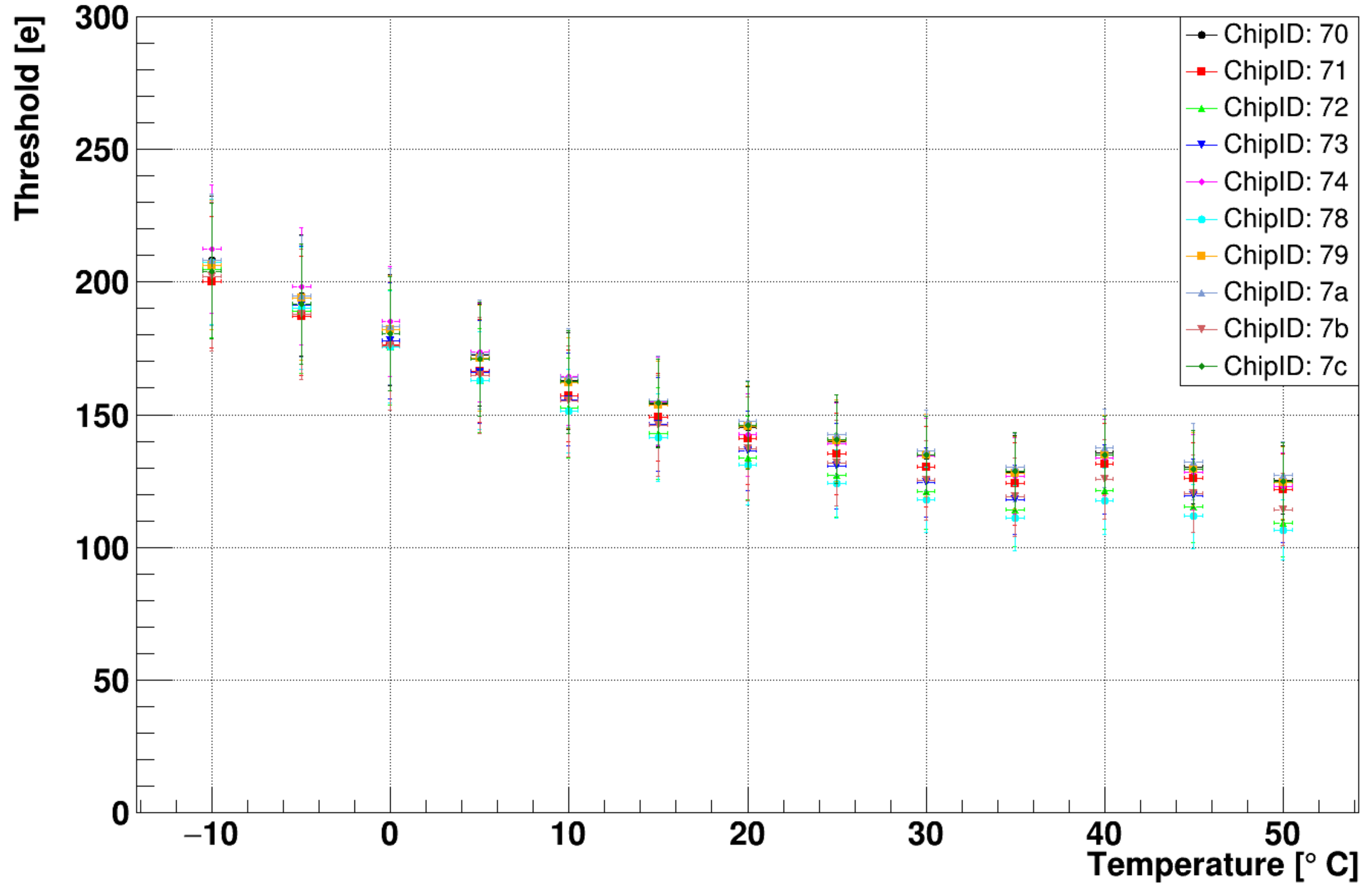
Requirements:
- stiffness to withstand the vibrational stresses occurring during the launch phase
- efficient thermal properties, to dissipate the heat produced by the ALTAI sensors (0.8W/stave)

Winner: K13D2U with cyanate ester prepreg resin EX1515

- Vacuum environment of 6.65 10^{-3} Pa and in presence of repeated thermal cycles
- Cooling system operates from one side with a temperature gradient of 6 K

CP with end blocks

Threshold vs Temperature



- Climatic chamber and on FPC dallas sensors (DS18B20U)
- temperature variation [263 to 323] K (requested [303 to 313] K)

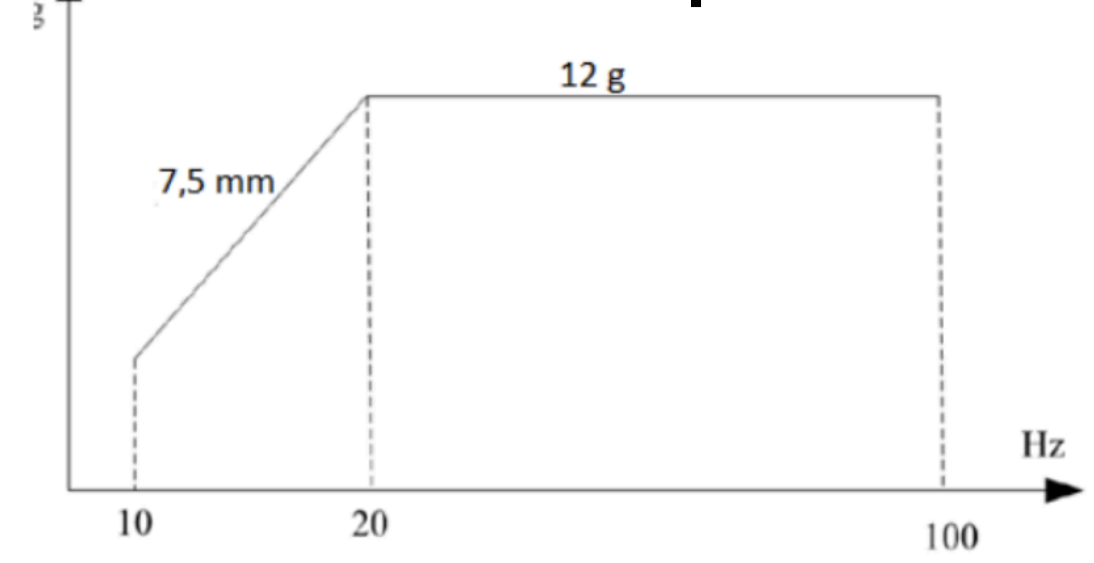
- Threshold variation of 60 e^- over ΔT of 60 K → 1 e^-/K
- Standard deviation of every-chip pixel threshold is 20 e^-
- The higher the back bias the lower the temperature influence

Qualification/acceptance tests

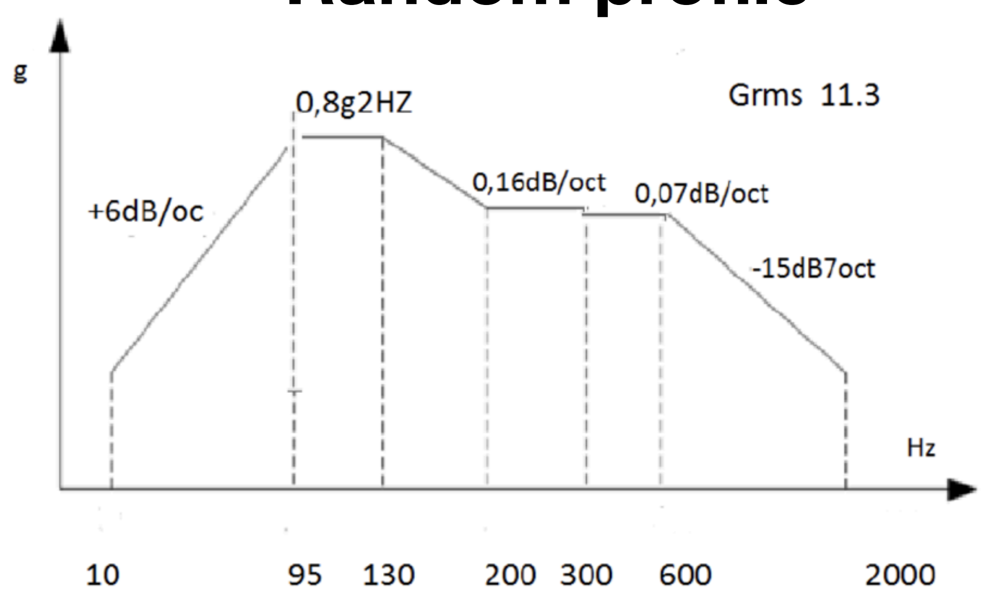
In compliance with CSES-02 satellite requirements

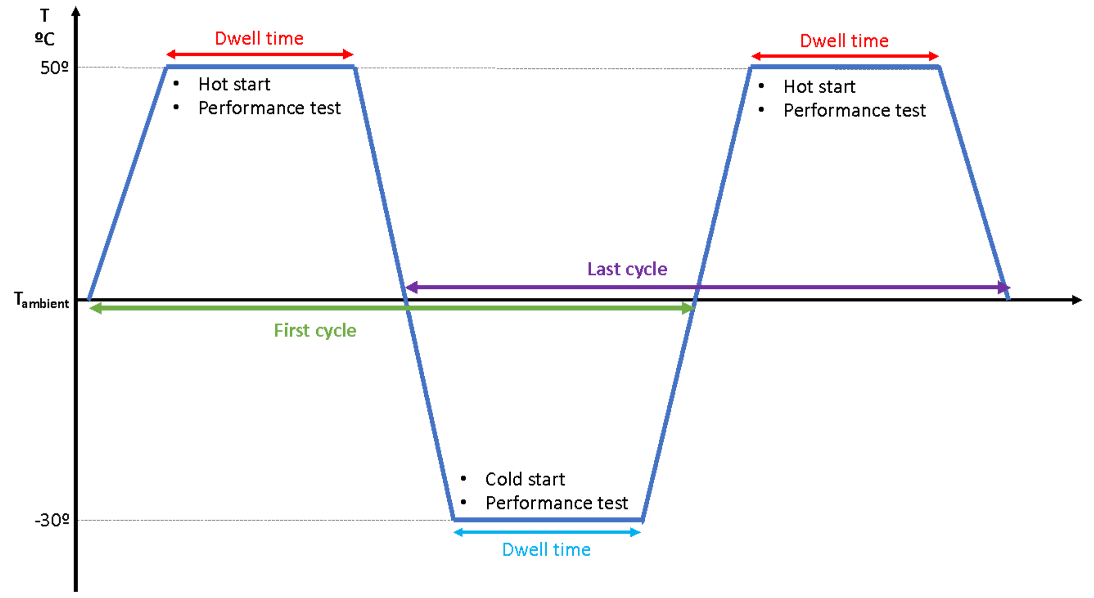
- **Vibrational test**
  - resonance search scan along the axis
  - apply Sine and Random vibration load levels
  - visual inspection and verification of the insulation resistance
- **Shock test** (only QM)
- **Thermo vacuum test**
  - temperature cycles from 318 to 253 K
  - pressure to nominal value ≤ 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

Sinusoidal profile



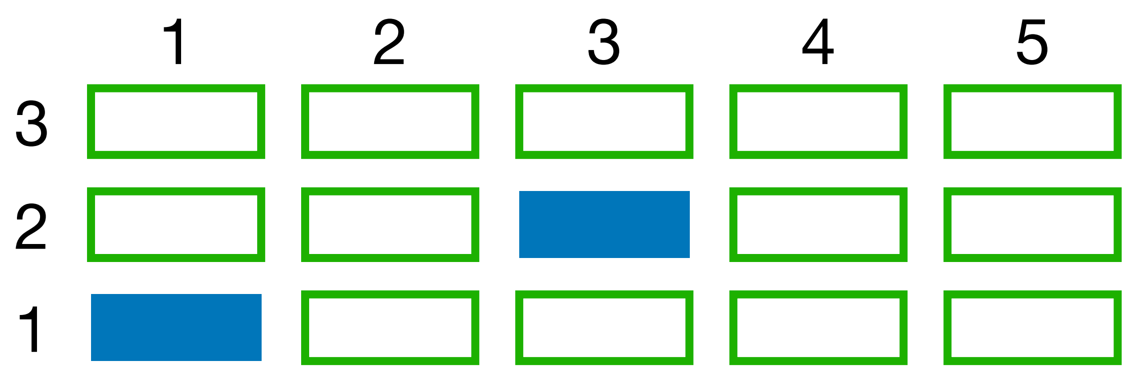
Random profile

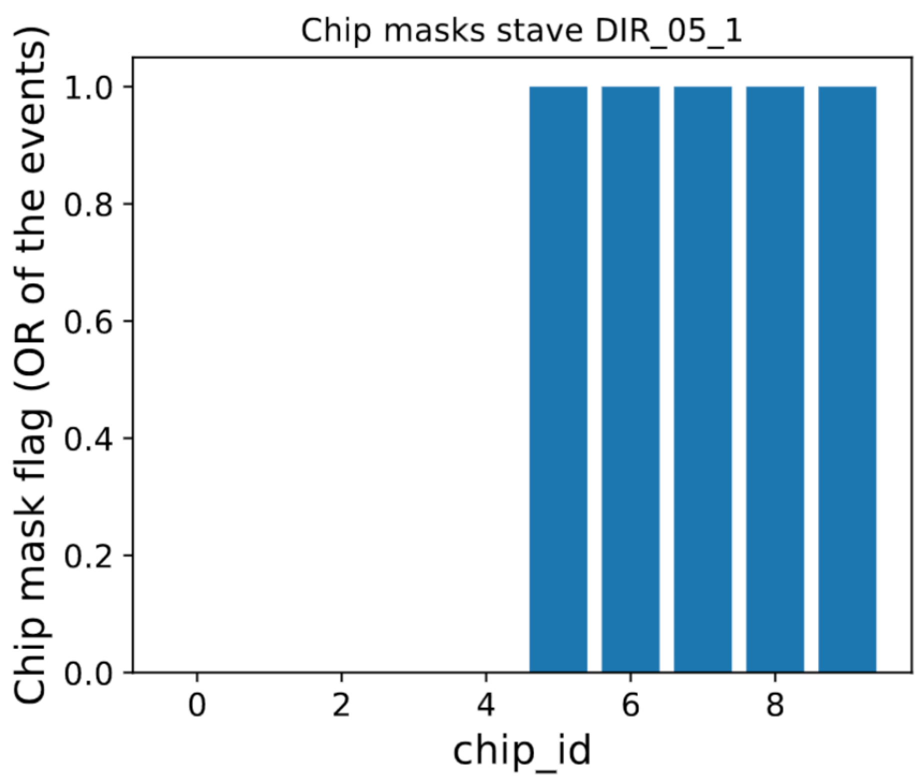


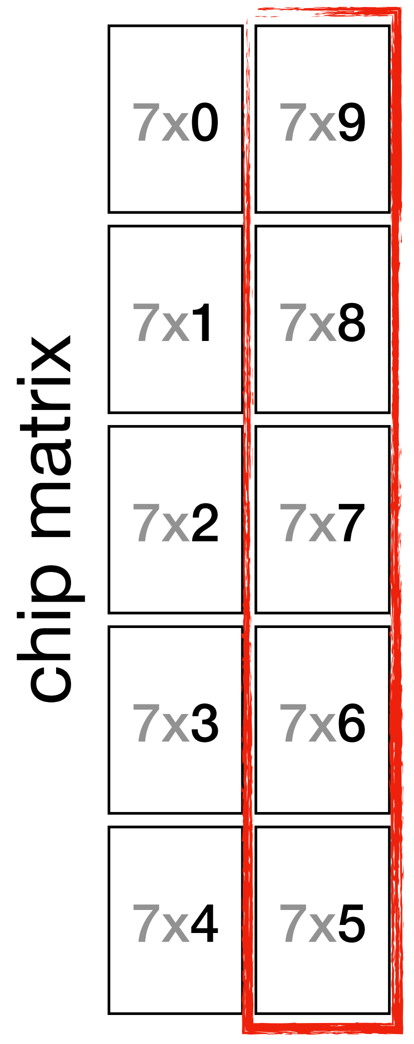


Thermal cycles

- **Test result: passed**
  - two half staves masked in DD





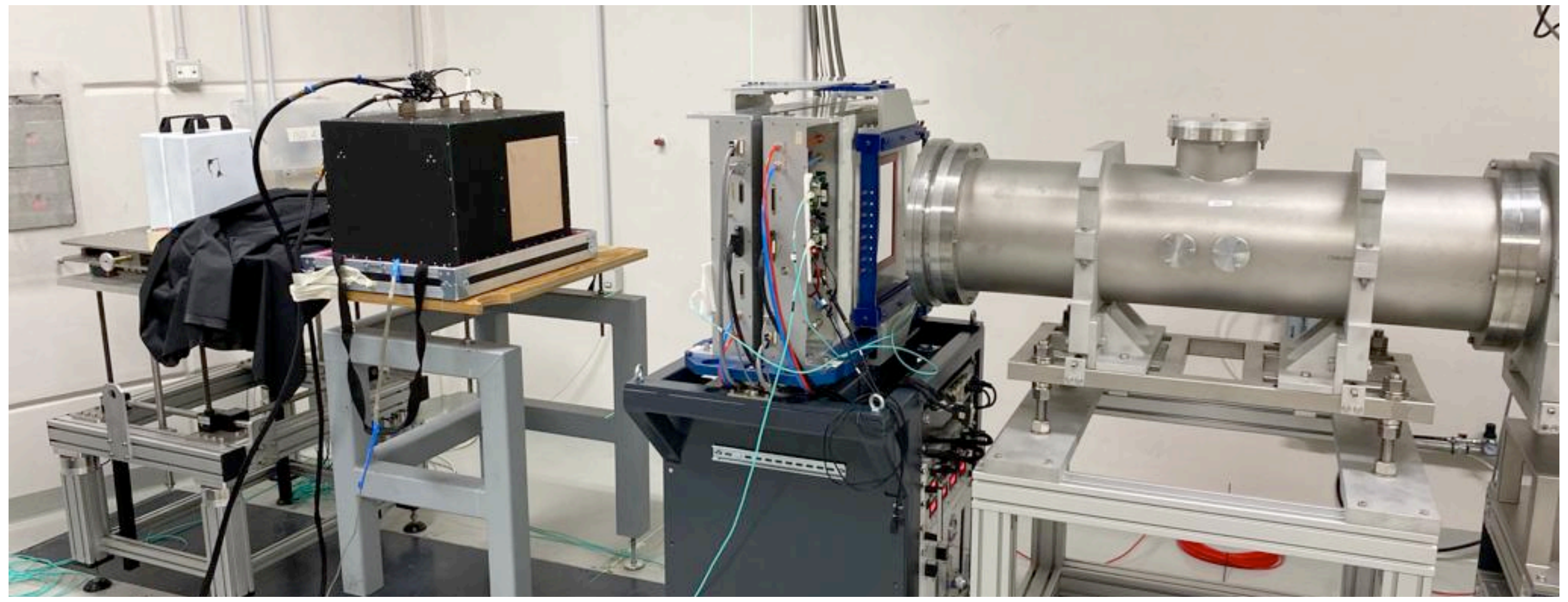


DD ground test - first results

- **Cosmic rays data acquisition**
- **Test beam** with:
  - ions (electrons, protons, carbon)
  - photons

Beam (particles/photons) energies

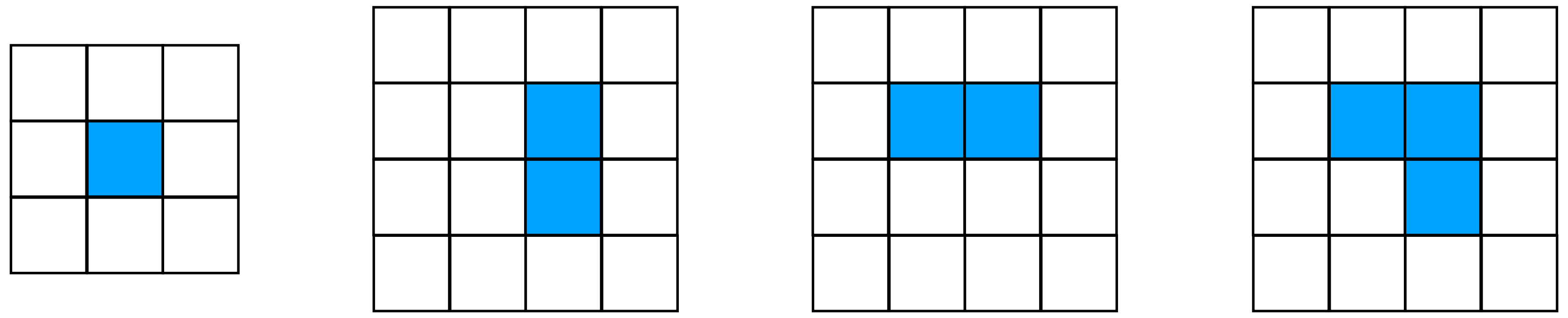
	energy range
electrons	6 -- 450 MeV
protons	10 -- 230 MeV
carbon	115 -- 400 MeV
photons	1 -- 10 MeV



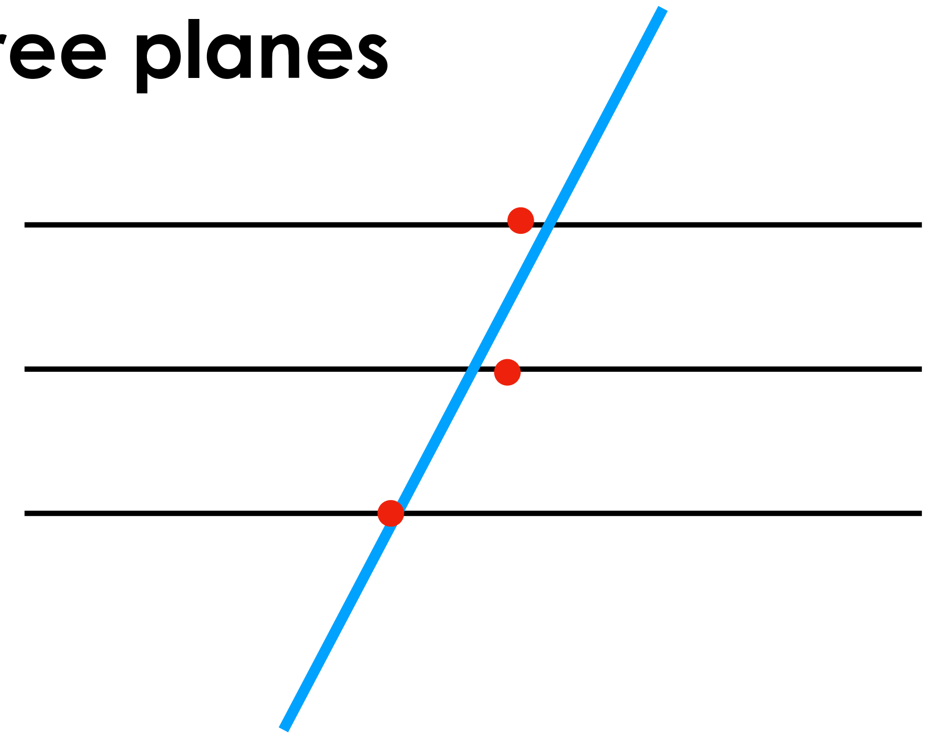
- **Fake hits removal**

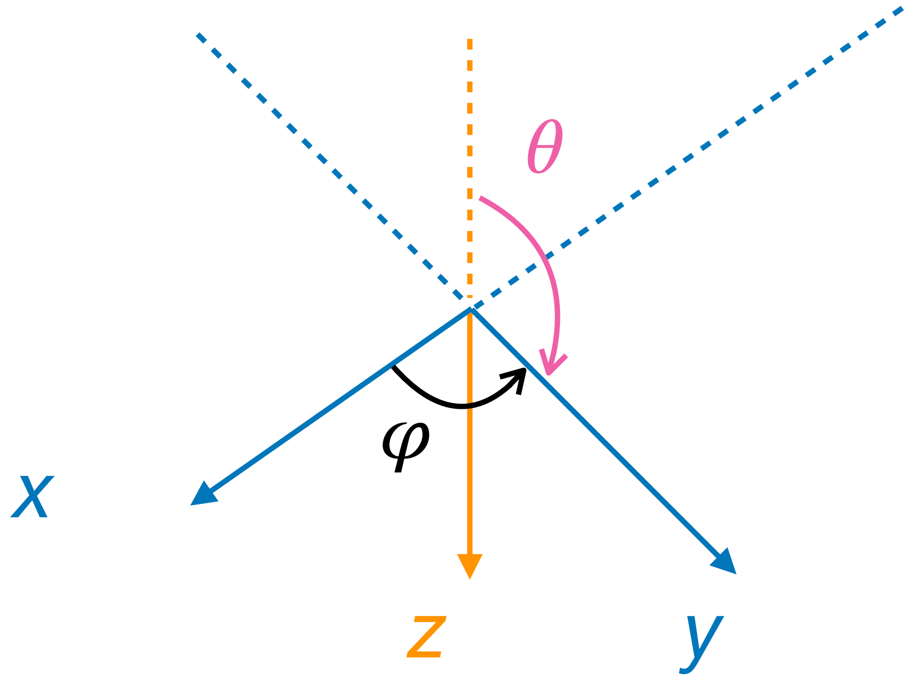
  dry run → identification of firing pixels → masking

- **Cluster definition**

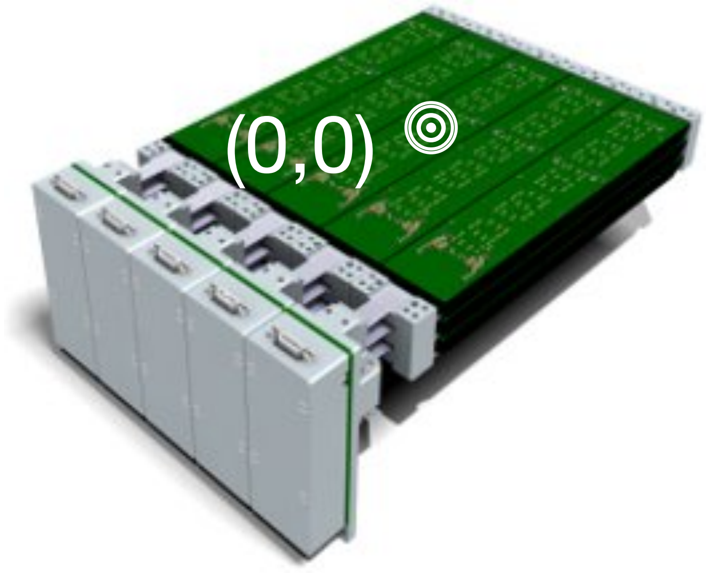


- **Fitting three planes**

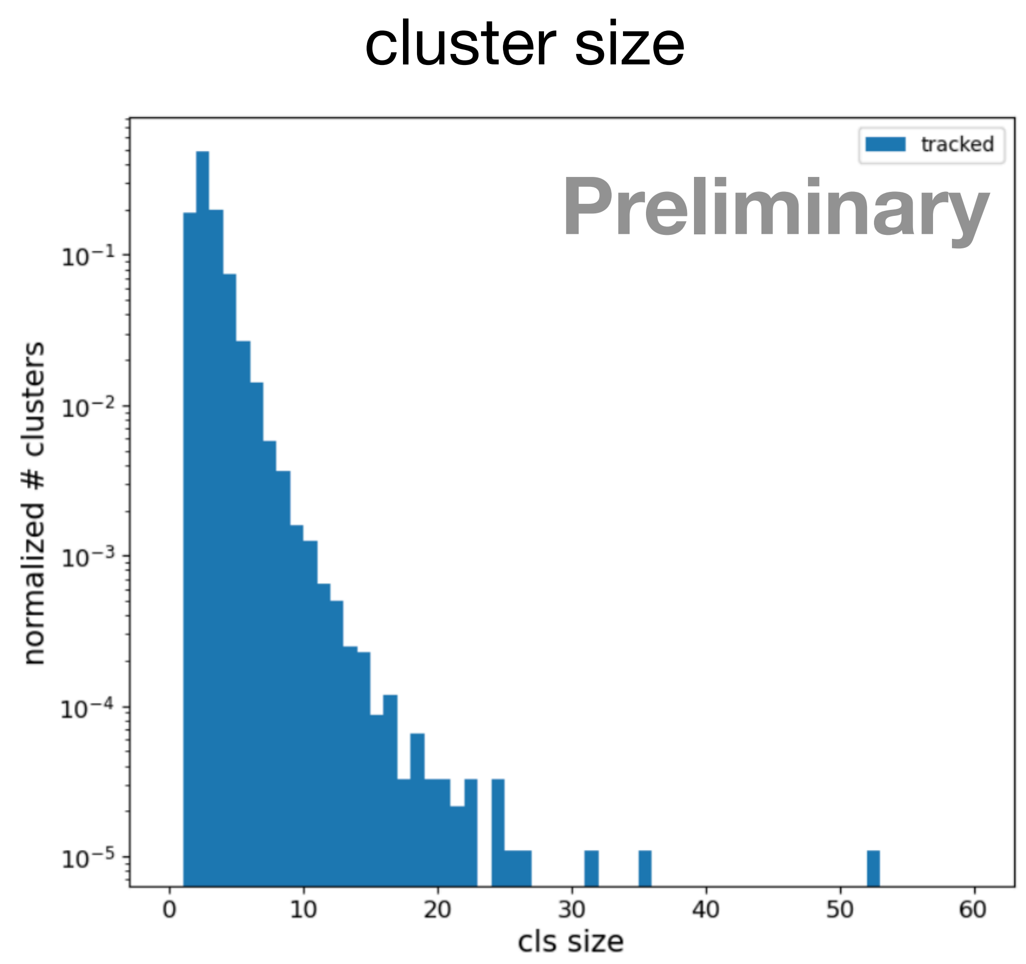


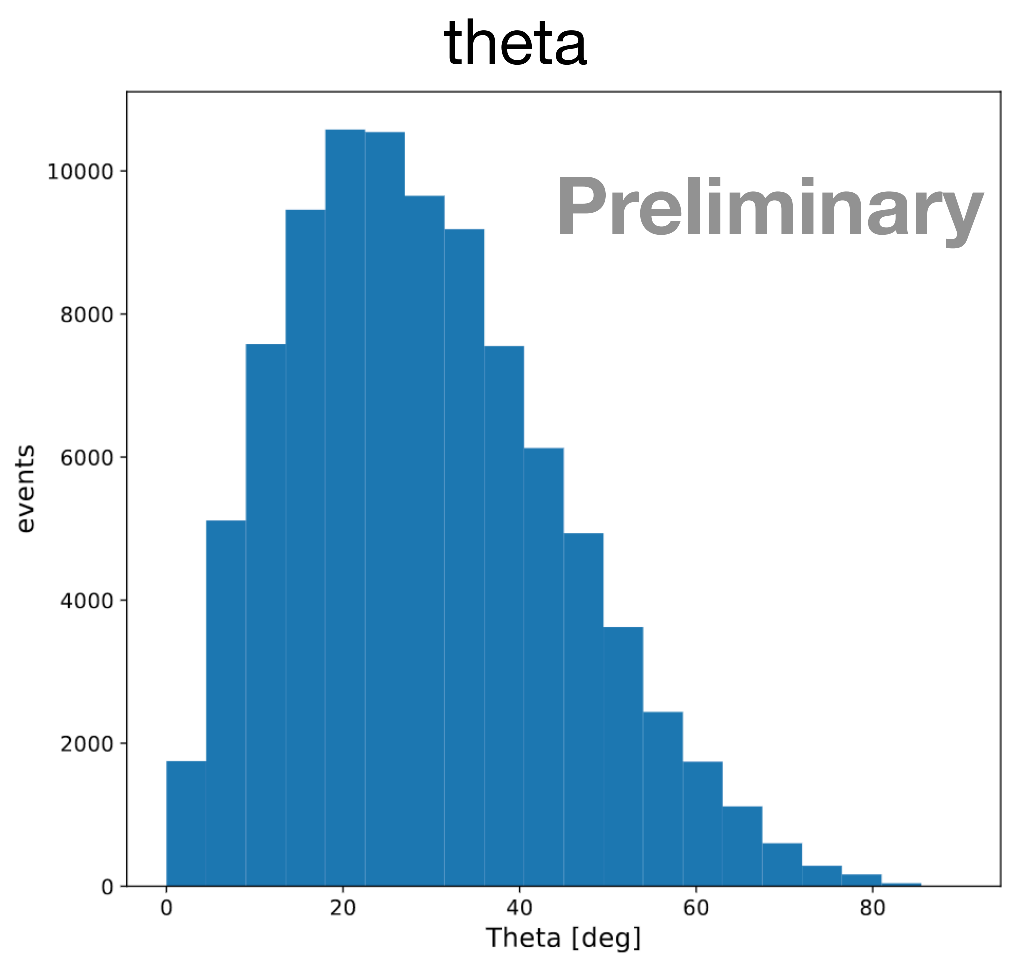


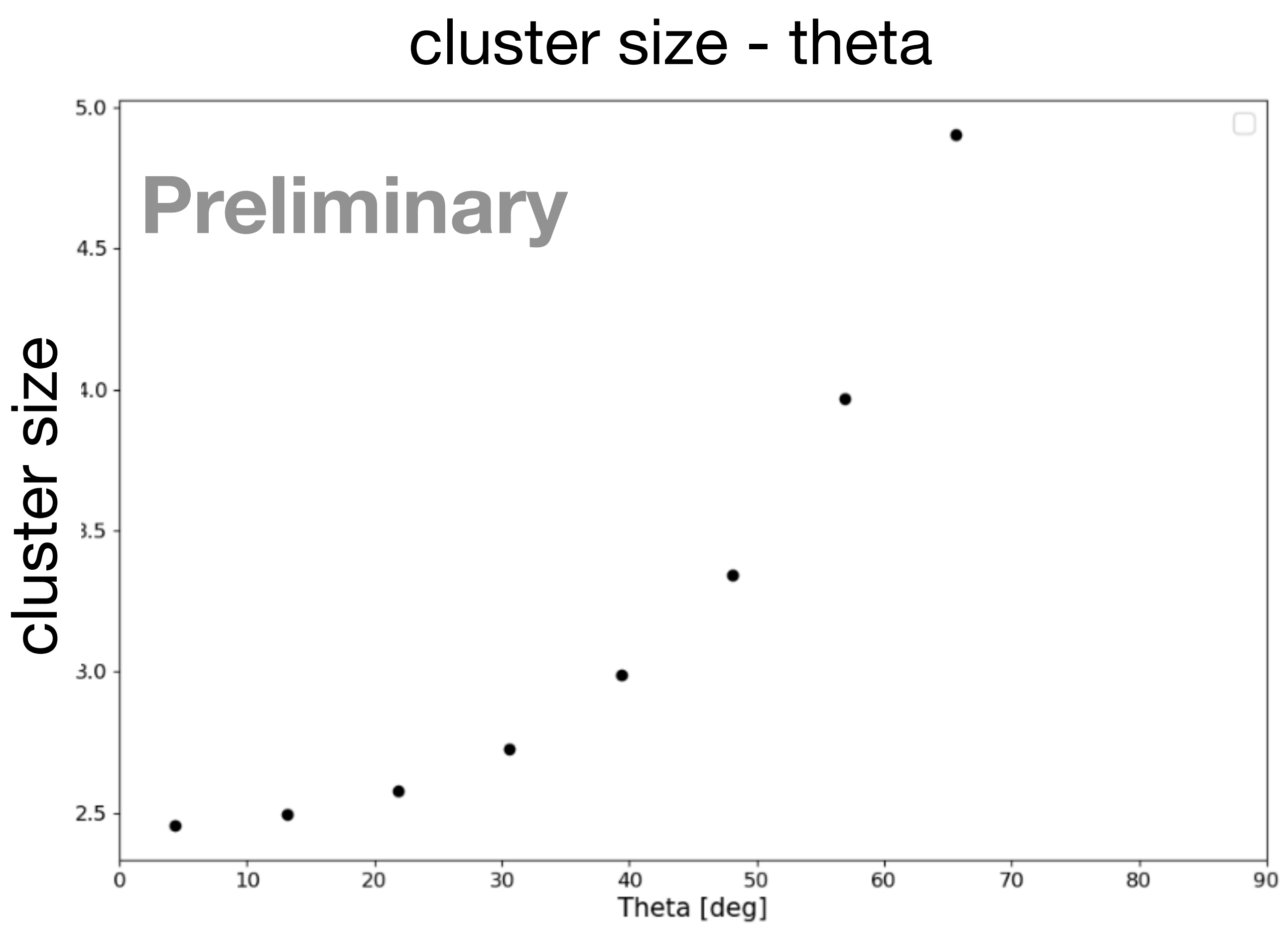
Reference system



DD performance - cosmic rays

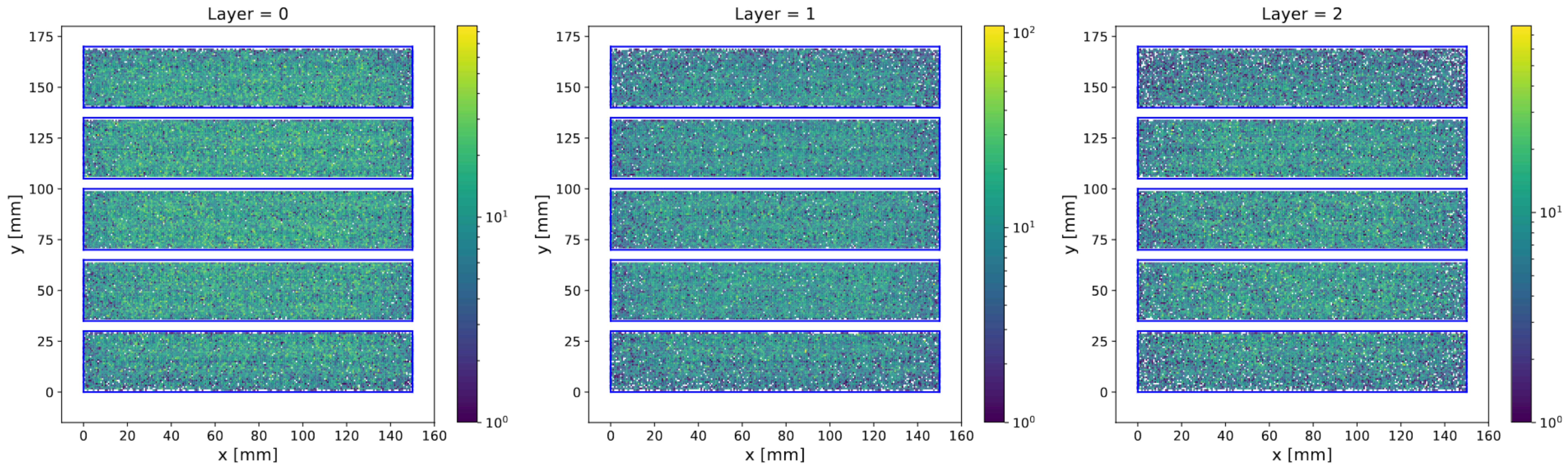






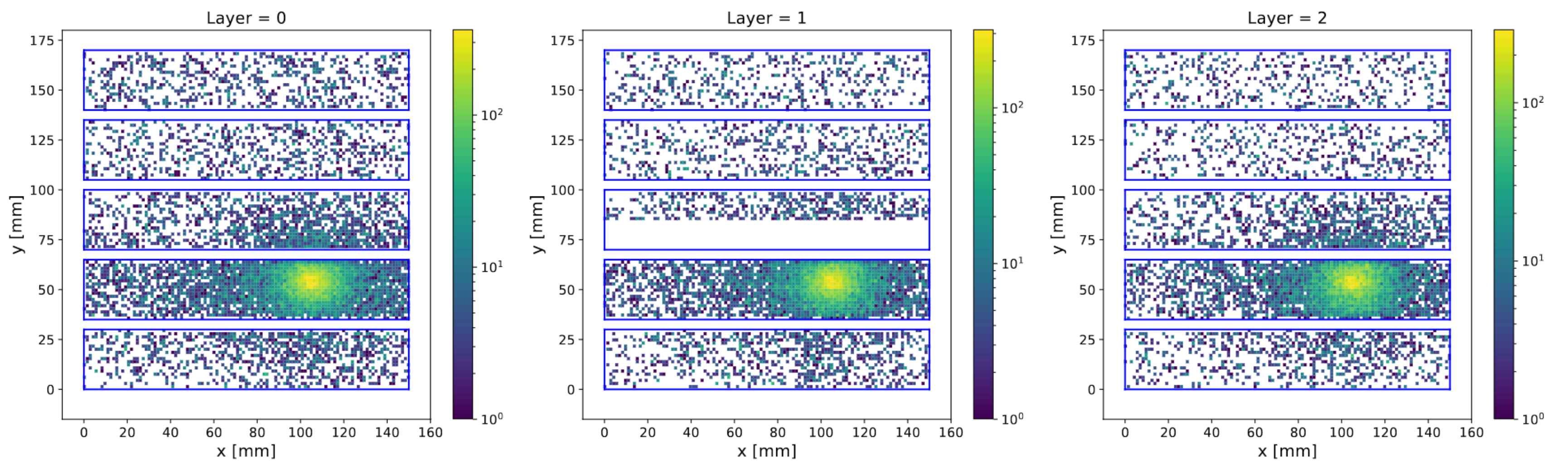
- Cosmic rays
- before Thermo Vacuum and Thermal Cycles
- statistics: 117,3875 events in 14.69 h

- **cluster size increasing with track inclination follows expectations from geometry**

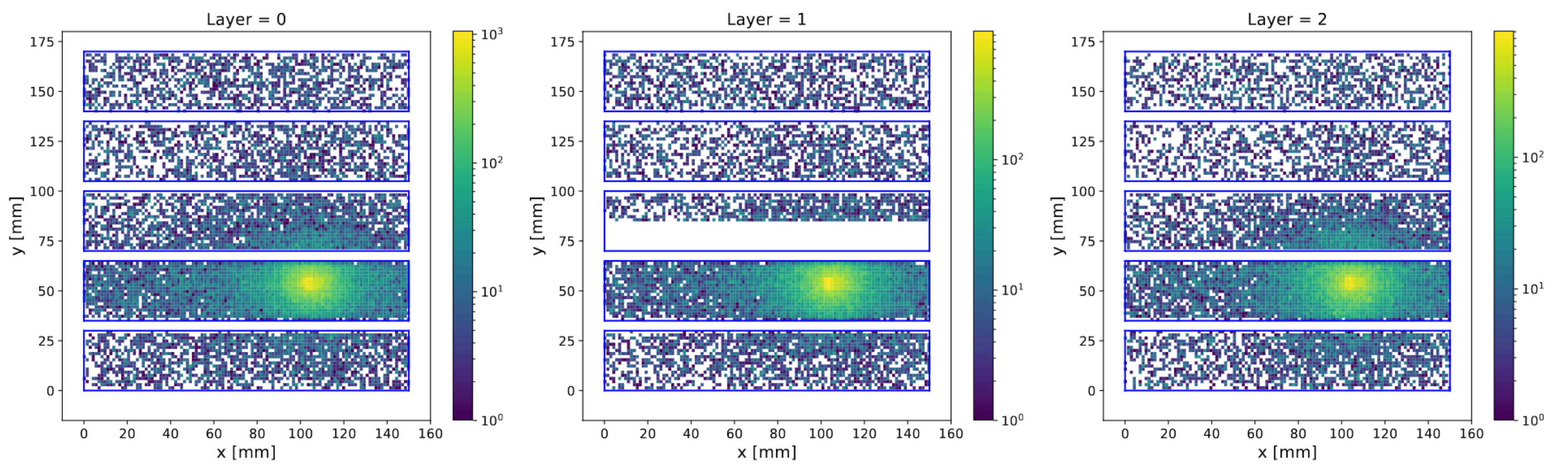


DD performance - particles

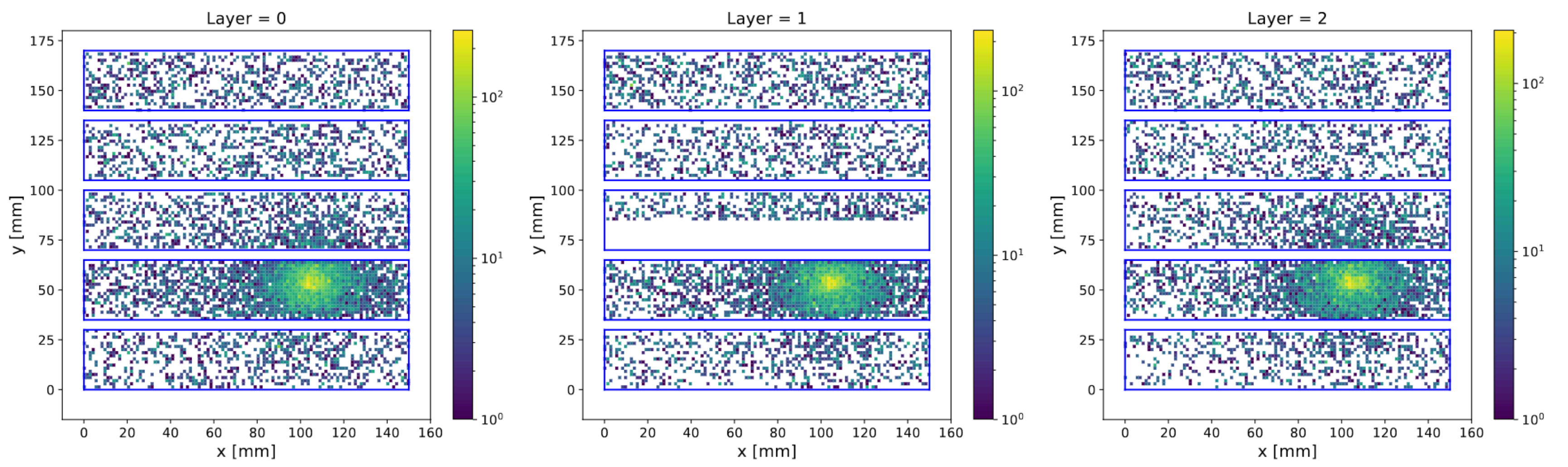
- HEPD-02 light-nuclei with kinetic energy as low as 50 MeV/Z **may generate in silicon up to 60 times the e-h pairs of a m.i.p.**
  [PoS(ICRC2021)070]



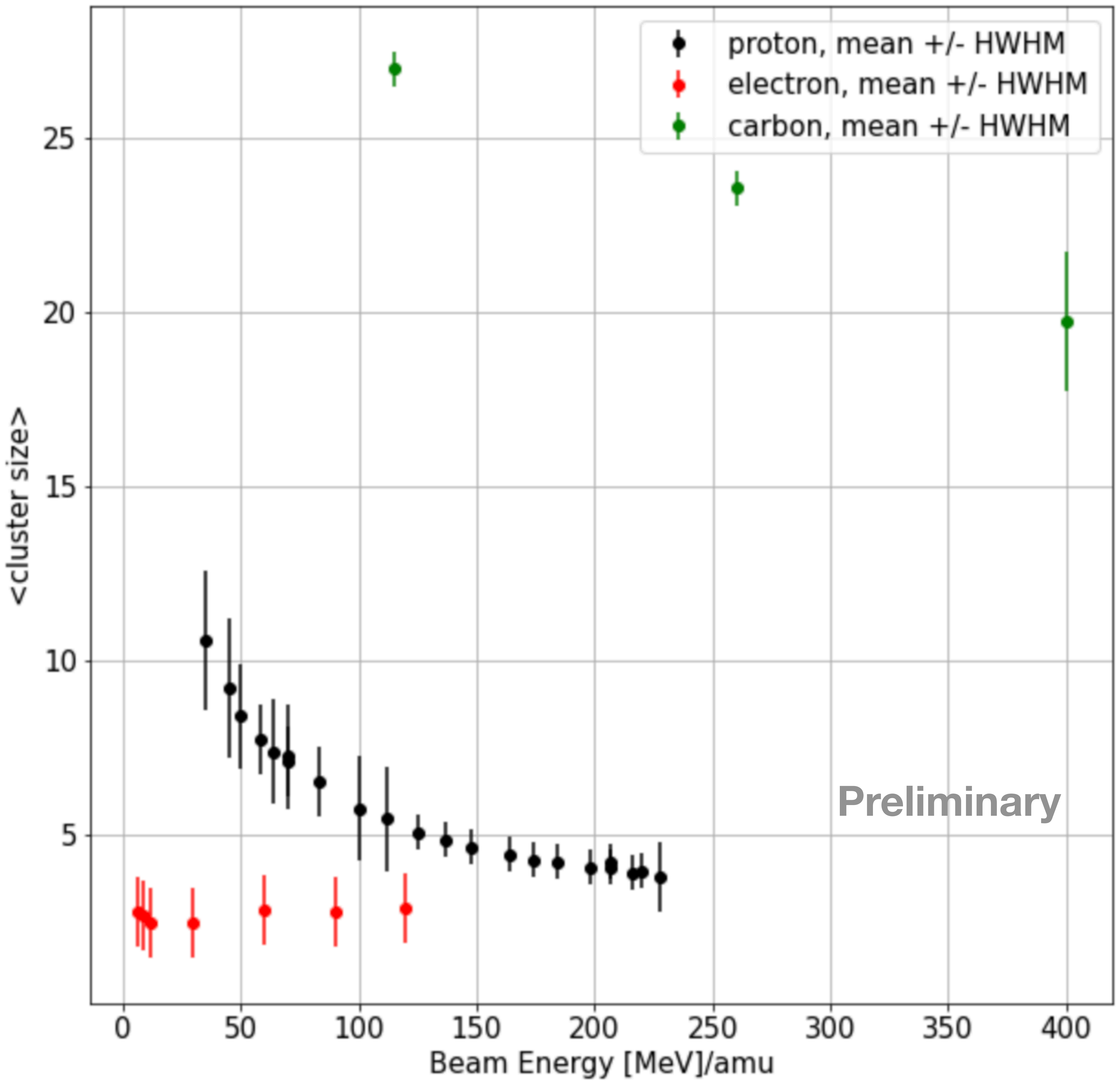
electrons
12 MeV
LINAC
ev. n. 39,436



electrons
9 MeV
LINAC
ev. n. 53,014

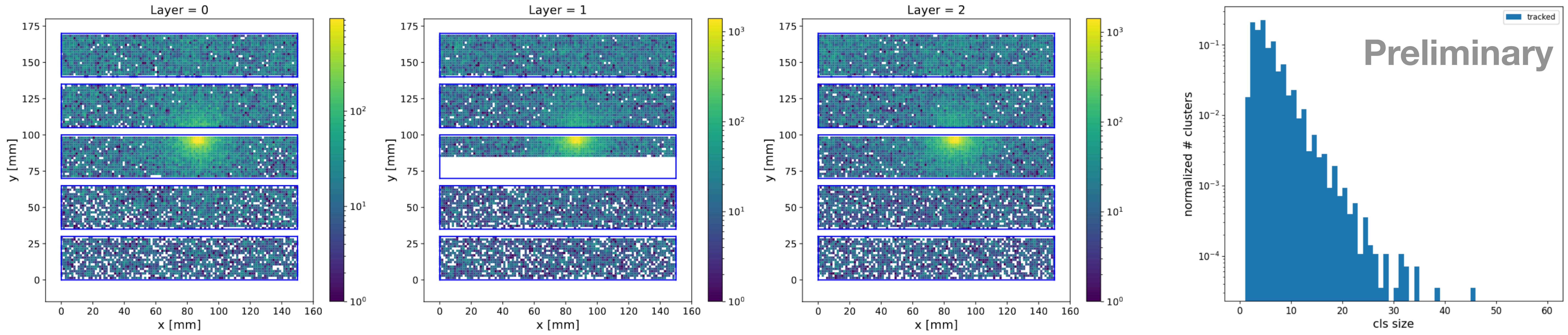


electrons
6 MeV
LINAC
ev. n. 25,895

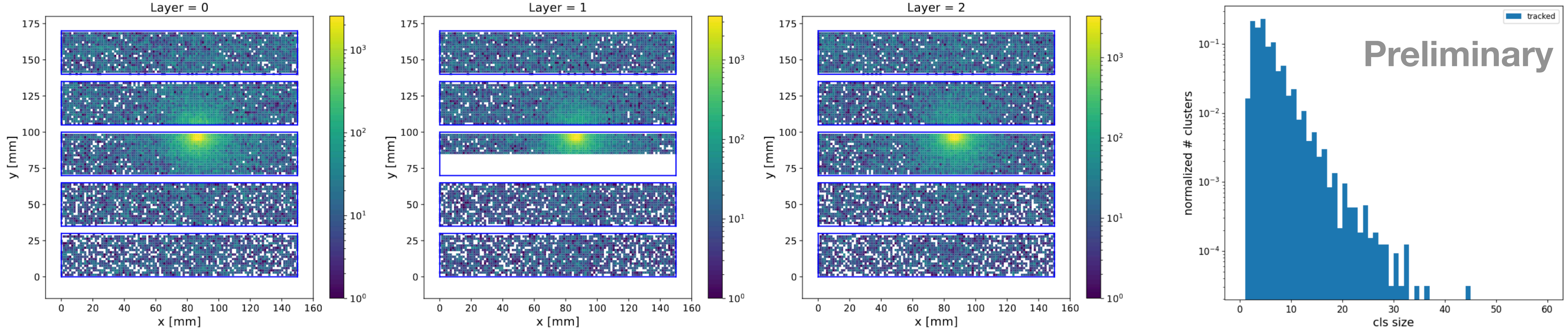


DD performance - gamma rays

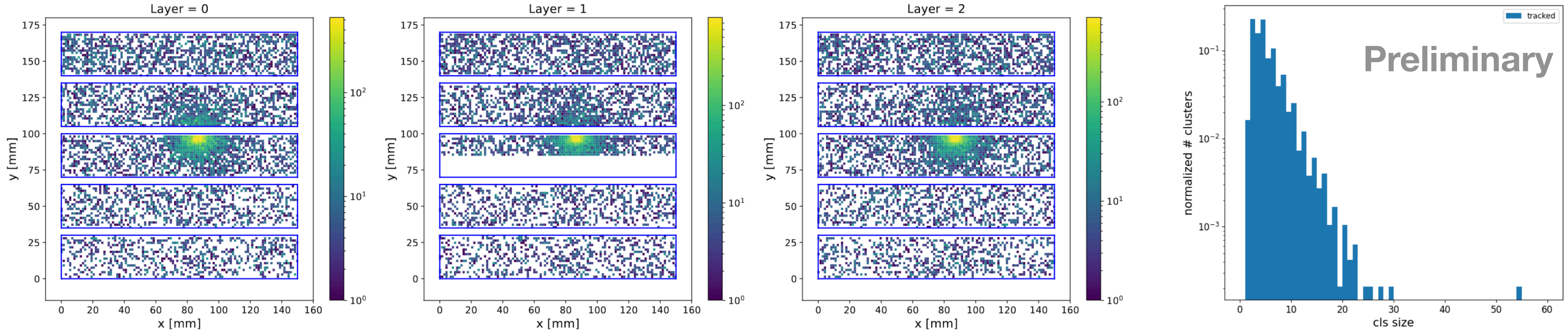
cluster size



Gamma
10 MeV
LINAC
ev. n. 53,653



Gamma
6 MeV
LINAC
ev. n. 47,563



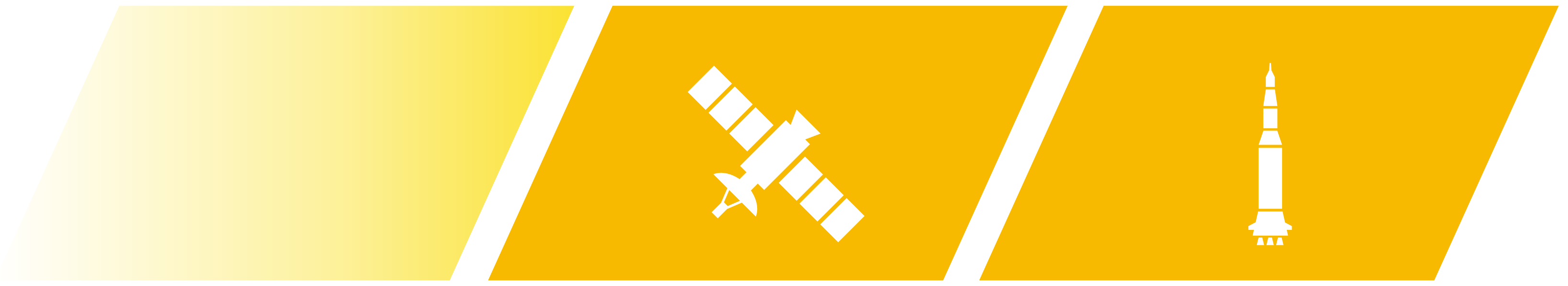
Gamma
4 MeV
LINAC
ev. n. 21,961

Conclusions and next steps

- 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)**
- **Several space compliance tests successfully performed on HEPD-02 paylod**
- Analysis on test beam data **currently ongoing**
- Integration in CSES-02 satellite and launch scheduled in **2024**

- data analysis

- HEPD-02 mount on satellite
- launch in 2024

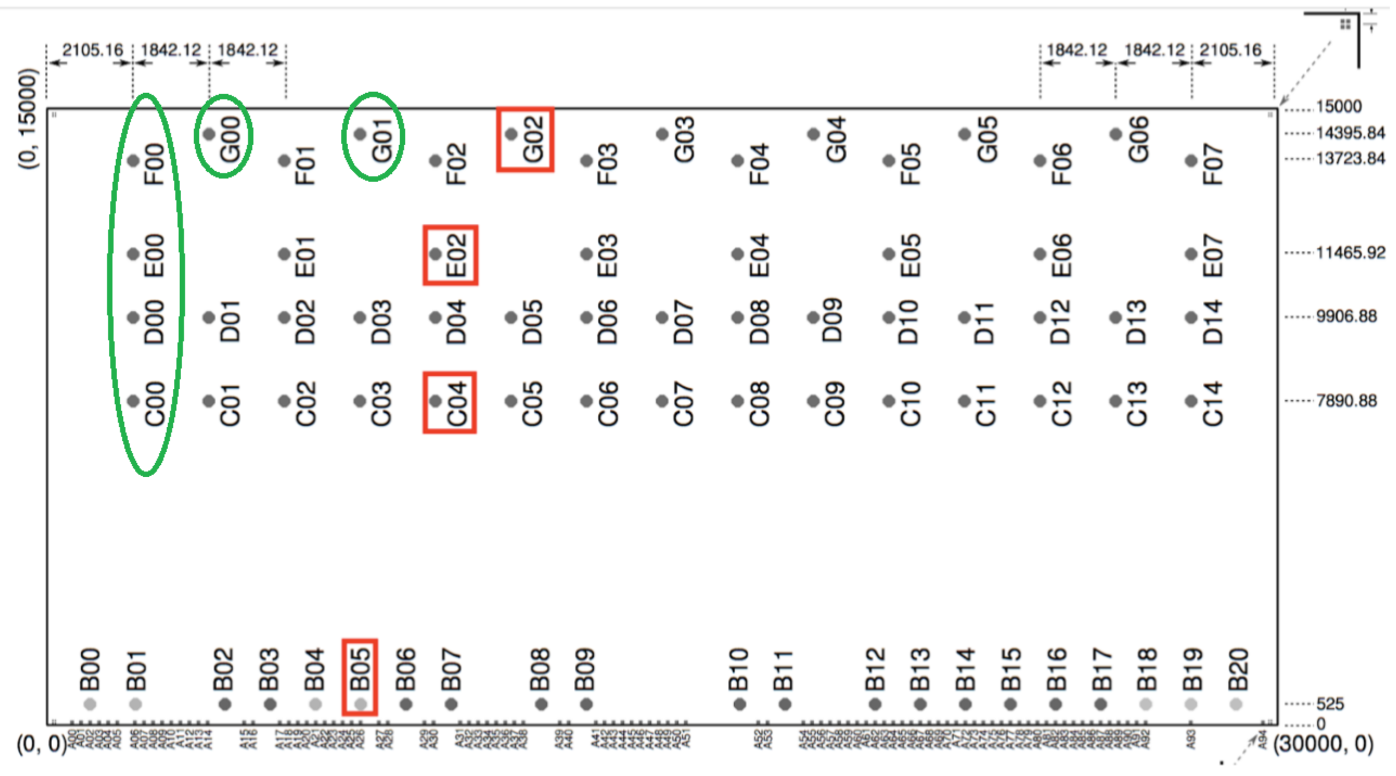


- STAVE assembly
- validation in the lab
- tracker assembly on QM and FM
- Shock and thermo vacuum tests for payload validation
- test beam and data acquisition

SPARE SLIDES

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 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.

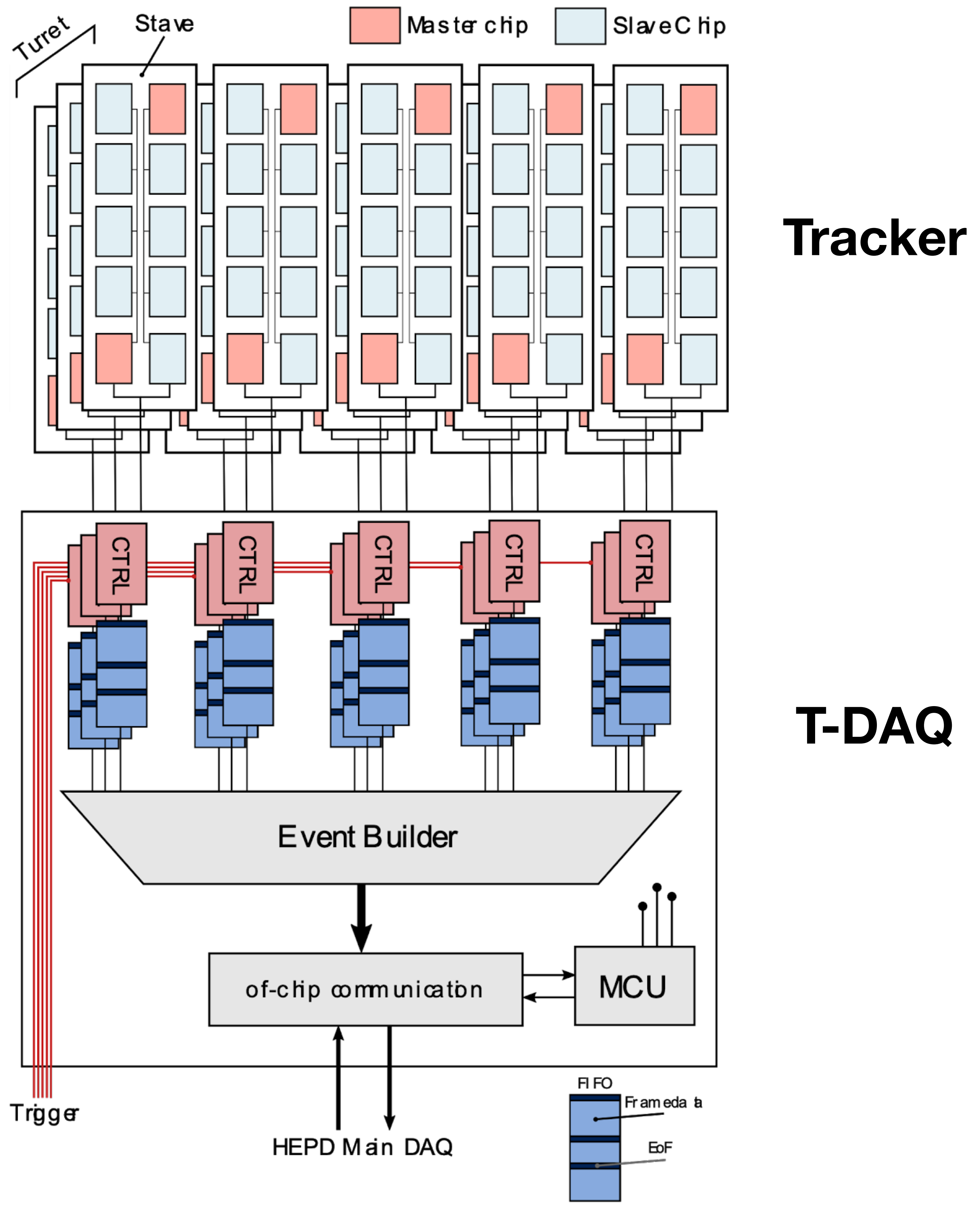
Material budget of STAVEs

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
  S. Coli et al., 2021, 22nd International Workshop on Radiation Imaging Detectors
  DOI: https://doi.org/10.1088/1748-0221/17/01/C01019
- Thermo/mechanical design for embedding ALPIDE pixel sensor chip in a High-Energy Particle Detector space module
  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

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.



Threshold tuning

Average threshold for different parameter configurations