The HEPD-02 cosmic-ray experiment ready for flight on-board the CSES-02 satellite

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on behalf of the CSES/Limadou collaboration

LIMADOU 利瑪竇

Summary

- **Introduction.**
  - **The China Seismo-Electromagnetic Satellite (CSES) mission.**
  - **The CSES-02 satellite.**

- **The High-Energy Particle Detector HEPD-02**, on-board CSES-02.
  - Structure, detectors and electronics.
  - Test campaign.
  - Scientific performances.

The CSES mission

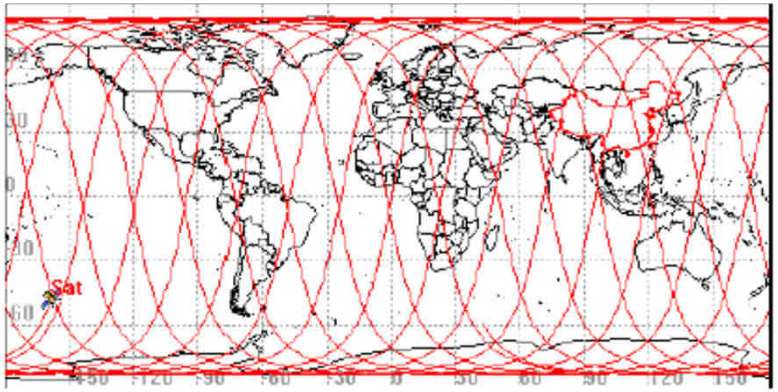
- **CSES: China Seismo-Electromagnetic Satellites.**
  - Program developed by Chinese and Italian Space Agencies.
  - CSES-01: launched on Feb 2018 and operating.
  - **CSES-02: launch scheduled on 12 Dec 2024.**

- **Main scientific objectives.**
  - Monitoring of **electromagnetic and plasma environment in near-Earth space.**
  - Measurements of **ionospheric and magnetospheric perturbations** of different origins: seismic phenomena, tropospheric and anthropic transients, solar activity...
  - Study of fluxes of **charged particles precipitating from the Van Allen radiation belts.**

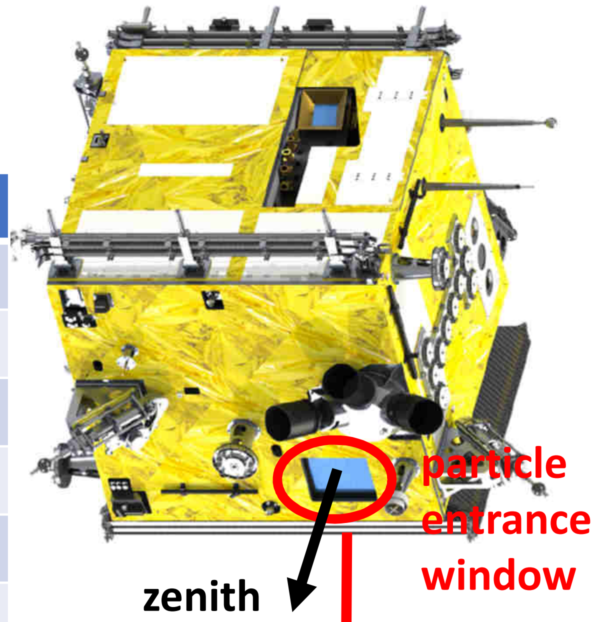
电磁监测卫星计划
China Seismo-Electromagnetic
Satellite Program

The CSES-02 satellite

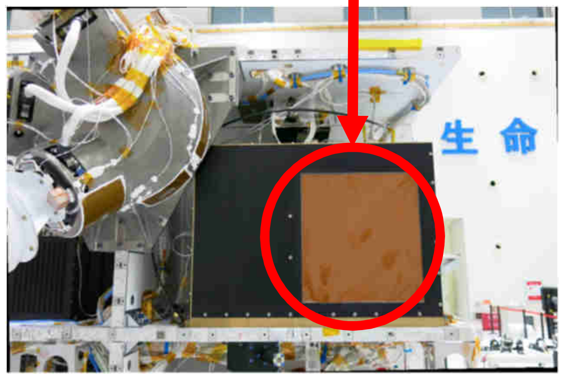
CSES-02 planned orbit
-82.6° to +82.6° latitude
500 km altitude
Sun-synchronous
180° phase difference with respect to CSES-01



CSES-02 main characteristics
Orbit maneuver capability
Earth-oriented 3-axis stabilization system
Full-time operational
Design life span > 6 years
Mass: 900 kg
Power: 900 W
Storage: 512 Gbyte



HEPD-02 (High-Energy Particle Detector 2)



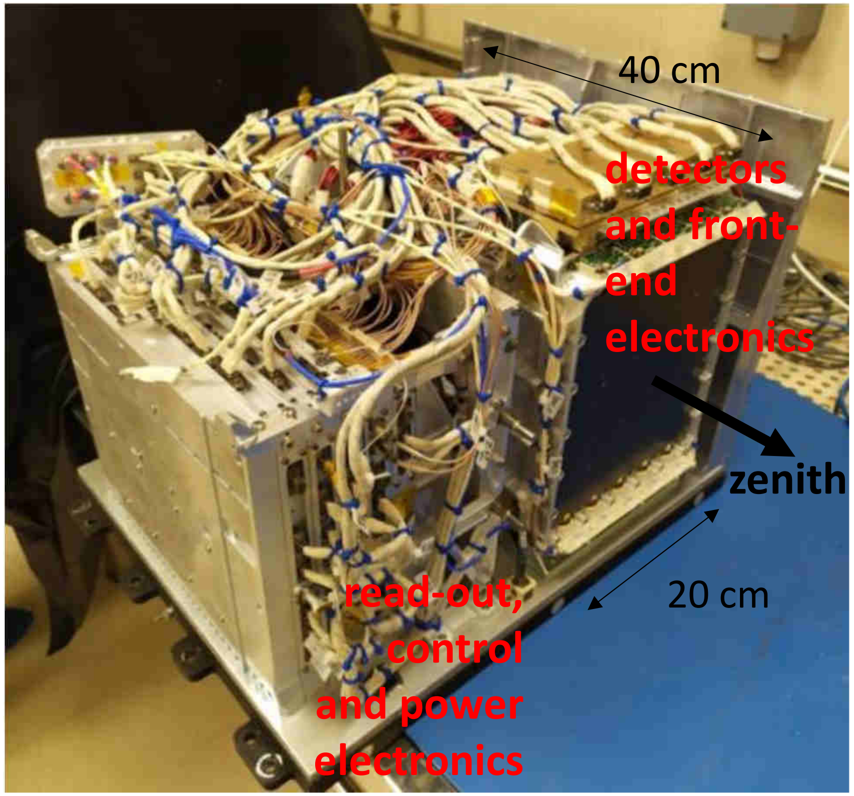
The HEPD-02 payload

- **Responsibility for design, assembly and test:**
  - **INFN,** with IFAC-CNR and Universities of Roma Tor Vergata, Torino, Trento.
- **Main scientific objectives:**
  - study of **variations of electron and proton energy spectra in the Van Allen belts** (particle precipitation) due to short-time perturbations related to terrestrial, anthropic and solar phenomena;
  - study of **galactic and trapped particle populations.**

Main HEPD-02 performance targets	
Electrons	**3 MeV to 100 MeV**
Protons	**30 MeV to 200 MeV**
Light nuclei	**up to 200 MeV/amu**
Angular uncertainty	**≤10° for E_{kin} > 3 MeV electrons**
Energy uncertainty	**≤10% for E_{kin} > 5 MeV electrons**

- **HEPD-02 features substantial innovations and improvements with respect to HEPD-01 (payload of CSES-01 satellite).**

HEPD-02 (with lateral panels removed)



Technical challenges on satellite

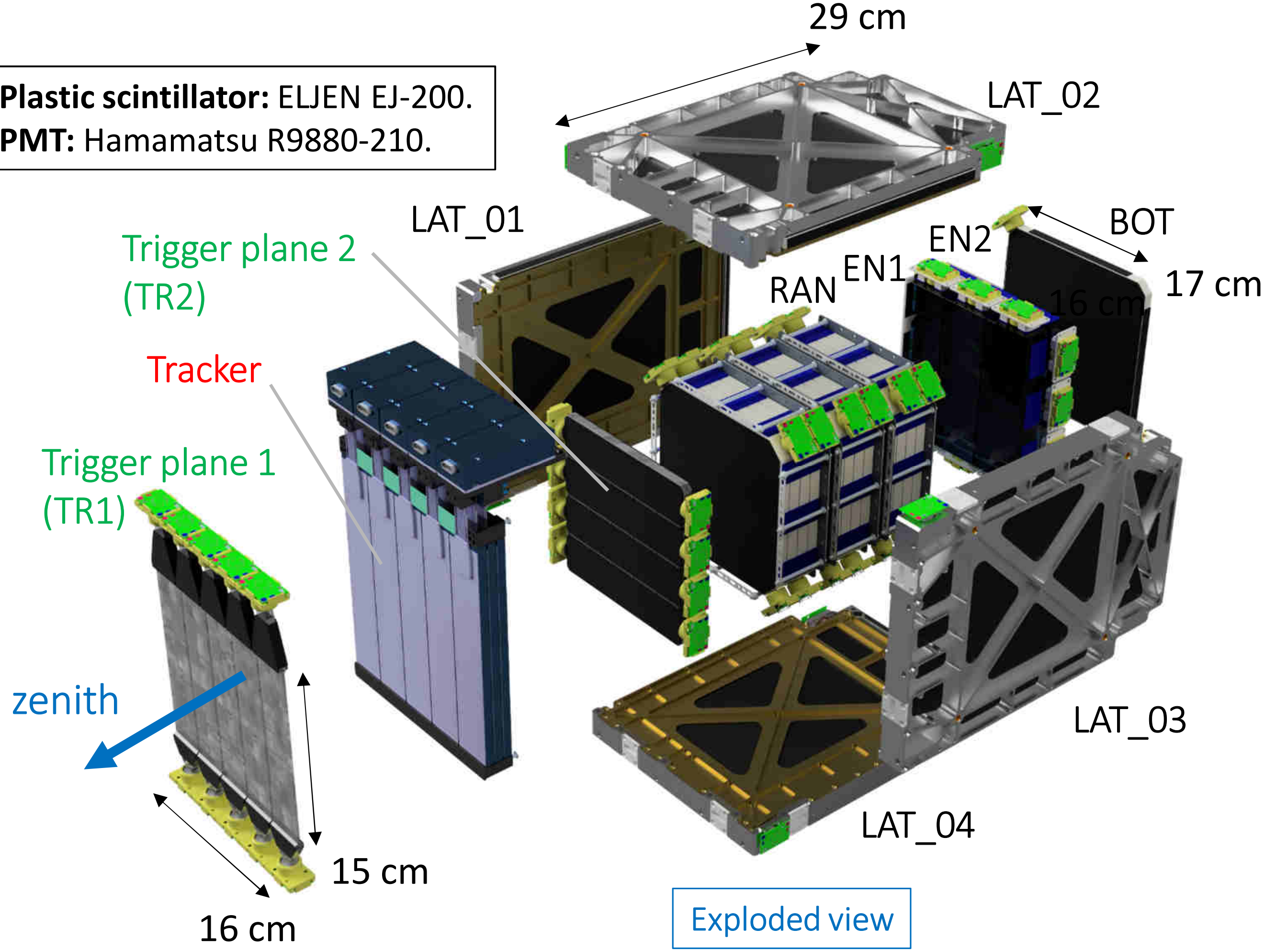
- **Reliability** to be assured for the whole life span **(> 6 years).**
- **Limits** in size, weight, power, data budget.
- **Mechanical stresses:** launch, orbital maneuvers.
  - **Up to 11 G** sustained RMS acceleration for qualification tests.
- **Thermal stresses** and wide range of operating temperatures.
  - **Operation between -30 °C to +50 °C** required for qualification tests.
- Operation in **vacuum,** critical for **high-voltage parts** (PMT bias).
- **Environmental radiation**: aging/malfunction of electronic, optic and soft materials, if not properly selected.
  - Total absorbed dose (~ 1 krad/year).
  - **SEE: single-event effects** on electronics (especially heavy ions).
- **Demanding electromagnetic compatibility** (EMC) for both emission and susceptibility.
- **Magnetic cleanliness** (ferromagnetic materials to be avoided) for compatibility with magnetic measurements made by other payloads.

HEPD-02 main technical specifications	
Dimensions	$38 \cdot 53 \cdot 40$ cm^3
Weight	47 kg
Power budget	45 W
Data budget	100 Gbit/day
Operating pressure	≤ 6.7 mPa
Operating temperature	-10 °C to +35 °C

The HEPD-02 instrument

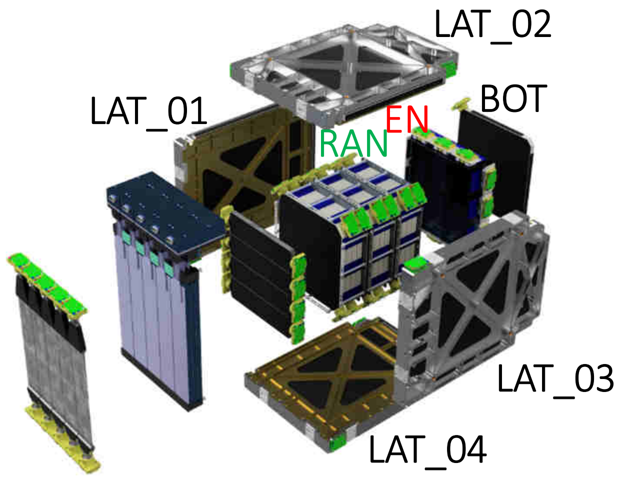
- **1/5. Trigger detectors (TR1, TR2).**
  - **Plastic scintillators / PMTs:** 2 planes, 5+4 mutually orthogonal bars.
  - *HEPD-01 had a single plane.*
- **2/5. Particle tracker.**
  - **Si Monolithic Active Pixel Sensors (MAPS):** 3 planes in 5 adjacent "turrets".
  - *HEPD-01 had double-sided Si microstrips, 2 planes.*
- TR1 and tracker **tightly packed together,** matching active area and segmentation.
  - **Asymmetric wave-guide read-out** on opposite ends of TR1 bar.
- **TR1 thickness minimized to** 2 mm (mechanically challenging).
  - This **reduces multiple scattering** before tracker **and energy threshold** for coincidence with TR2.

Plastic scintillator: ELJEN EJ-200.
PMT: Hamamatsu R9880-210.



The HEPD-02 instrument

- **3/5. Range detector (RAN).**
  - **Plastic scintillators / PMTs**: 12 planes in 3 mechanical units.
  - *HEPD-01 had 16 planes in a single unit (less stable configuration).*
- **4/5. Energy detector (EN).**
  - **LYSO scintillators / PMTs**: 2 planes, 3+3 mutually orthogonal bars. Bar: $15 \cdot 5 \cdot 2.5$ cm^3 (**record size for space**).
  - *HEPD-01 had a single, thinner plane of 9 cubes, each one read-out with single PMT.*
- **5/5. Lateral/bottom containment (LAT, BOT).**
  - **Plastic scintillators / PMTs.**



Plastic scintillator: ELJEN EJ-200.
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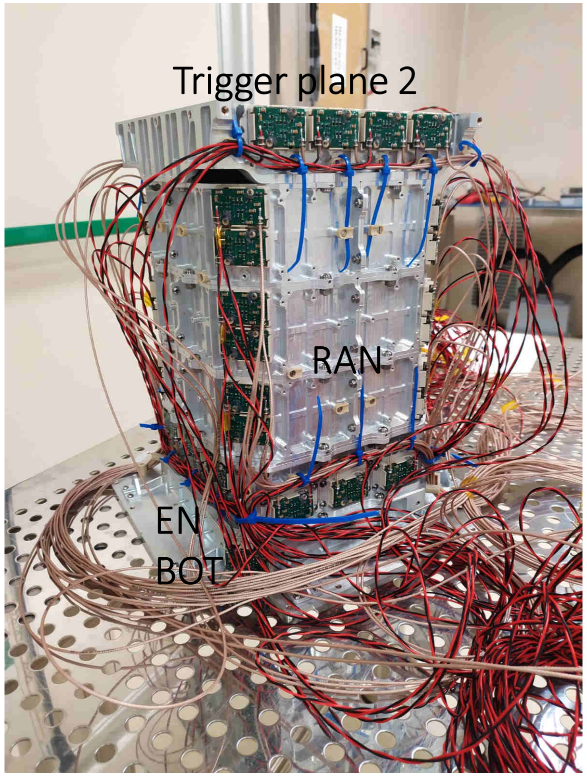
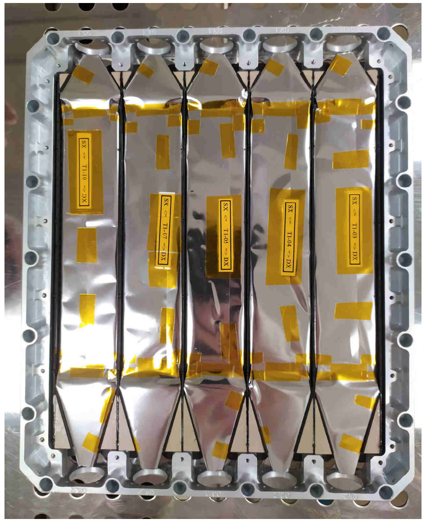


Partially integrated inner detectors with PMT bias boards

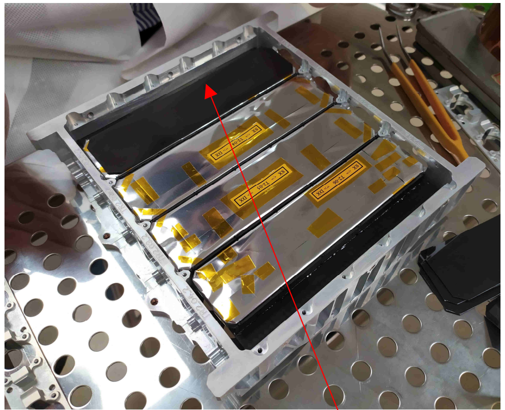
- Overall: 32 scintillator modules, read-out by **2 PMTs at opposite sides/edges, mounted on bias distribution boards.**
- Al/mylar film wrapping, with additional polyethylene black tape for LYSO.
- Bias (up to -1000 V) generated by regulated high-voltage supplies (**Aeropazio HV3**).
  - Low ripple, low non-linearity and temperature drift, low-power, compact, light weight, radiation resistant.

HEPD-02 scintillators

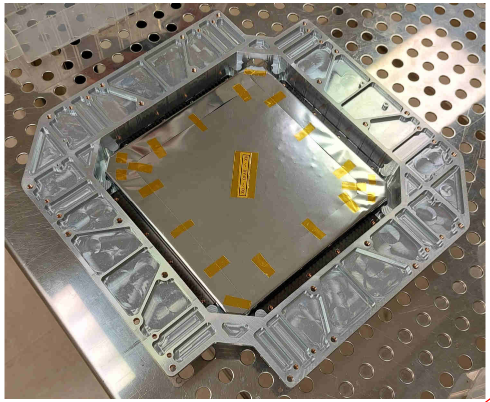
Trigger 1 plane



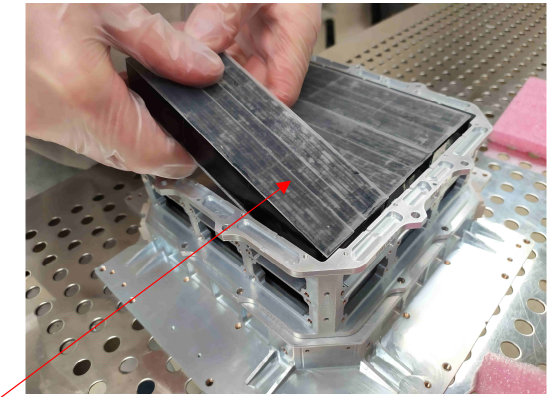
Trigger 2 plane (with polyurethane foam strip positioned on one bar)



Bottom containment plane

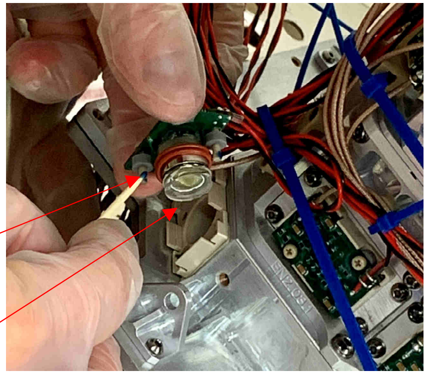


EN detector
(LYSO bars with Si gel strips)



- External frames in Al alloy.
- **Inner structural elements and covers in CFRP** (carbon fibre + epoxy resin) to reduce amount of inactive material crossed by particles in FOV.

Fragile part	Applied shock-absorbing, vibration-damping material
Plastic scintillator	Polyurethane foam strips.
LYSO bar	Silicon gel strips.
PMT	Silicon rubber rings on PMT body. Optically transparent pad on PMT window.
Bias board	Polyurethane rubber pads.

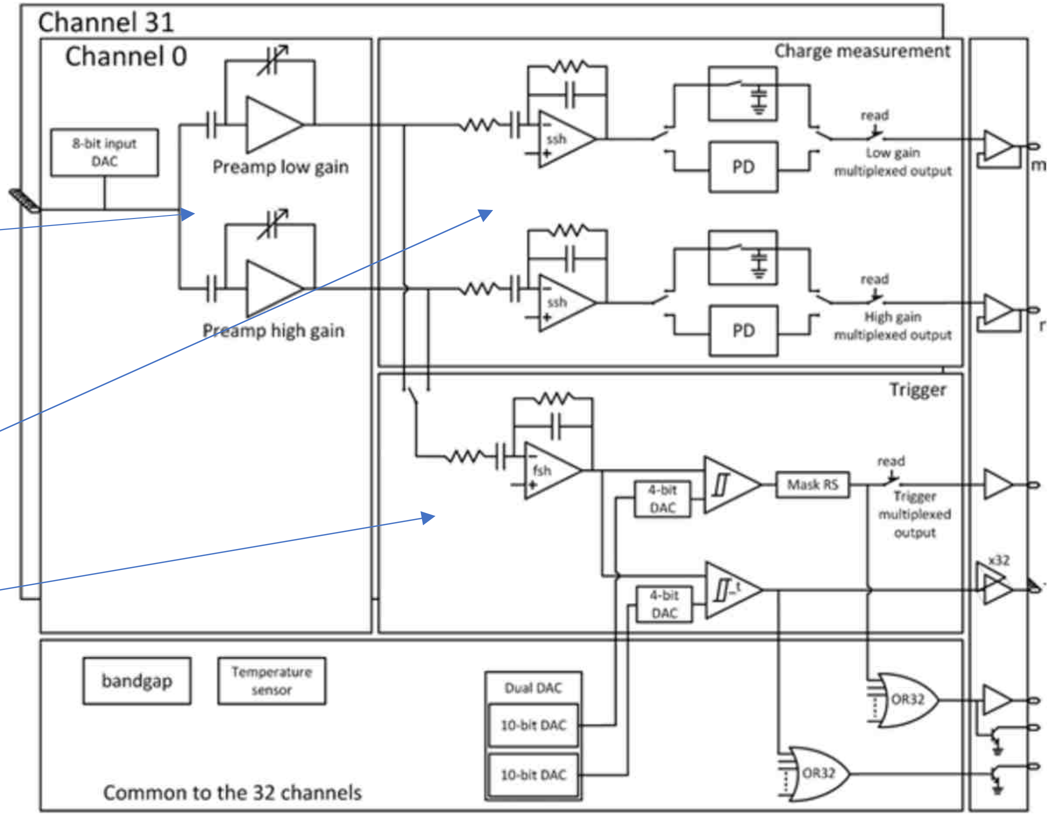


PMT on bias board

HEPD-02 scintillators read-out / triggering

- **Read-out and triggering of the 64 PMT signals** on dedicated board with two **Weeroc Citiroc 1A ASICs**.
  - **Citiroc 1A chosen for the wide dynamical range**, required to match scintillators of different material/thickness and non-MIP incoming particles with widely varying energy loss.
- **32 channels/ASIC,** each channel with two independent programmable preamplifiers:
  - low-gain (1 to 60);
  - high-gain (10 to 600).
- **Slow shaper and peak detector** for signal read-out.
- **Fast shaper and discriminator** for triggering (logics implemented on external FPGA, MicroSemi ProAsic3).
- **Main/spare redundancy** (i.e. two identical copies of the circuit in the same board) to increase overall reliability during flight.

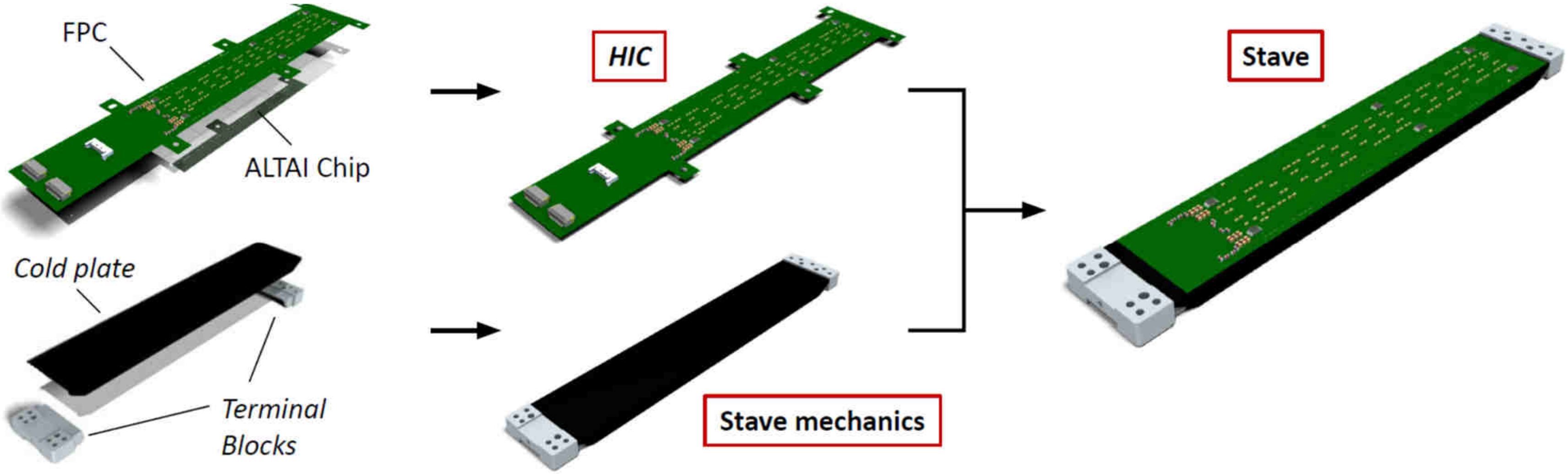
Citiroc 1A signal processing chain



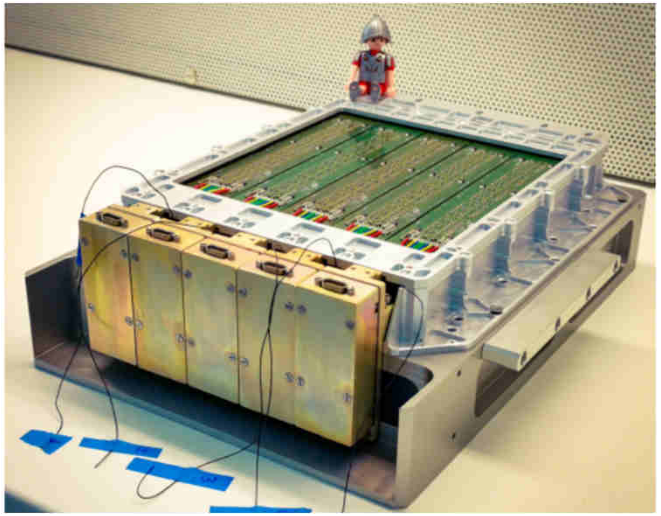
HEPD-02 tracker

- **Basic unit: stave.** Assembled with high mechanical/ thermal performance glues.
  - **FPC** (Flexible Printed Circuit) for inter-connections.
  - 5 · 2 **MAPS (Monolithic Active Pixel Sensors):** **ALTAI** by Tower Semiconductor LTD.
  - **Cold Plate** (CFRP: carbon fibre + epoxy resin) for mechanical stiffness and thermal drain.
  - **Terminal Blocks** (Al alloy) for mounting on support frame.

FPC/ALTAI connected via triple-redundancy bondings

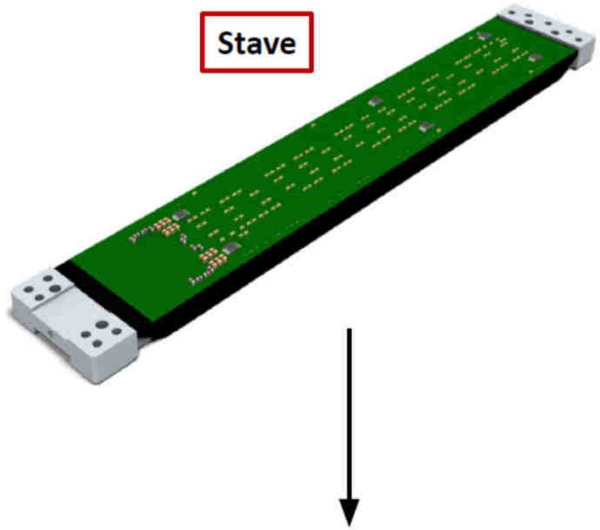


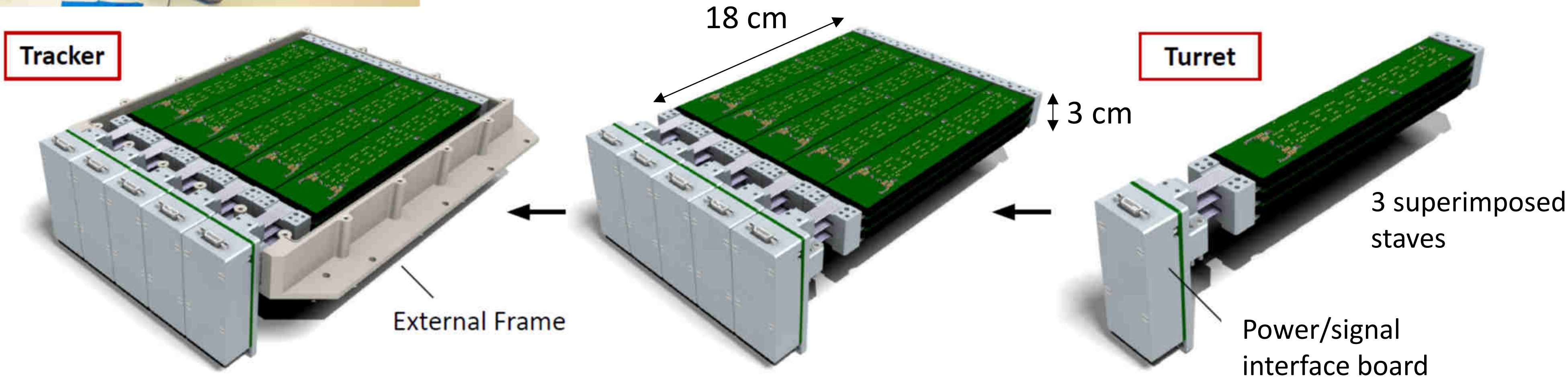
HEPD-02 tracker



Whole tracker: 5 turrets.

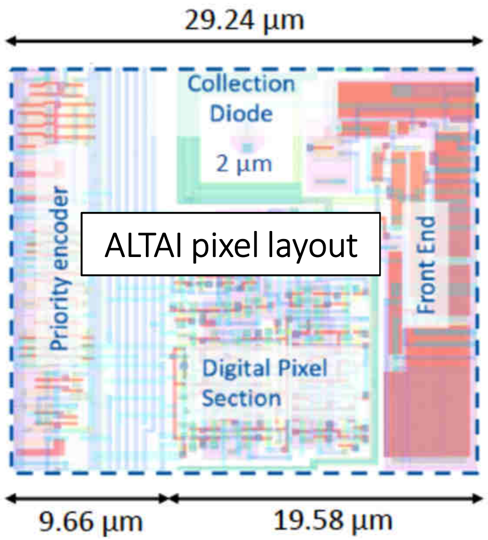
- 15 staves.
- 150 ALTAI chips.
- ~ 80 Mpixel in 3 planes.
- 15 · 15 cm^2 active area.



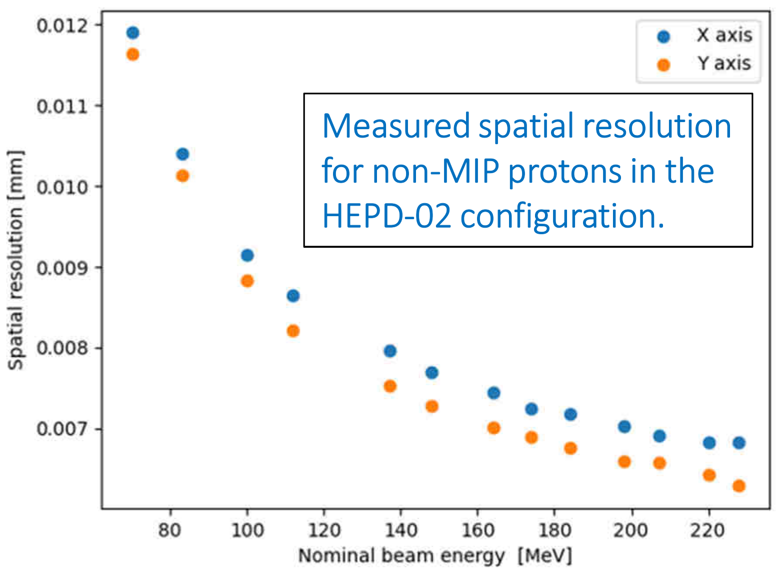


HEPD-02 tracker: ALTAI MAPS

ALTAI MAPS characteristics	
pixels	512 · 1024
area	15 · 30 mm^2
pixel pitch	28 µm
thickness	50 µm
back bias	up to -6 V
pixel response	binary (threshold)



- **Advantages:**
  - **compactness:** sensor and digital read-out circuit on the same Si substrate (180 nm CMOS technology);
  - **low noise** (~ 10 ENC / pixel);
  - **fine spatial resolution** (5 µm for Z=1 MIP).



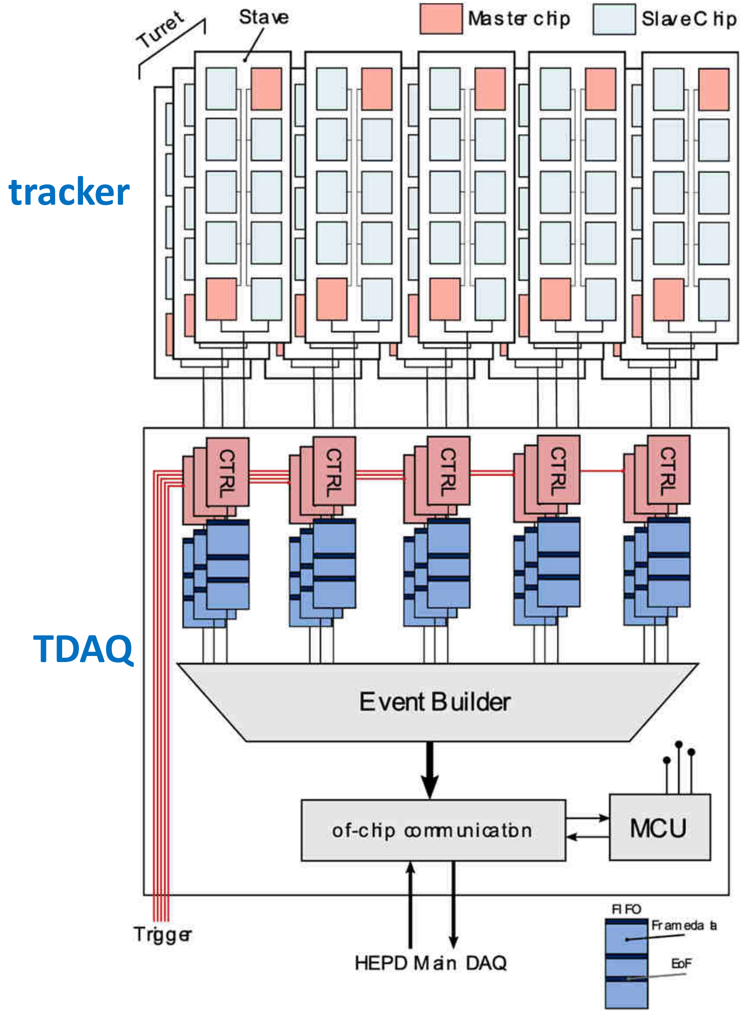
- **Challenges for use on satellite:**
  - **first ever use of MAPS in space;**
  - assembly must sustain **mechanical stresses and repeated thermal cycle tests** (-30°C to +50 °C) in vacuum;
  - thermal drain must be assured by **pure conduction (no air);**
  - at the same time, material **density/thickness in the FOV must be minimized** (multiple scattering, energy loss in inactive layers);
  - **power consumption must comply with budget** (~13 W i.e. 87 mW/ALTAI chip).

HEPD-02 tracker read-out

- Required **power reduction** implemented with specific read-out design:
  - **Master-slave architecture** (1 master out of 5 ALTAI chips) with sequential slave read-out through master.
  - **Read-out through serial slow-control line**, with acceptable dead time, given the relatively low trigger rate sustainable by the HEPD-02 system (up to ~500 Hz).
  - **Clock gating**: ALTAI clock normally off, set on with particle trigger.
  - **Tracker segmentation** allows read-out of a subset of the 5 turrets (or 2 planes only), if required to further reduce power or dead time.

- The whole tracker control and read-out circuit is housed in a single board (TDAQ) with **main/spare redundancy** to increase overall reliability during flight.

- Control logics and Microblaze soft processor implemented on **Xilinx Artix 7 FPGA**.
  - The soft processor implements pixel threshold calibration and service procedures (**switched-off most of time**, to save power).



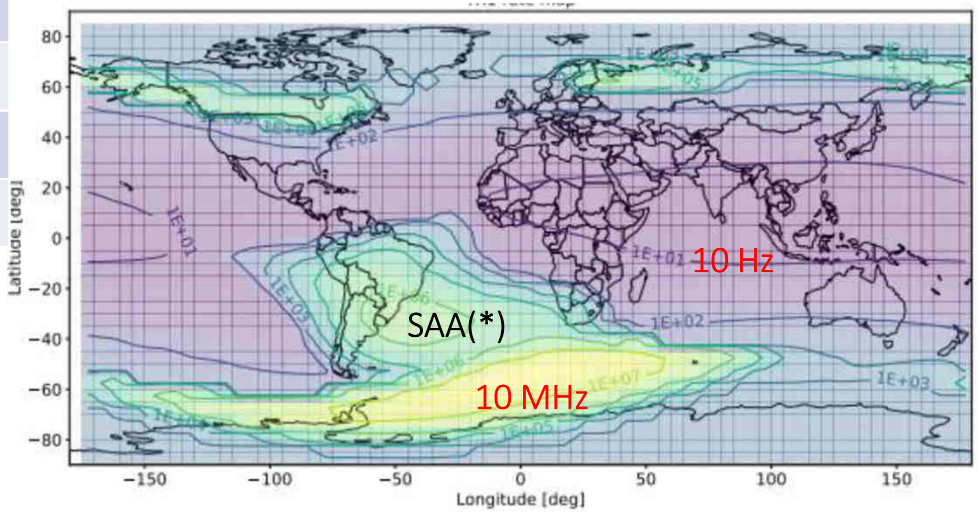
HEPD-02 control / acquisition system

- **Data processing and control unit (DPCU):** instrument configuration, control, monitoring, interface with satellite.
    - Full main/spare redundancy in single board.
- **DPCU automatically sets the trigger configuration** along the orbit, according to expected particle populations in **128 orbital zones, divided in 4 groups.**

Group	Particle population
SAA(*)	Trapped electrons and protons.
Equatorial	Re-entrant and cosmic protons.
Outer belt	Trapped electrons.
Polar	Cosmic electrons, protons, heavier nuclei.

- **Up to 6 concurrent trigger patterns of PMT signals**, with **independent prescaling** capability.
    - Simultaneous acquisition of different particle populations, while complying with **~500 Hz trigger frequency limit** (set by event data size and satellite data budget).
- Continuous monitoring of single PMT / trigger pattern hit counts (1 Hz sampling rate).

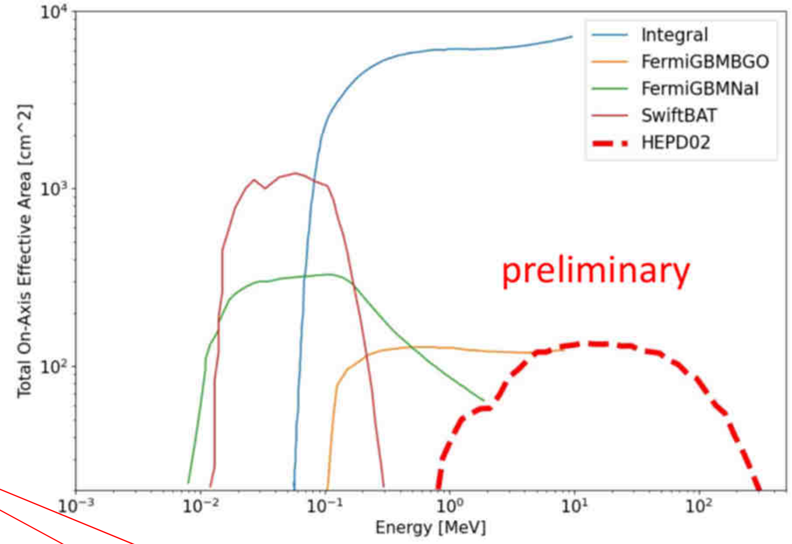
Expected hit rate on trigger TR1 plane

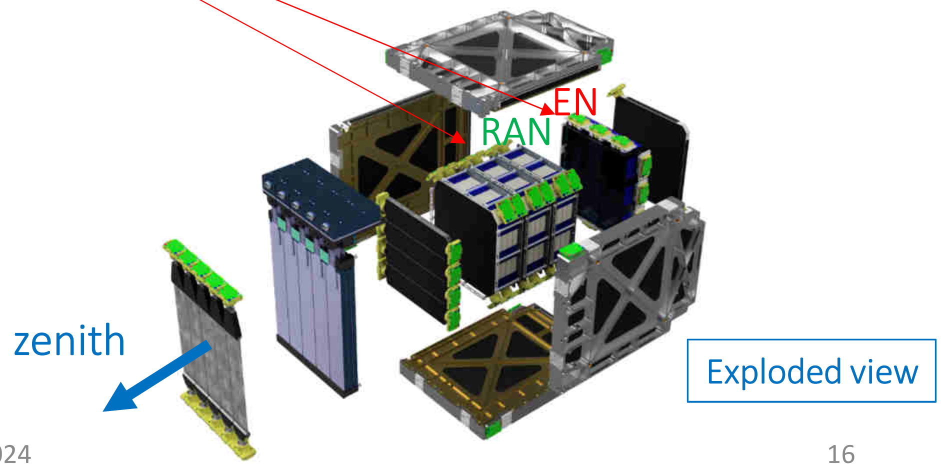


(*) South-Atlantic Anomaly

Gamma-ray bursts detection

- HEPD-02 also capable of detecting **gamma-ray burst (GRB) photons with energies in the range 2 to 20 MeV.**
  - Effective area similar to Fermi GBM in same range.
  - Range lower limit set by LYSO radioactivity background.
- **DPCU automatically starts GRB-specific data acquisition** when triggered by rate surge for GRB-specific PMT hit patterns.
  - Hits on central RAN unit (or EN detector) with no hits on the respectively surrounding scintillators (for charged particles rejection).
- **GRB-specific data acquisition:** 200 Hz sampling rate of GRB-specific hit pattern counters.
  - Stopped when rate surge disappears or memory buffer limit reached (few minutes).
- Feature disabled in high-radiation SAA and polar zones (too high rate of false triggers from charged particles).
- **Expected to detect 10 GRB/year.**





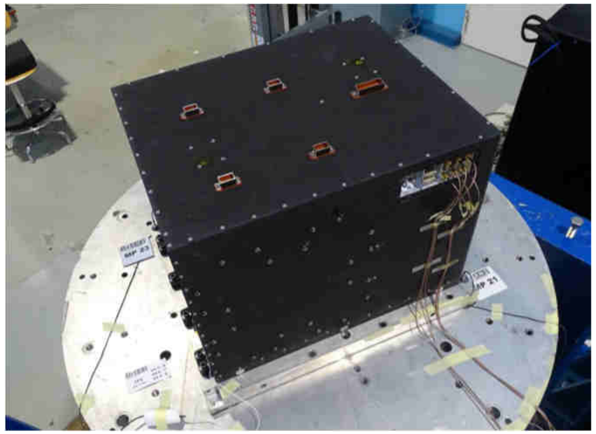
HEPD-02 assembly and test

- **Assembly completed of the HEPD-02 flight model (FM) and an identical qualification model (QM).**
- The two models underwent **successful acceptance (FM) and qualification (QM) campaigns**, with functional/electrical and environmental tests.

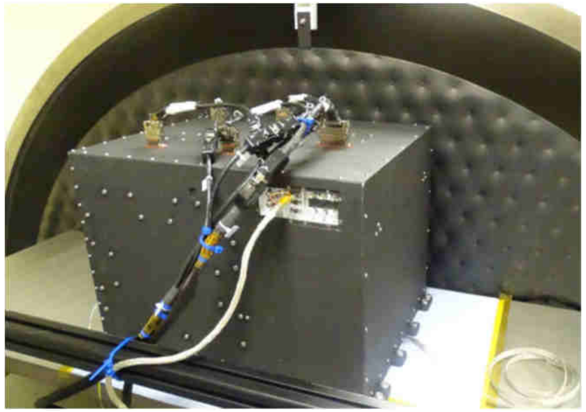
1. Vibration tests		FM	QM
Sinusoidal sweep	10 Hz to 100 Hz	up to 8 G 4 oct/min	**up to 12 G** 2 oct/min
Sustained random loading	10 Hz to 2 kHz	overall 7.6 G 1 min	overall 11.3 G 2 min
Shock pulse	100 Hz to 4 kHz	/	**up to 1000 G**

2. Thermal and thermal/vacuum tests	FM	QM
Temperature range with HEPD-02 operational (> 4 h dwell time at hot/cold points)	-20 °C to +45 °C	**-30 °C to +50 °C**
Number of cycles (**air**)	14.5	25.5
Number of cycles (**vacuum**, i.e. P < 6.7 · mPa)	3.5	6.5

HEPD-02 on shacker plate

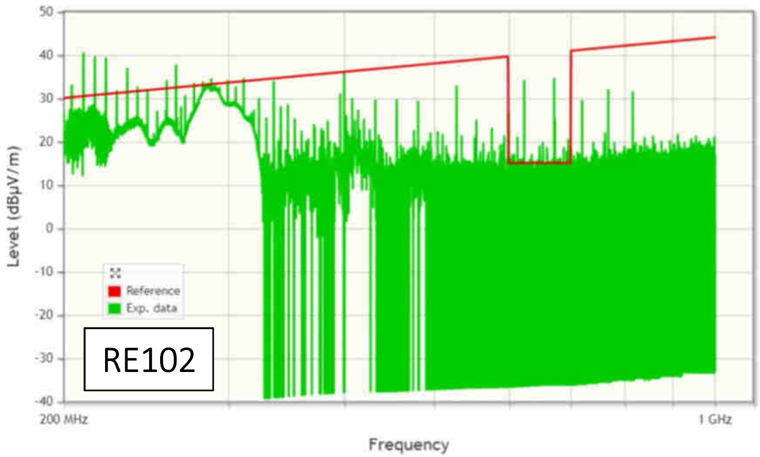


HEPD-02 inside thermal/vacuum chamber



HEPD-02 assembly and test

3. Electro-magnetic compatibility (EMC) tests (Customized following NASA MSFC-SPEC-521)	Conducted (capacitive or inductive coupling)	Radiated (antenna coupling)
Emission	CE102	RE102
Susceptibility	CS101, CS114	RS103



- **Beam-test campaign for scientific performance assessment** (see next slides).
- **Jan 2024: HEPD-02 FM integrated on CSES-02 satellite.**
- On-satellite tests ongoing.
- Transfer to launch site foreseen in Oct 2024.
- **Launch scheduled on 12 Dec 2024.**
- Full-operation will start after in-flight commissioning (middle 2025).

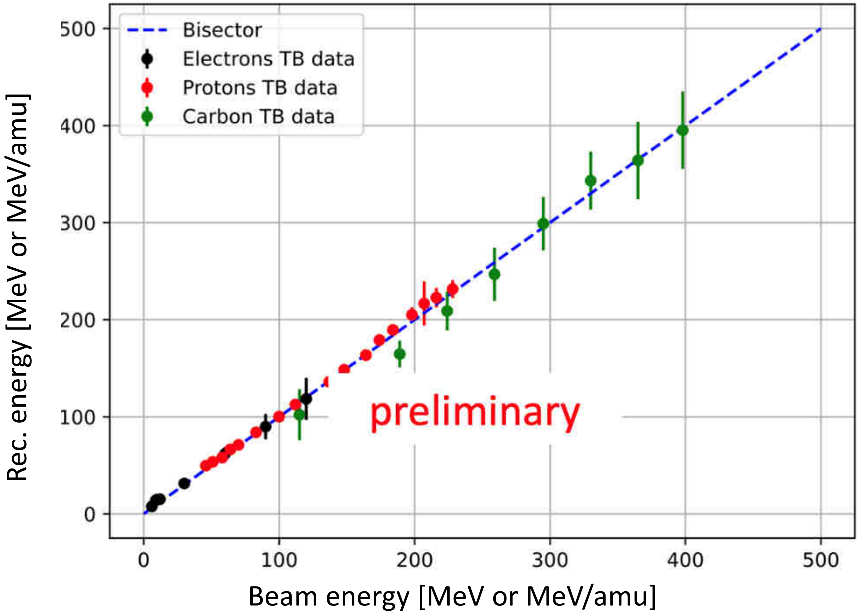
RE102 test set-up

Performance assessment: energy measurement

- Instrument calibration and performance assessment with several **beam tests** and cosmic rays (**atmospheric muons**).

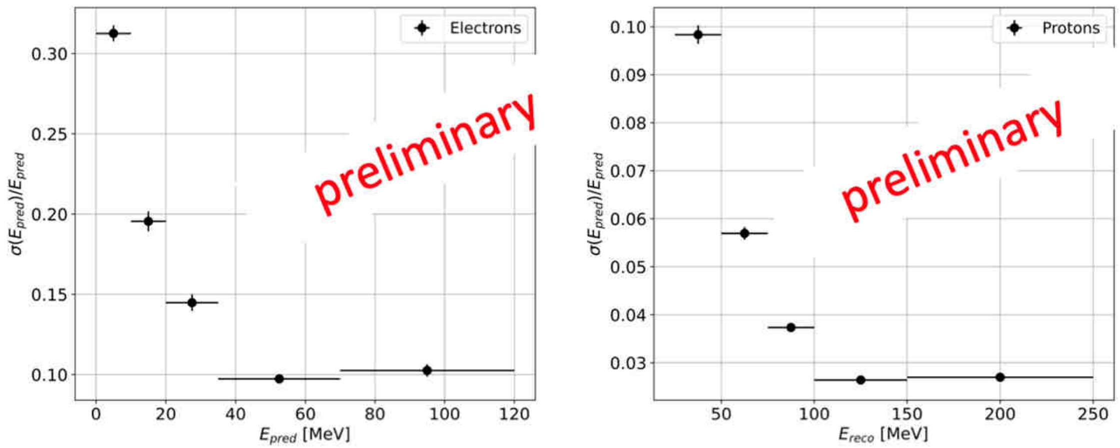
Reconstructed energy for contained events vs. nominal energy (various beam particles).

Sum of calibrated scintillator signals, corrected for losses in inactive layers.

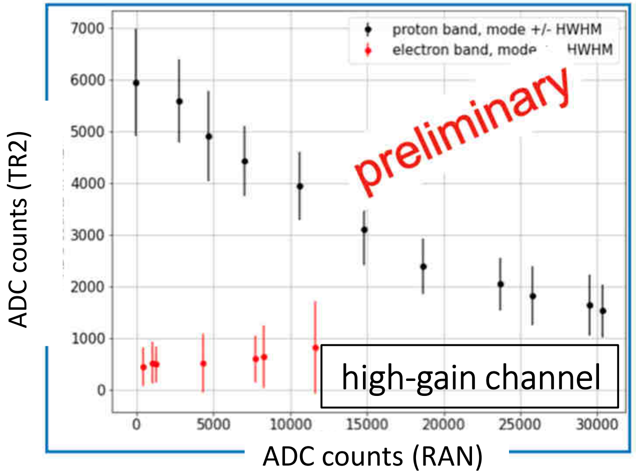


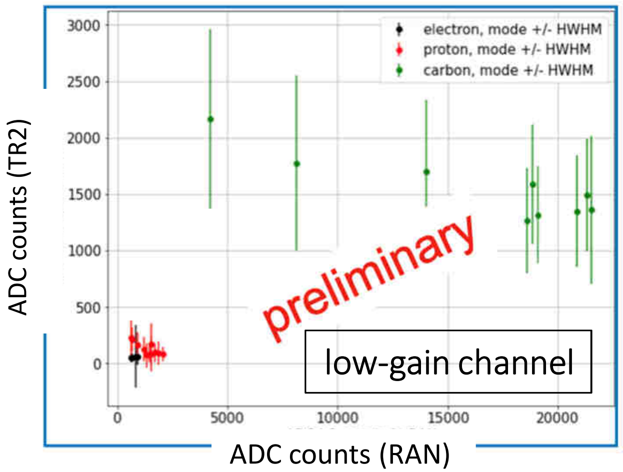
Beam particle	Energy	Facility
Electron	6 to 12 MeV	LINAC S. Chiara Hospital (Trento, IT)
Electron	> 30 MeV	DAFNE BTF (Frascati, IT)
Proton	70 to 230 MeV	Proton Therapy Center (Trento, IT)
Carbon/proton	60 to 400 MeV/amu	CNAO (Pavia, IT)
Photon	1 to 10 MeV	LINAC S. Chiara Hospital (Trento, IT)

Simulated **relative uncertainty of reconstructed energy**

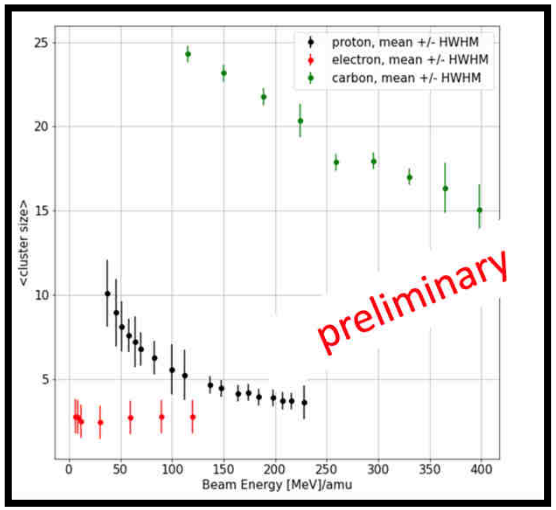


Particle identification



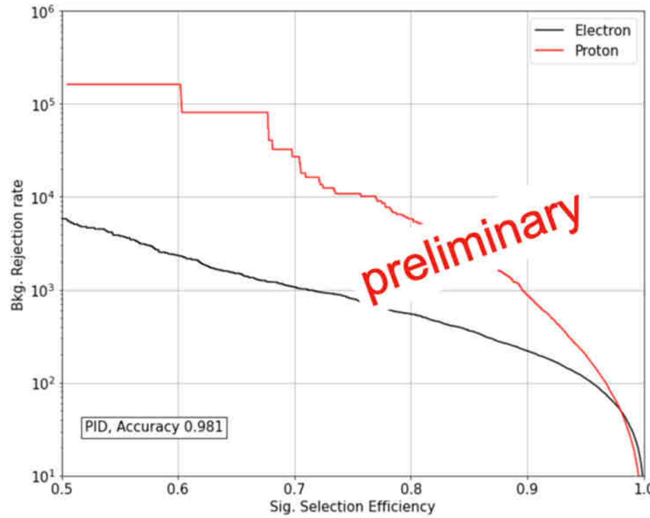


- **Clear beam particle (e^-/p/carbon) separation** by cross-correlation between release in front (TR2) and inner (RAN) scintillator layers.
- Additional separation by the energy dependence of tracker cluster size (pixel number).



- The relevant information is combined via **Deep Neural Network (DNN),** to optimize background rejection rate vs. selection efficiency.

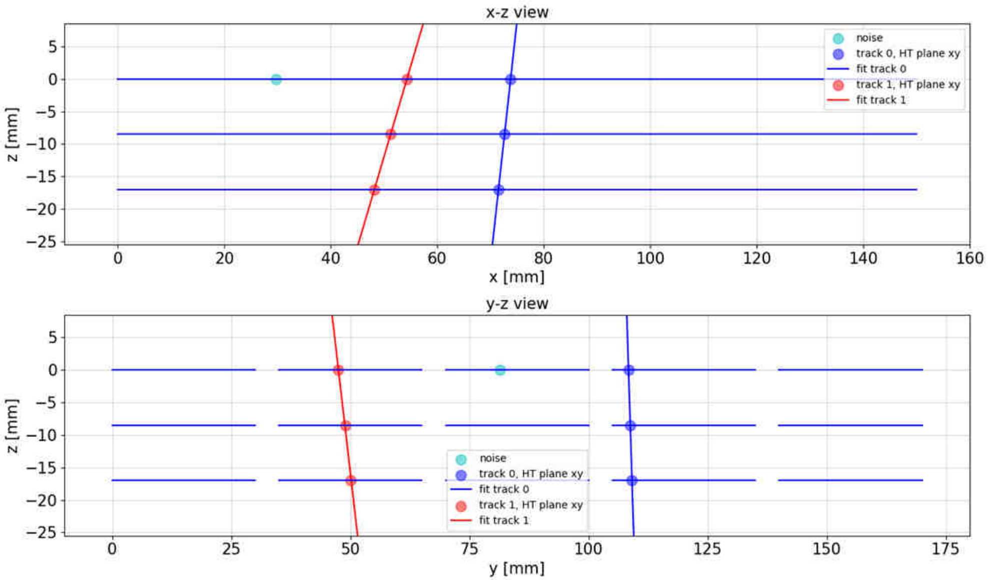
Simulated **e^-/p separation performance,** with expected particle flux along the orbit.



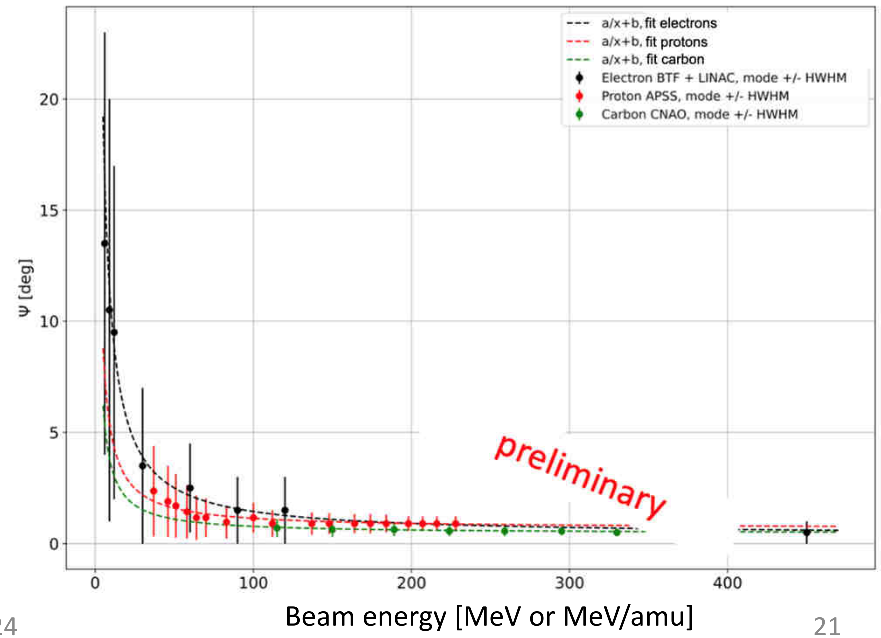
Arrival direction reconstruction

- **Map of tracker noisy pixels** (~ 1 k over 80 M) obtained with periodic on-line calibration.
- For each event, **"non-noisy" hit pixels are clustered** (DBSCAN) and **track seeds are identified** (Hough transform).
- **3D best-fit track** (or tracks, for multi-particle events) is determined.
  - Residual noise clusters are easily identified by requiring 3-planes tracks (efficiency > 70%).

Example: side views of a **real event with two cosmic-muon tracks and a noise cluster.**



Uncertainty ψ of reconstructed direction for quasi-vertical incidence (beam test data).



Conclusions

- The **High-Energy Particle Detector HEPD-02** is a state-of-the-art instrument on-board CSES-02 satellite.
- **Aimed at studying Van Allen belts and galactic particles** in the kinetic energy range from few MeV to hundreds MeV.
- Detectors, electronics and functionalities have been **substantially improved with respect to HEPD-01.**
- The instrument has been **fully qualified and installed on satellite.**
- **Launch foreseen in Dec 2024.**
- Preliminary analysis of beam test data demonstrates **more than satisfying scientific performances.**