INFN
Istituto Nazionale di Fisica Nucleare

ASI
Agenzia Spaziale Italiana

Technology & Instrumentation in Particle Physics (TIPP2023)
September 4th – 8th , 2023
CTICC Cape Town, South Africa

An innovative particle detector onboard the CSES-02 satellite

C. De Donato[1]
on behalf of the CSES-Limadou Collaboration

[1]INFN Sez. Roma “Tor Vergata”

OUTLINE

- China Seismo-Electromagnetic Satellite (CSES) space mission
- High Energy Particle Detector (HEPD-02)
  - Detector and Electronics
  - Major improvements
- HEPD-02 status:
  - acceptance and beam tests
  - Next steps

China Seismo-Electromagnetic Satellite (CSES) space mission

Bilateral Cooperation for CSES mission (september 2013):

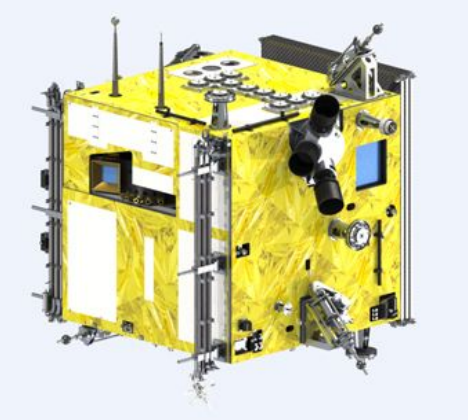
- Chinese National Space Agency (CNSA)
- Italian Space Agency (ASI)

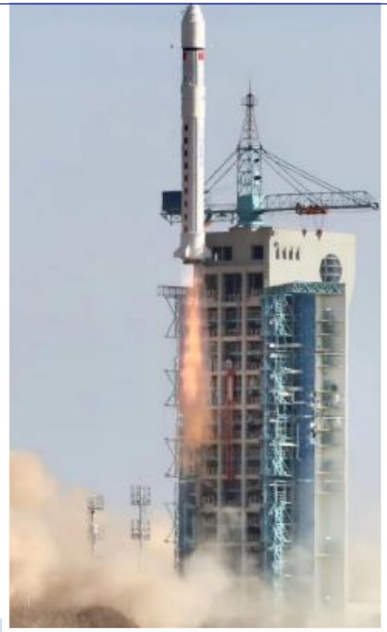
CSES scientific goals:

- study of electromagnetic, plasma and particles perturbations of atmosphere, ionosphere, magnetosphere and Van Allen belts induced by natural sources and anthropocentric emitters and their possible correlations with the occurrence of seismic events [SAMPEX,NOAA, Demeter].

CSES-01 launched on February 2nd 2018
-Chinese CAST2000 platform, Long March 2C rocket
-Mission Life Span ≥5 years
-operating zone: -70°<latitude< +70°
CSES-02 launch foreseen in 2024
-Chinese CAST2000 platform with some improvements
-180° Phase Difference wrt CSES-01
-Mission Life Span ≥6 years
-operating zone: all latitudes (full orbit)

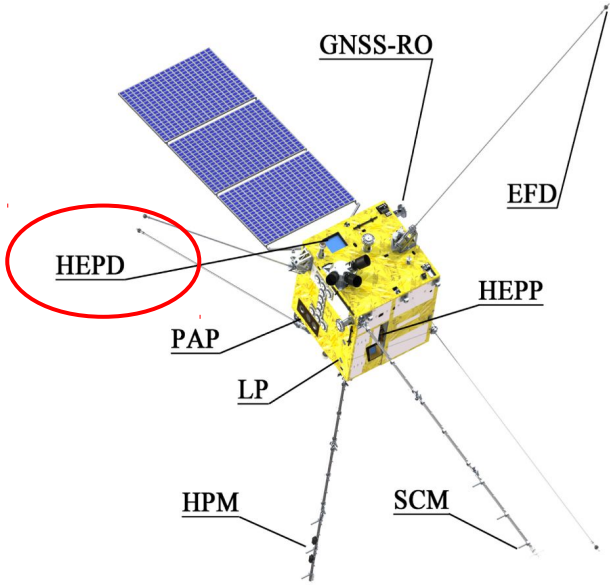
CSES ORBIT	
Type	Sun-synchronous
Inclination	97,4°
Altitude	507 km
Period	94.6 min
Local time descending node	14:00
Revisit period	5 days





China Seismo-Electromagnetic Satellite (CSES-02)

Category	Payload Name
Electro-Magnetic Field	Electric Field Detector (EFD)
	High Precision Magnetometer (HPM)
	Coherent Population Trap (CPT)
	Search Coil Magnetometer (SCM)
In Situ Plasma	Plasma Analyzer Package (PAP)
	Langmuir Probe (LP)
Plasma Construction	GNSS Occultation Receiver (GNSS-RO)
	Tri-Band Beacon (TBB)
	Ionospheric Photometer (IP)
Energetic Particle	High Energy Particle Detector (HEPD)
	Medium Energetic Electron Detector (MEED)



HEPD-02 specifications		
Energy range	Electrons	3 MeV - 100 MeV
	Protons	30 MeV- 200 MeV
Energy resolution		≤10% for E> 5 MeV (e^-)
Angular resolution		≤10° for E> 3 MeV (e^-)
Max. Detectable flux		10^3 cm^{-2} s^{-1} sr^{-1}
Particle Identification		>90%

High Energy Particle Detector (HEPD) - scientific objectives:

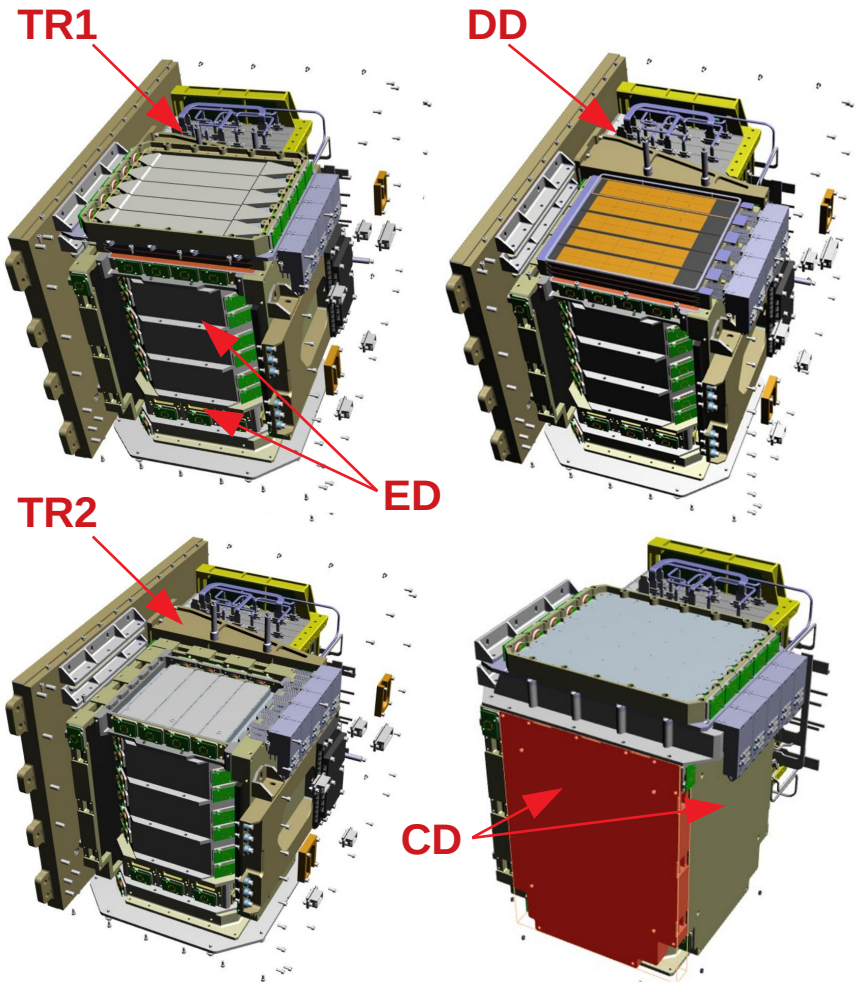
- study of bursts of Van Allen belt electron fluxes (particle precipitation) generated by high magnitude earthquakes;
- study the solar terrestrial environment, Solar Energetic Particle (SEP) events and low-energy galactic cosmic rays.

High Energy Particle Detector (HEPD-02)

The High Energy Particle Detector 02 (HEPD-02) is composed by:

- **Direction Detector (DD) - a tracker made of 5 independent turrets, each one made of 3 planes (staves)**
- **Trigger Detector (TD) - a trigger system made of 2 crossed layers of plastic scintillator counters:**
  - **TR1 - 1st plane segmented in 5 scintillator bars above the tracker;**
  - **TR2 - 2nd plane segmented in 4 bars orthogonally with respect to TR1 below the tracker;**
- **Energy Detector (ED) - a calorimeter which comprises:**
  - **a tower of 12 layers of plastic scintillator planes**
  - **2 crossed layers of LYSO inorganic scintillator, each one segmented in 3 bars**
- **Containment Detector (CD) - a veto system made of plastic scintillator planes, surrounding the calorimeter:**
  - **1 bottom plane**
  - **4 lateral planes**

Plastic scintillators: Eljen EJ-200 – PMTs: Hamamatsu R9880-210



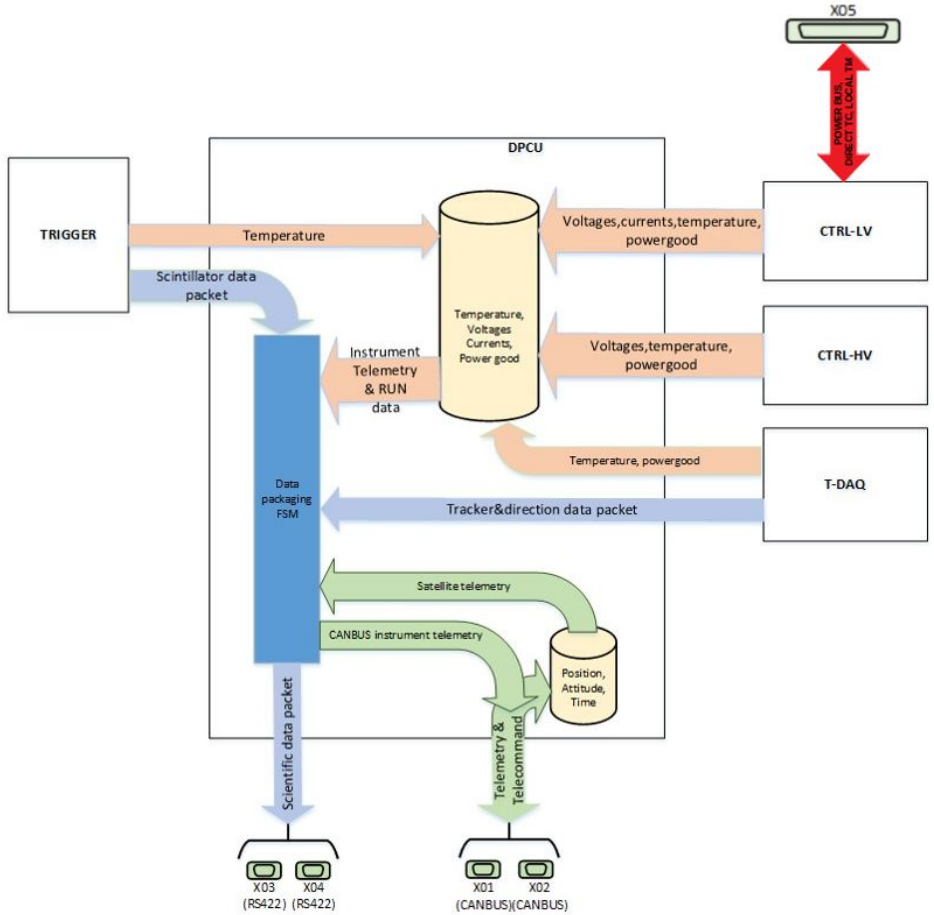
HEPD-02 Electronics and Power Supply Subsystems

The Electronic subsystems (ELS) is composed by all front-end electronics and three boards:

- **T-DAQ board: Direction Detector (Tracker) data acquisition;**
- **Trigger (TRIG) board: PMT data acquisition (TD, ED, CD) and trigger generation;**
- **Data processing and control unit (DPCU) board: HEPD-02 configuration, control, monitoring (slow control), Data and Satellite Communications management.**

The Power Supply Subsystem (PSS) is composed by:

- **Low Voltage Power Supply (LV-PS): low voltages generation and distribution to ELS and DD:**
  - **Low Voltage DC/DC converter (LV-DCDC) module (29.5V → 12V)**
  - **Low Voltage Control (HV-CTRL) board**
- **High Voltage Power Supply (HV-PS) for PMT bias:**
  - **16 High Voltage DC/DC converter (HV-DCDC) modules**
  - **High Voltage Control (HV-CTRL) board**



To avoid permanent failures, each electronic board and power supply is duplicated in a MAIN (or HOT) and SPARE (or COLD) side for redundancy.

HEPD-02 improvements

- **Major improvements of HEPD-02 detector with respect to HEPD-01:**
  - **Tracking Detector:**
    - first silicon-pixel tracker ever designed for space → increased tracking capability
  - **Trigger system:**
    - Concurrent trigger configurations and prescaling capability
  - **GRB detection**:
    - sensitivity to gamma-rays (2-20 MeV)

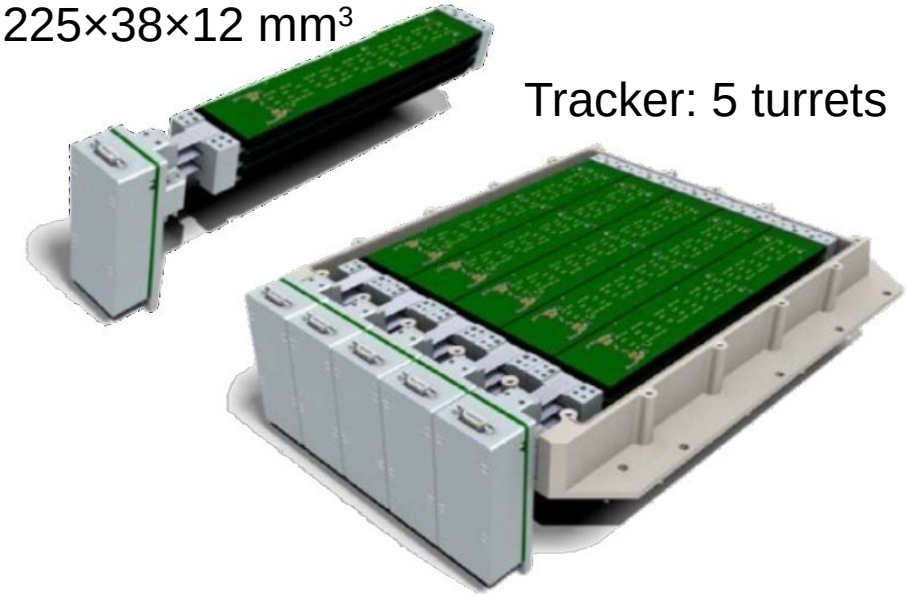
HEPD-02 Direction Detector

- **Tracking system Based on Monolithic Active Pixel Sensors (MAPS):**
  - first use in space
  - MAPS developed for ALICE experiment at LHC **(ALTAI CMOS pixel chips)**
- **5 independent turrets (225×38×12 mm³) made of 3 planes (staves) for tracking**
  - stave sensitive area composed by 10 ALTAI CMOS pixel chips
  - Chip 30×15×0.05 mm³, containing 1024×512 squared pixels each (28 μm).
  - Control and read-out based on ultra-thin (180 mm) flexible printed circuits → low material budget
  - 3 planes → high redundancy
  - Improved tracking resolution: systematic uncertainties on tracking down to 4um single-hit resolution
- **T-DAQ board → Direction Detector (Tracker) data acquisition**

- **Challenges for use in Space:**
  - Mechanical support (light support to avoid multiple scattering) for launch acceleration and vibrations
  - Limited power budget
  - Heat dissipation

Turret: 3 staves
225×38×12 mm³

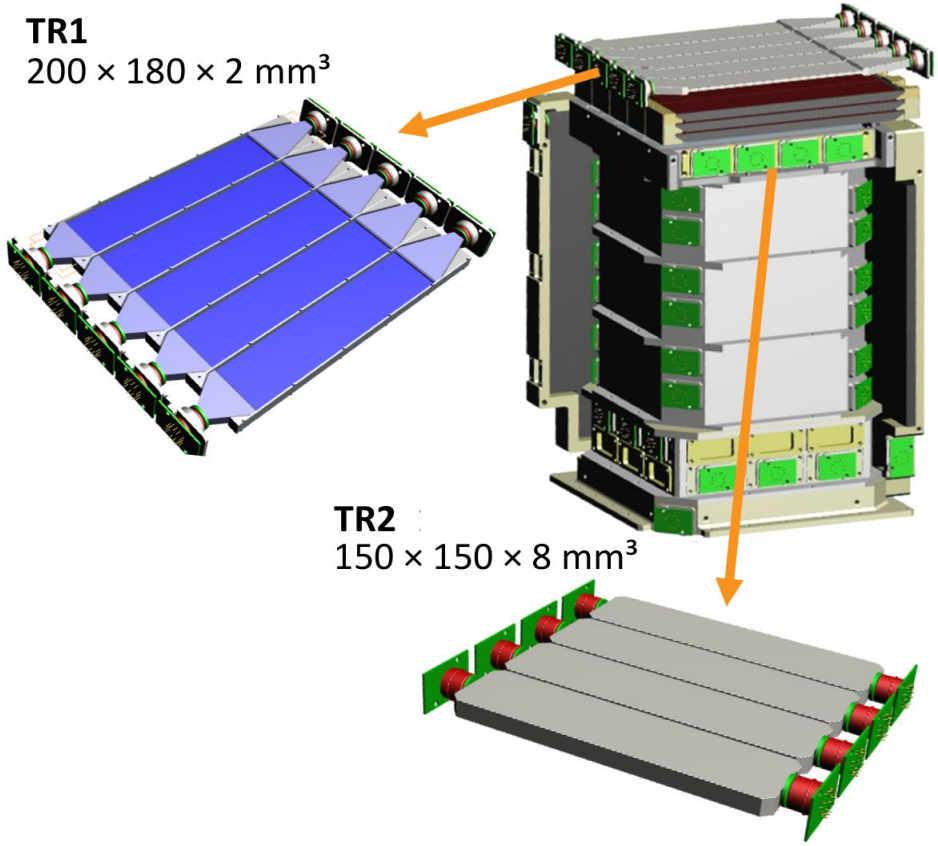
Tracker: 5 turrets



HEPD-02 – Trigger Detector

Trigger Detector (TD) - a trigger system made of 2 crossed layers of plastic scintillator counters:

- **TR1 - 1st plane above the tracker segmented into 5 counters to match the tracking modules**
  - read out by light-guides connected to PMTs
  - 2 mm thick → minimize multiple scattering and allow for a low threshold
- **TR2 - 2nd plane below the tracker segmented in 4 bars orthogonally with respect to TR1**
  - Read out by PMTs
  - 8 mm thick
  - good measure of the energy loss of charged particles



Trigger board → PMT data acquisition (TD, ED, CD) and trigger generation

Each counter read-out by 2 PMTs
Plastic scintillators: Eljen EJ-200
PMTs: Hamamatsu R9880-210

HEPD-02 Energy and Containment Detectors

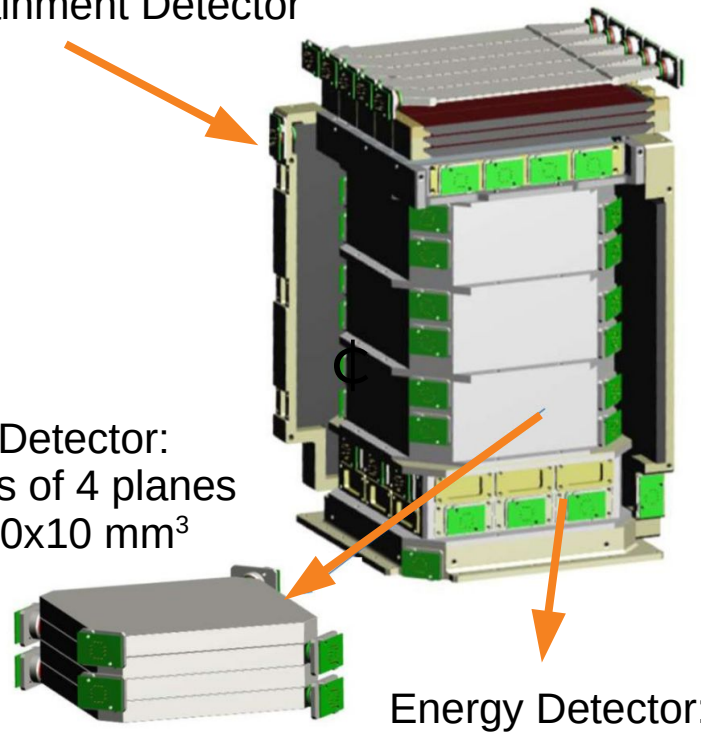
Energy Detector (ED) - a calorimeter which comprises:

- **RANGE Detector (RAN):**
  - a tower of 12 layers of plastic scintillator planes EJ 200 divided in 3 blocks
- **ENERGY Detector (EN):**
  - 2 crossed layers of LYSO inorganic scintillator, each one segmented in 3 bars
  - biggest LYSO scintillators ever produced for space
  - increased energy resolution and range

Containment Detector (CD) - a veto system made of plastic scintillator planes EJ 200, surrounding the calorimeter:

- 1 bottom plane 8 mm thick (166.5x166.5x8 mm^3);
- 4 lateral planes 8 mm thick, covering from T2 down to the CD bottom panel;
- CD panels used for configurable Veto (none/bottom/lateral/all CD)

Trigger board →PMT data acquisition (TD, ED, CD) and trigger generation

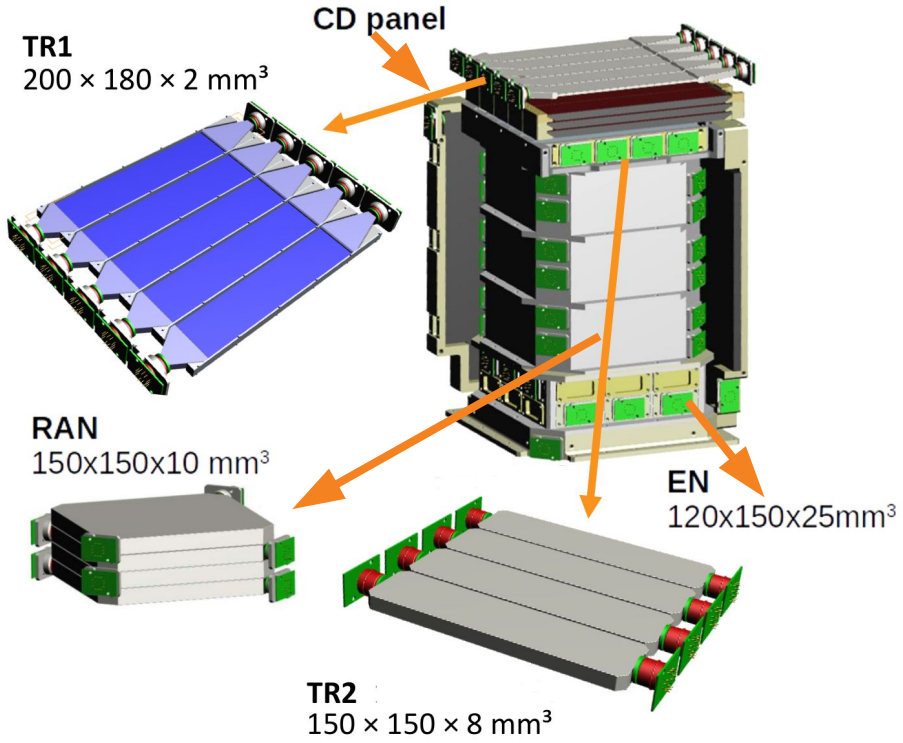


Each counter read-out by 2 PMTs
Plastic scintillators: Eljen EJ-200
PMTs: Hamamatsu R9880-210

HEPD-02 improvements – Trigger System

Trigger logic

- **Different combinations of signals from TR1, TR2 and CALO planes form HEPD trigger configuration which can be selected during the flight**
  - 9 predefined trigger masks
  - 1 generic trigger mask (configurable as AND combination of scintillator planes)
- **Event trigger generation:**
  - **Up to 6 trigger masks in concurrence, 4 with pre-scaling factors**
    - Event acquisition & efficiency monitoring
    - 2 masks dedicated to GRB detection (E>2MeV)
  - **Configurable Veto (none/bottom/lateral/all)**



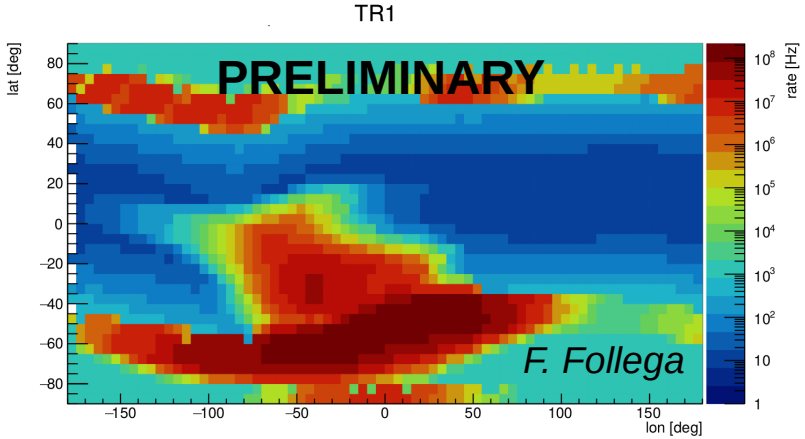
Rate meters

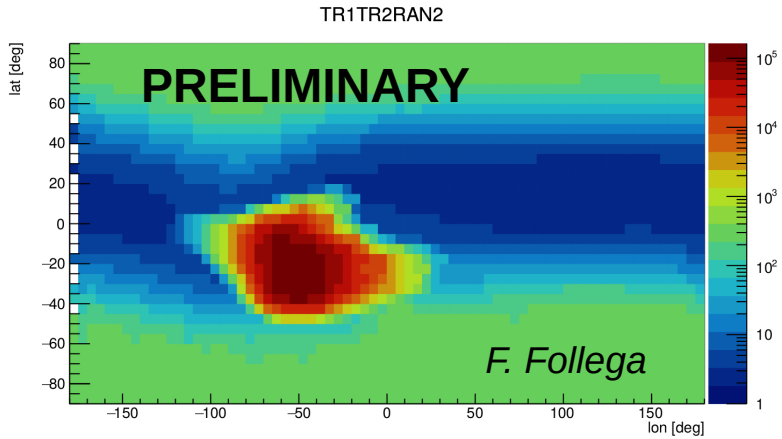
- PMT rate meters: 1Hz resolution for single PMT monitoring
- Trigger Mask rate meters: 1 Hz resolution, 1 counter for each trigger mask for rate measurements
- GRB rate meters: two rate meters with 200Hz resolution specifically designed for the GRB detection algorithm

HEPD-02 Trigger capability

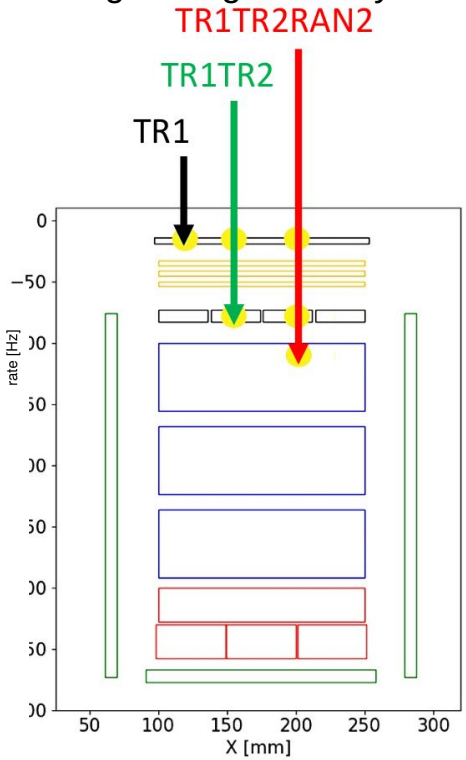
Along the orbit of CSES-02 particle fluxes span several orders of magnitude.

- **Concurrent trigger configurations and prescaling capability:**
  - **Concurrent trigger patterns** used in concurrence for **trigger generation**
  - **Pre-scaling factors** determined to match the amount of data the instrument can process and satellite data budget
  - **Trigger patterns optimized on the nature of particles** impinging in HEPD-02, with prescaling settings suitably adjusted along the orbit:
    - SAA: trapped electrons (dominant at 1MeV) and protons (dominant above 8MeV)
    - Equatorial: re-entrant and cosmic protons
    - Outer belt: low energy trapped electrons (below 10MeV)
    - Polar: primary electrons and protons and heavier nuclei
- 128 (8x16) Orbital zones with configurable trigger masks and pre-scaling factors





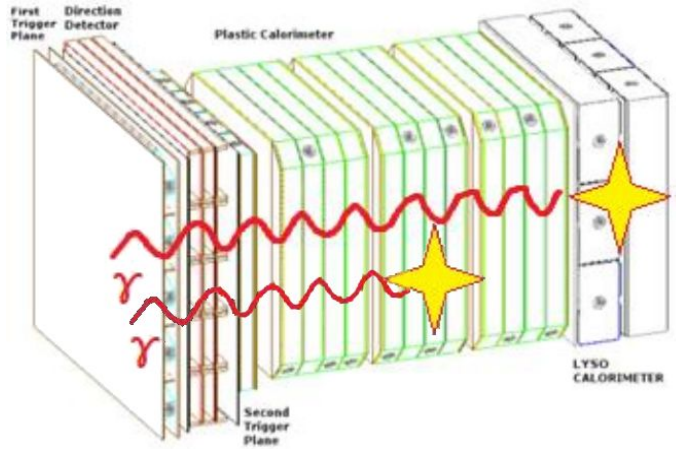
Expected rate (e-,p) with different trigger patterns selection (Energy threshold)

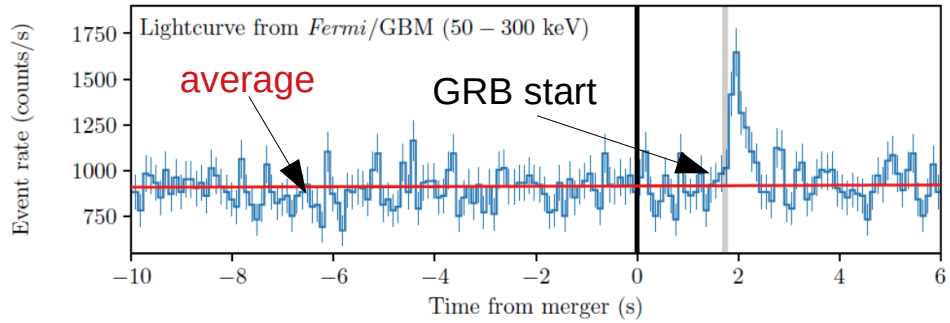


Gamma-ray detection (1/2)

Extension of the trigger capabilities for the detection of Gamma Ray Bursts, in the 2-20 MeV energy range.

- **Use of LYSO crystals and plastic scintillator planes (for low energies) to detect GRBs.**
- **LYSO radioactivity background: negligible effect above 2 MeV**
- **Trigger configurations dedicated to gamma-rays:**
  - $\text{GRB\_LYSO} = EN1 \cdot EN2 \cdot \overline{(RAN12 + LAT + BOT)}$
  - $\text{GRB\_RAN} = RAN5 + RAN6 + RAN7 + RAN8 \cdot \overline{(RAN4 + RAN9 + LAT)}$
- **Dedicated GRB rate meters (200Hz resolution) for GRB detection algorithm (implemented on DPCU):**
  - The algorithm makes use of GRB trigger masks and relative counters (updated each 5 ms) to evaluate the average counts and to trigger the GRB detection when the GRB mask counters, summed over different time intervals, significantly deviate from it.
- **Configuration flags are foreseen to enable/disable:**
  - GRB trigger on GRB_RAN/GRB_LYSO counters
  - GRB detection along the orbit (SAA and polar zones excluded)

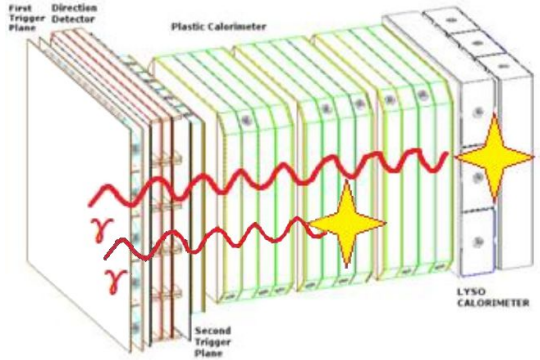




Gamma-ray detection (2/2)

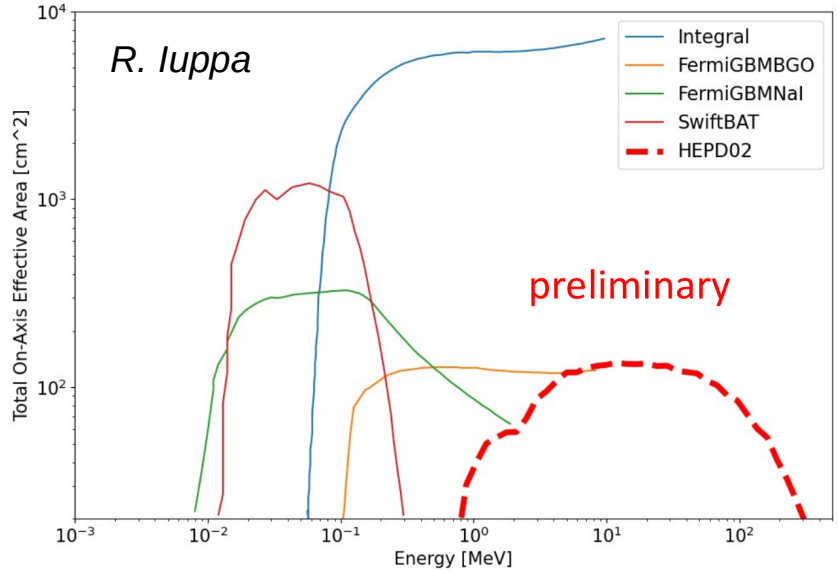
Extension of the trigger capabilities for the detection of Gamma Ray Bursts, in the 2-20 MeV energy range.

- **Use of LYSO crystals and plastic scintillator planes (for low energies) to detect GRBs.**
- **LYSO radioactivity background: negligible effect above 2 MeV**
- **Trigger configurations dedicated to gamma-rays:**
  - $\text{GRB\_LYSO} = EN1 \cdot EN2 \cdot \overline{(RAN12 + LAT + BOT)}$
  - $\text{GRB\_RAN} = RAN5 + RAN6 + RAN7 + RAN8 \cdot \overline{(RAN4 + RAN9 + LAT)}$
- **Dedicated GRB rate meters (200Hz resolution) for GRB detection algorithm (implemented on DPCU):**
  - The algorithm makes use of GRB trigger masks and relative counters (updated each 5 ms) to evaluate the average counts and to trigger the GRB detection when the GRB mask counters, summed over different time intervals, significantly deviate from it.
- **Configuration flags are foreseen to enable/disable:**
  - GRB trigger on GRB_RAN/GRB_LYSO counters
  - GRB detection along the orbit (SAA and polar zones excluded)



Possibility of 10 GRB observations per year

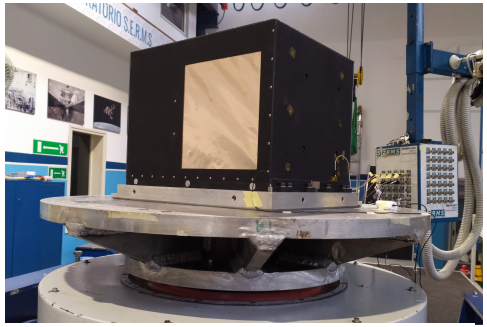
HEPD-02: similar effective area of Fermi in the range of 2-20 MeV



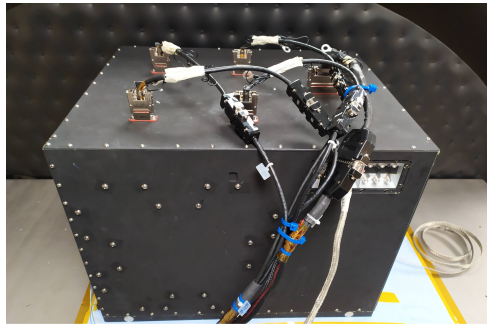
HEPD-02 FM TEST CAMPAIGN

- **HEPD-02 models & tests**
  - **Qualification model (QM)**
    - ✓ **Qualification tests**
      - Acceptance tests
      - Pyroshock tests
  - **Flight Model (FM)**
    - ✓ **Acceptance tests**
    - ✓ **Beam tests**

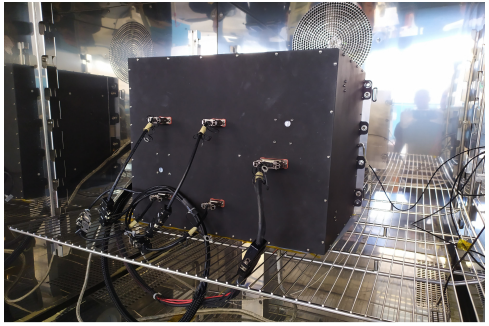
- **HEPD-FM Acceptance Tests:**
  - **Vibration Test** (sine & random) : 22/02/2023 –23/02/2023, 26/06/2023
  - **Thermal Cycling Test** (12.5 + 2 *burn-in* cycles, -20 °C ~ + 45 °C): 27/02/2023 – 14/03/2023
  - **Electromagnetic Cleanliness (EMC) Test:** 11/04/2023 – 27/04/2023
  - **Thermal Vacuum Test:** 08/05/2023 – 15/05/2023, 19/07/2023



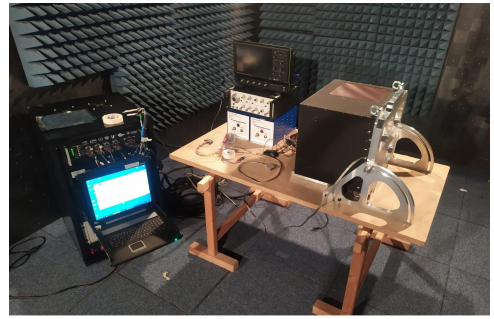
HEPD-02 FM vibration test



HEPD-02 FM in thermal vacuum chamber



HEPD-02 FM in thermal chamber



HEPD-02 FM EMC test

NEXT:

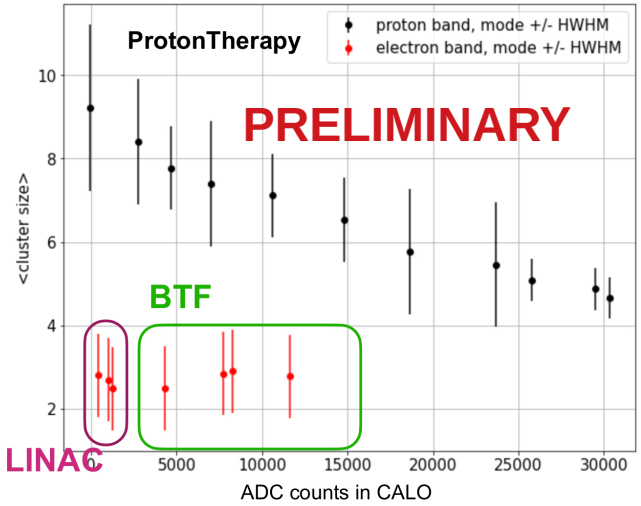
- **Acceptance Review (AR) and Pre-Shipment Review (PSR) w ASI**
- **Pre-Shipment Verification (PSV) w DFH**
- **HEPD-02 FM Shipment to China**

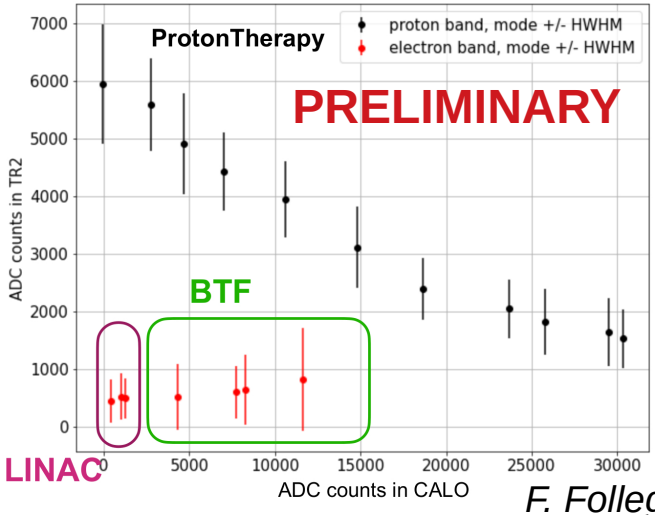
HEPD-02 FM TEST CAMPAIGN: Beam Tests

- **Electron Beam Test:**
  - **30-120 MeV, 450 MeV** at Beam Test Facility in Frascati
  - **6,9,12 MeV** at LINAC S. Chiara in Trento
- **Proton and nuclei Beam Test:**
  - **Protons, 70-228 MeV/amu** at Proton Therapy Center in Trento
  - **Protons 62, 227 MeV/amu** at the Centro Nazionale di Adroterapia Oncologica (CNAO) in Pavia
  - **Carbon nuclei 115-400 Mev/amu** at the Centro Nazionale di Adroterapia Oncologica (CNAO) in Pavia
- **X-rays (1-10 MeV)** at the S. Chiara LINAC in Trento (for GRB detection algorithm)

NEXT:

- **Acceptance Review (AR) and Pre-Shipment Review (PSR) w ASI**
- **Pre-Shipment Verification (PSV) w DFH**
- **HEPD-02 FM Shipment to China**





F. Follega

Conclusion

HEPD-02 developed and tested:

- **Main Improvements wrt HEPD-01**
  - Tracking Detector:
    - first silicon-pixel tracker ever designed for space → increased tracking capability
  - Trigger system
    - Concurrent trigger configurations and prescaling capability → Energy measurements over the poles and on the SAA
  - GRB sensitivity (2-20 MeV)
- **Acceptance tests and beam test performed on HEPD-FM**
  - Next steps:
    - Acceptance Review and Pre-Shipment Review (PSR) w ASI
    - Pre-Shipment Verification (PSV) w DFH
    - HEPD-02 FM Shipment to China for satellite integration and tests at satellite level
    - Launch foreseen in 2024

REFERENCES

- G. Ambrosi, et al., The HEPD particle detector of the CSES satellite mission for investigating seismo-associated perturbations of the Van Allen belts, Sci. China Technol. Sci., vol. 61, no.5 (2018) pp.643-652, DOI 10.1007/s11431-018-9234-9
- P. Picozza, et al., Scientific Goals and In-orbit Performance of the High-energy Particle Detector on Board the CSES, ApJS vol. 243 (2019) pp. 16, DOI 10.3847/1538-4365/ab276c.
- S. Bartocci et al., Galactic Cosmic-Ray Hydrogen Spectra in the 40–250MeV Range Measured by the High-energy Particle Detector (HEPD) on board the CSES-01 Satellite between 2018 and 2020, ApJ, 901:8 (7pp), 2020 September 20, DOI 10.3847/1538-4357/abad3e
- Palma F, et al. , The August 2018 Geomagnetic Storm Observed by the High-Energy Particle Detector on Board the CSES-01 Satellite, Appl. Sci. (2021) 11, 5680, DOI 10.3390/app11125680
- M. Martucci et al.,Trapped proton fluxes estimation inside the South Atlantic Anomaly using the NASA AE9/AP9/SPM radiation models along the China Seismo-Electromagnetic Satellite orbit, Appl. Sci. (2021) 11, 11(8), 3465, DOI 10.3390/app11083465
- Martucci M. et al., New results on protons inside the South Atlantic Anomaly, at energies between 40–250 MeV in the period 2018-2020, from the CSES-01 satellite mission, Phys. Rev. D 105, 062001, March 2022, DOI: 10.1103/PhysRevD.105.062001

Thanks for your attention

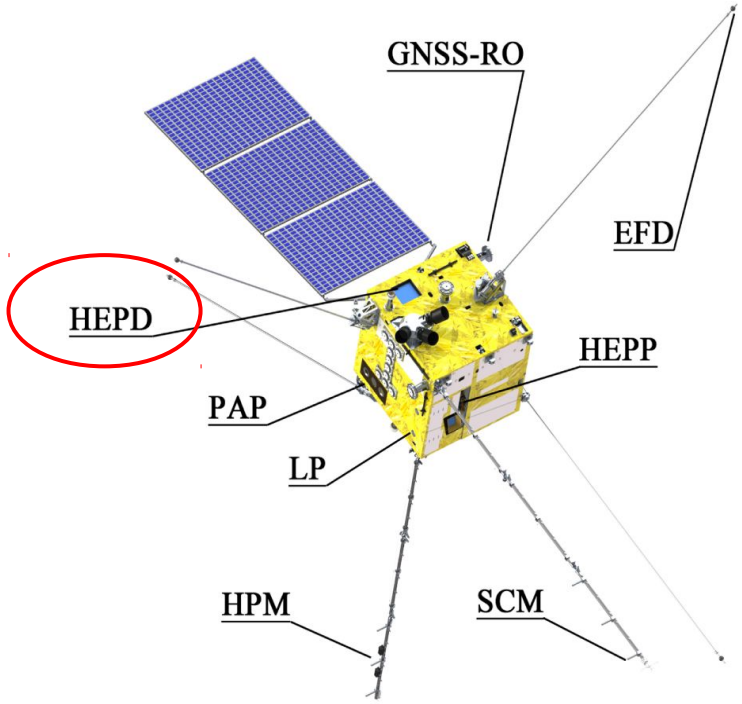
Backup slides

CSES specifications

CSES specifications	CSES-01	CSES-02
platform	CAST2000	
	Earth-oriented 3-axis stabilization system with orbit maneuver capability	
Mass	730 kg	900 kg
Peak Power Consumption	900 W	900 W
X-Band Data Transmission	120 Mbps	150Mbps
Storage	160 Gb	512Gb
Design Life-span	5 years	6 years
Operation mode	-65°<lat<65° → -70°<lat<70°	Full orbit

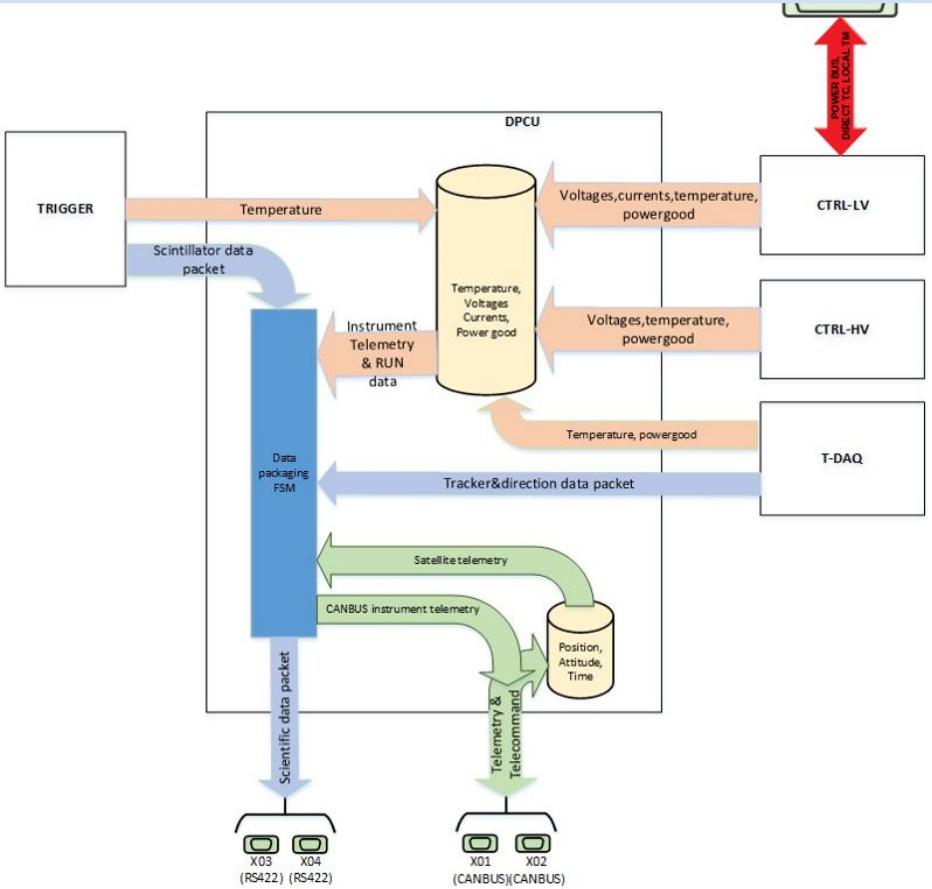
HEPD-02 specifications

HEPD-02 specifications		
Energy range	***Electrons***	**3 MeV - 100 MeV**
	Protons	**30 MeV- 200 MeV**
Energy resolution		**≤10% for E> 5 MeV (e^-)**
Angular resolution		**≤10° for E> 3 MeV (e^-)**
Max. Detectable flux		**10^3 cm^{-2} s^{-1} sr^{-1}**
Particle Identification		**>90%**
Pointing		**Zenith**
Operation temperature		**-10°C +35°C**
Operating pressure		**≤ 6.65 x 10^{-3} Pa**
Mass Budget		**<50 kg**
Power Consumption		**<45 W**
Data budget		**<100 Gb/day**
Scientific Data Bus		**RS-422**
Data Handling Bus		**CAN 2.0**

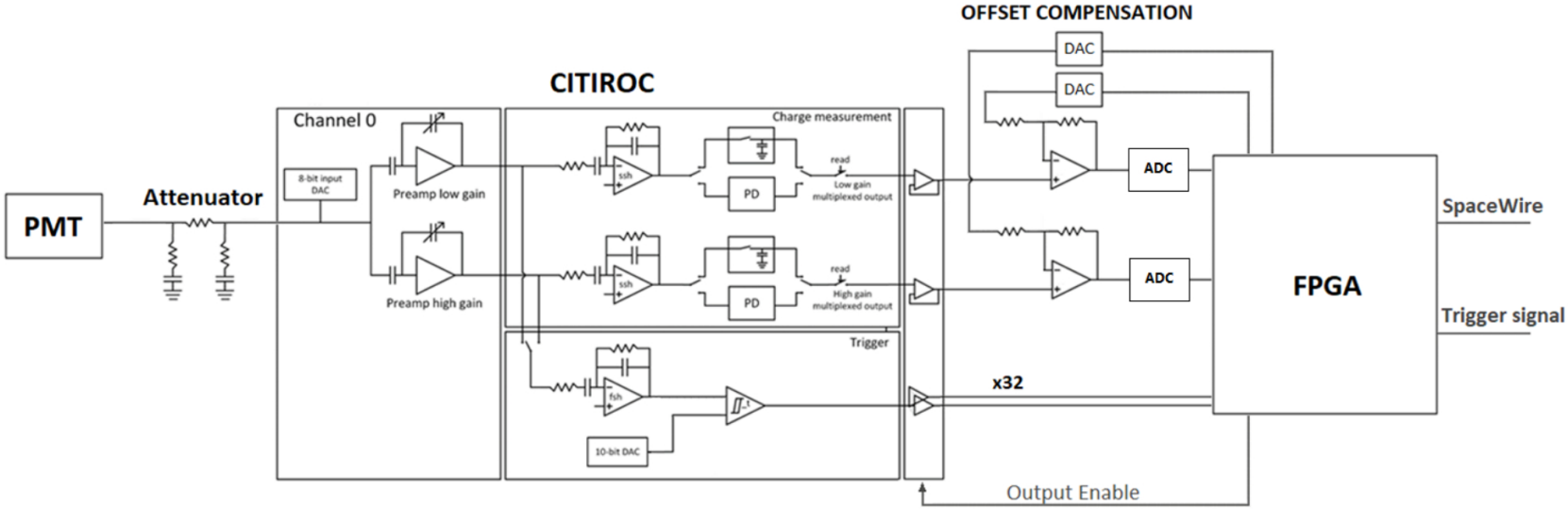


HEPD-02: other improvements

- **HEPD-02 - Other improvements:**
  - DPCU SW – improved redundancy:
    - The boot of the System on Chip (SoC) is managed by an Actel A3P device like in HEPD-01:
    - The SoC can boot from 4 independent flash memories.
      - The flash boot memory is selected by the A3P device with a round robin with timeout process (internal WD timer).
      - Flash boot memory selectable and rewriteble in flight by means of dedicated TC
    - Binary files stored into the boot memories are protected by CRC
  - Housekeeping system (DCPU): improved monitoring and control of HEPD subsystems



HEPD-02 – Trigger board



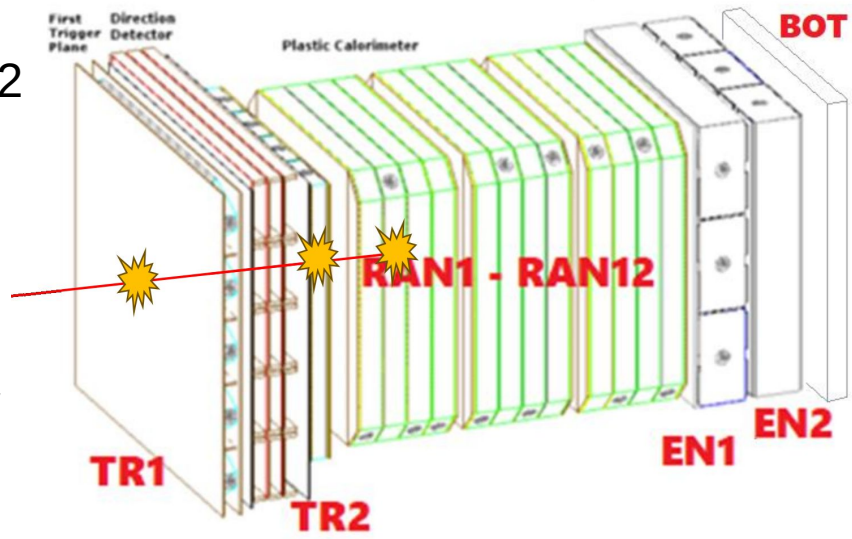
Responsible for event trigger generation and acquisition of PMT signals

- **CITIROCs readout integrated circuits by Weeroc**
  - 32 channels - amplify, shape and sample PMT signals and produce a trigger for each PMT
  - wide dynamical range: 2 independent Low and High Gain pre-amplification chains
  - Fast shaper and discriminator with configurable threshold for PMT trigger signal generation
  - Configurable Slow shaper and analog memory (Track&Hold or Peak Detector) for charge measurements
- **Microsemi A3PE3000L FPGA**
  - generation of event trigger signals enabling T-DAQ and PMTs acquisition:
    - implementation of logic conditions (trigger masks) of PMT trigger signals produced by CITIROC
  - Responsible for CITIROC configuration and management of 12-bits ADC conversion
- **FIFO**: for Trigger board data storage (PMTs data)

HEPD-02 – Trigger Masks

3 classes of trigger masks:

- **Event acquisition masks**:
  validating event acquisition using the TR1 and TR2 planes and the second plastic scintillator
  - TR1
  - TR1 · TR2
  - TR1 · TR2 · RAN2
- **Event monitor masks**:
  providing information about the detector efficiency
  - RAN1 · RAN7 · RAN12
  - TR2 · BOT
  - BOT · EN1 · EN2 · $\overline{TR1 + TR2 + LAT}$
  - RAN5 + RAN6 + RAN7 + RAN8 · $\overline{(RAN4 + RAN9)}$
- **GRB detection:**
  used for GRB detection algorithm
  - GRB_LYSO = EN1 · EN2 · $\overline{(RAN12 + LAT + BOT)}$
  - GRB_RAN = RAN5 + RAN6 + RAN7 + RAN8 · $\overline{(RAN4 + RAN9 + LAT)}$



HEPD-01

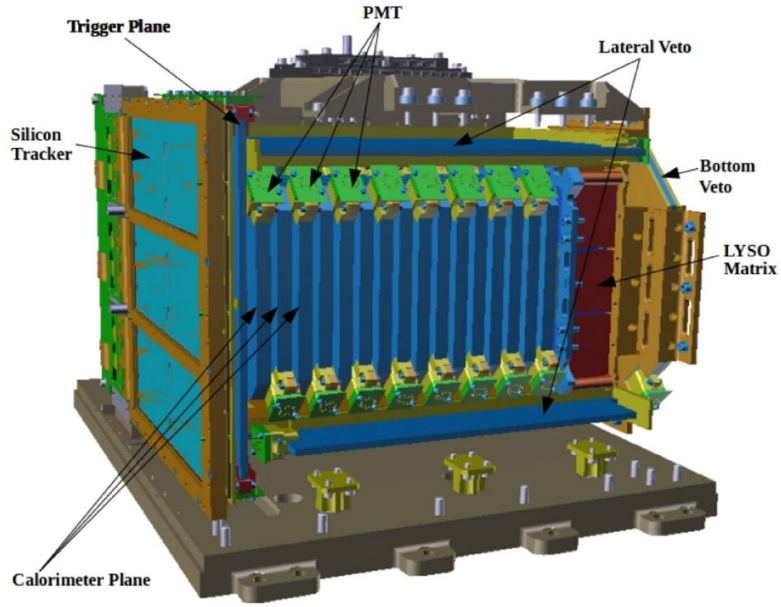
High Energy Particle Detector (HEPD)

Silicon Tracking Detector (FBK):

- two planes of double-side silicon microstrip (300 micron thick) detectors which provide the direction of the incident particle

Trigger Detector:

- one thin segmented layer of plastic scintillators for trigger (6 counters of dimension 20x3x0.5 cm^3 - EJ200) read out by PMTs



Energy Detector:

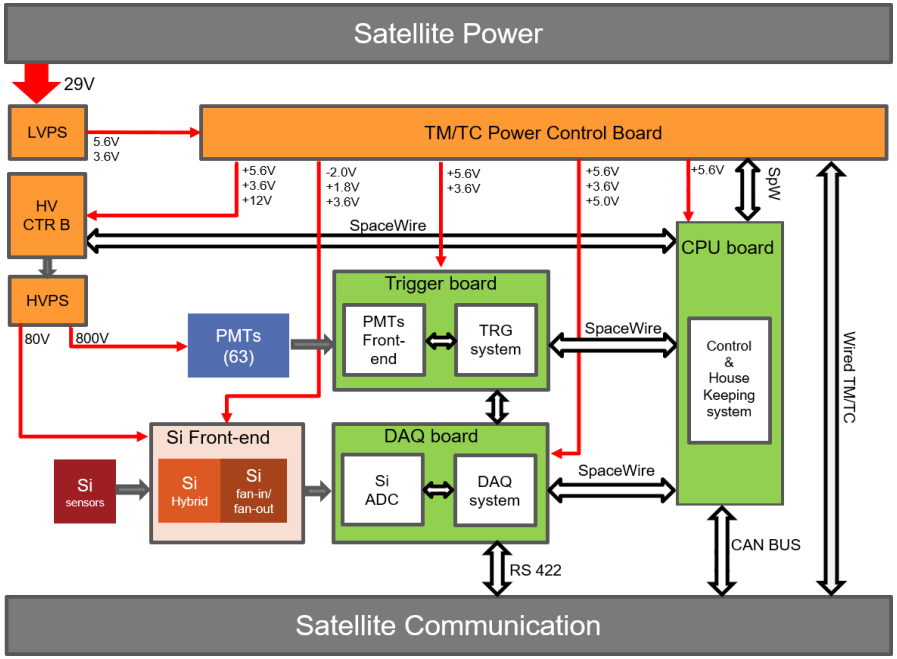
- UPPER CALORIMETER: tower of 16 plastic scintillator planes (15 × 15 × 1 cm^3 - EJ200) read out by PMTs
- LYSO CALORIMETER: a 3 × 3 matrix of inorganic scintillator LYSO (15 × 15 × 4 cm^3) read out by PMTs

Veto Detector:

- lateral and bottom plastic scintillator planes (5 mm thick) read out by PMTs surrounding the calorimeter volume

PMT HAMAMATSU R9880U-210

HEPD Electronics



Power supply:

- **Low Voltage Power Supply (LVPS)** generating two LV lines from satellite power bus (29V)
- **High Voltage Power Supply (HVPS)** for the Silicon sensors and PMTs bias.

- **TM/TC Power Control Board:**
  - LV distribution
  - Direct TeleCommands management
- **CPU board**
  - communication with the satellite computer (OBDH) via CanBus
  - management of system diagnostic routines and detector configuration
- **PMT/Trigger Board**
  - Acquisition and processing of PMT signals (EASIROC ASIC):
    - High/Low Gain Chain for plastic scintillators/LYSO crystals
  - Trigger Management: Trigger & Veto configurations and trigger signal generation
- **DAQ board**
  - Acquisition, processing and compression of Silicon Detector signals
  - Scientific data formatting and transmission to the satellite via RS-422