The trigger and DAQ of the HEPD-02 on CSES-02 satellite

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for the CSES-Limadou Collaboration

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Outline

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

- ❑ The High Energy Particle Detector (HEPD-02)
- ❑ The electronics of the HEPD-02
- ❑ DAQ system
- ❑ Trigger logic and capabilities
- ❑ Test beam results and outlook

HEPD: multipurpose, precise compact detector

See C. De Santis and F. Follega talks

CSES-02: China Seismo-Electromagnetic Satellite

- Orbit: 500 km, sun-synchronous, 97° inclination
- Design life cycle > 6 years, launch in 2024

Several payloads for electromagnetic and plasma measurements in the Van Allen belts

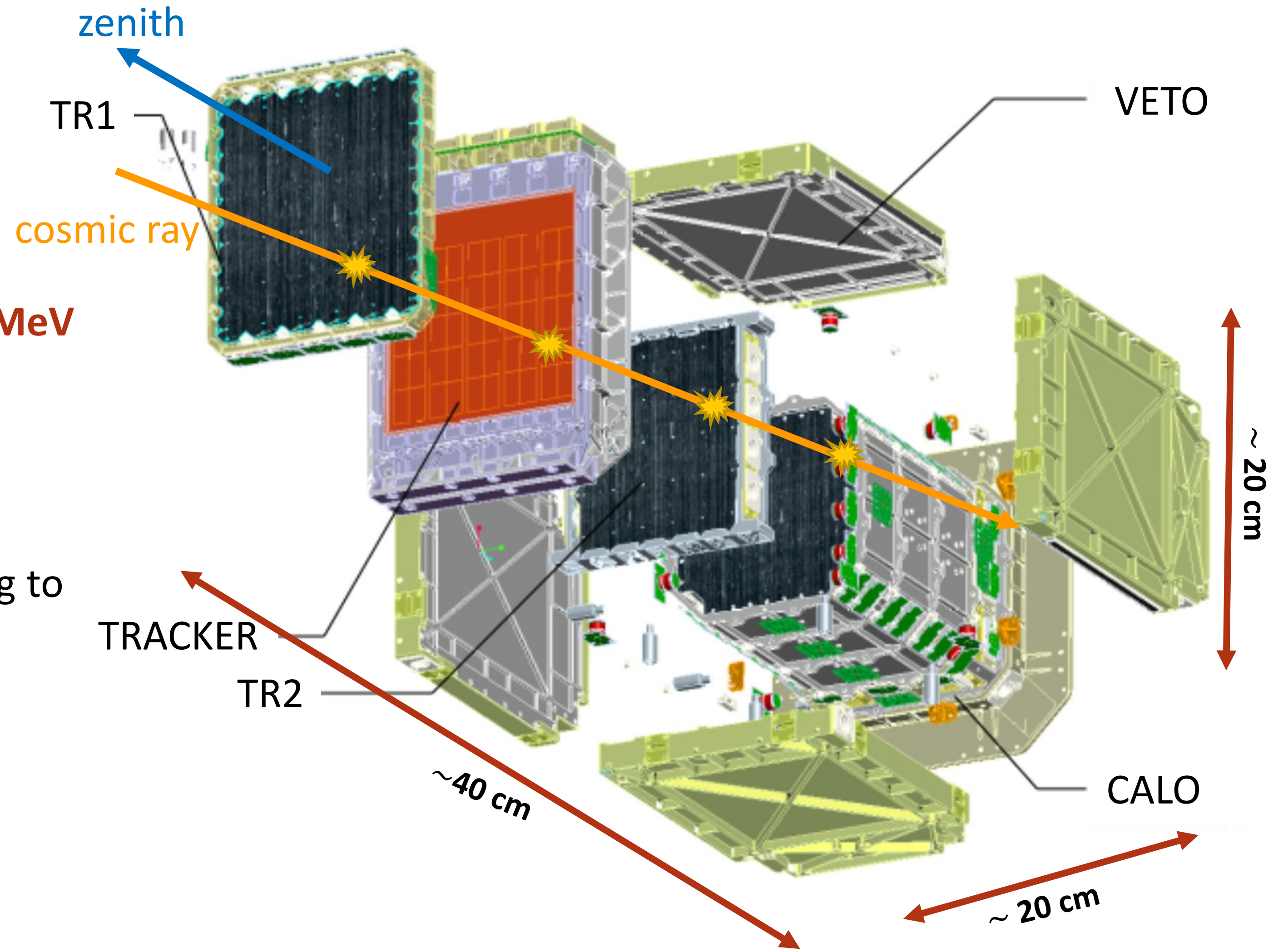
HEPD: Low energy Cosmic Rays with energy 3 ÷ 300 MeV

For each particle:

- identification (proton, electron, nucleus)
- energy
- pitch angle

Goal: **maximize the geometrical acceptance** according to weight and power budgets constraints

Operative temperature	-10°+35°
Mass	< 45 kg
Power Consumption	< 45 W
Data budget	< 100 Gb/day



The instruments

Trigger: 2 crossed layers of plastic scintillators EJ-200 enclosing the tracker [18 PMT]:

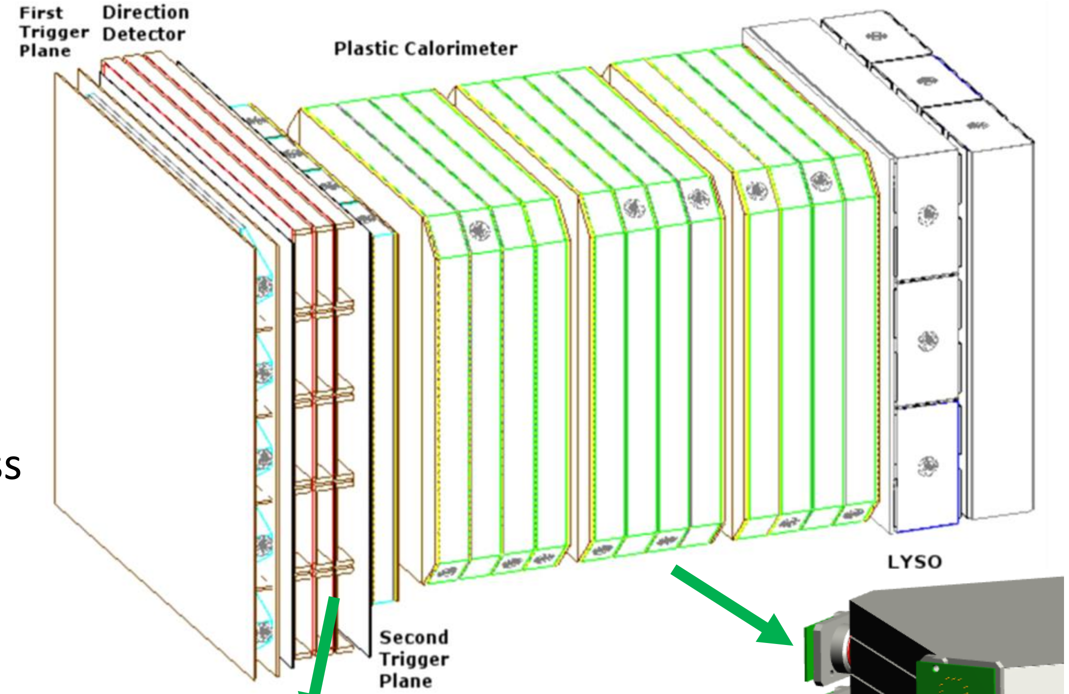
- **TR1**: 5 2-mm-thick counters read out by light-guides connected to PMTs: to match the tracking modules
- **TR2**: 4 8-mm-thick bars: good measure of the energy loss of charged particles

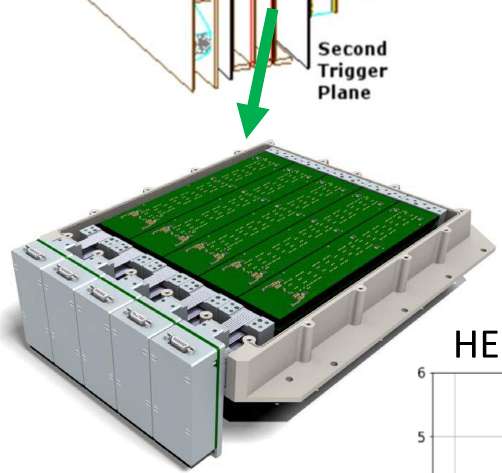
Tracker: 3 layers of **5 independent tracking modules** based on **Monolithic Active Pixel Sensor (MAPS)** after the 1st trigger plane to limit the effect of multiple scattering on the direction measurement

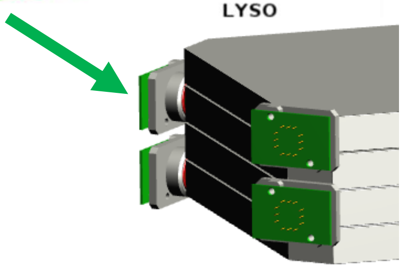
Calorimeter: **12 layers** of 1 cm thick **plastic scintillator** (EJ-200) planes [24 PMT] + **2** crossed **layers** segmented into 3 bars of **LYSO** scintillator crystals (high LY, slower) [12 PMT]

Veto: (not shown) 4 lateral + 1 bottom planes of 8 mm-thick plastic scintillators, surrounding the calorimeter [10 PMT]

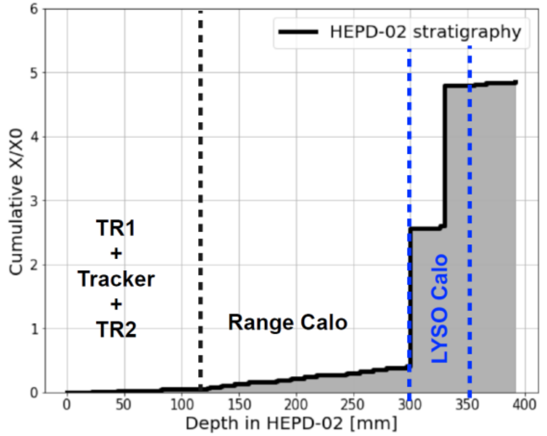
PMT: Hamamatsu R9880-210







HEPD-02 thickness in X/X0



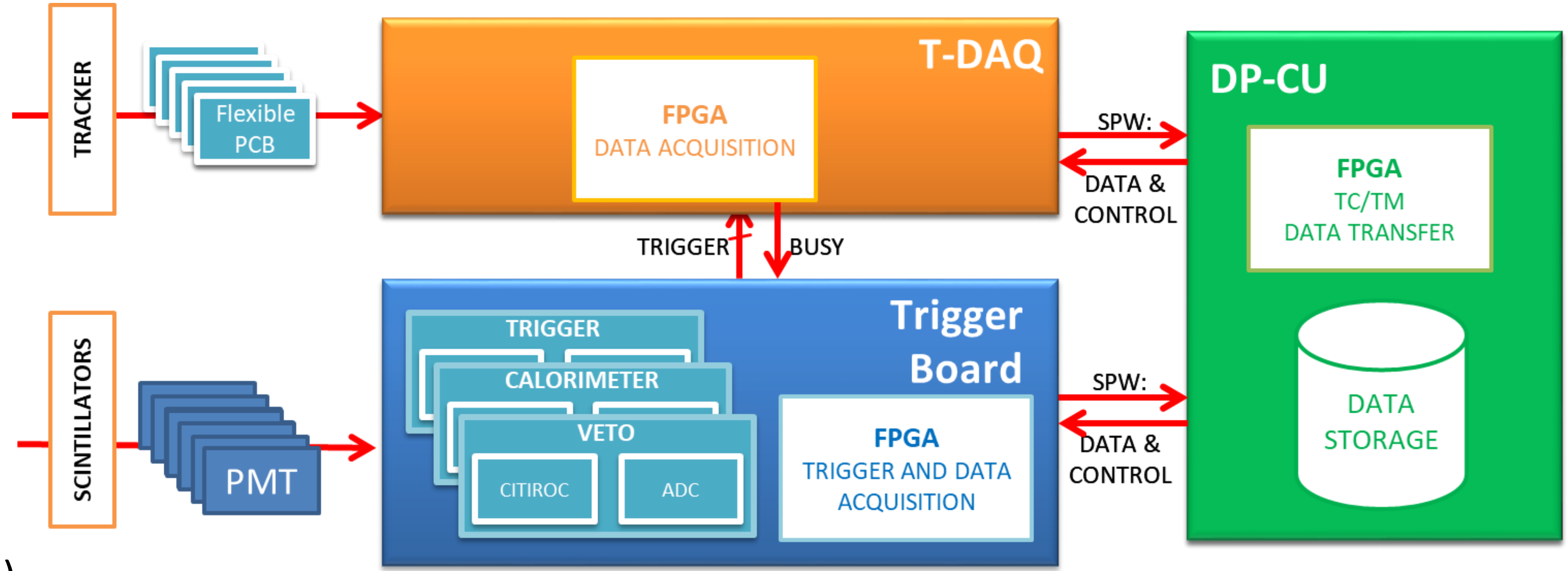
HEPD electronics

Data acquisition:

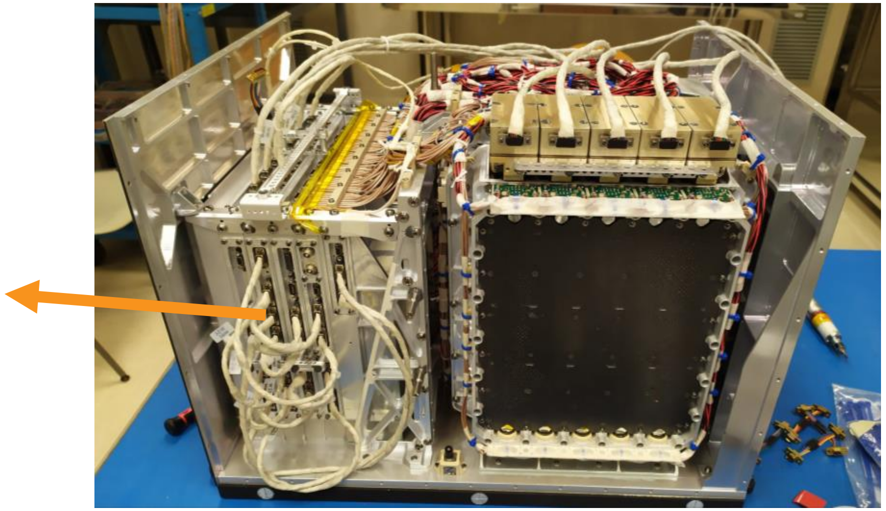
1. Tracker detector (T-DAQ)
2. Scintillator detectors: trigger, calo and veto (Trigger board)

Managing and control

1. Control and data managing (DP-CU)
2. LV-PS and HV-PS

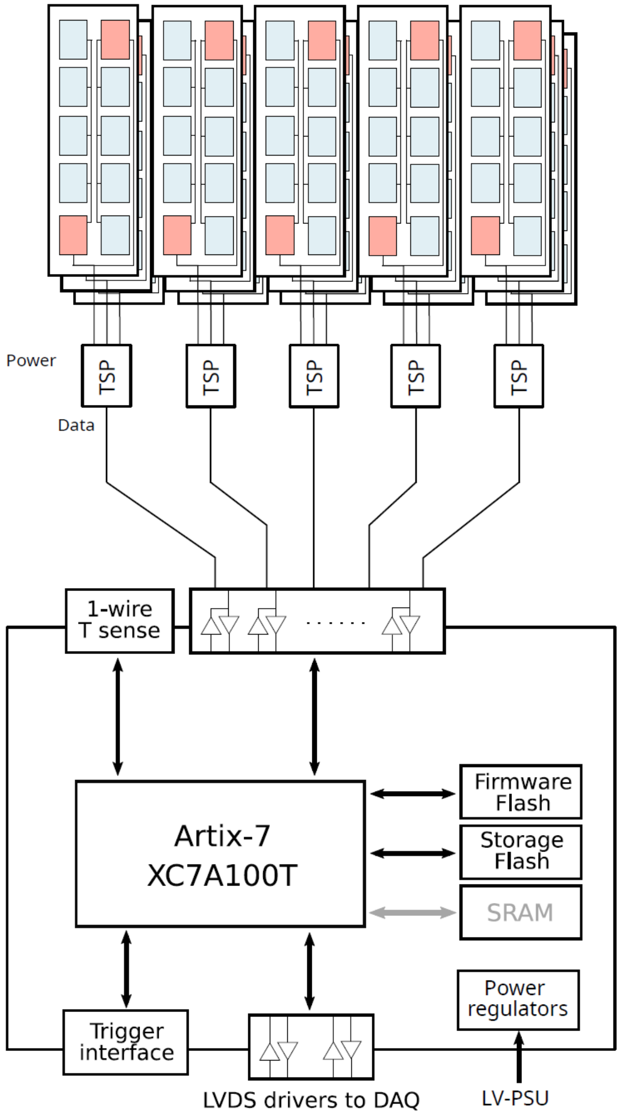


- Dedicated mechanics that allow anchoring to the HEPD-02 base plate and heat dissipation
- Communication via SpaceWire Light protocol
- Embedded “HOT/COLD” redundancy
- -30°C to +50°C qualification temperature range
- Max data transfer rate from satellite = 100 Gb per day



Tracker-DAQ board

See E. Ricci talk



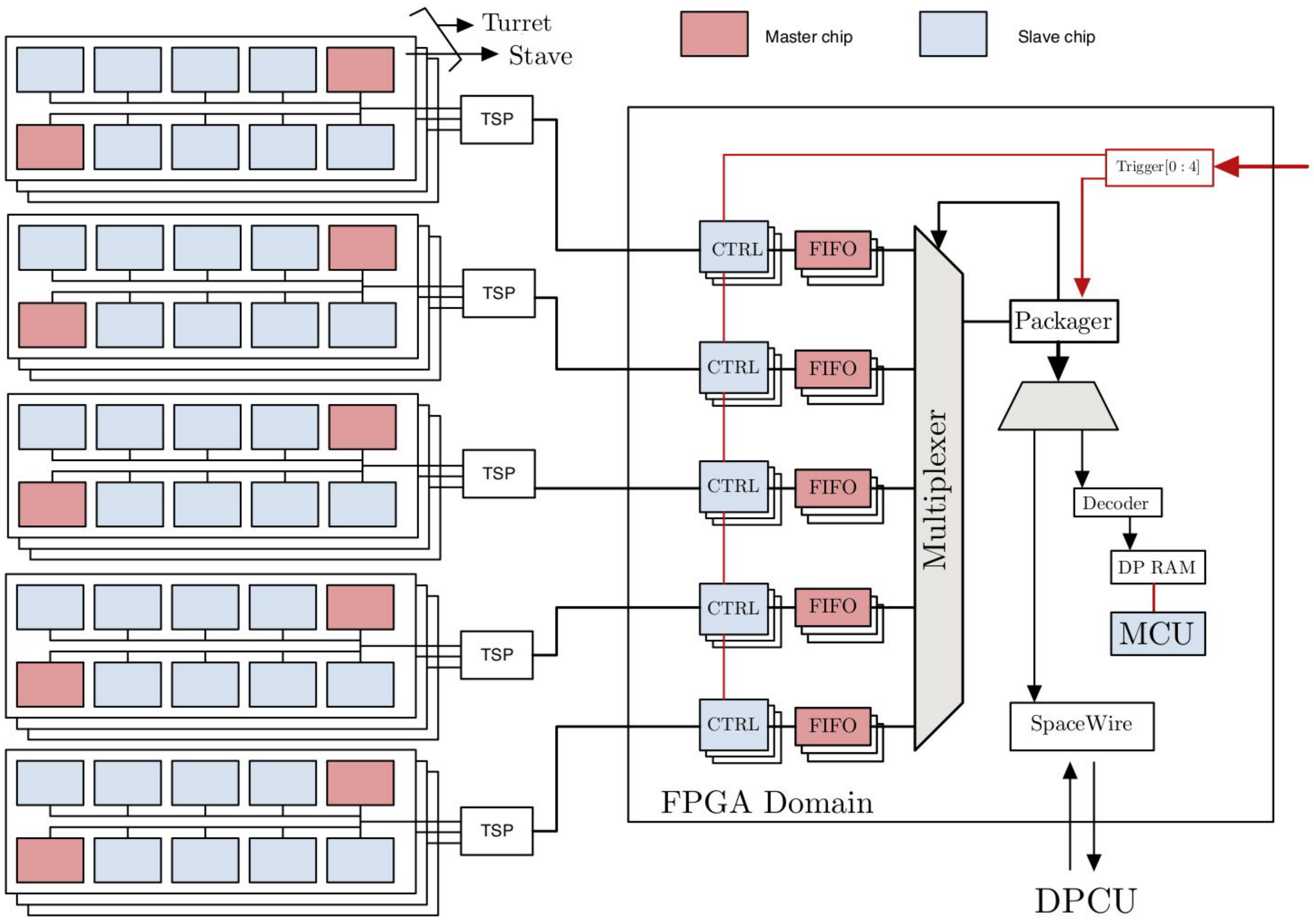
Custom tracker readout system developed to respect the tight power budget:

- Readout performed from the chip **slow control port** (~40 Mbps), still acceptable for the low trigger rate sustainable by HEPD-02
- **Clock gating**: clock signal is provided to a turret only when a trigger is received and then disabled after readout (typically 3 turrets enabled each time)
- Modular structure to implement a sparse readout

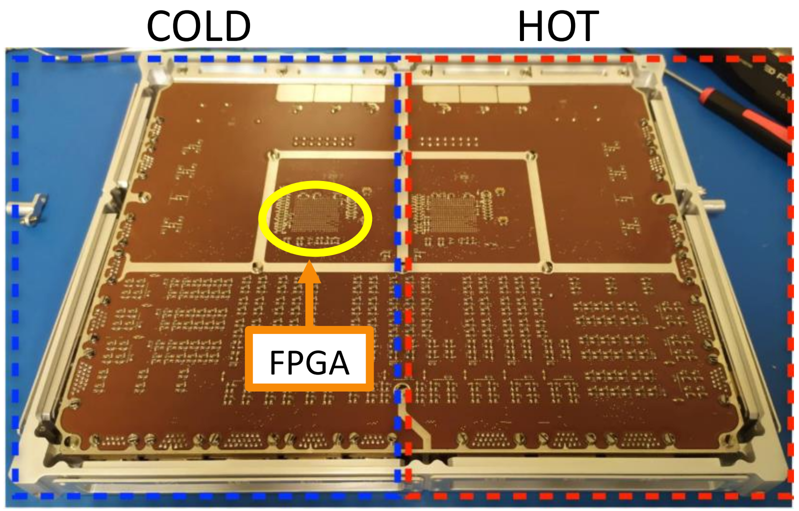
To deal with the slow data rate from the slow-control line, a custom FPGA-based (low power Xilinx Artix7) firmware was developed using as strategies:

- Parallelization
- Pipelining
- Redundant and modular design

T-DAQ board architecture



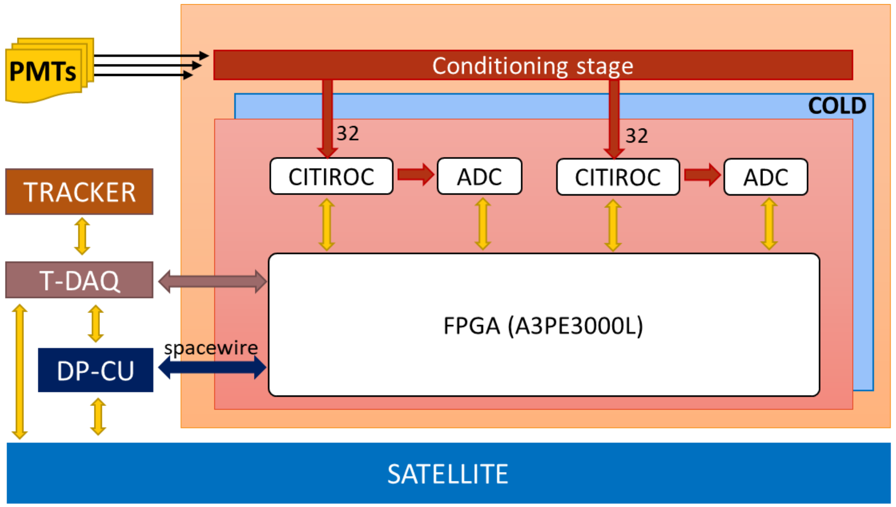
- **5 trigger lines** + busy output from/to the Trigger Board
- A packager collects data and organizes them in packets, sent to the DPCU via **SpaceWire** protocol
- **MicroController Unit (MCU)** implements higher-level tasks: threshold calibrations, noise scan, chip configurations, …

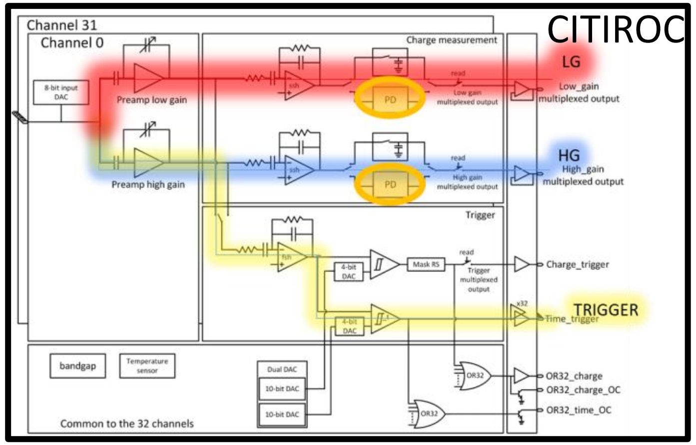


Trigger board

Functionalities:

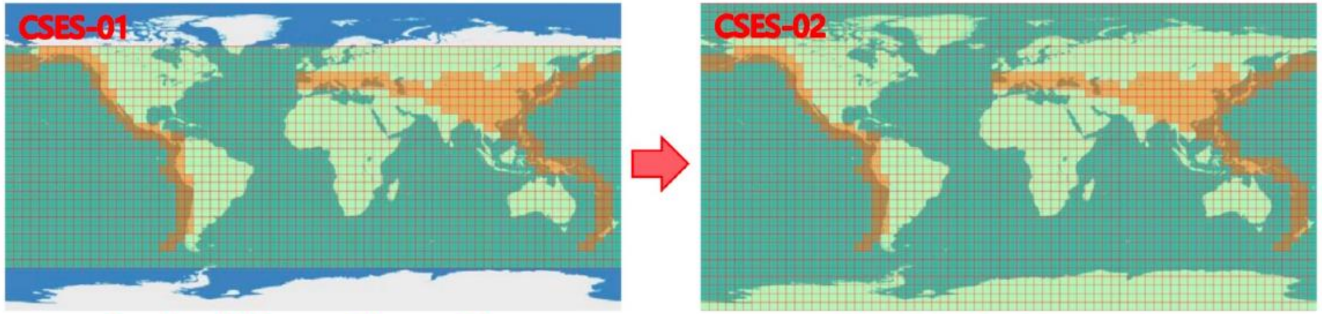
- Readout of 64 PMT: 2×32-channel ASICs CITIROC (Weeroc)
- Digitalization of PMT signals
- Configurable gain/trigger threshold to optimize the acceptance
- Two configurable gain chain
- Different trigger configurations to match different orbital zones and particles
- Rate meters for each PMT and trigger configuration





From HEPD-01 to HEPD-02:

- ➢ High trigger rate at polar regions: improved trigger logic and pre-scaling
- ➢ Larger amount of acquired data: mass memory on board for buffering

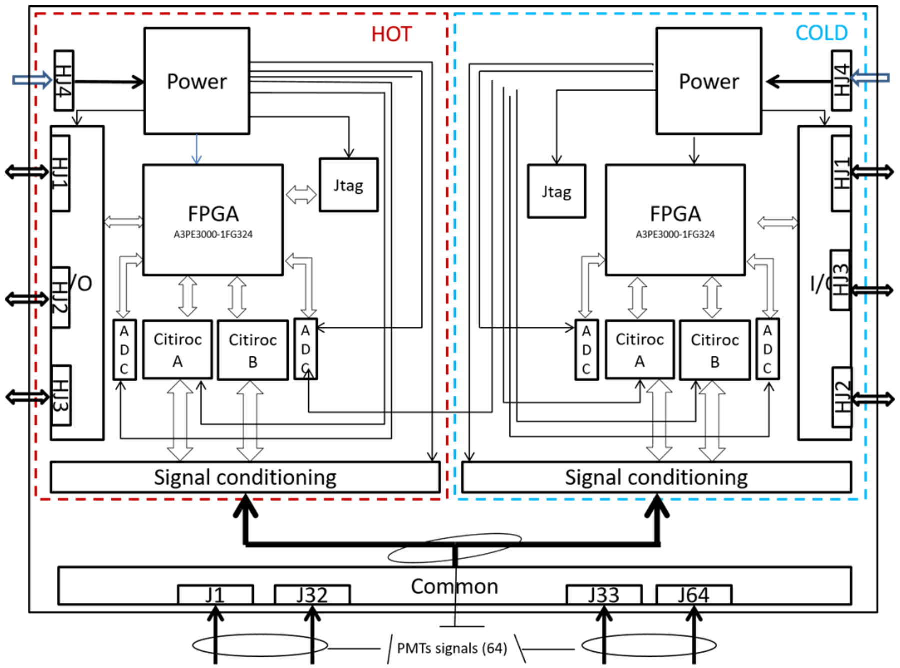


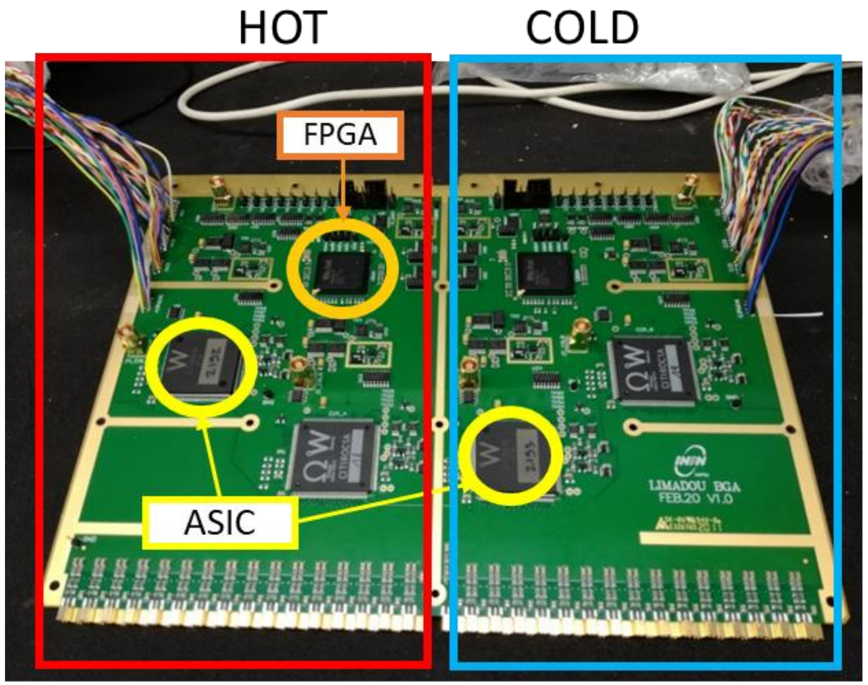
Confined Areas Observation

Global Wide Observation

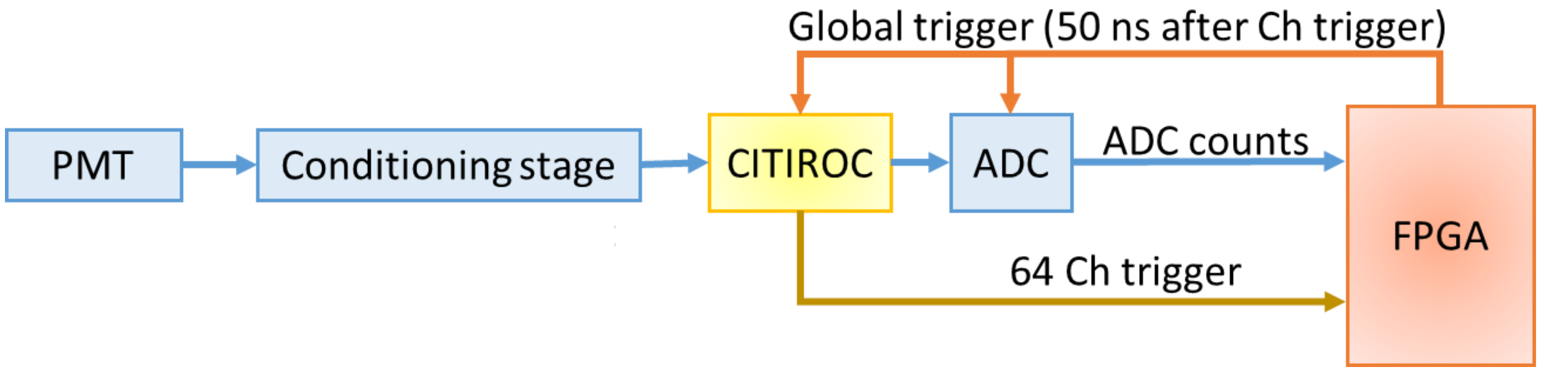
Trigger board architecture

- Custom designed
- 64 channels in common for HOT and COLD sides
- On each side (H&C):
  - FPGA: MicroSemi ProASIC A3PE3000
  - 2 ASIC: CITIROC 1A Weeroc
  - 4 ADC: AD7274 (12 bits, 24 MHz)
- Signals coming from the last dinode of PMTs
  - Reduce power consumption
  - Simplify design (no inverters)
- Coaxial cables RG178 to improve noise immunity

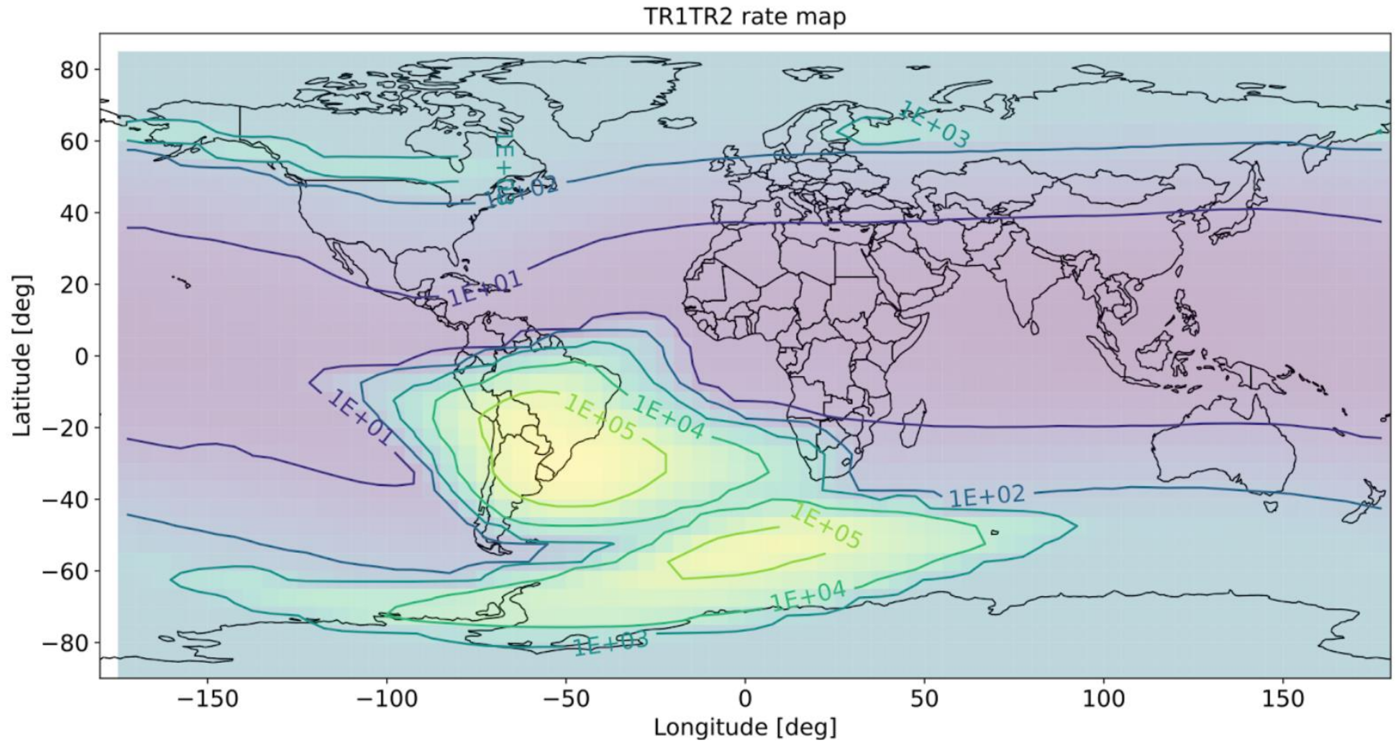




Trigger/PMT board (EM)



Trigger requirements



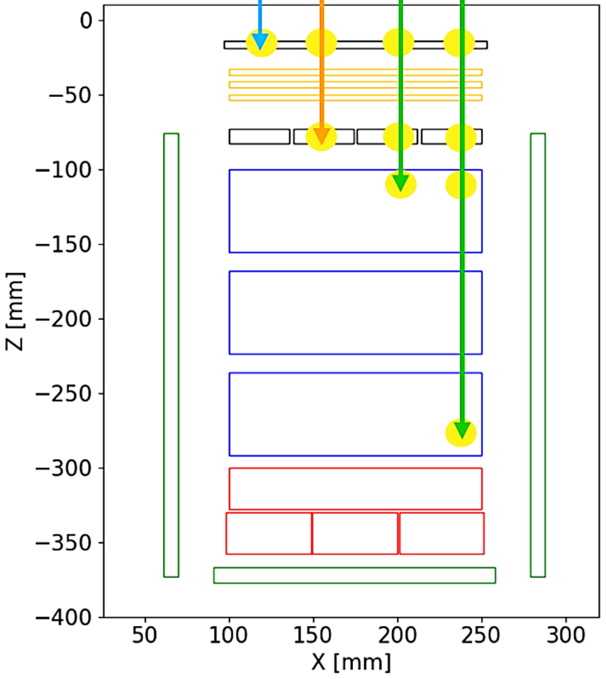
- Along the orbit of CSES-02 particle **fluxes span several orders of magnitude**
- **Expected rates up to 10 MHz** (SAA), not compatible with data budget nor with event acquisition dead time
- Low-energy triggers would determine the **saturation** of HEPD-02
- Data acquisition must guarantee the measurement of energy spectra with a high duty cycle

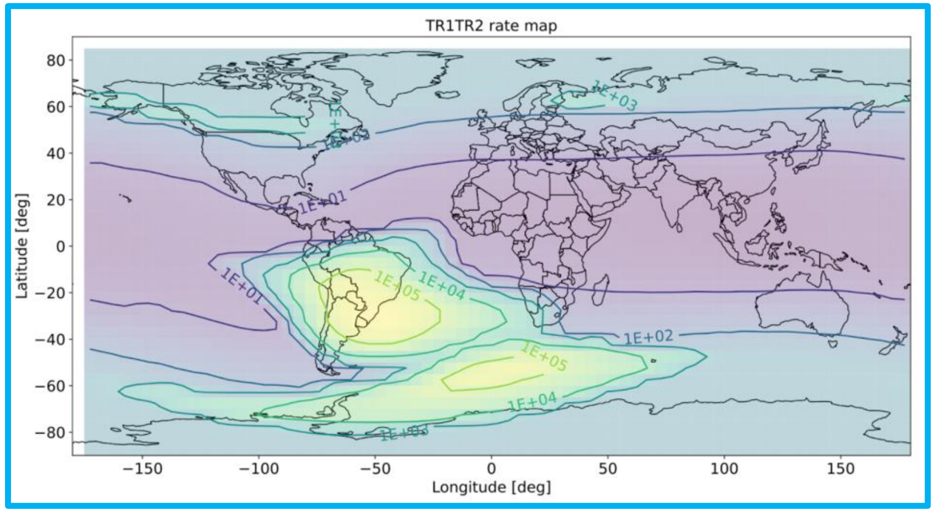
Trigger logic:

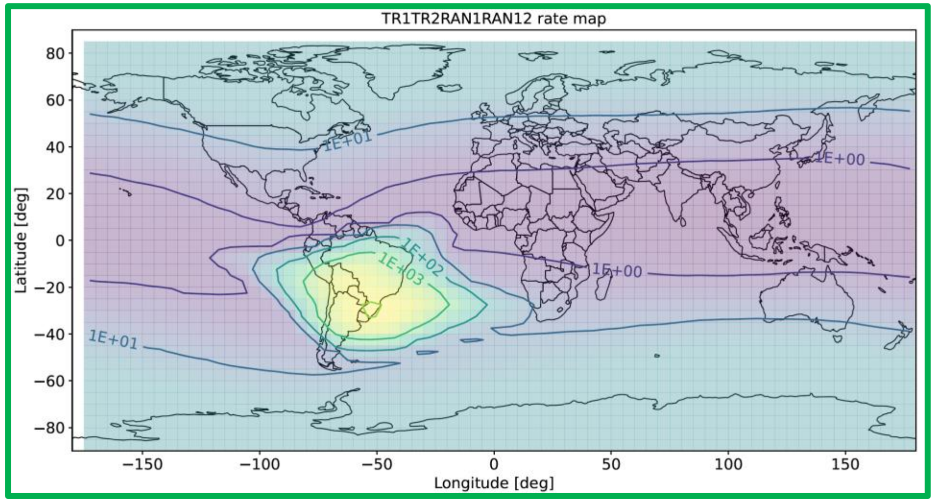
- **Flexible:** combinations of signals from TR1, TR2 and CALO form trigger configuration selectable in flight
- **Strong**: to cope with increased fluxes of particles at polar orbits

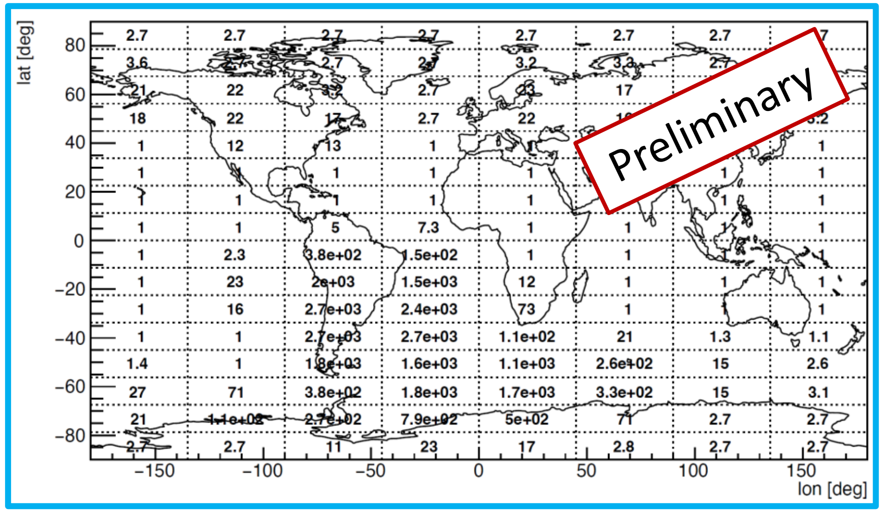
Concurrent trigger masks + orbital zones

trigger patterns for different particle penetration (i.e. different energy thresholds)

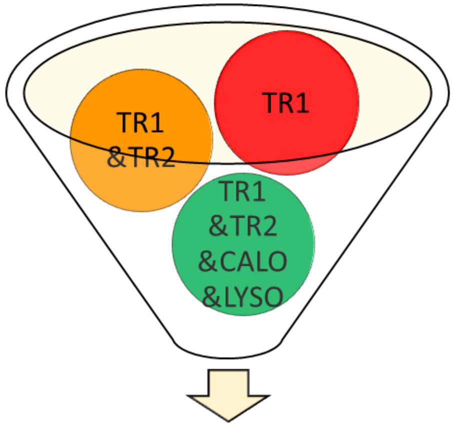






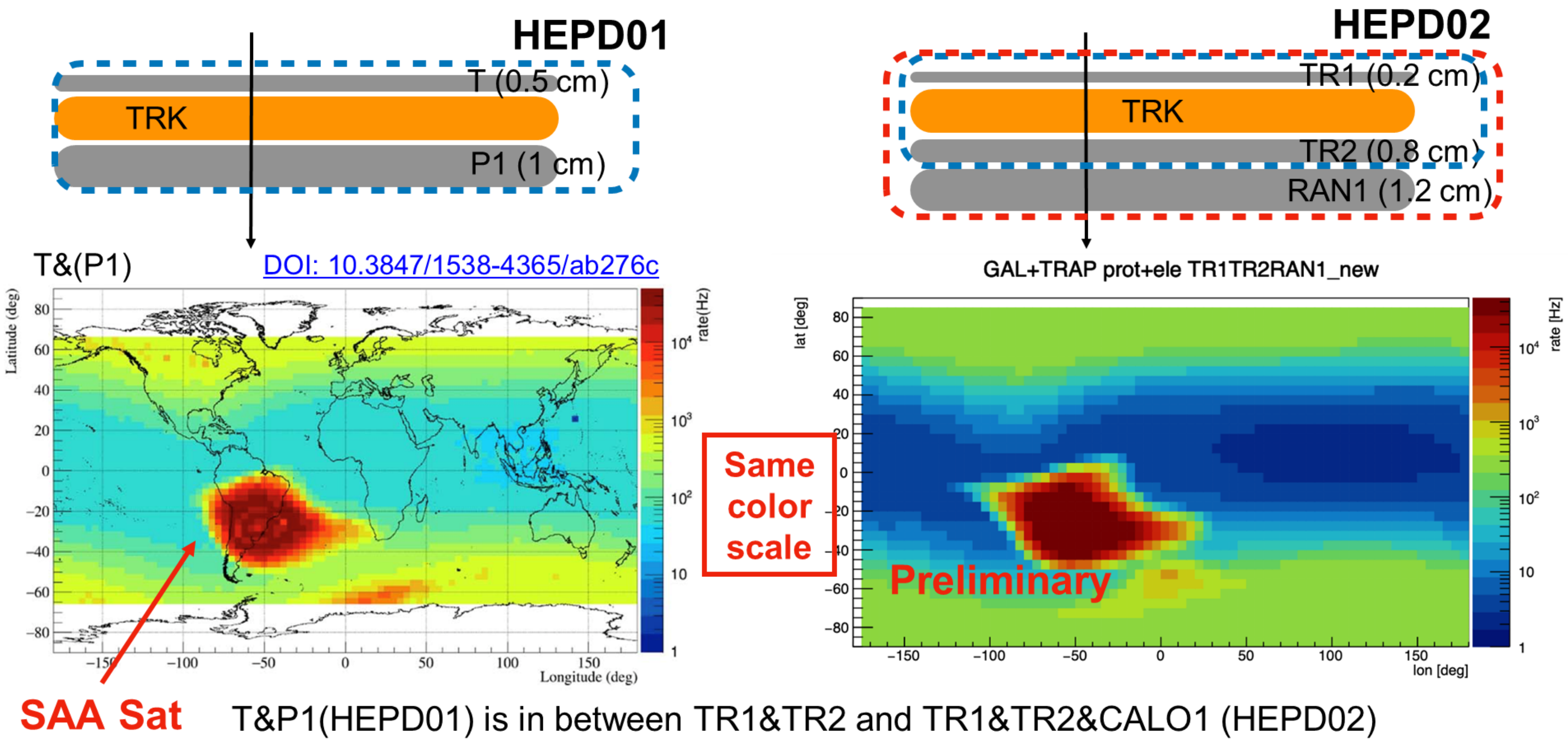


Capability to acquire data on the SAA by selecting appropriate trigger configurations



HEPD-02 trigger

Concurrent trigger and prescaling



T&P1(HEPD01) is in between TR1&TR2 and TR1&TR2&CALO1 (HEPD02)

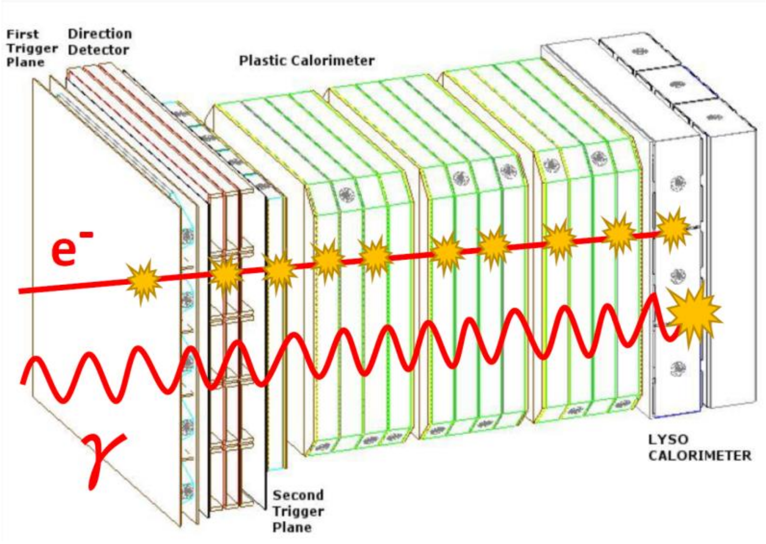
Usual approach: global prescale factor to prevent saturation keeping a "calibration" data-stream

HEPD-02 approach:

- **concurrent trigger** system allowing for measurements over the poles and on the SAA
- **prescaling factors** adjusted for each trigger pattern to share resources among different physics cases, optimized after scientific requirements about FoV and kind of particle

The data throughput is shared among different physics channels via online selection: the largest-rate triggers are prescaled to avoid bandwidth saturation

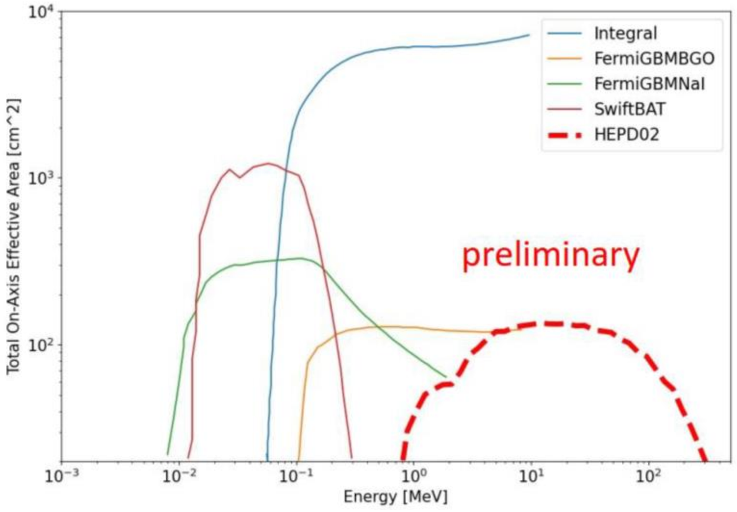
Trigger masks and gamma-ray observation

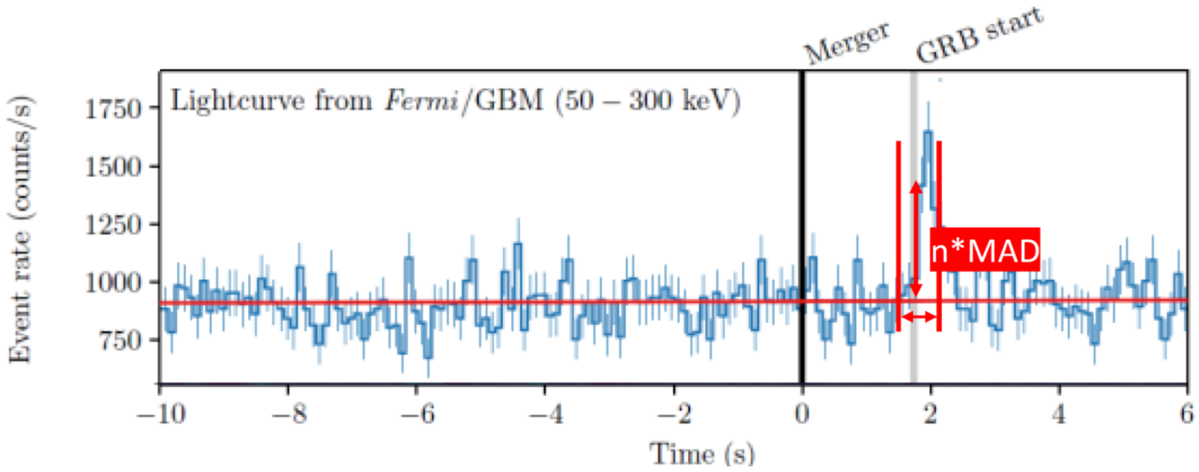


3 classes of trigger masks:

1. **Event acquisition**: validate the acquisition of the event and use the TR1, TR2 and CALO planes
2. **Event monitor:** provide information about the efficiency of the detector
3. **Gamma Ray Burst**: 6 LYSO bars as large as 150x25x50 mm^3 → excellent opportunity to detect MeV photons

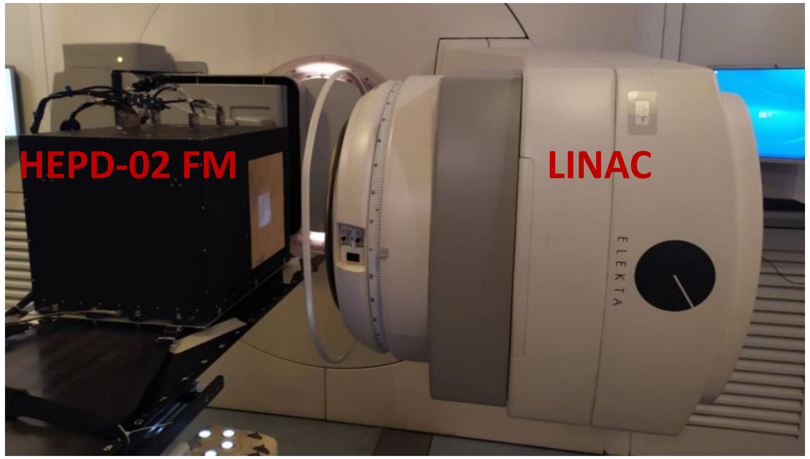
- Trigger configuration dedicated to γ-rays tracked on a time basis of 5 ms
- 2nd level trigger introduced to consider veto
- Moving average and MAD calculated in the DP/CU for GRB trigger rates on different time intervals (10, 40, 160, 360 ms)

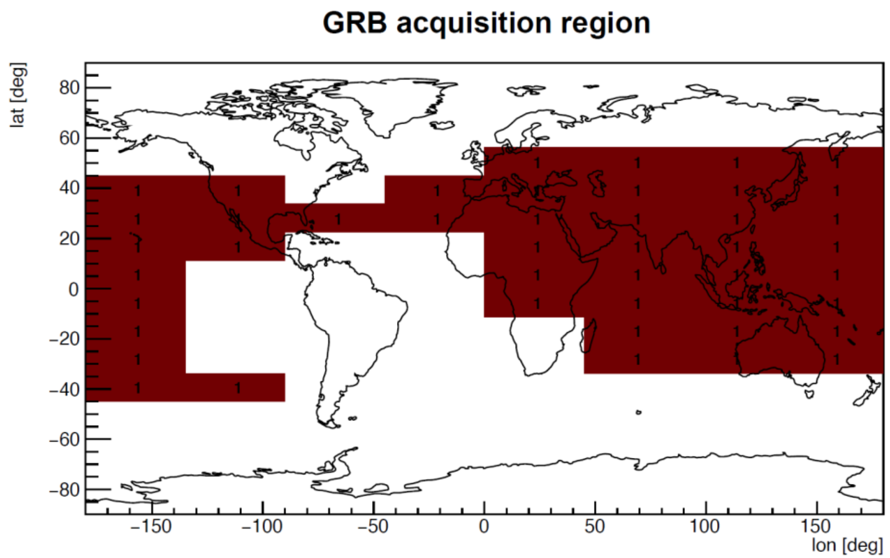


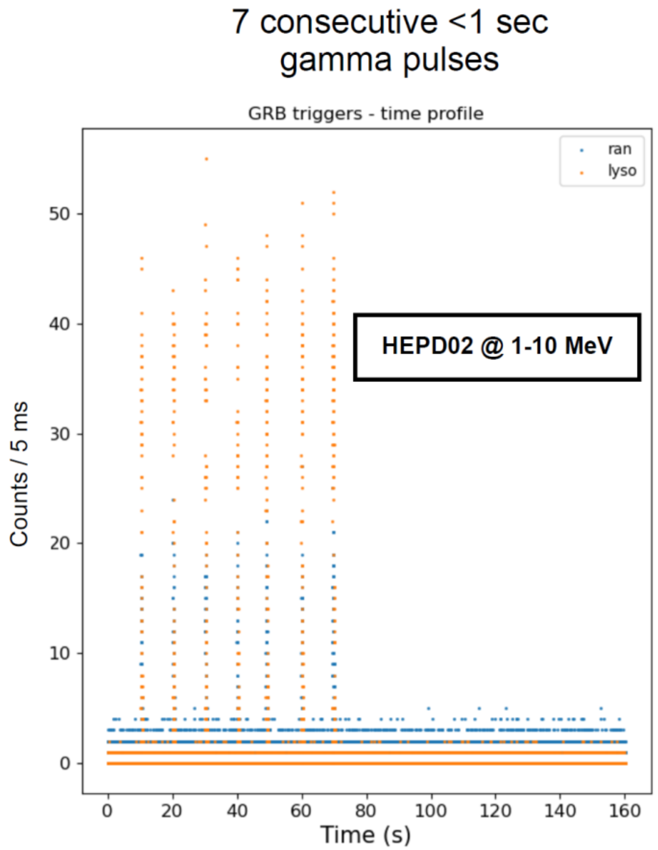


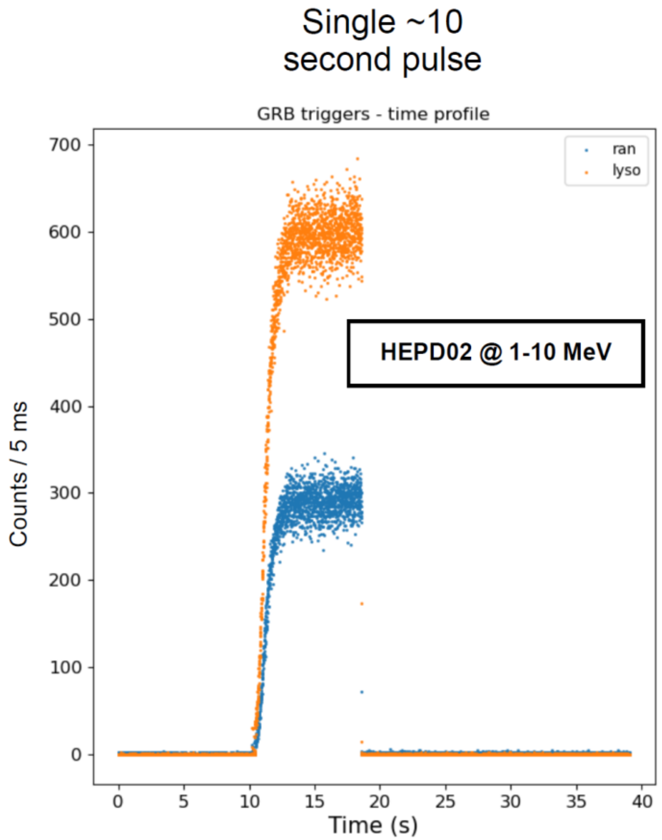
Trigger algorithm test

X-rays (1-10MeV) produced at the S. Chiara LINAC in Trento to test the GRB detection algorithm

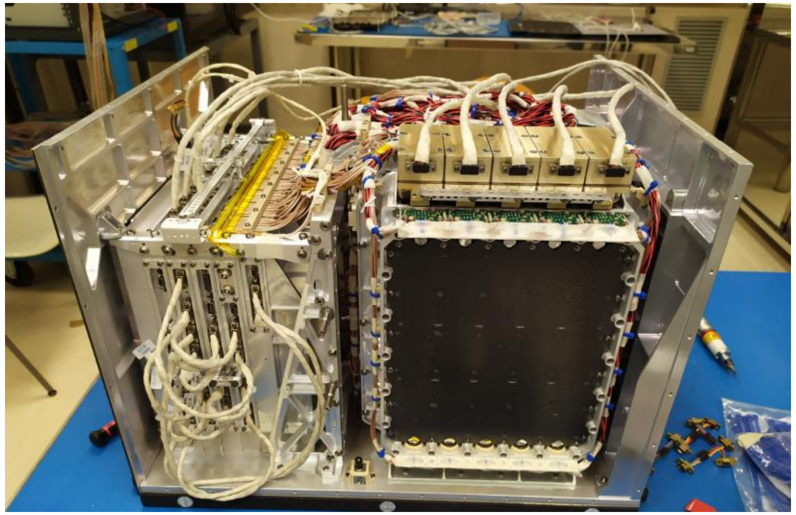








Summary and outlook



HEPD-02 DAQ and trigger:

- Improved instrument flexibility
- Detector operational in regions such as SAA and poles
- Extended scientific significance of the mission
- Concurrent and prescaled triggers:
  - ➢ different masks per orbital zone
  - ➢ GRB detection algorithm

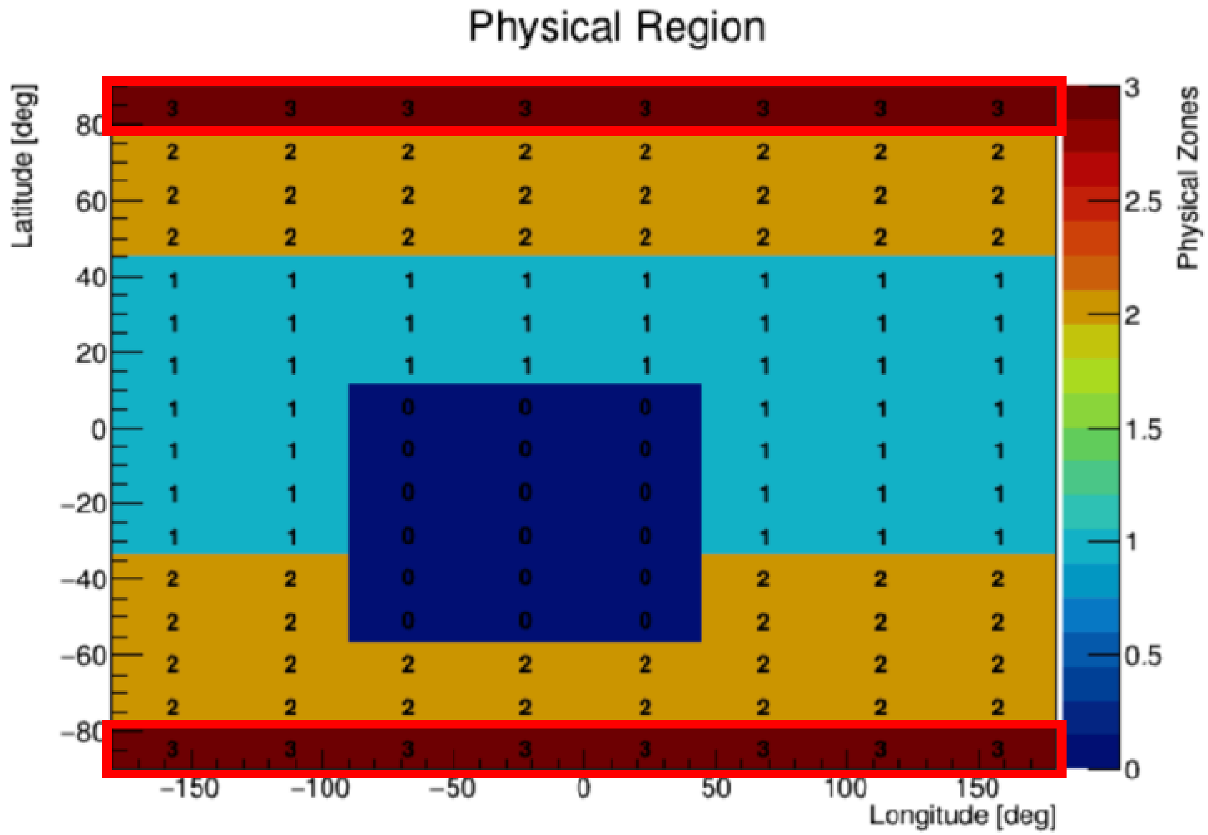
The system has been intensively tested and works as expected

2018-2022	Feb-Jul 2023	Oct 2023	2024
- Instrument concept and design - EM development and test	Thermal-vacuum, vibration, and beam test in Italy	Flight model delivery	Launch


Thank you!

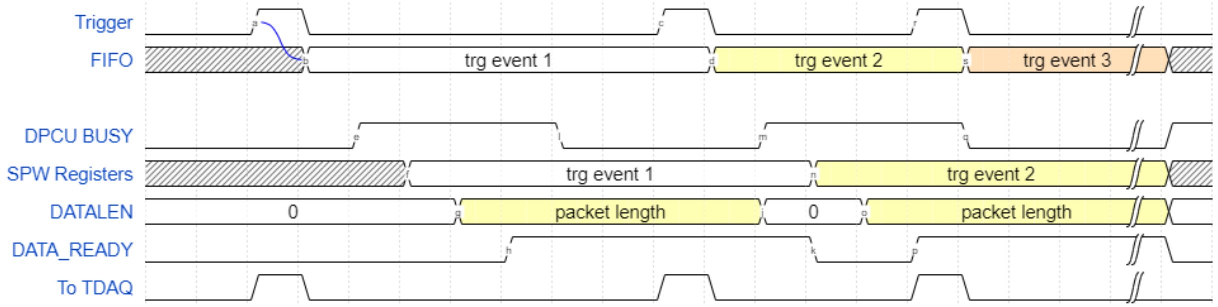
Orbital zones

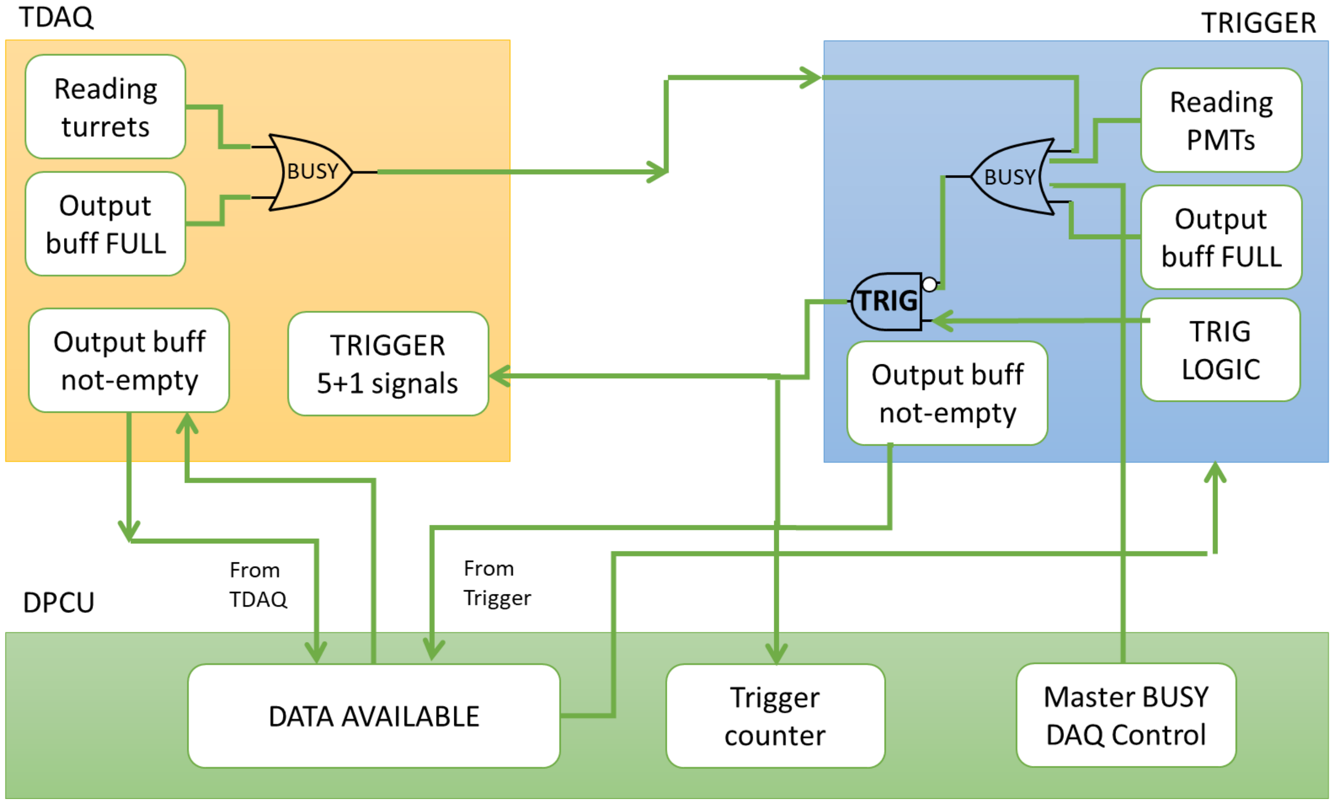
The trigger masks allows to study different physics cases depending on the orbital zone of the satellite. Four orbital zones are defined:



- **SAA**: trapped electrons (dominant at 1MeV) and protons (dominant above)
- **Equatorial**: re entrant and cosmic protons
- **Outer belt**: low energy trapped electrons (below 10MeV)
- **Polar**: primary electrons and protons and heavier nuclei

Communication protocol





- When a trigger occurs, PMT data are stored in a FIFO . The trigger signal is also sent to the TDAQ to start its acquisition
- If the BUSY signal from the DPCU is not asserted, the first packet in the FIFO is written in a series of SpaceWire registers, the total length of the data is stored in a separate register and a DATA_READY signal is asserted by the trigger board
- When the DATA_READY is asserted, the DPCU reads the DATALEN register and starts the reading of all the data registers.
- The DATALEN register is erased by the DPCU
- When the BUSY signal is deasserted, the next packet in the FIFO is moved to SpaceWire registers

Trigger board data

The data packet produced by the trigger board is 240 byte long and is stored in a FIFO that can collect up to 10 packets.

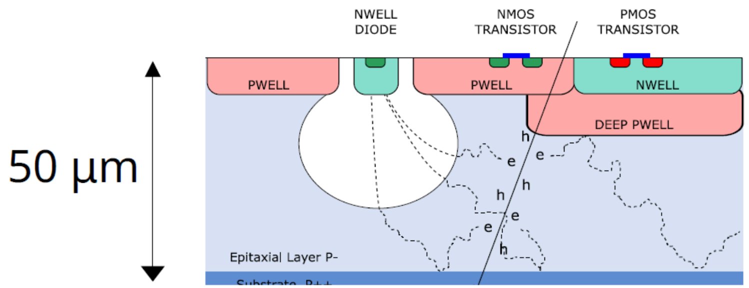
Beside various counters and flags for the reconstruction of the event, the data packet contains the digitized values for the 64 channels of the board.

Since the ADCs use 12 bits for the conversion, the total dimension of the ADC data is:
12 bits x 32 channels x 2 preamplifiers x 2 CITIROCs = 1536 bits 192 bytes

Name	Length (bytes)	Description
Trigger counter	4	Number of events acquired
Timestamp	4	Time from the power-on (16us resolution)
Trigger ID	1	Identificative number for the trigger configuration
ADC data	192	ADC conversion of the two CITIROC's output
Lost trigger	2	Triggers counted during dead time
Alive time	4	Alive time counter (5us resolution)
Dead time	4	Dead time counter (5us resolution)
Trigger flags	8	Flags indicating over-the-treshold channels
Turret flags	1	Flags indicating which tracker turret has been hit
Turret counters	20	Signals counted for each turret
Total	**240**	

The tracker

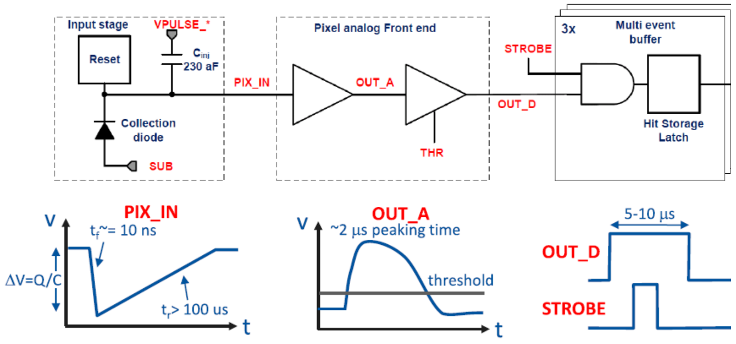
See E. Ricci talk



3 sensitive planes of 5 independent tracking modules MAPS:

- based on the MAPS developed for ALICE experiment at LHC
- ✓ reduces systematic uncertainties on tracking: up to 6x single-hit resolution
- ✓ no multi-hit degeneracy

- Each stave has 10 sensors of 512x1024 pixels in 15x30 mm^2
- Control and read-out based on ultra-thin (180 mm) flexible printed circuits
- Each pixel generates a binary output (hit/no-hit) after a trigger command



Challenges for use in Space:

- Tradeoff for mechanical supports: avoid multiple scattering but withstand launch acceleration and vibrations
- Heat dissipation and material outgassing in vacuum
- Limited power budget

Huge technological effort to spatialize the technology

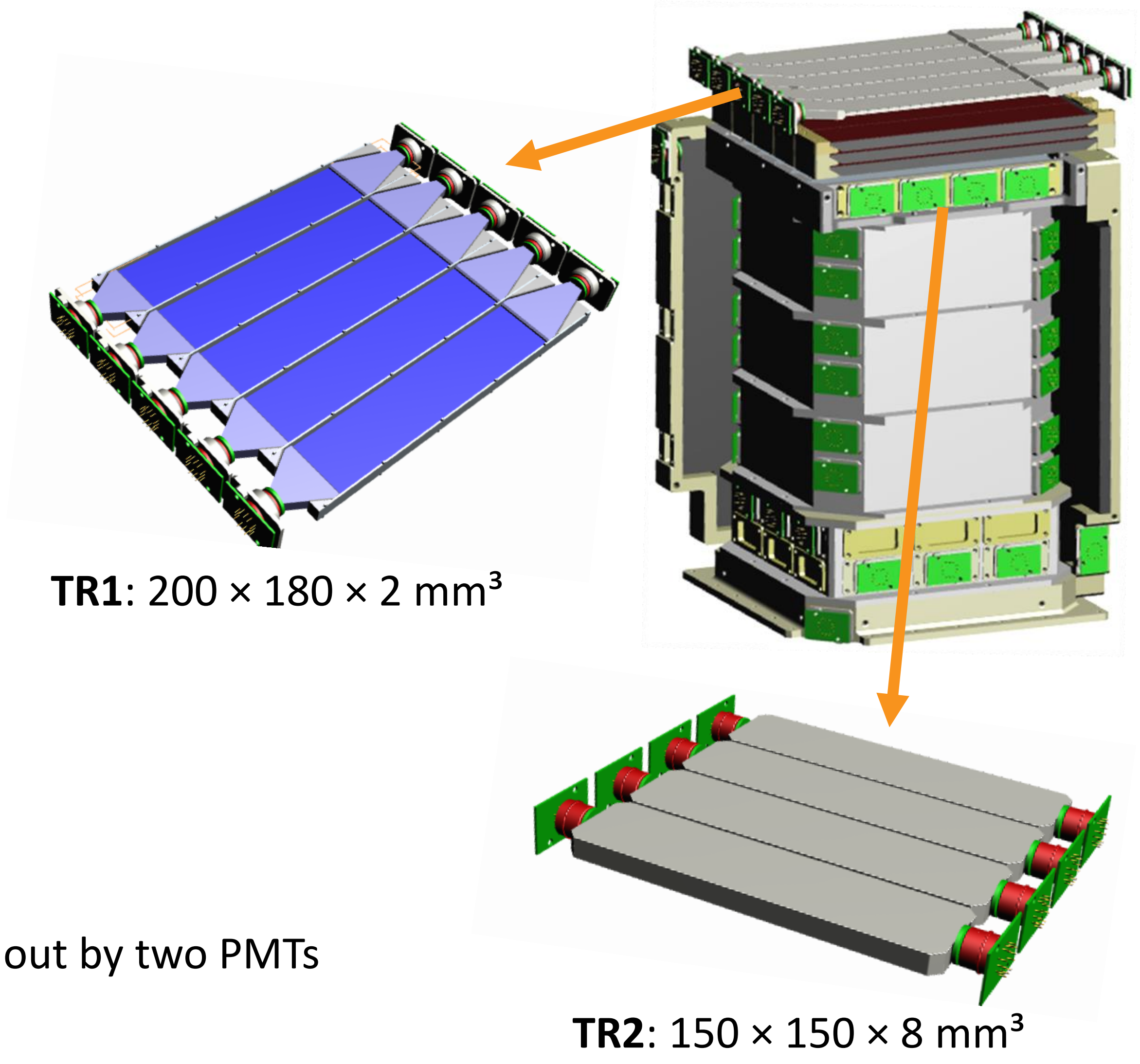
- 15 staves
- 150 MAPS
- 80 Mpixel

The trigger detector

2 crossed layers of scintillator planes EJ-200 enclosing the tracker

TR1:
- segmented into 5 counters read out by light-guides connected to PMTs: to match the tracking modules
- 2 mm thick: to minimize multiple scattering and allow for a low threshold

TR2:
- segmented into 4 8-mm-thick bars: to give a good measure of the energy loss of charged particles

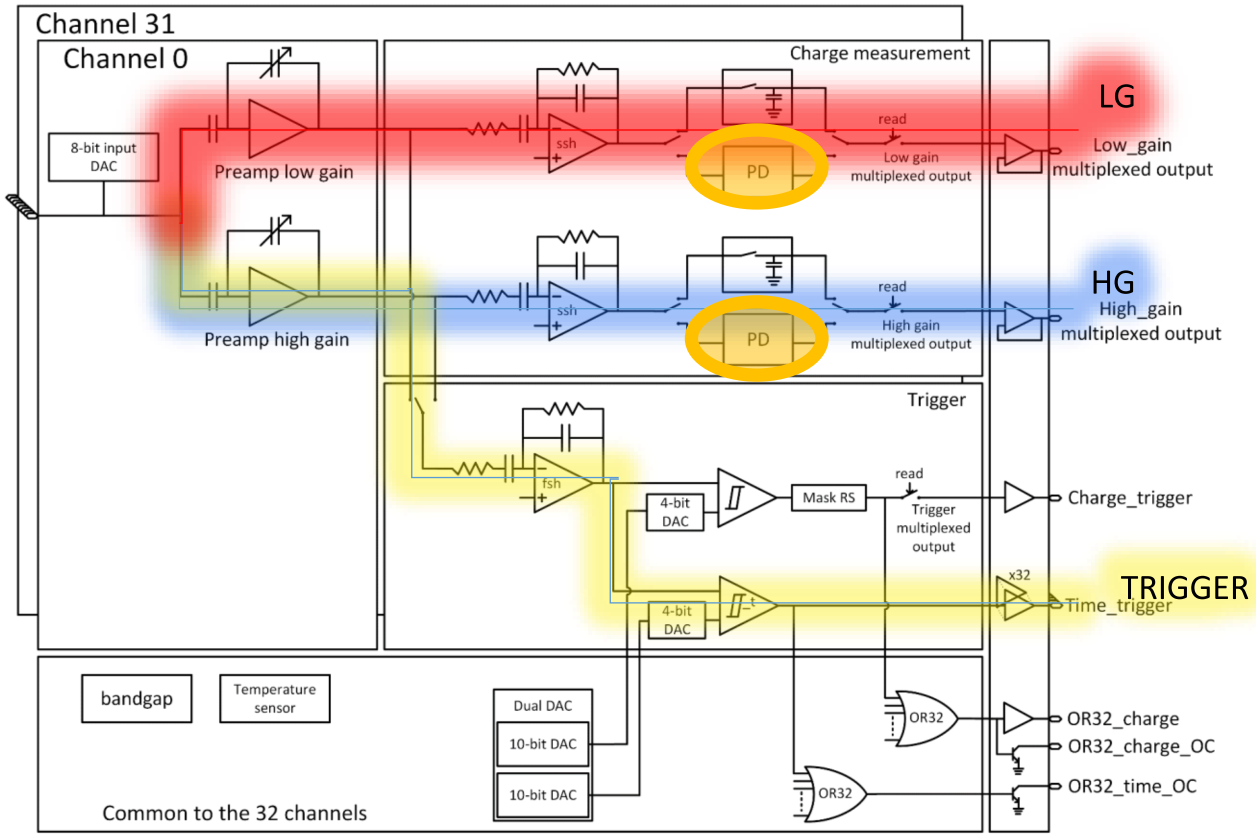


- All counters are covered with a reflective coating and read out by two PMTs

CITIROC ASIC

- low power
- HG&LG charge output: large dynamic range (0.16 – 400 pC)
- fast trigger output with adjustable threshold

- gain adjustment for each channel (6 bits)
- 4 bit to fine-tune the trigger threshold of each channel
- trigger from HG or LG
- peak detection (+ track&hold): γ time spread 10 ÷ 10^2 ns

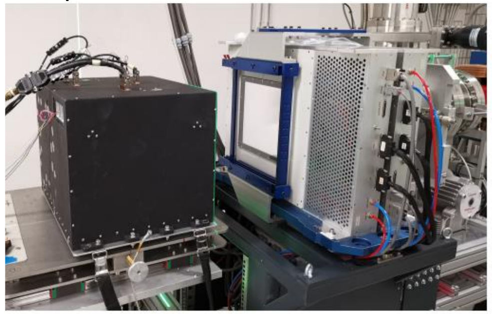


Power consumption = 7 mW/channel

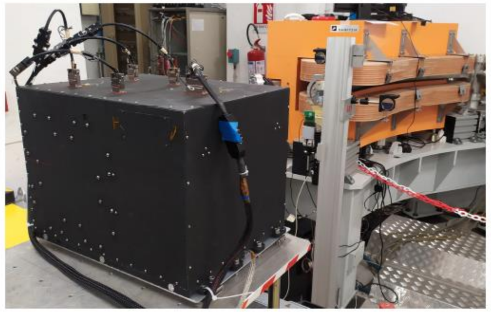
HEPD-02 FM test

- The FM has successfully passed the thermovacuum and electromagnetic compatibility tests.
- Electron, proton and nuclei beam test in a wide range of energies to study the detector response to different particles

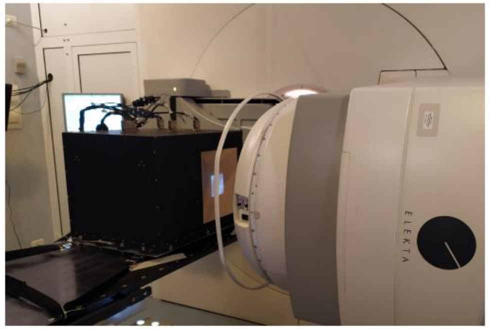
C/p @ CNAO Dec 2022 - Jan 2023



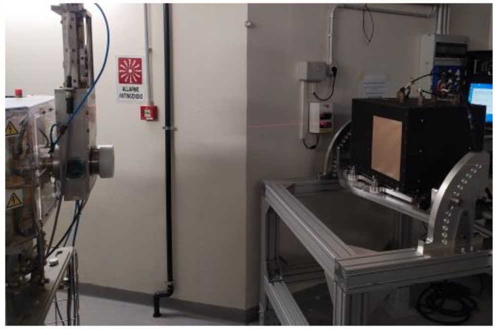
e- (>30 MeV) @ BTF Apr-Jul 2023

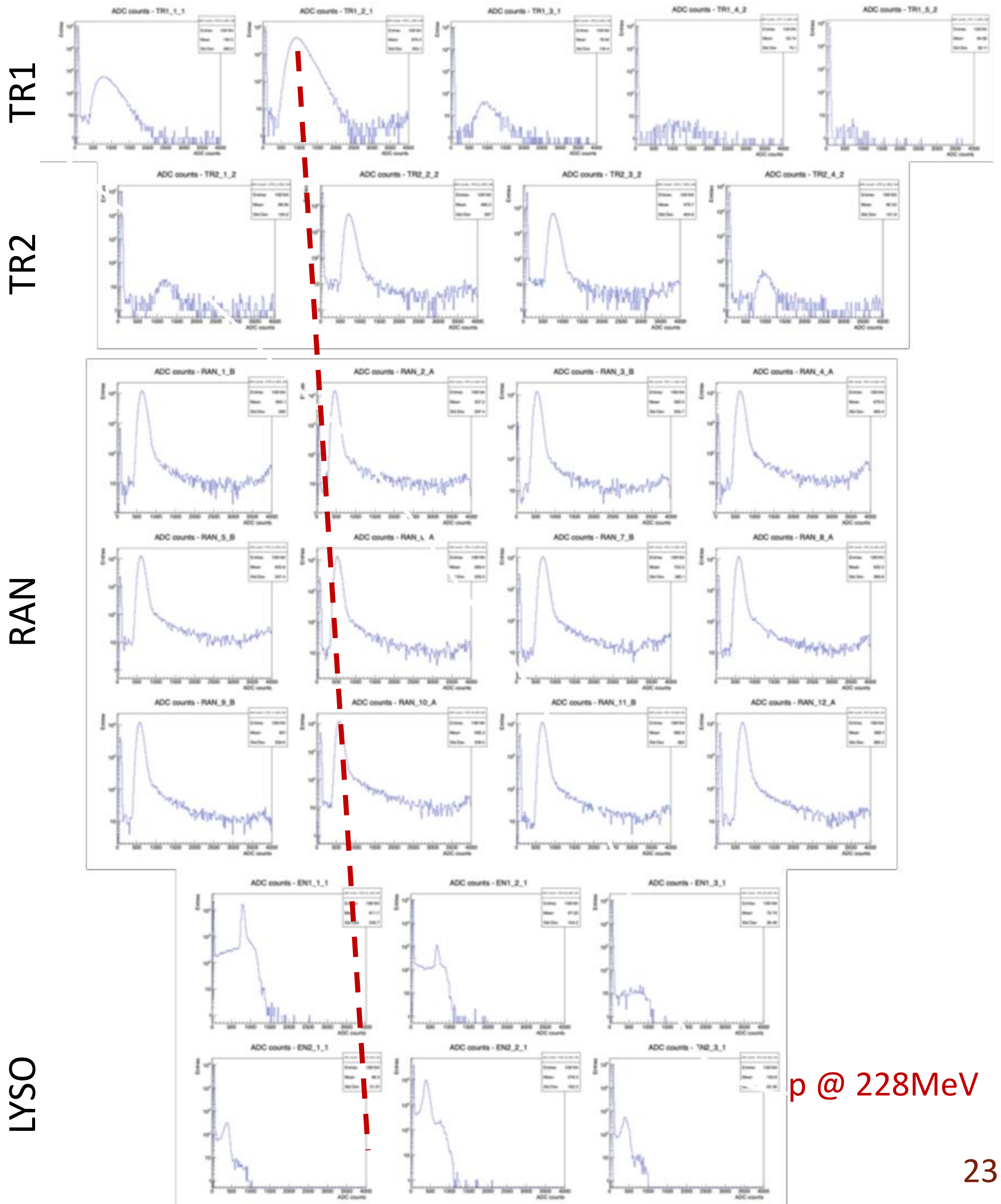


e- (6-12 MeV)/gamma @ Trento Jun 2023



p @ APSS Jun 2023

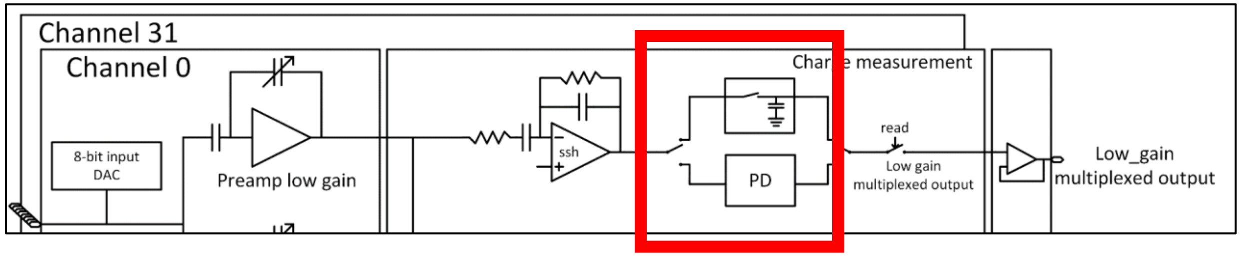




Peak Detector Vs Track&Hold mode

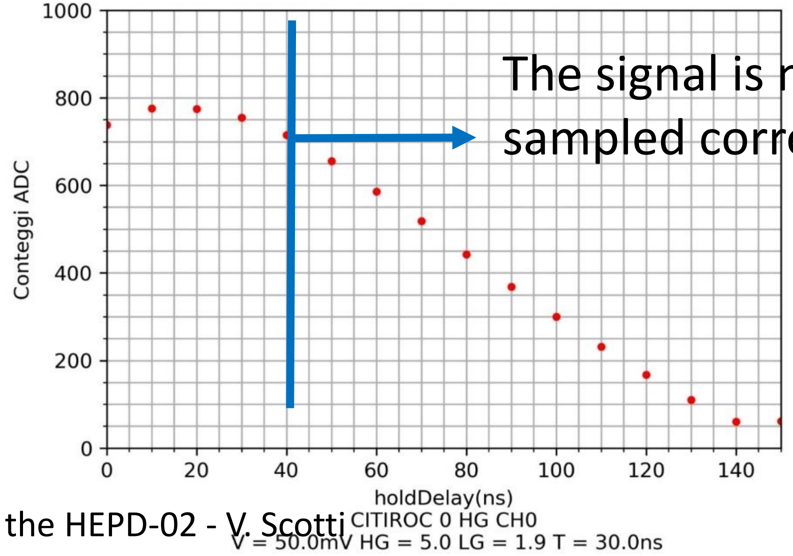
Longer acquisition window needed to acquire LYSO signals correctly

Peak Detector mode: suggested when incident γ come with a delay from channel to channel or if γ are spread in time in a single channel



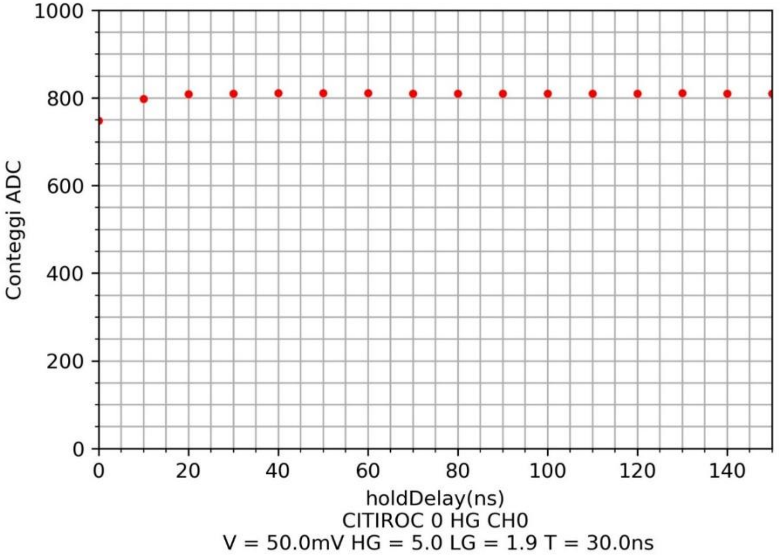
Test with different **hold** delays

Track&Hold

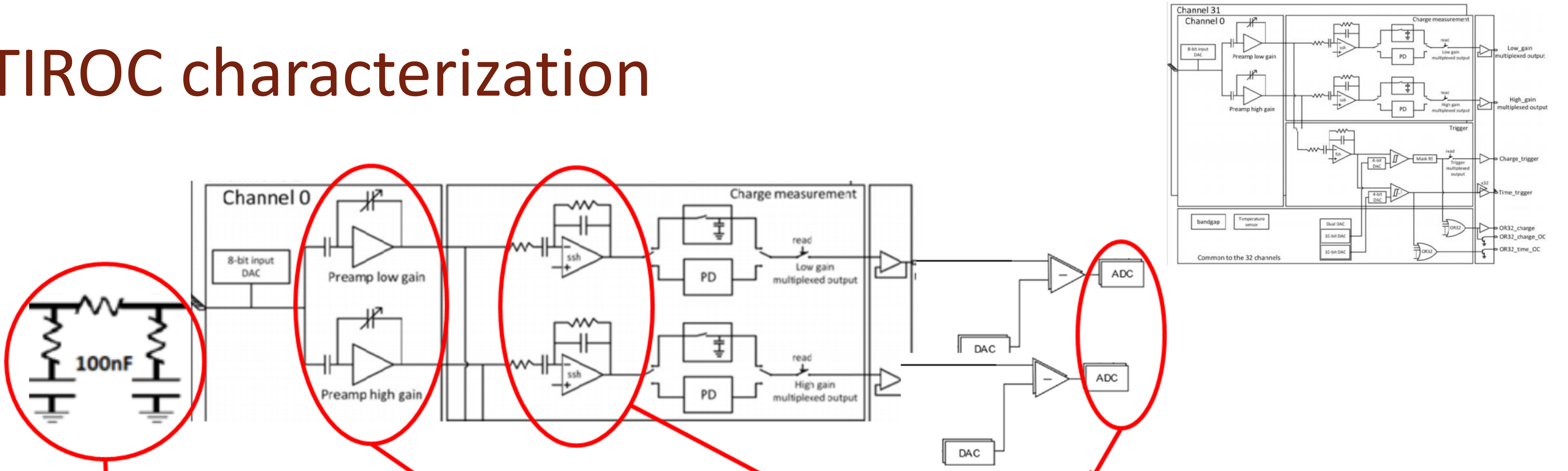


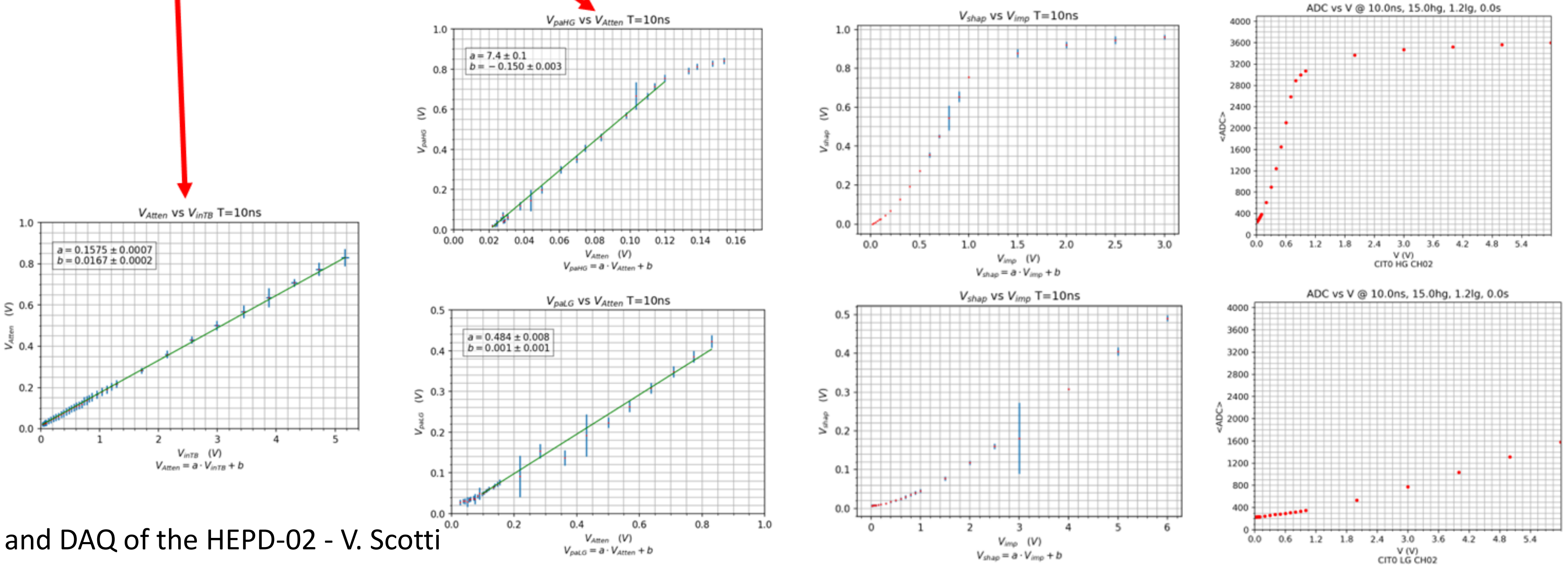
The signal is not sampled correctly

Peak Detector

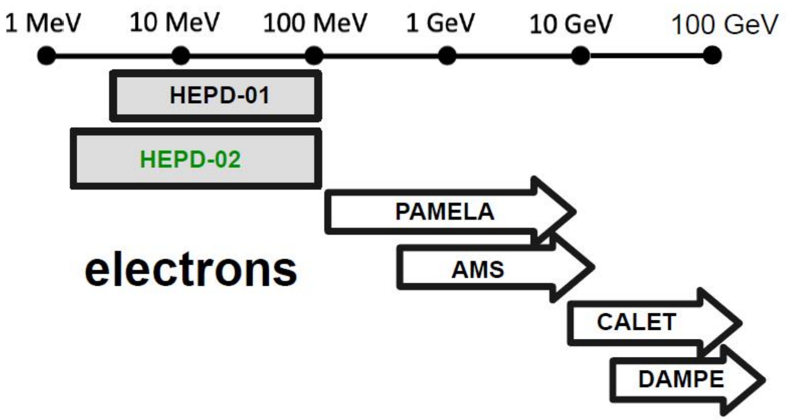


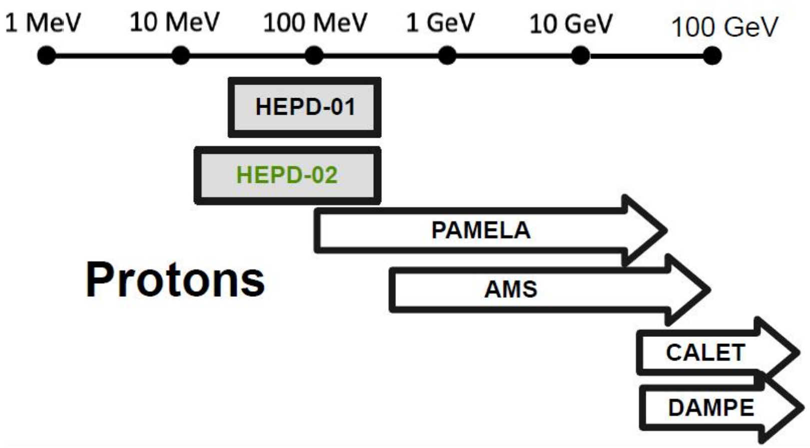
CITIROC characterization



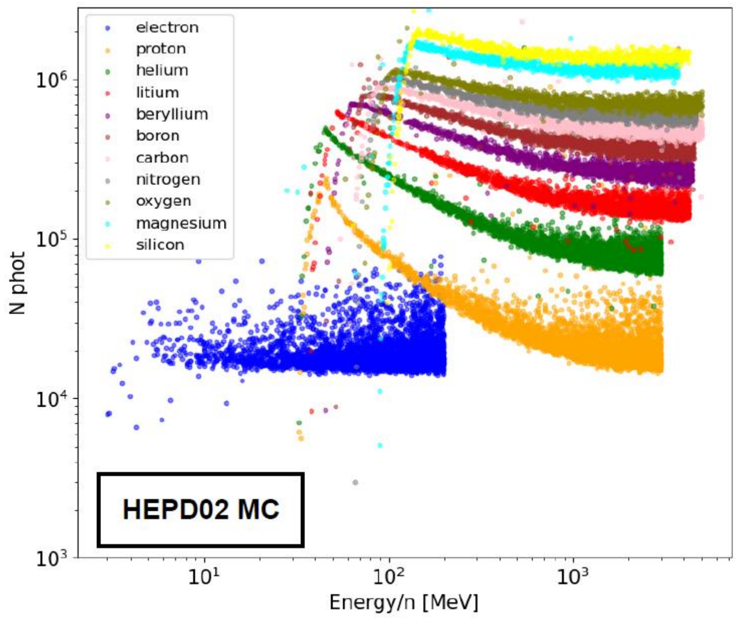


HEPD-02 physics





Nuclei



Sensitivity to Gamma Ray Burst