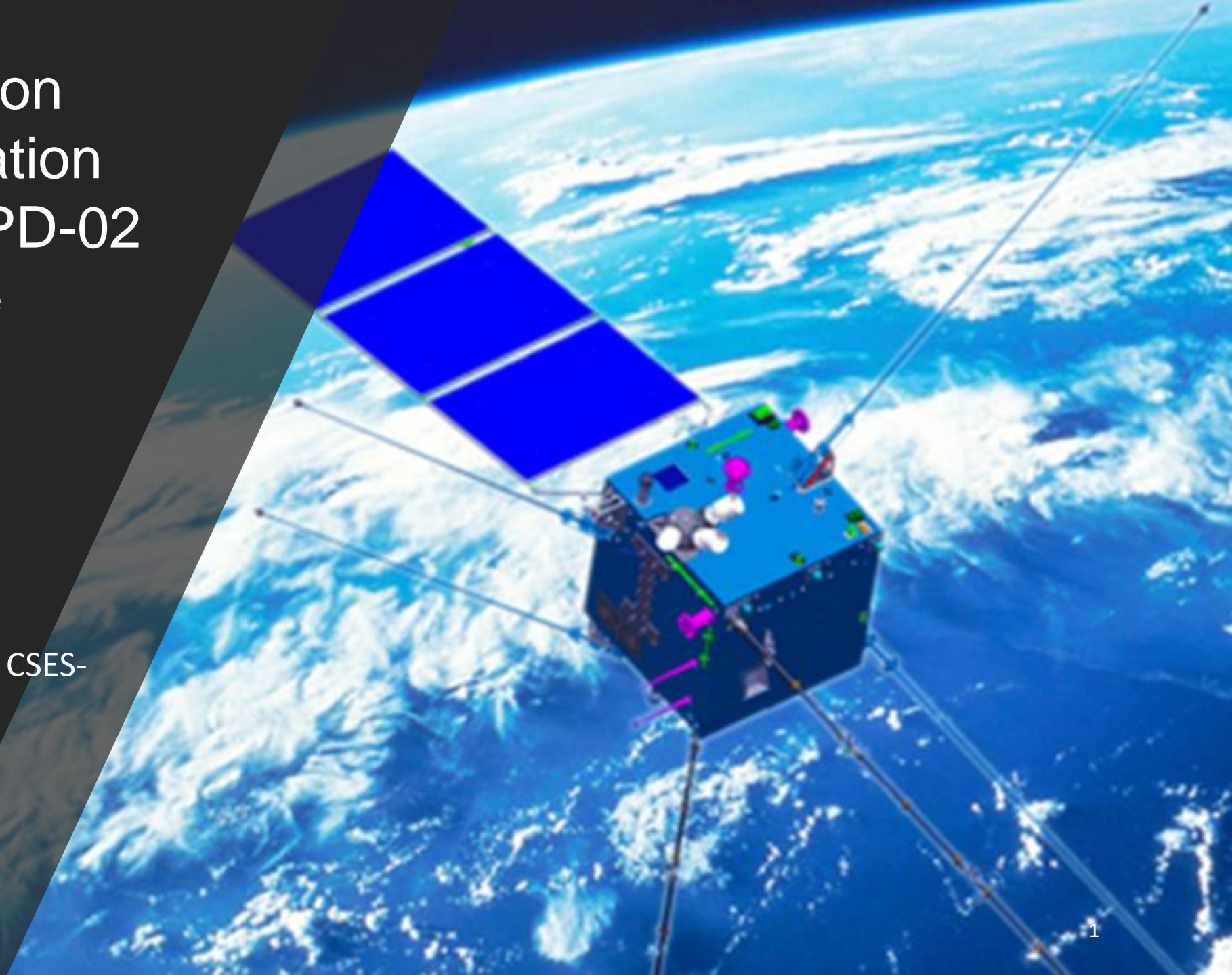


The PMT acquisition and trigger generation system of the HEPD-02 calorimeter for the CSES-02 satellite

Marco Mese^{1,2} on behalf of the CSES-Limadou collaboration

- 1) University of Naples Federico II
- 2) INFN – Section of Naples

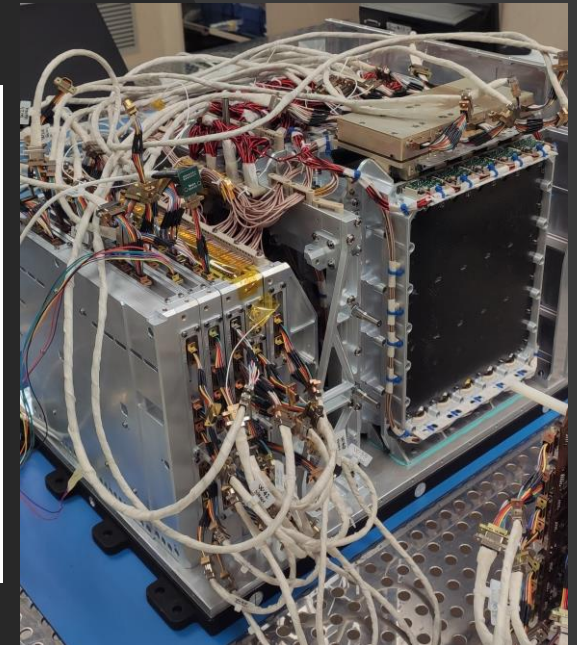
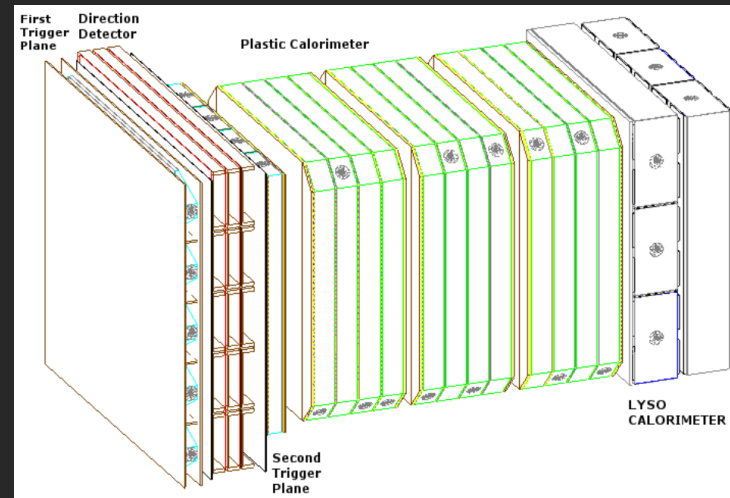
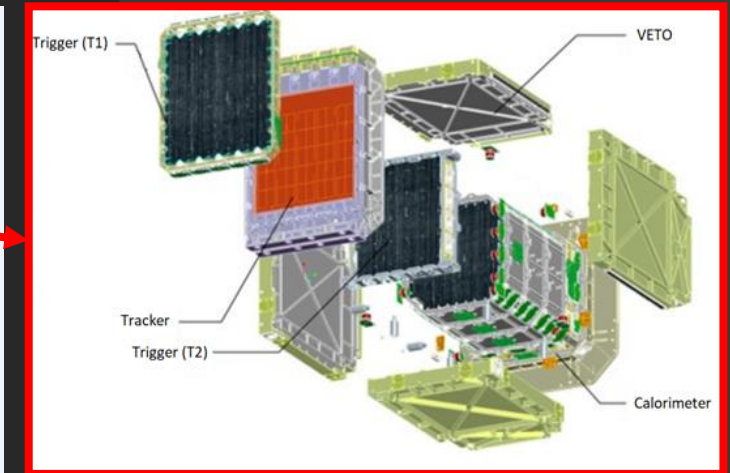
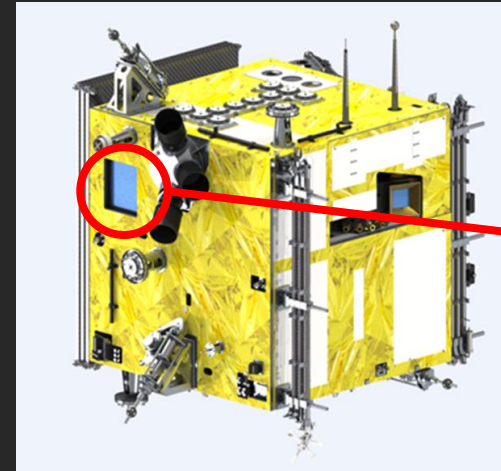


The HEPD-02 detector

The HEPD-02 will detect **electrons and protons** with kinetic energies that go from **3 to 100 MeV for electrons** and from **30 to 200 MeV for protons** (specifications).

The detector will be composed by:

- An 80 megapixel **tracker** made of MAP sensors (ALTAI sensors)
- A **trigger system** realized by 2 segmented planes of plastic scintillator (EJ-200) surrounding the tracker:
 - The **first plane (T1)** is made by 5 segments
 - The **second plane (T2)** is made by 4 segments placed orthogonally with respect of T1
- A range **calorimeter** composed by:
 - 12 planes of plastic scintillator
 - 2 segmented planes of inorganic scintillator (LYSO) used to extend the energetic range of the detector
- A **VETO** system realized by five scintillator planes that surround the entire detector



Each scintillator is coupled with two PMTs for a total of 64 PMTs.

Readout and trigger system

The board acquires signals from the PMTs and produces the trigger signal for the experiment is based on CITIROCs readout integrated circuits by Weeroc and on Microsemi A3PE3000L FPGA.

The board is divided in two identical sections for redundancy.

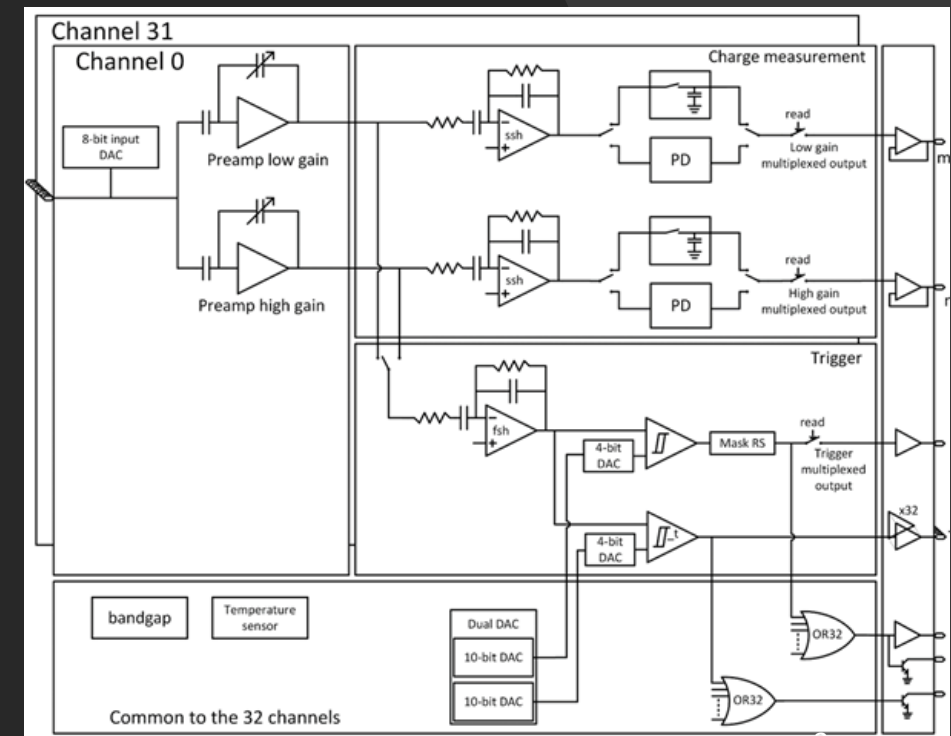
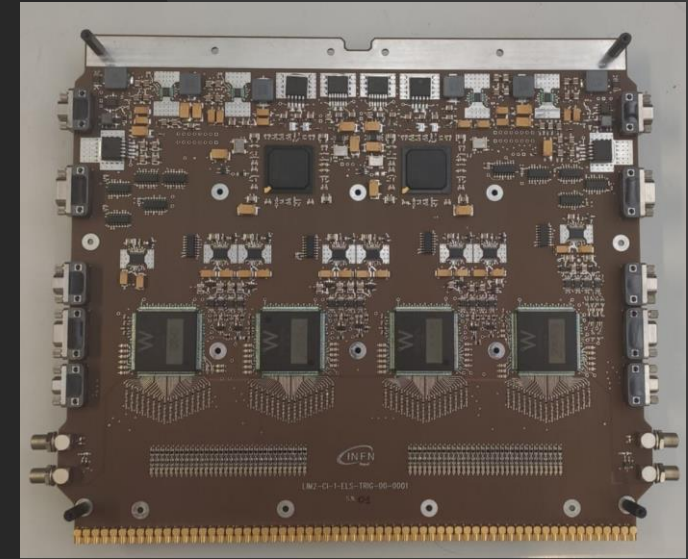
CITIROCs have 2 independent preamplifiers:

- the **High Gain** preamplifier can be configured with gain from 10 to 600
- the **Low Gain** with gain from 1 to 60

This ensures a wide dynamical range, required for the acquisition of signals from different scintillators, produced by particles in a wide energy range.

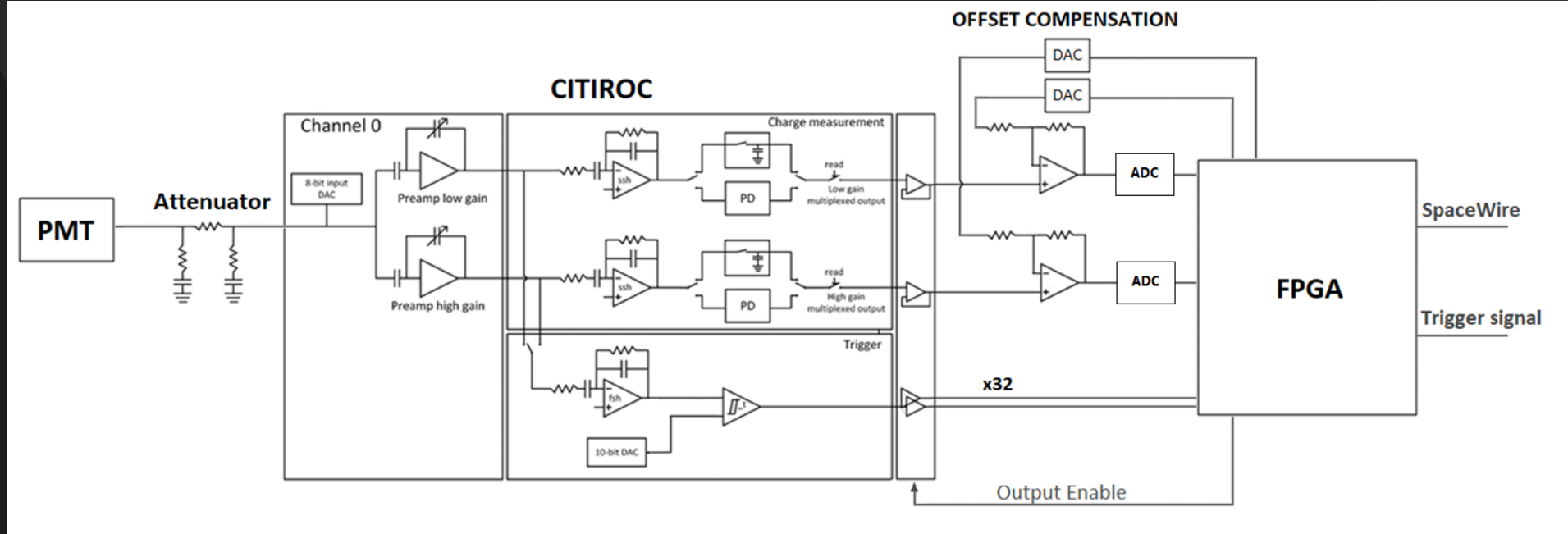
Each preamplifier is connected to a configurable **shaper** and an analog memory (Track&Hold or **Peak Detector**).

Trigger signals for the 32 channels are generated by a fast shaper and a discriminator with configurable **threshold**



Readout and trigger system

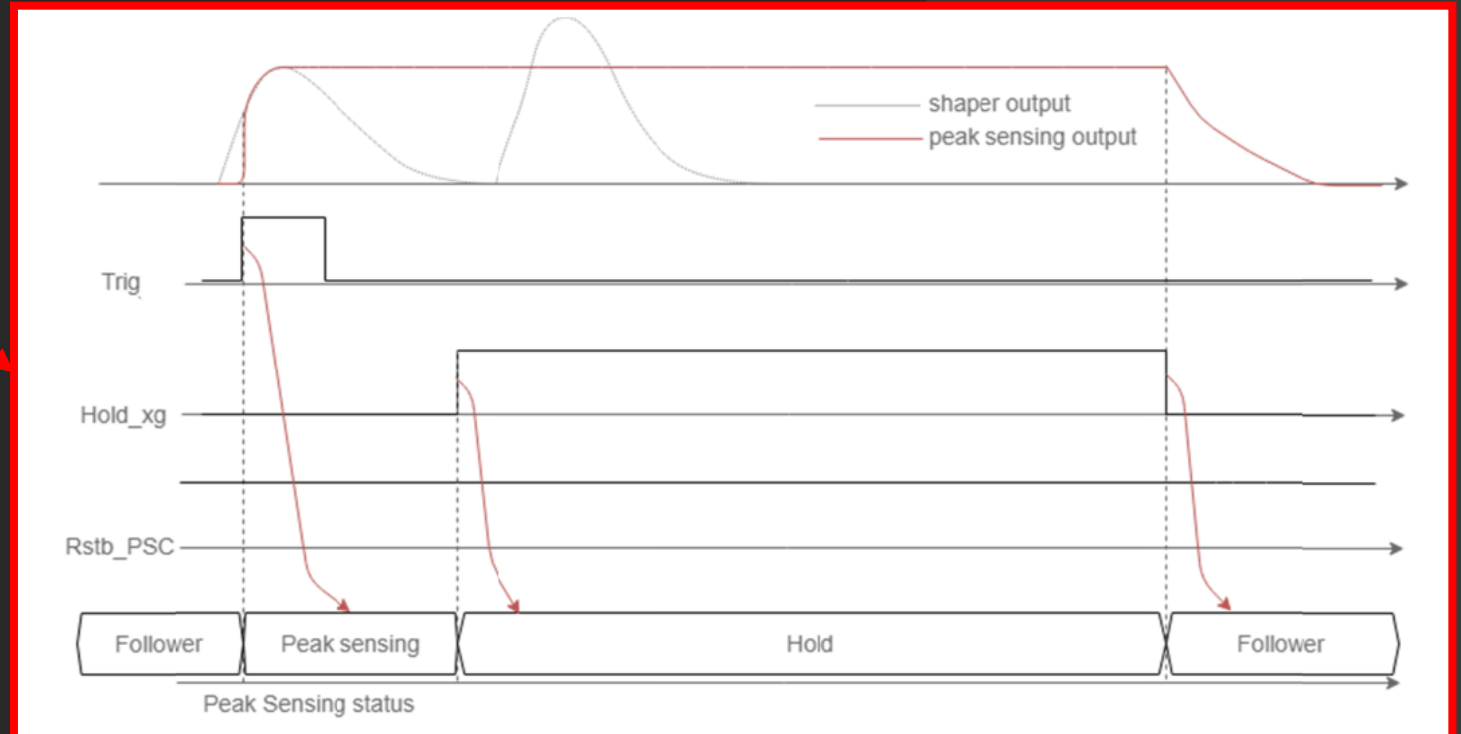
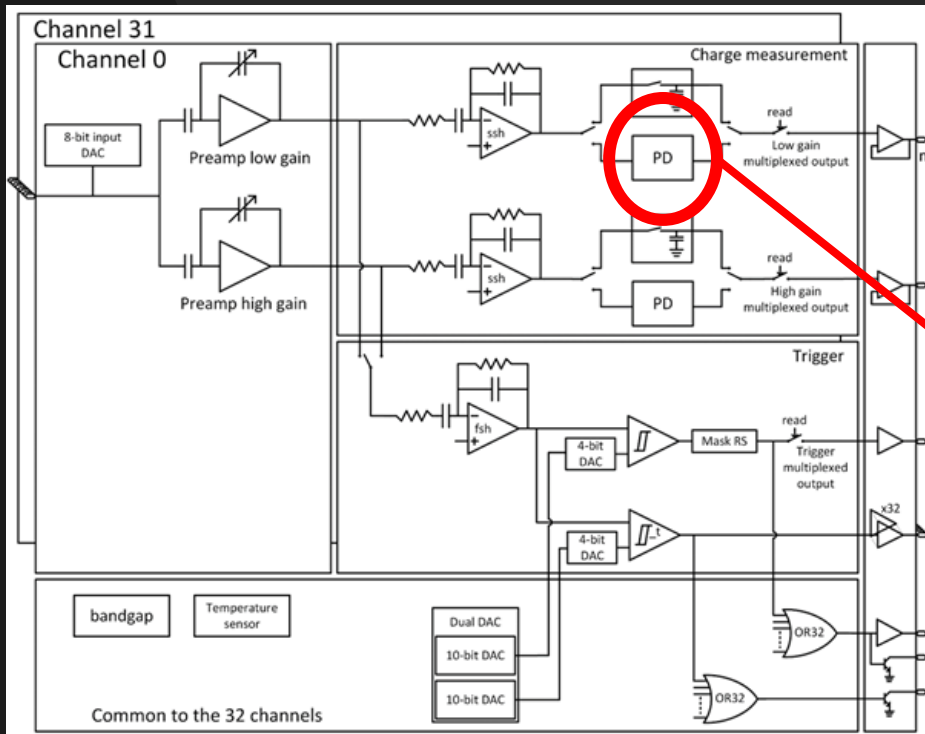
The board operation is described in the following schematic



- Signals from the last dynode of the PMT are **attenuated** in order to match the CITIROCs input range
- CITIROCs **amplify, shape and sample** photomultiplier signals and produce a **trigger** for each PMT
- Trigger signals produced by CITIROCs are acquired by an **FPGA** that implement various logic conditions, called **trigger masks**, that produce the **global trigger** signal
- The FPGA enables CITIROCs outputs and starts the ADC conversion

The FPGA also configures the CITIROCs and communicates with the other subsystems of the detector.

Peak Detector



The trigger board uses the **Peak Detector** circuit provided by CITIROC which allows to correctly sample the signals, even in presence of delays between the various channels.

To use the peak detector it is necessary that the peak-sensing window is opened before the peak produced by the shaper. This leads to constraints in the timing of the trigger signals that will be shown shortly.

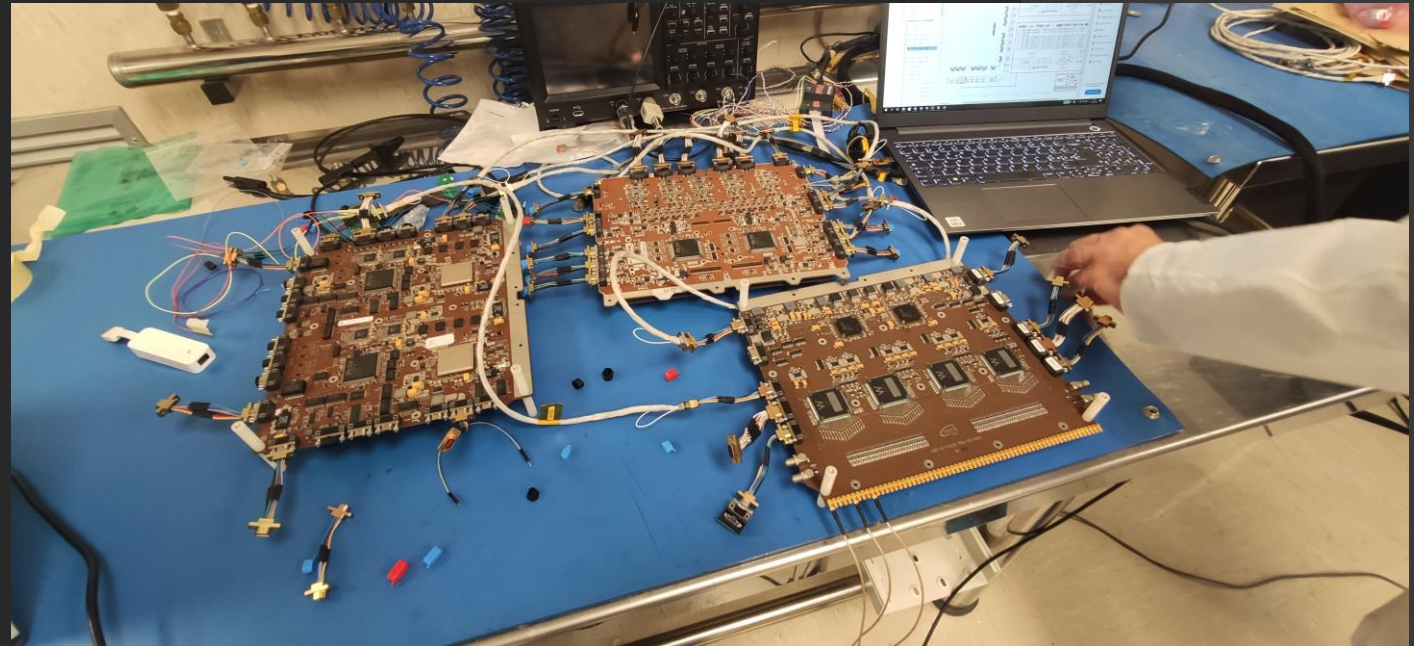
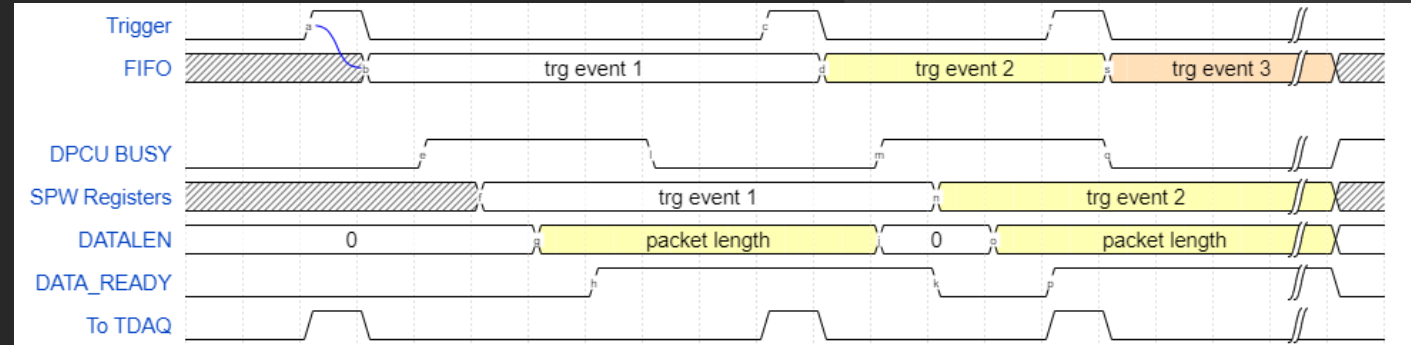
Boards interwork

The trigger board interfaces with:

- **TDAQ** board: that acquire data from tracker.
- **DPCU** board: that collects data from the TDAQ and the trigger board and communicate with ground.

The protocol, developed in collaboration with TDAQ and DPCU groups, is based on SpaceWire register-based communication and can be described as follows:

- When a trigger occurs, the **data produced** by the trigger board are **stored in a FIFO**. The trigger signal is also sent to the TDAQ to start its acquisition



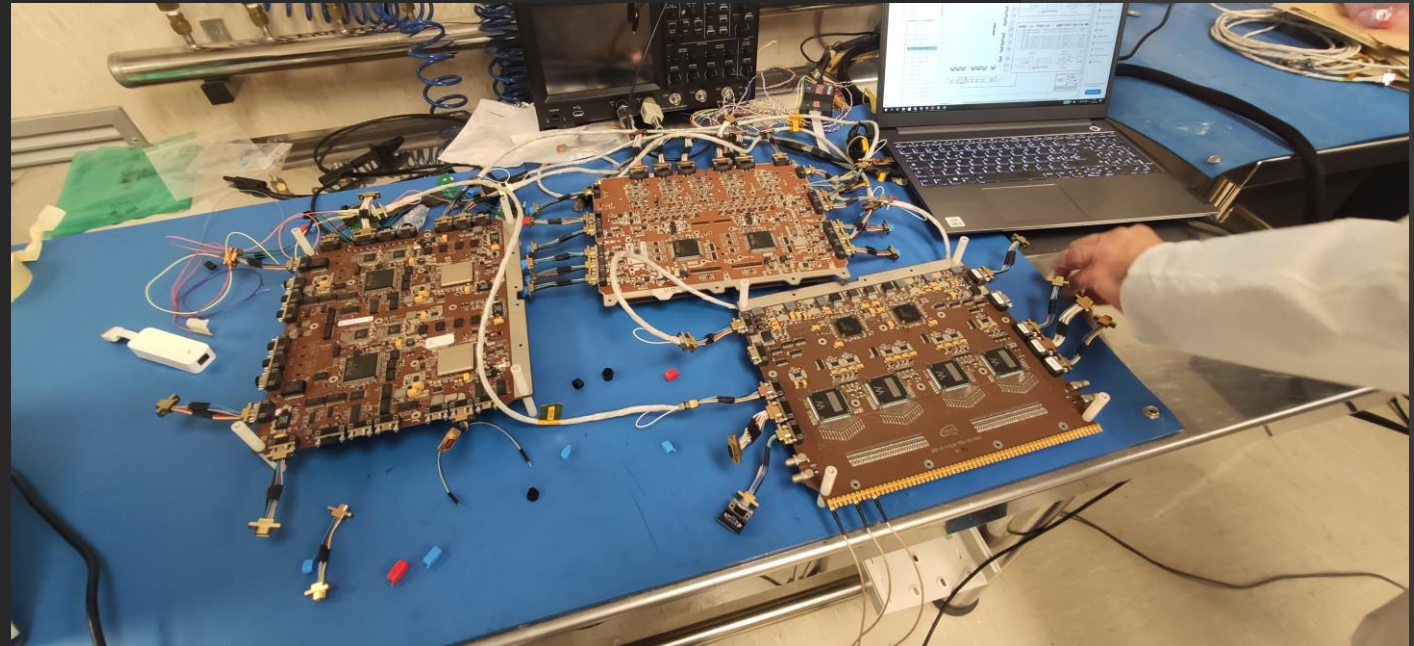
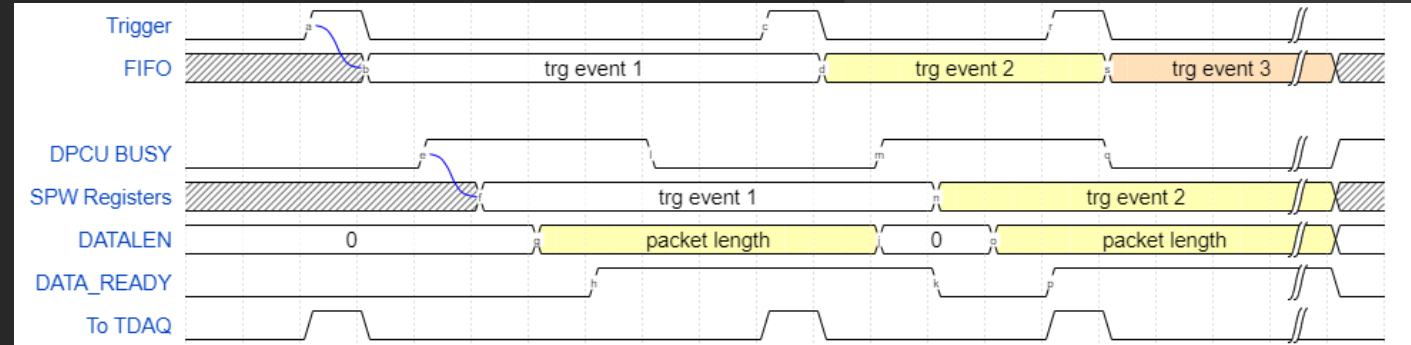
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- If the **BUSY** signal from the DPCU is not asserted, the first packet in the FIFO is written in a series of **SpaceWire registers**.



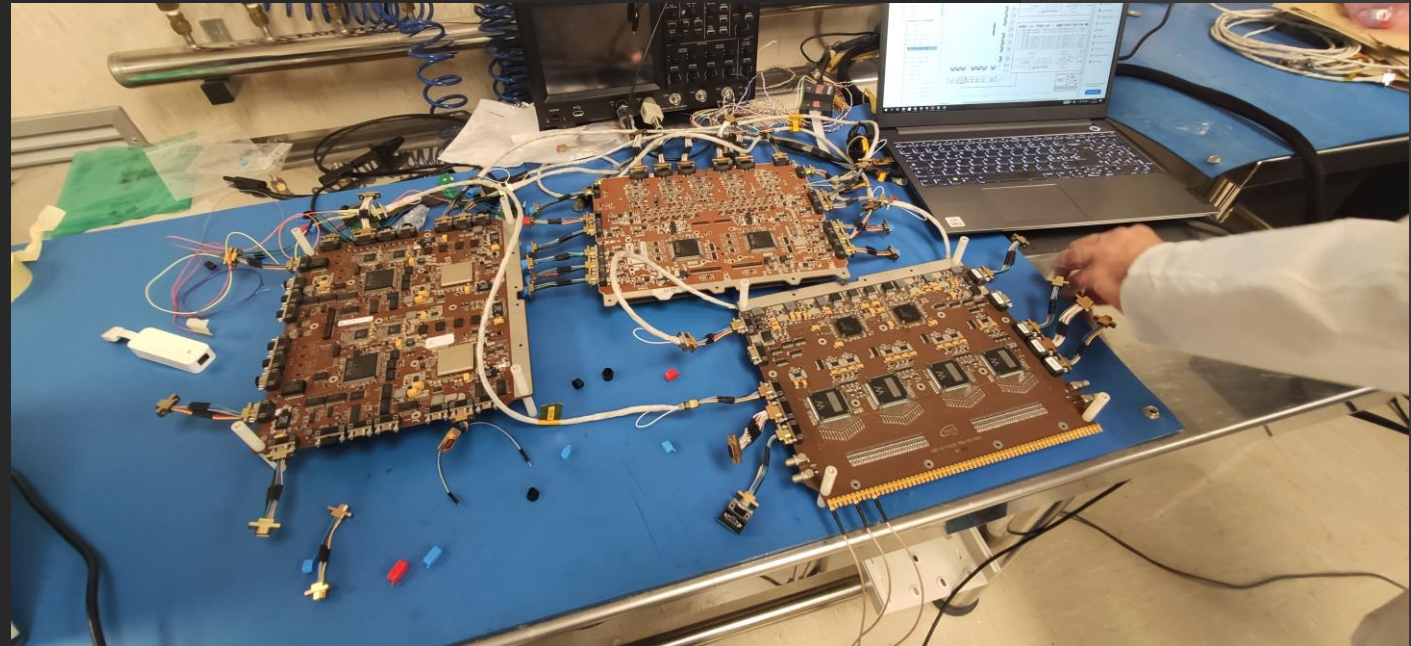
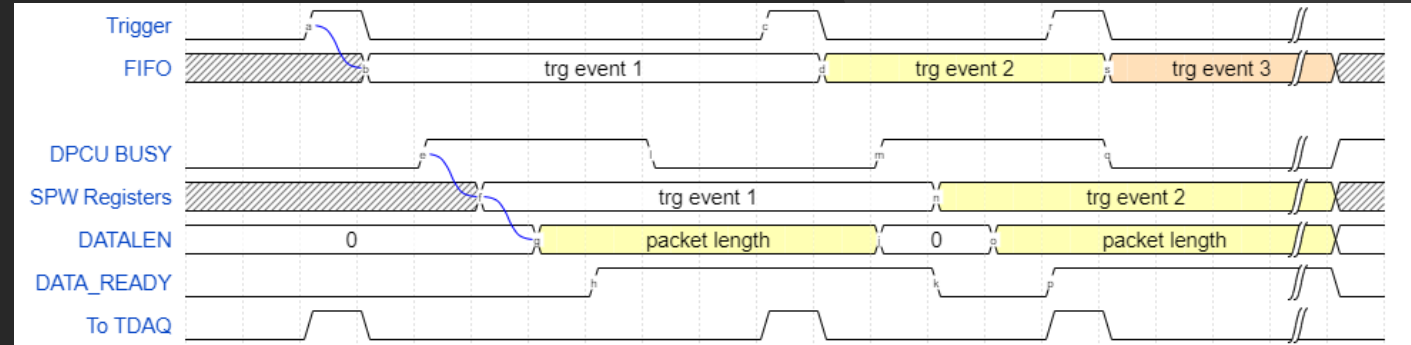
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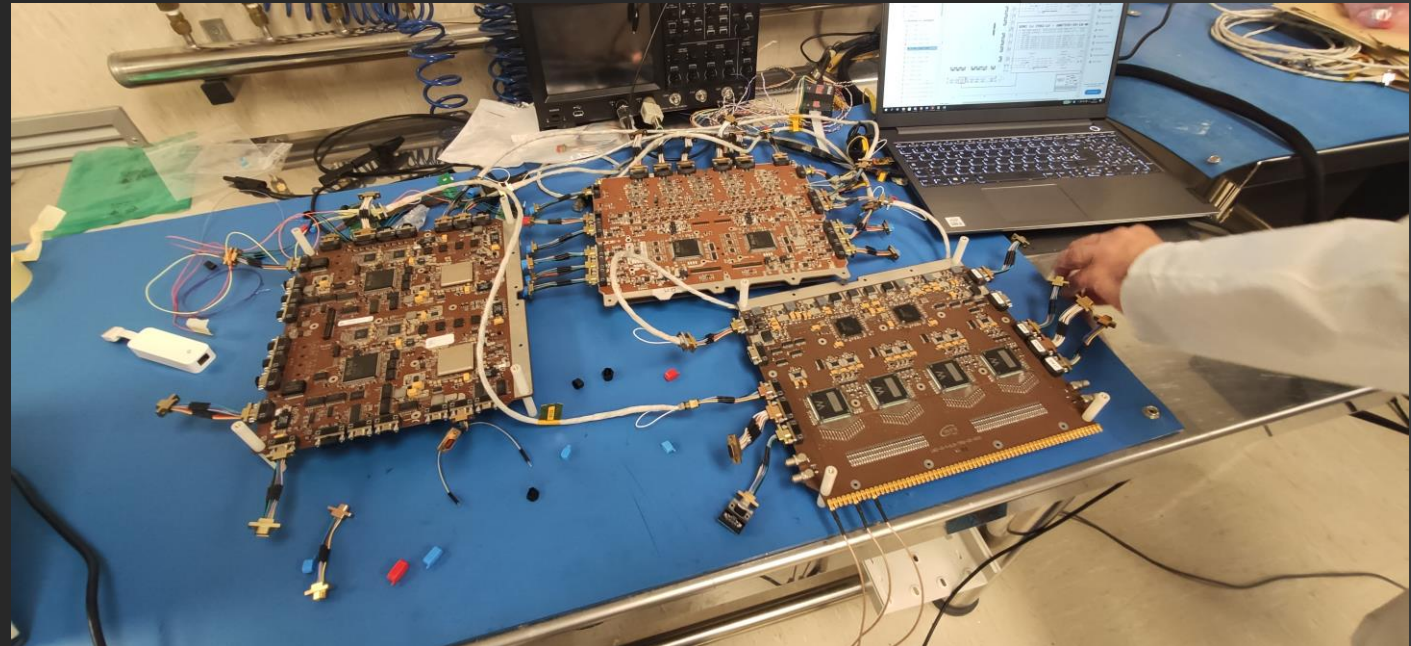
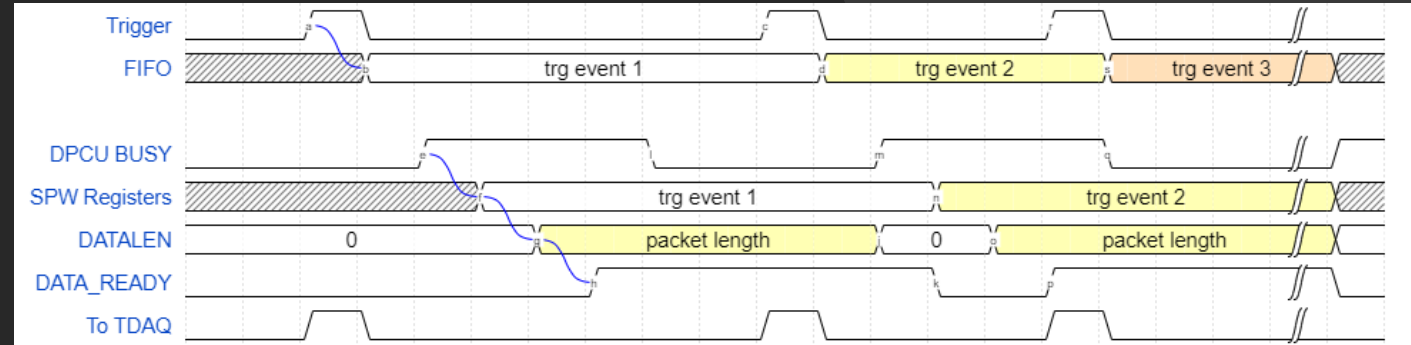
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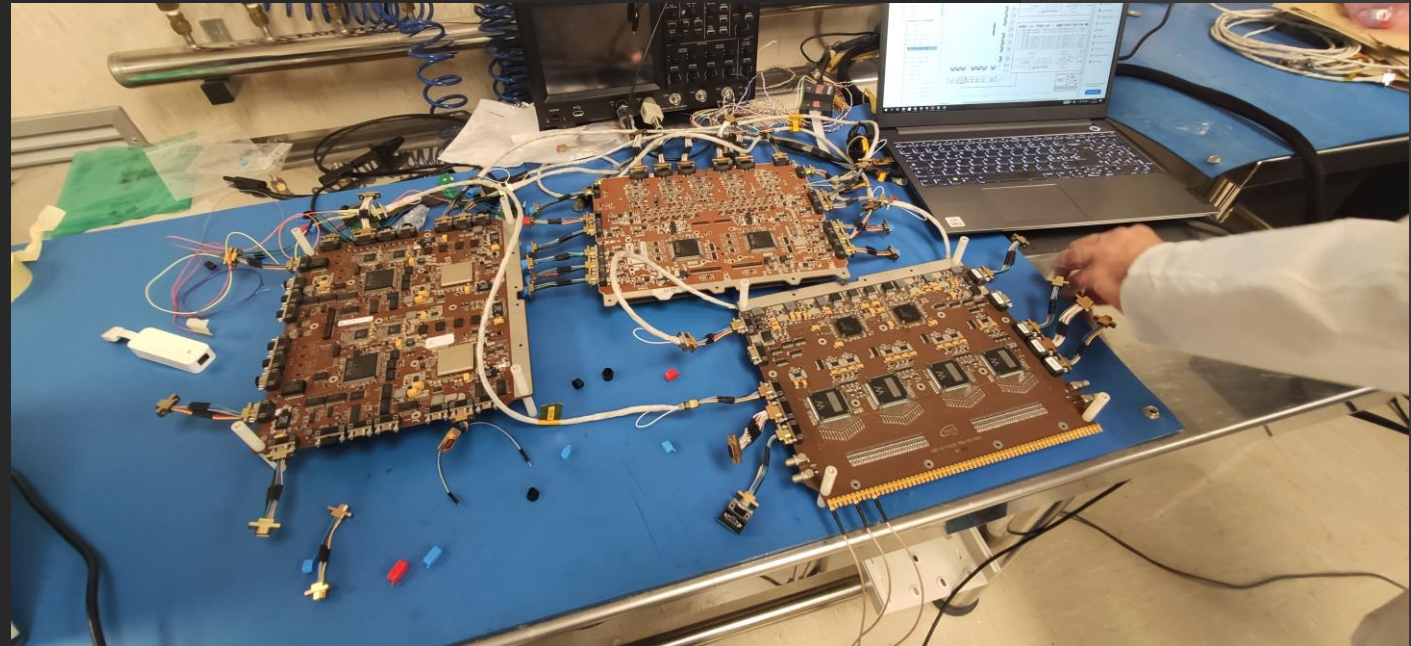
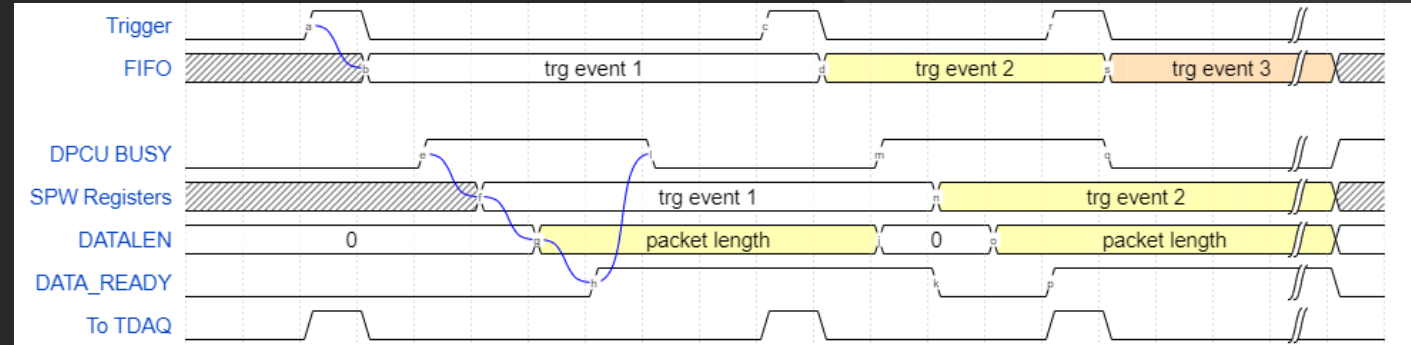
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- When the DATA_READY is asserted, the DPCU reads the DATALEN register and **starts the reading** of all the data registers.



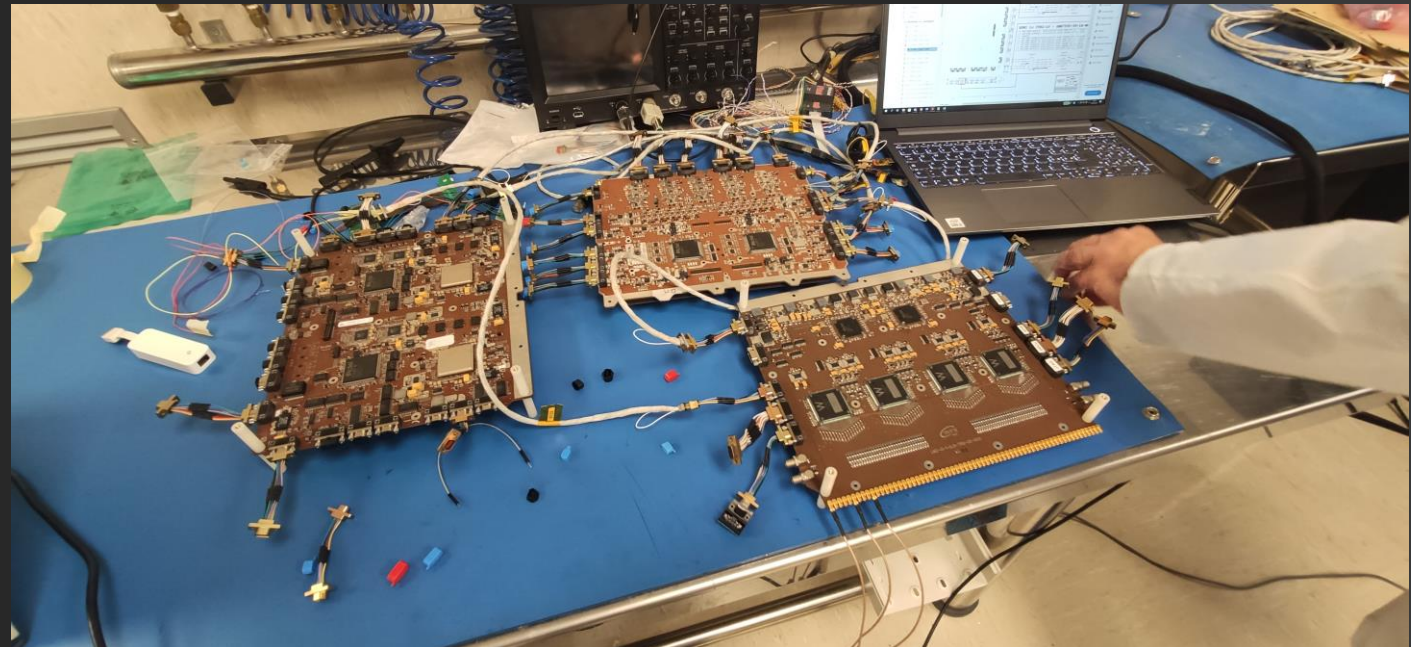
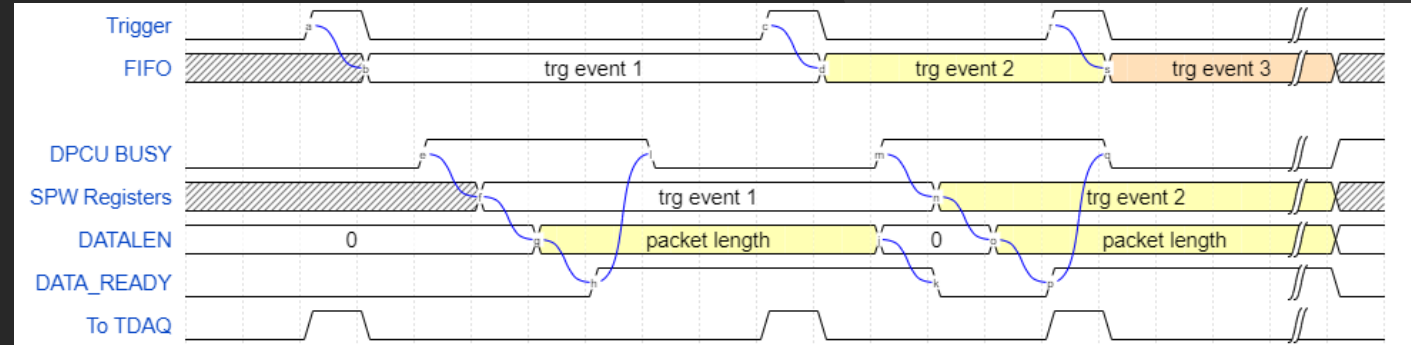
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- When the DATA_READY is asserted, the DPCU reads the DATALEN register and **starts the reading** of all the data registers.
- The DATALEN register is **erased** by the DPCU.
- When the BUSY signal is deasserted, the next packet in the FIFO is moved to SpaceWire registers.



Trigger board event 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:

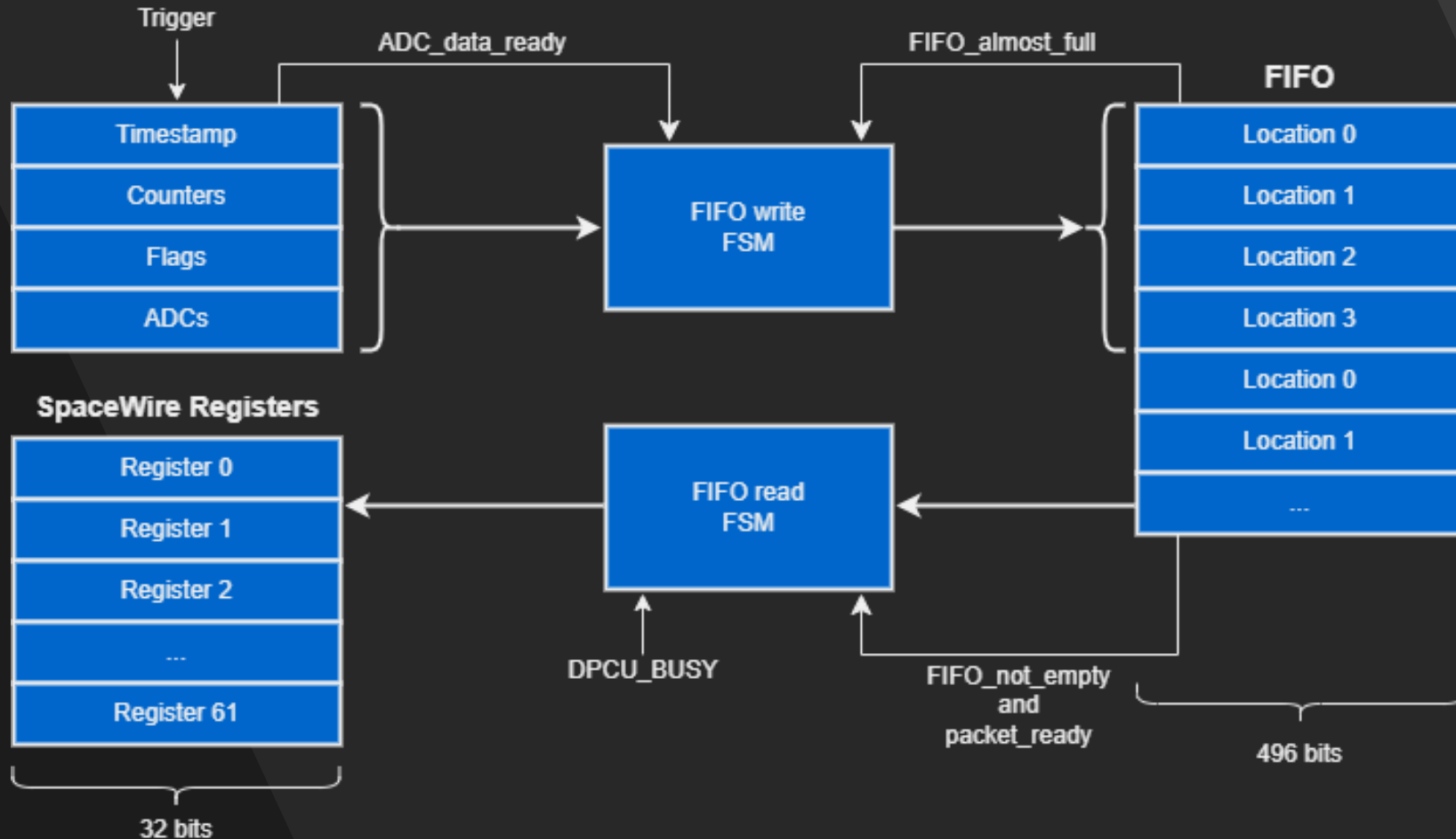
12 bits x 32 channels x 2 preamplifiers x 2 CITIROCs = 1536 bits (192 bytes)

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-threshold channels
Turret flags	1	Flags indicating which tracker turret has been hit
Turret counters	20	Signals counted for each turret
Total	240	

Trigger board event data

Since the FIFO width is limited to 496 bits, the data packet must be divided in 4 locations.

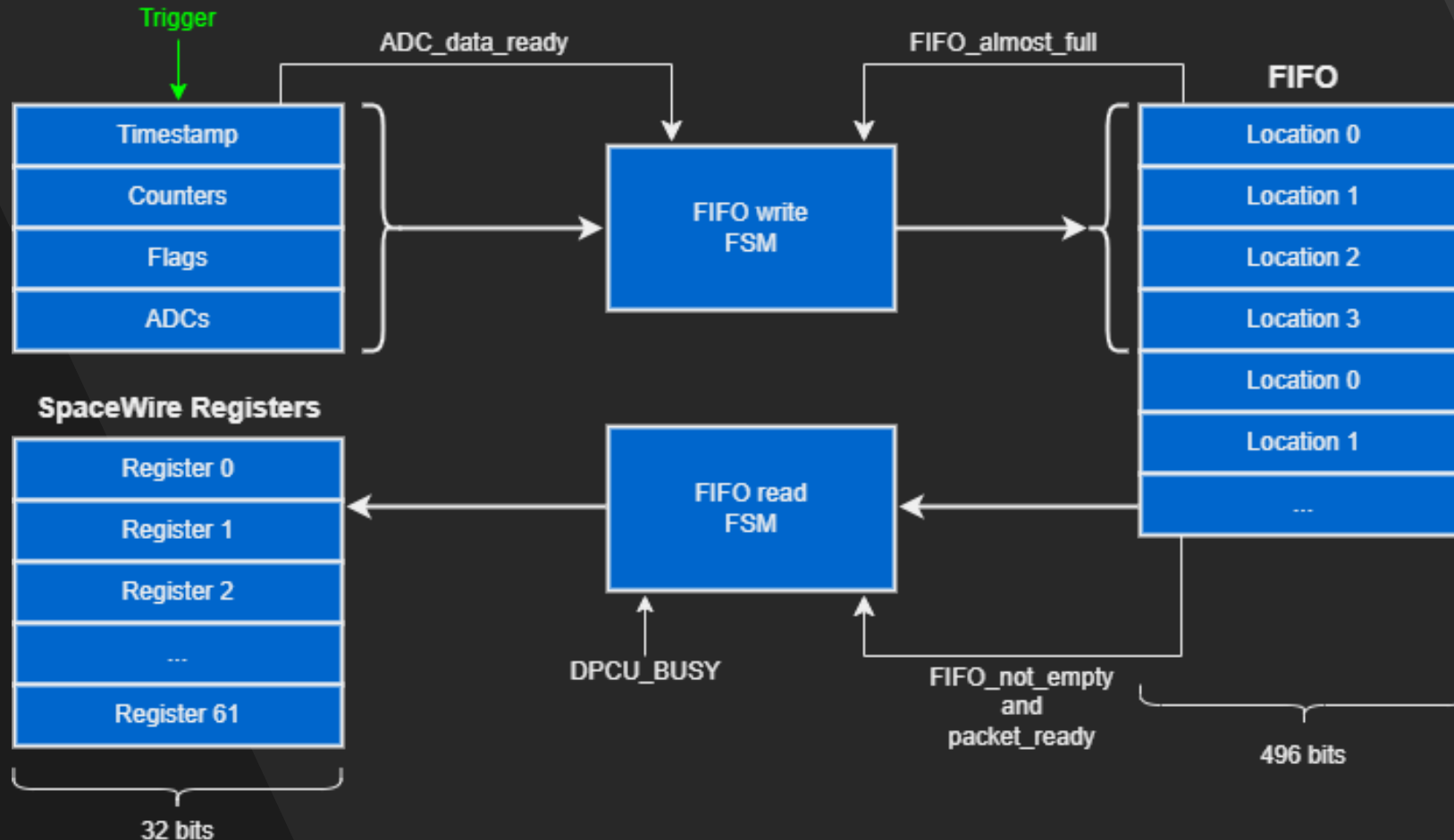
An FSM is dedicated to write each packet in these locations and another FSM reads the data from FIFO and transfers it to 62 SpaceWire registers (32 bits wide).



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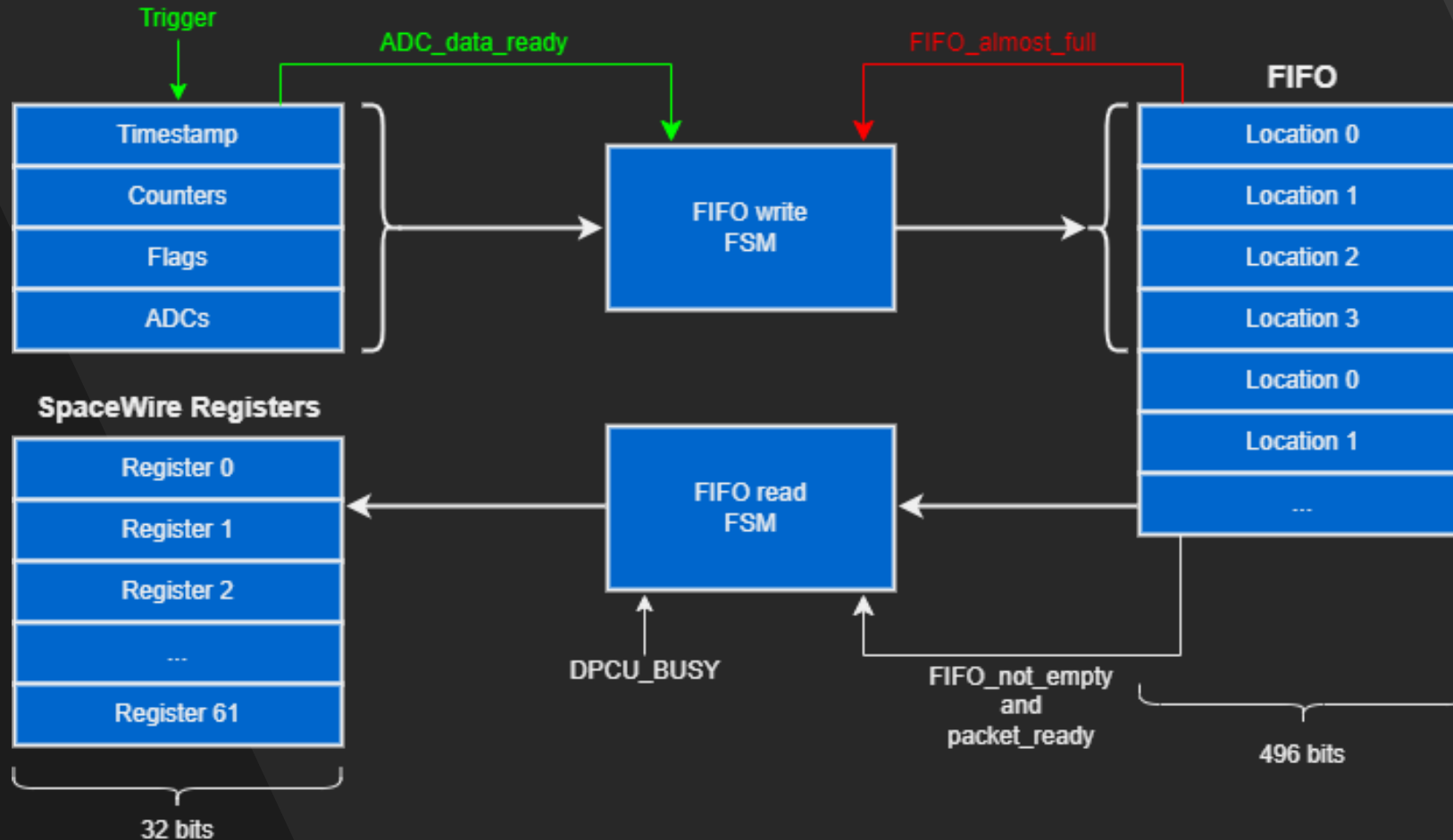
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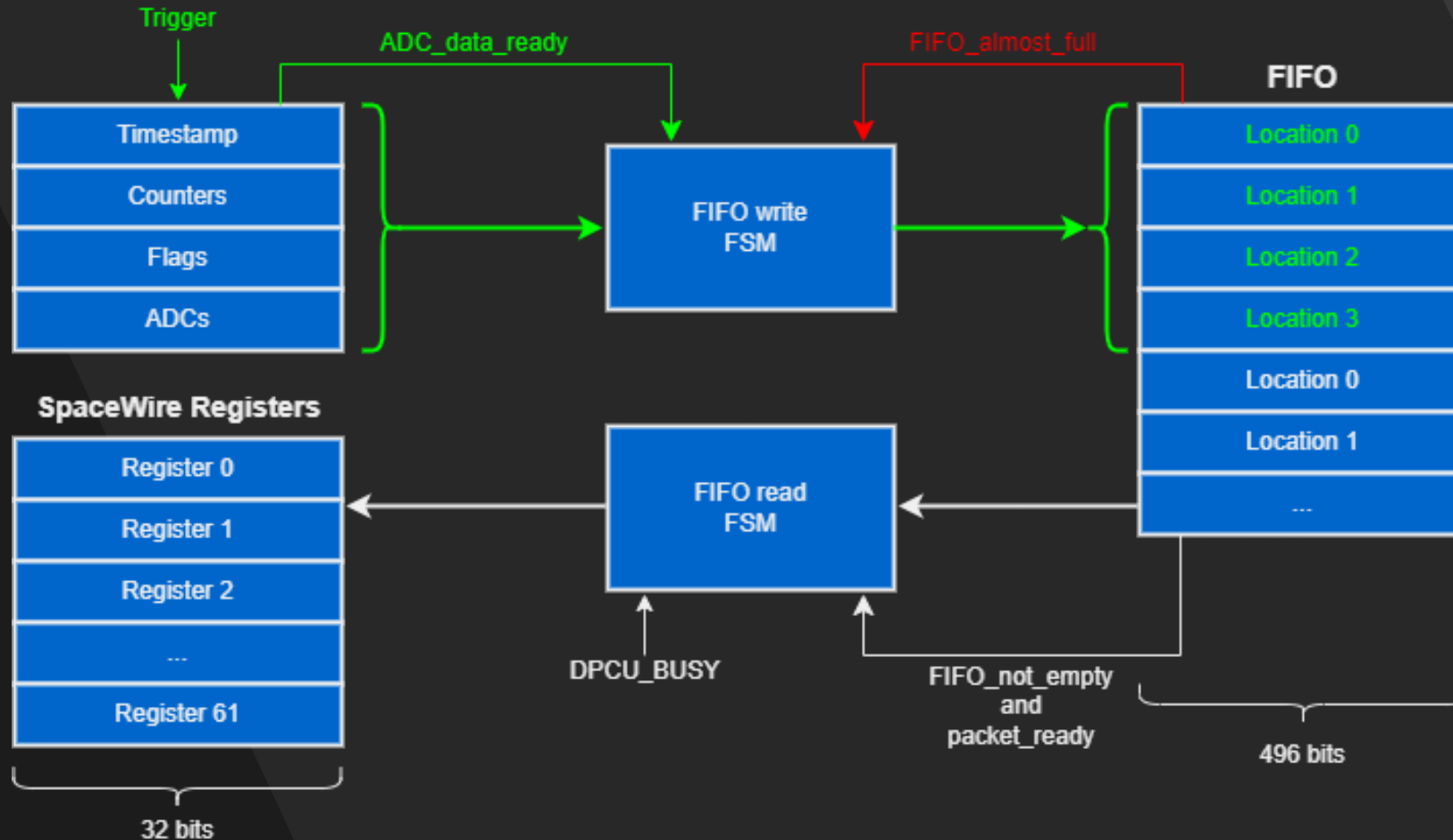
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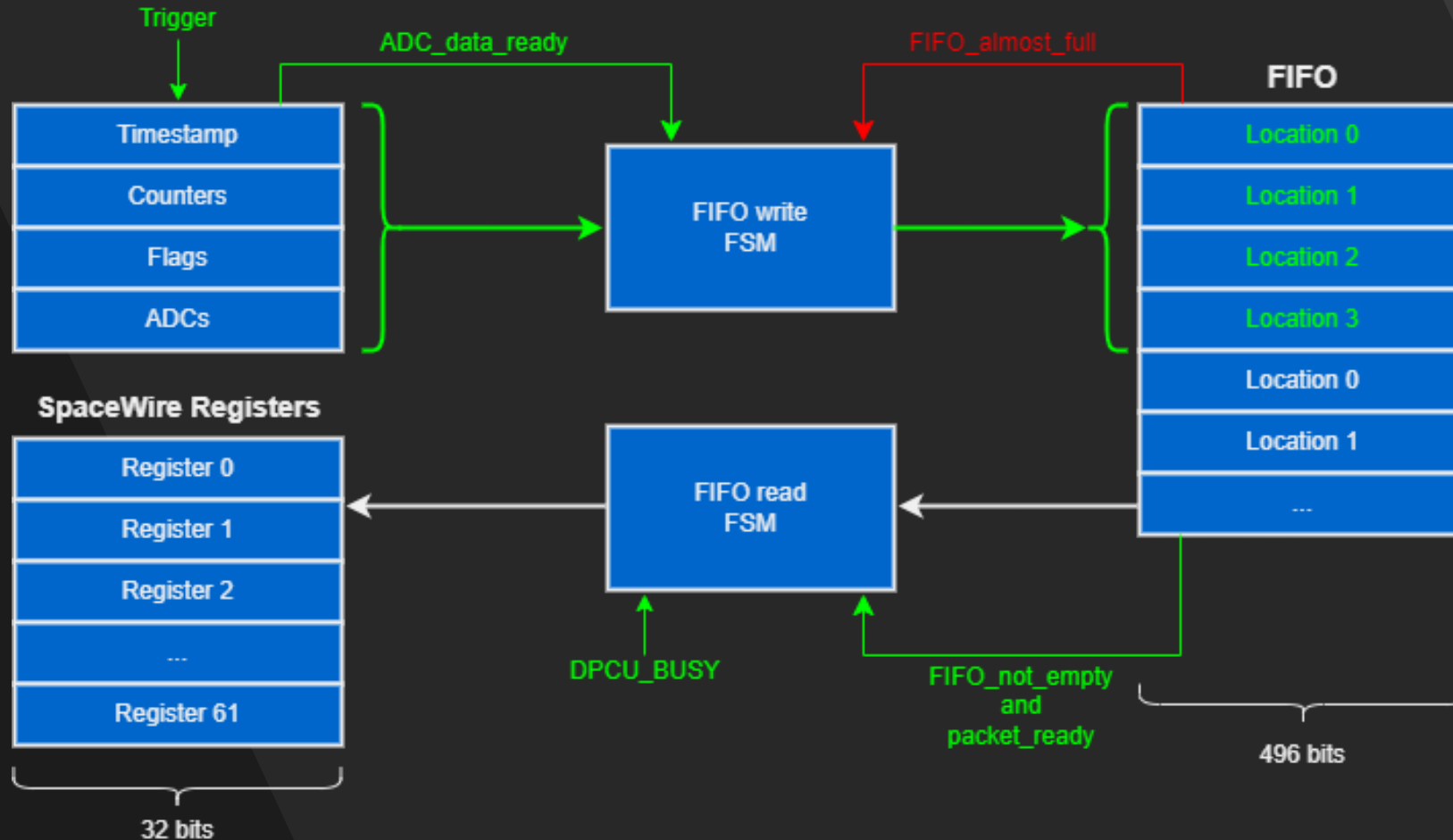
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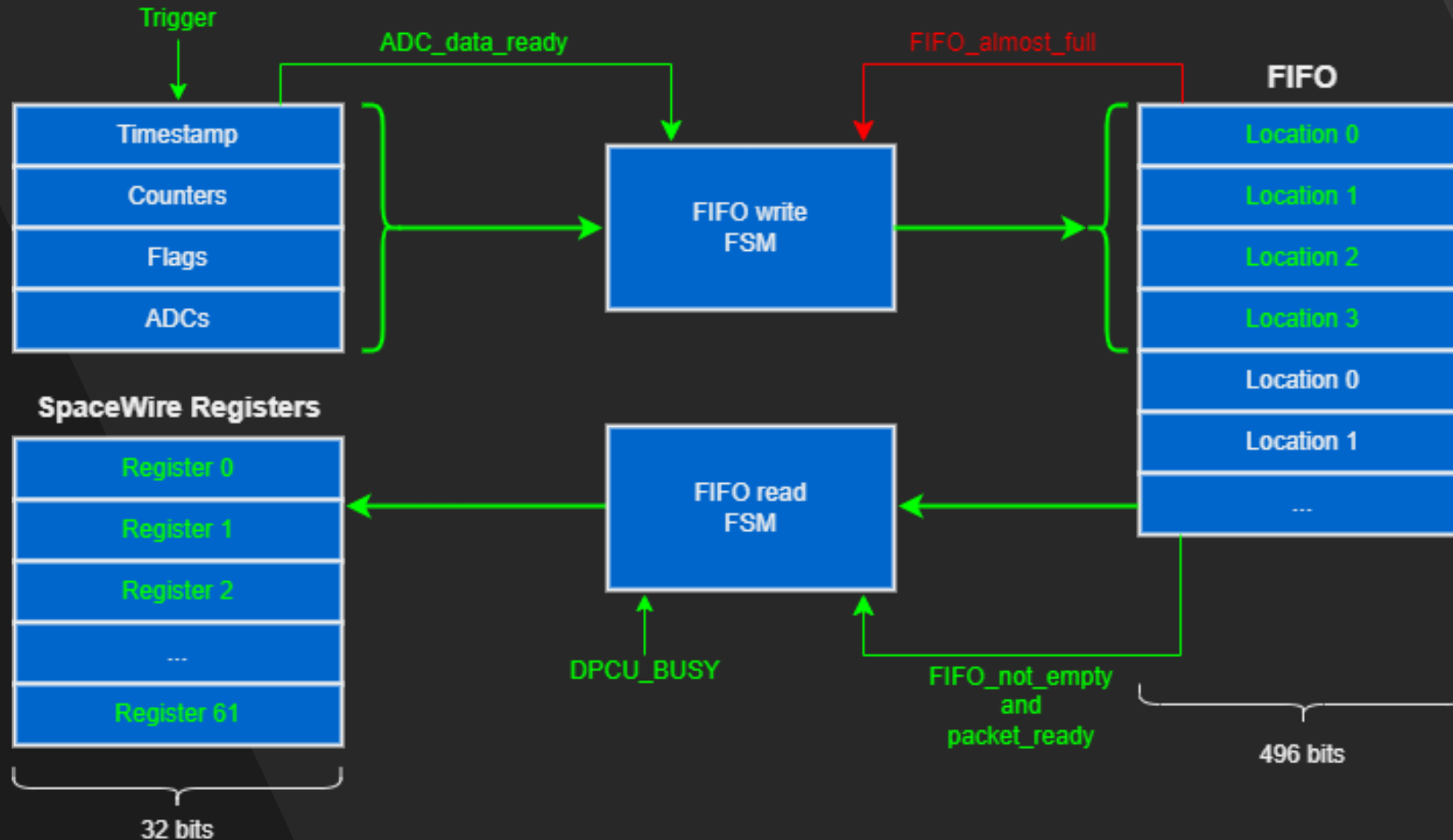
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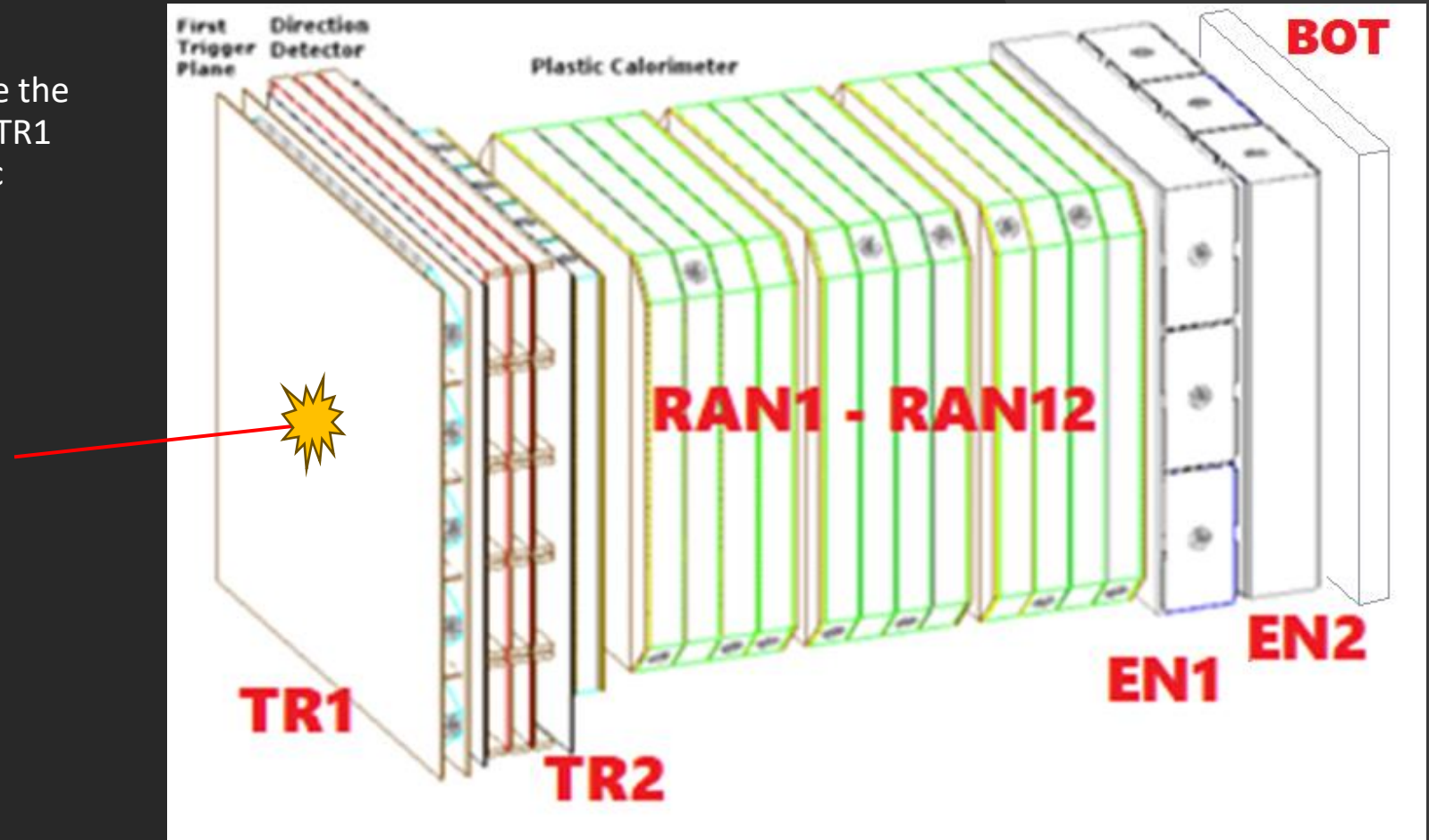


Trigger masks

Two classes of trigger masks are defined

- **Event acquisition masks:** that validate the acquisition of the event and use the TR1 and TR2 plane and the second plastic scintillator:

1. TR1

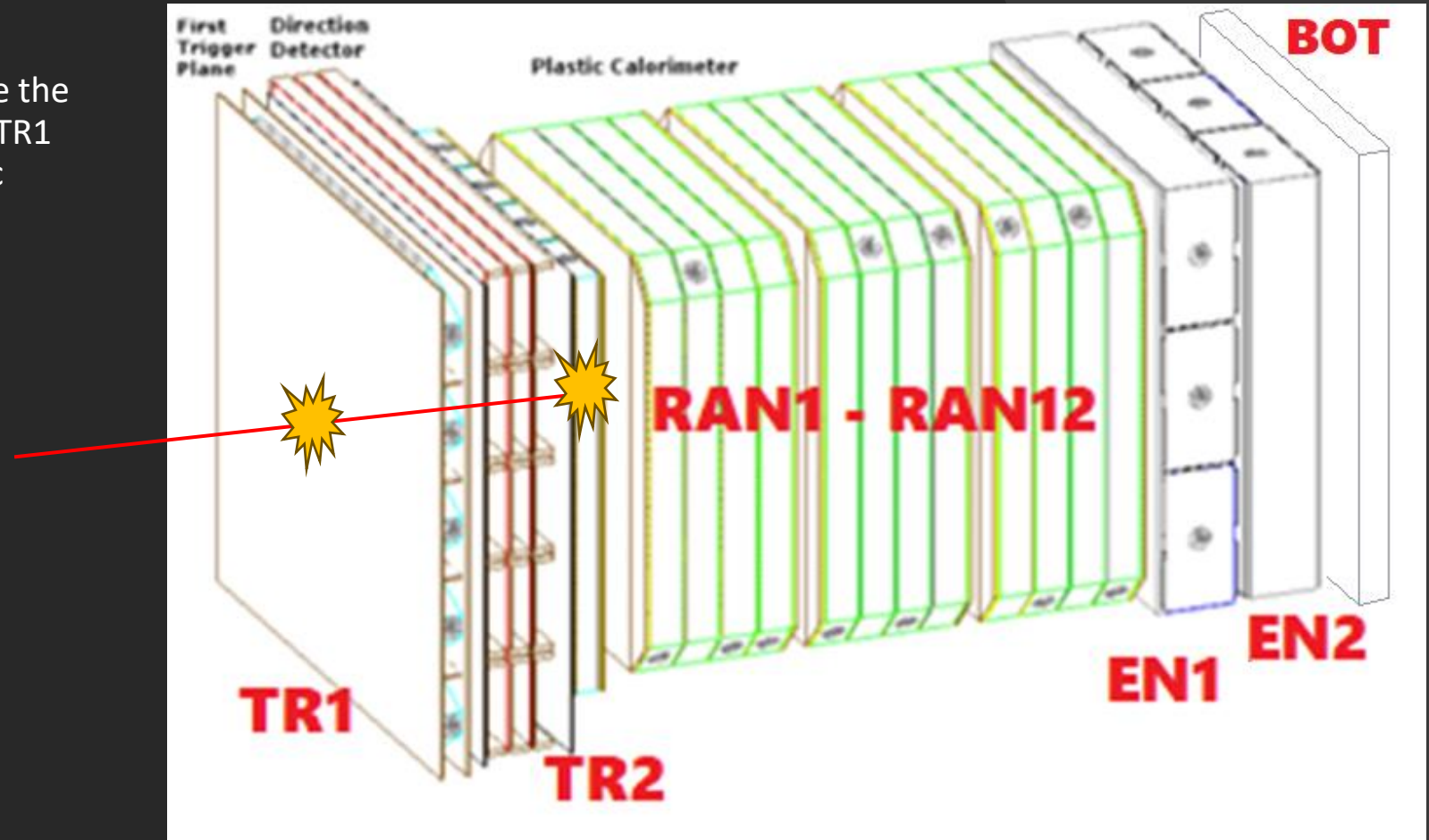


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1. $TR1$
2. $TR1 \cdot TR2$

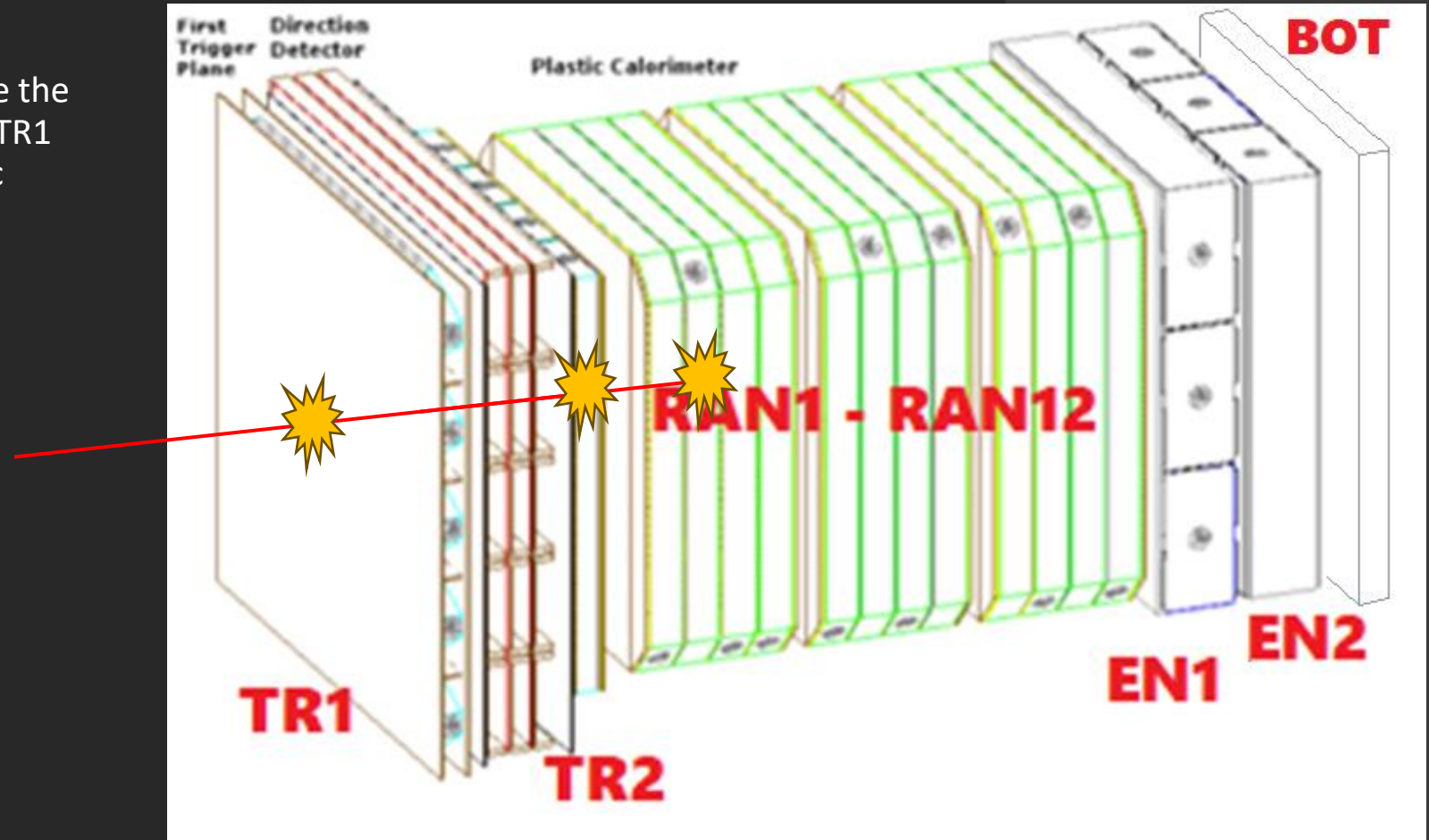


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3. $TR1 \cdot TR2 \cdot RAN2$



Trigger masks

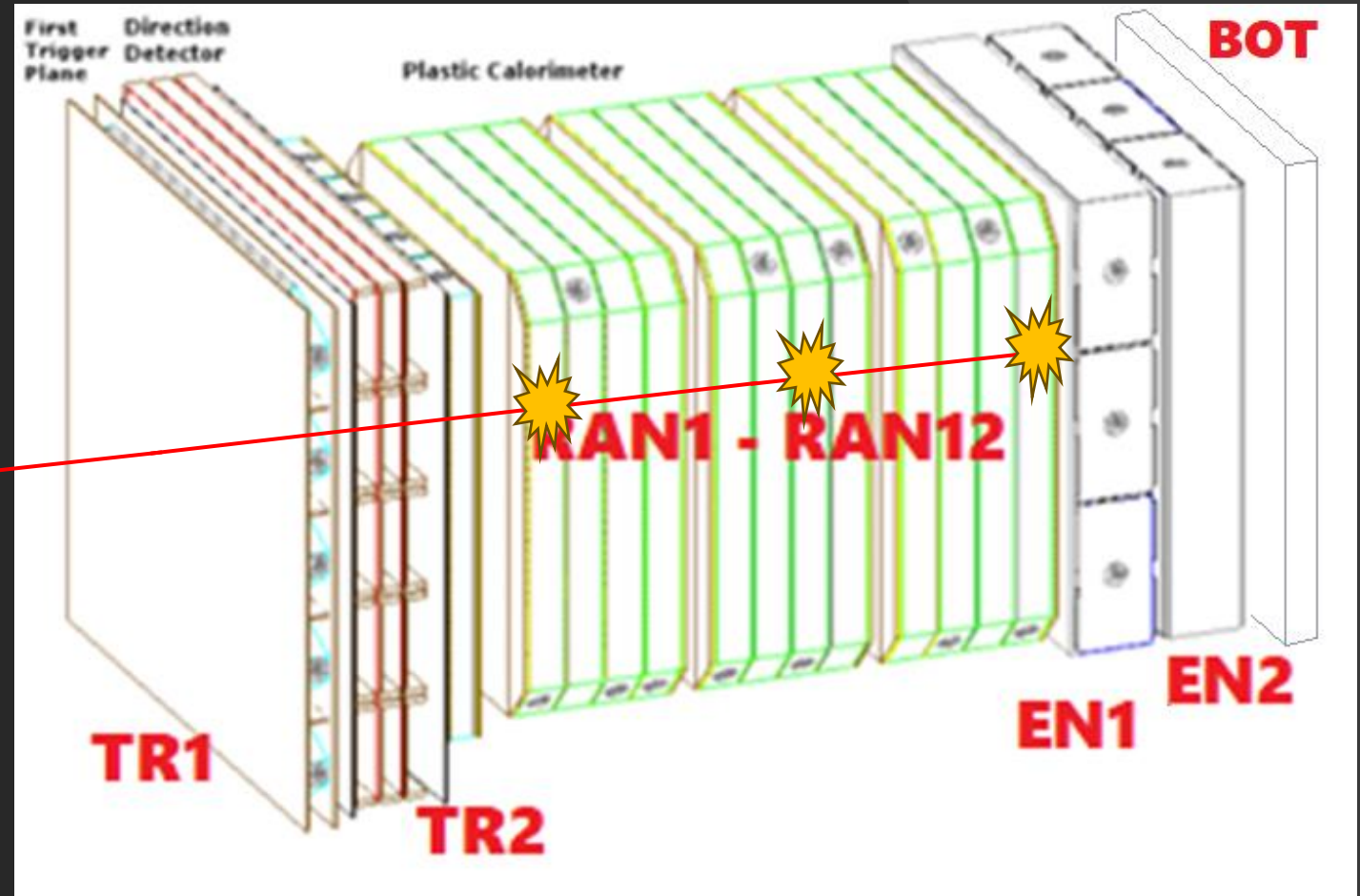
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- **Event monitor masks:** which provide information about the efficiency of the detector:

4. $RAN1 \cdot RAN7 \cdot RAN12$



Trigger masks

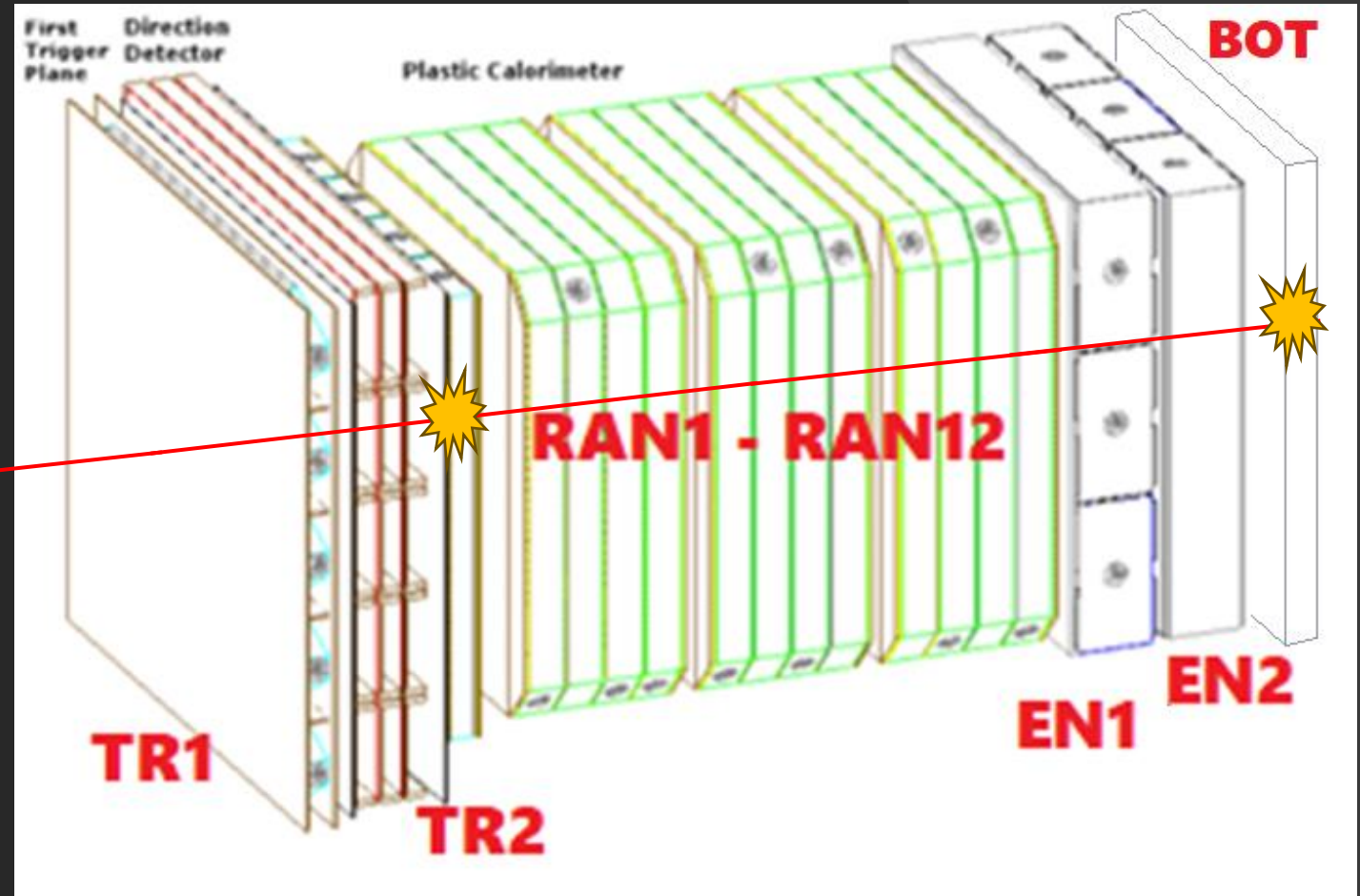
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5. $TR2 \cdot BOT$



Trigger masks

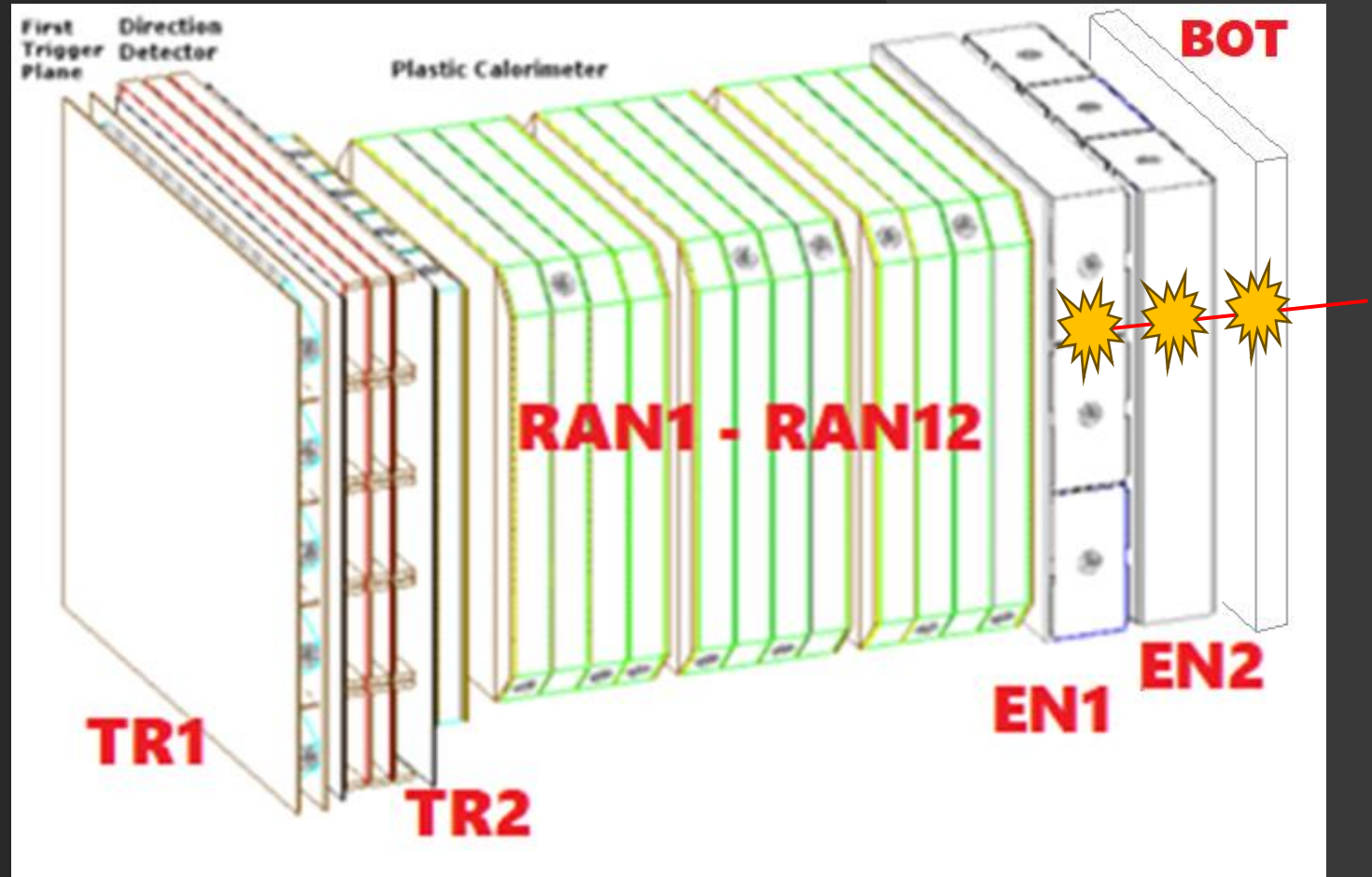
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4. $RAN1 \cdot RAN7 \cdot RAN12$
5. $TR2 \cdot BOT$
6. $BOT \cdot EN1 \cdot EN2 \cdot \overline{TR1 + TR2 + LAT}$



Trigger masks

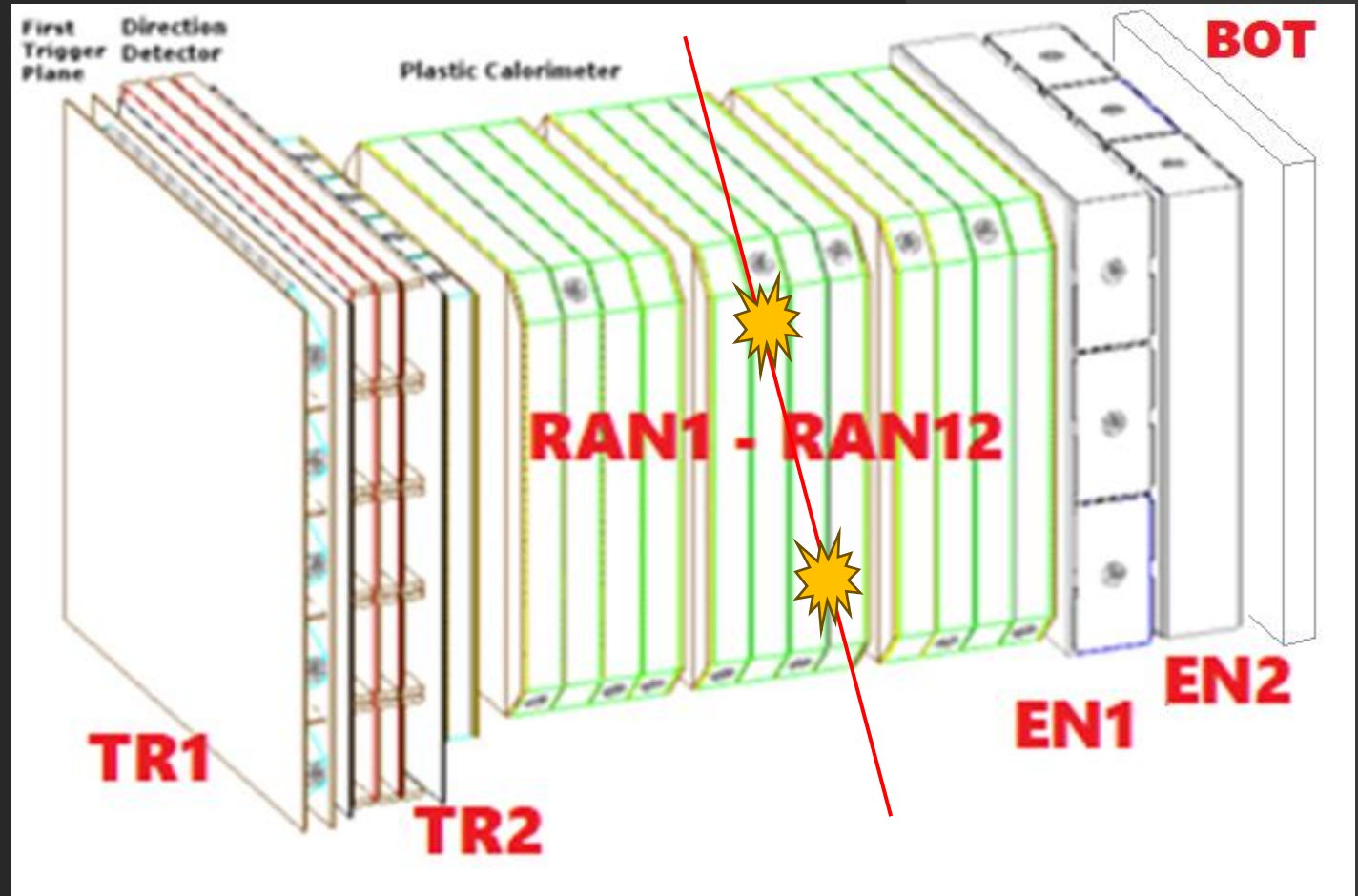
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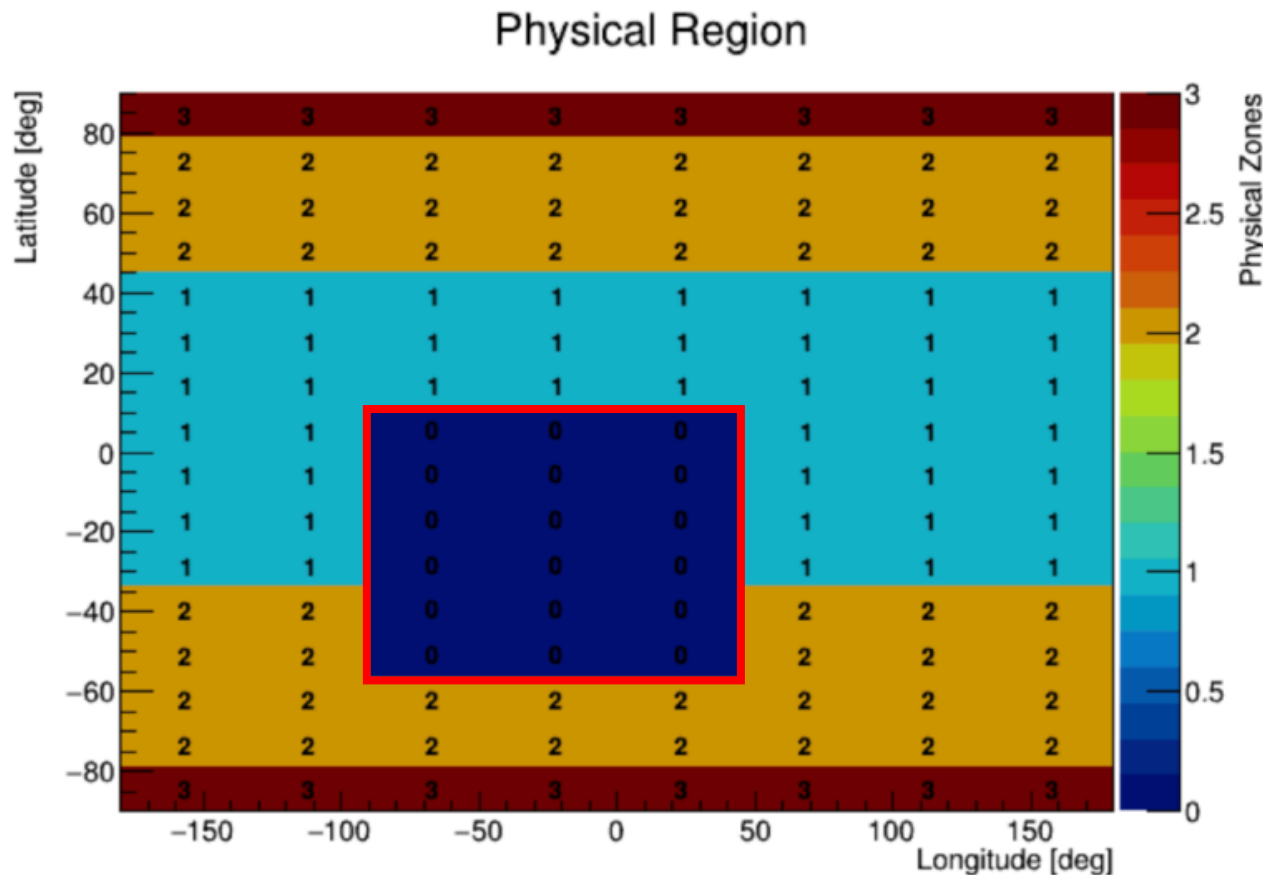
- **Event monitor masks:** which provide information about the efficiency of the detector:

4. $RAN1 \cdot RAN7 \cdot RAN12$
5. $TR2 \cdot BOT$
6. $BOT \cdot EN1 \cdot EN2 \cdot \overline{TR1 + TR2 + LAT}$
7. $(RAN5 + RAN6 + RAN7 + RAN8) \cdot \overline{(RAN4 + RAN9)}$



Orbital zones

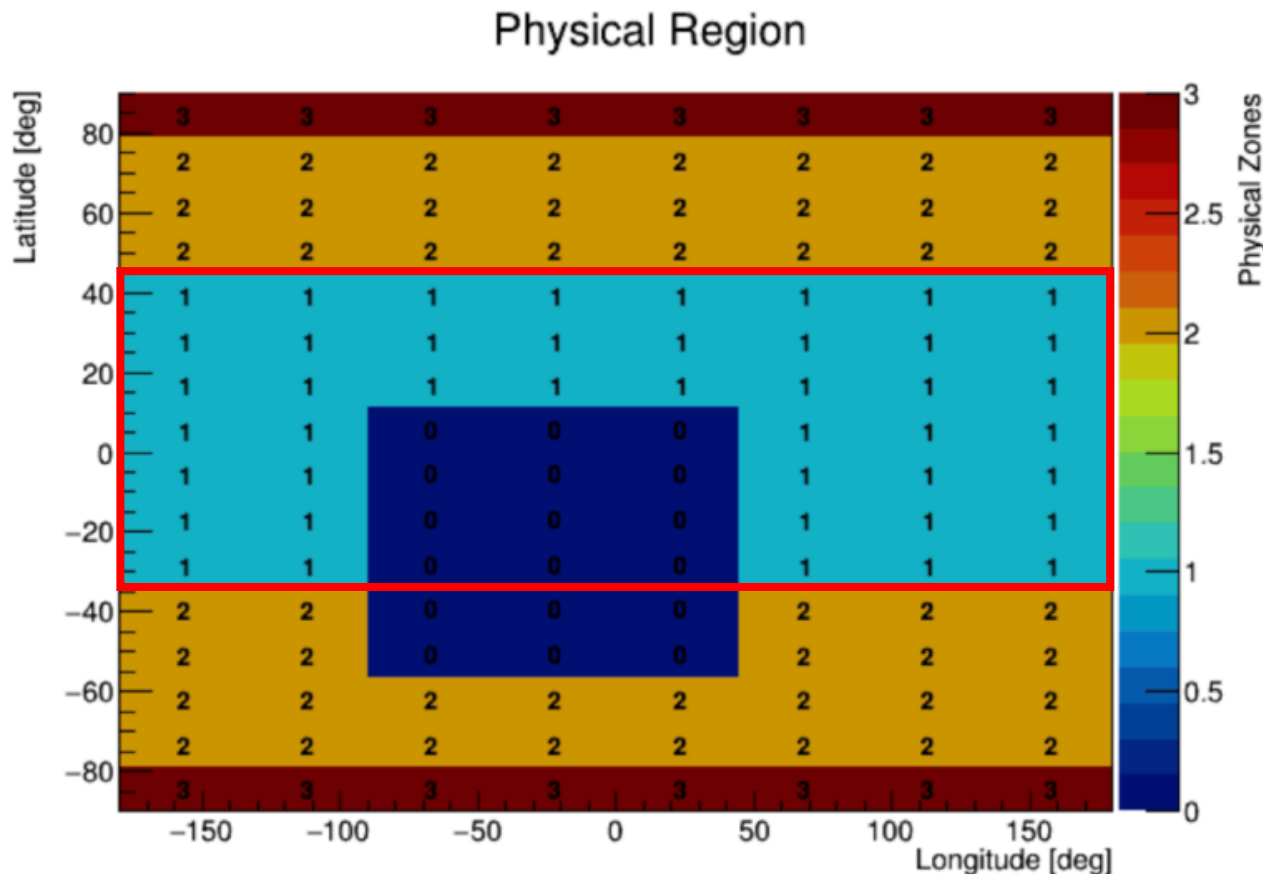
The trigger masks allows to study different physics cases depending on the orbital zone of the satellite.
Four orbital zones are defined:



- SAA (0): trapped electrons (dominant at 1MeV) and protons (dominant above 8MeV)

Orbital zones

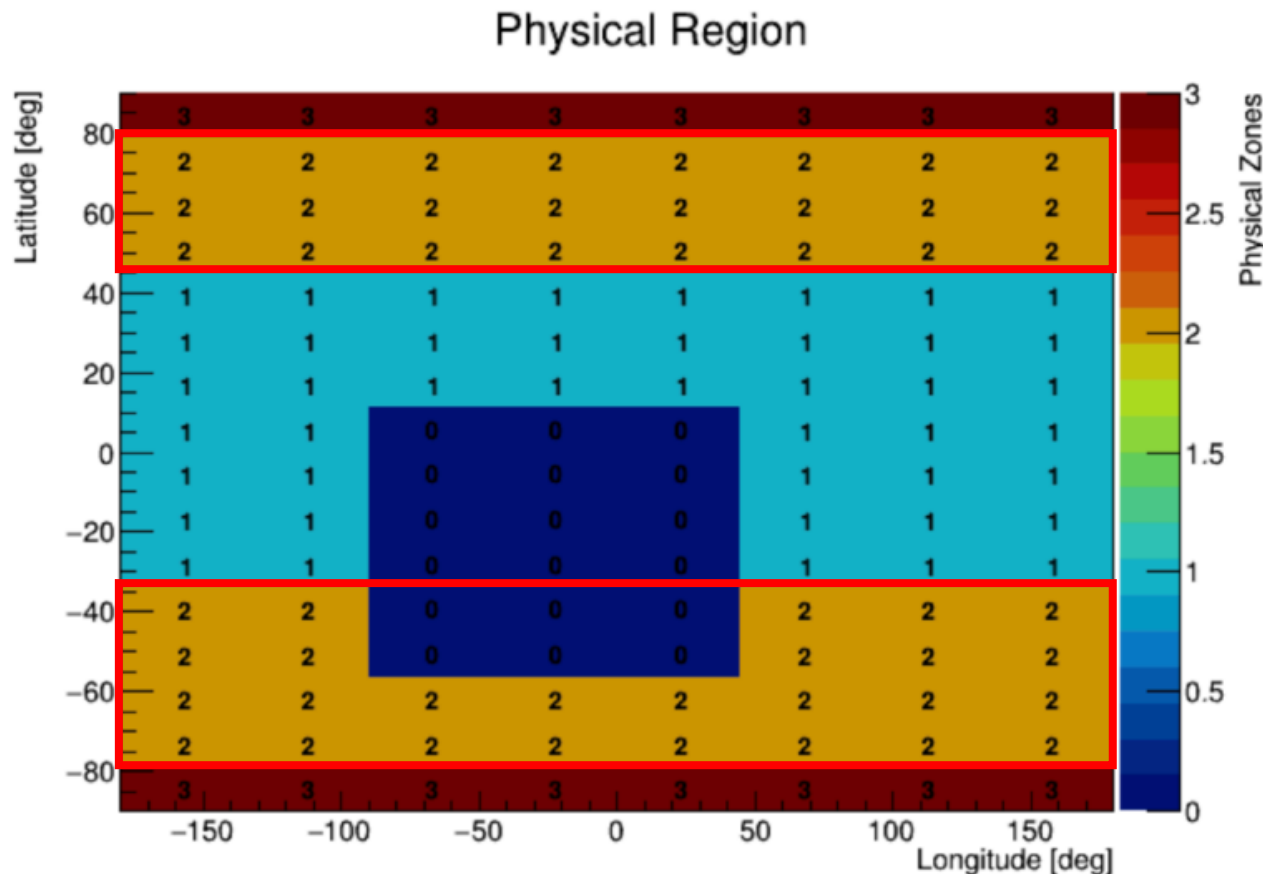
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Orbital zones

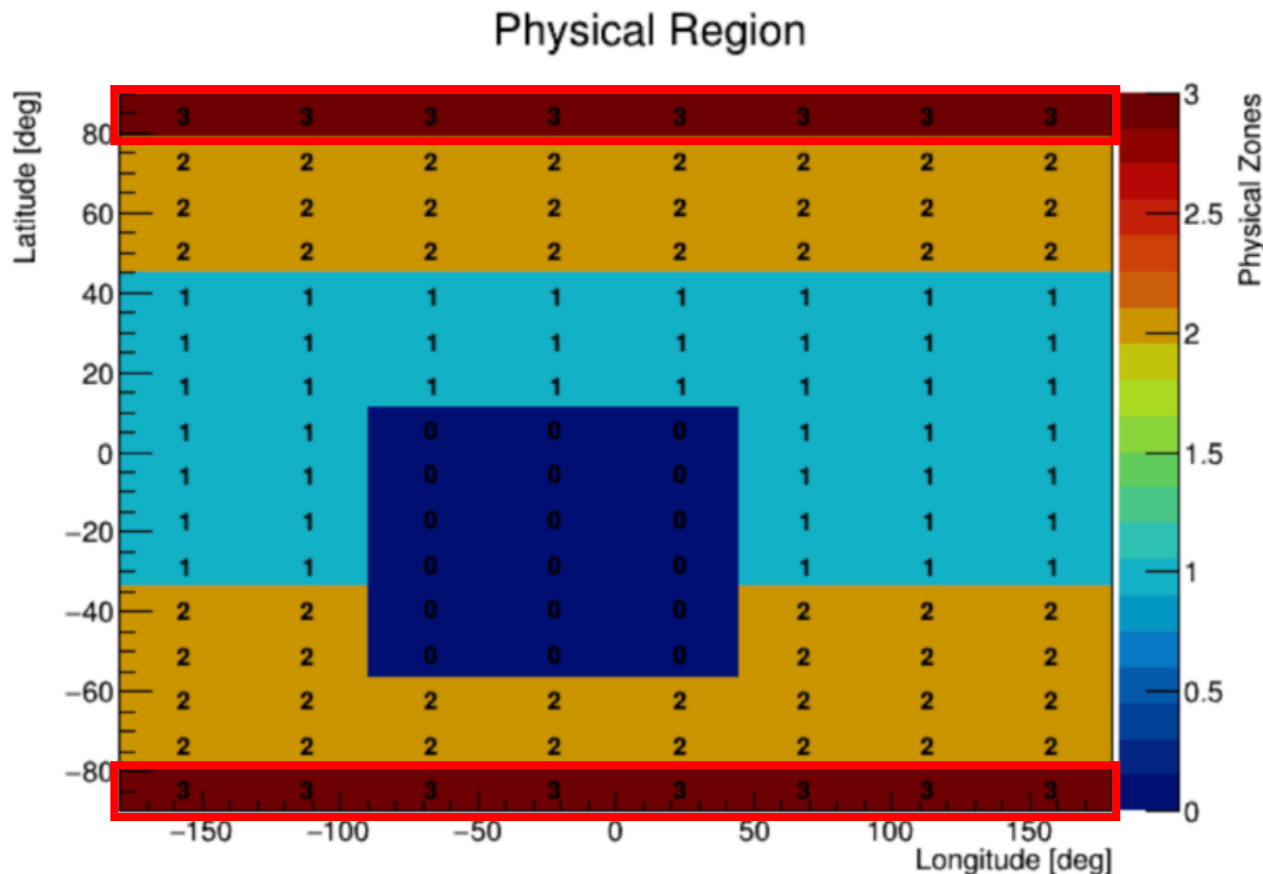
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- Outer belt (2): low energy trapped electrons (below 10MeV)

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- Outer belt (2): low energy trapped electrons (below 10MeV)
- Polar (3): primary electrons and protons and heavier nuclei

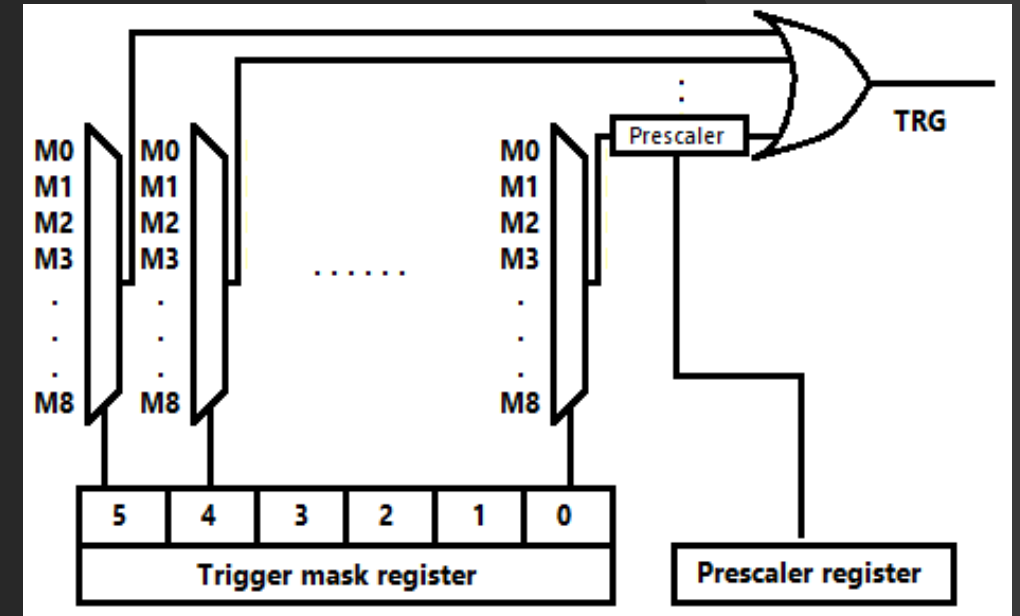
Concurrent trigger masks

To enrich the physics program of the mission, we don't want to be limited to select a single trigger mask per orbital zone: HEPD-02 will be able to use 6 of the predefined trigger masks in concurrency.

To achieve this functionality the trigger masks are connected to **six multiplexers** whose outputs are selected by a SpaceWire register.

The OR of these multiplexers produces the trigger signal.

Each multiplexer output is also registered to identify which mask produced the event trigger.



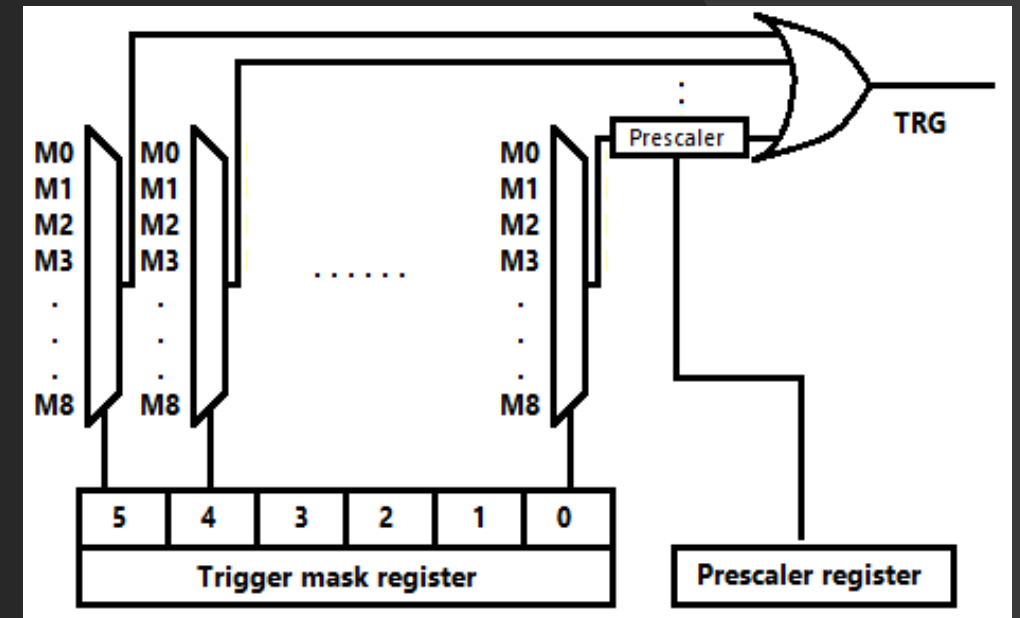
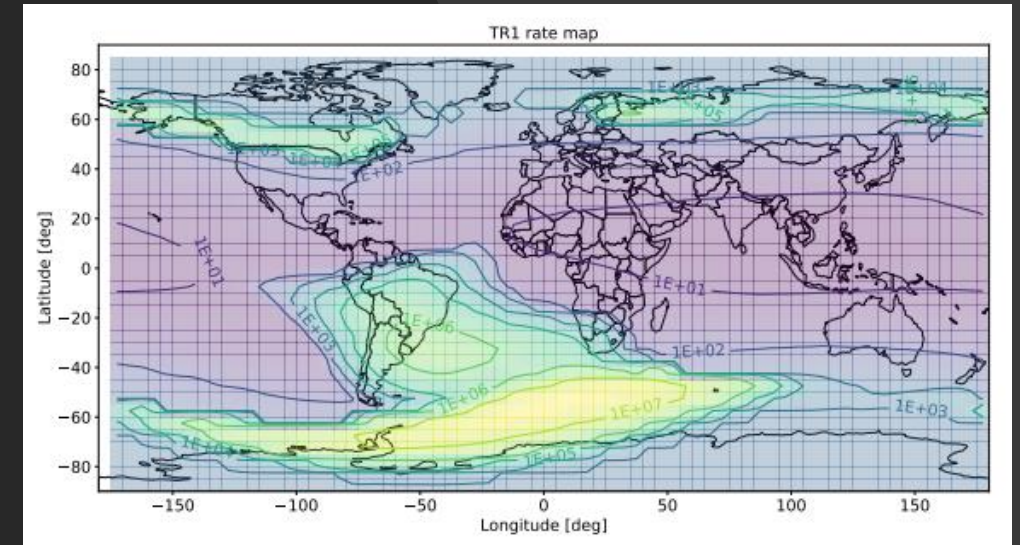
Trigger prescaling

CSES-02 is supposed to be operative in **polar regions** and in the **SAA**, where particle rate is higher.

For example $TR1$ and $TR1 \cdot TR2$ can reach rates of 10^6 Hz .

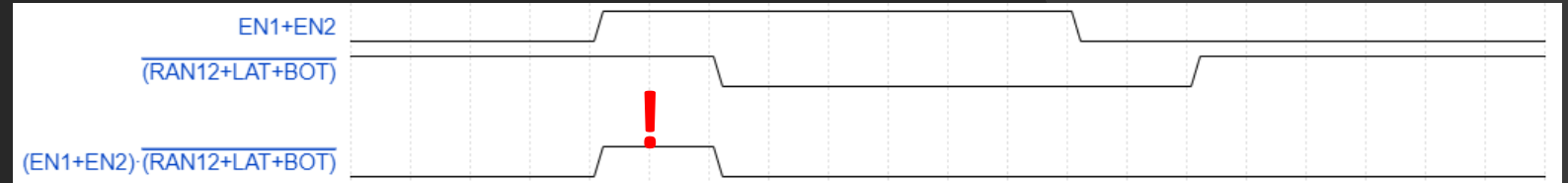
We control the sharing of data throughput among different physics channels via online selection: the largest rate trigger are prescaled to not saturate the available bandwidth.

Four prescalers are implemented to ignore a configurable number of triggers and limit the rate for the selected mask.

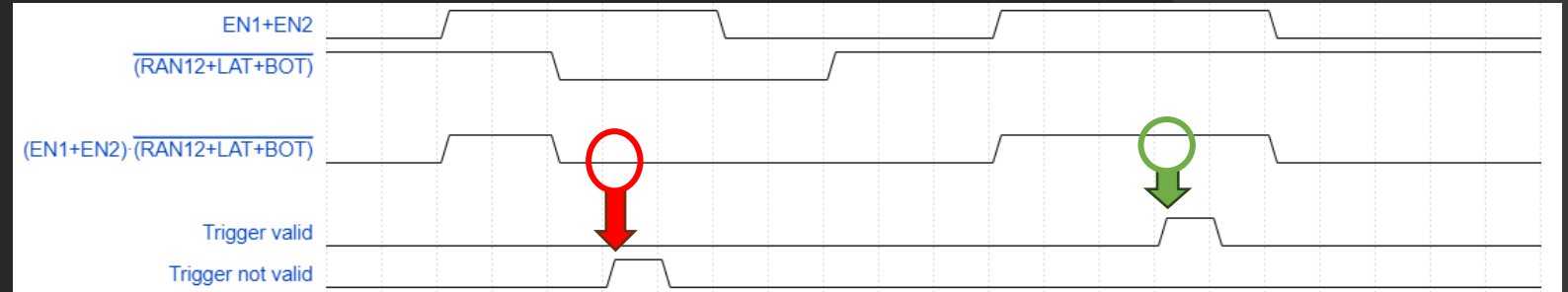


1st and 2nd level triggers

In some cases, spurious triggers can generate due to the different timing between signals.



To avoid this, a second-level trigger is implemented which checks the trigger masks status after a time interval.



This logic adds a delay of 80ns on the generation of a valid trigger signal. This delay is not compatible with the selected shaping time of 50ns, necessary for the correct integration of the LYSO crystal's signals.

For this reason the OR of the six selected trigger masks is used to open the **peak detector** window as soon as possible.

The second-level trigger confirms the event, enabling the CITIROCs output and starting ADC conversions, or discards it, clearing the peak sensing cell.

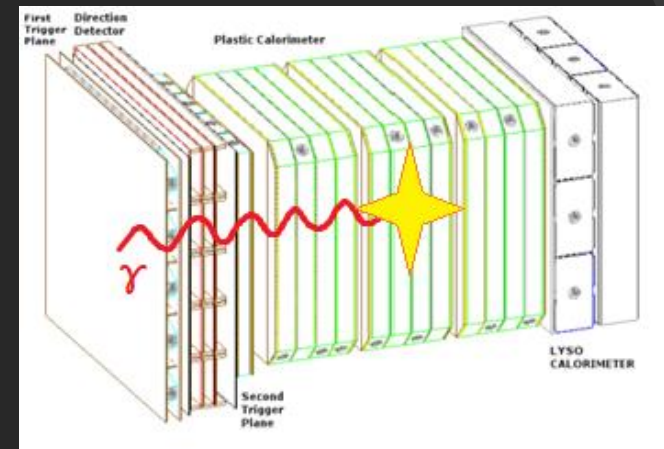
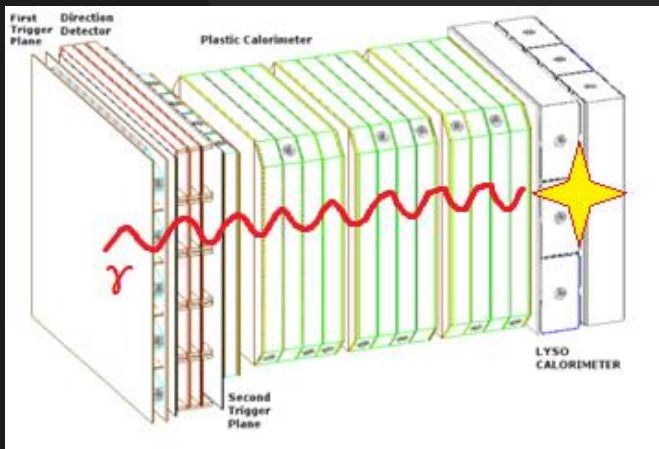
Additional functionalities: GRB masks

One of the improvements foreseen for the HEPD-02, is the extension of the trigger capabilities for the detection of **Gamma Ray Bursts**, in the 2-20MeV energy range.

The **LYSO crystals**, thanks to their high density, can be used to detect GRBs. Another possibility (for low energies) is to use the **central plastic scintillators** of the detector.

$$\text{GRB_LYSO} = (EN1 + EN2) \cdot \overline{(RAN12 + LAT + BOT)}$$

$$\text{GRB_RAN} = (RAN5 + RAN6 + RAN7 + RAN8) \cdot \overline{(RAN4 + RAN9 + LAT)}$$



Rate meters and GRB detection algorithm

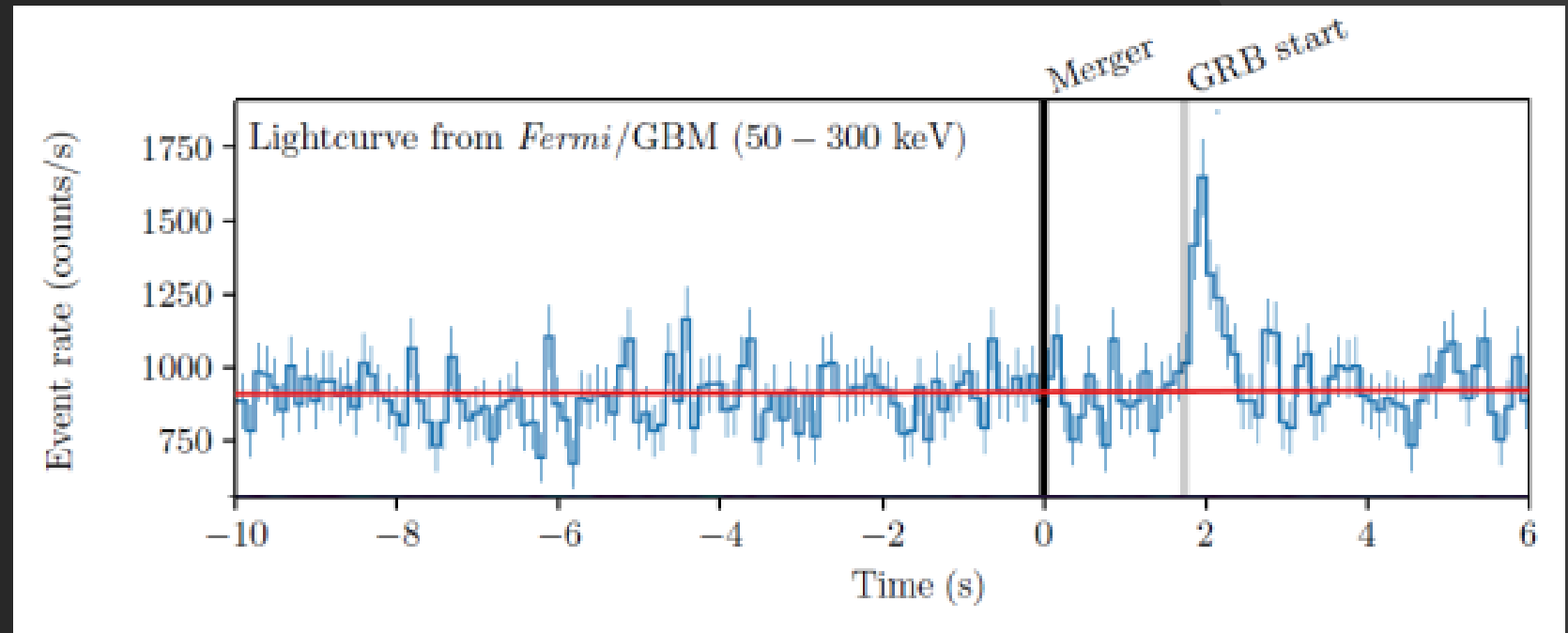
Three classes of rate meters are implemented:

1. **PMT rate meters:** counters with a 1Hz resolution used to monitor the rate of each PMT
2. **Mask rate meters:** used to measure the rate of each trigger mask with a 1Hz resolution
3. **GRB rate meters:** two rate meters with 200Hz resolution specifically designed for the GRB detection algorithm

The algorithm for GRB detection is based on the counts obtained from GRB rate meters and is implemented on the **DPCU**.

1. The DPCU calculates the **moving average** and the **mean absolute difference** (MAD) for both the GRB rate meters

GRB170817



Rate meters and GRB detection algorithm

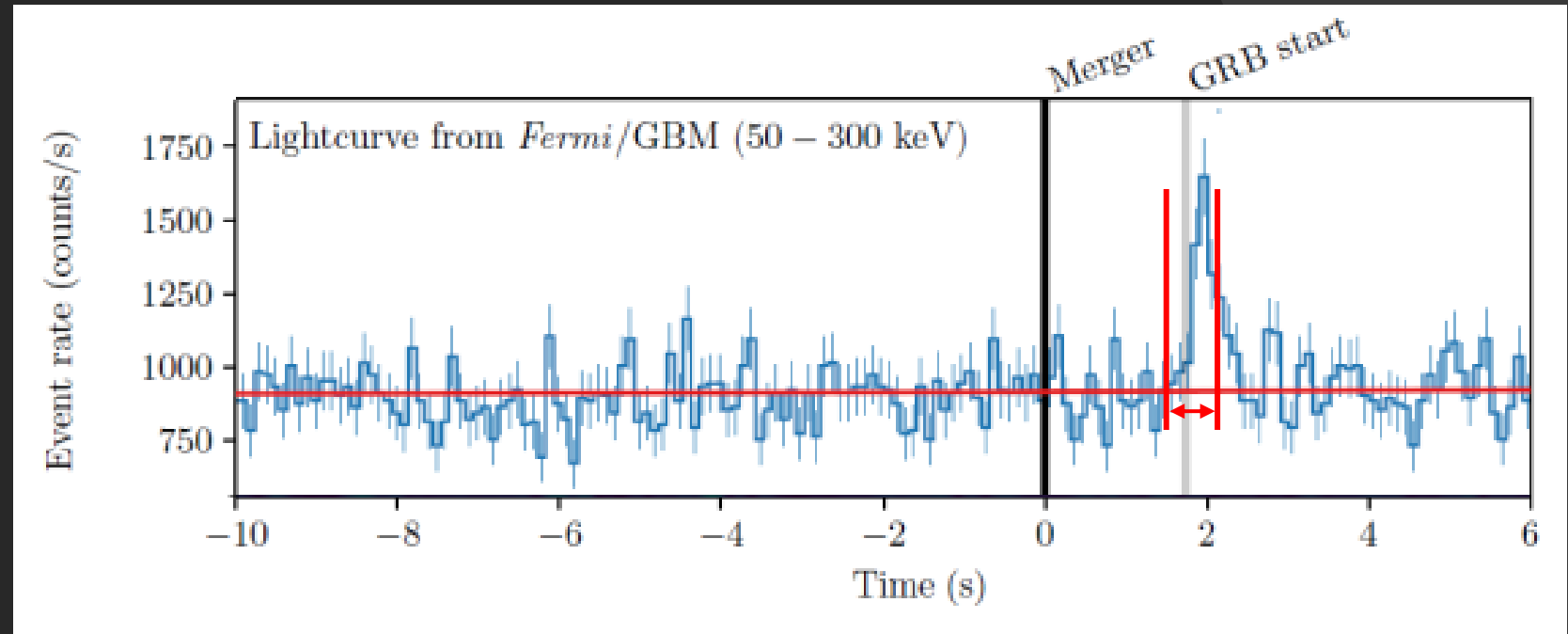
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R. Iuppa



Rate meters and GRB detection algorithm

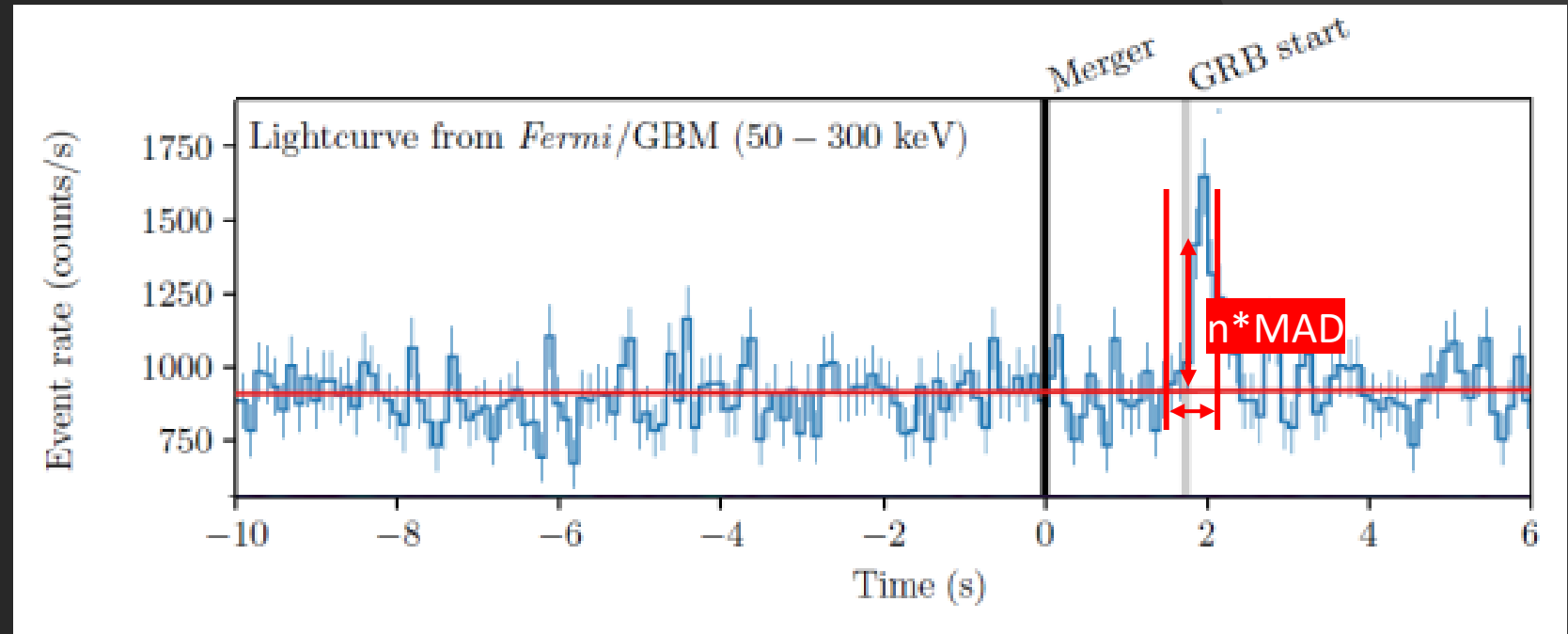
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3. If one of these sums exceed the average of a number of MAD, the DPCU stores the rate meter values from 10s before this event and 10s after

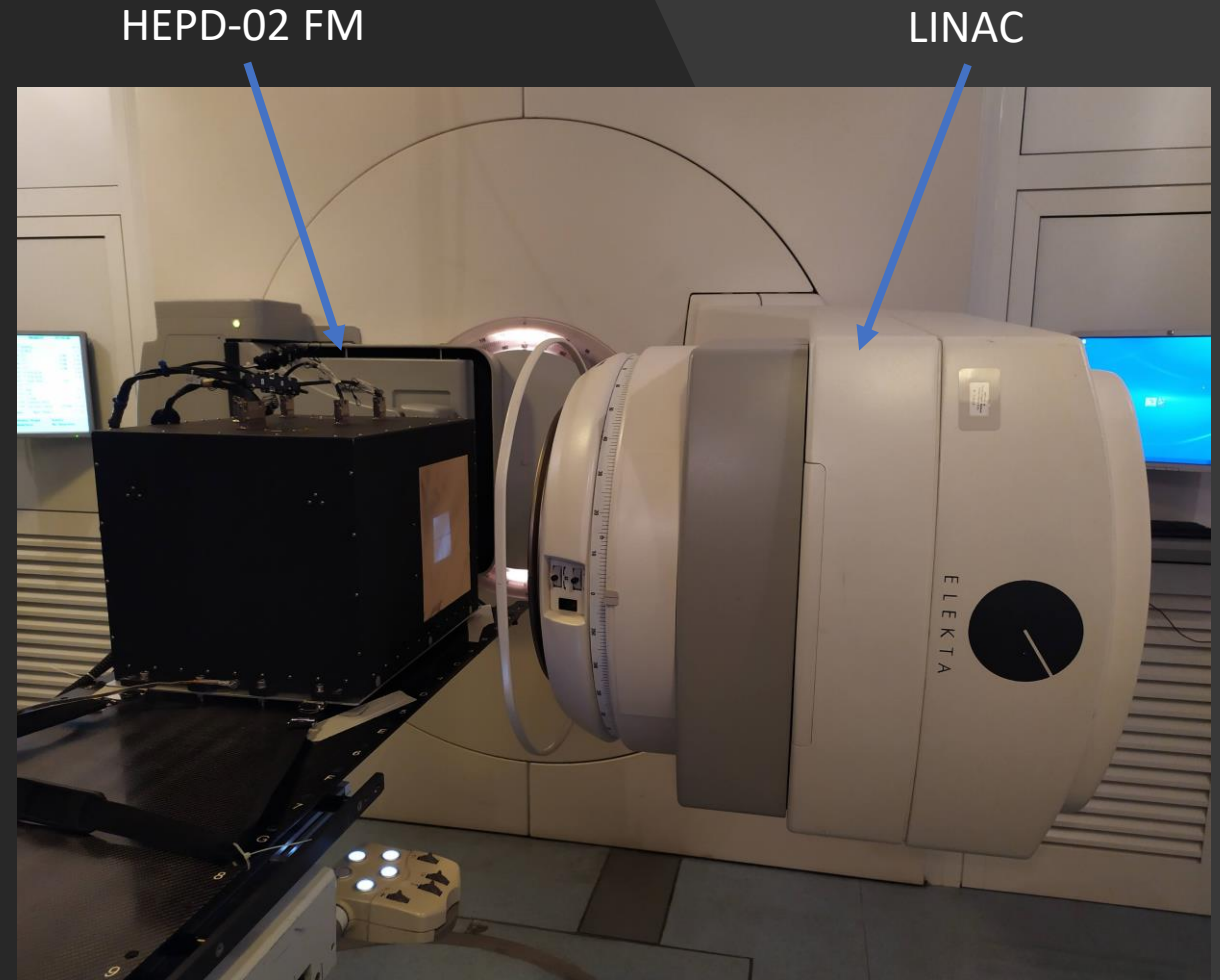
R. Iuppa



HEPD-02 FM beam tests

The FM has successfully passed the thermovacuum and electromagnetic compatibility tests.

A series of beam tests were also carried out and are still ongoing.

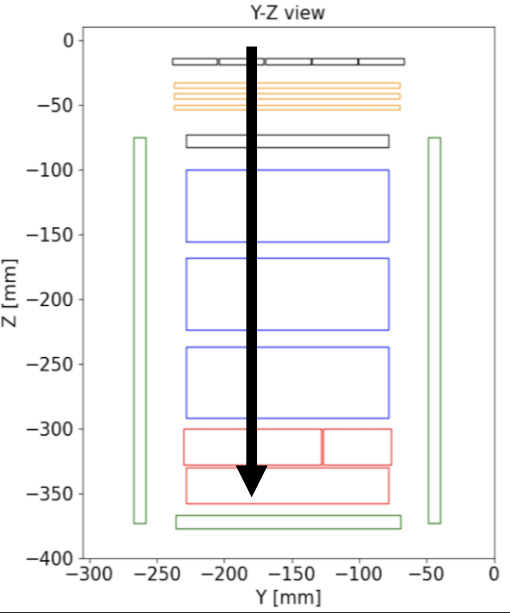


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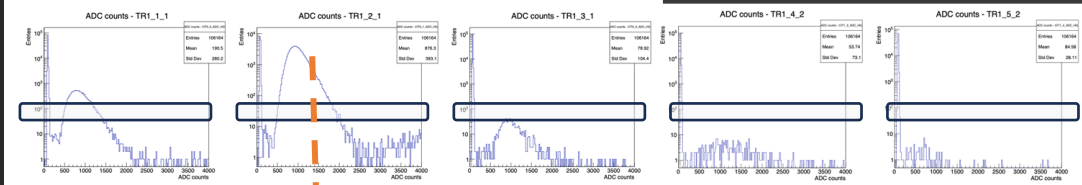
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We used electrons and protons in a wide range of energies to study the detector response to different particles.

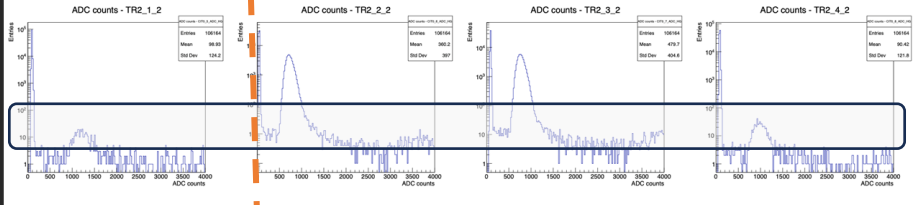


Protons at 228MeV

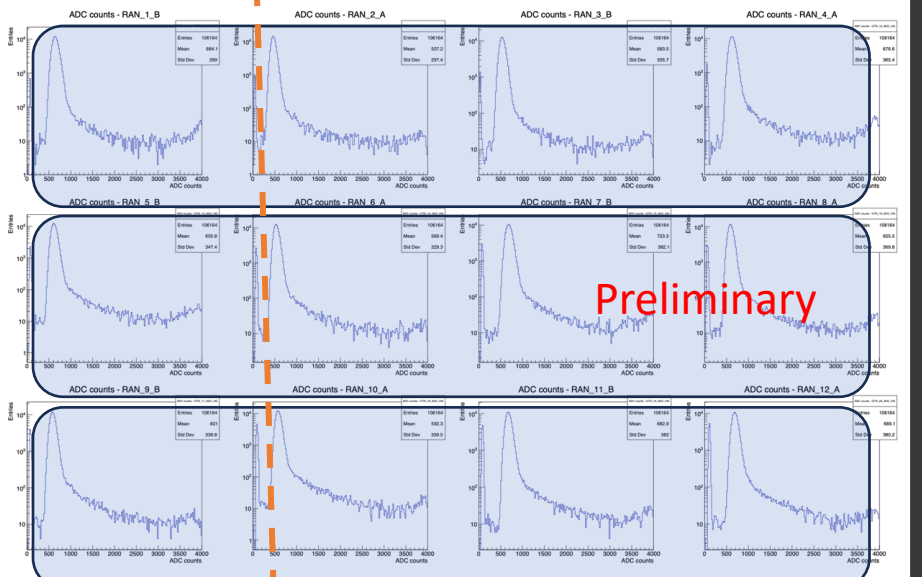
TR1



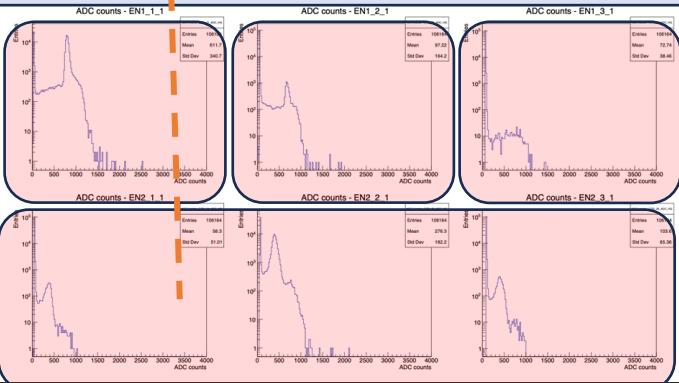
TR2



RAN



LYSO

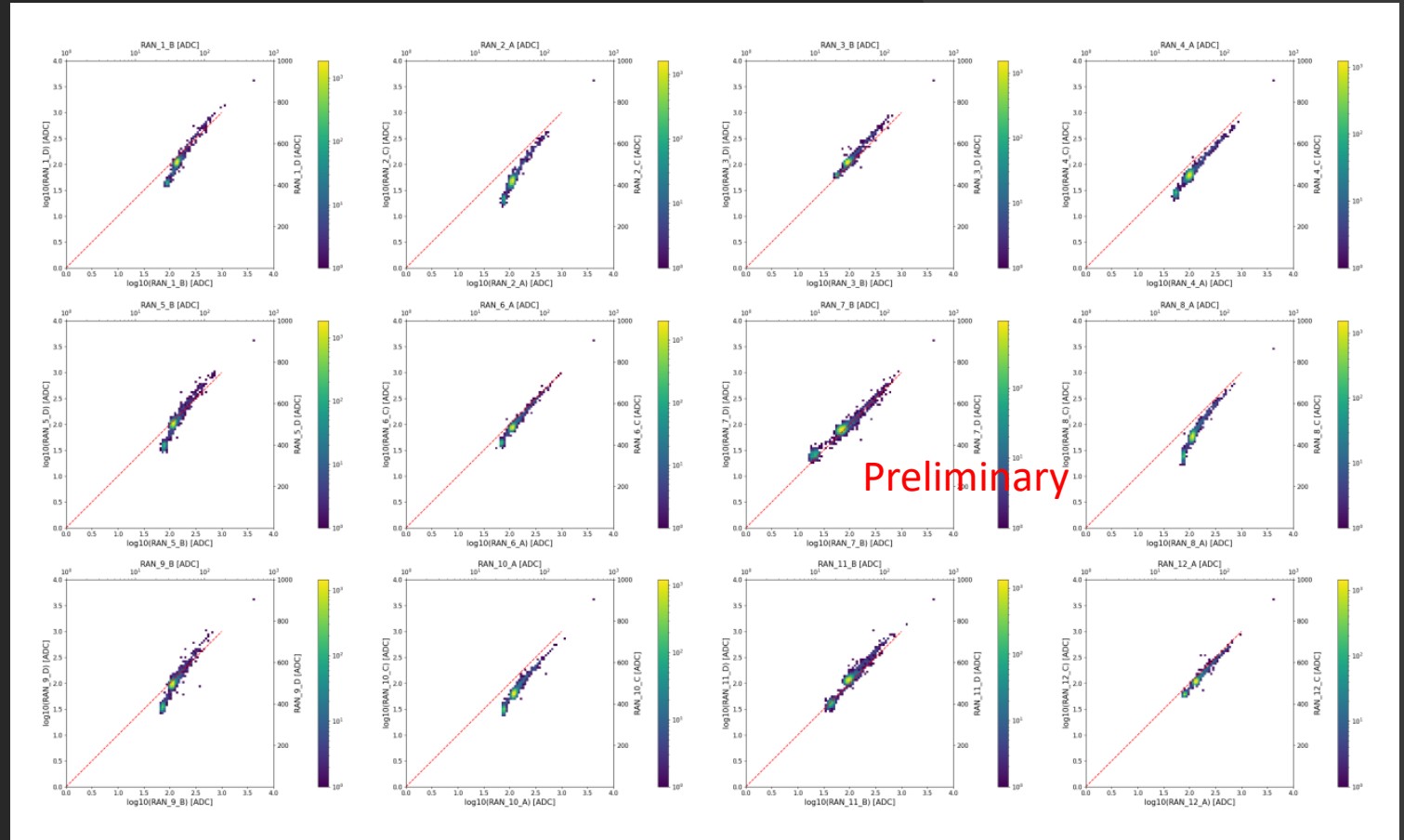


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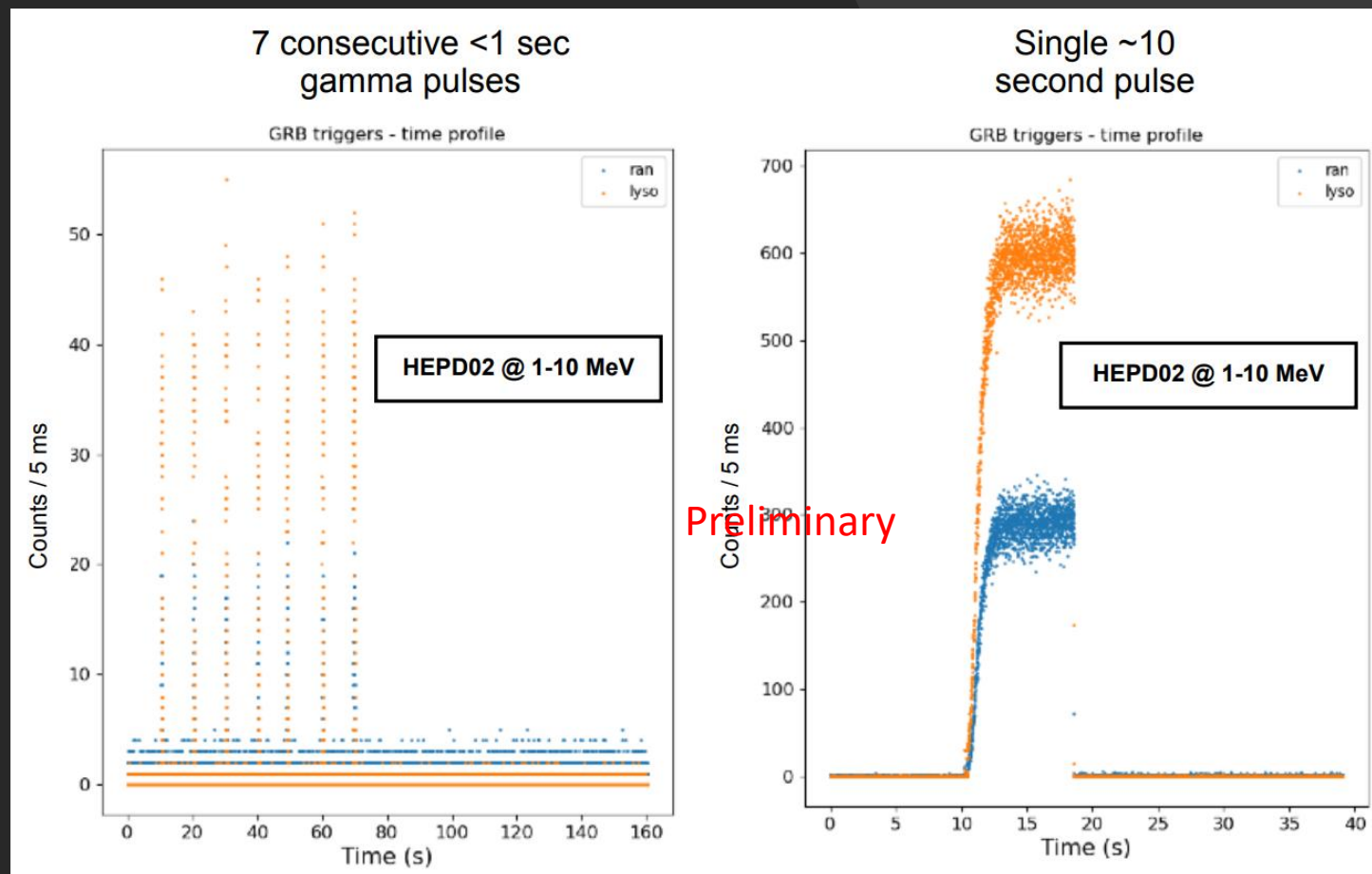
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We also used X-rays (1-10MeV) produced at the S. Chiara LINAC in Trento to test the GRB detection algorithm, but the work is still in progress.



Conclusions

- The PMT readout and trigger board, developed for HEPD-02, brings improvements on the flexibility of the instrument and allows the detector to operate in regions such as SAA and poles, extending the scientific significance of the mission.
- Concurrent and prescaled trigger allows to use different masks per orbital zone and also made possible the development of the GRB detection algorithm
- The added functionalities have been intensively tested and work as expected.
- Beam tests are still ongoing, also for validating the GRB detection algorithm.

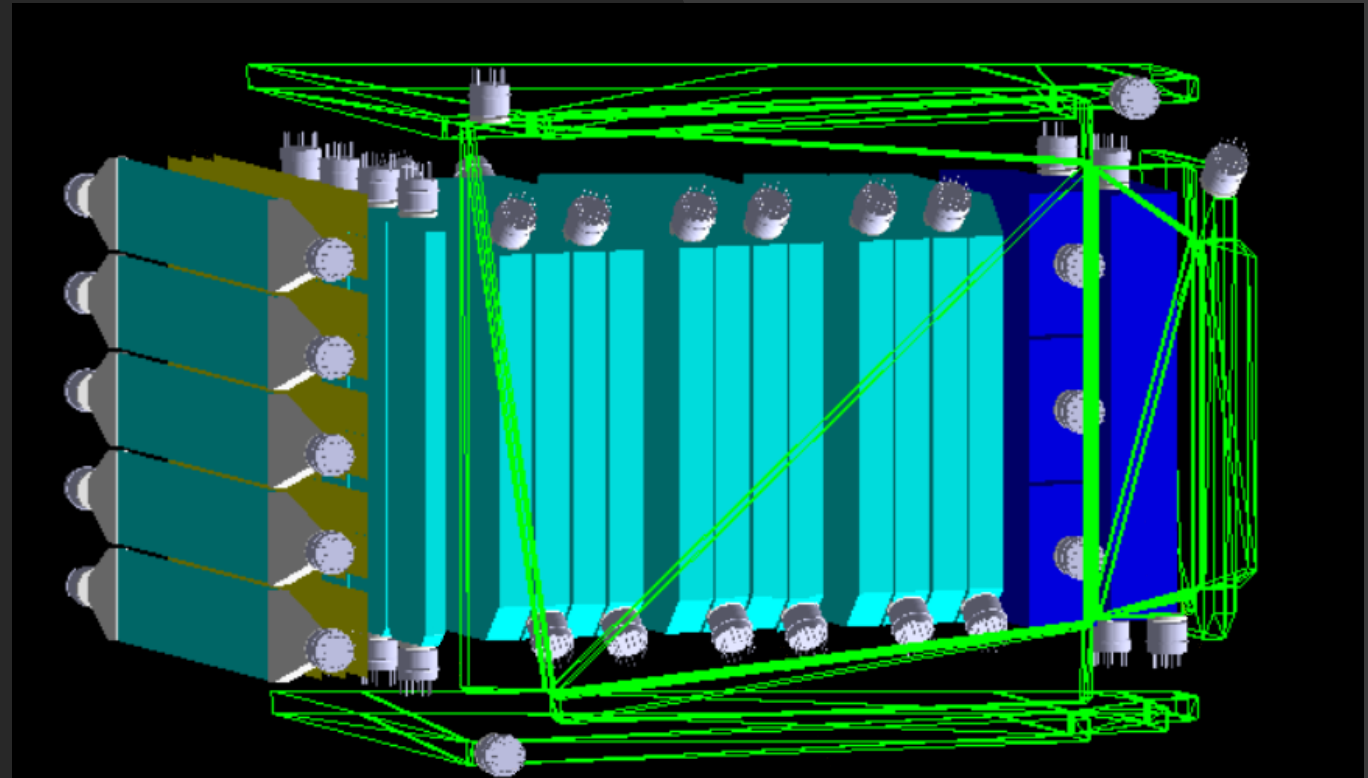
Thank you for your attention!

Backup slides

HEPD-02 details

Dimensions: 20x20x40 cm³

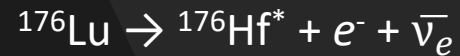
- First trigger plane: composed by 5 segments of EJ-200 plastic scintillator 2mm thick
- Second trigger plane: composed by 4 segments of plastic scintillator 8mm thick
- Calorimeter tower: composed by 12 planes of plastic scintillator (15x15x10 cm³) and 2 LYSO planes segmented in 3 bars (50mm thick)
- VETO system: 4 lateral planes and 1 bottom plane of plastic scintillators 8mm thick



	EJ-200	LYSO
Decay Time (ns)	2.1	40
Efficiency (photons/1MeV)	10000	27600
Attenuation lenght (cm)	380	1.14
Maximum emission wavelength (nm)	425	420

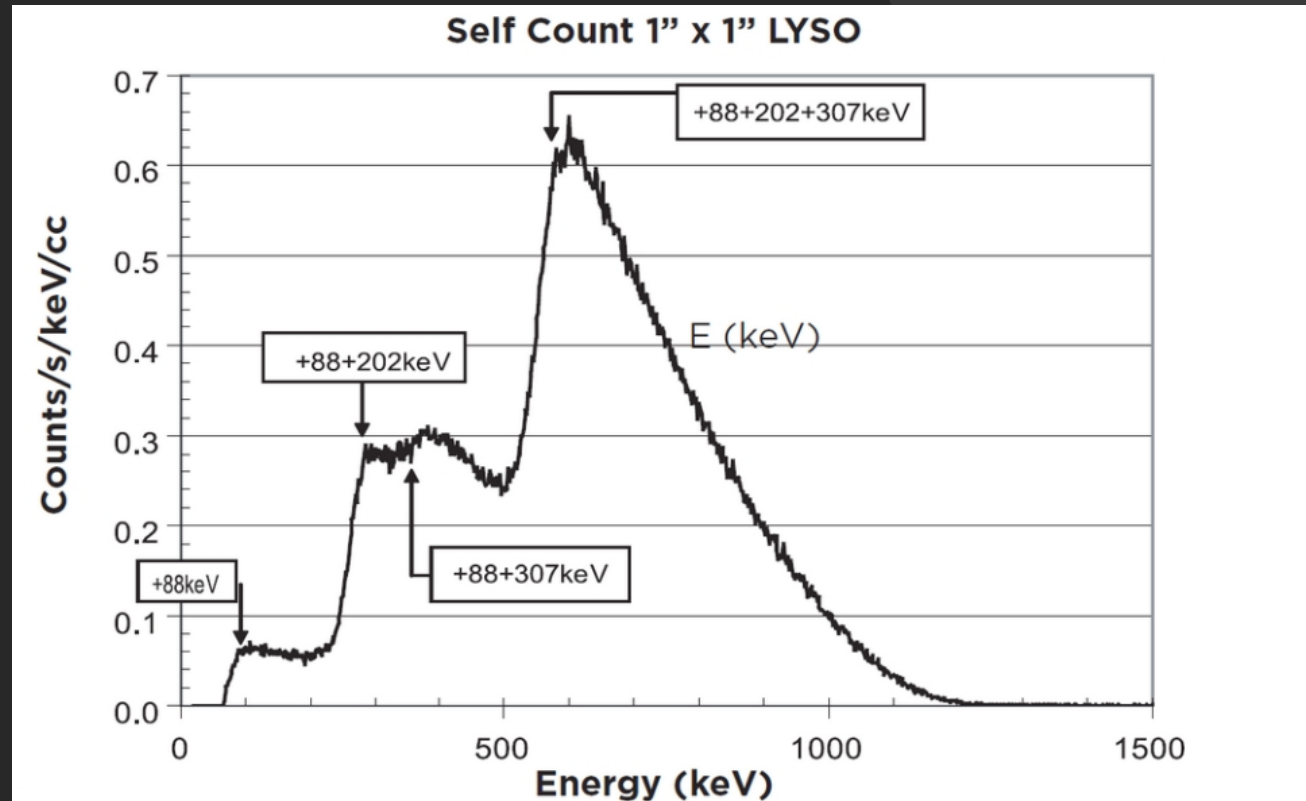
LYSO radioactivity

LYSO crystals contains lutetium and the 2.6% of natural lutetium is the ^{176}Lu isotope which decays beta to excited states of ^{176}Hf with the following reaction:



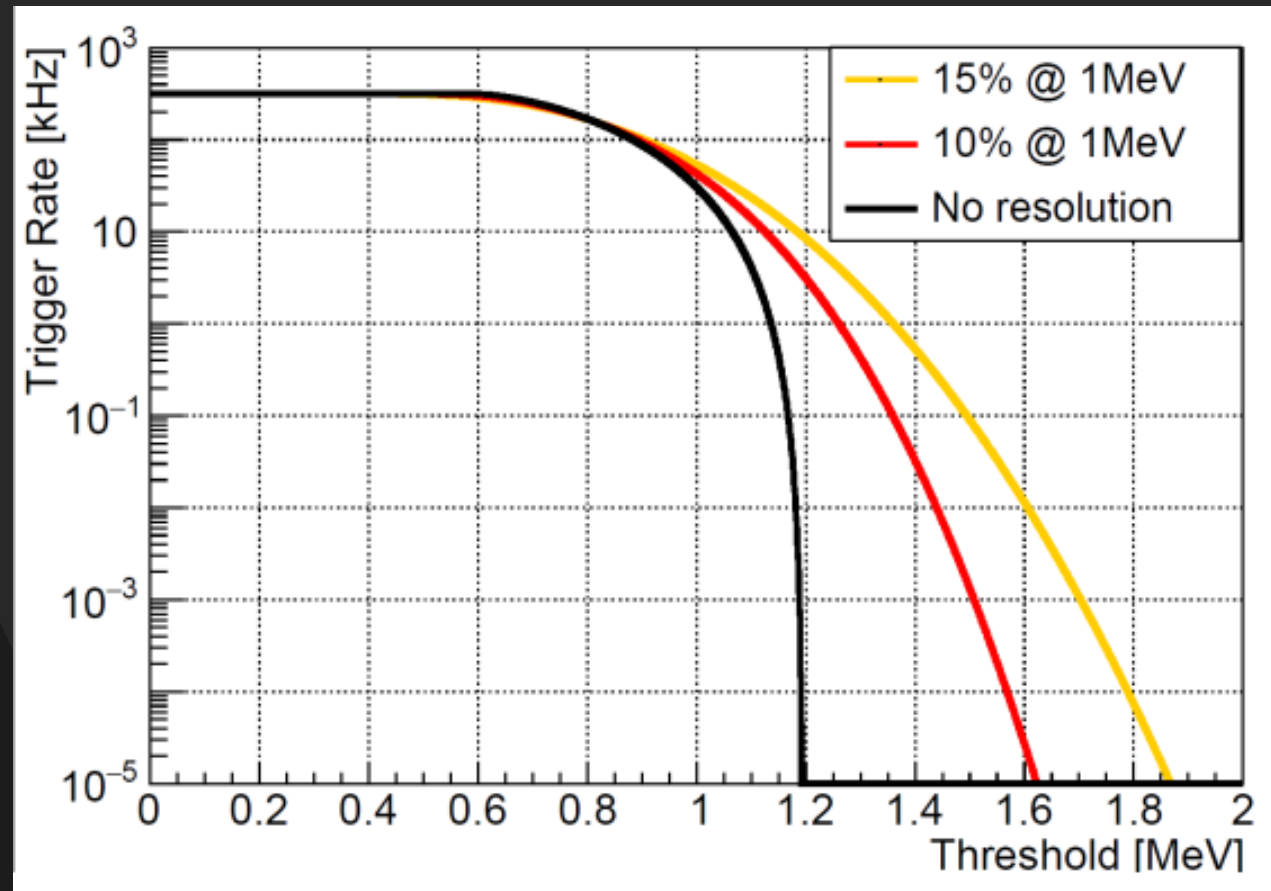
$^{176}\text{Hf}^*$ relaxation produces 3 X-rays (88keV, 202keV and 307keV)

The energy distribution is shown in figure: it can be seen that it extends up to 1.5MeV



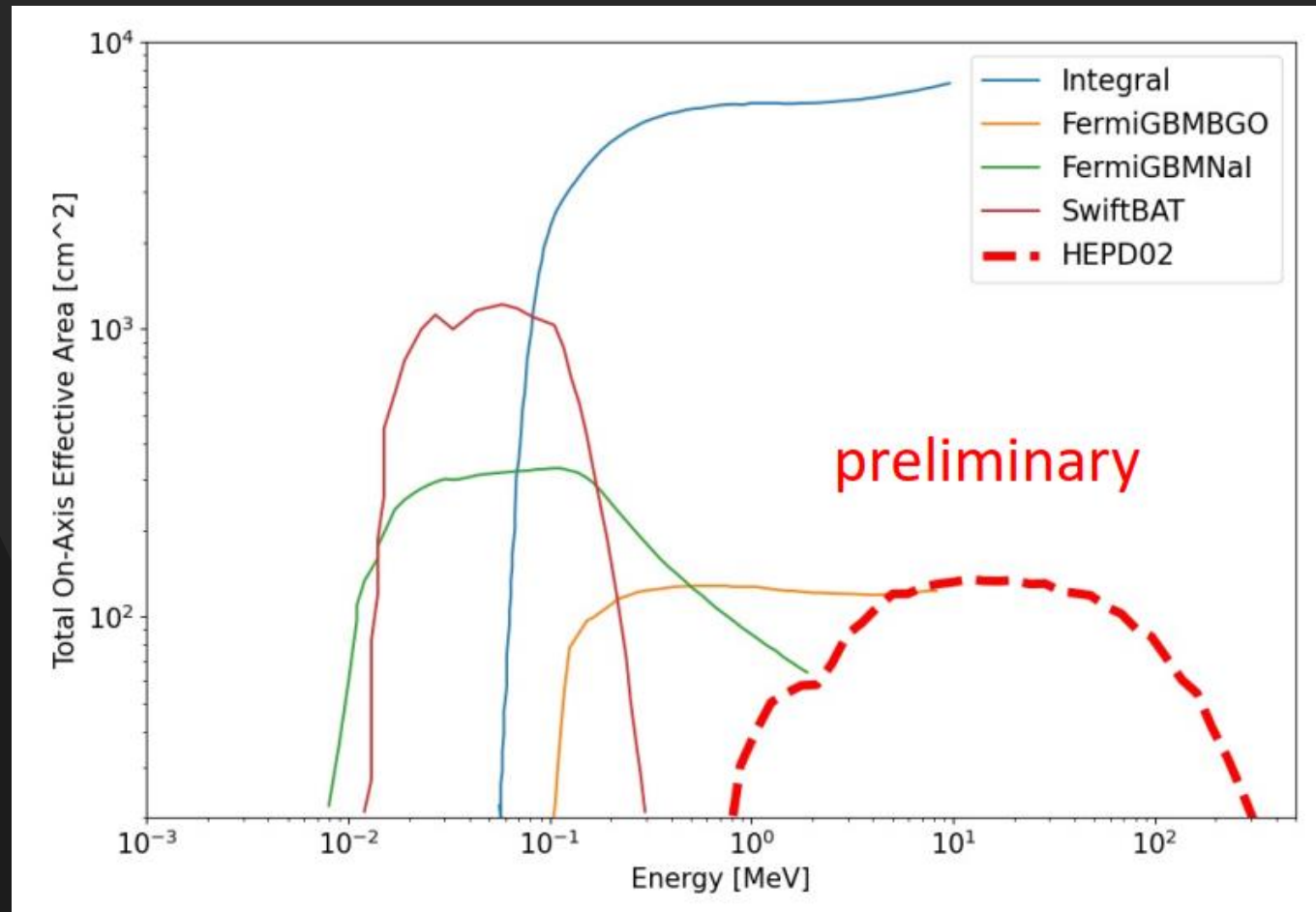
LYSO radioactivity

LYSO radioactivity has been characterized obtaining a rate of 1Hz with a threshold of 1.5MeV and assuming an energy resolution of 15%



GRB detection

Compared to Fermi HEPD will have a similar effective area in the range of 2-20MeV

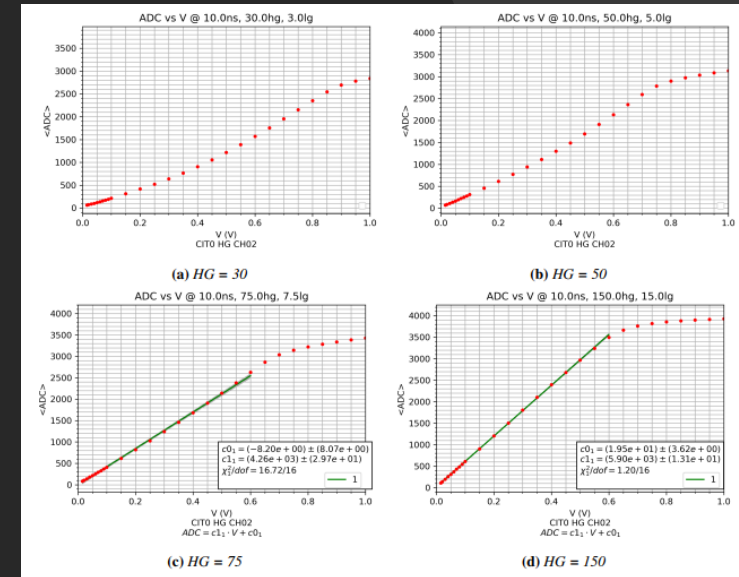


CITIROCs calibration

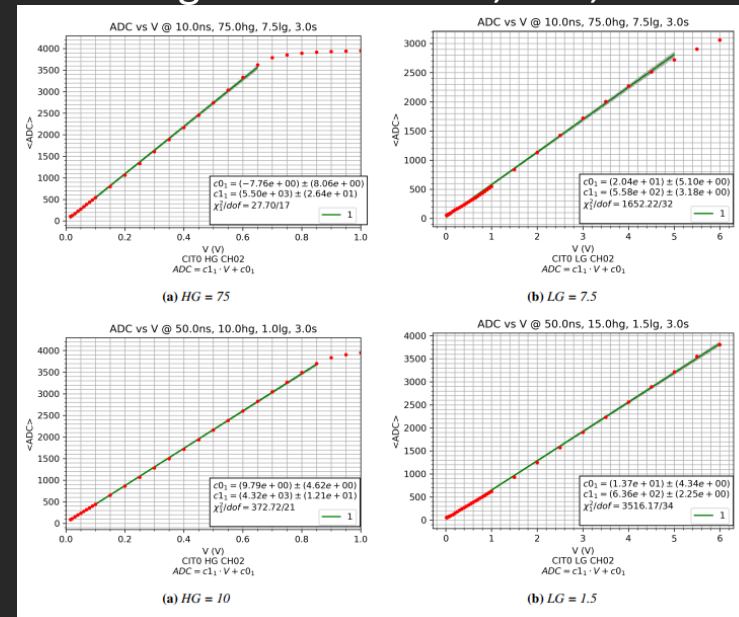
A first set of measurements, involving a limited set of channels of the board, has been carried out using a pulse generator:

- Tested different configuration for preamplifiers gain and shaping time to get the better linearity for plastic scintillators and LYSO crystals.

Calibration curves at different preamp. gains



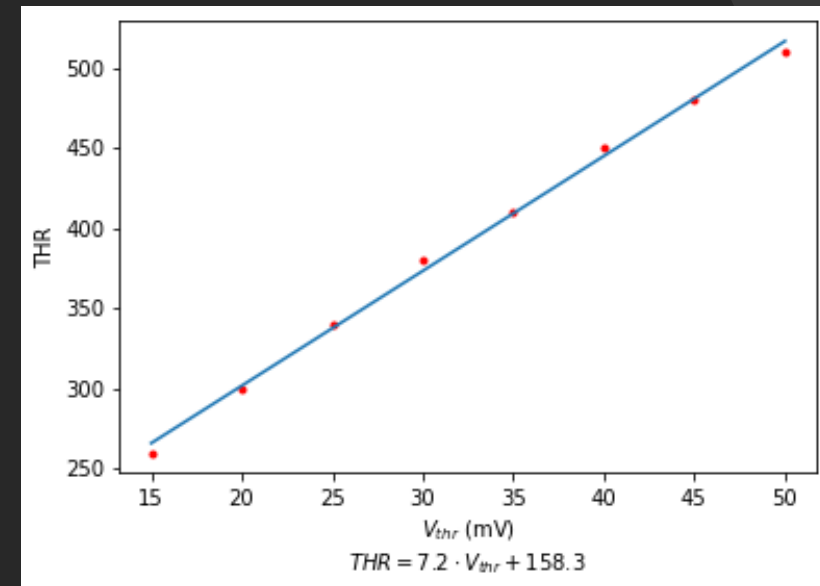
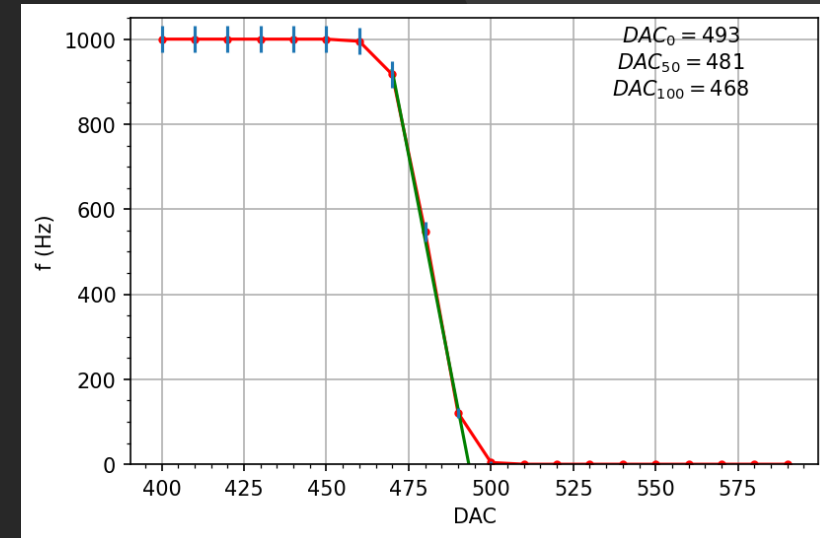
Proposed configuration for TR1, TR2, RAN and LYSO



CITIROCs calibration

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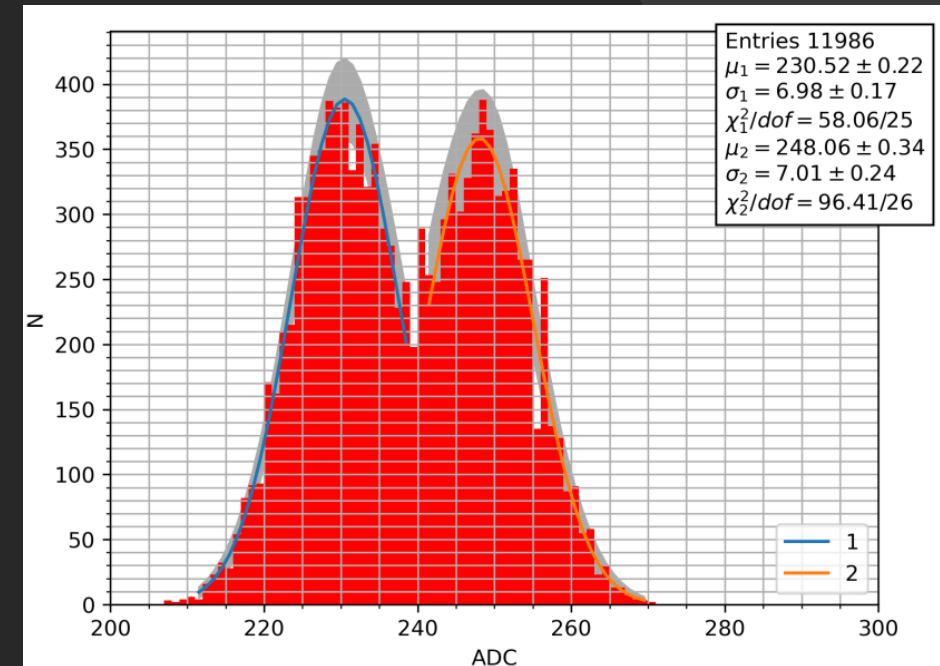
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- Acquired S-Curve for threshold characterization.



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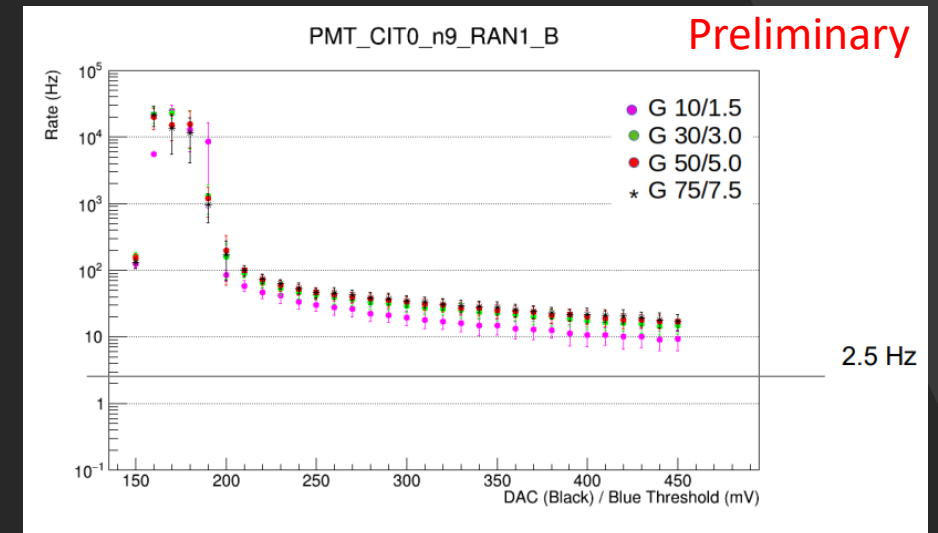
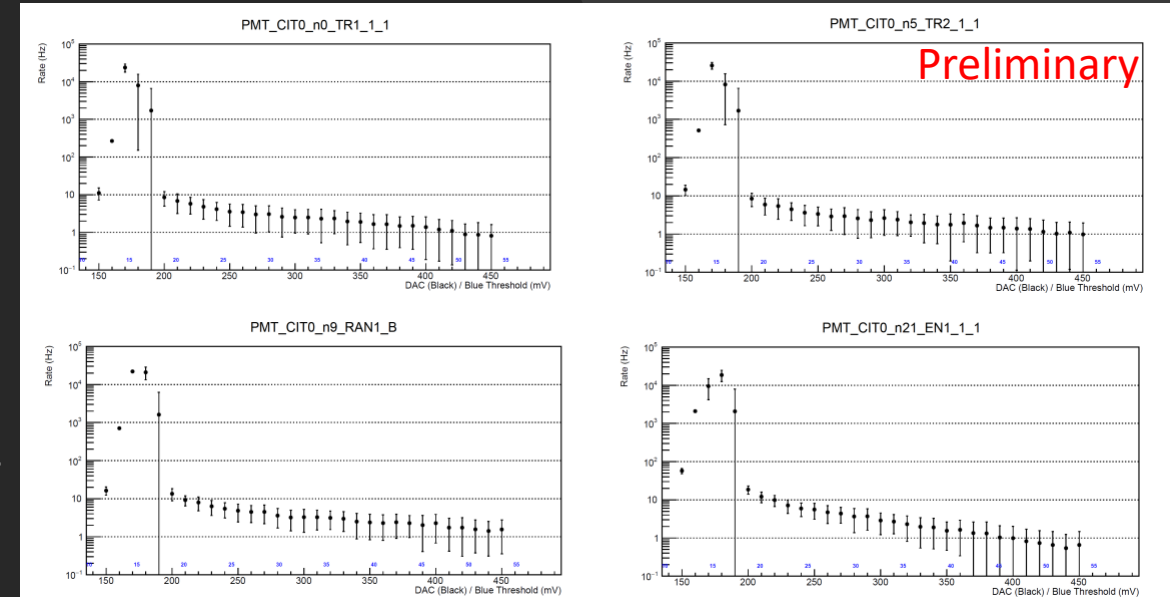
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- Acquired S-Curve for threshold characterization.
- Measured the SNR for 1/3 MIP signals (SNR=2.5).



HEPD-02 FM signals and parameters optimization

The Flight Model of HEPD-02 has been subjected to a series of tests and optimizations:

Using cosmic muons, **threshold scans** have been conducted, for different values of the preamplifier gain, in order to find a suitable value for all the scintillators.

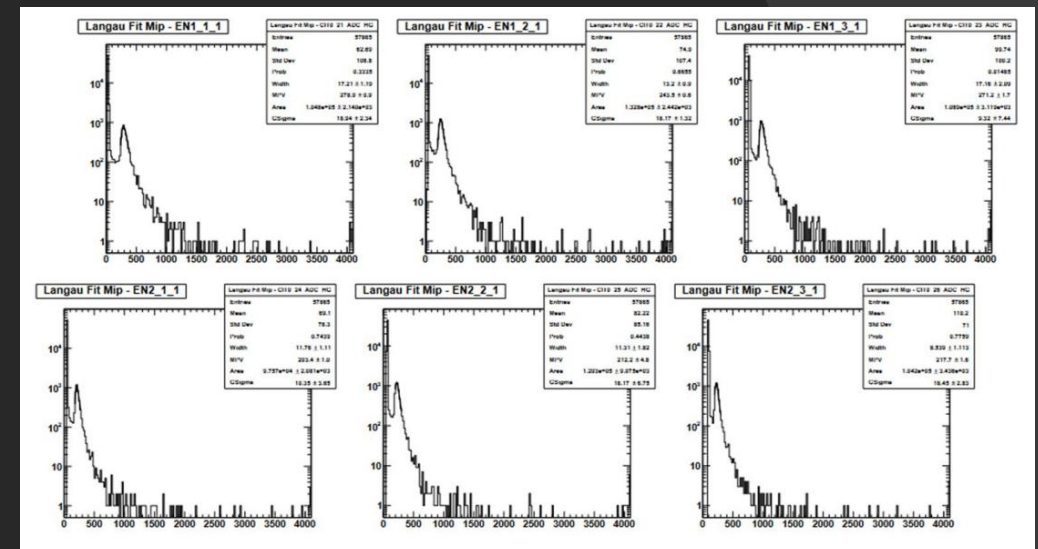
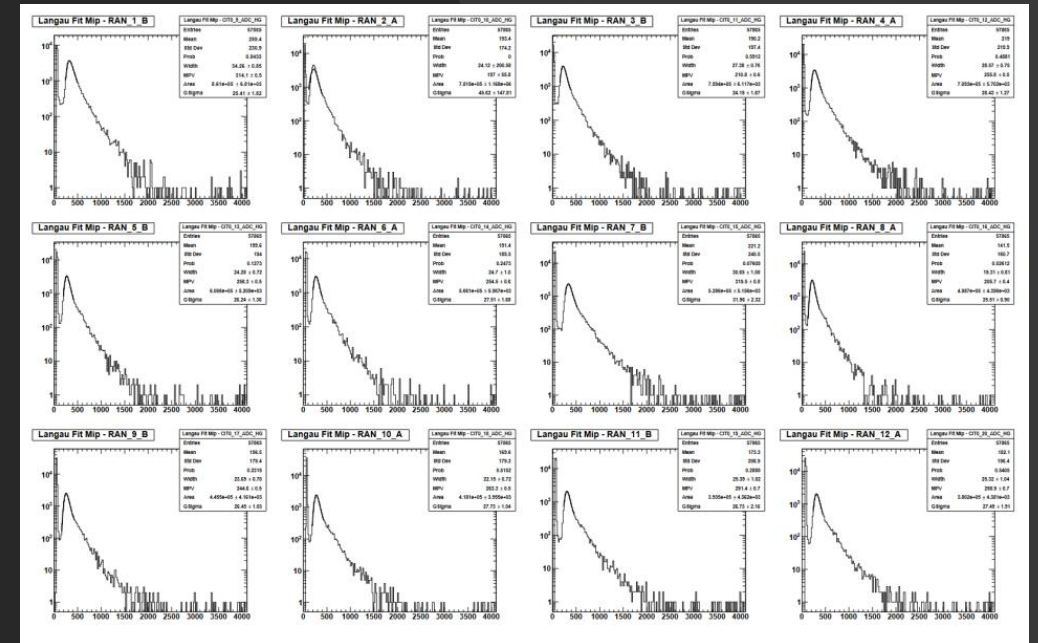


HEPD-02 FM signals and parameters optimization

Preliminary

The Flight Model of HEPD-02 has been subjected to a series of tests and optimizations:

Using cosmic muons, the **ADC value for MIPs** has been tuned for all the channels of the detector, changing the **gain of PMTs** and of **CITIROC's preamplifiers**.



Efficiency of the trigger system

Beam test with protons at 228MeV

TR1 efficiency ~84%

TR1&TR2 efficiency ~92%

