Development of the photo-diode subsystem for the HERD calorimeter double-readout

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The HERD experiment – Scientific objectives

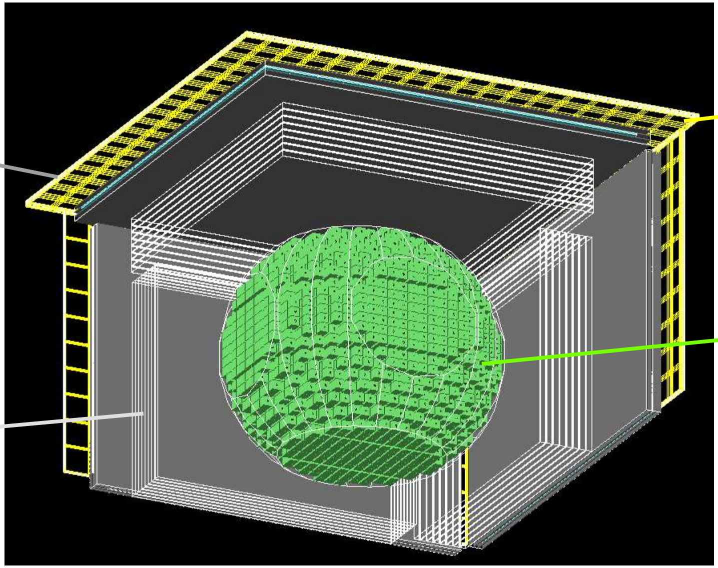
- Direct detection of high energy cosmic rays (low flux: $E^{-\gamma}$, $\gamma \sim 2.7$)
- Main scientific objectives:
  - Fluxes of hadrons up to PeV/n
  - Electron + positron flux up to tens of TeV
  - Gamma ray astronomy
  - Indirect search of dark matter

The HERD experiment – The Detector

Innovative geometry: 5 active faces to have an effective geometric factor more than 10 times that of the currently in orbit experiments (about 2.5 $m^2 sr$ for electrons and about 1 $m^2 sr$ for protons)

PSD (Plastic Scintillator Detector): photons identification and charge measurement

FIT (FIber Tracker): tracking



SCD (Silicon Charge Detector): charge measurement and tracking

CALO (CALOrimeter): energy measurement and electron-hadron discrimination

The HERD experiment – The Calorimeter

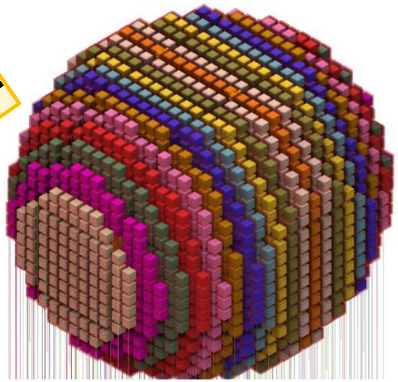
Calorimeter Characteristics:

- Finely segmented (about 7500 LYSO cubic scintillating crystals of side 3 cm)
- Spherical shape
- Homogeneous
- 3D
- Isotropic
- Deep (55 X_0, 3 λ_I)
- Large geometric acceptance
- Good energy resolution (about 2.5% for electrons, < 30% for protons)

Calorimeter requirements:

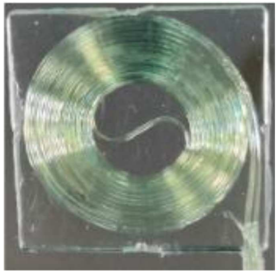
- Strong control of energy scale
- Independent triggers
- Redundancy

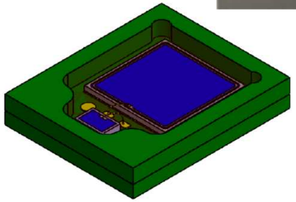
From the CaloCube R&D of our group in Florence!!!



Double read-out systems:

- Wavelength shifting fibers coupled to Intensified Scientific CMOS
- Double Photodiode





The HERD experiment – Calorimeter read-out requirements

Energy deposit to measure in every crystal:

- Calibration via MIP: ~30 MeV
- Hadrons up to PeV/n: ~250 TeV

-Extremely large dynamic range: >10^7

-Saturation level of the single channel more then 20 times of currently in orbit experiment

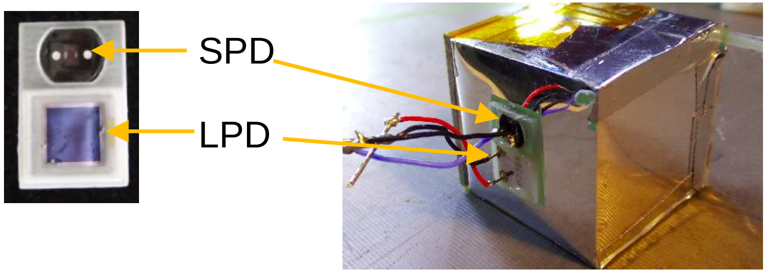
-Number of channels more then 20 times of currently in orbit experiments

Also needed:
Low power consumption
Low noise

Developing ad hoc sensors and read-out electronics

Double Photodiode read-out system – The sensors

Composed by two photodiodes with different active areas assembled in a plastic package (every PD has its own ceramic package):
LargePhotoDiode (LPD) → VTH2110, active area 25 mm^2
SmallPhotoDiode (SPD) → VTP9412, active area 1.6 mm^2
(both produced by Excelitas Technologies)



Different active areas means sensibility to different levels of the scintillation signal → extend dynamic range

- LPD sensible to larger signals, lower saturation level → calibrated via MIP particles
- SPD sensible to bigger signals, higher minimum detectable signal → calibrated via its correlation with LPD

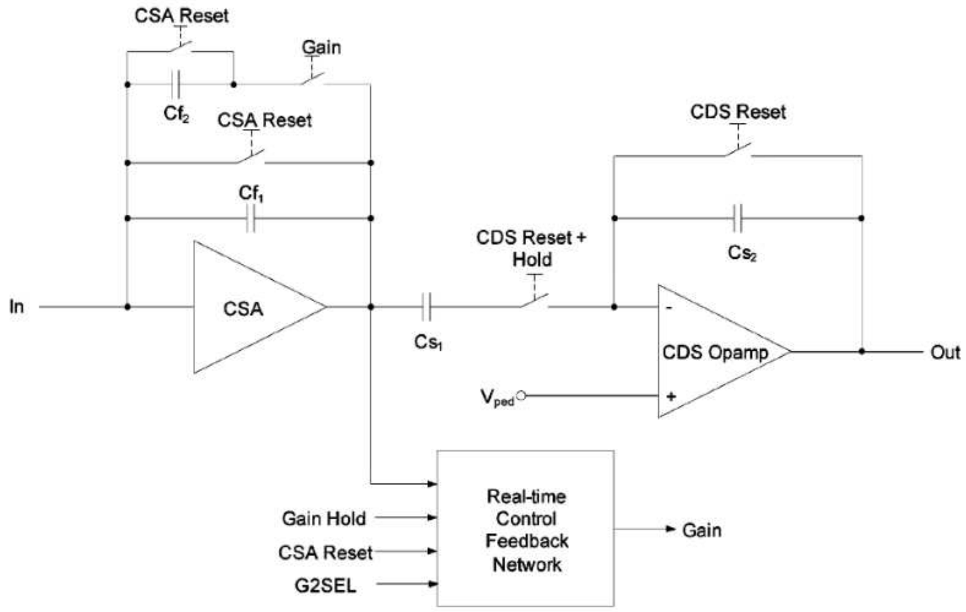
We need an overlapping region between the working ranges of the two photodiodes to calibrate the SPD

Double Photodiode read-out system – The FrontEnd Electronics

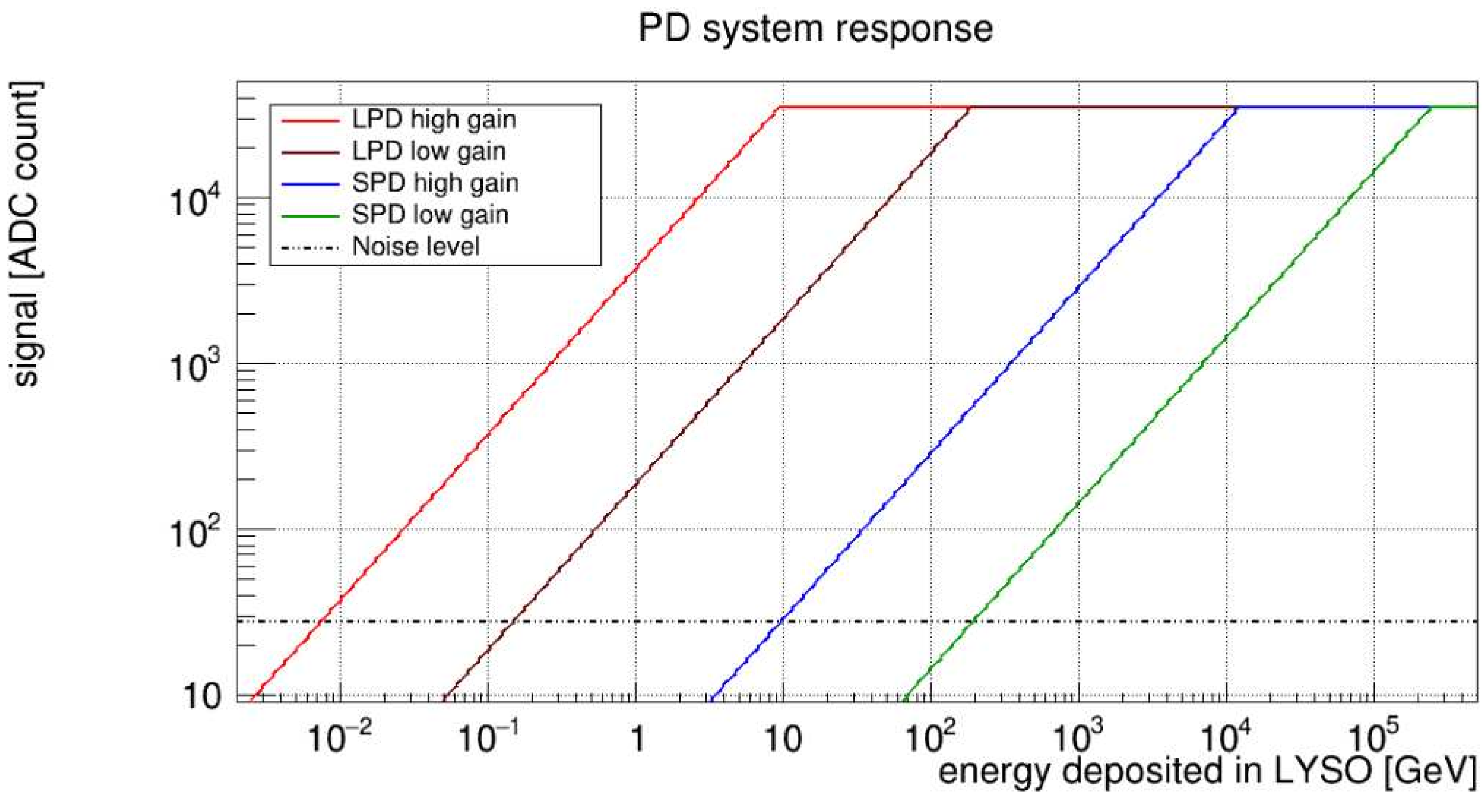
FEE developed for the experiment: HiDRA chip
- Low power consumption: 3.75 mW per channel
- Low noise: ENC ~ 2500 equivalent electrons
- High dynamic range: 10^5
- Self-trigger circuit

Composed by two main parts:
- Charge Sensitive Amplifier (CSA)
- Correlated Double Sampling (CDS)

High dynamic range reached thanks to the **automatic gain selection of the CSA**: HighGain / LowGain = 20



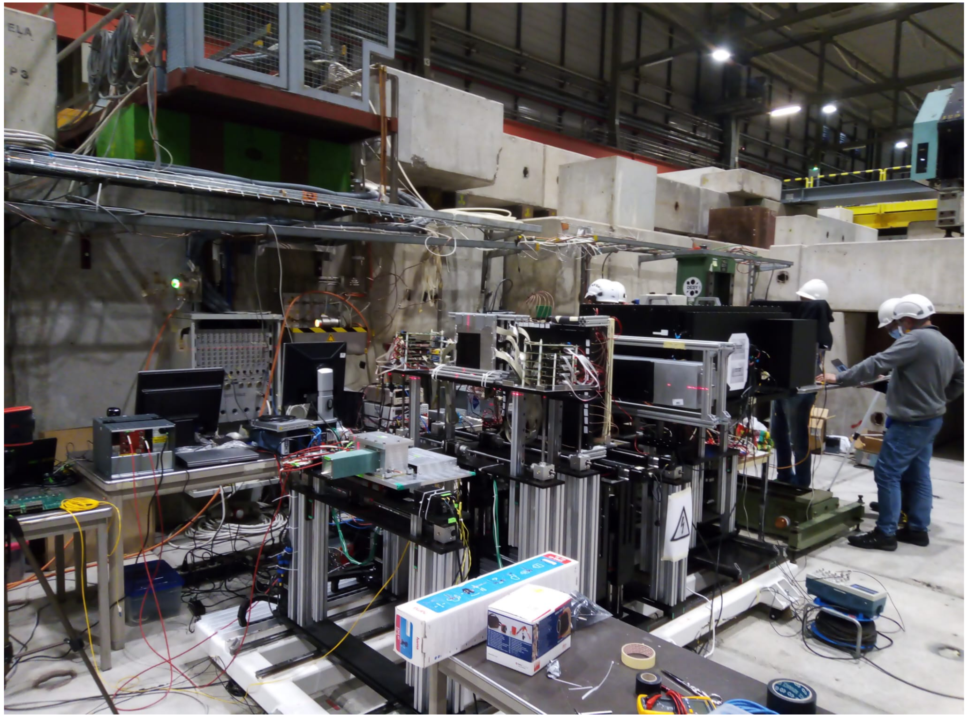
Double Photodiode read-out system – The system response

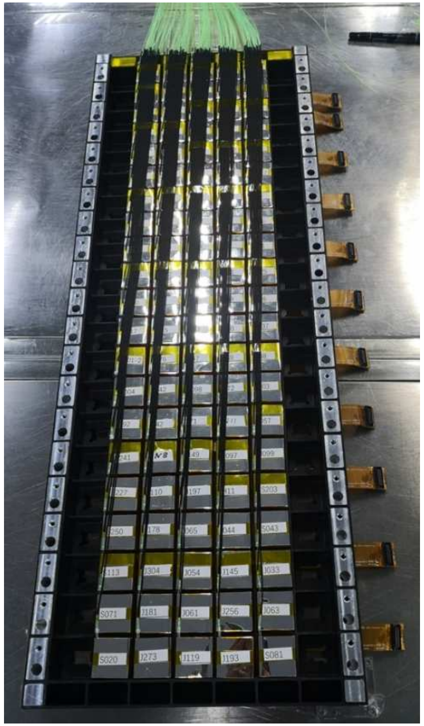


Double photodiode read-out system
Development of the sensors - 1

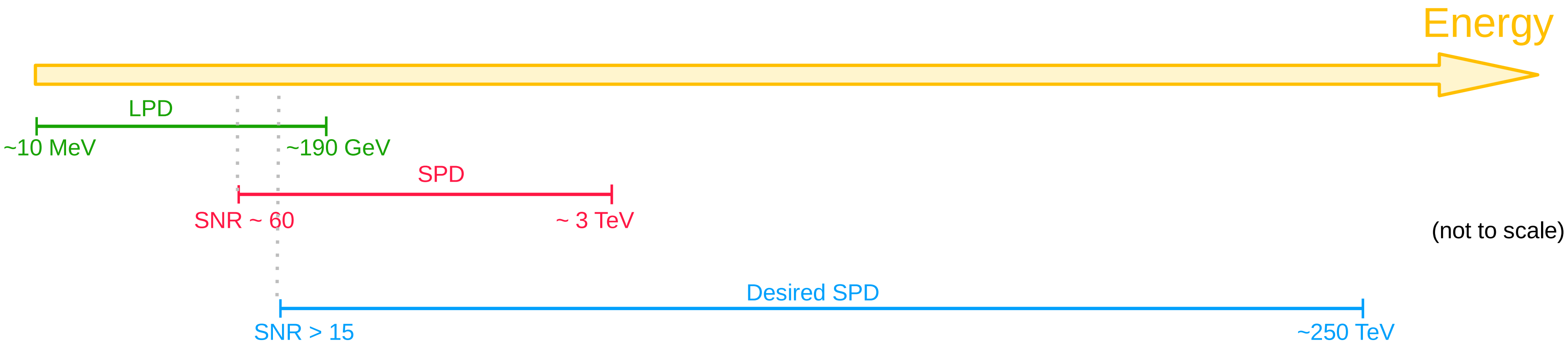
Homemade version
Tested in 2021 at SPS
63 crystals equipped

LPD/SPD~20





SPS2021 beam test – System characterization results



We need to reduce SPD signal of about 98.5%, corresponding to a ratio between LPD and SPD signals of about 1300 instead of 20

Developing a new sensor

Double photodiode read-out system
Development of the sensors - 2

Collaboration with Excelitas Technologies from 2022 to develop a new sensor

LPD and SPD in same FR4 package + SPD surface covered with inconel (metallic deposition) filter (requested transmittance of 1.5%)

Tested at Careggi hospital radiotherapy accelerator

LPD/SPD~50
Filter technology not controlled for isotropic light!

Double photodiode read-out system
Development of the sensors - 3

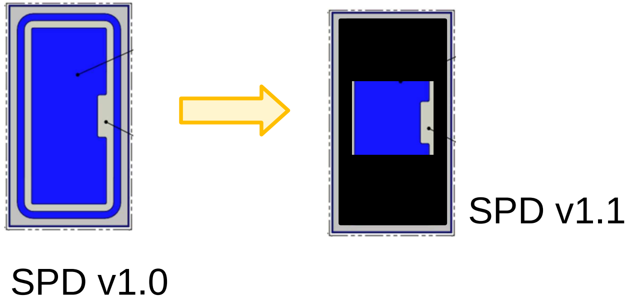
Second Excelitas development (end 2022): mask part of SPD active area

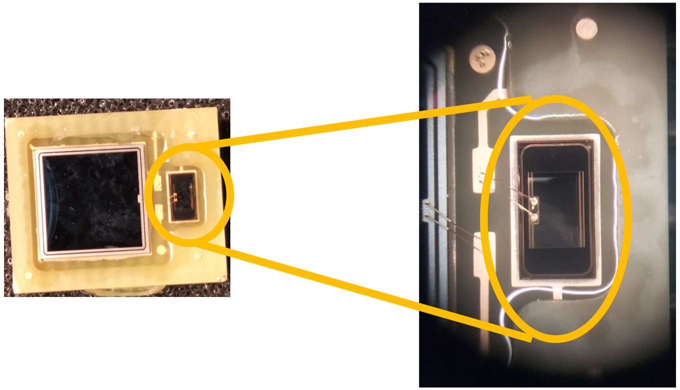
Tested at BTF Frascati
5 crystals equipped

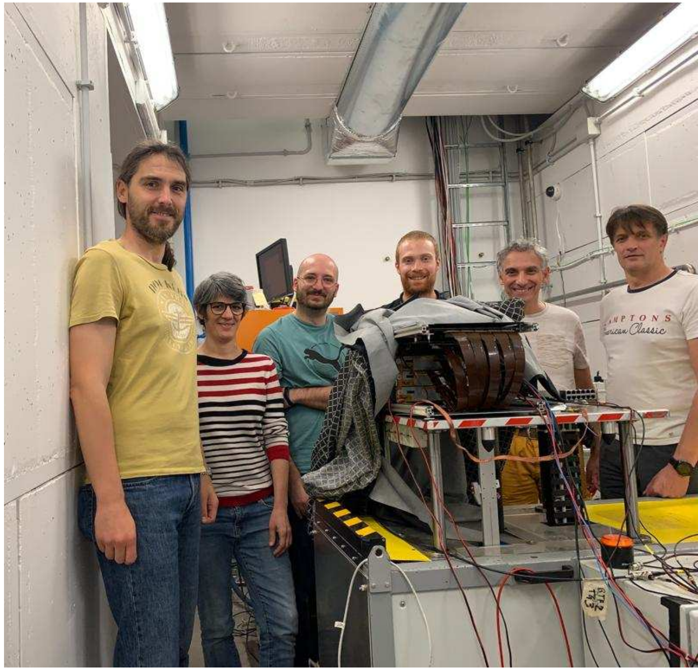
LPD/SPD~500

Signal from photons hitting outside the chip metallization

The mask reduce only light signal, not direct ionization signal!







Double photodiode read-out system
Development of the sensors

Homemade version
Tested in 2021 at SPS
63 crystals equipped

LPD/SPD~20

First Excelitas development (start 2022)

LPD/SPD~50

LPD and SPD in same FR4 package + SPD surface covered with filter

Second Excelitas development (end 2022)
Tested in PS-SPS2023
500 crystals equipped

LPD/SPD~500

Mask part of SPD active area

Third Excelitas development

LPD/SPD → 1300

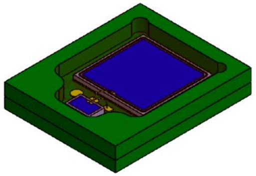
Epitaxial SPD
Active area: 0.02mm^2

First prototypes expected at the end of this year

Summary

Status of the PD read-out system:

- Very high dynamic range: $>10^7$
- Low noise
- Low power consumption
- New sensors expected at the end of this year

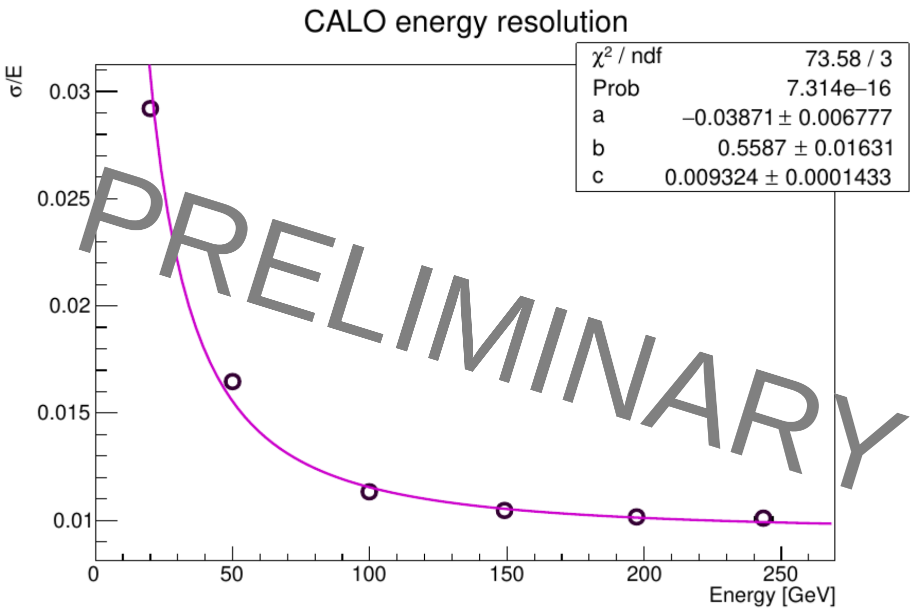


The innovative HERD double photodiode read-out system with high dynamic range, low power consumption and low noise is approaching the final steps of its definition. This will let us to measure from MIP releases in a crystal (~30 MeV) up to releases of PeV cosmic protons (~250 TeV).

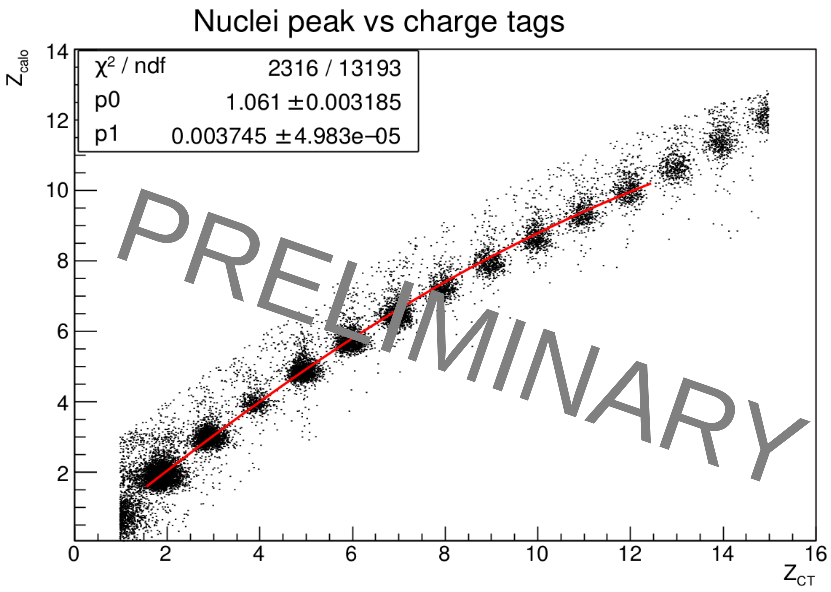
Development of the sensors – 3
SPS beam test in 2023

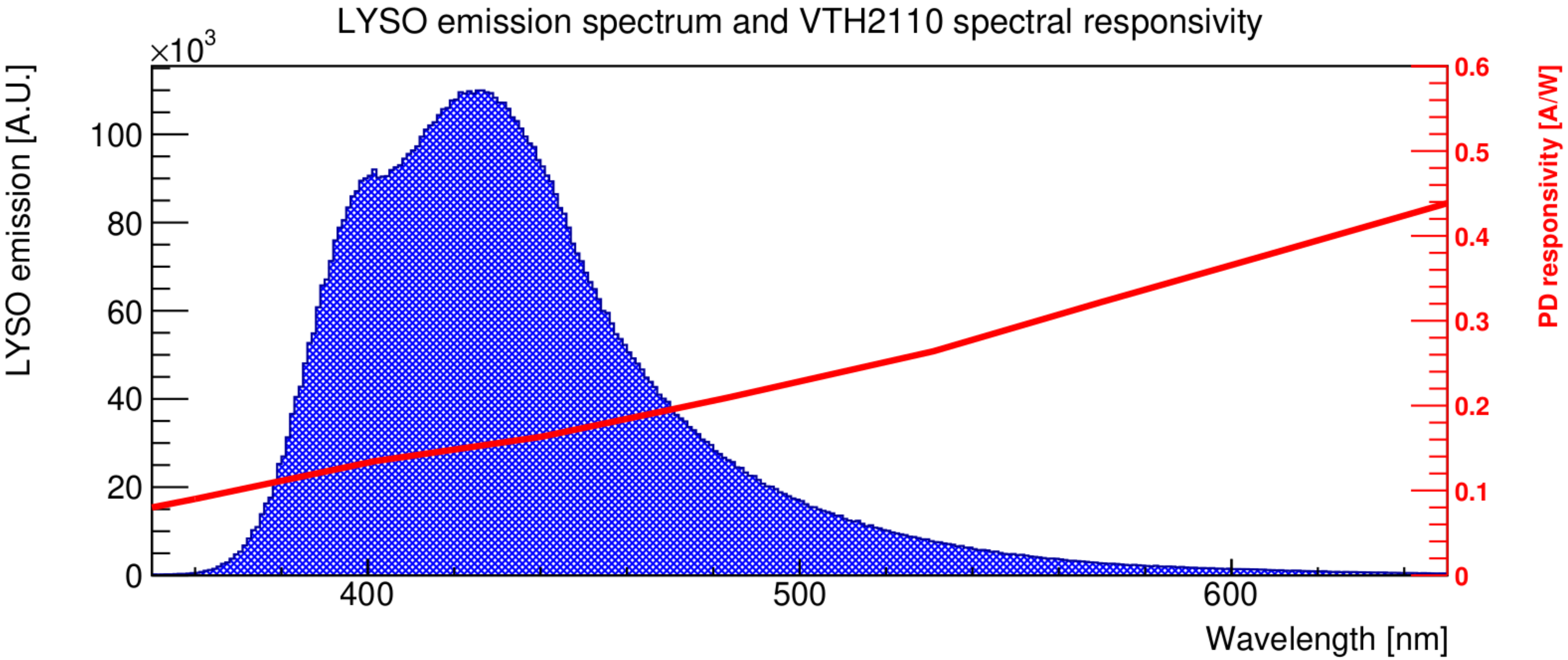
- Prototype of 1029 crystals

Energy resolution for electrons



Nuclei peaks in LYSO

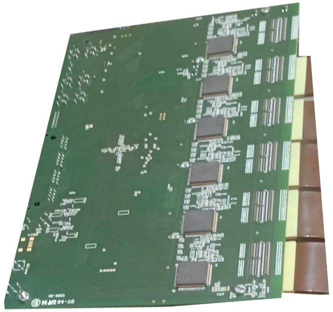



LYSO emission spectrum and VTH2110 spectral responsivity
×10^3
LYSO emission [A.U.]
0
20
40
60
80
100
400
500
600
Wavelength [nm]
PD responsivity [A/W]
0
0.1
0.2
0.3
0.4
0.5
0.6

Developing new features in the read-out electronics

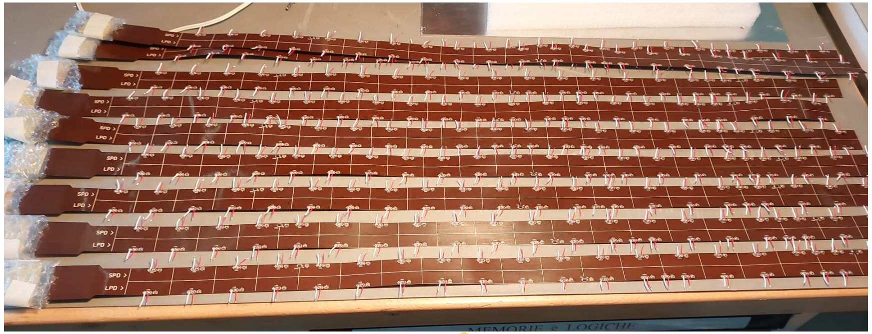
- HiDRA3 chip release

- Single-channel switch-off with settable threshold to avoid signal injection in neighboring channels when over-saturating
- Increase the number of channels for every chip (from 16 to 24)
- New front-end board hosting HiDRA3 chips and TROC2 logic

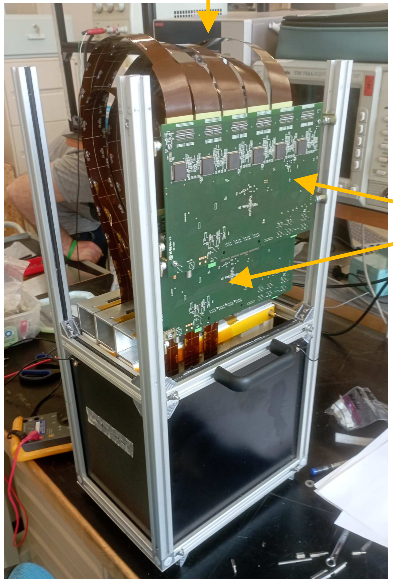


- New kapton cables for flight model

- Cable length extended for flight model (from 10 to 21 packages connections)
- Connections for 3 diodes for common noise subtraction
- Connections for 3 blinded photodiodes for direct ionization monitoring
- Shielding from electromagnetic interferences optimized



Developing new features in the read-out electronics – BTF beam test



Beam Test Facility at Laboratori Nazionali di Frascati, INFN
Facility for beam test with electrons up to about 450 MeV, multiplicity from 1 to 10^4-10^5

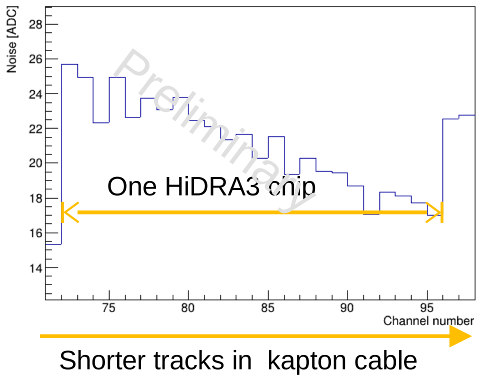
- Composed by 32 crystals: 27 equipped with v1.0 PD package, 5 with the v1.1
- Crystals placed on 3 trays with a maximum length of 5 crystals along the beam line (new version of PD package)
- Upstream pixel detector for beam monitoring

- Single particle runs: 450, 300, 150 MeV electrons
- Multiplicity scans from single particle up to 24k electrons per event

Developing new features in the read-out electronics – BTF beam test

- Analysis is just at the beginning
- Preliminary results:
  - Noise is compatible with previous FEE and kapton cables
  - Test of anti-saturation mechanism

Noise of one HiDRA3 chip
Variation due to length of tracks in kapton cable



Beam multiplicity scan to study saturation mechanism → if the signal overcome the threshold then the channel is switched off