Spanish contribution to the HERD space-based cosmic ray and gamma ray detector

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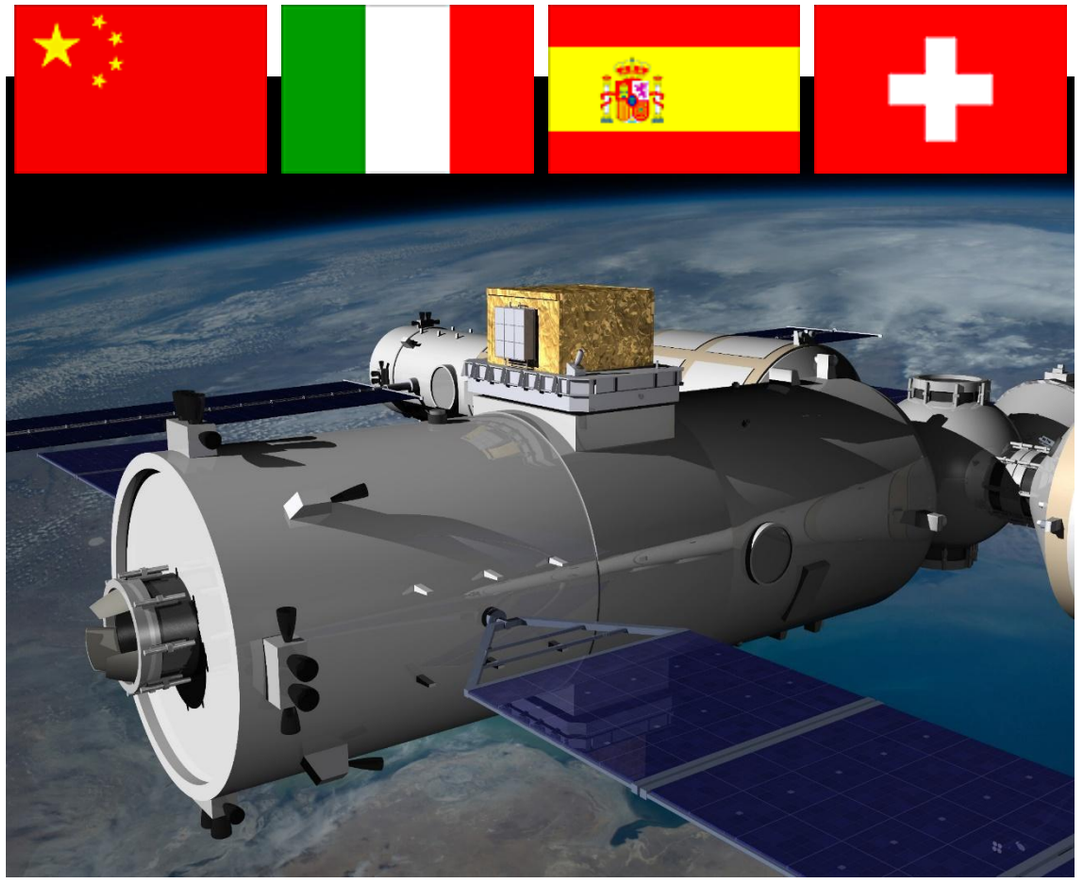
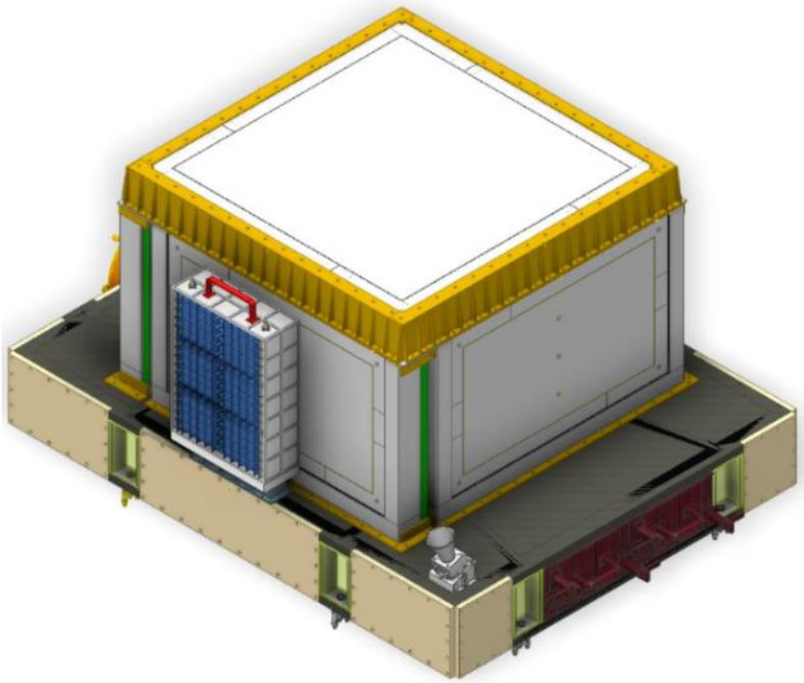
HERD

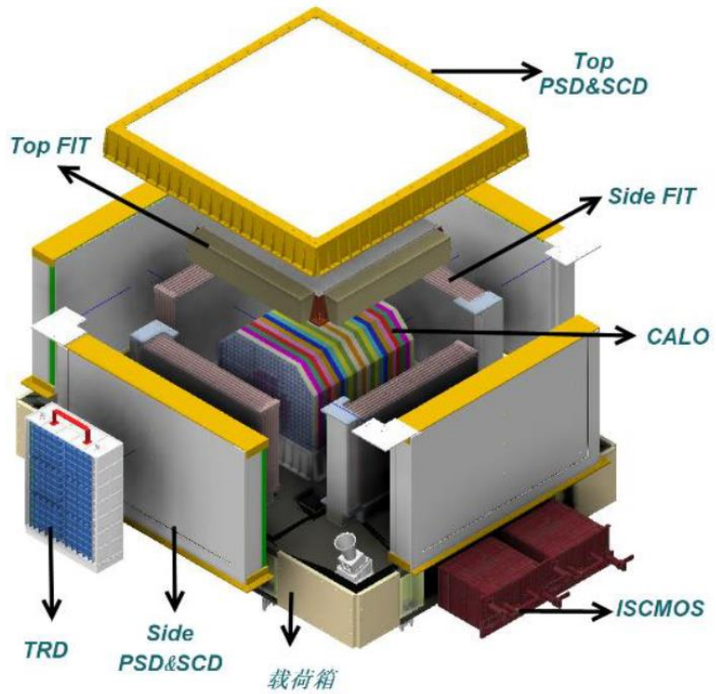
- Spaceborn cosmic-ray and gamma-ray detector
- Flagship scientific experiment in the China Space Station
- Installation foreseen in 2027, operation for 10 years
- China + Italy + Switzerland + Spain (Ciemat, ICCU, IFAE)
- Main objectives:
  - Cosmic-ray spectrum and composition up to 1 PeV
  - Dark matter from high-energy electron and gamma-ray spectra
  - Continuous monitoring of high-energy gamma-ray sky



G.F. (e)	>3 m^2sr@200 GeV
G.F. (p)	>2 m^2sr@100 TeV
Energy range (e/γ)	10 GeV - 100 TeV (e); 0.5 GeV - 100 TeV (γ)
Energy range (p)	30 GeV - 5 PeV
Charge meas.	Z=1-28; <0.15 c.u.@Z=1
Energy resolution (e)	1%@200 GeV
Energy resolution (p)	<25%@100 GeV – PeV
e/p separation	>3*10^5(90% eff.@100GeV)
Angular resolution	0.1 deg.@10 GeV

HERD payload

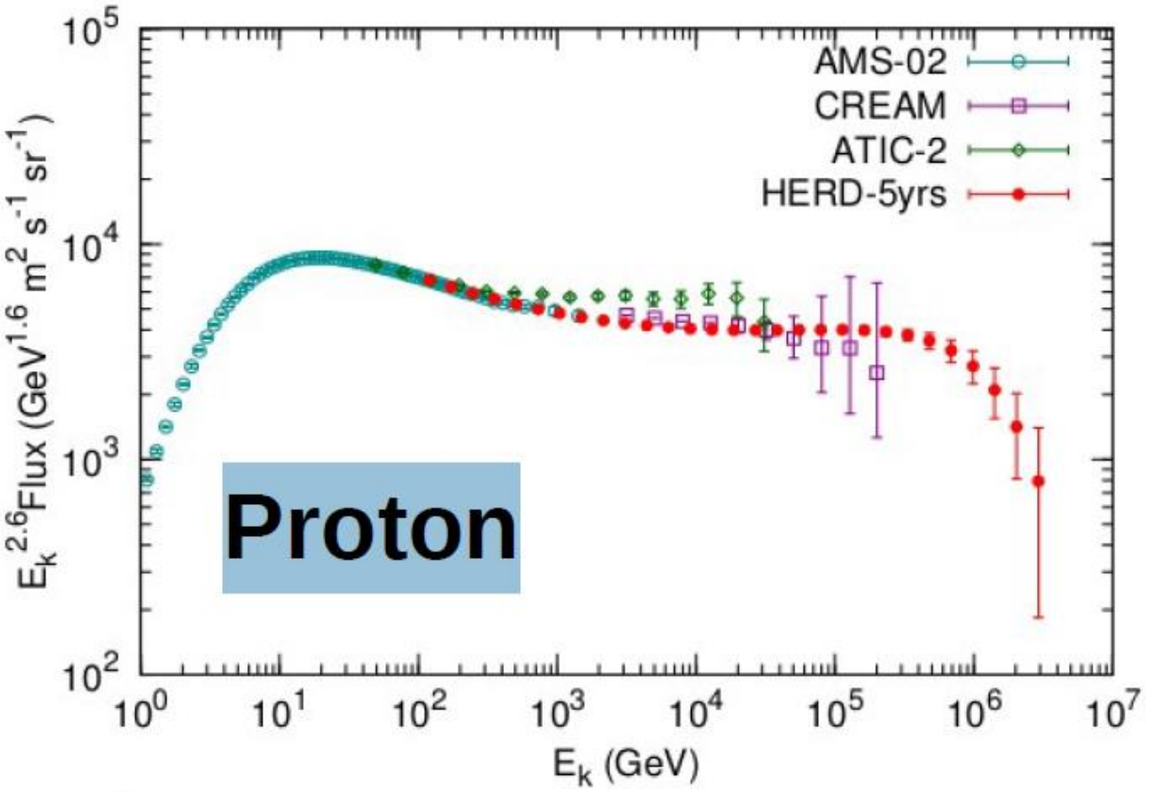


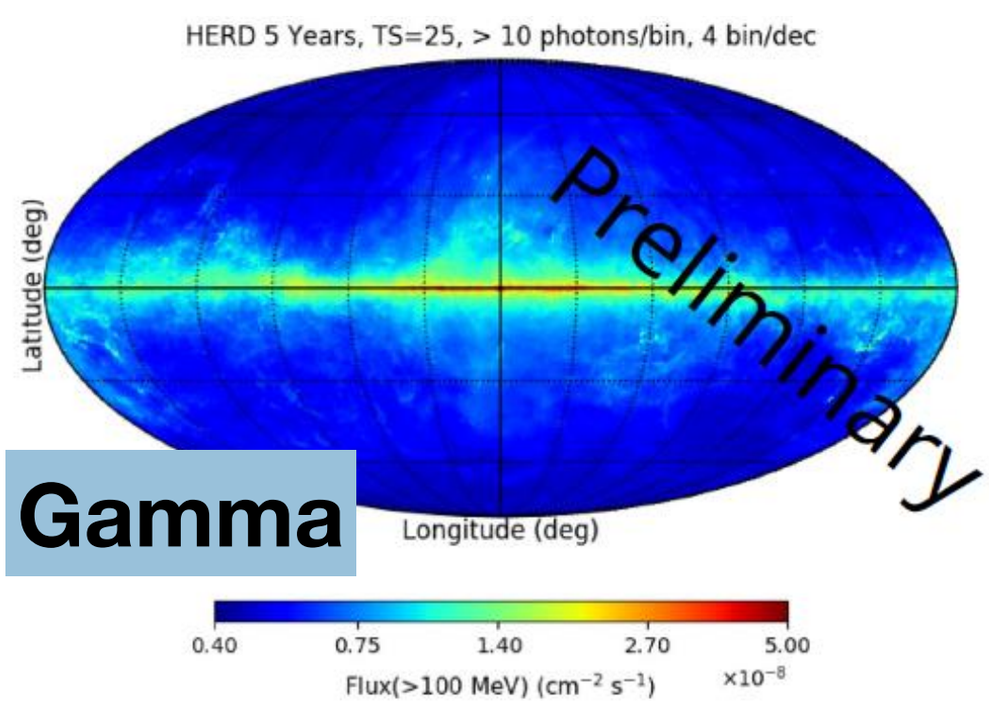


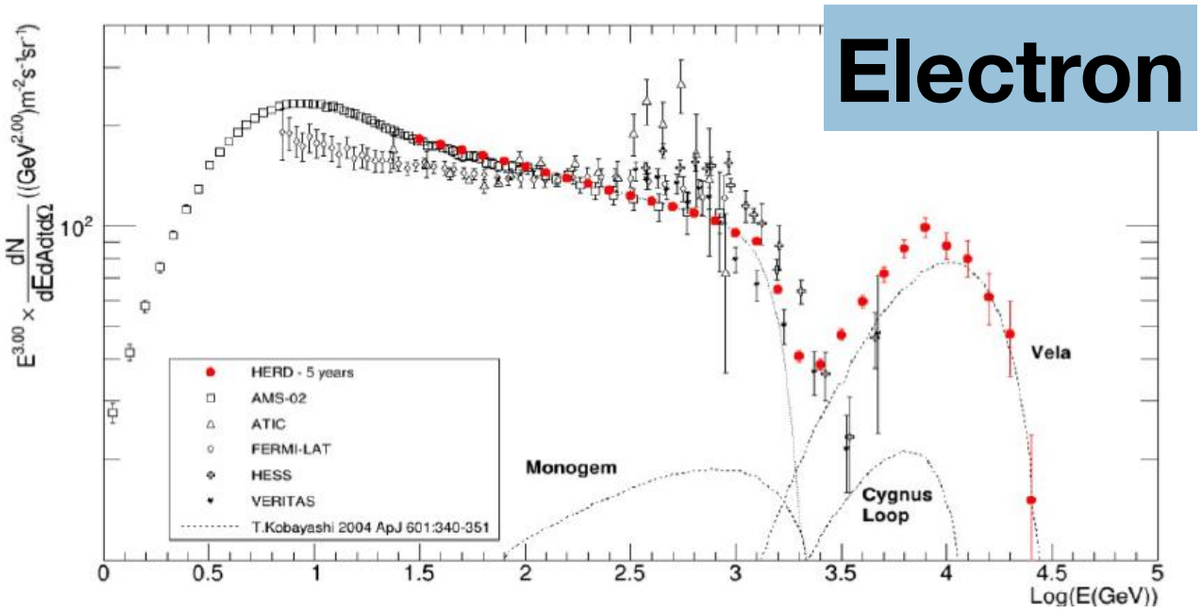
- ★ Increase geometrical factor by using lateral faces
- ★ HERD is composed of 5 subdetectors:
  - ✦ **CALO**: 7500 LYSO cubic crystals, 3D calorimeter for particle energy and electromagnetic particle identification
  - ✦ **FIT**: scintillating fiber tracker for gamma-ray conversion and direction reconstruction
  - ✦ **PSD**: plastic scintillator detector for gamma-ray identification
  - ✦ **SCD**: silicon charge detector for precise absolute charge determination
  - ✦ **TRD**: transition radiation detector (one side only) for absolute calibration of TeV protons

HERD science in a nutshell

- ★ Measure spectral features and composition with better precision and to the highest energies
  - ✦ CR acceleration and propagation
  - ✦ Origin of spectral features/anomalies (astrophysical or DM)
- ★ Wide FoV gamma-monitoring with improved energy and angular resolutions
  - ✦ Multi-messenger astronomy
  - ✦ Fundamental Physics searches







Spanish contribution to HERD

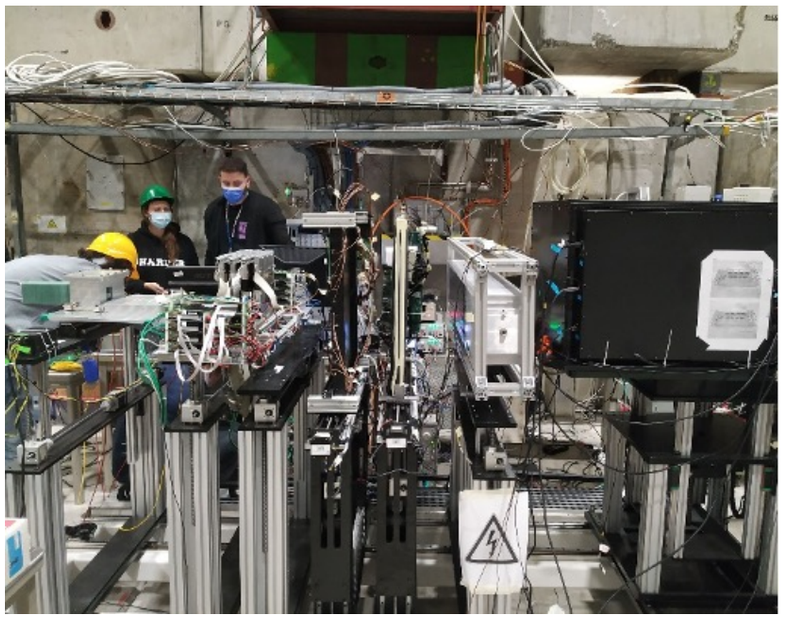
- The Spanish institutions in HERD (CIEMAT, ICCUB, IFAE) lead the development of the readout and trigger electronics of several subsystems (CALO, FIT and PSD)
  - **CIEMAT**: readout and trigger electronics of the photodiode system of CALO; coordinates the HERD trigger WG
  - **ICCUB**: application specific integrated circuit (BETA ASIC) for the FIT and PSD readouts
  - **IFAE**: FIT and PSD readout and trigger electronics and their integration on a “ultra” low energy gamma-ray (ULEG) trigger; coordinates the HERD gamma-ray WG
- We also participate in the assessment of HERD’s scientific capabilities with Monte Carlo simulations

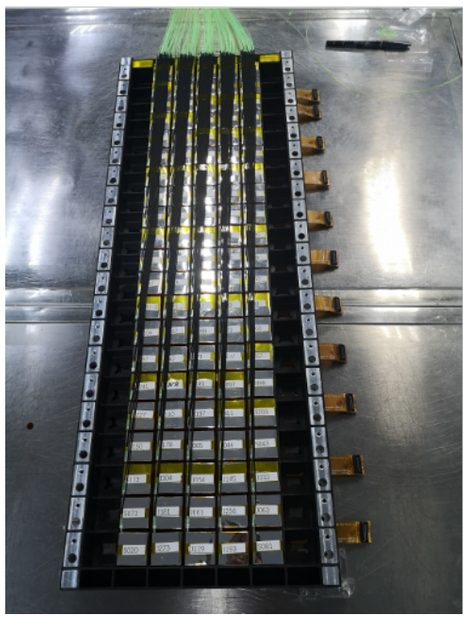
CALO photo-diode readout

- ★ CALO double read-out for robustness, redundancy and cross-check:
  - ✦ Fibers + CMOS camera
  - ✦ Photo-diodes (PD)
- ★ CALO PD readout+trigger electronics by Ciemat:
  - ✦ R&D activities within the Calocube project in collaboration with INFN
  - ✦ Design based on three successive stages of command distribution and data and trigger concentration

Readout tests at CIEMAT

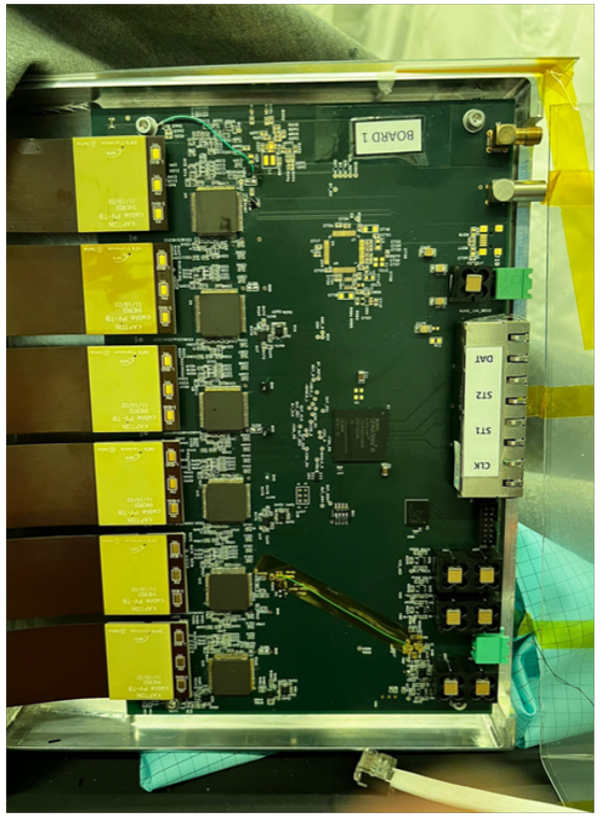
2021 beam test of first prototype at CERN



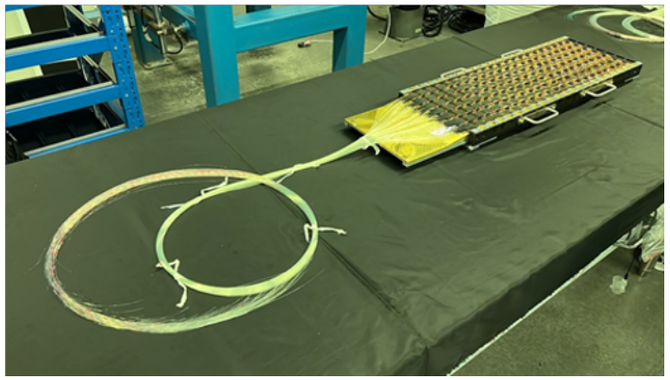


CALO PD readout status and next steps

- ★ Test with protons, electrons and nuclei at CERN PS and SPS during Fall 2023
- ★ Preliminary analysis of the 1,000 LYSO crystal prototype tests at SPS provides electron resolution consistent with specification
- ★ A 2,500 crystal QM prototype will be tested in 2025

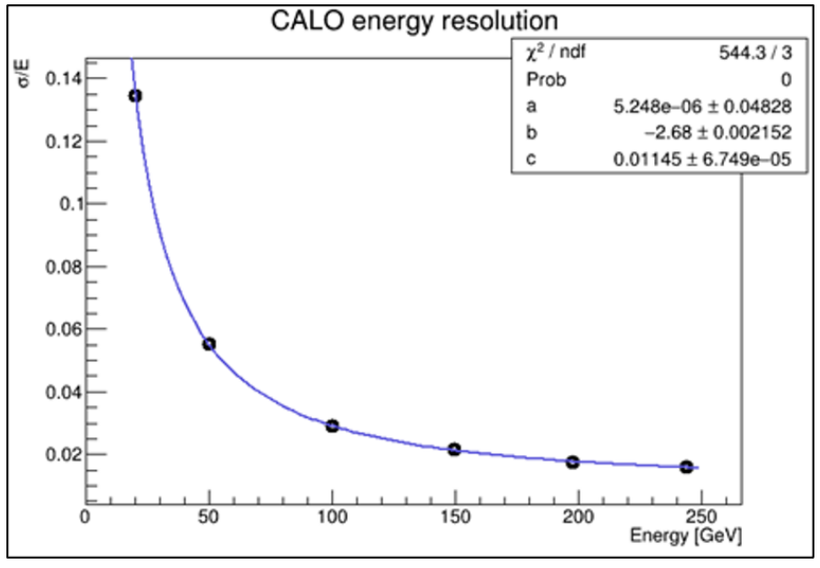


T-ROC2 prototype board



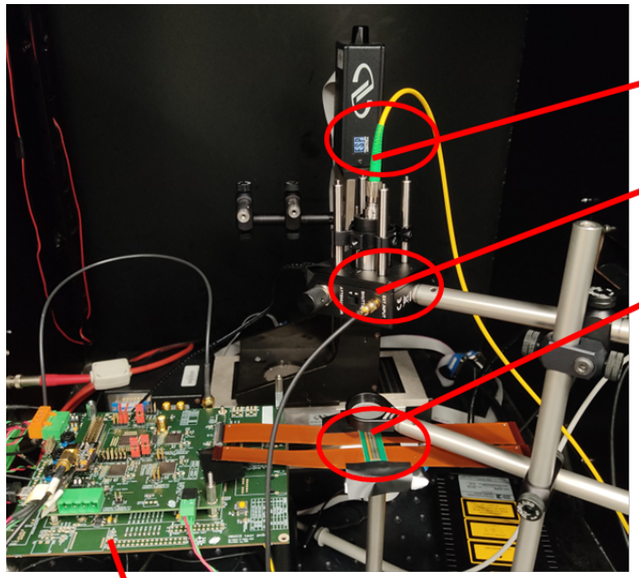
Fully assembled 21×7 crystal tray

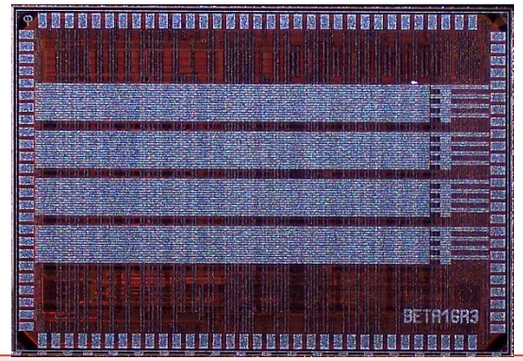
Assembly in Beijing June 2023



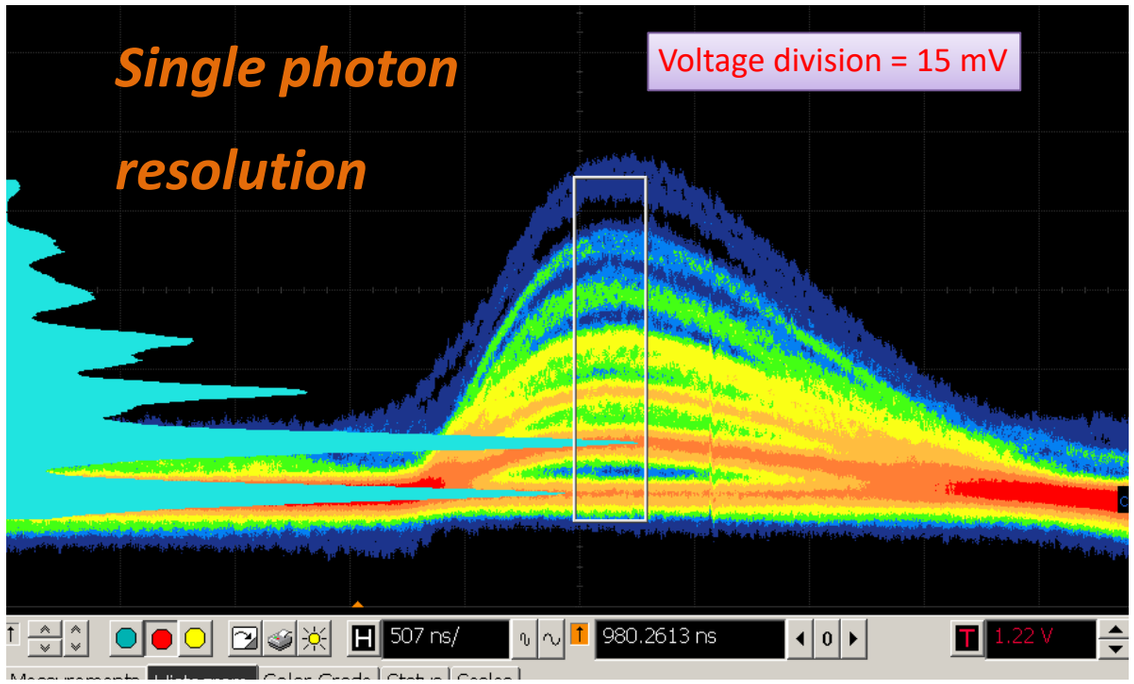
BETA ASIC

- ★ # channels: 16 (PSD) or 64 (FIT)
- ★ Max event rate: 10 kHz
- ★ Configurable preamplifer gain: 4 bits
- ★ Tunable shaping time: 300 ns to 1.5 us
- ★ Trigger output: < 250 ps time resolution
- ★ Single photon resolution: SNR >10
- ★ Dual path: automatic gain switching
- ★ On chip ADC: Wilkinson11 bit + 1bit (path selection)
- ★ Dynamic Range: 15 bit
- ★ Slow Digital Control: I2C
- ★ Power Budget: <1 mW/ch





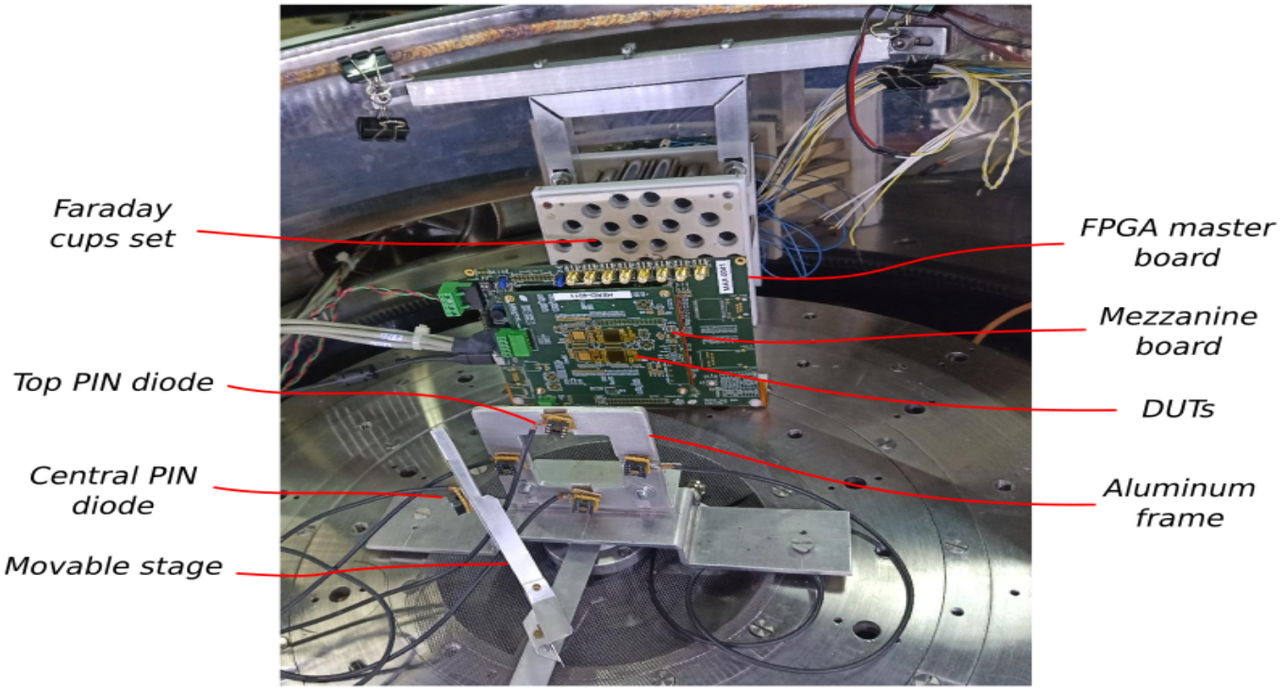
16 ch - 130 nm CMOS – 9 mm²



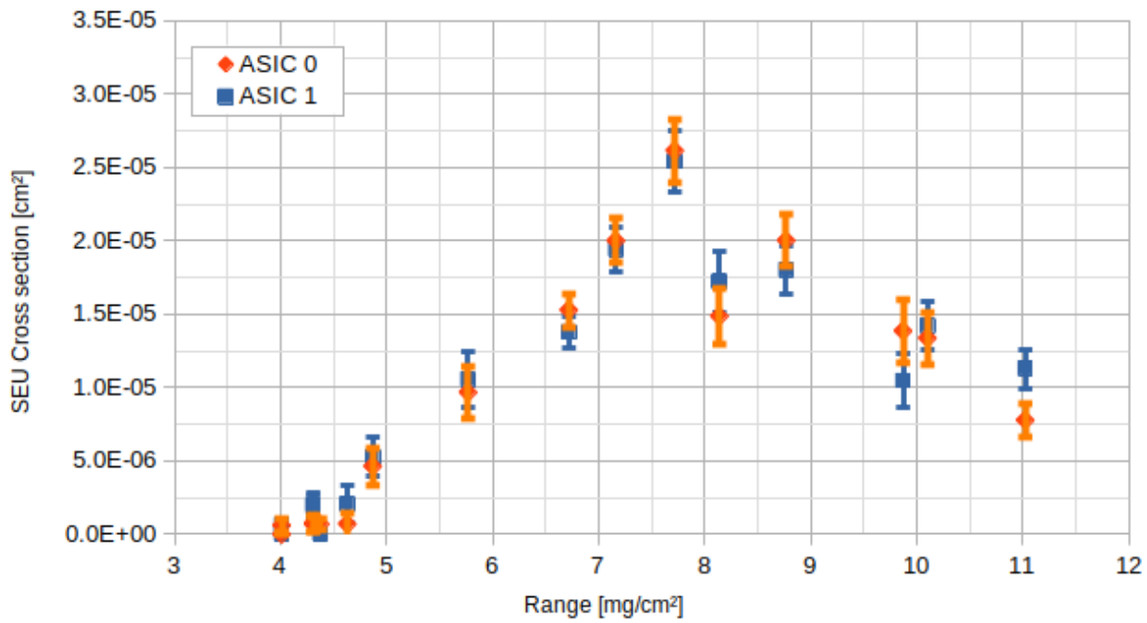
Sanmukh, A.. et al. Low-power SiPM readout BETA ASIC for space applications. NUCL SCI TECH 35, 59 (2024). https://doi.org/10.1007/s41365-024-01419-z

Status BETA (1/2)

- ★ BETA ASIC 16 channels (R1 and R2) tested with particle beams at CERN (PS & SPS) and CNAO:
  - ✦ Collaboration among ICCUB, IFAE, INFN/Bari and University of Geneva
- ★ The BETA16R2 ASIC has been prequalified for radiation
  - ✦ Total Ionizing Dose (TID): No degradation after 100 krads
    - ✣ Test performed at Nayade facility in CIEMAT
  - ✦ Limited Single Events (SEE) qualification: O @ 60 MeV Tests at the EDRA irradiation chamber at Tandar Accelerator, Buenos Aires, Argentina:
    - ✣ No Single Event Latchup (SEL) detected
    - ✣ some sensitivity of the I2C interface to Single Event Transients SETs

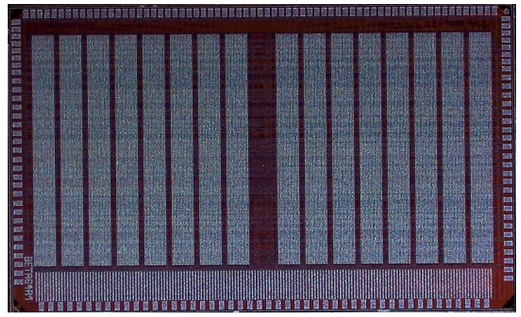


EDRA irradiation chamber

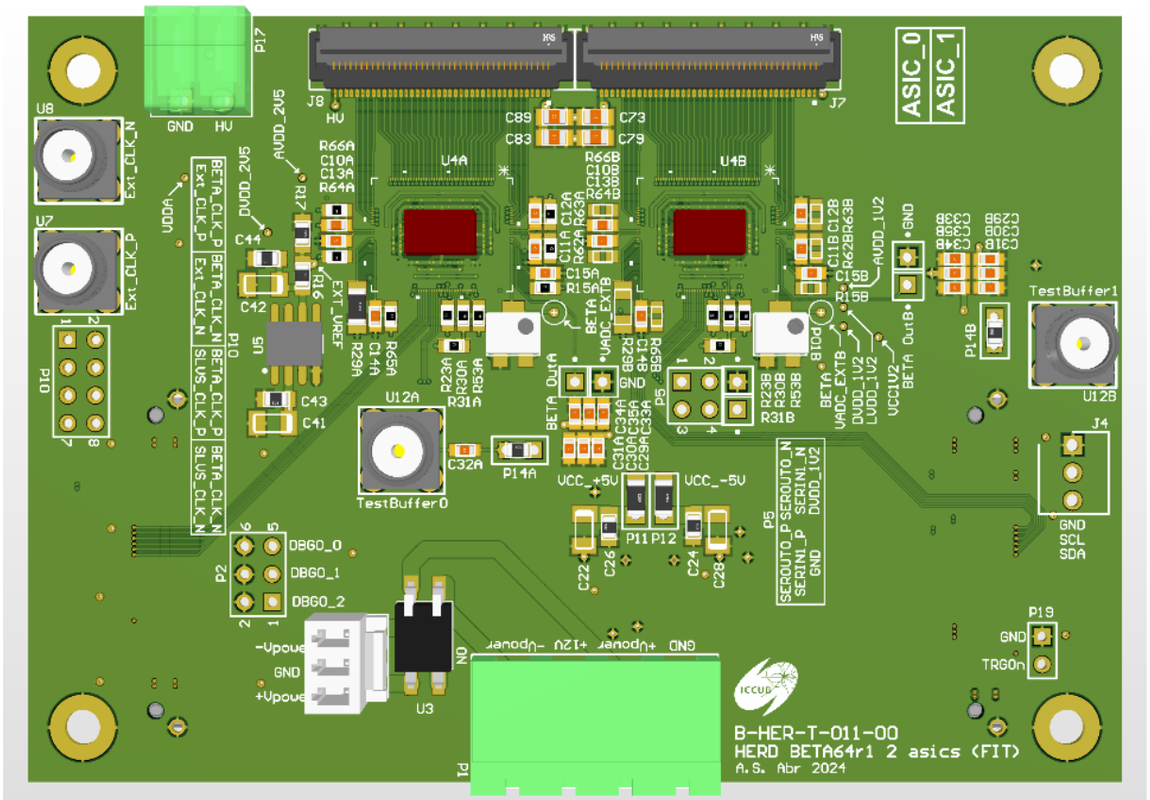


Status BETA (2/2)

- ★ BETA16R3 and BETA64R1 have been produced and are currently under evaluation
  - ✦ Radiation hardened version of the I2C interface
  - ✦ Improved temperature dependence
  - ✦ Additional trigger functionalities
  - ✦ Final space qualification expected for 2024 Q4



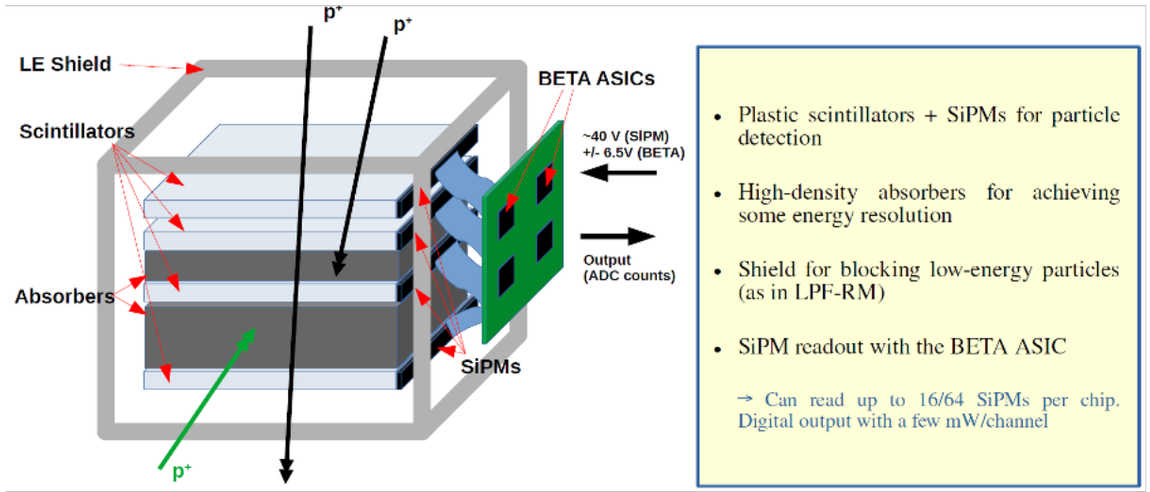
64 ch
130 nm CMOS
24 mm²

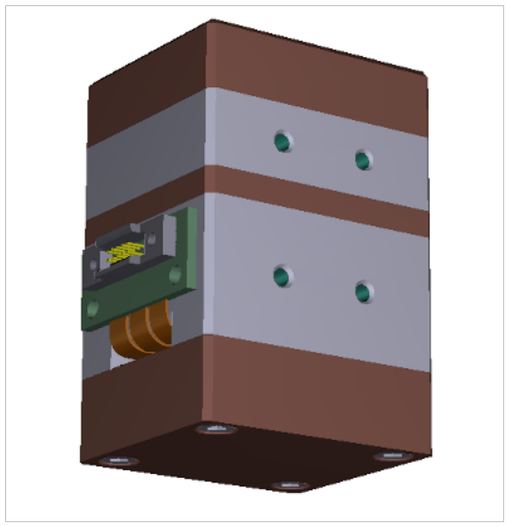


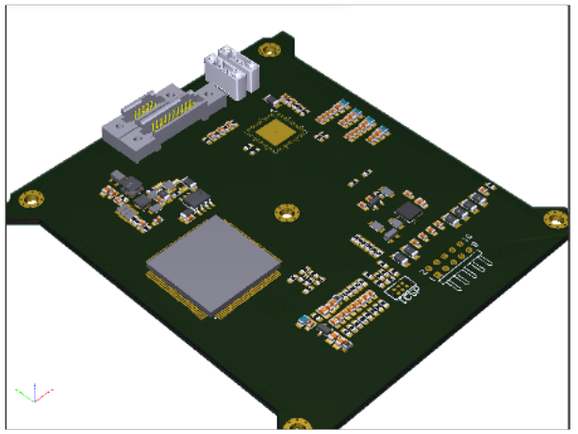
FIT FEB: 2 wire-bonded BETA64r1, 128 channels

Other space missions using BETA ASIC

★ A radiation monitor based on BETA-ASIC is being developed for LISA mission (IEEC project)



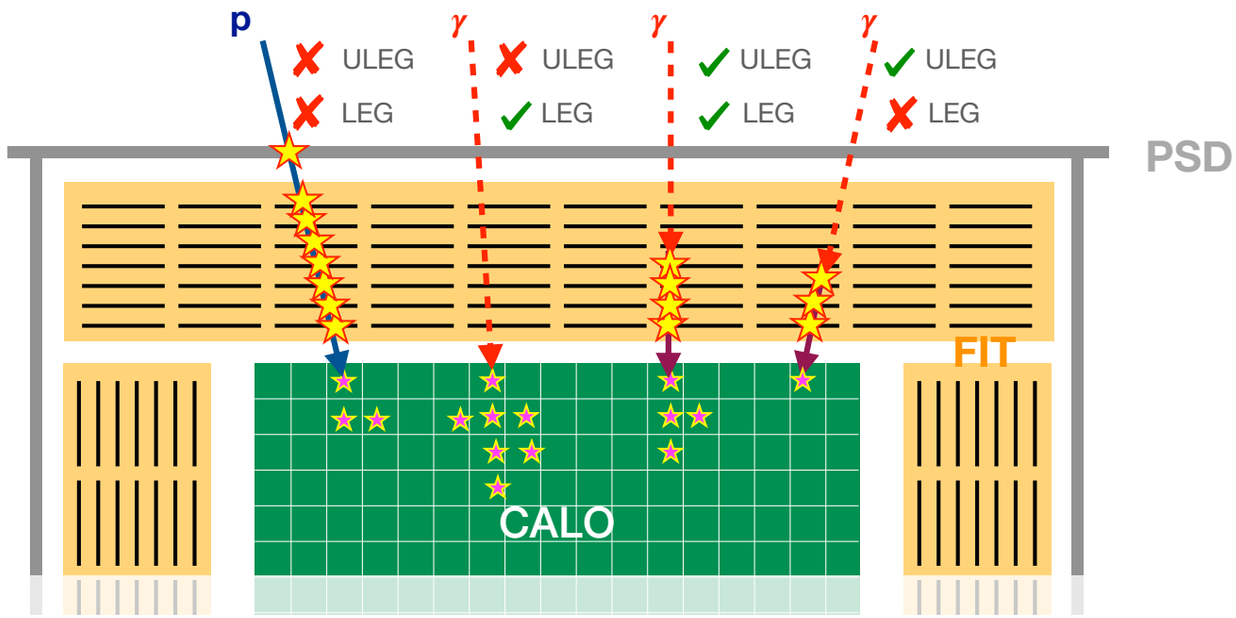




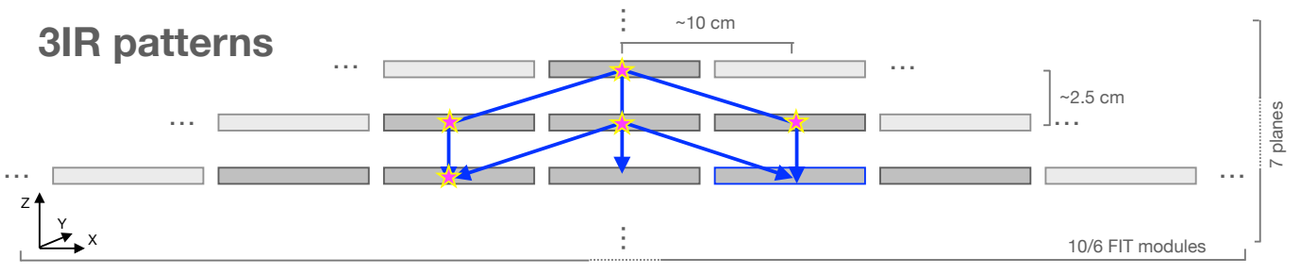
★ Other missions and CubeSat projects are considering BETA chip (ADAPT, GENEO-02,…)

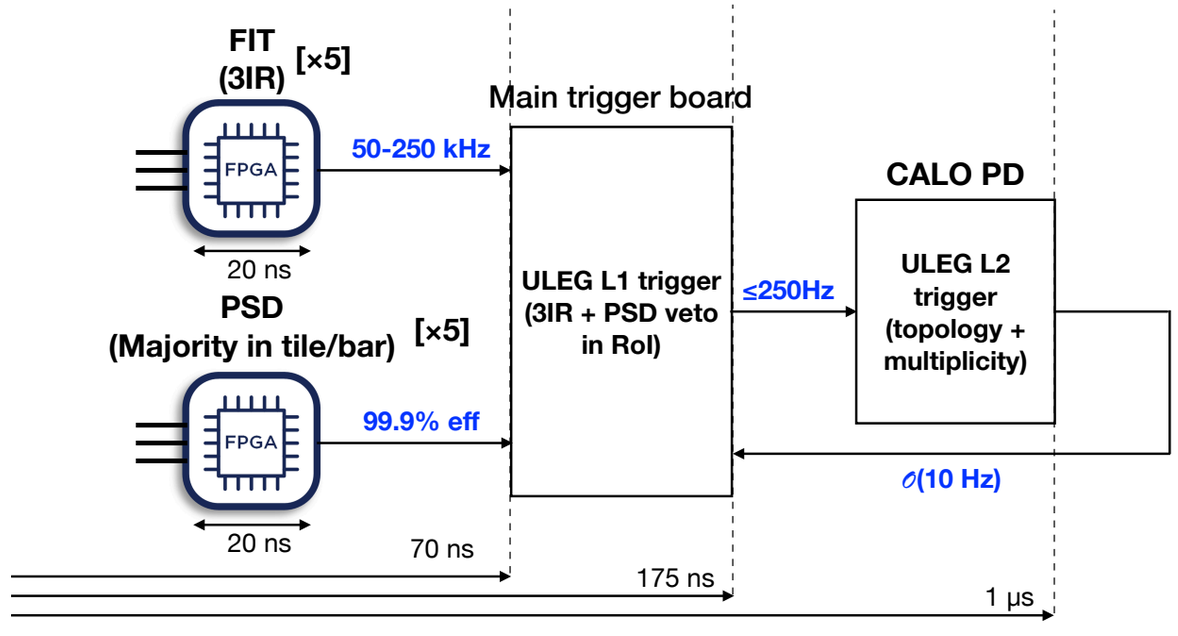
ULEG trigger

- The ULEG trigger concept:
  - 3-in-a-row (3IR) patterns in FIT
  - Absence of PSD veto
  - Energy deposition in CALO>100 MeV (L2)



- ULEG features:
  - Reduce threshold down to 100 MeV (baseline LEG 0.5-1 GeV)
  - Increase purity of gamma-sample with good direction reconstruction
  - Increases the capabilities of HERD for gamma-ray astronomy

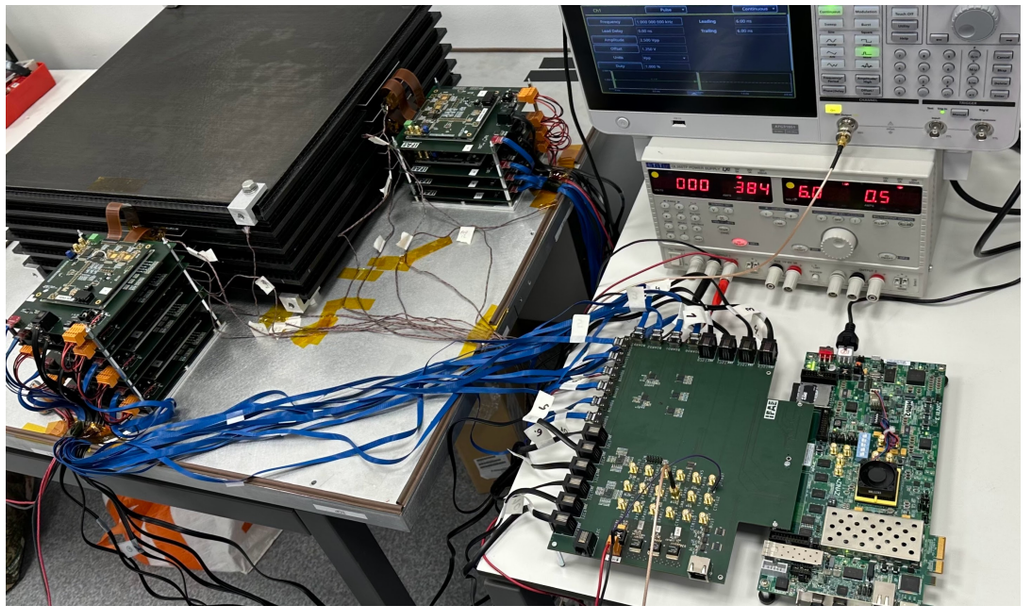




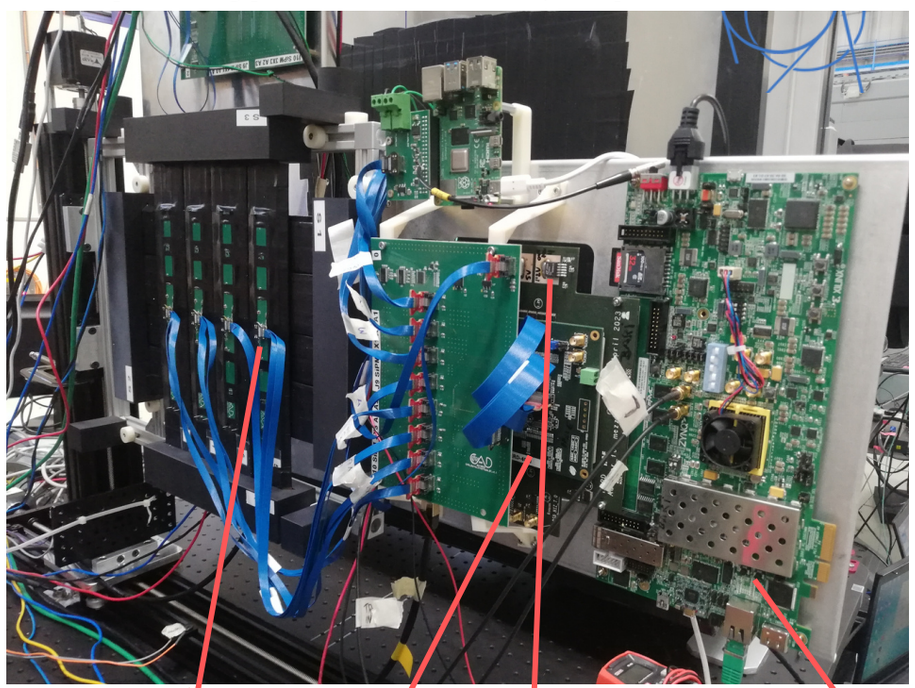
ULEG status

- ★ Concept and integration design approved by Collaboration
- ★ First prototypes (EFM):
  - ✦ Scaled-down detectors (with SiPMs) + BETA16r2 + FEE + FPGA evaluation board (Xilinx)
  - ✦ miniFIT prototype:
    - ✤ 4 layers (X+Y)
    - ✤ 320 signal/20 trigger channels
      ⇒ 8mm sensitive area
    - ✤ 3IR trigger logic
  - ✦ PSD prototype
    - ✤ 4 horizontal + 4 vertical bars
    - ✤ 64 signal/64 trigger channels
    - ✤ 3/4 majority trigger/veto logic

miniFIT prototype at Geneva Univ, September 2023



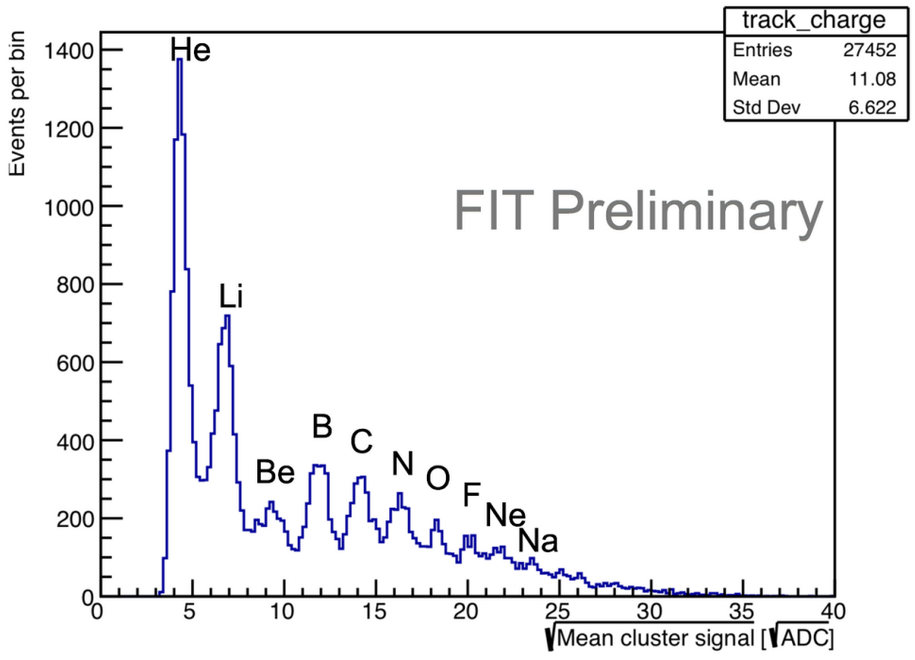
PSD prototype at CERN-PS, September 2023

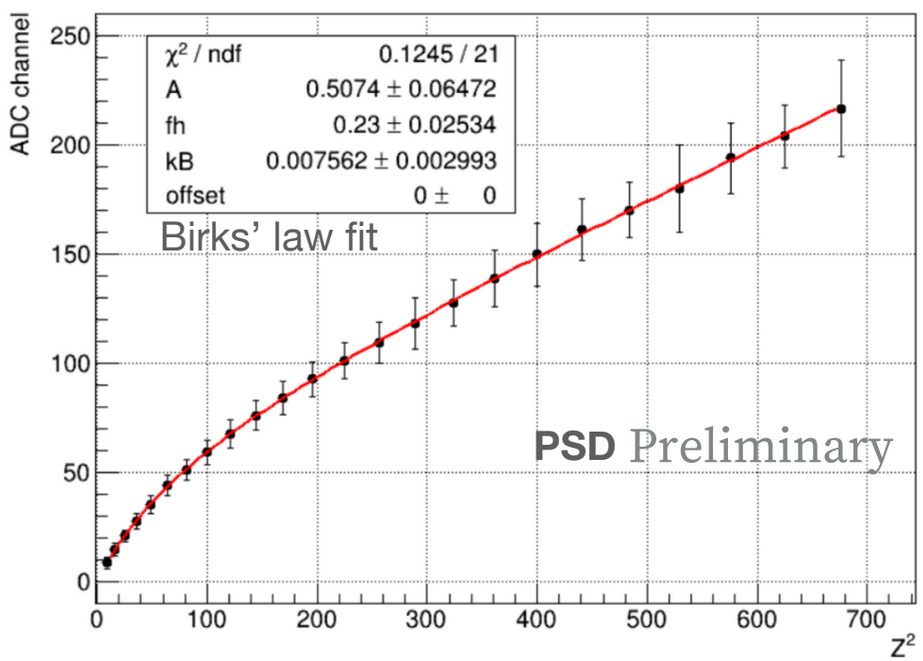


ULEG tests at CERN Fall 2023

- ★ Test with protons, electrons and nuclei
- ★ Main objectives
  - ✦ Integration of PSD and FIT prototypes in HERD trigger/DAQ systems
  - ✦ Study the performance of BETA16r2 ASIC (readout and trigger)
  - ✦ Verification of PSD veto
  - ✦ Validation of 3IR trigger concept with miniFIT

HERD beam test CERN PS September 2023

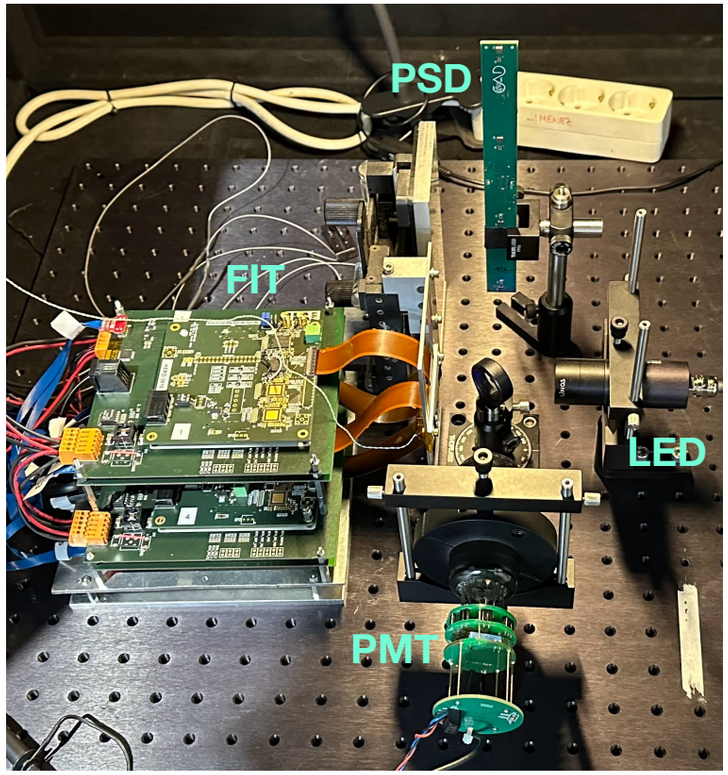




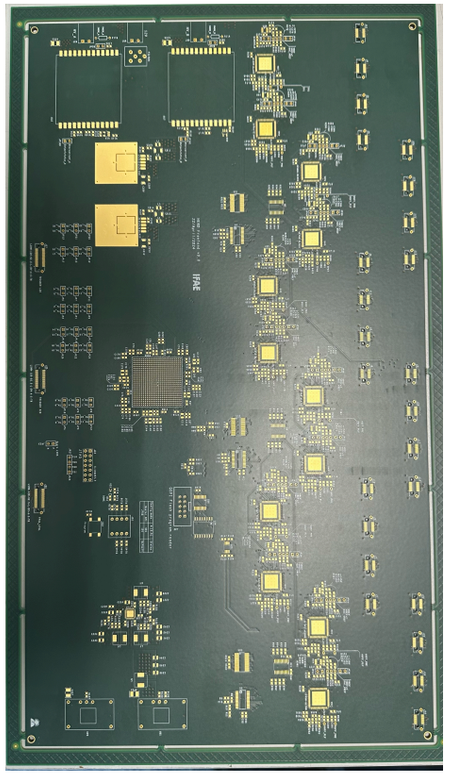
ULEG current activities

- SiPM+BETA configuration, optimization and calibration:
  - automatic procedure in optical setup
- EM for FIT and PSD readout+trigger electronics in production:
  - PSD:
    - BETA16r3 ASIC
    - FEB: 12 BETA + integrated FPGA and HV controllers
  - FIT:
    - BETA64r1 ASIC
    - Full SiPM array readout (32 mm sensitive area per layer)
    - 5 instrumented layers
- Next CERN beam tests in Fall 2024 and Spring 2025

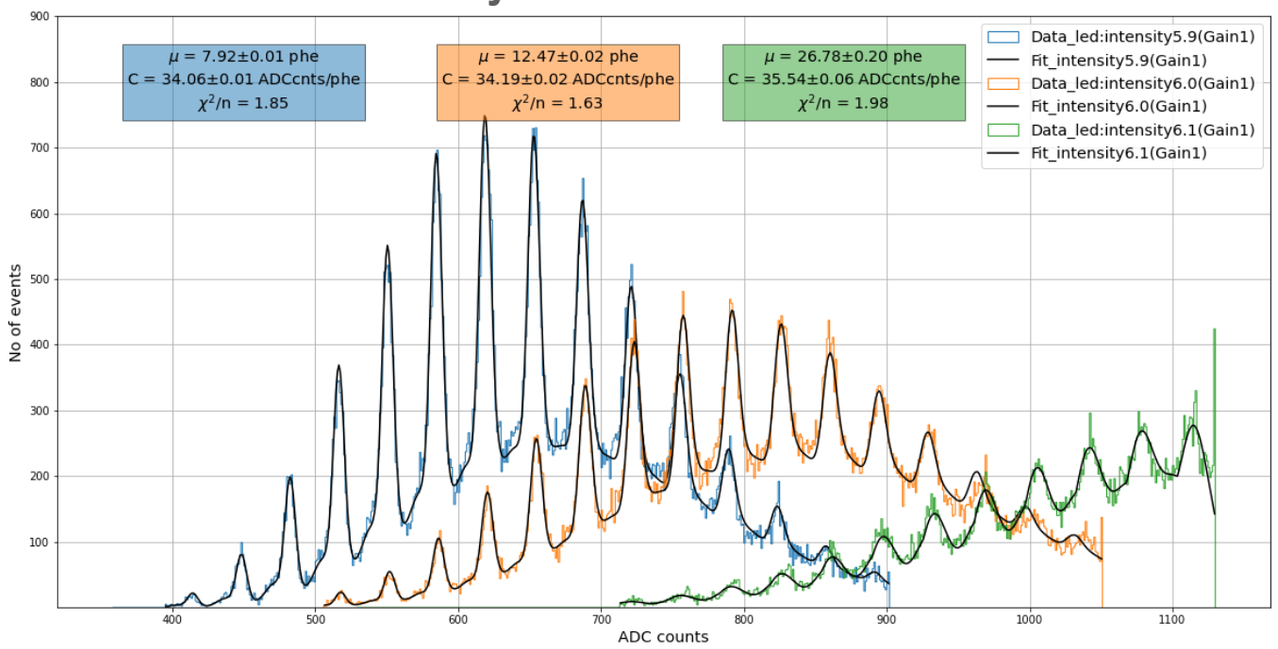
IFAE optical setup



PSD FEB pcb



Hamamatsu SiPM array S13552-10



Conclusions

- ★ Planes Complementarios have funded Ciemat, ICCUB and IFAE activities in the development of trigger+readout electronics for the HERD cosmic-ray and gamma-ray spectrum
- ★ By the end of the grant period (September 2025) we expect to have completed the Phase B study for:
  - ✦ Trigger+readout electronics for the PSD
  - ✦ Trigger+readout electronics for the FIT
  - ✦ PD trigger+readout electronics for the CALO
- ★ This places us in a position to contribute to the HERD and other space missions