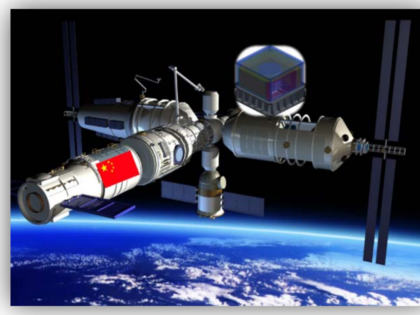
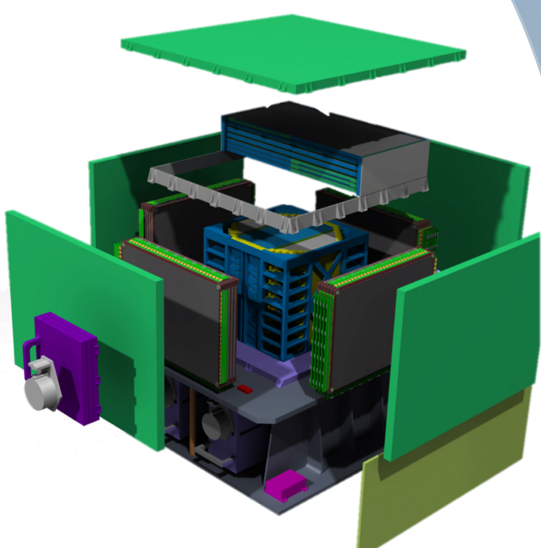
UNIVERSITÉ DE GENÈVE
FACULTÉ DES SCIENCES
Section de physique





The future of the high energy cosmic ray direct detection: HERD

Chiara Perrina on behalf of the HERD Collaboration
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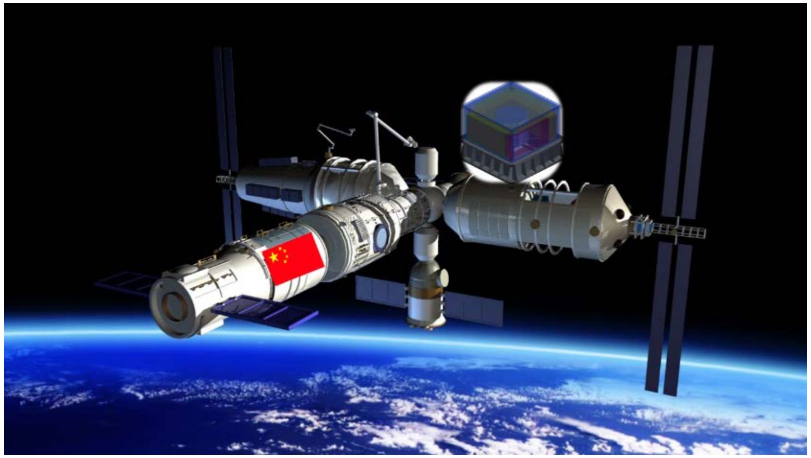
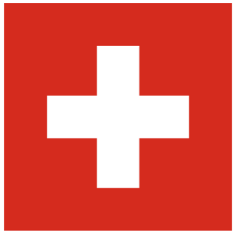
The High Energy cosmic-Radiation Detection (HERD) Facility

- Proposed as a space astronomy payload onboard the future **China's Space Station** (CSS).
- Planned to be operational **from 2025** for more than **10 years**.

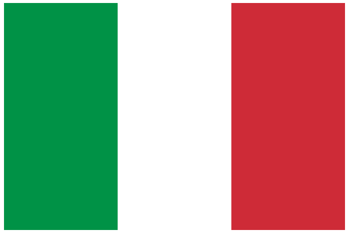


International scientific collaboration:

Lead by CSU and IHEP



University of Geneva

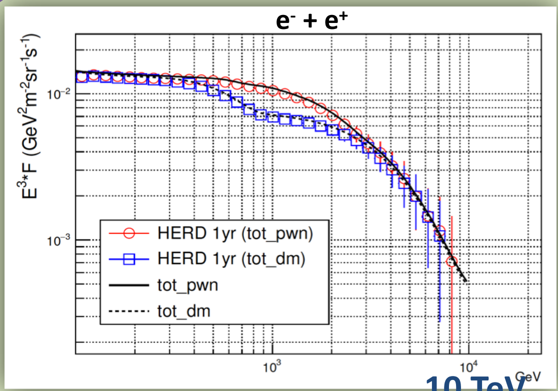


University and INFN of:
Bari, Florence, Lecce, Pisa/Siena, Pavia, Perugia, GSSI, …

CIEMAT of Madrid, …

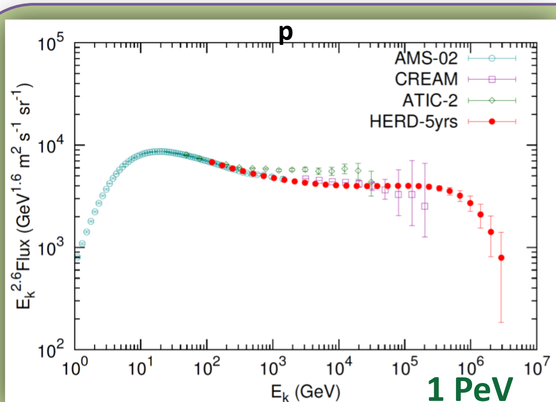
More to join

HERD: the objectives

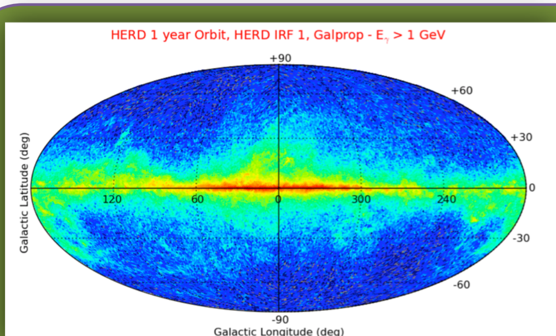


Search for signatures of annihilation/decay products of **dark matter** in

- energy spectrum and anisotropy of high energy electrons (10 GeV – 100 TeV)
- γ-rays (500 MeV – 100 TeV)



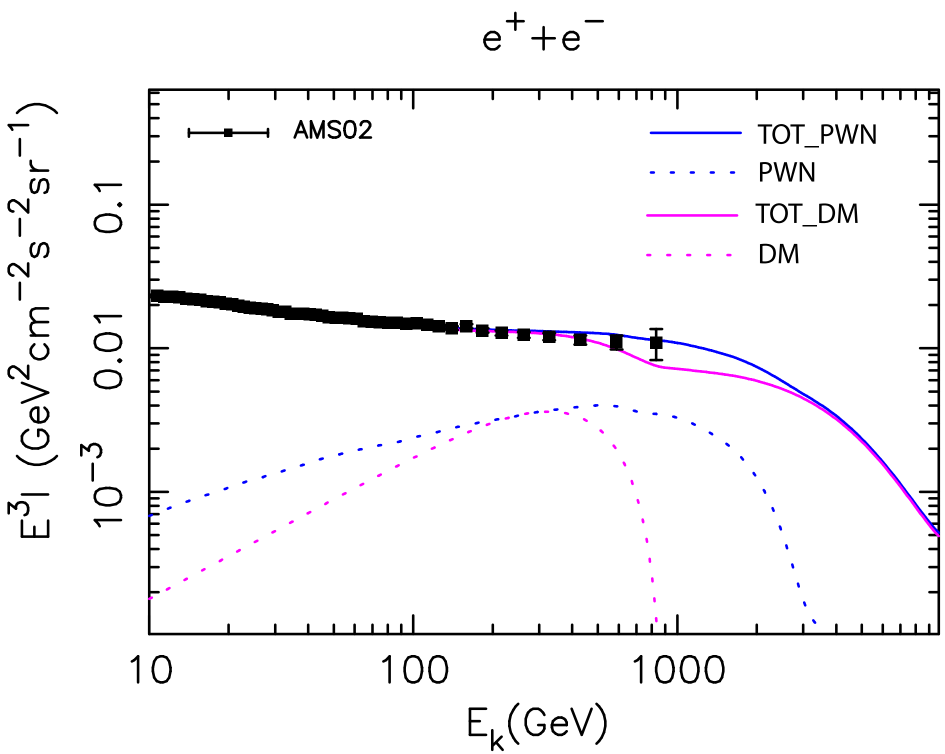
Measurements of **energy spectrum and composition** of primary cosmic rays from 30 GeV to PeV.

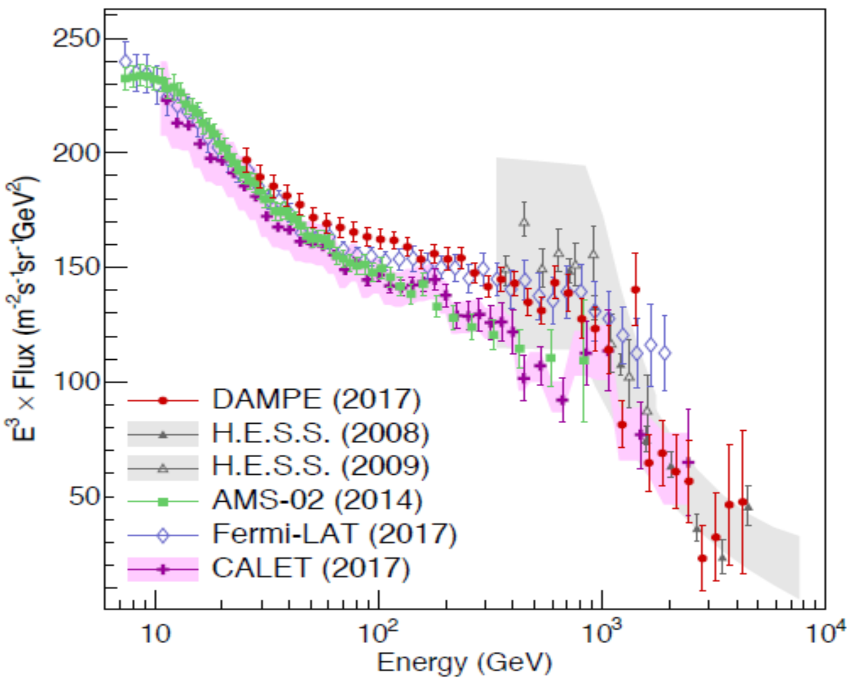


Wide FOV monitoring of gamma-rays from 500 MeV to study gamma-ray bursts, active galactic nuclei and galactic microquasars.

Energy range (e/γ)	10 GeV – 100 TeV
γ low energy range	500 MeV – 10 GeV
Energy range (nuclei)	30 GeV – 3 PeV
Angular resolution (e/γ)	0.1° @10 GeV
Charge resolution (nuclei)	10 % – 15 % for Z = 1 – 26
Energy resolution (e/γ)	< 1 % @200 GeV
Energy resolution (p)	20 % @100 GeV - PeV
e/p separation power	> 10^{-6}
Geometric factor (e)	> 3 m^{2}sr @200 GeV
Geometric factor (p)	> 2 m^{2}sr @100 GeV

Positron+electron flux measurements



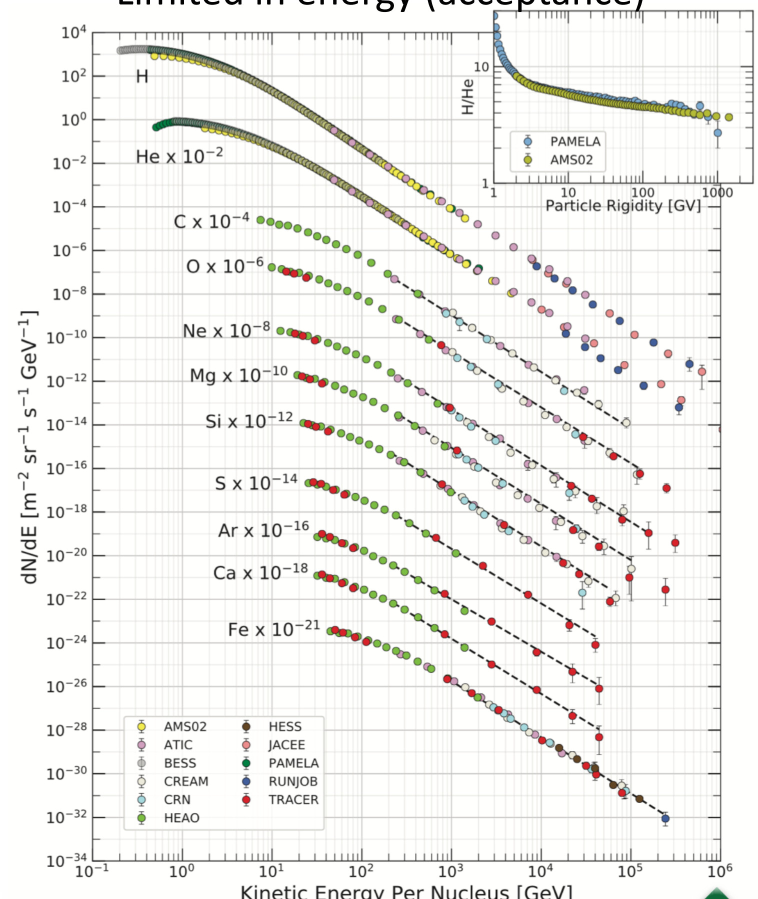


Cosmic ray spectrum

http://pdg.lbl.gov/2018/reviews/rpp2018-rev-cosmic-rays.pdf

Direct measurements

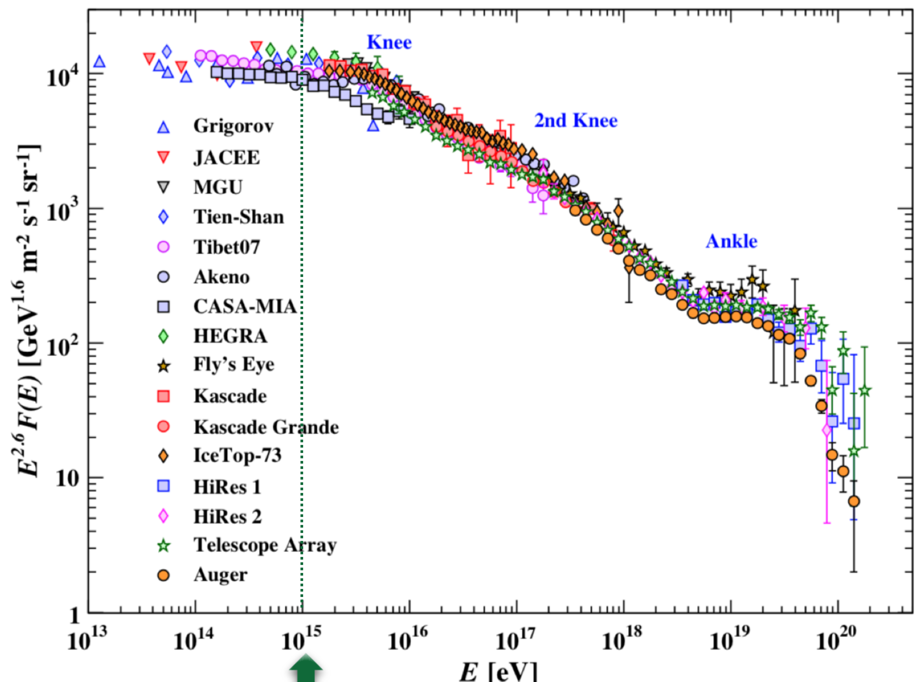
- Fluxes of single components
- High precision
- Limited in energy (acceptance)



1 PeV

Indirect measurements

- Difficult composition measurements
- Larger systematics
- Highest energies



1 PeV

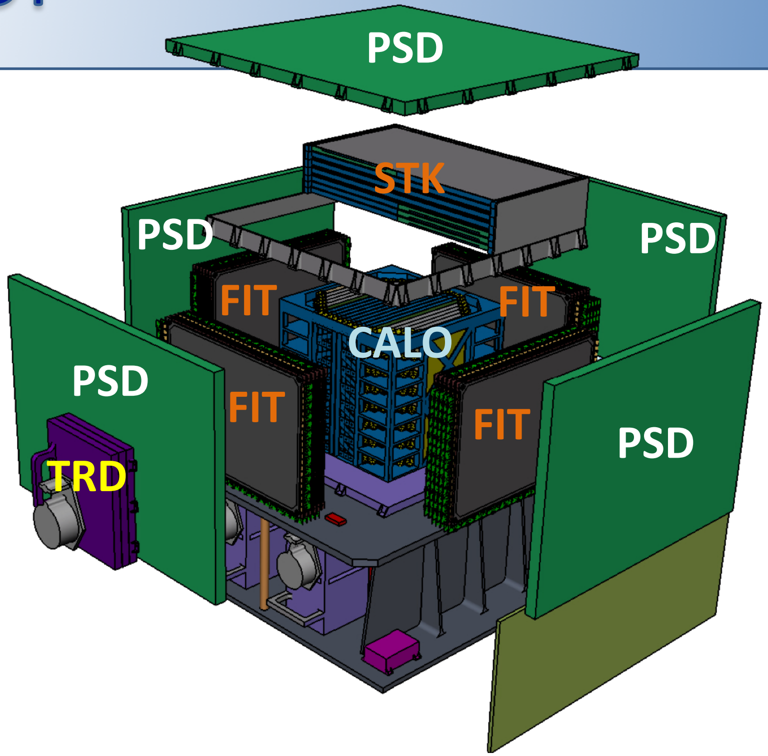
HERD: the detector

Calorimeter (CALO): 3D, e/γ/CR energy, e/p discrimitation

Tracker (5 STK «silicon tracker» or 1 STK + 4 FIT «fiber tracker»): particle trajectory, charge identification

PSD «plastic scintillator detector»: 6 sides, low energy γ, charge identification

TRD «transition radiation detector»: energy calibration



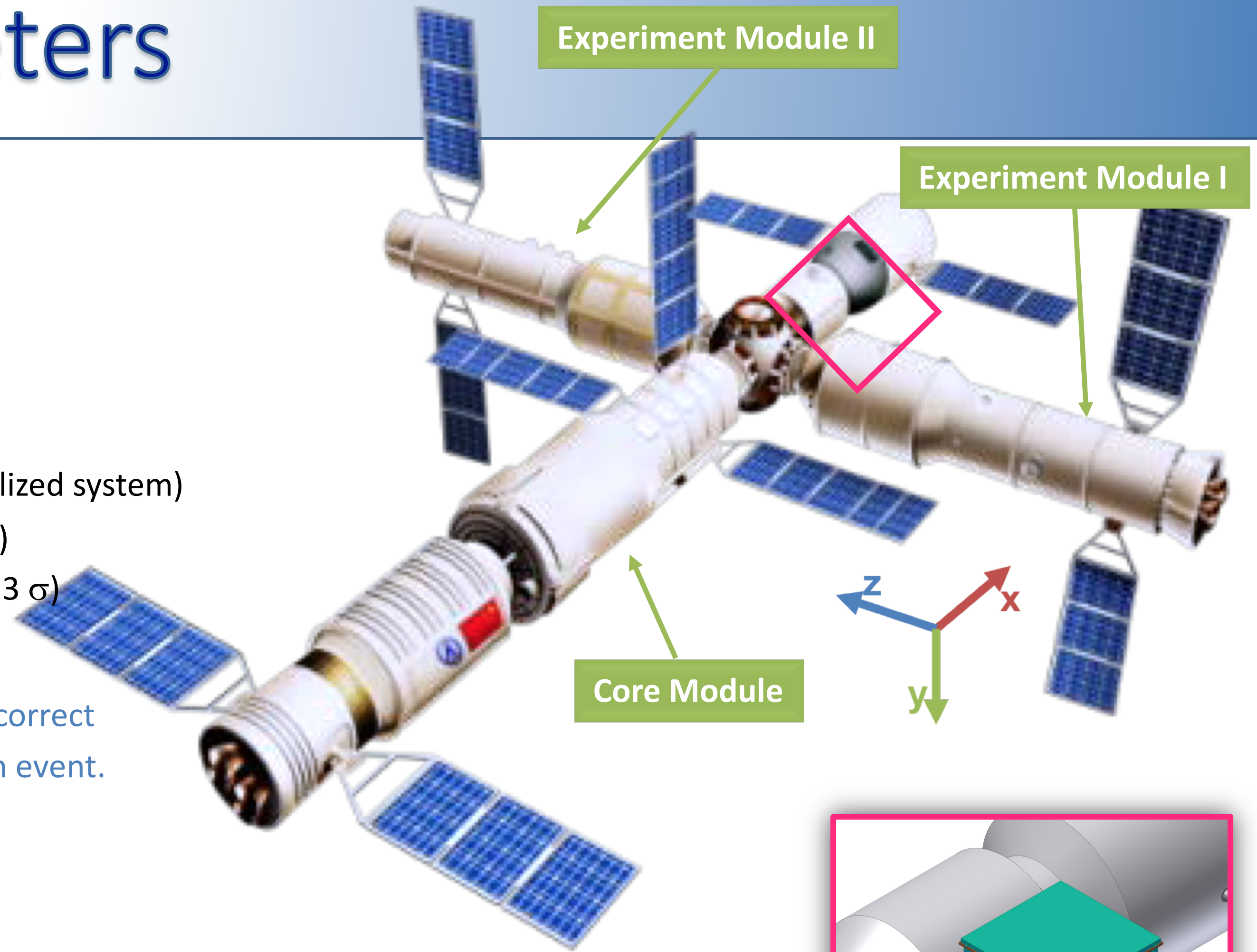
Mass	< 4 t
Envelope dimensions	~ 2.3 x 2.3 x 2.6 m^3
Field of View	± 70°
Power consumption	~ 1200 W
Lifetime	> 10 years (with in-orbit replacements)

CSS parameters

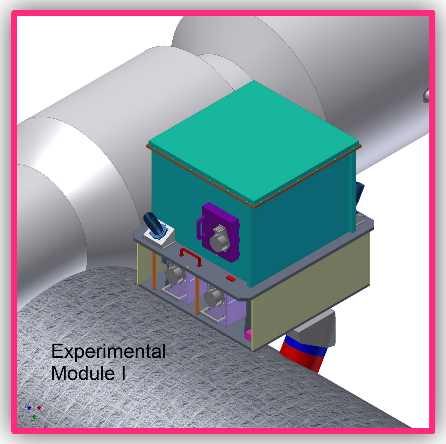
- **Orbit**
  - Circular
  - Altitude: 340 km - 450 km
  - Inclination: 41° – 43°
- **Pointing**
  - To the Earth (three axis stabilized system)
  - Pointing accuracy ≤ 0.1° (3 σ)
  - Pointing stability ≤ 0.005°/s (3 σ)

HERD will be equipped with two **star trackers** in order to know the correct pointing of the instrument for each event.

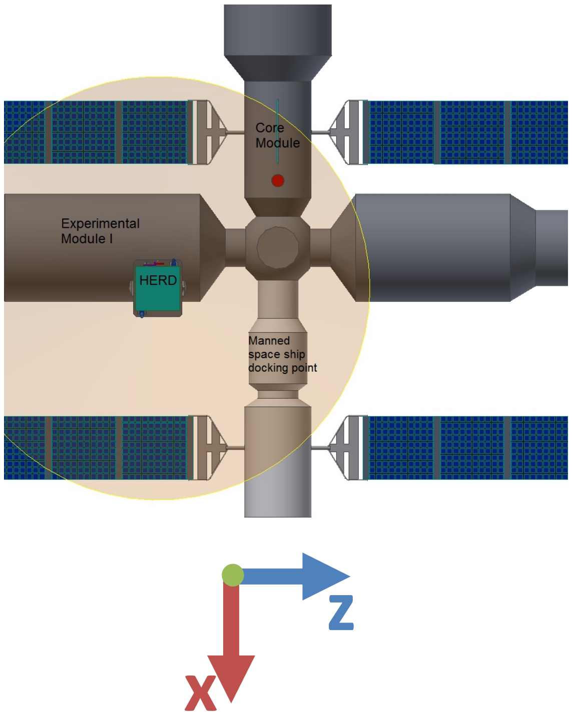
- **CSS to HERD buses**
  - FC-AE-1553 bus, 4 Gb/s
  - 1553B for TC/TM
  - GPU, 10 teraFLOPS;
  - 1'000 TB mass memory
  - 100 V primary power supply
- Data downlink 100 Mb/s with relay satellites

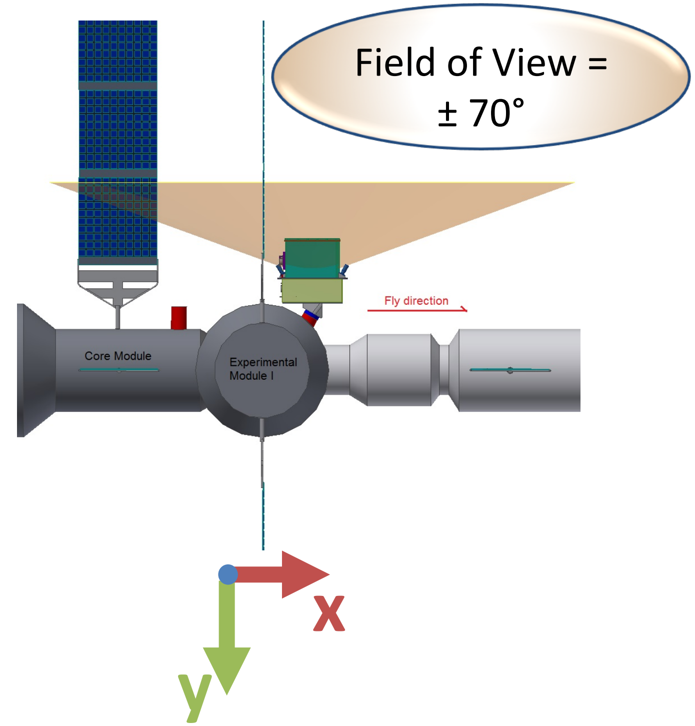


HERD will be a little bit off zenith and higher than the module to avoid interferences between antennas and star trackers.



Expected location of HERD on CSS



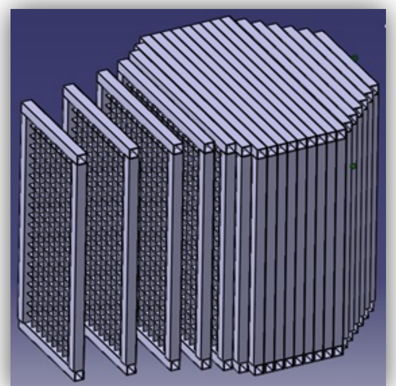


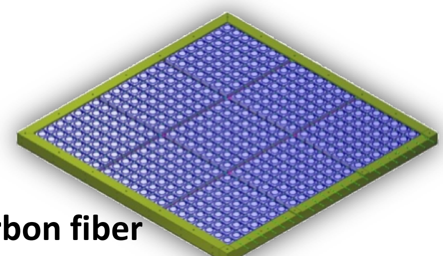
Astronauts can perform **upgrade/replacement** of HERD components on the instrument itself or on the equipment inside the Experimental Module. **Enhanced robotic arm** (9.5 m, 25 t) and **regular robotic arm** (5 m, 3 t) can be used individually or jointly for installation/upgrade/replacement activities.

The rotation of solar panels will have periodic **blocking** on HERD with a cycle of two orbital periods. The status data of solar panels can be recorded and then be used for correction of HERD science data.

Calorimeter (CALO)

1. <u>**Crystal array**</u>
2. Intensified scientific CMOS
3. Trigger



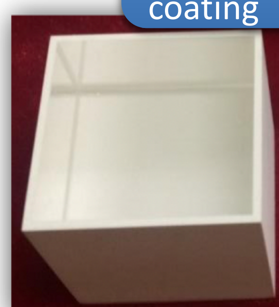


Carbon fiber layer

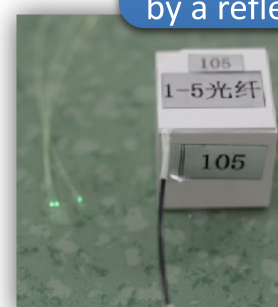
Number of crystals	**~ 7'500 LYSO (X_0 = 1.14 cm)**	
Crystal dimensions	**~ 3 x 3 x 3 cm^3**	
Radiation length	55 X_0	**~ 21 LYSO crystals**
Nuclear interaction length	3 λ_I (simulation → > 2 λ_I for 100 TeV & > 3 λ_I for PeV CR @20% energy resolution)	
Fiber readout	**3 WLSF (⌀ = 0.3 mm)/crystal** (low & high range, trigger)	
Non-uniformity in, between crystal	**< 5%, < 30%**	
Space between crystal	**< 4 mm**	
Alignment	**< 0.5 mm**	

Encapsulation of WLSF with optical cement

Titanium dioxide (TiO_2) coating

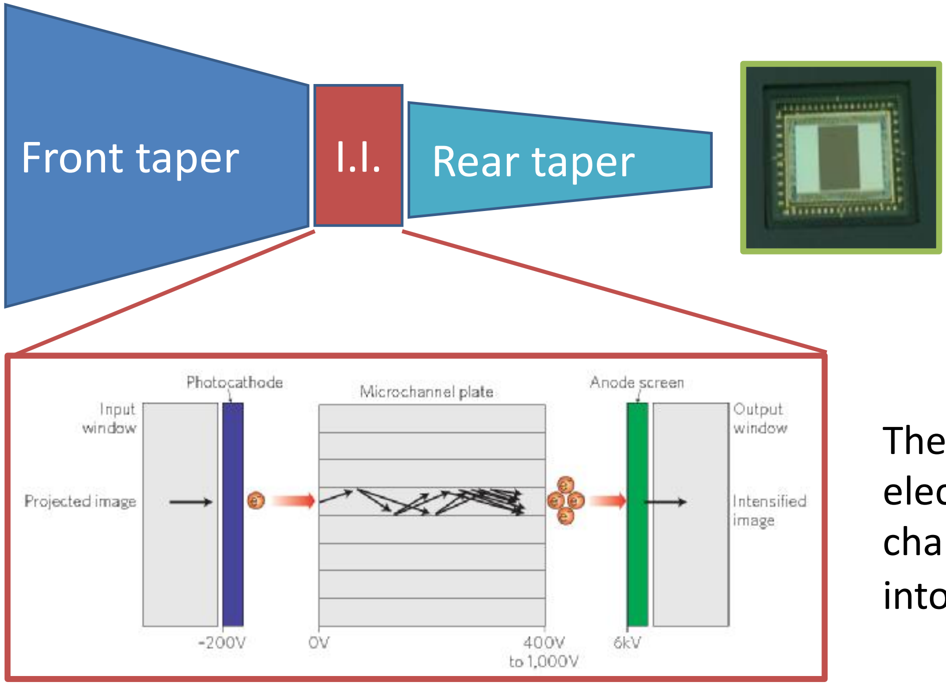


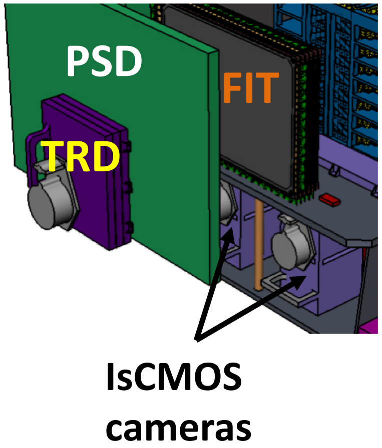
WLSF coupled to LYSO and covered by a reflector



CALO's readout: IsCMOS

- IsCMOS together with WLSF is adopted for its compactness, simple electronics and external power consumption.
- Each IsCMOS camera is composed of a **front taper**, an **image intensifier (I.I.)**, a **rear taper** and a **sCMOS** chip.





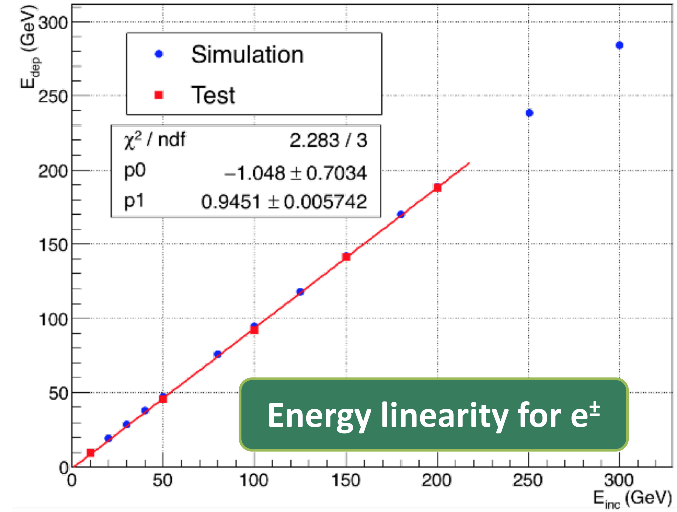
The complete MIP peak shall be visible in the spectrum. Dynamic range of the camera **from 10 MeV** (1/3 MIP) **to 20 TeV** (created by a PeV hadronic shower). → 10^7 → 2 different image intensifiers

The image intensifier converts weak light signals into electrons, multiplies the electrons using a micro-channel plate, and then converts the electrons back into photons using a phosphor screen.

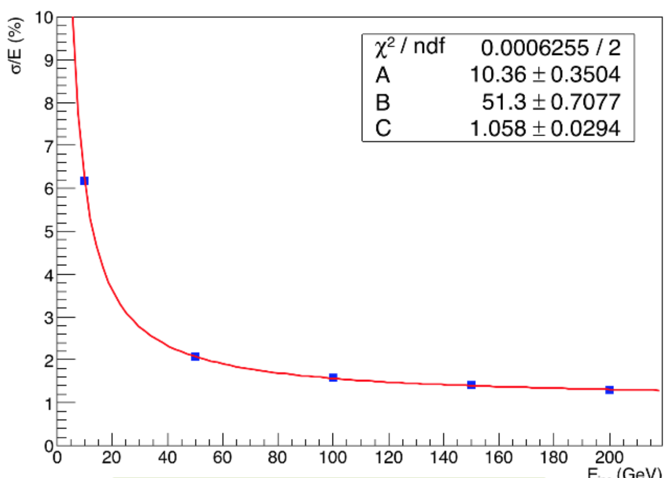
CALO prototype

5 x 5 x 10 LYSO calorimeter

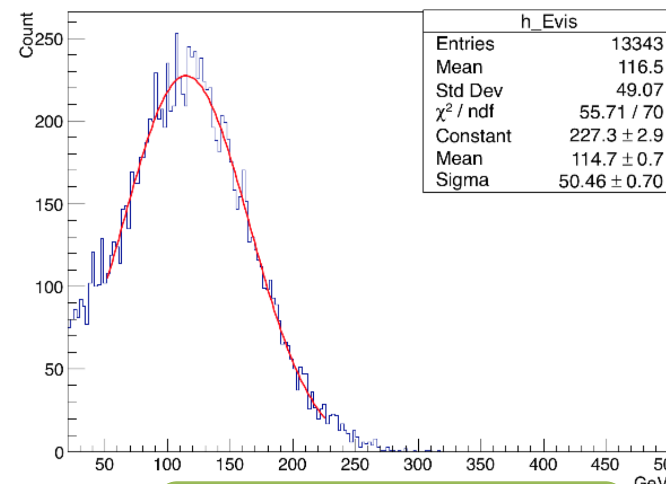
Tested @CERN SPS in 2017



Energy linearity for $e^{\pm}$



Energy resolution for $e^{\pm}$:
1.3 % @200 GeV



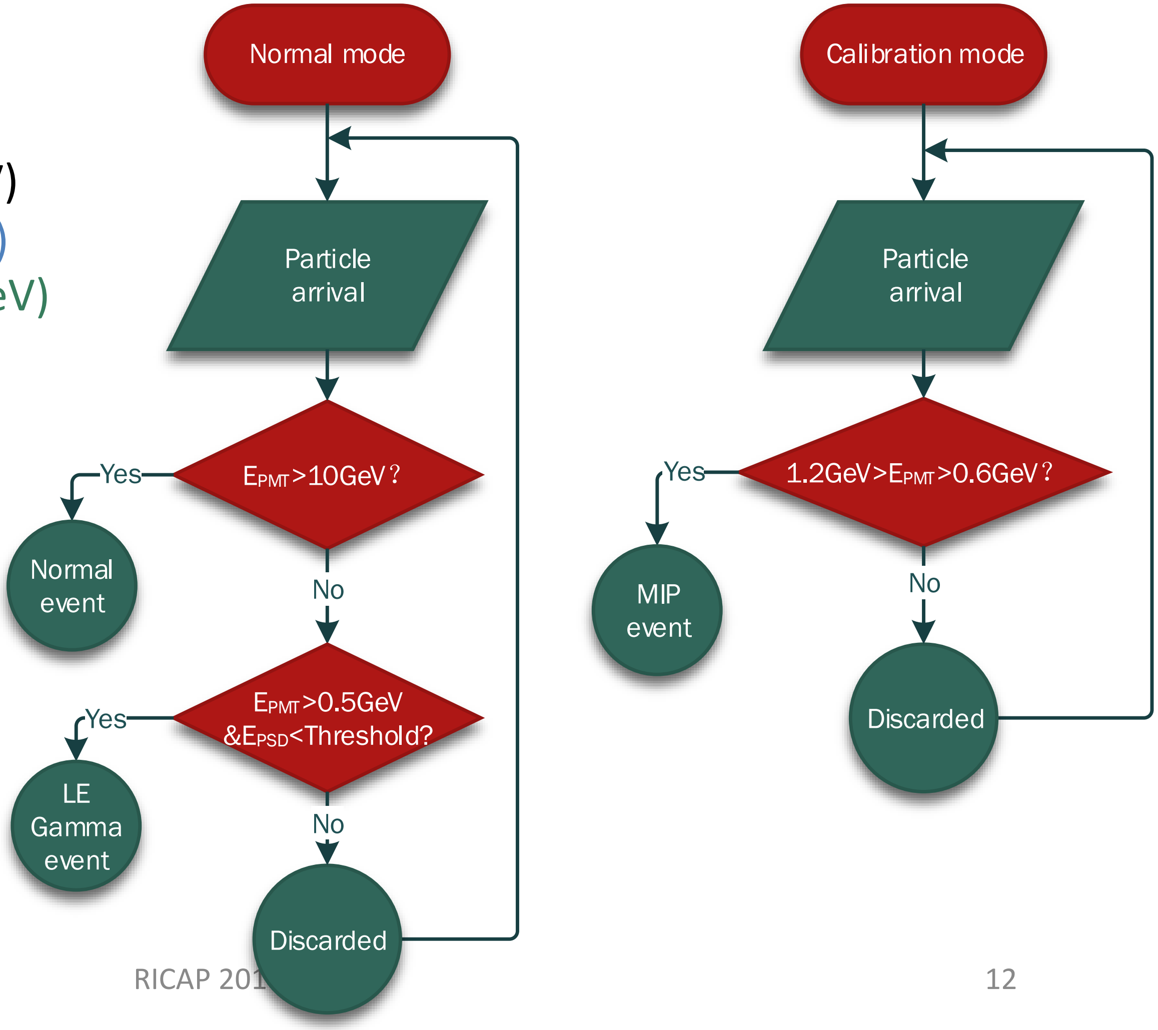
Energy resolution for p:
44 % @350 GeV

HERD Trigger Sub-system

All the 7500 trigger fibers are routed to the PMTs of the trigger sub-system, dedicated to providing common trigger signals to all the other instruments after veto and coincidence logic.

Event classification:

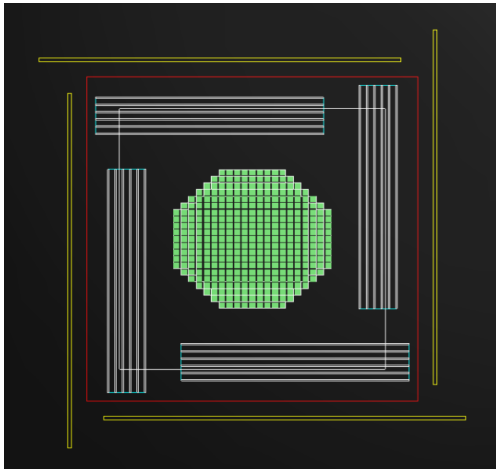
- HE particle (> 10 GeV)
- LE particle (0.5 GeV – 10 GeV)
- LE electron (0.5 GeV – 5 GeV)
- MIP proton (0.6 GeV – 1.2 GeV)



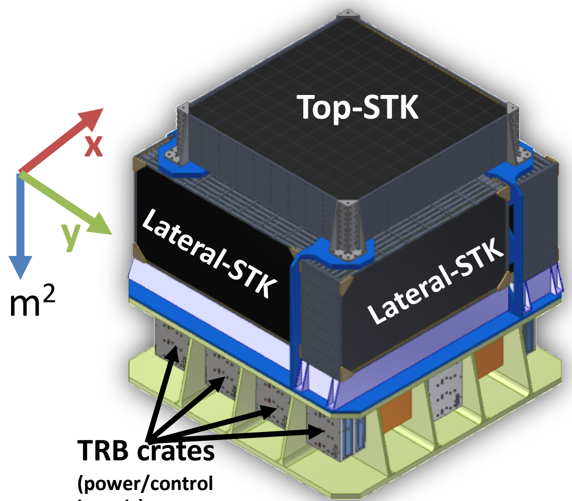
Silicon Tracker (STK)

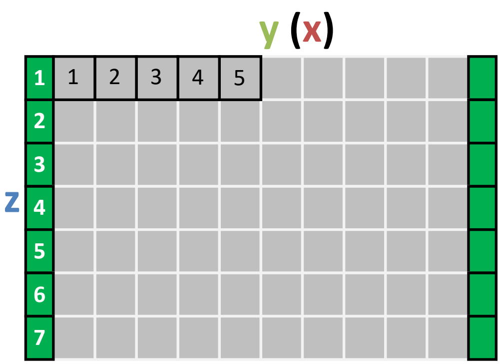
- ✓ Particle tracks reconstruction
- ✓ Particle charge measurements ($Z \leq 26$)

DAMPE Silicon Strip Detector (SSD) :
- area: $(95\ \text{mm})^2$

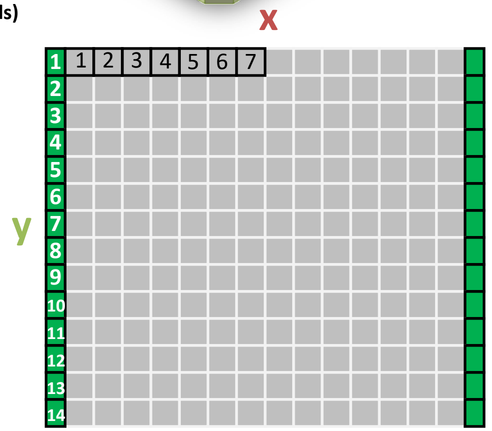


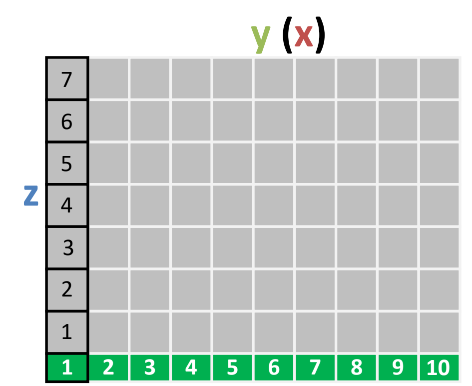
- **Top-STK (2’352 SSDs)**
  - 6 (x-y) layers
  - 28 ladders on each plane
  - 7 SSDs on each ladder
  - Layer active area: $(1.33\ \text{m})^2 = 1.77\ \text{m}^2$



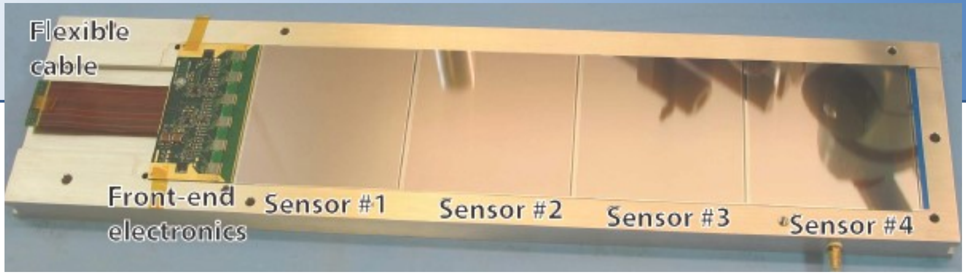


- **Lateral-STK (420 SSDs)**
  - 3 (y-z) or 3 (x-z) layers
  - 14 ladders on z plane and each ladder has 5 SSDs
  - 10 ladders on x or y plane and each ladder has 7 SSDs
  - Layer active area: 95 cm x 66.5 cm = $0.63\ \text{m}^2$
- **Top-STK + 4 Lateral-STK: 4’032 SSDs, ~ $36\ \text{m}^2$**

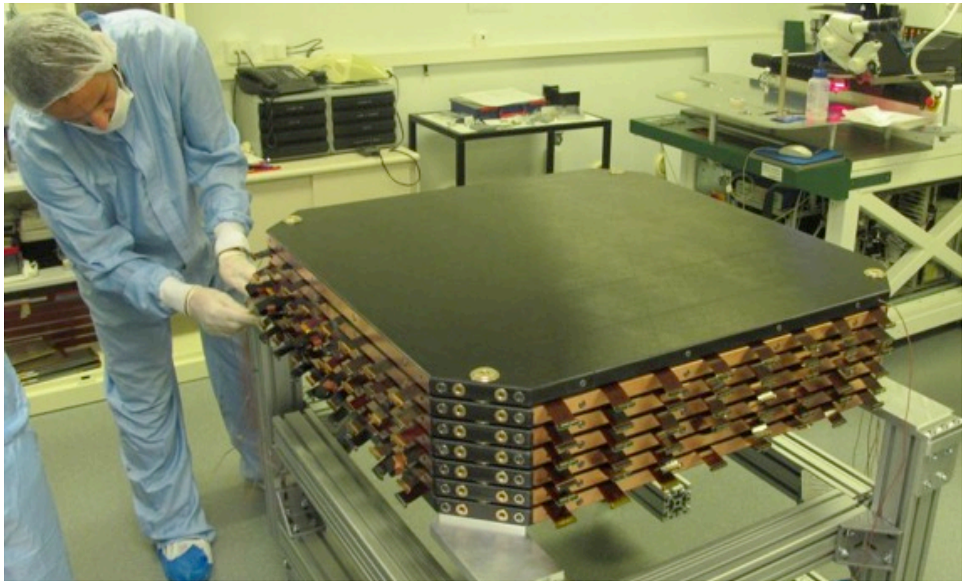




HERD STK



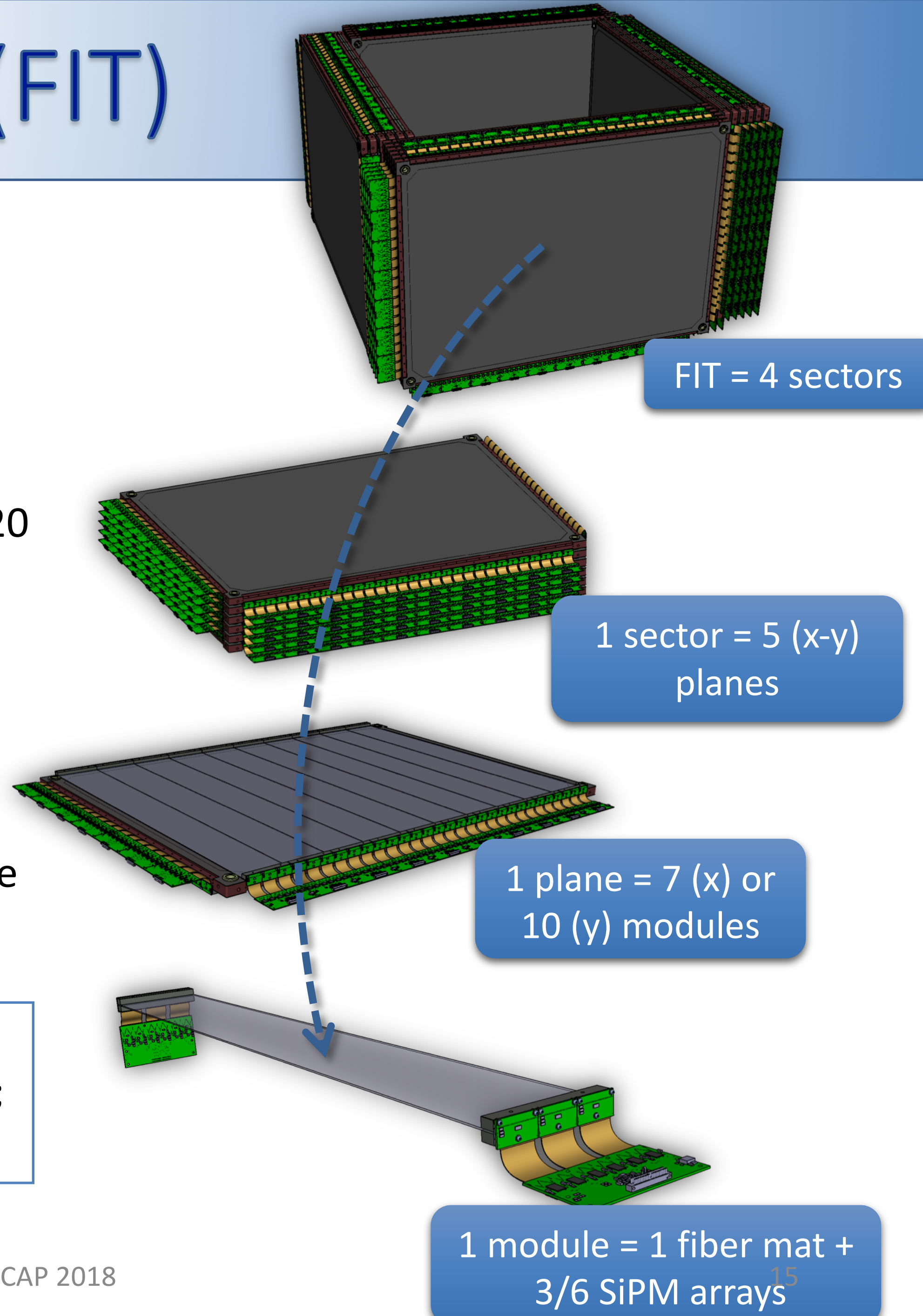
DAMPE SSD :
- Hamamatsu
- area: $(95\ mm)^2$
- thickness: 320 μm
- strip pitch: 121 μm
- readout pitch: 242 μm



- **Trays** provide support for ladders glued directly via dedicated jigs in aluminum (100 μm assembly precision).
- The material between active parts is minimized to ensure the physics performance while keeping the stability of the overall mechanics.
    - HERD: sandwich of an **AIREX®** core and a **carbon fiber** frame.
- The readout pitch is a balance among a good spatial resolution (**40 μm**) and a limited power consumption.

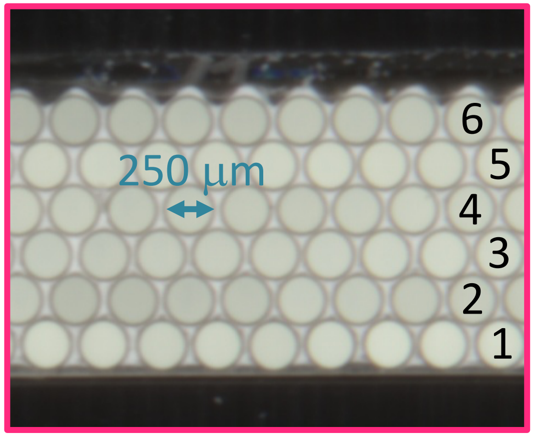
The Fiber Tracker (FIT)

- 4 identical **sectors**
- 5 (x-y) **planes** in each sector
  - 4 (x-y) with single readout to measure particles with Z = 1
  - 1 (x-y) with double readout to measure also nuclei with $1 < Z \leq 20$
- 7 **modules** (~ 1 m fiber length) in each x plane
- 10 **modules** (~ 70 cm fiber length) in each y plane
- 1 **fiber mat** + **3 (6) SiPM arrays** for single (double) readout in each module

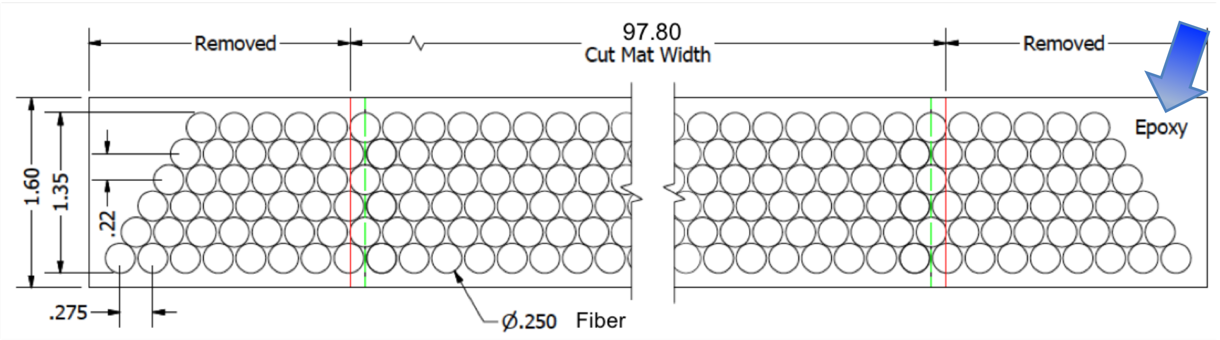


Overall mass: ~ 250 kg;
Overall dimensions: ~ $1.4 \times 1.4 \times 0.9$ m^3;
Overall consuption: ~ 180 W.

FIT module: the fiber mat

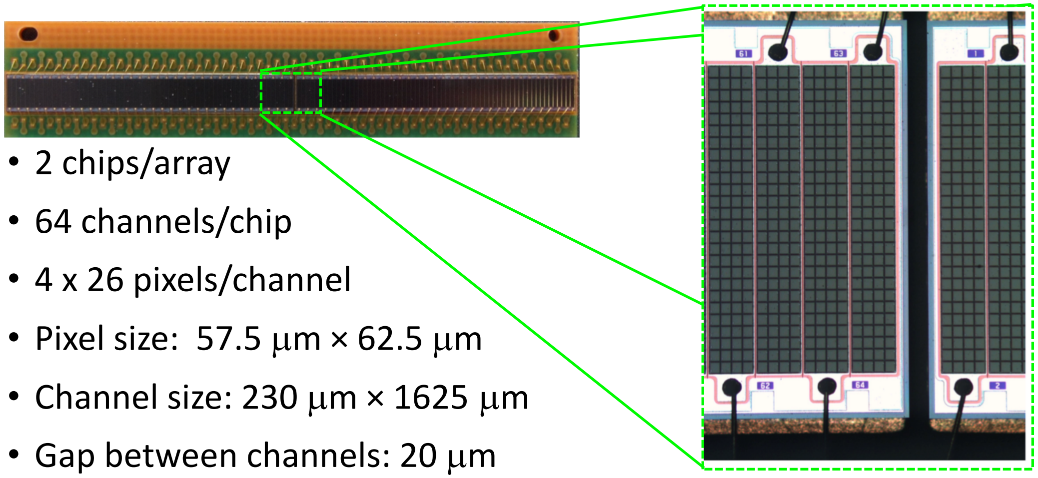


- Two possible lengths: 1.06 m and 77 cm
- **LHCb fiber tracker upgrade**
- Titanium dioxide coating (white paint) to avoid cross-talk between fibers
- 6 layers of fibers in each mat
- Fibers **KURARAY SCSF-78MJ**
  - round section
  - diameter 250 µm
  - Peak emission wavelength: 450 nm
- Mat width ≅ 97.80 mm to match 3 SiPM arrays → a layer contains ~ 350 fibers



FIT module: the Silicon Photomultiplier (SiPM) Array

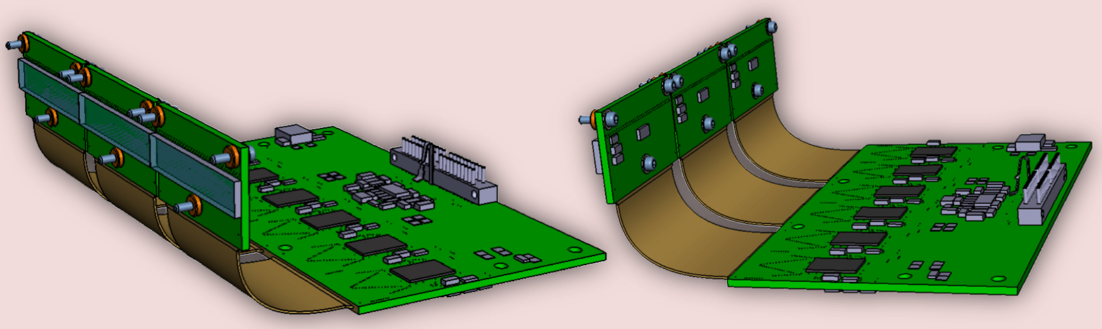
SiPM arrays from Hamamatsu (type S133552-HRQ)
(LHCb fiber tracker upgrade)



- 2 chips/array
- 64 channels/chip
- 4 x 26 pixels/channel
- Pixel size: 57.5 μm × 62.5 μm
- Channel size: 230 μm × 1625 μm
- Gap between channels: 20 μm
- Gap between chips: (220 ± 50) μm
- 105 μm epoxy resin on top

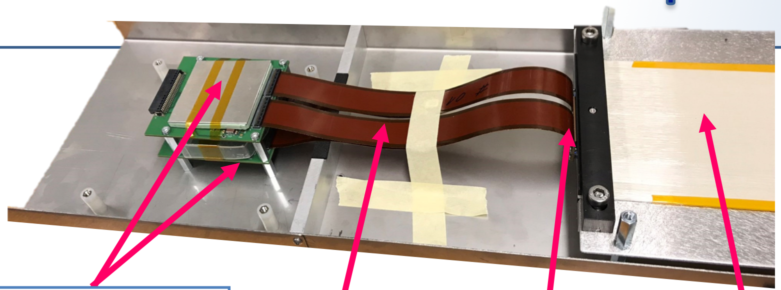
@ 25 °C:

- $V_{breakdown}$ = 48 V - 58 V
- $V_{op} = V_{breakdown}$ + 3.5 V
- Rq = 330 kΩ - 610 kΩ
- Gain @V_{op} = 3 x 10^6
- Photon detection efficiency @V_{op} = 45 %
- Sum of cross-talk + after-pulse prob. @V_{OP} = 8 %
- Temperature coefficient: $dV_{breakdown}/dT$ = 54 mV / °C



Prototype front-end board: 6 **VATAs 64ch HDR 16**, to readout 3 SiPM arrays.

Fiber Module prototype

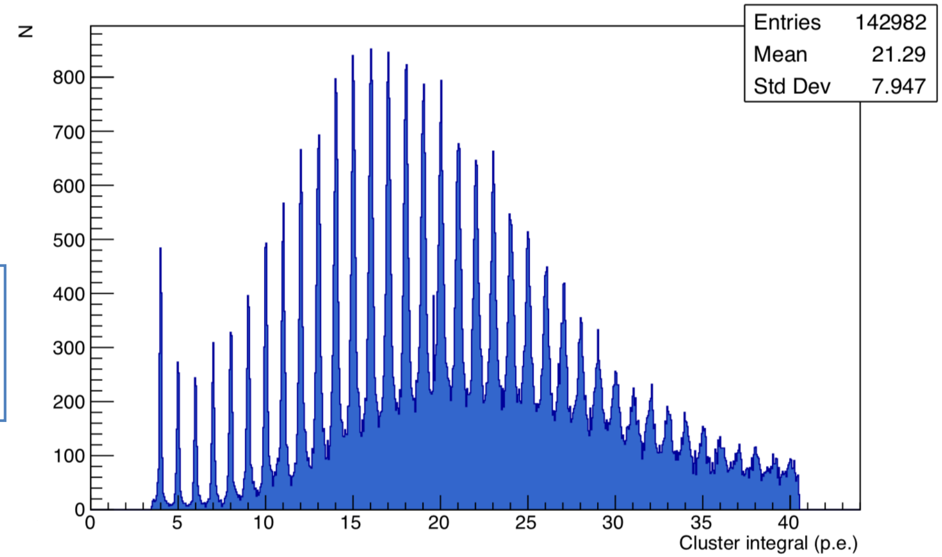


2 VATA boards (VATA 64 HDR 16) designed by UNIGE (R&D HERD)

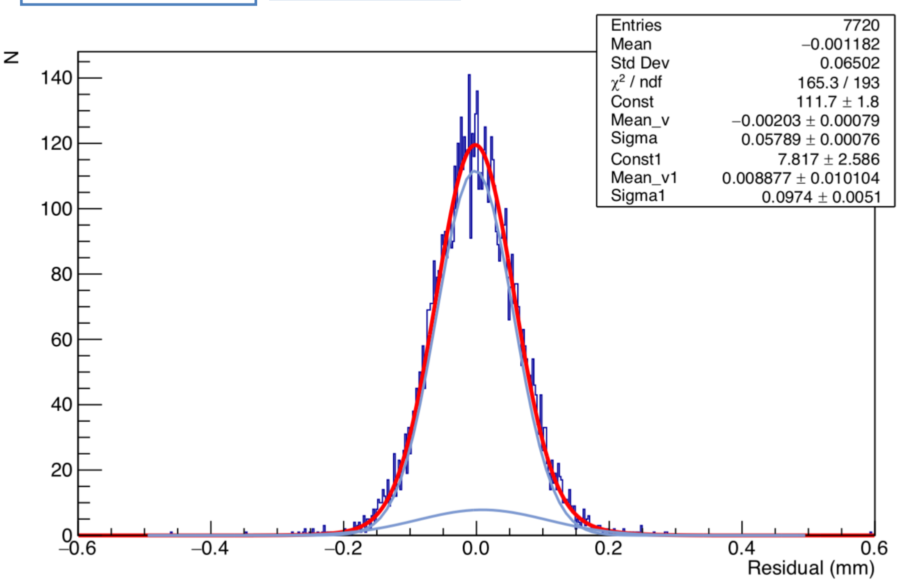
Rigid flex PCB (4 cables), designed by UNIGE (Mu3e)

One SiPM array (2 x 64-channel chips)

Fiber mat, 1 m lenght **(EPFL)**



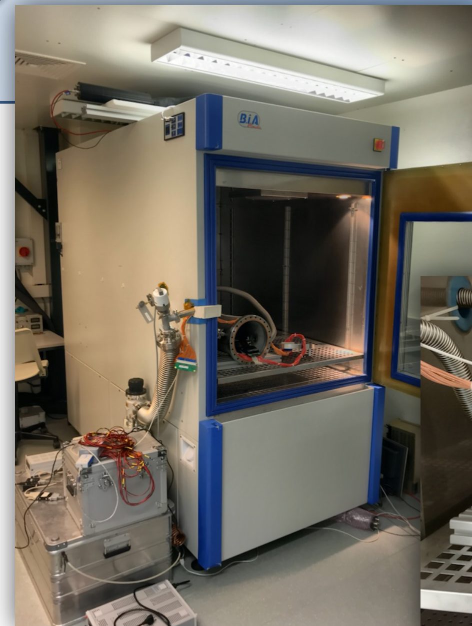
Signals up to 40 p.e. very well distinguishable.



- 100 GeV pions
- Cluster residual: 63.2 μm
- Spatial resolution: **59.6 μm** (corrected for beam telescope resolution)
- Efficiency = (99.7 ± 0.2)%

Why a fiber tracker?

- The **spatial resolution** is similar to the one of silicon strip detectors.
- Simpler to build **long detector** (of *e.g.* 1 m).
- **Reduced dead area** (no gap between sensors, no dead area on the silicon detector, FEE placed outside of support tray).
- **No wire bonds** on the detectors.
- Less expensive to add more layers.
- **Still the design needs to go through the space qualification process.**

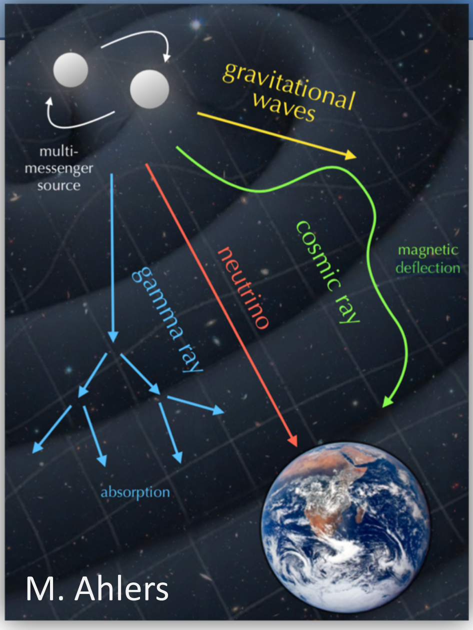


Thermal vacuum test of a fiber module prototype @UNIGE clean room.

Ideas to Reality

- **During the last two years, FIT has been becoming a reality.**
  - ✓ Advanced mechanichal and electronics project.
  - ✓ Two prototypes of fiber module realized and tested during 5 beam tests.
- **R&D in progress:**
  - Ten more prototypes will be assembled before the end of the year.
  - A front-end electronics board with three SiPM arrays is in production, and will be tested at 2 beam tests at CERN.
  - A DAQ board to readout multiple fiber modules is under design, and will be produced in 2019.
  - The first space qualification tests of the FIT module and readout electronics will start in September, continuing regularly until the end of 2019.
  - A simulation model of the FIT is under developement, the first results of the single mat simulation are very promising.

Multi-messanger astronomy



- HERD with its unusual large **field of view** and unique **energy coverage** will play a unique and complementary role in
  - multi-wavelength studies across the electromagnetic spectrum with other space and ground telescopes involving radio, optical, X-ray, γ-ray
  - search of electromagnetic counterpart of GW and for contemporaneous flaring in photon data and neutrinos (IceCube, Km3Net).
- HERD produces ToO Alerts: AGN, Crab, novae, binary systems.

- **HERD + CTA + LHAASO**
  - Simultaneous coverage of the same sources from few GeV to 1 PeV
  - Overlap of measured spectra
    - ➢ Distinguish diffuse emission from localized contributions, to disentangle acceleration and propagation mechanism in SNRs, PWN, pulsars, and in more extended objects as the Fermi bubbles.
    - ➢ Study transient phenomena, which is crucial to analyse the properties of jets, and can help determining the extragalactic background light, intergalactic magnetic fields, and the validity of the Lorentz invariance.

Summary and outlook

- HERD will operate on the CSS starting from 2025 for more than 10 years.
- It will be a calorimetric detector with unprecedent acceptance.
- Important and frontier scientific objectives in dark matter search, cosmic ray physics and gamma-ray astronomy.
- It could become the only space-borne high energy γ-ray detector, once the Fermi satellite will stop its operations.
- Detailed designs are under study:
  - The baseline detector is defined and fulfills the requirements;
  - To optimise the detector geometry a dedicated Monte Carlo simulation is being developed, based on the Geant4 framework;
  - There is still room for further improvements and optimization without compromising the schedule.

- Phase A: 2018.09 - 2020.02 (18 months)
- Phase B: 2020.02 - 2021.06 (16 months)
- Phase C: 2021.06 - 2022.10 (16 months)
- Phase D: 2022.10 - 2024.10 (24 months)
- Expected launch: 2025.

Thank you!!