European Physical Society
Conference on High Energy Physics
21-25 August 2023

The High Energy cosmic-Radiation Detection (HERD) Facility

EPS - HEP 2023

Hamburg

21/08/2023

Davide Serini

On behalf of the HERD collaboration

Istituto Nazionale di Fisica Nucleare
Sezione di Bari

davide.serini@ba.infn.it

The HERD collaboration

- The **High Energy cosmic-Radiation Detection** (HERD) facility is an international space mission that will be launched and installed onboard China's Space Station (CSS) in 2027
  - Space particle experiment and gamma ray observatory
  - Mission led by China with significant contributions from key European partners: Italy, Switzerland, and Spain
    - International scientific collaboration counting **180+** scientists from China and Europe.

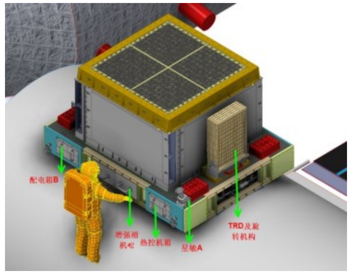
Lead by IHEP

University of Geneva
EPFL - Lausanne

University and INFN of Bari, Firenze, Lecce, Napoli, Pavia, Perugia, Pisa, Roma2, Trieste, LNGS and GSSI.

CIEMAT – Madrid
ICCUB – Barcelona
IFAE - Barcelona

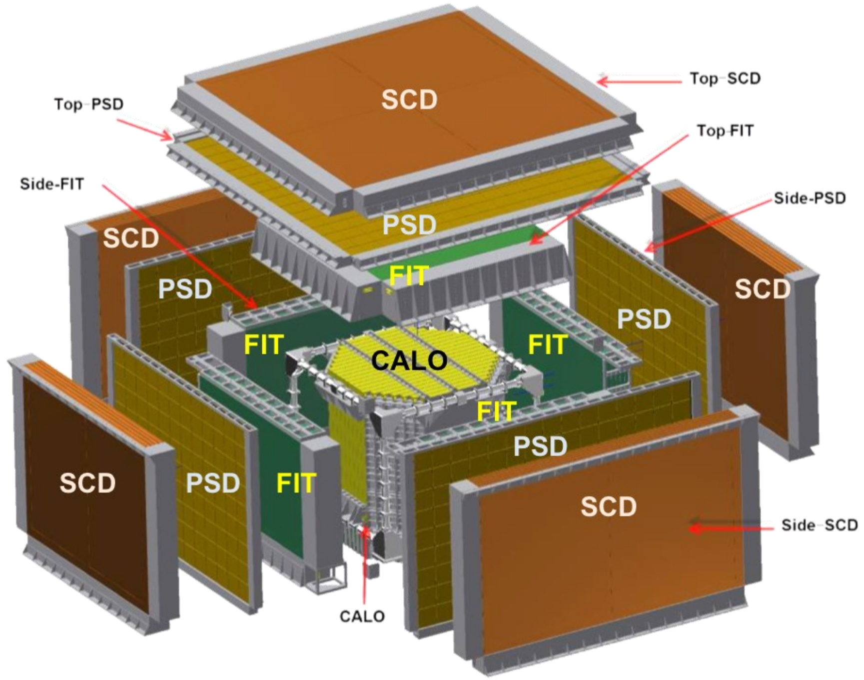

Artist's impression of HERD on the CSS



The experiment is based on a **3D, homogeneous, isotropic and finely-segmented calorimeter** that will measure the cosmic ray flux up to the knee region, search for indirect signal of dark matter and monitor the full gamma-ray sky

Xi'an (CN), 16-18 Dec 2019

Detector Overview



Silicon Charge Detector (SCD)	• Charge Reconstruction
Plastic Scintillator Detector (PSD)	• Charge Reconstruction • γ Identification
FIber Tracker (FIT)	• Trajectory Reconstruction • Charge Identification
Calorimeter (CALO)	• Energy Reconstruction • e/p Discrimination
Transition Radiation Detector (TRD)	• Calibration of CALO response for TeV protons

Chinese Space Station

Life time	> 10y
Orbit	Circular LEO
Altitude	340-450 km
Inclination	42°

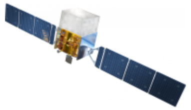
HERD on CSS

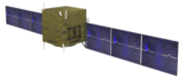
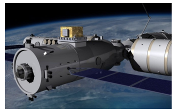
Life time	> 10y
FOV	+/- 70°
Power	< 1.5 kW
Mass	< 4 t

Main requirements

	γ	e	p, nuclei
Energy Range	>100MeV	10 GeV 100 TeV	30 GeV 3 PeV
Energy resolution	1% @ 200 GeV	1% @ 200 GeV	20% @ 100 GeV -1 PeV
Effective Geometric Factor	>0.2 m^2sr @ 200 GeV	>3 m^2sr @ 200 GeV	>2 m^2sr @ 100 TeV

HERD purposes



Experiment	Energy (e/γ)	Energy (p)	Calorimeter thickness (X_0)	Angular res. @ 100 GeV (deg)	Energy res. (e/g) @ 100 GeV	e/p ID	Geometrical acceptance (m^2sr)
Fermi-LAT (2008)	<100 MeV – 300 GeV	30 GeV – 10 TeV	8.6	0.1	10%	10^3	1
AMS-02 (2011)	1 GeV – 1 TeV	1 GeV - 2 TeV	17	0.3	3%	10^4 – 10^5	0.09
CALET (2015)	1 GeV – 10 TeV	50 GeV – 60 TeV	27	< 0.2	2%	10^5	0.12
DAMPE (2015)	5 GeV – 10 TeV	40 GeV – 300 TeV	32	0.2	< 1.5%	> 10^5	0.3
HERD (2027)	**10 GeV – 100 TeV 0.5 GeV – 100 TeV (γ)**	**30 GeV - PeV**	**55**	**0.1**	**< 1%**	**> 10^6**	**3**

HERD is a next generation experiment with much better performance on direct high energy e, p, gamma ray detection.

Main Scientific goals
Direct measurement of cosmic rays flux and composition up to the knee region
Gamma-ray monitoring and full sky survey
Indirect dark matter search (e^++e^-, γ,...)

HERD physics: electrons and positrons (1)

Present status

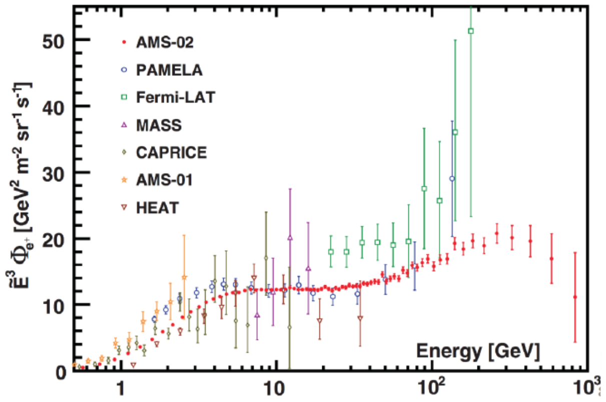
Positron excess

- excess of high-energy positrons observed in cosmic rays detected by the PAMELA and later confirmed by the AMS-02
  - This excess has a significant rise in energy at higher energies and suggests that there could be additional (local) sources contributing to the positron population.
  - consistent with expectations from various astrophysical sources: pulsars, … , DM annihilation

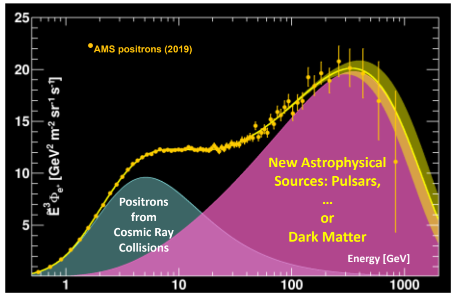
All electrons

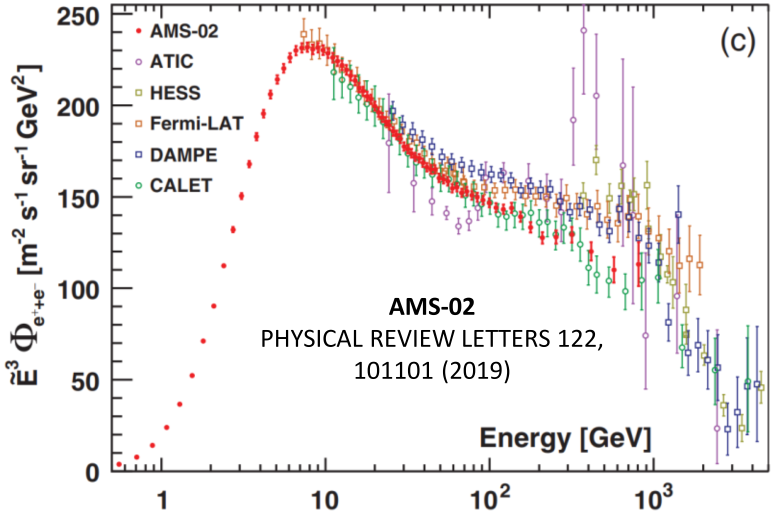
- The different behavior of the cosmic-ray electrons and positrons measured by AMS-02 is clear evidence that most high energy electrons originate from different sources than high energy positrons[1]
- Spectral break at ~ 1 TeV[2]
  - Significant discrepancies in current measurements (low statistic → systematics)

Precision measurements by AMS of the positron flux to 1 TeV.



The positron flux could be described by the sum of a diffuse term and a new source term with a finite energy cutoff (~ 800 GeV)





AMS-02
PHYSICAL REVIEW LETTERS 122, 101101 (2019)

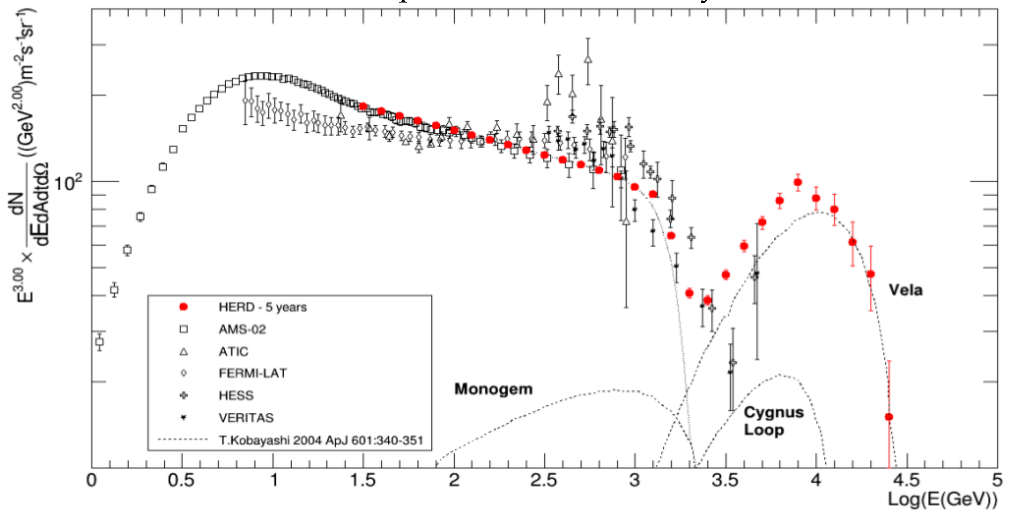
[1] PRL 122 041102 (2019)
[2] Nature, 552(7683), pp. 63–66.

HERD physics: electrons and positrons (2)

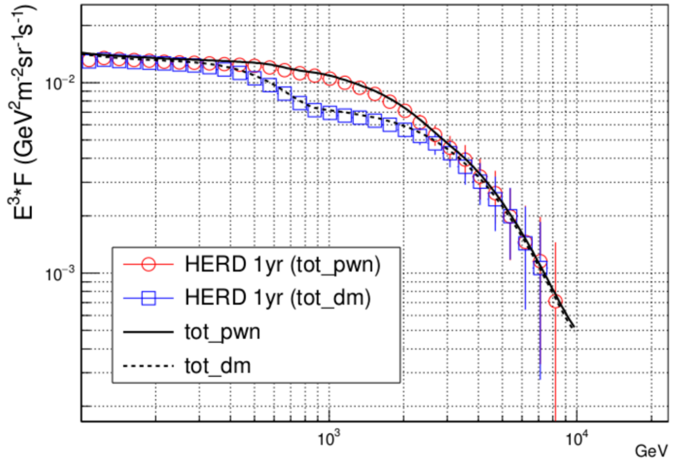
HERD aims to explain the positron excess through precise cosmic ray electron measurements up to tens of TeV and search for dark matter signals with high sensitivity.

- HERD will measure the all electron flux up to several tens of TeV in order to detect:
  - local nearby astrophysical sources of very high energy e^-
  - additional information from anisotropy measurement
  - confirmation of spectral cutoff at high energy
  - …
- HERD will give important indications on the origin of the positron excess
  - ***Indications of possible production from dark matter***
    - to distinguish the origin of the excess from DM hypothesis from other astrophysical explanations thanks to precise measurement of the different spectral shape in case of additional PWN or DM production

Expected e^++e^- flux in 5 years



Expected e^++e^- flux in 1 year with PWN or DM sources



HERD physics: Protons and nuclei (1)

Present status

Proton and Helium

- Feature-rich spectra emerged from power-law behavior thanks to recent accurate, statistically significant measurements:
  - Hardening at 200-400 GeV (PAMELA, AMS)
  - Softening in the 10-30 TeV region (DAMPE,CALET)

Implications for acceleration and propagation

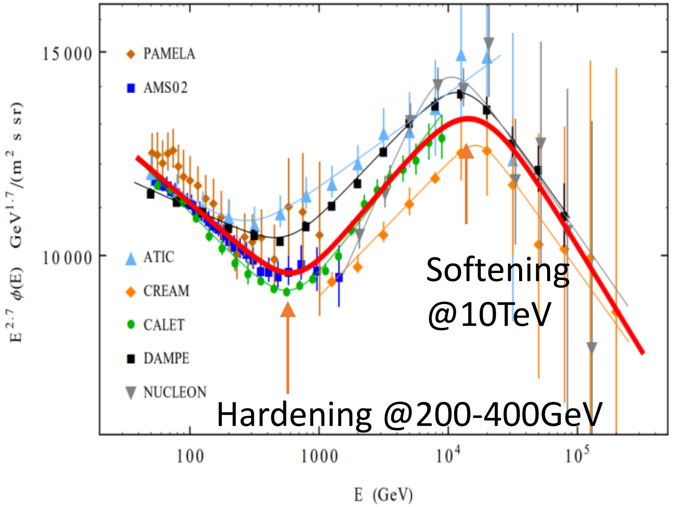
B/C ratio

- Current measurements limited to the ~ TeV/n region due to low statistics (calorimeters) or instrumental limits (spectrometers)

B/C is the "standard probe" for propagation models

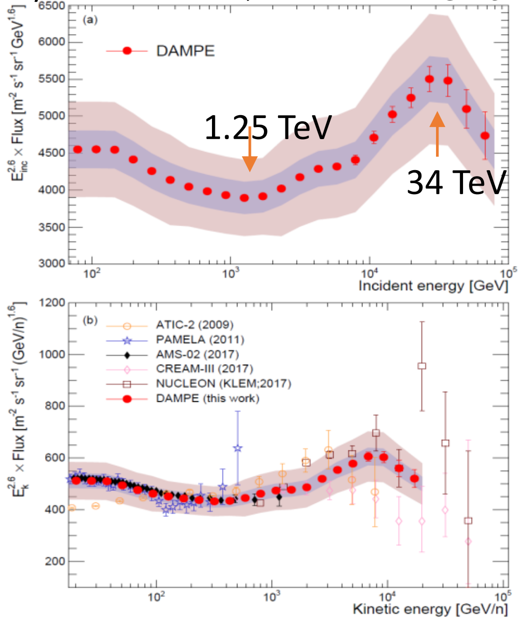
Lipari & Vernetto
Astroparticle physics 120 (2020): 102441

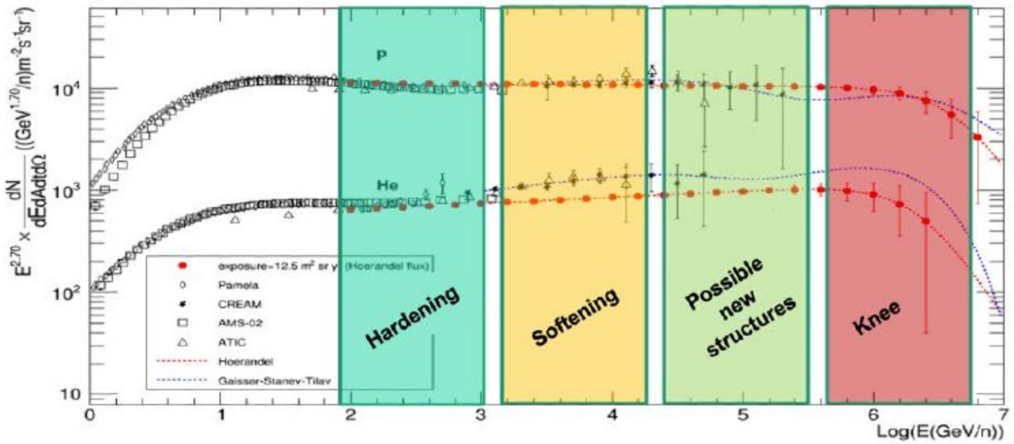
Proton



Phys. Rev. Lett. **126**, 201102

Helium





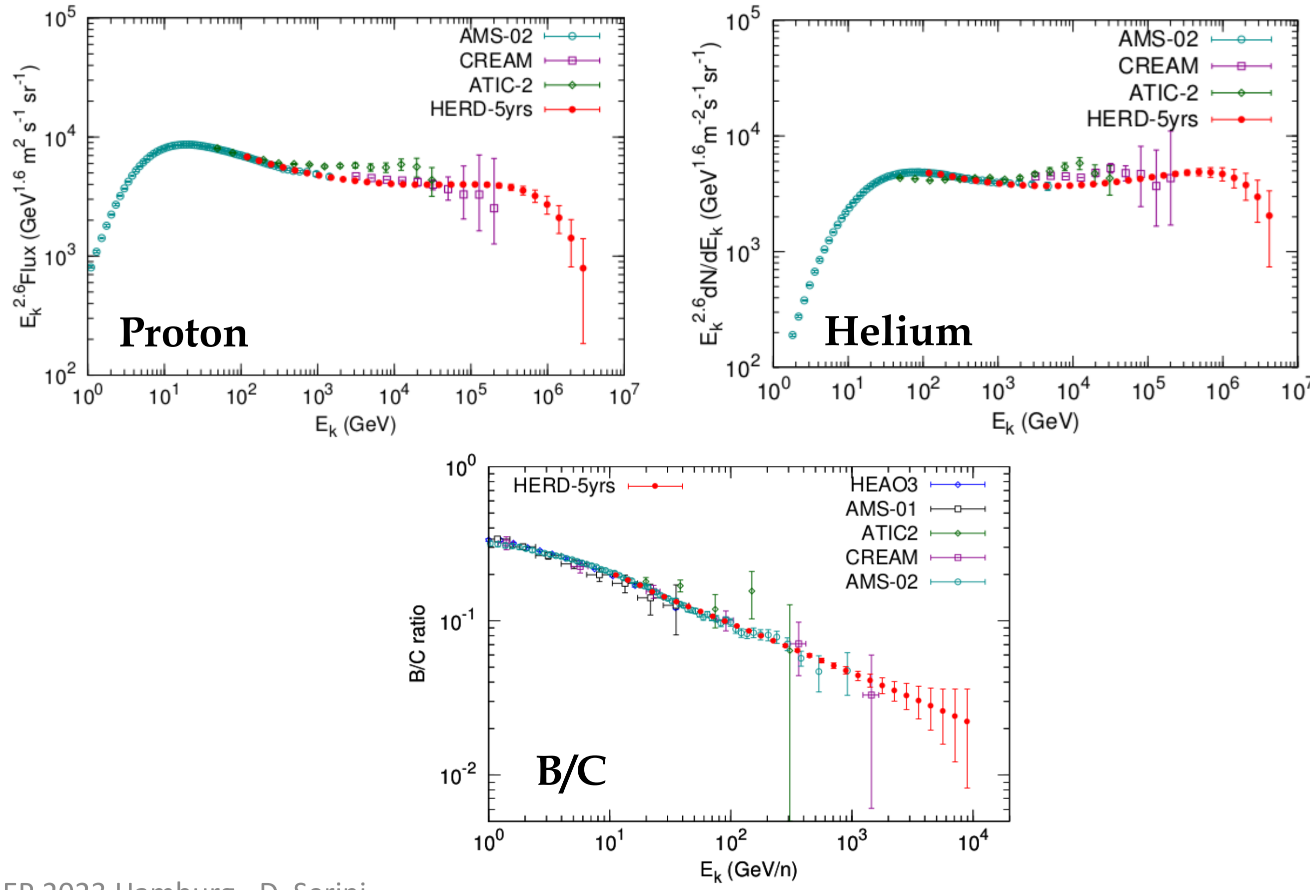
HERD physics: Protons and nuclei (2)

The picture of CR is much richer than we expected and measurements to higher energies are needed.

HERD will provide the first **direct** measurement of p and He knees and it will extend the measurements of B/C ratio at higher energies, shed light on our understanding of the knee origin and acceleration and propagation mechanisms.

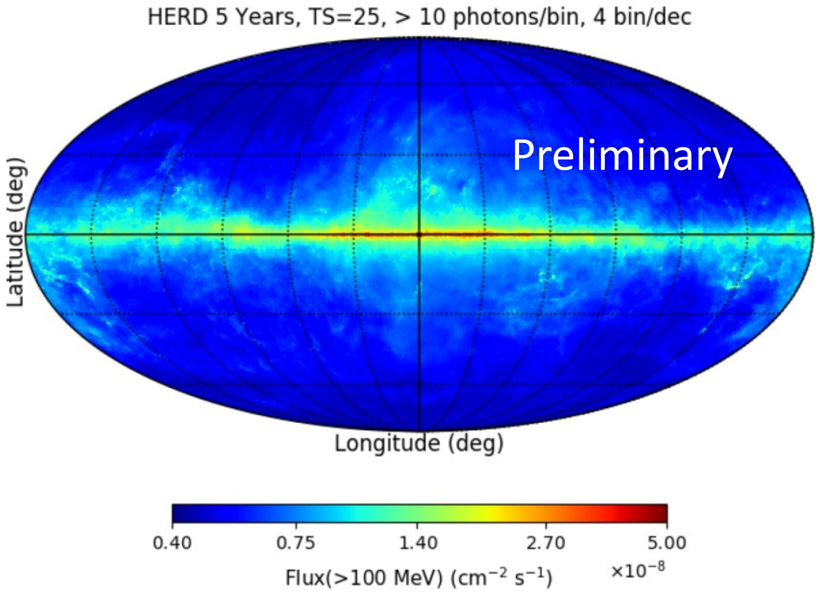
- HERD will measure the flux of nuclei:
  - p and He up to a few PeV
  - heavier nuclei up to a few hundreds of TeV/n
- First direct measurement of p and He knees
  - It will provide a strong evidence for the knee structure as due to acceleration limit
- Extension of the B/C ratio to high energy
  - It will provide further test for the propagation mechanisms of cosmic rays

Expected performance in 5 years



HERD physics: Gamma ray sky-survey

- Thanks to its large acceptance and sensitivity, HERD will be able to perform a full gamma-ray sky survey in the energy range > 100 MeV
  - extend Fermi-LAT catalog to higher energy (> 300GeV)
  - increase the chances to detect rare gamma events
- Targets of Gamma-Ray Sky Survey:
  - ***search for dark matter signatures***
  - study of galactic and extragalactic γ sources
  - study of galactic and extragalactic γ diffuse emission
  - detection of high energy γ Burst



Multi-messenger astronomy

Possible synergy with other experiments designed for

- γ (CTA, LHAASO)
- ν (KM3NeT, IceCube)
- GW (Ligo, Virgo)

HERD Design

- Innovative design: “isotropic”, 3D-mesh calorimeter + subdetectors on 5 sides
- Control over systematics:
  - Absolute energy scale → CALO double readout system + in-flight calibration with TRD
  - Nuclei fragmentation → charge detector as outermost detector

Silicon Charge Detector (SCD)	• Charge Reconstruction
Plastic Scintillator Detector (PSD)	• Charge Reconstruction • γ Identification
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Calorimeter (CALO)	• Energy Reconstruction • e/p Discrimination
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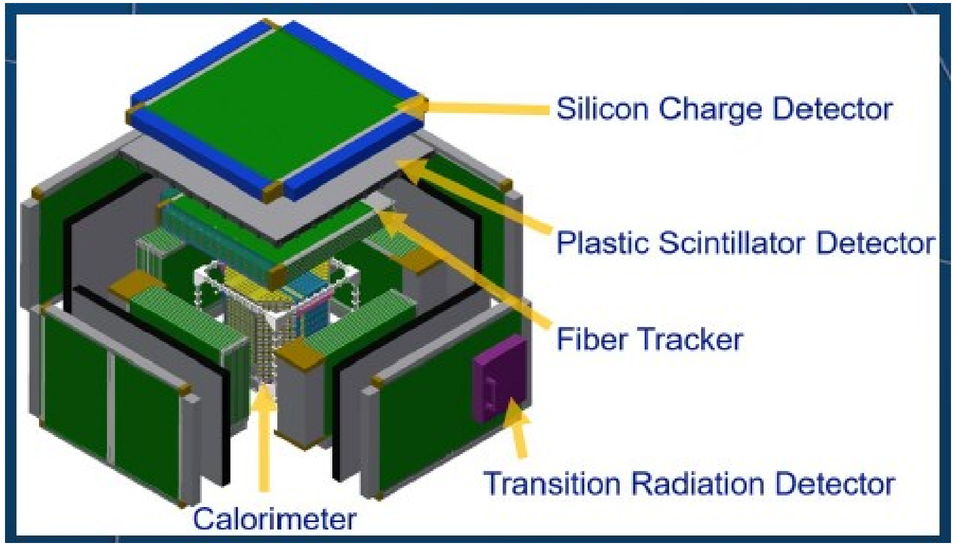
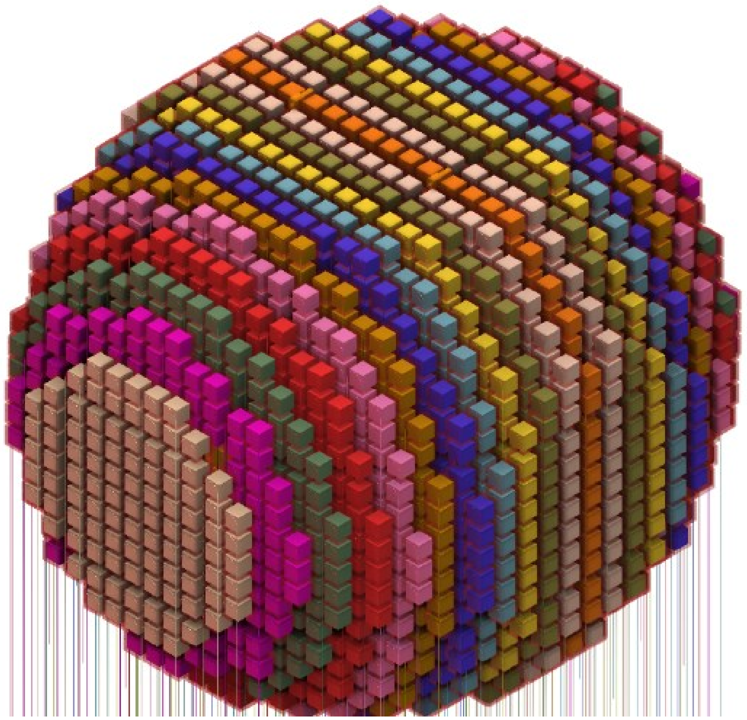
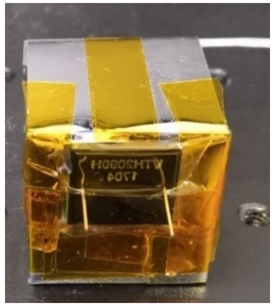


CALOrimeter (CALO)





CALO consists of about **7500 LYSO cubes** with edge length of 3 cm.

Deep homogeneous calorimeter (55 X_0, 3 λ_I)	High energy and good energy resolution
Isotropic 3D geometry	Large geometric factor (top + lateral faces)
Shower imaging with 3D segmentation	Good e/p discrimination, identification of shower starting point and shower axis

Each cube is readout by 2 systems. The double read-out system allows for **redundancy, independent trigger, and cross calibration** in order to reduce the systematic uncertainties (especially on the absolute energy scale).

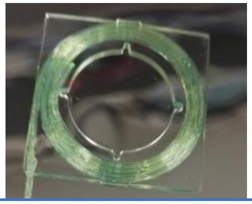
CALO read-out

Wavelength shifting fibers (WLS) read-out

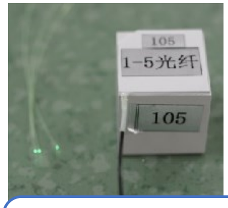
- Each cube is read-out by 3 WLS fibers.
- One fiber is used for triggering a fast PMT.
- The signal from the other two fibers is amplified by an Image Intensifier and readout by a IsCMOS camera

Photo-diode (PD) read-out

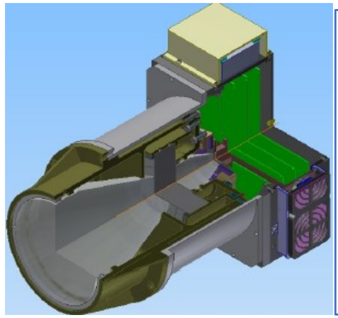
- Each cube is read-out by 2 PDs: the
- large PD (LPD, 25 mm^2) and the small one (SPD, 1.6 mm^2) connected to connected to custom front-end electronics (HIDRA chips).



Encapsulation of WLSF with optical cement

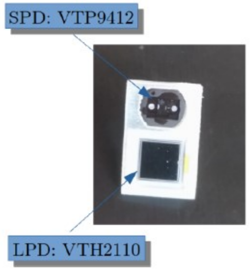


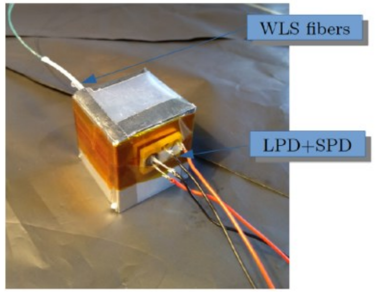
WLSF coupled to LYSO and covered by a reflector



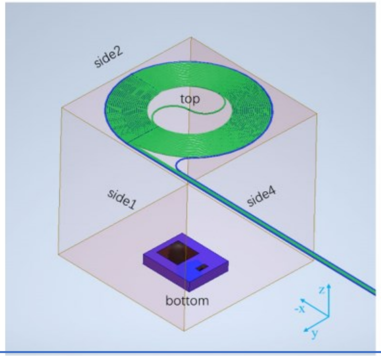
Each IsCMOS camera is composed of:

- front taper,
- image intensifier,
- rear taper,
- sCMOS chip.

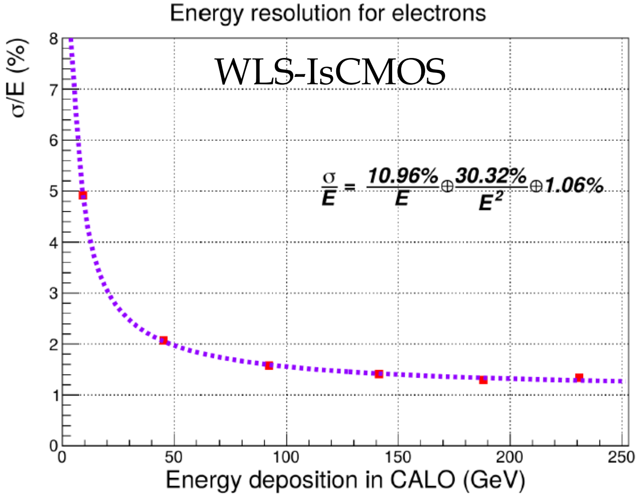




L. Pacini *et al*, POS (ICRC 2021) 066

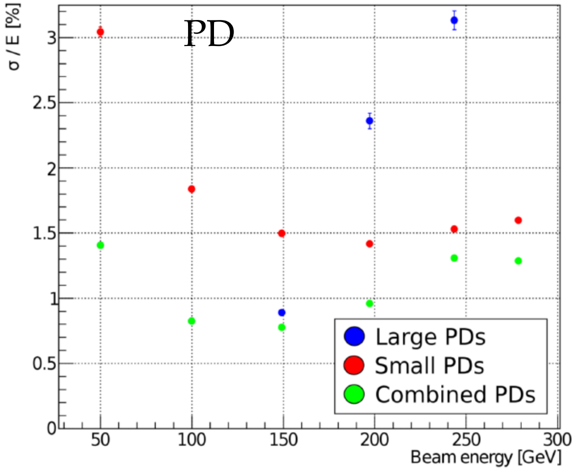


The top face of each cube is attached to WLSFs while the bottom face is glued to PDs.

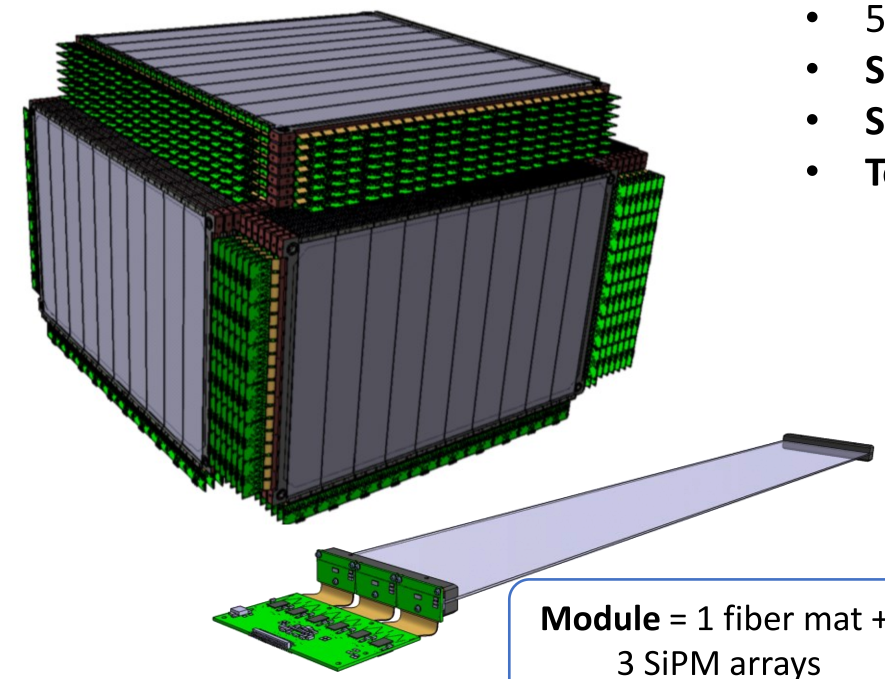


Energy resolution Beam test **electrons**

σ/E <2%
E > 50 GeV

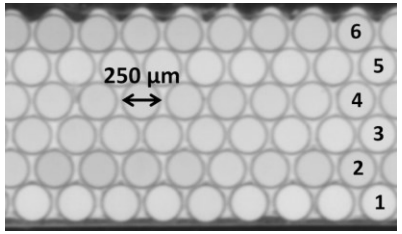


FIber Tracker (FIT)



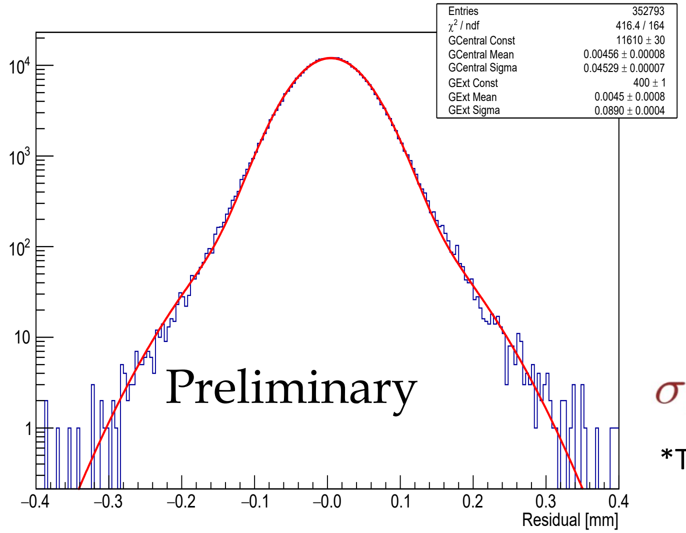
- 5 sectors
- **Sector:** 7 x-y tracking planes
- **Side planes:** 6 x + 10 y modules
- **Top plane:** 10 x + 10 y modules

- Fiber mat: 6 layers of fibers
- Fiber type: **KURARAY SCSF-78MJ**
  - round section with, diameter = 250 μm
- Mat width ≅ 97.80 mm to match 3 SiPM arrays

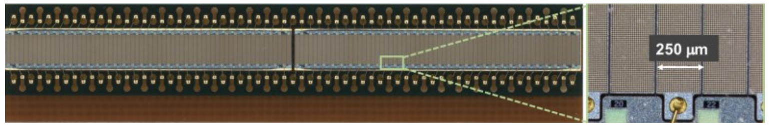


Module = 1 fiber mat + 3 SiPM arrays

Proton beam test results



- SiPM array (S13552-10): 2 chips with 64 channels
- Channel size: 230 μm × 1630 μm
- Pixel size: 10 μm × 10 μm
- 23 x 163 pixels/channel
- Gap between channels: 20 μm → pitch: 250 μm
- Gap between chips: 220 μm



$$\sigma_{\mathrm{FIT}} = (45.0 \pm 0.1)\ \mu\mathrm{m}$$

*Takes into account the external tracker resolution

Charge resolution for nuclei heavier than p

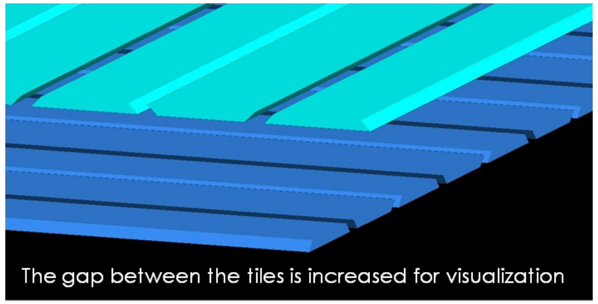
Preliminary results

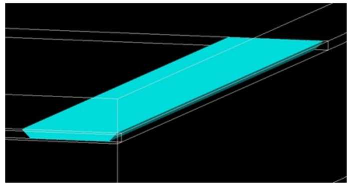
Z	μ_Z	σ_Z	σ_Z/μ_Z
2	1.99	0.31	15 %
3	3.07	0.40	13 %
4	4.01	0.51	12 %

Plastic Scintillator Detector (PSD)

PSD provide γ identification (VETO of charged particles) and nuclei identification (energy loss $\propto Z^2$)

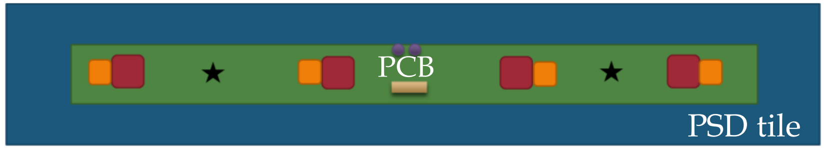
- Requirements:
  - high efficiency in charged particles detection (>99,98%)
  - high dynamic range to identify nuclei at least up to iron
  - highly segmented design to reduce the self-VETO due to back scattered charged particle
- TOP plane and 4 SIDE plane to be equipped:
  - SCD and PSD will share the same mechanical structure
  - Each plane is composed of two layers to increase the **hermeticity** and so the VETO efficiency
  - Each layer will be composed by short trapezoidal **plastic scintillating** tiles 40cm long and 5/4cm wide
    - TOP $180 \times 180 cm^2$ ~ 400 tiles
    - SIDE $170 \times 95 cm^2$ ~ 160 tiles
    - Total number of tiles: ~ 1000





Each tile will be readout by different SiPMs in order to increase the light detection efficiency and the dynamic range for nuclei identification

- 4 SiPM (3.0x3.0mm2 – 50umcell) - **Low Z**
- 4 SiPM (1.3x1.3 mm2 – 15um cell) - **High Z**



Led for calibration

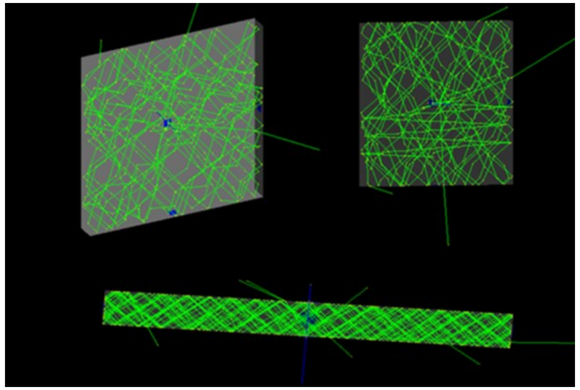
coaxial cable connector

★ Temperature sensors

custom front-end electronics based on β-chip

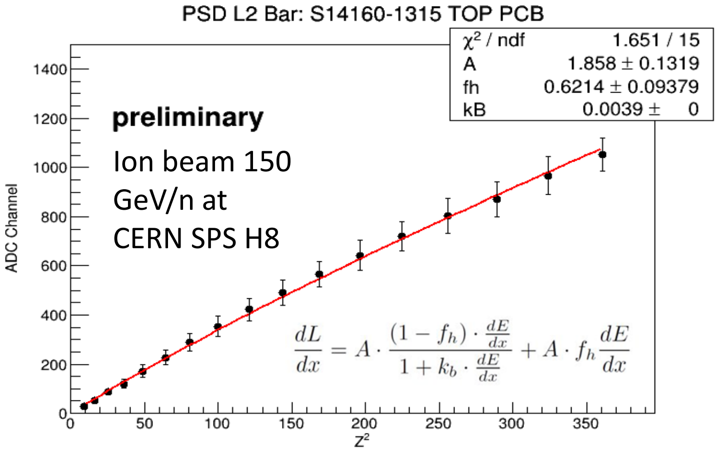
PSD prototypes and performance studies

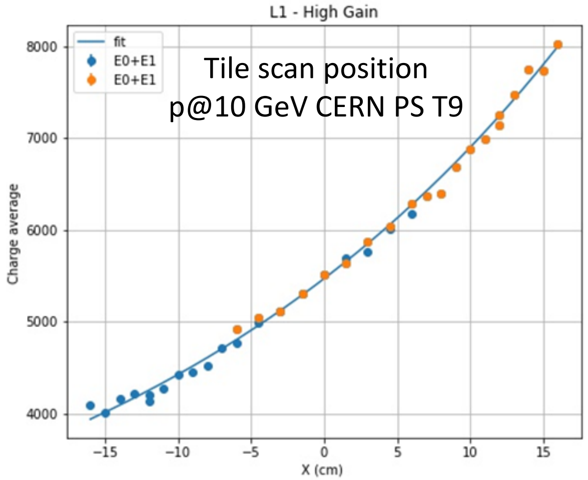
- Uniformity response of light collection
  - Each trapezoidal tile will be equipped with SiPMs placed in different positions along the tiles. The sensor positioning is optimized using dedicated Monte Carlo simulations to ensure uniform light collection[1]
- Nuclei identification performances studies (Beam Tests)[2]
  - Energy resolution
  - Investigation of the non-linearity of scintillation photon generation for high-energy releases, specifically in terms of quenching effects (Birk's law).



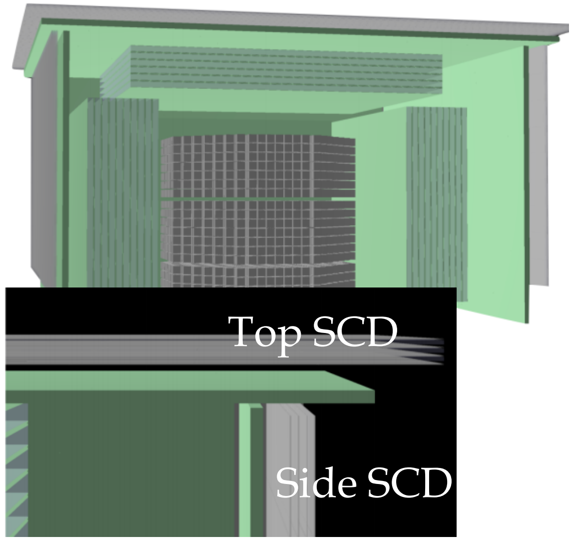
[1] Altomare C., Serini D., et al., Nucl.Instrum.Meth.A 982 (2020) 164479.
[2] Serini D. (HERD Collaboration), et al. IEEExplore special issue, IWASI 2023, (2023), p. 184-189.

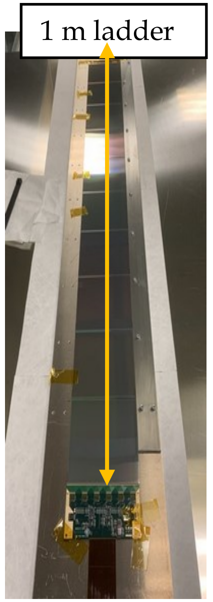
PSD prototypes under tests during BT campaigns at CERN and CNAO (2022-2023…)





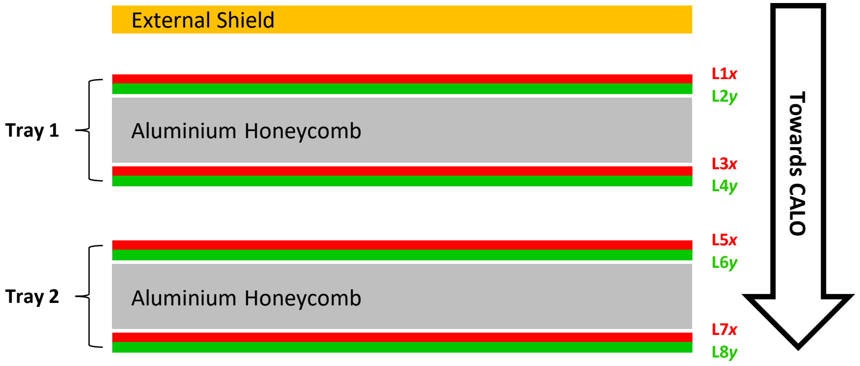
Silicon Charge Detector (SCD)





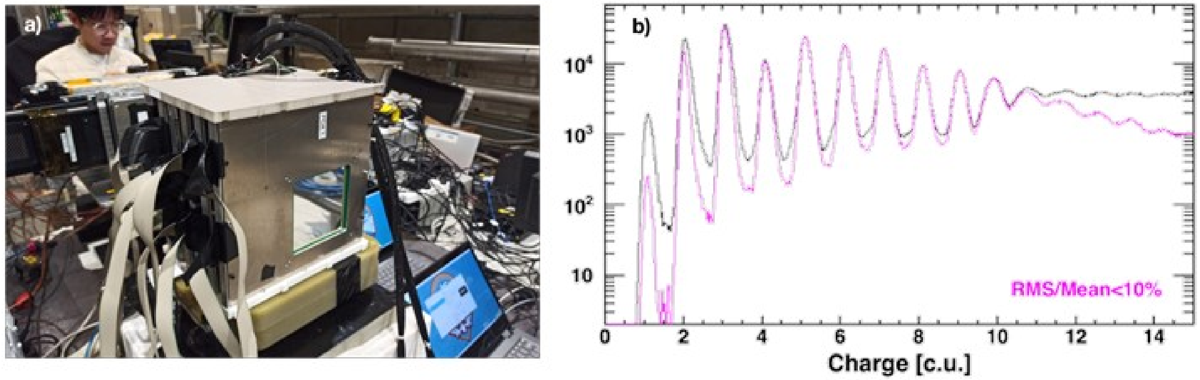
SCD is a **silicon micro-strip** detector that will measure with precision the impinging particle charge |Z|

- 4 double X-Y layers for each of the five sectors → 8 independent ionization measurements per sector → Z =1 to 28
- It is the **outermost** detector to avoid early charge-change interactions in the PSD and to reduce the systematic uncertainty on the reconstructed charge due to fragmentation
- It is highly **segmented** to minimize the unavoidable backscattered secondary particles coming from the CALO



SCD italian prototype tested at CERN SPS – H8 (2022) composed of 8 SSDs with a thickness of 150µm, 50µm implantation pitch and 2 floating strips[1]

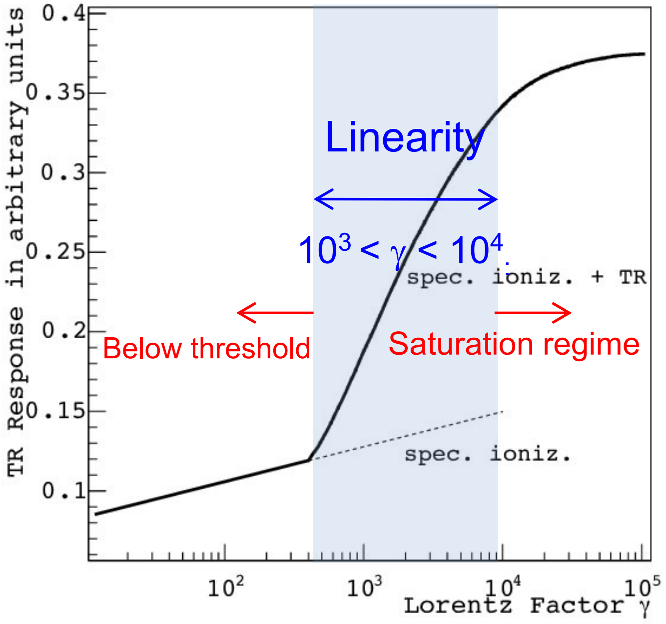
The device allows to clearly distinguish charges up to at least Z=10



[1] A.Oliva et. Al. The Silicon Charge Detector (SCD) of the High Energy cosmic-Radiation Detection (HERD) facility (ICRC2023)

Transition Radiation Detector (TRD)

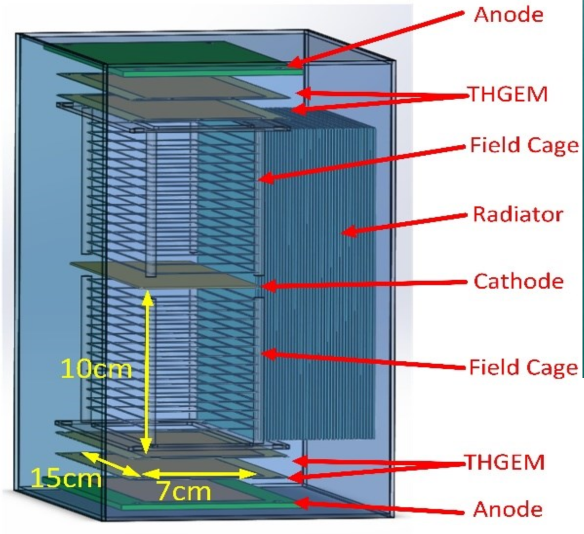
The TRD, installed on a lateral face of the detector, is needed to calibrate the response of the calorimeter to high energy hadronic showers

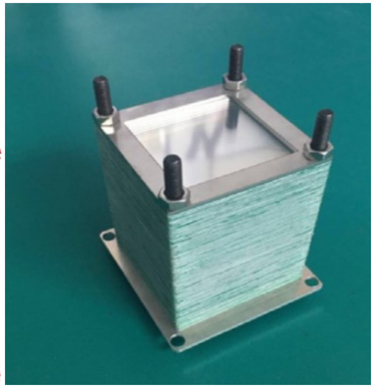


Linearity for $10^3 < \gamma < 10^4$

Electron 0.5 GeV < E < 5 GeV

Proton 1 TeV < E < 10 TeV





Radiator:
- multi-layer thin foils

Detector:
- 1 atm Xe
- side-on THGEM (THick Gaseous Electron Multiplier)

Calibration procedure
- calibrate TRD response using [0.5 GeV, 5 GeV] electrons in space (and beam test)
- calibrate CALO response using [1 TeV, 10 TeV] protons *from TRD* (3 months data required)

Summary

- The High Energy cosmic-Radiation Detection facility is an international space mission that will start its operation at the end of 2027 on board the China's Space Station (CSS).
  - Thanks to its novel design, based on a 3D, homogeneous, isotropic and finely-segmented calorimeter, HERD is expected to accomplish important and frontier goals relative to CR observations, DM search and Gamma-Ray astronomy
    - It will measure the spectra of charged cosmic rays at the highest-ever energies reached by a direct detection experiment
      - nuclei fluxes up to the knee region for probing propagation and acceleration models
      - e^+e^- fluxes up tens of TeV for testing the cutoff and the origin of positron excess (astrophysical vs. dark matter)
    - It will perform high-energy gamma-ray sky survey
      - searching for γ line associated to DM annihilation
      - detection of high energy γ Burst (transient phenomena)
      - Multimessenger astrophysics

- Currently HERD status
  - Phase B: Study of key technology and key components, prototype for beam tests