13th Cosmic-Ray International Studies and Multi-messenger Astroparticle Conference

HERD: an innovative detector to expand energy limits in direct detection of cosmic rays

CRIS - MAC 2024

Trapani

17/06/2024

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On behalf of the HERD collaboration

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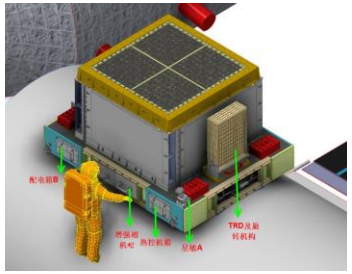
The HERD collaboration

- 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
  - International scientific collaboration counting **180+** scientists from China and Europe (Italy, Switzerland and Spain).

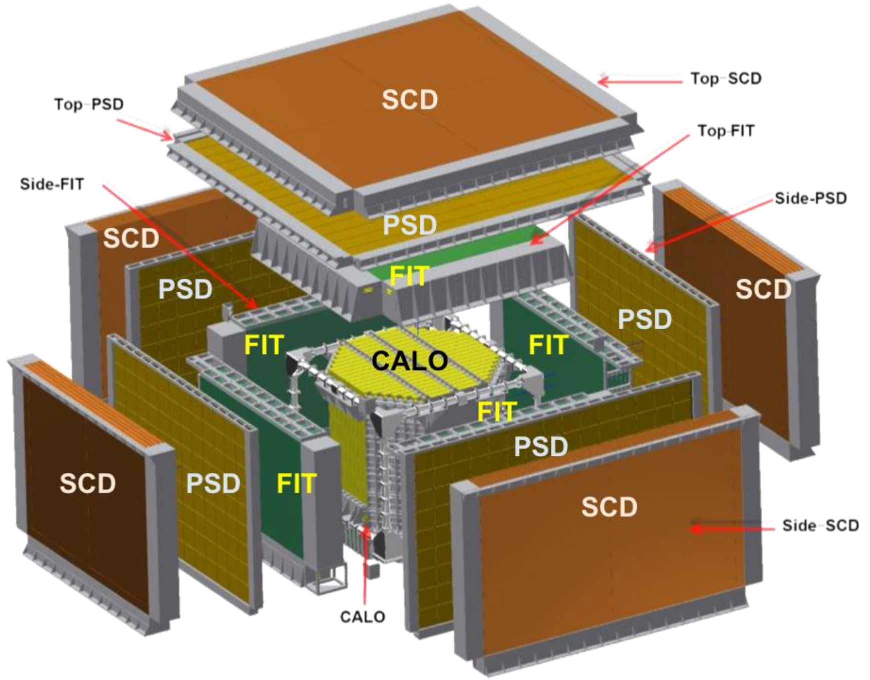
The experiment is based on a **3D, homogeneous, isotropic and finely-segmented calorimeter** that will measure the cosmic ray flux up to the knee region, search for indirect signal of dark matter and monitor the full gamma-ray sky


Artist's impression of HERD on the CSS



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°

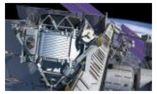
HERD on CSS

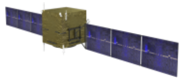
Life time	> 10y
FOV	+/- 70°
Power	< 1.5 kW
Mass	< 4 t

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

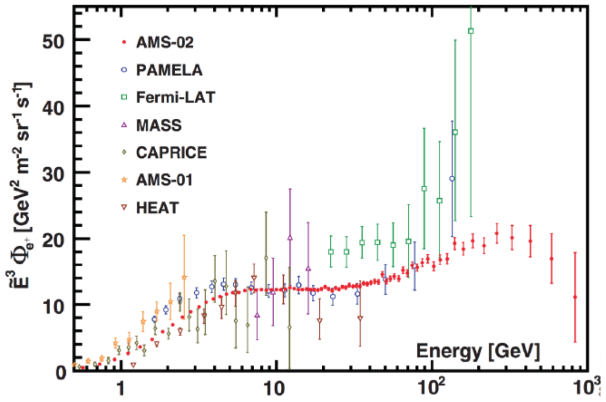
Positron excess

- 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

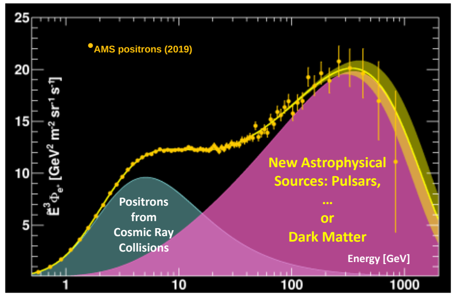
All electrons

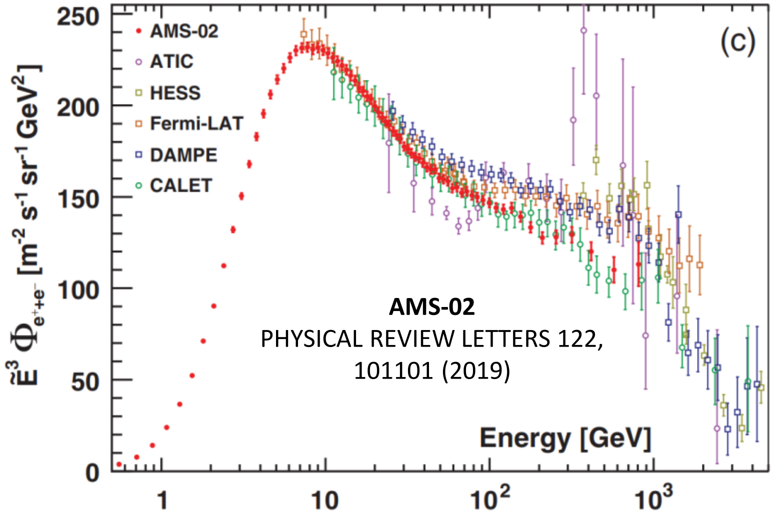
- The different behavior of the cosmic-ray electrons and positrons measured by AMS-02 is clear evidence that most high energy electrons originate from different sources than high energy positrons[1]
- Spectral break at ~ 1 TeV[2]
    - Significant discrepancies in current measurements (low statistic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

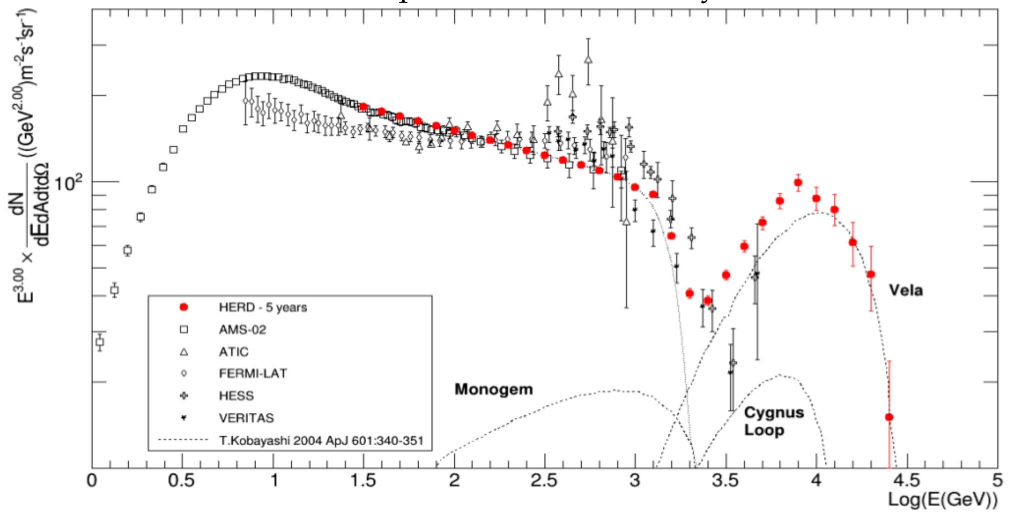
[1] PRL 122 041102 (2019)
[2] Nature, 552(7683), pp. 63–66.

HERD physics: electrons and positrons (2)

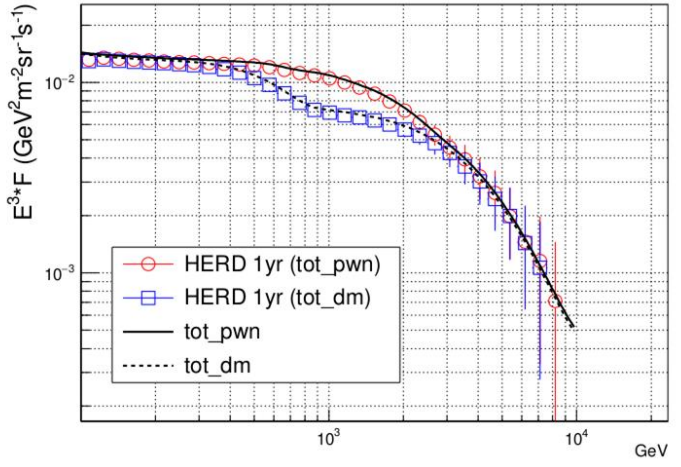
HERD aims to explain the positron excess through precise cosmic ray electron measurements up to tens of TeV and search for dark matter signals with high sensitivity.

- 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

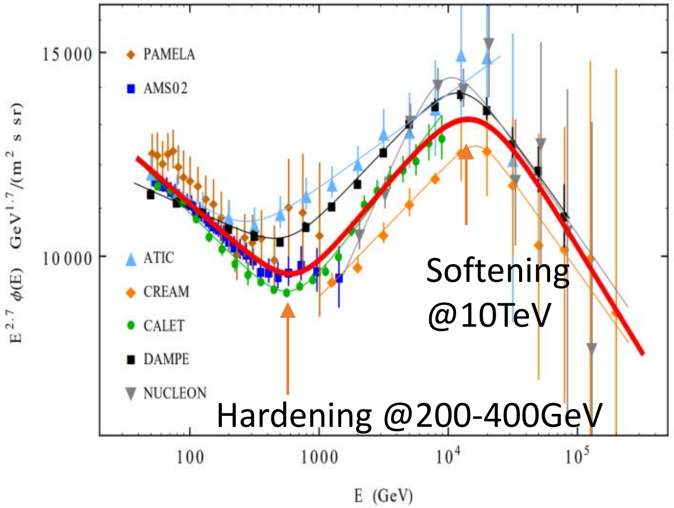
B/C ratio

- 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

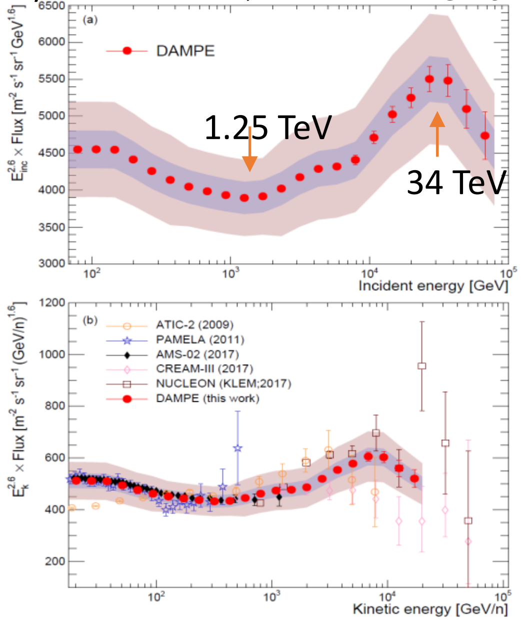
Lipari & Vernetto
Astroparticle physics 120 (2020): 102441

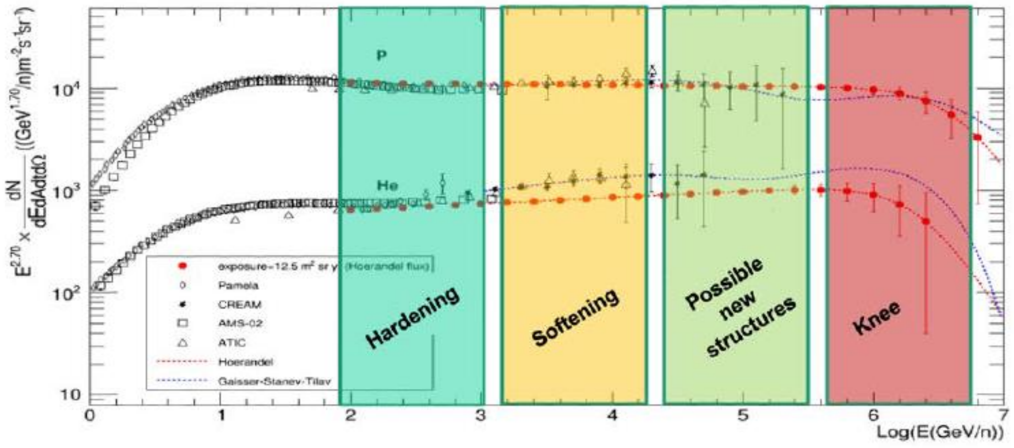
Proton



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

Helium



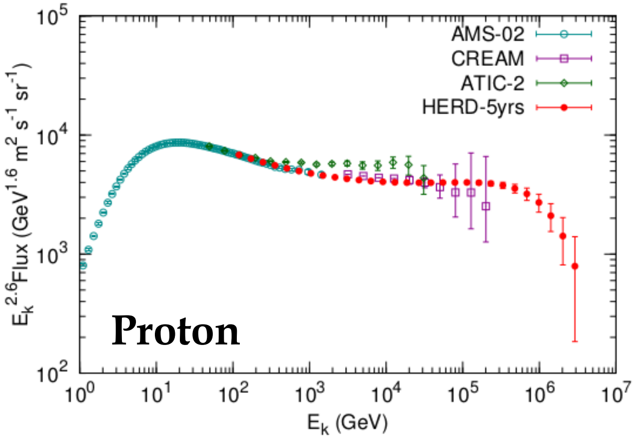


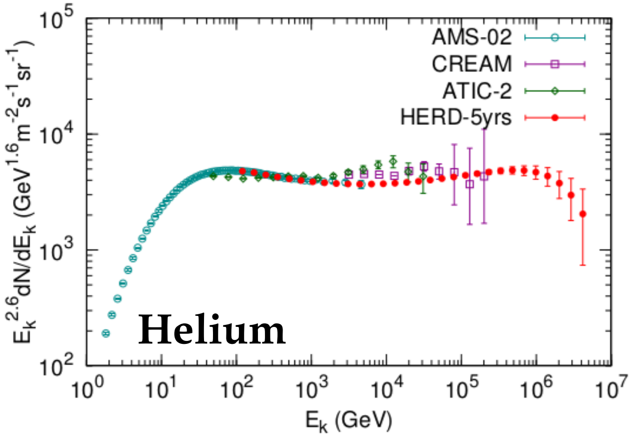
HERD physics: Protons and nuclei (2)

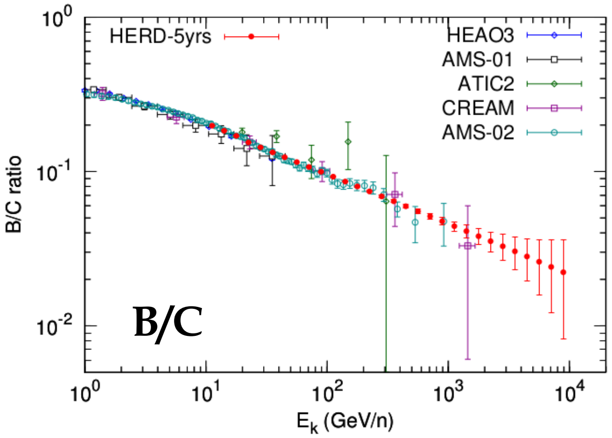
The picture of CR is much richer than we expected and measurements to higher energies are needed.
HERD will provide the first **direct** measurement of p and He knees and it will extend the measurements of B/C ratio at higher energies, shed light on our understanding of the knee origin and acceleration 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

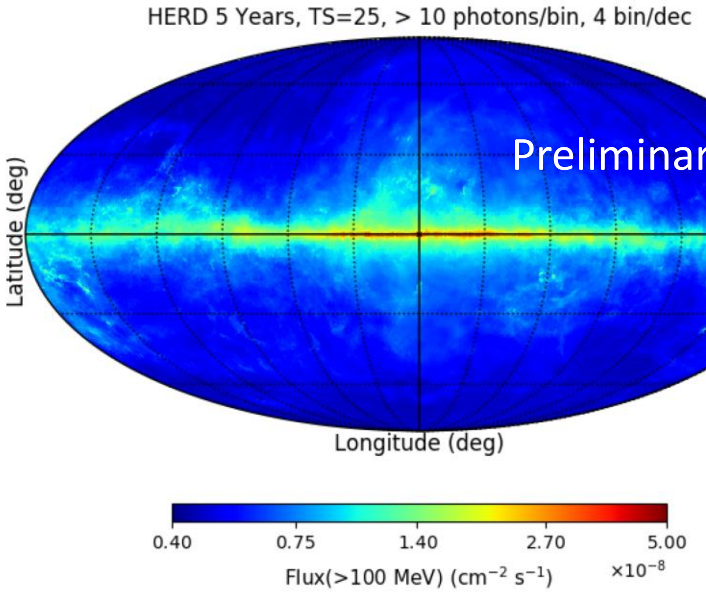






HERD physics: Gamma ray sky-survey

- 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

The main effort in the HERD collaboration is currently focused on the development and testing of all the subdetector prototypes to achieve the expected performance required to meet all the HERD scientific goals.

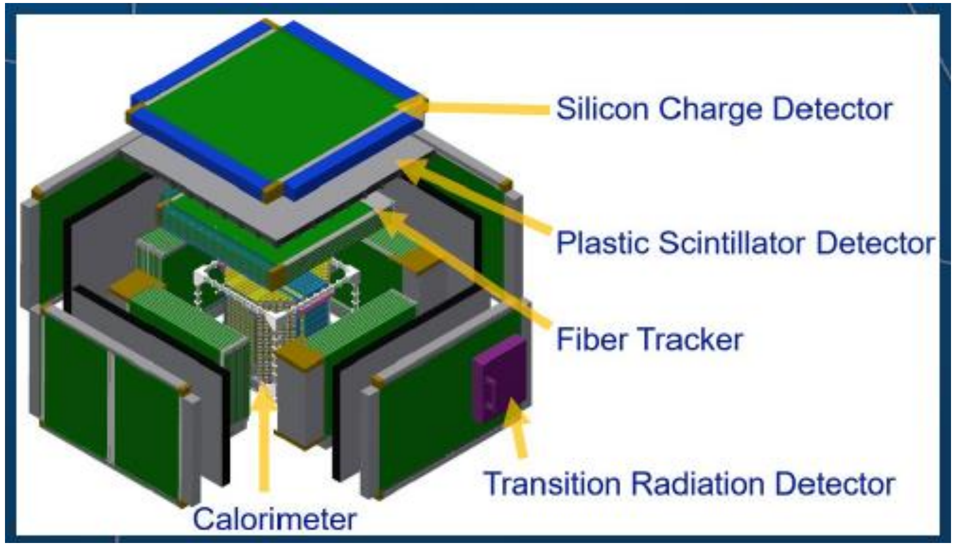
- Beam test has been performed in the last years (CERN PS, CERN SPS …)

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

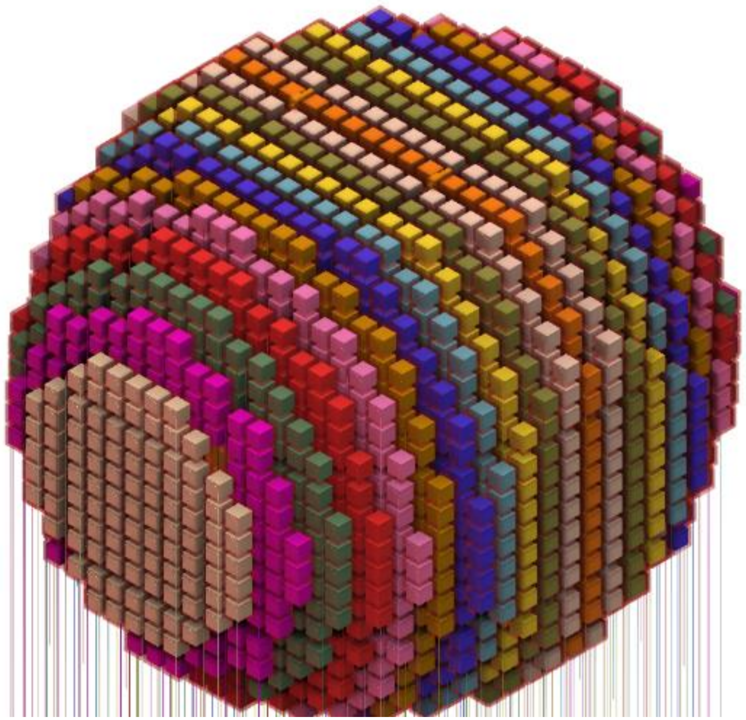
Control over systematics:

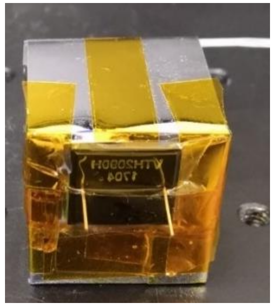
- Absolute energy scale → CALO double readout system + in-flight calibration with TRD
- Nuclei fragmentation → charge detector as outermost detector

Innovative design: "isotropic", 3D-mesh calorimeter + subdetectors on 5 sides



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).

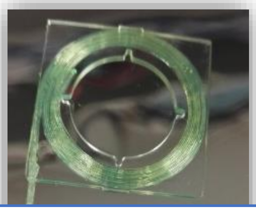
CALO read-out

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

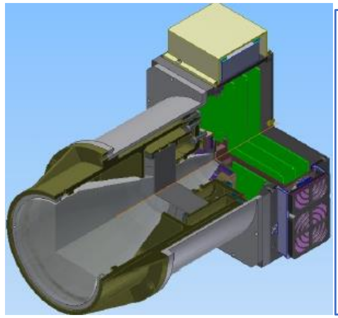
Photo-diode (PD) read-out

- 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).

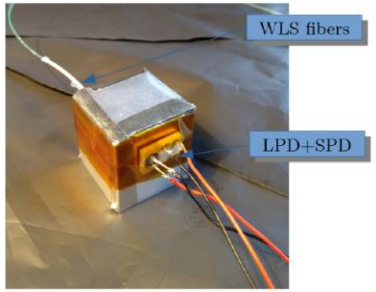


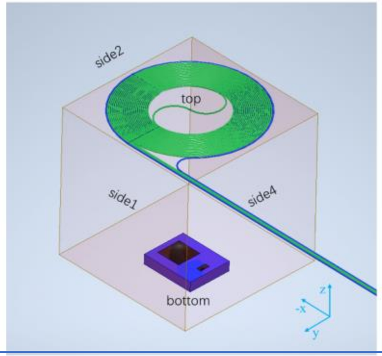
Encapsulation of WLSF with optical cement

WLSF coupled to LYSO and covered by a reflector

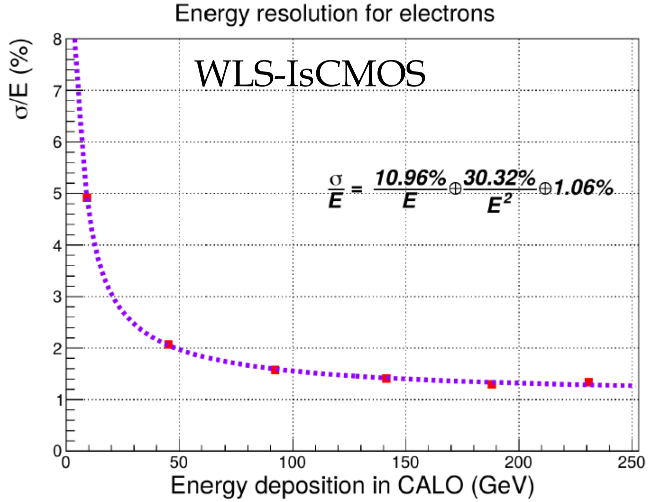


Each IsCMOS camera is composed of:
- front taper,
- image intensifier, rear taper,
- sCMOS chip.





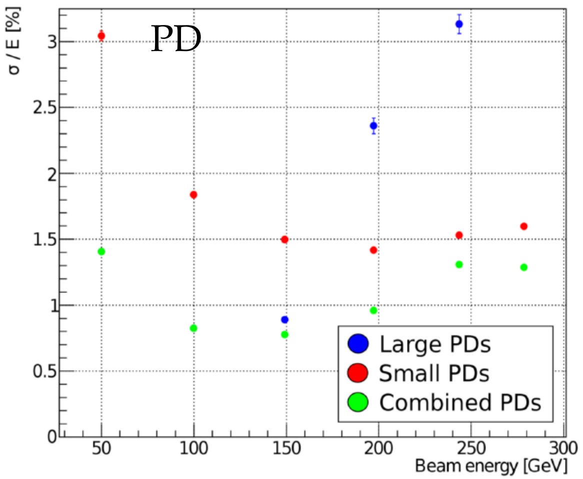
The top face of each cube is attached to WLSFs while the bottom face is glued to PDs.



Energy resolution 2022 Beam test **electrons**

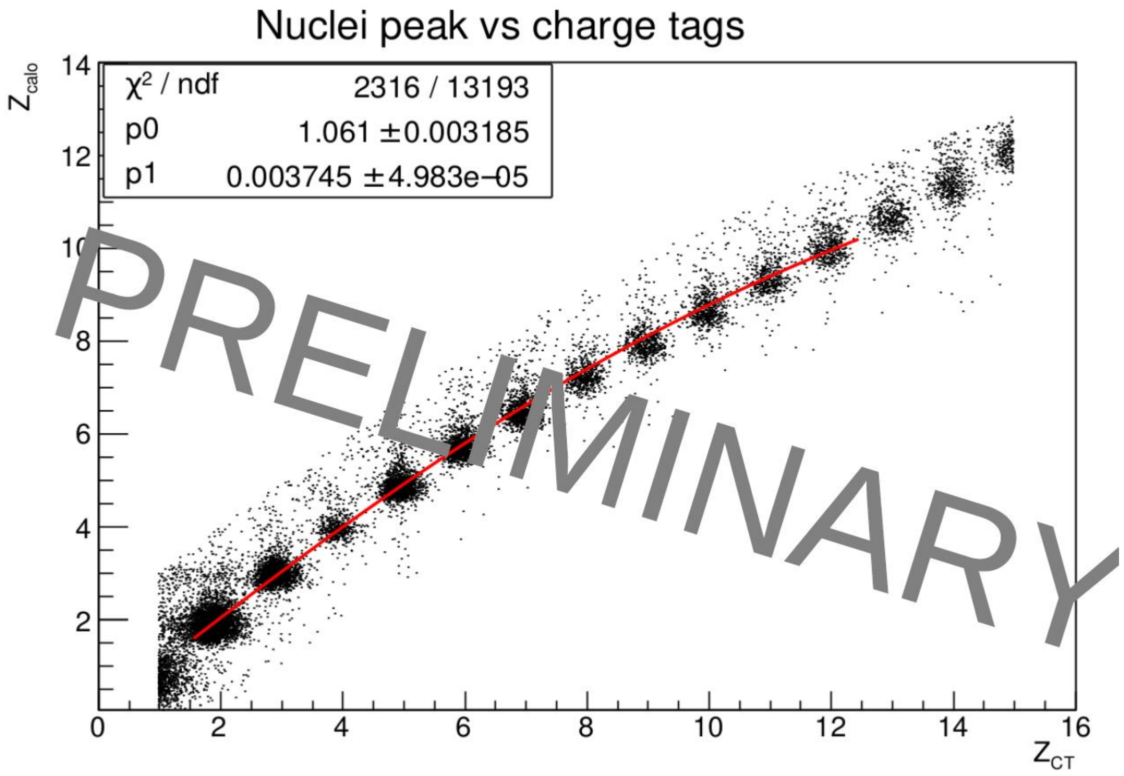
σ/E <2%
E > 50 GeV

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

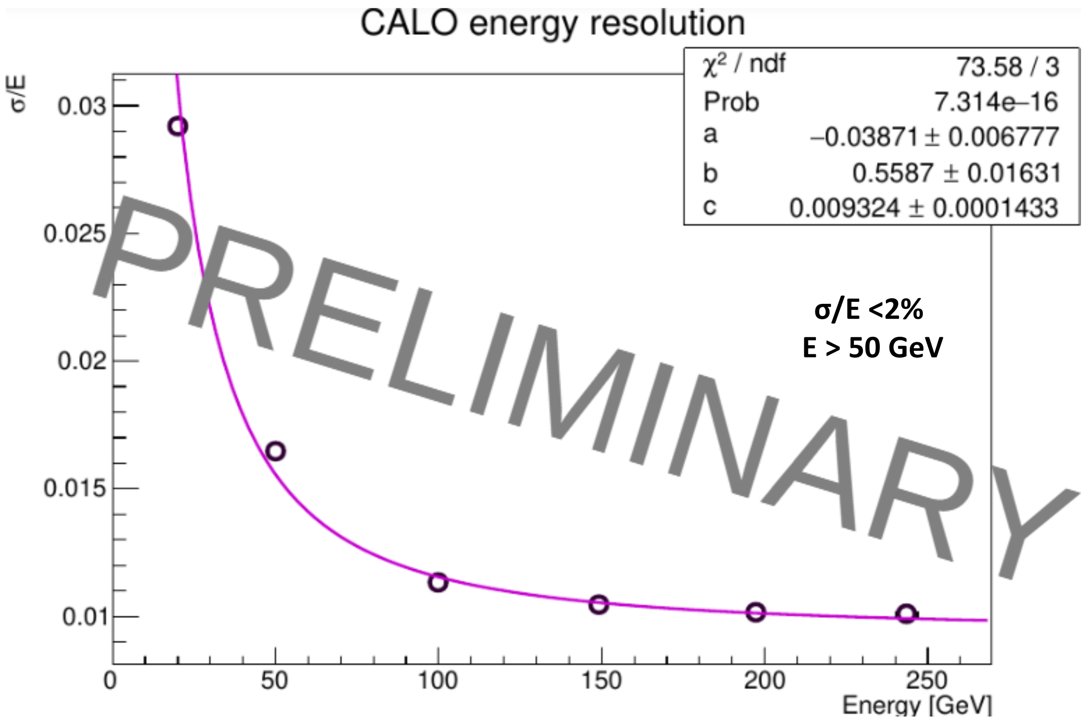


Calo-PD: Ion Identification and Energy Resolution (BT 2023)

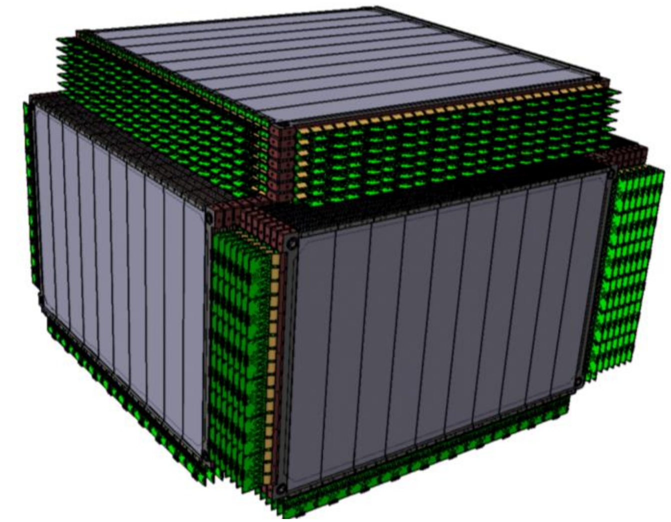
- The PD identification capability has been verified by analyzing the response of the first cubes hit by the beam.
  - The preliminary results are obtained without equalizing the response of each cube
    - an improvement is expected after equalization.
  - The single crystal identification capability and calorimeter shower containment very well match the required values.



Energy resolution for high-energy electrons

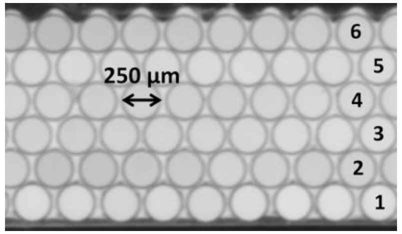


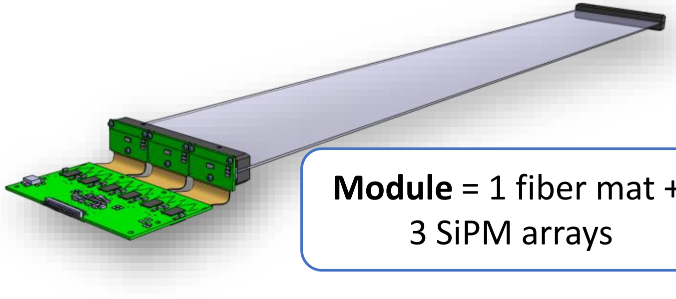
FIber Tracker (FIT)



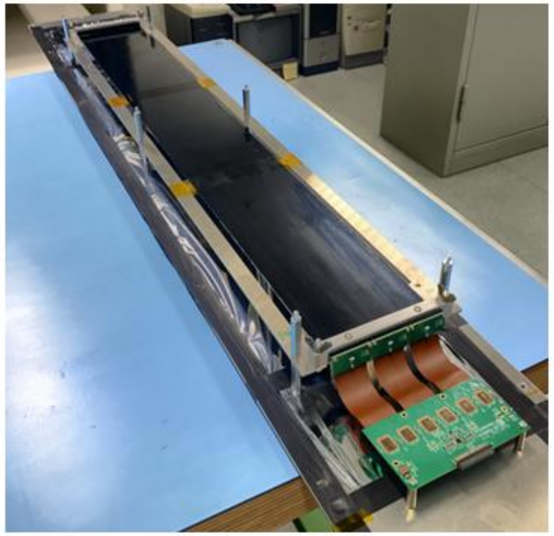
- 5 sectors
- **Sector:** 7 x-y tracking planes
- **Side planes:** 6 x + 10 y modules
- **Top plane:** 10 x + 10 y modules

- 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



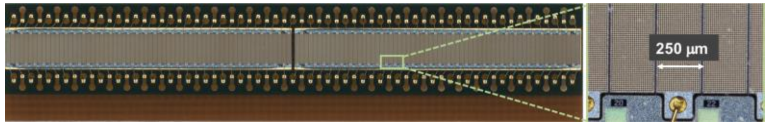


Module = 1 fiber mat + 3 SiPM arrays



FIT module prototype made of a 77 cm long fiber mat and one SiPM array tested at CERN

- 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

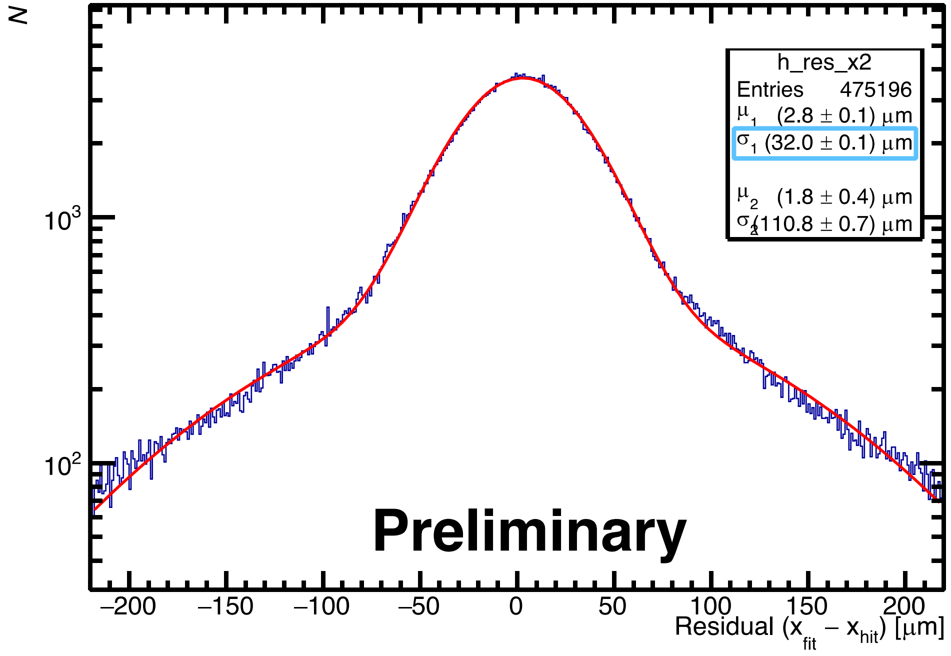


MiniFIT prototype performances

MiniFIT prototype

(4 x + 4 y config)

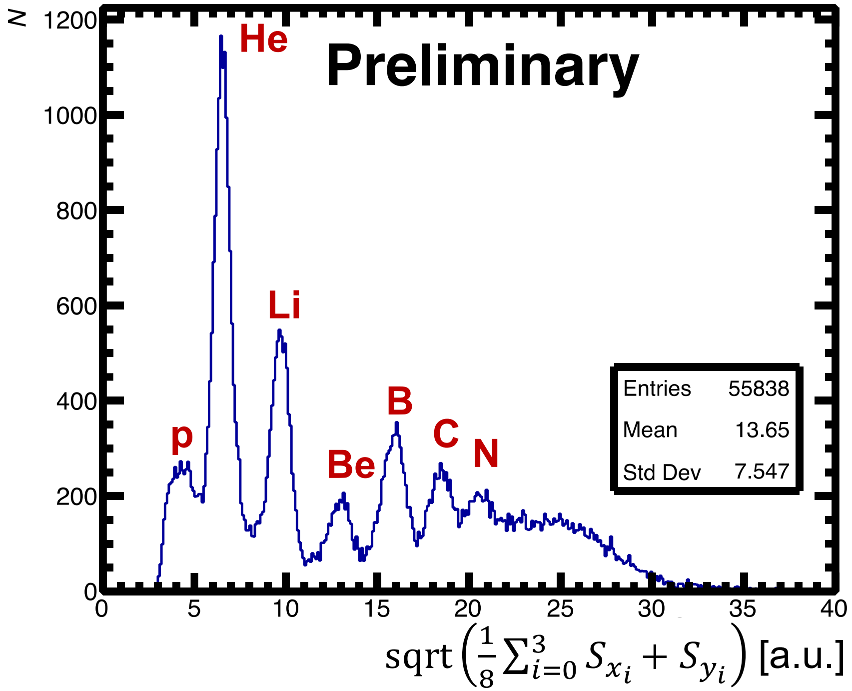
Position measurement



Spatial resolution = (32.0 ± 0.1) μm

Ionbeam 150 GeV/n
CERN SPS H8

Charge measurement



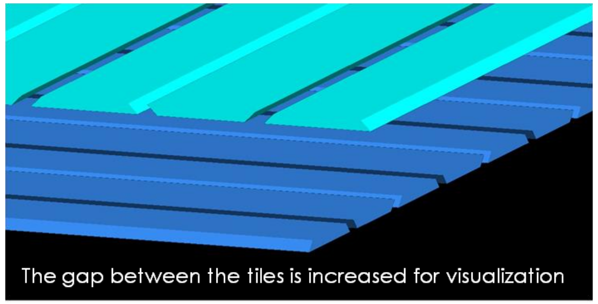
With the VATA64HDR16.2 front-end readout, MiniFIT can identify nuclei with charge up to $|Z|$ = 7
→ MiniFIT tested with the first BETA-16 prototype in Fall 2023 (new results to be released soon)

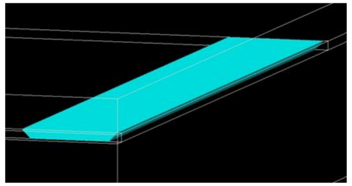
[1] C. Perrina et al, The scintillating-fiber tracker (FIT) of the HERD space mission from design to performance (ICRC 2023)

Plastic Scintillator Detector (PSD)

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

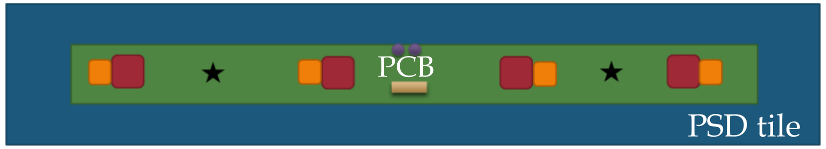
- Requirements:
  - high efficiency in charged particles detection (>99,98%)
  - high dynamic range to identify nuclei at least up to iron
  - highly segmented design to reduce the self-VETO due to back scattered charged particle
- TOP plane and 4 SIDE plane to be equipped:
  - SCD and PSD will share 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 180x180cm^2 ~ 400 tiles
    - SIDE 170x95 cm^2 ~ 160 tiles
    - Total number of tiles required: ~ 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

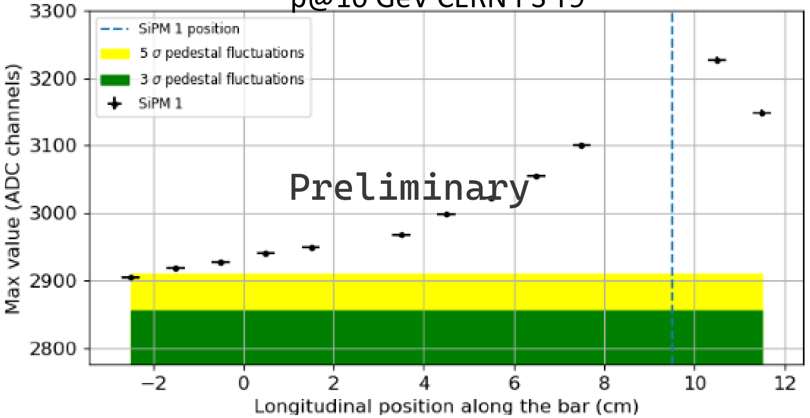
custom front-end electronics based on β-chip

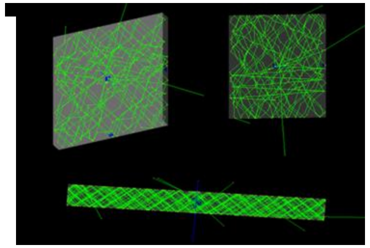
PSD prototypes and performance studies

[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.

- 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]
  - Low-Z SiPM detect enough light to have a signal above 5σ ensuring an **high detection efficiency**
  - The non-uniformity in light collection as a function of impinging position can be addressed during flight data acquisition by using a tracking system that provides information about the particle trajectory.
- Nuclei identification performances studies (Beam Tests campaigns at CERN and CNAO)[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).

Tile scan position
p@10 GeV CERN PS T9

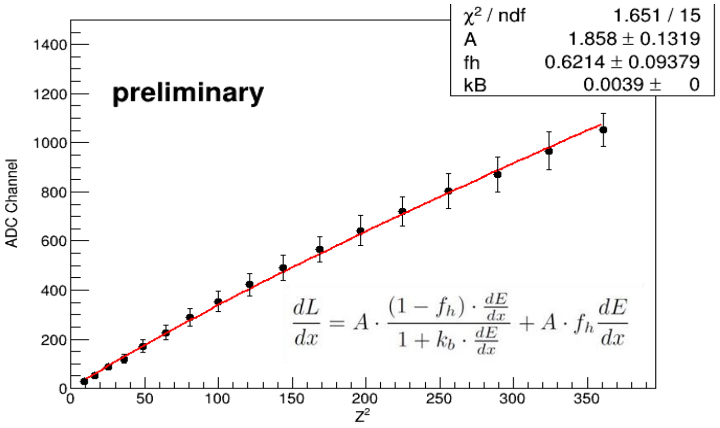




Optical photon simulation display

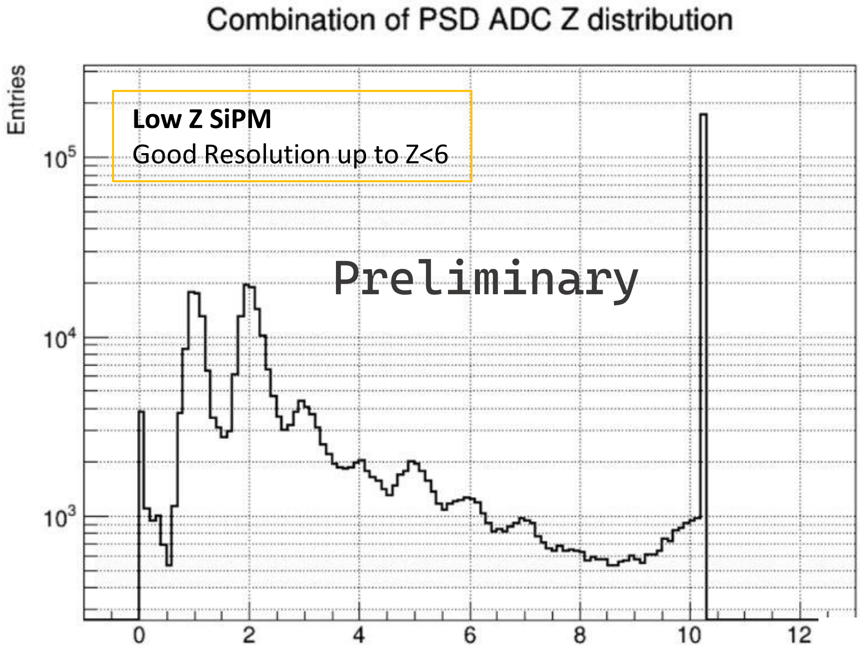
PSD prototypes under tests during BT campaigns

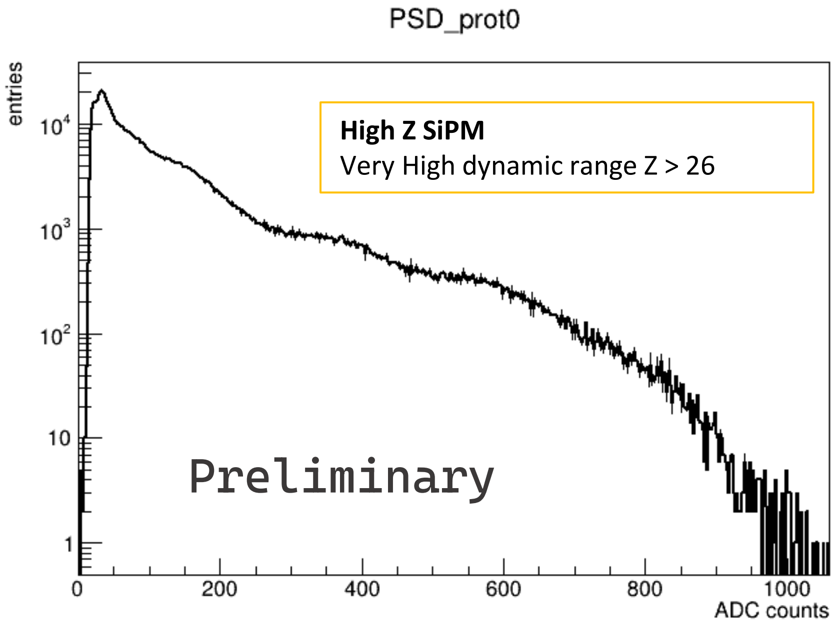
Ion beam 150 GeV/n at CERN SPS H8



$$\frac{dL}{dx} = A \cdot \frac{(1-f_h)\cdot \frac{dE}{dx}}{1+k_b \cdot \frac{dE}{dx}} + A \cdot f_h \frac{dE}{dx}$$

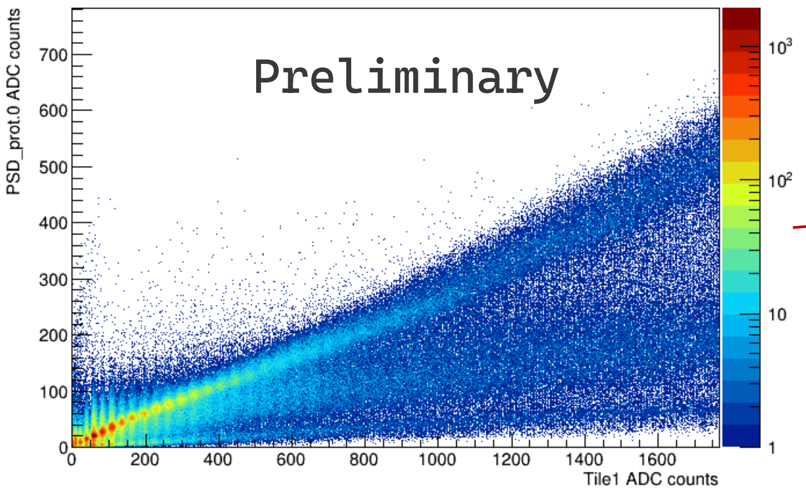
PSD prototype – Nuclei Identification Performances (BT 2023)

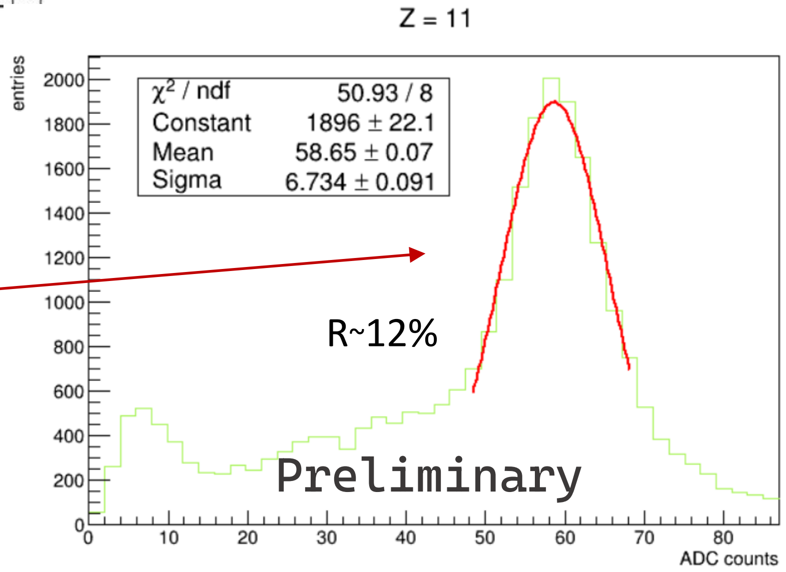




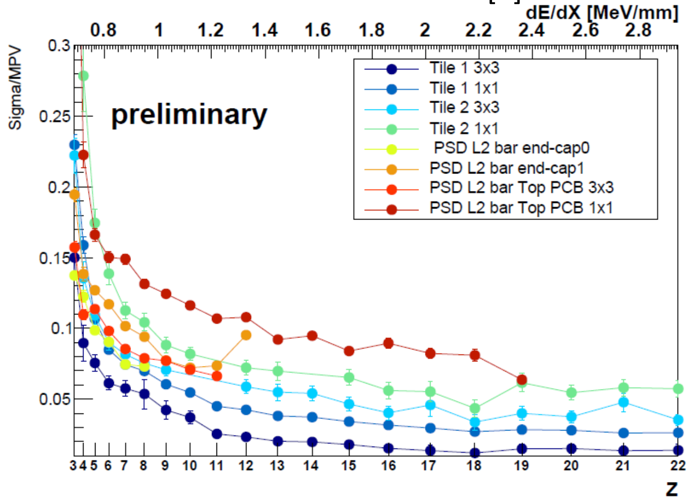
For Z >4 R<20.

- Resolution can be affected to the fragmentation
- We can use the impact point information provided by the SCD to better calibrate the PSD data



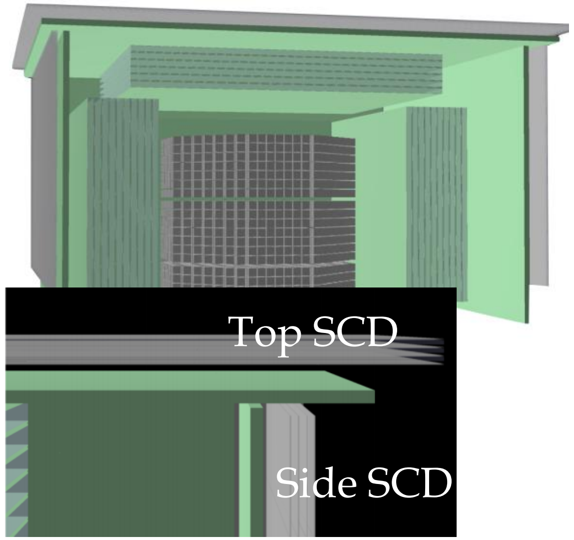


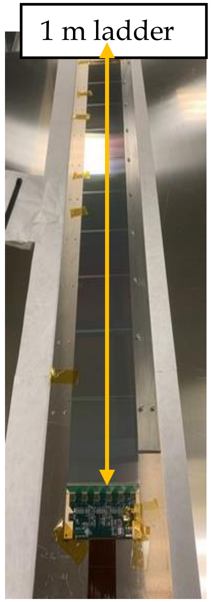
SPS-H8 2022 results [1]



[1] D. Serini et al, POS (ICRC 2023) 112

Silicon Charge Detector (SCD)



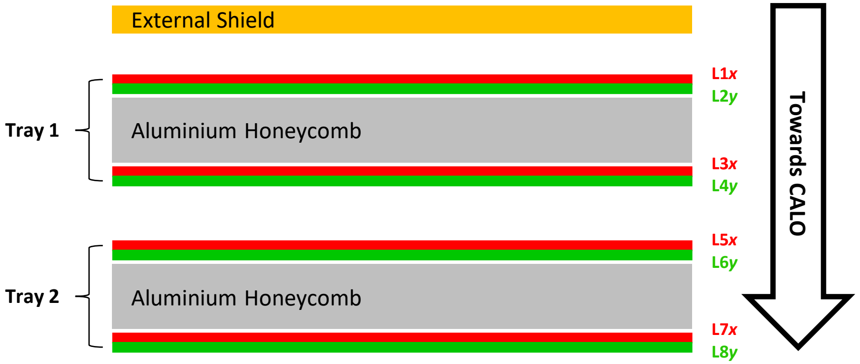


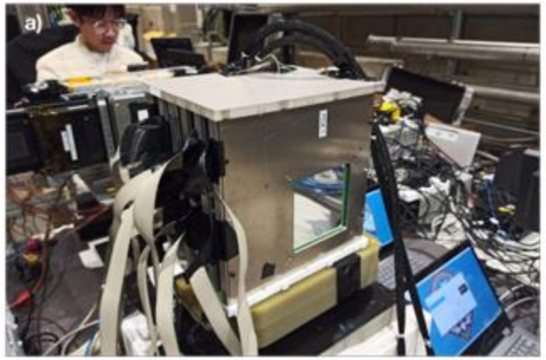
SCD is a **silicon micro-strip** detector that will measure with precision the impinging particle charge |Z|

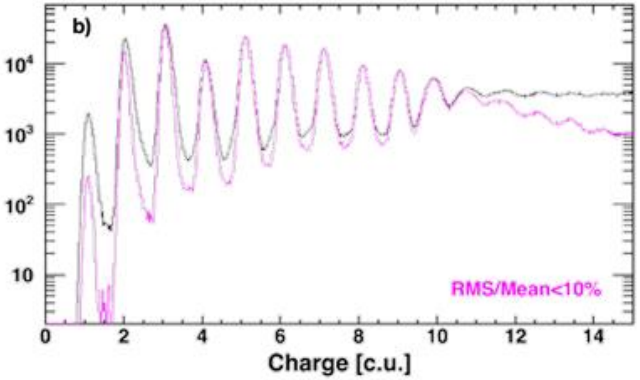
- 4 double X-Y layers for each of the five sectors → 8 independent ionization measurements per sector → Z =1 to 28
- It is the **outermost** detector to avoid early charge-change interactions in the PSD and to reduce the systematic uncertainty on the reconstructed charge due to fragmentation
- It is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

SCD 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



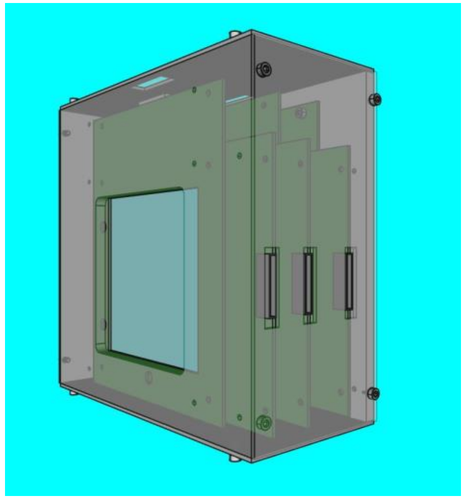


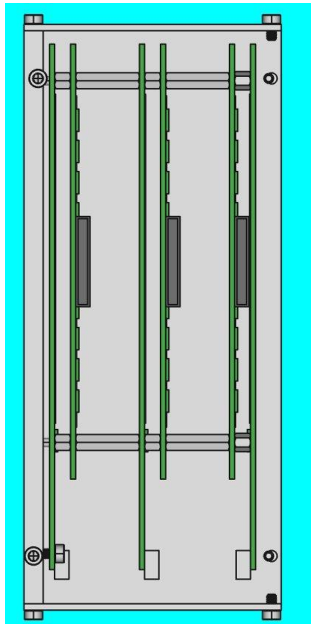


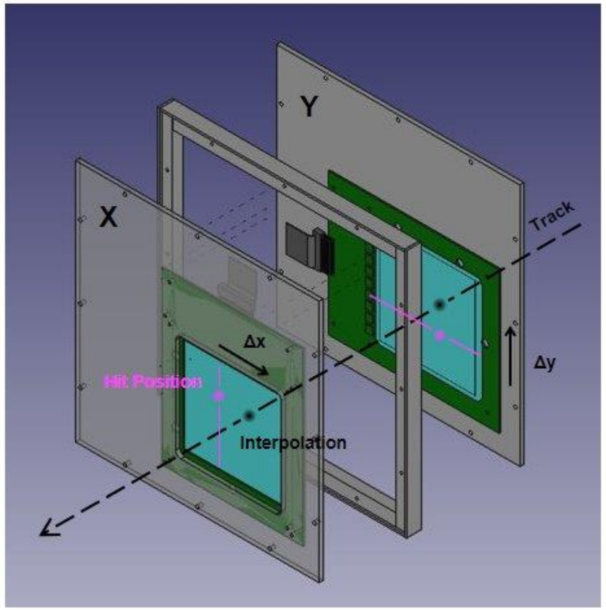
[1] A.Oliva et. Al. The Silicon Charge Detector (SCD) of the High Energy cosmic-Radiation Detection (HERD) facility (ICRC2023)

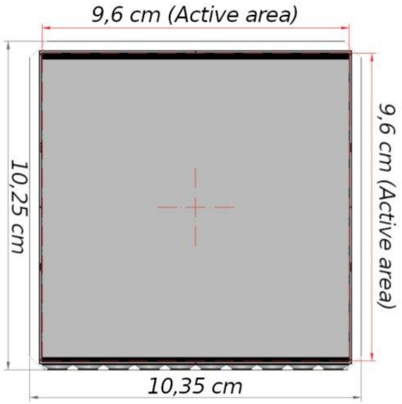
SCD prototype (BT 2023)

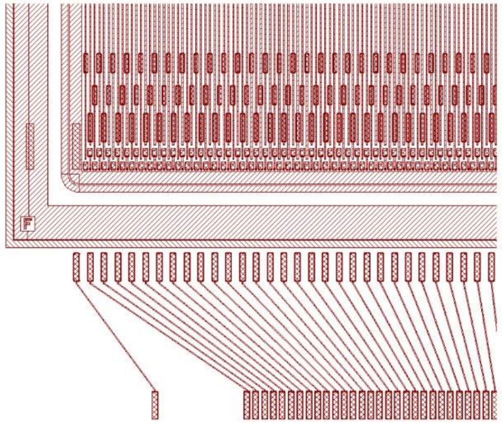
Single box solution containing 3 pairs of detectors







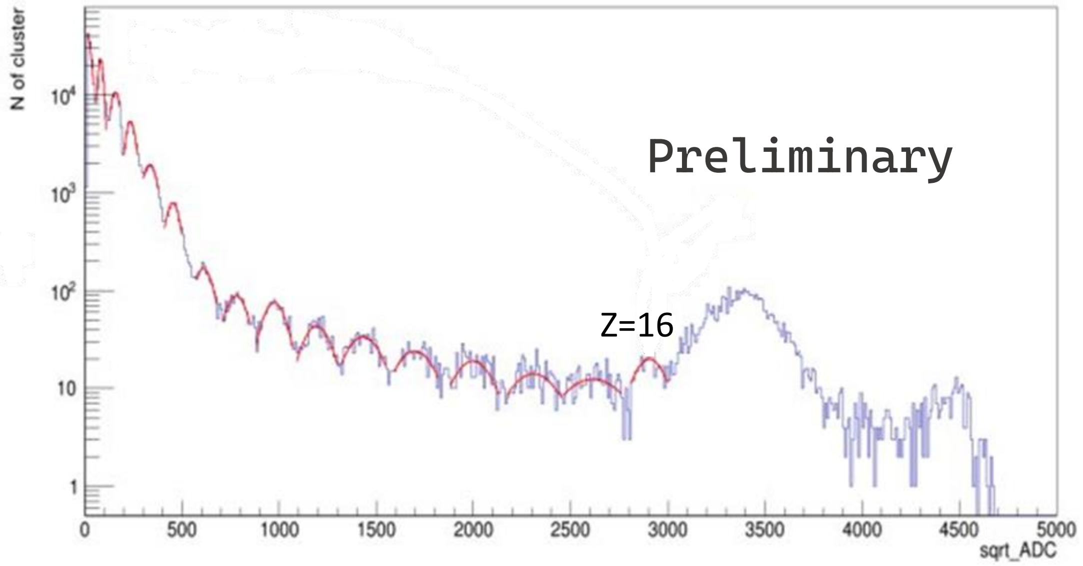




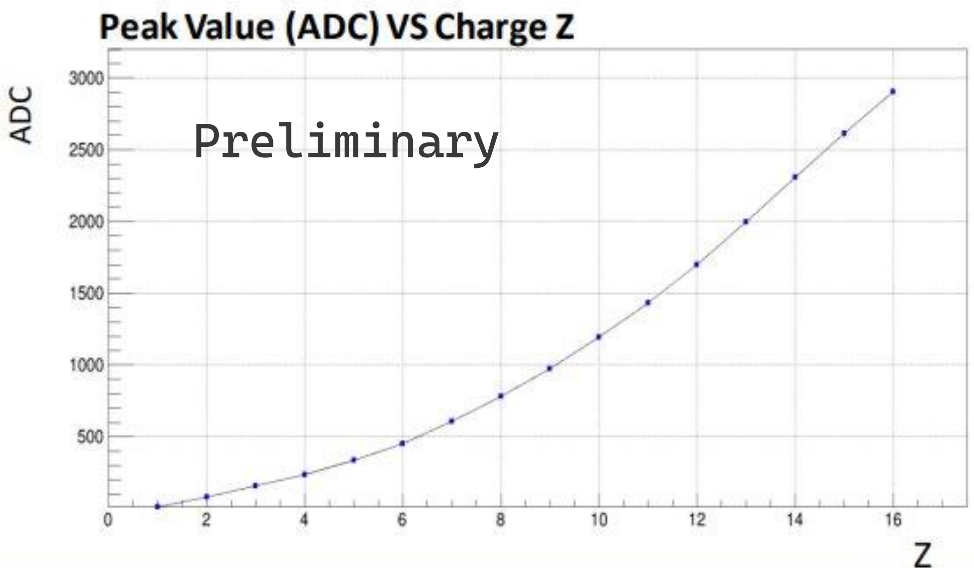
Thickness	150 μm
Overall dimensions	102.5 mm × 103.5 mm
Active area	96 mm × 96 mm
Total nr of strips	1920
Readout strips in FOOT	640
Readout pitch	150 μm
Implant pitch	50 μm
Mechanical edges	5 mm
Bonding pad dimensions	$80 \times 300\ \mu m^2$
Strip width	40 μm

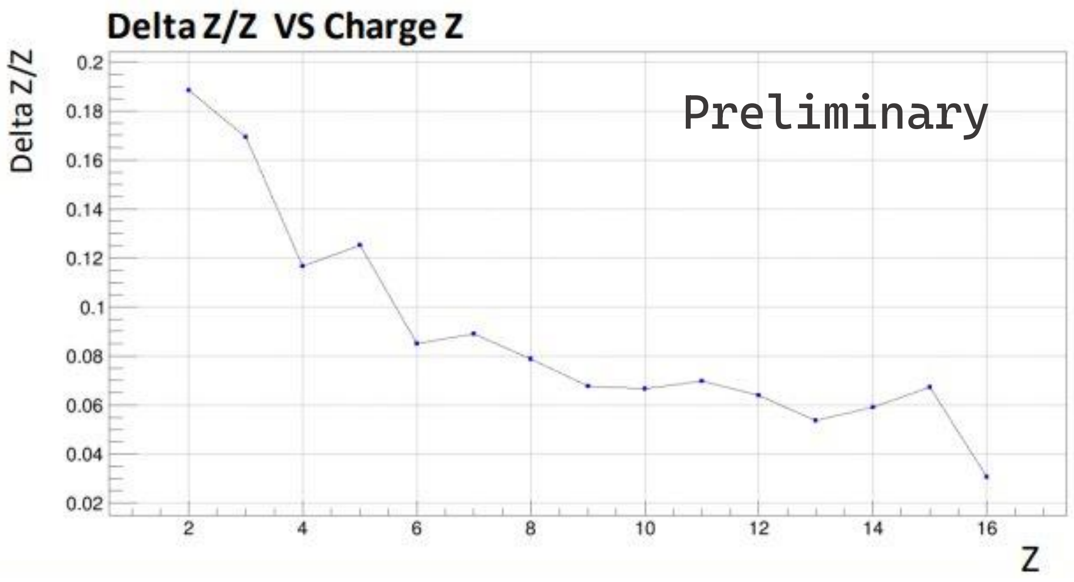
640 readout strips connected to 10 IDE1140 analog readout ASICs

SCD – Nuclei Performance Identification (BT 2023)



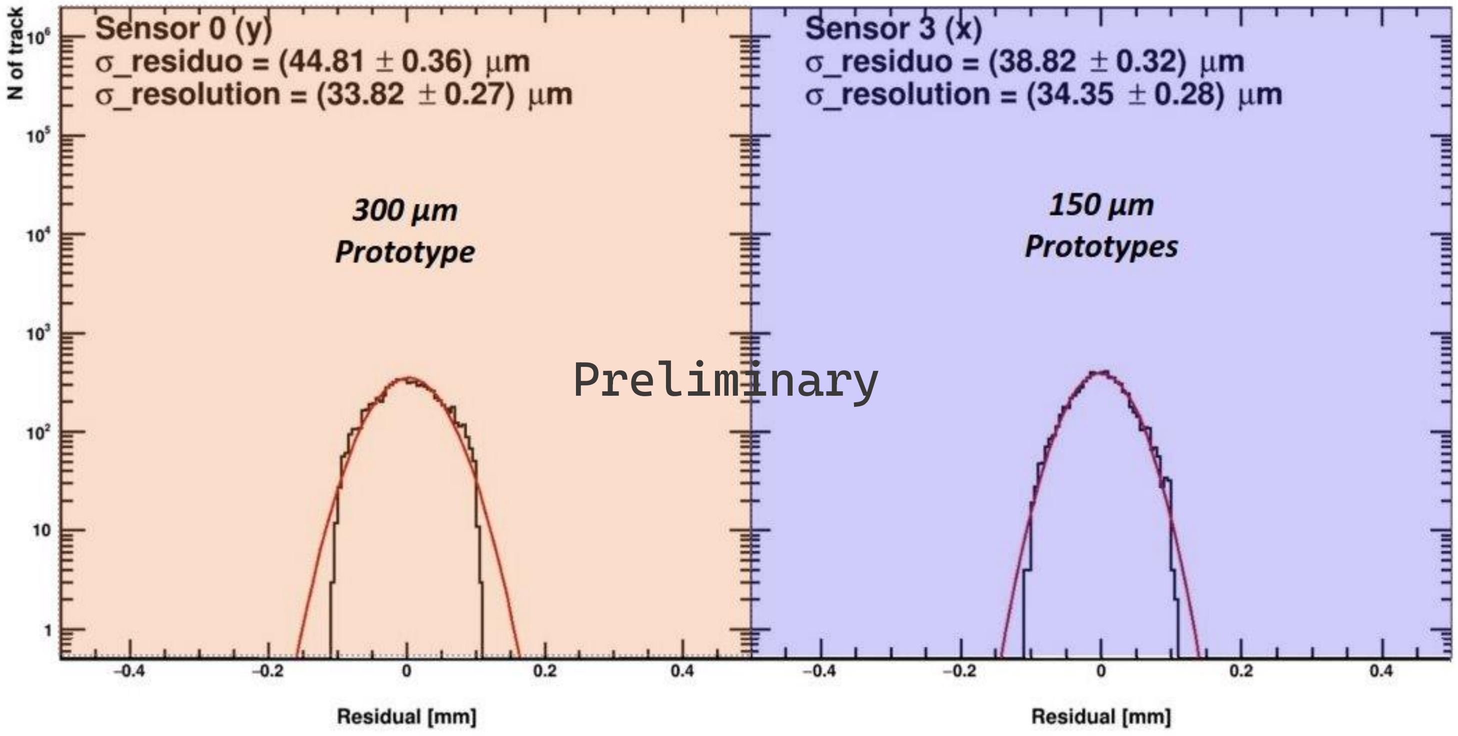
- Clearly distinguish up to Z = 16
- Charge resolution < 20%





SCD – Spatial Resolution (BT 2023)

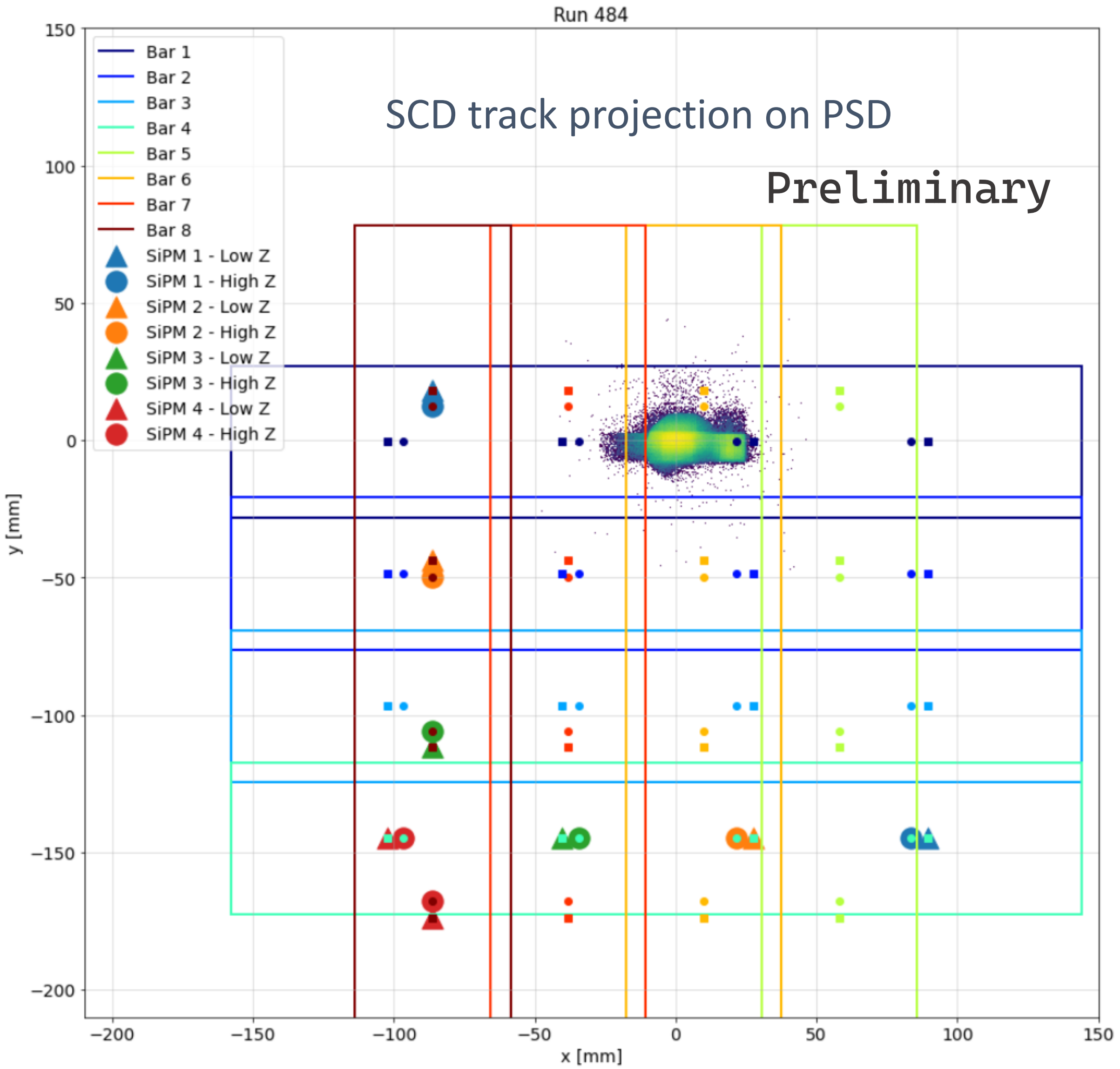
- Particle position: reconstructed particle positions agree with the reference beam monitors.
- Spatial resolution for Z = 1 (worst case scenario) < 40 μm
- Noisy strips (σ > 5 ADC) : less than 10%



PSD & SCD joint analysis (BT 2023)

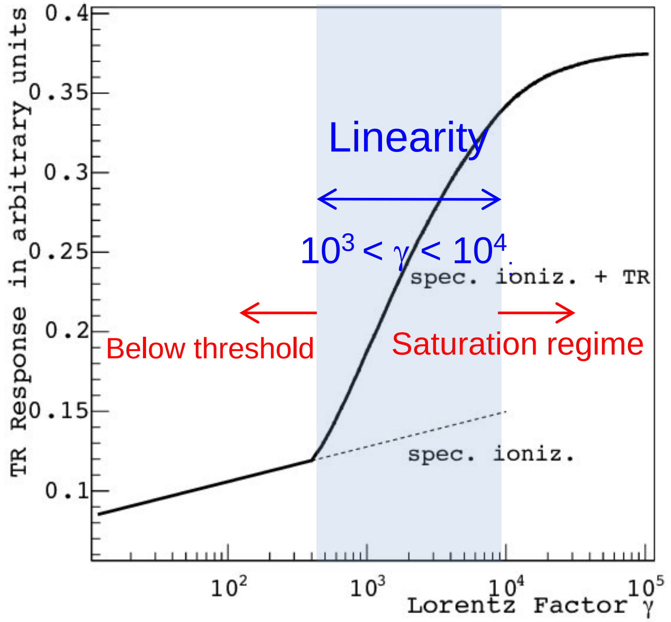
- Joint analysis of PSD and SCD prototypes can improve the overall performances of PSD
  - Calibration for addressing the non-uniformity in light collection as a function of impinging position
  - Calibration to improve the energy resolution
  - We can use the impact point information to better calibrate the PSD data (Studies ongoing)

- PSD in SCD reference frame according to beam survey and vertical offset
  - Region selection based on SCD track projection on PSD
  - We can use the impact point information to better calibrate the PSD data



Transition Radiation Detector (TRD)

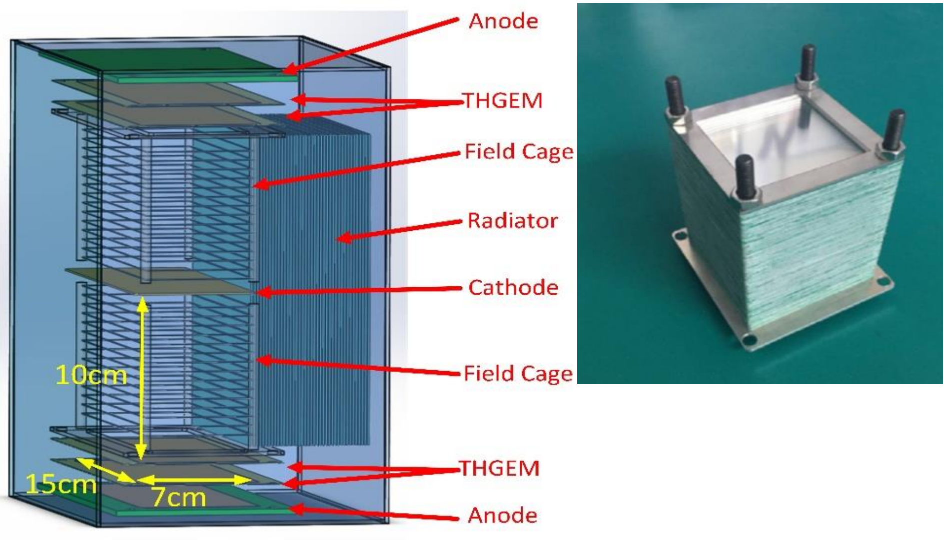
The TRD, installed on a lateral face of the detector, is needed to calibrate the response of the calorimeter to high energy hadronic showers



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

Electron 0.5 GeV < E < 5 GeV

Proton 1 TeV < E < 10 TeV



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)

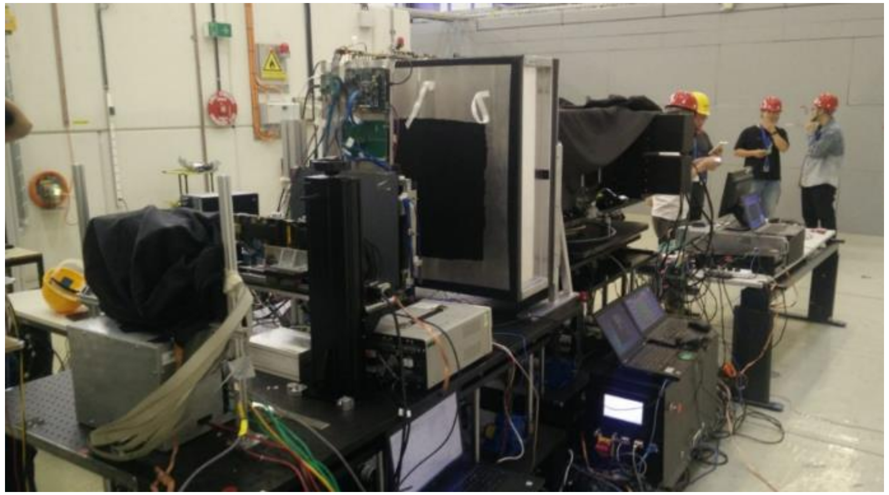
Radiator:
- multi-layer thin foils

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

[1] Cong Dai et. Al. Development of Transition Radiation Detector for the High Energy cosmic-Radiation Detection Facility PoS (ICRC2023) 113

Summary

- The High Energy cosmic-Radiation Detection facility 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 searches and Gamma-Ray astronomy
  - The main effort is currently focused on the development and testing of all the subdetector prototypes to achieve the expected performance required to meet all the HERD scientific goals.



Latest test beam setup at CERN SPS H8 Sept-Oct 2023