The High Energy cosmic-Radiation Detection facility (HERD):
a probe for high-energy cosmic rays’ physics and multimessenger astronomy

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- University of Geneva
The **High Energy cosmic-Radiation Detection** (HERD) facility is a China-led international space mission that will start operation around 2026.

The experiment is based on a **3D, homogeneous, isotropic and finely-segmented calorimeter** that fulfills the following requirements and goals.

### Main requirements

<table>
<thead>
<tr>
<th></th>
<th>γ</th>
<th>e</th>
<th>p, nuclei</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Energy Range</strong></td>
<td>0.5 GeV 100 TeV</td>
<td>10 GeV 100 TeV</td>
<td>30 GeV 3 PeV</td>
</tr>
<tr>
<td><strong>Energy resolution</strong></td>
<td>1% @ 200 GeV</td>
<td>1% @ 200 GeV</td>
<td>20% @ 100 GeV -1 PeV</td>
</tr>
<tr>
<td><strong>Effective Geometric Factor</strong></td>
<td>&gt;1 m^2sr @ 200 GeV</td>
<td>&gt;3 m^2sr @ 200 GeV</td>
<td>&gt;2 m^2sr @ 100 TeV</td>
</tr>
</tbody>
</table>

### 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,...)
<table>
<thead>
<tr>
<th></th>
<th>HERD</th>
<th>DAMPE</th>
<th>CALET</th>
<th>AMS-02</th>
<th>Fermi LAT</th>
</tr>
</thead>
<tbody>
<tr>
<td>$e/\gamma$ Energy res.@100 GeV (%)</td>
<td>&lt;1</td>
<td>&lt;1.5</td>
<td>2</td>
<td>3</td>
<td>10</td>
</tr>
<tr>
<td>$e/\gamma$ Angular res.@100 GeV (deg.)</td>
<td>&lt; 0.1</td>
<td>&lt;0.2</td>
<td>0.2</td>
<td>0.3</td>
<td>0.1</td>
</tr>
<tr>
<td>$e/p$ discrimination</td>
<td>$&gt;10^6$</td>
<td>$&gt;10^5$</td>
<td>$10^5$</td>
<td>$10^5$ - $10^6$</td>
<td>$10^3$</td>
</tr>
<tr>
<td>Calorimeter thickness ($X_0$)</td>
<td>55</td>
<td>32</td>
<td>27</td>
<td>17</td>
<td>8.6</td>
</tr>
<tr>
<td>Geometrical accep. ($m^2sr$)</td>
<td>&gt;3</td>
<td>0.3</td>
<td>0.12</td>
<td>0.09</td>
<td>1</td>
</tr>
</tbody>
</table>
Physics

Instrument
Electrons and Positrons (Pamela and AMS-02)

**Positron excess** respect to pure secondary production (PAMELA, AMS-02)

**Two hypotheses**
- Dark Matter (DM) annihilation
- Nearby Pulsar Wind Nebulae (PWN)

How to distinguish among them?

An important contribution to our understanding can be obtained by high energy (calorimetric) measurement of the $e^+e^-$ flux
**Electrons and Positrons (HERD)**

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

![Graph showing expected $e^+e^-$ flux in 5 years with data points and curves representing different sources like Monogem, Cygnus Loop, and Vela.](image)

**HERD** will measure the flux up to several tens of TeV in order to detect:

- spectral cutoff at high energy
- local SNR sources of very high energy $e^-$

... and additional information from anisotropy measurement!

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

![Graph showing expected $e^+e^-$ flux in 1 year with PWN or DM sources with data points and curves representing different scenarios.](image)

In case of additional PWN or DM production, **HERD** will give important indications on the two hypothesis thanks to precise measurement of the different spectral shape.
Recent calorimetric measurement of the $e^+e^-$ flux (Fermi-LAT, CALET, DAMPE) lead to very different results and no clear conclusion.

DAMPE data shows a cutoff at 1 TeV and a “sharp peak” at 1.4 TeV – NATURE 552 (2017)
CALET data are consistent with a single power law without cutoff - PRL 120 (2018)

**HERD** could help in resolving the “conflict” between different measurements:
- improving the precision of the measurement
- extending the measurement to higher energy
Proton flux measured up to 100 TeV but with large uncertainties:
spectral hardening at 200 GeV
spectral softening > 10 TeV
(DAMPE preliminary analysis)

Still no direct measurement of proton and helium knee
He spectral hardening > 100 Gev/n
(DAMPE preliminary analysis)
Protons and Nuclei (HERD)

HERD will measure the flux of nuclei:
- Protons and Helium up to a few PeV
- Nuclei up to a few hundreds of TeV/n

First direct measurement of p and He knees will provide a strong evidence for the knee structure as due to acceleration limit.

Extension of the B/C ratio to high energy will provide further test for the propagation mechanisms of cosmic rays.
Thanks to its large acceptance and sensitivity, HERD will be able to:

- improve Fermi-LAT measurements between 10 and 100 GeV
- extend Fermi-LAT catalog to higher energy (between 0.1 and 100 TeV)
- increase the chances to detect rare γ 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
Physics

Instrument
**CSS** expected to be completed in 2022

<table>
<thead>
<tr>
<th>Feature</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Life time</td>
<td>&gt; 10y</td>
</tr>
<tr>
<td>Orbit</td>
<td>Circular LEO</td>
</tr>
<tr>
<td>Altitude</td>
<td>340-450 km</td>
</tr>
<tr>
<td>Inclination</td>
<td>42°</td>
</tr>
</tbody>
</table>

**HERD** expected to be installed around 2026

<table>
<thead>
<tr>
<th>Feature</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Life time</td>
<td>&gt; 10y</td>
</tr>
<tr>
<td>FOV</td>
<td>+/- 70°</td>
</tr>
<tr>
<td>Power</td>
<td>&lt; 1.5 kW</td>
</tr>
<tr>
<td>Mass</td>
<td>&lt; 4 t</td>
</tr>
</tbody>
</table>
**HERD sub-detectors**

<table>
<thead>
<tr>
<th><strong>CALO</strong></th>
<th>Energy Reconstruction e/p Discrimination</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>STK</strong></td>
<td>Trajectory Reconstruction Charge Identification</td>
</tr>
<tr>
<td><strong>PSD</strong></td>
<td>Charge Reconstruction $\gamma$ Identification</td>
</tr>
<tr>
<td><strong>TRD</strong></td>
<td>Calibration of CALO response for TeV proton</td>
</tr>
</tbody>
</table>
Octagonal Prism made of about 7500 LYSO cubic crystals (80x80x80 cm³): each crystal has 3 cm side

Deep homogeneous calorimeter | Good energy resolution
Isotropic 3D geometry | Large geometric factor (top + lateral faces)
Shower imaging with 3D segmentation | Good e/p discrimination, identification of shower axis and of shower starting point
Dynamic range of $10^7$ is needed to detect from a MIP (~30 MeV released in a single crystal) to a PeV proton (~20 TeV released in a single crystal)

**WLS read-out**

Each cube is read-out by 3 WLS fibers.

One of the fiber is used for triggering and the light signal is readout by a fast PMT.

The light signal from the other two fibers is amplified by an Image Intensifier (two gains) and read-out by a IsCMOS camera.

**PIN-Diode read-out**

Each cube is read-out by 2 PIN-Diode of different area (1:100 ratio).

Each PIN-Diode is read-out by CASIS chip with two gains and trigger capability.
Beam Test at CERN – SPS (2017) with a prototype of 250 crystals with WLS read-out

Energy resolution < 1.3% at 200 GeV/c (electrons)
HERD Silicon TracKer (STK)

1 Top STK
- 6 Layers of XY SSD
- Baseline: W foils for $\gamma$ conversion (FERMI-LAT, DAMPE)
- Alternative: LYSO crystal as active converter
- Active Area 133 cm x 133 cm

4 Lateral STK
- 3 Layers of XZ or YZ SSD
- Active Area 95 cm x 66.5 cm

SSD
- Implantation Pitch = 121 $\mu$m
- Readout Pitch = 242 $\mu$m
- Expected resolution $\sigma = 40 \mu$m

Alternative design: Fiber Tracker instead of Silicon TracKer
HERD Tracker in Calorimeter (TIC)

W- converter

- Conversion in W foils in the STK
- Direction reconstructions by e+e- tracking in the Si-tacker planes

TIC

- Conversion in Lyso crystals in top layer of the CALO
- Fine sampling of the e.m. shower with Si-tracker planes inside the CALO

### TIC Pro
- Decrease the amount of mass used for passive material (W)
- Reduce hadron fragmentation in passive material
- Increase the geometric acceptance

### TIC Cons
- Worst PSF for low energy γ (< 10 GeV)
HERD Plastic Scintillator Detector (PSD)

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

Back-scattering can greatly degrade the performances

**Bar - option**
- Long bars 160x3x1 cm$^3$
- Each layer made by two staggered sub layer to increase hermeticity
- Read-out with 4 SiPM (two for each end)
- **PRO**
  - Less number of readout channel
- **CONS**
  - Higher Back-scattering problem

**Tile - option**
- Small square tile 10x10x1 cm$^3$
- Two layer of tiles to increase nuclei identification power
- Each tile is readout by 4 SiPM (one for each side)
- **PRO**
  - Reduce back-scattering problem
- **CONS**
  - Higher number of readout channel
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** $0.5 \text{ GeV} < E < 5 \text{ GeV}$
- **Proton** $1 \text{ TeV} < E < 10 \text{ TeV}$

**Calibration procedure**

- Calibrate TRD response using $[0.5 \text{ GeV}, 5 \text{ GeV}]$ electrons in space (and at beam test)
- Calibrate CALO response using $[1 \text{ TeV}, 10 \text{ TeV}]$ protons from TRD (3 months data required)
The **High Energy cosmic-Radiation Detection** facility is a China-led international space mission that will start its operation around 2026 on board the future China's Space Station.

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 DM search, CR observations and Gamma-Ray astronomy:

- extend the measurement of $e^+e^-$ flux up to several tens of TeV
  - testing the hypothesis of the expected cutoff at high energy
  - distinguishing between DM or astrophysical origin of positron excess

- extend the measurement of $p$ and He flux up to a few PeV
  - testing the theory of the knee structure as due to acceleration limit

- large acceptance, high sensitivity to $\gamma$ up to several tens of TeV
  - searching for $\gamma$ line associated to DM annihilation
  - accomplishing a $\gamma$ sky survey up to very high energy
BACKUP