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# Preliminary tests of Plastic Scintillator Detector for the High Energy cosmic-Radiation Detection (HERD) experiment

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**Abstract.** The High Energy Cosmic Radiation Detection (HERD) facility, onboard the future China's Space Station (CSS), will provide high quality data on charged cosmic rays and gamma rays in the energy range from few GeV to PeV. HERD will be equipped with a fine granularity cubic crystals calorimeter and a precision tracker detector. The entire instrument will be surrounded by a Plastic Scintillator Detector (PSD) that will be used to discriminate charged from neutral particles in order to correctly identify gamma-rays and nuclei. One proposed configuration for the HERD PSD consists of tiles of plastic scintillator, optically coupled to SiPMs. In 2019-2020, two beam tests were performed at CNAO (Centro Nazionale di Adroterapia Oncologica) in Pavia (Italy), exposing some PSD tiles, equipped with SiPMs, to low-beta p and C ion beams in order to evaluate the detector response to heavy ions. Spatial and temporal resolution were also evaluated using a radioactive source.

## 1 The High Energy cosmic-Rays Detector (HERD)

HERD is an interational space mission that will operate aboard the China's Space Station (CSS), currently being assembled. The launch is planned for 2027, and its operation will last for about ten years[1].

The main scientific objectives of the HERD mission are:

- the indirect dark matter search, with unprecedented sensitivity;
- the precise cosmic rays spectrum and composition measurements, up to the *knee* energy (about 1 PeV);

- the continuous $\gamma$-rays monitoring and full sky survey.

The HERD payload consists of multiple detectors, each with its own function (see Fig. 1). The main instrument, placed in the innermost part, is a 3-D imaging calorimeter (CALO) composed of about 8000 cubic LYSO crystals (each of size $3 \times 3 \times 3$ $cm^3$). This allows to have a very large geometrical factor ($\geq 3$ $m^2 sr$ for electrons and gamma rays) and to discriminate the detected particles by using 3D imaging of the events.

The calorimeter is surrounded by a precision tracker[2], composed of a silicon microstrip tracker (STK), made of multiple x-y layers put on its top side, and four Fibre Tracker (FIT) on the lateral sides, with the aim of precisely reconstructing the direction of the particles entering the calorimeter.

In turn, the tracker is surrounded by the Plastic Scintillator Detector (PSD), intended to identify low energy $\gamma$ and charged particles. According to the original design, each PSD side consists of two layers of plastic scintillator bars, oriented perpendicular to each other.

A Transition Radiation Detector (TRD) is placed on one side, for calibration purposes.

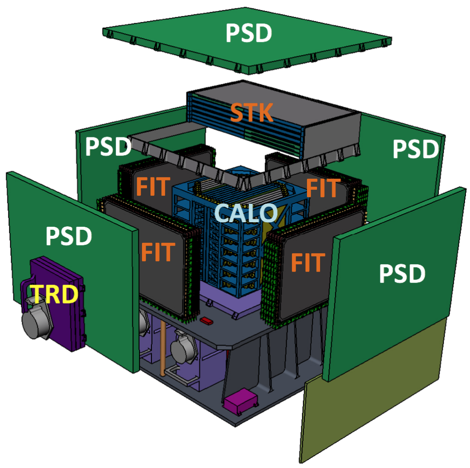


Figure 1: The HERD payload components, in exploded view. The innermost part (dark blue) is the CALO calorimeter: a fully 3D imaging calorimeter made of thousands of small cubic crystal scintillators. In the middle (dark grey) there are the tracker, elements (STK and FIT) designed to perform charge measurement and reconstruct particle trajectories. The outer elements (dark green) form the Plastic Scintillator Detector (PSD) used to recognize and measure the charged particles. The top side of PSD and its four lateral panels are composed of two layer of partially overlapping plastic scintillator bars, perpendicularly oriented, whereas the lower panel is composed of a single layer. The Transition Radiation Detector (TRD), is used for TeV energy scale calibration in space.

## 2 Test of the PSD elements

The PSD was originally designed to be composed of plastic scintillator bars (whose length is of the order of the meter). However, the possibility of using scintillator tiles (about 10 $cm$ in size) is being currently evaluated. This configuration would in fact have both the advantages of allowing a better identification of the backscattered particles and to realize more flexible trigger logics, through the more precise localization of the incoming charged particles.

For this reason, functional tests were carried out to measure the performances of some configurations using scintillator tiles. These tests were carried out using both a radioactive $\beta^-$ source and a hadron beam.

The tested element consists of a $10 \times 10 \times 0.5$ $cm^3$ tile of Eljen Technology EJ-200 plastic scintillator, equipped with 6 Hamamatsu S12572 SiPMs ($3 \times 3$ $mm^2$ area, with 3600 $50 \times 50$ $\mu m^2$ cells). The SiPMs are divided into two groups of 3 SiPMs each, connected in a parallel circuit and mounted on two PCB placed on two opposite edges of the tile (conventionally located at $y = -5.0$ $cm$ and $y = 5.0$ $cm$).

## 3 Measurements performed with the $^{90}Sr$ source

A first series of measurements was performed using a $^{90}Sr$ source, which is a 2.2 MeV $\beta^-$ emitter. The source was mounted on a mechanical support fixed on a $x$-$y$ translation stages which allows to place the source in any position (identified by the $x$ and $y$ coordinates) above the tile surface. The trigger is given by the coincidence of the signals produced by two small scintillators (1 $cm$ side) with very reduced thickness (less than 1 $mm$) placed above and below the tile, to form a telescope. In this way, the uniformity of the amplitude of the signal produced by the scintillator tile was obtained, as a function of the position.

The signals produced by each of the two groups of SiPMs, placed on the opposite edges, have been acquired without any amplification, using a digital oscilloscope Tektronix MSO64 (wich has 4 channels with 12-bit ADC and sampling rate up to 25 GS/s). The recorded pulses were than fitted with the analytical function

$$f(t) = b + A\frac{\exp((t_0 - t)/\tau_d)}{1 + \exp((t_0 - t)/\tau_r)}$$

where $A$ is the signal amplitude, while $\tau_r$ and $\tau_d$ are the rise time and decay time, respectively.

The average amplitude $A_m$ is therefore considered, defined as $A_m = (A_1 + A_2)/2$, and its values are evaluated for different positions of the source. The results are shown in Fig. 2, where the color code visually shows the good uniformity of the values of $A_m$ as a function of the position.

At the same time, the asymmetry parameter $A_s$ is defined as $A_s = \frac{(A_1 - A_2)}{(A_1 + A_2)}$ (ranging within the interval $[-1, 1]$). For a given position, the values of $A_s$ follow a gaussian distribution, the average value of which is shown in the Fig. 3. in this case the dependence of $A_s$ on $y$ is clearly evident, which is almost linear, while there is no dependence on $x$, and therefore its values can be advantageously used as a position sensitive parameter.

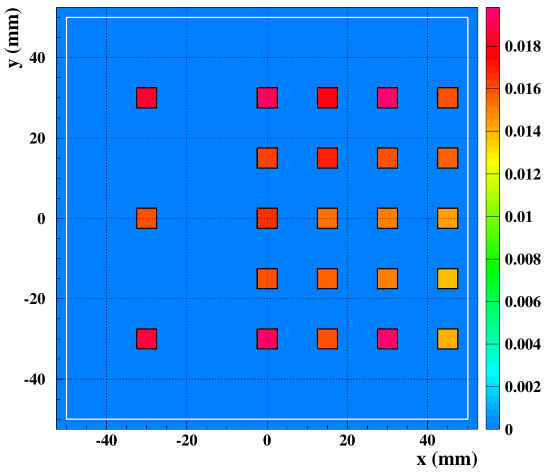


Figure 2: Measured average pulse amplitude $A_m$, the values of wich, espressed in V, are shown on the color scale on the right. The large square (white) corrisponds to the tile surface, while the small squares (black) represent the position where the measurements have been performed. A good signal amplitude uniformity and position independence are evident.

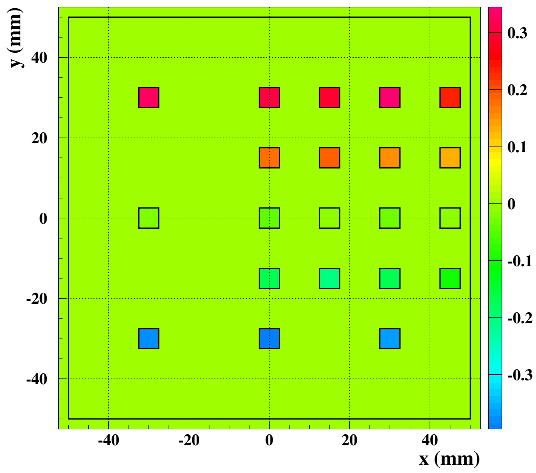


Figure 3: Measured asymmetry parameter $A_s$, the values of wich are shown on the color scale on the right. The large square corrisponds to the tile surface, while the small squares represent the position where the measurements have been performed. An evident dependence on the $y$ coordinate alone is well visible, which allows to have a position dependent signal.

## 4 Measurements performed with the hadron beam

These measurements were performed by exposing the tile to the hadron beam of the *Centro Nazionale di Adroterapia Oncologica*[3] (CNAO), which is located in Pavia, Italy.

The CNAO complex includes: the synchrotron with relative control rooms, three patient treatment rooms (with relative preparation areas) and the support hospital structure.

The accelerator can provide a proton beam in the energy range 60 ÷ 250 MeV and a C ions beam with energy 120÷400 MeV/u. These energies are chosen to obtain the optimal penetration and release of energy for the treatment of tumors in biological tissues. The beam intensity can reach up to $10^{10}$ p/s or $4 \times 10^8$ C/s, and can be scaled down by several orders of magnitude by simply intervening on the operating parameters of the accelerator. The beam profile is nearly gaussian with width $\sigma_{x,y} = 0.2 \div 0.8\ cm$, depending on energy and beam type. Outside the hours of therapeutic treatment (typically during the night, or on some weekends) the beam can be used for research purposes.

To carry out the tests, the tile was mounted on a mechanical support similar to the one already described above, directly positioned on the bed of one of the treatment rooms[4].

The interesting aspect of the preformed tests consists in the fact that using beams with a low value of $\beta$ it is possible to reproduce the behavior of particles with a higher charge $Z$ because, according to Bethe-Bloch formula, the value of the specific ionization $\frac{dE}{dx}$ is proportional to $Z^2/\beta^2$. Therefore a particle with charge Z and speed $\beta$ produces the same ionization density as a relativistic particle with charge $Z_{eq} = \sqrt{Z^2/\beta^2}$.

The characteristics of beam configurations used for the various test runs are reported in Tab. 1.

| **Beam** | $E_k$ | $\beta$ | $Z_{eq}$ | **Events** | $A_{av}$ **(V)** |
|---|---|---|---|---|---|
| p | 70 | 0.366 | 2.7 | 5000 | $0.47 \pm 0.04$ |
| p | 120 | 0.462 | 2.2 | 5000 | $0.32 \pm 0.03$ |
| p | 170 | 0.532 | 1.8 | 5000 | $0.35 \pm 0.03$ |
| p | 226 | 0.592 | 1.7 | 18270 | $0.22 \pm 0.03$ |
| **Beam** | $E_k$ | $\beta$ | $Z_{eq}$ | **Events** | $A_{av}$ **(V)** |
| C | 115 | 0.454 | 13.2 | 20000 | $2.86 \pm 0.05$ |
| C | 190 | 0.555 | 10.8 | 2500 | $2.59 \pm 0.05$ |
| C | 260 | 0.622 | 9.6 | 2500 | $2.44 \pm 0.05$ |
| C | 330 | 0.672 | 8.9 | 2500 | $2.34 \pm 0.05$ |
| C | 400 | 0.713 | 8.4 | 1182 | $2.27 \pm 0.06$ |

Table 1: Characteristics of the beam configurations used for the test. The proton beam energy is expressed in MeV, while for the C ion beam the energy is in MeV/u. The last column resume the values of the average signal amplitude, given by $A_{av} = (A_1 + A_2)/2$, where $A_1$ and $A_2$ are the SiPM signal amplitudes measured at the two opposite edges of the tile. The values of $A_{av}$ follow a nearly Gaussian distribution, of which the characteristic parameters are shown as $\mu \pm \sigma$.

The signal amplitude $A_{av}$ (defined as the average of the values obtained by the two SiPM groups, placed on the opposite edges of the scintillator tile) has been computed for each of the beam type and the resulting distributions are fitted with a gaussian function, whose parameters $\mu$ and $\sigma$ are also reported in Tab. 1.

The energy deposited into the scintillator tile for each type of used beam, can be determined assuming that for the used plastic scintillator the specific energy loss $dE/dx$, for a minimum ionizing particle, is about 2 MeV/cm. This allows the evaluation of the energy resolution up to about 180 MeV of deposited energy. The obtained values are well fitted with the analytical function $\frac{\Delta E}{E}(\%) = \frac{22.9}{\sqrt{E(MeV)}}$ as shown in Fig. 4.

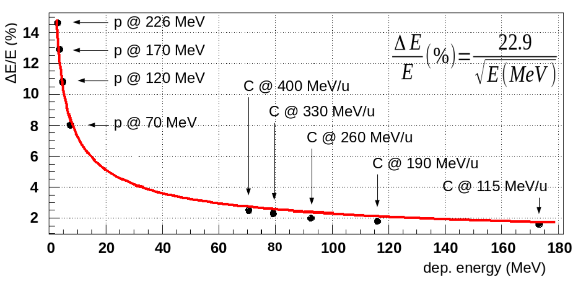


Figure 4: The energy resolution is determined considering the ratio $\frac{\Delta E}{E}$ between the width of the nearly gaussian distribution of the deposited energy and its mean value, for all beams used (corresponding to different values of deposited energy). The indicated funcion is the result of the data fitting (red line).

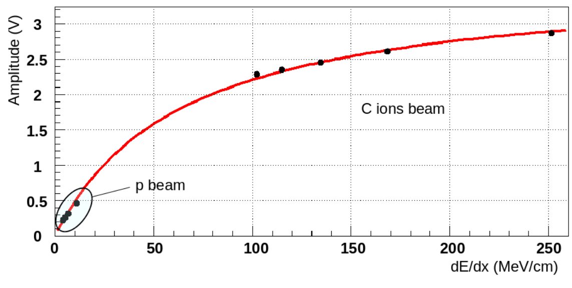


Figure 5: Absolute pulse amplitude (average of the two SiPM groups) as a funcion of the deposited energy. The loss of linearity (due to the quenching effect) can be well reproduced by the Birk's law, the parameters of which can be determined by fitting the data (red line).

The relation between the signal amplitude as a function of the deposited energy shows a loss of linearity that is well described by the Birk's law $A = S\frac{dE/dx}{1+K_b dE/dx}$ as shown in Fig. 5. The values of the parameter obtained fitting the data with the Birk's function are: $S = 0.056$ $Vcm/MeV$ and $K_b = 1.5 \times 10^{-2}$ $cm/MeV$. The latter is in good agreement with the values found in the literature $K_b = (1.26 \div 2.07)10^{-2}$ $g/MeVcm^2$ for polyvinyltoluene based plastic scintillator[5], such as EJ-200.

The readout dynamics of the SiPMs is such that even with highly ionizing beam (C ions with 115 MeV/u kinetic energy) the signal amplitude is far from being saturated. This can be seen by analyzing the results of the amplitude measurements performed by directing the beam to different positions of the tile. In particular, the four positions shown in the Fig. 6 were tested, located at 0.0, 1.0, 2.0, and 2.5 from the center of the tile. For each of these positions the amplitudes $A_1$ and $A_2$ of the signals detected by the two SiPM groups placed on opposite edges was then compared, and the results are shown in Fig. 7. It should be noted that, apart from the different equalization of the two channels, for both there is a basically linear relationship of the amplitude as a function of the distance between the center of the beam and the edge on which the SiPMs are facing and, as this distance decreases, the amplitude grows without showing deviations from the linearity that would be expected in case of SiPMs saturation.

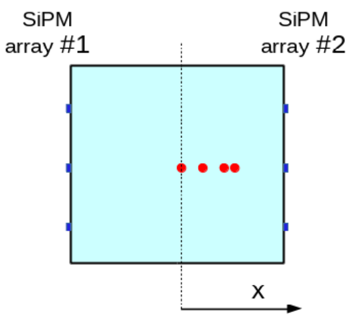


Figure 6: Beam positions used to verify the possible saturation effect of the SiPMs with very intense light signals. The positions are located at $x = 0$, 10, 20 and 25 mm with respect to the center of the tile.

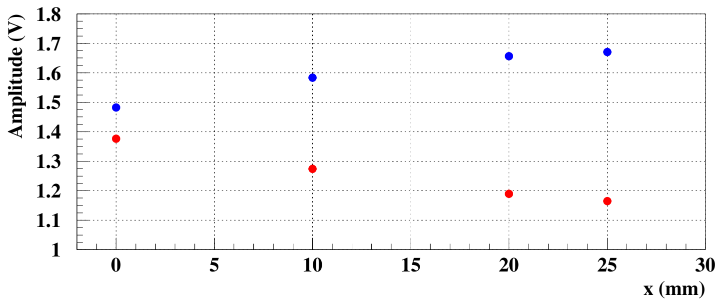


Figure 7: Pulse amplitude measured with the beam directed to the positions shown in Fig. 6. The red points refer to the SiPM array faced on the left edge, while the blue point refer to the SiPM array on the right one.

## 5 Conclusions

In order to characterize the PSD subsystem of the HERD space mission, some plastic scintillator tiles has been subjected to tests using both a radioactive source and a hadron beam. The obtained results show that, using a readout based of a system composed of multiple SiPMs, a good response uniformity is achieved, together with the possibility of estimating the interaction position. Furthermore, a wide dynamics in the amplitude of the signals is observed, ranging from minimum ionizing particles, up to ions with Z $\geq$ 12.

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