Characterization of a scintillator tile equipped with SiPMs for future cosmic-ray space experiments

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Abstract. Current gamma-ray and cosmic-ray satellite experiments employ plastic scintillators to discriminate charged and neutral particles and to identify nuclei. Scintillators are commonly read out using the classical photomultiplier tubes (PMTs). Recent measurements and R&D projects are demonstrating that Silicon Photomultipliers (SiPMs) are suitable for the detection of fast light signals with resolution up to the single photoelectron, with a lower power consumption. For these reasons, next generation missions are planning to replace PMTs with SiPMs. We tested a prototype plastic scintillator tile, equipped with a set of SiPMs and studied its response to a beam of electrons and pions at CERN. We used Near Ultraviolet (NUV) SiPMs of 1x1 mm^2 and 4x4 mm^2 area, placed along the edges of the tile. The tile was irradiated in different positions in order to study the dependence of the collected light on the impact point of the beam particles. We also varied the energy of the beam in order to study how this parameter affects the amount of collected light.

1. Introduction

Plastic scintillators are widely used as particle detectors and discriminators in satellite experiment. Gamma-ray telescopes, such as the Fermi-LAT and DAMPE, employ these systems as anti-coincidence in order to reject the charged cosmic-ray background [1, 2]. In other cases, plastic scintillators can be used to discriminate the charge of the incoming particle by measuring its energy loss in the scintillator. The detector is often segmented in small tiles to enhance gamma-ray selection efficiency which would be otherwise limited by the the back-splash of secondary particles produced in the electromagnetic showers initiated by gamma-rays. This effect is particularly important for gamma-ray energies above 10 GeV.

Usually, in most satellite experiments, scintillators are read-out with Photomultiplier tubes (PMTs). The high operation voltage required by PMTs (of the order of kV) makes this solution unpractical on satellites.

Recent developments in the field of Silicon Photomultipliers (SiPMs) have opened to the possibility of replacing PMTs. SiPMs are operated at much lower voltages (of the order of tens of V) and show a very good sensitivity to low light yields. For these reasons, plastic scintillators coupled to SiPMs are being tested for future missions such as e-Astrogam [3], AMEGO and HERD [4].

In recent years some tests of scintillators coupled to SiPMs have already been performed, exploring this possibility also for different applications [5, 6, 7].

In this work we present the measurements carried out on a plastic scintillator tile equipped with SiPMs produced by FBK and provided by AdvanSiD, sensitive to the Near Ultraviolet (NUV) photons.

2. Scintillator tile preparation

We used the plastic scintillator BC-404, which has a light yield of 68% of Anthracene and peak emission at 408 nm [8]. The tile used has a squared shape with a side of 15 cm and a thickness of 1 cm. Two angles were cut at 2.5 cm from the corner. The geometry of the tile is shown in figure 1.
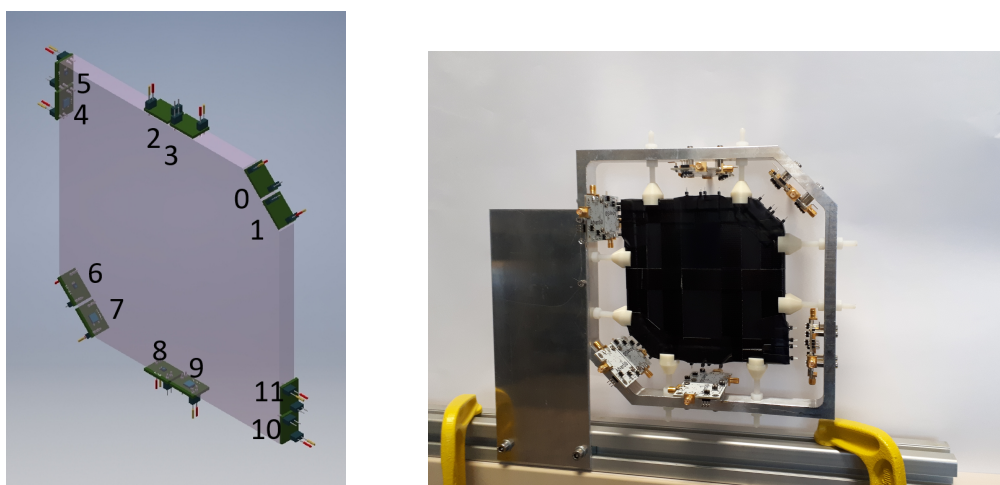

Figure 1. Left: Geometry of the tile and position of the SiPMs along the tile perimeter. Right: Photograph of the scintillator tile equipped with the 12 SiPMs and pre-amplifiers.

The scintillator was levigated and wrapped with a white paper as reflector and black paper as coverage. Small windows were cut in order to place SiPMs directly on the scintillator. The optical connection between the scintillator and the SiPM was achieved using optical grease.

We used NUV SiPMs produced by FBK of 1×1 mm^2 and 4×4 mm^2 area, with micro-cell pitch of 40 μm. The photon detection efficiency (PDE) peaks at 400 nm, matching the BC-404 emission, with a maximum value of 43% which is reached at 5 V of over-voltage [9]. We equipped the tile with 12 SiPMs, 6 for each size, placed in different positions of the tile perimeter, as shown in figure 1. We will refer to the 4×4 mm^2 SiPMs as *Large* SiPMs and to the 1×1 mm^2 as *Small* SiPMs. Each SiPM was read-out using a transimpedance amplifier with an RC filter for tail cancellation. The 12 analog signals were integrated and acquired with a Caen V792 QDC [10].

2.1. Beam test setup

The tile was tested at the CERN PS T10 beam line with 5 GeV/c particles and at the CERN SPS H8 beam line with 20 GeV/c particles. In both cases the beams were composed mainly by pions and electrons. A trigger system consisting of two plastic scintillators placed along the beam line was implemented. At PS-T10, a plastic scintillator with a hole was used as halo veto in order to select a circular beam spot of 3 cm diameter. In this case, we moved the tile with 2 cm steps in order to irradiate the scintillator in different positions and to study the dependence of the light collected by the SiPMs on the beam position. At SPS-H8 the tile was irradiated in the central position only.
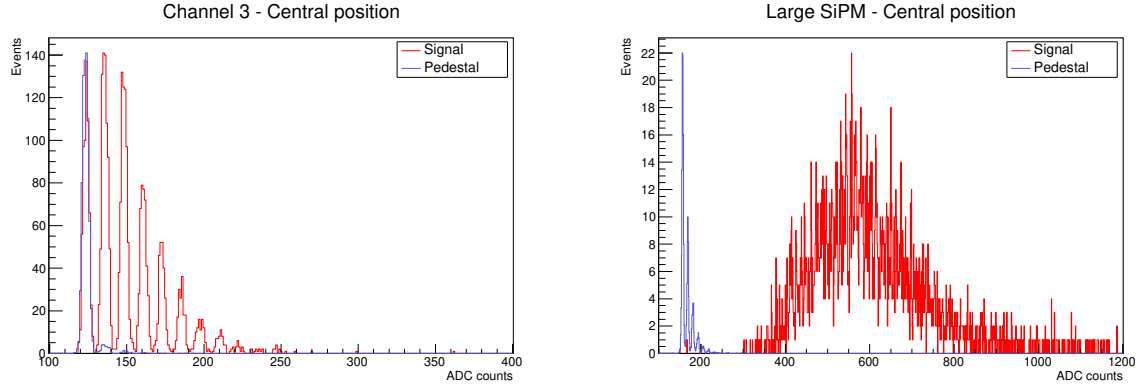
Figure 2. Sample spectra for the small (left) and the large (right) SiPM. Pedestal (blue) and signal (red) distributions are superimposed.
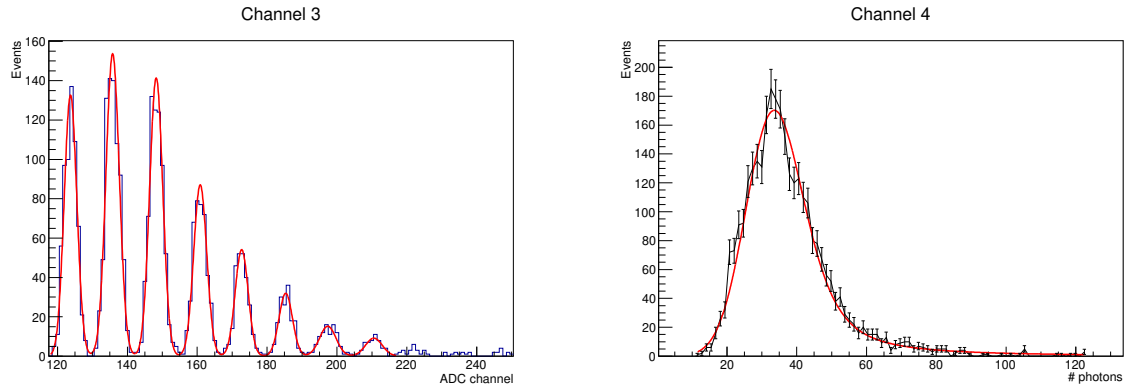

Figure 3. Left: spectrum of a small SiPM fitted with a multi-gaussian function. Right: spectrum of a large SiPM fitted with a Landau distribution folded with a Gaussian disitribution.

3. Data analysis and results

3.1. Position scan

As already mentioned in the previous section, we first tested the tile at PS-T10. We irradiated the tile in 33 different positions with beam spots of 3 cm diameter. For each run we obtained the average number of photons detected by studying the measured charge distributions of each SiPM.

Figure 2 shows two sample spectra measured for a small and a large SiPM. The pedestal distributions obtained without particles are superimposed on the same plots. The small amplitude peaks visible are due to the dark counts of the SiPMs which occur in the integration gate of the QDC. Similar spectra were obtained for all SiPMs and for all runs in different configurations.

In the case of small SiPMs the number of collected photons was very low (of the order of a few photons on average). We fitted the charge distributions with multi-gaussian functions and then fitted the peak areas with a Poisson distribution, obtaining the average number of photons detected.

In the case of large SiPMs the individual photon peaks could not be fitted individually, due to the higher intrinsic noise of the larger SiPMs and to the relative low statistics collected for each peak. We decided to reduce the number of bins and to fit the resulting histogram with
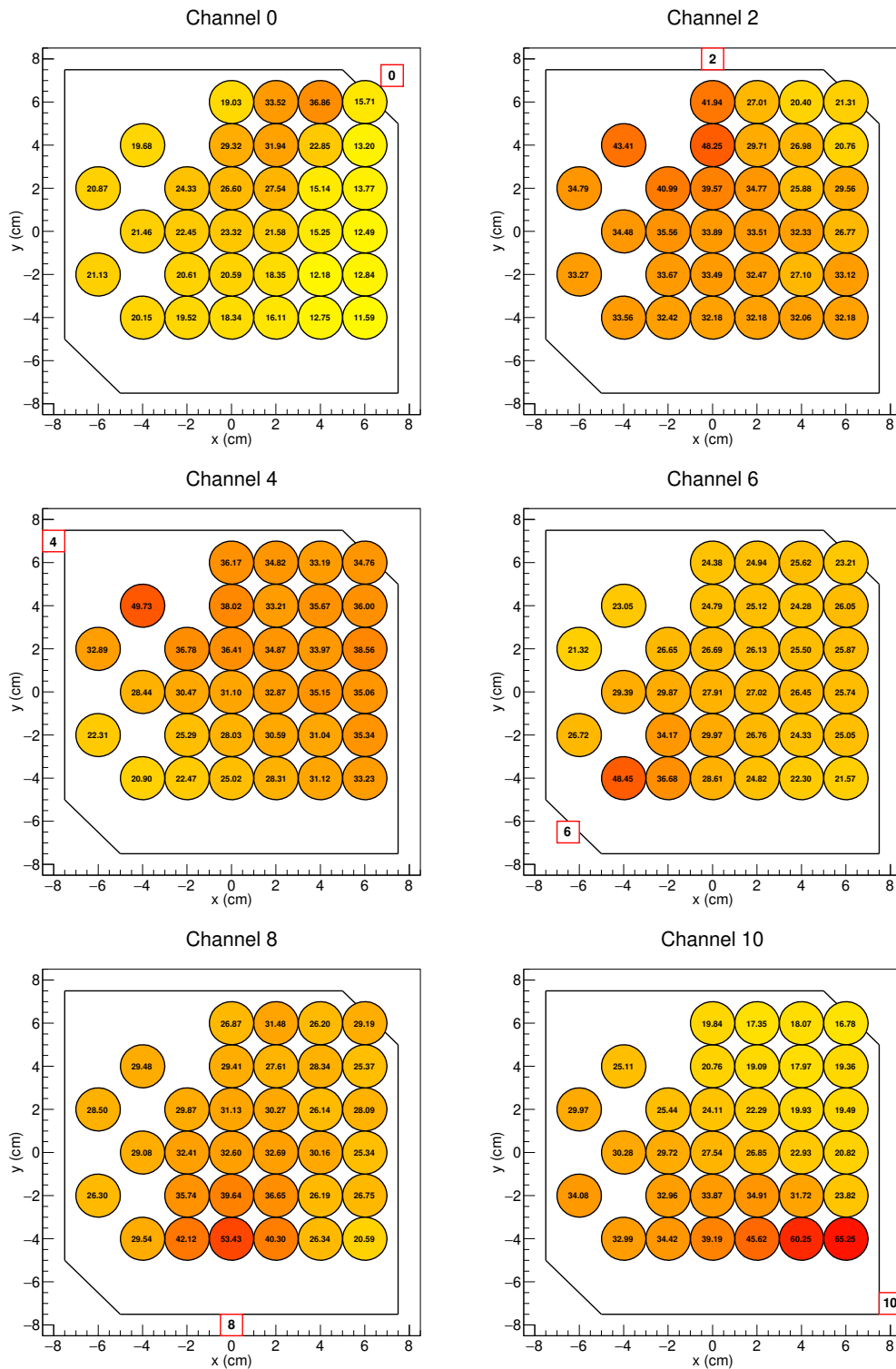
Figure 4. Maps summarizing the number of photons detected by each SiPM in the different beam positions tested. The numbers in the circles represent the detected photons, while the red boxes on the perimeter show the position of the SiPM.
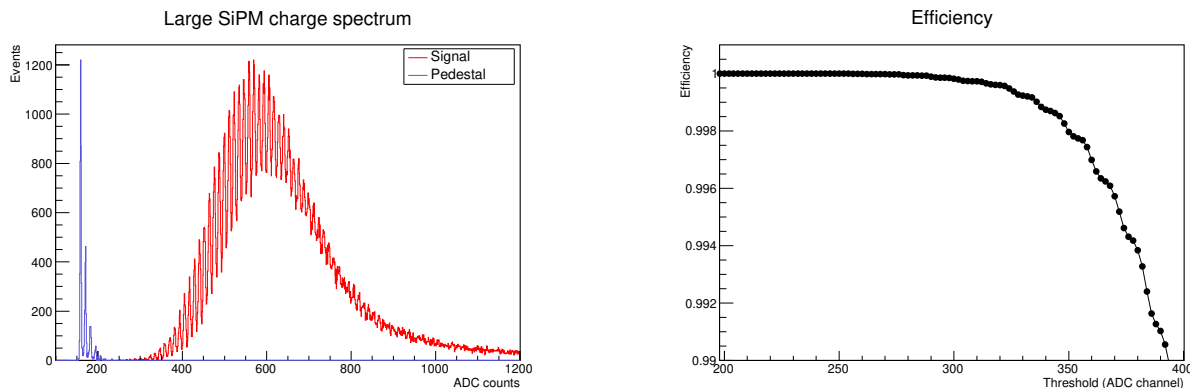
Figure 5. Left: sample pedestal (blue) and signal (red) spectrum for a large SiPM measured at SPS-H8. Right: efficiency as a function of the integration threshold.

a Landau distribution folded with a Gaussian distribution. The ADC charge corresponding to the peak of the Landau function was then converted into photons using the conversion factor from ADC counts to photons, which was obtained by fitting the pedestal distributions for each SiPM. Figure 3 shows two histograms and their fitting curves for a small and a large SiPM.

Plots in figure 4 summarize the results obtained when changing the position in which we irradiated the tile for all large SiPMs. Each plot shows the number of photons detected by one SiPM in all the positions tested, which is indicated by the numbers inside the circles and by the color scale. The red boxes on the edges represent the position of the SiPM along the tile, with the numbers inside these boxes indicating the arbitrary index we assigned to each SiPM.

The results show that the number of photons detected is almost constant ($\sim$30-40 ph.) in all positions and for all SiPMs, with peaks in positions close to the SiPMs. This effect is probably due to a higher contribution of direct light. Similar results were obtained for small SiPMs. However, in this case the number of detected photons (less than $\sim$3) was not sufficient to separate the particle signal from the pedestal.

3.2. Efficiency

As shown in figure 2, the large SiPMs provide a very good separation of pedestal and signal distributions and could be well suited to detect the passage of a charged particle. At SPS-H8 the tile was irradiated in the central position only and we collected enough statistics to evaluate the detection efficiency.

The left plot in figure 5 shows the pedestal and signal distributions measured for one of the large SiPMs. Individual photon peaks are visibile up to more than 50 photons. We evaluated the integral of the signal histogram with varying lower threshold in order to estimate the detection efficiency of a minimum ionizing particle. The result is shown in the right plot in figure 5. The visible steps are due to the individual peaks in the distribution. The result shows that a very high efficiency can be reached with this simple configuration, fulfilling the requirements of anti-coincidence systems in cosmic ray satellites.

4. Conclusions

The measurements performed show that SiPMs can be coupled to scintillators to detect the passage of charged particles. The 4$\times$4 mm^2 SiPMs proved to be appropriate to detect the passage of a minimum ionizing particle above the background. On the other hand, the 1$\times$1 mm^2 SiPMs detect too few photons to separate the signal from the pedestal and to efficiently detect

particles. However, they could be used to extend the dynamic range and to detect or reject heavier ions.

The beam position scan shows that the response is almost uniform in the tile, with the exception of the impact points close to the SiPM positions, for which the contribution of direct light is higher. This aspect must be taken into account when measuring the energy deposition in the scintillator.

Finally, the detection efficiency achieved with this configuration is close to the requirements of ACD detectors for satellites. Improvements can be obtained by summing or implementing coincidence of multiple SiPMs.

More tests are planned in order to study different tile and SiPM configurations and to fully explore the potentiality of these detectors for cosmic ray experiments.

Acknowledgements

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