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Time and amplitude characteristics of large scintillation detectors with SiPM

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Abstract

A large plastic scintillation detector system with silicon photomultiplier (SiPM) readout has been developed as a prototype for future astroparticle experiments' detectors. A set of SiPM connected in parallel was used in order to enlarge the light collection effective area and thus enhance the detector's amplitude and timing performance. Here we report on the values of time resolution and scintillation detection efficiency of such a system for different types of SiPM as a function of the distance between the scintillation strip edge with photomultipliers attached to it, and the penetrating particle. Results of a special simulation study of the system's amplitude and timing performance as a function of the SiPM radiation aging are also presented.

Keywords: SiPM; plastic scintillator; time-of-flight; radiation aging;

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1. Introduction

Future astroparticle experiments based on the operation of gamma-ray telescopes (such as the GAMMA-400 experiment, described in detail elsewhere [1-2]) often require the presence of time-of-flight or anticoincidence systems in the telescope's structure. These systems are usually expected to have good timing characteristics (better then 1 ns FWHM) and high particle detection efficiency (up to 99.999%) and could be composed of large area scintillation detectors (up to ~100x10x1 cm^3, or even larger) with advanced photodetecting instrumentation.

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By replacing the conventionally used in this purposes vacuum photomultiplier tubes by silicon photomultipliers (SiPM) one could greatly simplify the design of a gamma-ray telescope and additionally optimize its dimensions and reliability for the space experiment conditions.

In order to evaluate the achievable performance of scintillation detectors with SiPM readout, a set of measurements has been carried out using a detector consisting of a scintillation strip and a number of SiPMs manufactured by different companies. Time and amplitude characteristics of such detectors were measured, and their dependence on the level of simulated radiation damage consequences was evaluated.

2. The experimental setup

The measurements were carried out using a scintillation strip made of plastic scintillator BC-408 from Saint-Gobain Crystals sized 100x10x1 cm^3 (see Fig.1). A set of six SiPM SensL (B-series, 6x6 mm^2 active area) forming a single circuit was optically coupled to one edge of the strip. A common signal from all six devices was fed to the readout circuit as shown in Fig.1. A set of six SiPM KETEK (PM6660, 6x6 mm^2 active area) was coupled to the opposite edge of the strip. Measurements with both SiPM sets were performed consecutively. The optical contact was provided with Rhodorsil Pâte-7 optical grease.

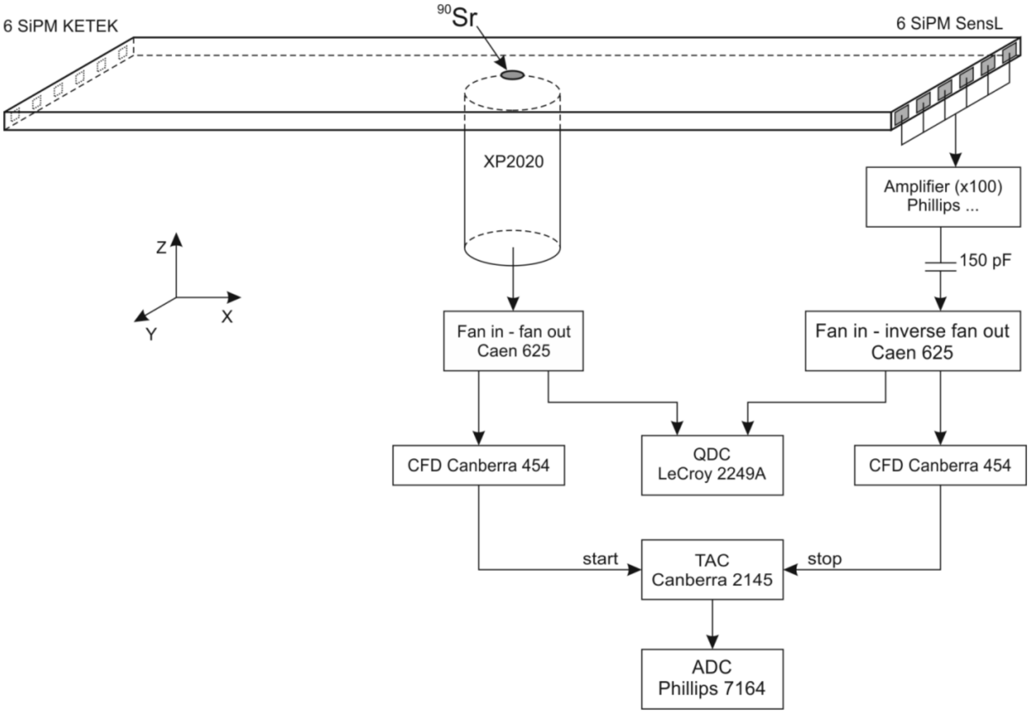

Fig.1. Test setup for the detector's time and amplitude characteristics study

A radioactive source ^{90}Sr with a maximal energy of the beta-spectrum of emitted particles equal to 2.3 MeV was placed at different points along the central axis on the top XY plane of the scintillation strip. An additional XP2020 PMT placed under the source as shown in Fig.1 was used for the selection of events with 2.0-2.3 MeV energy deposition generating trigger signals. The PMT contribution to the resulting time resolution did not exceed 100 ps.

The mean energy deposited by electrons in 1 cm thick scintillator volume (~2 MeV) selected by a signal discrimination based on the XP2020 trigger signals resulted in a well-separated peak in the QDC spectrum of scintillations, detected by a SiPM set. Typical QDC spectra of signal and noise events are shown in Fig. 2.

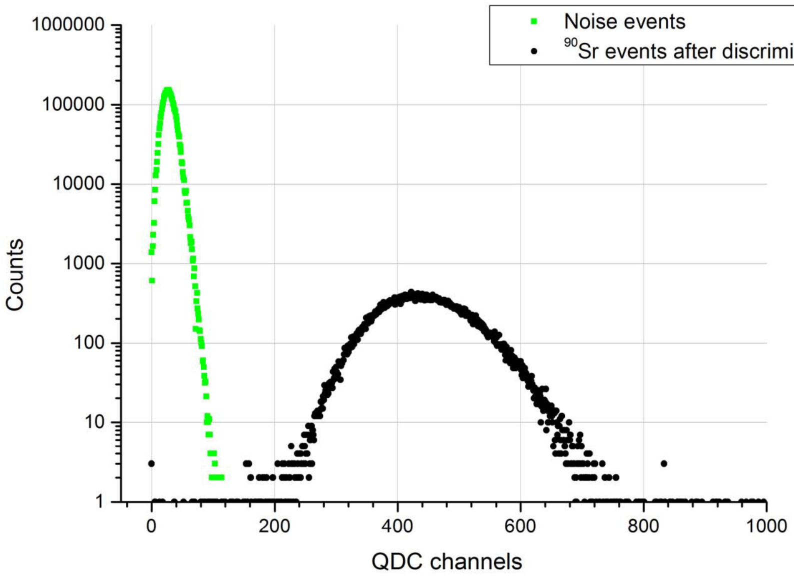

Fig.2. Typical signal and noise QDC spectra distributions. The measurements errors are inside experimental points.

3. Amplitude and timing performance

3.1. Measurements under normal conditions

Fig. 3 gives the time resolution of the tested scintillation detector as a function of the distance between the beta-source and the set of SiPM used in the measurements.

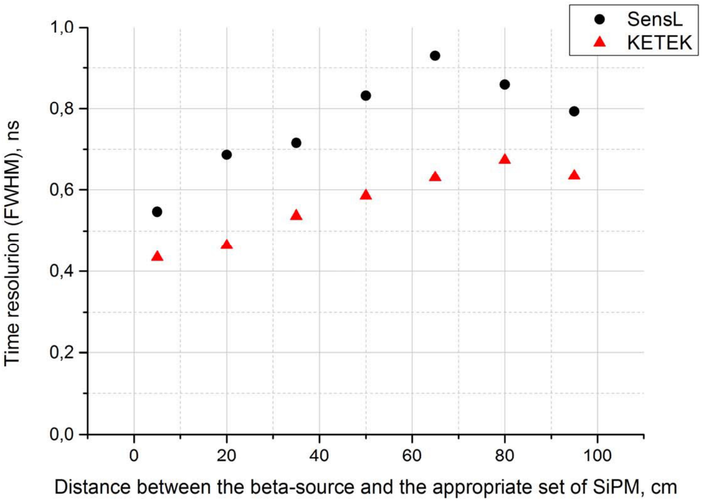

Fig.3. Time resolution for the tested scintillation detector as a function of the distance between the beta-source and the appropriate set of SiPM. The measurements errors are inside experimental points.

The data shown in Fig. 3 demonstrates the possibility of achieving ~800 ps time resolution for a large scintillation detector of such a type using the SensL devices and ~600 ps in case of KETEK devices when the scintillations occur in the center of the scintillation strip. Simultaneous operation of photosensors attached to both edges of the scintillation strip and additional use of a mean-timer electronic circuit may slightly improve these values and make them nearly independent of the impact point.

Basing on the data given in Fig.3 we suppose that reflections of scintillation photons from the far edge of the strip could affect the timing performance of the scintillation detector while registering events occurred in the middle of the strip.

The smaller is the ratio of area of the far edge of a scintillation strip, covered by a light-absorbing surface (such as a SiPM active surface or a PMT window) to the total area of the far edge, the larger amount of reflected and thus delayed photons would be detected by photosensors attached to the opposite edge of the strip.

Though the active area of SensL and KETEK SiPMs used in the measurements described is equal, the area of the front surface of the SensL SiPMs' housing is 1.6 of that for the KETEK SiPMs. This fact could help to explain the significant difference between the value of the time resolution deterioration in the central region of the scintillation strip for the SensL and KETEK SiPM readout detector options.

Fig. 4 shows the signal amplitude attenuation depending on the distance between the beta-source and the appropriate SiPM set for both types of the devices. One can see that the signal amplitude decreases exponentially along the entire length of the strip except of the region nearby the far edge of the strip.

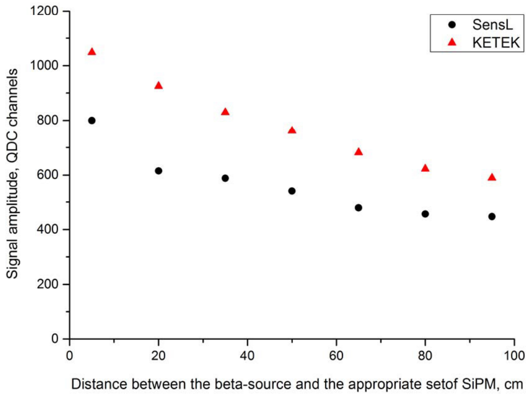

Fig. 4 The signal amplitude as a function of the distance between the beta-source and the detecting set of SiPM. The measurements errors are inside experimental points.

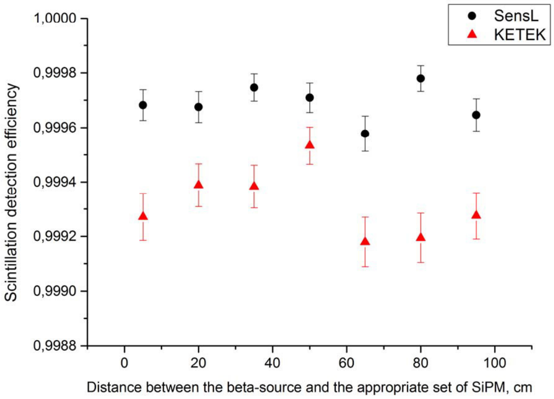

Fig. 5 The dependence of the scintillation detection efficiency for the tested scintillation detector on the distance between the beta-source and the detecting set of SiPM

Dependence of the scintillation detection efficiency on the distance between the detecting SiPM set and the beta-source is shown in Fig.5. We determine the value of the scintillation detection efficiency as a ratio of the number of events, counted by a SiPM set to the number of XP2020 triggers. The presented data shows the possibility to achieve the value of the particle detection efficiency of 0.999 relatively easily and enhance it by more than an order of magnitude utilizing at least two layers of scintillation detectors.

3.2. Characteristics under the radiation damage consequences simulation

Radiation aging of SiPMs is a serious obstacle to their widespread use in space and accelerator experiments. One of the main consequence of a SiPM radiation aging is an increase of its dark current, i.e. increase of the number of fired SiPM pixels per unit time. This may lead to a significant reduction of the useful signal's amplitude and to an increase of the average noise signal amplitude, resulting in both amplitude and timing performance deterioration.

To estimate the influence of the increased dark current on SiPM characteristics special measurements were carried out in order to simulate the SiPM radiation aging. At first, the increase of the SiPM dark current was stimulated by a continuous low-intensity illumination of individual SiPM samples, while the physical signals were created by short LED flashes with constant amplitude. As a result, the gradual increase of the intensity of the continuous illumination brought to a steady reduction of the physical signals amplitude (Fig. 6).

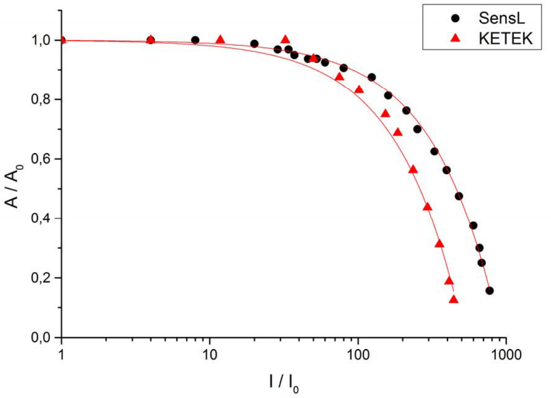

Fig. 6 The physical signal amplitude reduction (A/A_0) as a function of the SiPM dark current increase (I/I_0), where A and I are the physical signal amplitude and the SiPM dark current respectively measured at different levels of continuous SiPM illumination; A_0 and I_0 – the initial values of physical signal amplitude and SiPM dark current respectively, measured with no additional illumination. The measurements errors are inside experimental points.

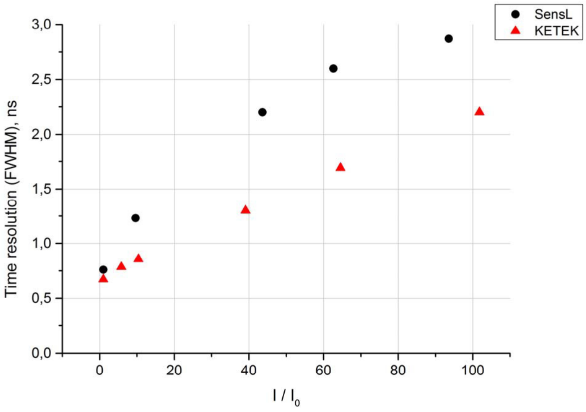

Fig. 7 Time resolution for the scintillation detector as a function of the SiPM dark current increase (I/I_0). The measurements errors are inside experimental points.

To estimate the effect of the increasing dark current on the timing performance of the scintillation detector with a SiPM readout a setup was used, which was similar to the one shown in Fig. 1 but a LED has been included into the scheme providing for a continuous low-intensity illumination of the scintillation edge with SiPMs attached. The results are shown in Fig. 7.

Comparison of the data shown in Fig.6 and Fig. 7 lead to the conclusion, that the main reason of deterioration of the timing performance of the scintillation detectors with SiPM readout is the increase of the average noise amplitude. Fig. 7 justifies the need to optimize the thickness of SiPM shielding in case of operation under adverse radiation environment conditions in order to eliminate the SiPM dark current increase stronger then a factor of 10. For other SiPM types with different initial dark current values this parameter could probably differ.

4. Conclusion

The results obtained demonstrate the possibility of the silicon photomultiplier readout application to the time-of-flight and anticoincidence systems' detectors of future gamma-ray space telescopes. For example, application of the reported above SensL B-series SiPMs to the GAMMA-400 gamma-ray telescope subsystems could result in the appropriate performance of particle detection and rejection of the telescope, though it is planned to utilize recent and more suitable SensL C-series SiPM with fast output [3-4] for this purpose.

Results of the measurements using the simulation of the SiPM radiation aging show the need to carefully consider the thickness of the photosensors' shielding and select the appropriate type of SiPMs in terms of their radiation hardness.

It is also important to achieve the largest possible margin in the detectors' time resolution at the stage of its on-ground calibration in order to avoid unacceptable level of the timing performance deterioration during the last years of the device's space mission. Such margin could be achieved by increasing the number of SiPMs in each set, thus increasing the signal to noise ratio.

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