Timing scintillation detector with SiPM incorporated throughout a scintillator’s body

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Abstract. A timing scintillation detector based on a plastic scintillator strip sized $35 \times 5 \times 1 \text{ cm}^3$ and SiPM optical readout has been developed and characterized. For the best uniformity of the detector’s response to particle hits across its area, a set of SiPM optical sensors has been incorporated into the scintillator throughout its volume. Time resolution better than 260 ps (sigma) has been achieved for each point of the device. Uniformity of the detector’s response is confirmed by amplitude measurements along the strip as well as measurements of the efficiency of scintillation detection, which, on average, is ~99%.

1. Introduction
Vast majority of modern experiments in the field of high-energy physics require the use of large detector panels, able to detect relativistic particles with a relatively high efficiency (>90%) and accurate timing (time resolution $\sigma<0.5$ ns). Such detectors are often used as parts of anticoincidence and time-of-flight systems (see, for example, [1-3]).

Effective and relatively low-cost solution for the discussed large area detectors are plastic scintillation detectors with photomultiplier-based optical readout. Before the rapid progress in the technology of silicon photomultipliers (SiPM) [4] the optical readout of such scintillation detectors was most commonly organized with the help of conventional vacuum PMTs optically coupled to opposite ends of scintillation strips. First prototypes of silicon photomultipliers were characterized with small effective area ($\sim 1 \times 1 \text{ mm}^2$) and sensitivity to photons with $\lambda>500$ nm only, enabling one to construct relatively large plastic scintillation detectors with WLS fiber readout to SiPMs [5].

Development of large-area ($\sim 36 \text{ mm}^2$) SiPMs with peak sensitivity to photons at $\lambda \approx 400$ nm (matching the typical emission spectrum of a plastic scintillator) paved the way for SiPM application to direct light readout from the opposite ends of scintillation strips. It is confirmed, that such detectors are characterized with relatively good timing (time resolution better 300 ps (sigma) for a $100 \times 10 \times 1 \text{ cm}^3$ strip) and high detection efficiency (better than 0.999 for a $100 \times 10 \times 1 \text{ cm}^3$ strip) [2, 6, 7]. However, performance of the mean-timer circuit used to equalize the signals delay from SiPMs at the opposite ends of the strip could be compromised in case if two particles hit the strip in different points along it. Furthermore, amplitude homogeneity of scintillation signals read out from the opposite sides of very large area scintillation strips could be insufficient for some critical applications.

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Below we present amplitude and timing characteristics of a scintillation detector with an atypical optical readout scheme: scintillation photons are read out by an array of electrically interconnected silicon photomultipliers incorporated throughout the scintillator’s body.

2. The experimental set up

The detector under study is based on a plastic scintillator strip sized $35 \times 5 \times 1 \text{ cm}^3$ employing 16 Ketek PM6660TS-SB0 SiPM with $6 \times 6 \text{ mm}^2$ effective area. The SiPMs are located back-to-back in four pairs of hollow slots sized $7 \times 9 \times 9 \text{ mm}^3$ inside the strip (see figures 1-3 for the layout of the scintillator, photo of the SiPM supporting structure and the general view of the detector). The hollows are filled with a special liquid for a better optical contact between SiPMs and the scintillator bulk. Outer surface of the scintillator is covered with metallized maylar film used as light reflector.

![Figure 1](image1.png)

**Figure 1.** Layout of the plastic scintillator used in the detector under study. All dimensions are given in mm.

![Figure 2](image2.png)

**Figure 2.** Picture of the PCB for mechanical support, power supply and signal readout from two pairs of SiPMs.
Each of the four dedicated PCBs shown in figure 2 features serial connection of four SiPMs for their faster response. Their common signal is preamplified with LMH6629 op amp installed at each PCB. The combined and preamplified signals from each of the four PCBs are passed through coaxial cables to the common PCB (“patch panel” in fig.1) to be further added and amplified with the OPA695 summing amplifier.

A set of measurements with signals from cosmogenic muons was conducted in order to determine amplitude and timing characteristics of the described detector. For the purposes of time triggering and signal counting, a movable telescope of two additional detectors was included to the experimental setup. The top counter is based on a plastic scintillator tile sized 5×4×1 cm$^3$ and a 6×6 mm$^2$ Sensl B-series SiPM optically coupled to one side of the tile. The tile is covered with a metallized mylar film used as light reflector. The bottom detector of the telescope is based on a 3×4×3 cm$^3$ plastic scintillator optically coupled to Philips 56 AVP vacuum PMT (inherent time resolution ~100 ps).

Charge of the signals from all three detectors was recorded by Phillips Scientific 7166 QDC triggered by the signals from the bottom detector of the telescope. Efficiency of the tested detector was determined for the triple coincidence events selected offline basing on the charge spectra from the detectors. Time resolution of the tested detector was counted relatively to the timing of the signals from 56 AVP PMT with the help of Canberra 454 constant fraction discriminator, Canberra 2145 time-to-amplitude converter and Phillips Scientific 7164 ADC.

3. Experimental results
The measurements were carried out for 7 regions along the central axis of the tested detector by moving the detectors of the telescope. Regions #1-5 represent the uniformity of the detector’s response to those particles, penetrating the scintillator bulk only, while the regions #6-7 represent the parameters of the detector’s response to those events, occurred in the very close proximity of the hollow slots with SiPM, including the volume of the slot itself. Please, refer to figure 4 for the correspondence between the bottom telescope detector outline and the location of the hollows in the scintillator.

![Figure 4](image.png)

**Figure 4.** To scale drawing of the bottom telescope detector projection to the tested scintillation detector.
As could be seen from the plot in figure 5, the detector under study is characterized with a very good timing uniformity along the scintillator – up to 110 ps spread in signal delay only (even including the regions 6 and 7). This value is twice smaller, than the obtained time resolution of ~200 ps for all tested regions except one of those, containing the SiPM slots in its center. Time resolution for this region was measured to be ~260 ps.

Mean amplitude distribution for the signals along the scintillator axis presented in figure 7 shows notable amplitude nonuniformity (up to 40%) of the device. It is most probably caused by different light collection efficiency in the center of the scintillator and nearby its edges. This phenomenon should be less significant for such detectors of a much larger scale, and could also be corrected with the optimisation of SiPM distribution across the scintillator area.

![Figure 5](image5.png)  
**Figure 5.** Relative signal delay for different regions along the scintillation strip.

![Figure 6](image6.png)  
**Figure 6.** Time resolution as measured for different regions along the scintillation strip.

![Figure 7](image7.png)  
**Figure 7.** Mean signal amplitude as measured for different regions along the scintillation strip.

![Figure 8](image8.png)  
**Figure 8.** Scintillation detection efficiency for different regions along the scintillation strip.

Scintillation detection efficiency of the tested detector, as could be seen from figure 8, is found to be ~99% for all the tested regions of the device except those matching the SiPM slots. Although the area of all eight slots is small relatively to the whole area of the scintillator (~3%), one could further increase the efficiency of scintillation detection of this device by choosing the optimal size and shape of the SiPMs used and refining the construction of the supporting structures of the SiPMs. Use of several stacked layers of such detectors with different layout of the SiPM location could further increase the
scintillation detection efficiency so, that such detectors could become applicable to the anticoincidence system of the GAMMA-400 space observatory [1].

4. Conclusion
Prototype of a plastic scintillation detector with SiPM optical readout of an atypical construction has been produced and tested. The concept of the light readout with an array of electrically interconnected SiPMs incorporated throughout the scintillator’s body enables one to enlarge the achievable size of the detector, preserving the homogeneity of its response across the area. In particular, it becomes possible to construct large-area anticoincidence and time-of-flight detectors characterized with relatively good timing and amplitude parameters even for those scintillators whose light attenuation length is significantly smaller, than the linear dimensions.

The prototype under study based on a 35×5×1 cm³ plastic scintillator strip with 16 6×6 mm² SiPMs incorporated into it has shown uniform response timing (delay spread up to 110 ps) and relatively good time resolution (180-260 ps). Efficiency of scintillation detection is found to be ~99% across the major part of its area. Further optimization of the detector’s construction and SiPM type could significantly improve its amplitude homogeneity (~40% spread for the tested prototype) and efficiency of scintillation detection for those regions of the device containing the slots with SiPMs.

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