Scintillator tiles read out with silicon photomultipliers

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ABSTRACT: A detector prototype based on a fast plastic scintillator read out with silicon photomultipliers is presented. All studies have been done with cosmic muons and focus on parameter optimization such as coupling the SiPM to the scintillator or wrapping the scintillator with reflective material. The prototype shows excellent results regarding the light-yield and offers a detection efficiency of 99.5% with a signal purity of 99.9% for cosmic muons.

KEYWORDS: Scintillators, scintillation and light emission processes (solid, gas and liquid scintillators); Photon detectors for UV, visible and IR photons (solid-state) (PIN diodes, APDs, Si-PMTs, G-APDs, CCDs, EBCCDs, EMCCDs etc); Front-end electronics for detector readout

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1 Introduction

Scintillation-detectors with SiPM readout are of large interest in many fields where reliable and affordable detectors for ionizing particles are needed. The variety of scintillating materials that are combined with SiPMs is vast in research and running applications. Fast organic scintillators are used [1, 2] as well as inorganic crystals [3] and scintillation fibres [4]. The field of applications stretches from astro particle physics [5] to medical imaging systems [6].

This report presents dedicated studies on detector modules based on fast plastic scintillators and SiPMs, one of which is shown in figure 1. Section 2 describes the developed frontend electronics for the SiPMs used for all measurements presented in this paper as well as a short performance test of SiPMs under temperature variation. A detector prototype with a $10 \times 10$ cm$^2$ scintillator is described in section 3. Different optimization measurements are presented, and the detector efficiency and signal purity is determined with cosmic muons.

2 Frontend electronics and SiPMs

The used frontend electronics is called Multi Pixel Photon Counter Duo Controller (MPPC D, figure 2). It was designed as a multi purpose dual SiPM voltage regulator and amplifier, that could be used for precise timing and energy measurements. This requires a compromise between fast pulses and stable pulse shapes. The MPPC D features independent voltage regulators for two SiPMs, a platinum resistor based temperature probe, two single SiPM signal LEMO outputs and an analogue sum channel LEMO output. The dual SiPM system was chosen to counter high noise rates in SiPMs. In an analogue sum signal the signal to noise ratio is expected to be higher, since signal pulses will occur in both SiPMs but noise pulses are uncorrelated. The MPPC D is based around an ATmega88P, an 8-bit microcontroller designed for low power consumption [7]. It features a USART interface, 10-bit DACs, a serial peripheral interface, 512 B of EEPROM and runs at 1 MHz system clock. The ATmega88P enables the MPPC D to process temperature measurements and correct the SiPM’s bias voltages without the need for remote control. The voltage regulators use pulse width modulation to adjust the bias voltage with 16 bit resolution between 0 V and 82 V.
Figure 1. The prototype detector: 1. 10 × 10 cm$^2$ scintillator tile with reflective wrapping; 2. Two 3 × 3 mm$^2$ SiPMs; 3. Frontend electronics (see also figure 2).

Figure 2. The MPPC D module: 1. Boxed six pin bus connector; 2. ATmega88P with its six pin ISP header on the bottom left; 3. Temperature probe circuit. The platinum resistor is located on the front plate between both SiPMs. Its analogue signal is passed to this circuitry; 4. Two voltage regulator circuits for the SiPMs; 5. Operational amplifiers; 6. Jacks for the SiPMs.

Amplifier circuits. The output pulses of SiPMs are current pulses in the order of $\mu$A. Therefore, signal amplification is necessary before further signal processing. The MPPC D uses two amplification stages (figure 3). The core part of the amplification on the MPPC D is the MAX4228 current feedback amplifier with a gain-bandwidth product of 1.2 GHz [8]. This makes it a very fast and suitable operational amplifier for SiPM pulses, which have high speed rising edges. The first amplification stage, the preamplifier, is a transimpedance amplifier, which converts, inverts, and amplifies the current pulses into voltage pulses in the order of mV. The output pulses of the preamplifier are fed into the second amplification stage as well as the summing amplifiers. The second stage is a non-inverting amplifier, which sets the total amplification to a factor of 5.7, the bandwidth to 210 MHz, and output pulses to the order of 10 mV for single photons. The AC part of the signals is decoupled from the DC part with a capacitor, because current feedback amplifiers may produce offset voltages. Finally, a resistor matching the impedance of standard LEMO cables is used to protect against voltage reflections at the output stage. The sum signal is generated with
two additional stages (figure 4). A summing amplifier adds and inverts the signals of both preamplifiers. The output is fed into an second inverting amplifier resulting in a total amplification of 4.56 for the sum channel.

**MPPC D performance.** The MPPC D has been tested with SiPMs of different *Hamamatsu* series. The following values were measured with a S12572-050C model. The pulse height distribution of noise pulses, recorded with an FADC (figure 5), shows an SiPM characteristic finger spectrum, amplified with the MPPC D. The peaks are clearly separated which demonstrates a stable amplification. The rise time (10%–90% of maximum amplitude) has been measured to 5ns, which corresponds to the 210MHz bandwidth of the MPPC D’s second amplifier stage. Power consumption of the MPPC D was measured to around 300mW when running with two SiPMs. Furthermore, the RMS of the temperature measurement was determined to 0.1°C. The bias voltage generated by pulse width modulation was measured to be very stable with an RMS of 1.4mV at $U_{\text{Bias}} = 67.70\text{V}$.

**SiPM behaviour under temperature variation.** Silicon photomultipliers are very sensitive to ambient temperature changes. Therefore, their bias voltage has to be adjusted constantly to assure a stable signal gain. *Hamamatsu* provides temperature regression coefficients for this purpose, which have been validated for SiPMs of two series with the MPPC D. The SiPM gain was measured at 25°C with the bias voltage recommended by *Hamamatsu*. The temperature was then lowered down to 15°C in steps of 1°C. At each point, the bias voltage was adjusted until the initial gain was reached. A temperature regression coefficient is determined by a linear fit (figure 6). For
Figure 5. Pulse height distribution of an Hamamatsu S12572-050C SiPM amplified by an MPPC D.

Figure 6. Determination of the temperature regression coefficient.

an SiPM of the S10362 series the coefficient is measured to (56.6 ± 0.5) mV/K which agrees with Hamamatsu’s value of 56 mV/K [9] and for an S12572 SiPM the measured value of (59.7 ± 0.7) mV/K is in agreement with Hamamatsu’s 60 mV/K [10] as well. With the voltage regulated to ensure constant gain the one-pixel noise rate of both SiPMs was measured as well (figure 7). As expected the noise rate increases with temperature due to the increased probability of thermally-generated charge carriers in the SiPM starting an avalanche.
3 Prototype module

3.1 Experimental setup

The presented studies were performed with the prototype shown in figure 1. The module consists of a fast $100 \times 100 \times 5$ mm$^3$ organic scintillator of type BC-404 by *Saint-Gobain* [11] and is read out by two SiPMs of type S10362-33-100C by *Hamamatsu*. The BC-404 scintillator was chosen for its fast timing capabilities (decay time of 1.8 ns) and the highest light output in the BC-400 series with the drawback of the shortest light attenuation length of 140 cm. The emission spectrum of the scintillator (figure 8 (a)) has its maximum at $\lambda_{\text{max}} = 408$ nm and is limited roughly in the range between 380 nm and 500 nm. The scintillator is wrapped in PTFE tape (Polytetrafluoroethylene, widely known by *DuPont*'s brand name Teflon®) which is a diffuse reflector.

The S10362-33-100C SiPMs have an active area of $3 \times 3$ mm$^2$ with a pixel pitch of 100 $\mu$m which leads to a total pixel number of $300 \times 300$. Figure 8 (b) shows the detection efficiency of the similar SiPM type S10362-33-050C which has the same active area but smaller pixel pitch. The figure clearly shows that the detection efficiency of the S10362 series is highest for wavelengths between 400 nm and 500 nm, which makes them a good match for the chosen scintillator BC-404. The SiPMs are operated at the bias voltages recommended by *Hamamatsu*, which are given for each SiPM separately. The temperature compensation coefficient is set to 56 mV/K.

A typical signal spectrum of the detector, externally triggered with cosmic muons, is shown in figure 9. A small inefficiency is visible and clearly separated from the Landau shaped signal distribution with the most probable value around 230 mV. The second peak at roughly 600 mV is due to a saturation effect of the preamplifiers.

The amplification factors of the used MPPC D has been modified during certain measurements, therefore the resulting signal gains differ from the default values described in section 2. Especially the amplification of the sum signal has been lowered. The relation of the signal heights is roughly given by $V_{\text{Sum}} = 0.3 \cdot (V_{\text{SiPMA}} + V_{\text{SiPMB}})$. All measurements presented in the next chapter have been performed with cosmic muons, triggered by the coincidence of two scintillators read out with photomultiplier tubes.
### Figure 8
The emission spectrum of Saint-Gobain scintillator BC-404 (left) and spectral detection efficiency of Hamamatsu S10362-33-050C type SiPM (right) match.

### Figure 9
Pulse height spectrum of the prototype module for cosmic muons.

#### 3.2 Parameter optimization

To achieve the best possible light yield and to gain a deeper understanding of the prototype, several parameters have been investigated separately. To compare different setups, each configuration has been tested with 3000–5000 cosmic muons and a Landau fit was performed on the resulting QDC or FADC spectrum (as shown in figure 9). The most probable values (MPV) of these fits are used as quality criteria for the given configuration and will be presented for all three signal outputs (SiPM A, analogue sum, SiPM B) in bar charts in the following.

**Wrapping material.** A very important component of the detector is the reflective wrapping material of the scintillator since it directly affects the light yield. Therefore, aluminium foil has been tested as a specular reflector and compared to a multi layer wrapping of PTFE tape as a diffuse reflector. The result is shown in figure 10. Wrapping the scintillator with PTFE tape leads to a significant increase in the signal height of about 70%–90% compared to aluminium foil. Therefore, all further measurements have been performed with PTFE tape as reflector, applied in three
layers. In later prototypes DuPont’s Tyvek® is used giving comparable results to PTFE tape at easier handling and application.

**Scintillator thickness.** The effect of the scintillator thickness is of interest for many applications and a comparison between a 5mm and a 10mm thick scintillator was made. The results of this comparison are depicted in figure 11. The light yield drops when changing the 10mm scintillator to a 5mm thick one in the order of 10%–15%, which is an acceptable trade off for a 50% decrease in detector thickness in many applications. All further measurements have been performed with the 5mm thick scintillator.

**Coupling between SiPM and scintillator.** One of the most critical points of scintillator based detectors is the optical coupling between the scintillator and the light detector. In early prototypes, optical coupling was done with the BC-630 optical grease of Saint-Gobain (figure 12 (a)) [12]. After applying the grease, the detector signals dropped significantly within a week’s time, which can be explained with figure 12 (b). The figure shows the scintillator edge to which the grease was applied. The grease has dried out or partially evaporated on the surface and thus the optical connection between the SiPM and the scintillator deteriorated significantly. With this result the BC-630 can obviously not be considered as a long-term solution for detectors. Therefore, two

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**Figure 10.** Comparison between aluminium foil and PTFE tape as reflective wrapping material.

**Figure 11.** Comparison between a 5mm and a 10mm thick scintillator.
other methods of coupling the SiPM to the scintillator were tested: the silicone gel RTV 6156 by GE Silicones [13] and silicone rubber pads made out of RT 604 by ELASTOSIL [14]. Pictures of both options are depicted in figure 13. Both alternatives are silicone based and mixed of two components. Remaining air pockets are removed from the mixture under a vacuum bell jar. The RTV 6156 was applied directly to the scintillator, cured in the assembled module and, therefore, adopted perfectly to the SiPM geometry. On the other hand, a 1 mm thick layer of RT 604 was cast and hardened on a glass surface from which small pads can be cut. The idea to produce these pads is inspired by conventional photo multiplier tubes, where similar pads have been used for many years as optical coupling between scintillators and light guides. The great advantage of these pads is their reusability and the simple detector assembly.

Measurements with all these coupling methods, including one without any additional optical layer, were performed with cosmic muons (figure 14). The importance of an optical medium is
clearly visible since all three methods lead to a significant increase of light yield. BC-630 provided the best result, even though it cannot be used long-term as described above. The other two methods are slightly, but not significantly, worse. The RTV 6156 should be used as the long term solution. However, for testing purposes the RT 604 pads have been chosen for all following measurements due to their flexibility and ease of use.

**Coupling reproducibility.** It is important to investigate how the assembly procedure of the module effects the quality of optical coupling and therefore the detectors signals. For this purpose the frontend electronics were separated from the module and reassembled with new silicone pads four times. The results (figure 15) show uncritical fluctuations in the order of $\leq 5\%$ (RMS).

**Wrapping reproducibility.** Similar to the investigation of the coupling reproducibility, the wrapping of the scintillator with PTFE tape was tested by means of rewrapping the whole scintillator four times. The rewrapping was done with particular attention to the scintillator edges and the reduction of possible air pockets under the PTFE layers. The results are shown in figure 16. The cautious rewrapping clearly increases the light yield, which was up to 30\% lower with the old wrapping. The fluctuations of the signal height when rewrapping the scintillator are at about 8\% (RMS).
3.3 Prototype performance

Signal purity. Since all prototype studies were done with cosmic muons, the purity is also calculated with respect to cosmics. Purity is hereby defined as the probability that a detector pulse over a certain threshold was triggered by a real muon passing the detector and not due to high SiPM noise. The fraction of muon pulses and SiPM noise pulses for any given threshold are used to calculate the purity. Two measurements of pulse rate versus threshold were performed. First, pulses of the whole prototype module were recorded, including noise and muon pulses (total rate). Secondly, the signal rate of the same module was recorded without the scintillator and thereby eliminating the muon signals (noise rate). The purity can then be calculated by:

$$\text{purity} = \frac{\text{muon rate}}{\text{total rate}} = \frac{\text{total rate} - \text{noise rate}}{\text{total rate}}. \quad (3.1)$$

With a trigger threshold of around 40 mV a signal purity of more than 99.9% is reached (figure 17).
Detector efficiency. The detection efficiency of the prototype module is determined as a function of potential trigger thresholds from the combined data of the previous measurements investigating the coupling and scintillator wrapping reproducibility. The calculation and error estimation follows the guidelines given in [15]. Figure 18 (a) shows the combined efficiency of the analogue sum signal plotted against the full dynamic range of the module and figure 18 (b) is a magnification of the interesting region. The red shaded area in 18 (b) includes all efficiency graphs calculated from the rewrapping measurements and the green shaded area corresponds to efficiency lines calculated from the reassembly measurements. Therefore, the width of the shaded areas provides information about the systematic fluctuations of the efficiency due to the wrapping of the scintillator and the assembly of the module. The data points represent the combined efficiency for all measurements. For trigger thresholds between 50mV and 100mV the efficiency is compatible with 99.5%. For single thresholds the efficiency $\epsilon$ and its uncertainty can be extracted, for instance for $z = 65$ mV:

$$\epsilon(z = 65 \text{ mV}) = (99.49 \pm 0.04)\% .$$  \hspace{1cm} (3.2)

The width of the shaded areas can be used as a conservative estimate for the systematic uncertainties at the given point. For instance at $z = 65$ mV:

$$\Delta\epsilon(\text{wrapping}) = 0.24\%$$  \hspace{1cm} (3.3)

and

$$\Delta\epsilon(\text{assembly}) = 0.16\% .$$  \hspace{1cm} (3.4)

Single SiPM readout. The presented studies show that good detection quality (> 99.9% purity and 99.5% efficiency) is achieved with trigger threshold between 40mV and 100mV with the
analogue sum signal. Further analysis revealed that the same conditions can be sustained with either of the single SiPM channels, when setting the threshold between 100 mV and 140 mV. The corresponding efficiency plots are shown in figure 19. The range of possible thresholds is shifted to higher values due to a higher amplification of the single channels compared to the sum channel. The width of the window is smaller because of a lower light yield in the single channel. This underlines the improvements that can be achieved with a dual SiPM readout and also shows, that for $10 \times 10 \text{cm}^2$ scintillators one SiPM is sufficient.

### 4 Conclusion

The developed frontend electronics work reliable with excellent technical characteristics. Furthermore, the recommended temperature compensation coefficient given by Hamamatsu could be validated for SiPMs of two different series. Even though Hamamatsu’s S12572 series shows cleaner signal spectra, the older S10362 series is still used in the prototypes because of lower noise rates. The prototype module shows a very good performance as a muon detector. The ideally matched components lead to a high light yield, which allows operation with 99.5% detection efficiency and over 99.9% signal purity in the analogue sum channel. The same studies were done with the single SiPM channels and the same detection conditions, meaning high efficiency and purity, can also be reached with single SiPM readout. Further studies with this prototype will investigate the timing resolution of the module, which is an important attribute for a trigger detector. In addition the homogeneity of the signal height as well as the homogeneity of the timing resolution will be determined. Also DuPont’s Tyvek® paper is being considered as an alternative for the PTFE tape as diffuse reflector. Larger prototypes with $300 \times 300 \times 5 \text{mm}^3$ scintillators have been tested in a 2.95 GeV proton beam of the COSY accelerator at Forschungszentrum Jülich, Germany.
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