Romanian Reports in Physics, Vol. 64, No. 3, P. 831–840, 2012

PRELIMINARY RESULTS OF PLASTIC SCINTILLATORS DETECTOR READOUT WITH SILICON PHOTOMULTIPLIERS FOR COSMIC RAYS STUDIES[*]

D. STANCA[1,2]

[1]National Institute for Nuclear Physics and Engineering, P.O.Box MG-6, RO-077125 Bucharest-Magurele, Romania, E-mail: denis.stanca@gmail.com
[2] University of Bucharest, Department of Physics, P.O.B. MG-11, Romania

Received July 27, 2011

Abstract. A significant advance in the field of photodetection has been registered in the past few years thanks to the development of a new class of silicon devices, the Silicon Photomultipliers (SiPMs). With a high gain (10^5-10^6), very good single photon detection resolution, fast counting, low-bias voltage (~70 V) and a low price, these devices could become an alternative to traditional PMTs in many applications.

Providing a large, proportional signal for low to moderate photon flux, SiPMs are ideal for low light intensity measurements, such as gamma ray astronomy or underground experiments.

In this study, we analyze the possibility of implementing this technology on a scintillator detector for cosmic ray showers muonic component measurements in an underground medium. Some preliminary results are presented and some conclusions are drawn.

Key words: silicon photomultiplier, SiPM, cross-section, scintillation detector, multi-pixel photon counter.

1. INTRODUCTION

The atmospheric muons are one of the three components of an extensive air shower (EAS), generated when a primary cosmic ray particle interacts with an atmospheric nuclei. Being the most penetrating component, it carries information about the mass and the energy of the primary particle.

The cosmic ray muon flux is an important observable that offers a lot of information in numerous fields, like: Standard Model testing, background measurements for low radiation background laboratories placed in underground, astrophysical investigations, studies of radiation induced damages in materials, even in Earth cartography.

---

[*] Paper presented at the Annual Scientific Session of Faculty of Physics, University of Bucharest, June 17, 2011, Bucharest-Magurele, Romania.

One common technique used in muon detection employs scintillators read by classical photomultipliers (PMTs), *e.g.* the WILLI detector from IFIN-HH [1]. Numerous studies were performed with such a device, like muon charge ratio measurements [2] or observation of the muon flux modulation by solar events [3].

We propose a new approach of the detection technique based on scintillators, by using silicon photodiodes instead of PMTs. Our aim is to build a detector for high energy muons measurements in underground medium, at the Slanic Prahova salt mine. A better muon identification and a good arrival direction reconstruction it is expected. In this context, simulation studies using CORSIKA and MUSIC were made [4]. A cut-off energy of about 150 GeV was observed. Characterisation studies of the underground site were also carried on [5, 6]. Some measurements of the high energy muon flux, both on the surface and in underground, at Slanic Prahova salt mine, have been performed using the mobile detector of IFIN-HH [7].

In this paper, a new technology detector, based on SiPMs, for measuring the muon flux is under investigation.

1.1. DETECTOR DESCRIPTION

The detector will be built at IFIN-HH Bucharest and will be installed in Unirea salt mine from Slanic Prahova, Romania. It will consist of four plates, 100×100 cm^2, of plastic scintillator crossed by optical fibers. Every plate being composed of 4 plastic scintillator sheets (Polystyrol 80%, Methylmetacrylate 20%) having $100\times25\times1$ cm^3. Every sheet is crossed by 13 longitudinal strips, 12 of them being filled with one optical fiber. The light signal will be read out by Silicon Photomultipliers (MPPC S10362-33-100C from HAMMAMATSU [8]). We use an optical fiber with output in the green region of the electromagnetic spectrum, for which the SiPM photon detection efficiency (PDE) is ~45%. For this device, the maximum PDE is in the blue region of the spectrum, around 450 nm [9].

The plates will be placed two by two with 1 m in between, as it can be seen in Fig. 1. With optical fibers on perpendicular directions. The resolution in position is 2×2 cm^2.

The photodiodes are semiconductor devices that, when illuminated, generate an electrical output.

A Silicon Photomultiplier (SiPM) is a matrix of hundreds of independent micro-cells, named pixels, connected in parallel. Each pixel is represented by a serial link between a photodiode and a quenching resistor. Each photodiode is operated in Geiger mode, the output being independent from the input signal. The device being operated at a few volts above the breakdown voltage, if a photon interacts with the active volume and generate a photoelectron, the breakdown is produced. The number of electrons from the output signal of one cell is independent of the position of the cell in the lattice, that indicating a very good photoelectron resolution of the device [10–11].

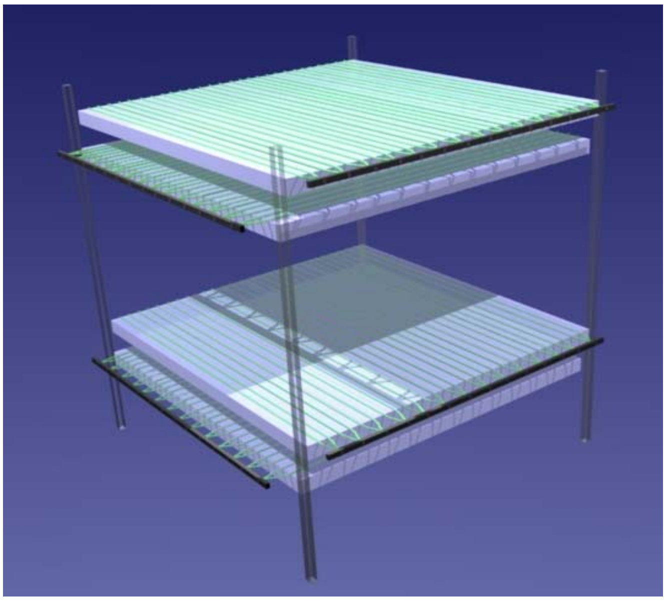

Fig. 1 – Detector concept.

1.2. SiPM PHOTODIODES

Other advantages of SiPM are the high gain (10^5–10^6), the low operating voltage (~70 V) and the low acquisition price.

Among drawbacks are the high thermal noise rate, and the presence and amount of crosstalk and afterpulsing effects in the output signal [12–13].

The MPPC S10362-33-100C model is a compact opto-semiconductor, with a very good single photon resolution, protected by a ceramic coating.

It has an effective active area of 3×3 mm, with a fill factor of 78.5% and a total of 900 pixels, with the pixel size of 100×100 μm^2. From the input light sensitivity point of view, the wavelength domain is from 320 nm to 900 nm, with a greater efficiency around 440 nm [8].

In [9], the MPPC S10362-11-100C model, similar with MPPC S10362-33-100C model, also from Hamamatsu, but with an effective active area of 1×1 mm, is analyzed. Properties like Photon Detection Efficiency (PDE), gain and cross-talk were measured. Variation of PDE and gain with overvoltage and variation of crosstalk with gain are drawn. An increase of PDE with overvoltage and a linear growth of the gain are observed.

From those two tendencies it is clear that, with the increase of the overvoltage, the gain and PDE are improved. But the probability of crosstalk also increases with the gain. So an optimum bias voltage for high gain, good PDE and small cross-talk probability must be found.

We also studied the behavior of the device with some parameter variation, like temperature, bias voltage, light intensity input. The tests were made at Max Plank Institute for Physics, Munchen. The experimental setup was composed of an MPPC S10362-33-100C Hamamatsu device, implemented in the electronic configuration shown in Fig. 2, a signal 50× amplifier and a pulsed laser diode PDL 800-B from PicoQuant, all being contained in a box with the role of an optical screen. The bias voltage was provided by a stable voltage source. The laser was triggered by a signal generator (Synthesized Function Generator – model DS345 – Stanford Research Systems), and the output was read by an oscilloscope (LC684DXL 1.5GHz Oscilloscope).

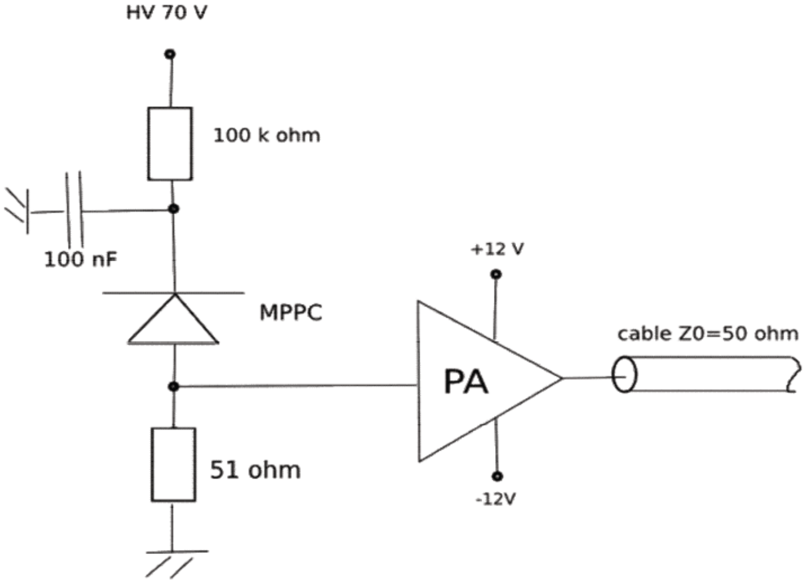

Fig. 2 – The integrated circuit that supplies the photodiode and collects the output signal**.**

We observed that when we increase the bias voltage, the gain is increased and also the cross-talk and after-pulse probabilities. Another important observation was that SiPM characteristics (PDE, gain, cross-talk) are very sensitive with the medium temperature. That is an advantage for placing the detector underground. For instance, in the Unirea salt mine from Slanic, the temperature is 12–13°C, regardless of the time of the year or diurnal variations. This constant temperature will provide stability to the SiPM’s properties.

Also we see in Fig. 3 the amount of the thermal noise, represented by the 0 photoelectron (0phe) peak, and the peaks corresponding to 1, 2, 3, ..7 phe. We observe a very good single photon resolution.

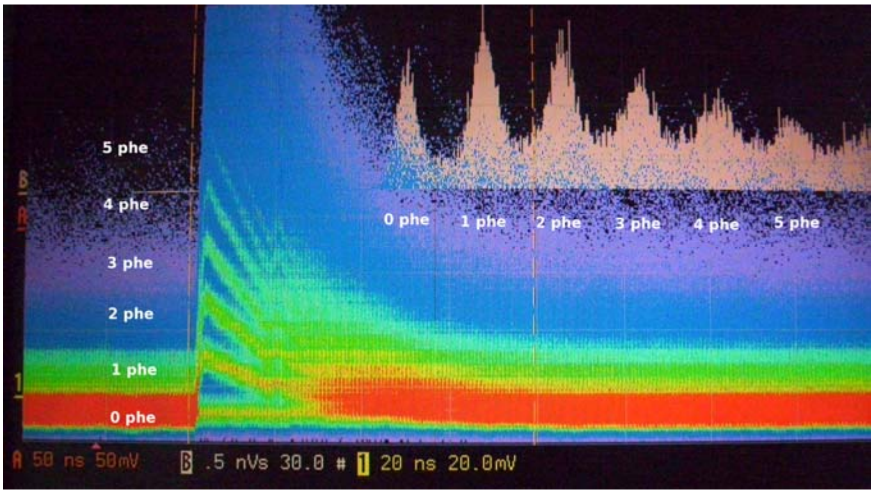

Fig. 3 – Oscilloscope view of laser triggered MPPC S10362-33-100C Hamamatsu device**.**

2. TESTS ON THE CONSTITUTIVE UNIT OF THE DETECTOR

Tests on the constitutive unit of the detector have been performed at IFIN-HH Bucharest. The purpose of these tests is to find the best way to collect the scintillation light obtained from passing muons (from cosmic rays Extended Air Showers), using a system composed by one plastic scintillator sheet with longitudinal ditches, with two optical fibers insertions, the signal being collected by one MPPC S10362-33-100C device. The constitutive unit of the detector is presented in Fig. 4.

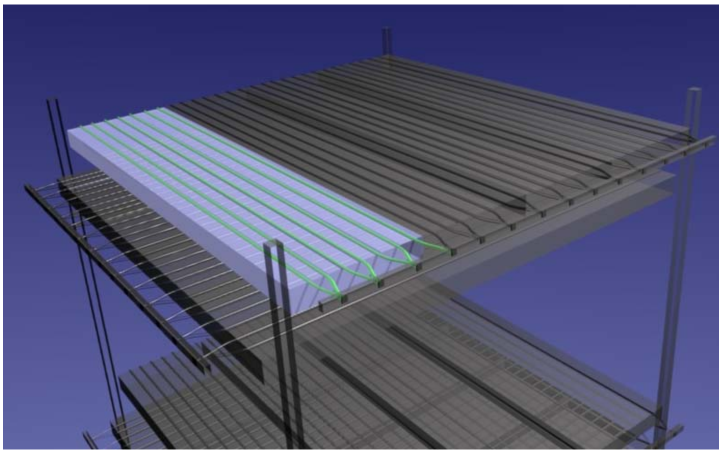

Fig. 4 – The constitutive unit of the detector.

On its surface, there are 13 parallel and equidistant ditches. In two adjacent strips (both near one of the scintillator borders), we put an 1.5 mm diameter optical fiber, both passing, at one end, through a slit and connected to the SiPM device. The slit has a 3 mm elipsoidal section, especially made for placing within it those two 1.5 mm optical fibers. The entire configuration is optically sealed in a box. All this system represents the **T**esting **D**evice (DT).

The block scheme of the measuring device is represented in Fig. 5.

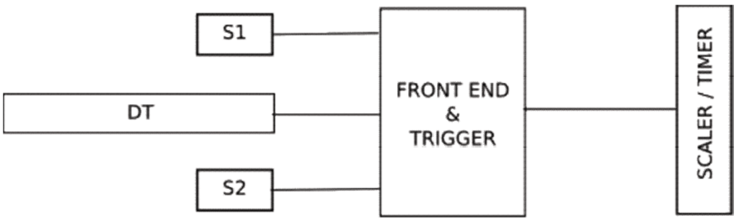

Fig. 5 – The block scheme of the measuring device.

In order to measure the counting rate of muons, the Testing Device (DT) is placed between two plastic scintillator probes, 10 × 10 × 5 cm^3, each connected with a photomultiplier, probes that mark the boundaries of measuring area and contribute to the signal formation.

The coincidence between those three devices (S1, S2 and DT) is made. Those three signals are passed through a FRONT END & TRIGGER module, the resulting pulses being measured by a SCALER-TIMER module.

The MPPC device was integrated into a circuit, like the one represented in Fig. 2. Also, in Fig. 6, a measuring channel from the FRONT END & TRIGGER module is presented.

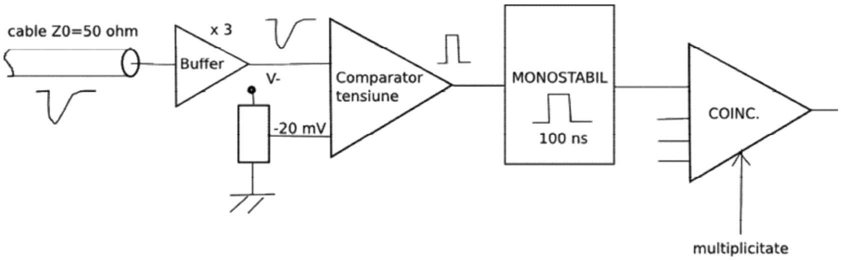

Fig. 6 – A channel from the FRONT END & TRIGGER module.

The buffer has the input impedance 50 Ω and adapts the circuit at the characteristic cable impedance, achieving also a signal amplification (3 times). After that, the pulses are passed through a variable threshold voltage comparator. That it is used to separate the signals from noise. It also transforms the signal from analogical type into a logical one, with a variable length, given by the time that the input signal remained over the threshold. After that, those pulses are passed through a monostable. The output signals are constant in length and amplitude ~100 ns. Then, through the coincidence circuit, that permits the selection of the multiplicity order (the number of coincidence channels can be selected).

Different measurements are made, using those two test probes (S1 and S2) and the Testing Device in different configurations. In the following, the results obtained from those tests are presented. The supplying voltages and the threshold voltage are set at the values presented in Table 1.

Table 1

The bias and threshold voltages for probe 1, probe 2 and Testing Device

Device	**HV(bias voltage)**	**$U_{threshold}$(threshold voltage)**
S1 (probe 1)	-1760 **V**	-20 **mV**
S2 (probe 2)	-1710 **V**	-20 **mV**
DT (**Testing Device**)	70.20 **V**	-20 **mV**

Table 2

The counting rates of probe 1, probe 2 and Testing Device

Device	**Configuration**	**Counting rate**	**Observations**
S1	-	12.27 pulses/s	The counting rate of probe 1
S2	-	17.03 pulses/s	The counting rate of probe 2
DT	No optical fiber connected	78000 pulses/s	Considered as noise
	Only one optical fiber connected	131 000 pulses/s	The counting rate is increasing with the numbers of optical fibers

Table 3

Coincidence measurements of The counting rates of **S1** & **S2** & **DT** in different configurations

Device	**Configuration**	**Counting rate**	**Observations**
S1 & S2 & DT in coincidence (S1 and S2 superposed with DT, along optical fibers)	No optical fiber connected	0 pulses/100s	Normal outcome, taking into account that the signals from DT are the MPPC thermal noise
	At the preamplifier	38 pulses/1000s	Normal decrease due to attenuation in the plate, attenuation given by the scintillation plate or the optical fiber
	50 cm from the preamplifier	33 pulses/1000s	
	1m from preamplifier	30 pulses/1000s	

There are two possibilities for increasing the detection efficiency of MPPC: decreasing the threshold voltage or increasing the MPPC's bias voltage. The second alternative was chosen for the next measurement.

Table 4

The bias and threshold voltages for probe 1, probe 2 and Testing Device; with the difference regarding the precedent configuration being in the variation of bias voltage for the Testing Device

Device	**HV(bias voltage)**	**$U_{threshold}$(threshold voltage)**
S1 (probe 1)	-1760 **V**	-20 **mV**
S2 (probe 2)	-1710 **V**	-20 **mV**
DT (**Testing Device**)	Varies between 70.10**V** and 70.45**V**	-20 **mV**

This test measured the pulse rate of the testing device and the coincidence rate of **S1** & **S2** & **DT**, when the supplying voltage of MPPC is varied. The results are presented in the next table.

Table 5

The counting rate of DT and coincidence rate of S1 & **S2** & **DT** when varying the bias voltage of the MPPC device

Bias voltage of MPPC	Rate of **DT**	Coincidence rate between **S1 & S2 & DT**
70.10 **V**	18 400 pulses/s	12 pulses/1000s
70.15 **V**	42 500 pulses/s	20 pulses/1000s
70.20 **V**	96 000 pulses/s	33 pulses/1000s
70.25 **V**	180 000 pulses/s	39 pulses/1000s
70.30 **V**	330 000 pulses/s	49 pulses/1000s
70.35 **V**	530 000 pulses/s	59 pulses/1000s
70.40 **V**	640 000 pulses/s	88 pulses/1000s
70.45 **V**	930 000 pulses/s	107 pulses/1000s

From Table 5 we see that the coincidence rate is increasing with the increasing of the MPPC's supplying voltage. An important detail is that, before the test was performed, the coincidence rate between superposed S1 and S2 was measured, resulting a $N = 167$ pulses/1000s rate. This means that for a 100% DT efficacity, the coincidence rate between **S1** & **S2** & **DT** needs to be 167 pulses/1000s.

It was observed on the oscilloscope (Fig. 3) that the pulses measured with the photodiode have about 200 ns duration. For limiting the pileup effect, the average period of random pulses given by the MPPC should be ten times bigger than a pulse duration, in our case 2μs, meaning a 5×10^5 pulses/s maximum allowed rate. So, in the last table, the bias voltage must be smaller than 70.35V for limiting that effect.

3. CONCLUSIONS

The paper presents tests performed with plastic scintillators readout through optical fibers by SiPM devices (MPPC S10362-33-100C), as a constitutive part of a future underground muon detector. Also, the MPPC S10362-33-100C devices from Hamamatsu have been tested separately and their properties have been investigated.

The SiPM device is capable to observe individual photons, being ideal for low intensity measurements, like secondary muon rates in the underground.

One other important aspect is that characteristics of the device (like PDE, gain or cross-talk probability) are very sensitive with temperature variations. We recommend the stabilization of temperature inside the detector system, or the temperature measurement in parallel with the output of the photodiode and the application of a correction factor.

Those characteristics (PDE, gain, cross-talk) also vary from one MPPC to another, requiring an individual analysis and calibration, to get a similar response. The optimum bias voltage varies from one device to another and must be set up so that the cross-talk and after-pulse effects to be minimal and the gain maximum.

From the 200 ns output pulse duration of MPPC S10362-33-100C Hamamatsu photodiodes, limiting the pile-up effect will mean a maximum accepted rate of 5×10^5 pulses/s (5 kHz). This imposes another limitation on the photodiodes bias voltages.

In conclusion, this technique is proved to work, although more tests are required.

We work at the construction of a testing device using a similar experimental setup, but with PMTs instead of SiPMs. The comparison of the results obtained with the two techniques will lead to new conclusions.

Simulations of the muon flux at the ground level, using CORSIKA [14], are in progress, the results being subsequently passed through detector geometry using GEANT4 [15].

Acknowledgements. This work was supported by the Romanian Authority for Scientific Research, UEFISCDI, PNII-PARTENERIAT nr. 82104/2008 and grant POSDRU/88/1.5/S/56668. The author thanks to the Astroparticle Physics group from IFIN-HH, I. Brancus, B. Mitrica, M. Petcu, A. Saftoiu and G. Toma for the help and the guidance of this activity. The author is thankful to Prof. A. Jipa and Prof. I. Lazanu for fruitful discussions. The author is grateful for the help of Prof. M.Teshima and Prof. R. Mirzoyan and for the kind hospitality in performing the tests with SiPM at Max-Planck-Institut für Physik.

REFERENCES

1. B. Mitrica *et al.*, Rom. Rep. Phys., **56**, 733–740 (2004).
2. B. Vulpescu *et al.*, Nucl. Instr. and Meth. A, **414**, 205 (1998).
3. A. Saftoiu *et al.*, Rom. J. Phys., **56**, 664 (2011).
4. B. Mitrica *et al.*, Rom. Rep. Phys., **62**, 750–757 (2010).

5. R. M. Margineanu *et al.*, Applied Radiation and Isotopes, **66**, 1501–1506 (2008).
6. R. M. Margineanu *et al.*, Applied Radiation and Isotopes, **67**, 759–761 (2009).
7. B. Mitrica *et al.*, Nucl. Instr. and Meth. A, **654**, 176–183 (2011).
8. *** http://sales.hamamatsu.com/en/products/solid-state-division/si-photodiode-series/mppc/part-s10362-33-100c.php
9. Eckert *et al.*, Nucl. Instr. and Meth. A, **620**, 217–226 (2010).
10. D. J. Herbert *et al.*, IEEE Transactions on Nuclear Science, **53**, 389–394 (2006).
11. P. Eraerds *et al.*, Optics Express, **15**, 14539–14549 (2007).
12. D.J. Herbert *et al.*, Nucl. Instr. and Meth. A, **567**, 356–359 (2006).
13. P. Buzhan *et al.*, Nucl. Instr. and Meth. A, **610**, 131–134 (2009).
14. D. Heck *et al.*, *CORSIKA: A Monte Carlo Code to Simulate Extensive Air Showers*, Karlsruhe Report FZKA 6019, Forschungszentrum Karlsruhe, Germany, 1998.
15. GEANT4 Collaboration, Nucl. Instr. and Meth. A, **506**, 250 (2003).