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Characterization of the Hamamatsu MPPC S11834 as photon sensor for RICH

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ABSTRACT

Recent development of SiPMs makes them a promising candidate for replacement of photomultiplier tubes in Ring Imaging Cherenkov (RICH) counters. A commercially available 8×8 SiPM array, Hamamatsu MPPC S11834 with a rather low dark count rate, was tested as a single photon sensor in a RICH counter. To increase its overall geometrical acceptance, light concentrators were employed. The various factors that influence their efficiency are estimated and the results of measurements with polarized light are presented, showing a good agreement with a Monte Carlo study.

1. Introduction

Silicon photomultipliers (SiPM) are solid state detectors with many appealing characteristics [1,2]. They work in the Geiger avalanche regime at a low operating voltage and have a high gain ($\approx 10^6$), high photon detection efficiency (PDE) and good timing properties. Their operation has been successfully tested in high magnetic fields [3].

A device with such properties is a promising candidate for use in Ring Imaging Cherenkov (RICH) counters that are usually mounted inside a spectrometer with a strong magnetic field. In our previous studies we tested a module of single channel SiPMs as position sensitive single photon detectors of Cherenkov light [4–6]. In spite of the principal disadvantage of SiPMs, the high dark count rate on the order of 10^6 Hz/mm^2, we showed that the 1 mm^2 devices can be successfully used in a RICH.

Recently, Hamamatsu Photonics developed a 64-channel SiPM array, Multi-Pixel Photon Counter (MPPC) S11834-3388DF, that consists of 9 mm^2 SiPMs with a considerably smaller dark count rate ($\approx 10^5$ Hz/mm^2), compared to the previous devices. The SiPMs are spaced at 5 mm pitch in the 8×8 array, while the cells inside a single SiPM are spaced at 50 μm. As already reported, we demonstrated in a test beam that such a device can be an excellent photon detector in a RICH counter [7]. Our prototype RICH consisted of two layers of aerogel radiator (20+20 mm thick) in the focusing scheme, 160 mm of ring expansion volume and the MPPC array as a photon detector. In order to increase the geometrical acceptance of the array, we employed light concentrators in the form of truncated pyramids (Fig. 1).

One of the open questions of the beam test was the collection efficiency of the light concentrators. The geometrical acceptance of the SiPM array equals to the ratio of the active area and the pad area $(3/5)^2 = 0.36$. If all the light rays coming to a pad were collected with the light concentrators and guided to the SiPM active area, the collection ratio would be $(5/3)^2 = 2.78$. However, in the beam test we have found that the collection ratio was only 1.90. In this contribution we therefore estimate the influence of various factors on the efficiency of light collection, present measurements with linearly polarized light and address the problem of the optical coupling between the light concentrators and the MPPC.

2. Experimental set-up and methods

We constructed a prototype photon detector module (Fig. 2) that consists of the Hamamatsu MPPC in an aluminium frame, with the light concentrators in front and front-end electronic boards at the back. The light concentrators were produced by cutting and polishing 64 truncated pyramids made of glass [8], which were then glued to a common plate of the same material (Fig. 1). To determine the pyramid length, we used a simple ray tracing Monte Carlo (MC) simulation, with the rays at angle $\theta \in [0^\circ, 30^\circ]$ relative to the entry surface normal and uniformly distributed over the solid angle. In this way, we studied the efficiency of light collection as a function of the pyramid length

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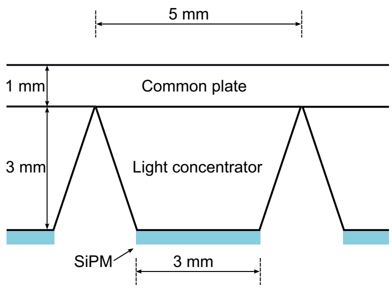

Fig. 1. Light concentrators and SiPMs.

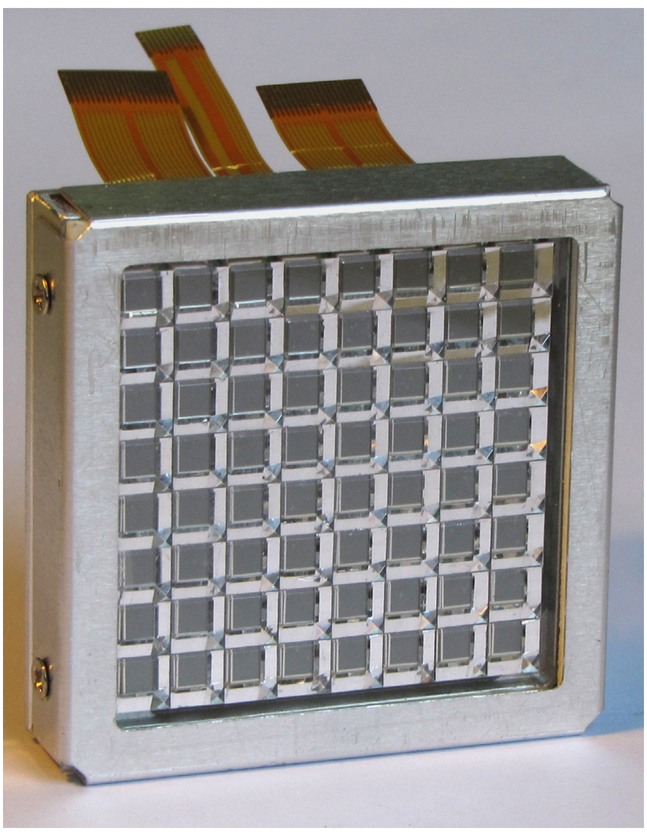

Fig. 2. Prototype photon detector. MPPC and light concentrator assembled together in aluminium frame.

and for production we chose the length (3 mm) at which the efficiency reached 90%. An optical grease was used to improve the optical coupling between the SiPMs and the concentrators.

The response of the module to the low intensity light was measured in a laboratory set-up. For that purpose, the module was positioned inside a light-tight dark box and illuminated with a light source: a diode laser[1] emitting short pulses (≈ 70 ps FWHM) of $\lambda = 404$ nm light. The light intensity was decreased to a single photon detection level by neutral density filters and focused to the detector surface with a lens. In addition, a polarizer was used to study the influence of polarized light on the collection ratio of the concentrators. The lens (and the polarizer) was attached to the motorized stages.[2]

The signals from SiPMs were fed to the front-end electronic boards for amplification and digitization. We used the read-out electronics based on the ASD-8 (Amplifier-Shaper-Discriminator)

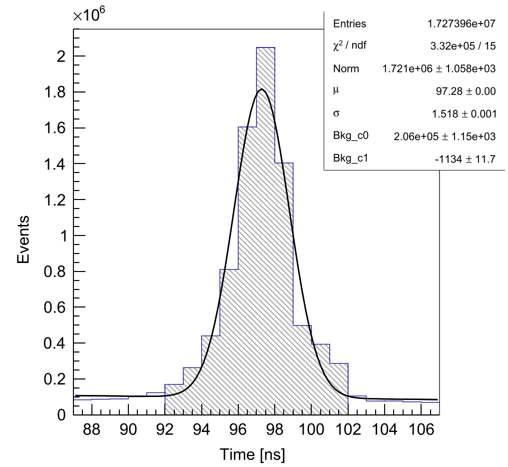

Fig. 3. Time of arrival distribution of hits in a typical channel. The accepted hits (10 ns window, hatched) lie approximately in $\pm 3\sigma$ interval.

ASIC [9], with a low operational threshold (1 fC) and high amplification (2.5 mV/fC). The digital signal was fed through a level translator to a TDC,[3] operating in the common stop mode. The TDC was read-out by a personal computer software developed in LabWindows/CVI. The laser trigger served as the common stop signal which was vetoed by the acquisition signal from the PC.

We used only signal arrival time information in order to discriminate between signal and background noise. With the detection window of 10 ns the probability to detect dark counts was much lower than the probability to detect photons coming from the laser pulse (Fig. 3). Time resolution of a typical channel was approximately 1.5 ns, which is sufficient for a RICH detector.

3. Results and discussion

The average number of detected photons in the laser pulse was registered for different laser spot positions. The laser beam was focused to a $\sigma \approx 60$ μm spot on the detector surface, slightly larger than the cell pitch of 50 μm, and the step size was 50 μm. The collection ratio of light concentrators was determined from the ratio of the average number of detected photons with the concentrators and the number of photons without the concentrators on the photon detector (Fig. 4). The observed collection ratio in the laboratory set-up was 1.60 without the grease and 2.13 with it, significantly away from 2.78 (the ideal value for the perpendicular incidence).

To understand the low efficiency bands in the detector response (Fig. 4, right), we used the MC simulation. The initial MC study included reflections at the contact of the following surfaces: air–common plate (Fig. 1), concentrator exit window–grease and grease–epoxy (a 300 μm protective layer above the active SiPM surface, Fig. 5). However, the initial MC study did not take into account two effects. The first one is the imperfect coupling between the light concentrators and the SiPMs. In fact, the PCB, on which the SiPM array was assembled, was slightly deformed. Due to this deformation, there was an additional gap between the concentrators and the SiPMs, in the central part of the module. As a consequence, the surface of some of the channels was only partially coupled to concentrators, if the amount of applied grease was insufficient (Fig. 5). This was the case in the beam test set-up (Fig. 6). In the case the grease was applied in excess, as in the case of the laboratory set-up, the light would escape at the lateral sides

[1] Advanced Laser Diode System EIG1000D with PiL040 head.

[2] National Aperture motorized stages MM-3M-F, positioning precision 0.5 μm.

[3] Multihit 64-channel CAEN V673A TDC with 1.04 ns LSB.

of the pyramid, producing the effect of low efficiency bands. The estimate of the loss fraction due to an excess of grease, based on the width of low efficiency zones, is 4%. The second effect that contributed to the low efficiency bands was the misalignment of the SiPMs and the concentrators. This effect alone can be observed in Fig. 7 (left, no grease applied), and it resulted in a further 7% loss. On the right of both Figs. 4 and 7 the combined effect of misalignment and excess of grease can be seen. The summary of the loss factors with light perpendicular to the entry surface is given in the Table 1 (three leftmost columns). Taken all previously discussed estimates into account, the expected ratio dropped to 2.47 in the laboratory set-up.

A similar analysis can be carried out for the beam test geometry. The losses are estimated by simulating rays at fixed polar angle $\theta = 18.5^{\circ}$ and at azimuthal angle in range $\varphi \in [-19.4^{\circ}, 19.4^{\circ}]$ relative to the entry surface normal, thus imitating the Cherenkov light in our prototype RICH. Because of the finite thickness of the grease and the epoxy protective layer, some rays can miss the SiPM active surface. Therefore, the initial loss of 3% for the oblique incidence (Table 1, three rightmost columns) is higher than the corresponding loss for perpendicular incidence.

To understand the losses due to imperfect optical coupling in case of the beam test data, we studied the response of the module, assembled without the optical grease, to polarized light. In that case, there is an air gap between the light concentrator and the SiPM, and the light collection efficiency shows a pronounced dependence on the polarization state of light. In the response of the module (Fig. 7, left) one can observe several distinctive zones. The central $3 \times 3\ \mathrm{mm}^2$ zone corresponds to the light rays that pass through the concentrator without reflections. The two zones of lower efficiency (A) and the two zones with the approximately equal efficiency as the central zone (B) include rays that reflect once at the lateral sides before hitting the exit window. The zones C comprise rays that reflect from two adjacent lateral sides and show no detected photons at all.

The difference in efficiency can be understood using the Fresnel formulae. A ray incident above the zone A will totally reflect from the lateral side ($\alpha = 71.6^{\circ}$, Fig. 5) and will hit the exit window at an incidence angle of $\beta = 36.8^{\circ}$. Suppose the ray is s-polarized at the exit window. At this β, which is smaller than the critical angle $\beta_c = 41^{\circ}$, about 26% rays will internally reflect. The same ray is p-polarized if incident above zone B, in which case the internal reflection is negligible. The ray incident above zone C will reflect twice and the incident angle will be $\beta = 51^{\circ}$. Since this is larger than β_c, all such rays will be totally reflected, independent of their polarization state.

As already pointed out, certain SiPMs in our prototype module were only partially coupled with grease due to the PCB deformation (Fig. 6). Since Cherenkov light is polarized, the polarization of light therefore contributed to losses observed in the prototype RICH. Using the MC simulation, we estimated this loss to be 5% with the systematic uncertainty of 2%. Taken into account the misalignment loss of $4 \pm 2\%$, the resulting cumulative loss was $12 \pm 3\%$ (systematic uncertainties added in quadrature) and expected collection ratio dropped to 2.45.

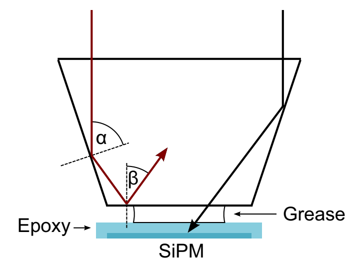

Fig. 5. Light concentrator and SiPM partially coupled with optical grease. The grease thickness is exaggerated.

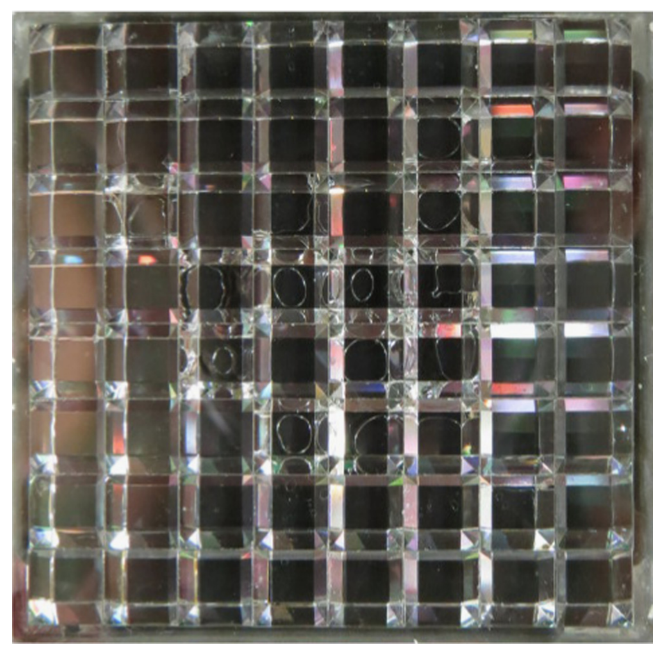

Fig. 6. Photon detector module in the test beam set-up. Certain SiPMs in the central part are only partially coupled to concentrators.

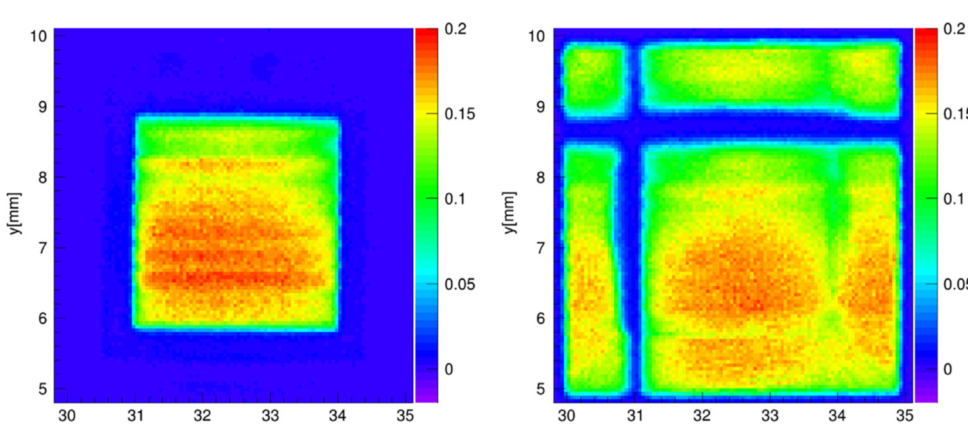

Fig. 4. Average number of detected photons for a typical SiPM without (left) and with the light concentrator (right).

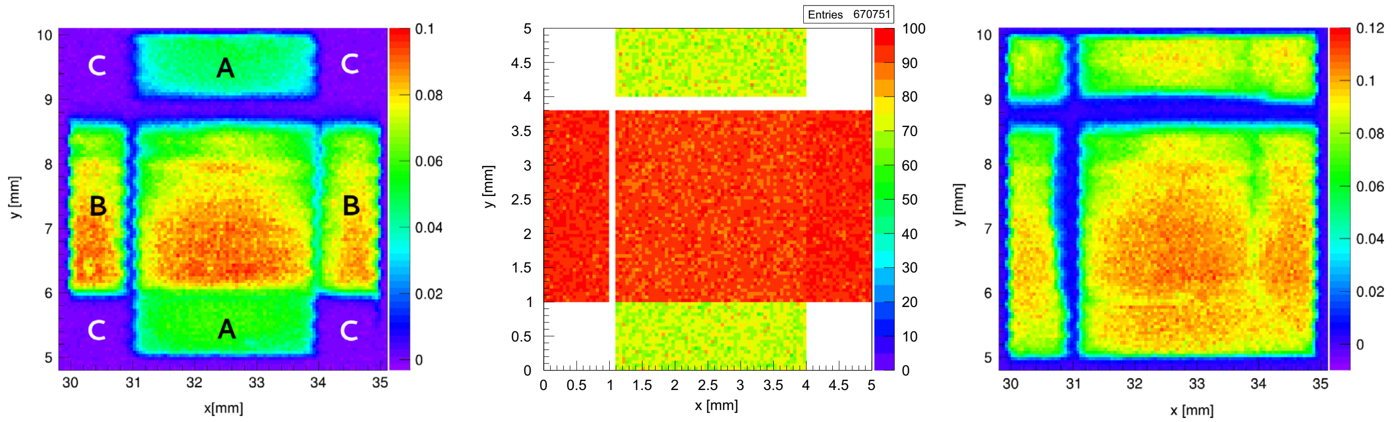

Fig. 7. Average number of detected photons in response to linearly polarized light without the optical grease (left), MC study with the same parameters (middle); and the polarization effect vanishes in response to the optical grease (right).

Table 1
Net, cumulative losses and collection ratio in the case of rays simulated at 0° and 18.5° to the surface normal.

Sources of loss	Incidence 0°			Incidence 18.5°		
	Net (%)	Cumulative (%)	Ratio (%)	Net (%)	Cumulative (%)	Ratio (%)
Ideal coupling	0	0	2.78	3	3	2.70
Grease coupling	4	4	2.67	(5 ± 2)	(8 ± 2)	2.56
Misalignment	7	11	2.47	(4 ± 2)	(12 ± 3)	2.45
Measured		26	2.13		34	1.90

Between the collection ratio as measured in the beam test (1.90) and the MC value (2.45), there still remains a difference which we attribute to an imperfect polishing of the pyramid lateral sides, air bubbles in the glue between the pyramids and the common plate, PDE variation among the cells inside a single SiPM (as observed in Figs. 4 and 7) and double photon hits on one SiPM channel.

4. Summary

The Hamamatsu MPPC S11834 array proved to be an excellent sensor of Cherenkov photons. With the light concentrators, the geometrical acceptance of the array improved, and, as a consequence, the number of detected photons increased almost by a factor of two (1.90). However, this is lower than the ideal value of 2.78, as discussed in the text. This departure is explained to be caused by mechanical imperfections of the MPPC array, due to which the ratio dropped to 2.45. The still remaining difference between the measured (1.90) and the expected (2.45) ratio is attributed to deficiencies in the light concentrators fabrication (polishing and air bubbles), multiple photon hits on single MPPC channel and cell-to-cell PDE variation inside a single channel.

References

[1] P. Buzhan, et al., ICFA Instrumentation Bulletin 21 (2001) 28.
[2] D. Renker, E. Lorenz, Journal of Instrumentation 4 (2009) P04004.
[3] B.J. Pichler, et al., Journal of Nuclear Medicine 47 (2006) 639.
[4] S. Korpar, et al., Nuclear Instruments and Methods in Physics Research Section A 594 (2008) 13.
[5] R. Dolenec, et al., Nuclear Instruments and Methods in Physics Research Section A 628 (2011) 398.
[6] R. Pestotnik, et al., Nuclear Instruments and Methods in Physics Research Section A 639 (2011) 99.
[7] S. Korpar, et al., Nuclear Instruments and Methods in Physics Research Section A 766 (2014) 107.
[8] Sinoceramics Inc., China Glass K9, ref. ind. 1.53, other spec. similar to Schott BK7 or Hoya BSC7, 2012.
[9] F.M. Newcomer, et al., IEEE Transactions on Nuclear Science NS-40 (4) (1993) 630.