Measurements of Cherenkov Photons with Silicon Photomultipliers

S. Korpar\textsuperscript{ab}, I. Adachi\textsuperscript{c}, H. Chagani\textsuperscript{b*}, R. Dolenec\textsuperscript{b}, K. Hara\textsuperscript{d}, T. Iijima\textsuperscript{d}, P. Krizan\textsuperscript{be}, S. Nishida\textsuperscript{c}, R. Pestotnik\textsuperscript{b} and A. Stanovnik\textsuperscript{bf}

\textsuperscript{a}Department of Chemistry and Chemical Engineering, University of Maribor, Maribor, Slovenia
\textsuperscript{b}Jožef Stefan Institute, Ljubljana, Slovenia
\textsuperscript{c}KEK, Tsukuba, Japan
\textsuperscript{d}Nagoya University, Nagoya, Japan
\textsuperscript{e}Department of Mathematics and Physics, University of Ljubljana, Ljubljana, Slovenia
\textsuperscript{f}Department of Electrical Engineering, University of Ljubljana, Ljubljana, Slovenia

A novel photon detector, the Silicon Photomultiplier (SiPM), has been tested in proximity focusing Ring Imaging Cherenkov (RICH) counters that were exposed to cosmic-ray particles in Ljubljana, and a 2 GeV electron beam at the KEK research facility. This type of RICH detector is a candidate for the particle identification detector upgrade of the BELLE detector at the KEK B-factory, for which the use of SiPMs, microchannel plate photomultiplier tubes or hybrid avalanche photodetectors, rather than traditional Photomultiplier Tubes (PMTs), is essential due to the presence of high magnetic fields. In both experiments, SiPMs are found to compare favourably with PMTs, with higher photon detection rates per unit area. Through the use of hemispherical and truncated pyramid light guides to concentrate photons onto the active surface area, the light yield increases significantly. An estimate of the contribution to dark noise from false coincidences between SiPMs in an array is also presented.

1. INTRODUCTION

Silicon Photomultipliers (SiPMs) are semiconductor photosensitive devices consisting of an avalanche photodiode matrix on a common silicon substrate, working in limited Geiger mode\textsuperscript{[1]}. When compared with other position sensitive detectors used in Ring Imaging Cherenkov (RICH) counters, they possess the favourable property of insensitivity to high magnetic fields. They operate at lower voltages than conventional photomultiplier tubes, have a high peak photon detection efficiency that can be as high as 65% at 400 nm, high gain of $10^6$ and good time response. Due to their small dimensions, they allow compact, light and robust mechanical designs. These factors make them a very promising candidate for a Cherenkov photon detector in a RICH counter. However, due to the serious disadvantage of a very high dark rate ($\sim 10^6$ Hz/mm$^2$), they have not been considered until now in such detectors where single photon detection is a major requirement.

One of the main goals of the present study is to verify the performance of SiPMs as single photon detectors in a proximity focusing RICH counter\textsuperscript{[2]} proposed for the particle identification detector upgrade of the BELLE detector at the KEK B-factory\textsuperscript{[3]}. An array of silicon photomultipliers has been tested with Cherenkov photons from cosmic muons. Different light guides have been machined and evaluated in an effort to improve the efficiency of such a detector. Additionally, an $8 \times 8$ array of the new Surface Mounted Device (SMD) SiPMs coupled to individual light guides has been exposed to a 2 GeV electron beam at the KEK research facility. Finally, tests have been performed to estimate the contribution to dark noise from false coincidence between SiPM
2. COSMIC-RAY TESTS

The detection of Cherenkov light emitted by cosmic-ray particles traversing a 2.5 cm thick aerogel radiator of refractive index 1.045 is described in further detail in [4]. The procedure and results are outlined briefly here.

An array of 12 Hamamatsu R5900-M16 Multianode Photomultiplier Tubes (MAPMTs) and six Hamamatsu S10362-11-100U SiPMs of active surface area 1 mm$^2$ and pitch 100 µm [5] are mounted below the aerogel radiator, and this entire set-up is contained within a light tight box. The larger pixel size is preferred as the resultant increase in photon detection efficiency outweighs the increased noise rate. The M16 MAPMTs have been used by our group [6], so their characteristics are well known and they serve as a reference against which the parameters of the SiPMs are investigated. An incident cosmic-ray particle passes through a scintillation counter mounted above the box, providing a trigger signal. The path taken by the particle is mapped by a series of three Multiwire Proportional Chambers (MWPCs) located between the scintillator counter and the light tight box. The arrival time and photon detector channel are recorded for each event.

A clear peak in the Cherenkov angle distribution of SiPM hits within a 3 ns time window is observed. A factor of $5.4 \pm 0.2$ more photons are detected per unit area by the SiPMs compared to the MAPMTs, in good agreement with the expectation of 5.1 from the manufacturer [5].

3. IMPROVING THE PHOTON YIELD WITH LIGHT GUIDES

The signal-to-noise ratio can be improved by increasing the number of hits per single sensor. This can be achieved through the use of SiPMs with larger active surface areas. However, this results in a marked increase in noise, and hence diminishing returns.

Alternatively, the same result can be achieved by collecting light over a larger area, and focusing it onto the smaller SiPM active surface with light guides. The tops of blue light emitting diodes were attached to the six SiPMs in the cosmic-ray set-up described above, and the procedure repeated, in an attempt to ascertain the effects of hemispherical light guides. The resultant Cherenkov angle distribution is shown in Fig. 1. A clear improvement in the light yield by a factor of $3.6 \pm 0.2$ is witnessed, which is in good agreement with the simulated value of 3.3. Further information on the procedure and results is given in [4,7].

Hemispherical light guides are suitable when the angle of incidence is limited and the air gap between the SiPM active surface and the light collector is large, as is the case in cosmic-ray set-up above. However, it is difficult to machine a hemispherical light guide array for the 2 GeV electron beam tests at KEK, and is unnecessary if using a SiPM with a reduced epoxy protective layer, such as the Hamamatsu S10362-11-100P Surface Mounted Device (SMD) with 1 mm$^2$ active surface area and 100 pixels [5]. Therefore, a more suitable light collector, such as that in the shape of a truncated pyramid, should be used when building a multi-channel module for this purpose.

The geometry of the module, where each SiPM lies next to another, constrains the maximum size of each light guide’s entry surface to a square of

![Figure 1. The distribution of SiPM hits from cosmic-ray tests, that are inside of the Cherenkov time window, as a function of the Cherenkov angle when hemispherical light guides are attached.](image)
An outline of the experimental apparatus for the measurement of Cherenkov photons is shown in Fig. 2. Following the detection of an incident electron by the plastic scintillator counter, its track coordinates are obtained through delay line readout of the cathode plane signals from the MWPCs located either side of a light tight box. The electron interacts with a 2 cm thick aerogel radiator of refractive index 1.045 contained within the box. Cherenkov light is detected by the $8 \times 8$ array of Hamamatsu S10362-11-100P SMD SiPMs (Fig. 3) that lie 20 cm from the radiator. Every $2 \times 2$ block of SiPMs are added together to form a single channel, resulting in a total of 16 SiPM channels. A Hamamatsu Microchannel Plate Photomultiplier Tube (MCP-PMT), located the same distance away from the aerogel radiator, acts as a reference for comparison with the parameters of the SiPMs.

Tests have been performed without and with light guides attached to the SiPM array. The signal-to-noise ratio improves by a factor of $\sim 2.7$ when light concentrators are used. The distribution of hits in Cherenkov space is shown in Fig. 4. Due to the small size of the detector, the whole Cherenkov ring is not shown. It is clear that there is a significant improvement in the ratio of photons detected per unit area by the SiPMs to that by the MCP-PMT through the use of light guides. Further analysis reveals that this ratio is $\sim 1.1$ without light guides, and increases to $\sim 2.5$ when the light guide array is attached.
5. FALSE COINCIDENCE RATE

In a proximity focusing RICH detector, the light emitted from Geiger discharge in one SiPM, reflected off the radiator and detected by another is a source of crosstalk between channels.

The experimental set-up to measure the optical crosstalk, or false coincident rate, between two SiPMs is shown in Fig. 5. A Hamamatsu S10362-11-100C SiPM (SiPM A), of 1 mm² active surface area, 100 pixels and 232 kHz dark rate at an operating voltage of 70 V, is placed on a move-able stage. SiPM A faces a Hamamatsu S10362-11-050C SiPM (SiPM B), of 1 mm² active surface area, 400 pixels and 372 kHz dark rate at an operating voltage of 71 V, a distance of 1 mm away. SiPM A moves perpendicular to SiPM B, and they overlap when \( x = 3 \) mm.

As shown in Fig. 5, the coincident dark noise rate at around 2.4 kHz, rises by approximately 1 kHz when the SiPMs overlap. For a planar geometry, under conservative assumptions of reflectivity, this corresponds to an increase of \( \sim 0.1\% \) in the dark count rate, which is negligible.

6. CONCLUSIONS

Single Cherenkov photons have been observed for the first time with SiPMs in a RICH counter triggered by cosmic-rays. In an effort to improve the signal-to-noise ratio, small light guides have been designed, manufactured and tested. An \( 8 \times 8 \) SMD SiPM array coupled to individual light guides, which were machined from UV transparent perspex used in HERA-B, has been tested in a 2 GeV electron beam at the KEK research facility. Tests of the false coincidence rate between SiPMs indicates that this provides a negligible contribution to the dark noise rate. Despite their relatively large dark noise, SiPMs are promising Cherenkov photon detectors.

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Figure 4. Hits in Cherenkov angle space without (top) and with (bottom) truncated pyramid light guides.

Figure 5. Experimental set-up to measure the optical crosstalk between a Hamamatsu S10362-11-100C SiPM (SiPM A) and a Hamamatsu S10362-11-050C SiPM (SiPM B).

Figure 6. False coincidence rate as a function of distance $x$. The two SiPMs overlap when $x = 3 \text{ mm}$.