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Measurement of Cherenkov photons with silicon photomultipliers

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ABSTRACT

In addition to their other advantages, silicon photomultipliers (SiPMs) are insensitive to magnetic fields, so they would be attractive as photon detectors for ring imaging Cherenkov counters inside large magnetic spectrometers. In view of the foreseen upgrade of the particle identification system of the Belle spectrometer, we have investigated the possibilities offered by these new photon detectors. Cherenkov photons emitted by cosmic ray particles in an aerogel radiator have been detected with SiPMs for the first time. Estimates and tests show that light concentrators may improve the detection efficiency, thus showing promise for an SiPM based RICH detector.

1. Introduction

Silicon photomultipliers (SiPMs) are novel semiconductor photosensitive devices consisting of an avalanche photodiode (APD) matrix on a common silicon substrate, working in the limited Geiger mode [1–3]. They are proving to be competitive to traditional detectors of photons. Among their advantages is the insensitivity to magnetic fields, low supply voltage, they are relatively robust, do not require much space and their single photon detection efficiency typically exceeds that of vacuum photomultiplier tubes. However, the relatively large dark noise rate represents a difficulty for measurements of weak light signals, especially of single photons as is required in Cherenkov ring imaging. If one measures only signals in a sufficiently narrow time window, one might reduce the dark counts while preserving the detected Cherenkov photons. The signal-to-noise ratio can be further improved by using light concentrators to increase the effective active area. It is therefore a challenge to attempt to use SiPMs for detection of Cherenkov rings.

The intended upgrade of the particle identification system of the Belle spectrometer will include a ring imaging Cherenkov counter (RICH), which is required to separate kaons from pions up to a momentum of 4 GeV/c [4]. Due to limited space, the best option seems to be a proximity focusing RICH detector with aerogel as Cherenkov radiator. Multianode PMTs with metal foil dynode structure, micro-channel plate PMTs and hybrid avalanche photodiodes (HAPDs) have been studied as possible detectors of Cherenkov photons [5–7]. The appearance of SiPMs, with their promising characteristics, offers new possibilities. This work represents an effort towards an evaluation of these options.

2. Experimental set-up

The experimental set-up for measurement of Cherenkov photons is shown in Fig. 1. After generating a trigger signal in a scintillator, the cosmic ray particle is registered by three multiwire proportional chambers, from which the track coordinates are obtained by delay line readout of cathode plane signals. The charged particle then enters a light tight box, inside which a 2.5 cm thick aerogel radiator ($n = 1.045$) and photon detectors are mounted on appropriate supports (Fig. 2). The photon detector consists of an array of 12 multianode PMTs (Hamamatsu R5900-M16) and six SiPMs (also by Hamamatsu). The M16 PMTs have been previously used by our group [8,9], their characteristics are well known, so they serve as a reference against which we compare the parameters of the SiPMs. The silicon PMs are of type Hamamatsu MPPC S10362-11-100U with 1 mm^2 area and 100 μm pixels [10]. The larger pixel size (100 μm) compared to SiPMs with smaller pixels (50 and 25 μm) was preferred because the positive effect of increased photon detection efficiency (due to increased fraction of sensitive area) outweighs the negative effect of

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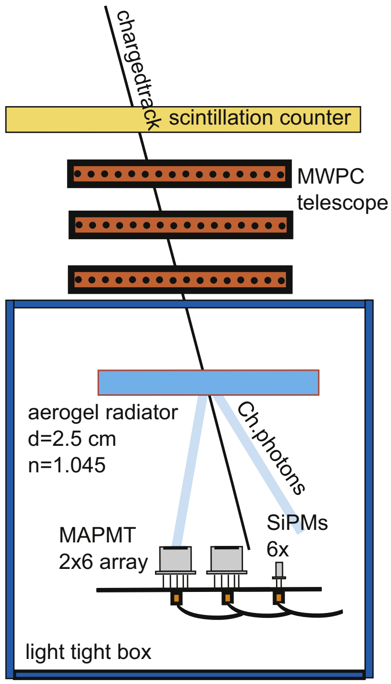

Fig. 1. The experimental set-up.

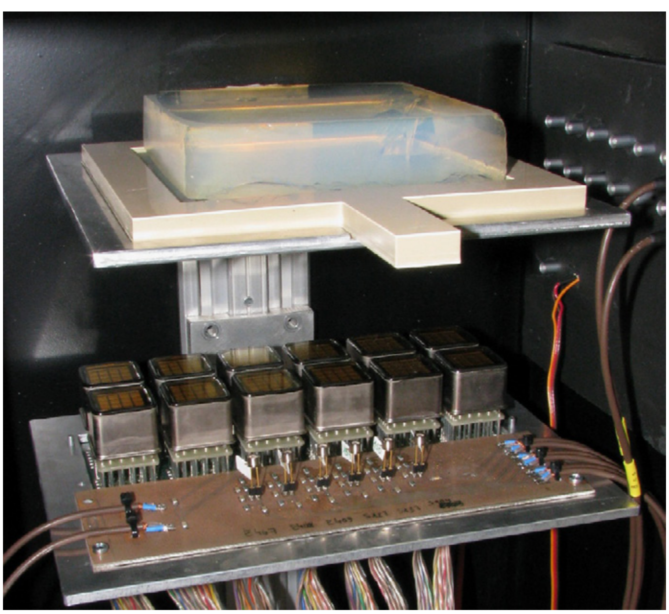

Fig. 2. A close-up view of the aerogel radiator and the photon detectors on their supports in the dark box.

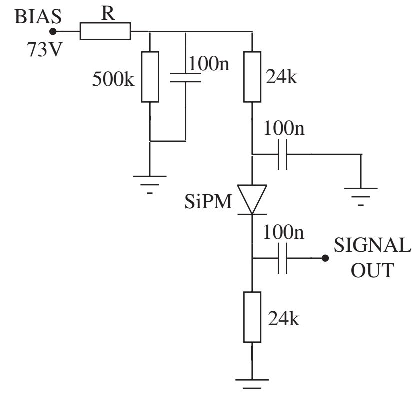

Fig. 3. The circuit diagram for connecting the silicon photomultipliers; the resistor R was adjusted for each individual SiPM.

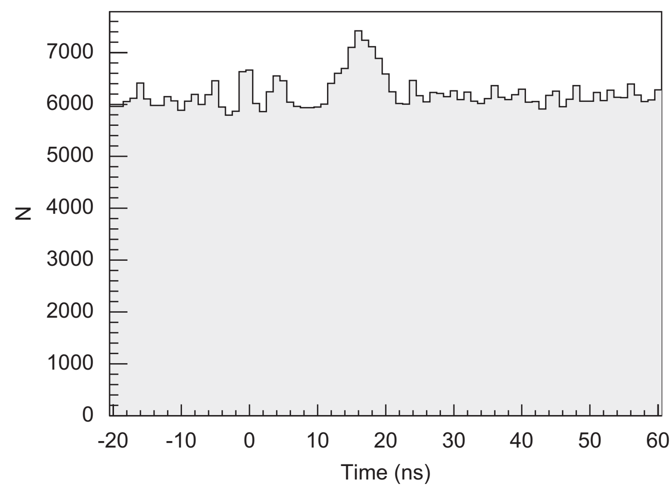

Fig. 4. The raw measured time spectrum of all signals registered by the silicon photomultipliers.

increased noise rate. The circuit through which voltage was applied and the signal was read out is shown in Fig. 3.

The signals from the SiPMs are amplified (Ortec FTA820), discriminated (EG&G CO8000, used in the leading edge mode) and registered by multi-hit VME TDCs (CAEN V673A). So for each hit, the time of arrival is measured in addition to information of the hit position given by the position of the particular photon detector channel.

3. Results

The raw distribution of all SiPM signals, with respect to time relative to the scintillation counter trigger signal, is shown in Fig. 4. Although on a relatively high background, there is clear evidence of a peak in the time distribution. By correcting for the time offset of individual SiPMs and plotting only those signals which correspond to a hit in the range of $\pm 2\sigma$ within the expected Cherenkov angle relative to the charged particle track, we obtain the time distribution of Fig. 5. It is seen that the peak of Cherenkov photons is better pronounced and the background is considerably reduced, mainly on account of the reduction of dark noise. The distribution of hits as a function of their Cherenkov angle is shown in Fig. 6, for the MA-PMTs (Fig. 6a), for the SiPM signals that are out of the peak time window (Fig. 6b) and for the SiPM signals that fall within a 3 ns time window of the peak (Fig. 6c). Since the resolution of the Cherenkov angle is in the present set-up dominated by the uncertainty in determination of the charged particle track parameters, the widths of the Cherenkov photon peaks in both types of detectors should be about equal. Therefore, the fitting of the SiPM distribution (Fig. 6c) has been performed by fixing the peak position and width to the values obtained from the MA-PMTs (Fig. 6a), and by fixing the background shape to that of the out-of-time spectrum (Fig. 6b), so only the normalization was allowed to vary. This procedure results in 597 photons detected by the SiPMs, while about 67,000 photons were detected by the MA-PMTs. As the area covered by the SiPMs is only $6\,mm^2$, whereas the area covered by the MA-PMTs is $3645\,mm^2$, this means that 5.4 ± 0.2 times more photons are detected per unit area of the SiPMs than per unit area of the MA-PMTs. Such a result

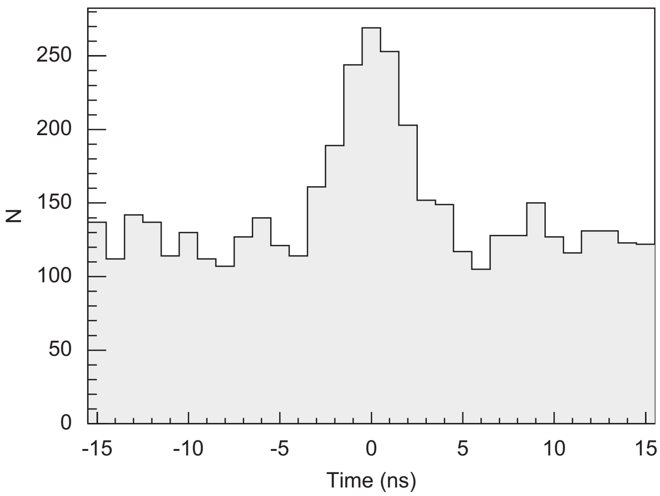

Fig. 5. The offset-corrected time spectrum for only those SiPM signals that correspond to a Cherenkov angle within 2σ of the expected value.

agrees with the expected ratio of 5.1, based on photon detection efficiencies provided by the manufacturer [10].

The ratio of the sensitive surface to the overall area occupied by the SiPM detector could be increased by using light concentrators in order to gather the Cherenkov light from a larger surface. This technique would increase the number of detected photons at unchanged level of dark noise, and would therefore improve the signal-to-noise ratio. We have tested a hemispherical light concentrator obtained by removing the cap from a blue light emitting diode. The system of SiPM and a hemispherical light concentrator is shown schematically in Fig. 7. The position dependent response for perpendicularly incident light (Fig. 8) shows a fourfold increase in the sensitive area (from $1 \times 1\,\text{mm}^2$ to $\approx 2 \times 2\,\text{mm}^2$). With six such light guide and SiPM detectors (Fig. 9), we have measured Cherenkov photons emitted by cosmic particles in a silica aerogel radiator. A clear improvement resulting from the addition of the hemispherical light concentrators may be seen in the plots of hits for the cases without and with the light guides (Fig. 10). The measured increase in light yield is 3.6 ± 0.2, which is in good agreement with the simulated value of 3.3.

Simulation calculations indicate that an even better configuration is obtained with a light guide in the form of a truncated pyramid, possibly with a focusing entry window and reflective side walls [11]. However, such a light guide produces a relatively large divergence of photons at the exit window. In connection with the gap between the SiPM glass entry window and its sensitive volume (Fig. 7), this divergence would reduce the acceptance. Further investigations will therefore include SiPM detectors with a considerably reduced gap and with pyramidal light guides.

4. Conclusions

With silicon photomultipliers we have detected Cherenkov photons radiated by cosmic particles in a 2.5 cm thick aerogel radiator. The accumulated distribution of hits shows a peak in the raw time spectrum. By selection of events within a narrow time window, the signal-to-background ratio is improved, so the number of detected Cherenkov photons could be extracted by fitting the distribution versus Cherenkov angle. We found about 5 times more Cherenkov photons per unit area of the sensitive surface for SiPMs than for the MA PMTs. This is in agreement with estimates based on quantum efficiencies provided by the

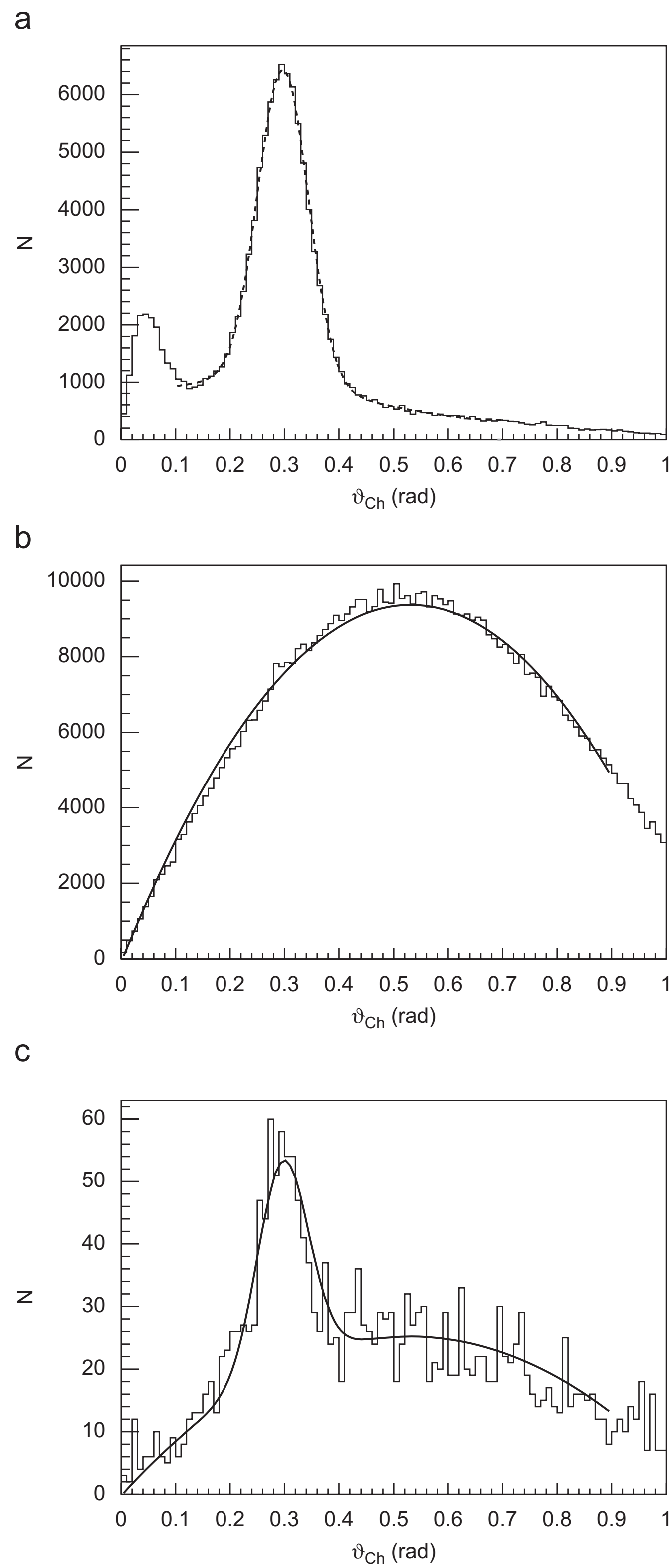

Fig. 6. (a) The distribution of MA-PMT hits with respect to their corresponding Cherenkov angle and the fitted distributions (Gaussian + polynomial). (b) The distribution of SiPM hits, that are outside of the Cherenkov time window, as a function of the corresponding angle relative to the charged particle track. The fit is 2nd order polynomial. (c) The distribution of SiPM hits, that are inside of the Cherenkov time window, as a function of the Cherenkov angle. Except for normalization factors, the fit parameters are taken from the fits to distributions in (a) and (b).

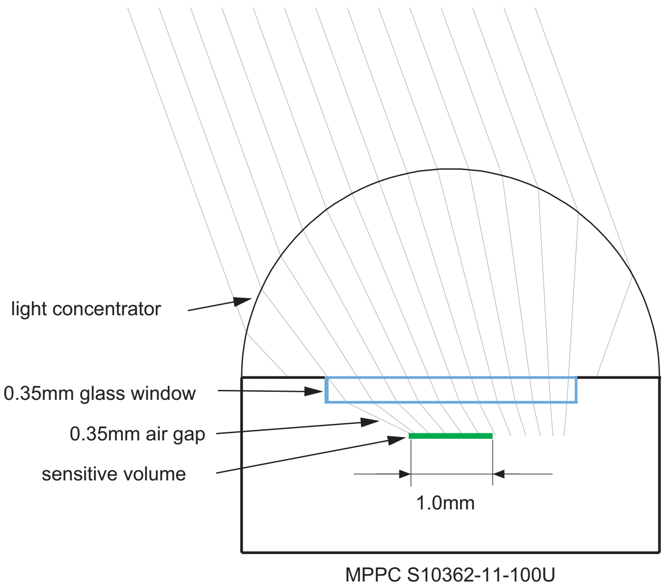

Fig. 7. A hemispherical light concentrator; also shown are the main elements of the SiPM, the sensitive volume, the glass window, the air gap and the metal package.

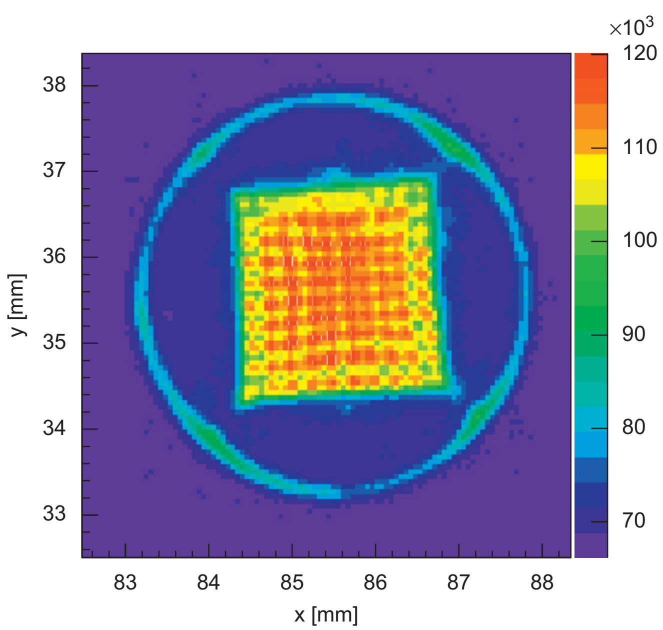

Fig. 8. Position dependent sensitivity of the SiPM with a hemispherical light concentrator, for perpendicularly incident light ($\lambda = 610\,\text{nm}$). The observed structure reflects the internal segmentation of the SiPM.

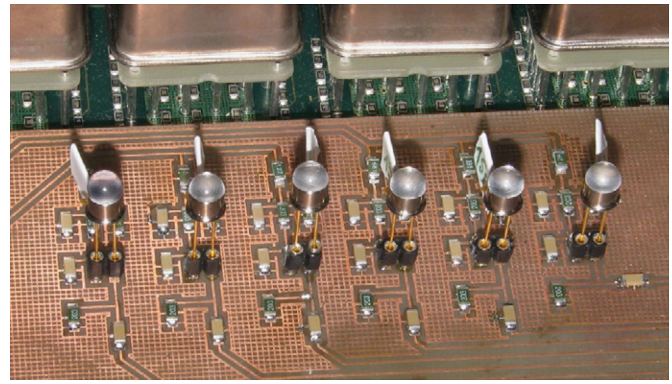

Fig. 9. The SiPMs equipped with light guides.

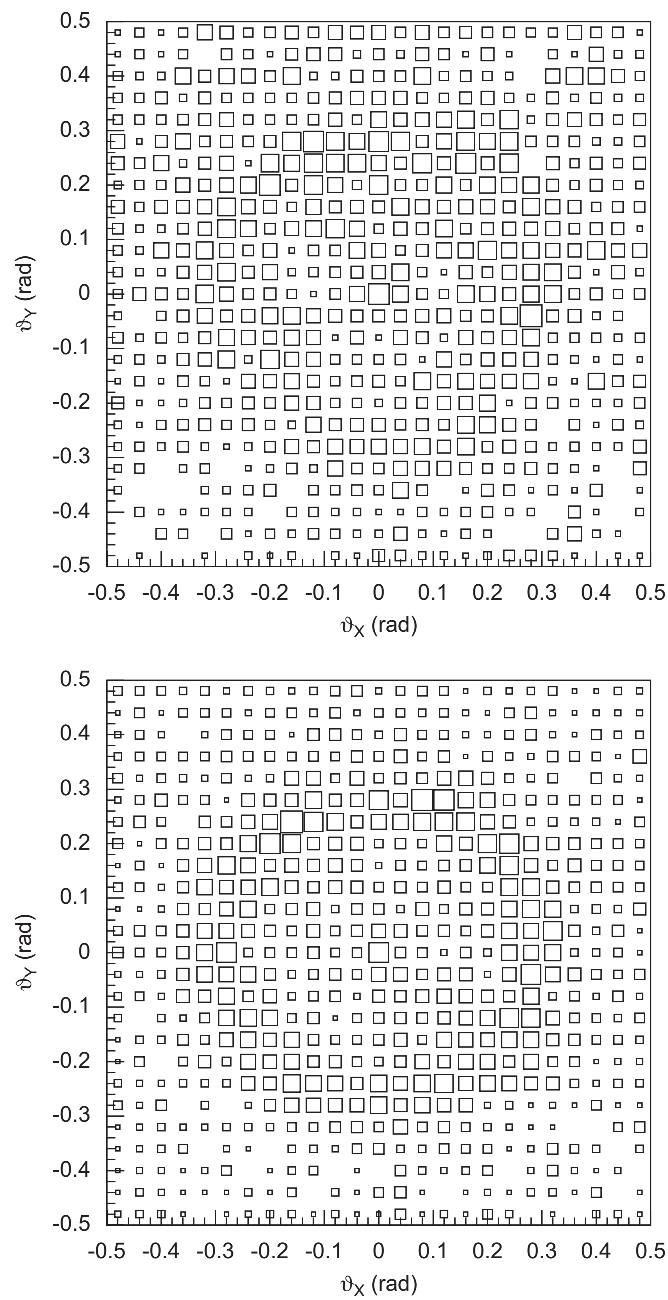

Fig. 10. Plots of hits in Cherenkov angle space for the SiPMs without (top) and with (bottom) the hemispherical light guides.

manufacturer [10]. Cherenkov rings in the accumulated hit distributions were observed in both types of detectors.

We have also succeeded in increasing the SiPM detection efficiency by increasing the surface from which photons are collected with simple hemispherical light concentrators. Although an increased detection efficiency has been achieved, the limiting factor seems to be the SiPM protective structure in front of the sensitive layer. A further considerable improvement is expected with the new SMD mounted SiPM type (e.g., Hamamatsu S10362-11-100P) with a greatly reduced protective layer thickness.

Finally, we believe that we have demonstrated that despite the relatively large dark noise of the SiPM detectors, they are promising as detectors of Cherenkov photons inside large magnetic spectrometers.

Acknowledgement

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