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Tests of a silicon photomultiplier module for detection of Cherenkov photons

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ABSTRACT

Silicon photomultipliers, whose main advantage over conventional photomultiplier tubes is the operation in high magnetic fields, have been considered as position sensitive, single photon detectors in a proximity focusing RICH with aerogel radiator. A module, consisting of 64 (8×8) Hamamatsu MPPC S10362-11-100P silicon photomultipliers, has been constructed and tested with Cherenkov photons emitted in an aerogel radiator by 120 GeV/c pions from the CERN T4-H6 beam. In order to increase the efficiency, i.e. the effective surface on which light is detected, the potential of using light guides has been investigated.

1. Introduction

Silicon photomultipliers (SiPMs) [1–3] have been considered as detectors for single photons in the proximity focusing RICH with aerogel radiator [4,5] for the upgrade of the Belle detector at the KEK B-factory [6]. There, a detector capable of efficiently detecting single Cherenkov photons, while operating in a magnetic field of 1.5 T, is required. Silicon photomultipliers meet this requirement well: they have a photon detection efficiency higher than photomultiplier tubes, while being insensitive to high magnetic fields. Among their other advantages are their low operation voltage and small dimensions. The main disadvantage of silicon photomultipliers is the relatively high dark noise count rate (few 100 kHz/mm^2). We have already shown [7] that single Cherenkov photons can be detected using silicon photomultipliers, if the signal to noise ratio is improved by selecting only signals, arriving inside a narrow time window, and by collecting more photons per detector with the use of light guides. We continued our studies by constructing a module of 64 SiPMs and a matching array of light guides. In this work we present the results obtained with a SiPM module used in an aerogel RICH counter and the improvement obtained by using light guides.

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2. Experimental set-up

A module of 64 ($=8\times 8$) Hamamatsu MPPC S10362-11-100P silicon photomultipliers has been constructed (Fig. 1, left). Blocks of 2×2 neighbouring SiPMs were connected to a single channel, resulting in a total of 16 readout channels. The pad size is 5.08×5.08 mm^2, out of which only 4 mm^2 represent the SiPM active surface. The pad geometric acceptance was therefore 15.5%. The SiPM module was used in a Cherenkov detector, consisting of a 1 cm thick slab of aerogel (with $n=1.03$ and 1.4 cm attenuation length at $\lambda=400$ nm), positioned 115 mm upstream of the silicon photomultipliers. We tested this Cherenkov detector in a 120 GeV/c pion beam at CERN. A scintillation counter was used to provide the start signal for timing information and two multiwire proportional chambers (MWPCs) provided the charged particle track information.

3. Light guide array

In order to improve the performance of the SiPM module we have investigated the potential of using light guides to collect more photons per single SiPM. Since the dark count is not affected by light guides, this would improve the signal to noise ratio.

Two types of light guides, that are simple to manufacture, are a hollow light guide, composed of four mirror walls (Fig. 2, top), and a solid light guide, shaped in the form of a truncated pyramid (Fig. 3, top). Both types collect light by reflecting it from the side walls onto a smaller surface, the former type by reflection on the side walls and the latter type by total internal reflection. The solid light guide also benefits from refraction on the entry surface.

To evaluate the performance of different light guides we wrote a simple ray-tracing simulation computer programme, which propagated the rays through the light guide. For the mirror type light guide, the simulation only accounted for the reflection from side walls (at 90% reflectivity), while for the pyramidal light guide (an index of refraction $n=1.5$ was assumed) refraction on the entry surface and, when applicable, total internal reflections from side walls were taken into account. The collection efficiency (acceptance) was obtained as the fraction of incoming rays reaching the light guide exit surface.

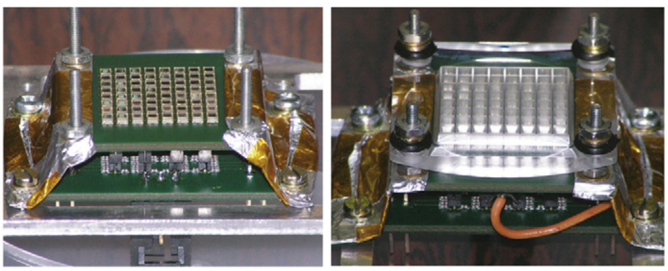

Fig. 1. The photon detector module consisting of 64 SiPMs without (left) and with (right) the pyramidal light guide array attached.

Using this simulation we found the optimal geometry for both types of light guides, in the case where a light collection from a surface of $2\times 2\,\text{mm}^2$ to a surface of $1\times 1\,\text{mm}^2$ is required. In the case of the mirror light guide, some light is lost at all incoming angles due to the finite reflectivity. Also light may reflect back through the light guide entry even at small incident angles of $\approx 15^\circ$ (Fig. 2). The solid pyramidal light guide performs better, the light starts to escape through the side walls due to the loss of total internal reflection at angles of $\approx 30^\circ$ (Fig. 3, bottom). About 4% of the light gets lost at all incident angles due to reflections on the entry surface.

We decided to use the solid pyramidal light guides for our SiPM module. Due to the pitch of the SiPM array the light guide entry surface dimensions would be $2.54\,\text{mm}\times 2.54\,\text{mm}$. Also, the method we used for light guide production imposed a 10° inclination of the lateral sides. This means that the only free parameter of light guide geometry is its length. We repeated our ray-tracing simulation, this time also taking into account the propagation through the 0.3 mm thick epoxy gap protecting the SiPM active surface. We obtained the acceptance as the fraction of incoming rays reaching the SiPM active surface. Incoming rays were uniformly distributed over the light guide entry surface and isotropically in angles up to 30°. We found the optimal geometry

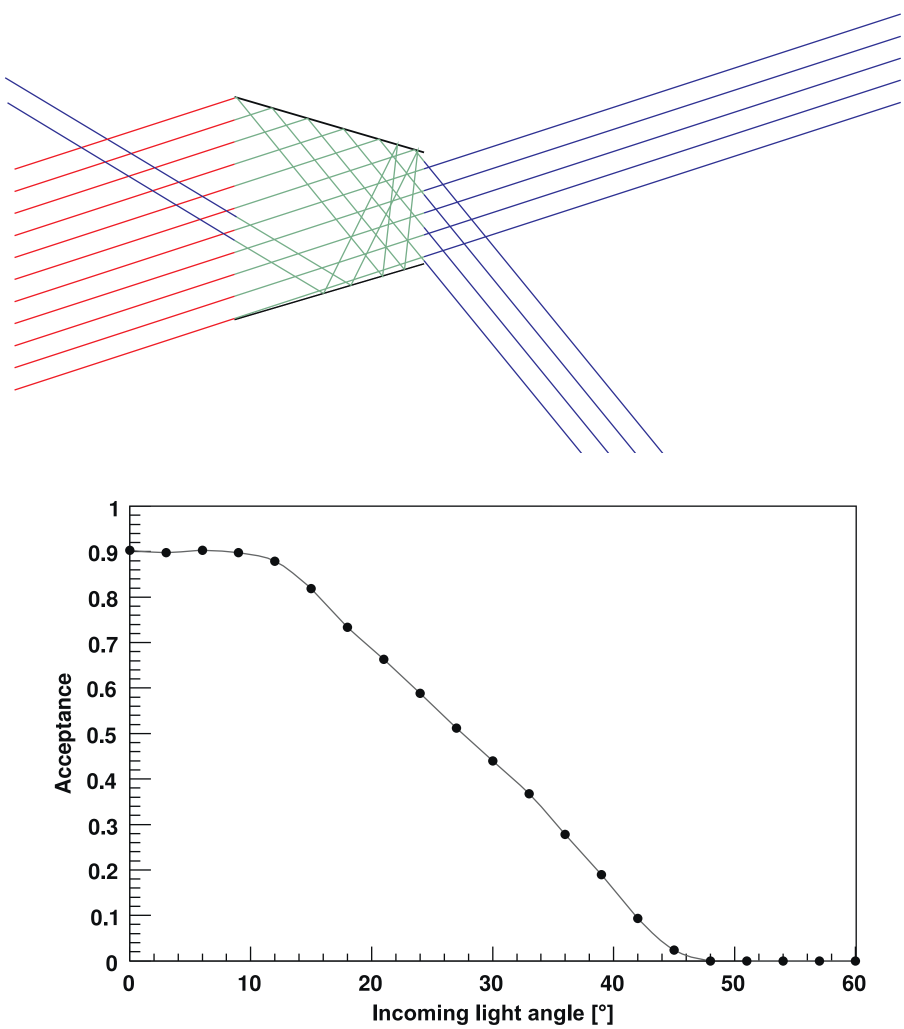

Fig. 2. Light guide composed of mirrors: side view of ray-tracing simulation (top); light guide acceptance as a function of angle of incoming light rays (bottom).

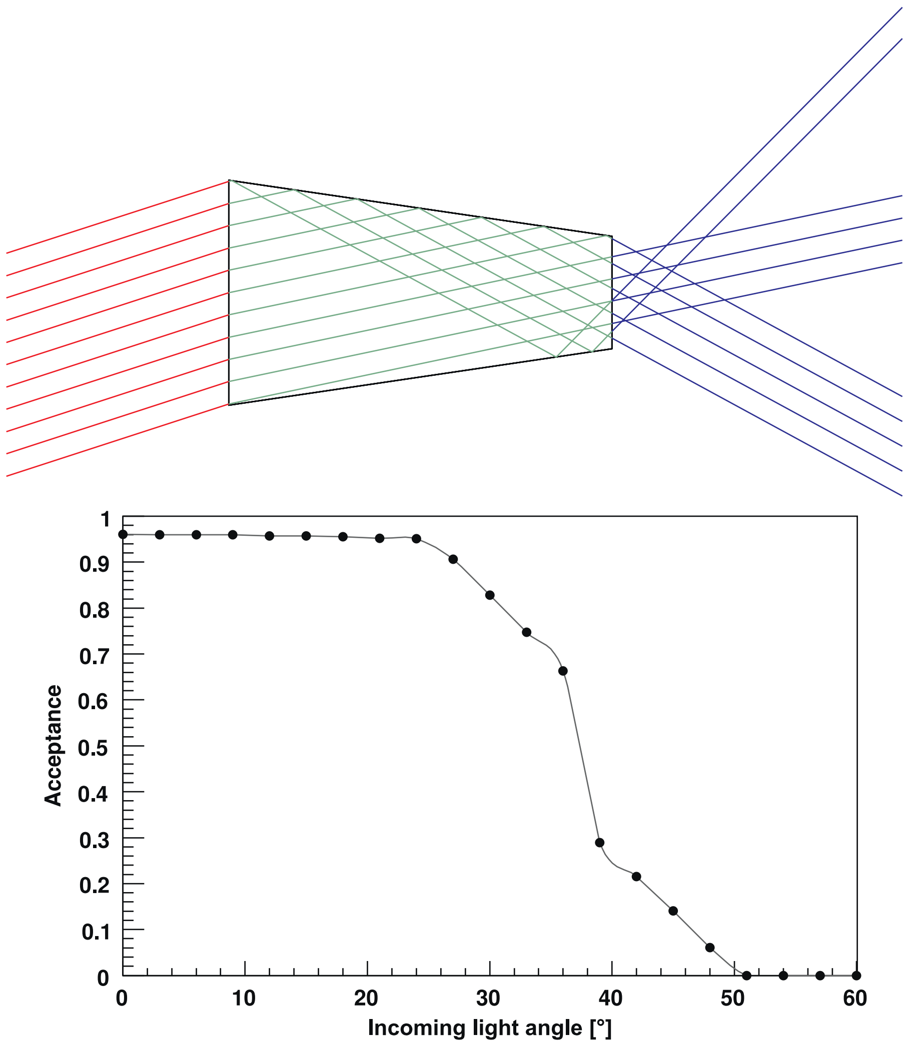

Fig. 3. Light guide shaped as a solid truncated pyramid: side view of ray-tracing simulation (top); light guide acceptance as a function of angle of incoming light rays (bottom).

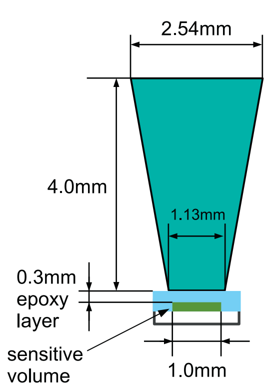

Fig. 4. A pyramidal light guide with dimensions optimized by simulation; also shown are the main elements of the Hamamatsu MPPC S10362-11-100P, the protective epoxy layer and the sensitive volume.

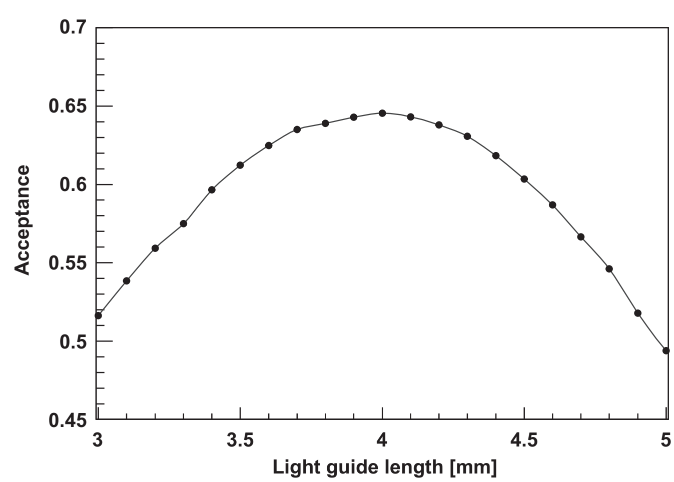

Fig. 5. Light guide acceptance as a function of light guide length.

(Fig. 4) for light guide length of 4.0 mm. According to simulation (Fig. 5), such light guides have a collection efficiency of $\approx 65\%$. Most of the lost rays are due to the epoxy gap between the light guide exit and the SiPM active surface, as they propagate laterally and miss the active surface.

We have machined an array of light guides out of a UV grade perspex lens used in the HERA-B RICH [8] (Fig. 1, right). Due to the limitation of the available machining procedure, the entry

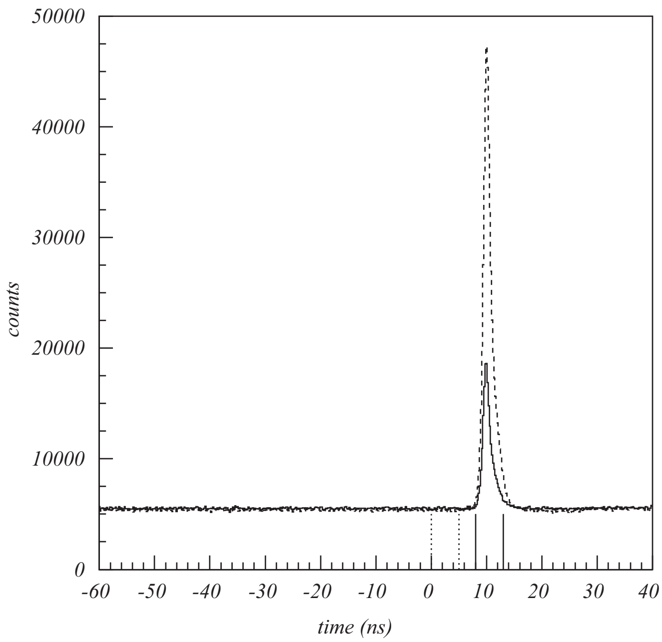

Fig. 6. The time spectra for the SiPM pulses in the case without (solid) and with (dashed) the light guides. The indicated cuts correspond to a 5 ns time window.

window of the light guides obtained was 2.3 mm × 2.3 mm instead of 2.54 mm × 2.54 mm. By using such a light guide array we expected to increase the pad geometric acceptance from 15.5% to 54%, thus increasing the number of detected photons by a factor of 3.5.

4. Results

The time distribution spectra obtained without and with the light guide array are shown in Fig. 6. An improvement in the number of detected photons as well as the signal to noise ratio, with the light guides, is evident. For hits, arriving within a 5 ns time window at the Cherenkov peak, the distribution in Cherenkov angle as well as the ring image in Cherenkov angle space are shown on Fig. 7 for the case without, and on Fig. 8 for the case with the light guides. In order to cover the whole Cherenkov ring area, the measurements had been made with the SiPM module in 9 different positions on a 3 × 3 grid.

The Cherenkov peak has a width of $\sigma \approx 14$ mrad for the case without and $\sigma \approx 16$ mrad for the case with the light guides. By fitting the peaks, we obtained the number of detected Cherenkov photons per incident charged particle. Assuming that the entire area of the Cherenkov ring is covered by SiPM modules (as described above), we would obtain 1.6 photons per ring without the light guides and 3.7 photons per ring with the light guides. This improvement is by a factor of 2.3, less than the factor of 3.5 expected from geometric considerations and from the light guide acceptance simulations. We attribute this discrepancy mainly to the fact, that the sides of the light guides were not properly polished. Instead of undergoing total internal reflection, some photons thus refract out of the light guide or reflect isotropically and so miss the SiPM active surface.

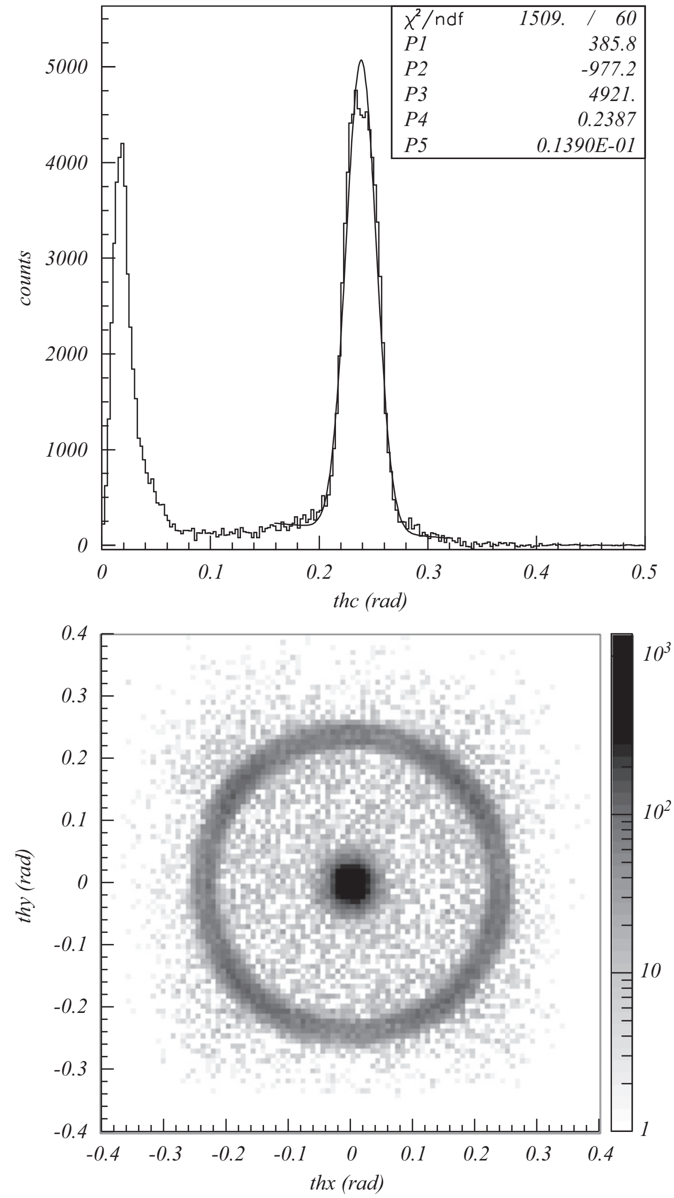

Fig. 7. The distribution of hits in Cherenkov angle (top) and in Cherenkov angle space (bottom) with noise distributions subtracted. The plots are for the case without the light guides.

5. Conclusions

We have successfully detected Cherenkov photons produced in a 1 cm thick aerogel slab by 120 GeV/c pions with a module of silicon photomultipliers. The SiPMs can therefore be used as photon detectors in a proximity focusing ring imaging Cherenkov detectors, despite their high dark noise count rate. We have improved the signal to noise ratio by accepting only signals, coming inside a 5 ns time window, and additionally by using light guides to collect more photons per SiPM. For the upgrade of the Belle detector, a 3 cm thick aerogel with $n = 1.05$ and 5 cm attenuation length, is forseen, with an expected increase of the photon yield by a factor of 5. Another factor of 2 might be obtained by improving the production of the light guides, resulting in about 30 photons per ring.

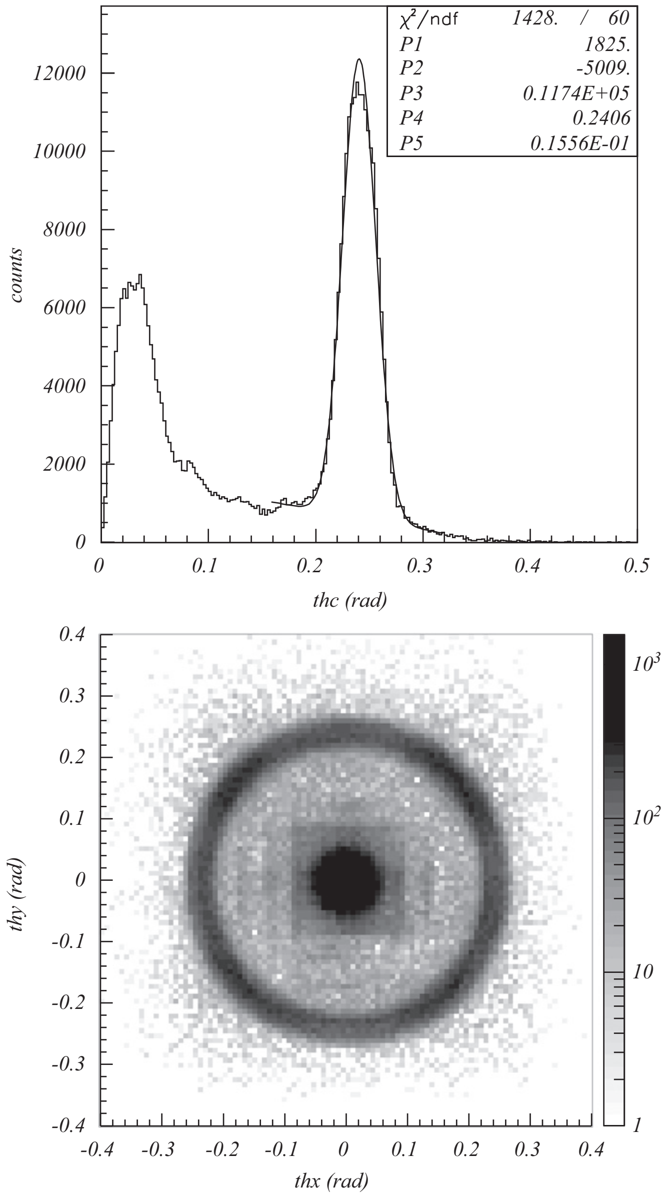

Fig. 8. The distribution of hits in Cherenkov angle (top) and in Cherenkov angle space (bottom) with noise distributions subtracted. The plots are for the case with the light guides.

Acknowledgements

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