Nuclear Instruments and Methods in Physics Research A 613 (2010) 195–199

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research A

journal homepage: www.elsevier.com/locate/nima

A module of silicon photo-multipliers for detection of Cherenkov radiation

Samo Korpar [a,b,*], Hassan Chagani [b], Rok Dolenec [b], Peter Križan [c,b], Rok Pestotnik [b], Aleš Stanovnik [d,b]

[a] Faculty of Chemistry and Chemical Engineering, University of Maribor, Smetanova 17, SI-2000 Maribor, Slovenia
[b] Jožef Stefan Institute, Jamova cesta 39, SI-1000 Ljubljana, Slovenia
[c] Faculty of Mathematics and Physics, University of Ljubljana, Jadranska 29, SI-1000 Ljubljana, Slovenia
[d] Faculty of Electrical Engineering, University of Ljubljana, Tržaška cesta 25, SI-1000 Ljubljana, Slovenia

ARTICLE INFO

Article history:
Received 11 September 2009
Received in revised form
21 October 2009
Accepted 9 November 2009
Available online 18 November 2009

Keywords:
Silicon photo-multiplier
Geiger mode APD
Ring imaging Cherenkov detector
Silica aerogel radiator

ABSTRACT

A module, consisting of 64 ($=8\times8$) Hamamatsu MPPC S10362-11-100P silicon photomultipliers, has been constructed and tested as a position sensitive detector of Cherenkov photons. In order to increase the efficiency, i.e. the effective surface over which Cherenkov light is collected, we have manufactured and tested suitable light guides. In addition to the increase in efficiency, it is shown that such light guides considerably improve the signal-to-noise ratio. The results of our measurements indicate that the performance of such a Cherenkov counter with aerogel radiator could meet the requirements of particle identification at the foreseen upgraded Belle detector.

1. Introduction

The upgrade of the Belle particle identification system [1,2] will require a 4σ separation of kaons from pions up to a momentum of 4 GeV/c. The limited available space of approximately 20 cm has led to the decision for a proximity focusing ring imaging detector with aerogel radiator. Among the photon detector candidates that have been studied [3,4] none are completely immune to the high magnetic field (≈ 1.5 T) present inside the Belle spectrometer. The recent appearance of silicon photomultipliers (SiPMs) [5–8] may change the situation. In addition to their insensitivity to magnetic fields, silicon photomultipliers have other advantages: they are small and robust and do not require high voltages. Among their disadvantages is the relatively high dark count rate ($\approx 1\,\mathrm{MHz/mm^2}$) and, in the present state of technology and costs, a low fraction of sensitive surface compared to the full area covered by the photon detector. These deficiencies may be reduced with light concentrators, which would collect the light from a larger surface, thereby increasing the overall geometric acceptance of the detector as well as the signal-to-noise ratio. Silicon photomultipliers therefore represent a challenge and a promise in the area of ring imaging Cherenkov counters. The present measurements with a SiPM module follow the initial successful investigations of the performance of individual SiPM detectors, i.e. a smaller number of them, in a ring imaging Cherenkov counter [9].

2. Experimental set-up

A Cherenkov detector consisting of a 1 cm thick aerogel slab (with $n=1.03$ and 1.4 cm attenuation length at $\lambda=400$ nm) and a photon detector array of 64 ($=8\times8$) Hamamatsu MPPC S10362-11-100P silicon photomultipliers has been assembled and tested in an 120 GeV/c pion beam at CERN. The arrival of a beam particle is triggered by a scintillation counter and its trajectory is registered with two multiwire proportional chambers (MWPCs). The incident particle hit coordinates are obtained by delay line readout of the cathode wire planes.

In a tile of aerogel, the pions radiate Cherenkov photons at an angle of ≈ 240 mrad relative to their track direction. These photons are detected by a photon detector plane at a distance of 115 mm from the aerogel upstream surface. The array of 64 SiPMs has been grouped into pads of 5.08 mm $\times$ 5.08 mm, consisting of 4 SiPMs each (Fig. 1), therefore requiring 16 signal lines per module. As the SiPM sensitive area is 1 mm^2, the geometric acceptance of a pad would be 15.5%. Additional inefficiency due to a 100 μm structure within the 1 mm^2 sensitive area of the MPPC S10362-11-100P is already included in the average photon detection efficiency given by the manufacturer (Fig. 2, [10]).

In order to increase the rather low geometric acceptance of the SiPM detectors within an array (15.5%), we have investigated the

* Corresponding author at: Faculty of Chemistry and Chemical Engineering, University of Maribor, Smetanova 17, SI-2000 Maribor, Slovenia.
Tel.: +386 2 229 4490; fax: +386 2 252 7774.
E-mail address: Samo.Korpar@uni-mb.si (S. Korpar).

0168-9002/$ - see front matter © 2009 Elsevier B.V. All rights reserved.
doi:10.1016/j.nima.2009.11.043

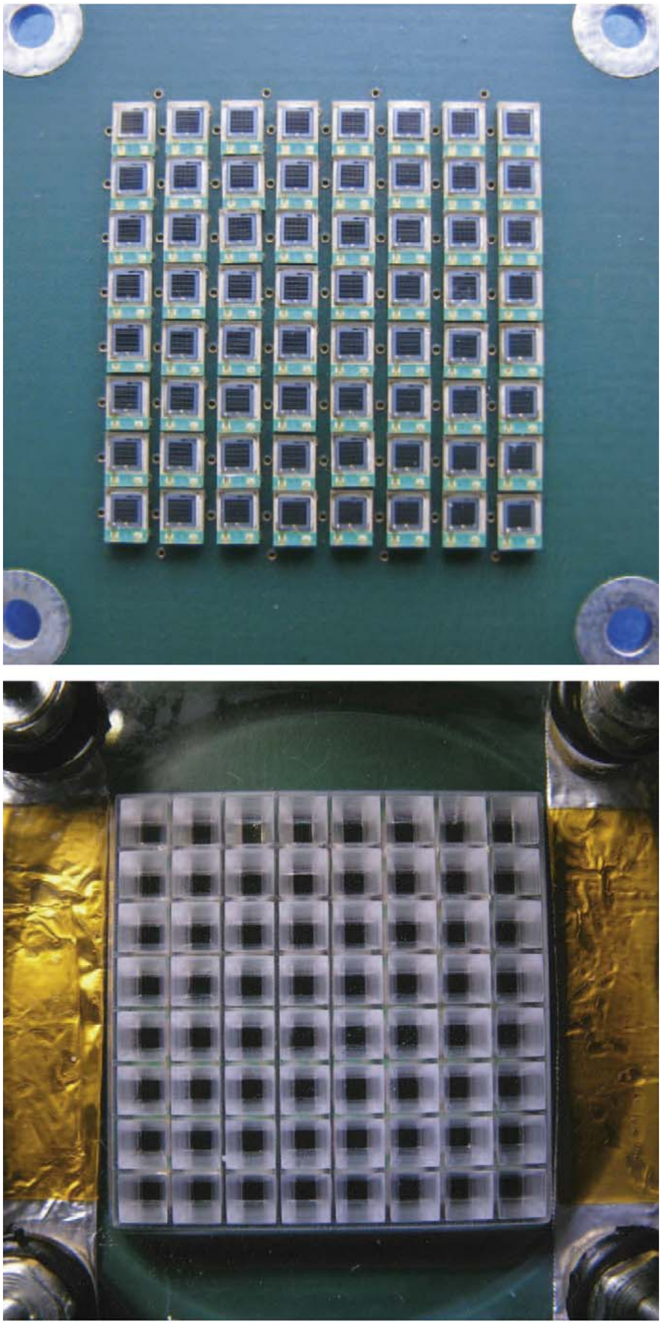

Fig. 1. The photon detector module consisting of 64 SiPMs without (above) and with (below) the pyramidal light guides. Four SiPMs are grouped into a single readout channel.

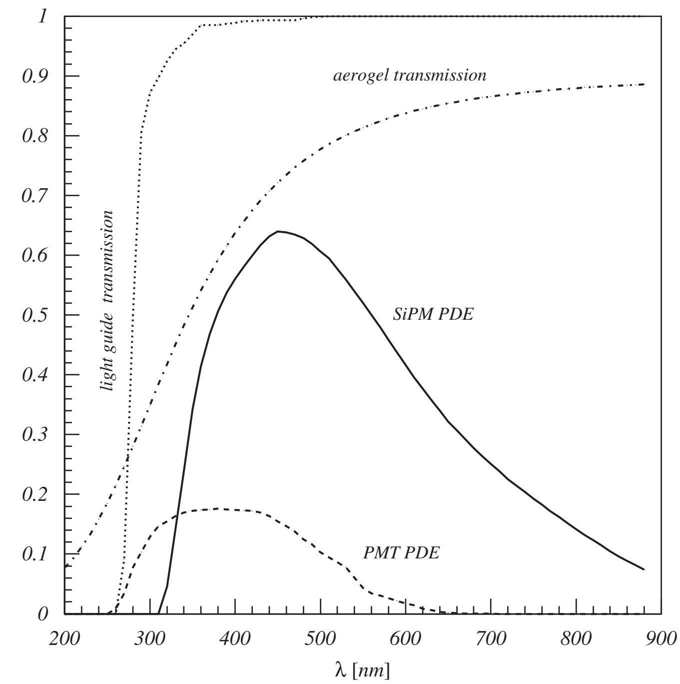

Fig. 2. The wavelength dependence of the photon detection efficiency (PDE) of one SiPM detector. Shown also is the efficiency for a typical bialkali multianode photomultiplier (PMT-PDE, including the photoelectron collection efficiency), the aerogel transmission and the light guide transmission.

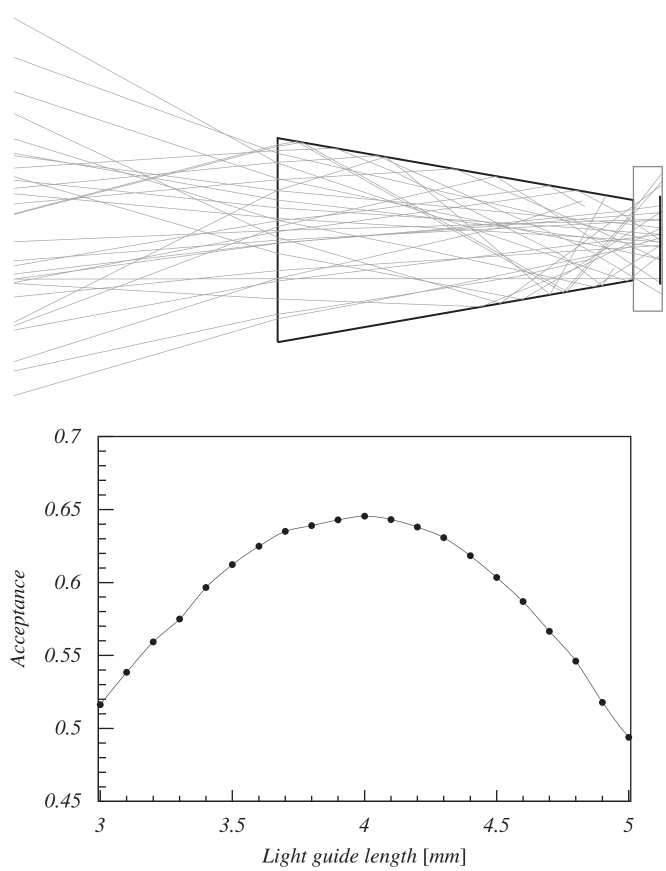

Fig. 3. (above) Trajectories of photons through the light guide and into the SiPM sensitive volume (shown as a thick line). (below) Acceptance, i.e. the fraction of generated photons that hit the SiPM volume, as a function of light guide length.

possibility of increasing the acceptance with light guides. Light guides in the form of truncated pyramids have been studied. The acceptance as a function of light guide length, at fixed, 10° inclination of the lateral planes, is shown in Fig. 3. Photons have been generated with isotropic incident angle distribution up to $\theta = 30^{\circ}$ and with uniform distribution over the $2.54\,\mathrm{mm} \times 2.54\,\mathrm{mm}$ surface of the light guide entry window. The loss of 35% of the photons is mainly due to the 0.3 mm gap between the light guide exit window and the sensitive volume of the SiPM and, to a lesser extent, also to refraction out of the light guide and to absorption. Therefore, the acceptance of an ideal light guide is about 65%, which is about 4 times larger than the bare geometric coverage of the SiPM sensitive surface in a module as described above. In order to test these estimates, we have manufactured a light guide array matching the array of SiPM detectors (Fig. 1). The array has been machined out of a UV grade perspex lens used in the HERA-B RICH [11]. Due to the limitation of the available machining procedure, the entry window of the light guide was 2.3 mm × 2.3 mm instead of 2.54 mm × 2.54 mm and the length 4 mm; these changes resulted in a somewhat lower acceptance of 54%.

3. Results

Measurements have been performed with and without the light guide array on top of the SiPM array. Fig. 4 shows both time spectra of SiPM pulses for an equal number of triggered events. A clear improvement with the light guide system may be observed.

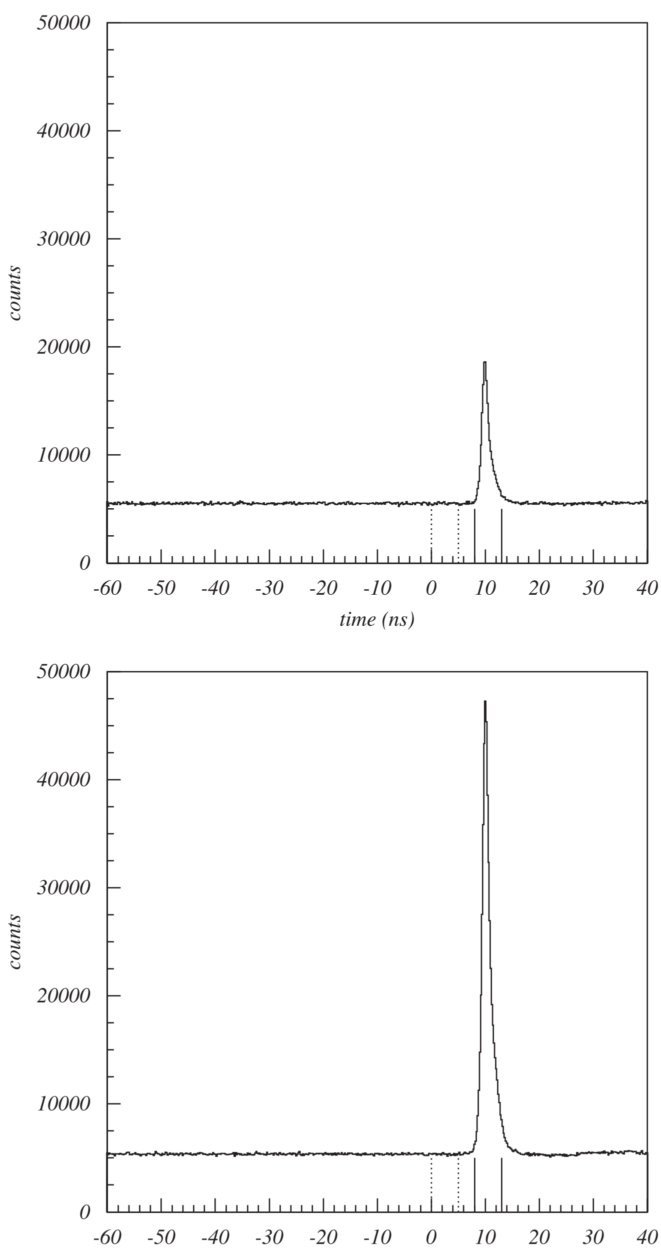

Fig. 4. The time spectra for the SiPM pulses in the case without (above) and with (below) the light collection system. The indicated cuts correspond to a 5 ns time window.

The light guides have increased the number of detected Cherenkov photons, while not affecting the number of dark pulses. Selecting pulses only within a narrow time window, say 5 ns of the Cherenkov photons, will further reduce the background, i.e. increase the signal-to-noise ratio, to the level at which a measurement of Cherenkov rings is possible.

As the SiPM photon detector module was smaller than the Cherenkov ring area, measurements had to be made in 8 positions on a 3 × 3 grid, with the central position excluded. The distribution of hits with respect to their corresponding Cherenkov angle is shown in Fig. 5 for hits within two 5 ns time intervals, one in coincidence and the other out of coincidence with the Cherenkov pulse. By subtracting one from the other, we obtain the distributions shown in Fig. 6 for cases with and without the light guides. Fitting of the Cherenkov peak in the distribution gives the number of measured Cherenkov photons per incident charged particle. Assuming that the entire area of the photon detector 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.

The width of the Cherenkov photo peak ($\sigma \approx 14$ mrad) roughly agrees with the expectation based on estimates of photon position resolution, i.e. pad size, emission point uncertainty due to aerogel radiator thickness and tracking accuracy. This study was not mainly concerned with the resolution of the single photon Cherenkov angle [12], but rather with the achievable yield.

The Cherenkov ring image in Cherenkov angle space for SiPM pulses within the 5 ns time window and with the out-of-time distribution subtracted, may be seen in Fig. 7, for both cases, without and with the light guides.

4. Discussion

From estimates based on the photon detection efficiency of the MPPC S10362-11-100P supplied by Hamamatsu [10], geometric coverage and electronic efficiency, we would expect to detect about 2.3 Cherenkov photons per ring, while the actually

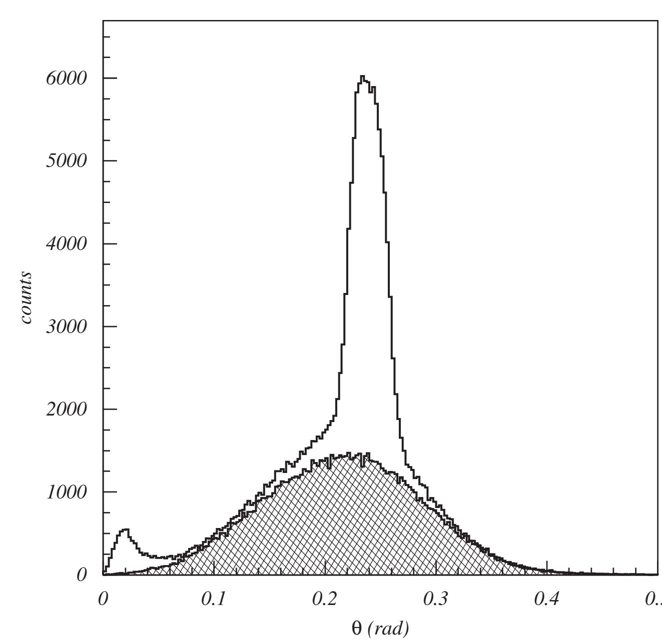

Fig. 5. The distribution of SiPM hits with respect to their corresponding Cherenkov angle for pulses inside the 5 ns time window (open histogram) and for pulses in a corresponding out-of-time window (shaded). The data are from measurements without the light guides.

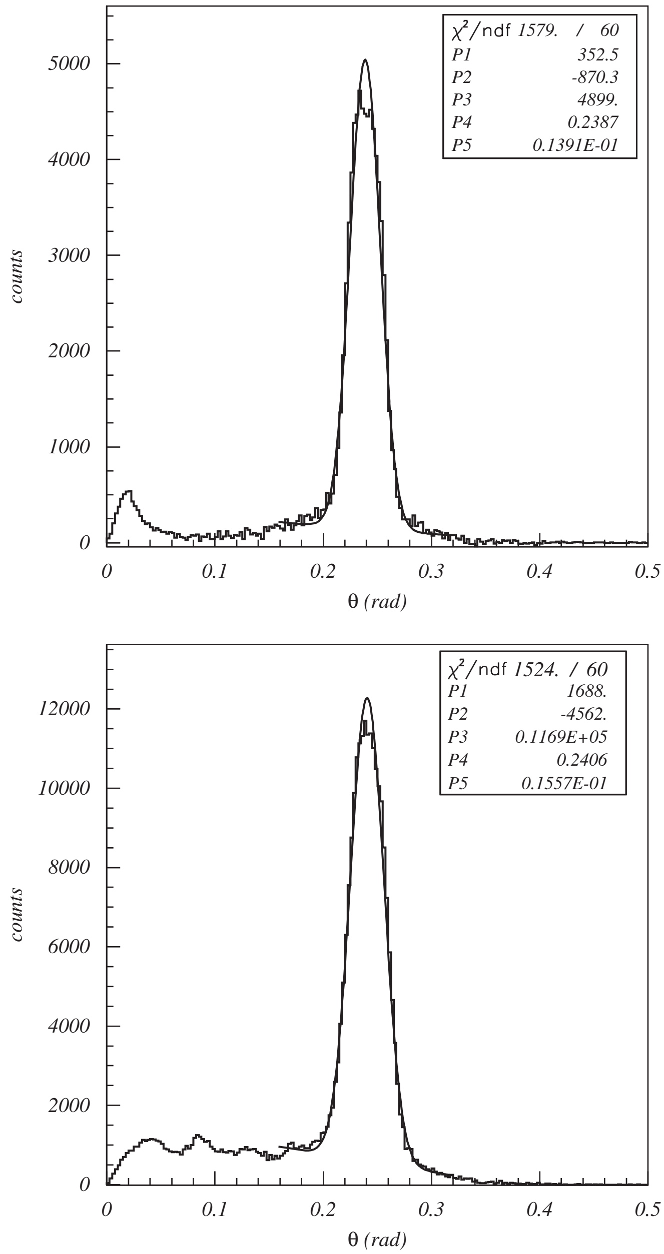

Fig. 6. The distribution of hits in Cherenkov angle with the out-of-time background subtracted for the case without (above) and with (below) the light guide system.

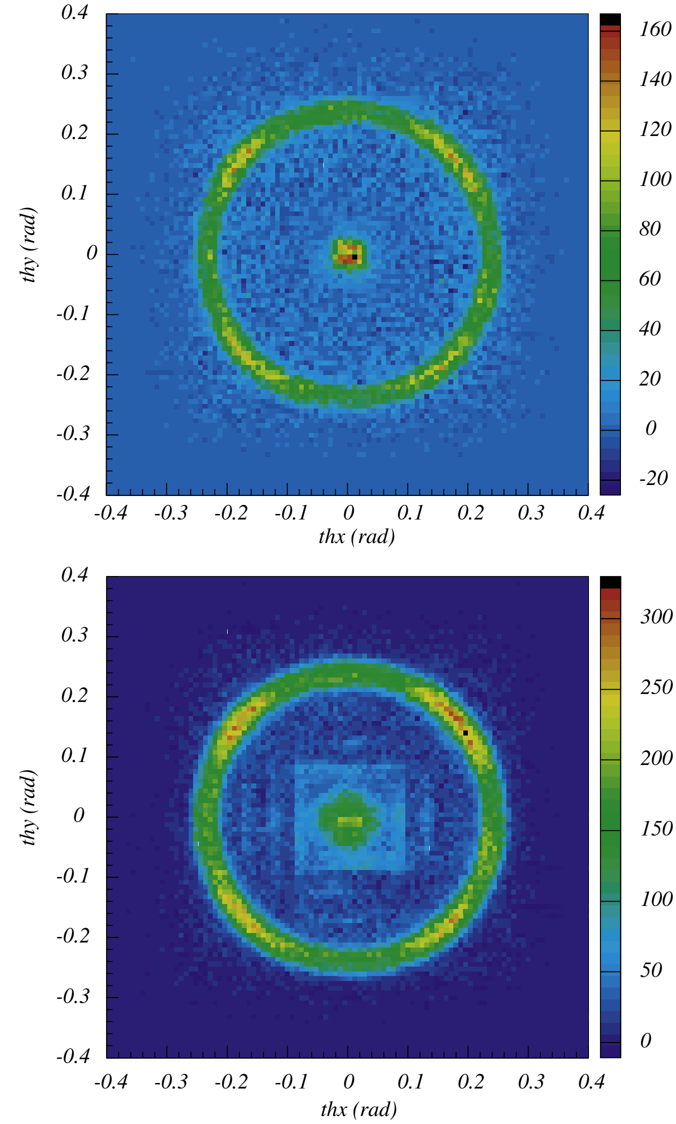

Fig. 7. The accumulated SiPM hits represented in Cherenkov angle space for measurements without (above) and with (below) the light collection system. The azimuthal distribution on the Cherenkov ring is uneven due to limitations in acceptance.

measured number is 1.6 photons/ring. Some, if not most of this discrepancy seems to be explained by an overestimation in the manufacturer data on photon detection efficiency of the SiPM, which includes effects of crosstalk and afterpulses (Fig. 2, [10]). Also other authors [13] indicate that the data given by the manufacturer could be too optimistic.

The measured improvement by a factor of 2.3 due to light concentrators with perspex pyramids is also less than the estimated factor of 3.5, which is the ratio of the expected acceptance of 54% to the bare geometric coverage of 15.5% of the SiPM sensitive surface in the module (Fig. 1). This discrepancy is probably partly due to non-specular reflection and refraction on the side walls of the light guide. An additional contribution to the discrepancy could come from less than perfect overlap of the light guide exit window with the SiPM sensitive surface. Also reflection on the light guide exit window and effects of inaccurate cutting have not been accounted for in the calculated acceptance.

We expect to gain a factor of 5 in photon yield by increasing the radiator thickness to 3 cm and simultaneously switching to $n = 1.05$ aerogel with 5 cm attenuation length. Optimistically, another factor of 2 might be obtained by improved production of the light guides and their coupling to SiPMs. Thus, we may conclude that our investigations have demonstrated that such a proximity focusing ring imaging Cherenkov detector is feasible.

Acknowledgments

We thank CERN for hospitality during the beam test, and Harris Kagan of Ohio State University for letting us share the test beam period with him. This work was supported in part by the Slovenian Research Agency under Grants nos. J1-9840 and J1-9339.

References

[1] K. Abe, et al., in: S. Hashimoto, M. Hazumi, J. Haba, J.W. Flanagan, Y. Ohnishi (Eds.), Letter of Intent for KEK Super B Factory, KEK Report 2004-04 〈http://belle.kek.jp/superb〉.
[2] I. Adachi, et al., sBelle Design Study Report, arXiv:0810.4084 [hep-ex].
[3] P. Križan, et al., Nucl. Instr. and Meth. A 567 (2006) 124; S. Korpar, et al., Nucl. Instr. and Meth. A 595 (2008) 169.
[4] S. Nishida, et al., Nucl. Instr. and Meth. A 595 (2008) 161.
[5] P. Buzhan, et al., An advanced study of silicon photomultiplier, ICFA Instrumentation Bulletin, vol. 23 (2001).
[6] D. Renker, Nucl. Instr. and Meth. A 567 (2006) 48.
[7] J. Haba, Nucl. Instr. and Meth. A 595 (2008) 154.
[8] M. Danilov, Nucl. Instr. and Meth. A 604 (2009) 183.
[9] S. Korpar, et al., Nucl. Instr. and Meth. A 594 (2008) 13.
[10] MPPC data sheet, Hamamatsu Photonics.
[11] I. Ariño, et al., Nucl. Instr. and Meth. A 516 (2004) 445.
[12] T. Iijima, S. Korpar, et al., Nucl. Instr. and Meth. A 548 (2005) 383.
[13] H. Miyamoto, et al., talk given at 11th Pisa Meeting on Advanced Detectors, Elba, May 2009; A. Vacheret, et al., talk given at TIPP09, Tsukuba, March 2009.