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Module of silicon photomultipliers as a detector of individual Cherenkov photons

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ABSTRACT

We have studied the possibility of using silicon photomultipliers as single photon detectors in a proximity focusing RICH with aerogel radiator. Such a counter is considered for the upgrade of the Belle detector. The main advantage of silicon over conventional photomultiplier tubes is their operation in high magnetic fields. Their disadvantage is the relatively high dark noise count rate ($\approx$ MHz/mm^2) which can be overcome by using a narrow time window in the data acquisition. A module, consisting of 64 (8×8) Hamamatsu MPPC S10362-11-100P silicon photomultipliers, has been designed, constructed and tested with Cherenkov photons emitted in an aerogel radiator by 120 GeV/c pions from the CERN T4-H6 beam. To increase the signal-to-noise ratio, i.e. to increase the effective surface on which light is detected, light concentrators have been employed.

1. Introduction

We are studying the proximity focusing ring imaging detector with aerogel radiator for particle identification at the foreseen upgraded Belle spectrometer [1,2]. Several photon detector candidates have been studied [3,4], none of which are completely immune to the high magnetic field present inside the Belle spectrometer. Silicon photomultipliers (SiPMs) [5] may change the situation. In addition to their insensitivity to magnetic fields, they are also small, robust and do not require high voltages. Among their disadvantages is the relatively high dark count rate (≈ 1 MHz/mm^2) and a low fraction of sensitive surface compared to the full area covered by the photon detector. These deficiencies may be reduced with light concentrators collecting light from a larger surface. In this way the geometric acceptance of the detector as well as the signal-to-noise ratio may be increased. 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 [6].

2. Experimental setup

A module of $64(8\times8)$ Hamamatsu MPPC S10362-11-100P silicon photomultipliers has been constructed (Fig. 1). The module consists of two printed circuit boards (Fig. 2). The main board houses the voltage divider chain, the filtering capacitors and the signal outputs, while the "piggy" board has silicon photomultipliers soldered on one side in a 8×8 matrix at 2.54 mm pitch. On the main board four neigbouring SiPM's are connected together, so that the module has 16 electronic readout channels. The voltage divider chain is adjusted with individual resistors such that all the SiPM have approximately equal gain. The output signals are amplified by the fast amplifier (Ortec FTA820), then discriminated (CAEN V814) and finally fed to a time to digital converter (CAEN V673A). A typical signal is shown in Fig. 3.

The module has been used as a photon detector in a proximity focusing Cherenkov detector (Fig. 4) with a 1 cm thick aerogel radiator ($n=1.03$ and 1.4 cm attenuation length at 400 nm). The detector was tested in a 120 GeV/c pion beam at the CERN T4 H6N beam line. The arrival of a beam particle was triggered by a scintillation counter and its trajectory was registered with two multiwire proportional chambers (MWPCs). The incident particle hit coordinates were obtained by delay line readout of the cathode wire planes.

In the aerogel, pions radiate Cherenkov photons at an angle relative to their track direction. These photons were detected by a photon detector plane at a distance of 115 mm from the aerogel upstream surface. As the SiPM sensitive area is 1 mm^2 and the pitch is 2.54 mm, the geometric acceptance of a pad is only 15.5%.

The rather low geometric acceptance of the SiPM detectors within an array can be increased by employing light guides. We have studied light guides in the form of truncated pyramids (Fig. 5). The geometric parameters for the simulation have been

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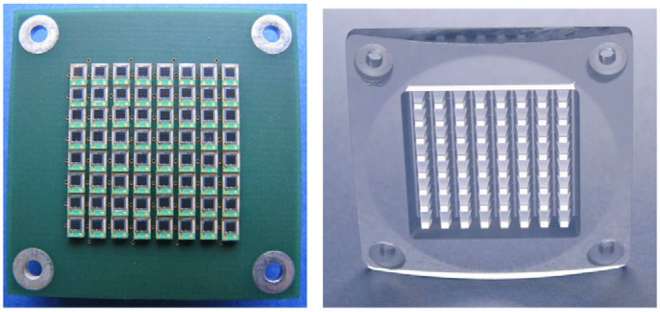

Fig. 1. The photon detector module consisting of 64 SiPMs (left) and the pyramidal light guides (right). Four SiPMs are grouped into a single readout channel.

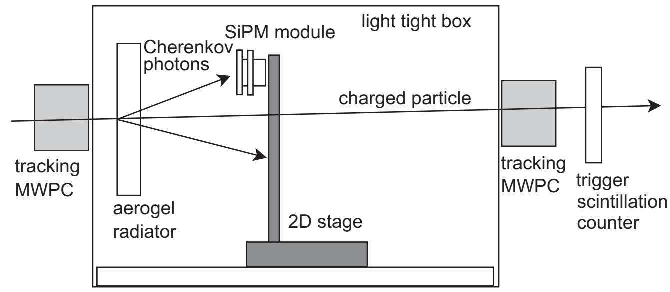

Fig. 4. The experimental setup: Cherenkov photons emitted by the charged pion in the aerogel slab are registered by the silicon photomultiplier module. The particle trajectory is measured by two multiwire proportional chambers and the data acquisition is triggered by the plastic scintillation counter.

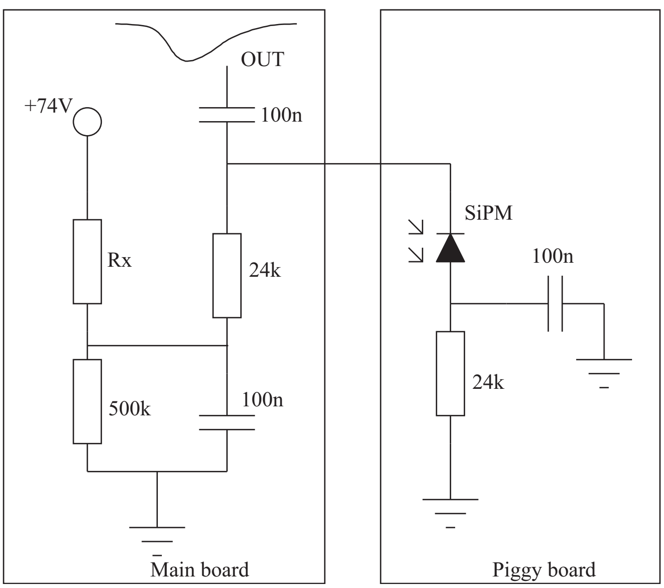

Fig. 2. The printed circuit boards schematic of electrical connections. The resistors Rx were chosen such that all the SiPM gains were approximately equal.

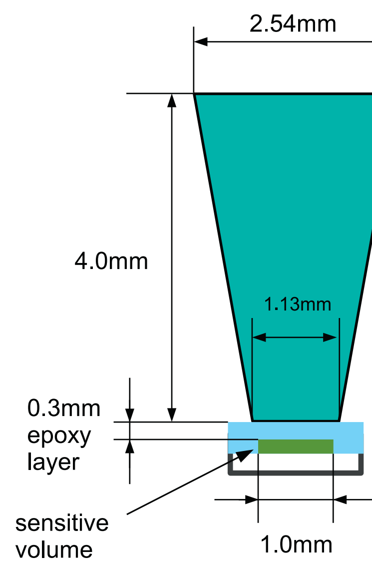

Fig. 5. A pyramidal light guide with dimensions optimized by simulation. Also shown are the main elements of the Hamamatsu MPPC S10362-11-100P, the protective epoxy layer and the sensitive volume.

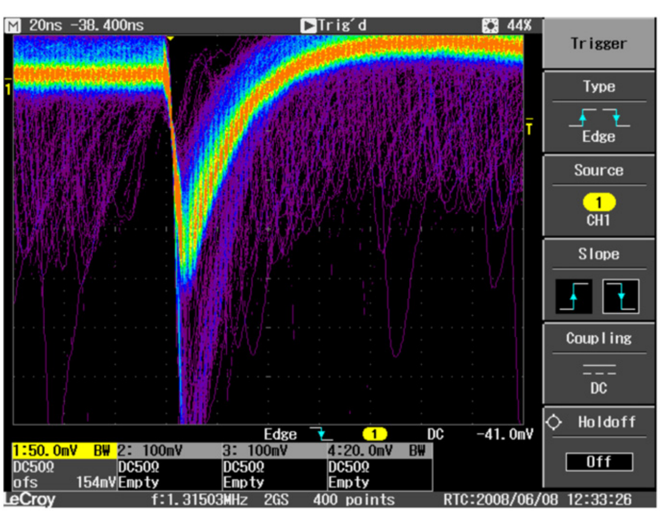

Fig. 3. The SiPM signal output corresponding to dark counts amplified by the Fast timing amplifier (Ortec FTA820).

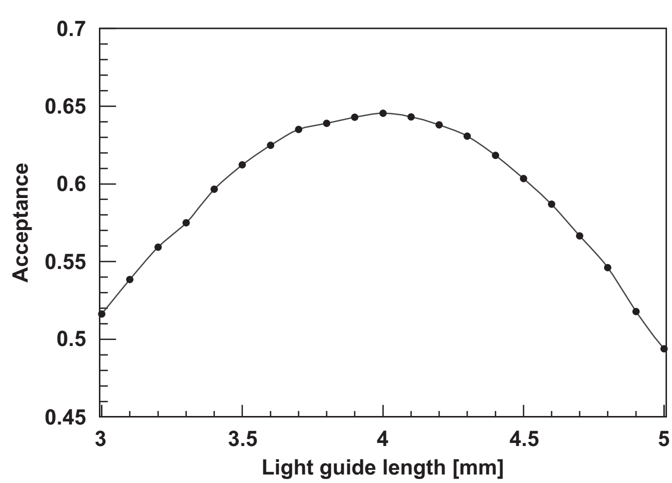

Fig. 6. Light guide acceptance as a function of light guide length.

such that the inclination of the pyramid lateral planes, as well as the size of the entrance window have remained fixed, while the length of the light guide has been varied. Photons have been generated with isotropic incident angle distribution up to $\vartheta = 30^{\circ}$ and with a uniform distribution over the surface of the light guide entry window. The acceptance as a function of light guide length is shown in Fig. 6. The loss of 35% of the photons is mainly due to

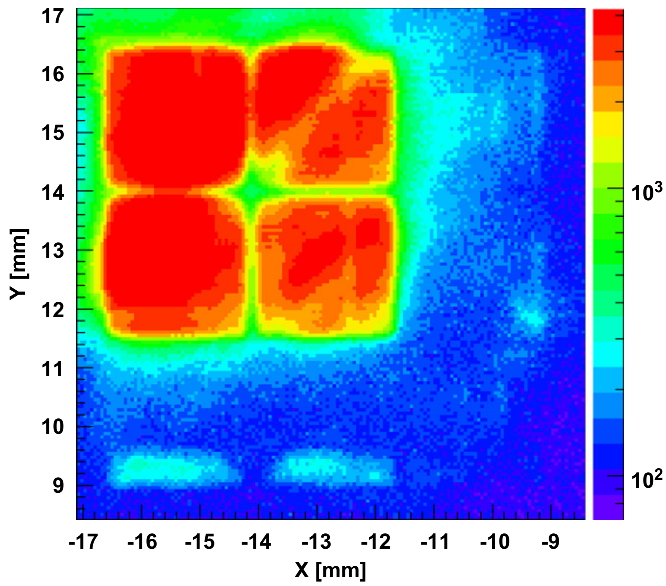

Fig. 7. The response to a perpendicular light beam of one of the electronic channels of the SiPM module with the light guides. The measured average acceptance increase for the module with the light guides is 2.4 for light incident at an angle of 18° (typical angle of Cherenkov photons in the beamtest setup).

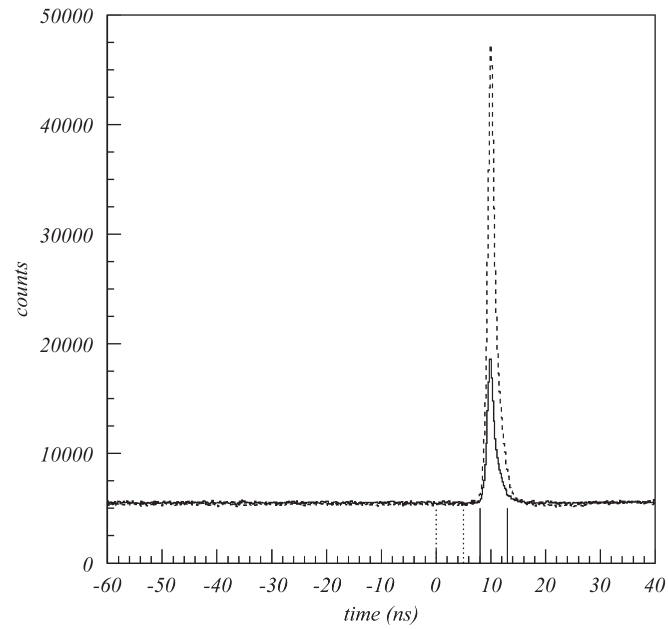

Fig. 8. The time spectra for the SiPM pulses in the case without (full line) and with (dashed line) the light collection system. The indicated cuts correspond to 5 ns time windows.

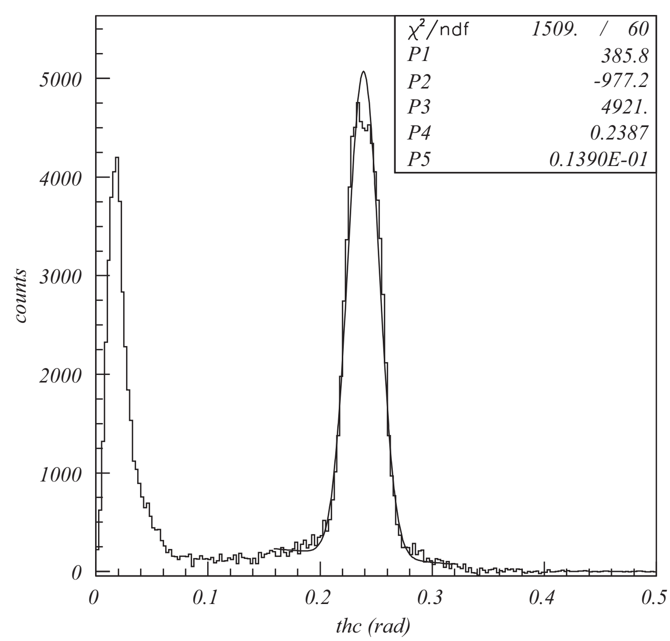

Fig. 9. The distribution of hits in Cherenkov angle with noise distributions subtracted. The plot is for the case with the light guides.

the 0.3 mm gap between the light guide exit window and the sensitive volume of the SiPM (Fig. 5) 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 four 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 [8]. Due to a limitation of the available machining procedure, the final 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 expected acceptance of 54%. A two-dimensional scan with the single photon light beam over the surfaces of the light guides (Fig. 7) shows that the response is uniform.

3. Results

We have measured a proximity focusing RICH prototype with a silicon photomultiplier module, with and without a light guide array. In Fig. 8, the time spectra of the SiPM pulses are shown for an equal number of triggered events, where a clear improvement with the light guide system may be observed. 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, e.g. 5 ns around the peak, will further increase the signal-to-noise ratio, to the level at which a measurement of Cherenkov rings is possible.

Due to the small size of the detector, data were acquired in eight positions on a 3 × 3 grid, with the central position excluded. For the module without the light guide the distribution of hits with respect to their corresponding Cherenkov angle is shown in Fig. 9 for hits within a 5 ns time interval. The background hits corresponding to the hits out of coincidence with the Cherenkov pulse were subtracted. By fitting the Cherenkov peak one obtains 1.6 detected photons per ring without the light guides and 3.7 detected photons per ring with the light guides for the case when the full ring is covered by the detector.

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.

4. Discussion

From estimates based on the photon detection efficiency of the MPPC S10362-11-100P supplied by the producer [7], geometric coverage and electronic efficiency, we would expect to detect about 2.3 Cherenkov photons per ring, while the actually

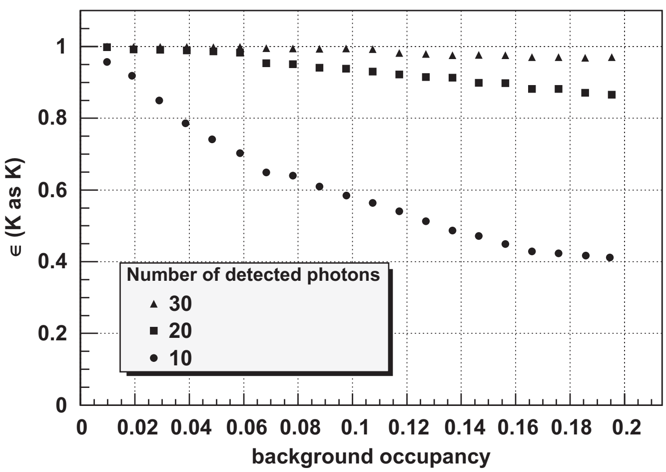

Fig. 10. Simulated identification efficiency at 1% misidentification probability for kaons at 4 GeV/c as a function of background level for three different yields of detected photons per ring. The simulated proximity focusing Cherenkov detector with an aerogel radiator consists of a focusing radiator [11] ($n_1=1.043$, $d_1=15$ mm and $n_2=1.05$, $d_2=15$ mm and attenuation length of 40 mm at 400 nm) and square photon detector array of SiPM modules at a distance 200 mm from the radiator. The background is simulated uniformly over the detector area.

measured number is 1.6 photons/ring. Most of the discrepancy can be explained by an overestimation in the manufacturer data on photon detection efficiency of the SiPM, which includes effects of crosstalk and afterpulses. This is in agrement with other authors [9] who also indicate that the manufacturers data are 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. This discrepancy is probably partly due to non-specular reflection and refraction on the side walls of the light guide and is in agreement with the bench tests (Fig. 7). 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 [10].

We hope 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.

We have also simulated detector response for prototype proximity focusing Cherenkov detector using different numbers of detected photons N_{det} and different backgrounds for pions and kaons [12,13]. $N_{det}=10$ corresponds to the use of conventional photomultipliers, and $N_{det}=20$ and 30 correspond to the detector with higher detection efficiency, e.g. to SiPM's. The kaon identification probability at 1% misidentification rate considerably improves with the increase of the number of photons (Fig. 10). For a typical background occupancy of 0.1 (1 MHz/mm^2 background rate and 10 ns detection time window) the kaon identification efficiency for $N_{det}=30$ is well above 95%.

We conclude that our investigations have demonstrated that such a proximity focusing ring imaging Cherenkov detector is feasible.

Acknowledgments

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