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Silicon photomultiplier as a position sensitive detector of Cherenkov photons

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Abstract

A novel photon detector, silicon photomultiplier, whose main advantage over photomultiplier tubes for RICH applications is the operation in high magnetic field environments, has been tested in view of measuring Cherenkov photons in a RICH counter. Results of the measurements of single photo-electron pulse height and timing distributions and of uniformity of the response are presented. Feasibility of a proximity focusing RICH counter using this type of photon detector is discussed.

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Keywords: Cherenkov detectors; Silicon photomultiplier

1. Introduction

Silicon photomultipliers are semiconductor photo-sensitive devices build from an avalanche photo-diode (APD) matrix on a common silicon substrate, working in the limited Geiger mode [1–3]. One of the benefits if compared to other position sensitive detectors used in the Ring Imaging Cherenkov (RICH) Counters is their insensitivity to the high magnetic fields. They have several other advantages (lower operation voltage, less material) over the conventional photomultiplier tubes. They also have a high peak photon detection efficiency (up to 70%), a high gain of about 10^6 and a good time response. Due to their dimensions, they allow compact, light, and robust mechanical designs.

All this would make them a very promising candidate for a photon detector of Cherenkov photons in a RICH counter. However, due to their serious disadvantage, a very high dark rate ($\approx 10^6\,\mathrm{Hz/mm^2}$), they have up to now never been used in RICH detectors, where single photon detection is required at low noise. Because the Cherenkov light is prompt, this problem can in principle be solved by using a narrow time window ($<10\,\mathrm{ns}$) for signal collection. In addition, it is possible to further increase the signal-to-noise ratio by using light collection devices.

One of the main issues of the present study was therefore to adapt this photo-sensor to single photon counting. We measured single photo-electron pulse height and timing distribution, and uniformity of the response of individual silicon photomultipliers.

2. Experimental setup

The silicon photomultiplier mounted on a motorized two-dimensional stage (National Aperture XY-MM-3M-ST) is enclosed in a light tight dark box (Fig. 1). It is illuminated by 635 nm light pulses from a laser head (Advanced Laser Diode System PiL063 with pulse width 35 ps FWHM). The light beam of $5\,\mathrm{mm} \times 2\,\mathrm{mm}$ cross-section is first attenuated using transmission filters and then collimated in the optical fiber which is fed in the experimental box. The beam is then expanded using another beam collimator. Using a semitransparent mirror, a part of the beam is deflected into the reference

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photomultiplier. The rest is focused using a biconvex lens ($f = 12$ mm) to a light spot of $\sigma = 5\,\mu$m. By using different transmission filters, the light intensity could be adjusted such that the probability to detect more than one photon is less than 1%.

The light spot was scanned across the surface of the silicon photomultiplier window in steps of $5\,\mu$m. The silicon photomultiplier was plugged in the PCB board with the output signal lines and the supply bias voltage, which was set to 3–4 V above the breakdown voltage. The signal was amplified (Ortec FTA 820) and part of it discriminated (Ortec CF8000 discriminator in leading edge mode). The analog part was fed in the charge sensitive ADC (LeCroy 2249A), while the discriminated signals were fed in the multihit TDC with 25 ps LSB (CAEN V1290A). The data acquisition system controlled by the LabWindows (National Instruments) program via the Wiener PCIADA PCI to VME adapter was triggered by a trigger pulse from a ALDS EIG1000D laser controller unit.

3. Results

Two different types of the silicon photomultiplier have been extensively tested: 1156 pixel MePhI/PULSAR TESLA type with square active surface, and a 556 pixel MRS APD by CPTA(Moscow) with approximately round active surface.

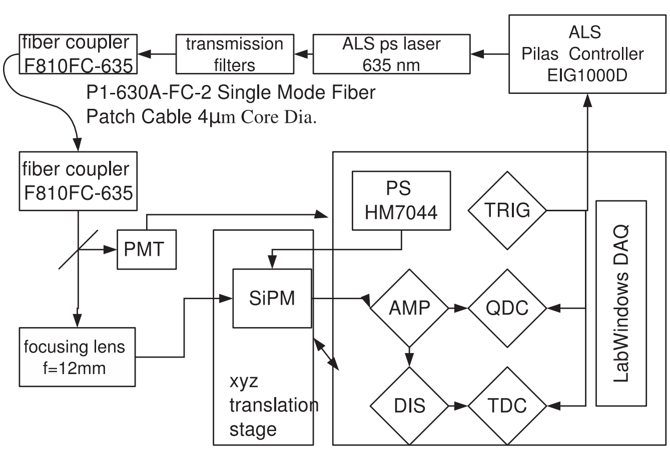

Fig. 1. Experimental setup.

To confirm that silicon photomultipliers can be used in an application such as RICH counters, where the single photon counting is necessary, we have first measured the time distribution of the signals, as well as their charge distribution (Fig. 2). The time distribution of detected hits shows a clear peak (pulse width 300 ps FWHM) corresponding to the photons from the laser. If a 10 ns timing cut is applied, the pulse height spectrum is dominated by single photon hits.

By measuring the time and charge distribution spectra across the surface, we obtained a two-dimensional response of the silicon photomultiplier for single photons. In Fig. 3 the height corresponds to the number of detected events with the signal within a 10 ns window. Note that the measured position intensity with clearly separated pixels reflects the underlying structure and shows that single photon detection is possible. The response of single pixels is for both silicon photomultiplier types fairly uniform.

4. Simulation study

A simulation study has been made to check whether such a photon detector can be used in a proximity focusing RICH with aerogel radiator as foreseen for the Belle upgrade [4–6]. In the simulation, the proposed geometry of the detector has been used (2 cm aerogel tiles with refractive index $n = 1.05$ and a 45 mm transmission length at 400 nm, and a proximity expansion gap of 18 cm). We assumed 20 detected photons per ring. The photon detector for such a counter would be comprised of silicon photomultipliers with an active area of $4\,\text{mm}^2$ and a light collector to concentrate the light from a pad size of up to $6 \times 6\,\text{mm}^2$. A 4 MHz background rate per silicon photomultiplier results in about 4% background hit probability in a 10 ns electronic window. To enhance the ratio of the number of detected Cherenkov photons over background hits, electronics with narrower time window (down to 2 ns) could be used, leading to a background hit probability of

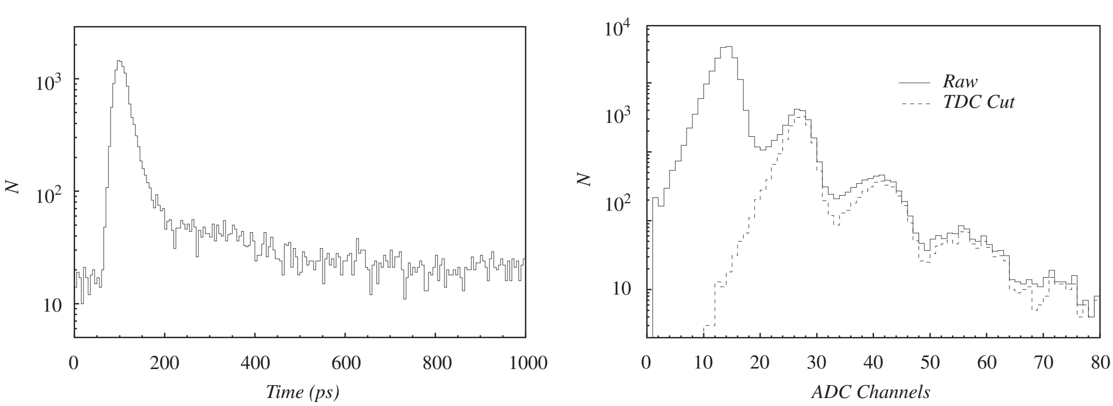

Fig. 2. Time distribution (left) and charge distribution (right) of the response of the 1156 pixel MePhI/PULSAR silicon photomultiplier to the pulsed light source. In the charge distribution the raw spectrum (full lines) and a spectrum for signals within 10 ns window around the peak (dashed) are shown.

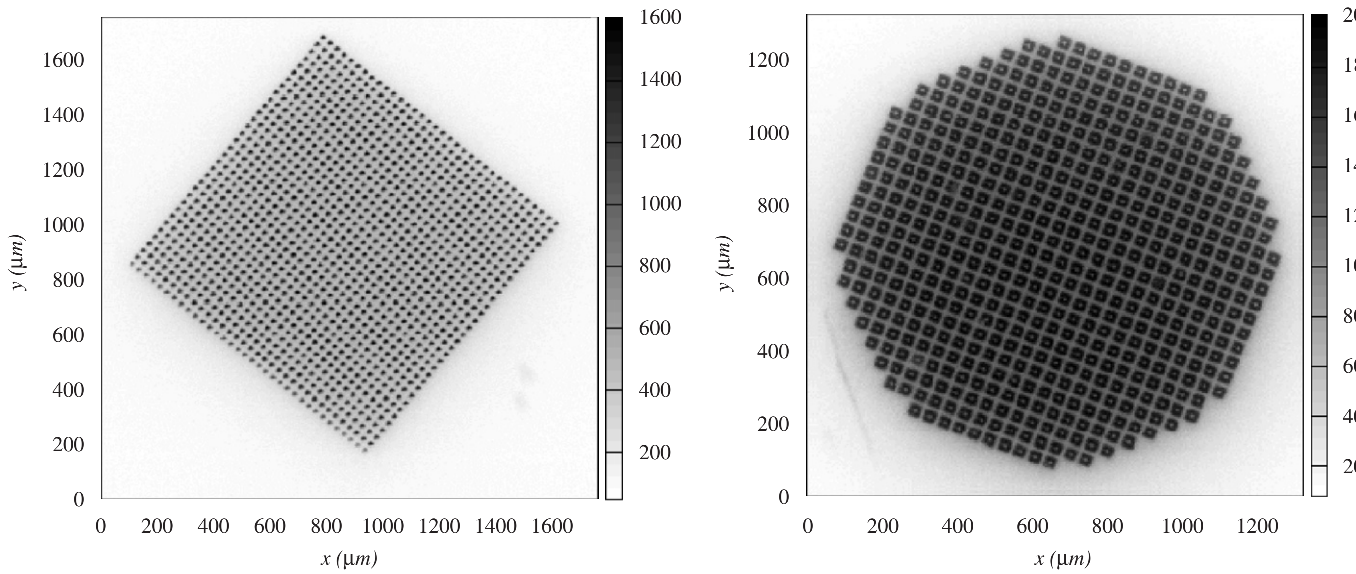

Fig. 3. Surface sensitivity to single photons for 1156 pixel MePhI/PULSAR silicon photomultiplier (left) and for 556 pixel MRS APD by CPTA (Moscow) (right).

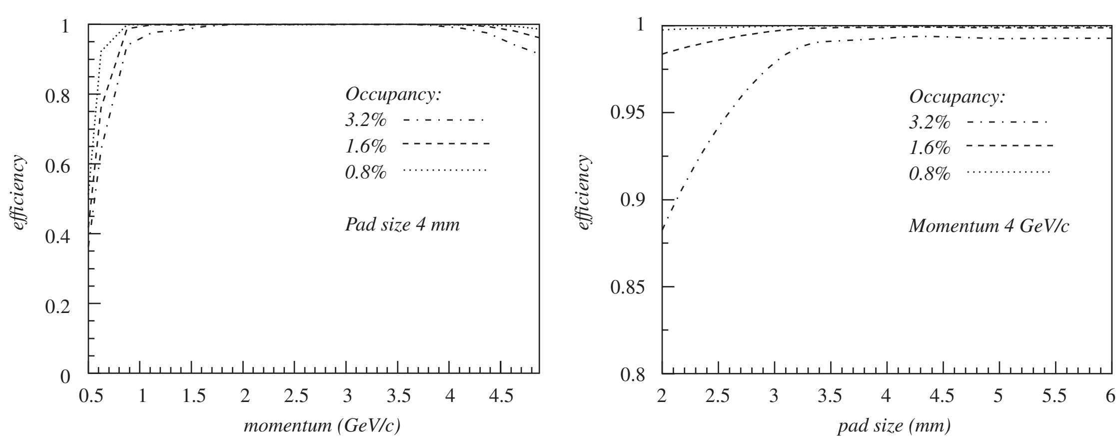

Fig. 4. Kaon identification efficiency at 1% pion misidentification probability as a function of particle momentum for a detector with a pad size of $4 \times 4\,\mathrm{mm}^2$ (left) and as a function of the detector pad size for $4\,\mathrm{GeV}/c$ kaons (right), both for different background hit occupancies.

0.8 MHz. Fig. 4 shows the kaon identification efficiency for several different background hit probabilities. It can be seen that the kaon identification efficiency is high in the kinematic region $1-4\,\mathrm{GeV}/c$, while the pion misidentification probability is kept low (at 1%). Some decrease in the efficiency can be observed at $4\,\mathrm{GeV}/c$ for high background hit probabilities, if the effective pad size is reduced to the silicon photomultiplier size, i.e. in the case without light collection.

5. Conclusions

We have measured the position dependence of the silicon photomultiplier signal for single photons for two different types of the silicon photomultipliers: a 1156 pixel MEPhI/PULSAR silicon photomultiplier and a 556 pixel MRS APD by CPTA(Moscow). By scanning a 5 μm wide single photon 635 nm light beam across the photosensitive surface of the silicon photomultiplier, we have measured the variation of sensitivity, which mainly reflects the underlying structure of the device. We observe that the position response is fairly constant for pixels, although there is somewhat more variation within the pixel. If read out with a suitable electronics with a 10 ns time window, the background hit probability is 4%, which can be further reduced with a narrow time window. Our study shows that silicon photomultipliers are a possible candidate for the photon detectors in RICH counters.

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