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Study of a 144 channel multi-anode hybrid avalanche photo-detector for the Belle II RICH counter

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ABSTRACT

A new hybrid avalanche photo-detector has been developed as a photon sensor for the Belle II RICH counter. Single-photon response was investigated in the presence of a magnetic field and excellent performance was demonstrated. In addition, the radiation damage due to the neutron dose was studied. By building a prototype consisting of six photo-detectors, a test beam experiment was carried out. We successfully obtained a single-photon Cherenkov resolution of 13.5 mrad with 15.3 photoelectrons and achieved a π/K separation of more than 6σ at 4 GeV/c.

1. Introduction

Excellent particle identification, in particular, π and K separation, is of prime importance in a B-factory experiment [1]. For the Belle II experiment at KEK, a proximity focusing RICH counter with a silica aerogel radiator has been studied to extend π/K separation capability beyond 4σ at 4 GeV/c in the end-cap region. A proximity focusing arrangement featuring a 200-mm expansion distance is a unique choice because the space available is acutely limited owing to the present Belle end-cap structure. In case that silica aerogel having a refractive index (n) of 1.05 is used as the radiator, the Cherenkov angle difference between π and K at 4 GeV/c is calculated as 23 mrad.

The photon sensor is one of the most critical components of this RICH counter, and it should satisfy the following requirements: (1) high sensitivity to a single photon, (2) large active area, (3) pixel size of $5\times5\,\text{mm}^2$, and (4) proper operation under a magnetic field. To fulfill these requirements, we have been developing a new hybrid avalanche photo-detector (HAPD) with Hamamatsu Photonics K.K. (HPK). This device is a vacuum tube coupled with the solid state sensors of the avalanche photo-diodes (APDs). Fig. 1 shows the schematic of the HAPD operation. Cherenkov photons emitted from a silica aerogel radiator enter a bi-alkali photocathode through a quartz window to generate photoelectrons. These photoelectrons are accelerated via an electric field generated by a high voltage of -7 to -8 kV applied to the vacuum tube. The accelerated photoelectrons are bombarded on the APD chips, each of which is pixelated into 6×6 pixels with a pad size of $5\times5\,\text{mm}^2$. The APD sensor further amplifies the input signal ~50 times via an avalanche process owing to the application of a reverse bias voltage. Four APD chips are housed in one HAPD; hence, there are 144 channels in total. Therefore, the overall gain is obtained to be 10^4-10^5 as a product of bombardment gain and avalanche gain. New HAPDs have been delivered since 2008 from HPK and detailed studies have been carried out.

In this paper, the fundamental characterizations including a test under a magnetic field are described in Section 2. Section 3 is devoted to the effect of neutron radiation damage on the HAPD. The results from a test beam experiment are presented in Section 4. Finally, in Section 5, we summarize the paper.

2. HAPD development and bench test

In an HAPD, the typical quantum efficiency (QE) at a wavelength (λ) of 400 nm is around 20–25%. A new technique,

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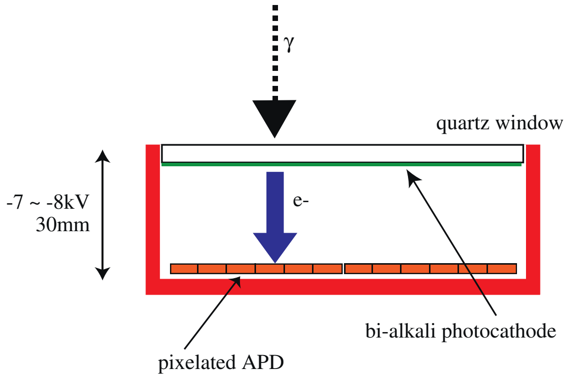

Fig. 1. Schematic view of HAPD operation.

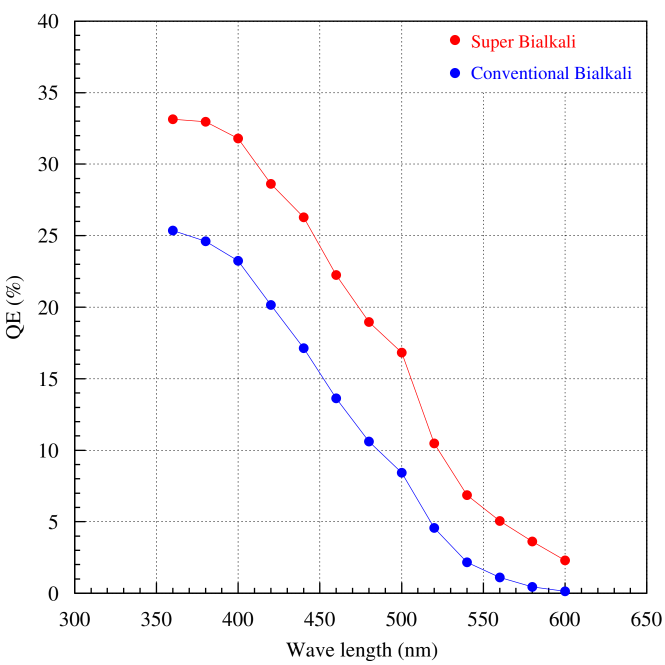

Fig. 2. Quantum efficiencies (%) as a function of wavelength (nm), where measurements were carried out using a Xenon lamp followed by a monochromator. The red and blue curves denote the high QE sample and the conventional one, respectively. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

which is used to fabricate the so-called "super bi-alkali" photocathodes, was applied to HAPD photocathode fabrication for the first time at HPK. As a result, peak QE was enhanced and 33% at $\lambda = 360$ nm was achieved, as shown in Fig. 2.

By illuminating with a blue LED, the single-photon response was investigated. Fig. 3 shows the pulse height distribution for multiple photons. As can be seen, a clear single-photon peak was detected. The total gain of this device was measured to be 9.1×10^4. The signal-to-noise (S/N) ratio derived by dividing the gain by a σ value obtained from a Gaussian fit to the pedestal peak was 16.4.

The detailed response of all the HAPD channels was investigated using a custom-made readout system based on ASIC technology. This electronics involves signal amplification and digitization; the threshold values can be externally loaded [2], and only digitized data are recorded using a personal computer. In our study, the threshold was set to be ~ 0.5 photoelectrons. A laser light source ($\lambda = 440$ nm) was placed on the movable stage, which can be remotely controlled. The position of the incident light was moved in a two-dimensional way so as to cover the entire HAPD surface and hence check all the pad responses. We performed this scan with and without an axial magnetic field of 1.5 T, and the obtained results were compared with each other. Fig. 4 shows the

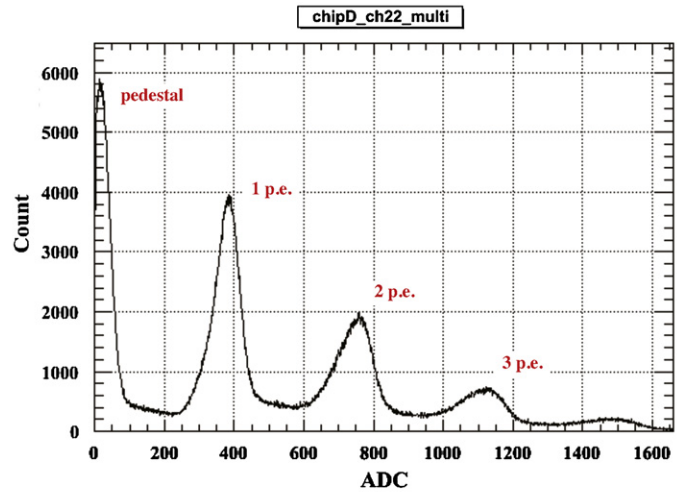

Fig. 3. Pulse height distribution for multiple photons.

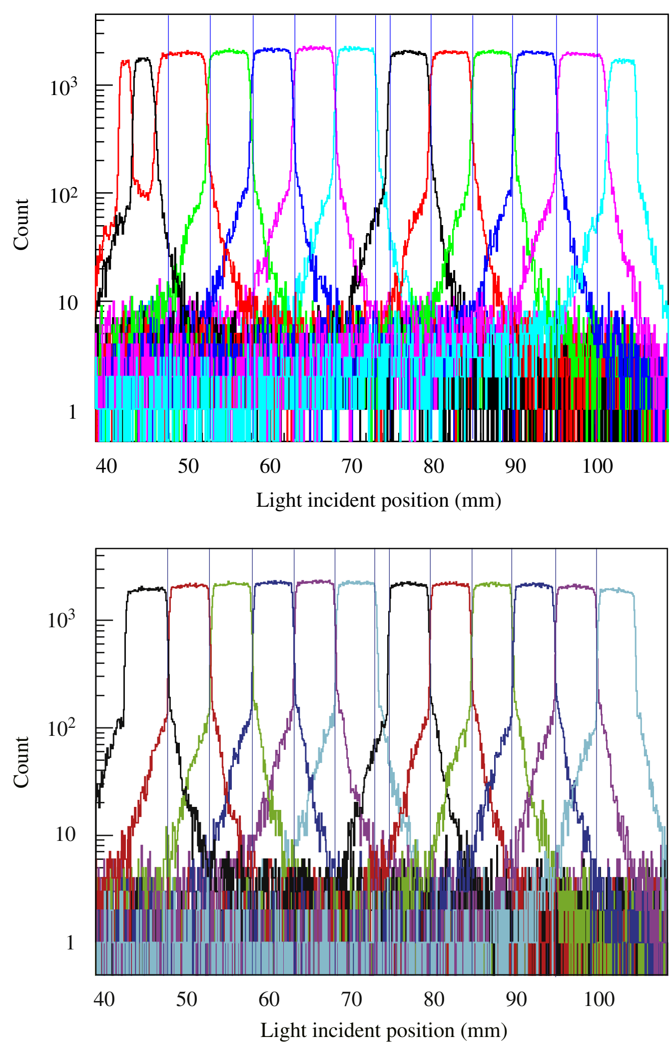

Fig. 4. Hit distribution for one HAPD row scan without (top) and with (bottom) a magnetic field of 1.5 T.

hit distributions obtained by scanning one HAPD row with and without a magnetic field. The distinct response from each APD pixel was measured in both cases, and no degradation in the photon sensitivities was observed in the presence of the magnetic field. The unusual response observed in the leftmost pixel in the absence of the magnetic field was caused by electric field distortion near the HAPD tube edge; this response was eliminated on the application of the magnetic field.

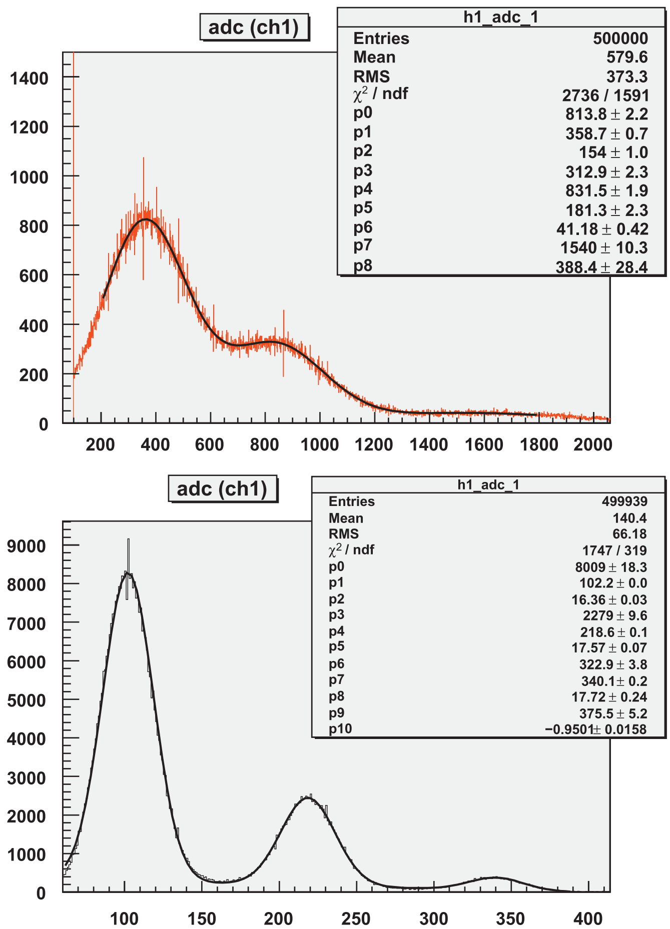

Fig. 5. Pulse height distributions of HAPD after 5×10^{11} neutrons/cm^2 irradiation with a peaking time of 1 μs and HV of −7 kV (top) and a peaking time of 20 ns and HV of −8.5 kV (bottom).

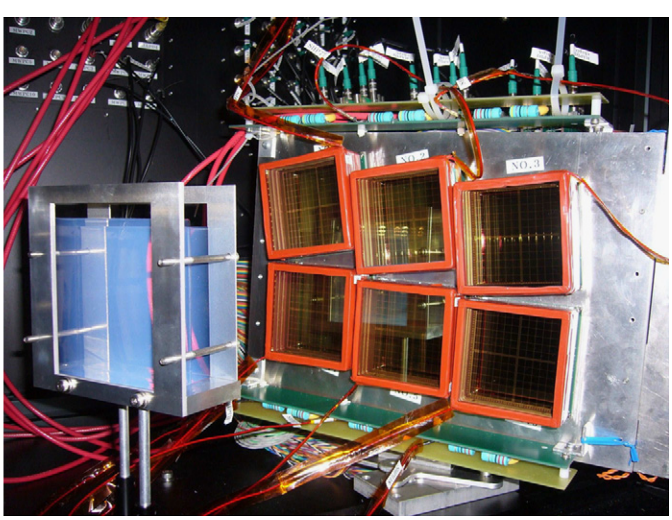

Fig. 6. RICH prototype counter.

3. Neutron radiation damage

In the Belle experimental environment, the neutron background turned out to be one of the most serious hindrances to the operation of our detector. From a naive extrapolation at the present value, a neutron flux of 1×10^{11} neutrons/cm^2 is estimated for a Belle II year [3]. In the case of an HAPD, the silicon device of the APD chips could get damaged due to neutron exposure and an increase in the APD leakage current could result in further generation of noise and hence a degraded single-to-noise ratio. To examine this effect, we performed several neutron irradiation tests using the "Yayoi" nuclear reactor [4]; the average neutron energy is 370 keV. We irradiated the HAPDs up to 5×10^{11} neutrons/cm^2, corresponding to a 5-year operation of the Belle II, and checked the quantum efficiency and single-photon sensitivity. No degradation was found in the quantum efficiency, however, an increase in the APD leakage current was observed in

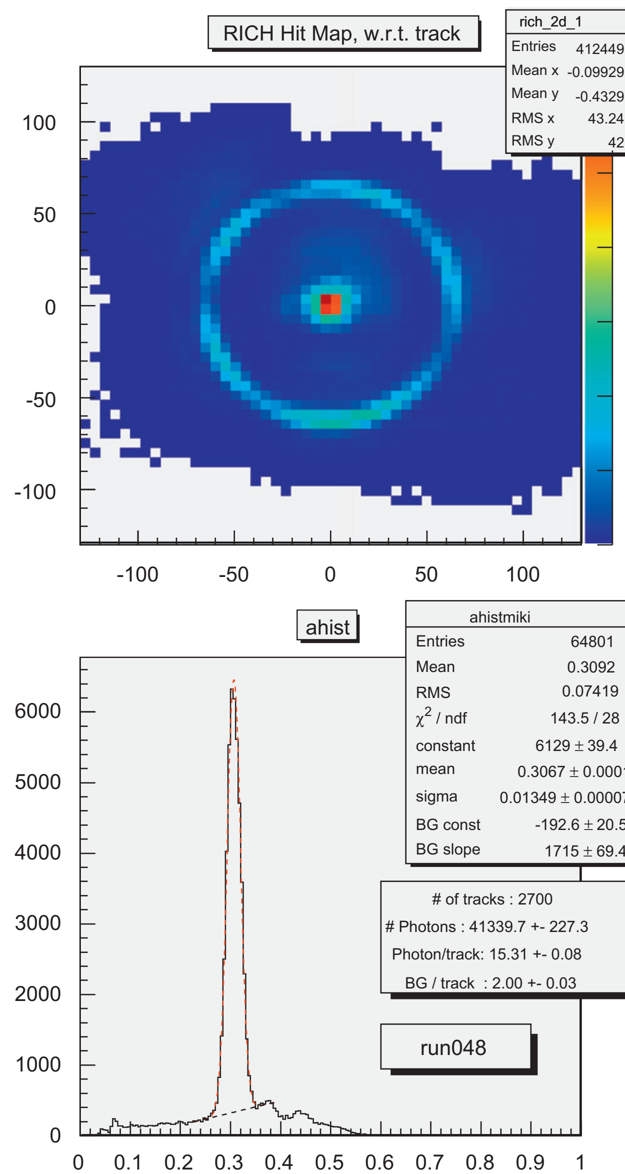

Fig. 7. Obtained Cherenkov image and Cherenkov angle distribution.

the irradiated sample. A degradation in the signal-to-noise ratio was then detected, as shown in Fig. 5 (top). Initially, S/N was ~ 17. However, after the neutron exposure of 5×10^{11} neutrons/cm^2, S/N was ~ 3; the single-photon signal was barely distinguishable from the pedestal peak. This can be rectified by shortening the peaking time adopted in the readout electronics. As an ultimate case, the response using a peaking time of 20 ns is shown in Fig. 5 (bottom), where HV is also increased to -8.5 kV. The single-photon peak can be clearly observed and S/N is calculated to be about 7.

By optimizing the parameters of the readout electronics, i.e. by shortening the peaking time, the radiation damage can be mitigated for the practical HAPD operation. Further tests by irradiating with 1×10^{12} neutrons/cm^2 are in progress. In addition, as an alternative approach, a new radiation-tolerant APD sensor is being developed at HPK. New radiation-tolerant HAPDs will be fabricated this year, and they will be irradiated to examine their performance.

4. Test beam experiment

To carry out a test beam experiment, we built a RICH prototype counter using silica aerogel radiators. The photon detector system was configured as a 2×3 array of HAPDs, as shown in Fig. 6. The readout electronics was the same as the one described in Section 2. The remaining experimental setup was almost identical to that mentioned in Ref. [5]. The incident track parameters were determined by two multi-wire proportional chambers located upstream and downstream of the prototype RICH counter. The KEK Fuji test beam line, where 2-GeV/c electrons are available, was used.

As Cherenkov radiator, two layers ($n=1.054$ and 1.065), each of which was a 20-mm-thick silica aerogel tile, were placed with keeping the expansion distance to be 200 mm. Their refractive indices were selected so that the two Cherenkov ring images generated from each layer overlapped onto the HAPD surface plan [5]. The transmission lengths at $\lambda=400$ nm were 47.8 mm for $n=1.054$ and 55.2 mm for $n=1.065$. The production procedure and optical quality measurements for these samples can be found in Ref. [6].

A clear Cherenkov image was obtained, as shown in Fig. 7 (top). The Cherenkov angle distribution is also shown (Fig. 7, bottom); a single-photon angle resolution (σ_0) was extracted to be 13.5 mrad by fitting this peak to a Gaussian. By integrating the fitting function over a $\pm3\sigma$ area, the photoelectron yield N_{pe} was calculated to be 15.3, where the background was assumed to be a one-dimensional polynomial. Based on a naive calculation, one can expect the angle resolution per track to be $\sigma_0/\sqrt{N_{pe}}=$ 3.5 mrad, corresponding to 6.6σ π/K separation capability at 4 GeV/c.

5. Conclusions

A new HAPD was developed as a photon sensor for the Belle II RICH counter with HPK. Excellent single-photon sensitivity was demonstrated with and without a magnetic field, and recent improvement in quantum efficiency was achieved to be more than 30% at peak. Possible damage due to the neutron dose was investigated; our HAPD can detect single-photon signals up to 5×10^{11}/cm^2. Further studies to realize single-photon detection after exposure to a neutron flux of 10^{12}/cm^2 are in progress. The test beam results indicate that a full size detector will achieve π/K separation of more than 6σ.

References

[1] Belle II Collaboration, Technical Design Report, 2010, to be published.
[2] S. Nishida, et al., Nucl. Instr. and Meth. A, to be published, doi:10.1016/j.nima.2010.03.051.
[3] I. Nakamura, J. Phys. Conf. Ser. 160 (2009) 012003.
[4] Yayoi Nuclear Reactor at the University of Tokyo, Tokai, Ibaraki 〈http://www.nuclear.jp/index-e.html〉.
[5] T. Iijima, S. Korpar, et al., Nucl. Instr. and Meth. A 548 (2005) 383.
[6] I. Adachi, et al., this issue;
M. Tabata, et al., Nucl. Instr. and Meth. A 623 (2010) 399.