Performance evaluation of the HAPD in the Belle II Aerogel RICH counter

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The Hybrid Avalanche Photo Detector (HAPD) is used as a photon detector for Aerogel Ring Imaging Cherenkov counter (ARICH), a particle identification device at Belle II. ARICH measures Cherenkov angles of photons emitted in silica aerogel radiators, hence a high photon detection efficiency is required by the HAPD module, a combination of HAPD and front-end electronics board. We evaluate the performance of the HAPD modules by measuring the noise level, the offset value, the pulse height, temperature dependency and the variation of performance in the beam commissioning period. This article describes the results of performance evaluation of the HAPD and shows that it fulfills the requirements of ARICH.

KEYWORDS: Cherenkov detector, particle identification, hybrid photon detector

1. Introduction

The Hybrid Avalanche Photo Detector (HAPD) has been developed with Hamamatsu Photonics K.K. and is used as a photon detector for the Belle II Aerogel Ring Imagine Cherenkov counter (ARICH). ARICH is a particle identification device located at the endcap region of the Belle II spectrometer [1–3] and consists of 248 silica aerogel tiles forming Cherenkov radiator, an expansion volume, 420 HAPDs and front-end electronics [4–6]. Particle identification based on ARICH uses a Cherenkov angle information to discriminate...
charged particles pions, kaons, electrons, muons and protons. The number of detected pho-
tons per each track is approximately 10 and photon detection inefficiencies result in the
degradation of discrimination among particle species. Good performance of the HAPDs is
essential for ARICH.

2. Mechanism of the HAPD

An HAPD consists of a photo-cathode and four Avalanche Photo Diodes (APDs), and is
packed in a vacuum tube (Fig.1). Each APD chip has 36 pixels, and the size of each pixel
is $4.9 \times 4.9$ mm$^2$. An HAPD has two amplification mechanisms: bombardment amplification
and avalanche amplification as shown in Fig.2. In an HAPD, an incident photon is converted
to a photo-electron, which is accelerated by a negative high voltage applied up to $-8500$ V,
and enters into an APD, where electron-hole pairs are generated. The generated electrons
are multiplied in the high field region of an APD created by a reverse bias voltage. The
bombardment gain is around 1800 and the avalanche gain is around 40. As the result, the
gain of HAPD is around 72000 in total.

3. Performance evaluation of the HAPD

We evaluate the performance of the HAPD modules, a combination of HAPDs and front-
end electronics boards, for the following items: noise level, offset value, pulse height, temper-
ature dependency and the variation of performance during the beam commissioning period.
The HAPDs are operated with lower high voltage ($-6000$ V) during the all measurements
and the bombardment gain is around 1200. Thus, total gain at operation voltage is around
48000.

3.1 Noise level, offset value, pulse height

We measure noise level, offset value and pulse height. The noise level should be sufficiently
smaller than the pulse height for single photon. The zero voltage level of each channel is
different from each other, and an additional voltage is applied for each channel to adjust the
offset value. This offset can be also used to adjust the effective threshold for each channel.

We measure the noise level with and without bias voltage. When we apply bias, the
depletion region is generated in side the APDs, and hence the noise level decrease as seen in
Fig 3. The measured noise level averaged over all channels is 13.3 mV without applying bias
voltage. On the other hand, the measured average noise level is 6.5 mV while applying bias voltage and it is equivalent to the signal of 3800 electrons. This value is sufficiently small compared to the expected signal of 48000 electrons.

The distribution of offset value is shown in Fig. 4. The target offset value during the detector calibration was set to 60 mV and the mean of the measured distribution is 61.7 mV with the variation of 2.3 mV. The variation is required to be sufficiently smaller than noise level since we set common threshold voltage for all channels. Therefore, we conclude offset is well adjusted.

The pulse height is measured with a monitor system equipped inside ARICH [7]. It injects light from LEDs via optical fiber into ARICH. We measure the hit rate while changing threshold voltage and then make a histogram and fit to find a shoulder that correspond to the pulse height. The distribution of the pulse height is shown in Fig. 5. The mean value of pulse height is 59.7 mV. For a part of channels, the fit is not successful due to incomplete modeling of the shoulder, and this causes a lower tail of the distribution. Comparing the noise level, the signal-to-noise ratio is 9.1 and it is sufficiently large.

![Bias:OFF](bias_off.png)  ![Bias:ON](bias_on.png)  ![Bias:OFF](bias_off.png)

**Fig. 3.** The distribution of the noise level. Red line and blue line are with and without bias voltage.

**Fig. 4.** The distribution of the offset value by setting to be 60 mV.

**Fig. 5.** The distribution of the pulse height.

### 3.2 Temperature dependency

During the beam commissioning period, we find that the temperature of the electronics is higher than our expectation. It is caused by insufficient cooling system and for the most of the time we operated only part of the electronics. We evaluate the temperature dependency of the HAPD performance measuring the average offset value, the variation of the offset value, the noise level and pulse height at three different temperatures: 30°C, 36°C and 41°C. The results are written in Table I. Bias voltage is only applied during the measurement of pulse height. The offset values are not changed significantly and pulse height is still well above the noise level considering reduction of noise level by applying bias voltage. As a result, good performance is kept at higher temperature.

**Table I.** The results of temperature dependency for the HAPD performance.

| Temperature | Offset Value [mV] | Variation of Offset Value [mV] | Noise Level [mV] | Pulse Height [mV] |
|-------------|-------------------|--------------------------------|------------------|-------------------|
| 30 degree   | 61.7              | 2.3                            | 13.4             | 66.4              |
| 36 degree   | 60.8              | 1.7                            | 15.8             | 62.0              |
| 41 degree   | 60.5              | 1.8                            | 15.7             | 55.7              |
3.3 **Operation during the beam commissioning**

We evaluate the variation of the HAPD performance during 3 months of the beam commissioning period. We measure the signal-to-noise ratio (Fig.6), calculated from the noise level and pulse height, and the fraction of dead channels (Fig.7). The fraction of dead channels in used HAPDs is measured comparing number of hits LED on/off using LED monitor system. The signal-to-noise ratio is kept greater than 6. The fraction of dead channels is kept below 1 %. Therefore, no degradation is seen during the beam commissioning period.

![Fig. 6. Trend of the signal-to-noise ratio.](image)

![Fig. 7. Trend of the fraction of dead channels.](image)

4. **Summary**

The HAPD is used in ARICH as a photon detector. We evaluate the performance of the HAPDs by measuring the noise level, the offset value, pulse height, the temperature dependency and the variation in the beam commissioning period. The noise level is sufficiently smaller than the pulse height, and the offset value is well aligned. The good performance of the HAPD is kept even at the higher temperature. No degradation is seen during the beam commissioning period. We conclude that the HAPD has good performance in the beam commissioning period.

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