Development and Performance Evaluation of Large-Aperture Hybrid Photo-Detector for Hyper-Kamiokande

Tianmeng Lou for the Hyper-Kamiokande Proto-Collaboration
University of Tokyo, Department of Physics, Tokyo, Japan
E-mail: lou@hep.phys.s.u-tokyo.ac.jp

Abstract. We have been developing the 50 cm Hybrid Photo-Detector (HPD) for Hyper-Kamiokande, a next generation underground large water Cherenkov detector, to improve the detection capability of the Cherenkov photons compared to Photo-Multiplier Tube used in Super-Kamiokande (SK PMT). A 20 mm diameter size is required for an avalanche diode (AD) to reach a sufficient collection efficiency. By developing segmented and low capacitance ADs, we successfully suppressed a noise accompanied with the large junction capacitance of the AD. Compared with the SK PMT, the HPD has three times better single photo-electron resolution of 10\(\times\)15\% and twice better timing resolution of 1.5 ns with bias voltage of 570V.

1. Hyper-Kamiokande project
Hyper-Kamiokande (HK) is a next generation underground large water Cherenkov detector, based on the Super-Kamiokande (SK) experiment [1]. HK consists of two cylindrical water tanks which are 60 m in height and 74 m in diameter. Its fiducial (total) mass is 0.37 (0.52) Mtons, which is 17 times of that of SK. Forty thousand of photodetectors with 50 cm diameter will be used in the inner detectors and six thousand and seven hundred of photodetectors with 20 cm diameter will be used in outer detectors to veto cosmic-ray muons. HK has rich physics targets: precise study of neutrino oscillation (determination of mass hierarchy and \(\theta_{23}\) octant) and the measurement of CP violation in lepton sector using beam and atmospheric neutrinos, search for proton decay to verify grand unified theory, observation of astrophysical neutrino and neutrino geophysics.

2. Hybrid Photo-Detector
A Hybrid Photo-Detector (HPD) is a photo-detector using an Avalanche Diode (AD) instead of metal dynodes for a PMT. Photo-electrons produced at the photocathode are accelerated by a high electric field (8 kV) to the AD, resulted in multiplication by bombardment. Electron-hole pairs are created inside the AD, where a high bias voltage of 400 - 500 V is applied to amplify electrons by a factor of \(~50\) in avalanche multiplication. The gain of only an HPD becomes \(~10^5\) and a preamplifier is employed to obtain the total gain equivalent to a SK PMT (\(~10^7\)). Because of the high gain at the first amplification stage, a HPD has better charge resolution than that of a SK PMT. The fluctuation of the drift path in the AD is small, therefore the timing resolution of a HPD is better than those of a SK PMT.
3. Development of HPD
As a prototype of a large aperture HPD, a 20 cm HPD with a 5 mm diameter (ϕ) AD was developed [2]. The prototypes are now under a proof test in a 200 ton water tank where they showed good performances [3]. With using the same 5 mm ϕ AD, we developed a 50 cm HPD for an initial production test and confirmed good performances as well [4]. To improve collection efficiency over 90%, a 20 mm ϕ AD is required. However, it is accompanied with a large noise by a large 800 pF junction capacitance, increased from 50 pF in the 5 mm ϕ AD.

One of two solutions we tried is increasing thickness of AD in order to decrease the junction capacitance. The other is using segmented AD and decreasing the junction capacitance of each channel. Trans-impedance preamplifiers are used to amplify the signal of each channel and the signals are read out individually or summed to the output. Following these solutions, we have developed three types of HPDs: HPD with 5ch AD (160 pF/ch), HPD with 2ch half capacitance AD (200 pF/ch), HPD with 1ch half capacitance AD (400 pF/ch).

4. Performance evaluation of 50 cm HPD

4.1. Detection capability of single photo-electron
The detection capability of single photo-electron (p.e.) is evaluated by the ratio of sigma to mean of 1 p.e. peak of the charge distribution (Figure 1). The distribution is evaluated by a composite function of two Gaussian and two error functions with taking into account contamination of photo-electron backscattering on the AD. As a result compared in Table 1, the 1 p.e. resolution of HPD is three times better than that of SK PMT which is used in Super-K for 20 years and twice better than Box&Line PMT (B&L PMT) which is another candidate of photo-detector for HK.

4.2. Timing resolution
We developed a fast preamplifier, while keeping the high charge resolution. It was only used to evaluate the timing resolution so far because it only recently becomes available. The timing resolution of HPD is evaluated by measuring the transit time spread (TTS) of 1 p.e. signal. The transit time is defined by the time from a trigger of light source to 0.5 p.e. threshold. The TTS of 1ch HPD in sigma is 2.2 ns with bias voltage ~520 V and 1.5 ns with bias voltage ~570 V after time walk correction. This is twice better than that of SK PMT’s and the same level as that of B&L PMT’s.

4.3. Dark rate
The dark rate of HPD is measured as a function of threshold at room temperature (25°C). Figure 2 shows the measured dark rate of 1ch HPD and 2ch HPD. The dark rate of HPD is ~10 kHz with a threshold of 0.5 p.e. Considering the temperature dependency, the dark rate of HPD is expected to be the same level as that of SK PMT (~4 kHz) at lower water temperature (~16°C) in HK operation. It is still not stabilized completely and there might be room to reduce the level further.

4.4. Rate tolerance
If supernova explosion occurs at 10 kpc from the earth, O(10^5) Hz event rate in low energy are expected at HK. Therefore, it is necessary for the photo-detectors to have sufficient high rate tolerance. We measured rate tolerance of the HPD signal (or output) charge by changing the frequency of light pulse. As shown in Figure 3, the output is constant within 5% up to 1.2 MHz for 50 p.e. signal. It is sufficient to detect any supernova burst events, while the preamplifier limits the performance by a pulse width of ~100 ns.

1 This is the result updated in September 2016.
Figure 1. Charge distribution of single readout of each HPD’s type. The blue line shows 5ch HPD, the red line shows 2ch HPD and the green line shows 1ch HPD.

Table 1. 1 p.e. charge resolution of each photo-detector (PD). The 1 p.e. resolution of HPD is three times better than that of SK PMT and twice better than Box&Line PMT.

| PD Type         | 1 p.e. Resolution [%] |
|-----------------|-----------------------|
| 5ch HPD (Single)| 10.0                  |
| 2ch HPD (Single)| 10.3                  |
| 2ch HPD (Sum)   | 14.8                  |
| 1ch HPD         | 17.7                  |
| B&L PMT         | 35                    |
| SK PMT          | 53                    |

Figure 2. The threshold scan of the dark rate of HPDs. The red line shows 1ch HPD and green line shows 2ch HPD. At the 0.5 p.e. threshold, the dark rate of HPD is ~10 kHz.

Figure 3. The stability of output signal charge of HPD by changing the frequency of light pulse. The output is constant within 5% up to 1.2 MHz for 50 p.e. signal.

5. Summary
We have developed 50 cm HPDs with 20 mm φ AD and evaluated the performance. The single photo-electron resolution is 10~15%, achieving three times better than that of SK PMT and twice better than B&L PMT. The dark rate of an HPD is about 10 kHz at temperature 25°C and it is expected to be the same level of SK PMT at the water temperature 16°C. The output of the HPD keeps the gain in 5% up to 1.2 MHz, which means that it is enough rate tolerance to detect most of supernova events. The timing resolution of the HPD is 1.5 ns with bias voltage of 570V by using the latest faster preamplifier, which is twice better than that of SK PMT’s and the same as that of B&L PMT’s. It is confirmed that the HPD has good performance as a HK photo-detector. As the next step, the preparation of the long proof test in water is now ongoing.

References
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