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The development and performance evaluation of a hybrid photo-detector for Hyper-Kamiokande

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We have been developing a new hybrid photo-detector (HPD) for Hyper-Kamiokande, which is a proposed next generation megaton-class water Cherenkov detector. The prototypes of the 50 cm HPD with ϕ5 mm avalanche diode (AD) [1] and the 50 cm HPD with ϕ20 mm AD (R12850, Hamamatsu Photonics K.K.) were designed and produced after successful fabrication of 20 cm HPD. For the 50 cm HPD with ϕ5 mm AD, the transit time spread, linearity and temperature dependence of gain have been evaluated. For our target design of the 50 cm HPD with ϕ20 mm AD, two solutions by the segmented AD and the transformer coupling were tried to suppress the capacity seen by preamplifier since it is difficult to design a high speed preamplifier with low noise level for a large area AD due to the large junction capacitance. They successfully reduced the noise, and the performance of HPD showed significant improvements.

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1. Hyper-Kamiokadande Project

Hyper-Kamiokande (Hyper-K) is a next generation megaton-class water Cherenkov detector (Fig. 1) [2]. It has rich physics targets such as search for proton decay, study of neutrino properties using neutrino oscillation, detection and study of astrophysical neutrinos. Its total (fiducial) water mass of 0.99 (0.56) million tons would be approximately 20 (25) times as large as that of Super-Kamiokande (Super-K) [3]. In the baseline design, for the inner detector and the outer detector, 99,000 ϕ50 cm photosensors and 25,000 ϕ20 cm photosensors are needed, respectively. The photo-coverage of the inner detector is 20% which is a half of that of Super-K.

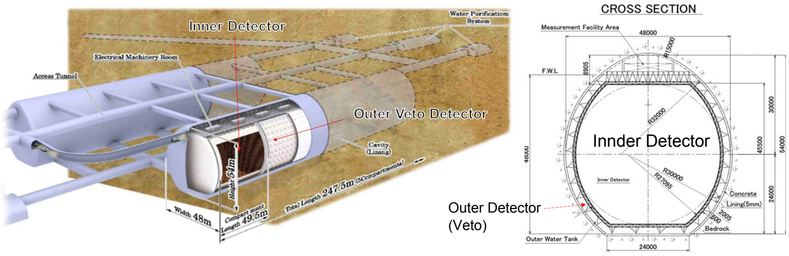

Figure 1: The schematic view (left) and cross section view (right) of the Hyper-Kamiokande detector.

2. Development of Hybrid Photo-Detector for Hyper-K

A large aperture hybrid photo-detector (HPD), which is a hybrid of a vacuum tube and an avalanche diode (AD), is under development for Hyper-K. The principle of HPD is shown in Fig. 2. The photo-electron produced at the photocathode is accelerated by a high electric field between the photocathode and the AD, then multiplied by the avalanche multiplication process at a high bias voltage in the AD. A preamplifier is employed to gain the observed signal further (Fig. 3). Because of the shorter drift path in the AD than that in the dynodes of a photomultiplier tube (PMT) and the high gain at the first amplification stage, the HPD has better timing and charge resolution than those of the PMT.

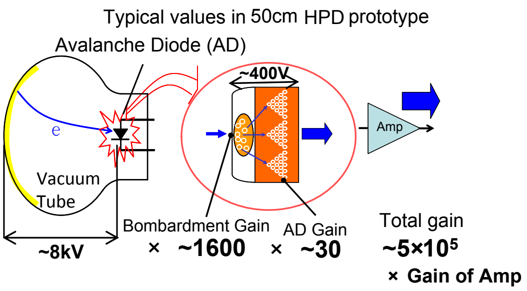

Figure 2: Principle of the HPD amplification and typical values of the 50 cm HPD.

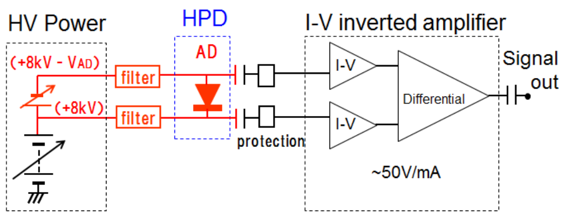

Figure 3: The schematic view of the circuit in the HPD.

We developed three kinds of HPDs in the order of difficulty as follows.

1. 20 cm HPD with ϕ5 mm AD
   The prototypes are being tested in a 200 tons water tank after performance evaluation [1].

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2. 50 cm HPD with ϕ5 mm AD
   The prototype of this kind of HPD was developed and evaluated firstly to test the large diameter HPD production technology. The ϕ5 mm AD allows the sharing of the preamplifier design with the 20 cm HPD's.

3. 50 cm HPD with ϕ20 mm AD
   The 50 cm HPD with a ϕ20 mm AD and its circuit were developed and evaluated. On the issue of the large AD junction capacitance, two proposed solutions, the segmented AD and the transformer coupling have been tested.

3. Performance evaluation of 50 cm HPD with ϕ5 mm AD

3.1 Signal response of single photoelectron

The signal response of single photoelectron (p.e.) of 50 cm HPD with ϕ5 mm AD has been evaluated and summarized in Table 1 [1]. The single p.e. resolution and ratio of peak to valley of HPD is better than that of Super-K PMT (R3600, Hamamatsu Photonics K.K.). The HPD itself has faster response: the 20 cm HPD with ϕ5 mm AD had a rise time of 1.7 ns and a fall time of 2.7 ns when no preamplifier was employed.

3.2 Transit time spread

A good time resolution is important for the event reconstruction in Hyper-K. The time resolution of a photo-sensor is evaluated by the transit time spread (TTS), which is temporal fluctuation from photon emission to signal appearance. The signal time is measured when the output signal reaches a certain threshold level (0.5 p.e. for HPD, 0.25 p.e. for PMT), referring to the laser diode emission time measured according to the synchronization output with a precision less than 0.01 ns.

	50 cm HPD w/ ϕ5 mm AD	Super-K PMT [1]
Rise time (ns)[1]	7.4	10.6
Fall time (ns)[2]	11.5	13.1
Pulse width (FWHM) (ns)	17.1	18.5
1 p.e. resolution (1σ)[3]	16%	53%
Peak / valley ratio[4]	3.9	2.2

Table 1: Signal response comparison between HPD and PMT. [1]

[1]: The 10% to 90% rise time. [2]: The 90% to 10% fall time.
[3]: The ratio of 1 σ width to the peak value of the 1 p.e. signal in the charge distribution.
[4]: The height ratio of 1 p.e. peak to the valley between 1 p.e. peak and pedestal peak in the charge distribution.

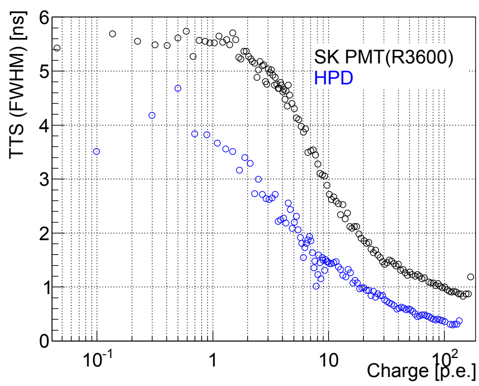

Figure 4: The TTS of the HPD and the Super-K PMT as functions of pulse intensities with the time walk corrected by charge. The light is incident into the center of HPD cathode with a beam diameter less than 1 mm.

Fig. 4 shows the TTS of the HPD as a function of pulse intensities with the time walk corrected by charge. Obviously, the TTS of the HPD is better than that of the Super-K PMT in the full range.

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Ideally the intrinsic resolution of the HPD at single p.e. shows 0.75 ns at FWHM as indicated by the simulation. Currently, the measured resolution is still limited by the preamplifier design with the slow response and a certain fluctuation on the baseline.

3.3 Linearity and dynamic range

The linearity of the HPD's output charge was measured by comparing with the light intensity. In a high light intensity, the AD or the preamplifier might be saturated and the output of HPD would be deviated from the linearity. The photosensor in Hyper-K should have a good sensitivity in the range from 1 to 1,000 p.e. because the Hyper-K detector needs to observe the events in a wide dynamic range: from several MeV to several GeV.

The linearity of HPD in high light intensity is confirmed by the comparison of the output of two coincident lights and the sum of the separated light using two light sources. By changing the light intensity of the light source, the linearity could be evaluated in a wide range. Comparing with the method used in [4], multiple light sources can measure the linearity without bias because there is no other photo-sensor for reference.

Fig. 5 shows the output charge as a function of the number of the input photoelectrons. It is confirmed that the linearity holds up to around 140 p.e., with the maximum drift of 6%, which is limited by the maximum output voltage (about 800 mV) of the preamplifier. It will be improved in the future by the redesign of the preamplifier.

3.4 Temperature dependency of gain

The temperature dependency of gain is evaluated in a thermostatic room (Fig. 6). The gain temperature coefficient is about -2.1 %/°C at 20 °C. Since the water temperature of Hyper-K is expected to be stable at 13 °C in the order of 0.1 °C, the stability of HPD in operation will not be influenced by the thermal factor. Furthermore, this result can also be used to estimate HPD's performance in Hyper-K tank according to the performance in the laboratory where the temperature is 24 °C.

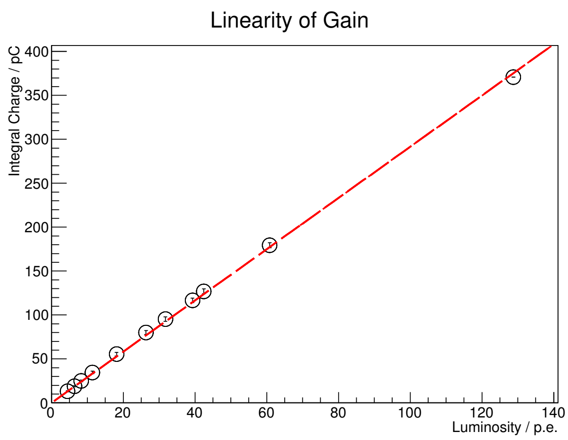

Figure 5: Relationship between output charge and the light intensity. Measured at 8 kV with 293 V of AD bias.

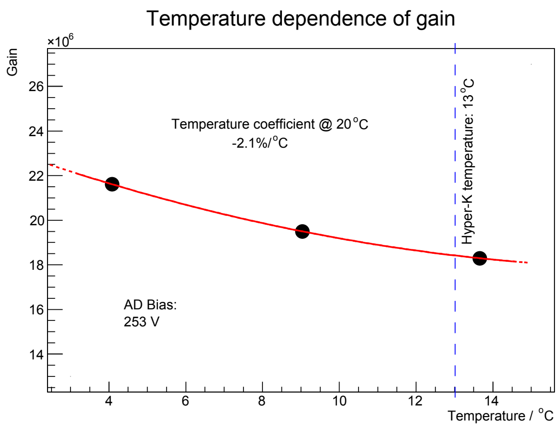

Figure 6: Temperature dependency of gain of 50 cm HPD with ϕ5 mm AD. Measured at 8 kV with 253 V of AD bias.

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4. Research and development of 50 cm HPD with large area AD

As has been stated above, a larger area AD is desired for 50 cm HPD to ensure a high collection efficiency (CE), which is defined as the efficiency to collect the photoelectrons on the AD surface from photocathode. According to the result provided by Hamamatsu, a single channel ϕ20 mm AD can make the CE reach to about 93.3% while the CE of a ϕ5 mm AD is less than 10%. However, with the increasing area of AD, the junction capacitance also becomes larger: about 800 pF for ϕ20 mm AD, while about 60 pF for ϕ5 mm AD. A larger junction capacitance leads to a higher noise level, a longer time constant of the readout circuit, therefore to worse energy and time resolution.

Two countermeasures, the application of segmented AD and the transformer coupling, were tried to reduce the noise level.

4.1 Application of segmented AD

A prototype of segmented 5-ch ϕ20 mm AD (Fig. 7) was developed. Each channel is amplified by an isolated trans-impedance preamplifier and all the signal are summed to the output (Fig. 8). The lower input capacitance makes it easier to develop a high speed preamplifier with low noise level.

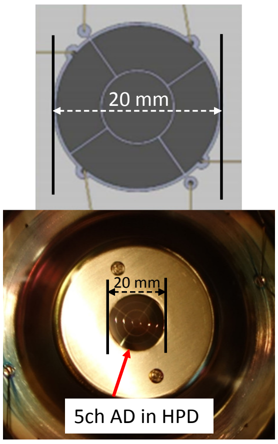

Figure 7: 5-ch ϕ20 mm AD.

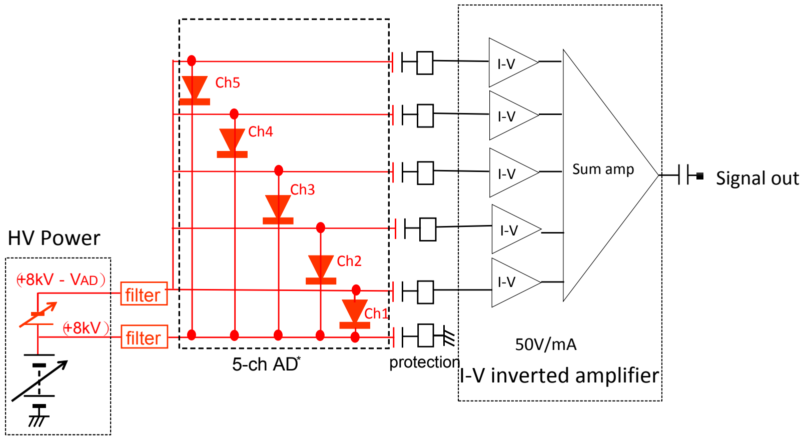

Figure 8: The HPD system with multi-ch AD.

Comparing with the 50 cm HPD with ϕ5 mm AD, the 50 cm HPD with 5-ch ϕ20 mm AD has a slightly slower response and a worse 1 p.e. resolution (Table 2), which is caused by the large AD junction capacitance. In fact, even though the capacitance in each channel is reduced to 1/5 (i.e. 160 pF), it is still larger than that of ϕ5 mm AD (60 pF). Nevertheless, the AD with more channels are not developed because of the difficulty in the pin arrangement and the smaller effective area due to more isolate trench between each channel. Currently, the 1 p.e. resolution of the 50 cm HPD with 5-ch ϕ20 mm AD is better than that of Super-K PMT, although its response is still slower than that of Super-K PMT (Table 2).

4.2 Application of coupling transformer

Coupling transformer can be used to suppress the noise gain of the preamplifier by reducing the capacitance seen by the amplifier [5]. The performance of coupling transformer is tested on a

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	50 cm HPD w/ 5-ch ϕ20 mm AD	50 cm HPD w/ ϕ5 mm AD[1]	Super-K PMT[1]
Rise time (ns)	20.3*	7.4	10.6
Fall time (ns)	21.1*	11.5	13.1
Pulse width (FWHM) (ns)	32.3*	17.1	18.5
1 p.e. resolution (σ/μ)	28%	16%	53%
Peak / valley ratio	3.1	3.9	2.2

Table 2: Comparison of the single photoelectron response of 50 cm HPD with 5-ch ϕ20 mm AD and other detectors. The HPD with 5-ch ϕ20 mm AD is measured with a 20 MHz bandwidth filter at 415 V of AD bias and 8 kV of HV. The result of the HPD with 1-ch ϕ20 mm AD is not shown because the single photoelectron pulse can not be seen at 8 kV of HV.

*: The value of the pulse shape after low pass filter.

prototype of the 50 cm HPD with 1-ch ϕ14.7 mm AD at first.

We compared the pulse shape (Fig. 10), the integral charge distribution (Table 3) of the 50 cm HPD signal with and without the coupling transformer with a bombardment voltage (HV) of 11 kV. Obviously, the coupling transformer brings a faster response and a better 1 p.e. resolution to the 50 cm HPD.

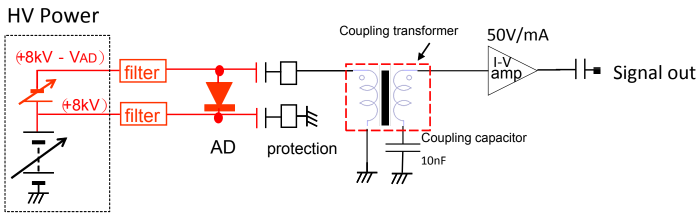

Figure 9: Circuit of the 50 cm HPD with ϕ20 mm AD (C_{AD}=800 pF) using coupling transformer.

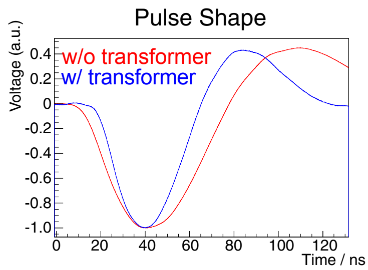

Figure 10: Signal of 50 cm HPD with and without transformer.

	w/ trans	w/o trans
Rise time (ns)	13.9	19.3
Fall time (ns)	16.7	23.9
Pulse width (FWHM) (ns)	28.8	42.2
1 p.e. resolution (σ/μ)	26.9%	49.1%
Peak / valley ratio	4.9	1.4

Table 3: Effect of coupling transformer on the multi photoelectron response of 50 cm HPD w/ ϕ14.7 mm AD. Measured at 11 kV with 415 V of AD bias and 20 MHz of bandwidth.

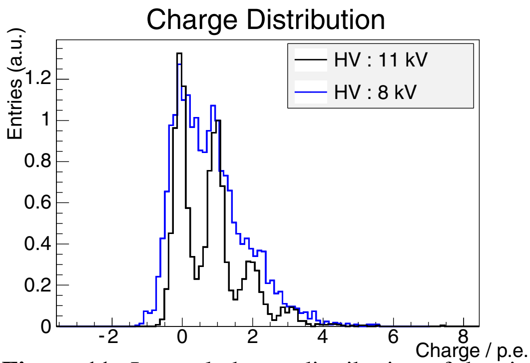

Figure 11: Integral charge distribution of the signal of the HPD with ϕ14.7mm AD and coupling transformer. Measured with a 20 MHz bandwidth filter at 415 V of AD bias.

Considering the safety, a lower HV (e.g. 8 kV) is preferred although the signal response at a higher HV (e.g. 11 kV) is better as shown in Fig. 11. However, for the signal response at a HV of 8 kV, a ratio of peak to valley of 1.1 does not satisfy the requirement of Hyper-K, although the single

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p.e. charge resolution is about 51.7%, which is the same level as Super-K PMT. The combined use of the multi-channel AD and the transformer coupling is expected to give a better performance and will be tested in the future.

The transit time spread of the HPD with coupling transformer at 1 p.e. level is also evaluated to be 6.0 ns (FWHM) with a HV of 8 kV, which is larger than that of Super-K PMT (5.5 ns). As in Section 3.2, this value is also constrained by the preamplifier currently.

The dark count rate, which is defined as the average rate of hit without any incident light, is measured by counting the pulse above threshold level in the waveform recorded by the oscilloscope with a long gate (50 $\mu s \times 1000$ waveforms). The 50 cm HPD with ϕ20 mm AD (CE: 93.3%) is estimated to be 9.4 kHz based on the result of the 50 cm HPD with ϕ14.7 mm AD (CE: 83%): 8.33 kHz. After considering the temperature dependency of dark count rate, the dark rate of 50 cm HPD with ϕ20 mm AD operating under the Hyper-K environment (13°C) can be reduced to 1/2 (i.e. 4.7 kHz) [6], which is the same level as the Super-K PMT.

5. Summary

We have been developing a new hybrid photo-detector for Hyper-Kamiokande. The detailed performance, including linearity, time resolution and temperature dependency of the 50 cm HPD with ϕ5 mm AD, was evaluated. The linearity is confirmed in 6% up to 140 p.e. Although it does not satisfy the requirement of the photosensor for Hyper-K currently, the performance will be improved with a revised preamplifier since the the linearity range is constrained by the preamplifier output. Furthermore, the time resolution of 50 cm HPD with ϕ5 mm AD, 3.6 ns at 1 p.e. (FWHM), is better than that of Super-K PMT (5.5 ns at 1 p.e.), while it will be also tested again with the new preamplifier after developed. The temperature dependence of gain, -2.1 %/°C at 20 °C will have little influence on the stability of the HPD during operation in Hyper-K environment.

Comparing with the 50 cm HPD with ϕ5 mm AD, the 50 cm HPD with ϕ20 mm AD, which is the target design, has a slower signal response and a higher noise level due to the larger capacitance from the larger area of AD. Two solutions, transformer coupling and segmented AD, were found to suppress the noise level and improve the single p.e. resolution effectively. The 50 cm HPD with ϕ20 mm AD showed great potential as a Hyper-Kamiokande photo-detector and the version which can operate in water tank will be ready by the end of 2015.

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