Performance evaluation of 3 inch PMT for Hyper-Kamiokande

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Abstract. Hyper-Kamiokande is a next generation water Cherenkov detector for the study of neutrino oscillations including the search for leptonic CP violation. In order to reduce the systematic uncertainty, a 1 kton scale intermediate water Cherenkov detector (IWCD) is planned to be constructed at around 1 km downstream the J-PARC neutrino beamline. The multi-PMT modules, which consist of 19 3 inch PMTs will be installed in the IWCD to improve the detector performance with their higher granularity. We have measured the characteristics of candidate 3-inch PMTs such as gain, peak to valley ratio, timing resolution and after pulses, and checked the impact to the detector performance.

1. Hyper-Kamiokande and IWCD

Hyper-kamiokande (Hyper-K) is a next generation underground water Cherenkov detector based on well established technology by the current Super-Kamiokande. Its fiducial volume will be 188 kton which is 8.4 times larger than that of Super-K. Hyper-K is aiming for measurement of leptonic CP violation. In order to reduce the systematic uncertainties down to $\sim 3\%$, a new near detector, intermediate water Cherenkov detector (IWCD), is planned to be installed around 1km downstream the J-PARC neutrino beamline[1]. The size of IWCD is $\sim$1 kton with the fidutial volume 1/600 of Hyper-K.

2. Multi-PMT modules

A new photo sensor, multi-PMT module is being developed by the Hyper-Kamiokande collaboration. Multi-PMT is assembly module instrumented with 19 3 inch PMTs with the HV power supply and digitizer encapsulated in the vessel. With its higher granularity, multi-PMT improves the resolution of Cherenkov ring image so that the performance of event reconstruction will be improved especially for those close to the wall of the detector. Therefore, multi-PMT wil be employed in IWCD.

3. Measurement of 3 inch PMT

We tested two types of candidate 3 inch PMTs for multi-PMT. One is R14374 made by Hamamatsu Photonics K.K. (quoted as HPK), and the other one is a prototype 3.5 inch PMT made by other company (quoted as PMT-A). As a part of multi-PMT development for Hyper-K and IWCD, we have measured basic characteristics to understand the performance of 3 inch PMT. The schematic setup is shown in figure 1. The main PMT, for which we measure the characteristics, is set inside a dark box and illuminated by laser oscillator (LDB-200, Tama Electric Inc.). The laser light illuminates the photocathode uniformly by arranging diffuser and lens. The laser fiber is splitted by 9-1 ratio and monitor PMT measures high intensity laser to check the laser stability. The signals are recorded by 1 GHz sampling rate Flash-ADC (DT5751, CAEN).

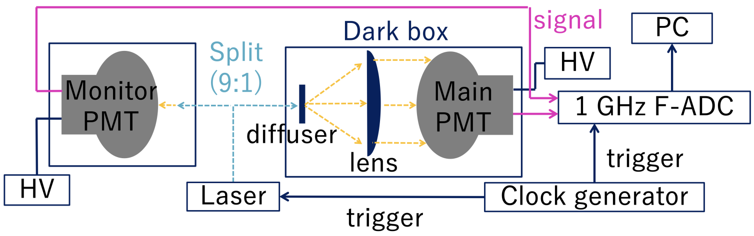

Figure 1. Schematic view of the uniform light setup.

3.1. Gain and Peak to Valley ratio

Figure 2 shows distribution of the integrated charge of the signals from both PMTs. The distribution of PMT-A (right) is widely distributed in more than 1 p.e. region which is deviated from the Poisson distribution. The peak of 1 p.e. is determined by a fit with Gaussian×Poisson distribution function. The ratio of 1 p.e. peak and the minimum value between the pedestal and 1 p.e. is defined as Peak to Valley (P/V) ratio.

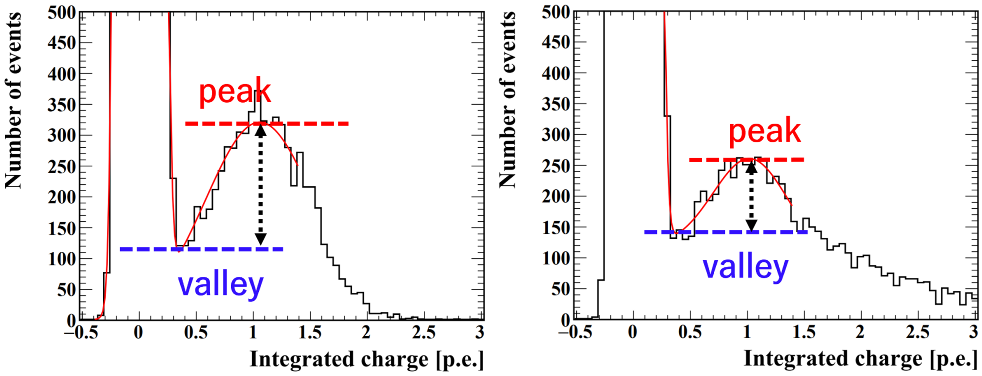

Figure 2. Integrated charge distribution of HPK#1, −1250 V (left) and PMT-A, −1350 V (right)

Figure 3 shows the gain value and P/V ratio. Gain was determined by a conversion from integrated FADC counts to pC. The gain is proportional to exp(V) and reaches 10^7 gain at around 1250-1450 V for both PMTs. It was clear that the P/V ratio of HPK was better than that of PMT-A. Large P/V ratio helps to distinguish the signal from the noise.

3.2. Transit Time Spread (TTS)

Left-hand plot in figure 4 shows the distribution of relative time difference between the PMT signal and trigger signal and the right-hand plot shows the TTS value as a function of relative gain. Time response parameter, transit time spread (TTS), was defined as FWHM of this distribution which is derived by a Gaussian distribution from a fit to the data. TTS of HPK is better than that of PMT-A.

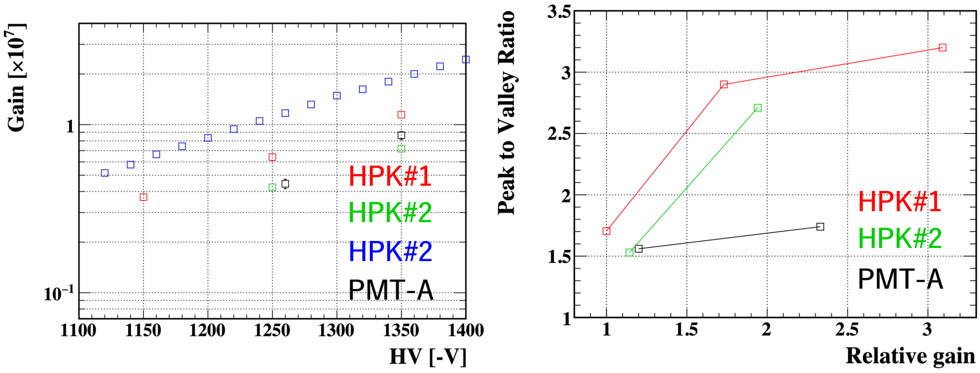

Figure 3. Gain of HPK PMTs and PMT-A as a function of supplied HV value (left) and P/V ratio of HPK PMTs and PMT-A as a function of relative gain which 1 equals to 3.7×10^6 gain (right).

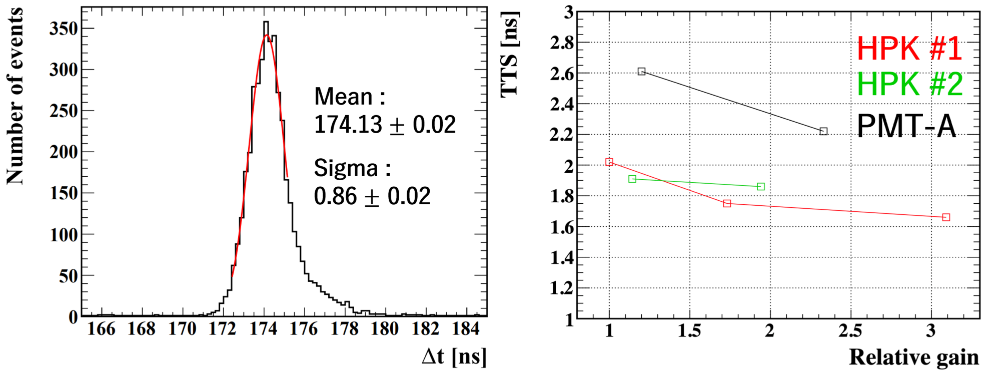

Figure 4. Relative timing distribution of HPK#1, −1150 V fitted with Gaussian (left) and TTS of HPK PMTs and PMT-A (right).

We have checked the impact of timing resolution to the performance of vertex position reconstruction in IWCD by the simulation. Left-hand plot of figure 5 shows the distance between true and reconstructed vertex for 10 MeV/c electron with 7 different TTS values. The distribution becomes wider with higher TTS. Right-hand plot in figure 5 shows the vertex resolution of 10 and 30 MeV/c as a function of TTS value. TTS affects vertex reconstruction of lower energy event and resolution becomes worse at around 3 ns. Both PMTs we have measured have better resolution than 3 ns.

3.3. After pulse rate

After pulse is caused by ion feedback inside PMT. We found after pulses with 1 p.e. level signal at around 2-4 μs after the main pulse. Left-hand plot in figure 6 shows the after pulse occurrence rate as a function of integrated charge of the main pulse. The rate is proportional to the integrated charge for both PMTs, but the rate of HPK was higher than that of PMT-A. Reduction of after pulse is in progress by Hamamatsu.

After pulses with μs order may have some impact to the delayed coincidence signal detection, such as decay electron and neutron tagging. We have simulated decay electron signals with and without after pulses event. After pulse rate and timing are based on the measurement. As a result, we found there is not a large difference due to after pulse in such detection efficiency, vertex and direction reconstruction. However, right-hand plot in figure 6 shows the momentum

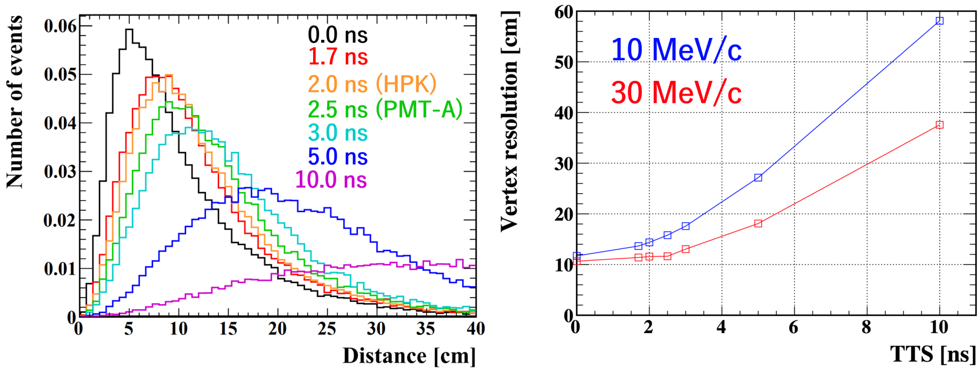

Figure 5. Distance between true and reconstructed vertex (left) and vertex resolution as a function of TTS value (right).

of decay electron has changed by 6% at around 2-4 μs which corresponds to after pulse time interval. It should be noted that the simulation is based on single muons and the pile-up (multiple neutrino interactions in the same bunch or spill) effects are not accounted in the simulation studies shown in this article.

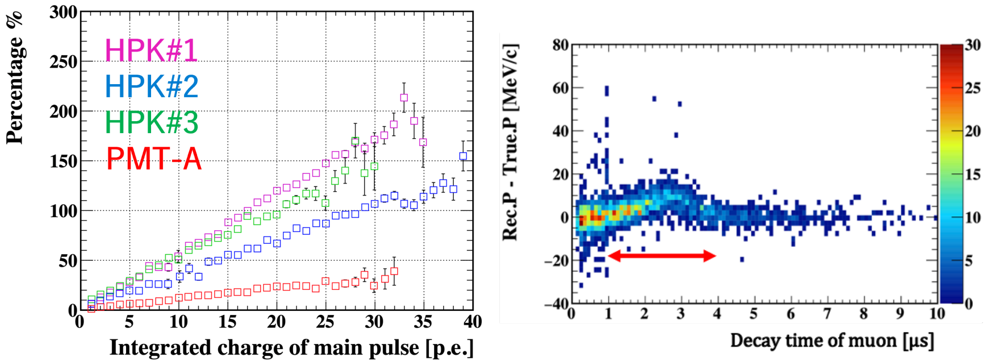

Figure 6. After pulse occurrence rate as a function of integrated charge (left) and difference between reconstructed and true momentum of decay electron as a function of decay time of muon evaluated by the IWCD simulation with the after pulse (right).

4. Conclution

We have measured the characteristics of candidate 3 inch PMTs for multi-PMT and evaluated the impact to IWCD measurement by the simulation. The measured performances are satisfactory for IWCD. We found after pulses but the impact is limited and the reduction is expected by the modifications of the design.

References

[1] K. Abe *et al.* (Hyper-Kamiokande Proto-Collaboration), arXiv:1805.04163 [physics.ins-det].