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Multi-PMT modules for Hyper-Kamiokande

Benjamin QUILAIN[1], Mark HARTZ[1,2], Yasuhiro NISHIMURA[3], Masahiro KUZE[4], Haruya MORIKAWA[4], Michitaka INOMOTO[5], Masaki ISHITSUKA[5], Nao IZUMI[5]

[1] *Kavli Institute for the Physics and Mathematics of the Universe, The University of Tokyo, WPI,*
5-1-5 Kashiwanoha, Kashiwa, 277-8583, Japan
[2] *TRIUMF*
[3] *Institute for Cosmic Ray Research, The University of Tokyo*
[4] *Tokyo Institute of Technology*
[5] *Tokyo University of Science*

E-mail: benjamin.quilain@ipmu.jp

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Hyper-Kamiokande, a 260 kton water Cherenkov detector to be built in Japan, is the next generation of the Super-Kamiokande experiment. Its broad physics program includes nucleon decay, neutrinos from astronomical and human-made beam, with the main focus to determine the leptonic CP violation. To detect the weak Cherenkov light generated by neutrino interactions or proton decay, the primary photo-detector candidate are 20-inch "Box & Line" PMTs (Hamamatsu R12860). In order to enlarge Hyper-Kamiokande physics program, the use of multi-PMT modules is considered as a complement of the primary candidates. A multi-PMT Optical Module based on a pressure vessel instrumented with multiple small diameter photosensors, readout electronics and power, offers several advantages as weaker sensitivity to Earth's magnetic field, increased granularity, reduced dark rate, improved timing resolution and directional information with an almost isotropic field of view.
We will present the multi-PMT module developed for Hyper-Kamiokande and its near detector, E61, as well as the measurement of the performances of its individual 3-inch PMTs (R14374). We will finally show the impact of these modules in Hyper-Kamiokande physics in both the high and low energy sectors.

KEYWORDS: Neutrino, Hyper-Kamiokande, Multi-PMTs, R14374

1. Introduction

In the last decades, large underground water Cherenkov detectors have provided successful discoveries including the detection of the 1987a supernovae neutrinos in Kamiokande, the discovery of neutrino oscillations in Super-Kamiokande and first observation of electron neutrino appearance in T2K. Hyper-Kamiokande, of which construction will start in 2020, will be the next generation of these water Cherenkov detectors. It relies on a 260 kton detector (Figure 1) that aims to explore vast list of crucial open questions in modern physics at both high energy (E> 100 MeV):

- Is there a CP violation in the lepton sector? Could it be one cause of the observed matter-antimatter asymmetry in the universe ?
- What is the hierarchy of neutrino masses ?
- Is there a grand unification of QCD and electroweak theory at high energy ?

and low energy (E< 100 MeV) sectors:

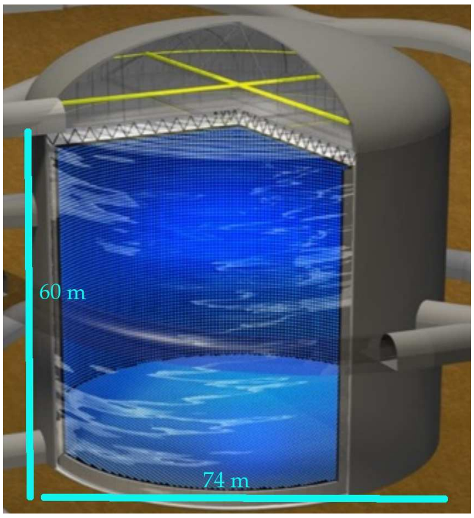

Fig. 1. An illustration of the designed HK detector.

- How does neutrino oscilation is affected by dense matter, especially, in the Sun ?
- What will the detection of ν-background from supernovae explosion since the beginning of time teach us about the cosmic star formation history ?

To answer these questions, HK relies on detecting the Cherenkov light produced by the daughter particles of neutrinos when they interact in the detector (Figure 1) by photomultipler tubes (PMT). Choosing the type and density is currently one priority of the HK project. At the present time, the primary candidates are 20-inch Hamamatsu R12860 PMTs [1] [2]. Their very high efficiency coupled to their excellent time resolution allows respectively an increased resolution in the measurement of the ν energy and its interacting position in the detector compared to Super-Kamiokande. However, a single photo-sensor type cannot be optimal on a broad energy range of neutrinos from few MeV (for solar or supernovae-ν) and up to few TeV (for atmospheric-ν). These 20-inch PMT has *e.g.* a dark rate (8.4 kHz, goal is 4 kHz) two times higher than Super-Kamiokande PMT **at the present time**, which makes difficult to detect low energy neutrinos creating electrons below 5 MeV.

2. The multi-PMT photosensor

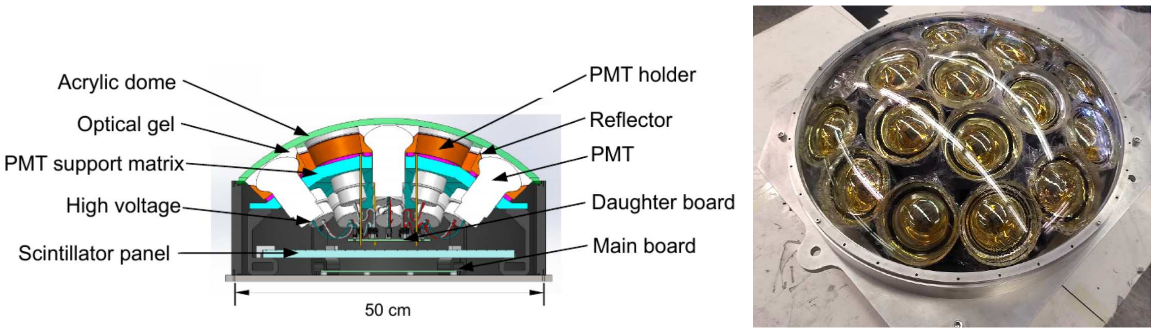

Fig. 2. The mPMT schematics (left) and photo (right).

To overcome these limitations, the HK collaboration explores complementary photodetectors, and among them, the multi-PMT module (mPMT) [1]. It is based on a 20-inch acrylic pressure vessel that can be installed in HK similarly to 20-inch PMT, but is instrumented with nineteen 3-inch diameter Hamamatsu R14374 PMTs, sharing the same readout electronics and power as shown on Figure 2. These mPMTs are the primary photosensor candidates of the future Hyper-Kamiokande near-detector, E61, and are now considered also for the far detector.
We will first present the results of the individual PMT tests. We will then introduce the very first simulation results showing how using these mPMTs can support and improve the physics possibilities of the HK experiment.

3. Tests of the 3-inch PMTs

The PMT efficiency, gain and Transit Time Spread (TTS) has been measured in Japan using two different setups. Each test is realized on two different PMTs (BC00035 and BC00038) of the same model in order to investigate the stability of our results with the PMT production.

3.1 PMT response to uniform light source

The PMT responses are first measured using a source of uniform light producing a parallel photon beam illuminating the whole photocathode. For this purpose, we use a 402 nm laser diode whose photons are diffused and then focused using a 2 lenses system. Both laser diode and the DAQ system are triggered by an external 2 MHz clock producing a signal of 50 ps, which is set to be negligible compared to the PMT time response. The PMT is readout by a CAEN-V1743 flash ADC. Figure 3 summarizes the variation of the PMT gain and TTS with respect to the PMT high voltage for both PMTs operated in negative or in positive high voltages. We concluded that:

- the gain behaves as a high order polynomial as expected & a gain of 1×10^7 is reached for a HV between 1170V and 1200V depending on the PMT.
- depending on the PMT, the TTS is measured between 1.5 ns and 1.6 ns at the gain = 10^7 functioning point.
- the characteristics of the PMT in negative and positive high voltage are unchanged within the measurement statistical uncertainties.

In particular, the impact of a highly reduced TTS compared to 20-inch PMTs (1.5 ns compared to 2.6 ns [2]), as well as the possibility to operate the PMTs in positive high voltage mode without changing their gain or TTS characteristics will be studied in Section 4.

3.2 PMT response as a function of position of the light source

The PMT response has then be tested as a function of the photon source position on the photocathode. For this purpose, a 402 nm laser diode is mounted on a motorized stage that can vary the laser position and angle. The laser spot size on the photocathode has been measured to 8 mm. The laser direction is kept perpendicular to the center of the PMT photocathode. The PMT response is measured for 64 data points on the photocathode spaced by 10 mm. Figure 4 shows the PMT as well as the position from the first to second dynode and the different measurement points on the photocathode. It also shows the gain and TTS variation as a function of the position. These measurements has shown that:

- the PMT efficiency is stable within ±5% on the photocathode, apart from the PMT edges where the efficiency falls quickly. More precise measurements are required in the edges region to quantify this decrease.

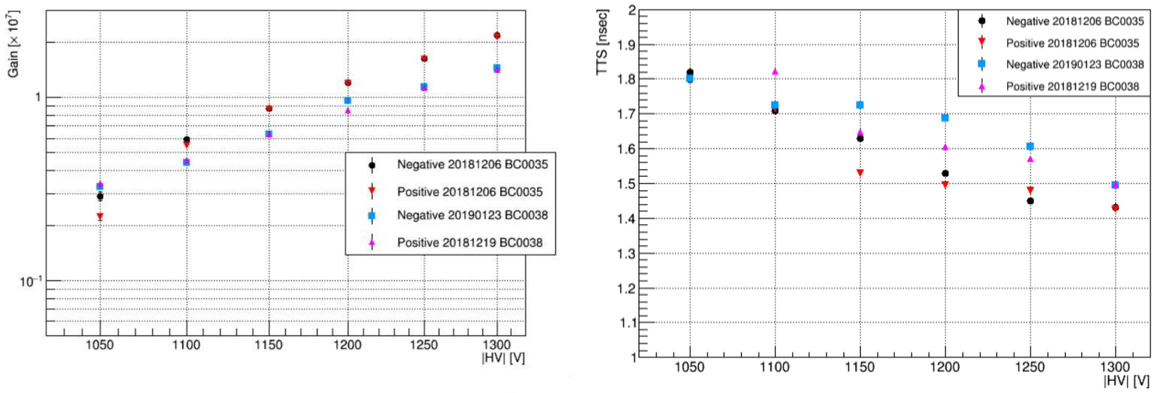

Fig. 3. Variation of the gain (left) and TTS (right) with respect to PMT high voltage. Results are shown for both PMT BC00035 and BC00038 operated in negative or positive high voltage.

- the PMT gain shows an asymmetry. We have investigated this asymmetry by rotating the PMT around the cathode-anode direction by 180°, operating the PMT is both negative and positive high voltage modes and by checking another PMT (BC00035). We have concluded that this asymmetry is a consequence of the two first dynode orientations.
- the transit time shows an asymmetry which is anti-correlated with the gain asymmetry. This conclusion remains unchanged for each operating mode (positive or negative) and PMT.

In particular, the transit time variation with the position, are currently being reported to Hamamatsu in order to possibly reduce the PMT TTS for the final production.
We are currently undertaking the measurements of the PMT response as a function of the laser angle with respect to the photocathode with the very same setup.

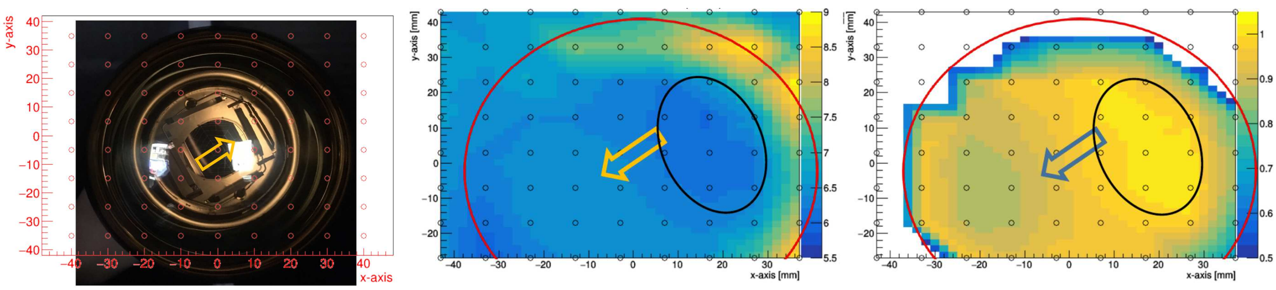

Fig. 4. The PMT photocathode is shown on the left along with the laser position used to estimate the PMT response as a function of position. Center and right plots show the variation of the gain (center) and TT (right) with respect to laser position on the PMT. Results are shown for PMT BC00038 operated in positive high voltage. In every plot, the arrow represents the direction from the second to first dynode.

3.3 Dark rate measurements

Finally, the PMT dark rate was measured in Canada and Poland at different temperatures. Figure 5 shows the results at 5°C for both negative and positive high voltage modes. For a 1 p.e detection efficiency of 50%, we observe a dark rate of 200 Hz for negative high-voltage and only 20 Hz for positive high-voltage. This final observation opens interesting possibilities in particular for the low energy neutrino physics that we will introduce briefly in Section 4.

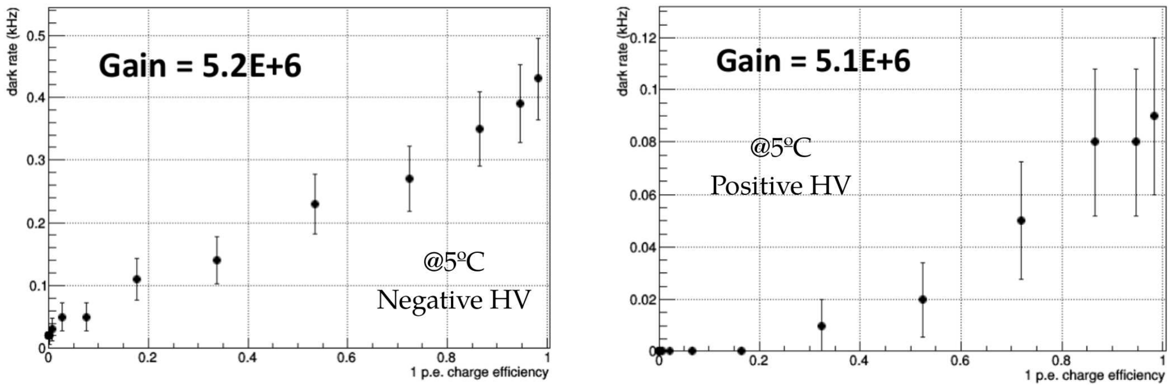

Fig. 5. Variation of the PMT dark rate with respect to 1 p.e. charge efficiency threshold at 5°C for negative (left) and positive (right) high voltage.

4. Multi-PMT simulation

Consecutively to these measurements, we developed the HK simulation and reconstruction to integrate mPMT modules. Their impacts has been tested on both the near and far detectors of HK. In all simulations, the signal for individual PMT in an mPMT are treated independently.

4.1 Impact on the HK near detector

The HK near detector, E61, will be a water Cherenkov detector of cylindrical shape (10 m diameter for 8 m height) located at $\sim$ 1 km away from the JPARC neutrino production point in order to constrain the ν_μ and ν_e fluxes before oscillation, as well as the cross-section ratio $\overline{\nu}_e/\overline{\nu}_\mu/\nu_e/\nu_\mu$. To achieve this goal, the detector is required to achieve a very high ν_μ/ν_e separation, as well as a high vertex resolution to minimize the systematic uncertainty on the fiducial volume cut. However, due to the E61 reduced size compared to the far detector, these performances will be highly degraded if we use the very same 20-inch PMT. Therefore, the mPMTs are currently considered as the primary photosensor candidate for the E61 detector. Indeed, the 3-inch PMT compact size and high timing resolution allows both to improve the vertex resolution and the particle identification. These effects are shown in Figure 6, comparing the mPMT configuration to 8-inch or 20-inch PMTs. It has been independently shown that these increased of performances are higher for events located near the edge of the detector fiducial volume.

4.2 Impact on the HK far detector

Naturally, similar improvements in particle identification and vertex resolution near the wall are expected for the HK far detector. It may lead for example to extend the fiducial volume of the detector. Moreover, if operated in positive high-voltage mode, the mPMT signal-to-noise ratio becomes significantly higher than 20-inch PMTs, leading to potentially decrease the experiment energy threshold. In order to estimate the potential of the mPMTs and compare them with 20-inch ones, we have simulated HK replacing all the 40,000 20-inch

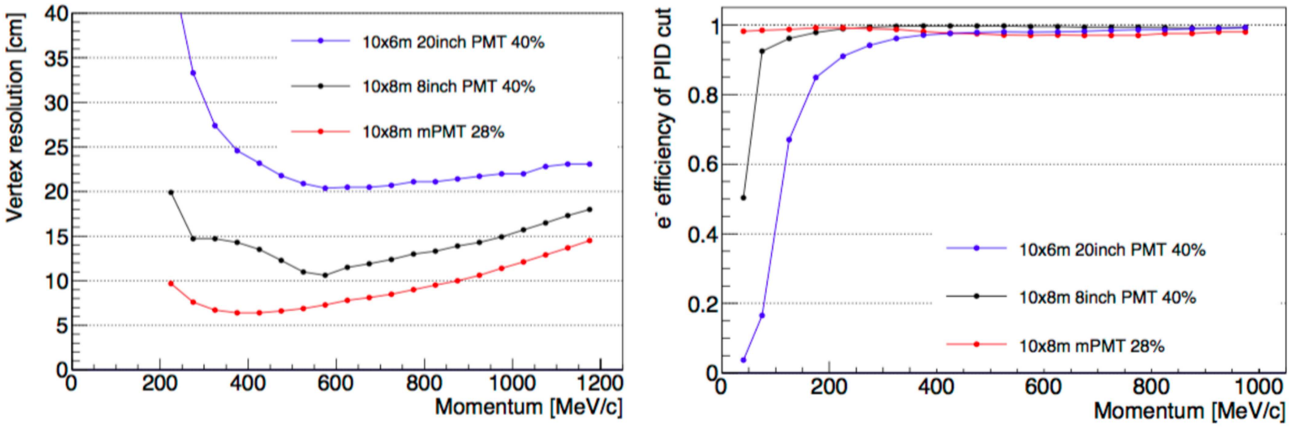

Fig. 6. Impact on the vertex resolution (left) and electron/muon separation (right) of using 20-inch (blue), 8-inch (black) and mPMT (red) in E61. The vertices as been generated uniformly in the whole tank fiducial volume, while the directions has been generated isotropically.

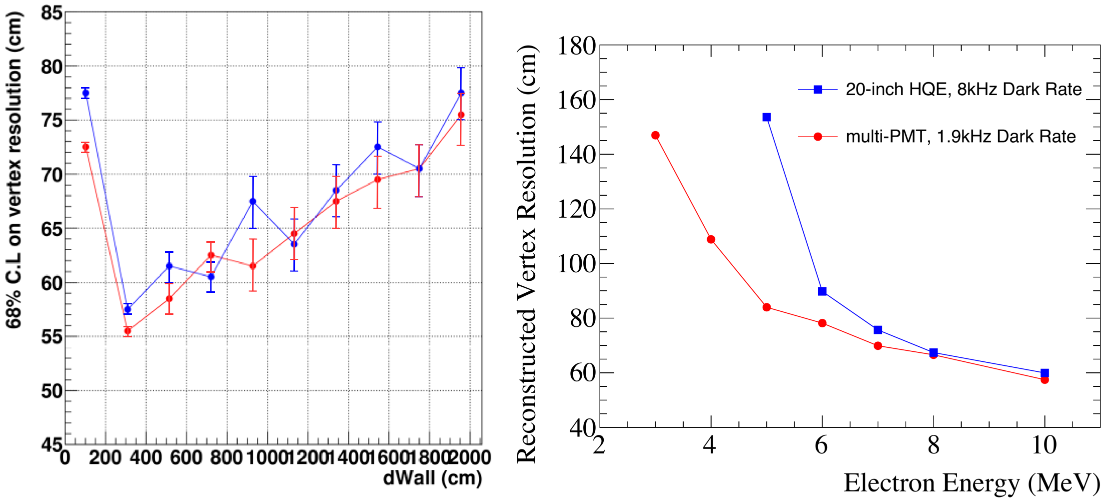

Fig. 7. Neutrino vertex resolution as a function of the vertex distance to the wall for 10 MeV electrons (left) and as a function of the electron energy (right). The results are shown in blue for 20-inch PMT and in red for mPMTs. The vertices as been generated uniformly in the whole tank fiducial volume, while the directions has been generated isotropically.

PMTs by mPMTs.
We have shown that using mPMTs helps to:

- improves the vertex resolution at high energy (e.g. by 7 cm for 500 MeV electrons).
- improves the vertex resolution at low energy, and especially, near the edges of the fiducial volume as shown in Figure 7.
- reduces the energy threshold which may lead to probe the solar upturn with a higher sensitivity.

5. Summary

The next generation of neutrino experiment, HK, will rely on detecting the Cherenkov light produced by the daughter products of neutrinos interactions in the detector. The main candidate for the far detector are 20-inch R12860 Hamamatsu PMTs. In order to instrument the HK near detector, but also, to enhance HK physics possibilities, the multi-PMT is considered as a promising candidate. We have confirmed their operation voltage, as well as their excellent timing resolution and reduced dark rate compared to 20-inch PMTs. We also identify transit time asymmetry which is investigated in order to improve the PMT time resolution further. After finalization of these results this summer, we are planning to proceed to the first test of the fully assembled mPMT in a water tank, MEMPHYNO [3].
Finally, we have shown the mPMT impact on the HK near and far detectors. Following these results, the mPMTs are considered as the primary candidates for the near detector. As for the far one, these promising first results for both low and high energy are a very first step towards a more reasonable detector configuration made of a mixture of 20-inch and mPMTs. This configuration is currently being studied by the collaboration.

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