Development and performance of the 20" PMT for Hyper-Kamiokande

C Bronner¹, Y Nishimura², J. Xia³ and T. Tashiro³

¹Kamioka Observatory, ICRR, The University of Tokyo, Higashi-Mozumi 456, Kamioka-cho, Hida-city Gifu 506-1205, Japan

² Faculty of Science and Technology, Department of Physics, Keio University, 3-14-1 Hiyoshi, Kohoku-ku, Yokohama, Kanagawa 223-8522, Japan

³ Research Center for Cosmic Neutrinos, ICRR, The University of Tokyo, 5 Chome-1-5 Kashiwanoha, Kashiwa-shi, Chiba-ken 277-8582, Japan

E-mail: cbronner@km.icrr.u-tokyo.ac.jp

Abstract. The inner detector of the future Hyper-Kamiokande experiment will be instrumented with 40000 20" photo-multiplier tubes (PMTs). Two models of PMTs are considered: the R12860 from Hamamatsu Photonics (nominal option), and the GDB-6203 from North Night Vision Technology (alternative option). Both models show improved performances compared to the PMTs used in the currently running Super-Kamiokande experiment. We present here the measurements of the performance of the nominal and alternative option PMTs done in the context of the Hyper-Kamiokande project, as well as the first use of those new PMTs in a running experiment, and other on-going developments for their future use in the Hyper-Kamiokande detector.

1. Introduction

Hyper-Kamiokande [1] is the next generation water Cerenkov experiment in Japan, scheduled to start construction during the Japanese fiscal year 2020 and expected to start taking data in 2027. This new experiment will build on the successful strategies developed in the currently running Super-Kamiokande (Super-K) experiment [2], and be able to study the oscillation of neutrinos from different sources with unprecedented precision, as well as to search for proton decay and neutrinos produced by supernovae. This increase in precision comes from the larger size of the detector, providing large statistics, and the use of high performance photo-detectors. In the baseline design, the inner part of the detector will be instrumented with 40000 20" PMTs. Two alternative PMT models are considered for this part: the nominal option is to use the R12860 produced by Hamamatsu Photonics (HPK) while the GDB-6203 produced by North Night Vision Technology Co. (NNVT) is studied as an alternative option.

2. Hamamatsu R12860

The HPK R12860 PMT is an evolution of the R3600 model used in Super-K. The two main differences are the change of dynode type from Venetian blind to box and line, and the higher quantum efficiency with an increase of the peak quantum efficiency from 22% to 30%. The change to a box and line dynode provides a more uniform drift path for the electrons, improving the timing resolution, and reduces the probability that an electron misses the first dynode,

Content from this work may be used under the terms of the Creative Commons Attribution 3.0 licence. Any further distribution of this work must maintain attribution to the author(s) and the title of the work, journal citation and DOI. Published under licence by IOP Publishing Ltd

improving the collection efficiency. For single photo-electron events, the transit time spread (TTS) is improved from 6.73 ns to 2.59 ns (FWHM), and the charge resolution from 60.1% to 30.8%.

3. Installation of R12860 PMTs in Super-Kamiokande

During the summer of 2018, the Super-K detector was opened for refurbishment to prepare for the SK-Gd project, where gadolinium will be dissolved in the water to provide additional ability to detect neutrons. At this occasion, the PMTs of the inner-detector which had stopped working properly were replaced with R12860 PMTs, making Super-K the first experiment to use a significant number of this new model of PMT.

140 R12860 PMTs were purchased and tested in a pre-calibration setup to ensure they satisfied the requirements to be installed in Super-K. All of the 140 PMTs passed the selection. Those measurements also provided a first look at the consistency of the production quality of the R12860 through the variations of the performances from one PMT to the other. The performances were found to be quite consistent, as can be seen on Fig. 1 for the timing and charge resolutions.



Figure 1. Measured performances of the R12860 PMTs in the pre-calibration setup: timing (left) and charge (right) resolutions. The dashed purple lines indicate the acceptable range for installation in Super-K.

During the refurbishment work, 136 of those PMTs were installed in Super-K. Their performances in the detector were measured during the initial calibration campaign at the restart of data taking, and confirmed the improved performances compared to the R3600 PMTs. The charge resolution of the installed R12860 PMTs was measured to be $27 \pm 3.8\%$, and their timing resolution to be 1.50 ± 0.07 ns (RMS, corresponding to 3.53 ns FWHM). This timing resolution is larger than the one measured in the pre-calibration setup, but this is due to the limitation of the Super-K electronics which was not designed for PMTs with such a low timing resolution. Finally, the detection efficiency of the R12860 PMTs installed was measured to be 1.9 times the one of the R3600 PMTs present in the detector. Fig. 2 shows the measured timing resolution of the two types of PMTs during this calibration campaign, while Fig. 3 shows the charge distribution around the 1 photo-electron peak for the different PMTs, highlighting the clearer separation between the single photo electron and pedestal peaks for the new model. On this

last figure, R3600 PMTs are further sub-divided in 2 categories depending on whether they were installed before or during the Super-K reconstruction of 2006.



Figure 2. Transit time spread (RMS) measured during the calibration campaign.



Figure 3. Average charge distribution around the single photo-electron peak measured during the calibration campaign.

4. Uniformity of the performance of the R12860 PMT

Additional measurements were done on 9 of the 140 R12860 PMTs purchased for the Super-K refurbishment to evaluate how their performance varied as a function of the position at which the photon hits the PMT surface and of the ambient magnetic field. A set of Helmholtz coils was used to vary the magnetic field along 3 perpendicular directions, and the position dependence was measured by injecting light through fibers attached at different positions on the surface of the PMTs. The gain and timing resolution were measured to be mostly uniform on the PMT surface, with a worsening of the performance at the edge of the PMT's photocathode. It was found that there was more variation in the performance when looking at different positions along the direction going from the line to the box dynode than in the perpendicular direction. The effect of the magnetic field was found to depend strongly on the position at which the photon hit the PMT. For photons hitting the PMT at the center, or away from the center but in a direction parallel to the applied magnetic field, no dependence was seen. If the photon was hitting the surface away from the center in a direction perpendicular to the magnetic field, a dependence of the performance on the value of the magnetic field was observed. This dependence changed with the position at which the photon was hitting the surface, but the total effect was measured to be less than 10% for fields varying between -100 mG and +100mG, therefore satisfying the requirements for use in Hyper-Kamiokande.

5. Additional development for the R12860 PMT

Current R&D effort for the R12860 PMT focuses on the reduction of the dark rate. A low dark rate is critical in Hyper-Kamiokande for low energy physics and to be able to detect neutrons from their capture on hydrogen. The target for Hyper-Kamiokande is to reach a dark rate of 4 kHz or less in detector conditions (13-15°C water, using a 1 μ s count width). The PMTs installed in Super-K were seen to have a rate larger than this target, although the final rate measurement was not available at the time of this presentation. HPK has since managed to reduce the rate of the R12860 PMT: measurements in the air at room temperature show a decrease of the dark rate from (9.53 ± 2.91) kHz to (6.53 ± 1.93) kHz (comparing the rates measured on two batches

of PMTs, one of them produced before the improvements and the second one after). Studies are on-going to try to reduce the radio-isotope concentration of the glass, which would allow to reduce the noise coming from scintillation in the glass.

A second topic of on-going work is the development of protective covers for the PMTs, which are used to prevent a chain implosion in the case where a PMT would break and implode in the detector. Such protective covers are already used in Super-K, but were found to produce noise due to radio impurities, and were not designed to function at the high pressure expected at the bottom of Hyper-Kamiokande. Three different designs are being considered for Hyper-Kamiokande: 2 of them made of stainless steel (SUS) - one conical and the other cylindrical and the third one made of resin. The covers are validated through implosion tests, in which the PMT inside the cover is made to implode, triggering a shock wave. The test is a success if bare PMTs attached near the cover do not implode. A cover is considered to have been validated for use in Hyper-Kamiokande if it passes the test three times at a depth of 80 meters. So far, the SUS conical cover has been validated and the two others are still under development.

6. NNVT GDB-6203

NNVT has been producing 20" PMTs based on micro-channel plates (MCP) to amplify the electrons for the JUNO experiment [3]. Those PMTs had a good detection efficiency (30%), good pressure tolerance and low radio-isotope glass. However, their weak point was their timing resolution of approximatively 20 ns, which was insufficient for use in Hyper-Kamiokande. NNVT developed a new version with focusing electrodes to improve the timing resolution. Coupled with an optimization of the voltage divider circuit, they allowed this new model to reach a timing resolution of 4.3 ns (FWHM), better than the resolution of the HPK R3600 used in Super-K (6.73 ns). This improved MCP PMT, the GDB-6203, is now tested as an alternative option for the Hyper-Kamiokande inner detector. Its timing performance, gain and detection efficiency were found to be satisfactory. The uniformity of its performance was checked using the same setup as for the R12860 PMTs. Finally, its performance was found to be largely unaffected by magnetic fields within the range \pm 100 mG. Long term stability tests are now on-going to establish it as an alternative option for Hyper-Kamiokande.

7. Summary

The Hyper-Kamiokande experiment will be using 40000 high performance 20" PMTs to instrument its inner detector. Two models of PMT are considered for this: the HPK R12860 and the NNVT GDB-6203. Both show improved performances compared to the HPK R3600 used in Super-K, in terms of timing and charge resolution, as well as detection efficiency. The R12860 is the baseline option for Hyper-Kamiokande, and has started being used in Super-K with the installation of 136 PMTs in the detector during the summer of 2018. Calibration measurements done since have confirmed good performance under real detector conditions. The GDB-6203 is a modified version of the MCP-based 20" PMT used in the JUNO experiment, equipped with focusing electrodes to improve its timing resolution. It is now being tested to be established as an alternative option for Hyper-Kamiokande.

References

- [1] K. Abe, et al., KEK-PREPRINT-2016-21, ICRR-REPORT-701-2016-1 (2016)
- [2] Y. Fukuda, T. Hayakawa, E. Ichihara, M. Ishitsuka, Y. Itow, et al., Nucl.Instrum.Meth. A501, 418462 (2003).
- $[3]\,$ F. An et al. , J. Phys. G ${\bf 43},\,030401$ (2016)