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Performances of the Hyper-Kamiokande 20" PMT

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We present measurements of the performances of the 20" PMTs considered for the Hyper-Kamiokande experiment, as well as on-going studies to improve some of their properties. In the baseline design, the Hyper-Kamiokande inner detector will be instrumented with 40000 Hamamatsu R12860 PMTs. We measured the performances of 140 PMTs of this model, and the uniformity of those performances as a function of the ambient magnetic field and photon hit position for 9 of them. An alternative PMT candidate is produced by North Night Vision Technology Co. and is based on a micro-channel plate system. For this alternative option, we measured the performances of the recent GDB-6203 model as well as their uniformity.

KEYWORDS: PMT performance, 20 inch, Hyper-Kamiokande, R12860, GDB-6203

1. Introduction

The next generation water Cerenkov experiment in Japan, Hyper-Kamiokande [1], will begin construction in 2020. Its physics goals include the study of the oscillations of neutrinos of different sources, in particular to search for a potential violation of the CP symmetry, the search for proton decay and the study of supernovae neutrinos, including both the neutrinos which would come from the explosion of a nearby supernova and relic neutrinos from past supernovae. This new experiment builds on the successful approach used in the current Super-Kamiokande experiment (Super-K) [2], and will have increased sensitivity owing to its larger size (providing larger statistics) and improved photo-detectors. The detector design is similar to the Super-K one, with a cylindrical cavern optically separated into an inner (ID) and an outer detector (OD), but larger, providing a total fiducial volume of 190 kton compared to 22.5 kton for Super-K. The ID will be used for precise reconstruction of events, which requires large photo-coverage from high performance photo-detectors, whereas the OD is used to veto external particles and can be more sparsely instrumented. The options considered for the OD were reported in a different presentation at this workshop [3]. In the baseline design, the ID will be instrumented with 40000 Hamamatsu R12860 20" PMTs (see [4] from this workshop for other options considered). In this presentation, we focus on the performances of the R12860 PMTs, and on those of an aternative 20" PMT option, the micro-channel plate based PMTs by North Night Vision Technology Co (NNVT).

2. Hamamatsu R12860

The Hamamatsu R12860 is an evolution of the R3600 20" PMT used in the Super-K experiment. The dynode type was changed from a 'Venetian blind' type to a 'box and line' type. As a result, the electrons are less likely to miss the first dynode, giving higher detection efficiency. Coupled with a larger quantum efficiency, this gives the R12860 about twice the detection efficiency of the R3600 model. This change of dynode type is also beneficial for the timing resolution, as the electrons follow a more uniform path, reducing the measured transit time spread (TTS) from 6.73 ns to 2.59 ns (full width half maximum). Additionaly, the charge resolution is also improved compared to the PMTs used in Super-K, from 60% to 31%.

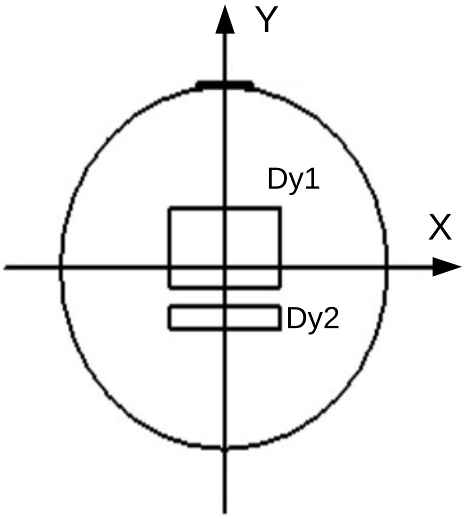
Since the previous edition of this workshop, development efforts focused on the reduction of the dark noise, which is currently the main disadvantage of the R12860 model compared to the R3600. Improvements by Hamamatsu led to a reduction from 9.5 kHz (average over 121 PMTs in a previous production batch) to 6.35 kHz (average over 60 PMTs in a recent production batch). Those rates were measured at room temperature, and it can be expected that the dark rate would be lower at the lower temperature of the Hyper-Kamiokande water. On-going studies on background light in glass [5] could lead to additional dark noise reduction. In parallel, the dynamic range of those photo-detectors was increased by optimizing the voltage divider ratios [6], and protective covers to prevent chain implosions of the PMT containing less radio-isotopes than the ones used in Super-K are being developped.

3. Measurement of the uniformity of the performances of the Hamamatsu R12860

The Super-Kamiokande detector was open for refurbishment during the 2018 summer, and as part of this operation 140 R12860 PMTs were purchased to replace the PMTs which were no longer functionning properly in Super-K. The PMTs properties were measured in a pre-calibration system [7], and all of them were found to match the requirements for installation in Super-K. As a result, 136 R12860 PMTs were installed in Super-K, providing high quality photo-detectors to Super-K to replace the ones which had failed, and data from long term operation of those PMTs for Hyper-Kamiokande studies.

3.1 Uniformity measurements

Before being installed in the detector, nine R12860 PMTs were put in a system allowing to measure how their performances change as a function of the ambient magnetic field and of the position at which a photon hits the PMT surface. The system consists of a dark room located inside a set of coils which allow to modify the value of the magnetic field along 3 axes. A set of fibers is then placed on the surface of the PMTs, allowing to inject light at different fixed positions along an axis, measured by the angle with the axis of the PMT. Measurements were done along two axes: the y axis goes from the line to the box dynode, and the x axis is the perpendicular direction on the PMT surface (fig. 1, left image). The results will be shown as ratios or differences with respect to a default setting (usually no magnetic field and hit at the center of the PMT): this allows to only focus on the effects of magnetic fields or hit positions, and not be affected by the fact that the 9 PMTs have different reference values in the standard setting. To show the values from the measurements of 9 PMTs on the same figures, the data points will correspond to the mean value obtained in the 9 measurements, and the error bars to their dispersion (and so do not represent measurement errors but differences in the non-uniformities between the 9 PMTs measured).



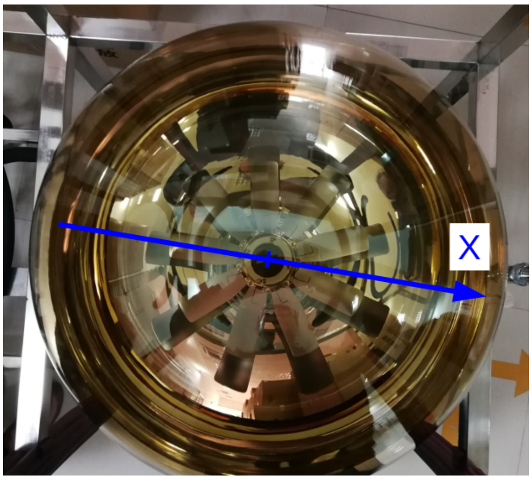


Fig. 1. Definition of the axis used for the uniformity measurements. Left: schematic top view of the Hamamatsu R12860. "Dy1" corresponds to the box dynode, and "Dy2" to the line dynode. Right: top view of the NNVT GDB-6203 PMT.

3.2 Variation as a function of position

The gain as a function of the photon hit position (fig. 2) was found to be uniform within 5%, except on the very edges of the PMTs were it becomes lower. An asymmetry is seen on the y axis, with the region located behind the box dynode having a lower gain than the corresponding region in the other direction.

When looking at the timing performances as a function of the hit position (fig. 3) the TTS is found to be uniform within 10% on most of the surface of the PMT. Along the x axis, the TTS increases progressively as we move away from the center of the PMT, while the pattern is more complicated along the axis going from the line to the box dynode, especially in the region behind the box dynode.

For the R12860, a fraction (2-3%) of the hits arrive around 100 ns later than expected. This is believed to be due to electron back scattering, and the fraction of those late hits is seen to depend strongly on the hit position (fig. 4).

3.3 Variation as a function of magnetic field

The effect of the magnetic field on the performaces of the R12860 was found to depend on the position of the photon hit. Within the range considered (-100 mG to 100 mG), the

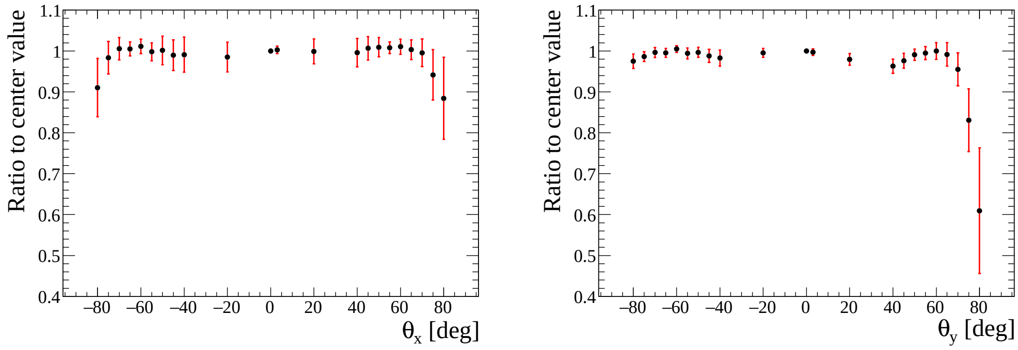


Fig. 2. Relative gain as a function of the photon hit position (1 for a hit at $\theta = 0$). Points correspond to the average ratios obtained for the 9 measured R12860 PMTs, and error bars to the dispersion over the 9 PMTs. Axes x and y are defined on fig. 1.

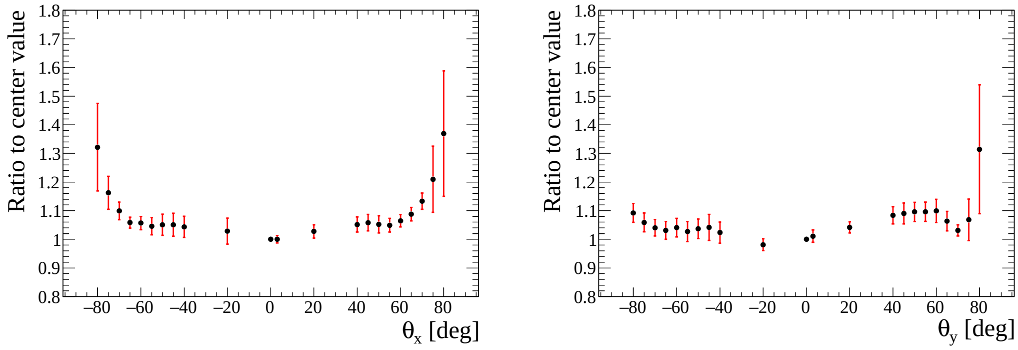


Fig. 3. Relative TTS as a function of the photon hit position (1 for a hit at $\theta = 0$). Points correspond to the average ratios obtained for the 9 measured R12860 PMTs, and error bars to the dispersion over the 9 PMTs. Axes x and y are defined on fig. 1.

magnetic field did not affect the performances for hits at the center of the PMT, or displaced from the center in a direction parallel to the magnetic field (fig.5, left plot). For displacements in the perpendicular direction, effects are seen, and their amplitude varies significantly with the position of the hit (fig.5, right plot). The largest effects are seen for magnetic fields along the x direction, and hits behind the box dynode ($\theta_y > 75°$). In all other cases, the observed changes of performances are less than 10% within the range of magnetic fields expected in Hyper-Kamiokande.

4. NNVT MCP PMTs

4.1 Development

NNVT produces 20" PMTs based on a multi-channel plate system, which will be used in the coming JUNO experiment, and are being tested as an alternative option for Hyper-Kamiokande. Those PMTs have a number of interesting features: high detection efficiency, high pressure tolerance (important given the expected size of the Hyper-Kamiokande detector), and low radio-isotope glass which would reduce the background for low energy physics.

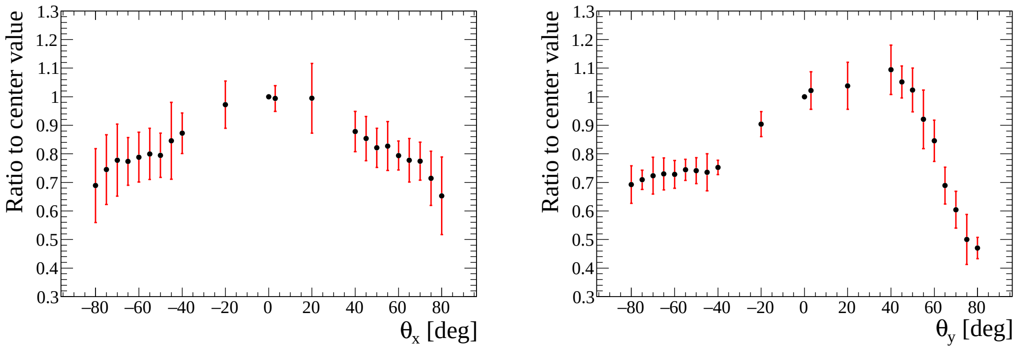


Fig. 4. Relative fraction of hits arriving late as a function of the photon hit position (1 for a hit at $\theta = 0$). Points correspond to the average ratios obtained for the 9 measured R12860 PMTs, and error bars to the dispersion over the 9 PMTs. Axes x and y are defined on fig. 1.

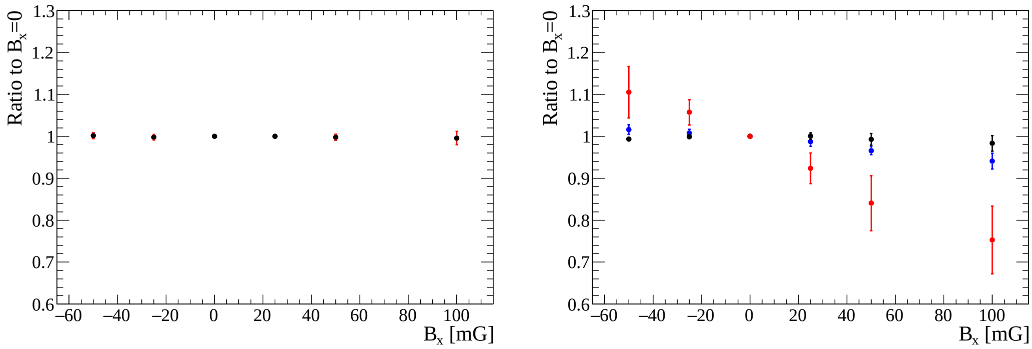


Fig. 5. Relative gain as a function of magnetic field along the x axis (1 for B_x=0) for hits at different positions. Left plot: $\theta_x = 75°$. Right plot: $\theta_y = -40°$ (blue), $\theta_y = 60°$ (black) and $\theta_y = 75°$ (red). Points correspond to the average ratios obtained for the 9 measured R12860 PMTs, and error bars to the dispersion over the 9 PMTs.

Their weaker point was the timing resolution, but this has been improved through successive developments for Hyper-Kamiokande: the first model we measured (GDB-6201) had a TTS of 11.5ns, while for the latest one (GDB-6203) we measured a TTS of 4.3 ns, lower than that of the PMTs currently used in Super-K (6.73 ns) although not as good as the Hamamatsu R12860 (2.59 ns).

4.2 Measurement of the uniformity of the performances

A GDB-6203 PMT was studied in the setup used to measure the uniformity of the performances of the R12860. In this case, the measurements were performed only along one axis given the symmetry of this PMT. The negative region of the axis goes over an electrode, while the positive region goes between two electrodes (fig. 1, right picture).

It was observed that the gain was about 10% larger on the side of the PMT than in its center region, and that in each of those regions the gain was uniform within 5% (fig. 6, left plot). A similar pattern was seen for the timing performances: the TTS was measured to be larger on the side regions than at the center (fig. 6, right plot). It was also observed that the PMT was largely unaffected by magnetic fields in the range expected for Hyper-

Kamiokande, as the largest effect seen was around 5%, and in most cases the impact on measured performances was much smaller than this.

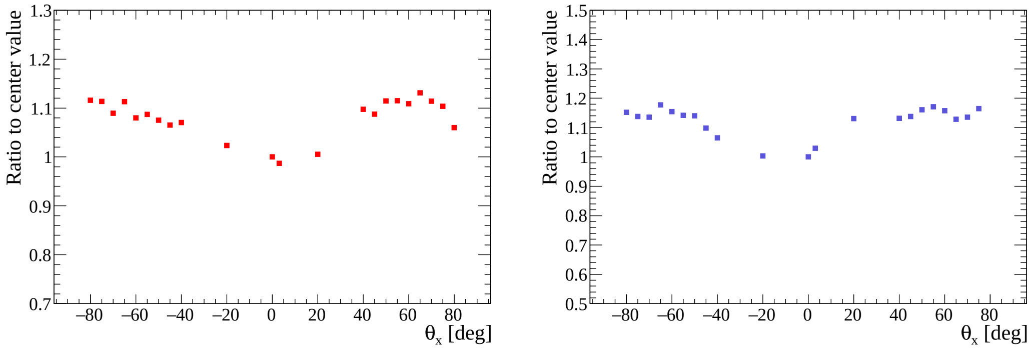


Fig. 6. Relative gain (left plot) and TTS (right plot) as a function of the photon hit position (1 for a hit at $\theta = 0$) for the NNVT GDB-6203 PMT tested.

5. Summary

The next generation water Cerenkov experiment Hyper-Kamiokande will be using improved photo-sensors compared to the currently running Super-Kamiokande. The baseline design uses the Hamamatsu R12860, which has twice the detection efficiency, twice as good charge resolution and more than twice as good timing resolution as the R3600 PMTs used in Super-K. 136 of those PMTs were installed in Super-K during the 2018 summer, and all of them satisfied the requirements to be used in the experiment. MCP based PMTs produced by NNVT are being studied as an alternative option. After several improvements the latest version of those MCP PMTs has better timing resolution than the current Super-K PMTs. The uniformity of the performances as a function of hit position and ambient magnetic field were measured for the two candidate PMTs, and no problems were found. The results of those uniformity measurements can now be used to construct a more precise model of the PMTs for the Hyper-Kamiokande simulations, to study how the non-uniformities can affect the physics performances and determine if specific calibration measurements are needed for the experiment to reach its physics goals.

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