Development of a Bleeder Circuit of 50 cm Diameter Photomultiplier Tubes for Hyper-Kamiokande

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The design of the bleeder circuit of the photomultiplier tubes for Hyper-Kamiokande was optimized to satisfy required specifications. We achieved the wide dynamic range over 1,000 photo-electrons. We also confirmed the gain stability within 10% change for the light amount up to 650 photo-electrons and the rate tolerance up to 90 MHz for single photo-electron level signal.

KEYWORDS: PMT, Gain linearity, Rate tolerance, Bleeder circuit, Hyper-Kamiokande

1. Introduction

Hyper-Kamiokande (HK) is a next-generation gigantic water Cherenkov detector to pursue high-precision neutrino physics and nucleon decay searches [1]. 40,000 50 cm diameter photomultiplier tubes will be installed to the inner detector of HK. The required charge dynamic range to detect the signal charge is from single to over 1,000 photo-electrons (p.e.) to measure a few GeV to TeV neutrinos precisely. The required rate tolerance for single p.e. signal is 10 MHz for collecting neutrino event burst by nearby supernova.

The R12860 PMT made by Hamamatsu (hereinafter called "HKPMT") with Box & Line dynodes is the leading candidate for the inner detector. This provides about two times detection efficiency and better timing and charge resolution compared to the R3600 PMT used in the Super-Kamiokande (hereinafter called "SKPMT").
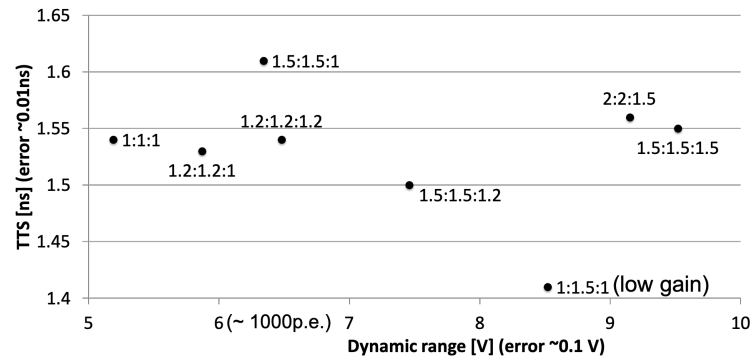
2. Bleeder circuit optimization

The PMT for HK requires a wide dynamic range over 1,000 p.e., however, non-linear output response of the charge was confirmed in early prototype PMTs over 800 p.e. We optimized the bias voltages between dynodes to aim at reaching about 6 V pulse height at least in the 6 mV/p.e. gain, then confirmed a response linearity of the charge.

HKPMT has 11 dynodes and their voltage ratios determined by a bleeder circuit are shown in Table I. First of all, we changed downstream 3 voltage ratios to prevent the space charge saturation, considering that the distance between the 10th dynode and the 11th dynode is shorter than others. Fig. 1 shows the comparison of their maximal pulse heights and transit time spreads (TTSs). We decided to use 1.5:1.5:1.2 version for narrower TTS and over 6 V dynamic range, since 1:1.5:1 version needs more than 200 V additional voltage for $1.4{\times}10^7$ gain. The ratio also satisfies other properties shown in Table II.

Next, we changed the voltage ratio between the cathode and the first dynode to keep the same voltage at the first dynode as designed to avoid a collection efficiency (CE) loss. The CE of a PMT with the final version bleeder circuit was evaluated by comparing the counting rates of a single p.e.

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Table I. The original and final version voltage ratios among dynodes (DYs) and cathode (K) is shown.

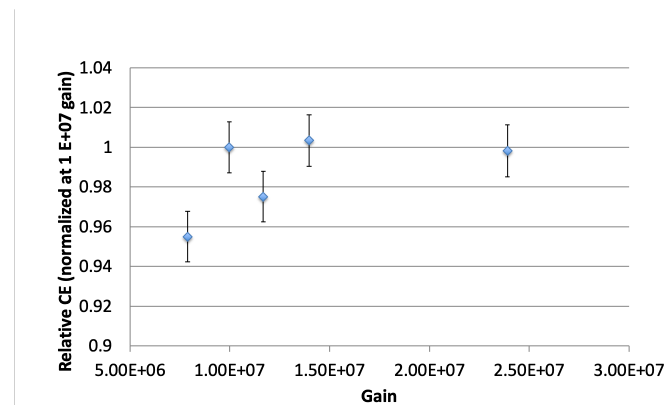| Version	K - DY1	DY1-2	DY2-3	DY3-4	DY4-5	DY5-6	DY6-7	DY7-8	DY8-9	DY9-10	DY10-11
Original	11.5	4.5	4	2	2	1	1	1	1	1	1
Final	13	4.5	4	2	2	1	1	1	1.5	1.5	1.2

Fig. 1. The TTS and the maximal pulse height as a dynamic range is shown by various voltage ratios between downstream 3 dynodes, DY8-9 : DY9-10 : DY10-11. 1.5:1.5:1.2 has the sufficient dynamic ranges over 6 V and good TTS. It indicates that a larger voltage for downstream dynodes is needed to enlarge the dynamic range, in order to relieve space charge saturation between downstream dynodes.

Table II. The original and optimized PMT properties are compared. More dynamic range, less after-pulse and lower HV, with keeping TTS are achieved.

version	HV for 1.4×10^7 gain [V]	TTS [ns]	After pulse fraction [%]	Dynamic range [-V]
original	1819	1.54	5.1	5.19
optimized	1707	1.50	3.6	7.46

level light source at each gain. Since, in Fig. 2, the relative CE normalized at the gain of 1.0×10^7 is stable to higher gains within the measurement errors, we can conclude that the final version does not degrade the CE in a possible range of the 1.0×10^7 gain or more. Furthermore, we confirmed other properties like TTS or dynamic range are not much changed from Table II. In Table I, the conclusive voltage ratio among dynodes is shown.
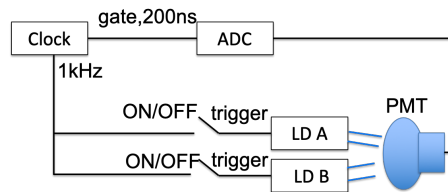

Fig. 2. The CE of a PMT with the final version bleeder circuit, which is shown in Table I, as a function of gain is measured.
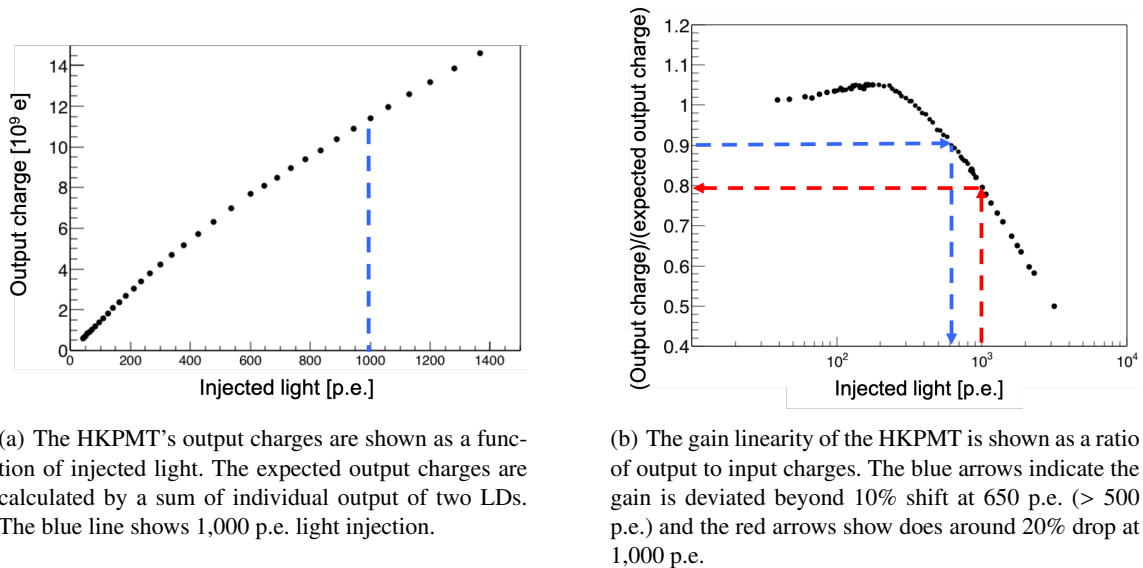
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3.   Gain linearity evaluation

The gain linearity of the signal charge was evaluated after the voltage ratios tuning. The PMT for HK requires a gain linearity within 10% up to 500 p.e. and a dynamic output range without saturation to exceed 1,000 p.e. [1].

To measure the gain linearity of HKPMT, two laser diodes (LDs) were used. A coincident emission by two LDs was compared with a sum of individual emissions by using the setup of Fig. 3.

Fig. 3.   The circuit to measure the gain linearity of the HKPMT. An output of LD A+B lightning at the same time was compared with a sum of individual output of LD A and LD B.

Fig. 4(a) shows the output does not saturate at 1,000 p.e. light injection. Using the same data, Fig. 4(b) shows the gain is kept within 10% at 650 p.e. light injection, which is larger than the HK experiment requirement value 500 p.e.

(a) The HKPMT's output charges are shown as a function of injected light. The expected output charges are calculated by a sum of individual output of two LDs. The blue line shows 1,000 p.e. light injection.

(b) The gain linearity of the HKPMT is shown as a ratio of output to input charges. The blue arrows indicate the gain is deviated beyond 10% shift at 650 p.e. (> 500 p.e.) and the red arrows show does around 20% drop at 1,000 p.e.

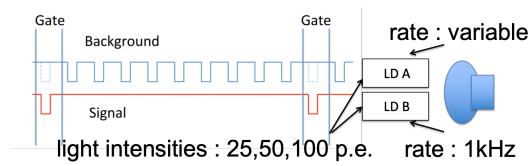**Fig. 4.**   The gain linearity of the HKPMT with the optimized bleeder circuit is evaluated.

4.   Rate tolerance evaluation

High rate tolerance is also needed to keep the gain within 10% deviation at single p.e. for 10 MHz supernova burst detection at maximum in HK. A gain dependency by varying a rate of background
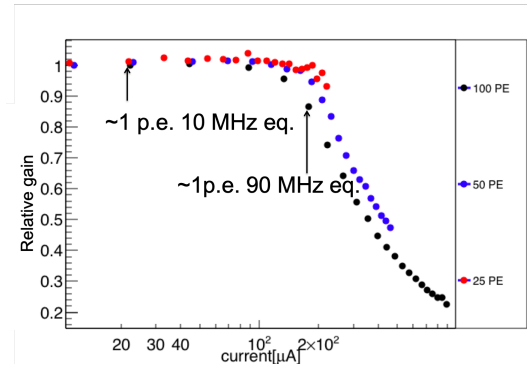
light injection was evaluated by using the setup in Fig. 5. The light intensities were set to 25, 50 and 100 p.e., while we converted it to the current to estimate the single p.e. case.

The relative gain defined in Eq. (1) is plotted by the total pulse current in Fig. 6. The curve has similar shape each other in three different intensities, compared with that by the rate only instead of the current. Therefore, we can roughly convert these results into rate tolerance for 1 p.e. light injection by calculating the PMT output current. At the gain of this measurement (1.4×10^7), 1 p.e. light injection at 10 MHz leads to about 22 μA. It indicates the gain is kept within 10% up to 90 MHz by 1 p.e. light. It satisfies the requirement of the HK experiment, 10 MHz.

$$\text{Relative gain} = \frac{\text{Signal charge with background}}{\text{Signal charge without background}} \tag{1}$$

Fig. 5. The setup to measure the rate tolerance of the HKPMT. A gain was measured by a signal charge in the gate at 1 kHz. Gains were measured with and without high background rate with changing the light intensities of both LDs and varying the LD A frequency.

Fig. 6. The rate tolerance of the HKPMT with the optimized bleeder circuit was evaluated. The relative gain behaves in a similar way as a function of the PMT output current. By using this relationship, the relative gain at 1 p.e. 10 MHz and 90 MHz are pointed.

5. Conclusion

The voltage ratio of photomultiplier tubes among the dynodes was optimized. It is confirmed that we made PMTs with better transit time spread, enough collection efficiency and improved dynamic range, compared to the early prototype PMTs. The wide dynamic range over 1,000 photo-electrons was achieved. A sufficient gain stability within 10% change was confirmed for the light amount up to 650 photo-electrons and the rate tolerance up to 90 MHz for single photo-electron level signal.

Reference

[1] K. Abe *et al.* (Hyper-Kamiokande Proto-Collaboration), "Hyper-Kamiokande Design Report" arXiv:1805.04163v1, 2018.