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Study on the performance of photomultiplier tube in liquid scintillator detector

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Abstract

The SWCDA (Stereoscopic Water Cherenkov Detector Array) project is a next-generation ground-based array experiment designed to enhance gamma-ray observation sensitivity by one order of magnitude while lowering the energy detection threshold down to 100 GeV. It consists of a liquid scintillator (LS) array and a stereoscopic water Cherenkov detector array. In the LS detector design, the collected scintillation light is transmitted to a Photomultiplier Tube (PMT). In this paper, we have assembled a test system to evaluate the PMTs' performance by measuring the high voltage linearity, the dynamic range, and the Transit Time Spread (TTS) of PMT output.

Introduction

SWCDA is a research and development initiative aimed at creating a HE gamma-ray observatory capable of detecting photons in the energy range from 100 GeV up to 100 TeV. Its primary scientific objectives involve the continuous monitoring of HE gamma-ray emitters and transient phenomena, such as Blazars and GRBs.

The observatory integrates both an LS array and a stereoscopic water Cherenkov detection system. In the SWCDA project, the LS detector is primarily used to measure the charge and timing information of secondary particles. In the LS detector, PMTs are employed to convert the scintillation light signals into electrical signals, which serve as the basis for further data acquisition and event reconstruction. As such, the performance of the PMTs plays a critical role in determining the overall detection efficiency, energy resolution, and background rejection capability of the LS detector.
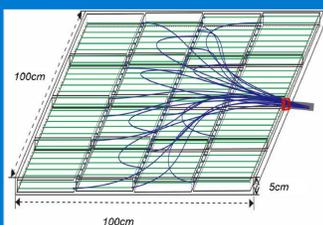
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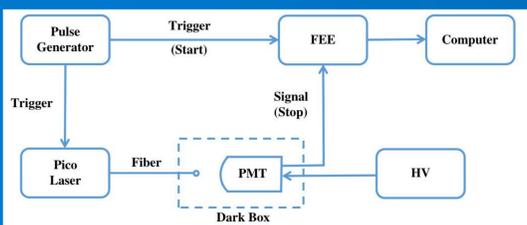

Figure 1. The Schematic view of LS detector.

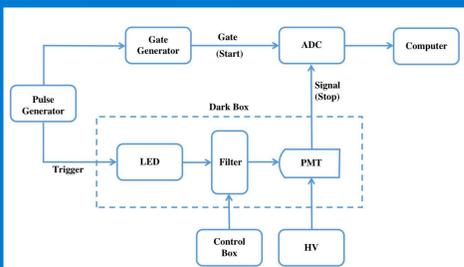Figure 2. Schematic view of PMT's transit time spread testing system.

Figure 3. Schematic view of PMT's high voltage linearity calibration and dynamic range extension testing system.

The LS detector (Fig.1) is composed of LS, a polymethyl methacrylate container, optical fibers, and a PMT. These components operate together to enable the effective detection and precise measurement of high-energy particles.

Fig. 2 shows the schematic of the PMT transit time spread (TTS) testing system. A trigger signal from the pulse generator is split into two channels: one serves as the start signal for the front-end electronics (FEE), and the other triggers the Picosecond Injection Laser (PiLas) to generate a single photoelectron optical pulse for the PMT. The PMT output determines the stop time. The time difference between start and stop signals forms a distribution, whose full width at half maximum (FWHM) defines the TTS.

Fig.3 shows schematic view of PMT's high voltage linearity calibration and dynamic range extension testing system. The pulse generator controls both the TTL pulse frequency applied to the LED and the generation of NIM trigger signals for the gate generator, while the control box adjusts the LED light intensity via filters. The high voltage (HV) supply regulates the PMT's operating voltage. The filter assembly consists of two rotating wheels, each equipped with neutral density filters of varying attenuation levels.

Reference

1. Zhang, Y. et al. , "Design and optimization of a liquid scintillator detector for new EAS hybrid experiment," J. Instrum. , vol. 20, no. 06, p. P06017, Jun. 2025.
2. Zhang, Y. et al. , "Calibration of the Yangbajing air-shower core detector," J. Instrum. , vol. 15, no. 07, p. P07014, Jul. 2020.
3. Lin, Y.H. et al. , "Dynamic range extension of the Tibet underground muon detectors for measurements up to the knee energy region with 3-inch photomultipliers," J. Instrum. , vol. 16, no. 06, p. P06010, Jun. 2021.

Results

We have five PMT candidates: N2014-1113, N2014-1018, N2023 from North Night Vision Science Technology Research, and CR332, CR285, R4125-6280 form HAMAMATSU. We evaluate their performance by the following three aspects:
1. High voltage linearity.
2. Dynamic range extension.
3. Transit time spread.

High voltage linearity

The gain G of PMT is highly dependent on the applied high voltage V. This relationship can be approximated by a power-law function: $G = \alpha \cdot V^{\beta}$, where β is an empirical exponent that characterizes the sensitivity of the PMT gain to changes in the applied high voltage.

Fig.4 shows an example of how to measure the coefficient β of PMTs. Detailed parameters of tested PMTs are shown in Table 1. The value of coefficient β is important for measuring the dynamic range extension of PMTs. To compare the dynamic range extension performance of different PMTs, we need to fix their gains to the same value by adjusting the high voltage, which requires β to be caculated.
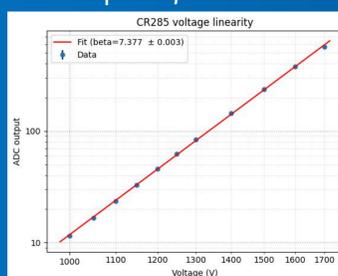

Figure 4. High voltage linearity of PMT CR285.

Table 1: Coefficient β of tested PMTs.

PMT	Standard Voltage (V)	Standard Gain	Coefficient β
N2014-1113	1000	7×10^6	7.771 ± 0.005
N2014-1018	980	7×10^6	7.973 ± 0.006
CR332	1250	2×10^6	7.623 ± 0.004
CR285	1250	1×10^6	7.377 ± 0.003
N2023	960	2×10^6	8.102 ± 0.003
R4125-6280	1500	8.7×10^5	7.482 ± 0.002

Dynamic range extension

The dynamic range of a PMT refers to the range of light intensities it can accurately detect from single photoelectrons to high-intensity signals. Measuring the dynamic range extension is essential to ensure that the PMT can reliably respond to both weak and strong optical signals without distortion or saturation. According to equation $G = \alpha \cdot V^{\beta}$ and values of β in Table 1, we can caculate the values of voltages for specific gains (3×10^6 and 7×10^6) of each PMT.

Fig.5 shows measuring dynamic range extension of PMT CR332 who has a gain of 3×10^6 at 1019 V and 7×10^6 at 1138 V. Dynamic range extensions of each tested PMTs at a gain of 3×10^6 and 7×10^6 are listed in Table 2. From only the perspective of dynamic range extension, the PMTs N2023 and R4125-6280 performs better.
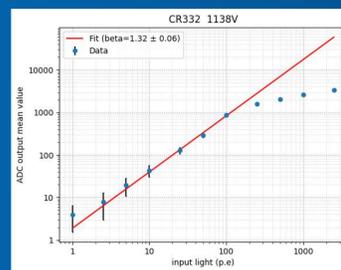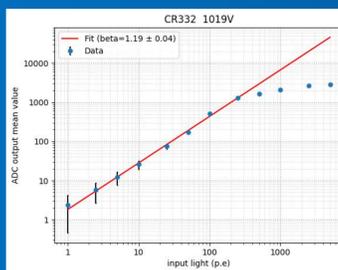

Figure 5. Dynamic range extension of PMT CR332 at voltages of 1019 V and 1138 V.

Table 2: Dynamic range extensions of tested PMTs.

PMT	Gain	Votage (V)	Photoelectrons
N2014-1113	3×10^6	896	1–250
	7×10^6	1000	1–250
N2014-1018	3×10^6	877	1–250
	7×10^6	980	1–250
CR332	3×10^6	1019	1–250
	7×10^6	1138	1–100
CR285	3×10^6	1301	1–250
	7×10^6	1460	1–100
N2023	3×10^6	1010	1–1000
	7×10^6	1122	1–500
R4125-6280	3×10^6	1688	1–500
	7×10^6	1892	1–250

Transit time spread

The transit time spread (TTS) of a PMT refers to the variation in electron transit time from the photocathode to the anode after photon absorption. TTS measurement is critical as it directly impacts the system's timing resolution; a smaller TTS indicates better performance.

Fig. 6 shows the Time of Flight (TOF) distributions for PMT R4125-6280 at 1688 V and 1890 V. The TTS is defined as the FWHM of these distributions. Higher voltage results in reduced TTS, consistent with theoretical predictions.

Although PMT N2023 demonstrates the best dynamic range extension (Table 2), it also exhibits the largest TTS among all tested PMTs (Table 3), degrading its overall performance. Considering both factors, PMT R4125-6280 offers the best balance, though its higher cost must be considered in the final selection.
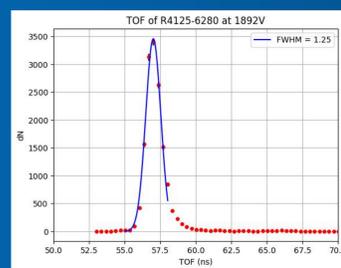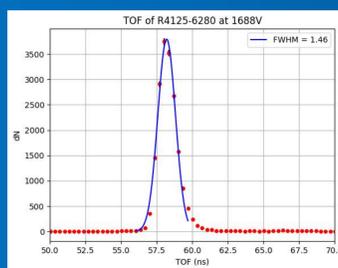

Figure 6. Transit Time Spread PMT R4125-6280 at voltages of 1688 V and 1890 V.

Table 3: Transit Time Spreads of tested PMTs.

PMT	Gain	Voltage (V)	Transit Time Spread (ns)
N2014-1113	3×10^6	896	1.90
	7×10^6	1000	1.53
N2014-1018	3×10^6	877	1.82
	7×10^6	980	1.38
CR332	3×10^6	1019	1.57
	7×10^6	1138	1.38
CR285	3×10^6	1301	2.28
	7×10^6	1460	1.94
N2023	3×10^6	1010	5.14
	7×10^6	1122	4.21
R4125-6280	3×10^6	1688	1.46
	7×10^6	1892	1.25

Summary

Considering dynamic range extension, transit time spread and cost of the PMT, we find PMT N2014 from North Night Vision Science Technology Research meets our expectations best. This PMT offers an acceptable dynamic range of 1–250 photoelectrons and an average TTS (less than 2 ns at a gain of 3×10^6), while its cost remains within our budget.