PMT Overshoot Study for JUNO Prototype Detector Postprint

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Abstract

The quality of PMT signal is one of the key items for a large and high precision neutrino experiment, like Daya Bay, JUNO, while most of the experiments are affected by the PMT signal overshoot from its positive HV-single cable scheme. For JUNO prototype detector, we have a detailed study on the PMT overshoot and successfully reduced the ratio of overshoot amplitude to signal to ~1% from previous typical ~10%, with no affection to PMT other parameters. Furthermore, we calculated that the overshoot is a result of discharging of capacitors in the HV-signal splitter and the PMT voltage divider. The study result is extremely important for JUNO and other similar experiments.

Full Text

Preamble

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Abstract: The quality of PMT signals is critical for large-scale, high-precision neutrino experiments, yet most such experiments are affected by signal overshoot in the positive HV-single cable scheme. Overshoot impacts trigger efficiency, dead time, and charge measurement in a detector. For the JUNO prototype detector, we have performed a detailed study and calculation of PMT signal overshoot to control the overshoot-to-signal amplitude ratio to approximately 1% without affecting other PMT parameters.

Key words: JUNO, PMT, PMT overshoot
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Introduction

The JUNO project proposes to determine the neutrino mass hierarchy using a 20 kton underground liquid scintillator detector. As a multipurpose underground neutrino observatory, JUNO will also measure neutrino oscillation parameters with better than 1% accuracy and detect neutrinos or antineutrinos from both terrestrial and extra-terrestrial sources. The experiment will provide exciting opportunities to address important topics in neutrino and astroparticle physics, including supernova bursts, the diffuse supernova neutrino background, geoneutrinos, atmospheric neutrinos, and solar neutrinos. According to its preliminary design, JUNO will deploy approximately 17,000 20-inch PMTs to achieve better than 3% energy resolution at 1 MeV.

In accordance with the JUNO schedule and R&D requirements, particularly for newly developed high-quantum-efficiency, large-area PMTs, a JUNO prototype detector is planned at the Institute of High Energy Physics (IHEP), Chinese Academy of Sciences. The prototype detector incorporates 51 PMTs from three manufacturers: 8 dynode PMTs and 20-inch PMTs from NNVT, 9 PMTs from Japan' s Hamamatsu, 8 Micro-Channel Plate (MCP) PMTs from Nanjing Night Vision Technology Co., and dynode PMTs from Hainan Zhanchuang Photonics Co. (HZC). These PMTs employ the positive HV scheme, in which a 50-Ω coaxial cable carries both high voltage and signals.

This scheme is widely used in many experiments, such as Daya Bay, Borexino, Chooz, and Double Chooz. A simplified schematic of the positive HV-single cable scheme is shown in Fig. 1, where a capacitor serves as a decoupler to separate the signal from the high voltage. While this scheme offers advantages including lower PMT noise, fewer cable connections, and reduced cost, the overshoot following a signal creates problems for charge measurement and system triggering, as demonstrated by Double Chooz, KamLAND, SNO, Borexino, and Daya Bay. Specifically, overshoot reduces trigger efficiency for low-energy events and distorts charge measurements for signals adjacent in time or following large signals from muons traversing the detector.

Various experiments have attempted to mitigate these disadvantages: Double Chooz installed two data dead-time monitor systems to quantify inefficiency from overshoot, while SNO, KamLAND, and Borexino developed specialized triggering or data acquisition systems. However, no common strategy for handling overshoot has emerged among these experiments. This paper presents a detailed study of the overshoot ratio and demonstrates how to control overshoot through optimization of the PMT HV divider and HV-signal decoupler.

[Figure 1: see original paper]

2 The Overshoot

A schematic of the PMT test system with positive HV and single cable is shown in Fig. 2. An LED was used to illuminate the PMT, and waveforms were sampled by an oscilloscope.

[Figure 2: see original paper]

The PMT and LED were placed in a dark box, with the LED driven by a program-controlled pulse generator. A synchronized gate from the pulse generator was sent to a low-threshold discriminator (LTD) to trigger the oscilloscope. High voltage was supplied by a CAEN Mod.A1733P in a CAEN SY4527 crate, and the PMT anode signal after the decoupler was sent to a 1 GHz sampling oscilloscope. Sampled PMT waveforms are shown in Fig. 3, where the recovery time is defined from the rising edge of the PMT pulse until the overshoot amplitude returns to 0.5% of the signal maximum amplitude. The measured overshoot-to-signal amplitude ratio is approximately 10.8%, which would significantly impact charge measurements of temporally adjacent signals, as observed in Daya Bay. Minimizing this overshoot is therefore essential.

[Figure 3: see original paper]

3 Circuit Optimization

We further simplified the positive HV PMT + decoupler + oscilloscope circuit as shown in Fig. 4, where C2 is the decoupler capacitor and R2 is the electrical load. Charge collected at the PMT anode is released through capacitors C1 (in the PMT HV divider) and C2, and the discharge of C1 and C2 affects overshoot. In the following sections, we measure the relationship between overshoot and C1 × R1 or C2 × R2, model the overshoot behavior, and optimize the circuit to minimize overshoot for the JUNO prototype.

[Figure 4: see original paper]

Signal overshoot results from capacitor discharge through resistors. We measured the relationship between overshoot and R1, which was varied from 1 Ω to 10 kΩ according to the scheme in Fig. 4 (all other components remained as shown). The results are presented in Fig. 5 and Table 1. The discharge through R2 × C2 contributes more significantly to overshoot.

We cross-checked this with different C2 values: when C2 was 4.7 nF, 10 nF, 15 nF, and 22 nF, the overshoot-to-signal amplitude ratios were approximately 5%, 2.5%, 2%, and 1%, respectively, consistent with the R2 × C2 time constant.

4 Overshoot Model

Based on our understanding that overshoot originates from discharge of capacitors in the PMT HV divider and decoupler, we further simplified the system as shown in Fig. 6. The output of PMT + decoupler can be modeled as:

[Figure 6: see original paper]

$$V_o(t) = V_i(t) \times h(t)$$

where $V_i(t)$ is the PMT output (system input), $h(t)$ is the response model of the PMT HV divider + decoupler + oscilloscope, and $V_o(t)$ is the final waveform viewed by the oscilloscope.

We used Fourier transformation to analyze the entire process, as shown in Fig. 7.

[Figure 7: see original paper]

Adopting the transformation from time to frequency domain, the system output signal can be expressed as:

$$V_o(\omega) = V_i(\omega) \times H(\omega)$$

where $H(\omega)$ is the system response in the frequency domain. According to the simplified circuit in Fig. 6, this can be expressed as:

$$H(\omega) = \frac{j\omega}{j\omega + 1/\tau}$$

where τ is the time constant of the differential circuit, which is $22\,\mathrm{nF} \times 50\,\Omega \sim 1100\,\mathrm{ns}$ in our case.

We further simplified the input signal $V_i(t)$ as an exponential pulse with time constant τ_i (the anode output time constant, typically $< 12\,\mathrm{ns}$):

$$V_i(t) = -\frac{Q}{C_i} \times \exp(-t/\tau_i)$$

For equivalent calculation, we assume a positive pulse instead of a negative pulse. The input in the frequency domain becomes:

$$V_i(\omega) = \frac{Q}{C_i} \times \frac{1}{j\omega + 1/\tau_i}$$

Combining these equations, we obtain:

$$V_o(\omega) = V_i(\omega) \times H(\omega) = \frac{Q}{C_i} \times \frac{j\omega}{(j\omega + 1/\tau) \times (j\omega + 1/\tau_i)}$$

Through inverse Fourier transform, the system output is:

$$V_o(t) = \frac{Q}{C_i} \times \frac{1}{\tau_i - \tau} \times (\tau_i \exp(-t/\tau) - \tau \exp(-t/\tau_i))$$

This equation describes the circuit output for an exponential pulse input. According to this expression, the output exhibits overshoot. When $\tau \gg \tau_i$, the overshoot ratio can be expressed as:

$$\frac{V_-}{V_M} \approx \frac{\tau_i}{\tau}$$

where V_- is the overshoot amplitude and V_M is the signal maximum amplitude. Thus, V_-/V_M is about 1.1% for $\tau_i \sim 12\,\mathrm{ns}$ and $\tau \sim 1100\,\mathrm{ns}$, or approximately 8% for $\tau \sim 140\,\mathrm{ns}$.

For the JUNO prototype, we selected a single-ended 50-Ω matching design with $R_1 = 10\,\mathrm{k\Omega}$, $C_1 = 4.7\,\mathrm{nF}$, and $C_2 = 22\,\mathrm{nF}$. The final output waveform is shown in Fig. 8. The signal overshoot is about 1%, consistent with our model calculation.

[Figure 8: see original paper]

5 PMT Performance with Updated Circuit

The PMT HV divider plays a crucial role in PMT performance. Timing and linearity of the PMT response serve as good indicators for evaluating the HV divider design. We have successfully reduced overshoot from approximately 10% to approximately 1% as discussed above. We tested all five PMT types used in the JUNO prototype and obtained consistent results. Here we present typical results using the HZC XP1805 PMT as an example.

5.1 Rise Time and Fall Time

With the optimized HV divider for the HZC XP1805 PMT, we measured rise time and fall time using the system shown in Fig. 2. We obtained waveforms of single photoelectron (SPE) signals using an LED producing photoelectrons at an average occupancy of 10%. These waveforms were recorded by the oscilloscope at 1 GHz sampling, as shown in Fig. 9.

[Figure 9: see original paper]

From the measured waveform, the PMT with our updated HV divider maintains fast timing properties, achieving a rise time of 2.2 ns and a fall time of 5.6 ns at a gain of 1.2×10^7, which meets our expectations.

5.2 Linearity of the PMT

PMT linearity is significantly influenced by the HV divider design. Pulse linearity is defined as the ratio of input to output photoelectrons in pulse operation mode. The measurement scheme is shown in Fig. 10.

[Figure 10: see original paper]

A pulse generator drives two blue LEDs, flashing them simultaneously. The light intensity of each LED can be adjusted separately to cover the entire PMT dynamic range. The PMT receives a sequence of light pulses: pulse (A) from LED1, pulse (B) from LED2, and the combined pulse (C) from both LEDs flashing together. A FADC system with 1 GHz sampling records waveforms corresponding to these three light pulses.

For an ideally linear PMT, we would have $C = A + B$. In reality, PMT response exhibits nonlinearity. The linearity deviation is defined as:

$$\text{Nonlinearity} = \frac{C - (A_{\text{corrected}} + B_{\text{corrected}})}{A_{\text{corrected}} + B_{\text{corrected}}}$$

where $A_{\text{corrected}}$ and $B_{\text{corrected}}$ are corrected for measured nonlinearity effects in the lower intensity range. The measurement results are shown in Fig. 11. The data indicate that 5% deviation is reached at approximately 700 photoelectrons. The measured PMT linearity satisfies our requirements and achieves performance comparable to previously measured R5912 PMTs.

[Figure 11: see original paper]

6 Conclusion

In this work, we confirmed a large PMT output overshoot at the 10% level as observed by the Daya Bay experiment and clarified that PMT overshoot originates from discharge of the capacitors in both the HV-signal decoupler and the HV divider. We optimized the HV divider and decoupler design to reduce overshoot for charge measurements, identifying $R_1 \times C_1$ and $R_2 \times C_2$ as the primary contributors.

We verified PMT performance using the proposed parameters. Further optimization will be needed for future JUNO HV dividers and decouplers to meet additional detailed requirements. Moreover, minimizing overshoot in positive-voltage PMTs is crucial for charge measurements in high-precision neutrino experiments and will benefit waveform sampling measurements.

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Note: Figure translations are in progress. See original paper for figures.