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Suppressing ringing caused by large photomultiplier tube signals^{*}

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Abstract: We describe here the characteristic features of the ringing we observed following large PMT signals in the Daya Bay reactor antineutrino experiment. We conclude that the ceramic capacitors used in the circuitry of the PMT bases and the HV-signal decouplers are the primary cause for this ringing. We present some possible schemes to reduce the ringing when replacing these ceramic capacitors is not feasible.

Key words: PMT, ringing, piezoelectric, Daya Bay, antineutrino

PACS: 85.60.Ha, 84.32.Tt, 84.30.Sk **DOI:** 10.1088/1674-1137/36/3/008

1 Introduction

The Daya Bay reactor anti-neutrino oscillation experiment will measure the mixing angle θ_{13} with unprecedented precision [1].

The experiment will use eight identical antineutrino detectors that are deployed at three different locations from the reactor cores. Each anti-neutrino detector (AD) consists of three concentric cylindrical volumes separated by transparent acrylic walls. The inner volume is filled with 20 t of a Gadolinium-loaded liquid scintillator for detecting both the primary anti-neutrino interaction, $\bar{\nu}_e + p \rightarrow e^+ + n$, and the subsequent neutron capture in Gd. The middle volume is filled with 20 t of pure liquid scintillator for detecting the gamma-rays escaping from the inner volume. The outer volume is filled with 40 t of mineral oil that acts as a shield against externally produced low-energy radiation. The light produced in the liquids is detected by 192 20-cm-diameter Hama-

matsu R5912 photomultiplier tubes (PMTs) that are mounted near the surface of the outermost stainless-steel cylinder. The ADs are submerged in water pools that are lined with PMTs to detect the Cherenkov light produced by cosmic-ray muons, and thereby to reject this source of background with high efficiency.

The signals from the PMTs are transmitted via 50-ohm coaxial cables to the front-end electronics (FEE). The long lengths of these cables represent a significant cost, and therefore it was decided to use a single coaxial cable to transmit both the high voltage to the PMT and the pulse produced at the PMT anode to the FEE. With this scheme the PMT must be operated at positive high voltage, and the signal from the anode must be capacitively terminated. Furthermore, a capacitor in the decoupler has to be inserted to isolate the signal processing circuitry from the high voltage. A simplified schematic diagram of the circuits used for this purpose is shown in Fig. 1.

Of particular relevance to the topic of this paper

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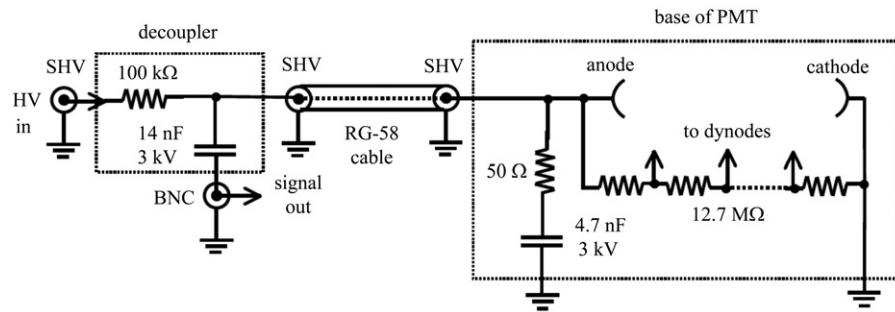


Fig. 1. Simplified schematic diagram of circuitry used to transmit PMT signals.

are the various coupling capacitors for they were the culprits in the ringing saga that is presented here. In particular, the ceramic capacitor in the base circuit, which is sealed, turned out to be one of the sources of the observed ringing. The moral of the story is that the choice of capacitors can have a major impact on the shape of the waveform that has to be processed by the FEE, and therefore care should be taken in choosing them properly. In the following sections we discuss the characteristics of the observed ringing, the capacitors used, and the various remedies that were considered to suppress the problems caused by the ringing.

2 Observation of ringing

We used a blue LED as the light source for our PMT tests. The PMT with the base circuitry shown in Fig. 1, and the pulsed LED light source were enclosed in a dark box. The PMT collected light from the LED that was driven by a pulse generator. After filtering out the high voltage in the decoupler, the PMT signals were sent to the oscilloscope for further study. A typical PMT pulse has a rise (fall) time of about 5 (15) ns, and an overshoot that is a consequence of the AC coupling mentioned in the introduction. The temporal structure of the ringing lasts for tens of microseconds and has a period of about 1.9 μ s. The amplitude of the ringing is proportional to that of the initiating PMT pulse and, for large pulses of the type induced by muons passing through the liquid scintillator, it can exceed several millivolts. One example is given in Fig. 2. These large pulses can produce ringing signals that are above the threshold of the trigger circuitry in the FEE; consequently, they can produce spurious triggers and introduce dead time into our experiment. It is therefore important to understand the cause of the ringing, and try to come up with remedial schemes to minimize any adverse impact they may have.

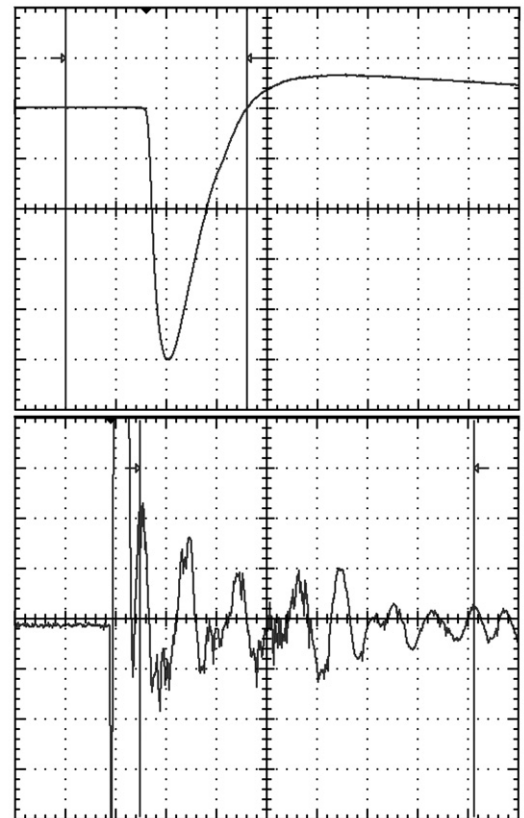


Fig. 2. Captured large PMT output signal with scales of 500 mV/div and 40 ns/div (top), 2 mV/div and 2 μ s/div (bottom). The peak amplitude is about 2.5 V. Ringing is present in the microsecond region with a period of about 1.9 μ s. The peak-to-peak amplitude of the ringing is typically a few mV.

Selection of HV capacitors

In order to understand the origin of the ringing, we replaced various individual components. No effect was observed when we used a different PMT or when we changed the value of the decoupling capacitors. The first hint as to what may have been going on is the change of ringing pattern when the ceramic capacitor in the decoupler is replaced with a polypropylene

one. This leads us to suspect that the cause of the ringing is due to the fact that we used ceramic capacitors in the PMT base. That is indeed the case which was confirmed by our test results. The full procedure of the test is described below.

We set up the test stand as described before in which the capacitors in both the PMT base and the decoupler were of the ceramic type. A PMT pulse with a peak value of about 2.5 V was sent to the scope. In this original configuration, ringing was present as shown in the upper panel of Fig. 3. After replacing the 13.2 nF ceramic capacitor in the decoupler with a polypropylene one of about the same value, the ringing pattern changed as shown in the middle of Fig. 3. We continued modifying the configuration by replacing the ceramic type capacitor in the base with a polypropylene one of about the same value. In this final configuration, the capacitors in both the PMT base and the decoupler were of a polypropylene type. The ringing disappeared completely as shown at the bottom of Fig. 3.

We did a full systematic study to see the ringing effect for different combinations of capacitors used in the PMT base and the decoupler. The result is given in Table 1. We can confidently conclude that the ceramic capacitors in the PMT base and the decoupler caused ringing.

On the basis of these results we replaced the capacitors in the decoupler, but unfortunately the capacitors in the bases were no longer accessible and

therefore they could not be changed. In the following section we suggest some possible remedies to reduce the effects of ringing under this circumstance.

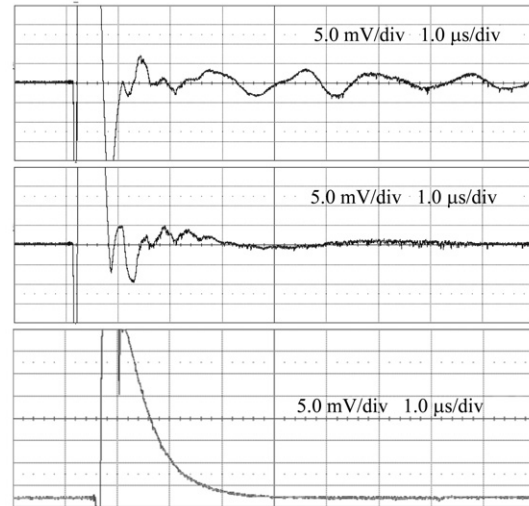


Fig. 3. Comparison of ringing with different kinds of high-voltage capacitors in the decoupler and the PMT base. Upper: the base and the decoupler were populated with ceramic capacitors. A 13.2 nF capacitor was used in the decoupler. Middle: the ceramic capacitor in the decoupler was replaced with a 10 nF polypropylene capacitor. Lower: polypropylene capacitors used in both the PMT base and the decoupler.

Table 1. A systematic study of ringing.

capacitor (PMT base)	capacitor (decoupler)	with ringing?	ringing Amp. (compare to row 1)
4.7 nF Cera.	13.9 nF Cera	yes	1
9.4 nF Cera.	13.9 nF Cera	yes	1
4.7 nF Cera.	10 nF Pp.	yes	0.9
9.4 nF Cera.	10 nF Pp.	yes	0.9
10 nF Pp	13.9 Cera	yes	0.6
3.3 nF Pp	13.9 Cera	yes	0.6
10 nF Pp	10 nF Pp	none	0
3.3 nF Pp	10 nF Pp	none	0

3 Schemes of suppressing effects due to ringing

Compared with the fast PMT signal, the observed ringing components have a much slower time structure with a period in the μs range. We can thus suppress this type of ringing while preserving most

of the signal integrity of the PMT pulse with “differentiation” circuits. We have considered three circuit designs shown in Fig. 4.

3.1 Circuit response in the time and frequency domain

To investigate the performance of these circuits

analytically, the ringing feature is modeled with a simple function: $V_{\text{Ringing}}(t) = A\sin(2\pi t/T_{\text{Ring}})$. In the time domain, for an input as described above, the output is given by $|V_{\text{out}}| = |V_{\text{Ringing}}| \times (2\pi\tau/T_{\text{Ring}})$, which implies that the amplitude of the ringing will be reduced greatly when a small time constant τ is chosen.

The frequency domain response is expressed in the form of the transfer function $H(S) = V_o(S)/V_{\text{IN}}(S)$, where $S = j\omega$. The gain dependence of the frequency for the three circuits is: $\sqrt{1/(1+1/(2\pi f\tau))}$ for the CR circuit, $2\pi f\tau$ for the differentiator circuit, and $2|\sin(\pi f\tau)|$ for the delay-line circuit.

3.2 Results of prototype circuits

A prototype board containing these three designs shown in Fig. 5 has been built and evaluated. In the differentiator circuit, we added a capacitor in parallel with the feed-back resistor so that, at high frequency, this circuit becomes an integrator [2]. The layout is arranged to minimize changes to the existing FEE PCB (Printed Circuit Board) layout.

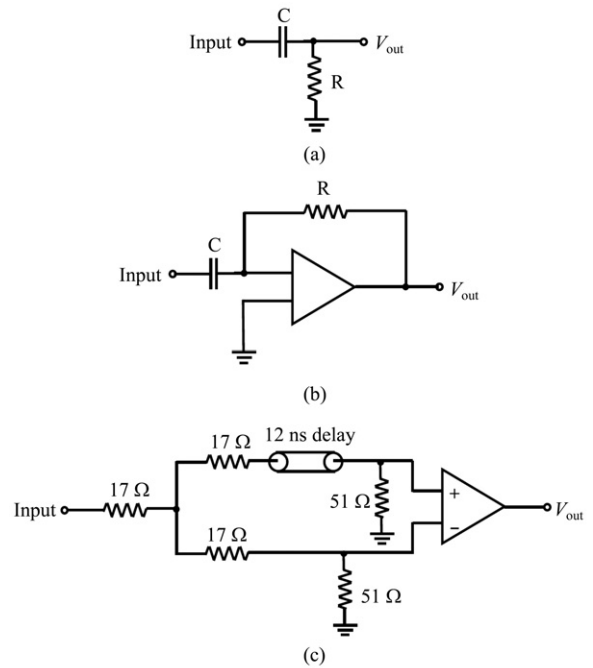


Fig. 4. Circuits that can suppress ringing. (a) CR circuit; (b) Differentiator circuit; (c) Delay-line circuit.

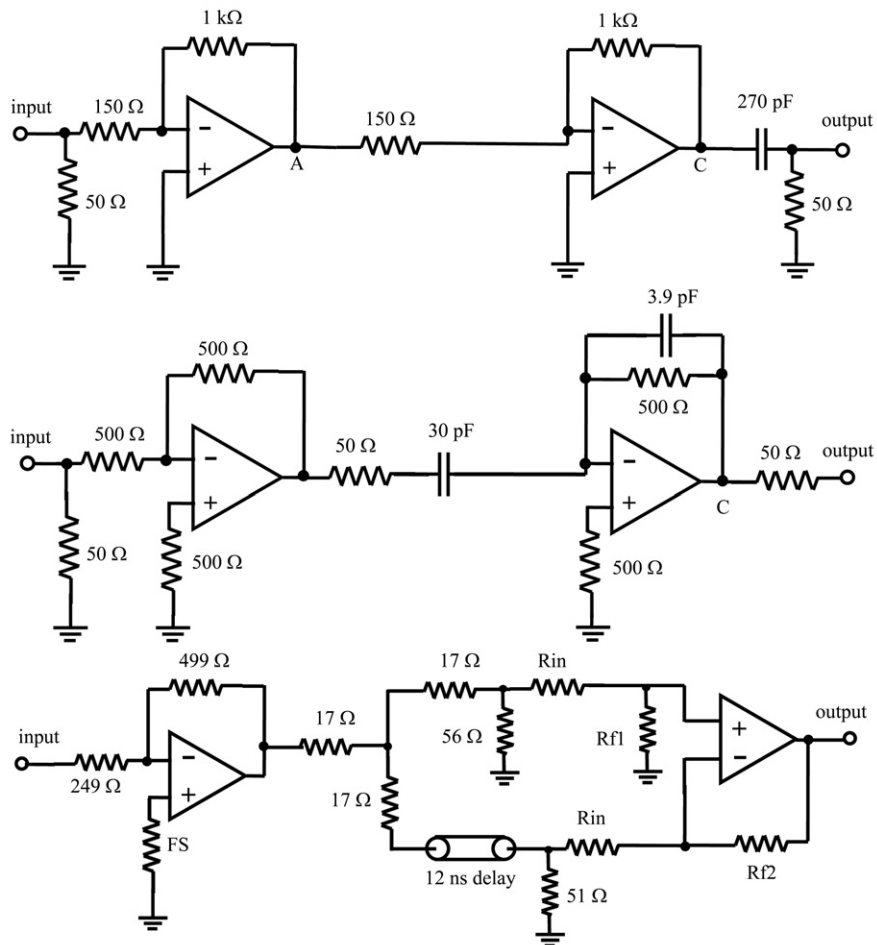


Fig. 5. Schematics of prototype circuits.

For very large PMT pulses (e.g., 2000 photoelectrons), ringing is very much suppressed by all three designs as shown in Fig. 6.

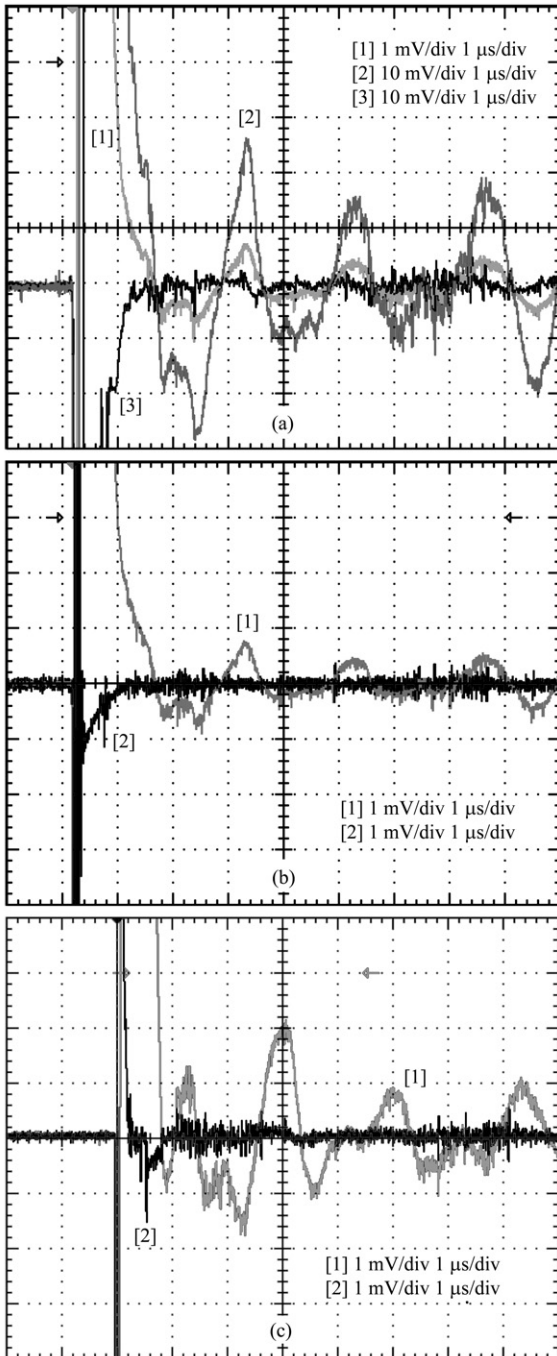


Fig. 6. Effect of the three circuits on a big input PMT pulse. In (a), Trace 1 represents the original PMT pulses, Trace 2 illustrates pulses at point C and Trace 3 is the waveform after the CR circuit. In (b) and (c), Trace 1 is the input PMT pulse and Trace 2 is the output signal.

In addition, it is important to understand how each design handles the main PMT pulse. As shown

in Fig. 7, the original pulse becomes bipolar. In the Daya Bay Experiment where the charge measurement circuitry is separated from the trigger part in the FEE, the charge-measuring features of the FEE system are unchanged. And for the purpose of triggering, only the negative-going part of the bipolar pulse plays a role. To keep the same trigger efficiency with

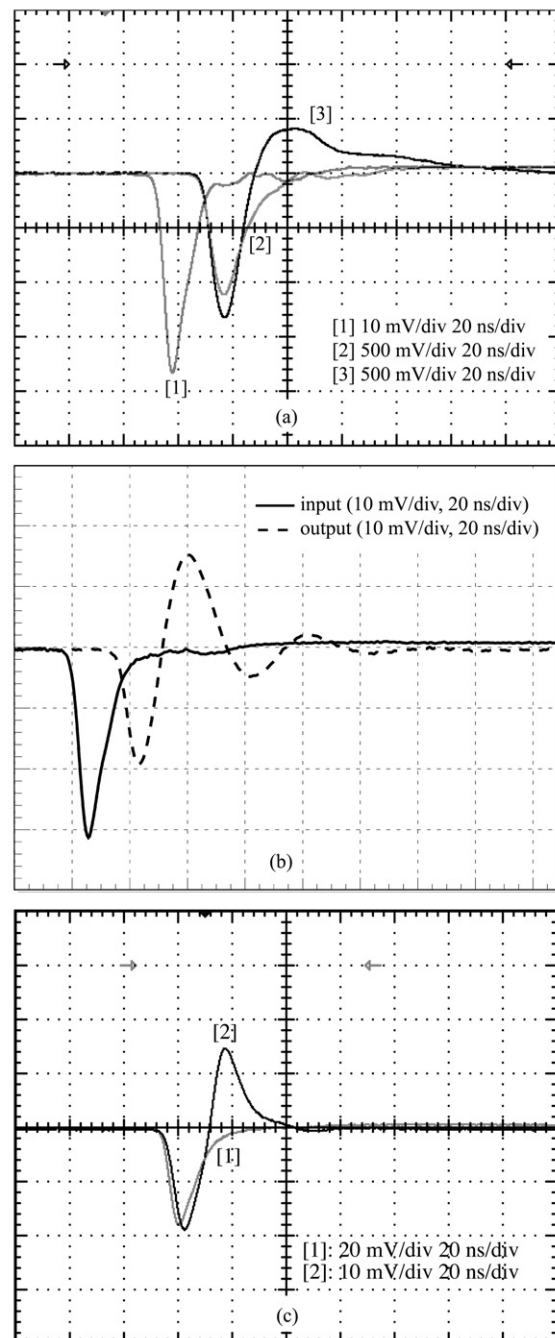


Fig. 7. Effect of the three circuits on a small PMT pulse. In (a), Trace 1 represents the original PMT pulses, Trace 2 illustrates pulses at point C and Trace 3 is the waveform after the CR circuit. In (b) and (c), Trace 1 is the input PMT pulse and Trace 2 is the output signal.

the existing FEE system, the amplitude of the negative part cannot be reduced.

For the CR circuit (Fig. 7(a)), the amplitude of the main pulse is much reduced. Increasing the RC time constant increases the output amplitude. However, the amplitude is never completely restored to the original value. On the other hand, the amplitude of the output in the differentiator design can be tuned by changing the time constant. The drawback is an innate instability [2] that is hard to get rid of. Fig. 7(b) shows oscillations in the output. In the delay-line scheme (Fig. 7(c)), the pulse has to be split into two equal parts. As a result, the amplitude of each part is only half of that of the original pulse. However, this reduced amplitude can be restored quite easily by amplifying the recombined signal by a factor of two.

In summary, evaluation of the prototype circuits shows that all three designs can effectively eliminate ringing. In the case where the amplitude of the out-

put signal is allowed to change, the CR circuit provides a simple solution. If the amplitude has to be preserved, the delay-line method is a good choice. Utilizing the true differentiator requires additional consideration such as selection of the op-amp and circuit design in order to eliminate instability.

4 Conclusions

We found that the ceramic high-voltage capacitors used in the PMT base and the decoupler introduce ringing. The most likely cause of the ringing is due to the piezoelectric effect in these capacitors when they are subject to high voltage [3]. This problem can be fixed by using polypropylene capacitors. In the case that the ceramic capacitors in the PMT bases are not accessible, we have showed that the effects due to ringing can be effectively mitigated with a CR, a differentiator or a delay-line circuit.

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