The high-speed after-pulse measurement system for PMT

Y. Cheng, S. Qian, Z. Ning, J. Xia and Z. Wang

Abstract: A system employing a desktop FADC has been developed to investigate the features of 8-inch Hamamatsu PMT R5912. The system stands out for its high-speed and informative results as a consequence of adopting fast waveform sampling technology. Recording the full waveforms allows us to perform pulse shape analysis. High-precision after-pulse time and charge distribution results are presented in this manuscript. Other characteristics of the photomultiplier tube, such as the gain of charge, dark rate and transit time spread, can be also obtained by this system.

Keywords: Data acquisition concepts; Optical detector readout concepts

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1 Introduction

Photomultiplier tubes (PMT) have been widely used in nuclear and particle physics experiments as a result of their outstanding characteristics, such as high gain, low noise and fast response. Neutrino experiments (refs. [1, 2]) employ hundreds of PMTs to detect low intensity light, for example water Cherenkov detector Super-Kamiokande and liquid scintillator detector Daya Bay.

Before PMTs start the data taking mission, a series of tests have to be made to check whether every single PMT has reached their desired specifications. Couples of criteria are set to decide whether a PMT is eligible or not, concerning the gain, the transit time spread (TTS), the dark count rate or the dark current and so on (refs. [3, 4]). After-pulse occurs some time later after the initial photoelectron signal, and cannot be distinguished from the true physical signals (ref. [5]). Thus for low background neutrino experiments which use tens of thousands of PMTs, after-pulse is a troublesome background, and its features need fully studied and put into simulation to evaluate its impacts (refs. [6, 7]). The mechanism of after-pulse was found to be the ionization of the residual gases inside the PMT by the accelerated photoelectrons (refs. [5, 8]). In order to generate a 20-μs or larger time window, the oscilloscopes were introduced even if their data taking speed was not so fast (ref. [9]). In case of large batch PMT testing, high speed becomes a prominent requirement for the testing system. Compared with conventional oscilloscope test system, the flash ADC (FADC) test system can continue without dead-time. While all oscilloscopes have dead-time between repetitive acquisition of waveforms and their dead-time could be orders of magnitude longer than acquisition time (ref. [10]). In our lab we have successfully implemented a high speed test system based on a desktop flash ADC (ref. [11]).
2 Test facility

The test system was based on a 1 GHz desktop FADC (CAEN DT5751) (ref. [12]). With the 1800 V operation voltage, the averaged amplitude of the waveforms induced by the dark hit was about 10 mV at the $1.0 \times 10^7$ gain. With the digitizer’s 1 Vpp input dynamics range and a programmable DC-offset, signals as large as 100 p.e. could be directly sampled by the FADC and then read into the DAQ computer and analyzed by ROOT.

A laser diode was used to light the PMT. As shown in figure 1, a pulse generator (model AFG3102) was used to drive the laser diode and its synchronizing signal, which was converted to NIM level, served as the trigger signal of FADC. With this coincidence, triggers caused by noise can be largely suppressed. The voltages to the PMTs were supplied by the high voltages system SY1527. Both the HV module and the intensity as well as the frequency of the light source were controlled by the DAQ computer. The pulse from pulse generator used to drive the laser diode had 10 ns pulse-width. Its voltage was carefully tuned to get single photon and multi-photons.

![Figure 1. The setup used for PMT performance measurements.](image)

Another option for the test instrument was Lecroy WavePro 7100. Their technical performances and specifications were listed in table 1 (refs. [13, 14]). Since we need speed up our test procedure and have the demand for a large buffer memory, DT5751 was our final choice.

| Instrument | DT5751 | WavePro 7100 |
|------------|--------|--------------|
| Sampling Frequency | 1 GHz | 10 GHz |
| Memory Depth | 1.835 Mpts | 1 Mpts |
| Dead time | 0 $\mu$s | <6 $\mu$s |
| Band Width | 500 MHz | 1 GHz |
| Sensitivity | 1 (mV/div) 10-bit | 2 (mV/div) |
| Weight | 680 gr | 18 Kg |
| Price | 50 K | 150 K |
3 Results and discussions

A detailed measurement of the after-pulse time and charge pattern of the 8-inch hemispherical PMT R5912 (ref. [15]) was performed with this measurement system. Not only the characteristic of the after-pulse, but also other information could be derived by this testing system, such as the SPE spectrum, TTS, dark current and so on.

3.1 Timing and charge distribution of after-pulse

Figure 2 demonstrated the timing pattern of the after-pulse of the R5912. The time of the after-pulse was defined as the time interval between the main pulse and the second pulse, namely after-pulse, time difference larger than 500 ns was shown in the plot. There were two groups which have distinct characteristics, representing two different ions types. For R5912, two ion peaks were at around 1.56 µs and 6.37 µs, corresponding to methane and caesium ionization (refs. [16, 17]). This results were consistent with oscilloscope test results (ref. [18]). A scattered plot of after-pulse charge in units of p.e. versus arrival time was also shown in figure 2. Most after-pulses are SPE pulses, irrelevant to the main pulse charge. PMT dark noise, which were mostly SPE, were uniformly distributed in the temporal range.

Figure 2. (Left) Distribution of the after-pulse time. (Right) After-pulse time (x axis) and charge (y axis, units of p.e.) distribution.

Besides the after-pulse signal reported in refs. [16–18], we have observed after-pulse that appeared close behind the main pulse. They occurred around 50 ns later after the main pulse, with the leading edge of the main pulse as reference time-zero, and they were mainly SPE charge pulses. Since many PMT test systems use discriminator, this type of after-pulse could not be discriminated due to the dead-time (200 ns) of the discriminator (ref. [19]). Compared with the µs-scale after-pulse, we can call this kind of after-pulse the fast component after-pulse. The charge and time characteristics of fast component after-pulse were presented in figure 3.

3.2 Transit time and transit time spread

The absolute transit time is the time interval between the arrival of a light pulse at the photocathode and the appearance of the output pulse (ref. [20]). Since the absolute value of the transit time may be biased by cable lengths, proceeding electronics etc., we focused on the transit time of photoelectrons from the photocathode to the first dynode. Transit time follows a Gaussian distribution, the spread is due to different traveling trajectories.
Hamamatsu R5912 uses box and line focused type of dynode structures, with good collection efficiency and good uniformity. The fast component after-pulse we observed arose from photoelectrons back-scattering on the first dynode. The back-scattered photoelectrons were decelerated by the electric field and then accelerated again towards the electron multiplying system (ref. [21]). In our case, only elastic scattering was considered. In the right plot of figure 3, we used exponential function to estimate the contribution from inelastic scattering. From the fitting result (Constant1 and Cosntant2 in the upper panel), we can see it’s a proper assumption. Thus the resulting delay time of fast after-pulse, with reference to the main pulse, were twice the transition time between the photocathode to the first dynode. As a result, transit time and transit time spread can be estimated from hit time distribution of fast after-pulses. The results were shown in figure 4 and table 2. Using the results from high statistics after-pulse, the transit time of photoelectrons from the photocathode to the first dynode for R5912 was 22.0 ± 2.05 ns and the transit time spread is 5.6 ns. We assumed that the absolute transit time from photocathode to the first dynode can be represented by half of the difference between the mean value of the first peak and the second peak. The sigma value of the first peak (the main pulse peak) was taken as the transit time spread. Due to the way we calculate transit time, we can also get transit time spread based on the sigma values of the first two peaks, the result is 5.2 ns, close to the value 5.6 ns from the simple approach.

3.3 After-pulse rate and dark rate

There were various after-pulse rate definitions in the literature, such as defining the ratio between the total after-pulse charge and main pulse charge as the after-pulse rate, or regarding the ratio of after-pulse number and main pulse charge as the after-pulse rate (ref. [22]). Here we chose the definition that the after-pulse rate was the average number of after-pulse induced by per p.e. of the initial pulse (ref. [18]). After-pulse rate was proportional to the main pulse charge, shown in figure 5. By this definition, we derived the after-pulse rate by performing a one-degree-polynomial fit to the plot of after-pulse number versus main pulse charge. The offset of the linear fit function

Figure 3. (Left) Fast after-pulse time distribution (right) Fast after-pulse charge distribution in units of p.e.
Table 2. Fitting results of hit time using three Gaussian functions.

| Item                        | Main peak/ns  | AP peak/ns   | 2nd AP peak/ns |
|-----------------------------|---------------|--------------|----------------|
| Intensity (Constant value of Gaussian) | 8783.75 ± 51.64 | 248.54 ± 7.35 | 10.44 ± 1.36 |
| Hittime (Mean value of Gaussian)   | 295.69 ± 0.03  | 339.70 ± 0.22 | 387.78 ± 1.38 |
| Spread (Sigma of Gaussian)       | 5.59 ± 0.02    | 8.65 ± 0.17   | 10.75 ± 1.15  |

Figure 4. Hit time of three peaks: main pulse, fast component after-pulse, the recursive one (i.e. the fast component after-pulse again of the second peak). The dashed line was fitting curve using three Gaussian functions, fitting results were presented in table 2.

can be regarded as dark count, also illustrated in figure 2, which is independent of the main pulse charge. The slope of the linear fit function was after-pulse rate, i.e. 1.794%. This result was in consistence with ref. [18], 1.7%. From the offset and the inspection time period, we can get PMT dark rate. In our test, the time window was 20 µs, thus PMT dark rate at this temperature was 0.235/(20 × 10⁻⁶), i.e. ~ 10 KHz.

4 Single photoelectron spectrum and the SPE waveform

Typical SPE spectrum system was set up as in ref. [23]. However employing NIM crate and VME framework made the system lack of flexibility and mobility. Using the light-weighted FADC system, PMTs can be tested almost anywhere and anytime. In the testing procedure, we measured the SPE response to calibrate the FADC. To do this, we turned our light source intensity down to ensure that the occupancy of the SPE pulses was less than 10% (ref. [24]). The gain of charge and the SPE waveform can be derived using this FADC system. From the averaged SPE waveform (figure 6), peak amplitude and rise-time can be measured, served as references for the design of the PMT readout system. To detect pulses, a scan for threshold-crossing point in the pedestal-subtracted waveform was performed. Some algorithms (ref. [25]) were applied to extract peaks from the
waveform and estimate the charge and hit time for each peak. From the averaged SPE waveform, 
we could derive some information, such as the rising time was 4.8 ± 0.3 ns and the SPE amplitude 
is 10.9 ± 0.3 mV @ 1.0 × 10^7 Gain (1800 V operation voltage), etc. In order to confirm the testing 
result of DT5751, the QDC with the type of V965 (ref. [11]) was used to find the charge of the SPE 
waveform for the PMT under a operation voltage of 1700 V. The gain of charge of this PMT can be 
calculated from the charge spectrum by doing a double Gaussian fit to the spectrum:

\[
\text{Gain} = \frac{Q^{\text{spe}} - Q^{\text{pedestal}}}{Q^{\text{electron}}}. \tag{4.1}
\]

Here, \(Q^{\text{spe}}\) and \(Q^{\text{pedestal}}\) was from double Gaussian fit, the gain by DT5751 is 6.375 × 10^6, with 
agreement to the result from V965, 6.438 × 10^6, shown in figure 7. In a similar way, we found the 
correct high voltage with gain 1.0 × 10^7.

![Figure 5. After-pulse number as the function of main pulse charge in p.e.](image)

![Figure 6. Typical SPE waveform (averaged from 13992 frames).](image)

5 Conclusion

We studied the possibility to measure the after-pulse with FADC and designed an experiment 
scheme which can finalize after-pulse test in almost one hour taking advantage of the almost zero
dead-time of FADC. Meanwhile, it took over ten hours for oscilloscope to get equivalent statistics of after-pulse. We observed two after-pulse clusters, they arose at 1.56 $\mu$s and 6.37 $\mu$s after the main pulse. The intensity of these two clusters represented the level of residual gas in the PMT glass. We also observed ns-scale after-pulse since we are using FADC. This kind of after-pulse is important because it would affect the charge and time of the signal in the same readout window.

We measured the after-pulse of one 8-inch Hamamatsu PMT with high precision and get plenty of useful information by employing waveform analysis. These characters of every single PMT, such as gain, dark rate, after-pulse, absolute PMT transition time and its spread can be derived by applying this FADC testing system. The system can be used for PMT performance study and will play an important role in the PMT batch testing for next generation reactor neutrino experiments, such as the Jiangmen Underground Neutrino Observatory.

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