Study of TTS for a 20-inch dynode PMT *

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Abstract: The neutrino detector for the Jiangmen Underground Neutrino Observatory (JUNO) requires a large number of photomultiplier tubes (PMTs), including 15000 MCP PMTs and 5000 dynode PMTs. The TTS (transit time spread) of the PMTs is very important for vertex and track reconstruction of the neutrinos in the detector. In this paper, we study the TTS of a 20-inch dynode PMT (R12860) from Hamamatsu for different high voltage, light intensity, light spot size and different photocathode regions. The impact from Earth's magnetic field is also studied. The results achieved in this paper will be very useful for the JUNO experiment.

Keywords: TTS, 20-inch dynode PMT, transit time, Earth's magnetic field

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1 Introduction

After the measurement of the non-zero neutrino oscillation parameter θ_{13} at the Daya Bay neutrino experiment [1], construction has started on the Jiangmen Underground Neutrino Observatory (JUNO), which is one of the next generation of neutrino experiments. The major goal of JUNO is to determine the neutrino mass hierarchy and precisely measure the neutrino oscillation parameters [2]. A 20 kton liquid scintillator (LS) detector will be constructed for JUNO. The scintillation photons emitted by the LS will be collected by about 18000 20-inch PMTs. In addition, approximately 2000 20-inch PMTs will be installed in the water pool to detect the Cherenkov light from cosmic-ray muons, acting as a veto detector. To reach a vertex reconstruction resolution of 18 cm, which has negligible impact on energy resolution, the TTS of those dynode PMTs is required to be less than 2 ns. In the case of multiple photons that hit the same PMT, only the time determined from the first hit is used for the event reconstruction. So the vertex and track reconstruction of the event is based on the timing of the PMT signals [3]. An important parameter is the TTS (transit time spread) which is defined as the standard deviation(σ) of a Gaussian fitting of the transit time (TT) spectrum [4].

In this paper, we study TTS versus high voltage, light intensity, light spot size and different photocathode regions. Since the performance of PMTs, especially those with large area photocathodes, is sensitive to the magnetic field [5], the TTS in the presence of the Earth's magnetic field is also studied.

2 Test system setup and TTS analysis

The system for TTS study is mainly comprised of a laser diode (LD), a pulse generator, a low threshold discriminator (LTD), a TTL-NIM adaptor and an oscilloscope, as shown in Fig. 1.

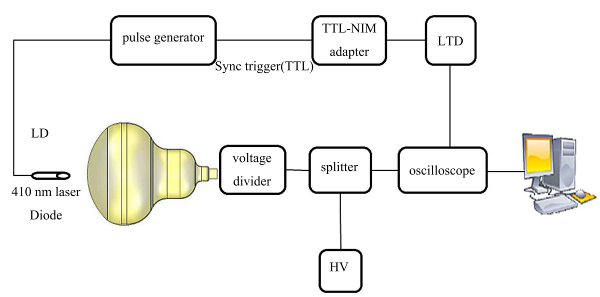

Fig. 1. (color online) Setup for the test system.

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In our test we used a 20-inch dynode PMT (type R12860) produced by Hamamatsu Photonics. The PMT and LD were put in a dark box, and the LD, which had a wavelength of 410 nm, was driven by the pulse generator to illuminate the PMT. At the same time, a synchronized gate signal from the pulse generator was sent to the LTD to produce a trigger for the oscilloscope. The anode signal of the PMT was measured by the oscilloscope, which had a sampling rate of 5 GHz, and then stored in a computer. Since the anode signal is strongly coupled with the PMT base, the circuit of the base is also presented, as shown in Fig. 2.

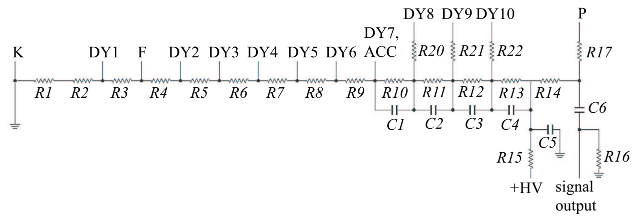

Fig. 2. Schematic of the base circuit.

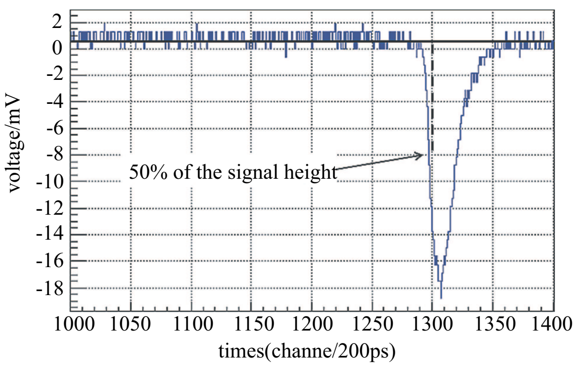

Fig. 3. A typical PMT signal.

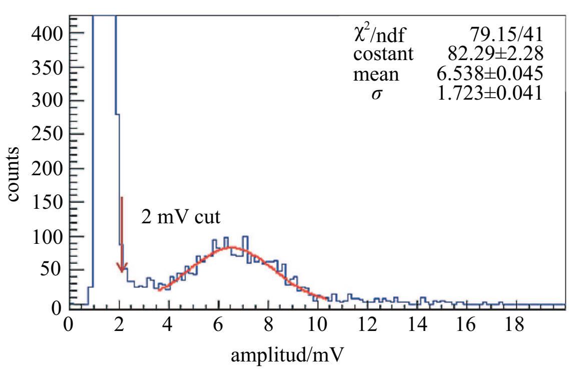

Fig. 4. (color online) The pulse height distribution of a single photoelectron.

The TTS was analyzed offline from the data measured by the oscilloscope. Since the time to peak of PMT signals are the same, the hit time of each signal is firstly determined by a waveform processing method (Constant Fraction Discrimination, CFD) which sets the noise rejection threshold to 2 mV and the constant fraction to 50% , and then filled into a histogram (TT spectrum). The TTS is finally extracted from a Gaussian fitting of the spectrum [6]. Figure 3 shows the PMT output signal with the 50% fraction set, and Fig. 4 shows a pulse height distribution of a single photoelectron where one can see the noise magnitude is about 2 mV. Figure 5 shows a typical TT spectrum with Gaussian fitting. A slightly non-Gaussian distribution in the tail is because of the timing uncertainties from small signals.

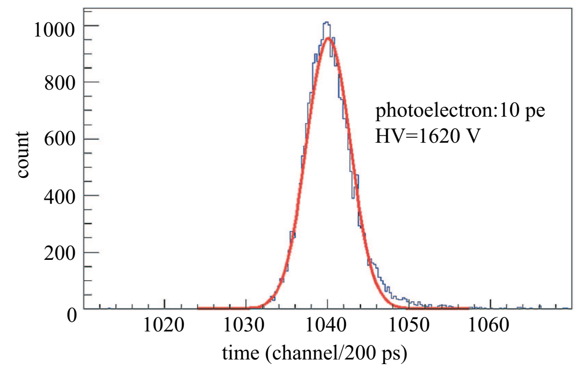

Fig. 5. (color online) A typical transit time spectrum.

3 TTS without Earth's magnetic field

At the JUNO site, the measured strength of the Earth's magnetic field is about 55 μT, which has a significant effect on PMT performance. JUNO is planning to use coils to compensate the geomagnetic field for the central detector PMTs. For the veto PMTs, since they are close to the coils, additional passive shielding with high permeability foils is needed. To study how the magnetic field impacts the TTS and give an input for the JUNO design, the TTS was measured both with and without shielding of the geomagnetic field.

In these studies, the Earth's magnetic field in the laboratory site was shielded by a cylinder made of 0.5 mm thick μ-metal around PMT, as shown in Fig. 6. After

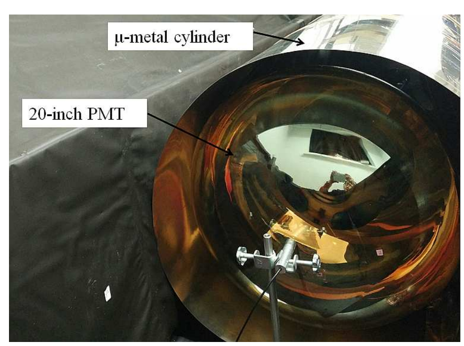

Fig. 6. (color online) PMT with a μ-metal cylinder for shielding from Earth's magnetic field.

shielding, the residual magnetic field in the center is only 5 μT, and before shielding it was 55 μT, the same value as that at the JUNO site. The results are shown in Fig. 7, where the X-axis is different positions along the 1.3 m long μ-metal cylinder and the Y-axis is the absolute value of the total strength of the Earth's magnetic field measured by a Gauss meter. The PMT was placed at the center of the cylinder for all the following studies.

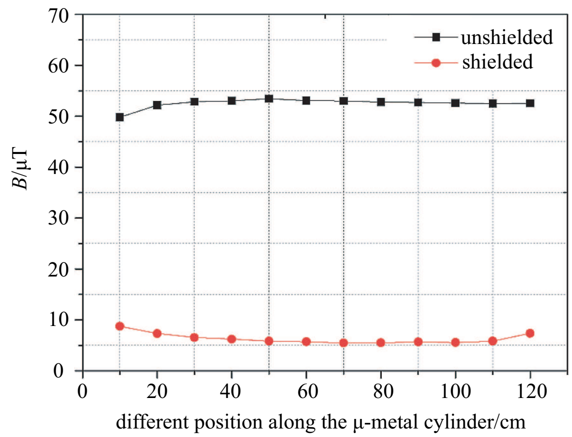

Fig. 7. (color online) Magnetic field measured with and without shielding.

3.1 TTS for different high voltage

The JUNO PMTs will work at a gain of 10^7, which requires high voltage typically at 1600 V for those dynode PMTs. We therefore measured the TTS for different operating voltages around 1600 V for the single photoelectron condition. The PMT was illuminated from the top center by the LD with a spot size of 4 mm (point-like light source). The LD intensity can be tuned into so-called single photon mode. The results are shown in Fig. 8, where one can see that there is no large variation for different voltages, and a typical TTS of 0.92 ns is obtained for 1620 V. The LD we used was calibrated and it had a negligible contribution to the measurement.

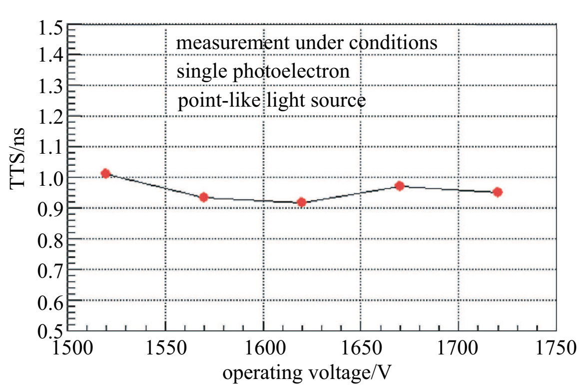

Fig. 8. (color online) TTS for different operating voltages.

3.2 TTS for different photocathode regions

The same point-like light source was used as described in Section 3.1, but it was moved along the profile of the PMT photocathode from the top center to the equator, as shown in Fig. 9, where α is defined in the X-Y plane and β in the X-Z plane. The results of TTS are shown in Fig. 10(a). The values are centered at about 1 ns, and overall there are no significant changes in different photocathode regions. Slightly larger changes are observed in the region near the equator, with the large

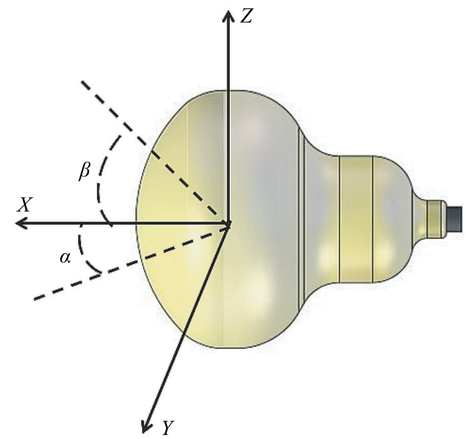

Fig. 9. (color online) Incident angles of illumination on the photocathode.

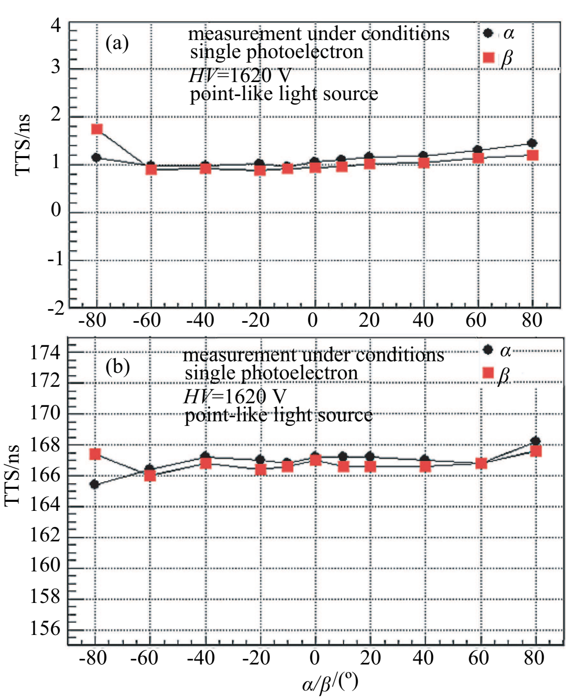

Fig. 10. (color online) (a) TTS for different photocathode regions; (b) TT for different photocathode regions.

α and β angle, where the electric field is not uniform compared to the top center due to the presence of the photocathode edge there. The electric field might also be asymmetrical along the equator circumference, which will cause a slightly asymmetrical distribution for different α and β angles. This is not serious for the JUNO situation, because most of the light will have small incident angles since the PMTs are far from the LS center. The corresponding TT values are also shown in Fig. 10(b). They are centered at 167 ns with minor variation of ±1 ns.

3.3 TTS for different light spot size

Point-like light sources are preferred in laboratory based PMT characterization systems [7]. However, in the central detector of JUNO, scintillating photons may reach the PMTs anywhere on the photocathode. In order to imitate the JUNO condition, we added a divergent lens in front of the LD and diffused the light to illuminate the whole PMT photocathode. Figure 11 shows the results for both point-like light source and diffused light source, under different light intensities. For the single photon condition, the TTS of the point-like source is 1.0 ns, while for the diffused light, the TTS is 1.5 ns, about 0.5 ns worse. This is mainly due to the different drifting trajectories of photoelectrons from different photocathode positions to the first dynode when light is diffused and illuminates the whole PMT, which will cause divergent transit time and hence larger TTS. From this measurement, one can see that the TTS of the dynode PMT can meet the JUNO requirement of 2 ns for both point-like and diffused light sources.

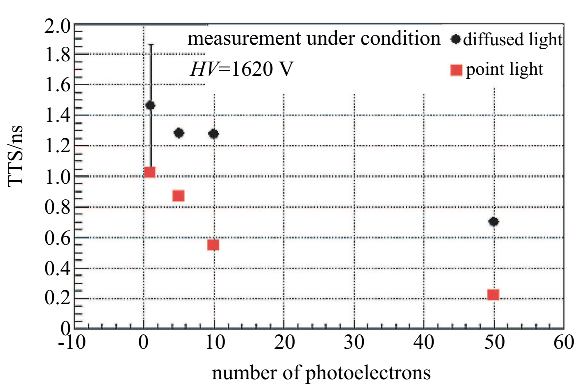

Fig. 11. (color online) TTS for different light spot sizes (the first data point of the diffused light has large error, due to the number of collected photoelectrons being relatively low).

3.4 TTS for different light intensity

The TTS was also measured when varying light intensity from a single photon to a few hundred photons. The results are shown in Fig. 12, where different operating voltages are applied to the PMT. We observed that TTS is strongly dependent on light intensity and follows roughly $a+b/\sqrt{N}$ (N is the number of photoelectrons) behavior, which is a Poisson distribution [8–10]. The TTS for a single photoelectron is about 0.92 ns, as mentioned before, but it can be reduced to 0.2 ns for 100 photoelectrons. We also see that the TTS under different voltages is similar and follows the same behavior when increasing the light intensity. This behavior might be useful for muon reconstruction in JUNO, since muons will produce very dense light in the detector and the vertex resolution can be improved.

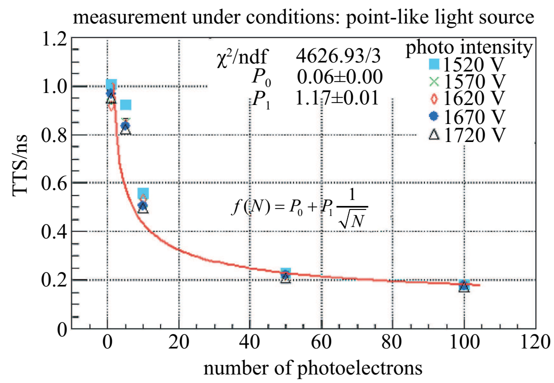

Fig. 12. (color online) TTS for different light intensity.

4 TTS with Earth's magnetic field

Large diameter PMTs are sensitive to Earth's magnetic field. The performance of the PMT could be significantly worsened by the presence of magnetic field, because of divergent trajectories of photoelectrons from the photocathode to the first electrode and from there to the dynode chains and finally to the anode, which will cause a wide spread in transit time [5, 11].

4.1 TTS in different directions

To study the impact of the Earth's magnetic field on TTS, we rotated the PMT in the X-Y plane with respect to the Z-axis as shown in Fig. 13 [11]. A point-like light source was used in single photoelectron mode, and the PMT was illuminated from the top center.

Figure 14(a) shows the values of TTS. For comparison, the TTS measured with the magnetic field shielded is also plotted. At $\varphi = 0°$ and 180° (i.e., the East to West direction), the TTS is about 5 ns and 4 ns, respectively; and at $\varphi = 90°$ and 270° (the South to North direction), the TTS is about 1.5 ns. With the magnetic field shielded, the TTS is always at about 1 ns level. The worst TTS appears in the East to West direction ($\varphi = 0°$ and 180°), due to the trajectories of photoelectrons being just orthogonal to the Earth's magnetic line, which at our location is in the direction of South to North, so the impact is largest. The TTS in the direction of South to

North (φ= 90° and 270°) is only slightly affected, due to the trajectories being somewhat parallel to the magnetic line, so the impact is relatively smaller.

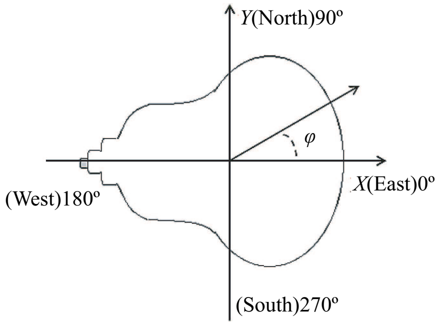

Fig. 13. Top view of the PMT rotation.

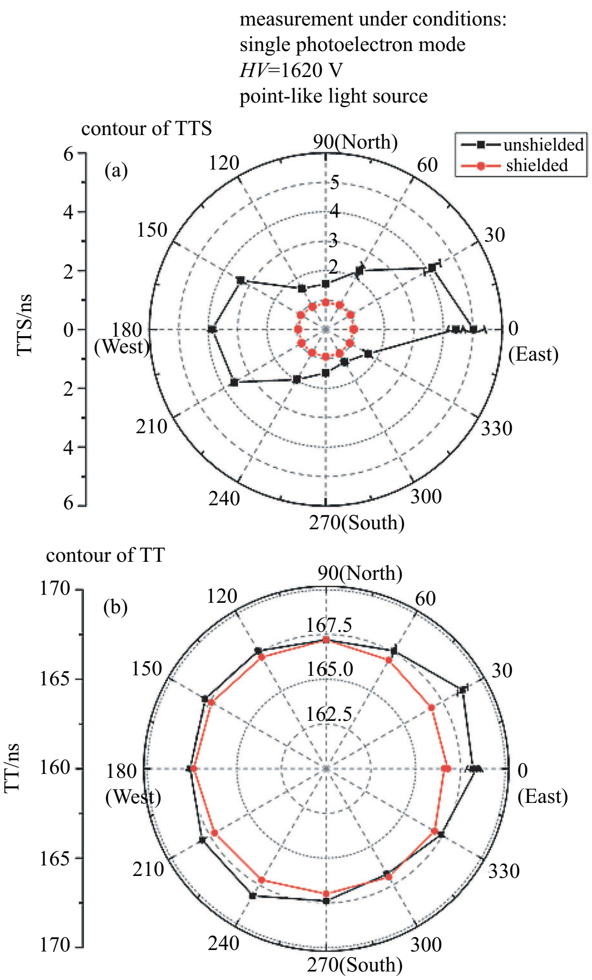

Fig. 14. (color online) (a) TTS in different directions; (b) TT in different directions (the values of the TTS and TT contours in the map are shown by the axis on the left).

To understand better the effect of the Earth's magnetic field, the TT was also measured, as shown in Fig. 14(b). There are also variations observed around φ = 0° and 180°, compared to the case with the magnetic field shielded.

4.2 TTS for different light intensity

The TTS for different light intensity in the presence of geomagnetic field is also measured. The result is shown in Fig. 15. The value strongly depends on light intensity and follows the same behavior $a+b/\sqrt{N}$ (N is the number of photoelectrons) as described in Section 3.4. One different feature is that the TTS of a single photoelectron under lower operating voltage is more sensitive to the magnetic field. For example, it can rise to 7 ns for the lowest voltage of 1520 V.

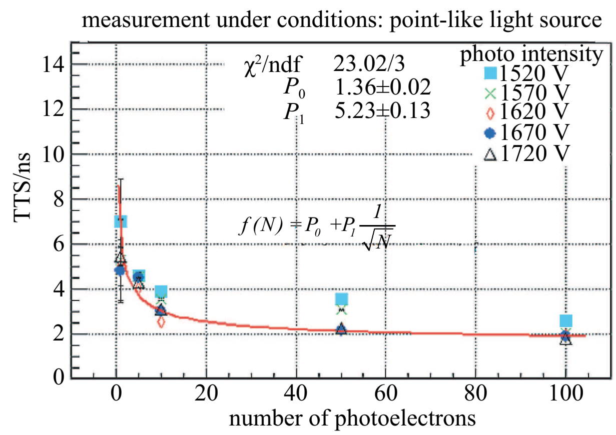

Fig. 15. (color online) TTS for different light intensity.

5 Conclusions

In this paper, the TTS of a 20-inch dynode PMT from Hamamatsu was studied. We measured the TTS characteristics under different conditions, with and without the Earth's magnetic field. The results show that in the case without magnetic field, the TTS of this dynode PMT is about 1 ns for a single photoelectron and point-like light source, which is consistent with the value in the datasheet from Hamamatsu (2.7 ns at FWHM) [12]. The TTS is 1.5 ns when the light is diffused and illuminates the whole photocathode. We have also shown that there are no large variations when the operating voltage changes and for different photocathode regions. In the case with magnetic field, the TTS of a single photoelectron under normal operating voltage becomes worse, reaching 5 ns in the direction orthogonal to the magnetic line, and even worse (about 7 ns) for lower voltage. Both with and without the Earth's magnetic field, the TTS as a function of light intensity follows the behavior of a Poisson distribution $a+b/\sqrt{N}$. The above results will provide important information for the JUNO experiment.

Finally, the measured TTS in this paper shows that the 20-inch dynode PMT can meet the JUNO requirements for vertex and track reconstruction when the Earth's magnetic field is well shielded. In the case that the geomagnetic field is not shielded properly, the TTS will become significantly large and unacceptable for JUNO.

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