The R&D of the Ultra-Fast MCP-PMTs for High Energy Physics

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Abstract. Micro-channel plate photomultiplier tube (MCP-PMT) is a kind of photosensitive device with single photon detection capability and great time resolution, which is also called Fast-PMT (FPMT). The characteristic of MCP makes the MCP-PMT capable of reaching great spatial resolution with multi-anodes. With the experience of successfully R&D of the 20-inch MCP-PMT, the researchers in IHEP are now developing the multi-anodes FPMT with great time resolution and spatial resolution. By now, the single-anode, 2×2 anodes, 4×4 anodes and 8×8 anodes FPMT prototypes have been successfully produced. With the fast-timing test system, the performance of these prototypes has been tested. The best TTS can reach 76 ps for single photoelectron and 15 ps for multi photoelectrons.

1. Introduction

The microchannel plate photomultiplier tube (MCP-PMT) is a new type of weak light detection device. It applies the MCP as its multiplication structure, which ensures it with great time response and time resolution for its relatively short electron flight trajectory compared with the traditional dynode-PMT. Compared with the Silicon photomultiplier tube (SiPM) which also has a good time resolution, the FPMT has a larger sensitive area and s more stable performance which will not change greatly with the working temperature. The great time resolution of FPMT makes it widely used in various areas, including high-energy physics experiments, high-precision medical imaging device [1], biofluorescence detection [2] and nucleic acid detection devices [3]. What's more, the single connectivity of micro-channel in MCP makes the position of the photon to get photoelectric converted on the cathode associated with the position of the anode current output, which makes it capable of achieving great spatial resolution. Therefore, the multi-anode MCP-PMT (MA-MCP-PMT) has excellent time resolution (in the order of picoseconds) and excellent spatial resolution (in the order of less than millimeters) at the same time. The MA-MCP-PMT is expected to be of wide use in various areas where high precision timing and positioning are needed.

Led by IHEP, CAS (Institute of High Energy Physics, Chinese Academy of Sciences) and cooperated with NNVT (North Night Vision Technology Co., LTD), the 20-inch MCP-PMT with high quantum efficiency [4-6] has been successfully developed and industrialized. The 20-inch prototype with high detection efficiency which can meet the requirements for JUNO (Jiangmen Underground Neutrino Observatory) successfully got 75% (15k) order of the JUNO PMT contrast. The 15k 20-inch MCP-PMTs have been produced and delivered to Jiangmen for the JUNO experiment by August of 2020 [7].

Therefore, IHEP has rich MCP-PMT R&D experience and NNVT has a complete and mature MCP-PMT production line. On this basis, we have carried out the R&D of small-sized Ultra-Fast MCP-PMTs (FPMT) with high quantum efficiency, high gain, fast time response and great time resolution [8]. The most important thing is to break through the technical challenges and reduce the development cost of FPMT, making it possible to apply the FPMT for a universal use in large-scale high-energy physics experiments and high-precision imaging devises.

By now, the single anode, 2×2 anodes, 4×4 anodes and 8×8 anodes FPMT prototypes have been successfully produced and their characteristics are evaluated. In this manuscript, we will introduce the structure of the FPMT, the fast-timing test system and the performance evaluation results of the FPMT prototypes with different number of readout anodes.

2. Basic structure of FPMT

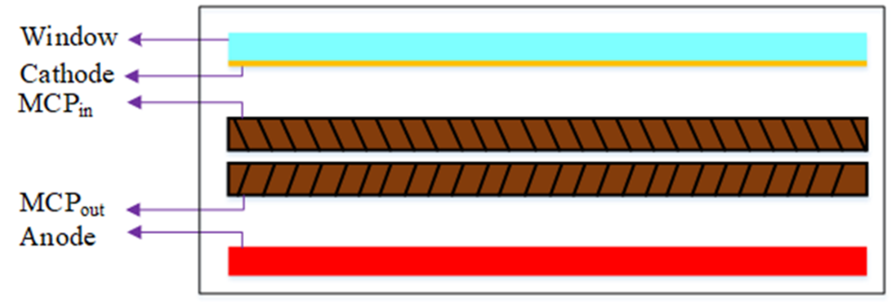

Figure 1. The schematic of FPMT.

The MCP is a plate-like structure composed of many tightly packed bundles of thin glass tubes with a diameter of 6-20 μm, each of which is an independent electron multiplier. The MCP is made of lead glass and the surface of the MCP is deposited with the high secondary-electron-yield material using the atom layer deposition technology to increase the gain and collection efficiency [9] of the FPMT. When the primary photoelectrons enter the MCP channel and impinge on the inner wall, more secondary electrons are produced and then accelerated by the electric field. These second electrons bombard the channel again and produce more secondary electrons, causing an avalanche. The gain for single slice of MCP can reach 10^4 under proper voltage. Due to the short multiplication path of the MCP system, the rise time (RT) and transit time spread (TTS) of the output signal will be quite small. According to the required spatial resolution, the anode of the FPMT can be divided to different grid arrays. The electrons at certain area are collected by the corresponding anode and realize a great spatial resolution.

As shown in **figure 1**, the FPMT is mainly composed of the window, the bi-alkali cathode whose peak wavelength is around 390 nm, two slices of MCPs and the anode which can be designed to different sizes according to the requirements.

3. The fast-timing test system

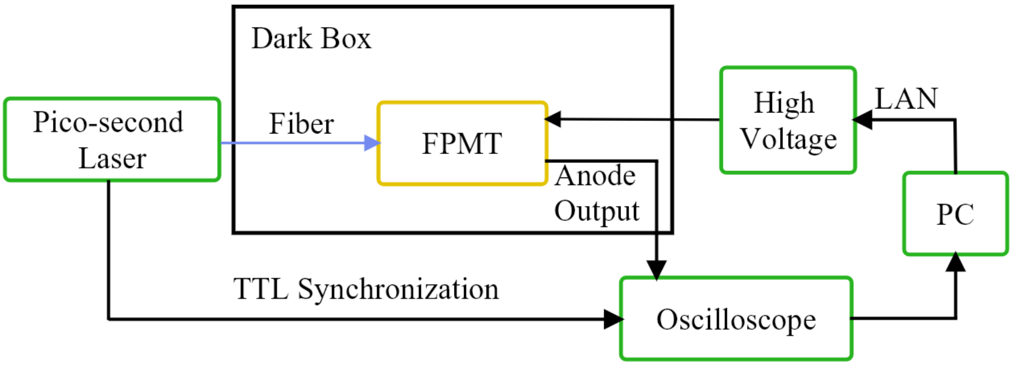

Figure 2. The schematic of FPMT fast-timing test system.

In order to precisely evaluate the time performance of the FPMT whose TTS is on the order of tens of picoseconds, the fast-timing test system is built and tested with another ultra-fast MCP-PMT whose RT is 100 ps and TTS is 46 ps. The results prove the reliability of the test system. The time jitter and width of the light source has a great effect on the performance calibration of FPMT [10]. Therefore, a picosecond laser diode is used as the light source and the laser is with 405 nm wavelength and 40 ps pulse width. As shown in **figure 2**, the laser is guided with the fiber towards the FPMT. When calibrating the performance of MA-FPMT, the laser will be guided precisely towards the certain anode tested. A dark box is used to shield the FPMT and the fiber from the ambient light. The output signal from the FPMT is recorded with a high-performance oscilloscope (LeCroy HDO9404) which has a 4GHz bandwidth and a 40 GS/s sampling rate. The TTL sync signal output from the picosecond laser is used as the trigger for the oscilloscope for data sampling. The waveforms obtained by the oscilloscope are analyzed offline to obtain more information.

Considering the whole system, the measured TTS is a combination of three factors including the light source, the FPMT and the oscilloscope. The whole TTS can be expressed as

$$TTS_{Result}=\sqrt{TTS^2_{PSlight}+TTS^2_{FPMT}+TTS^2_{Oscilloscope}} \quad (1)$$

With the increase of the light intensity, it is found that the TTS of the FPMT decreases, as shown in **figure 3**, and the TTS reaches a stable value at a high enough light intensity which is defined as TTS_{limit}. The TTS_{limit} can represent the intrinsic time resolution of the FPMT.

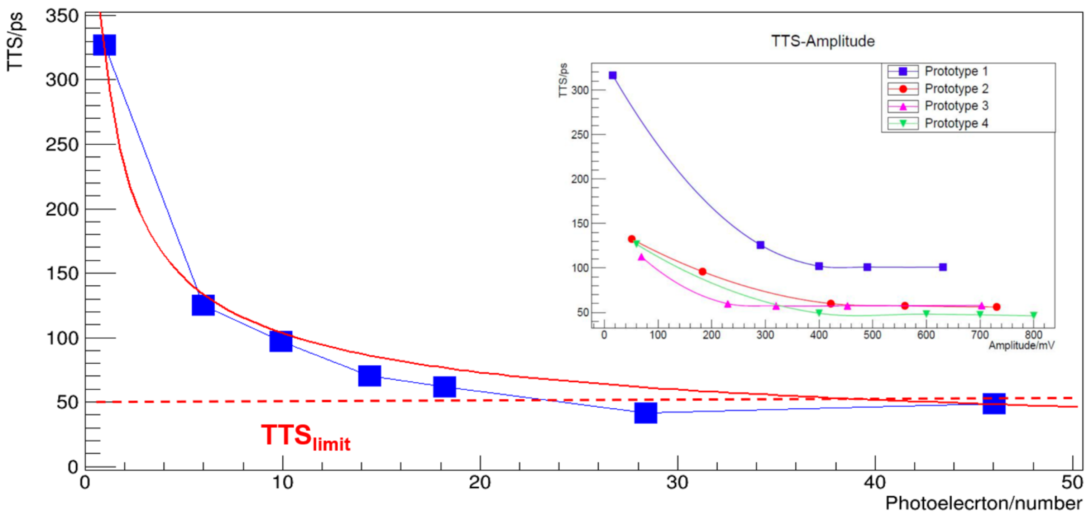

Figure 3. TTS for FPMT changing with the number of incidence photoelectrons.

4. Characteristics of FPMT prototypes

By now, the single anode, 2×2 anodes, 4×4 anodes and 8×8 anodes FPMT prototypes have been successfully produced and evaluated with the fast-timing test system. **Figure 4** and **figure 5** present the pictures of 1-inch round single-anode FPMT and 2×2 anodes FPMT. The cathodes of these two types of FPMT are both made of bi-alkali material. As shown in **Table 1**, under a negative voltage of 1570 V, the single-anode FPMT can reach a gain of 1×10^{7}. The TTS can reach 30 ps at MPE and 205 ps at SPE for single-anode FPMT. For the 2×2 anodes FPMT, the typical gain is 2×10^{6} at a negative voltage of 2500 V. The TTS cam reach 76 ps at SPE and 15 ps at MPE.

Figure 4. Round single-anode FPMT prototype.

Figure 5. Round 2×2 anode FPMT prototype.

Table 1. The characteristics of the 1-inch and 2-inch FPMTs.

FPMT	HV [V]	gain	P/V	Amplitude [mV]	RT [ps]	FT [ps]	Width [ps]	TTS@SPE [ps]	TTS_{limit} [ps]
single-anode	-1570	1E7	13	-	1400	-	2300	205	30
2×2 anodes	-2500	2E6	8	26	228	694	402	76	15
4×4 anodes	-1660	1E7	2	21	431	-	-	107	28
8×8 anodes	-1500	1E7	11	93	374	588	718	85	16

Besides the 1-inch round FPMT with single anode and 2×2 anodes, the 2-inches square FPMT with 4×4 anodes and 8×8 anodes have also been produced. The square shell ensures it with better array integration capabilities and the dense anode readout ensures it with great spatial resolution. As shown in **figure 6** and **figure 7**, the 2-inches square FPMT uses the needle array with a diameter of 0.5 mm to read the signal which can directly connect to the MCX interface and achieve a good impedance matching to avoid the overshoot and ringing. **Table 1** also presents the typical performance for the two types of 2-inches square FPMT. Under a negative voltage of around 1600 V, both of them can reach a gain of 1×10^{7}. For the 4×4 anodes FPMT, the typical TTS can reach 107 ps at SPE and 28 ps at MPE. For the 8×8 anodes FPMT， its typical amplitude is 93 mV. The TTS can reach 85 ps at SPE and 16 ps at MPE.

Figure 6. Square 4×4 anodes FPMT prototype.

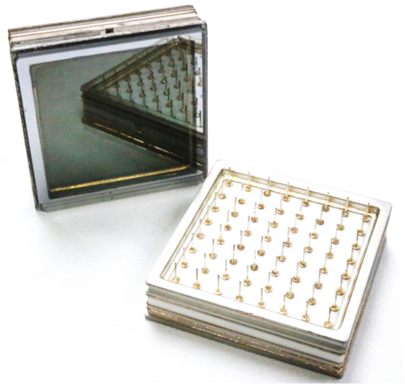

Figure 7. Square 8×8 anodes FPMT prototype.

5. Summary

The MCP-PMT group in IHEP has successfully developed the multi-anodes MCP-PMT with great time resolution and spatial resolution. The performance of the FPMT with single-anode, 2×2 anodes, 4×4 anodes and 8×8 anodes are evaluated with the fast-timing test system. Under a proper voltage, they can all reach the gain to detect the single photon. The best TTS can reach 76 ps for SPE and 15 ps for MPE.

Acknowledgement

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References

[1] R Ota et al., Coincidence time resolution of 30 ps FWHM using a pair of Cherenkov-radiator-integrated MCP-PMTs, 2019 Phys. Med. Biol. 64 07LT01

[2] Wang H., Su W., and Tan M., Endogenous Fluorescence Carbon Dots Derived from Food Items, The Innovation 1 (1), 100009

[3] Wu J., Tan C.S., Yu H. et al., Recovery of Four COVID-19 Patients via Ozonated Autohemotherapy, The Innovation 1 (3), 100060

[4] Yifang Wang, Sen Qian, Tianchi Zhao, et al. A new design of large area MCP-PMT for the next generation neutrino experiment, NIMA, 695(2012)113-117.

[5] Feng Gao, Guorui Huang, Yuekun Heng, et al. Status of the 20 inch MCP-PMT prototype development for JUNO experiment, IOP Conf. Series: Journal of Physics: Conf. Series 888 (2017) 012050.

[6] Ping Chen, Jinshou Tian, Tianchi Zhao, et al. Design of the large area MCP-PMT, NIMA, 912(2018)163-166.

[7] Wu Qi, Qian Sen, Cao Yiqi et al., The mass production and batch test result of the 15k 20-inch MCP-PMT in NNVT for JUNO, 40th International Conference on High Energy physics (ICHEP2020) POS, vol 390.

[8] Ma Lishuang, Qian Sen, Guo Hao et al., The status of the R&D of Ultra-Fast 8 times 8 readout MCP-PMTs in IHEP, 40th International Conference on High Energy physics (ICHEP2020) POS, July 28 - August 6, 2020

[9] Chen L,Tian JS,Liu CL,et al. Optimization of the electron collection efficiency of a large area MCP-PMT for the JUNO experiment, NIMA , 827(2016)124-130

[10] Yao Zhu, Sen Qian et al., Study of time characteristic test method of the fast timing MCP-PMT, 2019 IEEE Nuclear Science Symposium and Medical Imaging Conference (NSS/MIC).