Performance of the MCP-PMTs of the TOP Counter in the First Beam Operation of the Belle II Experiment

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We developed a square-shaped micro-channel-plate photomultiplier tube (MCP-PMT), and successfully produced and installed 512 MCP-PMTs into the TOP counter of the Belle II experiment in 2016. The TOP counter is the first-ever detector that is equipped with such a large number of MCP-PMTs. All of them have a time resolution better than 50 ps for single photon detection and a peak quantum efficiency of 29.3\% on average at a wavelength around 360 nm. Those excellent time resolution and efficiency are essential for the TOP counter to reconstruct the Cherenkov image for particle identification. The MCP-PMTs were operated in success for the first beam data taking of the Belle II experiment in 2018. The number of detected photons per track from the beam collisions was evaluated, and it was found to be larger than expected, which is yet to be investigated.

**KEYWORDS:** micro-channel-plate, time resolution, time of propagation, Cherenkov detector

1. Introduction

We developed a square-shaped multi-anode micro-channel-plate photomultiplier tube (MCP-PMT) \cite{1–6} in collaboration with Hamamatsu Photonics K.K. for the TOP counter \cite{7–10} of the Belle II experiment \cite{11}. The MCP-PMT is required to have a time resolution better than 50 ps for single photons and a high photon detection efficiency. The photodetector of this high performance is essential for the TOP counter to reconstruct the Cherenkov image for particle identification. It is also required to be tolerant of several MHz/PMT background hits by the severe beam background from the accelerator. That is a major issue because the quantum efficiency (QE) of the photocathode drops due to the out-gassing from the MCPs as the output charge is accumulated \cite{3, 5}. In addition, the unprecedented production and testing of as many as 512 MCP-PMTs to be used for the TOP counter were also big challenges.

This paper summarizes the performance of the 512 MCP-PMTs installed into the TOP counter, where a 1.5 T magnetic field is applied perpendicular to the MCPs. The performance of every MCP-PMT was evaluated in test benches before the installation and was also checked in the first beam operation of the Belle II experiment.

2. Design of the MCP-PMT

The size of the photocathode is 23 $\times$ 23 mm$^2$ while the outer size of the MCP-PMT is 27.6 $\times$ 27.6 mm$^2$. The composition of the photocathode is multi-alkali or NaKShCs. The photoelectrons are multiplied by two 400-\textmu m thick MCPs, the pore size of which is 10 \textmu m in diameter with a 13-degree bias angle. The open area ratio of the pores is about 60\%. The collection efficiency is roughly equal to it. The multiplication of the photoelectron in the short and small pores makes the transit time spread (TTS) as small as about 30 ps. The anode is divided into 4 $\times$ 4 pixels.
Fig. 1. Typical QE spectrum of the MCP-PMT. The black squares represent the QE at each anode position, and the red circles represent the average QE over the photocathode area.

Fig. 2. Typical output charge (left) and hit time (right) distributions for single photon detection by one of the conventional MCP-PMTs at the gain of $5 \times 10^5$. A double Gaussian (red line) fitted on the time distribution is superimposed.

3. Mass production and testings of the MCP-PMTs

The mass production of the MCP-PMTs started in 2011. To improve the lifetime of the MCP-PMTs, atomic layer deposition (ALD) coating [12] was applied to the MCP surface from the middle of 2013. Further extension of the lifetime was achieved after R&D in 2014 and 2015. Eventually there are three versions of the MCP-PMT [13], called conventional, ALD, and life-extended ALD MCP-PMTs in order from the first version. About 20 MCP-PMTs were produced per month. Right after the delivery, the performance of all the 16 channels of every MCP-PMT was evaluated in automated test benches in a systematic way. The details of the test benches are described elsewhere [14, 15].

The QE was measured at 18 × 18 points over the photocathode including the periphery in a wavelength range from 280 to 760 nm. The QE peaks around 360 nm as shown in Fig. 1.

The gain, TTS, and relative collection efficiency without magnetic field were measured at several high voltages by using single photons from a pico-second pulse laser. The output charge distribution is shown in Fig. 2 (left). The mean of the distribution divided by the elementary charge is defined as the gain. In this figure, the gain is $5 \times 10^5$. The gain increases as an exponential function of the high voltage. A typical high voltage for the gain of $5 \times 10^5$ is 3.0 kV for the conventional MCP-PMTs, and is lower by several hundreds volts for the ALD and life-extended ALD ones due to a higher secondary
electron yield. The distribution of the measured hit time after time-walk correction is shown in Fig. 2 (right). The tail on the right side of the peak is attributed to recoil of the photoelectron on the first MCP surface [16]. The hit time distribution is fitted by a double Gaussian, and the standard deviation of the primary Gaussian, from which the laser pulse width ($\sigma \approx 17$ ps) and the electronics jitter ($\sigma \approx 24$ ps) have been deducted, is defined as the TTS. In this figure, the TTS is 29.2 ps. The TTS does not depend on the gain. The relative collection efficiency was measured by counting the hit rate normalized by the laser intensity, which was monitored by another PMT. It does not depend on the gain, either.

Differences of the gain, TTS, and relative collection efficiency in 0 and 1.5 T were evaluated in another test bench with a dipole magnet. They were measured at only one high voltage corresponding to about $2 \times 10^6$ gain in 0 T. Data at the other high voltages were not necessary because the dependence of the gain on the high voltage is the same in 0 and 1.5 T, and the TTS and relative collection efficiency do not depend on the gain in 1.5 T, either.

The results of the above measurements for all the MCP-PMTs are given in Figs. 3 and 4. The mean of the peak QEs is 29.3%, which is beyond the requirement. The collection efficiency of the ALD and life-extended ALD MCP-PMTs is higher by 10–20% than the one of the conventional MCP-PMTs. That is attributed to the higher collection efficiency for the recoiled photoelectrons by the ALD coating because the difference appears only in the right tail of the time distribution. There are no significant differences in the TTS among the three versions. The mean of the TTSs is 34.3 ps.
In 1.5 T, the gain drops down to 60–90% of the one in 0 T for the conventional MCP-PMTs or 20–40% for the ALD and life-extended ALD ones. It is due to the cyclotron motion of the secondary electrons, which results in a shorter bounce distance or a lower energy of the electrons on the MCP channel and thus a lower secondary electron yield. In 1.5 T, the collection efficiency also drops down to 95% of the one in 0 T. The TTS, however, does not change in 1.5 T.

4. Installation

There are 16 modules of the TOP counter enclosing the beam interaction point. The upper (lower) half of the modules are called slot 01–08 (09–16). The conventional MCP-PMTs were concentrated on slot 10–16 in order to make it easier to replace them after the QE degradation. Each module was equipped with $2 \times 16$ arrayed MCP-PMTs. Figure 5 shows the MCP-PMTs attached to the quartz radiator bar through the wedge-shaped quartz block called prism as well as the readout electronics. Four MCP-PMTs were packed in a PMT module with a piece of wavelength filter which cuts out ultraviolet light below 340 nm to suppress chromatic dispersion. One of the assembled PMT modules is shown in Fig. 6 (left). Bubble free optical contact between the wavelength filter and the prism was made by a soft cast silicone cookie. It was checked through the prism with the CCD cameras. The
readout electronics was installed on the rear side of the PMT module as shown in Fig. 6 (right). The waveform of the MCP-PMT signal is sampled at a rate of $2.7 \times 10^9$ s$^{-1}$ by a switched-capacitor array ASIC named IRSX [17], and only feature extracted data such as the hit time and the pulse height are sent out to a back-end readout system in an electronics hut. For in-situ calibrations, a pico-second pulse laser is injected from the fibers attached over the slope of the prism to all the MCP-PMTs.

5. Performance in the first beam operation

The gain of all the MCP-PMTs was set at $3 \times 10^5$ by adjusting the applied high voltage one-by-one. It was the optimal gain to suppress the output charge as much as possible for mitigation of the QE degradation while keeping the signal discrimination efficiency of the readout electronics reasonably high. The signal discrimination efficiency is determined by a threshold for discrimination of the photon signal from the noise and the pulse height of the MCP-PMT signal. It was measured for single photons from the in-situ laser system to be greater than 90% for all the MCP-PMTs.

After the first collisions of the SuperKEKB beams on 26 April 2018, we commissioned the Belle II detector with collision data until 17 July 2018. The hit rate of the MCP-PMT was about 0.5 MHz/PMT, which was dominated by the accelerator beam backgrounds. The accumulated output charge of each MCP-PMT was kept below 0.023 C/cm$^2$, which was low enough compared to the lifetime of the conventional MCP-PMT, 0.3–1.7 C/cm$^2$, when the QE drops down to 80% of the beginning.

To understand the performance of the TOP counter during the beam collision runs, the number of hits per charged track, which counted the detected Cherenkov photons and some noise, was compared with the expectation by a Monte Carlo simulation using di-muon events as shown in Fig. 7. The simulation was based on the following measured parameters: the internal reflectance and transmittance of the quartz bars, the QE and collection efficiency of the MCP-PMTs, the efficiencies of the readout electronics, hits by some noise (only a few % of the total hits), and hits by the beam backgrounds (about 2.5 hits per slot on average). The readout efficiency was as low as 84% during the runs because of an issue of the readout firmware, which was fixed after the runs. Mainly due to the difference of the QE and the collection efficiency among the MCP-PMT versions, the mean number of hits differed slot-by-slot. For example, the one expected in the simulation was 26.1 for slot 01 with the life-extended ALD MCP-PMTs and 20.2 for slot 11 with the conventional ones. The measured mean number of hits was 29.8 for slot 01 and 20.7 for slot 11. The larger number of hits in the data than the simulation by 29% at most was found for the slots with the ALD and life-extended ALD versions,
while the agreement was better for the slots with the conventional ones. The difference between the data and the simulation is under investigation.

6. Summary

The MCP-PMT is one of the key components which bring the novel TOP counter into life. We succeeded in developing and producing 512 MCP-PMTs. All of them were tested and confirmed to have the required performance. They worked well in the first beam operation in 2018. Though the larger number of hits than expected is yet to be investigated, the understanding of the whole photo-detection system of the TOP counter is shaping up for the full-swing operation of the Belle II experiment from March 2019.

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References