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Development of the micro-channel plate photomultiplier for the Belle II time-of-propagation counter

Shigeki Hirose [a,*], Toru Iijima [a,b], Kenji Inami [a], Daiki Furumura [a], Tomokatsu Hayakawa [b], Yuji Kato [b], Kodai Matsuoka [b], Ryo Mizuno [a], Yutaro Sato [b], Kazuhito Suzuki [a], Takuya Yonekura [a]

[a] Department of Physics, Nagoya University, Japan
[b] KMI, Nagoya University, Japan

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ABSTRACT

The time-of-propagation counter for the Belle II experiment is a new particle identification device using ring imaging Cherenkov technique. In order to detect each Cherenkov photon with a timing precision of 30–40 ps in a 1.5 T magnetic field, a micro-channel plate photomultiplier tube is a suitable device for the TOP counter. By introducing an atomic layer deposition technique on the micro-channel plate surface, the tube lifetime was improved by a factor of 3–10 relative to more conventional devices. A total of 530 tubes have been produced. To ensure appropriate tube performance, the quantum efficiency, gain and transit time spread have been measured for all units. The results from each measurement are discussed. Results from a beamtest with a 2 GeV/c positron beam are also reported and demonstrate the good tube performance.

1. Introduction

The time-of-propagation (TOP) counter [1–6] is a new particle identification (PID) device for the Belle II experiment [7]. The TOP counter is composed of a quartz bar with a size of $450 \times 20 \times 2700\ \text{mm}^3$ and a photodetector array at the one end of the bar. A mirror is mounted on the opposite end. Cherenkov photons are conically emitted in the quartz bar by an incident charged particle, and propagate in the bar. About 100 photons reach the end of the bar, and are detected by the photodetectors. To realize a compact PID device which can be installed in the limited space of the Belle II detector, photon detection timing as well as position is used to reconstruct a Cherenkov ring image. The velocity of the incident particle is estimated from the ring image. The incident particle is identified by combining the velocity measurement at the TOP counter with the momentum measurement at the inner drift chamber.

Our target is to distinguish 3 GeV/c K and π mesons with more than 95% efficiency and less than 5% fake rate. Since the difference of the photon detection timing between a 3 GeV/c K and π meson is about 100 ps, the photodetector is required to have a transit time spread (TTS) of less than 50 ps and a good single photon detection efficiency in a 1.5 T magnetic field. A square shape is necessary to maximize the photo-coverage when arrayed. And a pixel size of about $5\ \text{mm}^2$ is required to reconstruct a Cherenkov ring image. Because of the excellent TTS and operability in a 1.5 T magnetic field, we chose a micro-channel plate photomultiplier tube (MCP-PMT) as a photodetector for the TOP counter.

2. Development of the MCP-PMT for the TOP counter

We developed the MCP-PMT (R10754-07-M16(N)) [8–11] shown in Fig. 1 with HAMAMATSU Photonics K.K. It has a square shape with a size of $27.6 \times 27.6\ \text{mm}^2$. The size of the NaKSbCs photocathode is $23 \times 23\ \text{mm}^2$. The MCP-PMT contains two 400 μm thick MCPs for electron multiplication. The MCP has a 10 μm pore size and an aperture ratio of about 60%. The photoelectron collection efficiency is about 55%. Because the quantum efficiency (QE) of 28% on average (more than 24%) around the 360 nm wavelength is required to obtain the target performance of the TOP counter, we selected a NaKSbCs photocathode. The anode pad is pixelized to 4×4. The size of each pixel is $5.3 \times 5.3\ \text{mm}^2$. About 3 kV is applied between the photocathode and the anodes to obtain a gain of 2×10^6 and TTS of 30–40 ps. We confirmed that the MCP-PMT maintains a TTS less than 50 ps and a gain larger than 5×10^5 in a 1.5 T magnetic field [10]. Each TOP counter module is equipped with a 16×2 array of MCP-PMTs.

While the MCP-PMT has an excellent performance to fulfill the requirements for the TOP counter, the lifetime of the MCP-PMT

* Corresponding author.

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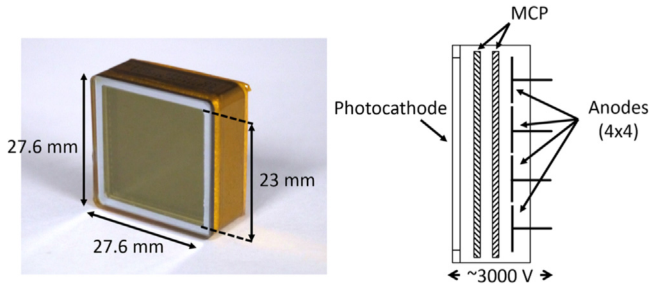

Fig. 1. Photograph of the MCP-PMT (left) and its cross-section view (right).

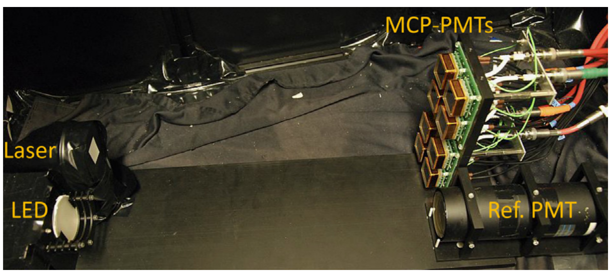

Fig. 2. Photograph of the lifetime test setup.

was one of the critical issues. During the operation, residual gases produced by collisions of secondary electrons on the MCP surfaces degenerate alkali components of the photocathode, and deteriorate the QE. In this process, the amount of gas molecules released from the MCPs depends on the total amount of produced secondary electrons, or the total output charge. We define the lifetime as the total output charge to cause the relative QE drop down to 80%. According to a Monte Carlo simulation, 20% QE drop has no significant impact on the PID performance of the TOP counter. While the output charge of 2–3 C/cm^2 at the gain of 5×10^5 is predicted during the Belle II operation, the lifetime of the MCP-PMT was about 1 C/cm^2 [11].

In 2012, it was reported that the atomic layer deposition (ALD) coating on the MCP is effective to improve the lifetime [12]. We tried further lifetime improvement with the ALD technique.

3. Lifetime of the ALD MCP-PMT

We tested the lifetime of the ALD MCP-PMTs in the setup shown in Fig. 2. An LED light with a wavelength of about 400 nm was irradiated to the MCP-PMT at the output charge rate of about 1 C/cm^2/month to degrade the photocathode. Once in a day, the LED was turned off and the MCP-PMT was irradiated with a single photon from a pulse laser to measure its performance. The QE was monitored by the single photon hit rate of the MCP-PMT. A reference PMT was used to correct change of the laser intensity during the test.

Fig. 3 shows the relative QE of six MCP-PMTs. Three of them have the ALD-coated MCPs (ALD MCP-PMT). And the rest of them are the conventional MCP-PMTs, which have two lead glass MCPs and, to protect a photocathode from residual gases, a thin aluminium layer on the second MCP surface and ceramic insulators [11].

The lifetime of the conventional MCP-PMTs is about 1 C/cm^2 on average. This is the 1–3 times shorter lifetime than the predicted output charge during Belle II. Although we can reduce the output charge with the lower gain than the operation gain of 5×10^5, this is a trade-off between extension of the lifetime and degradation of the TTS and single photon detection efficiency.

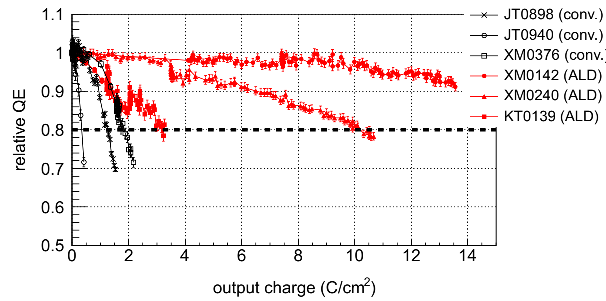

Fig. 3. The relative QE as a function of the output charge. Open and cross (filled) markers show the relative QE of the conventional (ALD) MCP-PMTs.

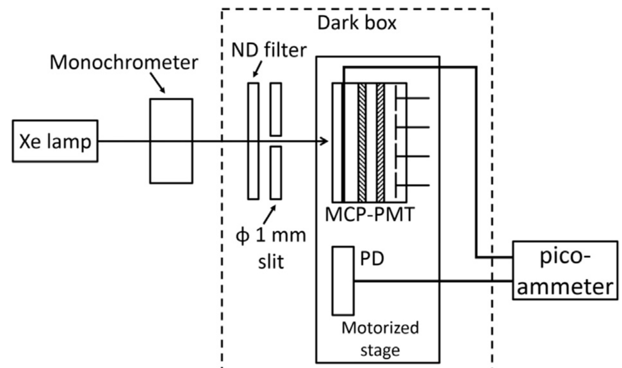

Fig. 4. Schematic of the QE measurement system.

The lifetime of the MCP-PMTs is significantly improved to 3–10 C/cm^2 by the ALD technique. This is 1–3 times longer lifetime than the Belle II operation so that the ALD MCP-PMT can maintain the single photon detection efficiency in Belle II.

4. MCP-PMT mass production

In 2011, we started mass production of 512 MCP-PMTs for 16 TOP counter modules. As of March 2014, 530 MCP-PMTs were produced at HAMAMATSU Photonics K.K., among which 237 pieces are ALD MCP-PMTs and the remaining 293 pieces are conventional ones. We use the conventional MCP-PMTs for the TOP counter module as well as the ALD ones, and plan to exchange them during the Belle II operation.

In order to assure the quality and understand the performance of each MCP-PMT, we measure QE, gain and TTS for all of the produced MCP-PMTs. We also measure the gain and TTS in a 1.5 T magnetic field.

4.1. QE measurement

Fig. 4 outlines the QE measurement system. Light from a Xe lamp (L2195 Xenon Lamp, Hamamatsu) is introduced into a dark box through a monochromator (SPG-1205 Compact Monochromator, Shimazu). The wavelength is scanned every 20 nm from 280 nm to 660 nm. In the dark box, the monochromatic light is irradiated to the MCP-PMT, and also to a photodiode (Si photodiode S1337-BQ; the QE is calibrated with a precision of less than 1.7%) by turns, after passing through a neutral density (ND) filter and a ϕ 1 mm slit. The output current either from the photocathode of the MCP-PMT or the photodiode is measured by a picoammeter (Model 6487 Picoammeter/Voltage source, Keithley). The QE is calculated by the ratio of the current from the MCP-PMT and the photodiode.