Abstract

The results of verifying focusing system for Time Of Propagation (TOP) counter is presented. The TOP counter have been developed as a new detector for particle identification at Belle-II experiment, which is a Ring Imaging Cherenkov counter with precise timing information. Performance of the TOP counter is directly depended on the time resolution for single photon detection. Propagated Cherenkov photons have group velocity related to wavelength. It generates fluctuation of propagation time approximately 53 ps/m. Chromatic dispersion provides serious deterioration of time resolution. Against this problem, the focusing mirror is planed to introduce. It focuses Cherenkov light to different channels of MCP-PMT by different wavelength, and so that the deterioration of time resolution is suppressed. We verified focusing mechanism using 120 GeV/c π beam at CERN. Using a prototype TOP counter with the focusing mirror, we could confirm a work of focusing mechanism. The time resolution improved from 147 ps to 95 ps by using focusing mirror.

1. Introduction

Particle identification (PID) of $K^\pm$ and $\pi^\pm$ is an important subject for high precision measurements with high-intensity, such as B-factory experiments. Especially, a good PID power for a momentum range of up to 4 GeV/c contributes to obtain a high signal-to-background ratio for rare $B$ decays. In the Belle detector [1], $K/\pi$ identification was carried out by combined information from Aerogel Cherenkov counters, Time-Of-Flight (TOF) counters and $dE/dx$ measurements in the central drift chamber. The current detector covers PID for a momentum of up to 3 GeV/c. Concerning the barrel PID upgrade for the super B-factory [2], we have proposed a Cherenkov ring imaging counter, named TOP counter [3], by means of measuring the time of propagation of Cherenkov photons inside a quartz radiator precisely.

The TOP counter utilizes total internal reflection of Cherenkov photons produced in a quartz radiator, and measures the position and precise arrival time of propagated photons at the radiator ends. Figure 1 shows an overview and a schematic side-view of the TOP counter. The supposed quartz radiator size is $\sim 200 \times 40 \times 2$ cm$^3$. In order to separate $K^*$ and $\pi^*$ accurately, we need to measure the particle’s velocity, $\beta$, very precisely. To measure $\beta$, the TOP counter uses two kinds of information. One is the difference of the Cherenkov angle, $\theta_c$, which depends on $\beta$ as $\cos \theta_c = 1/(n\beta)$, where $n$ is the refractive index of the radiator.
The difference of $\theta_c$ causes a difference of path length of the Cherenkov photons inside the radiator, i.e., the difference of the propagation time. Another is the time of flight from the interaction point to the counter, which affects the difference of the photon’s arrival time additively in most cases. For instance, when 3 GeV/c $K^\pm$ and $\pi^\pm$ pass through the TOP counter, the difference of TOP is $\sim 75$ ps for 1 m propagation, and that of TOF is $\sim 50$ ps for a 1 m flight length. Compared to the DIRC system [4], the TOP counter reconstructs the ring image using timing information, including the TOF, which contributes to improve the separation power.

![Fig. 1. Overview (left) and a schematic side-view (right) of TOP counter.](image)

In order to detect single-photons with precise time resolution, we employ an MCP-PMT as the photon detector. We have developed a square-shape multi-anode MCP-PMT with Hamamatsu Photonics, which realize a good ability of time resolution ($< \sim 40$ ps for single photon detection) [5].

### 2. Chromaticity

The improvement of the PID power is limited by the broadened time resolution due to the chromaticity, which causes a dependence of the detection time on the wavelength of a Cherenkov photon. Figures 2 show the detected time distributions for a channel around the center of the TOP counter, obtained by a Monte-Carlo (MC) simulation. It indicates that the detection time shifts by about 500 ps, depending on the wavelength from 300 nm to 600 nm. Because of the dependence, the time resolution deteriorates.

![Fig. 2. Wavelength ($\lambda$) dependence of the detection time (top) and the projected time distribution (bottom) for a channel at the center of TOP counter.](image)

The dependence is because of changing the propagation velocity as a function of the wavelength inside the quartz bar, which is shown in Fig. 3(a). Because of the range of sensitive wavelength region for MCP-PMT, which is shown in Fig. 3(b), the propagation speed has a fluctuation. For the multialkali photocathode, the fluctuation of the propagation time becomes $\sigma \sim 53$ ps/m, which depends on the propagation length.

### 3. Focusing system

The chromatic effect makes about 100 ps time fluctuation, which is the same order of the time difference between $K$ and $\pi$ detection. To suppress the chromatic effect, we introduce a focusing system. The
Cherenkov angle, $\theta_c$, depends on the photon wavelength according to $\cos \theta_c = 1/(n(\lambda)\beta)$, where the refractive index, $n$, varies as the wavelength, $\lambda$ (nm), following a function of $n(\lambda) = 1.44 + 8.2/(\lambda - 126)$. Therefore, we can correct the chromaticity directly using the $\lambda$ dependence of $\theta_c$. In order to measure $\theta_c$ information, a focusing mirror is put at the bar end, and the multi-anode PMT is set at another end to detect Cherenkov photons with the 2-dimensional position, as shown in Fig. 4. The cross section of the quartz bar is a rectangle. We can therefore expand the light trajectory into the mirror-image region and create a virtual readout screen. PMT’s form the matrix readout channels with $\sim 20 \times 5$ mm$^2$ on the virtual screen. The Cherenkov photons of different $\theta_c$ will focus onto the different PMT channels. Therefore, we can restrict $\lambda$ range and obtain improved time resolution. The focusing TOP reconstructs the ring image from 3-dimensional information of time, $x$ and $y$.

In this configuration, the difference of $\theta_c$ is $\sim 12$ mrad for a sensible $\lambda$ range. Since the bar length from the mirror to the MCP-PMT is $\sim 2000$ mm long, for the prototype described later, the difference of the $y$ position becomes $\sim 24$ mm for this range. This is comparable to the quartz thickness. Therefore, we can measure the $\lambda$ dependence and obtain an improved performance, even with the narrow mirror and readout plane. The focusing TOP counter does not require a large focusing block and fine readout channels. By focusing system, the time resolution improves by a factor of about 2.

4. Prototype test

We have produced the prototype counter to check the focusing system. It comprises a quartz radiator with a spherical focusing mirror (5m radius) and 8 square-shape MCP-PMT’s with a multalkali photocathode and 4 linear anodes. The quartz size is $1830 \times 400 \times 20$ (mm$^3$). The surface roughness is 0.5 nm.
A wavelength-cut filter of \( \lambda > 400 \text{ nm} \) is put between the radiator and the MCP-PMT’s. We checked the MCP-PMT’s with pulse laser, and obtained a stable gain (\( \sim 10^6 \)) and good time resolution (< 40 ps for single photon detection) for all channels. We used constant-fraction-discriminator modules as a high-speed readout that uses a fast amplifier (MMIC, 1GHz, \( \times 20 \) gain) and a comparator (180 ps propagation delay). Its time resolution is \( \sim 5 \text{ ps} \) for a test pulse.

Using the prototype counter, we performed beam test with 120 GeV/c pions at the CERN SPS T4-H6-B beam line in 2010. The TOP counter was located between trigger scintillation counters and tracking chambers. To determine the beam timing precisely, we put the timing counter [6] along the beam line, which consisted of a small quartz radiator (10 mm\(^6\) \( \times \) 10 mm\(^3\)) and a round-shape MCP-PMT (Hamamatsu R3809-50-11X). The time resolution was obtained to be 15 ps during the beam test. We checked the number of detected photons and time resolution for normal incidence and found the consistency with the previous beam test [7].

Then, to check the focusing system, the TOP counter was tilted by 30-degree along the beam line from the normal incidence. The beam was injected at the center of the radiator. The distance between the incident position and MCP-PMT was 1467 mm. Figures 5(a,b) show TDC distributions for the center MCP-PMT. We obtained TDC distributions clearly shifted along channel (= y position), as expected by a simulation. It indicates that the arrival photons are separated by the wavelength. By fitting Gaussian functions to TDC distribution, we evaluated the time resolutions of peaks. For the channel 3 of center MCP-PMT, shown in Fig. 5(c), we obtained the mean of resolutions to be \( \sigma = 95 \pm 11 \text{ ps} \).

![TDC distribution](image)

**Fig. 5.** TDC distribution depends on channels for the center MCP-PMT obtained from (a) MC and (b) data. (c) TDC distribution for the channel 3. Curves show the fitted Gaussian functions.

To check the improvement for the chromatic dispersion effect, we plotted the dependence of the time resolution as a function of the corresponding propagation length. Figure 6 shows the time resolution as a function of propagation length obtained by the beam test in 2008 and 2010. We obtained the worse time resolution for the longer propagation length, as expected, in the normal incidence. Although the evaluated time resolutions fluctuated due to overlaps of the TDC peaks, the averaged dependence of the data agrees well with the expectation of \( \sigma = \sqrt{40^2 + (53x)^2} \text{ (ps)} \), where \( x \text{ (m)} \) is propagation length, indicated by the dashed curve in Fig. 6. With the focusing system, the time resolution was improved as shown in Fig. 6. For the propagation length of 2.5 m, the expected time resolution without focusing is 147 ps. In the beam test, we obtained the improved time resolution of (95 \( \pm \) 11) ps for 2.5 m length with the focusing mirror, which is consistent with MC expectation of 103 ps.
5. Summary

Separation power of TOP counter is limited by time resolution, which is determined by group velocity depending on the wavelength of Cherenkov photons. To reduce this effect, we consider the focusing system. We have produced a prototype of TOP counter with a focusing mirror, and test it using 120 GeV/c π beam at CERN. As a result, we verify the shift of detected timing by the focusing system. We obtained the improved time resolution of 95 ps with the focusing system, from 147 ps resolution without mirror expected by MC.

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