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Test result of time-of-propagation Cherenkov counter

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Abstract

A new concept concerning Cherenkov detector for particle identification by means of measuring both the Time-of-Propagation (TOP) and horizontal emission angle (Φ) of Cherenkov photons is described here. Some R&D works are also reported. © 2000 Elsevier Science B.V. All rights reserved.

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1. Introduction

Measurement of Cherenkov ring image requires two-dimensional photon information such as x and y coordinates as RICH and DIRC do [1,2]. With the use of a quartz bar as a Cherenkov radiator and also a light-guide like the DIRC counter [2], a combination of Time-of-Propagation (TOP) of Cherenkov photons to a bar-end and their emission angles at the bar-end also provide the ring image information. Here, we briefly describe the principle of such a device, named TOP-counter (its detail is given in Ref. [3]) and explain some results of its R&D works. The specific aspect of this counter is its compactness relying on a horizontal focussing approach described below. We intend to develop this counter in a bid to upgrade the BELLE pid detector.

Fig. 1 illustrates a side view of Cherenkov photons propagating in a quartz bar. TOP is inversely proportional to z (quartz-axis direction)-component of the light velocity, which produces TOP differences of, for instance, about 100 ps or more for normal incident 4 GeV/c K and π at 2 m long propagation. The TOP difference is a function of photon's horizontal (x–z plane) emission angle (Φ). Time measurement for a single photon with a 100 ps resolution provides 1σ separation, and therefore expected number of 30 photons in this case give us, briefly speaking, a factor of $\sqrt{30}$ times higher separation. Furthermore, a detection of backward-going (BW) photons reflected at the other-end as seen in the figure enhances, in principle, the separation by another factor of $\sqrt{2}$ for normal incident particle. As is easily noticed, the TOP measurement inevitably includes also the Time-of-Flight (TOF) from an interaction point to the TOP counter both of whose difference between K and π could have the same sign with each other in most of the cases. Adding the TOF information, therefore, helps the separation, as a result, TOP is hereafter defined as TOP + TOF.

In order to estimate the achievable separability of TOP counter, we optimized its parameters as illustrated in Fig. 2, where the butterfly-shaped horizontal focussing mirror with an arc radius of 250 mm was designed to have the Φ-aperture of $\pm 45^\circ$ and dispersion of $d\Phi/dx = 0.5^\circ/1$ mm.

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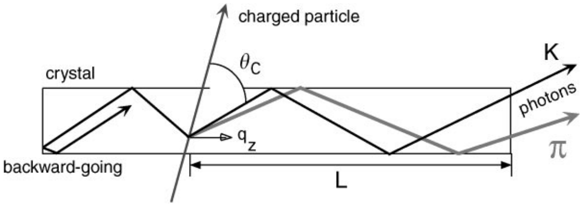

Fig. 1. Side view of propagating photons. TOP is inversely proportional to z-component q_z of the light velocity: TOP $= (L \times n(\lambda))/cq_z = 4.90$ ns $\times\, L$ m$/q_z$. θ_C is the Cherenkov angle and L is the particle injection position from the bar-end. At the opposite end, a mirror is placed to reflect the BW photons.

Root-mean square of the focussed accuracy is $\Delta x \approx \pm 0.4$ mm. The bar and mirrors are made of synthetic optical quartz with refractive index (n) of 1.47 at $\lambda = 390$ nm. These counters are supposed to be placed 1 m radially away from the interaction point of KEKB-BELLE to form a cylindrical structure.

2. Expected separability

There are three dominant contributions to TOP measurement: (1) chromatic effect of Cherenkov lights, (2) aberration effect of the focussing mirror and (3) transit time spread (TTS) of photomultiplier tube (PMT). Since BELLE-CDC (Central Drift Chamber) [4,5] provides precise enough track information such as position, angle and momentum for particles, track relating ambiguity is about 10 ps which is much smaller than the above three contributions. As a necessary item to be considered, TDC start-signal is assumed to have a 25 ps uncertainty in the calculation.

It is worth mentioning that the quartz bar-thickness produces a harmless effect on the measurement, since the variation of a sum of a particle's travel time in a quartz bar up to Cherenkov radiation point and the photon propagation time to the bar end is about 20 ps or less for particles of any incident angle. Consequently, this contribution is also minute compared with the others. The width of the crystal bar, on the other hand, is effectually nullified, in principle, due to the horizontal focus, and in practice, within the achievable focussing accuracy. This is the reason to choose the horizontal instead of the vertical focus, otherwise the ring image would grow dim by a finite size of the bar width. As a result, both the finite sizes of thickness and width now can be disregarded; therefore we do not need any lengthy image projection to nullify the bar cross-section.

A PMT (Hamamatsu, R5900U-00-L16: linear-arry 16-anodes) is used for R&D works without magnetic field (B). Its specific parameters are: surface area of 30×30 mm^2, sensitive area of 16×15 mm^2, the anode size of 0.8 mm wide with 1.0 mm pitch and 15 mm long, quantum efficiency (QE) of 20–25%, gain of 2×10^6, risetime of 0.6 ns, and TTS of $\sigma = 70$–80 ps. Specific modification of L16 and development of a PMT (R6135MOD-L24: fine-mesh 24 anodes) operatable under a magnetic field is in progress in cooperation with Hamamatsu Co. For the latter PMT, a position resolution of better than 0.5 mm is achieved under $B > 0.2$ TG and TTS of $\sigma = 130$ ps is currently realized under $B < 0.6$ TG.

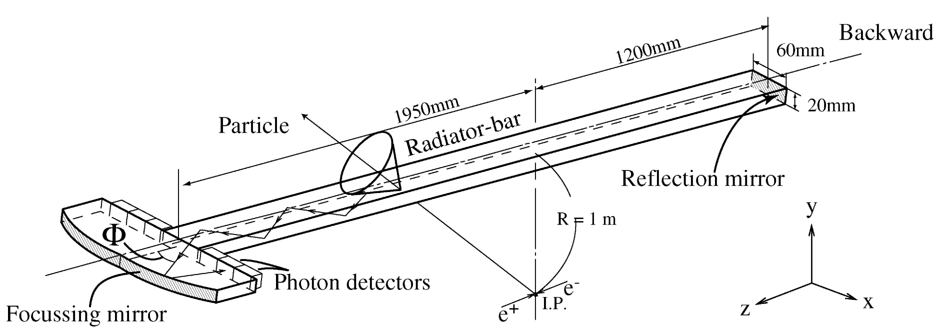

Fig. 2. Structure of the TOP counter. Basic parameters are indicated in the figure. Since KEKB is an asymmetric collider, the quartz bar is accordingly configured z-asymmetric relative to the interaction point (IP).

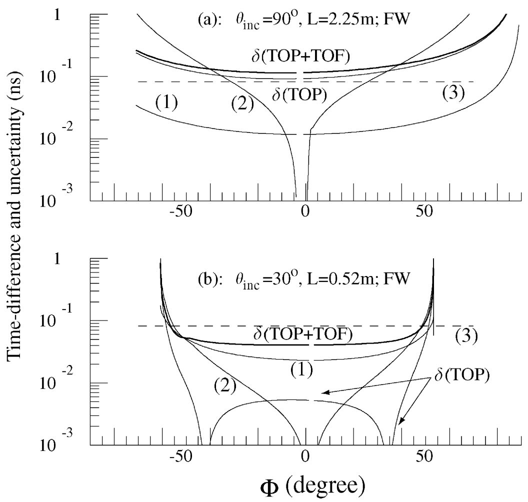

Fig. 3. TOP difference and three dominant contributions for 4 GeV/c K and π. The counter is supposed to be configured at KEKB-BELLE under $B = 1.5$ TG, as shown in Fig. 2, and only FW photons are detected. δ(TOP) and δ(TOP + TOF) are the difference of respective times between K and π, and (1), (2) and (3) are the smearing contributions described in the text.

Calculated TOP differences between 4 GeV/c K and π and the above-mentioned three contributions are illustrated for two cases in Fig. 3, where TTS is set as 80 ps to include other small uncertainties such as the start-signal. When the particle incident polar angle (θ_{inc}) gets around or smaller than 40°, TOP difference reverses its sign against the TOF difference, as seen in Fig. 3(b), and the separability power reduces a bit. While the expected number of detectable forward-going (FW) photons is at an average 35 and 115 at (a) and (b), respectively, only the early arrived photons at the individual anodes are taken into account for the time measurement. When the BW photons are also regarded for detection, they come more than 15 ns later than FW photons which are widely separated enough for measurement to take place and for distinguishing between each other.

As a sample of simulation study, Fig. 4(a) shows a log-likelihood distribution in the case of the FW photon detection for 4 GeV/c K and π with $\theta_{inc} = 90°$. Resulted separability is $S(=\sqrt{2\Delta \ln \mathscr{L}}) = 5.7$. Over-all expected π/K separability is shown in Fig. 4(b) in the case of BELLE configuration. High momentum limit is indicated by a thick line for the pions in B → ππ decay. It is found that $S > 5$ is achieved at any barrel region of $\theta_{inc} = 30°$–130°.

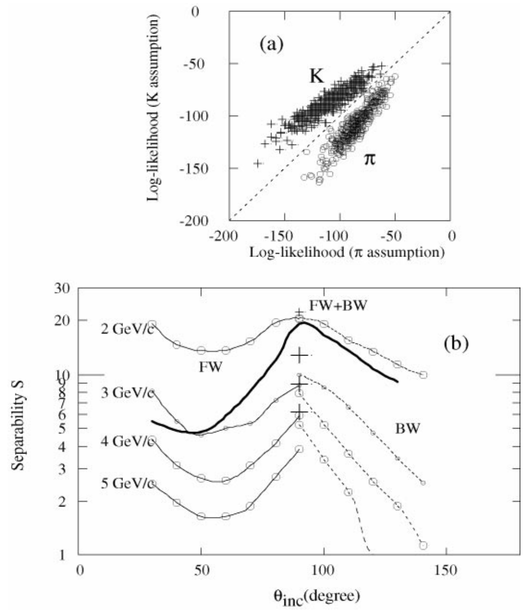

Fig. 4. (a) shows a log-likelihood distribution with FW photon detection for 4 GeV/c K and π with $\theta_{inc} = 90°$, where the horizontal and vertical axes correspond to the π and K hypotheses to the track, respectively. The resulting separability is $S = 5.7$. (b) is the calculated S in a case of BELLE application, where thin and dotted lines are for only FW and BW photon detections, respectively, and crosses at $\theta_{inc} = 90°$ are by detection of both FW and BW photon. Thick line is the momentum and polar-angle relation of π's in B → ππ.

3. Beam test

A test counter 1 m long quartz bar was constructed with the structure as described in Fig. 2 but an absorptive filter, instead of a reflection mirror, for BW photons at the bar end is prepared. Six L16 PMTs (96 anode channels in total) were attached to the mirror. Since the photoelectron detection efficiency of L16 PMT is about $\frac{1}{2}$ and an effective mirror surface coverage by six PMTs with our configuration is approximately 40%, the total photon detection efficiency, besides PMT's QE, is nearly 20%. The above photon-insensitive area, most of which is the structural space of PMT, would reflect the photons and resultantly hit other wrong anodes. To avoid this phenomena, absorptive filters were inserted in front of such areas. Measurement was performed using π^- beam at KEK-PS.

First, beam was tuned to normally hit the counter at $L = 0.02$ m. Recorded data are shown in Fig. 5. Single photon peak is clearly seen in ADC spectrum. Besides Cherenkov photons, two small contributions of knock-on electrons and reflected photons are found on TDC spectrum. Resultant time resolution over all 96 channels is about $\sigma = 85$ ps, as plotted in Fig. 6. Since the chromatic contribution can be ignored at this configuration, the resulting resolution is dominated by TTS of L16 PMT.

Next, beam position was moved to $L = 1$ m and three different momenta of 1.1, 2 and 4 GeV/c were

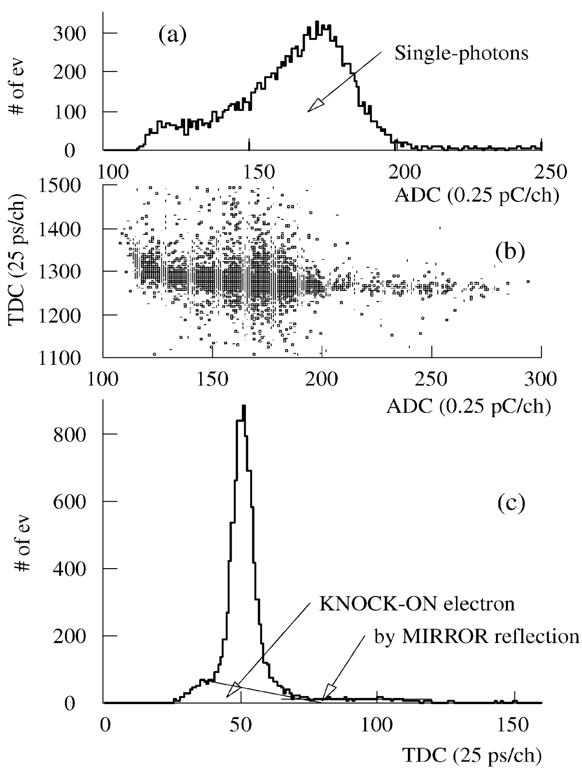

Fig. 5. ADC and TDC distributions of 20th channel for the normal incident 2 GeV/c π's with $L = 0.02$ m. Timewalk correction was applied in (c) and the time resolution of trigger uncertainty subtracted is $\sigma = 80$ ps.

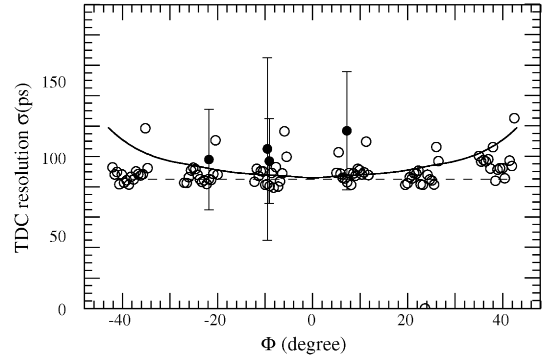

Fig. 6. Measured time resolutions for normal incident 2 GeV/c π's. Open circles are obtained at $L = 0.02$ m. The closed circles are obtained at $L = 1$ m as described in the text and the curve is the expected one based on the measurement of $L = 0.02$ m.

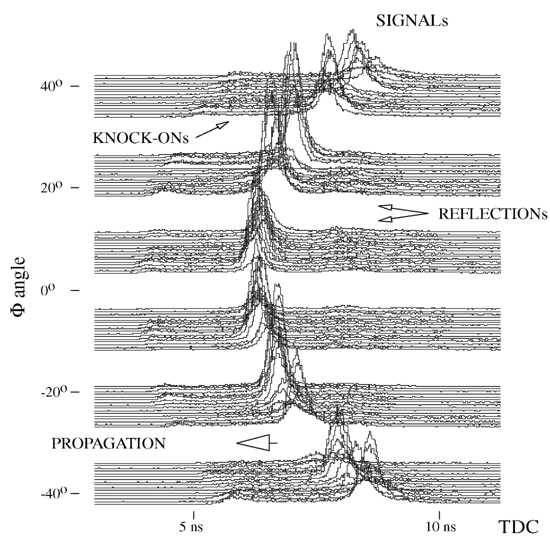

Fig. 7. Cherenkov ring image measured by TOP counter for normal incident 4 GeV/c π's at $L = 1$ m.

set. Expected number of fired anodes was around 6, while we observed 6.3 at an average including both the contributions from the knock-on electron and reflected photons for individual three different momenta. Cherenkov ring image is clearly observed as a function of Φ-angle, as seen in Fig. 7. In order to extract the resolution in this case, a simple tricky analysis had to be applied, because the beam divergence defined by trigger counters were not sufficiently small enough as expected at the BELLE detector system to make its contribution ineffectual. That is, the triggered samples are required to have a signal at a certain channel, for example, 27th channel, within the first 150 ps part of the measured raw time distribution of 350 ps (FWHM). This bias would restrict the beam divergence somehow but not explicitly. Thus obtained resolutions are plotted in Fig. 6: fairly good agreement with the expectation can be seen. The parabolic rise of the calculated resolution at large Φ is due to the aberration effect of the mirror rather than the chromatic contribution of the Cherenkov light at $L = 1$ m case.

4. Summary

TOP counter is quite compact and has high separability. Due to the horizontal focussing and thin radiator thickness, the size of quartz bar's cross-section can be disregarded so that it does not need a large standoff projection space such as DIRC. It is still at an early R&D stage and needs more essential studies as mentioned below.

First, confirmation of basic TOP behavior, especially the performance at $L = 1$ m or longer distances, should be done using tracking chambers at the next beam test.

Increasing the detected number of photons is the most important issue and two approaches for enlarging the sensitive area are being examined: one way is to use a light-guide, and the other is to develop L16 PMT. When a way to successfully collect sufficient number of photons is established, TOP counter can be used as a real detector under certain experimental condition, for instance, fixed target experiment with no magnetic field. It needs much less space compared to Gas Cherenkov counter, and can be configured to make the counter normal to incident particles so that the separability is enhanced by detecting both the FW and BW photons.

In order to utilize the TOP counter as the next BELLE pid detector, the second most important issue is to develop a single photon and position-sensitive, high time-resolving detector operational under a magnetic field of 1.5 TG. R&D work of L24 PMT is being earnestly proceeded so that a successful outcome can be within our grasp in the near future.

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References

[1] J. Va'vra, Nucl. Instr. and Meth. A 453 (2000) 262.
[2] B. Ratcliff, Nucl. Instr. and Meth. A 453 (2000) 301.
[3] M. Akatsu, M. Aoki, K. Fujimoto, Y. Higashino, M. Hirose, K. Inami, A. Ishikawa, T. Matsumoto, K. Misono, I. Nagai, T. Ohshima, A. Sugi, A. Sugiyama, S. Suzuki, M. Tomoto, H. Okuno (KEK, Tsukuba), DPNU-99-08, March 1999, 19pp; e-Print Archive: physics/9904009.
[4] J. Haba, Nucl. Instr. and Meth. A 368 (1995) 74.
[5] T. Nozaki, Nucl. Phys. B (Proc. Suppl.) 50 (1996) 288.