ELSEVIER

Nuclear Instruments and Methods in Physics Research A 494 (2002) 430–435

NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH Section A

www.elsevier.com/locate/nima

Progress report on Time-Of-Propagation counter—a new type of ring imaging Cherenkov detector

Y. Enari*, M. Akatsu, T. Hokuue, T. Igaki, K. Inami, A. Ishikawa, Y. Kawakami, T. Matsuishi, T. Matsumoto, Y. Miyabayashi, T. Ohshima, K. Senyo, A. Sugi, A. Sugiyama, S. Tokuda

Department of Physics, Nagoya University, Chikusa-ku, Nagoya 464-8602, Japan

Abstract

The Time-Of-Propagation (TOP) counter measures both the time and position information of radiated photons with high resolutions to distinguish the Cherenkov angles between different particle species. Current R&D status is reported. We also propose a further simplified version of the TOP-counter.

PACS: 29.40.Mc; 42.70.Ce

Keywords: PID; Cherenkov detector; RICH

1. Introduction

The Time-Of-Propagation (TOP) counter, see Fig. 1, comprises a long quartz bar as a Cherenkov radiator and photon's light guide, a butterfly-shaped focusing mirror and an array of photon detectors [1,2]. The Cherenkov lights propagated to an end of the quartz bar are focused at certain points depending on their horizontal emission angles (Φ) and then detected by position sensitive photo-multipliers (PMT) with high time resolution. The TOP-counter thus detects both the TOP and the Φ or x-position to compose the Cherenkov ring image and forms a compact size, instead of the commonly adopted method of measuring two-dimensional spatial coordinates of the photons on a projection plane with a large detector volume.

TOP is simply expressed as $\mathrm{TOP} = (L/c/n(\lambda)) \times (1/q_z)$, where L is the distance from the particle's incident point to the PMT along the bar axis (z-axis), $n(\lambda)$ is the refraction index at wavelength λ, c is the light velocity in a vacuum, and q_z is the directional z-component of the radiated photon. q_z is a function of Φ and relates to the Cherenkov angle (θ_C). As an example, the TOP difference between the normal incident 3 GeV/c π and K is 120 and 200 ps in the case of $L = 1$ and 2 m, respectively. Therefore, when we measure the TOP with $\sigma = 90$ and 150 ps resolutions as expected from MC for the above cases, the π/K separation is $\sim 1.3\sigma$ for a single photon and 6.5σ for an expected ~ 30 photons under these conditions.

Aiming at the next generation of Belle's particle identification devices, our R&D has been devoted

*Corresponding author.
E-mail address: enari@hepl.phys.nagoya-u.ac.jp (Y. Enari).

0168-9002/02/$ - see front matter © 2002 Elsevier Science B.V. All rights reserved.
PII: S 0 1 6 8 - 9 0 0 2 (0 2) 0 1 5 1 4 - 0

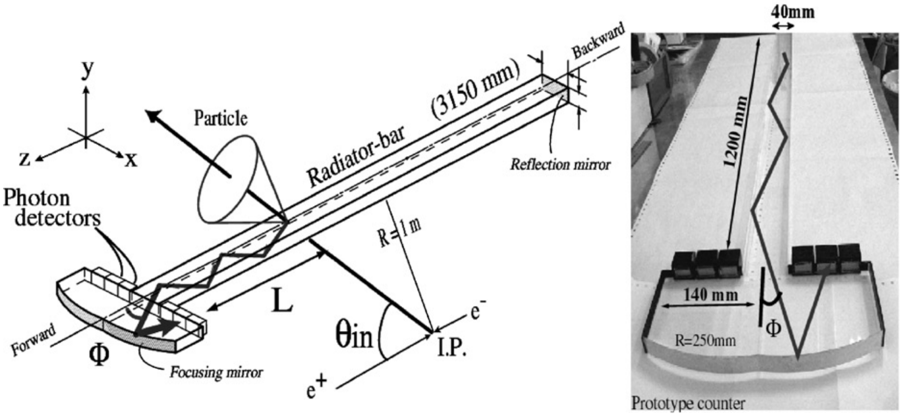

Fig. 1. Schematic drawing of the TOP-counter (left) and the photograph of a prototype counter (right). The counter in principle comprises a quartz bar, a butterfly-shaped focusing mirror and photo-detectors. Backward-going photons are reflected by a mirror attached at the other bar end.

to (1) confirming the basic optical performance of the TOP-counter and (2) developing a single photon and position sensitive photon detector with a Transit Time Spread $\sigma_{\mathrm{TTS}} \leqslant 100$ ps operational under a 1.5 T of strong magnetic field. Achievements of R&Ds on multi-anode fine-mesh PMTs [3] and a Hybrid Avalanche PhotoDiode (HAPD) [4] are separately reported in this Symposium [5]. We here report on our current situation of the first issue.

2. TOP-counter with a focusing mirror

A prototype counter shown in Fig. 1 comprises a quartz bar of $1200\ \mathrm{mm}^{\mathrm{L}} \times 40\ \mathrm{mm}^{\mathrm{W}} \times 20\ \mathrm{mm}^{\mathrm{H}}$ size, a mirror with a curvature of 250 mm and six R5900-U-L16 Hamamatsu Photonics PMTs. The PMT has 16-channel linear-array anodes of $0.8 \times 16\ \mathrm{mm}^2$ area and 1 mm channel pitch with $\mathrm{TTS}(\sigma) = 70$–$80$ ps.

There exist three dominant intrinsic contributions to TOP uncertainty: (1) TTS of PMT, (2) the chromatic effect of the quartz bar, and (3) the aberration effect by the focusing mirror. The other contributions can be ignored due to their smallness compared to these. Uncertainty from the aberration shows strong Φ-dependence: it is disregarded around $\Phi = 0^\circ$ but not when it gets 100 ps around $\Phi \sim 40^\circ$ at $L = 2$ m. The chromatic effect is the largest contribution and amounts to about 120 ps at $L = 2$ m. The total uncertainty is therefore about 100 ps at $L < 1$ m and 150 ps at $L = 2$ m. Details of these uncertainties and detector performance are discussed in Ref. [1]. In reality, another primary factor affects the TOP performance, i.e., polishing accuracy of the quartz-bar surface.

We have carried out beam tests at KEK-PS π2 beam line. Fig. 2(a) shows an observed Cherenkov ring image for $4\ \mathrm{GeV}/c\ \pi$ beams with a small component of knock-on electrons that form a plateau under the Cherenkov peak. The achieved TOP resolution is plotted by open symbols in Fig. 2(b) as a function of the path length (L_{path}) along the propagation trajectory. In this measurement, the expected TOP resolution of $\sigma_{\mathrm{TOP}} \leqslant 100$ ps is attained at $L < 1$ m, while it is two to three times worse than the anticipated one at $L > 1$ m. A detailed examination of the quartz bar by means of an interferogram and others indicates insufficient polishing accuracy that fails to meet our demand. A newly qualified quartz bar is prepared and replaced with the old one. Their performances are compared in Table 1; it is obvious that the new quartz bar has yielded a much better performance compared to the previous one.

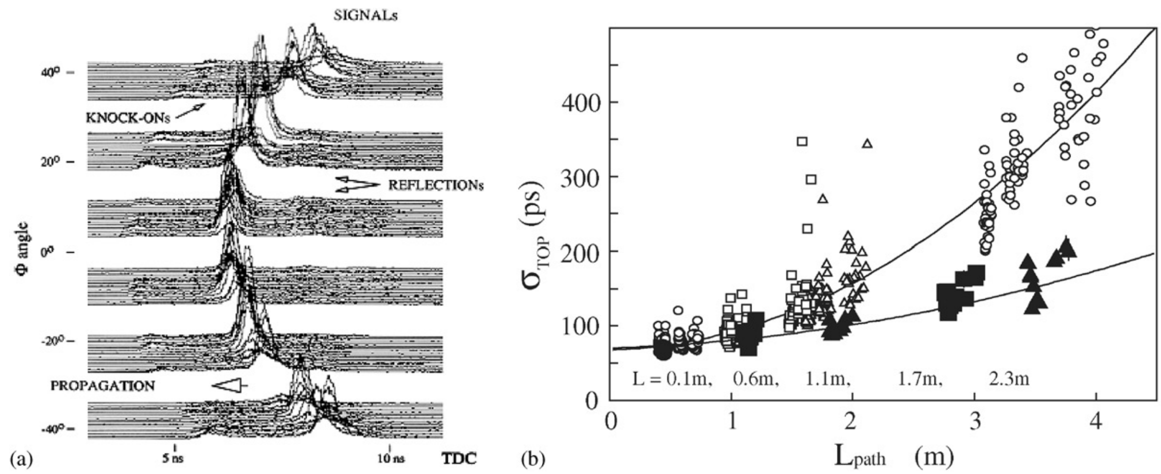

Fig. 2. (a) Measured Cherenkov ring image formed by forward-going photons produced by normal incident 4 GeV/c π's at $L = 1$ m. Time-walk effect is not corrected. (b) TOP resolution attained by the beam tests for TOP-counters with the butterfly-shaped focusing mirror. Open symbols are obtained by the insufficiently polished quartz bar, while the closed ones are obtained by the newly prepared bar. Horizontal axis is the path length along the propagation trajectory.

Table 1
Polishing performance for the two prepared quartz bars

	Polish (nm)	Figure (μm)	Squareness (mrad)	Edge radius (μm)	Time resolution (ps)
Old bar	2	5	2	50	300
New bar	0.5	0.6	0.6	5	150

The closed symbols in Fig. 2(b) are the TOP resolution obtained using the new quartz bar. Improvement of the polishing accuracy certainly results in the expected TOP resolution. For instance, the resolution has improved from $\sigma_{\rm TOP} \sim 300$ to 150 ps at $L = 2$ m: this is equivalent to the single-photon Cherenkov-angle resolution of $\sigma_{\theta_{\rm C}} = 10.6$ mrad.

It can be concluded that from these R&Ds we have confirmed the basic performance of the TOP-counter. And, developing a photon collecting method over an expected sufficient amount is the next R&D issue waiting for our attention. Accordingly, both the developments of a new photo-detector with high detection efficiency and a light guide to PMTs with high collection efficiency have been carried out in preparation for this very next step.

3. Further simplified TOP-counter

The distinguished feature of the TOP-counter is its simplicity and compactness as well as its high π/K separation. We here provide a brief idea of what a further simplified version should be: it comprises only a quartz bar and photon detectors directly attached at a bar end. A prototype is shown in Fig. 5. It is much simpler and easier to construct; it avoids the mirror-induced uncertainty of tracing the photons.

Because of the non-focusing property, the Φ aperture sustained by an anode is extremely small: $\Delta\Phi = \arctan(\Delta x / L_{\rm path})$ where Δx is the anode width. And while the aberration effect can be disregarded in this new counter, it predominates full TOP uncertainty at $\Phi \geqslant 50^\circ$ under most conditions in the case of the previous type of TOP-counter. Therefore, better TOP resolution is achievable at large Φ-angle in this new version. The Φ aperture can be accordingly extended and resultantly the number of detectable photons is increased, for instance, a factor of 1.7. Or, the anode width of PMT can be widened, for example, 10 mm instead of 1 mm as in the previous one, to reduce the number of readout channels.

The expected ring images to be observed are shown at the upper half in Fig. 3. Photons having different Φ-angles are detected by an anode so that a unique relation between the TOP and Φ is no longer maintained. With a narrow quartz width (w) such as 40 mm of the TOP-counter with the mirror, the ring image cannot be practically identified with finite TOP resolution due to many turn-ups. However, when the width is set wider, for instance, 200 mm, the separation of the turn-ups becomes larger than the TOP resolution to recover the original TOP's π/K separation power as illustrated at the lower half of Fig. 3.

Analysis for this new counter gets somewhat more complex. A Monte-Carlo simulation is performed as follows. A reference TOP-vs.-x relation is calculated with an average reflection index $n = 1.47$ ignoring the chromaticity and TTS. A χ^2 is formed by the TOP of the individual generated photons having full simulated uncertainties and its closest reference TOP among many possible solutions for each anode. The least χ^2 is searched for by varying the θ_C-angle. As is illustrated in Fig. 3, the wider the bar width, the larger the separation achieved. The achieved θ_C resolution is 4.8 and 5.0 mrad in the case of a normal incident particle at $L = 1$ and 2 m, respectively, with the Φ aperture of $|\Phi| \leqslant 50^\circ$.

We have beam tested the prototype new counter with a bar size of $1000\ \mathrm{mm}^L \times 200\ \mathrm{mm}^W \times 20\ \mathrm{mm}^H$, as shown in Fig. 5. The observed TOP vs. x distribution is found in Fig. 4(a). Since the beam hits the quartz bar 50 mm apart from the bar axis, Cherenkov ring image shifts and accordingly exhibits an asymmetrical parabolic shape. It shows multiple turn-ups as expected and a TOP-resolution of $\sigma = 80$ ps is found at $L = 260$ mm, which is the same resolution achieved by the TOP-counter with the mirror.

4. Summary

We have observed the Cherenkov ring image and attained the expected time resolution of $\sigma = 80$ and 150 ps for $L = 0.2$ and 2.3 m, respectively.

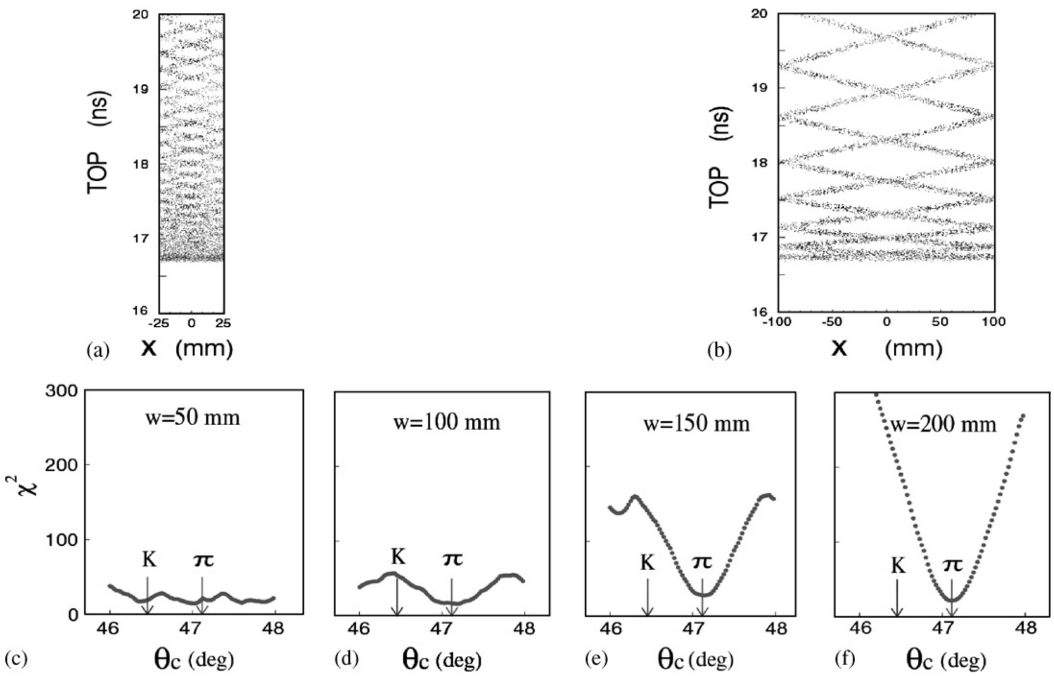

Fig. 3. The ring images to be observed by the simplified TOP-counter are illustrated for a normal incident 3 GeV/c π beam at $L = 2$ m: (a) for a bar width of $w = 50$ mm and (b) $w = 200$ mm. For illustration purpose, the TOP smearing effects of the chromaticity and TTS are not included in the figures. But, these effects are considered in the numbers described in the text. Expected Cherenkov-angle resolution is examined in terms of the least χ^2 method: with wider bar width from (c) to (f).

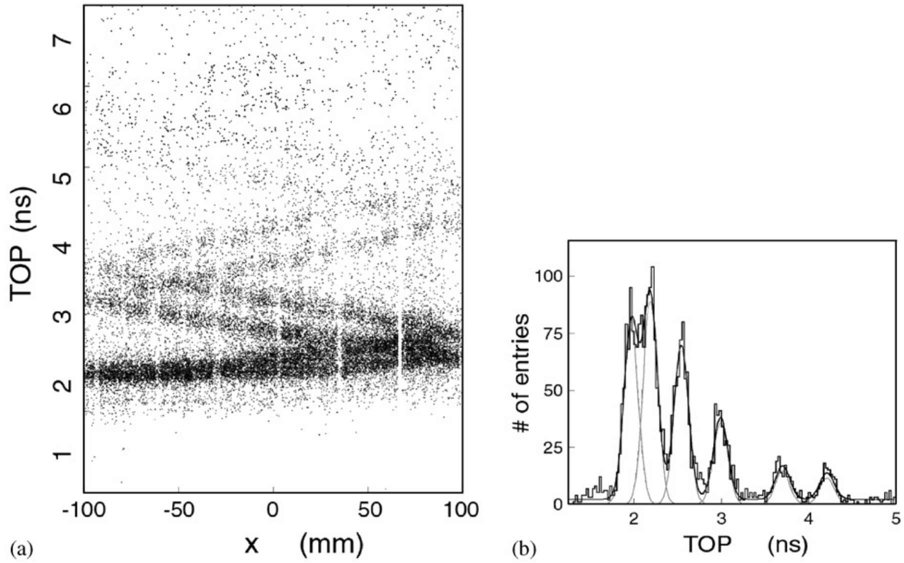

Fig. 4. (a) Measured Cherenkov ring image by the simplified TOP-counter using 3 GeV/c π beam. (b) TDC distribution measured by a certain PMT-anode attached at $x = 11.3$ mm. Six peaks are seen in (b). The distribution is fitted with 6 Gaussians with a common sigma.

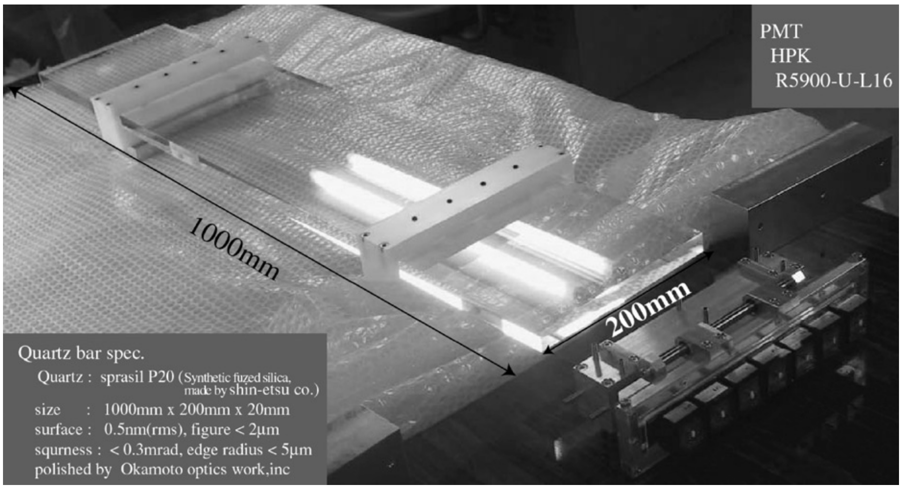

Fig. 5. A prototype of the further simplified TOP-counter. This counter comprises a quartz bar and an array of photon detectors. Seven multi-anode PMTs are mounted on the bar end which can be seen at the right bottom side in the photograph.

The Cherenkov-angle resolution for single photons is $\sigma_C = 10.6$ mrad at $L = 2.3$ m for the TOP-counter with the butterfly-shaped mirror. The designed basic performance is now confirmed. The simplified version of the TOP-counter looks quite promising and its R&D will be eagerly continued further.

Acknowledgements

This work was supported by a Grant-in-Aid for Science Research on Priority Area (Physics of CP violation) from the Ministry of Education, Culture, Sports, Science, and Technology of Japan.

References

[1] M. Akatsu, et al., Nucl. Instr. and Meth. A 440 (2000) 124.
[2] T. Ohshima, ICFA Instr. Bull. 20 (2000) 2.
[3] M. Hirose, et al., Nucl. Instr. and Meth. A 460 (2001) 326.
[4] S. Matsui, et al., Nucl. Instr. and Meth. A 463 (2001) 220.
[5] T. Hokuue, et al., R&D on fine-mesh multi-anode PMT with T.T.S. = 100 ps under $B \leqslant 1$ T, Nucl. Instr. and Meth. A 494 (2002), these proceedings.