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TOP counter for particle identification at the Belle II experiment

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ABSTRACT

Ring imaging Cherenkov counter, named TOP counter, utilizing precise photon detection timing has been developed as a particle identification detector for the Belle II experiment. The real size prototype has been produced and tested with 2 GeV positrons at Spring-8 LEPS beam line. The quartz radiator production and assembling with microchannel plate photomultipliers was successfully carried out. The beam test data shows good agreement with full Monte-Carlo simulation results in the ring image and the distribution of number of detected photons and timing information.

1. Introduction

We have been developing the Cherenkov ring imaging counter, named TOP counter [1], as the particle identification device, mainly for the separation of $\pi^\pm$ and $K^\pm$, for the upgrade to the SuperKEKB/Belle II experiment [2]. At the Belle II experiment, the target peak luminosity is $8\times10^{35}\ \mathrm{cm}^{-2}\,\mathrm{s}^{-1}$, which will be realized by the higher beam current and smaller beam size, to produce the order of 10^{10} B-mesons, τ leptons and charmed particles. The particle identification of K/π is important for the B physics study (flavor tag and full reconstruction) and also charm studies at Belle II experiment and will be carried out by the ring imaging Cherenkov detectors. The expected fake rate for K/π separation is 2–5 times smaller than that of the previous Belle experiment. In the barrel region, TOP counter will be installed.

The TOP counter utilizes total internal reflection of Cherenkov photons produced in a quartz radiator and measures the position and precise arrival time of the propagated photons at the radiator ends. Fig. 1 shows the schematic overview and the concept of the TOP counter. In order to separate the $\pi^\pm$ and $K^\pm$ accurately, we need to measure the particle's velocity β very precisely. To measure β, TOP counter uses two ways. One is the difference of Cherenkov angle θ_c. The θ_c depends on β as $\cos\theta_c = 1/(n\beta)$, where n is the refractive index of the radiator. The difference of θ_c causes the difference of the propagation time (TOP) inside the radiator. Another is the time of flight (TOF) from the interaction point to the counter, which enhances the difference of the photon's arrival time in most cases. In the Belle II situation, the typical time difference between K and π is about 150–200 ps, which is measured with the precise time resolution of $\sigma\sim40$ ps for each photon. Because of the simple structure, the counter is compact and suitable for the detector geometry at collider experiments. The key technologies are the single photon detection with precise timing and accurately polished quartz bar.

The resolution of TOP counter is limited due to the chromatic dispersion effect in the quartz. The dispersion smears the TOP by the order of 100 ps. We have introduced a focusing mirror and 3D imaging into TOP counter, to correct the chromaticity, as shown in Fig. 2. The focusing mirror is attached to the back end of the bar, the PMT readout is on the front end. The PMT channels are segmented in the direction of thickness of the bar. Because of wavelength (λ) dependence of Cherenkov angle, the focused position of Cherenkov light has a dependence on the λ. Therefore, the ring image reconstruction from 3D information (x, y and time) improves the resolution. Furthermore, long focusing length (about 2.5 m) enlarges the position difference (about 14 mm for 350 nm to 550 nm light). The difference is fit to the quartz thickness and matches the 5 mm pixel size. The focusing scheme has been confirmed in the previous beam test using small size prototype [3].

2. TOP counter for Belle II

The TOP counter for the Belle II experiment consists of the quartz radiator (2.7 m $\times$ 45 cm $\times$ 2 cm) with focusing mirror (6.5 m radius) and expansion block, quartz support, microchannel plate photomultiplier tubes (MCP-PMT) and the fast readout electronics (32 PMTs, 512 channels per module).

The quartz radiator is constructed with two quartz bars (1.25 m length), focusing mirror and expansion block, which are glued with each other. They need high quality surface, whose roughness is 0.5 nm, to keep total reflectance, and flatness is $<10\lambda(6.3\ \mu\mathrm{m})$ over full aperture, to

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keep ring image. Two prototype quartz bars are made by two vendors, Zygo and Okamoto optics works. The polished surface meets our requirement. The obtained roughness is 0.44 nm and the flatness is about 5 μm for 1.2 m length. The optical quality has been confirmed by our laser system. The measured internal surface reflectance is 99.92–99.97%. We found no evidence of striae inside the quartz material. For the gluing quartz parts, we built optical stage to align precisely. The glued radiator shows good accuracy, the relative angle less than 0.1 mrad and displacement less than 100 μm. The produced radiator is shown in Fig. 3. The status of recent development is shown in Ref. [4].

The radiator is supported by quartz bar box (QBB), which consists of the honeycomb panels, side rails and small buttons made of PEEK. Because the rigid support is required for the final system, round shaped honeycomb panel will be adopted and each QBBs will connect to adjacent modules. The strength by those mechanism has been confirmed by the prototype QBBs. The details are discussed in Ref. [5].

To detect the Cherenkov photons with precise timing and large effective area, the square-shaped MCP-PMT (27.5×27.5 mm^2) has been developed with Hamamatsu Photonics K.K. [6]. The MCP-PMT has 16 channels with 5 mm pixel size and 64% sensitive area. The photo-cathode is an enhanced multi-alkali, whose quantum efficiency is $>28\%$ at peak wavelength and the sensitive range is 280–650 nm. The MCP-PMT signal is read out by newly developed ASICs, named IRS series. The new ASIC realizes the fast waveform sampling (2.5 GHz) with high density and multi-hit buffering with 30 kHz trigger rate. The prototype with the nearly final form factor (Fig. 4) reads out the clear PMT signal waveform (1 ns pulse width) and the measured clock jitter is about 20 ps.

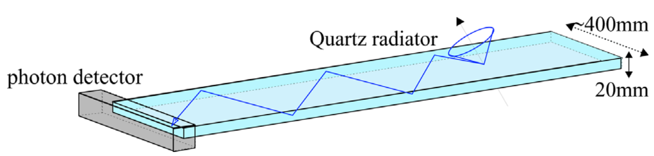

Fig. 1. Schematic overview of TOP counter. The emitted Cherenkov lights are propagated inside quartz radiator and detected photon detector at the bar end. TOP counter measures the propagation time.

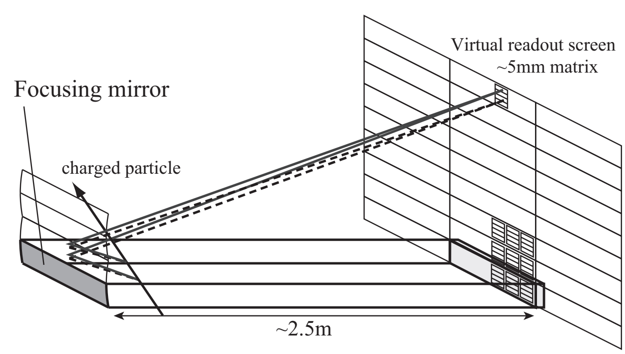

Fig. 2. Schematic overview of focusing system. The Cherenkov lights emitted by charged particle are propagated in the virtual quartz space and reflected by focusing mirror and arrived at readout screen. The lights for the different Cherenkov angles are focused at the different position.

3. Beam test

We have carried out the beam test with the prototype TOP counter, which has almost full size quartz radiator and full aperture PMTs. During the test, we took data with two different run conditions, using two types of readout electronics, prototype ASIC and conventional constant-fraction-discriminator (CFD) front-end. The CFD readout has 1×4 channel readout per PMT, by combining 4 channels, therefore, 128 channels are read out per TOP module. The CFD module prototype and the mounted situation are shown in Fig. 5. The measured time resolution is about 40 ps with the MCP-PMT, CAEN VME TDC (V1290A, 24.47 ps digitization) and pulse laser in a single photon level.

The beam test has been performed at the Spring-8 LEPS beam line, where 2.4 GeV gamma-rays, generated by back-scattering of 351 nm laser with 8 GeV electron beam, produce e^+e^- pairs at 1.5 mm^t lead target. After the 0.7 T dipole magnet, 2 GeV positrons have been triggered with four scintillation counters. The triggered beam size is 5×5 mm^2. Between those trigger counters, the TOP prototype and fiber-scintillator trackers are located. In the down stream, timing counters and TOF counters are placed. The trigger rate during the test is about 10 Hz. During the beam test, the TOP counter is rotated to check the performance for several incident angles.

The beam timing for all measurements has been derived from RF clock provided by the accelerator. The timing precision from the RF clock was cross checked using timing counters located at downstream, consisting of 10 mm$^{\phi}$ $\times$ 10 mm^{L} quartz and

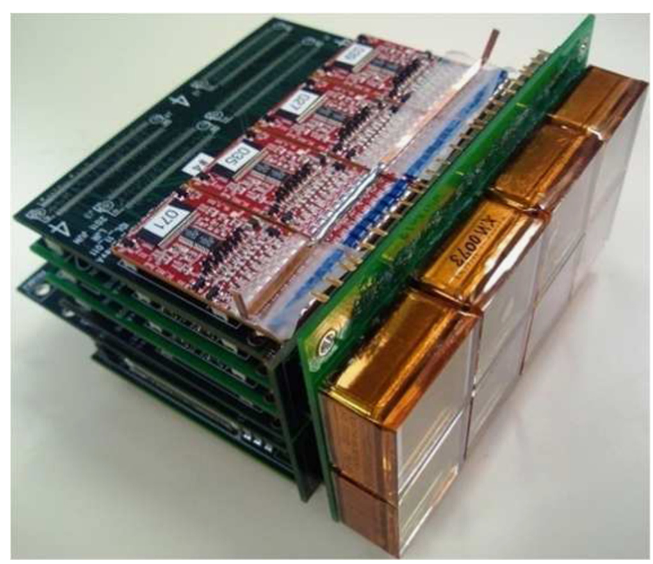

Fig. 4. IRS readout front-end prototype with 8 MCP-PMTs.

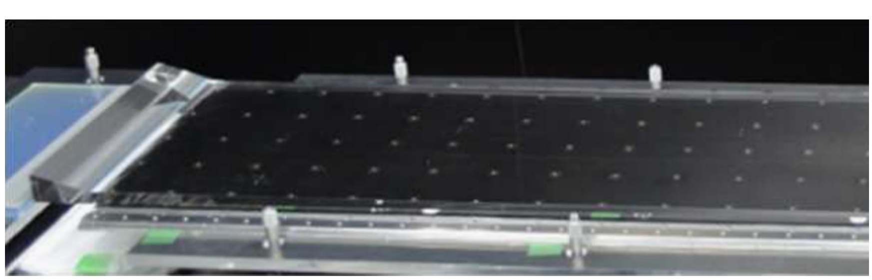

Fig. 3. Quartz radiator of the TOP counter prototype.

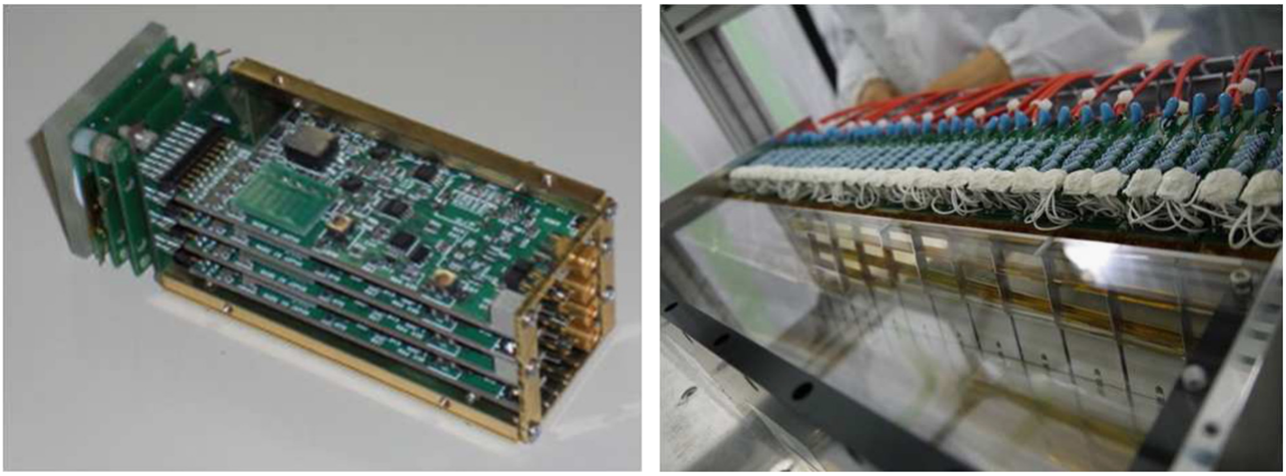

Fig. 5. CFD readout front-end prototype for one MCP-PMT (left) and the PMT modules mounted on the TOP counter (right). The size of one readout module is 26 × 26 mm^2.

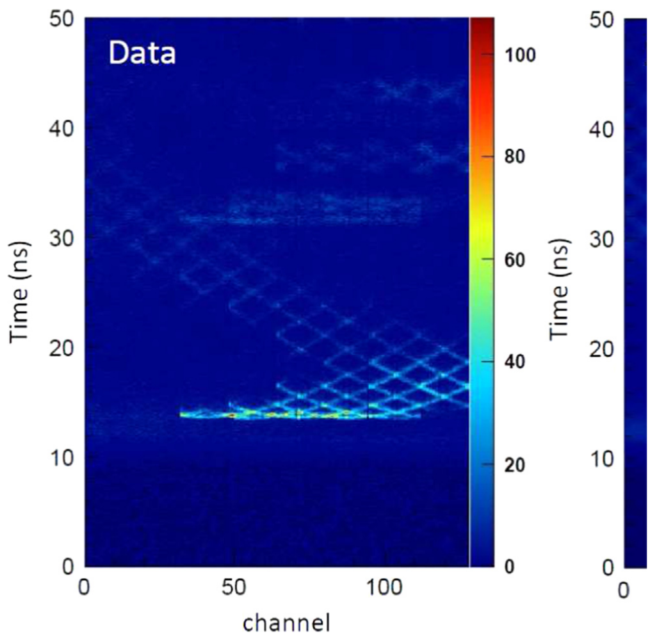

Fig. 6. Ring image obtained by beam test (left) and its expectation by MC simulation (right). The horizontal axis is a channel number from upstream row to downstream row, and the vertical axis is the measured time.

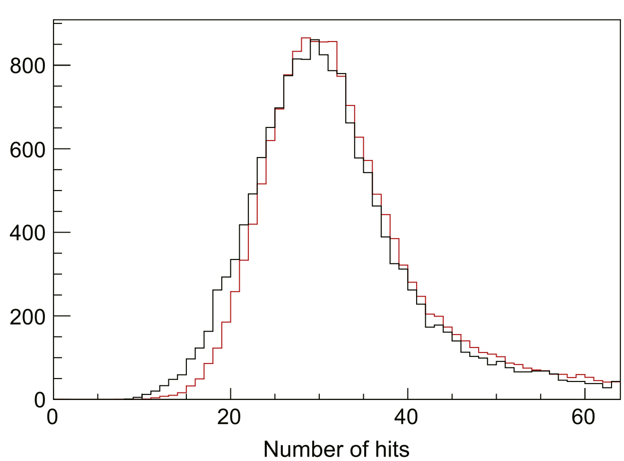

Fig. 7. Number of hits per event for data (black) and MC expectation (red) with normal incident condition. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this paper.)

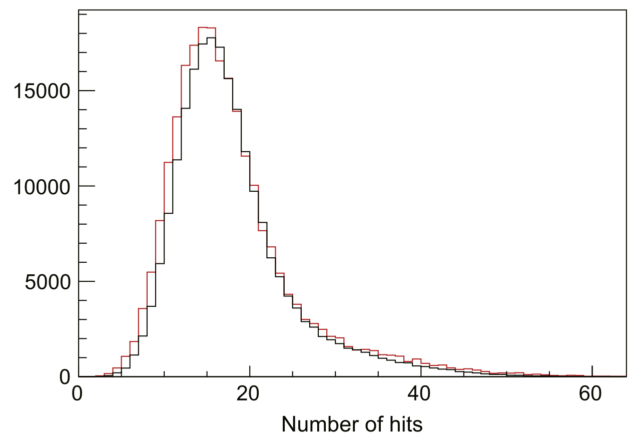

Fig. 8. Number of hits per event for data (black) and MC expectation (red) with 66° tilted incident condition. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this paper.)

MCP-PMT [7]. The evaluated beam timing resolution is about 40 ps, with the RF digitization resolution of 24 ps.

The obtained Cherenkov ring image is shown in Fig. 6, which is measured with normal incident condition with the CFD readout. Since the prototype counter has 8 rows of readout pixels with 16 channels in each row, the ring image shows 8 similar patterns repeated along the channel. The comparison with the Monte-Carlo (MC) full detector simulation shows good agreement. The photons from δ-ray background and mirror reflection as well as the main Cherenkov ring are observed clearly.

The number of hits is obtained as expected, as shown in Figs. 7 and 8. The peak is 25 hits for normal incidence and 15 hits for 66° tilted tracks. The MC expectation is calculated considering the path length, photon acceptance, QE curve (29% average at peak wavelength with the range of 340–650 nm considering cutoff filter), collection efficiency (55%), cross-talk and charge sharing hits in PMT (13%). The higher tail component is due to the δ-ray and shower tracks generated in the front of TOP counter (at triggers and trackers) and TOP radiator itself.

The comparison between the data and MC on the time distribution in each channel also shows good agreement. The plots are shown in Figs. 9 and 10. The background component, especially for the data before first peak, is from the δ-ray and showering tracks by the beam interaction with the material in the front of detector. The tail component in each peak is well reproduced by the effect of cross-talk hits and the background.

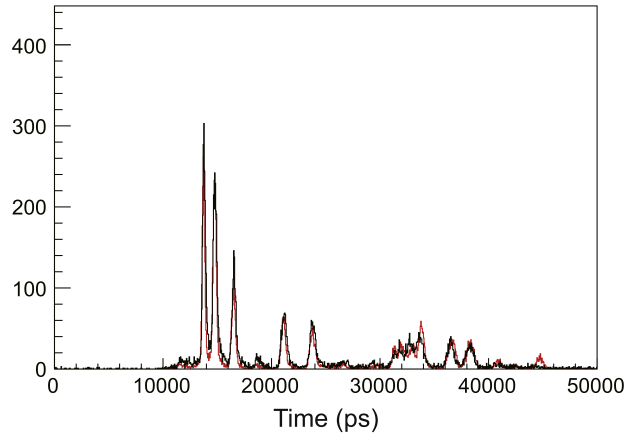

Fig. 9. Observed time distribution of channel 64 for data (black) and MC expectation (red) with normal incident condition. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this paper.)

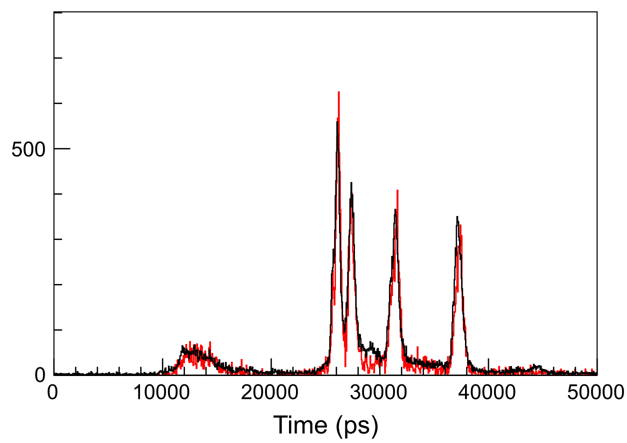

Fig. 10. Observed time distribution of channel 34 for data (black) and MC expectation (red) with 66° tilted incident condition. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this paper.)

The IRS readout has also measured the good ring image and expected timing resolution with the beam, although several channels are dead due to trouble related on the high voltage. The evaluated time resolution is about 100 ps, including IRS intrinsic resolution, PMT fluctuation, distributed clock jitter, beam timing jitter and so on.

Further study by the reconstruction program for the Belle II analysis is in progress with the beam data and the calibrated MC simulation [8]. Other details of the prototype studies are shown in Ref. [9].

4. Summary

We have developed the Cherenkov ring imaging detector, TOP counter, which utilizes photon arrival timing. The novel PID detector will significantly improve our physics reach at the Belle II experiment. We have produced the TOP counter prototype and tested with the 2 GeV positrons in the LEPS beam line. The quartz production and assembling procedure worked well. The prototype readout module shows adequate performance. The beam test data shows good agreement with MC expectation, after the calibration on the data and correction on the simulation. The ring images, number of detected Cherenkov photons timing information as well as background levels are in agreement with the expectations.

Acknowledgments

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