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Operational status of the Belle II Time-Of-Propagation counter readout and data acquisition system

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ABSTRACT

The front-end electronics system for the Belle II Time-Of-Propagation (TOP) counter was fully installed in May 2016. The detector is a novel particle identification device for the barrel region, where Cherenkov ring images are reconstructed with precise timing information of each photon. The readout electronics need to have excellent timing performance for single photon detection. To exploit the benefit of high luminosity, the electronics must also be able to cope with a high input trigger rate (30 kHz) and have buffer memory which is deep enough to wait for a trigger decision (> 5 μs). The TOP electronics has switching capacitor arrays to sample waveforms with 2.7 GSample/s, which allows a timing resolution of 50 ps for a single photon signal. The programmable logic and the processing system are the effective implementation to meet these requirements, where flexible optimization and step-by-step development of readout logic are possible. The system has been successfully operated in the first accelerator commissioning runs with beam collisions in 2018, where the typical trigger rate was 500 Hz. Operation with a 20 kHz trigger rate was also tested.

1. The Belle II TOP counter and its readout system

The Belle II Time-Of-Propagation (TOP) counter [1] is a novel particle identification device to cover the barrel region of the Belle II spectrometer. Cherenkov light is generated in the passage of a charged particle through a 2 cm-think fused quartz plate. Each photon propagates to an edge of the plate with total internal reflection and its arrival time is measured with fast photosensors and readout electronics. Particles with different mass and the same momentum give different Cherenkov angles and hence result in different arrival times, which allows to identify the particles. Since this time difference is as short as O(100 ps), excellent timing performance of the photosensor and readout is necessary. We adopted Micro Channel Plate Photomultiplier Tubes (MCP-PMT)s [2] as a photosensor, where the transit time spread is better than 50 ps. The timing performance for the readout electronics must be as good as this. The electronics are also required to satisfy various specifications from the Belle II data acquisition system (DAQ) [3], such as 5 μs trigger latency, 30 kHz input trigger rate and output data size less than 16 kB/event to fully exploit the benefit of high luminosity.

2. Specifications of the TOP readout electronics

Overview. A diagram of a readout electronics module is shown in Fig. 1. A single Subdetector Readout Module (SRM) consists of four ASIC carrier boards and one Standard Control for ReadOut and Data (SCROD) board. Signals from the MCP-PMTs go to an ASIC through two stages of amplifier with gain of 175. Each board is equipped with Xilinx Zynq System on a Chip (SoC), which controls various parameters of ASICs, performs online data processing for data reduction, and communicates with other systems. One SRM services 128 channels and we use 64 SRMs in total to cover 8192 channels. For calibration purposes, each SRM has a test pulse input and arbitrary external signals can be injected.

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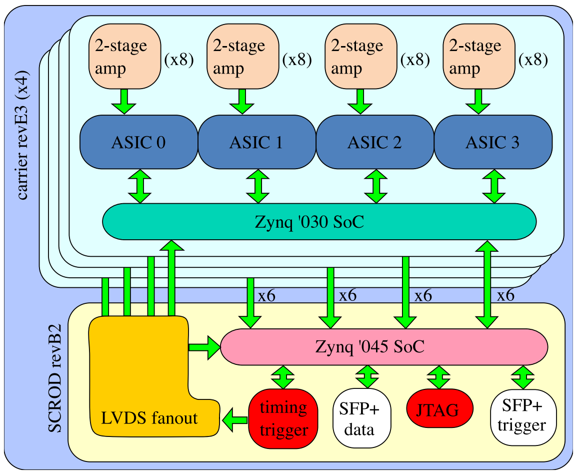

Fig. 1. Diagram of a TOP readout electronics module.

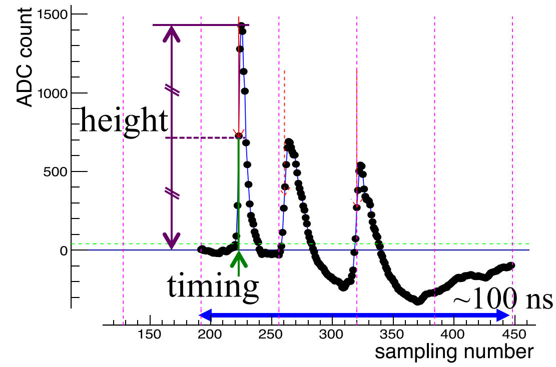

Fig. 2. An example of recorded waveform data with the TOP readout system. The first peak is a single photon hit from a laser pulse and the following two peaks are test pulses.

ASIC. For readout of fast signals, a dedicated ASIC named "Ice Ray Sampler Version. X (IRSX)" [4] has been developed. Each ASIC processes signals from 8 channels and four ASICs are mounted on each carrier board. This ASIC samples input waveforms with a 2.7 GSample/s rate and stores them in a 11 μs-long analog buffer with switching capacitor arrays. Although sampling intervals are not uniform, they are calibrated using consecutive double pulses with a fixed interval as a test pulse (Time Base Calibration, TBC). The ASIC also continuously records hit timing (timestamp) of each signal with a comparator, which is used for selective readout and is used in the TOP trigger system [5]. Waveform digitization is conducted with 12 bit Wilkinson analog-to-digital converters.

Programmable Logic (PL) and Processing system (PS) of Zynq SoC. The Zynq SoC is a combination of Programmable Logic (PL) and Processing system (PS). Each ASIC carrier board is equipped with a Xilinx Zynq SoC 7030. The PL part utilizes a Field Programmable Gate Array (FPGA), which is used for control of ASIC configuration and transfer of digitized data to the SCROD board. A Zynq SoC 7045 with a larger resource is mounted in each SCROD board. The SCROD PS works for feature extraction of waveform data. Here, hit timing and pulse height are calculated by programs written with C++ codes and only that information is sent to the data acquisition system to reduce the data size. Two optical fiber transceivers are on the board, and one of them is used to send feature-extracted data to downstream components of the Belle II data acquisition system. The other is used to send timestamp information for the TOP trigger system. The SCROD PL provides management of data from the carrier boards and to the DAQ system.

Trigger system. Timestamp information is sent to the TOP trigger system [5] to provide precise trigger timing, which helps to reduce the data size of the silicon vertex detector (SVD). The system also works as a scaler because hit rates are obtained by counting the number of timestamps. This is also helpful to know real-time hit rates for beam background monitoring [6] during accelerator operation.

3. Performance of readout system operation

The TOP readout performance depends on the firmware implemented in the Zynq chips. We developed various versions of firmware in accordance with progress of the Belle II detector construction.

Full waveform readout. In the initial stage, just after the TOP counter installation in 2016, we adapted a robust algorithm called "full waveform readout". Here, all waveform sample data for all the channels were read out without any selections. Due to the huge output data size, the tolerable input trigger rate was only 10 Hz. The buffer size was also limited to 1.5 μs. This made data taking with other Belle II subsystems difficult as their latency to make trigger decisions is longer than this value. Feature extraction was not implemented and done in offline analysis. Despite these limitations, various helpful data samples were collected to examine initial detector performance just after installation. Test-pulse data and laser data [7] were collected with an external clock trigger. An example of recorded waveform data is shown in Fig. 2. Using test-pulse data, TBC was performed and the timing resolution from the electronics was evaluated to be as small as 30 ps. Cosmic ray data were also collected with coincidence signals of plastic scintillator trigger counters which were additionally installed [8]. These data successfully demonstrated an expected response of the detector to cosmic ray particles.

Intermediate version. As a next step, in 2017, selective readout was introduced, where we read data only for channels with hits. Only 256 waveform samples, corresponding to 95 ns, were digitized and online feature extraction was performed by the SCROD PS. For debugging purposes, 256 sample waveform data were also saved within the allowed output data size. Although only a single hit for each channel could be recorded, the waveform data enabled us to extract multiple hits in offline analysis, which was necessary for TBC. Data size was significantly reduced and full-length analog memory of 11 μs was available. These updates made combined data taking with other Belle II subsystems possible. Although there was a limitation of trigger rate (<500 Hz) due to the large dead time of 1.5 ms, cosmic ray data-taking was possible with the Central Drift Chamber (CDC) and the Electromagnetic Calorimeter (ECL).[3] This was critical as track information from the CDC was the basis to reconstruct ring images. Higher rate capacity also enabled collection of larger data samples for calibration with test pulse data and laser. Various detector calibration, especially calibrations of timing difference of channel-by-channel offset using large-statistics laser data and cosmic ray data, were performed [9], which subsequently was necessary to obtain the design performance of the detector.

For the Phase2 operation. For the Phase2 operation of Belle II in 2018, where the first electron and positron collision data were collected, further upgrades of the firmware were made to cope with higher trigger rates by reducing the maximum number of digitized samples to 32. Online multi-hit extraction was also available, where offline waveform

[3] The ECL was used to trigger cosmic ray events and provide trigger timing.

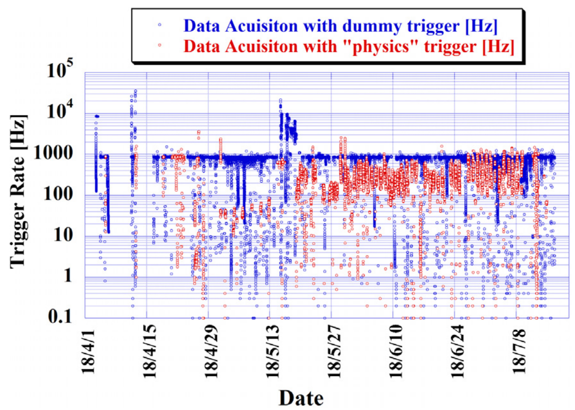

Fig. 3. History of trigger rates during the Phase2 run period. Here, "physics trigger" is for physics data-taking with beam collisions and "dummy trigger" is for DAQ test runs usually with a 1 kHz trigger with random time intervals. The DAQ test runs were done during accelerator studies with the high voltage of most detectors off.

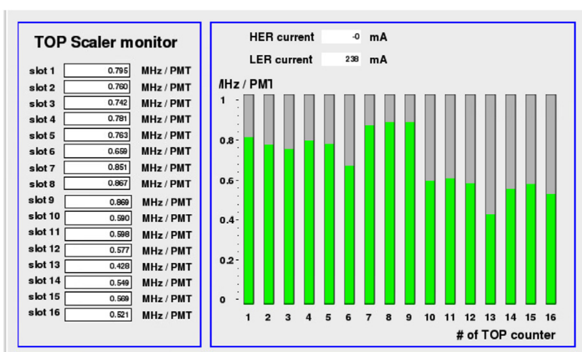

Fig. 4. A screenshot of the online monitor for PMT hit rates.

analysis was not needed. In a test environment with TOP standalone DAQ, data taking with up to a 20 kHz trigger rate was shown to be possible. In physics data taking of the Phase2 run, the TOP readout system was operated stably with a typical (maximum) trigger rate of 500 Hz (< 2 kHz) as shown in Fig. 3. The TOP as well as the other Belle II subsystems joined almost all runs. Although a time interval of 200 μs between two triggers was required by some Belle II subsystems in these runs, The TOP itself was able to take data with a 0.2 μs time interval, which is requirement from the Belle II DAQ.

The scaler function was also useful in beam operation to monitor the beam background level and its detailed study. Fig. 4 shows an online monitor of PMT hit rates. Monitored values were also saved with the EPICS [10] archiver for offline analysis.

Although there was some inefficiency from missing channels and the readout logic of this firmware, the collected physics data are well calibrated and understood to reconstruct "ring" images. The fraction of missing channels is less than 5% of the total number of channels. Some were found to be due to a problem of the high voltage power supply to the PMTs. They were fixed soon after the Phase2 run and mostly recovered. Due to inefficiency of the firmware algorithm, 22% of hits were lost. This will be fixed and the loss will be eliminated by the next physics runs. Despite these issues, as reported in Ref. [11], reasonable PID performance was successfully demonstrated using $K_S \to \pi^+\pi^-$, $D^0 \to K^-\pi^+$ and $D^{+*} \to \pi^+ D^0$ decays.

Prospects for the Phase3 run. Toward the Phase3 run, starting early 2019 with the vertex detectors, further development of TOP firmware is in progress. The 22% inefficiency is being fixed and modification for higher trigger rates is on-going. In order to improve the timing resolution and signal-to-noise ratio, template fitting technique in online feature extraction is being consideration.

4. Summary

The front-end electronics for the Belle II TOP counter were fully installed in 2016. The system can sample waveforms at a rate of 2.7 GSample/s, which makes it possible to detect single photon hits from MCP-PMTs with excellent timing resolution. The hardware is also designed to cope with a 5 μs latency for a trigger decision and a 30 kHz input trigger rate. In the Phase2 run, the system was stably operated under the typical trigger rate of 500 Hz. Operation with 20 kHz trigger rate was also tested with a TOP standalone condition. Further modification for a higher trigger rate and readout efficiency is on-going to achieve the design performance.

Acknowledgments

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