Progress on the Electromagnetic Calorimeter Trigger Simulation at the Belle II Experiment

I. S. Lee, S. H. Kim, C. H. Kim, H. E. Cho, Y. J. Kim, J. K. Ahn, E. J. Jang, S.-K. Choi, Y. Iwasaki, A. Kuzmin, Y. Unno, and B. G. Cheon

Abstract—The Belle II experiment at the High Energy Accelerator Research Organization (KEK) in Japan started gathering data in Phase II in April 2018 to unravel new physics beyond the standard model by precisely measuring charge conjugation parity symmetry (CP) violation and rare weak decays of heavy quarks and leptons. It was performed at the SuperKEKB electron–positron collider mainly running at the \( \Upsilon(4S) \) resonance energy with the goal to reach the maximum instantaneous luminosity of \( 8 \times 10^{35} \text{ cm}^{-2} \text{ s}^{-1} \). A new algorithm is needed to operate the Belle II calorimeter trigger system stably in the much higher luminosity and beam background environment of SuperKEKB compared with the KEKB collider. In order to develop an appropriate algorithm, a detailed simulation study of the Belle II calorimeter trigger system is crucial. In this article, we report the results of the simulation of the electromagnetic calorimeter (ECL) trigger using physics and beam background Monte Carlo (MC) events and compare them with the ECL trigger performance in the Phase II operation. The simulation package is developed with the Belle II Geant4-based analysis framework called Basf2.

Index Terms—Belle II, electromagnetic calorimeter (ECL), simulation, trigger.

I. INTRODUCTION

THE Belle II [1], a successor to the Belle experiment [2], [3], started a luminosity run as Phase II operation in April 2018. It accumulated events of electron–positron collisions with a designed target of an instantaneous luminosity of \( 8 \times 10^{35} \text{ cm}^{-2} \text{ s}^{-1} \) and an integrated luminosity of 50 ab\(^{-1}\) using the SuperKEKB collider at the High Energy Accelerator Research Organization (KEK), Japan [4]. This amount of experimental data is necessary to significantly improve the precision of beauty- and charm-quark as well as tau–lepton decays to probe the signs of new physics beyond the standard model [5]. In 2016, the collider was commissioned without the Belle II detector (Phase I operation). In the Phase II operation, the Belle II detector accumulated physics data without the vertex detector achieving the maximum instantaneous luminosity of \( 5 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1} \). We expect to reach \( 10^{34} \text{ cm}^{-2} \text{ s}^{-1} \) in the early operation stage of Phase III with the entire Belle II detector in 2019. Since the beam background level is anticipated to be 50–100 times higher than that at Belle, with the nominal beam background of 10 MHz under the 508-MHz beam bunch crossing rate, the robust and flexible trigger system is indispensable to cope with such a harsh situation and operate the detector smoothly.

The Belle II trigger system consists of two components: a Level 1 hardware trigger (TRG) and a high-level software trigger (HLT). The Belle II detector yields a data flow with the event size of \(~1 \text{ MB} \) with a maximum rate of 30 kHz at the TRG. The HLT [6] is designed to reduce the rate up to 10 kHz by performing the real-time full event reconstruction and applying the event selection as a software trigger.

We describe the electromagnetic calorimeter (ECL) trigger system used in the TRG and report its performance in the Phase II operation.

II. ELECTROMAGNETIC CALORIMETER

Since one-third of B-decay products are \( \pi^0 \) mesons or other neutral particles that decay mostly to photons with a wide range of energies from 20 MeV to 4 GeV, a high-resolution ECL is an important component of Belle II. The ECL calorimeter placed inside the superconducting magnet consists of 8736 CsI(Tl) counters. The barrel calorimeter has 6624 counters, whereas the forward and the backward endcap calorimeters have 1152 and 960 counters, respectively, as shown in Fig. 1. The coverage in the polar angle (\( \theta \)) with respect to the electron beam axis is 12.4° < \( \theta < 155.1° \) in the laboratory frame. The barrel part has an inner radius of 1250 mm. The mechanical support structure is comprised of an aluminum inner wall and fins suspended from stainless-steel-made reinforcing bars and outer walls. The details of the ECL detector are given in [7].

In the Belle II detector, the existing CsI(Tl) crystals, p-i-n photodiodes (PDs), and preamplifiers are reused with

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I. S. Lee, S. H. Kim, C. H. Kim, H. E. Cho, Y. Unno, and B. G. Cheon are with the Department of Physics, Hanyang University, Seoul 04763, South Korea, and also with the Research Institute for Natural Sciences, Korea under Grant NRF-2019K1A3A7A9003857.

Y. J. Kim and J. K. Ahn are with the Department of Physics, Korea University, Seoul 02841, South Korea.

E. J. Jang and S.-K. Choi are with the Department of Physics, Gyeongsang National University, Jinju 52828, South Korea.

Y. Iwasaki is with the Institute of Particle and Nuclear Studies, High Energy Accelerator Research Organization (KEK), Tsukuba 305-0801, Japan.

A. Kuzmin is with Budker Institute of Nuclear Physics SB RAS, Novosibirsk State University, 630090 Novosibirsk, Russia, and also with the Department of Physics, Novosibirsk State University, 630090 Novosibirsk, Russia.

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the existing cables to reach new shaper digital-signal-processing (DSP) modules. Each shaper-DSP channel generates the slow shaping ($\tau_d = 0.5 \mu s$) signal for precise energy measurement. Besides, it includes fast shaping ($\tau_d = 0.2 \mu s$) and gain adjustment circuits for our calorimeter trigger purposes. A fast analog sum signal, which is a combination of 16 gain-corrected fast shaping channels, is delivered to a flash analog-to-digital converter (FADC) analysis module (FAM).

### III. Level 1 Trigger System

During the Belle II detector operation with beam collisions, the data acquisition (DAQ) system should store raw data from each subdetector. Since the DAQ buffer storage is not sufficient to store all raw data due to limited data handling at high collision rate and short bunch spacing, a Level-1 hardware trigger (TRG) system is necessary to determine the data selection of physics-oriented events from the continuous data flow. TRG is an online system operating with field-programmable gate array (FPGA) chips and includes the subsystems of four detectors to collect the information from various types of particles.

The central drift chamber (CDC) TRG reconstructs charged particle trajectories to obtain tracking parameters. ECLTRG provides a total energy, the number of clusters with their energy and timing, and various physics trigger outputs, including Bhabha and low-multiplicity events from the topology information on the clusters. The time-of-propagation counter (TOP) TRG mainly generates the event timing for the Belle II DAQ operation. The $K_L$ and muon detector (KLM) TRG detects the muon tracks. In addition, TRG contains two central trigger systems with a global reconstruction logic (GRL) and global decision logic (GDL). GRL generates the matching information mainly between the CDC and ECL trigger outputs and delivers it to GDL. After that, GDL performs the final trigger decision, as shown in Fig. 2.

For the stable DAQ operation, several constraints have to be fulfilled in the TRG system: $\gtrsim 100\%$ efficiency of $\Upsilon(4S)$ events, a maximum trigger rate of 30 kHz at the designed instantaneous luminosity, total processing latency within 4.4 $\mu s$ including 3.63 $\mu s$ from ECLTRG system, a timing resolution of less than 10 ns, and a minimum event separation of 500 ns for the stable signal readout of the silicon vertex detector. The trigger efficiencies of low-multiplicity physics events, such as dark photons and two-photon processes, should be kept high as much as possible. To meet these requirements, we plan to use the Belle triggering scheme based on new technologies [8].

### IV. ECL Trigger System

The basic framework and idea of the Belle II ECLTRG system are the same as in the case of Belle [9], [10]. The schematic overview of the ECL trigger system is shown in Fig. 3. In order to handle a higher trigger rate caused by the high luminosity and beam background level, we adopted a new trigger scheme that makes trigger performance more flexible using a readout electronics architecture with FADC (ADS6424) and FPGA (XC7K160T) components and high-speed serial data transfer at 2.54-Gb/s bandwidth with 52 optical link cables.

The shaper-DSP module receives an analog signal through PDs and a preamplifier attached to the CsI(Tl) crystal counter and generates an analog signal with 0.2-$\mu s$ shaping time for trigger purposes. Sixteen shaping analog signals from neighboring $4 \times 4$ counters, called a trigger cell (TC), are combined in the shaper-DSP module. The TC is the basic unit
of the ECL trigger system, and a total of 576 TCs are formed, as described in Table I. Fifty-two FAM modules receive all TC analog signals. The FADC digitizes the TC analog signal with 8-MHz sampling speed and FPGA performs extracting each TC energy and timing by the least-squares method. Then, each TC output is sent to the TMM only if the extracted TC energy is larger than a threshold of 100 MeV. The digitized TC information is sent to a trigger merger module (TMM). Seven TMM modules merge all TC data and deliver them to the ECL trigger master (ETM). The FPGA (XC6VHX565T) firmware of the ETM performs the analysis of all TC data and generates various physics triggers, Bhabha trigger, and event timing [11].

V. ECL TRIGGER SIMULATION

Performance of ECL trigger algorithms should be studied using the ECL trigger simulation (TSim-ecl) package that is a C++-based program implemented in the Belle II Geant4-based analysis framework called Basf2 [12]. Basf2 is supposed to be used in both online and offline event processing simultaneously. It is designed to utilize a software pipeline architecture so that a large-scale event processing can be performed by combining a set of small modules for specific purpose. This modular structure makes the framework flexible and easy to maintain Monte Carlo (MC)/DST production, user analysis, and the DAQ software. Here, DST stands for the data summary table employed for data reconstruction and analysis at Belle II.

In order to develop and confirm appropriate trigger algorithms for high trigger efficiencies from diverse physics processes, TSim-ecl MC studies are performed with the same structure and function as of the ECLTRG system. Fig. 4 shows the schematic of TSim-ecl C++ object structure of ECLTRG simulation with TrgEclFAM and TrgEcl packages. The numbers of each ECL electronics module in TSim-ecl package are given in parentheses.

Main physics triggers are the total energy (Etot) and isolated cluster counting (ICN) components. The energy trigger is one of the fastest and simplest triggers, which should allow the detection of physics-oriented events and rejection of the beam background events whose energy deposition in the calorimeter is usually small. The pattern of TC signals is applied to the ICN logic that performed well during the Belle operation [9]. The total energy should be greater than 1 GeV with a Bhabha veto, and the ICN should be greater than three clusters in order to trigger an event.

The Bhabha trigger is important for luminosity measurements but should be prescaled because it is the most dominating interaction process in the electron–positron beam collision. In the phase II operation, we used the Belle-type 2-D Bhabha tagging algorithm with respect to the \( r-\theta \) plane. In order to get \( \theta \) information, we use the 17 \( \phi \)-ring sets by each TC \( \theta \) ID. The 2-D Bhabha tagging logic was updated using the back-to-back topology due to the beam energy changes from 8.0/3.5 to 7.0/4.0 GeV (electron and positron, respectively) [11]. As a result, 14 types of \( \phi \)-ring combinations and their thresholds are determined from our trigger simulation study. The \( \phi \)-ring combination types of 2-D Bhabha logic are summarized in Table II.

A harmful point of Bhabha events is the production of the main physics background having not only a very high production cross section but also event topology similar to low-multiplicity physics processes, such as tau–lepton and initial-state-radiation (ISR) events. Due to these reasons, the 2-D Bhabha logic has a weak point that misidentifies a low-multiplicity process as a Bhabha event. In order to avoid such cases, we should develop the 3-D Bhabha logic applying back-to-back topology in an additional \( r-\phi \) plane with a tighter Bhabha veto scheme than in the previous Belle algorithm.
VI. Results

The $E_{\text{tot}}$ and ICN trigger efficiencies were measured with respect to both CDC minimum two tracks and 2-D Bhabha veto simultaneously and compared with the TSim-ecl expectation, as shown in Fig. 5. The trigger efficiency turns out to be $\sim98\%$ if both ECL main triggers are considered. Fig. 6 shows the Bhabha trigger efficiency measured using a Bhabha skinned data sample processed in offline event reconstruction using raw data from each subdetector. The differences between data and MC values are mainly due to incomplete energy conversion correction of some TCs in the endcap region used in the skinned data production. The problem will be fixed in the Phase III run.

Table III shows how the Bhabha trigger affects various physics processes due to Bhabha veto using 2-D and 3-D Bhabha tagging logics. As we can see, the three dimension gives better performance, while Bhabha tagging efficiencies are the same between 2-D and 3-D logics. In addition, it was confirmed that 3-D veto logic is better than 2-D logic in order to trigger low-multiplicity physics events, including ISR and tau–lepton decays that are sensitive to probe new physics signals. Therefore, we plan to use the 3-D Bhabha trigger algorithm for the Phase III run.

In the Phase II operation, our ECL trigger timing was used to be the main source of event trigger timing in order to take data in the DAQ system. Fig. 7 shows a typical event timing distribution obtained by the Bhabha skimmed data. The timing resolution is less than 10 ns, fulfilling the DAQ requirement with room to improve it by performing more precise calibration of the ECL trigger system in the Phase III operation.

VII. Conclusion

In the Phase II operation in April 2018, the Belle II accumulated 500 pb$^{-1}$ of beam collision data in order to perform physics analysis and various experimental calibrations for detector hardware, firmware, and software tools.
In this operation, the ECL trigger system performed well after the implementation of the robust and flexible trigger scheme using FADC and FPGA firmware combined architecture. The TSim-ecl simulation software was also developed in order to test and debug current ECL trigger algorithms implemented in FAM, TMM, and ETM firmwares. From the TSim-ecl simulation study, we confirmed that physics trigger efficiencies of the ECL trigger system for various physics processes are high enough. In addition, the 3-D Bhabha trigger logic does provide a better selection of low-multiplicity events, which is crucial for the Belle II physics potential in probing the new physics.

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