Recent operation status of Belle II electromagnetic calorimeter and relevant systems

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Abstract. The electromagnetic calorimeter of Belle II experiment consists of the 8736 CsI(Tl) crystals with their PIN-photodiode readout. Those detector hardware components have been inherited from the Belle experiment. In order for high rate capability and immunity against high beam background, waveform sampling readout with digital signal processing is introduced into the frontend electronics, the ShaperDSP boards. At the beginning of Belle II experiment, the COPPER system was used to receive the digitized signal output from the ShaperDSP boards, and now it is replaced by the PCIe40 system for higher throughput and maintainability. We report recent status of the Belle II electromagnetic calorimeter system including its peripheral system such as the online luminosity monitor.

1 Introduction

Photon detection is indispensable at a *B*-factory experiment, because one third of *B* meson decays has π^0 and there are key radiative decay processes such as measurement of $B \rightarrow K^*\gamma$ decay, search for $\tau^+ \rightarrow \mu^+\gamma$ and so on. The required dynamic range is wide, from 20 MeV up to 7 GeV. To become compatible with the requirement, CsI(Tl) crystal scintillator coupled with PIN-PD readout has been chosen as the technology for electromagnetic calorimetry at the Belle experiment. The calorimeter detector hardware has been donated to the Belle II experiment and readout electronics upgrade was done for high rate capability and beam background immunity.

SuperKEKB e^+e^- collider began its beam collision operation with fully equipped Belle II detector from 2019, after having the long shutdown from 2022 summer until 2023 year end (the long shutdown 1, LS1), then operation resumed from 2024 Jan. We report Belle II electromagnetic calorimeter operation and its performance during these operation periods.

2 Detector construction and operation

The electromagnetic calorimeter that Belle II inherited from Belle experiment to cover the region of $12° < \theta < 157°$ where θ is the polar angle and the bisector line of 83 mrad finite angle crossing between e^+ and e^- beams is taken as z-axis is in the laboratory frame and its positive direction is nearly parallel with the e^- beam. There are 8736 CsI(Tl) crystals in total, where 1152 pieces in the forward endcap, 6624 pieces in the barrel and 960 pieces in the backward endcap [1]. The $r-z$ view cross section of the Belle II electromagnetic calorimeter is shown in Fig. 1 to explain overall configuration.
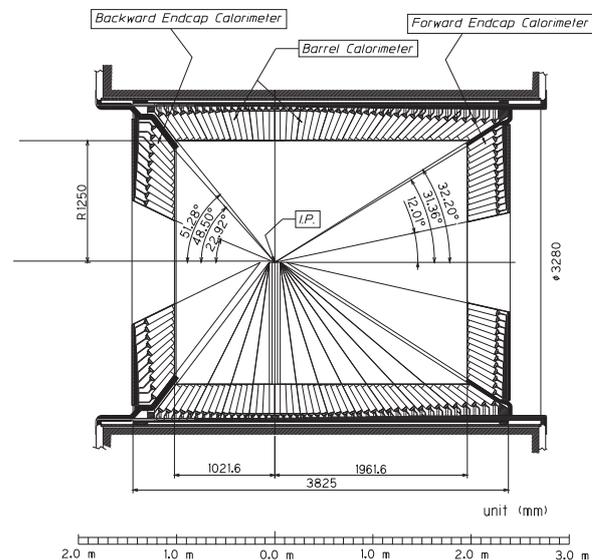

Figure 1. The $r-z$ view cross section of the Belle II electromagnetic calorimeter. There are 1152 CsI(Tl) in the forward endcap, 6624 pieces in the barrel and 960 pieces in the backward endcap, in total 8736 CsI(Tl) crystals.

The CsI(Tl) crystal is 30 cm long corresponding 16 X_0 thickness and cross section is approximately 5.5×5.5 cm^2 at the front surface facing to the interaction point (IP). Two pieces of PIN-Photodiode (PIN-PD) are attached on the rear surface of each crystal. Each PIN-PD is connected to its own preamplifier inside the metal casing on the crystal to minimize noise pickup.
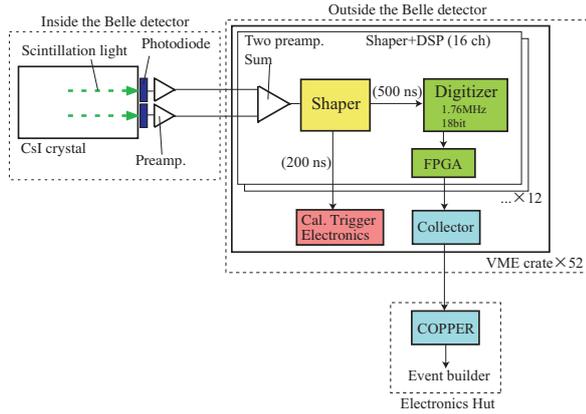
Figure 2. The block diagram of the readout electronics for Belle II electromagnetic calorimeter. The scintillation light read out by the PIN-PD is fed to the Shaper+DSP module, where waveform fit is performed. Via the collector module, the digitized detector signal is sent to the COPPER system functioning as each detector subsystem backend. During the LS1, the COPPER system is replaced by the PCIe40 system.

The block diagram of the readout electronics for Belle II electromagnetic calorimeter is shown in Fig. 2. Two PIN-PDs' signals for each CsI(Tl) crystal are summed at the first stage of Shaper+DSP board and there are 500 ns and 200 ns time constant shapers for energy deposition measurement and trigger, respectively. Energy measurement is done by 18-bits digitizer driven by 1.76 MHz clock and waveform fitting instruction on the FPGA to obtain signal amplitude and timing. When the trigger comes, 31 sample and hold data points are taken, timing is adjusted to let us use early half of them to obtain the pedestal and the net signal waveform is digitized by the last half of them.

Each Shaper+DSP module accommodates up to 16 channels and its outputs are sorted up by the collector module at the detector side and sent via optical link to the COPPER module in the electronics hut. Taking care of the fact that more than 10 years has past since the COPPER system development, recently it has been replaced by the PCIe40 system for higher throughput and maintenance sustainability. The COPPER board is made to fit 9U VME form factor and one board has four input channels, while the PCIe40 is made with PCIExpress form factor and one board equips a large FPGA with 48 optical transceivers. Transition from the COPPER to the PCIe40 took place during the LS1, after fixing some teething trouble, it has been stably operated.

3 Calibration, reconstruction and performance

For electronics calibration, a local run with test pulse is daily taken. Energy response of individual crystals is calibrated using $e^+e^- \to \gamma\gamma$ events. Only the most-energetic crystal in each shower is considered. The maximum energy deposition does not depend on inactive material distribution in front of the electromagnetic calorimeter. The

calibration constant distribution exhibits 11% standard deviation for barrel calorimeter, it reflects the variation of light output among crystals.

Since energy deposition by an incident particle spreads over multiple crystals, so that finding clusters of crystal hits is essential to reconstruct incoming particle's energy. At first, the seed crystal that contains the local maximum energy exceeding 10 MeV is found. The neighboring crystals of 5×5 crystal matrix surrounding the seed crystal is considered to form the cluster. In Belle, all the crystal hits exceeding proper thresholds (typically 0.5 MeV, depending on the polar angle of crystal location θ) inside the crystal matrix are included, while Belle II algorithm considered highest N hits are considered among 21 crystals excluding corner crystals of 5×5 crystal matrix, where N is optimized as a function of the cluster energy and beam background hits. This treatment is in order for the immunity against beam background.

In hadronic events, the mass resolution for $\pi^0 \to \gamma\gamma$ where each γ exceeds 25 MeV is found to be 5.4 MeV/c^2 and $\eta \to \gamma\gamma$ exhibits 11 MeV/c^2 mass resolution when each γ is required to be more than 400 MeV as shown in Fig. 3.

Radiative muon-pair production, $e^+e^- \to \mu^+\mu^-\gamma$ events are also visited and energy and timing resolution are obtained to be 2.2% and 4 ns, respectively, for 1 GeV γ. In CsI(Tl) crystal, time evolution of scintillation depends on the energy deposition density, therefore a difference in CsI(Tl) detector waveform is there between hadronic and electromagnetic interactions, such phenomena is used to an alternative particle identification method, called the pulse shape discrimination [2].
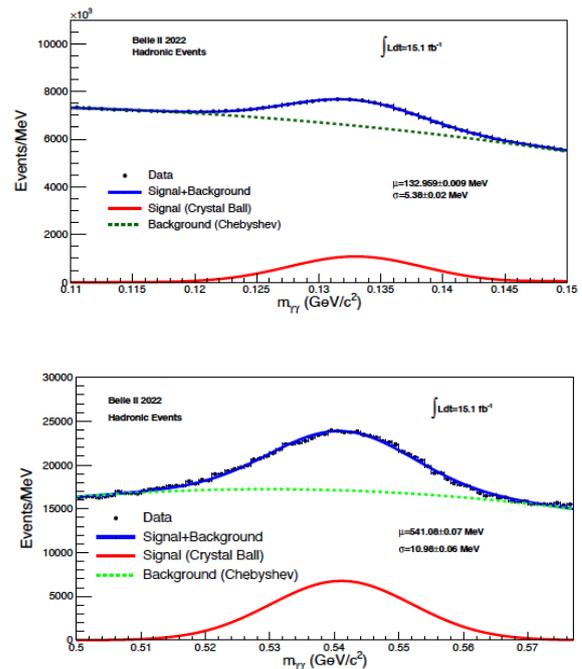

Figure 3. The $\pi^0 \to \gamma\gamma$ (upper) and $\eta \to \gamma\gamma$ (lower) candidates' invariant mass resolutions in the hadronic events recorded by the Belle II detector. $\sigma_{\gamma\gamma}$ =5.4 MeV/c^2 for π^0 and 11 MeV/c^2 for η have been observed.

4 Luminosity monitoring

In e^+e^- colliding beam experiment, measurement of accelerator's luminosity is indispensable. Online luminosity monitoring is done by counting the Bhabha events detected by the endcap calorimeters in Belle II. Each endcap calorimeter is divided into 16 sectors in azimuthal angle ϕ and back-to-back large energy depositions are identified by at most two adjacent endcap sectors. Energy thresholds are set to be 4 GeV at forward endcap and 1.5 GeV for backward endcap. Online luminosity measurement exhibits about 2% systematic discrepancy from offline integrated luminosity determination, it is within possible uncertainty.

5 Summary

The SuperKEKB collider is aiming at 30 times as high as the KEKB luminosity to explore signatures of the physics beyond the Standard Model by performing various measurements and searches by B, charm and τ decays. To satisfy the needs to detect their decays containing γ, π^0, η and so on, the Belle II experiment features the CsI(Tl) electromagnetic calorimeter inherited from Belle experiment with electronics upgrade for high rate capability and beam background immunity. Recently, the COPPER system receiving the output from the frontend electronics has been replaced by the PCIe40 system to ensure sustainable operation. π^0 and η mesons' signatures are seen in hadronic events, where the observed invariant mass resolutions are 5.4 MeV/c^2 and 11 MeV/c^2. Online luminosity monitor is stably functioning, and the measured value is consistent with the offline integrated luminosity determination within the possible uncertainty.

The Belle II electromagnetic calorimeter system has been stably working, and all the 8736 CsI(Tl) counters are still operational. It continues to play an important role to reconstruct neutral particles and constrain missing particles for the physics events created by the e^+e^- collision provided by the SuperKEKB collider.

Acknowledgement

References

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