The energy reconstruction algorithm for high injection background

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Abstract. The SuperKEKB e^+e^- collider is operated with the continuous injection that tops up the beams during colliding beam operation for physics data taking to maximize integrated luminosity. When the beam bunch is injected to the collider ring, there is an unavoidable disturbance by the injected bunch. At the Belle II electromagnetic calorimeter, countermeasure for the injection background using the detector's waveform readout data is being considered. We report its concept and recent development status.

1 Introduction

The SuperKEKB e^+e^- collider and Belle II experiment are the luminosity frontier facilities to explore signatures of physics beyond the Standard Model via decays of $b-$, $c-$hadrons and τ leptons. Electron and positron beams are accelerated by the injector linear accelerator up to the energies of 7 GeV and 4 GeV for the operation at $\Upsilon(4S)$ peak to be stored in the high energy ring (HER) and the low energy ring (LER), respectively. Thus both beams are continuously injected to the two rings via the beam transport (BT) to top up beam currents during colliding beam operation. This feature is especially important to increase integrated luminosity to maximize the sensitivity to probe new physics. Typical one day operation summary plots are shown in Fig. 1, observed on 2024 May 22nd.

Here, in order to let the bunch already stored in its corresponding ring accept the top up injection, we need to activate the kicker magnet to guide the circulating bunch to be smoothly merged with the injected bunch coming in via the BT. This action is indispensable to carry out injection, but there is an unavoidable disturbance on the bunch that receives injection. This disturbance is gradually stabilized because electron or positron bunch in ring accelerator emits photons by synchrotron radiation and it reduces beam emittance down to the nominal value that corresponds to the equilibrium by the ring accelerator's lattice setting. It takes typically a few thousands turns to become stably stored status in the ring, it corresponds to a few tens ms.

Until the injected bunch's motion is stabilized, its passing through the interaction point (IP) causes the background radiation to the Belle II detector system, thus there is data quality deterioration in the events taken under such a circumstance. Therefore the data acquisition is vetoed to avoid such events. Even such a treatment is done, the beam background increase due to the bunch injection influence can still deteriorate the energy reconstruction at the electromagnetic calorimeter. In this report, we describe the countermeasure that is under development.

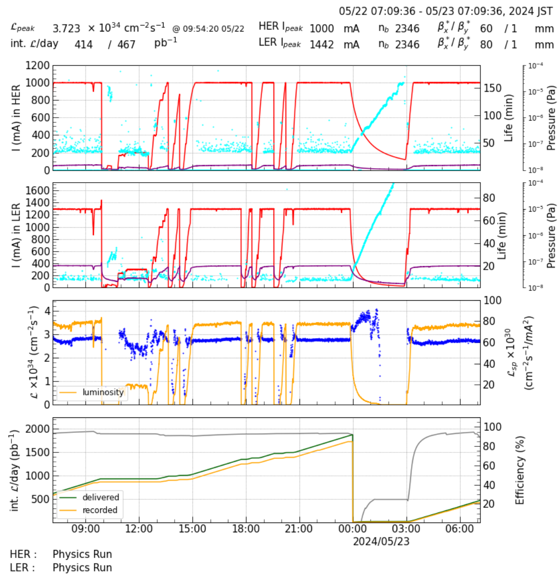

Figure 1. SuperKEKB collider and Belle II detector one day operation summary plots observed on 2024 May 22nd. Top and 2nd top plots are HER (e^-) and LER (e^+) status, respectively. Each beam current is drown by red line (color online), one can see that it is kept constant at 1000 mA (e^-) and 1440 mA (e^+) during stable collision thanks to continuous injection.

2 Timing structure of the beam injection background and electromagnetic calorimeter readout

The electromagnetic calorimeter at Belle II experiment uses in total 8736 CsI(Tl) crystals with PIN-Photodiode readout. A combination of about 1 μs scintillation decay time and shaper time constant of 0.5 μs determines the signal waveform shown in Fig. 2.

In order for proper waveform fitting to get pulse height and timing for each crystal hit, the CsI(Tl) detector signal at the shaper output is fed to 18-bit ADC driven by 1.76

MHz sampling clock. Thirty-one samples and hold data is taken for the shaper output signal and waveform fitting is carried out to obtain energy deposition and timing. It means the timing window to capture detector signal has the width of 17 μs. The digitizer's timing is adjusted to let physics particle incident signal starts from the middle of the timing window, i.e. the first 16 data points are used to calculate pedestal and net signal pulse is captured by the remained 15 points [1], as shown in Fig. 2.

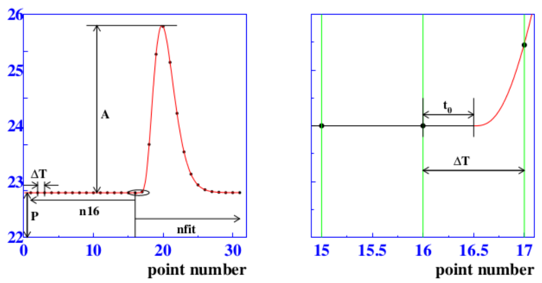

Figure 2. Waveform of the Belle II electromagnetic calorimeter's CsI(Tl) detector. Using 18-bit ADC with 1.76 MHz sampling frequency, 31 sample and hold data points are taken. The first 16 points are used to calculate pedestal and trigger timing is adjusted to capture the net signal in the remained 15 points (left). Magnified view of signal pulse start (right).

The frequency of beam injection to SuperKEKB HER and LER is 50 Hz at most and can be adjusted to 25 Hz, 12.5 Hz or 5 Hz upon the required injection rate to fill or top up. Since HER and LER circumference is approximately 3 km, one turn of the bunch takes 10 μs. Since 1000 ~ 2000 bunches are stored on the HER and LER, bunch crossing interval is a few ns, so the timing of the physics events caused by the e^+e^- collision varies continuously compared to the injected bunch circulation period.

To avoid heavy beam background just after the bunch injection, the data acquisition is fully vetoed for the first 1 ms, then the gated veto is applied to synchronize with the injected bunch's crossing at the IP in Belle II, where veto width is 1 μs~2 μs. The duration of the injection veto is typically 20 ms and it is automatically adjusted by monitoring beam condition. Even if such a treatment is done, still beam injection originated background radiation may cause some extra pulse in the waveform at the CsI(Tl) calorimeter, because its frontend electronics timing window is 17 μs as mentioned above. When it becomes the case, a pedestal shift happens and it results in the bias that reconstructed energy deposition becomes lower than the true one. The influence of this phenomena and idea of the countermeasure is described in the next section.

3 Influence of injection background and countermeasure

We observed decrease of the number of CsI(Tl) crystal hits exceeding 1 MeV for about 20 ms after bunch injection. This is caused by underestimation of the energy deposition in the crystals because of the pedestal shifts. The π^0 signal also exhibits mass peak shifts down to 131 MeV/c^2 at most (it is 134 MeV/c^2 in nominal case) and deteriorated mass resolution up to 8 MeV/c^2 at maximum (nominally ~ 6 MeV/c^2) during 10 ms after injection.

Necessary treatment is handling waveform data to extract net physics particle incident signal pulse height assuming that injection background may coincide within the 17 μs sample and hold readout timing window and to get unbiased pedestal by reducing injection background effects. To figure out an appropriate procedure, a simulation study has been carried out. Electronics noise and pile up from the background radiation by the stored bunches can be generated by a proper assumption. Information about the injection background is taken from the recorded waveform data for the events within 2 ms after injection.

With currently used algorithm to fit the waveform assuming that pedestal data are distributing flat as a function of time and single physics particle incident pulse, mean of reconstructed energy becomes 1.5% lower and its spread gets factor 2.7 wider in 100 MeV deposition case.

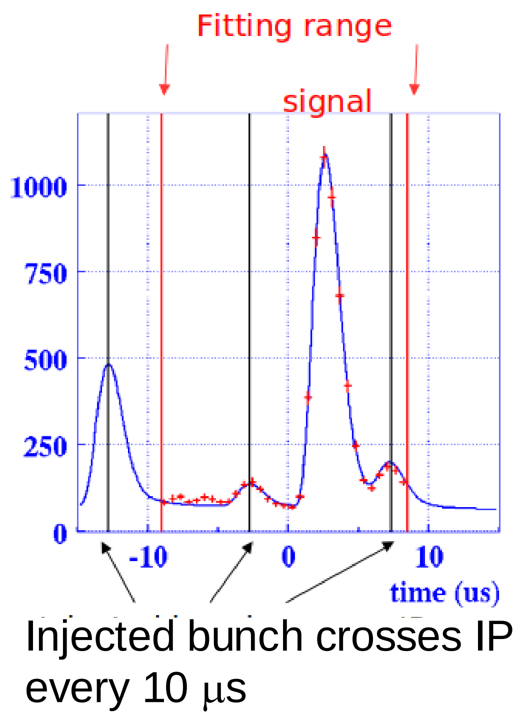

Figure 3. Since the injected bunch influence comes to the detector every turn, its interval is 10 μs. This effect should be properly subtracted to minimize the bias to get pedestal. For this purpose, at most three additional pulses with the fixed interval are taken into account in the function to perform waveform fit.

The injection background can affect the taken waveform at most three turns, thus the fitting function is to be modified to add at most three additional pulses. Pedestal calculation is also changed to fit 16 points before the trigger signal with the function to take pedestal itself and two additional overlapping injection background pulses into account, as shown in Fig.3.

At this stage, the reconstructed pulse height still has a dependence on the difference between the pedestals by the modified signal extraction fit and the pedestal calculation fit, it is found to be possible to correct with a first order polynomial function. By this procedure, we find the reconstructed energy deposition becomes almost same as the one without injection background. Timing resolution for 50 MeV energy deposition is estimated to be 15 ns, slightly worse than the without injection background case, 12.5 ns. Validation of this approach was made by embedding 300 MeV simulated energy deposition into the waveform data of random triggered events without injection veto. Resultant energy shift is found to be controlled within 0.5%.

4 Summary

SuperKEKB e^+e^- collider is operated with continuous injection mode to maximize the delivered integrated luminosity for Belle II experiment. Since it takes several tens ms for the injected bunch to be stabilized down to the nominal emittance in the corresponding ring, HER (e^-) and LER (e^+). The disturbance of the injected bunch gives a periodic background radiation incident for Belle II detector at each turn having 10 μs interval. Modified waveform fitting algorithm for the electromagnetic calorimeter has been proposed and validation by simulation as well as the waveform data of random triggered events with embedding simulated energy deposition. The proposed algorithm is going to be implemented into the FPGA in the frontend electronics.

Acknowledgement

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References

[1] T. Abe *et al.* (Belle II collaboration), *Belle II Technical Design Report* KEK-REPORT-2010-1, KEK, 2010.