Belle Electromagnetic Calorimeter and its sBelle Upgrade
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Abstract. Electromagnetic calorimeter for the Belle experiment on KEKB asymmetric e⁺e⁻ collider is being operated successfully for 9 years. In this presentation, systems and operation of the calorimeter are described. The Belle detector will be upgraded to cope with higher luminosity running of KEKB collider aiming for accumulating 10 ab⁻¹. In this talk, a plan of electromagnetic calorimeter upgrade will also be shown.

1. Belle Calorimeter
The Belle experiment is for detailed measurement of B meson properties using the asymmetric e⁺e⁻ collider, KEKB operated at Υ(4S) resonance. The Belle detector[1] is a general purpose detector consists of tracking devices, Čerenkov detector and calorimeter placed inside the 1.5 T solenoidal magnetic field surrounded by muon detector instrumented in the iron yoke. The main purpose of the electromagnetic calorimeter is to detect γ and π₀ from B meson decay. Energy of such γ ranges from MeV to GeV. Energy resolution is very important because for some analyses one has to separate signal and background events only with mass distribution. To separate two photons from high momentum π₀, fine granularity is required. Hermeticity is also very important to study final states with neutrino. The Belle electromagnetic calorimeter consists of 8736 CsI(Tl) crystals with typical dimension of 6×6×30 cm³. The length corresponds to about 16 X₀. Figure 1 shows the schematic view of the calorimeter. The calorimeter has pointing geometry and covers polar angle from 12° to 155°. The scintillation light of the CsI(Tl) crystal has λ = 560 nm with rather slow decay constant of 1.3 μsec but abundant light output of about 50000 p.e./MeV. The light is read out by two independent sets of silicon PIN photodiodes[2] with sensitive area of 10×20 mm² connected to charge sensitive preamplifier. The signals are sent to the front-end electronics with cable of typically 10m long. Two signals from preamplifiers are first added and then processed with two shaper with 0.3(fast) and 1μsec(slow) shaping time. The fast signal are used to generate trigger signal while the slow signal is then sent to LeCroy MQT300A charge-to-time converter. The MQT converts 3 range/12 bit charge information into 15 bit timing information which corresponds to 18 bit dynamic range. The time encoded energy information is then recorded with LeCroy 1877S Fastbus TDC. The readout system consists of about 100 TDC boards in five crates read out by three VME systems. It takes about 30 μsec to read out one physics event. The trigger rate is about 300 Hz with instantaneous luminosity of 10³⁴ cm⁻²sec⁻¹, which corresponds to about 1% readout deadtime. Although the signal is recorded with TDC, only energy is recorded. No event timing information is available.
2. Operation
Calorimeter energy is reconstructed from the TDC count \( T \) as

\[
E = C \cdot G(T - T_0),
\]

(1)

where \( C, G \) and \( T_0 \) are time-to-energy conversion factor, electronics gain constant and pedestal, respectively. The gains and pedestals are monitored by dedicated calibration runs performed every morning. Calibration circuit is implemented in the frontend board so that test pulse can be injected to the preamplifiers. The conversion factor \( C \) is calibrated using bhabha events collected in typically one month period by minimizing chi squared defined as,

\[
\chi^2 = \sum \frac{(E_{\text{exp}} - \sum_i \text{cls} C_i \cdot E_i)^2}{\sigma^2},
\]

where \( E_{\text{exp}} \) is energy expected from the direction obtained from the track associated to the cluster, \( C_i \) is the conversion factor in equation 1, \( E_i \) is the energy measured in one crystal and \( \sigma \) is resolution. The sum runs all bhabha events. Taking derivatives of the \( \chi^2 \) by each eight thousand \( C_i \)s, minimization of \( \chi^2 \) turns to the inversion of large 8000×8000 sparse matrix. Since tracking is not available in the very forward and backward regions, channels in those regions are calibrated with cosmic muon events which deposit mip signal to the counter.

To keep good performance it is important to keep environment stable. For this purpose, temperature and humidity are controlled by circulating water and dry air in the detector. Environment of the calorimeter is monitored by 312 temperature probes and 104 humidity probes. The bias current, temperature and current of power supplies are monitored and logged by every a few minutes, and are watched by safety shifters during operation.

3. Problems
3.1. Radiation Damage
Radiation damage is serious issue for experiments with high intensity accelerators. Radiation damages of crystals and photodiodes due to \( \gamma \) rays had been tested before the start of the experiment up to dose of several krad. However unexpected increase of dark current has been observed in the forward and backward regions of calorimeter. Figure 2 shows the dark current of the photodiode in barrel and forward endcap as a function of days after beginning of experiment. Dark current increase in the forward region is more than 100 nA while only several nA increase is observed in the barrel. Since the beams cross every several nsec, signal

![Figure 1. (Left) The Belle Electromagnetic Calorimeter. (Right) A counter.](image-url)
from beam induced $\gamma$ become continuous current. Thus, $\gamma$ ray does of the calorimeter can be measured by integrating the current in the photodiode in the following relation.

$$\int (I_{on} - I_{off}) dt \sim \int E_{\gamma} dt,$$

where $I_{on}$ and $I_{off}$ are bias current with beam on and off, respectively. According to this evaluation $\gamma$ ray dose in the forward endcap is estimated to be $\mathcal{O}(100)$ rad. If we translate the 100 nA increase of dark current using the radiation damage test using $^{60}$Co performed before experiment, it corresponds to $\mathcal{O}(100)$ krad, that is 1000 times too high.

On the other hand it turned out that neutron background is rather high. Either spent electrons or $\gamma$s from radiative bhabha hit accelerator element near the detector and back scattered neutron reach detector. Since radiation damage by neutrons have not been considered seriously, series of neutron radiation test ware performed for both crystals and photodiodes using the reactor 生 (YOYOI)[3]. Figure 3 shows the dark current increase as a function of neutron fluence. According to the result the neutron fluence at forward endcap is estimated to be $10^{11}$/cm$^2$, that is consistent with independent estimation by simulation. It is also confirmed that the crystals and photodiodes can be used up to $10^{13}$/cm$^2$ that is enough for future upgrade of KEKB accelerator[4].

![Figure 2. Dark current in barral(Left) and foward endcap(Right) as functions of time after beginning of experiment.](image)

### 3.2. Accelerator background

As the beam current increase, $\gamma$s from accelerator background become visible. These background photons are studied in the random triggered events. Figure 4 show the sum of energies measured in the calorimeter as functions of total beam current. In the top figure energies are summed for all cells(crystals) with energy larger than 0.5 MeV while the bottom is for the sum of cluster energy. In the recent high current running, each event has roughly 2–3000 hit cells with $E > 0.5$ MeV, total energy of 3 GeV from background photons. This is quite large as the beam energy of KEKB detector is 11.5(8+3.5) GeV. After applying clustering algorithm the effect is reduced to several background clusters and 500 MeV additional energy. Beam background produce not only additional clusters but also overlap to the clusters by the physics
events. The effect is illustrated in the Figure 4(Right). The Figure shows the additional energy caused by the background photons as a function of theta index of calorimeter with typical beam condition with luminosity of $10^{34} \text{cm}^{-1} \text{sec}^{-1}$. One can see that each cluster has about 0.5 MeV additional energy in barrel and it increase in the endcaps to 1 MeV.

In the physics analysis, these background makes additional fake photons, shifts energy scales and deteriorate energy resolution. Photon reconstruction efficiency is also degraded because the background hits change cluster shapes that is used to identify low energy photons.

The above effect is roughly proportional to product of beam current and vacuum pressure. Since the vacuum is also proportional to current, background increase as current squared. We assume that the background level at the upgraded KEKB, which can provide luminosity of several $\times 10^{35} \text{cm}^{-1} \text{sec}^{-1}$ with stored current of 13 A, becomes 20 times higher than current situation.

Figure 4. (Left) Total energy observed in random triggered events as functions of total stored current. (Right) Average additional energy in physics cluster due to background as a function of theta index of calorimeter.
4. Upgrade Plan

With very successful operation of the KEKB accelerator and the Belle experiment, integrated luminosity recorded is approaching to 1 ab$^{-1}$. Now it is planned to improve further KEKB accelerator aiming at instantaneous luminosity of $8 \times 10^{35}$ cm$^{-2}$sec$^{-1}$[4]. With that luminosity 10 ab$^{-1}$ can be accumulated in several years. To achieve the luminosity beam current will be increased to more than 13 A. With such high current, background from accelerator will be 20 times higher than now and the trigger rate will be as high as 10 kHz. Current detector is not sufficient to be operated in the condition. For example, the dead time at 10 kHz is 30%. To cope with upgraded accelerator, calorimeter will also be upgraded.

To discriminate background events from physics events, timing information is useful. In order to record time stamps and eliminate readout deadtime, waveform is sampled with pipelined readout system. In the new readout electronics, the signals are shaped with shorter shaping time of 0.5 $\mu$sec and sampled by 18 bit ADC with 2 MHz frequency. The waveform is stored in pipe of 128 deep waiting for trigger. After trigger is initiated, 16 samples of waveform is fitted to extract timing and amplitude. With new electronics introduced, it is expected to obtain factor 7 reduction of background. Figure 5 shows expected timing distribution with new electronics obtained by simulation.

In the forward and backward regions where background is severe, replacement of current CsI(Tl) crystal to faster undoped CsI crystals are planned. Undoped CsI crystal has time constant of 10–30 ns which is much faster than that of CsI(Tl), though the light output is one tenth. To cope with small light output and 310 nm wavelength, photomultiplier(PMT) will be used for photodetection. The PMT has only three multiplication stages to make length short in order to fit in the current crystal containers and has finemesh structure to maintain gain of $\sim 50$ in the 1.5 Tesla magnetic field. The signal from the PMT will be read out with 42 MHz sampling. With all these improvement more than 100 times background rejection can be achieved.

![Figure 5. Expected timing distribution with new electronics.](image)

References
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[2] S2744-08, Hamamatsu Photonics, KK
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[4] SuperKEKB Letter of Intent, KEK Report 04-4