Electromagnetic calorimeter of the Belle II detector

B. Shwartz, on behalf of BELLE II calorimeter group
Budker Institute of Nuclear Physics Novosibirsk 630090, Russia
Novosibirsk State University, Novosibirsk 630090, Russia
E-mail: shwartz@inp.nsk.su

Abstract.
At present new SuperKEKB collider is under commissioning at KEK (Japan) while the Belle II detector for experiments at this collider is at the final stage of the construction. The luminosity of this collider will exceed the previous one by about 40 times, amounting to $8 \times 10^{35}$ cm$^{-2}$s$^{-1}$. The electromagnetic calorimeter is a very important component of the BELLE II detector. This calorimeter is described in this report.

1. Introduction
An energy-asymmetric $e^+e^-$ collider, SuperKEKB, is under commissioning now at KEK (Japan) [1]. The luminosity of this collider will exceed the previously achieved by KEKB [2] by about 40 times, amounting to $8 \times 10^{35}$ cm$^{-2}$s$^{-1}$. New experiments with the Belle II detector in the center-of-mass (CMS) energy range within $\Upsilon$-meson family (9 – 11.5 GeV) will continue and widen the studies that began by the previous experiments. However, high luminosity which requires high circulation beam currents is unavoidably accompanied by the high event rate and background. Then the detector should be drastically upgraded. Schematic view of the Belle II detector is presented in Fig. 1.

The Belle II detector contains new vertex detector, central drift chamber and particle identification system. The $K_L$-meson and muon identification subsystem (KLM) is partially upgraded. The ECL scintillation crystals and mechanical structure of the electromagnetic crystal calorimeter (ECL) is kept unchanged from the previous experiment. The calorimeter is based on CsI(Tl) crystals which provide highest energy resolution for medium energy photons and widely used in the experiments on particle physics [3, 4, 5].

The first priority of the ECL upgrade is the calorimeter electronics modification following the general strategy of the Belle upgrade. The main idea is to shorten the shaping time from 1 $\mu$sec to 0.5 $\mu$sec and to use a pipe-line readout with waveform analysis. An option for later stage of the replacement of the part or all CsI(Tl) crystals in the end caps to pure CsI crystals with much shorter scintillation decay time is under development.

2. Design and properties of the Belle II electromagnetic calorimeter (ECL)
The electromagnetic calorimeter includes of a 3 m long barrel section with an inner radius of 1.25 m and the annular endcaps at $z = 2.0$ m (Forward part) and $z = -1.0$ m (Backward part) from the interaction point. The calorimeter covers the polar angle region of $12.4^\circ < \theta < 155.1^\circ$ except two gaps ~ $1^\circ$ wide between the barrel and endcaps. The barrel part has a tower structure projected to the vicinity of the interaction point. It contains 6624 CsI(Tl) elements of 29 types.
Each crystal is a truncated pyramid of the average size about $6 \times 6$ cm$^2$ in cross section and 30 cm (16.2$X_0$) in length. The endcaps contain altogether 2112 CsI crystals of 69 types. The total number of the crystals is 8736 with a total mass of about 43 tons.

Each crystal is wrapped with a layer of 200 $\mu$m thick Gore-Tex porous teflon and covered by the 50 $\mu$m thick aluminized polyethylene. For light readout two $10 \times 20$ mm$^2$ Hamamatsu S2744-08 photodiodes are glued to the rear surface of the crystal and connected to the attached preamplifiers. The average output signal of the crystal measured in a calibration run with cosmic rays is about 5000 photoelectrons per 1 MeV while the noise level is equal to about 200 keV. The energy resolution for photons, $\sigma_E/E$, slightly changed from about 2.5% at 100 MeV to 1.7% at 5 GeV. Detail description of the Belle ECL and its performance in the previous experiments can be found in [6].

3. ECL performance in a high background environment
Electron and positron beam currents in the SuperKEKB collider will have to be up to 3–4 A to achieve the project luminosity. This inevitably results in much higher background in comparison with previous experiment.

An obvious concern is about a radiation induced degradation of the parameters of scintillation crystals. The main effect of the degradation is caused by low energy gamma flux. The measured integrated dose absorbed by Belle ECL crystals at integrated luminosity 1000 fb$^{-1}$ is about 100 rad for the barrel part and about 500 rad in the most loaded part of the endcaps. The light output of the crystals is around 7% in the barrel and up to 13% in the endcap parts close to the beam pipe. These results are in a good agreement with previous measurements of the crystal radiation hardness [7]. Since these studies showed the loss of the light output to be less or about 30% at 3.6 krad, an increase of the absorbed dose by one order of magnitude will not provide serious problems. According to simulation the absorbed dose at CsI(Tl) crystals

Figure 1. Schematic view of the Belle II detector.
at Belle II will be below 500 rad per year or less than 5 krad for five years. A simulation of
the radiation background at Belle II detector shows the neutron component with the flux up
to $2 \times 10^{10}/(\text{year} \cdot \text{cm}^2)$ in the forward endcap. Such a background does not induce considerable
effect for crystals but causes an increase of the dark current of photodiodes. However, the dark
current induced by the expected neutron flux will be still below 1 $\mu$A and corresponding noise
contribution should be below 1 MeV, still much smaller than pile-up noise.

High-energy photon part of the background appears as random clusters in the calorimeter
which can overlap with the triggered events. At the Belle experiment each event contained in
average 6 background clusters (3 in barrel and 3 in the both endcaps) of the energy exceeding
20 MeV. We expect that the background cluster rate at Belle II will not be higher due to much
better time resolution of the upgraded ECL electronics.

Soft background photons with average energy of about 1 MeV and high rate overlap with
signal pulses producing so called pile-up noise. The fluctuation of the number of these photons
coming during the integration time contributes to the total noise level. According to the
background simulation the pile-up noise level at the Belle II ECL will be from 3 to 8 MeV
even with upgraded electronics which deteriorates considerably the energy resolution for the
photons of the energy below 300 MeV.

4. Readout electronics of the Belle II calorimeter

The ECL readout electronics channel includes Shaper-Digital Signal Processor (Shaper-DSP)
and Collector modules. Shaper-DSP boards contain 16 channels per module. Each channel
consists of a shaping amplifier CR-(RC)$^4$ (τ = 0.5µs) and 18-bit flash ADC (Analog Devices
AD7641) which digitizes the signal with 2 MHz clock frequency. The ADC data are read out
by the digital processor realized in the XILINX FPGA. Initiated by the trigger pulse, 16 points
within the signal are fit to the signal shape function $F(t)$: $F(t) = A_0 \times f(t - t_0)$ where $A_0$ is a
pulse height and $t_0$ is an event time.

The data from the Shaper-DSP, pulse height and pulse time, are sent to the Collector module
which packs the data of 8-12 Shaper-DSP modules and sends this via ROCKET-I/O line to
COPPER FINNESSE module of Belle II DAQ. The collector module contains also a test pulse
generator for the calibration of the response of each channel. Each Shaper-DSP module generates
also a fast analog pulse which is a sum of gain-corrected fast shaped (τ$_d$ = 0.2 µs) signals from
all 16 channels corresponding to 4x4 crystals Trigger Cell (TC). Detail description of the new
ECL electronics can be found in [8, 1].

By now all 576 Shaper-DSP modules as well as all Collectors have been produced and tested.
All tested modules showed the proper characteristics. All barrel counters are connected to DAQ
and tested with cosmic rays.

5. Development of the pure CsI option

As mentioned earlier even after ECL electronics upgrade the pile-up noise expectation is up to
8 MeV in the backward endcap. The drastic way to improve ECL characteristics is a replacement
of slow CsI(Tl) crystals with faster ones, at least in the end cap parts of the calorimeter. Then the
natural option is to use pure CsI crystals of the same shape and size as the presently used CsI(Tl)
counters. The advantages of this crystal are a short scintillation decay time, 30ns, and moderate
cost in comparison to other fast scintillation crystals. Since physical properties of the pure CsI
are the same as CsI(Tl) the present sizes of the calorimeter element as well as the mechanical
structure can be kept. However, the light output of pure CsI crystals is approximately ten times
lower than that of doped crystals. Then one needs to use photo detectors with internal gain.
Proposed solution is to use vacuum photopenthodes (PP), i.e. PM tubes with three dynodes.
Since pure CsI emission wavelength is about 300 nm the photosensor should be UV sensitive.
Such a device of 2-inch diameter with a low output capacity $C \approx 10$ pF has been recently developed.
by the Hamamatsu Photonics. The low capacity is important since the noise level depends on this value. The new developed PP have a quantum efficiency of about 20-25% and internal gain factor of 120-200 at zero magnetic field which reduces by factor 3.5 times for the B=1.5 T.

In the tests with the counter we obtained the signal of about $2 \times 10^4$ electrons per 1 MeV (without magnetic field) and the noise of about 900 electrons. These results can be extrapolated to the 1.5 T magnetic field as 6000 e/MeV and 200 keV of the noise energy equivalent. The beam test with 20 pure CsI crystals was carried out at BINP photon beam [9]. Measured energy resolution ($\sigma_E/E \approx 2.5\%$ in the energy range 70-150 MeV) is consistent with the CsI(Tl) ECL energy resolution [10] and MC predictions. The time resolution better than 1 ns for energy more than 20 MeV has been obtained. The alternative method of the scintillation light readout using silicon avalanche photodiodes (APD) is under study as well. Recently very promising results were obtained [11]: the electronics noise level was measured better than 0.5 MeV when a readout with wavelength shifter bar and four APDs were used.

We performed a study of radiation hardness of the full size pure CsI crystals produced in Kharkov (Ukraina) [12, 13]. It was found that all the crystals which satisfy the requirements on the light output and fast/total ratio lose less than 20% of the light output after irradiation by the 14.3 krad of absorbed dose. This applied dose is well above the expectation for the Belle II after ten years of running.

6. Conclusion and Acknowledgments

- New electronics modules of the Belle II electromagnetic calorimeter are produced and tested. The barrel calorimeter is completely connected to the electronics and tested with cosmic rays. All channels shows proper parameters.

- R&D works on the endcap calorimeter based on pure CsI counters with modified electronics is going on. This modification should provide drastic suppression both pile-up noise as fake clusters rate in the endcaps.

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