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Electromagnetic calorimeter of the Belle II detector

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The electromagnetic calorimeter of the BELLE II detector for experiments at Super B-factory SuperKEKB is described. This calorimeter based on the CsI(Tl) scintillation crystals inherited all crystals, mechanical structure, PIN diodes for light readout and preamplifiers from the previous Belle experiment. But new signal processing and DAQ electronics were developed and produced. An option with fast pure CsI crystals in end caps is under depelopment now. This is discussed in this report as well.

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1. Introduction

The KEKB B-factory [1], energy-asymmetric collider with world highest luminosity, $2 \times 10^{34}\text{cm}^{-2}\text{s}^{-1}$, was in operation from 1999 until 2010. Experiments with the Belle detector [2] in the energy range of 10-11 GeV collected an integrated luminosity exceeding 1000 fb^{-1}. This huge data sample provided a number of important results concerning the CP symmetry violation in the quark sector, heavy quarkonium spectroscopy, tau lepton decays and two-photon physics.

Due to the large photon and neutral pions multiplicity in the studied energy range high energy resolution and detection efficiency for photons are very important. The Belle electromagnetic calorimeter (ECL) based on CsI(Tl) scintillation crystals well satisfies to these conditions. During more than 10 years of operation electromagnetic crystal calorimeter (ECL) of the Belle detector demonstrated its high quality and good performance [3].

At present new SuperKEKB collider and Belle II detector are under construction at KEK [4]. This new experiment will continue and widen the studies began at the previous experiments. The luminosity of this collider will exceed the previous one by about 40 times, amounting to $8 \times 10^{35}\text{cm}^{-2}\text{s}^{-1}$. However, high luminosity is unavoidably accompanied by the high event rate and background. Then the detector should be drastically upgraded. Schematic view of the Belle II detector (top half) in comparison to the previous Belle detector (bottom half) is presented in Fig. 1. The vertex detector, central drift chamber and particle identification sytem will be replaced by

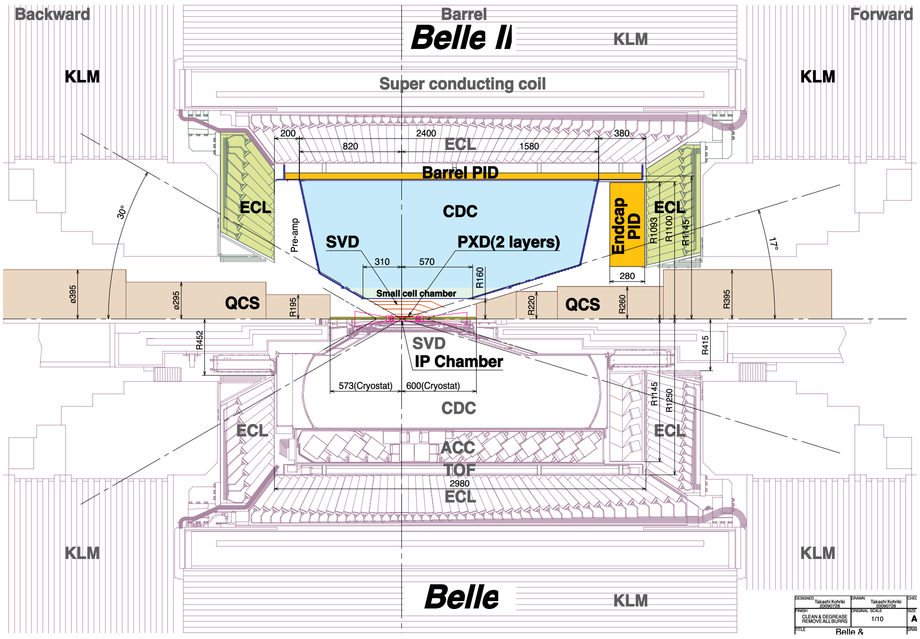

Figure 1: Schematic view of the Belle II detector (top half) in comparison to the previous Belle detector (bottom half).

the completely new ones. The KLM will be partially upgraded. The ECL scintillation crystals and mechanical structure is kept from the previous experiments. The first priority of the electromagnetic crystal calorimeter (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 μsec to 0.5 μsec and to use a pipe-line readout with waveform analysis.

2. Electromagnetic crystal calorimeter (ECL) of the Belle/Belle II detector

The electromagnetic calorimeter (ECL) consists 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 $\sim 1^\circ$ 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 6×6 cm^2 in cross section and 30 cm ($16.2X_0$) 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 μm thick Gore-Tex porous teflon and covered by the 50 μm thick aluminized polyethylene. For light readout two $10 \times 20\,\mathrm{mm}^2$ Hamamatsu S2744-08 photodiodes are glued to the rear surface of the crystal via an intervening 1 mm thick acrylite plate. The LED attached to the plate can inject the light pulses to the crystal volume to control the optical condition stability. A preamplifier is attached to each photodiode providing two independent output lines from each crystal. These two pulses are summed at the shaper board. For the electronics channel control the test pulses are fed to the inputs of the preamplifier. The average output signal of the crystals measured by calibration with cosmic rays is about 5000 photoelectrons per 1 MeV while a noise level is equal to about 200 keV. The energy resolution for photons, σ_E/E, slightly changed from about 2.5% at 100 MeV to 1.7% at 5 GeV.

3. ECL performance in a high background environment

To acieve the project luminosity the KEKB collider will operate wth the electron and positron beam currents up to 3–4 A that inevitably results in much higher background in comparison with previous experiment. Let us consider effects which can be caused by such a high background.

An obvious concern is a probable radiation induced degradation of the scintillation crystal parameters. 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 [5]. Since these studies show 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. The results of the background simulation for the Belle II are shown in the Table 1.

Table 1: Beam background simulation results.

	Forward	Barrel	Backward
Crystal radiation dose (Gr/year)	3.0	0.8	4.5
Crystal neutron flux ($\times 10^9$/(year$\times$cm^2))	23	5	14
Diode neutron flux ($\times 10^9$/(year$\times$cm^2))	23	5	15
Pileup Noise (MeV)	4.3	3.1	8.2

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The neutron component of the radiation background causes an increase of the dark current of photodiodes. At present the increase of the dark current in the barrel part is not substantial, less than 10 nA, while it is noticable in the endcap calorimeter – up to 200 nA. However, the dark current induced by the expected neutron flux will be still below 1 μA and corresponding noise contribution should be below 1 MeV, still not much smaller than pile-up noise.

Most serious effect due to high background is so called pile-up noise caused by the soft background photons with average energy of about 1 $\lesssim$ MeV. The fluctuation of the number of these photons coming during the integration time contributes to the total noise level. The noise level, σ, measured at the luminosity of $L = 10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ at the Belle experiment already approaches to 1 MeV in the end caps that substantially exceeds the electronics noise (0.2-0.3 MeV). As seen in Table 1 the calculated pile-up noise at the Belle II ECL is from 3 to 8 MeV even with upgraded electronics.

High-energy background photon produces random clusters in the calorimeter. 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.

4. New ECL electronics

At least at the first years of the Belle-II experiment, all CsI(Tl) crystals, both in the barrel and endcaps connected to PIN photodiodes and preamplifiers as well as the cables transmitting signals to the shaper will be used. However, following analog, digitizing and DAQ electronics will be replaced.

A block diagram of the new ECL electronics is presented in Fig. 2. New shaper-digitizer

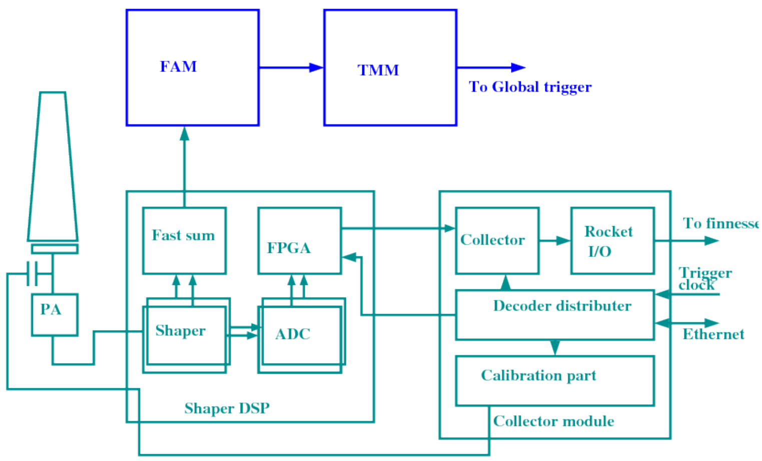

Figure 2: Block diagram of ECL electronics to read out CsI(Tl) crystals at Belle-II experiment.

boards contain 16 channels per module. Each channel consists of a shaping amplifier CR-(RC)^4 ($\tau_s = 0.5\mu$s) 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 signal shape function, $f(t)$, is evaluated from separate measurements. Both amplitude (A_0) and time (t_0) are obtained by the on-line shape fit:

$$\chi^2 = \sum_{i,j} (A_i - F(t_i)) S^{-1}_{ij} (A_j - F(t_j)), \tag{4.1}$$

where A_i is an amplitude at the time t_i and S_{ij} - covariance matrix.

The data from the Shaper-DSP 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 ($\tau_d = 0.2\,\mu$s) signals from all 16 channels corresponding to 4x4 crystals Trigger Cell (TC). This signal is delivered to the FAM (Flash-ADC trigger Module) which produces a TC signal if the input pulse exceeds a threshold ($\sim$ 100 MeV). These TC signals are collected and processed by the TMM (Trigger and Monitoring Module) where ECL subtrigger arguments are formed and sent to GDL (global Desicion Logic) module. Shaper-DSP modules as well as collector and FAM modules are placed in the VME crates on the detector while COPPER FINNESSE modules are installed in the electronics hut.

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. Pure CsI option for the endcaps

As seen from the Table 1 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 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. Properties of pure CsI in comparison with CsI(Tl) scintillation crystals are listed in the Table 2.

Table 2: Properties of pure CsI and CsI(Tl) scintillation crystals

	ρ, g/cm^3	X_0,cm	λ_{em}, nm	$n(\lambda_{em})$	N_{ph}/MeV	τ_d, ns	dL/dT, %/° (20°C)
pCsI	4.51	1.85	305	2.0	2000-5000	20/1000	- 1.3
CsI(Tl)	4.51	1.85	550	1.8	52000	1000	0.4

As seen in the Table 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. A suitable 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≈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 (see Fig. 3).

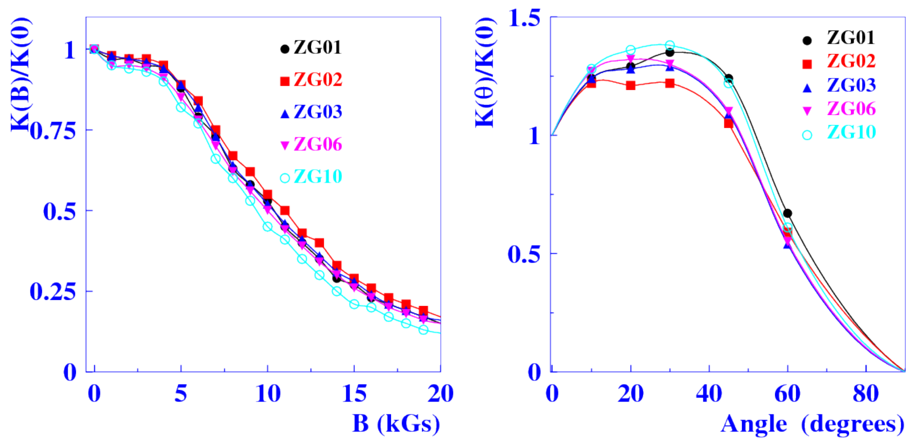

Figure 3: The photopenthode gain in dependence on the magnetic field and the angle device axis to the field direction for the five devices.

It is proposed to keep the same general scheme of the electronics channel as for the barrel part (see Section 4). Each channel includes a differential receiver, CR-(RC)^4 shaper with shaping time $\tau = 30$ ns and two 14-bits fast flash ADCs. Usage of two ADCs allows to have effective 18-bit digitization for a full dynamical range. Digitization of the signals from the shaper outputs will be performed under the control of the common clock of 43 MHz. The digitized data are processing in FPGA to obtain the amplitude(A_0), time(t_0) and quality bits(Q) for each hit.

In the tests with the counter and electronics prototypes we obtained the signal of about $2 \cdot 10^4$ 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.

Shorter scintillation decay time with matched shorter shaping time of the electronics channel allows to suppress the pile-up noise by a factor of about 5 in comparison to the present end cap parts of the calorimeter. The fake photon rate is suppressed by a factor of more than 100 due to a good timing providing by the mentioned scheme.

We performed a study of radiation hardness of the full size pure CsI crystals produced in Kharkov (Ukraina) [6]. In these study five samples were irradiated by the wide gamma beam with the average energy of about 1 MeV generated by the 1.5 MeV electron accelerator ELV-6 at BINP. Four of these samples were found to satisfy the super B-factory conditions. The light output reduction for them does not exceed 15% at 13krad of absorbed dose. One sample had poor radiation resistance.

The beam test with 20 pure CsI crystals coupled with PP and prototypr electronics was carried out at BINP photon beam [7]. The photon beam was produced by the Compton back scattering of the laser photons by the high energy electron beam circulating in the VEPP-4M storage ring.

Measured energy resolution ($\sigma_E/E \approx$2.5% in the nergy range 70-150 MeV) is consistent with the CsI(Tl) ECL energy resolution [8] 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 avalanch photodiodes (APD) is under study as well. Very promising results of these studies are described by D.Epifanov's in his talk at this conferece [9].

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.

I would like to thank organizers for inviting me to this very interesting and well organized Conference.

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