Upgrade of the electromagnetic calorimeter for Belle-II

A.Kuzmin[*†]
BINP
E-mail: a.s.kuzmin@inp.nsk.su

At the present time an upgrade of the KEKB e^+e^- collider and Belle2 detector is going on at KEK to prepare a new experiment with high luminosity up to 8×10^{35} cm^{-2}s^{-1}. We report an upgrade of the electromagnetic calorimeter which will provide good energy and time resolution in a high background environment. The Belle calorimeter is based on 8736 CsI(Tl) crystals with light readout using PIN diodes. The calorimeter thickness is 16.1 X_0. The electronics is modified to shorten shaping time to 0.5 mks and provide pipeline readout of ECL information with further analysis of wave shape of readout data in FPGA. An algorithm of wave shape analysis reconstructs the amplitude and time of the signal. The second stage of the upgrade includes a replacement of endcap counters with pure CsI crystals. Measurements with new electronics and results obtained with a prototype are presented.

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[*] Speaker.
[†] For ECL team of the Belle-II collaboration.

1. Introducton

The Belle experiment was carried out in 1999-2010 at KEK. The Belle detector was operated at the KEKB e^+e^- accelerator complex in which 3.5 GeV positrons collided with 8 GeV electrons providing the world highest luminosity of 2.1×10^{34} cm^{-2}s^{-1}. The Belle experiment was providing a lot of interesting physical results for 10 years. To keep being at the frontier of physics an upgrade of both collider and detector is carried out.

The electromagnetic calorimeter of the Belle [1] detector consists of the barrel part and two endcaps and includes 8736 CsI(Tl) crystals of 30 cm length which corresponds to 16.1 X_0. Light from each crystal is detected by two silicon photodiodes of 2 cm^2 which are connected with two preamplifiers mounted on the crystal. During 10 years of operation the calorimeter had demonstrated high performance.

The KEKB upgrade plan implies the luminosity increase up to more than 8×10^{35} cm^{-2}s^{-1}[2]. High electron and positron beam currents will unavoidably cause an increase of the background especially in the endcap regions. To keep good performance the upgrade of all the detector systems is necessary. The high background can cause both radiation damage of the detector components and degradation of the calorimeter performance.

The radiation dose accumulated in the crystals during 10 years is about 100 rad in the barrel and more than 350 rad in the endcaps. Assuming the background for the new collider will be 20 times larger, we expect up to 7 krad in the inner endcaps for the new calorimeter. Thus, the new counters should survive such a dose.

Neutron radiation leads to the increase of the dark current of the PIN diodes. In the barrel region the dark current increase is about 6 nA while in the inner endcap region it is 200 nA, so these photodetectors should be modified.

Background photons are produced by the lost beam electrons interacting in the accelerator and detector material. Photons with relatively high energy (of more than 20 MeV) give fake clusters. For a luminosity of 10^{34} $cm^{-2}s^{-1}$ the number of fake clusters is about 6 per event. The energy deposition from the very soft photons overlaps with a real photon signal resulting in the pile-up noise. At the present calorimeter the pile-up noise is larger than the electronics noise and is about 400 keV in the barrel and about 800 keV in the inner endcap.

To keep calorimeter performance we perform the following upgrade [2]. The barrel part crystals with preamplifiers are kept without change but their shaping electronics is modified. The shaping time is reduced twice down to $0.5\mu s$ and the wave form analysis(WFA) will be performed to reconstruct both the amplitude and time information from the counter. The shorter shaping time together with WFA analysis allows to reduce the pile-up noise factor by 1.5-2 times. Applying the time cut for the high energy photons we reduce the fake cluster rate by a factor of 7.

For the end cap, where the background environment is more severe, at the second stage of upgrade we are going to replace the CsI(Tl) with pure CsI crystals which have about 30 ns decay time. For the light readout the vacuum photopentrodes are going to be used. The electronics will include the fast shaper (τ =30 ns) with the subsequent WFA. Such a scheme allows to have the pile-up noise of about 600 keV and suppress the fake cluster rate by a factor of 200.

2. Electronics modification

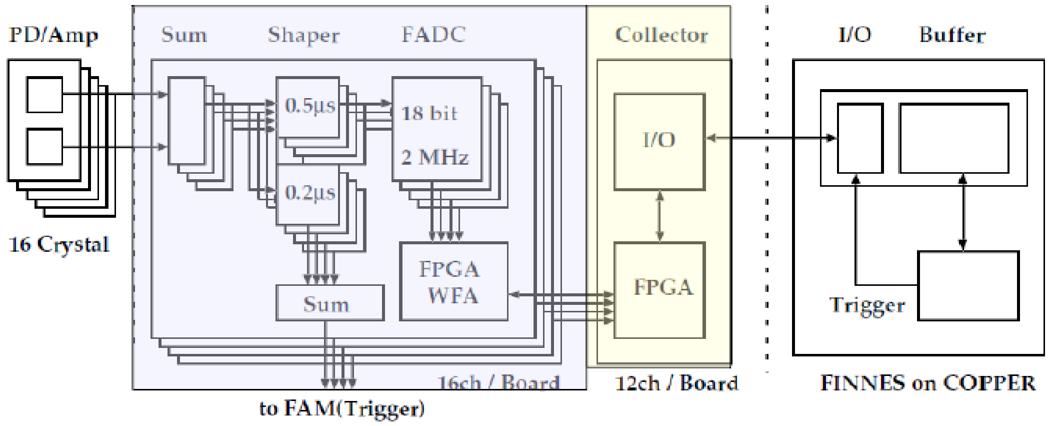

Figure 1: Scheme of Belle II calorimeter electronics.

In Figure 1 the scheme of the new calorimeter electronics is shown. The main electronics module is a ShaperDSP which provides: sum of signals from two preamlifiers of each counter; shaping with time of 500 ns; digitizing the shaped signal with about 2 Msps/sec rate at 18-bits ADC and processing the digitized data in FPGA. The amplitudes and times of the signals reconstructed in FPGA are readout by the Collector module and are sent to Belle II DAQ system. The collector module serves 12 ShaperDSP modules installed in one 9U VME crate. One ShaperDSP module contains 16 channels. Together with each signal digitization, the ShaperDSP forms a fast signal with a sum of 16 channels for neutral trigger. The module provides a possibility to vary the attenuation of each of the summed signals to have the same threshold in energy units.

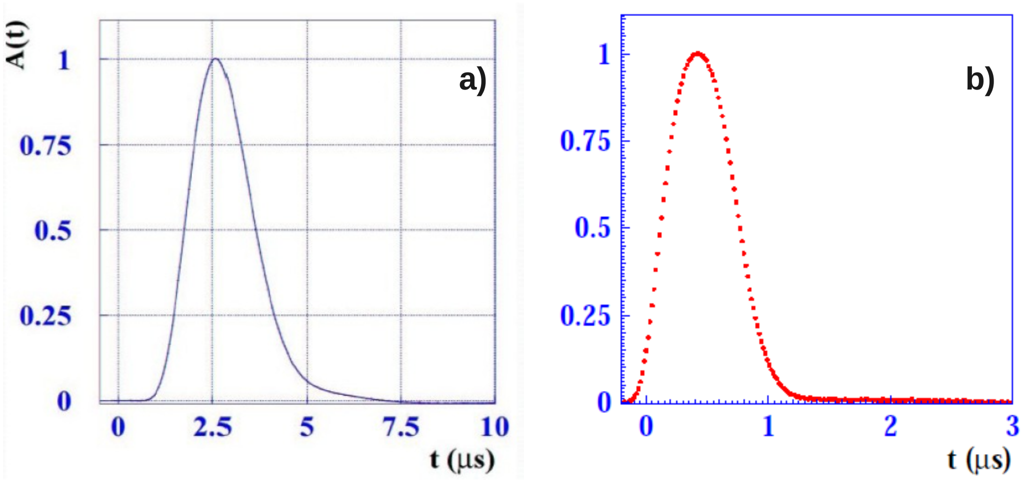

Figure 2: Shape of the signal from: a) specrometric channel; b) trigger output.

The shape of the signal at the ADC input is shown in Fig. 2a. The algorithm implemented in the FPGA provides a fit of the signal to the reference shape tabulated for each particular channel. The shape of the reference signal and information about the noise correlations are stored in the array uploaded to the FPGA memory. As a result of the algorithm, the amplitude, time and fit quality information is calculated and recorded in a 32 bit word (18 bits for amplitude, 12 bits for time and 2 bits for quality). For a test of the reliability of the FPGA algorithm, raw information can be recorded together with fitted information for part of events and the fitting algorithm can be performed offline.

The incoherent energy noise equivalent for a reconstructed amplitude is about 300 keV while the coherent noise contribution is less than 20 keV. Time resolution measured at cosmic events with energy deposition of 35 MeV is about 18 ns and decreases with a growth of the deposited energy. Nonlinearity of the electronics channel measured with a test pulse system in the full range is better than $\Delta A/A < 210^{-3}$.

The upgraded KEKB collider will work in the continuous injection mode. The DAQ system will be vetoed for short time of order 50-100 mks and after beam injection. Since the injected bunch is unstable and noisy for about 1 ms, DAQ will be vetoed for 1 mks when this bunch is crossing the interaction region. To keep the neutral trigger workable in such a scheme, we need to have a short trigger signal without substantial tail. The obtained trigger signal shape is shown in Fig. 2b.

The electronics scheme and energy and time reconstruction algorithm were tested at the Belle detector.

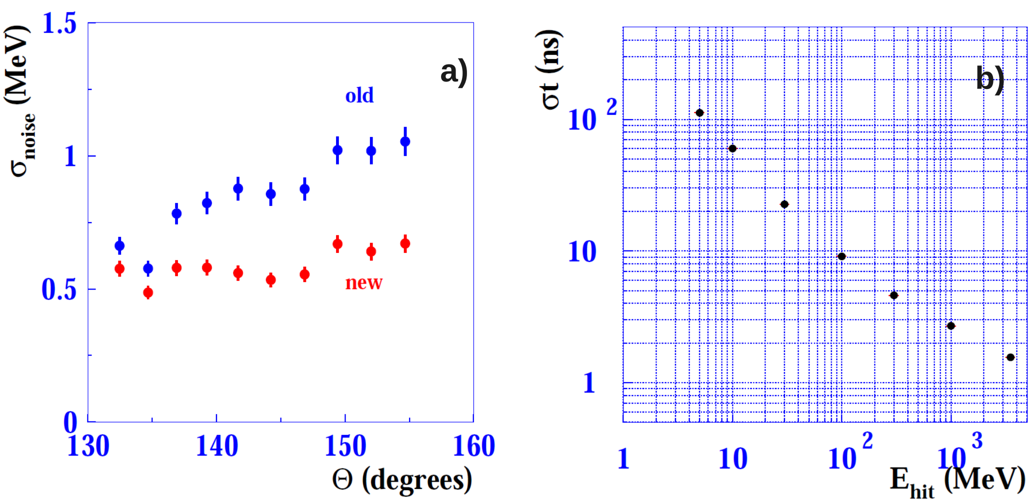

Figure 3: a) Pile-up noise dependence on the angle for new and old electronics. b) Time resolution as a function of the energy deposition.

In summer 2008 one sector of the backward endcap calorimeter (120 channels) was equipped with new shaper-digitizer boards which have a similar scheme as the new electronics. Other ECL channels kept the usual status. This electronics was operated in autumn 2008 and in the seasons of 2009-2010. The electronics showed good performance.

The noise and coherent noises were measured with and without a beam. The incoherent noise without a beam was 330-410 keV depending on the theta angle. With the beam the incoherent noises are deteriorated by the pile-up noise and are about 500-600 keV as shown in Fig. 3. The obtained value of the pile-up noise with the new electronics is smaller than for the case of Belle electronics. In the most inner region the pile-up noise suppression is about a factor of 1.5. The coherent noise within one module was about 70 keV.

The time resolution dependence on the energy deposition in the counter is shown in Fig. 3(b). It is about 100 ns for 5 MeV energy deposition and improves up to 3 ns for 1 GeV. The beam background has uniform time distribution and applying a cut depending on the energy deposition one can suppress the fake clusters. Applying cuts of about 3 σ one can suppress the fake cluster rate by a factor of 7 keeping the efficiency of about 97%. These values are in good agreement with estimation.

We started mass production of ShaperDSP modules and about one third of the barrel modules have been produced.

The barrel calorimeter is kept inside the detector and counters were not tested since 2010. A setup to test barrel counters was assembled based on the new electronic modules. The barrel calorimeter has been tested with cosmic rays. Measurements showed that all counters are workable and provide the expected response for the energy deposition from cosmic particles. The distribution of the cosmic peak position is shown in Fig. 4.

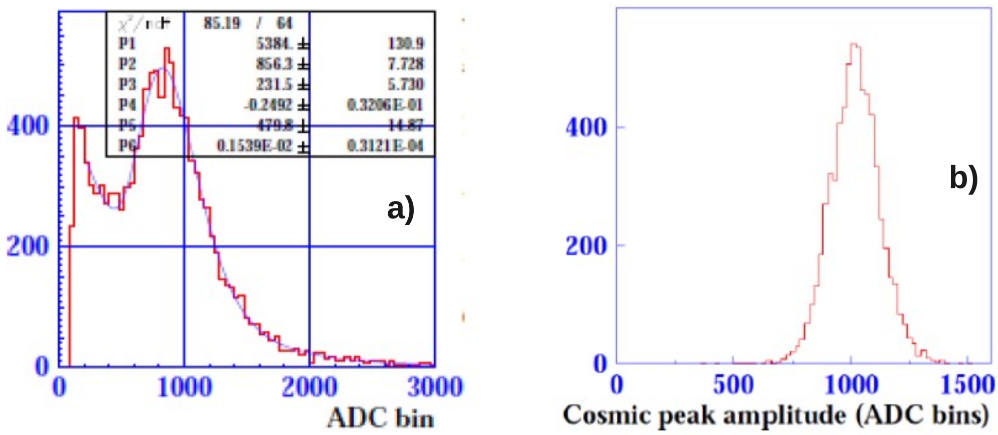

Figure 4: a) Spectrum of the energy deposition of cosmic particles; b) Distribution of the cosmic peak position.

3. Second stage of upgrade

To improve the calorimeter performance in the endcap region, the CsI(Tl) should be replaced by a faster scintillator. The parameters of the scintillation crystals with short decay time are listed

Crystal	X_0, cm	λ_{em}, nm	n	N_{ph}/MeV	τ, ns
CsI(Tl)	1.86	550	1.8	52000	1000
CsI	1.86	305/400	2	5000	30/1000
BaF_2	2.03	220/310	1.56	2500/6500	0.6/620
CeF_3	1.65	310	1.62	600	3
$PbWO_4$	0.89	430	2.2	25	10
$LuAlO_3$(Ce)	1.08	365	1.94	20500	18
$Lu_3Al_5O_{12}$(Ce)	1.37	510	1.8	5600	60
Lu_2SiO_5(Ce)	7.41	420	1.82	26000	12/40

Table 1: Parameters of the fast scintillation crystals

in Tab. 1. To provide good performance for photons with small energy, a scintillator should have high lightoutput to suppress the electronics noise with short decay time. A pure CsI scintillator has decay time of about 30 ns and is a good candidate as a material for the Belle endcap calorimeter.

Pure CsI has emission spectrum in the UV region with the maximum at 320 nm. To detect such light, two-inch vacuum photopentrodes developed by Hamamatsu are planned to be used. The photopentrodes (PP) have low anode capacity of 10 pF which gives about a 1000 electron noise equivalent for the 30 ns shaping time. We need to have an internal gain factor of the photodetector to decrease the equivalent electronics noise. The gain factor of PP is 150-250 without magnetic field. Measurements of the gain factor dependence on the axial magnetic field were carried out in BINP [3]. The gain factor decreases about 3.5 times in the magnetic field of 1.5 T. The gain recovers by about 20-30 % for the angle of 20-45° relative to the magnetic field.

Pile-up noise suppression has been tested for the assembled counters. The pile-up noise was simulated by the γ-quanta from a powerful ^{60}Co source. The CsI(Tl) and pure CsI counters were compared and the measurements confirm that the pile-up suppression is a factor of 5.5 which agrees with simulation.

Twenty counters based on pure CsI crystals and PP with preamplifiers were assembled in an array 4×5. The signal from each preamplifier was formed by the CR-(RC)^4 shaper with 30 ns shaping time and digitized with 40 MHz flash ADC. The obtained data were fitted to the known shape of the signal. The amplitude and time of the signal were reconstructed. The energy noise equivalent was measured to be 43 keV. In the magnetic field it corresponds to less than 150 keV.

Energy and time resolution of this array were studied at the BINP photon beam of the backward scattered photons [2]. The spectrum of the backward scattered photons has the sharp edge and the energy resolution was obtained from the fit of the measured energy distribution by the convolution of the spectrum shape and calorimeter response. The obtained resolution is in good agreement with both Monte Carlo prediction and measurements with the CsI(Tl) prototype [4].

Together with time information the readout scheme allows to get time information. The obtained time resolution is better than 1 ns for the energy deposition of more than 20 MeV. For the magnetic field of 1.5 T it is expected that such a time resolution will be obtained for the energy more than 60 MeV.

Radiation hardness of 14 pure CsI crystals produced by the Amcrys company was tested up to 14 krad. The drop of lightoutput after irradiation by 14 krad is shown in Fig. 5. For most of the crystals the drop of the light output is less than 20% which is acceptable for Belle II operation. In addition, the irradiation of the crystals with a neutron flux of $10^{12} cm^{-2}$ did not reveal a degradation within 5%.

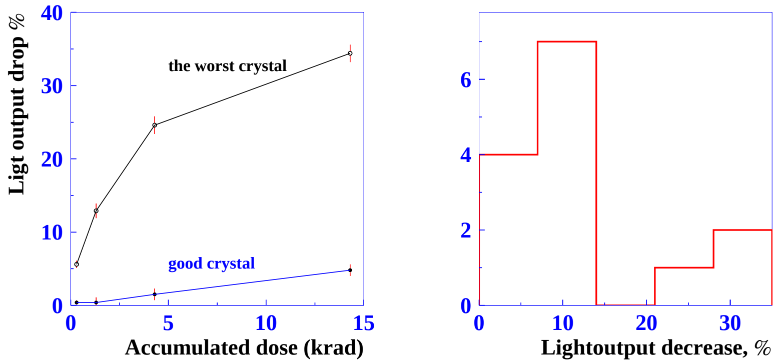

Figure 5: a) Dependence of the lightoutput decrease on the accumulated dose; b) Lightoutput decrease distribution after 14 krad irradiation.

4. Summary

Belle calorimeter worked for more than 10 years and showed good performance. Modification of the electronics allows to suppress the pile-up noise and reject fake clusters keeping good performance of the calorimeter. Electronics has been developed and production started. For the endcap region the second stage - replacement of CsI(Tl) to pure CsI crystals with PP readout allows an essential improvement of beam-background immunity to keep performance.

References

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