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Study of a pure CsI crystal readout by APD for Belle II end cap ECL upgrade

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A B S T R A C T

A scintillation counter consisting of a pure CsI crystal and avalanche photodiodes (Hamamatsu APD S8664-55 and S8664-1010) has been studied for the upgrade of the end cap electromagnetic calorimeter of Belle II detector. An essential increase of the light output was achieved with wavelength shifters based on nanostructured organosilicon luminophores.

1. Introduction

Belle experiment was operated at KEKB accelerator, the world's highest luminosity e^+e^- collider, and investigated CP-violating effects in B meson decays. Belle II, as an upgrade of Belle, aims at searching for New Physics with 40 times higher luminosity. In order to cope with higher luminosity, fast pure CsI scintillation crystals with 30 ns scintillation decay time were proposed for the upgrade of the end cap electromagnetic calorimeter (ECL) of Belle II. Two options are considered for the photosensitive elements: vacuum photopentodes and silicon avalanche photodiodes (APD). We investigate the second option with APD (Hamamatsu S8664-55 and S8664-1010). Hamamatsu APDs of S8664 series, compact photosensors insensitive to magnetic field, are operated at the reverse bias voltage of about 400 V to provide a gain of about 50 and dark current of only few nanoamperes (at the temperature $T = 25\,^{\circ}$C). High equivalent noise charge (ENC), arising from the large junction capacitance of APD (100–300 pF) and short shaping time (30–50 ns), in combination with the small light yield of pure CsI crystals (one order of magnitude smaller than that of CsI(Tl)) result in a large equivalent noise energy (ENE). In the scheme with the actual size crystal ($5.5 \times 5.5 \times 30\,\mathrm{cm}^3$) and 1 APD (S8664-1010), ENE was measured to be about 2 MeV, which is 4 times the acceptable level ($\lesssim$0.5 MeV) [1].

2. Study of equivalent noise charge

As the suppression of electronic noise is crucial in the scheme with pure CsI crystal and APD, we chose low noise fast rise time CAEN A1422B045F3 charge sensitive preamplifier, optimized for the work with short shaping time and large photodetector capacitance (up to 1000 pF). The readout electronics also comprises a Clear Pulse 4467A shaping amplifier and a Hoshin C008 CAMAC peak hold ADC. The ENC squared in the spectrometric channel without effect of the APD gain is [2]:

$$Q_n^2 = \left(2|\mathrm{e}|I_d + \frac{4k_bT}{R_b}\right)K_iT_s + \frac{4k_bTR_sK_\nu C^2}{T_s} + K_{\nu f}A_fC^2, \quad (1)$$

where e is the electron charge, I_d the dark current of APD, k_b the Boltzmann constant, T the temperature, T_s the peaking time of the pulse, R_b bias resistance, R_s equivalent series resistance, C junction capacitance of APD, A_f the noise coefficient of $1/f$ noise. $K_i, K_\nu, K_{\nu f}$ are the factors depending on the shape of the signal from the shaping amplifier. Taking into account APD gain, fluctuation of the avalanche and additional noise in the other components of the spectrometric channel ($D \simeq 600$ el.), the former equation can be written in the form (term with large $R_b = 120\,\mathrm{M\Omega}$ is neglected):

$$ENC^2 = \frac{2 \cdot I_d \cdot K_i \cdot g \cdot F \cdot \tau}{|\mathrm{e}|} + \left(\frac{B^2}{\tau} + E^2\right)C^2 + D^2, \quad (2)$$

where g is the gain of APD, F its excess noise factor and τ shaping time. The shot noise (first term), thermal noise (second term) and additional noise were measured separately. Calibration pulses were applied to the test input of the preamplifier and the r.m.s. of the corresponding output amplitude spectrum was a measure of the ENC. The thermal noise coefficient $B = (26.2 \pm 0.8 \pm 4.8)\sqrt{\mathrm{ns}}/\mathrm{pF}$, $1/f$ noise coefficient $E = (6.1 \pm 0.1 \pm 0.4)$ 1/pF and signal shape factor $K_i = 0.44 \pm 0.02$. Good agreement between measured total ENC and the calculated one indicates sufficient suppression of the correlated noises in our spectrometric channel, see Fig. 1.

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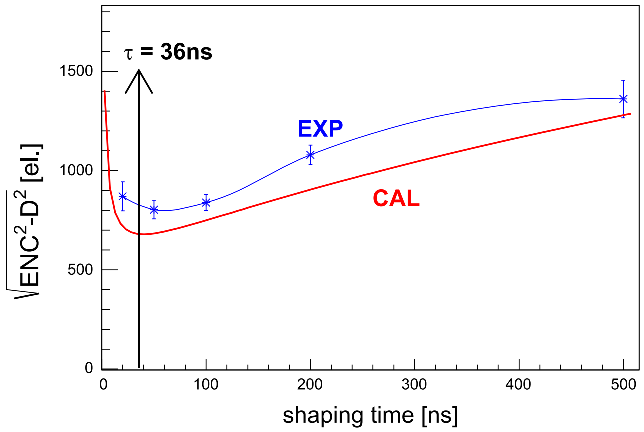

Fig. 1. Thermal⊕ noise in the scheme with one S8664-55 APD. Blue line indicates the measured ENC, red line shows calculated ENC. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this paper.)

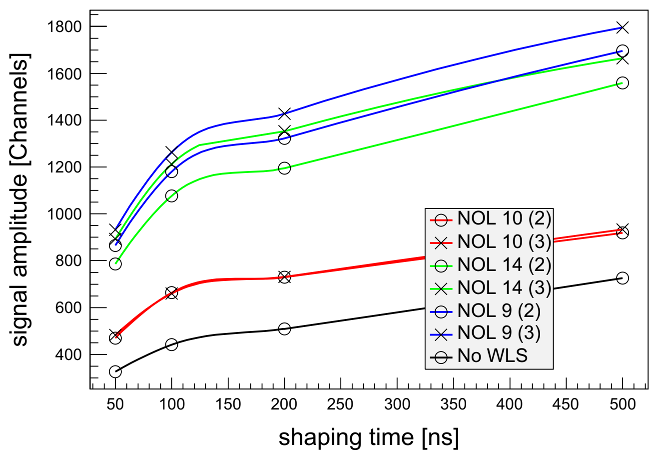

Fig. 2. Signal from the counter with 2 S8664-1010 APDs and WLS plate. The luminophores of three types (NOL-9,10,14) were tested, optical density of the layer with luminophores is shown in parentheses.

3. Measurement of equivalent noise energy

A pure CsI crystal [3] ($5.5 \times 5.5 \times 30\ cm^3$) is wrapped by one layer of a Gore-Tex teflon of 200 μm thickness and placed in a 40−μm aluminized mylar envelope. Optical grease OKEN-6262A is used to couple APD to the crystal. Simulation of the interaction of cosmic muons with the crystal shows that the most probable energy deposition passing through about 5.5 cm thick crystal (position of the cosmic peak) is about 33 MeV. The ENE of the counter has been evaluated from ENC and ADC scale in the units of energy (MeV) obtained from cosmic calibration. In the schemes with 2 and 4 S8664-1010 APDs ENEs were measured to be (1.1 ± 0.1) MeV and (0.8 ± 0.1) MeV, respectively. In the case of 2 or 4 S8664-55 APDs per crystal, we obtained ENE = (1.7 ± 0.2) MeV or ENE = (1.2 ± 0.1) MeV, respectively.

4. Improvement of the light output

To increase the amount of collected scintillation light several studies were performed. Three types of the silicon optical grease, OKEN-6262A, BC-630 and TSF451-50M have been studied. The measured signal ratio is 1:0.95:0.85 (OKEN-6262A: BC-630: TSF451-50M). OKEN-6262A was used in the subsequent studies.

Table 1
Relative temperature gain variation, $(1/G)(dG/dT)(\%)$, for Hamamatsu S8664-55 and S8664-1010 APDs at different operating points with gain of 30, 50 and 100.

APD type	APD gain		
	30	50	100
S8664-55	-2.4 ± 0.1	-3.3 ± 0.1	-5.0 ± 0.2
S8664-1010	-2.3 ± 0.1	-3.1 ± 0.1	-4.9 ± 0.2

It was shown [4] that the Gore-Tex teflon has the largest reflectivity even in the ultraviolet (UV) range. We measured signals from the crystal wrapped by teflon of different thicknesses. It was shown that the optimal thickness of teflon is 200 μm, its further increase improving the signal by only about 5%. The scintillation light of pure CsI is in the UV range (peak at 320 nm), where the quantum efficiency of the APD is only about 30%. Novel wavelength shifting (WLS) plates containing nanostructured organosilicon luminophores (NOLs) [5–7] were developed by LumInnoTech LLC [8]. The NOLs are composed of modified p-terphenyl, responsible for the absorption of UV light, luminophores (derivatives of benzothiadiazole), for the emission of visible light, and Si atoms, binding the former two fragments together. With these WLS plates, the spectrum of the scintillation light is shifted to the visible range, where the quantum efficiency of APD is about 85%.

The WLS plate with NOL-9 luminophore provides the largest signal increase (by a factor of 3), see Fig. 2. With this WLS plate, the ENE of counter with 2 S8664-1010 APD's was reduced to (0.55 ± 0.05) MeV and for the counter with 4 S8664-55 APD's we obtained ENE = (0.45 ± 0.05) MeV.

5. Characteristics of APD

APD is a dominant source of the temperature variations of the signal from the counter. To provide stable ECL response these variations are to be compensated. At the operating point ($U_{bias} = 394$ V), the dark current of the S8664-1010(S8664-55) APD varies from 1 nA(1 nA) up to 30 nA(8 nA) for the temperatures from 10 °C to 43 °C. Relative temperature gain variations for S8664-55 and S8664-1010 APDs are shown in Table 1. At the operating point the excess noise factor of the S8664-1010(S8664-55) APD was measured to be $F = 3.4 \pm 0.4 (5.1 \pm 0.5)$.

6. Conclusion

Hamamatsu APDs of S8664 series provide a promising option for Belle II end cap ECL upgrade. An essential increase of the light output was achieved with WLS plates based on the nanostructured organosilicon luminophores. Several APDs per crystal allows us to decrease ENE and provide redundancy in the signal readout. The ENE of the counter with four S8664-55 APDs was measured to be (0.45 ± 0.05) MeV, which satisfies project requirements.

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