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Radiation hardness study of CsI(Tl) scintillation crystals for the Belle II calorimeter

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Abstract: The electromagnetic calorimeter of the Belle II detector contains CsI(Tl) crystals of 30 cm length which have been used at the Belle experiment. We measure the light output degradation of CsI(Tl) crystals exposed to uniformly distributed absorbed dose. Four Belle typical crystals with known scintillation characteristics are irradiated with photons at a total dose of about 35 krad. Results show acceptable radiation hardness for the Belle II experiment conditions where the accumulated dose in crystals could reach 10 krad.

Keywords: Calorimeters; Radiation damage to detector materials (solid state); Radiation-hard detectors

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1 Introduction

The electromagnetic calorimeter (ECL) of the Belle II detector [1] contains 8736 CsI(Tl) crystals of 30 cm length which have been used at the Belle experiment [2]. The absorbed radiation dose collected by the crystals after 10 years operation of the Belle detector was about 100 rad for the barrel crystals and up to 400 rad for the endcaps. Herewith, the light output degradated on 7% in the barrel and up to 13% in the endcap parts. Since the Belle II experiment is expected to be operated at a large luminosity of up to 8×10^{35} $\text{cm}^{-2}s^{-1}$, higher beam-induced background conditions require an additional measurement of the radiation hardness for the CsI(Tl) crystals. According to the beam background Monte Carlo simulation, the radiation dose rate for the most radiation loaded parts of the calorimeter can exceed 500 rad/year [3].

The radiation hardness of the Belle typical CsI(Tl) crystals grown by Kharkov Institute for Single Crystals has been studied before (between 1998 and 2000 years) for an absorbed doses up to 3700 rad [4] and, recently, two typical crystals manufactured by Shanghai Institute of Ceramics have been irradiated with the total dose of 100 krad [5]. The study of ref. [4] has been performed with a large set of crystals (25 samples) which were selected from the set of crystals produced for the ECL of the Belle detector. All studied samples in refs. [4, 5] have shapes of truncated pyramids with of 30 cm height and slightly different transverse sizes. All crystals were polished, wrapped in 200 μm porous teflon and covered with a 20 μm aluminized mylar film to improve light collection efficiency.

The requirement for radiation hardness of the Belle ECL material was set such that the light output decreases to less than 3%, 10% and 20% at radiation dose of 10, 100 and 1000 rad, respectively [2]. All the crystals in refs. [4, 5] satisfy this requirement.

Since about 2/3 calorimeter elements were produced by Kharkov Institute for Single Crystals, it is still necessary to study their radiation hardness with doses equivalent of the Belle II conditions. To perform such study, we choose four crystals (No 83, 84, 94 and 95) with the best and the worst scintillation characteristics from the previous radiation hardness study [4]. All these samples have been irradiated before with total dose up to 3700 rad and were stored in a low humidity environment. The wrappers of the crystals are kept in the study. Light output degradation for the selected crystals measured in ref. [4] is shown in figure 1.

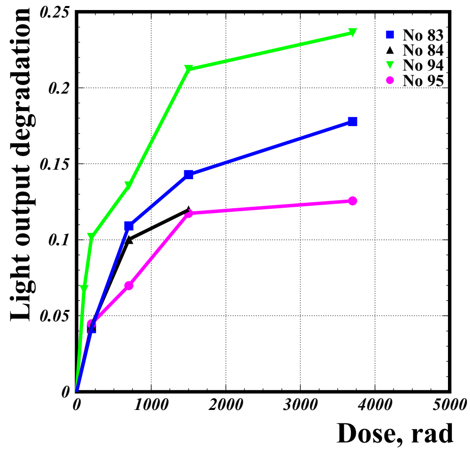

Figure 1. Light output reductions for the crystals No 83, 84, 94 and 95 measured in ref. [4].

2 Irradiation of crystals

The studied crystals are irradiated with the industrial electron accelerator ELV-6 [6] at Budker Institute of Nuclear Physics. The ELV-6 accelerator provides a continuous electron beam with the energy of 1.4 MeV and a current of accelerated electrons up to 70 mA. The power in the beam reaches 100 kW. The design and specific features of the ELV-type accelerators result in their long-term reliable operation, convenience and ease in control.

The scheme of irradiation is shown in figure 2. Electrons of the ELV-6 create wide beam of bremsstrahlung photons at the converter material made of a lead or tantalum. The lead converter is used for absorbed doses less than 7 krad because for higher doses the power absorbed in the converter can melt the lead plate. The lead plate located at the distance about 30 cm below the accelerator output is cooled by a water radiator and compressed air flux. The tantalum converter installed directly under the accelerator output consists of 0.5 mm of Ta, 2 mm of water and 2 mm

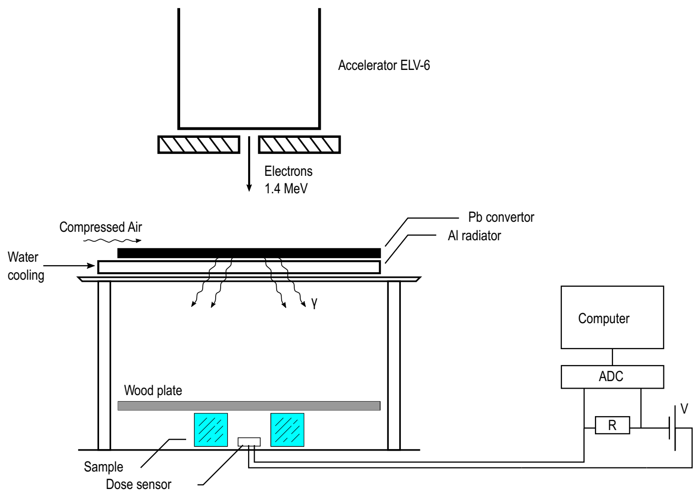

Figure 2. The crystals irradiation scheme with the ELV-6 accelerator. The configuration with the lead converter is shown.

of stainless steel. The bremsstrahlung photons uniformly irradiate the crystals which are located on the horizontal surface at distance about 100 cm below the lead converter and 130 cm below the tantalum converter.[1] The wood plate over the crystals absorbs the electrons scattered in air.

Two specially designed identical dose sensors are used to measure the dose rate deposited in the crystals. The dose sensor includes a small CsI(Tl) crystal of parallelepiped shape with sizes of $1 \times 2 \times 2\,\mathrm{cm}^3$ and two silicon-based photodiodes Hamamatsu S2744-08 which have an active area of $1 \times 2\,\mathrm{cm}^2$. The crystal in the sensor is coupled via an optical contact with one photodiode which measures the signal current. Another photodiode is placed without light connection and measures the dark current induced by the γ-irradiation. The photocurrent is the difference between the signal and dark currents. The currents measured by ADC L-CARD EI14-440 are proportional to the dose rates absorbed in the sensors. The measurements from two sensors are consistent with each other within uncertainties. In total, four expositions with the total dose of 30 krad have been performed.

3 Light output measurements

To study the radiation hardness of the crystals, the relative light output is needed to be measured before and after each exposition. The scheme of the testbench used in these measurements is shown in figure 3. The testbench consists of the photomultiplier tube (PMT) Hamamatsu R1847S; the

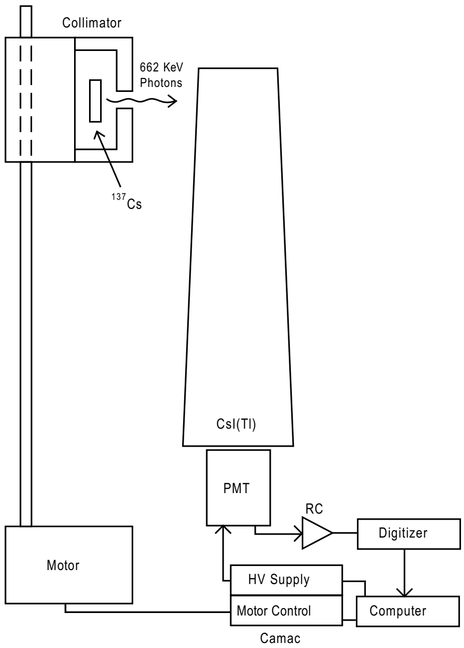

Figure 3. The scheme of the testbench used in the light output measurements.

radioactive source of ^{137}Cs placed in a lead collimator and irradiating the crystal with 662 keV photons; the motor moving the collimator along the crystal axis on definite distances; the RC-circuit with the time constant $\tau = 75$ nsec shaping the PMT pulse and the multifunctional desktop

[1]In a real experiment the crystals in the barrel part of the ECL are mainly exposed from the side of the small face, whereas the crystals closest to the beam pipe are irradiated almost uniformly. Therefore, the uniform irradiation in our study provides the conservative estimation of the radiation hardness.

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waveform digitizer CAEN DT5720A [7] digitizing and integrating the pulse waveform samples within programmable acquisition gate. The pulse integrated spectrum is fit by the sum of Gaussian function and polynomial function to determine the total absorption peak position $\mathcal{A}_i$ for each collimator position $i = 1, \ldots, 9$ with the step of 3 cm. The light output $\mathcal{L}_i = \mathcal{A}_i/\mathcal{A}_0$ is defined relative to the photoelectric peak position $\mathcal{A}_0$ for the reference crystal, which has the same shape as studied samples but not irradiated in our study. After each measurement we calculate two values: average relative light output $\mathcal{L} = \sum_{i=1}^{9} \mathcal{L}_i/9$ and non-uniformity $U = (\mathcal{L}_{\max} - \mathcal{L}_{\min})/\mathcal{L}$, where $\mathcal{L}_{\max}$ and $\mathcal{L}_{\min}$ are the maximum and minimum values of the light output.

Figure 4 demonstrates measured light output $\mathcal{L}$ for the crystals No 83, 84, 85 and 95. Different light output degradations are observed for the studied samples. The results can be well described without assumption about light output self-recovery after irradiations at available accuracy of about 2%.

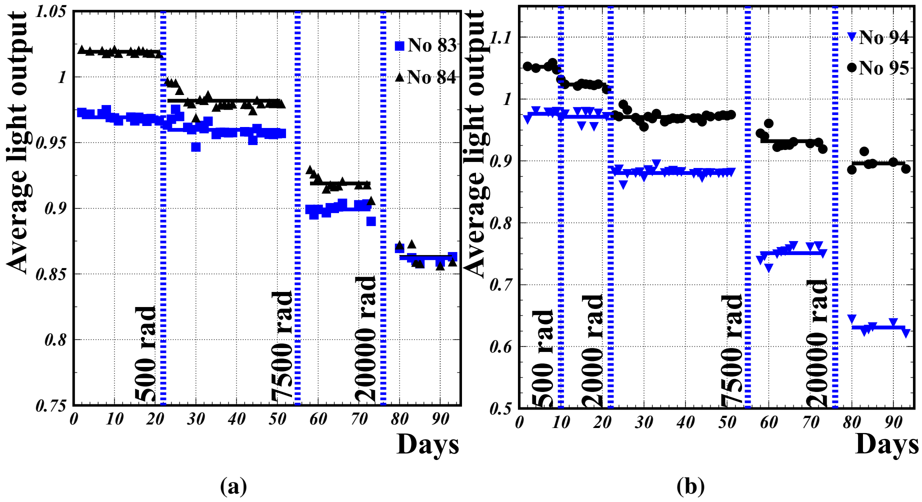

Figure 4. Time dependencies of average relative light output for the crystals (a) No 83, 84 and (b) No 94 and 95. Vertical lines show the absorbed dose during one exposition.

It makes sense to study the correlation with the previous results in ref. [4]. Unfortunately, our measurements can not reproduce the units of the previous measurements because the light output in absolute units is not measured in the studies. To combine the results, we assume that the natural self-recovery of the light output is not large during the period between the studies. Under this assumption, the results are normalised to the last measurement in ref. [4] for the crystal No 95 with the best radiation hardness. The average light output recalculated in units of ref. [4] and its degradation, $\Delta\mathcal{L}/\mathcal{L}$, versus the absorbed dose are shown in figure 5. The dashed lines correspond to the previous study and solid lines show the new results. Obtained curves for the average light output loss are not smooth functions everywhere. There are critical points at intersections of dashed and solid lines in figure 5 (b). It indicates that our assumption about the absence of natural self-recovery is not accurate. However, it adequately reflects a total behaviour of the light output loss because the last values of the previous study (dashed lines) are close to the first points of the new study (solid lines) as it is shown in figure 5 (a). The behaviour of the curves obtained from the previous study is similar in our study for each studied crystal. For example, the crystal No 94 has maximum

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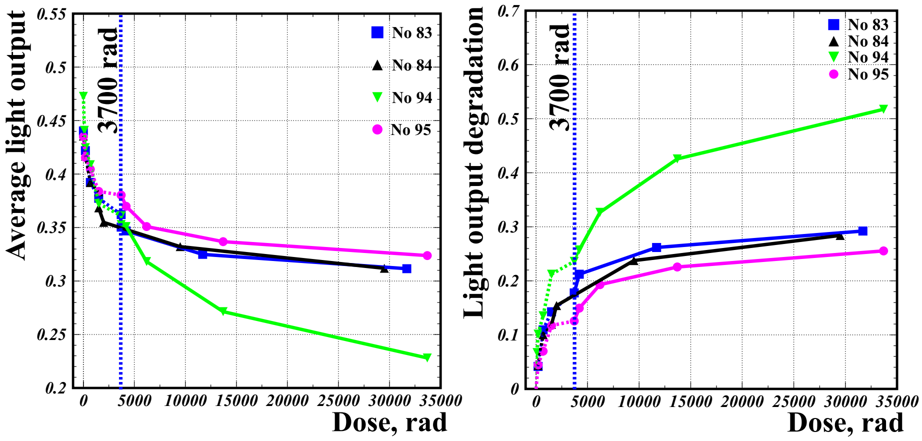

(a) **(b)**

Figure 5. The distributions of (a) the average light output recalculated in units of ref. [4] and (b) the light output degradation, $\Delta\mathcal{L}/\mathcal{L}$, versus the total absorbed dose for the crystals No 83, 84, 94 and 95 obtained in the previous study [4] (dashed lines) and in this study (solid lines). Vertical dashed line shows a conventional boundary between the studies.

light output loss in both studies. The light output degradation after a total dose of about 35 krad is about 30% for the crystals No 83, 84, 95 and 50% for the crystal No 94. The light output drops significantly after all expositions.

We also measure the light output non-uniformity along the crystal axis for the tested samples No. 83, 84, 94 and 95. The non-uniformity is not specially compensated as it was done for the crystals in the ECL. We observe the increasing of the light output when the radioactive γ-source moves away from the large face of the crystal. This effect is explained by the shape of the crystals (truncated pyramid) and can be described in geometric optics. However the irradiation of the crystals leads to the loss of the optical transparency. This radiation induced effect compensates the geometric effect for the light output non-uniformity. We clearly observe such behaviour for the crystal No 94. The light output non-uniformity deteriorates to 10.5% after the dose of 7 krad and drops to 8.5% after the dose of 30 krad. The non-uniformity values for all samples do not exceed 13%.

4 Conclusion

Since the expected absorbed dose for the CsI(Tl) crystals in the Belle II calorimeter can reach 6–10 krad after 10 years of the operation, an additional radiation hardness study is performed. We carry out four expositions with the total dose of 30 krad and measure scintillation characteristics for four samples manufactured by Kharkov Institute for Single Crystals for the Belle calorimeter. These crystals have been irradiated before with a total dose of about 3.7 krad. Our measurements are consistent with the previous study [4]. The light output degradation is found to be about 30% for three tested samples (No 83, 84 and 95) and 50% for the worst sample (No 94).

The contribution of the light output loss to the energy resolution (especially for low energies) is mostly due to the increasing of energy equivalent of the electronic noise. The average light output signal of the Belle crystals is about 5000 photoelectrons per 1 MeV of the energy deposited in the crystal. The electronic noise level is about 300 keV. Our study shows that the worst light output loss (corresponding to the crystal No 94) is about 40% at the total Belle II expected dose of 10 krad. Even in this case, the noise level increases to 500 keV that is still much smaller than the level of dominating pile-up noise (3–8 MeV) according to the Monte Carlo simulation [3]. Therefore, the radiation damage of the crystals is not the serious problem for the Belle II calorimeter.

The light output non-uniformity measurements along the crystal axis are also provided in our study. All measured values do not exceed 13%. There are no any stringent requirements on the CsI(Tl) non-uniformity measurements for the Belle II calorimeter because all the crystals used at Belle are kept to be used at Belle II.

It is also interesting to study the effect of irradiations on the CsI(Tl) scintillation decay time. This problem, which is out of our study, is discussed in ref. [5]. The measurements do not require any correlation between the decay time and the exposed doses up to 100 krad.

Acknowledgments

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