Gamma Ray Induced Radiation Damage in PWO and LSO/LYSO Crystals

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***Abstract*—This paper compares γ-ray induced radiation damage effect in two kinds of heavy crystal scintillators: PWO and LSO/LYSO. Scintillation emission, optical transmission, light output, decay kinetics and light response uniformity were measured for PWO and LSO/LYSO crystal samples of large size before and after γ-ray irradiations. γ-ray induced phosphorescence was also measured, and the corresponding readout noise was determined.**

I. Introduction

INORGANIC crystal scintillators are widely used in high energy physics experiments, where they suffer from radiation damage originated from electromagnetic energy deposition (γ-rays), neutrons and charged hadrons. This paper compares γ-ray induced radiation damage effects in two kinds of heavy crystal scintillators of large size: PWO and LSO/LYSO. Possible effects of γ-ray induced radiation damage include (1) damage to the scintillation mechanism; (2) radiation induced absorption; and (3) radiation induced phosphorescence (afterglow), which would cause an increase of the electronic readout noise. In this paper, results of photoluminescence and transmission spectra, light output and light response uniformity measured before and after irradiations as well as γ-ray induced phosphorescence and corresponding readout noise are reported.

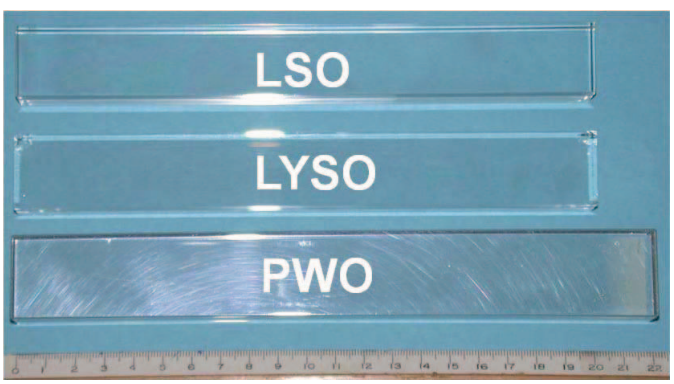

Fig. 1. A photo showing typical samples investigated in this paper.

Fig. 1 shows typical samples investigated in this work. The PWO crystals have slightly tapered shape: 30 × 30 mm at the large end tapering to 28.5 × by 28.5 mm at the small end, and are of 220 mm long. The LSO and LYSO samples are rectangular with a cross-section of 25 × 25 mm, and are of 200 mm long. All six faces of these samples are polished.

The photo-luminescence spectra were measured before and after irradiation by using a Hitachi F-4500 fluorescence spectrophotometer. The angle between the excitation UV light and the sample normal was set to be 10° so that the photoluminescence spectra collected are not affected by internal absorption in the sample [1]. The optical transmittance spectra were measured before and after irradiations by using a Perkin Elmer Lambda-950 spectrometer equipped with double beam, double monochromator and a general purpose optical bench with light path up to 40 cm. The systematic uncertainty in repeated measurements is about 0.15%. The scintillation light output and decay kinetics were measured before and after irradiations by using a Hamamatsu R2059 PMT, which has a bi-alkali photo-cathode and a quartz window, for PWO, and a Photonis XP2254b PMT, which has a multi-alkali photocathode and a quartz window, for LSO/LYSO. For the light output measurement, the large (PWO), or one (LSO/LYSO), end of the sample was coupled to the corresponding PMT with Dow Corning 200 fluid, while all other faces of the sample were wrapped with the Tyvek paper. A collimated ^{137}Cs source was used to excite the PWO sample. To reduce the effect of the intrinsic natural radioactivity, a collimated ^{22}Na source was used to excite the LSO/LYSO samples with a coincidence trigger provided by a BaF_2 crystal [2]. The γ-ray peak positions were obtained by a simple Gaussian fit, and were used to determine photoelectron numbers by using the calibrations of the single photo electron peak.

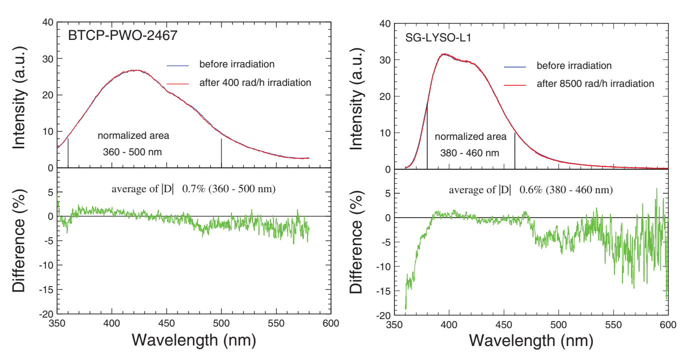

Fig. 2. Photo-luminescence spectra measured before (blue) and after (red) γ-ray irradiation and corresponding normalized difference (green) for samples BTCP-PWO-2467 (left) and SG-LYSO-L1 (right).

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II. Scintillation Mechanism

The top plots of Fig. 2 show the photo-luminescence spectra before (blue) and after (red) γ-ray irradiations for PWO (left) and LYSO (right) samples. Their normalized numerical difference (green) is shown in the bottom plots. No significant difference was observed between the photo-luminescence spectra taken before and after irradiations, indicating that γ-rays do not cause damage to the scintillation mechanism in these crystals.

III. γ-Ray Induced Absorption

The main consequence of γ-ray induced radiation damage in scintillation crystals is radiation induced absorption, or color center formation. Radiation induced absorption causes degradation of optical transmittance and light output. It may also affect crystal's light response uniformity and cause a unrecoverable degradation in the energy resolution if the light attenuation length is reduced significantly [3]. The γ-ray induced absorption may also spontaneously recover, leading to a dose rate dependent radiation damage [4], [5].

A. Recovery of γ-Ray Induced Damage

Fig. 3 shows recovery behavior of the longitudinal optical transmittance after γ-ray irradiations for PWO at 440 nm (left) and LSO/LYSO at 420 nm (right). Both PWO samples from SIC (blue) and BTCP (red) recover under the room temperature. Three recovery time constants were determined by an exponential fit. While the short time constant is at few tens hours, the medium time constant is at a few thousands hours, and the third time constant is longer, which may be considered as no recovery in the time scale of consideration. The transmittance damage in LSO/LYSO does not recover under the room temperature as shown in the right plot of the figure.

Because of the recovery, the γ-ray induced absorption in PWO is dose rate dependent. The optical transmittance and light output decreases when crystals exposed to a certain dose rate until reaching an equilibrium. At the equilibrium the speed of the color center formation (damage) equals to the speed of the color center annihilation (recovery), so that the color center density (radiation induced absorption) does not change unless the dose rate applied changes. More detailed discussion on the dose rate dependent radiation damage, or color center kinetics, can be found in [4], [5]. Because of no recovery the γ-ray induced damage in LSO/LYSO is not dose rate dependent. This means that an accelerated irradiation with a high dose rate would reach the same result as a slow irradiation with a low dose rate if the total integrated dose is the same.

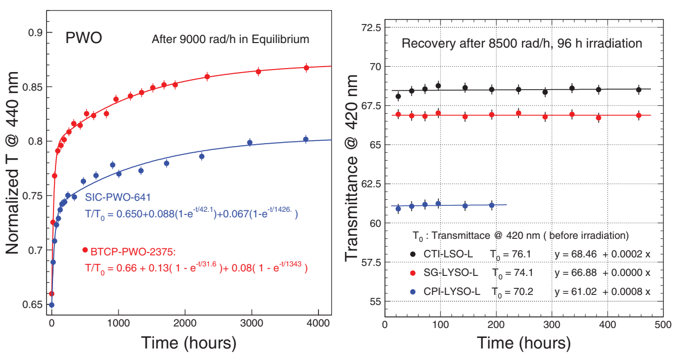

Fig. 3. The recovery of γ-ray induced transmittance damage is shown as a function of time after the irradiation for PWO (left) and LSO/LYSO samples (right).

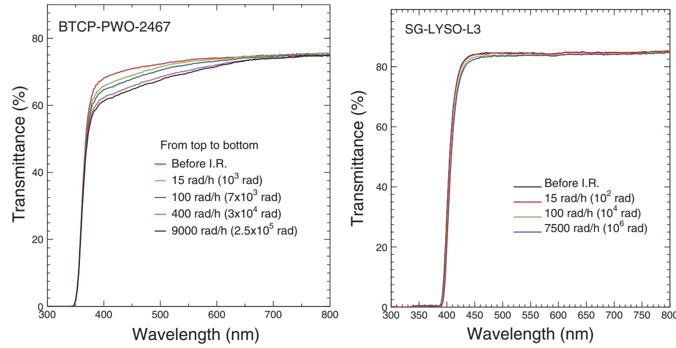

Fig. 4. The optical transmittance spectra before and after several steps of the irradiation are shown as a function of wavelength for samples BTCP-PWO-2467 (left) and SG-LYSO-L3 (right).

B. γ-Ray Induced Transmittance Damage

Fig. 4 shows the longitudinal optical transmittance as a function of wavelength before and after several steps of the γ-ray irradiations for samples BTCP-PWO-2467 (left) and SG-LYSO-L3 (right). While both the integrated dose and the dose rate, under which the irradiations were carried out step by step, are specified for the PWO sample, only the integrated dose is specified for the LYSO sample. This is due to the fact that the γ-ray induced absorption is dose rate dependent in PWO, and is not dose rate dependent in LSO/LYSO. It is clear that γ-ray induced absorption is significantly less in LSO/LYSO than PWO.

Fig. 5 shows an expanded view of the longitudinal transmittance spectra before and after several steps of the γ-ray irradiations for samples BTCP-PWO-2467 (left) and SG-LYSO-L3 (right). Also shown in the figure is the numerical values of the photo-luminescence weighted longitudinal transmittance

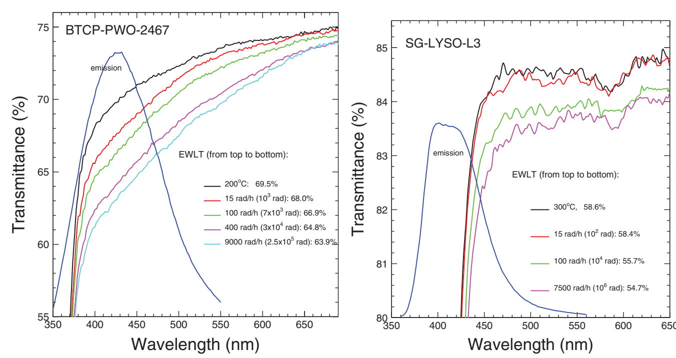

Fig. 5. Degradation on EWLT for BTCP-PWO-2467 (left) and SG-LYSO-L3 (right).

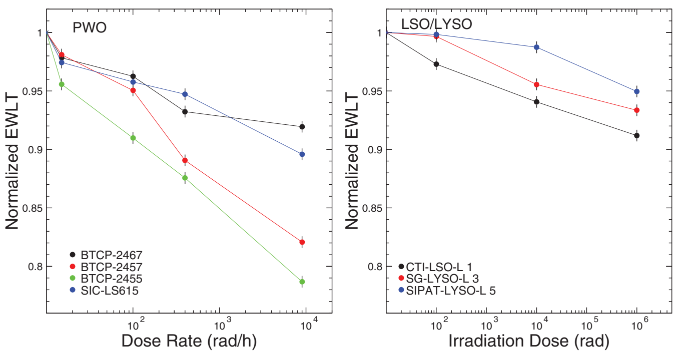

Fig. 6. Normalized EWLT as a function of dose rate applied for PWO (left) and LSO/LYSO samples (right).

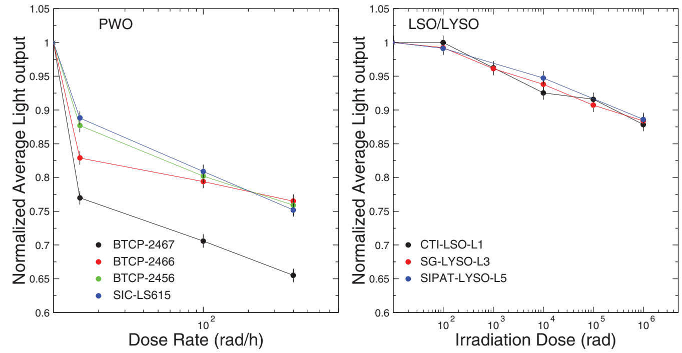

Fig. 8. Light output degradation after γ-ray irradiations is shown as a function of the dose rate and the cumulated dose for PWO (left) and LSO/LYSO (right) respectively.

(EWLT), which is defined as:

$$EWLT = \frac{\int LT(\lambda)Em(\lambda)d\lambda}{\int Em(\lambda)d\lambda} \quad (1)$$

The EWLT represents crystal's transparency better than the transmittance at the emission peak. This is particularly true for LSO/LYSO, which has non-negligible self-absorption [2].

Fig. 6 shows the normalized EWLT values as function of the dose rate applied for PWO (left) and the cumulated dose for LSO/LYSO (right). While the loss of EWLT is about 8–21% for the PWO samples after an integrated dose of 0.25 Mrad with a dose rate of 9,000 rad/h. The EWLT loss of the LSO/LYSO samples is about 5–9% after an integrated dose of 1 Mrad.

C. γ-Ray Induced Light Output Degradation

Fig. 7 shows light output degradation for the samples BTCP-PWO-2467 (left) and SG-LYSO-L3 (right) after several steps of γ-ray irradiations. The left plot of Fig. 7 shows the normalized light output as a function of time when the γ-rays are applied at defined dose rate up to 400 rad/h. The dose rate dependence of the γ-ray induced radiation damage in PWO is clearly shown. The right plot of Fig. 7 shows the light output as a function of the integration time together with exponential fits to the scintillation decay time for the LYSO sample SG-LYSO-L3 after several steps of irradiations with cumulated dose up to 1 Mrad. It is clear that while the light output degrades the scintillation decay time remains the same, indicating also that scintillation mechanism is not changed. The observation is the same for the PWO samples.

Fig. 8 shows normalized light output as a function of the dose rate and the cumulated dose for the PWO samples (left) and LSO/LYSO samples (right) respectively. The average of the light output loss is about 26% for the PWO samples after γ-ray irradiations up to 400 rad/h. The average loss of the light output is about 12% for LSO/LYSO samples after γ-ray irradiations with cumulated dose of up to 1 Mrad.

D. Effect on Light Response Uniformity

The light response uniformity of long crystals was measured by moving a collimated γ-ray source along the longitudinal axis of the sample at nine and seven points evenly distributed along the crystal for PWO and LSO/LYSO respectively. The corresponding response (y) was fit to a linear function

$$\frac{y}{y_{mid}} = 1 + \delta(x/x_{mid} - 1) \quad (2)$$

where (y_{mid}) represents the light output at the middle of the crystal, δ represents the shape of the light response uniformity and x is the distance from one end of the crystal. Fig. 9 shows the light response uniformity as a function of the distance

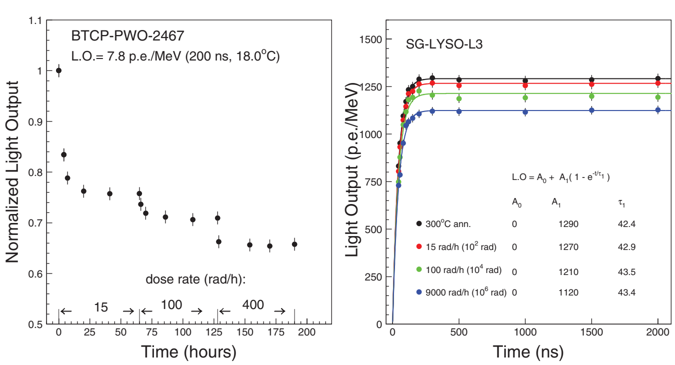

Fig. 7. Left: The normalized light output is shown as a function of time for the PWO sample BTCP-PWO-2467 during several steps of γ-ray irradiations with the dose rate up to 400 rad/h. Right: The light output is shown as a function of the integration time for the sample SG-LYSO-L3 after several steps of γ-ray irradiations with integrated dose up to 1 Mrad.

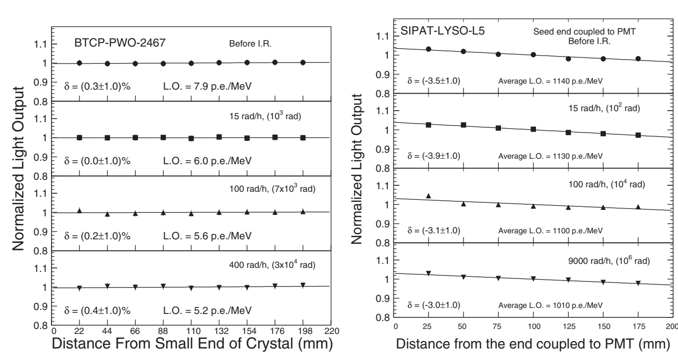

Fig. 9. The light response uniformity as a function of the distance to the small end and the end coupled to the PMT for samples BTCP-PWO-2467 (left) and SIPAT-LYSO-L5 (right) respectively after several steps of γ-ray irradiations.

TABLE I
SUMMARY OF GAMMA INDUCED COEFFICIENT AND READOUT NOISE IN PWO AND LSO/LYSO

Sample ID	L.Y. p.e./MeV	F^a p.e.s^{-1}(rad/h)$^{-1}$	Q_{bar} p.e.	Q_{end} p.e.	σ_{bar} MeV	σ_{end} MeV
SIC-S392 PWO	7.1	1.94E +08	290	9680	2.4	13.8
SIC-S411 PWO	6.7	1.76E +08	265	8820	2.4	14.0
BTCP-2133 PWO	5.8	1.52E +08	244	8120	2.7	15.6
BTCP-2162 PWO	7.1	1.89E +08	284	9460	2.4	13.7
CPI-LYSO-L	2060	4.74E +10	1.41E +05	4.71E +06	0.2	1.1
SG-LYSO-L	2270	4.80E +10	1.44E +05	4.80E +06	0.2	1.0
CTI-LSO-L	2020	5.10E +10	1.53E +05	5.10E +06	0.2	1.1
SIPAT-LYSO-L	2155	4.80E +10	1.44E +05	4.80E +06	0.2	1.0

to the small end and the end coupled to the PMT for the samples BTCP-PWO-2467 (left) and SIPAT-LYSO-L5 (right) respectively after several steps of γ-ray irradiations. The γ-ray irradiations were carried out under fixed dose rate for the PWO sample. It is clear that the shape of the light response uniformity was not changed for both crystals, indicating that the energy resolution is not compromised. This is due to the fact that the degraded light attenuation is long enough to maintain the uniformity [3].

IV. γ-RAY INDUCED PHOSPHORESCENCE AND READOUT NOISE

Fig. 10 shows the γ-ray induced photo-current, normalized to that during irradiations, as a function of time during and after γ-ray irradiations for a PWO sample and three LSO/LYSO samples as well as a BGO sample of the same size of the LSO/LYSO samples. Also shown in this figure is the electronic noise (E-Noice), which is measured without crystals. While the γ-ray induced phosphorescence (afterglow) is found approaching the E-Noice, so is negligible (at 10^{-5} level) in the PWO and BGO samples, it is between 10^{-3} and 10^{-4} in the LSO and LYSO samples. The LYSO sample from Saint-Gobain shows the lowest phosphorescence among all LSO/LYSO samples tested.

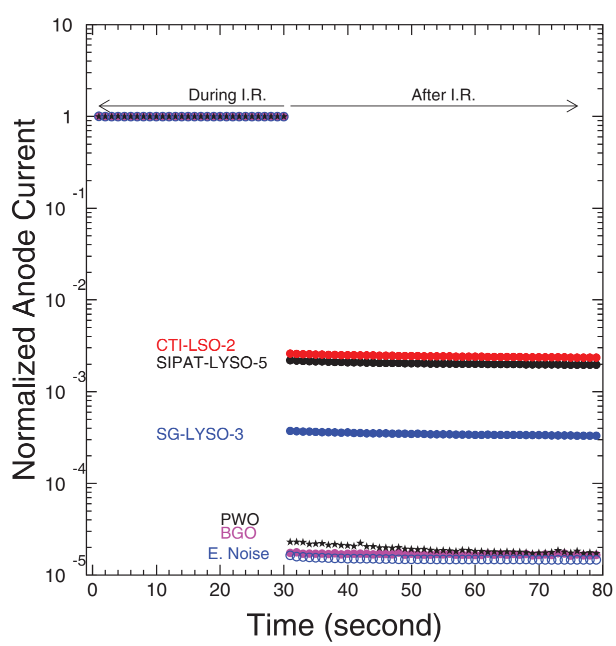

Fig. 10. Normalized anode current is shown as a function of time during and after γ-ray irradiations for the PWO, LSO/LYSO and BGO samples.

Fig. 11 shows γ-ray induced anode photo-current as a function of the γ-ray dose rate applied to the PWO (left) and LSO/LYSO (right) samples. The corresponding γ-ray induced readout noise for PWO and LSO/LYSO crystals was calculated using the algorithm described in reference [6]. Table I lists the equivalent readout noise induced by γ-ray dose expected at the CMS barrel and endcap at the LHC are about 2.5 MeV and 15 MeV respectively for PWO. The corresponding numbers for LSO/LYSO are 0.2 MeV and 1.0 MeV. The numerical values of the readout noise at the SLHC can be estimated to be increased by a factor of $\sqrt{10}$.

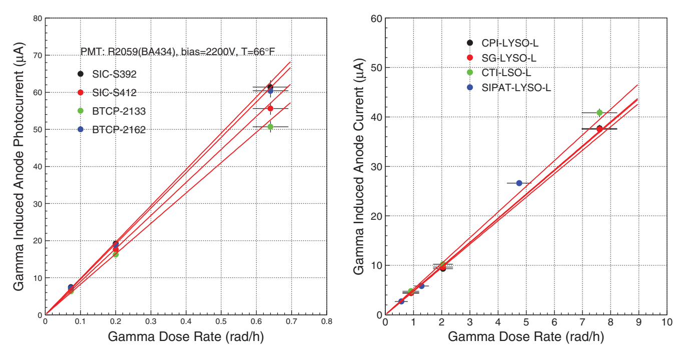

Fig. 11. γ-ray induced anode photo-current is shown as as a function of dose rate applied to the PWO (left) and LSO/LYSO (right) samples.

V. SUMMARY

γ-ray induced radiation damage in large size LSO/LYSO and PWO crystals are evaluated. No damage in the scintillation mechanism was observed in both crystals. While the γ-ray induced damage in PWO crystals recovers at the room temperature, leading to a dose rate dependent damage, LSO/LYSO shows no recovery so no dose rate dependence. Light output loss was found 26% after 10 krad with a dose rate of 400 rad/h for PWO, and 12% after 1 Mrad for LSO/LYSO. γ-ray induced phosphorescence was found at 10^{-5} level for PWO, and was between 10^{-3} to 10^{-4} for LSO/LYSO. Saint-Gobain

LYSO has the lowest afterglow. The equivalent readout noise induced by γ-ray dose expected at the CMS barrel and endcaps is about 2.5 MeV and 15 MeV, respectively, for PWO at the LHC. The corresponding numbers for LSO/LYSO are 0.2 MeV and 1.0 MeV.

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