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Monitoring LSO/LYSO Crystal Based Calorimeters

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Abstract. Precision light monitoring is important for keeping excellent energy resolution promised by LSO/LYSO crystals in severe radiation environment. In this paper, we report an investigation on the wavelength choice for monitoring LYSO crystal based calorimeters. Gamma-ray induced absorption and light output loss were measured for 20 cm long crystals from five different vendors. Monitoring sensitivity and divergence between crystals from different vendors were investigated. The pros and cons of two monitoring approaches using emission and excitation light and their practical implementation for a LYSO/W Shashlik test beam matrix are discussed.

1. Introduction

Because of their high density (7.4 g/cm^3), short radiation length (1.14 cm), fast (40 ns) and bright (4 times BGO) scintillation, cerium doped lutetium oxyorthosilicate ($\text{Lu}_2\text{SiO}_5\text{:Ce}$, LSO) [1] and lutetium yttrium oxyorthosilicate ($\text{Lu}_{2(1-x)}\text{Y}_{2x}\text{SiO}_5\text{:Ce}$, LYSO) [2,3] crystals have attracted a broad interest in the high energy physics community pursuing precision electromagnetic calorimeter for future high energy physics experiments [4-8]. Their excellent radiation hardness against γ -rays [9, 10], neutrons [11] and charged hadrons [12] also makes them a preferred material for calorimeters to be operated in a severe radiation environment. As a result, LSO/LYSO crystals were chosen by the SuperB and Mu2e experiments to construct total absorption electromagnetic calorimeters. LSO/LYSO crystals are also proposed as active material for a Shashlik calorimeter which is currently one of the two options for the CMS forward calorimeter upgrade at the HL-LHC. Precision light monitoring is crucial for keeping excellent energy resolution promised by LYSO crystals in severe radiation environment. It is usually carried out by two approaches, either injecting light pulses around crystal's emission peak, e.g. CMS at LHC [13], or around the excitation peak, e.g. PHENIX at RHIC [14].

In this paper, we report an investigation on the wavelength choice for monitoring LSO/LYSO crystal based calorimeters. Five 20 cm long LSO/LYSO crystals from different vendors were irradiated step by step from 100 rad to 1 Mrad with γ -rays. Longitudinal transmittance, light output and longitudinal response uniformity were measured at each step. Monitoring sensitivities, defined as the ratio between the variations of longitudinal transmittance and light output, was determined as a function of wavelength for the emission approach, and was compared to that of the excitation approach. An OPOTEK Opolette 355II laser based light monitoring system with precision at a level of 0.1% was built for a LYSO/W Shashlik matrix beam test at Fermilab. It is expected that such a monitoring system will provide a solid foundation for the final monitoring system design for the proposed CMS forward calorimeter upgrade for the HL-LHC.



2. Determination of the monitoring wavelengths

2.1. Crystal transmittance and light output

Figure 1 is a photo showing 5 LSO/LYSO crystals of $20 \times 20 \times 200$ mm³ from Crystal Photonics Inc. (CPI), CTI Molecular Imaging (CTI), Saint-Gobain Corporation (SG), Shanghai Institute of Ceramics (SIC) and Sichuan Institute of Piezoelectric and Acousto-optic Technology (SIPAT). The UV excited emission spectrum was measured by using a Hitachi F4500 fluorescence spectrophotometer. The longitudinal transmittance (LT) was measured 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 is about 0.15% [15]. Figure 2 shows the emission spectra, LT and emission multiplied longitudinal transmittance (EMLT) spectra (red) which represents the overall intensity of the monitoring signal as a function of wavelength in the crystal.



Figure 1. Five $20 \times 20 \times 200$ mm³ LSO/LYSO crystals from CPI, CTI, SG, SIC and SIPAT.

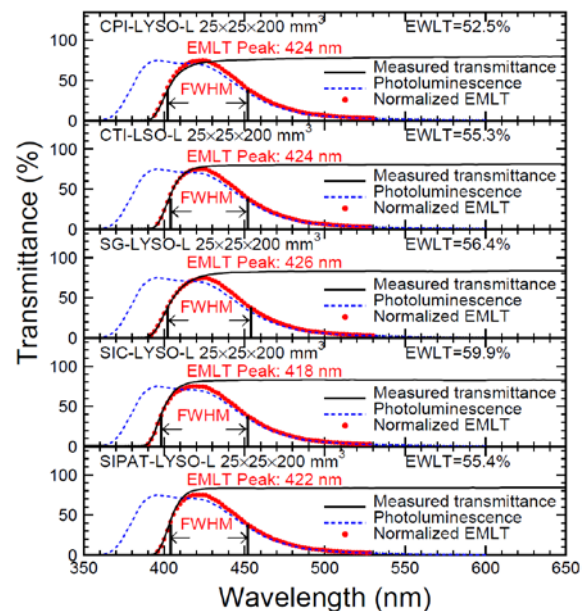


Figure 2. UV excited emission spectrum, longitudinal transmittance and EMLT.

Light output (LO) and longitudinal response uniformity (LRU) along the crystal were measured by injecting collimated γ -rays from a Na-22 source along the crystal with a coincidence trigger [4]. The light output (LO) is defined as the average of seven measurements uniformly distributed along the crystal [15]. The systematic uncertainty is less than 1% [15]. The LRU is parameterized as δ by a linear fit as follows,

$$\frac{LO}{LO_{mid}} = 1 + \delta \left(\frac{X}{X_{mid}} - 1 \right), \quad (1)$$

where LO_{mid} is the fitted value of the light output at the middle of the crystal (X_{mid}). Figure 3 shows that all crystals have good LO with LRU of better than 3% since the self-absorption effect caused by overlapping emission and transmittance is partially compensated by the cerium distribution along the crystal length [6].

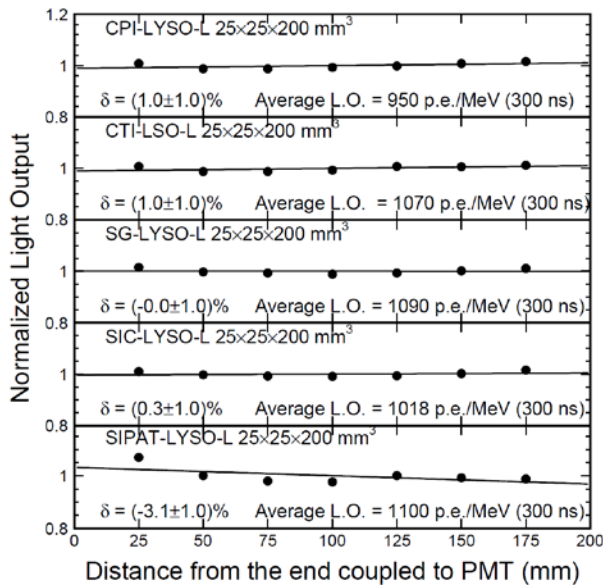


Figure 3. Initial light output and longitudinal response uniformity measured for 5 LYSO crystals.

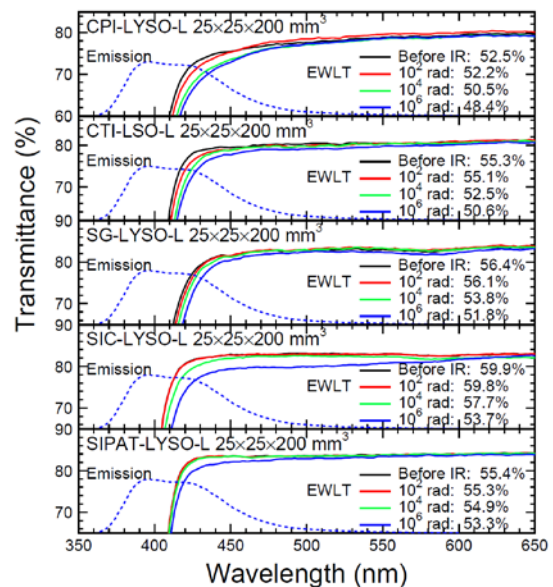


Figure 4. LT and EWLT before and after irradiation at 10^2 , 10^4 and 10^6 rad.

2.2. γ -ray induced absorption, light output loss and monitoring wavelength

All crystals were irradiated by γ -rays in steps of one order of magnitude from 100 rad to 1 Mrad. Figure 4 shows LTs before and after irradiation at 10^2 , 10^4 and 10^6 rad for each crystal. Also shown in the figure are the emission spectrum and the values of the emission weighted longitudinal transmittance (EWLT). One can see that all the crystals show consistent loss of about 10% at 1 Mrad in LT and EWLT. The longitudinal response uniformity (δ) is maintained in all five crystals up to 10^6 rad, as shown in figure 5 for crystal SG-LYSO.

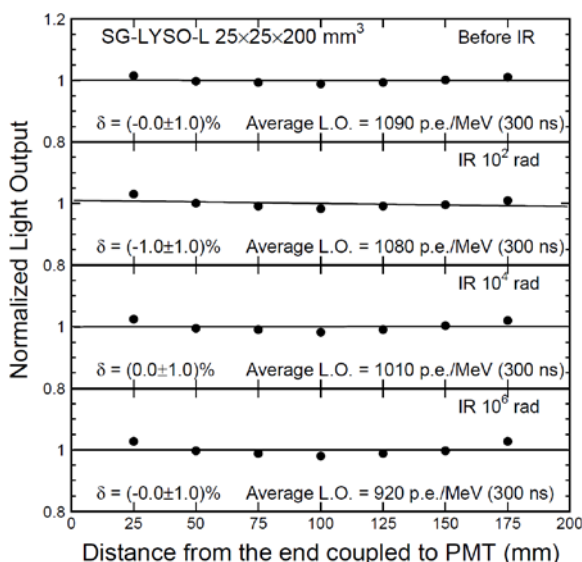


Figure 5. LO and LRU of SG-LYSO before and after irradiation at 10^2 , 10^4 and 10^6 rad.

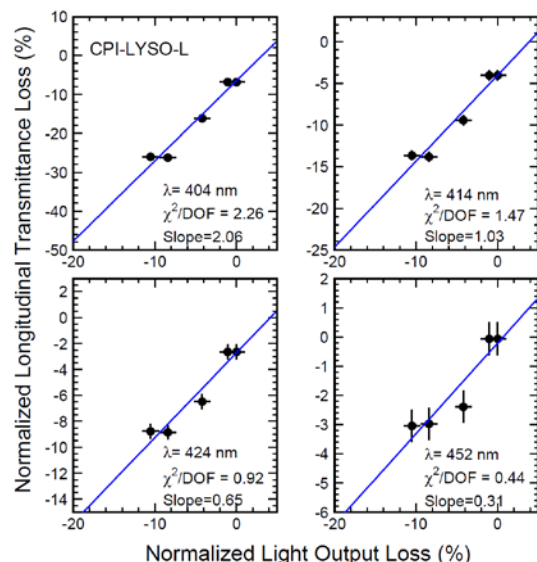


Figure 6. LO loss versus LT loss at 404, 414, 424 and 452 nm of crystal CPI-LYSO before and after irradiation at 10^2 , 10^3 , 10^4 , 10^5 and 10^6 rad.

Figure 6 shows the relations between the losses in LO and LT at different wavelengths for CPI-LYSO. A linear fit determines the slope, which is defined as the monitoring sensitivity. Figure 7 shows a similar relation between the losses of LO and EWL for five crystals. Figure 8 shows the average monitoring sensitivity (left scale) for five crystals and its divergence (right scale) defined as the rms over the average sensitivity as a function of wavelength. Also shown in the figure is the sensitivity and divergence obtained with EWL (dotted lines). Taking into account the emission light propagation (EMLT in figure 2) in the crystal, the monitoring wavelength of choice is around 420 nm for the emission approach. On the other hand, 355 nm would be the choice for the excitation approach since the main excitation band of LYSO is between 340 and 380 nm. This particular wavelength is commercially available from Nd:YAG lasers operated in third harmonic generation. As shown in Figure 8, the excitation approach (EWLT) will have a similar monitoring sensitivity and divergence as that using emission wavelength at 420 nm. The only difference would be the requirement to the intensity of the monitoring light pulse since the former involves an addition process of converting the excitation light into the emission light.

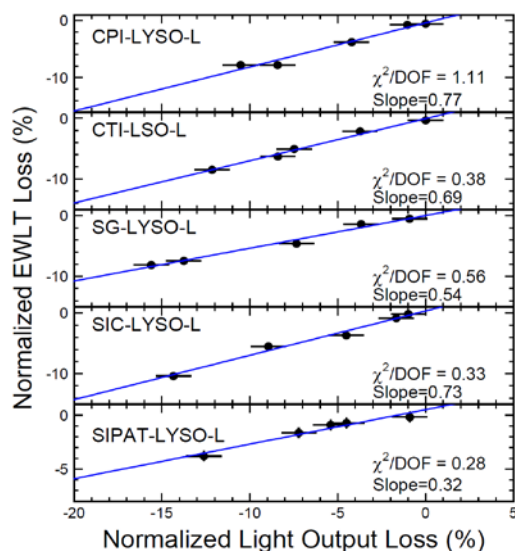


Figure 7. LO loss versus EWL loss for 5 LYSO crystals before and after irradiation at 10^2 , 10^3 , 10^4 , 10^5 and 10^6 rad.

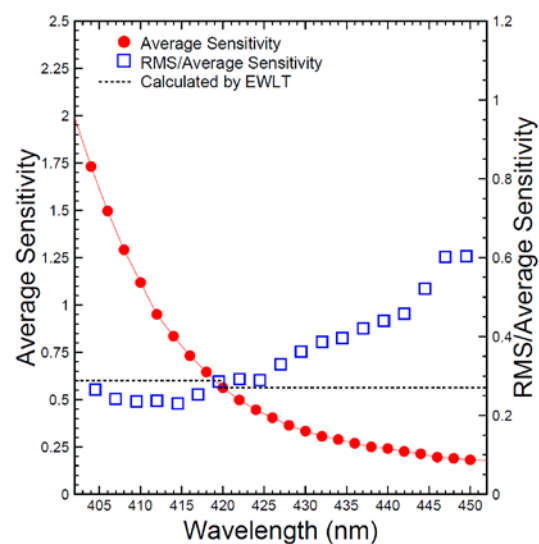


Figure 8. Average sensitivity and its divergence as a function of wavelength as well as the result using EWL.

3. Monitoring LYSO-W Shashlik tower

Figure 9 shows a tunable OPO laser (OPOTEK Opolette 355+UV) based light monitoring system constructed for a LYSO/W Shashlik matrix beam test at Fermilab. After passing through a beam sampler, fast shutter and two neutral density (ND) attenuators, the laser pulses at 420 nm were coupled into a quartz fiber of 30 m long. Two ND attenuators, one in logarithm and other variable from 1 to 100%, allow an amplitude scan in 5 orders of magnitude. The laser pulses at the other end of the transportation fiber were distributed via a 2" integrating sphere to 16 LYSO/W Shashlik towers through monitoring fibers as shown in Fig. 10.

The monitoring light is delivered to the LYSO plates through natural scattering in the quartz monitoring fibers. The total efficiency for the laser source to the photon electrons of photo-detector was measured to be about 110 dB. More efficient leaky fiber [14] is being developed. Two reference channels from the integrating sphere are read out directly by the same photo-detectors and electronics used to read out Shashlik towers.

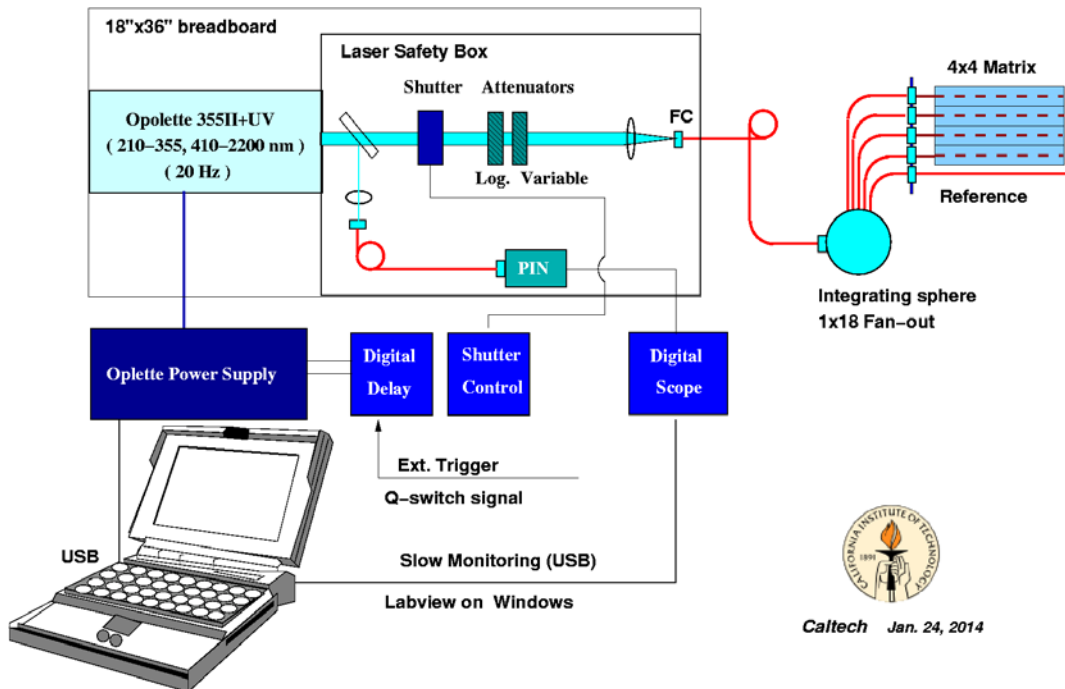


Figure 9. A schematic showing a tunable OPO laser (OPOTEK Opolette 355+UV) based light monitoring system for LYSO/W Shashlik beam test at Fermilab.

Figure 11 shows a distribution of the average ratio between two channels obtained with 500 pulses. They were readout by two identical Si Photo-detectors (Thorlabs DET10A) through a 500 MHz digital scope (Agilent 6052A). A precision at a level of 0.1% was achieved although the intrinsic rms fluctuation of the OPO laser pulse intensity was about 20%. The Opolette laser is being modified by the manufacturer to extract 355 nm directly. Monitoring performance using both 420 and 355 nm will be tested in the next run of the LYSO/W Shashlik matrix beam test at Fermilab.

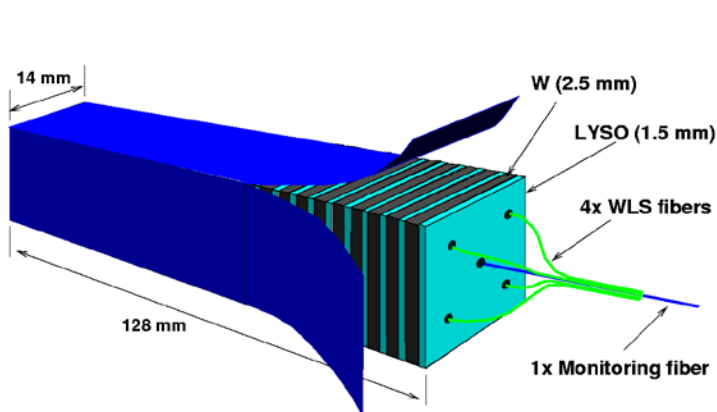


Figure 10. A schematic showing a LYSO/W Shashlik tower consisting of 30 LYSO plates of 1.5 mm thick and 29 tungsten plates of 2.5 mm.

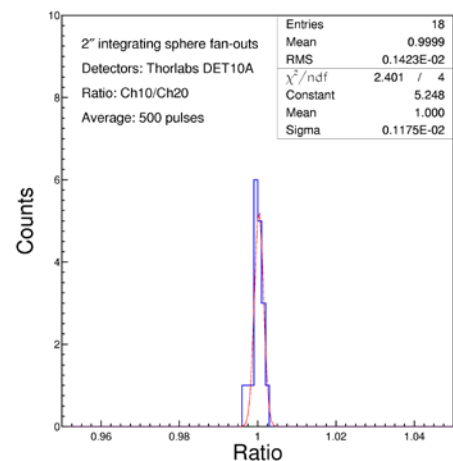


Figure 11. Average ratio of 500 pulses between two channels from the integrating sphere read out with the same Si photo-detectors.

4. Summary

LSO/LYSO crystals suffer from transparency loss, leading to light output loss. Variations of light output can be corrected by using variations of crystal response to monitoring light pulses. Precision light monitoring is important for achieving and maintaining excellent energy resolution promised by LYSO based calorimeters in severe radiation environment.

Two approaches may be used for monitoring LYSO crystal based calorimeters. One uses a wavelength around the emission peak. 420 nm is the choice for this approach. The other uses a wavelength at the excitation peak. 355 nm is the choice. The 2nd approach has three advantages: (1) crystal transparency is monitored with the entire emission spectrum; (2) crystal photo-luminescence production is also monitored and (3) cost-effective frequency tripled YAG laser at 355 nm is commercially available. The disadvantage of this approach is the requirement of high intensity monitoring light pulse.

A tunable OPO laser based light monitoring system is constructed and used for a LYSO/W Shashlik matrix beam test at Fermilab. The monitoring precision obtained with 500 pulse averages is about 0.1% although the instability of the laser pulse intensity is about 20%. It is expected that such a monitoring system will provide a solid foundation for the final monitoring system design for the proposed CMS forward calorimeter upgrade for the HL-LHC.

Acknowledgments

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