Characterization of Three LYSO Crystal Batches

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Characterization of Three LYSO Crystal Batches

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Abstract. We report on three LYSO crystal batches characterized at the Caltech crystal laboratory for future HEP experiments: Twenty-five 20 cm long crystals for the SuperB experiment; twelve 13 cm long crystals for the Mu2e experiment and 623 14×14×1.5 mm plates with five holes for a LYSO/W Shashlik matrix for a beam test at Fermilab. Optical and scintillation properties measured are longitudinal Transmittance, light output and FWHM energy resolution. Correlations between these properties are also investigated.

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 (Lu_2SiO_5:Ce, LSO) [1] and lutetium yttrium oxyorthosilicate ($Lu_{2(1-x)}Y_{2x}SiO_5$: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 gamma-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, such as the HL-LHC.

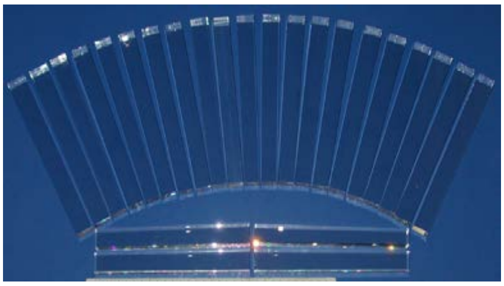

Figure 1. Twenty five 20 cm long LYSO crystals of tapered shape for SuperB

Figure 2. Twelve 13 cm long LYSO crystals for Mu2e

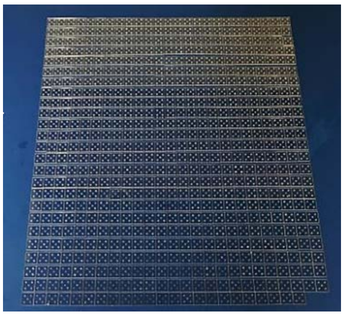

Figure 3. 623 14 x 14 x 1.5 mm LYSO plates for a LYSO/W Shashlik matrix

Figure 1 shows twenty five 20 cm long LYSO crystals of tapered geometry with about 20×20 mm^2 at the small end and 23×23 mm^2 at the large end for the SuperB experiment. They were grown by Czochralski method at Saint-Gobain (SG) Corporation, Shanghai Institute of Ceramics (SIC) and Sichuan Institute of Piezoelectric and Acousto-optic Technology (SIPAT). Figure 2 shows ten rectangular Mu2e crystals with dimension of 30×30×130 mm^3 and other two hexagonal crystals of 18.6 mm wide and 130 mm long. All the Mu2e crystals were grown at SIC. Figure 3 shows 623 14×14×1.5 mm^3 LYSO plates grown at SIC for a LYSO/W Shashlik matrix [6]. There are five holes in these plates to allow four wavelength shifters and one monitoring fiber to go through. All six faces of these crystals are polished.

The longitudinal transmittance (LT) was measured using a PerkinElmer LAMBDA 950 UV/Vis spectrophotometer with double beam, double monochromator and a large crystal compartment equipped with an integrating sphere. The systematic uncertainty in repeated measurements is 0.15%. The scintillation light output (LO) of SuperB crystals was measured by using a pair of Hamamatsu S8664-55 APDs. Their FWHM energy resolution (ER) was measured by a Hamamatsu R1306 PMT with a bi-alkali photo-cathode and a borosilicate glass window. The scintillation LO and ER were also measured by the Hamamatsu R1306 PMT for Mu2e crystals and Shashlik plates. In the LO measurement for long crystals the large (tapered crystals) or one (rectangular and hexagonal crystals) end of the crystals was coupled to the PMT with Dow Corning 200 fluid, while all other faces of the crystal were wrapped with Tyvek paper. A ^{22}Na source was used to excite the crystals, and provided the coincidence trigger. In the LO measurement for LYSO plates, one large face was coupled to the PMT with an air gap, while all other faces were wrapped with Tyvek paper. A ^{137}Cs source was used to excite the crystals. The γ-ray peak positions were obtained by a simple Gaussian fit. The systematic uncertainty in repeated measurements is less than 1%.

2. Properties of Long LYSO Crystals for the SuperB and Mu2e Experiments

2.1 Longitudinal Transmittance and Emission Weighted Longitudinal Transmittance

Figure 4 shows the LT at 420 nm for the SuperB LYSO crystals with divergences of less than 2% for crystals produced by each vendor. Among three venders SIPAT crystals have better average LT at 420 nm. Figure 5 shows the LT at 420 nm for the Mu2e LYSO crystals. Rectangular and hexagonal crystals have consistent LT with an overall divergence of less than 1%, where two crystals of different shape cut from the same ingot are shaded with red color. All crystals have LT at 420 nm better than the 75% specification, indicating good optical quality.

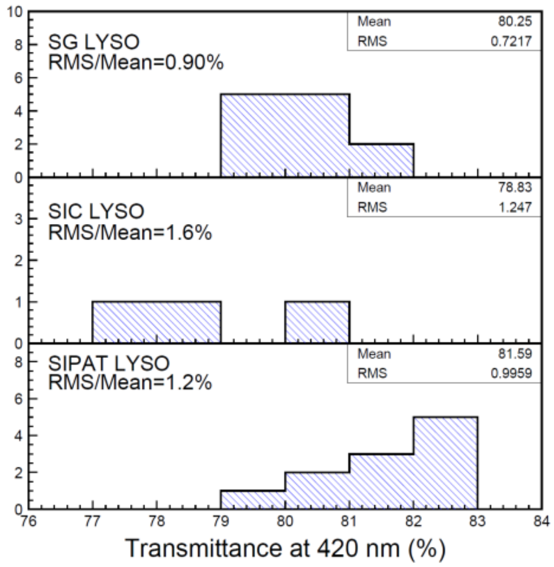

Figure 4. LT at 420 nm measured for twety five SuperB LYSO crystals

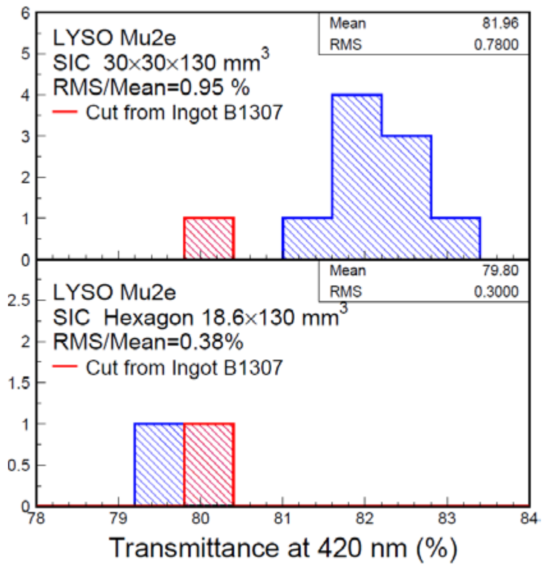

Figure 5. LT at 420 nm measured for twelve Mu2e LYSO crystals

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Figures 6 and 7 show emission weighted longitudinal transmittance (EWLT) for SuperB and Mu2e crystals respectively, where EWLT is defined as [4]:

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

EWLT presents crystal transmittance in the entire emission spectrum so is a better representation for crystal's transparency than the transmittance at 420 nm. Figure 6 shows that crystals grown at Saint-Gobain and SIPAT have better EWLT than that from SIC. Figure 7 shows that the rectangular and hexagon crystals have consistent EWLT, where two crystals cut from the same ingot are shaded with red color. A larger divergence for EWLT than the LT at 420 nm was observed since EWLT is affected by both transmittance and the UV cutoff wavelength, which is affected by the cerium concentration in the crystal [6]. A small divergence at a level of 1.7% was observed for the Saint-Gobain crystals as well as the Mu2e SIC crystals, indicating consistent cerium doping in these batches.

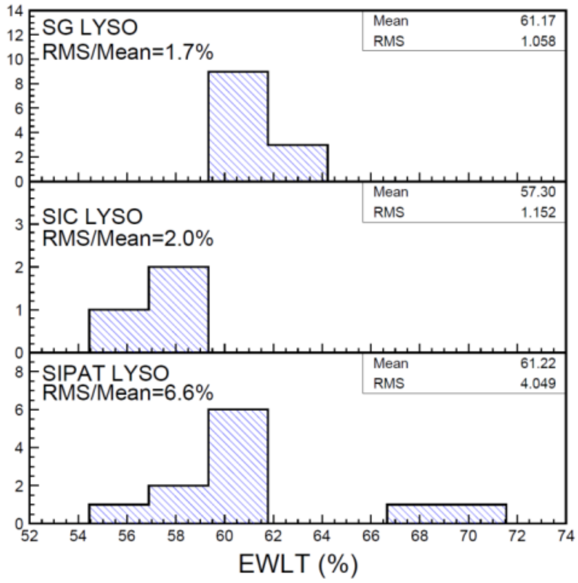

Figure 6. EWLT measured for twenty five SuperB LYSO crystals

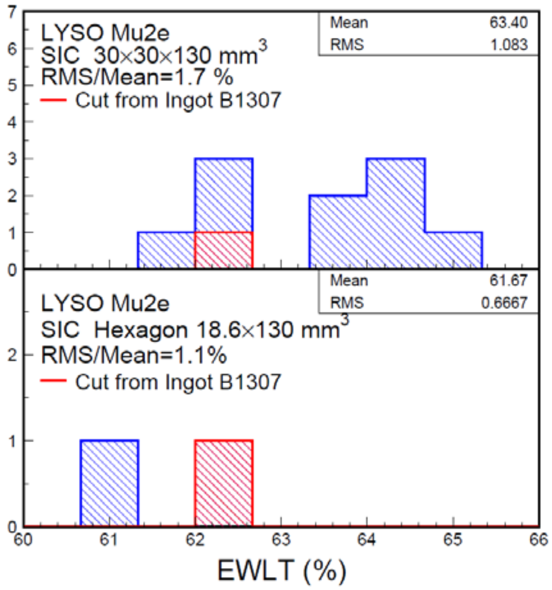

Figure 7. EWLT measured for twelve Mu2e LYSO crystals

2.2 Light Output and FWHM Energy Resolution

Figure 8 shows the LO measured by a pair of Hamamatsu S8664-55 APDs for twenty five SuperB LYSO crystals. While the SIPAT crystals have the best LO among three vendors, the Saint-Gobain crystals have the best consistency at about 3%. Figure 9 shows the LO measured by a Hamamatsu R1306 PMT with a divergence of less than 6% for twelve Mu2e crystals. The rectangular crystals appear to have higher LO than hexagonal ones cut from the same ingot. Further investigation, including a detailed ray-tracing simulation, however, is needed to understand this difference.

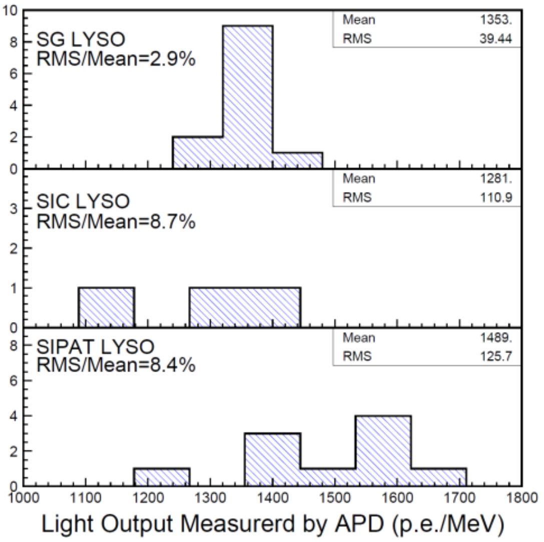

Figure 8. LO measured by APD for twenty five SuperB LYSO crystals

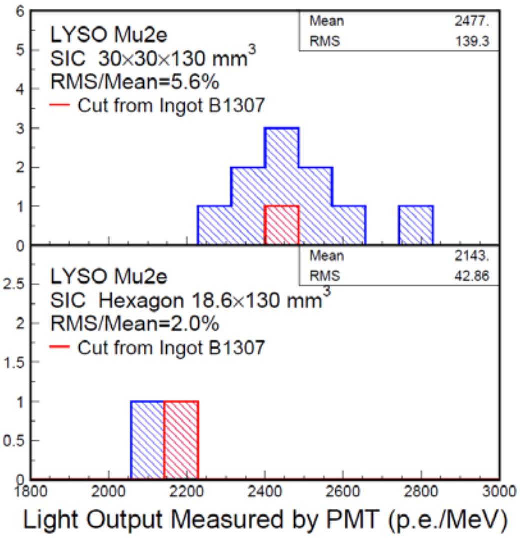

Figure 9. LO measured by PMT for twelve Mu2e LYSO crystals

Figure 10 shows the FWHM ER measured by a Hamamatsu R1306 PMT for twenty five SuperB crystals. The Saint-Gobain crystals have the best ER with a divergence of less than 2%. Figure 11 shows the FWHM ER measured by the Hamamatsu R1306 PMT for twelve Mu2e crystals. Consistent ER between the rectangular and hexagonal crystals is observed.

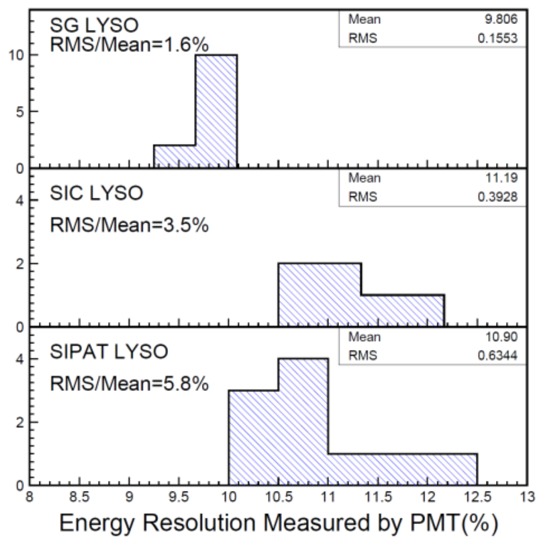

Figure 10. ER measured by PMT for twenty five SuperB LYSO crystals

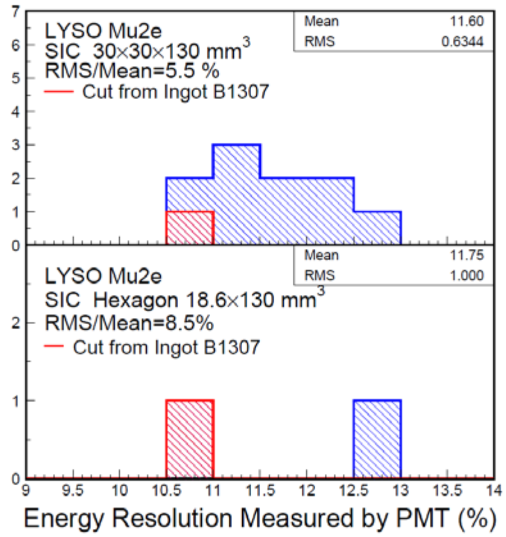

Figure 11. ER measured by PMT for twelve Mu2e LYSO crystals

2.3 Correlations between the Optical and Scintillation Properties

Figure 12 shows a slight correlation observed between the LO and the LT at 420 nm for twenty five SuperB crystals. Also shown in the figure is the corresponding linear correlation coefficients (CC), defined as [13]:

$$\mathrm{CC} = \frac{\sum(x-\bar{x})(y-\bar{y})}{\sqrt{\sum(x-\bar{x})^2 \sum(y-\bar{y})^2}} \qquad (2)$$

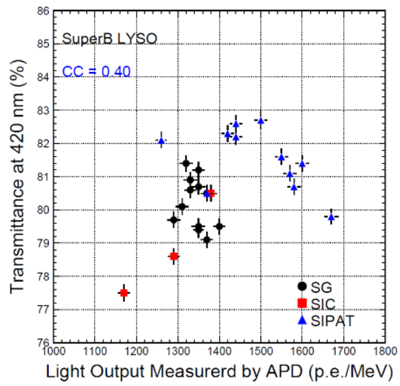

Figure 12. Correlation between the LO and the LT at 420 nm of 25 SuperB crystals

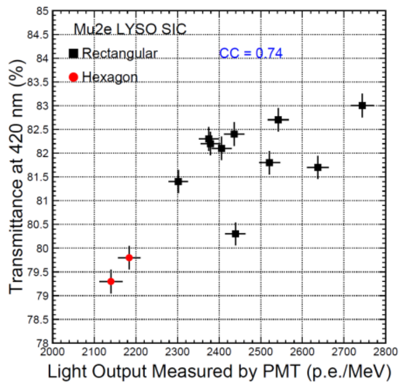

Figure 13. Correlation between the LO and the LT at 420 nm of 12 Mu2e crystals

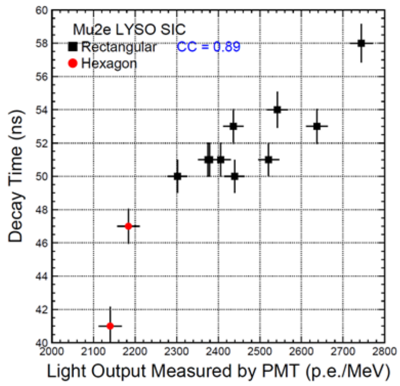

Figure 14. Correlation between the LO and the Decay time of 12 Mu2e crystals

Figure 13 shows a higher positive correlation coefficient at 74% observed between the LO and the LT at 420 nm for twelve Mu2e crystals than 40% observed for the SuperB crystals because of single crystal vendor. This positive correlation indicates that LO of long LYSO crystals is affected by their optical transparency through a light propagation process in the crystal. Figure 14 shows a strong positive correlation at 90% observed between the LO and the decay time for twelve Mu2e crystals. This positive correlation indicates that the decay time obtained by fitting the light output as a function of the integration time is affected by the light propagation in the crystal.

3. Properties of LYSO Plates for a LYSO/W Shashlik Test Beam Matrix

Figure 15 shows the LO measured by a Hamamatsu R1306 PMT for 623 LYSO plates for a LYSO/W Shashlik test beam matrix [6]. The plates can be divided into two groups according to their LO. While the high peak shows 3,284 p.e./MeV with a divergence of 3.6%, the 15% lower peak shows 2,793 p.e./MeV with a divergence of 3.2%. Plates in these two groups are actually from different ingots according to the manufacture. Figure 16 shows the FWHM ER measured for all plates, which can also be divided in two groups. The average ER value of the better group is 9.1% with divergence of 6.6% and that of the other group is 11.6% with divergence of 7.0%. Figure 17 shows a negative correlation between the light output and the energy resolution as expected.

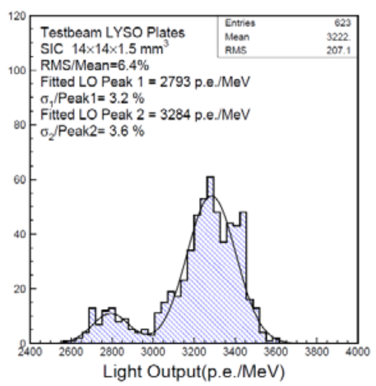

Figure 15. LO of 623 LYSO plates for a Shashlik matrix

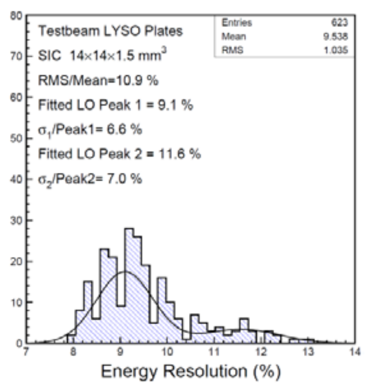

Figure 16. ER of 623 LYSO plates for a Shashlik matrix

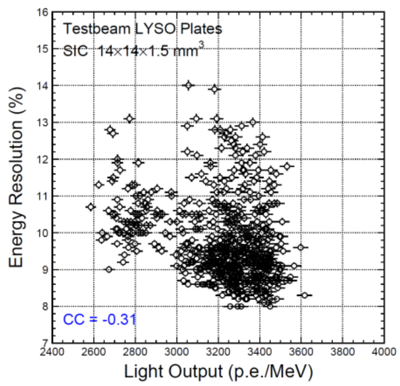

Figure 17. Correlation between the LO and the ER of 623 plates

Figure 18 shows very consistent transmittance at 420 nm for all LYSO plates except two with significantly lower transmittance. Figure 19 shows no correlation between the LO and the transmittance at 420 nm for these plates, indicating that the measured transmittance has negligible effect on the LO.

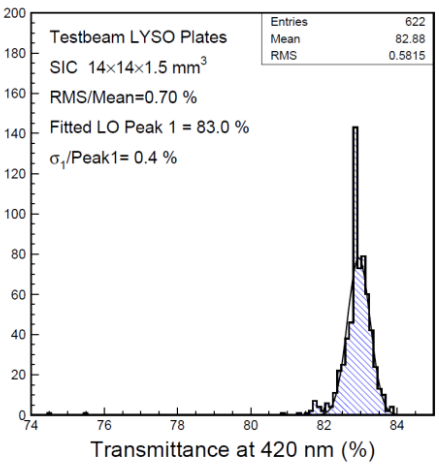

Figure 18. Transmittance at 420 nm is shown for LYSO plates foe a Shashlik matrix

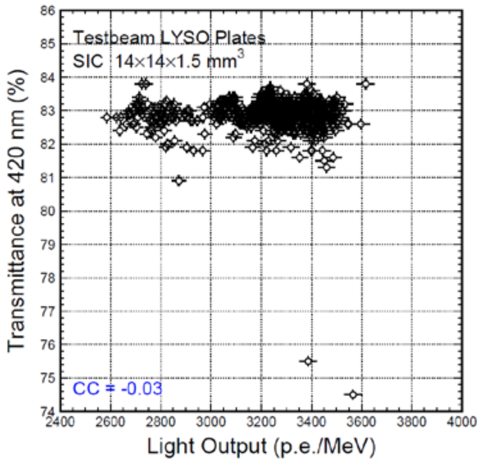

Figure 19. Correlation between the LO and the transmittance at 420 nm of 623 plates

4. Summary

Long LYSO crystals produced in industry show good transmittance exceeding 75% specification at 420 nm and good FWHM energy resolution better than 12.5% specification at 511 keV. Typical LO spread is at a level of 6% for long crystals, which may be reduced to about 3% in mass production. Correlations are observed between the LO and the LT at 420 nm as well as between LO and decay time for long LYSO crystals. A slight anti-correlation was observed between the LO and the energy resolution for 14×14×1.5 mm LYSO plates. Results of these investigations indicate that the quality of LYSO crystals grown in industry is adequate for future HEP calorimeters at both the energy and intensity frontiers.

Acknowledgments

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