Monitoring LYSO Crystals for the Mu2e Experiment

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**Experiments**

- Properties measured at room temperature before after irradiation: longitudinal transmittance (LT) & light output (LO).
- Step by step irradiations by $\gamma$-rays: 100, 1K, 10K, 100K and 1M rad.

**LYSO Samples Investigated**

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>Dimension (mm$^3$)</th>
<th>Polish</th>
</tr>
</thead>
<tbody>
<tr>
<td>CPI-LYSO-L</td>
<td>$25 \times 25 \times 200$</td>
<td>Six faces polished</td>
</tr>
<tr>
<td>CTI-LSO-L</td>
<td>$25 \times 25 \times 200$</td>
<td>Six faces polished</td>
</tr>
<tr>
<td>SG-LYSO-L</td>
<td>$25 \times 25 \times 200$</td>
<td>Six faces polished</td>
</tr>
<tr>
<td>SIC-LYSO-L</td>
<td>$25 \times 25 \times 200$</td>
<td>Six faces polished</td>
</tr>
<tr>
<td>SIPAT-LYSO-L</td>
<td>$25 \times 25 \times 200$</td>
<td>Six faces polished</td>
</tr>
</tbody>
</table>
Excitation, Emission & Transmittance

Photo-luminescence spectra for 1.5 $X_0$ cube samples with peaks:

- Excitation: 358 nm
- Emission: 402 nm

Part of scintillation light is self-absorbed for long samples.
Excitation, Emission & Transmittance

Photo-luminescence spectra for 20 cm samples with peaks:

Excitation: 358 nm
Emission: 402 nm

The cut-off wavelength of the transmittance is red-shifted because of the self-absorption.
EMLT (Emission Multiplied Longitudinal Transmittance):
\[ \text{EMLT}(\lambda) = \text{Em}(\lambda) \times \text{LT}(\lambda). \]

The average peak position of EMLT is at 423 nm.

The average FWHM of EMLT is 48 nm: from 404 nm to 452 nm.

EWLT (Emission Weighted Longitudinal Transmittance),
\[ \text{EWLT} = \int \text{Em}(\lambda) \times \text{LT}(\lambda) d\lambda, \]
represents the transparency for the entire emission spectrum.
Light output (LO) is defined as the average of seven measurements uniformly distributed along the sample.

All samples have good LO with light response uniformity (LRU) of better than 3%: the self-absorption effect is compensated by [Ce].
Effect of Cerium Segregation

It is known that cerium concentration along long LYSO crystals is not uniform, causing non-uniformity up to 10% at two ends, indicating up to 5% variation in $\delta$ is possible because of cerium segregation.

The graph shows the relationship between light output (p.e./MeV) and cerium concentration (ppmw) for SIPAT - LYSO. The equation $y = -0.0036X^2 + 1.96X + 1612$ is used to fit the data. The data points are shown for both cube: first batch and cube: second batch.

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Excellent Radiation Hardness in LT

Consistent & Small Damage in LT

Larger variation @ shorter $\lambda$

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**Graphs:**

- CPI-LYSO-L 25x25x200 mm$^3$
- CTI-LSO-L 25x25x200 mm$^3$
- SG-LYSO-L 25x25x200 mm$^3$
- SIPAT-LYSO-L 25x25x200 mm$^3$

**Data Points:**

- Before IR: 52.5%
- $10^2$ rad: 52.2%
- $10^4$ rad: 50.5%
- $10^6$ rad: 48.4%

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Excellent Radiation Hardness in LO

About 12% LO loss observed after 1 Mrad irradiation in all samples with LRU maintained. It can be corrected by light monitoring.
If scintillation mechanism is not damaged, light pulses with a wavelength close to the emission peak would be effective to monitor variations of crystal transparency.

CMS at LHC, for example, selects ~440 nm for PWO crystal monitoring (slide 15).
LT Loss vs. LO Loss after Irradiation

- SG-LYSO-L: $\lambda = 404 \text{ nm}$, $\chi^2/\text{DOF} = 1.78$, Slope = 1.78
- SIC-LYSO-L: $\lambda = 404 \text{ nm}$, $\chi^2/\text{DOF} = 1.65$, Slope = 1.82
- $\lambda = 414 \text{ nm}$, $\chi^2/\text{DOF} = 0.86$, Slope = 0.81
- $\lambda = 424 \text{ nm}$, $\chi^2/\text{DOF} = 0.24$, Slope = 0.40
- $\lambda = 452 \text{ nm}$, $\chi^2/\text{DOF} = 0.05$, Slope = 0.08
- $\lambda = 424 \text{ nm}$, $\chi^2/\text{DOF} = 1.09$, Slope = 0.44
- $\lambda = 452 \text{ nm}$, $\chi^2/\text{DOF} = 0.76$, Slope = 0.26
LT Loss vs. LO Loss after Irradiation

Fitting function: \[ \frac{LT_{IR} - LT_0}{LT_0} = \text{Slope} \times \frac{LO_{IR} - LO_0}{LO_0} \]

The slope represents the monitoring sensitivity at a particular wavelength.
LT Loss vs. LO Loss after Irradiation

- **SIPAT-LYSO-L**
  - $\lambda = 404$ nm
  - $\chi^2$/DOF = 0.45
  - Slope = 0.87

- **SIPAT-LYSO-L**
  - $\lambda = 414$ nm
  - $\chi^2$/DOF = 0.51
  - Slope = 0.51

- **SIPAT-LYSO-L**
  - $\lambda = 424$ nm
  - $\chi^2$/DOF = 0.19
  - Slope = 0.30

- **SIPAT-LYSO-L**
  - $\lambda = 452$ nm
  - $\chi^2$/DOF = 0.13
  - Slope = 0.13
The monitoring sensitivity increases at shorter wavelength because of larger variation in transparency. A shorter wavelength is preferred for a better sensitivity. A longer wavelength is preferred for a larger monitoring light signal. The EMLT peak position at ~423 nm would be the choice. Blue DPSS lasers, however, are expensive. See slide 18.
The observed degradation is well understood.

CMS PWO Monitoring Response

CMS Preliminary 2011-2012

LHC luminosity ($10^{33} \text{ cm}^{-2} \text{ s}^{-1}$)

Relative response

$|\eta| < 1.4$  
$1.5 < |\eta| < 1.8$  
$1.8 < |\eta| < 2.1$  
$2.1 < |\eta| < 2.4$  
$2.4 < |\eta| < 2.7$  
$2.7 < |\eta|$
2012 CMS Monitoring System

Photonics DP2-447 at 447 nm is added using the existing 5 x 1 switch.
CMS PWO Monitoring

<0.2% precision achieved for PWO at LHC

DPSS blue laser performance at LHC
Photonics DP2-447 Blue Laser

The price tag of the laser is @~$200k
Monitoring with Excitation Light

Light pulses with a wavelength at an excitation peak, e.g. 358 nm for LYSO, monitor both crystal transparency and scintillation light production.

PHENIX at RHIC selects 355 nm from an Nd:YAG laser for plastic scintillators (slide 22).
Monitoring Sensitivity with EWLT

RMS/Mean represents the divergence between 5 vendors

Calculated by EWLT

<table>
<thead>
<tr>
<th>Entries</th>
<th>Mean</th>
<th>RMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>0.6000</td>
<td>0.1590</td>
</tr>
</tbody>
</table>

- CPI-lyso-L: $\chi^2$/DOF = 1.11, Slope = 0.77
- CTI-LSO-L: $\chi^2$/DOF = 0.38, Slope = 0.69
- SG-lyso-L: $\chi^2$/DOF = 0.56, Slope = 0.54
- SIC-lyso-L: $\chi^2$/DOF = 0.33, Slope = 0.73
- SIPAT-lyso-L: $\chi^2$/DOF = 0.28, Slope = 0.32

Normalized EWLT Loss (%) vs Normalized Light Output Loss (%)
Choice of Monitoring Wavelength

A monitoring sensitivity at 60% level is observed for both the EWLT and the wavelength close to the emission peak.

A divergence at 25% level for crystals from five different vendors is observed for both the EWLT and the wavelength close or shorter than the emission peak.

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PHENIX Laser Monitoring System

G. David et al., IEEE TNS VOL. 45, NO. 3, JUNE (1998) 705-709

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# Required Monitoring Pulse Energies

## Two level fanout, 100 m quarts fiber, 1,000 channels & 1GeV

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Emission</th>
<th>Excitation</th>
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</thead>
<tbody>
<tr>
<td>Monitoring wavelength (nm)</td>
<td>423</td>
<td>355</td>
</tr>
<tr>
<td>LYSO light output (γ/MeV)</td>
<td>30,000</td>
<td>30,000</td>
</tr>
<tr>
<td>Dynamic range (GeV)</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Channel Number</td>
<td>1,000</td>
<td>1,000</td>
</tr>
<tr>
<td>2-Level fanout extra loss (dB)</td>
<td>24</td>
<td>24</td>
</tr>
<tr>
<td>100 m optical fiber loss (dB)</td>
<td>3</td>
<td>7</td>
</tr>
<tr>
<td>Ex-Em conversion loss</td>
<td>0</td>
<td>3</td>
</tr>
<tr>
<td>Total loss (dB)</td>
<td>27</td>
<td>34</td>
</tr>
<tr>
<td>Laser pulse energy (μJ)</td>
<td>7</td>
<td>42</td>
</tr>
</tbody>
</table>

Six times monitoring pulse intensity requirement for the excitation approach

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Cost-Effective UV Lasers at 355 nm

Frequency tripled DPSS YAG laser at 355 nm: @ $50k

<table>
<thead>
<tr>
<th>Parameters</th>
<th>XHE11903</th>
<th>Opolette 355 II+UV</th>
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</thead>
<tbody>
<tr>
<td>Pulse energy (mJ) at 355 nm</td>
<td>2</td>
<td>0.06</td>
</tr>
<tr>
<td>Repetition rate (Hz)</td>
<td>1 - 100</td>
<td>20</td>
</tr>
<tr>
<td>Pulse width (ns)</td>
<td>3</td>
<td>5</td>
</tr>
<tr>
<td>Pulse Stability (rms, %)</td>
<td>&lt; 5</td>
<td>~20</td>
</tr>
<tr>
<td>Divergency (full angle, mrad)</td>
<td>2</td>
<td>6</td>
</tr>
<tr>
<td>Beam diameter (1/e2)</td>
<td>4</td>
<td>3</td>
</tr>
<tr>
<td>Jitter (ns)</td>
<td>N/A</td>
<td>~1</td>
</tr>
<tr>
<td>TEM quality (M2)</td>
<td>5</td>
<td>N/A</td>
</tr>
<tr>
<td>Polarization</td>
<td>Random</td>
<td>Linear</td>
</tr>
<tr>
<td>Pump source</td>
<td>Diodes</td>
<td>Pulsed lamp</td>
</tr>
<tr>
<td>Cooling</td>
<td>Air</td>
<td>Internal water loop</td>
</tr>
<tr>
<td>Dimensions (cm)</td>
<td>18×9×8</td>
<td>36×14×44</td>
</tr>
</tbody>
</table>
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 transparency measured by using a light monitoring system.

Two approaches may be used for LYSO monitoring. One uses a wavelength around the emission peak, which is adapted by CMS for monitoring PWO crystals at LHC. The other uses a wavelength at an excitation peak, which is adapted by PHENIX for monitoring plastic scintillators in a Shashlik ECAL at RHIC.

The 2\textsuperscript{nd} approach has two advantages: (1) both crystal transparency and scintillation production are monitored; and (2) cost-effective frequency tripled DPSS YAG laser at 355 nm is commercially available. This approach, however, has one disadvantage: about six times more monitoring pulse intensity requirement because of the conversion of excitation to emission and the loss in quarts fiber at 355 nm as compared to 420 nm.