Update on LYSO Studies

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SIPAT Ø60 x 250 mm LYSO Ingots

Sep, 2007
Production of LYSO at SIPAT

Growth is mature. R&D on following Issues:

• Optimization of Cerium doping;

• Light response uniformity.
LYSO Longitudinal Uniformity

Good light response uniformity is crucial for a crystal calorimeter to achieve its designed energy resolution at high energies. The distribution of the cerium activator, however, is not uniform along the crystal.

Sipat’s Φ60 x 250 mm ingot may be cut to two SuperB crystals, significantly increasing the ingot usage. The key issue: longitudinally uniformity.
Cube Samples from SIPAT

Two ingots grown by Czochralski method at SIPAT were cut to 11 & 12 cubes of 1.7 cm.

1st ingot with high cerium
11 cubes of 17 (1.5 \(X_0\)) mm\(^3\)

2nd ingot with low cerium
12 cubes of 17 (1.5 \(X_0\)) mm\(^3\)
Consistent excitation (red) and emission (blue) spectra observed from seed to tail for both ingots.
Transmission Spectra

Transmissions are position dependent:

\[ \text{EWLT} = \frac{\int L_T(\lambda) E_m(\lambda) d\lambda}{\int E_m(\lambda) d\lambda} \]

1\textsuperscript{st} ingot

2\textsuperscript{nd} ingot

SIPAT - LYSO

Emission

Cutoff wavelength

Transmittance (%)

Wavelength (nm)

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Correlations exist between EWLT/cut-off and cube position, indicating possible correlation with the cerium concentration.
Light Outputs are position dependent, indicating possible correlation with the cerium concentration.
Energy resolutions are position dependent, indicating possible correlation with the cerium concentration.
L.O. and E.R. versus Position

Correlations exist between L.O./E.R. and cube position.

1st ingot

2nd ingot

Distance to the seed end (mm)

Light Output (p.e./MeV)

Energy Resolution (%)
Concentrations of cerium and yttrium were measured by using Glow Discharge Mass Spectrometry (GDMS) analysis. Segregation coefficients of cerium and yttrium in LSO were fitted to be 0.30 and 0.88 respectively:

\[
\ln \frac{C_{\text{crystal}}}{C_0} = \ln k_e + (k_e - 1)\ln (1 - g)
\]
Strong correlations observed between EWLT and the cut-off wavelength versus the Ce concentration.
A ‘plateau’ observed between 125 ~ 325 ppm, indicating a possibility to grow uniform crystal with optimized Ce doping. This observation consists with private data from C. Melcher.
Phosphorescence vs. Ce Concentration

Correlation observed between radiation induced phosphorescence and the Ce concentration, but not before gamma-ray irradiation.

Before irradiation

After irradiation

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No correlations were observed between the yttrium concentrations and EWLT, the light output and the intensity of phosphorescence after gamma-ray irradiations.
Light Response Uniformity

2.5 x 2.5 x 20 cm
Samples tested for their light response uniformity

\[ Y = Y_{mid} \left[ 1 + \delta \left( \frac{x}{x_{mid}} - 1 \right) \right] \]
Diverse light response uniformities observed with $\delta = 1.2/-3.3, 4.4/-3.9, -0.5/-2.8$ for CPI, CTI & SG respectively.
Progress Achieved in L.R.U.

The L.R.U. of SIPAT samples is improved from 0.9/-2.4 to -1.9/-2.2, opening a possibility to cut two crystals from one ingot. 1st SIC sample shows good L.R.U.: -0.4/-1.4

Before Optimization  After Optimization  1st SIC Sample

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Radiation Effect on L.R.U.: CTI-LSO-L1

Consistent uniformity before and after irradiations. Different slopes between PMT & APD readout.
Radiation Effect on L.R.U.: CTI-LSO-L1

Consistent uniformity before and after irradiations. Different slopes between PMT & APD readout.
Radiation Effect on L.R.U.: SG-LYSO-L3

Consistent uniformity before and after irradiations. Difference slopes between PMT & APD readout.
Radiation Effect on L.R.U.: SG-LYSO-L3

Consistent uniformity before and after irradiations
Difference slopes between PMT & APD readout.

- SG-LYSO-L3 NID end coupled to PMT Before I.R.
  \[ \delta = (-3.1 \pm 1.0) \]
  Average L.O. = 1300 p.e./MeV

- SG-LYSO-L3 NID end coupled to APD Before I.R.
  \[ \delta = (-5.4 \pm 1.5) \]
  Average L.O. = 1350 p.e./MeV

- SG-LYSO-L3 NID end coupled to PMT 10^6 rad
  \[ \delta = (-3.9 \pm 1.0) \]
  Average L.O. = 1290 p.e./MeV

- SG-LYSO-L3 NID end coupled to APD 10^6 rad
  \[ \delta = (-7.4 \pm 1.5) \]
  Average L.O. = 1240 p.e./MeV

- SG-LYSO-L3 NID end coupled to PMT 10^5 rad
  \[ \delta = (-4.0 \pm 1.0) \]
  Average L.O. = 1250 p.e./MeV

- SG-LYSO-L3 NID end coupled to APD 10^5 rad
  \[ \delta = (-5.6 \pm 1.5) \]
  Average L.O. = 1290 p.e./MeV

- SG-LYSO-L3 NID end coupled to PMT 10^6 rad
  \[ \delta = (-4.2 \pm 1.0) \]
  Average L.O. = 1140 p.e./MeV

- SG-LYSO-L3 NID end coupled to APD 10^6 rad
  \[ \delta = (-5.5 \pm 1.5) \]
  Average L.O. = 1200 p.e./MeV
Radiation Effect on L.R.U.: SIPAT-L5

Consistent uniformity before and after irradiations
Difference slopes between PMT & APD readout.

\[ \delta = (1.9 \pm 1.0) \quad \text{Average L.O. = 1140 p.e./MeV} \]
\[ \delta = (2.0 \pm 1.0) \quad \text{Average L.O. = 1130 p.e./MeV} \]
\[ \delta = (1.6 \pm 1.0) \quad \text{Average L.O. = 1100 p.e./MeV} \]
\[ \delta = (1.4 \pm 1.0) \quad \text{Average L.O. = 1010 p.e./MeV} \]

\[ \delta = (0.8 \pm 1.5) \quad \text{Average L.O. = 1210 p.e./MeV} \]
\[ \delta = (1.0 \pm 1.5) \quad \text{Average L.O. = 1050 p.e./MeV} \]
Radiation Effect on L.R.U.: SIPAT-L5

Consistent uniformity before and after irradiations
Difference slopes between PMT & APD readout.

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**SIPAT-LYSO-L5**

![Graph showing normalized light output vs. distance from the end coupled to PMT and APD](image)

- **PMT Readout**
  - Before I.R.: $\delta = (2.2\pm1.0)$, Average L.O. = 1140 p.e./MeV
  - $10^2$ rad: $\delta = (2.2\pm1.0)$, Average L.O. = 1130 p.e./MeV
  - $10^4$ rad: $\delta = (2.8\pm1.0)$, Average L.O. = 1190 p.e./MeV
  - $10^6$ rad: $\delta = (3.4\pm1.0)$, Average L.O. = 1020 p.e./MeV

- **APD Readout**
  - Before I.R.: $\delta = (-5.1\pm1.5)$, Average L.O. = 1190 p.e./MeV
  - $10^6$ rad: $\delta = (-6.7\pm1.5)$, Average L.O. = 1050 p.e./MeV
Radiation Effect on L.R.U.: SIC-L1

Consistent uniformity before and after irradiations
Difference slopes between PMT & APD readout.

\[ \delta = (-0.4 \pm 1.0) \quad \text{Average L.O.} = 1080 \text{ p.e./MeV} \]

\[ \delta = (-1.0 \pm 1.0) \quad \text{Average L.O.} = 1030 \text{ p.e./MeV} \]

\[ \delta = (-1.6 \pm 1.0) \quad \text{Average L.O.} = 1010 \text{ p.e./MeV} \]

\[ \delta = (-0.6 \pm 1.0) \quad \text{Average L.O.} = 870 \text{ p.e./MeV} \]
Radiation Effect on L.R.U.: SIC-L1

Consistent uniformity before and after irradiations. Difference slopes between PMT & APD readout.

- SIC-LYSO-L 1
  - Tail end coupled to PMT
  - Before I.R.
  - $\delta = (-1.4 \pm 1.0)$
  - Average L.O. = 1080 p.e./MeV
  - $10^7$ rad
  - $\delta = (1.2 \pm 1.0)$
  - Average L.O. = 1070 p.e./MeV
  - $10^4$ rad
  - $\delta = (0.5 \pm 1.0)$
  - Average L.O. = 1050 p.e./MeV
  - $10^6$ rad
  - $\delta = (1.1 \pm 1.0)$
  - Average L.O. = 920 p.e./MeV

- SIC-LYSO-L 1
  - Tail end coupled to APD
  - Before I.R.
  - $\delta = (6.1 \pm 1.5)$
  - Average L.O. = 1100 p.e./MeV
  - $10^9$ rad
  - $\delta = (4.4 \pm 1.5)$
  - Average L.O. = 930 p.e./MeV

Distance from the end coupled to PMT (mm) vs. Normalized Light Output

Distance from the end coupled to APD (mm) vs. Normalized Light Output
## LSO/LYSO L.R.U. Summary

Consistent L.R.U. before & after irradiations. Different slopes between PMT & APD readout. Investigations are under way.

<table>
<thead>
<tr>
<th>ID</th>
<th>Integrated dose (rad)</th>
<th>$\delta$ % (A or Seed end coupling)</th>
<th>$\delta$ (B or Tail end coupling)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>PMT (±1)</td>
<td>APD (±1.5)</td>
</tr>
<tr>
<td>CTI-LSO-1</td>
<td>0</td>
<td>1</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>$10^6$</td>
<td>-2</td>
<td>3</td>
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<td>-0.5</td>
<td>1.2</td>
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<tr>
<td></td>
<td>$10^6$</td>
<td>-2.1</td>
<td>1.1</td>
</tr>
<tr>
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<td>-1.9</td>
<td>0.8</td>
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<td></td>
<td>$10^6$</td>
<td>-1.4</td>
<td>1.0</td>
</tr>
<tr>
<td>SIC-LYSO-1</td>
<td>0</td>
<td>-0.4</td>
<td>-4.7</td>
</tr>
<tr>
<td></td>
<td>$10^6$</td>
<td>-0.6</td>
<td>-5.6</td>
</tr>
</tbody>
</table>
Ray-Tracing Simulation

LYSO crystals
$2.5^2 \times 20 \times 2.5^2 \text{ cm}^3$

PMT / APD

Silicon oil
$N=1.52$

Tyvek paper
Different area coverage of PMT (2.5 × 2.5 cm$^2$) and APD (2 × 0.5 × 0.5 cm$^2$) determines the different light collection efficiencies, but has no effect on the L.R.U.
Consistent L.R.U. by PMT & Mask

Data confirm simulation: no geometry effect.

PMT without Mask

PMT with Mask (APD coverage)

**Graphs:**

- **SIPAT-LYSO-L 5**
  - As received
  - Seed end coupled to PMT
  - Average L.O. = 1140 p.e./MeV (300 ns)
  - $\delta = (-1.9 \pm 1.0)$

- **SIPAT-LYSO-L 5**
  - As received
  - Tail end coupled to PMT
  - Average L.O. = 1140 p.e./MeV (300 ns)
  - $\delta = (-2.2 \pm 1.1)$

- **SIPAT-LYSO-L 5**
  - Seed end coupled to PMT
  - with mask

- **SIPAT-LYSO-L 5**
  - Tail end coupled to PMT
  - with mask

**Legend:**

- Distance from the end coupled to PMT (mm)
- Normalized Light Output

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L.R.U. by PMT and APD for BGO

No difference between PMT & APD readout. This seems a particular issue for LYSO.

\[ \delta = (0.4 \pm 1.0) \]
Average L.O. = 200 p.e./MeV (1000 ns)

Distance from the end coupled to PMT (mm)

\[ \delta = (0.1 \pm 1.0) \]
Average L.O. = 200 p.e./MeV (1000 ns)

Distance from the end coupled to APD (mm)

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Excitation, Emission, Transmission

It seems not caused by self-absorption

\[ T_s = (1 - R)^2 + R^2 (1 - R)^2 + \ldots = \frac{(1 - R)}{(1 + R)}, \]

with

\[ R = \frac{(n_{\text{crystal}} - n_{\text{air}})^2}{(n_{\text{crystal}} + n_{\text{air}})^2}. \]


No Self-absorption: BGO, PWO, BaF₂, NaI(Tl) and CsI(Tl)

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Emission Weighted QE

It may be due to the QE difference between PMT & APD. Investigation is under way with optical filters.
300°C Annealing: Absorption in SIC-L1

Transverse transmittance indicates color centers (impurities?) at the tail end after 300°C annealing.
500°C Annealing eliminated Absorption

Fully recovered after 500°C thermal annealing
300°C Sufficient for SIPAT-LYSO-L5

Fully recovered after 300°C annealing

![Graph showing transmittance and light output over wavelength and time](image)
Summary

- LYSO crystals with blight, fast scintillation and good radiation resistance is an excellent material for SuperB ECAL endcap.

- The optimized cerium concentration in LYSO was found to be between 125 and 325 ppmw. An optimized SIPAT sample shows a possibility of cutting one ingot into two tapered crystals.

- Different L.R.U. was found between the PMT and APD readout, which can not be explained by detector geometry. Investigation is under way to understand the nature of this difference.

- The 1st SIC sample shows adequate L.R.U.. Its thermal annealing induced absorption is suspected to be caused by contamination.