LSO/LYSO Crystals for HEP Applications

Ren-Yuan Zhu
California Institute of Technology
September 13, 2011
Why LSO/LYSO for HEP?

LSO/LYSO is a bright (200 times of PWO), fast (40 ns) crystal, and is a radiation-hard scintillator. The light output loss of 20 to 28 cm long crystals is at a level of 10% after 1 Mrad \( \gamma \)-ray irradiations, much better than all other crystal scintillators.

The longitudinal non-uniformity issue caused by crystal geometry, self-absorption and cerium segregation is addressed by roughening one side surface for uniformization.

Mass production capability exists in industry. Emerging growers in China would help in reducing the crystal cost.

# Crystals for HEP Calorimeters

<table>
<thead>
<tr>
<th>Crystal</th>
<th>NaI(Tl)</th>
<th>CsI(Tl)</th>
<th>CsI(Na)</th>
<th>CsI</th>
<th>BaF$_2$</th>
<th>CeF$_3$</th>
<th>BGO</th>
<th>PWO(Y)</th>
<th>LSO(Ce)</th>
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<tbody>
<tr>
<td>Density (g/cm$^3$)</td>
<td>3.67</td>
<td>4.51</td>
<td>4.51</td>
<td>4.51</td>
<td>4.89</td>
<td>6.16</td>
<td>7.13</td>
<td>8.3</td>
<td>7.40</td>
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<tr>
<td>Melting Point (°C)</td>
<td>651</td>
<td>621</td>
<td>621</td>
<td>621</td>
<td>1280</td>
<td>1460</td>
<td>1050</td>
<td>1123</td>
<td>2050</td>
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<td>Radiation Length (cm)</td>
<td>2.59</td>
<td>1.86</td>
<td>1.86</td>
<td>1.86</td>
<td>2.03</td>
<td>1.70</td>
<td>1.12</td>
<td>0.89</td>
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<td>3.57</td>
<td>3.57</td>
<td>3.57</td>
<td>3.10</td>
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<td>2.00</td>
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<td>Interaction Length (cm)</td>
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<td>39.3</td>
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<td>Refractive Index $^a$</td>
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<td>1.79</td>
<td>1.95</td>
<td>1.95</td>
<td>1.50</td>
<td>1.62</td>
<td>2.15</td>
<td>2.20</td>
<td>1.82</td>
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<tr>
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<td>Slight</td>
<td>Slight</td>
<td>Slight</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
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<td>Luminescence $^b$ (nm)</td>
<td>410</td>
<td>550</td>
<td>420</td>
<td>420</td>
<td>300</td>
<td>340</td>
<td>480</td>
<td>425</td>
<td>402</td>
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<td>(at peak)</td>
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<td>Decay Time $^b$ (ns)</td>
<td>245</td>
<td>1220</td>
<td>690</td>
<td>30</td>
<td>650</td>
<td>30</td>
<td>300</td>
<td>30</td>
<td>40</td>
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<td>Light Yield $^b,c$ (%)</td>
<td>100</td>
<td>165</td>
<td>88</td>
<td>3.6</td>
<td>36</td>
<td>7.3</td>
<td>21</td>
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<td>85</td>
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<tr>
<td>d(LY)/dT $^b$ (%/°C)</td>
<td>-0.2</td>
<td>0.4</td>
<td>0.4</td>
<td>-1.4</td>
<td>-1.9</td>
<td>0</td>
<td>-0.9</td>
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</table>

$^a$ at peak of emission; $^b$ up/lown row: slow/fast component; $^c$ QE of readout device taken out.

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Crystal Ball</th>
<th>BaBar</th>
<th>BELLE</th>
<th>BES III</th>
<th>KTeV</th>
<th>(L$^*$) (GEM) TAPS</th>
<th>L3</th>
<th>BELLE</th>
<th>CMS</th>
<th>ALICE</th>
<th>RANNA</th>
<th>Mu2e</th>
<th>SuperB</th>
<th>CMS?</th>
</tr>
</thead>
</table>

September 13, 2011

Talk given at SCINT2011, Giessen, by Ren-yuan Zhu, Caltech
Crystal Density: Radiation Length

1.5 $X_0$ Samples:
Hygroscopic: Sealed
Non-hygro: Polished

Full Size Crystals:

$BaBar$ CsI(Tl): 16 $X_0$
L3 BGO: 22 $X_0$
CMS PWO(Y): 25 $X_0$
Excitation, Emission, Transmission

\[ T_s = (1 - R)^2 + R^2 (1 - R)^2 + \ldots = \frac{(1 - R)}{(1 + R)}, \text{ with} \]
\[ R = \frac{(n_{\text{crystal}} - n_{\text{air}})^2}{(n_{\text{crystal}} + n_{\text{air}})^2}. \]


No Self-absorption: BGO, PWO, BaF\(_2\), NaI(Tl) and CsI(Tl)

September 13, 2011
Talk given at SCINT2011, Giessen, by Ren-yuan Zhu, Caltech
LSO & LYSO Crystal Samples

2.5 x 2.5 x 20 cm (18 $X_0$)

CTI LSO

CPI LYSO

Saint-Gobain LYSO

SIPAT-LYSO
20 cm Long LSO/LYSO under $\gamma$-Rays

Consistent radiation hardness better than other crystals

EWLT damage: 8% @ 1 Mrad

10% - 15% loss by PMT & APD
Excellent Radiation Hardness

1st 30 cm Ingot grown at SIPAT, Sep, 2009

SIPAT-LYSO-L7: 2.5 x 2.5 x 28 cm, Nov, 2009
LSO/LYSO ECAL for Mu2e

Four-vane calorimeter, comprised of 2,400 LSO/LYSO crystals of 30 x 30 x 130 mm
LYSO Endcap for Super$B$


Aiming at $10^{36}/\text{cm}^2/\text{s}$ luminosity for rare B decays

Need a fast detector with low noise at the endcap

LSO/LYSO

Need cost effective crystals

Talk given at SCINT2011, Giessen, by Ren-yuan Zhu, Caltech
The proposed SuperB ECAL endcap comprising 4,400 LYSO crystals in projective geometry.
Twenty Five Test Beam Crystals

All crystals are characterized in Caltech Crystal Laboratory
Two beam tests were carried out at CERN and Frascati
Dimensions and Surface Definition

Talk given at SCINT2011, Giessen, by Ren-yuan Zhu, Caltech
Summary: Dimension

All dimensions satisfy the tolerance specification: ±100 μm. Will move to +0/-100 μm for mass production.

September 13, 2011
Talk given at SCINT2011, Giessen, by Ren-yuan Zhu, Caltech
## Summary of SuperB Test Beam Crystals

<table>
<thead>
<tr>
<th>Caltech-ID</th>
<th>Vendor-ID</th>
<th>Test-Beam-Position</th>
<th>Type</th>
<th>LT @ 420 nm (%)</th>
<th>LY, ER &amp; Uniformity by PMT* (% or &lt;1%, &lt;2%, &lt;3%, &lt;7%, 9%)</th>
<th>LY, ER &amp; Uniformity by APD (As)* (p.e./MeV, % r.m.s., %)</th>
<th>LY, ER &amp; Uniformity by APD (Uni)* (p.e./MeV, % r.m.s., %)</th>
<th>LO Loss %</th>
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<td>47.6, 10.7, 5.3, 1420, 15.5, 12.9, 6.5</td>
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<td><strong>Average</strong></td>
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<td>78.9</td>
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<td>940,22.4,7.2,3.8</td>
<td>26.8</td>
<td></td>
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</tbody>
</table>

* Light Yield (LY) and Energy Resolution (ER) are the average of the seven points measured along the crystals.

Note 1 Light Yield (LY) for the APD readout is measured with a quartz plate between the crystal and the APDs.

Note 2 Width of the black band at the small end on the smallest side surface: 15 mm
Encouraging resolution measured at BTF, Frascati, with non uniformized crystals. Another test is planned in this Fall with uniformized crystals.

E. Monoli, SuperB Elba Meeting, 5/28/11
Light Response Non-Uniformity: $\delta$

\[
\frac{y}{y_{\text{mid}}} = 1 + \delta \left( \frac{x}{x_{\text{mid}}} - 1 \right)
\]
CMS Specification for Uniformity

D. Graham & C. Seez, CMS Note 1996-002

Optimum slope in rear 100mm is 8% rise

Slope < 0.3%/X₀ where most of the energy is

Can tolerate almost any slope at front

|δ| < 3% & 4% for 18 X₀ (SuperB) & 25X₀ (CMS)
It is well known that part of the emission light is absorbed in the crystal: self-absorption.
Effect of Cerium Segregation

It is also 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.

Light Output (p.e./MeV) vs. Ce Concentration (ppmw)

$y = -0.0036X^2 + 1.96X + 1612$
Ray-Tracing Simulation “set-up”

The simulation package was developed in early eighties, and was used for the L3 BGO and CMS PWO crystals.

SuperB LYSO crystals

2 Hamamatsu S8664-55
(2×5×5 mm²)

Silicon oil N=1.52

Tyvek paper

\[ LO(z) = LY(z) \int Em(\lambda) LCE(\lambda, z) QE(\lambda) d\lambda \]
How Rough it Should Be?

The $R_a$ matters.

A variation of 0.1 in $R_a$ causes a 3% variation in $\delta$. 

SuperB LYSO Crystal, Type-8
Detector: 2xS8664-55 APDs (5x5 mm$^2$)
Factors included: Light collection, Emission, Self-absorption and QE
Side-4 roughened

<table>
<thead>
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<th>$R_a$</th>
<th>$\delta$</th>
<th>rms</th>
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<tbody>
<tr>
<td>0.2</td>
<td>$3.0 \pm 0.4%$</td>
<td>1.7%</td>
</tr>
<tr>
<td>0.3</td>
<td>$-0.2 \pm 0.4%$</td>
<td>1.0%</td>
</tr>
<tr>
<td>0.4</td>
<td>$-3.5 \pm 0.4%$</td>
<td>2.1%</td>
</tr>
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</table>
Real Exercise: Roughening SIC-LYSO-L3

The smallest side surface of SIC-LYSO-L3 was roughened to Ra = 0.3 at SIC via a two step process:

1st: lapped to Ra = 0.5 by using 11 μm Al₂O₃ powder for 10 min with 2.5 kg weight.
2nd: lapped to Ra = 0.3 by using 6.5 μm SiC powder for 3 min with 1.5 kg weight.

Thanks to SICCAS for roughening this crystal.

Polished SIC-LYSO-L3

Roughened SIC-LYSO-L3
Relative Light Output & Uniformity

Ra = 0.3 uniformize this crystal to < 2%. Ra = 0.25 seems the best for this sample.
CMS ECAL endcap: Single Crystal: 160 cm$^3$
Total number: 16,000 Total Volume: 2.5 m$^3$
Expected Crystal Cost: ~$60M@$25/cc

Crystal Cost: <$10M

Issues: Radiation hardness of the photo-detector and Cost

Issue: Radiation hardness of the photo-detector
Performance of Scintillator Plates

**Crystals**

- LYSO
- LuAG
- YAG

**Ceramics**

- YAG
- LuAG

**LYSO Plates (Φ28.5 mm)**
- Transmission (%)
- Wavelength (nm)

- Graphs showing transmission of LYSO plates of different thicknesses.

**LYSO Plates (Φ28.5 mm)**
- Channel Number
- Events

- Graphs showing the channel number and events for LYSO plates.

**YAG / LuAG Ceramic**
- Transmission (%)
- Wavelength (nm)

- Graphs showing transmission of YAG and LuAG ceramic plates.

**YAG / LuAG Ceramic Plates**
- PMT: R1306
- Source: Cs-137
- QVT gate: 1000 ns

- Graphs showing the channel number and events for YAG and LuAG ceramic plates.

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As expected that LYSO is radiation hard.

Ceramics, on the other hand, seem not.

Need to investigate further to see position dependence.
LSO/LYSO crystals with bright, fast scintillation and excellent radiation hardness is a good candidate material for HEP & NP experiments, especially those experiments in a severe radiation environment.

The R&D work for SuperB is now concentrated on the optimization of the light response uniformity for the APD readout, which is affected by (1) the optical focusing, (2) the self-absorption and (3) the non-uniformity of the cerium concentration. Will roughen all 25 test beam crystals.

For applications in a severe radiation environment, such as the high luminosity LHC, R&D work concentrates on two directions:

- Growth of crystals of adequate length/size cost-effectively; and
- Looking into LSO/LYSO plates for a sampling option. Initial test with YAG and LuAG ceramics indicates they are not radiation hard.