The Next Generation of Crystal Detectors

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April 10, 2014
Why Crystal Calorimeter in HEP?

- Photons and electrons are fundamental particles. Precision $e/\gamma$ measurements enhance physics discovery potential.

- Performance of homogeneous crystal calorimeter in $e/\gamma$ measurements is well understood:
  - The best possible energy resolution;
  - Good position resolution;
  - Good $e/\gamma$ identification and reconstruction efficiency.

- Challenges at future HEP Experiments:
  - Radiation damage at the energy frontier (HL-LHC);
  - Ultra-fast rate at the intensity frontier;
  - Good jet mass resolution at the energy frontier (ILC/CLIC).
## Existing Crystal Calorimeters in HEP

<table>
<thead>
<tr>
<th>Date</th>
<th>75-85</th>
<th>80-00</th>
<th>80-00</th>
<th>80-00</th>
<th>90-10</th>
<th>94-10</th>
<th>94-10</th>
<th>95-20</th>
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<tbody>
<tr>
<td>Experiment</td>
<td>C. Ball</td>
<td>L3</td>
<td>CLEO II</td>
<td>C. Barrel</td>
<td>KTeV</td>
<td>BaBar</td>
<td>BELLE</td>
<td>CMS</td>
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<tr>
<td>Accelerator</td>
<td>SPEAR</td>
<td>LEP</td>
<td>CESR</td>
<td>LEAR</td>
<td>FNAL</td>
<td>SLAC</td>
<td>KEK</td>
<td>CERN</td>
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<tr>
<td>Crystal Type</td>
<td>NaI(Tl)</td>
<td>BGO</td>
<td>CsI(Tl)</td>
<td>CsI</td>
<td>CsI</td>
<td>CsI(Tl)</td>
<td>CsI</td>
<td>PbWO$_4$</td>
</tr>
<tr>
<td>B-Field (T)</td>
<td>-</td>
<td>0.5</td>
<td>1.5</td>
<td>1.5</td>
<td>-</td>
<td>1.5</td>
<td>1.0</td>
<td>4.0</td>
</tr>
<tr>
<td>$r_{inner}$ (m)</td>
<td>0.254</td>
<td>0.55</td>
<td>1.0</td>
<td>0.27</td>
<td>-</td>
<td>1.0</td>
<td>1.25</td>
<td>1.29</td>
</tr>
<tr>
<td>Number of Crystals</td>
<td>672</td>
<td>11,400</td>
<td>7,800</td>
<td>1,400</td>
<td>3,300</td>
<td>6,580</td>
<td>8,800</td>
<td>76,000</td>
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<tr>
<td>Crystal Depth ($X_0$)</td>
<td>16</td>
<td>22</td>
<td>16</td>
<td>16</td>
<td>27</td>
<td>16 to 17.5</td>
<td>16.2</td>
<td>25</td>
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<tr>
<td>Crystal Volume (m$^3$)</td>
<td>1</td>
<td>1.5</td>
<td>7</td>
<td>1</td>
<td>2</td>
<td>5.9</td>
<td>9.5</td>
<td>11</td>
</tr>
<tr>
<td>Light Output (p.e./MeV)</td>
<td>350</td>
<td>1,400</td>
<td>5,000</td>
<td>2,000</td>
<td>40</td>
<td>5,000</td>
<td>5,000</td>
<td>2</td>
</tr>
<tr>
<td>Photosensor</td>
<td>PMT</td>
<td>Si PD</td>
<td>Si PD</td>
<td>WS$^a$+Si PD</td>
<td>PMT</td>
<td>Si PD</td>
<td>Si PD</td>
<td>APD$^a$</td>
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<tr>
<td>Gain of Photosensor</td>
<td>Large</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>4,000</td>
<td>1</td>
<td>1</td>
<td>50</td>
</tr>
<tr>
<td>$\sigma_N$/Channel (MeV)</td>
<td>0.05</td>
<td>0.8</td>
<td>0.5</td>
<td>0.2</td>
<td>small</td>
<td>0.15</td>
<td>0.2</td>
<td>40</td>
</tr>
<tr>
<td>Dynamic Range</td>
<td>$10^4$</td>
<td>$10^5$</td>
<td>$10^4$</td>
<td>$10^4$</td>
<td>$10^4$</td>
<td>$10^4$</td>
<td>$10^4$</td>
<td>$10^5$</td>
</tr>
</tbody>
</table>

### Future crystal calorimeters in HEP:
- LSO/LYSO for HERD, (Mu2e, Super B) and HL-LHC (Sampling)
- BaF$_2$ for fast calorimeter for Mu2e and project X
- PbF$_2$, PbFCl, BSO for Homogeneous HCAL
CMS Experiment at LHC

CMS is one of the four detectors at the 14 TeV LHC.
The observed degradation is well understood.
The LO reached equilibrium during irradiations under a defined dose rate, showing dose rate dependent radiation damage.

\[
dD = \sum_{i=1}^{n} \left\{ -a_i D_i dt + \left( D_i^{all} - D_i \right) b_i R dt \right\}
\]

\[
D = \sum_{i=1}^{n} \left\{ \frac{b_i R D_i^{all}}{a_i + b_i R} \left[ 1 - e^{-(a_i+b_i R)t} \right] + D_i^0 e^{-(a_i+b_i R)t} \right\}
\]

- \( D_i \): color center density in units of m\(^{-1}\);
- \( D_i^0 \): initial color center density;
- \( D_i^{all} \) is the total density of trap related to the color center in the crystal;
- \( a_i \): recovery constant in units of hr\(^{-1}\);
- \( b_i \): damage constant in units of kRad\(^{-1}\);
- \( R \): the radiation dose rate in units of kRad/hr.

\[
D_{eq} = \sum_{i=1}^{n} \frac{b_i R D_i^{all}}{a_i + b_i R}
\]
Oxygen Vacancies Identified by TEM/EDS

TOPCON-002B scope, 200 kV, 10 uA, 5 to 10 nm black spots identified
JEOL JEM-2010 scope and Link ISIS EDS localized Stoichiometry Analysis

Atomic Fraction (%) in PbWO₄

As Grown Sample

<table>
<thead>
<tr>
<th>Element</th>
<th>Black Spot</th>
<th>Peripheral</th>
<th>Matrix₁</th>
<th>Matrix₂</th>
</tr>
</thead>
<tbody>
<tr>
<td>O</td>
<td>1.5</td>
<td>15.8</td>
<td>60.8</td>
<td>63.2</td>
</tr>
<tr>
<td>W</td>
<td>50.8</td>
<td>44.3</td>
<td>19.6</td>
<td>18.4</td>
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<tr>
<td>Pb</td>
<td>47.7</td>
<td>39.9</td>
<td>19.6</td>
<td>18.4</td>
</tr>
</tbody>
</table>

The Same Sample after Oxygen Compensation

<table>
<thead>
<tr>
<th>Element</th>
<th>Point₁</th>
<th>Point₂</th>
<th>Point₃</th>
<th>Point₄</th>
</tr>
</thead>
<tbody>
<tr>
<td>O</td>
<td>59.0</td>
<td>66.4</td>
<td>57.4</td>
<td>66.7</td>
</tr>
<tr>
<td>W</td>
<td>21.0</td>
<td>16.5</td>
<td>21.3</td>
<td>16.8</td>
</tr>
<tr>
<td>Pb</td>
<td>20.0</td>
<td>17.1</td>
<td>21.3</td>
<td>16.5</td>
</tr>
</tbody>
</table>
Predicted EM dose induced damage agrees well with the LHC data.

In addition, there is cumulative hadron induced damage in PWO.

BTCP-PWO

EWRIAC = 0.026*Log(X+1) + 0.080Log^2(X+1)

Light Output Loss (%)

Dose rate (rad/h)

Luminosity (cm^-2s^-1)
The proton induced absorption in LYSO is $1/5$ of PWO
Net effect of damage is smaller for short light path
# Bright, Fast Scintillator: LSO/LYSO

<table>
<thead>
<tr>
<th>Crystal</th>
<th>NaI(Tl)</th>
<th>CsI(Tl)</th>
<th>CsI</th>
<th>BaF$_2$</th>
<th>BGO</th>
<th>LYSO(Ce)</th>
<th>PWO</th>
<th>PbF$_2$</th>
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</thead>
<tbody>
<tr>
<td><strong>Density (g/cm$^3$)</strong></td>
<td>3.67</td>
<td>4.51</td>
<td>4.51</td>
<td>4.89</td>
<td>7.13</td>
<td>7.40</td>
<td>8.3</td>
<td>7.77</td>
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<tr>
<td><strong>Melting Point (°C)</strong></td>
<td>651</td>
<td>621</td>
<td>621</td>
<td>1280</td>
<td>1050</td>
<td>2050</td>
<td>1123</td>
<td>824</td>
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<tr>
<td><strong>Radiation Length (cm)</strong></td>
<td>2.59</td>
<td>1.86</td>
<td>1.86</td>
<td>2.03</td>
<td>1.12</td>
<td>1.14</td>
<td>0.89</td>
<td>0.93</td>
</tr>
<tr>
<td><strong>Molière Radius (cm)</strong></td>
<td>4.13</td>
<td>3.57</td>
<td>3.57</td>
<td>3.10</td>
<td>2.23</td>
<td>2.07</td>
<td>2.00</td>
<td>2.21</td>
</tr>
<tr>
<td><strong>Interaction Length (cm)</strong></td>
<td>42.9</td>
<td>39.3</td>
<td>39.3</td>
<td>30.7</td>
<td>22.8</td>
<td>20.9</td>
<td>20.7</td>
<td>21.0</td>
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<td><strong>Re refractive Index a</strong></td>
<td>1.85</td>
<td>1.79</td>
<td>1.95</td>
<td>1.50</td>
<td>2.15</td>
<td>1.82</td>
<td>2.20</td>
<td>1.82</td>
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<td><strong>Hygroscopicity</strong></td>
<td>Yes</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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<tr>
<td><strong>Luminescence b (nm) (at peak)</strong></td>
<td>410</td>
<td>550</td>
<td>310</td>
<td>300</td>
<td>480</td>
<td>402</td>
<td>425</td>
<td>420</td>
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<tr>
<td><strong>Decay Time b (ns)</strong></td>
<td>245</td>
<td>1220</td>
<td>26</td>
<td>650</td>
<td>300</td>
<td>40</td>
<td>30</td>
<td>10</td>
</tr>
<tr>
<td><strong>Light Yield b,c (%)</strong></td>
<td>100</td>
<td>165</td>
<td>3.7</td>
<td>36</td>
<td>21</td>
<td>85</td>
<td>0.3</td>
<td>0.1</td>
</tr>
<tr>
<td><strong>d(LY)/dT b (%/°C)</strong></td>
<td>-0.2</td>
<td>0.4</td>
<td>-1.4</td>
<td>-1.9</td>
<td>0.1</td>
<td>-0.9</td>
<td>-0.2</td>
<td>-2.5</td>
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</tbody>
</table>

**Experiment**

<table>
<thead>
<tr>
<th>Crystal</th>
<th>BaBar</th>
<th>BELLE</th>
<th>BES III</th>
<th>KTeV</th>
<th>TAPS</th>
<th>Mu2e</th>
<th>L3</th>
<th>BELLE</th>
<th>(Mu2e)</th>
<th>(SuperB)</th>
<th>HL-LHC</th>
<th>CMS</th>
<th>ALICE</th>
<th>PANDA</th>
<th>HHCAL?</th>
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<tbody>
<tr>
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<td></td>
</tr>
</tbody>
</table>

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a. at peak of emission; b. up/low row: slow/fast component; c. QE of readout device taken out.
LSO/LYSO is a bright (200 times of PWO), fast (40 ns) and radiation hard crystal scintillator. The longitudinal non-uniformity issue caused by tapered crystal geometry, self-absorption and cerium segregation can be addressed by roughening one side surface. The material is widely used in the medical industry. Existing mass production capability would help in crystal cost control.
Excellent Radiation Hardness in LT

Consistent & Small Damage in LT

Larger variation @ shorter $\lambda$

April 10, 2014

Talk Presented at Calor 2014, O4-10, by Ren-Yuan Zhu, Caltech
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.
28 cm Long LYSO Under $\gamma$-Rays

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

SIPAT-LYSO-L7: 2.5 x 2.5 x 28 cm, Nov, 2009

April 10, 2014 Talk Presented at Calor 2014, O4-10, by Ren-Yuan Zhu, Caltech
Damage in 2 x 2 x 0.5 cm Plates

5 mm thick LYSO plates show degradation of a few percepts up to 10 Mrad

Sample | EWLT (%) | L.O. (p.e./MeV) | EWLT loss (%) | L.O. loss (%) |
--- | --- | --- | --- | --- |
SIC-A1105-1 | 76.3 | 3657.9 | 0.9 | 1.3 |
 | | | 1.4 | 2.5 |
 | | | 1.8 | 3.4 |
25 LYSO test beam crystals are uniformized to $|\delta| < 3\%$ by roughening the smallest side surface.
SuperB LYSO Test Beam Result

198 MeV beam
With 1/2/3 e⁻

$\sigma(E)/E = 1.1 \sqrt{E} \oplus 0.4/E \oplus 1.2$

$\frac{\sigma(E)}{E} = \frac{1.1}{\sqrt{E \text{[GeV]}}} \oplus \frac{0.4}{E \text{[GeV]}} \oplus 1.2 \%$
Option for CMS FCAL Upgrade

Issues: Radiation hardness of the photo-detector and Cost

One of two options for CMS Upgrade TR

Issues: Radiation hardness of photo-detector and WLS fiber

Reduced Crystal Cost

CMS ECAL endcap: Single Crystal: 160 cm³
Total number: 16,000 Total Volume: 3 m³

Issue: Radiation hardness of the photo-detector
Two Measurement Setups

1) LYSO plates with Tyvek wrapping are readout directly by a R1306 PMT using a Cs-137 γ-ray source.

2) LYSO plates with Tyvek wrapping are readout with four Y11 WLS fibers of 40 cm long and a R2059 PMT using a Na-22 γ-ray source and coincidence.
PHS of 3 mm LYSO Plate

LYSO 25 × 25 × 3 mm³

Source: Cs-137, Gate = 200 ns
R1306 PMT, HV = -850 V
Light Yield: 3970 p.e./MeV
E.R. = 11.8%

3 mm plate & 4 x 40 cm Y11 fiber

Source: Na-22, Gate = 200 ns
R2059 PMT, HV = -2700 V
Net peak: 174 ch, Light Yield: 24.3 p.e./MeV

About 1% light collected via WLS
Shashlik Tower Assembly

- Coupled to PMT
- LYSO Plates (14×14×1.5 mm)
- W Plates (14×14×2.5 mm)
- 4 Y-11 WLS fibers
- Monitoring fiber
- Tyvek wrapping
- Monitoring fiber beam dump

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CMS Specification for Uniformity

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

Optimum slope in rear 100mm is 8% rise

\( |\delta| < 4\% \text{ for } 25X_0 \)

Slope < 0.3%/\(X_0\) where most of the energy is

Can tolerate almost any slope at front

Beam
LYSO/W Response Uniformity
LYSO/W Shashlik Uniformity

Front: 0.2%/X₀, Back: 8% rise

14×14×1.5 mm³ LYSO plate, 40 cm WLS fiber
Source: Na-22, Gain=200 ns, R2059 PMT, HV= -2700 V
Net peak: 198 ch, Light Yield: 26.9 p.e./MeV
L=2 cm

Net peak: 191 ch, Light Yield: 27.3 p.e./MeV
L=4 cm

Net peak: 199 ch, Light Yield: 28.5 p.e./MeV
L=6 cm

Net peak: 203 ch, Light Yield: 29.1 p.e./MeV
L=8 cm

Average LY = 27.7 p.e./MeV (200 ns)
RMS = 3.2%
Front Slope = (0.2±0.3)%/X₀
Back Slope = (0.7±0.3)%/X₀
# Alternative Fast Crystals

**Talk in CMS Forward Calorimetry Task Force Meeting, CERN, June 27, 2012**

<table>
<thead>
<tr>
<th></th>
<th>LSO/LYSO</th>
<th>GSO</th>
<th>YSO</th>
<th>CsI</th>
<th>BaF&lt;sub&gt;2&lt;/sub&gt;</th>
<th>CeF&lt;sub&gt;3&lt;/sub&gt;</th>
<th>CeBr&lt;sub&gt;3&lt;/sub&gt;</th>
<th>LaCl&lt;sub&gt;3&lt;/sub&gt;</th>
<th>LaBr&lt;sub&gt;3&lt;/sub&gt;</th>
<th>Plastic scintillator (BC 404)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density (g/cm&lt;sup&gt;3&lt;/sup&gt;)</td>
<td>7.40</td>
<td>6.71</td>
<td>4.44</td>
<td>4.51</td>
<td>4.89</td>
<td>6.16</td>
<td>5.23</td>
<td>3.86</td>
<td>5.29</td>
<td>1.03</td>
</tr>
<tr>
<td>Melting point (°C)</td>
<td>2050</td>
<td>1950</td>
<td>1980</td>
<td>621</td>
<td>1280</td>
<td>1460</td>
<td>722</td>
<td>858</td>
<td>783</td>
<td>70&quot;</td>
</tr>
<tr>
<td>Radiation Length (cm)</td>
<td>1.14</td>
<td>1.38</td>
<td>3.11</td>
<td>1.86</td>
<td>2.03</td>
<td>1.70</td>
<td>1.96</td>
<td>2.81</td>
<td>1.88</td>
<td>42.54</td>
</tr>
<tr>
<td>Molière Radius (cm)</td>
<td>2.07</td>
<td>2.23</td>
<td>2.93</td>
<td>3.57</td>
<td>3.10</td>
<td>2.41</td>
<td>2.97</td>
<td>3.71</td>
<td>2.85</td>
<td>9.59</td>
</tr>
<tr>
<td>Interaction Length (cm)</td>
<td>20.9</td>
<td>22.2</td>
<td>27.9</td>
<td>39.3</td>
<td>30.7</td>
<td>23.2</td>
<td>31.5</td>
<td>37.6</td>
<td>30.4</td>
<td>78.8</td>
</tr>
<tr>
<td>Z value</td>
<td>64.8</td>
<td>57.9</td>
<td>33.3</td>
<td>54.0</td>
<td>51.6</td>
<td>50.8</td>
<td>45.6</td>
<td>47.3</td>
<td>45.6</td>
<td>-</td>
</tr>
<tr>
<td>dE/dX (MeV/cm)</td>
<td>9.55</td>
<td>8.88</td>
<td>6.56</td>
<td>5.56</td>
<td>6.52</td>
<td>8.42</td>
<td>6.65</td>
<td>5.27</td>
<td>6.90</td>
<td>2.02</td>
</tr>
<tr>
<td>Emission Peak&lt;sup&gt;a&lt;/sup&gt; (nm)</td>
<td>420</td>
<td>430</td>
<td>420</td>
<td>420</td>
<td>310</td>
<td>300</td>
<td>340</td>
<td>300</td>
<td>371</td>
<td>335</td>
</tr>
<tr>
<td>Refractive Index&lt;sup&gt;b&lt;/sup&gt;</td>
<td>1.82</td>
<td>1.85</td>
<td>1.80</td>
<td>1.95</td>
<td>1.50</td>
<td>1.62</td>
<td>1.9</td>
<td>1.9</td>
<td>1.9</td>
<td>1.58</td>
</tr>
<tr>
<td>Relative Light Yield&lt;sup&gt;a,c&lt;/sup&gt;</td>
<td>100</td>
<td>45</td>
<td>76</td>
<td>4.2</td>
<td>1.3</td>
<td>42</td>
<td>8.6</td>
<td>141</td>
<td>15</td>
<td>153</td>
</tr>
<tr>
<td>Decay Time&lt;sup&gt;e&lt;/sup&gt; (ns)</td>
<td>40</td>
<td>73</td>
<td>60</td>
<td>30</td>
<td>6</td>
<td>650</td>
<td>30</td>
<td>17</td>
<td>570</td>
<td>20</td>
</tr>
<tr>
<td>d(LY)/dT&lt;sup&gt;d&lt;/sup&gt; (%)/°C</td>
<td>-0.2</td>
<td>-0.4</td>
<td>-0.3</td>
<td>-1.4</td>
<td>-1.9</td>
<td>0.1</td>
<td>~0</td>
<td>-0.1</td>
<td>0.1</td>
<td>0.2</td>
</tr>
</tbody>
</table>

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- Top line: slow component, bottom line: fast component.
- At the wavelength of the emission maximum.
- Relative light yield normalized to the light yield of LSO.
- At room temperature (20°C)
- Softening point

April 10, 2014

Talk Presented at Calor 2014, O4-10, by Ren-Yuan Zhu, Caltech
Damage in Long BaF\textsubscript{2} Crystals

Radiation damage in BaF\textsubscript{2} crystals saturates at a few tens of krad
SIC2012 is more radiation hard than other samples
Slow component is more radiation hard than the fast component

RIAC of mass produced BaF\textsubscript{2} may be controlled to less than 1.6 m\textsuperscript{-1}

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Damage in Long Pure CsI Crystals

Consistent damage between 30/20 cm long pure CsI from SIC/Kharkov

Induced absorption exceeding 2 m\(^{-1}\) after a few hundreds krad.

Comparison of Radiation Hardness

LYSO is the best in radiation hardness. BaF₂/CsI is good at high/low dose

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**Light Output**

![Graph showing Light Output vs. Integrated Dose for different materials](image)

**EWLT**

- **BaF₂ SIC2012** ($\lambda_{em} = 220nm$)
  - 25×25×250 mm³
- **CsI SIC2013**
  - 50×50×300 mm³
- **LYSO CPI**
  - 25×25×200 mm³

**RIAC**

- **BaF₂** ($\lambda_{em} = 220nm$)
- **CsI** ($\lambda_{em} = 310nm$)
- **LYSO** ($\lambda_{em} = 420nm$)
Rising Time for 1.5 $X_0$ Samples

Talk in the time resolution workshop at U. Chicago, 4/28/2011: Agilent MSO9254A (2.5 GHz) DSO with 0.14 ns rise time Hamamatsu R2059 PMT (2500 V) with rise time 1.3 ns

Measured rising time is dominated by photo-detector response, and is affected by light propagation in crystal.
**Figure of Merit for Timing**

FoM is calculated as the LY in 1st ns obtained by using light output and decay time data measured for 1.5 $X_0$ crystal samples.

<table>
<thead>
<tr>
<th>Crystal Scintillators</th>
<th>Relative LY (%)</th>
<th>$A_1$ (%)</th>
<th>$\tau_1$ (ns)</th>
<th>$A_2$ (%)</th>
<th>$\tau_2$ (ns)</th>
<th>Total LO (p.e./MeV, XP2254B)</th>
<th>LO in 1ns (p.e./MeV, XP2254B)</th>
<th>LO in 0.1ns (p.e./MeV, XP2254B)</th>
<th>LY in 0.1ns (photons/MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BaF$_2$</td>
<td>40.1</td>
<td>91</td>
<td>650</td>
<td>9</td>
<td>0.9</td>
<td>1149</td>
<td>71.0</td>
<td>11.0</td>
<td>136.6</td>
</tr>
<tr>
<td>LSO:Ca$_x$Ce</td>
<td>94</td>
<td>100</td>
<td>30</td>
<td></td>
<td></td>
<td>2400</td>
<td>78.7</td>
<td>8.0</td>
<td>110.9</td>
</tr>
<tr>
<td>LSO/LSO:Ce</td>
<td>85</td>
<td>100</td>
<td>40</td>
<td></td>
<td></td>
<td>2180</td>
<td>53.8</td>
<td>5.4</td>
<td>75.3</td>
</tr>
<tr>
<td>CeF$_3$</td>
<td>7.3</td>
<td>100</td>
<td>30</td>
<td></td>
<td></td>
<td>208</td>
<td>6.8</td>
<td>0.7</td>
<td>8.6</td>
</tr>
<tr>
<td>BGO</td>
<td>21</td>
<td>100</td>
<td>300</td>
<td></td>
<td></td>
<td>350</td>
<td>1.2</td>
<td>0.1</td>
<td>2.5</td>
</tr>
<tr>
<td>PWO</td>
<td>0.377</td>
<td>80</td>
<td>30</td>
<td>20</td>
<td>10</td>
<td>9.2</td>
<td>0.42</td>
<td>0.04</td>
<td>0.4</td>
</tr>
<tr>
<td>LaBr$_3$:Ce</td>
<td>130</td>
<td>100</td>
<td>20</td>
<td></td>
<td></td>
<td>3810</td>
<td>185.8</td>
<td>19.0</td>
<td>229.9</td>
</tr>
<tr>
<td>LaCl$_3$:Ce</td>
<td>55</td>
<td>24</td>
<td>570</td>
<td>76</td>
<td>24</td>
<td>1570</td>
<td>49.36</td>
<td>5.03</td>
<td>62.5</td>
</tr>
<tr>
<td>NaI:Tl</td>
<td>100</td>
<td>100</td>
<td>245</td>
<td></td>
<td></td>
<td>2604</td>
<td>10.6</td>
<td>1.1</td>
<td>14.5</td>
</tr>
<tr>
<td>CsI</td>
<td>4.7</td>
<td>77</td>
<td>30</td>
<td>23</td>
<td>6</td>
<td>131</td>
<td>7.9</td>
<td>0.8</td>
<td>10.6</td>
</tr>
<tr>
<td>CsI:Tl</td>
<td>165</td>
<td>100</td>
<td>1220</td>
<td></td>
<td></td>
<td>2093</td>
<td>1.7</td>
<td>0.2</td>
<td>4.8</td>
</tr>
<tr>
<td>CsI:Na</td>
<td>88</td>
<td>100</td>
<td>690</td>
<td></td>
<td></td>
<td>2274</td>
<td>3.3</td>
<td>0.3</td>
<td>4.5</td>
</tr>
</tbody>
</table>

The best crystal scintillator for ultra-fast timing is BaF$_2$ and LSO(Ce/Ca) and LYSO(Ce). LaBr$_3$ is a material with high potential.
Mu2e BaF$_2$ Calorimeter
BaF$_2$ for Very Fast Calorimeter

The fast component of BaF$_2$ crystals at 220 nm has a similar light output as pure CsI and sub-ns decay time.

Spectroscopic selection of fast component may be achieved with solar blind photocathode or short pass filter.
Delta-doping for CCD detectors

D. Hitlin, Talk in NSTR2014, February 28, 2014, with JPL

# Candidate Crystals for HHCAL

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Bi$_4$Ge$<em>3$O$</em>{12}$ (BGO)</th>
<th>PbWO$_4$ (PWO)</th>
<th>PbF$_2$</th>
<th>PbClF</th>
<th>Bi$_4$Si$<em>3$O$</em>{12}$ (BSO)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\rho$ (g/cm$^3$)</td>
<td>7.13</td>
<td>8.29</td>
<td>7.77</td>
<td>7.11</td>
<td>6.8</td>
</tr>
<tr>
<td>$\lambda_1$ (cm)</td>
<td>22.8</td>
<td>20.7</td>
<td>21.0</td>
<td>24.3</td>
<td>23.1</td>
</tr>
<tr>
<td>$n @ \lambda_{\text{max}}$</td>
<td>2.15</td>
<td>2.20</td>
<td>1.82</td>
<td>2.15</td>
<td>2.06</td>
</tr>
<tr>
<td>$\tau_{\text{decay}}$ (ns)</td>
<td>300</td>
<td>30/10</td>
<td>?</td>
<td>30</td>
<td>100</td>
</tr>
<tr>
<td>$\lambda_{\text{max}}$ (nm)</td>
<td>480</td>
<td>425/420</td>
<td>?</td>
<td>420</td>
<td>470</td>
</tr>
<tr>
<td>Cut-off $\lambda$ (nm)</td>
<td>310</td>
<td>350</td>
<td>250</td>
<td>280</td>
<td>300</td>
</tr>
<tr>
<td>Light Output (%)</td>
<td>100</td>
<td>1.4/0.37</td>
<td>?</td>
<td>17</td>
<td>20</td>
</tr>
<tr>
<td>Melting point (°C)</td>
<td>1050</td>
<td>1123</td>
<td>842</td>
<td>608</td>
<td>1030</td>
</tr>
<tr>
<td>Raw Material Cost (%)</td>
<td>100</td>
<td>49</td>
<td>29</td>
<td>29</td>
<td>47</td>
</tr>
</tbody>
</table>
Search for Scintillation in Doped PbF₂

116 samples tested

Will look performance at low temperature with the FLS920 fluorescence lifetime spectrometer

Doped PbF₂

Gamma ray excited (Gs-137)

Average value = 31 nA
Average value = 43 nA
Average value = 30 nA
Average value = 26 nA
Average value = 34 nA
Average value = 38 nA
Average value = 43 nA

Er  Eu  Gd  Ho  Pr  Sm  Tb

Anode Current (nA)
Other Materials: PbFCl & BSO

<table>
<thead>
<tr>
<th>ID</th>
<th>PbFCl-1</th>
<th>PbFCl-2</th>
<th>PbFCl-3</th>
<th>PbFCl-4</th>
<th>PbFCl-5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Doping</td>
<td>--</td>
<td>Na 0.5 at%</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Dimension (mm)</td>
<td>10x10x2</td>
<td>10x10x2</td>
<td>30x10x5</td>
<td>20x10x3</td>
<td>~10x10x9</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>ID</th>
<th>PWO</th>
<th>PbFCl-1</th>
<th>PbFCl-2</th>
<th>PbFCl-3</th>
<th>PbFCl-4</th>
<th>PbFCl-5</th>
</tr>
</thead>
<tbody>
<tr>
<td>X-luminescence</td>
<td>Peaked @ 420 nm</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>L.O. (% PWO)</td>
<td>100</td>
<td>14</td>
<td>64</td>
<td>33</td>
<td>35</td>
<td>31</td>
</tr>
<tr>
<td>L.O. (% BGO)</td>
<td>1.8</td>
<td>0.25</td>
<td>1.1</td>
<td>0.59</td>
<td>0.63</td>
<td>0.56</td>
</tr>
</tbody>
</table>

PbFCl-3: PMT R2059, HV = 2100 V, Na-22
Constant: 513.5, Mean: 186.2, Sigma: 29.49

BSO-1, BSO-2, BSO-3, BSO-4, BSO-5

BSO-6: BSO-7

Bi$_4$Si$_5$O$_{12}$ (1.5 $X_3$)

Preliminary

LO = $A_0 + A_1 (1 - e^{-t_2})$

LO = $A_0 + A_1 (1 - e^{-t_2})$

LO = $A_0 + A_1 (1 - e^{-t_2})$

LO = $A_0 + A_1 (1 - e^{-t_2})$

LO = $A_0 + A_1 (1 - e^{-t_2})$

LO = $A_0 + A_1 (1 - e^{-t_2})$

LO = $A_0 + A_1 (1 - e^{-t_2})$

LO = $A_0 + A_1 (1 - e^{-t_2})$
A $\Phi 22 \times 105$ mm BSO crystal shows good transparency and longitudinal uniformity. See talk O4-19 for the details.
Summary

• Bright, fast and radiation hard LSO/LYSO crystals may be used for a total absorption ECAL. LYSO/W Shashlik calorimeter is one of two options for CMS FCAL upgrade technical report for HL-LHC.

• Crystal calorimeters with more than ten times faster rate/timing capability require using very fast crystals, e.g. sub-ns decay time of the BaF₂ fast scintillation component.

• Crystals (PbF₂, PbFCl & BSO) may provide a foundation for a homogeneous hadron calorimeter with dual readout for both Cherenkov and scintillation light to achieve good jet mass resolution for ILC/CLIC.

• Novel materials, such as crystals, ceramics and glasses, may play important role in future HEP experiments.