Characterization and Applications of new high quality LuAG:Ce and LYSO:Ce fibers

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for the HP 3 – WP 22 and the Crystal Clear Collaboration
Outline and Motivation

1. Production Technology
2. Investigated Scintillators
   - LuAG:Ce (fibers)
   - LYSO:Ce (rods/fibers)

Advantages compared to organic fibers:
- Significantly higher light yield
- More effective interaction with electromagnetic probes
- Higher resistance to radiation damage

Envisaged applications:
- 2D beam monitor
- PET device
- Dual readout calorimetry
Fiber Growth and Investigated Scintillators

**Micro-Pulling-Down Method:**

![Diagram of Micro-Pulling-Down Method]

**Investigated Scintillators:**

<table>
<thead>
<tr>
<th></th>
<th>LuAG:Ce</th>
<th>LYSO:Ce</th>
</tr>
</thead>
<tbody>
<tr>
<td>density</td>
<td>6.7 g/cm³</td>
<td>7.1 g/cm³</td>
</tr>
<tr>
<td>$Z_{\text{eff}}$</td>
<td>63</td>
<td>66</td>
</tr>
<tr>
<td>rad. length</td>
<td>1.41 cm</td>
<td>1.20 cm</td>
</tr>
<tr>
<td>decay time</td>
<td>50 ns</td>
<td>45 ns</td>
</tr>
<tr>
<td>$\lambda_{\text{max-emission}}$</td>
<td>530 nm</td>
<td>420 nm</td>
</tr>
<tr>
<td>light yield (ph/MeV)</td>
<td>12000 - 25000</td>
<td>26000 - 32000</td>
</tr>
<tr>
<td>melting point</td>
<td>1980 °C</td>
<td>2050 °C</td>
</tr>
</tbody>
</table>

*installation @ FiberCryst*
Experimental Setup @ GI

SiPM readout:

<table>
<thead>
<tr>
<th>SiPM</th>
<th>cell size</th>
<th>size /mm²</th>
<th>pixel / mm²</th>
<th>PDE @ 450 nm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hamamatsu S12572-025C (1. gen.)</td>
<td>25 μm</td>
<td>3 x 3</td>
<td>1600</td>
<td>25 %</td>
</tr>
<tr>
<td>Hamamatsu S12572-050C (2. gen.)</td>
<td>50 μm</td>
<td>3 x 3</td>
<td>400</td>
<td>35 %</td>
</tr>
</tbody>
</table>

used radioactive source:
α - source: $^{241}$Am ($E_\alpha \approx 5.5$ MeV)
LuAG:Ce fibers (Ø 1.0 - 2.0 mm, length = 5.5 cm)
(produced in 2013 - varying parameters - 0.15 % Ce)

response to $^{241}$Am:

photons $\sim e^{-\mu d}$

![Graph showing photons seen by SiPM as a function of distance to SiPM.]

<table>
<thead>
<tr>
<th>fiber</th>
<th>$\mu$ /cm$^{-1}$</th>
<th>orient. of seed</th>
<th>distance to seed /cm</th>
<th>speed of pulling down</th>
</tr>
</thead>
<tbody>
<tr>
<td>1328</td>
<td>0.69</td>
<td>&lt;100&gt;</td>
<td>11.0</td>
<td>highest</td>
</tr>
<tr>
<td>1373</td>
<td>0.77</td>
<td>&lt;100&gt;</td>
<td>22.5</td>
<td></td>
</tr>
<tr>
<td>1368</td>
<td>0.40</td>
<td>&lt;100&gt;</td>
<td>2.5</td>
<td>average</td>
</tr>
<tr>
<td></td>
<td>0.13</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1369</td>
<td>0.68</td>
<td>&lt;100&gt;</td>
<td>22.5</td>
<td>↑ low pulling speed</td>
</tr>
<tr>
<td>1374</td>
<td>0.46</td>
<td>&lt;111&gt;</td>
<td>22.5</td>
<td>↑ lowest</td>
</tr>
</tbody>
</table>

Best $\mu$ values:
→ low pulling speed
→ short distance to seed
LuAG:Ce fibers (Ø 1.0 mm, length 10 cm)

investigation of different samples cut from one > 60 cm long fiber

response to $^{241}$Am

![Graph showing response to $^{241}$Am](image)

- 0.15 % Ce
- Higher Ce concentration
  - $\mu / \text{cm}^{-1}$
  - 1378.6: 1.14±0.12
  - 1378.5: 0.92±0.02
  - 1378.2: 0.32±0.06
  - 1378.1: 0.38±0.02

Less Ce is incorporated in the LuAG matrix

Less cracks and inhomogeneities
LuAG:Ce fibers (Ø 1.0 - 2.0 mm, length = 23 cm)

- All fibers grown with the same low pulling speed
- Fibers cut ~ 0.5 cm away from seed
- Ce concentration varied

\[ \mu_{2\text{mm}} = 0.05 - 0.12 \text{ cm}^{-1} \]
\[ \mu_{1\text{mm}} = 0.14 - 0.39 \text{ cm}^{-1} \]
light yield

Ø = 1 mm

LY (photons seen by SiPM) vs. Ce concentration (%)

Ø = 2 mm

LY (photons seen by SiPM) vs. Ce concentration (%)

att. coeff.

attenuation coefficient / cm⁻¹ vs. Ce concentration (%)

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Macroscopic fiber quality

old sample (2010) $\mu \sim 1.0 \text{ cm}^{-1}$, high pulling speed

best sample of run 1 – 2013 $\mu = 0.13 \text{ cm}^{-1}$, low pulling speed

best sample of actual run $\mu = 0.05 - 0.09 \text{ cm}^{-1}$, low pulling speed
Coincidence Readout of a $\varnothing$ 2.0 mm LuAG:Ce fiber ($L = 23$ cm)

50 $\mu$m Ham. SiPMs

$^{241}$Am - source

$\alpha$ source in center

$\alpha$ source close to SiPM 1

SiPM 1

SiPM 2

sum

photons seen by SiPM

0 50 100 150 200 250 300 350 400

counts

0 1000 2000 3000 4000 5000

photons seen by SiPM

0 100 200 300 400 500 600

counts

photons seen by SiPM 1

photons seen by SiPM 2

eventwise sum

photons seen by SiPM

0 50 100 150 200 250

photons seen by SiPM 1

0 2 4 6 8 10 12 14 16 18 20 22

distance to SiPM 1

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Coincidence Readout of a Ø 2.0 mm LuAG:Ce fiber (L = 23 cm)

**Position Reconstruction**

- Single sided readout: \( \mu_{\text{avg.}} = 0.09 \text{ cm}^{-1} \)

- Linear function for \( \mu = \text{const.} \)
  \[
  \ln \left( \frac{Amp_1}{Amp_2} \right) = -2 \cdot \mu \cdot x + \mu \cdot L
  \]

- But: \( \mu = \mu(x) \)

**Time Resolution**

(deduced from left-right coincidence)

\[
\sigma_t = \frac{\sigma(\Delta t)}{\sqrt{2}}
\]

- \(~ 120 \text{ ph seen on each side} \)
- \( \sigma_t = 800 \text{ ps} \)

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Response to $\gamma$ - sources

single sided readout of a LuAG:Ce fiber ($\varnothing = 2$ mm, $L = 23$ cm) wrapped with teflon

coincidence with BGO to define the interaction position:

comparison to simulation:
response dominated by low geometrical efficiency and light attenuation in the fiber

$LY_\gamma (d=1\text{cm}) = 270 \pm 25 \text{ ph/MeV}$ with a 50 $\mu$m SiPM
LYSO:Ce fiber \((\varnothing = 0.3 \text{ mm}, \text{ length} = 10 \text{ cm})\)

Response to \(^{241}\text{Am} - \text{ single sided readout}\)

Average attenuation coefficient: \(\mu \approx (0.68 \pm 0.02) \text{ cm}^{-1}\)

good homogeneity of all investigated fibers
LYSO:Ce rectangular rod (2.5 × 5.0 × 100 mm³)

Response to $^{137}$Cs γ – source PMT readout

Light attenuation

- Wrapped with teflon and aluminum foil: $\mu \approx 0.007$ cm$^{-1}$
- No wrapping: $\mu \approx 0.02$ cm$^{-1}$

Counts vs. signal amplitude / a.u.

Normalized light yield / a.u. vs. distance to photosensor / cm
Conclusion and Outlook

Comparison of the different fibers and the rectangular LYSO:Ce rods

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- Optimized crucible due to high melting point
- Significant improvement of quality and homogeneity of LuAG:Ce fibers
- Experience with growing parameters (speed, temperature gradient, Ce-concentration)
- Optimization of LYSO:Ce fibers will start this year (optimized crucible due to high melting point)
Thank you for your attention!

exhibition in the foyer!