Comparison of Single Crystalline and Composite Scintillators for Hadron Calorimetry at High Luminosity LHC
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M. Lucchini¹, M. Korjik², A. Fedorov², D. Kozlov², V. Mechinsky², J. Houzvicka³, S.Ochesanu³, M. Nikl⁴, E. Auffray¹

¹CERN, Geneva, Switzerland
²RINP, Minsk, Belarus
³Crytur, Turnov, Czech Republic
⁴Institute of Physics, Prague, Czech Republic
The CMS detector during High Luminosity LHC

- Since 2015 LHC increased the centre of mass energy from 7 to 13 TeV and the instantaneous luminosity up to $\sim 1 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$

- During High Luminosity LHC the proton collision rate will reach up to $\sim 200$ collisions each 25 ns

- The CMS detector will have to maintain adequate performance despite harsh radiation environment and high pile up conditions (200 vertices with 5 cm spatial spread and 150 ps time spread)

- An upgrade of the calorimeters is foreseen before HL-LHC phase
Challenges for the Back Hadron Calorimeter of HGC

- Radiation damage of PbWO and plastic scintillator requires replacement of current CMS endcap calorimeters
- New calorimeter (HGC) will consist of Silicon pads in the front part and Scintillator in the back (BH)

- Radiation levels in BH up to 100 kGy and $5 \times 10^{14}$ cm$^{-2}$ neutron fluence
  - Radiation tolerant scintillator
- BH covers a large area $\sim 443$ m$^2$ ($\sim 35$ m$^2$ highest radiation)
  - Mass production at low cost
Garnet crystals as radiation tolerant scintillators

- LuAG:Ce, YAG:Ce, GAGG:Ce crystals represent a family of well known bright inorganic scintillators
- Proved to be radiation tolerant up to high levels of hadron fluence and ionizing doses (∼100kGy)

Radiation tolerance of LuAG:Ce and YAG:Ce crystals under high levels of gamma- and proton-irradiation, IEEE Trans. on Nucl. Science, 63 (2016) 586-590

Effect of Mg$^{2+}$ ions co-doping on timing performance and radiation tolerance of Cerium doped Gd$_3$Al$_2$Ga$_3$O$_{12}$ crystals, NIM A 816 (2016) 176-183
Focusing on YAG:Ce single crystal

Further issues concerning HEP applications:

- Need to reduce signal background
  - YAG:Ce has no intrinsic radioactivity and low level of phosphorescence
- Scintillation kinetics need to be fast to reduce pile up at HL-LHC
  - Band structure in garnets can be engineered (e.g. by Mg-codoping) to obtain faster pulses*


Single crystal vs Composite scintillator

- **YAG:Ce single crystal grown via Czochralski technique**
  - Well known technology for growth and surface treatment of the samples

- **Grains of rad-hard scintillator embedded in a rad-hard glue**
  - Factorized approach based on radiation tolerance of single components
  - Cheaper and faster crystal production via easily synthesized powder, no need for cut and polishing
  - Lower density ($\sim 3 \text{ g/cm}^3$)
  - Poor light transmission
QE of Hamamatsu PMT R2059 for YAG emission (530 nm) is \(\sim 6.5\%\).

Read-out from the entire \(20 \times 10 \text{ mm}^2\) face of quartz

\[
\begin{align*}
\text{CRYSTAL + quartz} & \quad LO_{\text{grease}} = 19700 \pm 1000 \text{ ph/MeV} \\
& \quad LO_{\text{dry}} = 11600 \pm 600 \text{ ph/MeV}
\end{align*}
\]

\[
\begin{align*}
\text{COMPOSITE + quartz} & \quad LO_{\text{grease}} \approx 18000 \pm 2000 \text{ ph/MeV} \\
& \quad LO_{\text{dry}} \approx 10000 \pm 2000 \text{ ph/MeV}
\end{align*}
\]

Light output of composites is as high as for single crystal but photopeak events are fewer due to lower density and resolution is poorer.
Influence of thickness in composites

- Compare response to $\gamma$-rays and $\alpha$-particles in composites
  - $\alpha$-particles deposit energy on the surface of the sample
- Study influence of composite thickness on light output
  - Strong decrease of signal in thicker samples
  - Light produced far from the read-out face is not detected
  - Thickness of composites must be kept $\leq 1.5$ mm

![Graphs showing light output for different thicknesses and sources](image-url)
For a big calorimeter the **number of channels must be kept small** despite the large surface area to be covered

- Large scintillator tiles: $\geq 30 \times 30 \text{ mm}^2$
- Silicon Photomultipliers (SiPMs) must have small active area: $\leq 4 \times 4 \text{ mm}^2$ to maintain low cost and low power consumption

**Light collection is crucial** to guarantee sufficient signal for minimum ionizing particle detection:

- Need to optimize **surface treatment** and light extraction
- **Uniformity of light collection** is also important
Light collection test on YAG+Quartz sample

1. Read-out from $20 \times 10 \text{ mm}^2$ face
   \[ \text{LY}_{\text{dry}} = 11600 \text{ ph/MeV} \]

2. Using a black mask to cover the crystal face except a $\sim 4 \times 4 \text{ mm}^2$ area (expect a drop by a factor 13)
   \[ \text{LY}_{\text{dry}} \lesssim 900 \text{ ph/MeV} \]

3. Wrapping with reflective Teflon layers the whole extraction face, except a $\sim 4 \times 4 \text{ mm}^2$ area
   \[ \text{LY}_{\text{dry}} \sim 2300 \text{ ph/MeV} \]

- Light output drops “only” by a factor $\sim 5$, for wrapped+masked configuration (SiPM-like read-out)
- Using glue as optical couplant between crystal and SiPM would yield a factor 2 gain in light output
Characterization of single crystal tiles

- Single YAG:Ce crystal tiles of $30 \times 30 \text{ mm}^2$ area
  produced by Crytur company

- Different thicknesses: 1.5, 2.5, 5 mm

- Different surface states: as cut, fine grinded, fully polished, Al-reflective coating
Influence of thickness and surface state

- Light output was measured with one entire face coupled to PMT without optical grease and no wrapping (not real-detector configuration)
- For thin samples: **no need for polishing of all the faces**
- First attempt of **Al-coating on not-polished samples shows no increase of light extraction**

<table>
<thead>
<tr>
<th>Thickness [mm]</th>
<th>Surface state</th>
<th>Light Output [photons/MeV]</th>
</tr>
</thead>
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<tr>
<td>5</td>
<td>polished</td>
<td>6870</td>
</tr>
<tr>
<td>2.5</td>
<td>polished</td>
<td>8460</td>
</tr>
<tr>
<td>1.5</td>
<td>polished</td>
<td>9580</td>
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<td>1.5</td>
<td>fine grinded</td>
<td>10250</td>
</tr>
<tr>
<td>1.2</td>
<td>fine grinded</td>
<td>15340</td>
</tr>
<tr>
<td>1.2</td>
<td>fine grinded + Al coating</td>
<td>13730</td>
</tr>
<tr>
<td>1.2</td>
<td>as cut</td>
<td>15150</td>
</tr>
<tr>
<td>1.2</td>
<td>as cut + Al coating</td>
<td>13950</td>
</tr>
</tbody>
</table>
Light yield using SiPM-like readout

- Samples are wrapped and measured without grease using a $\sim 4 \times 4 \text{ mm}^2$ mask to simulate SiPM like read-out.

- **Light output in masked configuration is around** $1000 - 1800 \text{ ph/MeV}$

- Thicker samples show higher light output.
Choice of crystal thickness is crucial:

- thicker sample: higher energy deposits by mips:
  \[ E_{\text{dep}} \propto \rho \frac{Z}{A} \Delta x \]
  \( (E_{\text{dep}} \sim 720 \text{ keV/mm in YAG:Ce with } \rho = 4.6 \text{ g/cm}^3) \)

- thinner sample: cheaper calorimeter

- composites are disfavoured due to the lower density \( (\rho \leq 3.1 \text{ g/cm}^3) \)

- a \( \sim 2.5 \text{ mm thick YAG:Ce crystal with } 4 \times 4 \text{ mm}^2 \text{ SiPM on tile readout can yield about } 3000 \text{ ph/mip} \) (sufficient for good mip detection)

**Thickness of samples can be decreased \( \leq 2.5 \text{ mm} \) if light collection is further optimized**
Future work

Optimization of light collection and uniformity:
▶ study the effect of surface treatment on uniformity of light collection
▶ evaluate best SiPM-readout configuration (position) and shape of the crystal tile to enhance light output and uniformity through simulation
▶ test beam with mips or cosmic bench for validation of the simulation

Study of radiation damage:
▶ Irradiation of single crystals and composites with $\gamma$-rays and protons (ongoing campaign)
First results of YAG:Ce single crystal and composites comparison:

- Composites show stronger light attenuation which decreases light output in thick samples and increase non-uniformity of light collection
- YAG:Ce single crystals can provide a bright and radiation tolerant scintillator for usage in hadron calorimetry
- The main challenge is to obtain an efficient light extraction from a small fraction of the crystal surface
- Reduction of the cost per crystal tile (30 × 30 × 2.5 mm³) is important: no need for polishing of all the surfaces reduces production costs
backups
Previous results in test beam

► Test of YAG:Ce single crystal plates was performed at CERN H2 test beam facility with high energy muons

► Sub-optimal read-out of the tile via optical cones and fibers (poorer light collection efficiency wrt on-tile SiPM)
Uniformity of crystal-composite with low energy gamma

- Using Am-241 source and collimator to select 33 keV and 60 keV $\gamma$-rays
- QE of Hamamatsu PMT R2059 for YAG emission (530 nm) is $\sim 6.5$
- Read-out from the entire $20 \times 10 \text{ mm}^2$ face of quartz

### CRYSTAL + quartz

![Graph showing light yield for YAG Single Crystal - center and corner](image1)

### COMPOSITE + quartz

![Graph showing light yield for YAG Composite - center and corner](image2)