Materials for Calorimetry

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July 19, 2022

Presented in the Snowmass Community Summer Study 2022, University of Washington, Seattle
2019 DOE Basic Research Needs Study on Instrumentation for Calorimetry

<table>
<thead>
<tr>
<th>Priority Research Direction</th>
</tr>
</thead>
<tbody>
<tr>
<td>PRD 1: Enhance calorimetry energy resolution for precision electroweak mass and missing-energy measurements</td>
</tr>
<tr>
<td>PRD 2: Advance calorimetry with spatial and timing resolution and radiation hardness to master high-rate environments</td>
</tr>
<tr>
<td>PRD 3: Develop ultrafast media to improve background rejection in calorimeters and improve particle identification</td>
</tr>
</tbody>
</table>

Inorganic Scintillators

• Precision photons and electrons enhance physics discovery potential.

• Crystal performance is well understood:
  • The best possible energy resolution and position resolution;
  • Good $e/\gamma$ identification and reconstruction efficiency;
  • Excellent jet mass resolution with dual readout, C/S or F/S gate.

• Challenges at future HEP Experiments:
  • Fast and radiation hard scintillators for the HL-LHC and FCC-hh;
  • Ultrafast scintillators to break ps timing barrier & Mu2e-II ECAL;
  • Cost-effective crystals for the proposed Higgs factory.

• Inorganic scintillators at Caltech Crystal Lab:
  • Radiation hard LYSO:Ce and BaF$_2$ crystals, and LuAG:Ce ceramics;
  • Ultrafast BaF$_2$:Y, Cs$_2$ZnCl$_4$ and Ga$_2$O$_3$ crystals, and Lu$_2$O$_3$ ceramics;
  • BGO, BSO & PWO crystals, and heavy scintillating glasses.

arXiv:2203.06731/06788
Challenge: Radiation Damage at LHC

Use materials with monotonic damage: BaF$_2$, CsI, LYSO:Ce, LuAG:Ce

Neutron damage?
Use Materials with no Damage Recovery

Damage in PWO recovers at room temperature, requiring frequent calibration/monitoring.

No recovery in BaF$_2$, CsI and LYSO:Ce crystals, and LuAG:Ce ceramics, indicating dose-rate independent damage.

Presented by Ren-Yuan Zhu, Caltech, in the 2022 LANSCE User Group Meeting, Los Alamos, NM

6/2/2022
LYSO:Ce for CMS Barrel Timing Layer

MTD performance goal: 30-40 ps at the start degrading to < 60 ps at 3000 fb^{-1}

Barrel Timing Layer: arrays of LYSO crystal bars connected to SiPMs at both ends and readout by TOFHIR

Ultrafast inorganic scintillators would help to break the pico-second time barrier

BTL: LYSO bars + SiPM read-out

- TK / ECAL interface ~ 45 mm thick
- \(|\eta| < 1.45\) and \(p_{T} > 0.7\) GeV
- Active area ~ 38 m²; 332k channels
- Fluence at 3 ab^{-1}: \(2 \times 10^{14} \text{n}_{\text{eq}}/\text{cm}^2\)

ETL: Si with internal gain (LGAD)

- On the HGC nose ~ 65 mm thick
- \(1.6 < |\eta| < 3.0\)
- Active area ~ 14 m²; ~ 8.5M channels
- Fluence at 3 ab^{-1}: up to \(2 \times 10^{15} \text{n}_{\text{eq}}/\text{cm}^2\)

LYSO + SiPM with Thermal Electric Cooler (TEC) for CMS Barrel Timing Layer (BTL) in construction
LYSO Radiation Hardness

CMS LYSO spec: RIAC < 3 m⁻¹ after 4.8 Mrad, 2.5 x 10¹³ p/cm² and 3.2 x 10¹⁴ nₑq/cm²

Damage induced by protons is larger than that from neutrons
Due to ionization energy loss in addition to displacement and nuclear breakup
LuAG:Ce ceramics show a factor of two smaller RIAC values than LYSO:Ce up to $6.7 \times 10^{15}$ n$_{eq}$/cm$^2$ and $1.2 \times 10^{15}$ p/cm$^2$, promising for FCC-hh R&D on slow component suppression by Ca co-doping, and radiation hardness by $\gamma$/p/n.

Experiment 7638  
LuAG of of $10\times10\times3$ mm$^3$ $A_3=2.2\pm0.3\times10^{-15}$  
BaF$_2$ of $10\times10\times2$ mm$^3$ $A_2=(0.9\pm0.1)\times10^{-14}$  
LuAG of $\Phi 14.4\times1$ mm$^3$ $A_1=(1.1\pm0.4)\times10^{-15}$

LuAG:Ce Ceramic plates

Proton Experiments @ CERN  
irradiated by 24 GeV proton beam at CERN

BOET LFS 14-14-1.5 mm$^3$  
SIC LYSO 14-14-1.5 mm$^3$  
SIC LuAG $\Phi 15.4\times1$ mm$^3$  
irradiated by 800 MeV proton beam at LANL

SIOI LuAG $\Phi 17\times1$ mm$^3$

RIAC at Emission Peak (m$^{-1}$)  
RIAC = A$_n$ x Fluence

Lo in 200 ns (p.e./MeV)  
LO in 3000 ns (p.e./MeV)
RADiCAL: LYSO/LuAG Shashlik CAL

**RADiation hard CALorimetry**

Reducing light path length to mitigate radiation damage effect

Using radiation hard materials: LuAG:Ce ceramics excitation matches LYSO:Ce emission

Φ1x40 mm SIC LuAG:Ce ceramic LHPG fibers

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March 16, 2021 Presentation by Ren-Yuan Zhu in the EIC Calorimetry Workshop
Mu2e-II BaF$_2$::Y Calorimeter

Use ultrafast material to mitigate pile-up

- Energy resolution $\sigma < 5\%$ (FWHM/2.36) @ 100 MeV
- Time resolution $\sigma < 500$ ps
- Position resolution $\sigma < 10$ mm
- Radiation hardness
  - Crystals
  - Photosensors $1 \text{ kGy/yr and total of } 10^{12} n_{\text{1 MeV equivalent/cm}^2 \text{ total}}$
  - $3 \times 10^{11} n_{\text{1 MeV equivalent/cm}^2 \text{ total}}$

Mu2e-I: 1,348 CsI of 34 x 34 x 200 mm$^3$

CsI+SiPM

Mu2e-II: 1,940 BaF$_2$::Y

Mu2e-II: arXiv:2203.07596

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PIP-II/Mu2e-II: higher rates (~x3) and duty factor from higher ionizing radiation (10 kGy/yr) and neutron levels ($10^{13} n_{\text{1 MeV equiv/cm}^2 \text{ total}}$), which are particularly important at the inner radius of disk 1.
# Fast and Ultrafast Inorganic Scintillators

**Snowmass 2022 White Paper:** https://doi.org/10.48550/arXiv.2203.06788

<table>
<thead>
<tr>
<th>Material</th>
<th>BaF₂</th>
<th>BaF₂:Y</th>
<th>ZnO:Ga</th>
<th>YAP:Yb</th>
<th>YAG:Yb</th>
<th>β-Ga₂O₃</th>
<th>LYSO:Ce</th>
<th>LuAG:Ce</th>
<th>YAP:Ce</th>
<th>GAGG:Ce</th>
<th>LuYAP:Ce</th>
<th>YSO:Ce</th>
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<tbody>
<tr>
<td>Density (g/cm³)</td>
<td>4.89</td>
<td>4.89</td>
<td>5.67</td>
<td>5.35</td>
<td>4.56</td>
<td>5.94</td>
<td>7.4</td>
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<td>5.35</td>
<td>6.5</td>
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<td>1280</td>
<td>1975</td>
<td>1870</td>
<td>1940</td>
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<td>2050</td>
<td>2060</td>
<td>1870</td>
<td>1850</td>
<td>1930</td>
<td>2070</td>
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<tr>
<td>X0 (cm)</td>
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<td>2.03</td>
<td>2.51</td>
<td>2.77</td>
<td>3.53</td>
<td>2.51</td>
<td>1.14</td>
<td>1.45</td>
<td>2.77</td>
<td>1.63</td>
<td>1.37</td>
<td>3.10</td>
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<tr>
<td>Rₘ (cm)</td>
<td>3.1</td>
<td>3.1</td>
<td>2.28</td>
<td>2.4</td>
<td>2.76</td>
<td>2.20</td>
<td>2.07</td>
<td>2.15</td>
<td>2.4</td>
<td>2.20</td>
<td>2.01</td>
<td>2.93</td>
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<tr>
<td>λₜ (cm)</td>
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<td>30.7</td>
<td>22.2</td>
<td>22.4</td>
<td>25.2</td>
<td>20.9</td>
<td>20.9</td>
<td>20.6</td>
<td>22.4</td>
<td>21.5</td>
<td>19.5</td>
<td>27.8</td>
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<tr>
<td>Zₑff</td>
<td>51.6</td>
<td>51.6</td>
<td>27.7</td>
<td>31.9</td>
<td>30</td>
<td>28.1</td>
<td>64.8</td>
<td>60.3</td>
<td>31.9</td>
<td>51.8</td>
<td>58.6</td>
<td>33.3</td>
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</table>

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>dE/dX (MeV/cm)</td>
<td>6.52</td>
</tr>
<tr>
<td>λₚ (nm)</td>
<td>300, 220</td>
</tr>
<tr>
<td>Refractive Index</td>
<td>1.50, 1.50</td>
</tr>
<tr>
<td>Normalized Light Yield</td>
<td>42, 1.7</td>
</tr>
<tr>
<td>Total Light Yield</td>
<td>13,000, 2,000</td>
</tr>
<tr>
<td>Decay time (ns)</td>
<td>600, 0.5</td>
</tr>
<tr>
<td>LY in 1st ns (photons/MeV)</td>
<td>1200, 610</td>
</tr>
<tr>
<td>LY in 1st ns/Tot LY</td>
<td>9.2%, 60%</td>
</tr>
<tr>
<td>40 keV Att. Leng. 1/e, (mm)</td>
<td>0.106</td>
</tr>
</tbody>
</table>

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*.top/bottom row: slow/fast component; b at the emission peak; c normalized to LYSO:Ce; d excited by alpha particles; e ceramic with 0.3 Mg at% co-doping; f density for composition Lu₀.₇Y₀.₃AlO₅:Ce
**CalVision: A Longitudinally Segmented Crystal ECAL**

*arXiv: 2203.04312, see the DR session for details*

Followed by the IDEA DR HCAL, aiming at both EM and jet resolution

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**SCEPCal**

**Dual readout HCAL**

**Scintillating fibers**

$\varnothing = 1.05$ mm

**Cherenkov fibers**

$\varnothing = 1.05$ mm

**Brass capillary**

ID = 1.10 mm, OD = 2.00 mm

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M. Lucchini et al., JINST 15 (2020) P11005
The HHCAL Concept


R.-Y. Zhu, ILCWS-8, Chicago: a HHCAL cell with pointing geometry

Can we afford?
## Inorganic Scintillators for HHCAL

### Presentations
- Presented by Ren-Yuan Zhu at the 2022 Snowmass Community Summer Study, University of Washington, Seattle

### Table: Comparison of Inorganic Scintillators

<table>
<thead>
<tr>
<th></th>
<th>BGO</th>
<th>BSO</th>
<th>PWO</th>
<th>PbF₂</th>
<th>PbFCl</th>
<th>Sapphire:Ti</th>
<th>AFO Glass</th>
<th>BaO-2SiO₂ Glass¹</th>
<th>HFG Glass²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density (g/cm³)</td>
<td>7.13</td>
<td>6.8</td>
<td>8.3</td>
<td>7.77</td>
<td>7.11</td>
<td>3.98</td>
<td>4.6</td>
<td>3.8</td>
<td>5.95</td>
</tr>
<tr>
<td>Melting point (°C)</td>
<td>1050</td>
<td>1030</td>
<td>1123</td>
<td>824</td>
<td>608</td>
<td>2040</td>
<td>980³</td>
<td>1420⁴</td>
<td>570</td>
</tr>
<tr>
<td>X₀ (cm)</td>
<td>1.12</td>
<td>1.15</td>
<td>0.89</td>
<td>0.94</td>
<td>1.05</td>
<td>7.02</td>
<td>2.96</td>
<td>3.36</td>
<td>1.74</td>
</tr>
<tr>
<td>Rₘ (cm)</td>
<td>2.23</td>
<td>2.33</td>
<td>2.00</td>
<td>2.18</td>
<td>2.33</td>
<td>2.88</td>
<td>2.89</td>
<td>3.52</td>
<td>2.45</td>
</tr>
<tr>
<td>λ₁ (cm)</td>
<td>22.7</td>
<td>23.4</td>
<td>20.7</td>
<td>22.4</td>
<td>24.3</td>
<td>24.2</td>
<td>26.4</td>
<td>32.8</td>
<td>23.2</td>
</tr>
<tr>
<td>Z_{eff} Value</td>
<td>72.9</td>
<td>75.3</td>
<td>74.5</td>
<td>77.4</td>
<td>75.8</td>
<td>11.2</td>
<td>42.8</td>
<td>44.4</td>
<td>56.9</td>
</tr>
<tr>
<td>dE/dX (MeV/cm)</td>
<td>8.99</td>
<td>8.59</td>
<td>10.1</td>
<td>9.42</td>
<td>8.68</td>
<td>6.75</td>
<td>6.84</td>
<td>5.56</td>
<td>8.24</td>
</tr>
<tr>
<td>Emission Peak²</td>
<td>480</td>
<td>470</td>
<td>425</td>
<td>420</td>
<td>\</td>
<td>300</td>
<td>750</td>
<td>425</td>
<td>325</td>
</tr>
<tr>
<td>Refractive Index²</td>
<td>2.15</td>
<td>2.68</td>
<td>2.20</td>
<td>1.82</td>
<td>2.15</td>
<td>1.76</td>
<td>\</td>
<td>\</td>
<td>1.50</td>
</tr>
<tr>
<td>Relative Light Output by PMT³,c</td>
<td>100</td>
<td>20</td>
<td>1.6</td>
<td>0.4</td>
<td>\</td>
<td>0.2</td>
<td>0.9</td>
<td>2.6</td>
<td>5.0</td>
</tr>
<tr>
<td>LY (ph/MeV)³</td>
<td>35,000</td>
<td>1,500</td>
<td>130</td>
<td>\</td>
<td>150</td>
<td>7,900</td>
<td>450</td>
<td>3,150</td>
<td>150</td>
</tr>
<tr>
<td>Decay Time³</td>
<td>300</td>
<td>100</td>
<td>30</td>
<td>10</td>
<td>\</td>
<td>300</td>
<td>3200</td>
<td>180</td>
<td>25</td>
</tr>
<tr>
<td>d(LY)/dT (%/°C)²</td>
<td>-0.9</td>
<td>?</td>
<td>-2.5</td>
<td>\</td>
<td>?</td>
<td>\</td>
<td>\</td>
<td>-0.04</td>
<td>-0.37</td>
</tr>
<tr>
<td>Cost ($/cc)</td>
<td>6.0</td>
<td>7.0</td>
<td>7.5</td>
<td>6.0</td>
<td>?</td>
<td>0.6</td>
<td>?</td>
<td>?</td>
<td>?</td>
</tr>
</tbody>
</table>

### Notes:
- a. Top line: slow component, bottom line: fast component.
- b. At the wavelength of the emission maximum.
- c. Relative light yield normalized to the light yield of BGO.
- d. At room temperature (20°C) with PMT QE taken out.

### Additional Information:
- Low density crystals/glasses

### Snowmass 2022 White Paper:
https://doi.org/10.48550/arXiv.2203.06788
Organic, Liquid and Water-based Scintillators

- Plastic scintillator has modest cost ($10s/kg) and scale-up accessibility
  - Polyvinyltoluene (PVT) and polystyrene (PS) are the base resins for fabrication
  - New resins under development; 3D-printing can be employed to further reduce cost and labor request.
  - A new thermoplastics acrylic scintillator to load scintillators and high-Z elements directly into acrylic monomers is under investigation; a multilayer acrylic detector coupling with SiPMs could provide excellent position and energy reconstruction.

- Liquid scintillator has low cost ($1s/kg), fast timing (sub-ns) and adequate light-yield ($10^3 \sim 10^4$ ph/MeV)
  - New scintillator solvents enhance performance and improved chemical stability and compatibility with most plastics polymers have been developed for the neutrino frontier over the past decade.
  - Low density required loading high-Z elements at high mass fraction (capability~10%)

- Water-based Liquid Scintillator is novel for high-energy Cherenkov and low-energy scintillation detection
  - Bridging organic and water with long optical transparency (10s m) and more environmentally friend, enabling a broad physics program across a dynamic range from hundreds of keV to many GeV.
  - Low density required loading high Z elements (even more capable up to 30% and still has appreciable scintillation yield)
  - A 30T demonstrator is under construction at BNL to explore engineering parameters and scale-up performance of a kiloton-scale detector for next-generation particle physics experiments.
### Scintillator Comparison

#### Metal-doped Liquid Scintillators up to kton scale demonstrate the feasibility of high-Z doping

<table>
<thead>
<tr>
<th>Materials (noble gas not included)</th>
<th>LY (ph/MeV)</th>
<th>Cost* (per kg)</th>
<th>Decay Time (ns)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inorganic Scintillators</td>
<td>140 – 63,000</td>
<td>$1k$–$5k$</td>
<td>Sub to 1,000s</td>
<td>High density, easy deployment, low optical, scale-up challenge for large volume application, e.g. HHHCAL; RADICAL uses WLS*</td>
</tr>
<tr>
<td>Organic Scintillator Plastics</td>
<td>1,000s</td>
<td>$10s$</td>
<td>1s</td>
<td>Medium density, easy deployment, m-optical, scale-up challenge (3D-print?), WLS*</td>
</tr>
<tr>
<td>(High Z-doped, 15%) Organic Liquid Scintillator</td>
<td>9,000-14,000</td>
<td>$1s$</td>
<td>Sub</td>
<td>~10m-optical, low density (mitigated by high-Z?), large volume; WLS-doped</td>
</tr>
<tr>
<td>(High Z-doped, 10%) Water-based Liquid Scintillator</td>
<td>1,000s</td>
<td>&lt;$1s$</td>
<td>Sub</td>
<td>~10m-optical, low density (mitigated by high-Z?), environmentally-friendly, large volume, WLS-doped</td>
</tr>
</tbody>
</table>

* WLS (fibers) bridging emission to photosensor are required for plastics; direct coupling (no WLS) used by crystal calorimetry
+ See slide 27 of [http://www.hep.caltech.edu/~zhu/talks/ryz_210316_EIC_Crystal_CAL.pdf](http://www.hep.caltech.edu/~zhu/talks/ryz_210316_EIC_Crystal_CAL.pdf), for mass-produced crystal cost per cc.
Wavelength Shifter (WLS)

• WLS forms optical “bridges”:
  • Connect scintillation light emission from crystal, ceramic or organic scintillators to photosensors
    • Located proximately (or directly) within a detector region if the photosensors are radiation tolerant to the levels needed
    • Remotely - with fiberoptic connection - as needed for radiation protection of the photosensors.

• WLS are spectrally matched to a given scintillator and photosensor:
  • WLS Excited by the scintillation emission
  • WLS Emit at a longer wavelength that is accessible to photosensors.
  • Can be placed strategically to provide selective measurements.

• WLS in capillary or fiber/filament form are particularly effective in EM calorimetry:
  • Energy Measurement
  • Fast-timing Measurement
  • Precision spatial measurement of shower position
  • All of the above are potentially possible in ultracompact EM Calorimetry Modules (example RADiCAL)
  • These structures have the potential for application in challenging radiation environments, e.g. FCC-hh.
# WLS R&D for RADiCAL

<table>
<thead>
<tr>
<th>Scintillator material</th>
<th>Scintillator Emission Wavelength</th>
<th>Wavelength Shifter</th>
<th>WLS Emission Wavelengths</th>
<th>Photosensor Possibilities</th>
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<tbody>
<tr>
<td>LYSO:Ce</td>
<td>425nm</td>
<td>DSB1</td>
<td>495nm</td>
<td>SiPM, GaInP, new</td>
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<tr>
<td>LYSO:Ce</td>
<td>425nm</td>
<td>LuAG:Ce</td>
<td>520nm</td>
<td>SiPM, GaInP, new</td>
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<tr>
<td>LYSO:Ce</td>
<td>425nm</td>
<td>Direct - No WLS</td>
<td></td>
<td>SiPM, new</td>
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<tr>
<td>LuAG:Ce</td>
<td>520nm</td>
<td>Quantum Dots</td>
<td>560-580nm</td>
<td>SiPM, GaInP, new</td>
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<td>LuAG:Pr</td>
<td>310nm</td>
<td>pTP</td>
<td>360nm</td>
<td>SiPM, GaInP, new</td>
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<td></td>
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<td>TPB</td>
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<td>Flavenols</td>
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<td>LuAG:Pr</td>
<td>310nm</td>
<td>Direct - No WLS</td>
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<td>SiC</td>
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<td>CeF₃</td>
<td>330nm</td>
<td>pTP</td>
<td>360nm</td>
<td>SiPM, GaInP, new</td>
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<td></td>
<td></td>
<td>TPB</td>
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<td></td>
<td>Flavenols</td>
<td>560nm</td>
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<tr>
<td>CeF₃</td>
<td>330nm</td>
<td>Direct - No WLS</td>
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<td>SiC</td>
</tr>
<tr>
<td>BaF₂:Y</td>
<td>220nm</td>
<td>Direct – No WLS</td>
<td></td>
<td>Diamond</td>
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</tbody>
</table>
Summary

Future calorimetry requires fast, radiation hard and cost-effective material. Radiation-hard LYSO:Ce crystals and LuAG:Ce ceramics are proposed for an ultra-compact RADiCAL concept.

A BaF$_2$::Y ultrafast crystal calorimeter is proposed for Mu2e-II.

A segmented crystal ECAL with dual readout followed by the IDEA HCAL is proposed by CalVision for both EM and jet resolution for the Higgs factory. Homogeneous HCAL (HHCAL) promises the best jet mass resolution by total absorption. A critical issue is cost-effective mass-produced inorganic scintillator. Organic, liquid and water-based scintillators are very cost-effective, but have low density.

RADiCAL has a plan for novel WLS.

Novel materials are needed for all these calorimeter concepts.

Acknowledgements: DOE HEP Award DE-SC0011925, DE-SC0017810, DEAC02-98CH10886
Snowmass White Papers

RADiCAL: **RADiation hard innovative CALorimetry**
LYSO:Ce crystals and LuAG:Ce ceramics
arXiv: 2203.12806

Mu2e-II: 1,940 BaF$_2$:Y
arXiv:2203.07569

CalVision: A Longitudinally segmented crystal ECAL (BGO, BSO, PWO and glasses) followed by IDEA DR HCAL
arXiv:2203.04312
<table>
<thead>
<tr>
<th>Item</th>
<th>Size ((R_x \times R_y \times 25 \times X_0))</th>
<th>1 m³</th>
<th>10 m³</th>
<th>100 m³</th>
<th>Scaled to (X_0)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BGO</td>
<td>22.3(\times)22.3(\times)280 mm</td>
<td>$8/cc</td>
<td>$7/cc</td>
<td>$6/cc</td>
<td>1.23</td>
</tr>
<tr>
<td>BaF(_2):Y</td>
<td>31.0(\times)31.0(\times)507.5 cm</td>
<td>$12/cc</td>
<td>$11/cc</td>
<td>$10/cc</td>
<td>2.28</td>
</tr>
<tr>
<td>LYSO:Ce</td>
<td>20.7(\times)20.7(\times)285 mm</td>
<td>$36/cc</td>
<td>$34/cc</td>
<td>$32/cc</td>
<td>1.28</td>
</tr>
<tr>
<td>PWO</td>
<td>20(\times)20(\times)223 mm</td>
<td>$9/cc</td>
<td>$8/cc</td>
<td>$7.5/cc</td>
<td>1.00</td>
</tr>
<tr>
<td>BSO</td>
<td>22(\times)22(\times)274 mm</td>
<td>$8.5/cc</td>
<td>$7.5/cc</td>
<td>$7.0/cc</td>
<td>1.29</td>
</tr>
<tr>
<td>CsI</td>
<td>35.7(\times)35.7(\times)465 mm</td>
<td>$4.6/cc</td>
<td>$4.3/cc</td>
<td>$4.0/cc</td>
<td>2.09</td>
</tr>
</tbody>
</table>
### CMS MTD: Expected Radiation

**CMS BTL/EMEC:** $4.8/68 \text{ Mrad}, \ 2.5 \times 10^{13}/2.1 \times 10^{14} \text{ p/cm}^2 \ & \ 3.2 \times 10^{14}/2.4 \times 10^{15} \text{ n}_{eq}/\text{cm}^2$

<table>
<thead>
<tr>
<th>CMS MTD</th>
<th>$\eta$</th>
<th>$n_{eq}$ (cm$^{-2}$)</th>
<th>$n_{eq}$ Flux (cm$^{-2}$s$^{-1}$)</th>
<th>Proton Flux (cm$^{-2}$)</th>
<th>$p$ Flux (cm$^{-2}$s$^{-1}$)</th>
<th>Dose (Mrad)</th>
<th>Dose rate (rad/h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Barrel</td>
<td>0.00</td>
<td>2.5E+14</td>
<td>2.8E+06</td>
<td>2.2E+13</td>
<td>2.4E+05</td>
<td>2.7</td>
<td>108</td>
</tr>
<tr>
<td>Barrel</td>
<td>1.15</td>
<td>2.7E+14</td>
<td>3.0E+06</td>
<td>2.4E+13</td>
<td>2.6E+05</td>
<td>3.8</td>
<td>150</td>
</tr>
<tr>
<td>Barrel</td>
<td>1.45</td>
<td>2.9E+14</td>
<td>3.2E+06</td>
<td>2.5E+13</td>
<td>2.8E+05</td>
<td>4.8</td>
<td>192</td>
</tr>
<tr>
<td>Endcap</td>
<td>1.60</td>
<td>2.3E+14</td>
<td>2.5E+06</td>
<td>2.0E+13</td>
<td>2.2E+05</td>
<td>2.9</td>
<td>114</td>
</tr>
<tr>
<td>Endcap</td>
<td>2.00</td>
<td>4.5E+14</td>
<td>5.0E+06</td>
<td>3.9E+13</td>
<td>4.4E+05</td>
<td>7.5</td>
<td>300</td>
</tr>
<tr>
<td>Endcap</td>
<td>2.50</td>
<td>1.1E+15</td>
<td>1.3E+07</td>
<td>9.9E+13</td>
<td>1.1E+06</td>
<td>26</td>
<td>1020</td>
</tr>
<tr>
<td>Endcap</td>
<td>3.00</td>
<td>2.4E+15</td>
<td>2.7E+07</td>
<td>2.1E+14</td>
<td>2.3E+06</td>
<td>68</td>
<td>2700</td>
</tr>
</tbody>
</table>

Much higher at FCC-hh: up to $0.1/500 \text{ Grad}$ and $3 \times 10^{16}/5 \times 10^{18} \text{ n}_{eq}/\text{cm}^2$ at EMEC/EMF

M. Aleksa et al., Calorimeters for the FCC-hh CERN-FCCPHYS-2019-0003, Dec 23, 2019
BaF$_2$ has an ultrafast scintillation component @ 220 nm with 0.5 ns decay time and a much larger slow component @ 300 nm with 600 ns decay time.

Slow suppression may be achieved by rare earth doping, and/or solar-blind photo-detectors.

BaF$_2$ shows saturated damage from 10 krad to 100 Mrad, indicating good radiation resistance against $\gamma$-rays.

BaF$_2$ also survives after proton irradiation up to $9.7 \times 10^{14}$ p/cm$^2$, and neutron irradiation up to $8.3 \times 10^{15}$ n$_{eq}$/cm$^2$.

IEEE TNS 67, NO. 6 (2020) 1014-1019

IEEE TNS 340 (1994) 442-457

IEEE TNS 67 (2016) 612-619

IEEE TNS 65 (2018) 1086-1092

IEEE TNS 67 (2020) 1018-1024

July 19, 2022
Presented by Ren-Yuan Zhu in the 2022 Snowmass Community Summer Study, University of Washington, Seattle
BaF$_2$::Y for Ultrafast Calorimetry

Increased F/S ratio observed in BGRI BaF$_2$::Y crystals: Proc. SPIE 10392 (2017)

X-ray bunches with 2.83 ns spacing in septuplet are clearly resolved by ultrafast BaF$_2$::Y and BaF$_2$ crystals: for GHz Hard X-ray Imaging NIMA 240 (2019) 223-239
Gamma-ray Induced Readout Noise RIN:γ

BaF$_2$ crystals wrapped by Tyvek with an air gap coupling to a Hamamatsu PMT R2059, were irradiated by Co-60 with dose rates of 2 and 23 rad/h

\[
\frac{\text{Photocurrent}}{\text{Dose rate}_{\gamma-ray} \text{ or } \text{Flux}_{\text{neutron}}} = \sigma = \frac{\sqrt{Q}}{L_{\text{O}}} \quad \text{(MeV)}
\]

QE/PDE of four VUV photodetectors for BaF$_2$ and BaF$_2$:Y, IEEE TNS 69 (2022) 958-964
Cost-Effective Sapphire Crystals for HHCAL

Prof. Xu Jun of Tongji University: Sapphire crystals by Kyropoulos (KY) technology
A producer can grow 1,000 tons ingots annually with 400 to 450 kg/ingot
Cost of mass-produced Sapphire crystals including processing: less than $1/cc

<table>
<thead>
<tr>
<th>Weight (kg)</th>
<th>Size (cm)</th>
<th>Unit Price</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>ingot boule</td>
<td>400</td>
<td>Φ50×55</td>
<td>US$12000/pc</td>
</tr>
<tr>
<td>cutting/polishing</td>
<td>4</td>
<td>1×1×1</td>
<td>~US$0.6/cc</td>
</tr>
</tbody>
</table>
Sapphire:Ti Emission and Transmittance

A weak emission at 325 nm with 150 ns decay time
A strong emission at 755 nm with 3 μs decay time

<table>
<thead>
<tr>
<th>ID</th>
<th>Dimension (mm³)</th>
<th>#</th>
<th>Polishing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tongji Al₂O₃:Ti-1,2</td>
<td>10×10×4</td>
<td>2</td>
<td>Two faces</td>
</tr>
<tr>
<td>Tongji Al₂O₃:C-1,2</td>
<td>Φ7×1</td>
<td>2</td>
<td>Two faces</td>
</tr>
<tr>
<td>Tongji Lu₂O₃:Yb</td>
<td>6.4×4.8×0.4</td>
<td>1</td>
<td>Two faces</td>
</tr>
<tr>
<td>Tongji LuScO₃:Yb</td>
<td>Φ4.8×1.3</td>
<td>1</td>
<td>Two faces</td>
</tr>
</tbody>
</table>

Fast @325 nm
Slow @755 nm

EWLT for Fast & Slow
Fast = 162 ns
Slow = 3.2 μs