RADiCAL – Precision-timing, Ultracompact Radiation-hard Electromagnetic Calorimetry


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Table 1: Dimensions of the envelopes for the calorimeter sub-systems (including some space for services) and the maximum radiation load at inner radii (total ionising dose is estimated for 30 ab\(^{-1}\)). The abbreviations used in the first column are explained in the text.
RADiCAL - Ultracompact Sampling EM Calorimetry Modules for beam testing and comparison with simulation.

Objectives

Energy Resolution: $\sigma_E/E = 10%/\sqrt{E} \oplus 0.3/E \oplus 0.7%$ up to $|\eta| < 4.$

Fast response: $\sigma_t = 30-50$ps

Performant under FCC-hh operating conditions

- Scintillators
  - Crystals
  - Ceramics
- Wavelength Shifters
  - Fluorescent dyes
  - Liquids
  - Ceramics
- Optical Transmission Elements
  - Fiber optics/filaments
  - Capillaries
- Photosensors
  - SiPM
  - GaInP
  - SiC, Diamond, other
## Fast and Ultrafast Inorganic Scintillators

<table>
<thead>
<tr>
<th>Material</th>
<th>Density (g/cm²)</th>
<th>Melting Points (°C)</th>
<th>X₀ (cm)</th>
<th>Rₘ (cm)</th>
<th>λₗ (cm)</th>
<th>Zₜeff</th>
<th>dE/dX (MeV/cm)</th>
<th>λₚeak * (nm)</th>
<th>Refractive Index⁵⁺⁻⁺</th>
<th>Normalized Light Yield¹⁻⁻⁶⁺</th>
<th>Total Light Yield (ph/MeV)</th>
<th>Decay time* (ns)</th>
<th>LY in 1st ns (photons/MeV)</th>
<th>40 keV Att. Leng. (1/e, mm)</th>
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<tbody>
<tr>
<td>BaF₂</td>
<td>4.89</td>
<td>1280</td>
<td>2.03</td>
<td>3.1</td>
<td>30.7</td>
<td>51.6</td>
<td>6.52</td>
<td>300 220</td>
<td>1.50</td>
<td>42 4.8</td>
<td>13,000</td>
<td>600 &lt;0.6</td>
<td>1200</td>
<td>0.106</td>
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<tr>
<td>BaF₂ :Y</td>
<td>4.89</td>
<td>1280</td>
<td>2.03</td>
<td>3.1</td>
<td>30.7</td>
<td>51.6</td>
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<td>42 4.8</td>
<td>13,000</td>
<td>600 &lt;0.6</td>
<td>1200</td>
<td>0.106</td>
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<td>ZnO:Ga</td>
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<td>2.51</td>
<td>2.28</td>
<td>22.2</td>
<td>27.7</td>
<td>8.42</td>
<td>380</td>
<td>2.1</td>
<td>1.7 4.8</td>
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<td>&lt;1</td>
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<td>YAP:Yb</td>
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<td>1870</td>
<td>2.77</td>
<td>2.4</td>
<td>22.4</td>
<td>31.9</td>
<td>8.05</td>
<td>350</td>
<td>1.96</td>
<td>6.6d 0.19d</td>
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<td>0.314</td>
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<tr>
<td>YAG:Yb</td>
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<td>1940</td>
<td>3.53</td>
<td>2.76</td>
<td>25.2</td>
<td>30</td>
<td>7.01</td>
<td>350</td>
<td>1.96</td>
<td>6.6d 0.19d</td>
<td>2,000</td>
<td>4</td>
<td>60</td>
<td>0.314</td>
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<tr>
<td>β-Ga₂O₃</td>
<td>5.94(1)</td>
<td>1725</td>
<td>2.51</td>
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<td>20.9</td>
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<td>8.82</td>
<td>380</td>
<td>1.96</td>
<td>6.5 0.36d 100</td>
<td>13,000</td>
<td>4</td>
<td>60</td>
<td>0.407</td>
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### Comparison Table

<table>
<thead>
<tr>
<th>Material</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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<tr>
<td>Density</td>
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<td>1870</td>
<td>1850</td>
<td>1930</td>
<td>2070</td>
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<td>X₀</td>
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<td>1.45</td>
<td>2.77</td>
<td>1.63</td>
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<td>Rₘ</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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<td>λₗ</td>
<td>20.9</td>
<td>20.6</td>
<td>22.4</td>
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<td>19.5</td>
<td>27.8</td>
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<td>Zₜeff</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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<tr>
<td>dE/dX</td>
<td>9.55</td>
<td>9.22</td>
<td>8.05</td>
<td>8.96</td>
<td>9.82</td>
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<tr>
<td>λₚeak *</td>
<td>420</td>
<td>520</td>
<td>370</td>
<td>540</td>
<td>385</td>
<td>420</td>
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<td>Refractive Index⁵⁺⁻⁺</td>
<td>1.82</td>
<td>1.84</td>
<td>1.96</td>
<td>1.92</td>
<td>1.94</td>
<td>1.78</td>
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<tr>
<td>Normalized Light Yield¹⁻⁻⁶⁺</td>
<td>100</td>
<td>35e 48e</td>
<td>9 32</td>
<td>115</td>
<td>16 80</td>
<td></td>
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<tr>
<td>Total Light Yield (ph/MeV)</td>
<td>30,000</td>
<td>25,000°</td>
<td>12,000</td>
<td>34,400</td>
<td>10,000</td>
<td>24,000</td>
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<tr>
<td>Decay time* (ns)</td>
<td>40</td>
<td>820 50</td>
<td>191 25</td>
<td>800 80</td>
<td>1485 36</td>
<td>75</td>
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<tr>
<td>LY in 1st ns (photons/MeV)</td>
<td>740</td>
<td>240 391</td>
<td>640</td>
<td>125</td>
<td>318</td>
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<td>40 keV Att. Leng. (1/e, mm)</td>
<td>0.185</td>
<td>0.251</td>
<td>0.314</td>
<td>0.319</td>
<td>0.214</td>
<td>0.334</td>
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</tbody>
</table>

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Presentation by Ren-Yuan Zhu in the 2019 CPAD Workshop at Wisconsin University, Madison, WI
LYSO:Ce and LuAG:Ce Comparison under Irradiation by protons and neutrons

RIAC values as a function of proton fluence for LYSO/LFS crystals and LuAG ceramics irradiated at CERN

RIAC values as a function of 1 MeV equivalent neutron fluence for LYSO crystals and LuAG ceramics irradiated at LANSCE
New approach to the Fiberoptic Profile

Transmission Studies in capillaries as a function of successive 50Mrad $^{60}$Co gamma irradiation doses. ND Rad Lab.
Photosensor Development - SiPM

- Pixelated Geiger-mode devices with high photo efficiency across a broad spectral range.
- Intention is to exploit and further the development of localized cooling (TEC) of the SiPM to reduce noise and extend performance lifetime.
- Development of small pixel devices (5-7μm) to enhance efficiency and benefit from fast response time.

Pulse detected from a FBK SiPM with 5μm pixels.

Thermionic Cooling of HPK SiPM (CMS) Modeled scenario of operation up to 4000fb⁻¹ (CMS)

Blue – (-35c operation, no annealing)
Red – (-45c operation, annealing at 40c)
Photosensor Development – Large Band Gap Devices

• Larger Band-gap Technologies
  • For operation in very high radiation environments
  • GaInP pixelated devices have been fabricated.
  • Individual photon counting seen, similar to SiPM.
  • Device optimization needed to reduce surface currents seen in the latest version.

• Challenge here is the lack (currently) of a broad commercial market to help drive development. Pursuing interested industrial partnerships.

Photo of a 4x4 mm² GaInP Photosensor consisting of 10 arrays of 0.5 x 1.5mm² size and containing 25 µm pixels

GaInP Photospectrum showing individual photopeaks. Left most (0) is the pedestal. Illumination at λ = 405nm.

IV curves for GaInP photosensors under illumination and dark field (blue).
Test of a 4x4 array of W/LYSO:Ce with DSB1 WLS - filled Capillaries – CERN H4

Array tested at CERN H4 with both WLS capillaries and Y11 WLS fibers.

Capillaries with the ruby core blocking
Geant4 Simulation of Energy Resolution (module shown in slide 3).
Preliminary Study of Timing Measurement using W/LYSO:Ce and DSB1 WLS Fibers and Capillaries

LYSO/W module, single channel time resolution with SiPM readout. Waveshifter readout was either DSB1 WLS dye in a multiclad optical fiber (dots) or DSB1 WLS in a liquid-filled capillary (squares). FTBF, A. Bornheim et al.

Conclusion and not a surprise: the more light you can collect the better the timing resolution.

Motivates: Capillary use with clear ends rather than ruby quartz ends and read out from both downstream and upstream ends of the capillaries.
New approach to timing measurement with RADiCAL
Timing from WLS at Shower Max.

Specialized WLS Applications
1. To measure shower energy
   WLS runs the full length
2. To measure timing
   WLS filament at Shower Max
   Remainder of capillary is filled with Quartz Fiber and fused solid.
   Capillary can be read out from both ends.

WLS Light Yield as a function of distance from photosensor.
Blue: Energy Capillary
Orange: Timing Capillary
Geant4 Simulation of EM Shower of 50 GeV in a 3x3 array of RADiCAL Modules 14 x 14 x 114 mm³

Full energy measurement. Shower size set by Moliere Radius: $R_m = 13.7$ mm

Energy Fraction contained in Central Module

Energy Fraction contained in 3x3 array
GEANT4 simulation of the time resolution expected from Shower Max, using LYSO and DSB1 filament. Electrons of 50 GeV. Shower size at shower max $\sim X_0 = 4.7\text{mm}$

**Shower Max Timing Simulation with RADICAL**

**Time resolution vs detected light yield at Shower Max**

Profile of the energy at Shower Max

In a LYSO/W Module with WLS filament at the Shower Max location
Shower Max Timing Simulation with RADICAL

GEANT4 simulation of the time resolution expected from Shower Max, using LYSO and DSB1 filament. Electrons of 50 GeV
Shower size at shower max $\sim X_0 = 4.7\text{mm}$

Profile of the energy at Shower Max
In a LYSO/W Module with WLS filament at the Shower Max location. Module
Cross section imposed...

Time resolution vs detected light yield at Shower Max
Testing at Fermilab FTBF
Negative Beam $12 < E < 28$ GeV, Positive Beam $E = 120$ GeV

Upstream:
Silicon Tracking
MCP for Timing/Trigger

Downstream:
Pb glass for full EM shower containment.

RADiCAL Module
First Look at Energy signals: Pb glass vs RADiCAL Module
No tracking constraint (28 GeV negative beam)
Near term and Future

Near term (June 2022):
• Time Resolution for:
  12< E< 28 GeV negative beam
    Electrons – silicon tracking constraint
    “Gammas” – electrons without the tracking constraint
    MIPs – pions
  120 GeV positive beam
    Protons - Compare timing with BTL modules
• Spatial resolution of EM shower position reconstructed in the RADiCAL module vs incoming beam position from tracking

Future:
• Study of a Hexagonal Modules with simulation
• Advanced Rad-hard Photosensor R&D

Red: Energy Capillary
WLS runs full module depth

Blue: Timing Capillary
WLS at shower max only

Yellow: Calibration
Clear leaky fiber runs full module length for laser light injection
Summary

• RADiCAL R&D to develop highly efficient, ultra-compact and rad hard EM calorimetry elements that are precision timing capable.

• Development and testing of modular elements that can provide:
  1. Energy measurement.
  2. Shower Max timing measurement.
  3. EM Shower Position derived from the region of shower max where the shower cross section is confined within a radiation length.

• Potential applications of the technique or components in other areas:
  • Endcap and Forward Calorimetry
  • Timing detectors
  • Scintillation/WLS detection over compact regions

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