Inorganic Scintillators for Future HEP Experiments

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California Institute of Technology

May 16, 2022
Why Inorganic Scintillators?

• Precision photons and electrons enhance physics discovery potential in HEP experiments.

• Performance of crystal calorimeters is well understood for $e/\gamma$, and is promising for jets measurements:
  • The best possible energy resolution and position resolution;
  • Good $e/\gamma$ identification and reconstruction efficiency;
  • Excellent jet mass resolution with dual readout, either C/S and F/S gate.

• Challenges at future HEP Experiments:
  • Radiation hard scintillators at the energy frontier: HL-LHC and FCC-hh;
  • Ultra-fast scintillators at the intensity frontier: Mu2e-II;
  • Cost-effective crystals for Higgs factory.
# 2019 DOE Basic Research Needs Study on Instrumentation: Calorimetry

**Priority Research Direction**

**PRD 1:** Enhance calorimetry energy resolution for precision electroweak mass and missing-energy measurements

**PRD 2:** Advance calorimetry with spatial and timing resolution and radiation hardness to master high-rate environments

**PRD 3:** Develop ultrafast media to improve background rejection in calorimeters and improve particle identification

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Fast/ultrafast, radiation hard and cost-effective inorganic scintillators needed to achieve energy, spatial and timing resolution for future HEP calorimetry
Fast and **Ultrafast** Inorganic Scintillators

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

<table>
<thead>
<tr>
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<th>BaF$_2$:Y</th>
<th>ZnO:Ga</th>
<th>YAP:Yb</th>
<th>YAG:Yb</th>
<th>$\beta$-Ga$_2$O$_3$</th>
<th>LYSO:Ce</th>
<th>LuAG:Ce</th>
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<th>GAGG:Ce</th>
<th>LuYAP:Ce</th>
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<td>$\lambda_{peak}^a$ (nm)</td>
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<td>300 220</td>
<td>380</td>
<td>350</td>
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<td>380</td>
<td>420</td>
<td>520</td>
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<td><strong>Normalized Light Yield</strong>^a,c</td>
<td>42 4.8</td>
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<td>6.6a 0.19a</td>
<td>0.36a 6.5 0.5</td>
<td>100 35° 48°</td>
<td>9 32 115</td>
<td>16 15 80</td>
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<td>2,000</td>
<td>2,000a 57a</td>
<td>110a 2,100</td>
<td>30,000 25,000°</td>
<td>12,000 34,400</td>
<td>10,000 24,000</td>
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<td><strong>Decay time</strong>^d (ns)</td>
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<td>600 0.5</td>
<td>&lt;1 1.5 4</td>
<td>148 6 40</td>
<td>820 50 191 25</td>
<td>53 1485 36 75</td>
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<td>LY in 1st ns (photons/MeV)</td>
<td>1200</td>
<td>1200</td>
<td>610a 28a</td>
<td>24a 43</td>
<td>740 240 391</td>
<td>640 125 318</td>
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<td></td>
<td></td>
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<td>LY in 1st ns/Total LY</td>
<td>9.2%</td>
<td>60%</td>
<td>31%</td>
<td>49%</td>
<td>22%</td>
<td>2.0%</td>
<td>2.5%</td>
<td>1.0%</td>
<td>3.3%</td>
<td>1.9%</td>
<td>1.3%</td>
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<td>40 keV Att. Leng. (1/e, mm)</td>
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<td>0.106</td>
<td>0.407</td>
<td>0.314</td>
<td>0.439</td>
<td>0.394</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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$^a$ 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 Lu$_{0.7}$Y$_{0.3}$AlO$_3$:Ce

See C. Hu in this conference.
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
- |η| < 1.45 and p_T > 0.7 GeV
- Active area ~ 38 m²; 332k channels
- Fluence at 3 ab⁻¹: 2x10¹⁴ n_{eq}/cm²

**ETL: Si with internal gain (LGAD)**
- On the HGC nose ~ 65 mm thick
- 1.6 < |η| < 3.0
- Active area ~ 14 m²; ~ 8.5M channels
- Fluence at 3 ab⁻¹: up to 2x10¹⁵ n_{eq}/cm²

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, $2.5 \times 10^{13}$ p/cm$^2$ and $3.2 \times 10^{14}$ n$_{eq}$/cm$^2$

Damage induced by protons is a factor of ten larger than that from neutrons
Due to ionization energy loss in addition to displacement and nuclear breakup
LuAG:Ce Ceramics Radiation Hardness

IEEE TNS 69 (2022) 181-186

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 $\gamma/p/n$.
RADiCAL: LYSO/LuAG Shashlik ECAL

See R. Ruchti in this conference

Excitation of LuAG:Ce ceramics matches well LYSO:Ce emission:

RADiCAL
RADiation hard innovative CALorimetry

Φ1x40 mm³ SIC LuAG:Ce Ceramic LHPG fibers

Laser Heated Pedestal Growth
Mu2e Calorimeter Requirements

See S. Miscetti in this conference

- Energy resolution \( \sigma < 5\% \) (FWHM/2.36) \@ 100 MeV
- Time resolution \( \sigma < 500 \) ps
- Position resolution \( \sigma < 10 \) mm
- Radiation hardness
  - Crystals
  - Photosensors
    - 1 kGy/yr and a total of \( 10^{12} \) n_1 MeV equivalent/cm² total
    - \( 3 \times 10^{11} \) n_1 MeV equivalent/cm² total

Mu2e-I: 1,348 CsI of 34 x 34 x 200 mm³
CsI+SiPM

Mu2e-II: 1,940 BaF₂·Y


PIP-II/Mu2e-II: higher rates (~x3) and duty factor from higher ionizing radiation (10 kGy/yr) and neutron levels \( (10^{13} \) n_1 MeV equiv/cm² total), which are particularly important at the inner radius of disk 1.
Ultrafast and Radiation Hard BaF₂

BaF₂ 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.

BaF₂ shows saturated damage from 10 krad to 100 Mrad, indicating good radiation resistance against γ-rays.

BaF₂ also survives after proton irradiation up to $9.7 \times 10^{14}$ p/cm², and neutron irradiation up to $8.3 \times 10^{15}$ nₑq/cm².
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.

 photocurrent

\[ F = \frac{\text{Charge}_{\text{electron}} \times \text{Gain}_{\text{SiPM}}}{\text{Dose rate}_{\gamma-ray} \text{ or } \text{Flux}_{\text{neutron}}} \]

\[ \sigma = \frac{\sqrt{Q}}{LO} \text{ (MeV)} \]

QE/PDE of four VUV photodetectors for BaF$_2$ and BaF$_2$:Y, IEEE TNS 69 (2022) 958-964
Calvision: A Longitudinally Segmented Crystal ECAL

Aiming at excellent EM and jet resolutions for Higgs Factory

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


M. Demarteau, 2021 CPAD Workshop

Can we afford?

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

Presented by Ren-Yuan Zhu of Caltech in the 2022 Carlo Conference, University of Sussex, Brighton, UK

May 16, 2022

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

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<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>
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<td>1123</td>
<td>824</td>
<td>608</td>
<td>2040</td>
<td>980³</td>
<td>1420⁴</td>
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<td>420</td>
<td>300</td>
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<td>2.15</td>
<td>1.76</td>
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<td><strong>Relative Light Output by PMT</strong></td>
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<td>20</td>
<td>1.60</td>
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<td>0.9</td>
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<td>150</td>
<td>150</td>
<td>7,900</td>
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<td>10</td>
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<td>300</td>
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<td><strong>d(LY)/dT (%/°C)</strong></td>
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<td>0.6</td>
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**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.

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Low density crystals/glasses

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May 16, 2022

Presented by Ren-Yuan Zhu of Caltech in the 2022 Carlo Conference, University of Sussex, Brighton, UK

15
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

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<th>Unit Price</th>
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<td>Φ50×55</td>
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<td>1×1×1</td>
<td>~US$0.6/ccc</td>
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Large sapphire crystal of 400-450 kg
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

Fast @325 nm
Slow @755 nm

EWLT for Fast & Slow

Fast = 162 ns
Slow = 3.2 μs
Summary

The HL-LHC and FCC-hh require fast and radiation hard calorimetry. The **RADiCAL** concept uses radiation hard LuAG:Ce ceramics as wavelength shifter for LYSO:Ce crystals for an ultra-compact, fast timing and longitudinally segmented shashlik calorimeter.

Undoped BaF$_2$ crystals provide ultrafast light with sub-ns decay time and a good radiation hardness up to 100 Mrad. Yttrium doping suppresses its slow light and promises an ultrafast calorimeter. R&D is needed for optimizing yttrium doping and radiation hardness in large size BaF$_2$:Y crystals for Mu2e-II. Solar-blind VUV photo-detectors are also needed to control radiation induced readout noise.

The longitudinally segmented **Calvision** crystal ECAL with dual readout combined with the IDEA HCAL promises excellent EM and Hadronic resolutions for the Higgs factory.

Homogeneous HCAL (**HHCAL**) promises the best jet mass resolution by total absorption. R&D is needed for cost-effective mass-produced inorganic scintillators.

**Novel inorganic scintillators are needed for all these novel calorimeter concepts**

Acknowledgements: DOE HEP Award DE-SC0011925