The Next Generation Crystal Detectors for Future HEP Calorimeters

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Why Crystal Calorimetry?

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

• Performance of crystal calorimeter is well understood for $e/\gamma$, and is investigated 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.

• The next generation crystal detectors for HEP experiments:
  – Bright, fast and rad-hard LYSO and LuAG ceramics at the HL-LHC;
  – BaF$_2$:Y with $<$1 ns decay: ultrafast calorimetry for unprecedented rate;
  – Crystals with $<$1/cc for the homogeneous hadron calorimetry.
Application of Ultrafast Crystals

Mu2e-I: 1,348 CsI of 34 x 34 x 200 mm
Mu2e-II: 1,940 BaF$_2$:Y of 30 x 30 x 218 mm

### Fast and Ultrafast Inorganic Scintillators

<table>
<thead>
<tr>
<th></th>
<th>BaF$_2$</th>
<th>BaF$_2$ : Y</th>
<th>ZnO : Ga</th>
<th>YAP : Yb</th>
<th>YAG : Yb</th>
<th>β - Ga$_2$O$_3$</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><strong>Density (g/cm$^3$)</strong></td>
<td>4.89</td>
<td>4.89</td>
<td>5.67</td>
<td>5.35</td>
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<td>1940</td>
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<td>2060</td>
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<td>2.03</td>
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<td>2.77</td>
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<td>2.51</td>
<td>1.14</td>
<td>1.45</td>
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<td>3.1</td>
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<td>2.76</td>
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<td>2.15</td>
<td>2.4</td>
<td>2.20</td>
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<td><strong>λ$_i$ (cm)</strong></td>
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<td>22.4</td>
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<td>21.5</td>
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<td><strong>Z$_{eff}$</strong></td>
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<td>51.6</td>
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<td>51.8</td>
<td>58.6</td>
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<tr>
<td><strong>dE/dX (MeV/cm)</strong></td>
<td>6.52</td>
<td>6.52</td>
<td>8.42</td>
<td>8.05</td>
<td>7.01</td>
<td>8.82</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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<td><strong>λ$_{peak}$ (nm)</strong></td>
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<td>220</td>
<td>300</td>
<td>220</td>
<td>380</td>
<td>350</td>
<td>350</td>
<td>380</td>
<td>420</td>
<td>520</td>
<td>370</td>
<td>420</td>
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<td><strong>Refractive Index$^b$</strong></td>
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<td>1.50</td>
<td>2.1</td>
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<td>1.84</td>
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<tr>
<td><strong>Normalized Light Yield$^{a,c}$</strong></td>
<td>42</td>
<td>4.8</td>
<td>1.7</td>
<td>6.6$^{d}$</td>
<td>0.19$^{d}$</td>
<td>0.36$^{d}$</td>
<td>6.5</td>
<td>0.5</td>
<td>100</td>
<td>35$^{e}$</td>
<td>48$^{e}$</td>
<td>9</td>
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<tr>
<td><strong>Total Light yield (ph/MeV)</strong></td>
<td>13,000</td>
<td>2,000</td>
<td>2,000$^d$</td>
<td>57$^d$</td>
<td>110$^d$</td>
<td>2,100</td>
<td>30,000</td>
<td>25,000$^e$</td>
<td>12,000</td>
<td>34,400</td>
<td>10,000</td>
<td>24,000</td>
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<tr>
<td><strong>Decay time$^a$ (ns)</strong></td>
<td>600</td>
<td>&lt;0.6</td>
<td>&lt;1</td>
<td>1.5</td>
<td>4</td>
<td>148</td>
<td>6</td>
<td>40</td>
<td>820</td>
<td>50</td>
<td>191</td>
<td>25</td>
</tr>
<tr>
<td><strong>LY in 1st ns (photons/MeV)</strong></td>
<td>1200</td>
<td>1200</td>
<td>610$^d$</td>
<td>28$^d$</td>
<td>24$^d$</td>
<td>43</td>
<td>740</td>
<td>240</td>
<td>391</td>
<td>640</td>
<td>125</td>
<td>318</td>
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<tr>
<td><strong>40 keV Att. Leng. (1/e, mm)</strong></td>
<td>0.106</td>
<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>
</tr>
</tbody>
</table>
Expected Radiation at the HL-LHC

CMS MTD: 4.8 Mrad, $2.5 \times 10^{13}$ p/cm$^2$ & $3.2 \times 10^{14}$ n$_{eq}$/cm$^2$

CMS FCAL: 68 Mrad, $2.1 \times 10^{14}$ p/cm$^2$ & $2.4 \times 10^{15}$ n$_{eq}$/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>Protons (cm$^2$)</th>
<th>p Flux (cm$^{-2}$s$^{-1}$)</th>
<th>Dose (Mrad)</th>
<th>Dose rate (rad/h)</th>
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<tr>
<td>Barrel</td>
<td>0.00</td>
<td>2.48E+14</td>
<td>2.75E+06</td>
<td>2.2E+13</td>
<td>2.4E+05</td>
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<td>Barrel</td>
<td>1.15</td>
<td>2.70E+14</td>
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<td>2.6E+05</td>
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<td>150</td>
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<tr>
<td>Barrel</td>
<td>1.45</td>
<td>2.85E+14</td>
<td>3.17E+06</td>
<td>2.5E+13</td>
<td>2.8E+05</td>
<td>4.8</td>
<td>192</td>
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<tr>
<td>Endcap</td>
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<td>2.3E+14</td>
<td>2.50E+06</td>
<td>2.0E+13</td>
<td>2.2E+05</td>
<td>2.9</td>
<td>114</td>
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<tr>
<td>Endcap</td>
<td>2.00</td>
<td>4.5E+14</td>
<td>5.00E+06</td>
<td>3.9E+13</td>
<td>4.4E+05</td>
<td>7.5</td>
<td>300</td>
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<tr>
<td>Endcap</td>
<td>2.50</td>
<td>1.1E+15</td>
<td>1.25E+07</td>
<td>9.9E+13</td>
<td>1.1E+06</td>
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<tr>
<td>Endcap</td>
<td>3.00</td>
<td>2.4E+15</td>
<td>2.67E+07</td>
<td>2.1E+14</td>
<td>2.3E+06</td>
<td>67.5</td>
<td>2700</td>
</tr>
</tbody>
</table>
Particle Energy Spectra at the HL-LHC

FLUKA simulations: neutrons and charged hadrons peaked at MeV and several hundreds MeV, respectively. Neutron and proton induced damages were investigated at the East Port and the Blue Room of the Los Alamos Neutron Science Center (LANSCE), respectively.
Radiation induced readout noise (~30 keV) was determined by measuring the radiation induced photo-current in LYSO+SiPM under the expected dose rate and neutron fluence.

\[
F = \frac{\text{Photocurrent} \times \text{Gain}_{\text{SiPM}}}{\text{Dose rate}_{\gamma-ray} \text{ or Flux}_{\text{neutron}}} \quad \sigma = \frac{\sqrt{Q}}{LO} \quad (\text{MeV})
\]
Irradiation by 800 MeV protons in three experiments 6501, 6990 and 7324 up to $3 \times 10^{15} \, \text{p/cm}^2$ was carried out in the blue room of LANSCE, where crystals and shashlik calorimeter towers were measured \textit{in situ} by a home-made spectrophotometer.

Irradiation by neutrons in three experiments 6991, 7332 and 7638 up to $3 \times 10^{15} \, \text{neq/cm}^2$ in the East Port of LANSCE with 1 MeV equivalent neutron flux calculated by using MCNPX (Monte Carlo N-Particle eXtended) package tallied in the largest sample volume (averaging).
LYSO Radiation Hardness

CMS BTL radiation spec: < 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 an order of magnitude larger than that from neutrons due to ionization energy loss in addition to displacement and nuclear breakup.
LuAG:Ce Ceramic Samples

LuAG S1  
LuAG S2

Ce 0.1 Ce 0.2 Ce 0.3

LuAG:Ce SIC-S1 25×25×0.4 mm³
Transmittance (%)
Wavelength (nm)

EWLT=51.8%

LuAG:Ce SIC-S2 25×25×0.4 mm³
Transmittance (%)
Wavelength (nm)

EWLT=52.3%

LuAG:Ce Ceramics SIC-S1 25×25×0.4 mm³
Intensity (a.u.)
Wavelength (nm)

Em=500nm
Ex=450nm

LuAG:Ce Ceramics SIC-S2 25×25×0.4 mm³
Intensity (a.u.)
Wavelength (nm)

Em=500nm
Ex=450nm
Radiation Hard LuAG:Ce Ceramics

Investigated at LANSCE up to $3 \times 10^{14}$ p/cm$^2$ of 800 MeV, and at Sadia up to 220 Mrad

R&D on-going to suppress $\mu$s slow component by Pr doping or co-doping
γ-Ray Induced Damage in Large BaF$_2$

- BGRI-2015D
- BGRI-2015E
- BGRI-2015511
- Russo 2
- Russo 3

2017: SIC BaF$_2$:Y 32 x 32 x 182 mm$^3$

2017: BGRI BaF$_2$:Y 25 x 25 x 100 mm$^3$
Proton and Neutron Induced Damage in BaF$_2$
BaF$_2$ has an ultrafast scintillation component with sub-ns decay, and a 600 ns slow component.

The amount of the fast light is similar to undoped CsI, and is 1/5 of the slow component.

Selective readout of the ultrafast component may be realized by (1) selective doping in crystals or (2) selective readout with solar blind photodetector.
Yttrium Doped Barium Fluoride: $\text{BaF}_2:Y$

Significant increased F/S ratio in $\text{BaF}_2:Y$; Sub-ns FWHM by MCP-PMT
APS Beam Test: Other Fast Crystals

YAP:Yb, ZnO:Ga, YAG:Yb and GaO have pulse width less than 10 ns

 Decay time consists with our Lab data measured with $\gamma$-ray source
APS Beam Test: BaF$_2$ : Y, BaF$_2$, ZnO:Ga & LYSO

X-ray bunches with 2.83 ns spacing in septuplet are clearly resolved by ultrafast BaF$_2$:Y and BaF$_2$ crystals, showing a proof-of-principle for the type –I imager.

Amplitude reduction in BaF$_2$ and LYSO due to space charge in PMT from slow scintillation, but not in BaF$_2$:Y.
Progress in Large Size BaF$_2$:Y Crystals

Two large size BaF$_2$:Y samples grown at SIC and BGRI in 2019
Improved optical quality, F/S ratio and light response uniformity

SIC-2019: 30×30×140 mm$^3$
BGRI-2019: 35×35×270 mm$^3$

SIC BaF$_2$:Y long crystals
Light Path Length 140/182 mm

- Transmission (%)

- SIC-2019 30×30×140 mm$^3$
  - $T@$: 78.6% 85.1%
  - EWLT: 78.0% 85.8%
- SIC-2017 32×32×182 mm$^3$
  - $T@$: 74.2% 69.0%

- Emission

SIC BaF$_2$:Y-2019 30×32×140 mm$^3$

- Light Output (p.e./MeV)

- Seed end
  - $L_0 = A_0 + A_1 e^{-\frac{t}{\tau}}$
  - $A_0 = 125$, $A_1 = 55$, $\tau = 585$
  - F/S = 2.3 ± 0.3

- Tail end
  - $L_0 = A_0 + A_1 e^{-\frac{t}{\tau}}$
  - $A_0 = 141$, $A_1 = 86$, $\tau = 554$
  - F/S = 1.6 ± 0.2

- PMT: R2059, Grease, Tyvek wrapped

Normalized Light Output

- Ratio 50/2500

- Back Rise = (-53.7±3.8)%
- $\delta_0 = (-3.3\pm0.7)\%/X_0$
- RMS=12.8%
- Average $L_0$ = 162 p.e./MeV

- Back Rise = (-28.2±3.7)%
- $\delta_0 = (-0.23\pm0.7)\%/X_0$
- RMS=5.7%
- Average $L_0$ = 162 p.e./MeV

Distance from the end coupled to PMT (mm)

- PMT: R2059, Grease, Tyvek wrapped
  - 2500 ns gate

- PMT: R2059, Grease, Tyvek wrapped
  - 50 ns gate

December 8, 2019
Presentation by Ren-Yuan Zhu in the 2019 CPAD Workshop at Wisconsin University, Madison, WI
UV Photo-Detector for BaF$_2$ and BaF$_2$:Y

<table>
<thead>
<tr>
<th>Photo-detectors</th>
<th>EWQE$_{\text{fast}}$ (%)</th>
<th>EWQE$_{\text{slow}}$ (%)</th>
<th>BaF$<em>2$ LO$</em>{\text{fast}}$</th>
<th>BaF$<em>2$ LO$</em>{\text{slow}}$</th>
<th>BaF$_2$ F/S</th>
<th>BaF$<em>2$:Y LO$</em>{\text{fast}}$</th>
<th>BaF$<em>2$:Y LO$</em>{\text{slow}}$</th>
<th>BaF$_2$:Y F/S</th>
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</thead>
<tbody>
<tr>
<td>Hamamatsu R2059</td>
<td>15.2</td>
<td>20.9</td>
<td>0.15</td>
<td>1.07</td>
<td>1/7.0</td>
<td>0.15</td>
<td>0.32</td>
<td>1/2.1</td>
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<tr>
<td>Photek solar blind PMT</td>
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<td>10.6</td>
<td>0.26</td>
<td>0.54</td>
<td>1/2.1</td>
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<td>0.15</td>
<td>1/0.6</td>
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<tr>
<td>Hamamatsu s1337x</td>
<td>21.7</td>
<td>18.2</td>
<td>0.22</td>
<td>0.93</td>
<td>1/4.3</td>
<td>0.22</td>
<td>0.28</td>
<td>1/1.3</td>
</tr>
</tbody>
</table>

December 8, 2019 Presentation by Ren-Yuan Zhu in the 2019 CPAD Workshop at Wisconsin University, Madison, WI
A. Para, H. Wenzel, and S. McGill, Callor2012: GEANT simulations show a jet energy resolution at a level of 20%/$\sqrt{E}$.

R.-Y. Zhu, ILCWS-8, Chicago: a HHCAL cell with pointing geometry
Cost-Effective Sapphire Crystals for HHCAL

With Kyropoulos (KY) growth technology mass production capability of Sapphire crystal exists. A typical producer can grow 1,000 tons of Sapphire ingots annually with 400 to 450 kg/ingot. The mass production cost of undoped Sapphire crystals after processing is less than $1/cc.

<table>
<thead>
<tr>
<th>Sapphire Crystal</th>
<th>Weight (g)</th>
<th>Size (cm)</th>
<th>Unit Price</th>
<th>Comment</th>
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</thead>
<tbody>
<tr>
<td>Ingot Boule</td>
<td>400,000</td>
<td>Ø50×55</td>
<td>US$12,000/pc</td>
<td>Undoped</td>
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<td>Cutting/Polishing</td>
<td>4</td>
<td>1×1×1</td>
<td>~US$0.6/cc</td>
<td>Undoped</td>
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Preliminary Result of Ti-Sapphire Crystals

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

All samples received on April 15th 2019 (Monday)

Ti:Sapphire crystals show a weak emission at 325 nm with 150 ns decay time and a strong emission at 755 nm with 3 µs decay time. The latter may be used for the HHCAL concept.
LYSO crystals are radiation hard for applications at the HL-LHC, such as CMS BTL. BaF₂ shows a radiation hardness similar to LYSO at high radiation dose. LuAG:Ce ceramics may provide an alternative of LYSO, provided that its slow component is eliminated.

Commercially available undoped BaF₂ crystals provide ultrafast light with sub-ns decay time. Yttrium doping in BaF₂ crystals increases its F/S ratio significantly while maintaining the intensity of the sub-ns fast component. With a sub-ns pulse width BaF₂:Y promises an ultrafast calorimetry to cope with unprecedented event rate. Large size BaF₂:Y samples show significantly improved optical quality.

Mass production capability of Sapphire crystals exists with a cost of less than $1/cc. Ti-Sapphire crystals show a scintillation at 755 nm with 3 µs decay time and a cut-off wavelength at 280 nm, which may be used to construct an HHCAL with dual readout of both scintillation and Cerenkov light.

Additional ultrafast scintillators under development are ZnO:Ga films, quantum confinement based all inorganic Cs Pb halide perovskite QD.
All Inorganic Cs Pb Halide Perovskite QD

Absorption, emission wavelength and decay time can be tuned for size and composition with quantum efficiency up to 90%.
Figure 6. Quantum efficiency of diamond photoconductors at different temperatures and Arrhenius plot of the peak value (inset). (From [Sal00].)

**Fig. 4.** External quantum efficiency extended to visible and near infrared wavelength regions. The
## Properties of Heavy Crystal with Mass Production Capability

<table>
<thead>
<tr>
<th>Crystal</th>
<th>Nal:Tl</th>
<th>CsI:Tl</th>
<th>CsI</th>
<th>BaF$_2$</th>
<th>CeF$_3$</th>
<th>PbF$_2$</th>
<th>BGO</th>
<th>BSO</th>
<th>PbWO$_4$</th>
<th>LYSO:Ce</th>
<th>AFO Glasses</th>
<th>Sapphire:Ti</th>
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<tbody>
<tr>
<td>Density (g/cm$^3$)</td>
<td>3.67</td>
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<td>4.51</td>
<td>4.89</td>
<td>6.16</td>
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<td>7.13</td>
<td>6.8</td>
<td>8.3</td>
<td>7.40</td>
<td>4.6</td>
<td>3.98</td>
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<td>621</td>
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<td>1123</td>
<td>2050</td>
<td>\</td>
<td>2040</td>
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<tr>
<td>$X_0$ (cm)</td>
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<td>1.86</td>
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<td>1.15</td>
<td>0.89</td>
<td>1.14</td>
<td>2.96</td>
<td>7.02</td>
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<td>$R_M$ (cm)</td>
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<td>3.57</td>
<td>3.10</td>
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<td>2.23</td>
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<td>2.00</td>
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<td>2.89</td>
<td>2.88</td>
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<td>$\lambda_1$ (cm)</td>
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<td>39.3</td>
<td>39.3</td>
<td>30.7</td>
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<td>22.4</td>
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<td>20.9</td>
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<td>$Z_{\text{eff}}$</td>
<td>50.1</td>
<td>54.0</td>
<td>54.0</td>
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<td>51.7</td>
<td>77.4</td>
<td>72.9</td>
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<td>64.8</td>
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<td>$\lambda_{\text{peak}}$ (nm)</td>
<td>410</td>
<td>560</td>
<td>420</td>
<td>310</td>
<td>300</td>
<td>220</td>
<td>340</td>
<td>300</td>
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<td>480</td>
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<td>425</td>
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<td>Refractive Index</td>
<td>\</td>
<td>1.85</td>
<td>1.79</td>
<td>1.95</td>
<td>1.50</td>
<td>1.62</td>
<td>1.82</td>
<td>2.15</td>
<td>2.68</td>
<td>2.20</td>
<td>1.82</td>
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<tr>
<td>Normalized Light Yield$^{a,c}$</td>
<td>120</td>
<td>190</td>
<td>4.2</td>
<td>1.3</td>
<td>42</td>
<td>4.8</td>
<td>8.6</td>
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<td>25</td>
<td>5</td>
<td>0.4</td>
<td>0.1</td>
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<tr>
<td>Total Light yield (ph/MeV)</td>
<td>35,000</td>
<td>58,000</td>
<td>1700</td>
<td>13,000</td>
<td>2,600</td>
<td>\</td>
<td>7,400</td>
<td>1,500</td>
<td>130</td>
<td>30,000</td>
<td>450</td>
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<tr>
<td>Decay time$^a$ (ns)</td>
<td>245</td>
<td>1220</td>
<td>30</td>
<td>6</td>
<td>600</td>
<td>0.5</td>
<td>30</td>
<td>\</td>
<td>300</td>
<td>100</td>
<td>30</td>
<td>10</td>
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<td>Slight</td>
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<td>No</td>
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<tr>
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<td>CLEO BaBar</td>
<td>BELLE</td>
<td>BES III</td>
<td>KTeV</td>
<td>TAPS</td>
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<td>A4</td>
<td>L3 BELLE</td>
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<td>CMS ALICE PrimEx</td>
<td>Panda</td>
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*Note: Values in parentheses are estimated or approximate.*

### References
- December 8, 2019
- Presentation by Ren-Yuan Zhu in the 2019 CPAD Workshop at Wisconsin University, Madison, WI