Precision Crystal Calorimeters in High Energy Physics: Past, Present and Future

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Physics with Crystal Calorimeters

Charmonium system observed by CB through Inclusive photons

\[ \text{CMS PWO} \]

\[ \text{H} \rightarrow \gamma \gamma \text{ at LHC} \]
# Mass Produced Crystals

<table>
<thead>
<tr>
<th>Crystal</th>
<th>NaI(Tl)</th>
<th>CsI(Tl)</th>
<th>CsI</th>
<th>BaF₂</th>
<th>BGO</th>
<th>PWO(Y)</th>
<th>LSO(Ce)</th>
<th>GSO(Ce)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density (g/cm³)</td>
<td>3.67</td>
<td>4.51</td>
<td>4.51</td>
<td>4.89</td>
<td>7.13</td>
<td>8.3</td>
<td>7.40</td>
<td>6.71</td>
</tr>
<tr>
<td>Melting Point (°C)</td>
<td>651</td>
<td>621</td>
<td>621</td>
<td>1280</td>
<td>1050</td>
<td>1123</td>
<td>2050</td>
<td>1950</td>
</tr>
<tr>
<td>Radiation Length (cm)</td>
<td>2.59</td>
<td>1.86</td>
<td>1.86</td>
<td>2.03</td>
<td>1.12</td>
<td>0.89</td>
<td>1.14</td>
<td>1.38</td>
</tr>
<tr>
<td>Molière Radius (cm)</td>
<td>4.13</td>
<td>3.57</td>
<td>3.57</td>
<td>3.10</td>
<td>2.23</td>
<td>2.00</td>
<td>2.07</td>
<td>2.23</td>
</tr>
<tr>
<td>Interaction Length (cm)</td>
<td>42.9</td>
<td>39.3</td>
<td>39.3</td>
<td>30.7</td>
<td>22.8</td>
<td>20.7</td>
<td>20.9</td>
<td>22.2</td>
</tr>
<tr>
<td>Refractive Index a</td>
<td>1.85</td>
<td>1.79</td>
<td>1.95</td>
<td>1.50</td>
<td>2.15</td>
<td>2.20</td>
<td>1.82</td>
<td>1.85</td>
</tr>
<tr>
<td>Hygroscopicity</td>
<td>Yes</td>
<td>Slight</td>
<td>Slight</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Luminescence b (nm) (at peak)</td>
<td>410</td>
<td>550</td>
<td>420</td>
<td>300</td>
<td>480</td>
<td>425</td>
<td>402</td>
<td>440</td>
</tr>
<tr>
<td>Decay Time b (ns)</td>
<td>230</td>
<td>1250</td>
<td>30</td>
<td>630</td>
<td>300</td>
<td>30</td>
<td>40</td>
<td>60</td>
</tr>
<tr>
<td>Light Yield b,c (%)</td>
<td>100</td>
<td>165</td>
<td>3.6</td>
<td>1.1</td>
<td>36</td>
<td>0.29</td>
<td>83</td>
<td>30</td>
</tr>
<tr>
<td>d(LY)/dT b (%/°C)</td>
<td>~0</td>
<td>0.3</td>
<td>-0.6</td>
<td>-2</td>
<td>-1.6</td>
<td>-1.9</td>
<td>~0</td>
<td>-0.1</td>
</tr>
<tr>
<td>Experiment</td>
<td>Crystal Ball</td>
<td>CLEO BaBar</td>
<td>BELLE</td>
<td>BES III</td>
<td>KTeV</td>
<td>TAPS (L*) (GEM)</td>
<td>L3 BELLE</td>
<td>CMS ALICE PrimEx</td>
</tr>
</tbody>
</table>

a. at peak of emission; b. up/low row: slow/fast component; c. PMT QE taken out.
Crystal Density: Radiation Length

1.5 $X_0$ Samples:
- Hygroscopic Halides
- Non-hygroscopic

Full Size Crystals:
- $BaBar$ CsI(Tl): 16 $X_0$
- L3 BGO: 22 $X_0$
- CMS PWO(Y): 25 $X_0$
$$T_s = (1 - R)^2 + R^2(1 - R)^2 + \ldots = (1 - R)/(1 + R), \text{ with}$$

$$R = \frac{(n_{\text{crystal}} - n_{\text{air}})^2}{(n_{\text{crystal}} + n_{\text{air}})^2}.$$ 

Theoretical limit of transmittance: NIM A333 (1993) 422

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**Excitation, Emission & Transmission**

- **BGO**
  - Em: 480 nm
  - Ex: 304 nm

- **LSO**
  - Em: 402 nm
  - Ex: 358 nm

- **BaF$_2$**
  - X-ray luminescence
  - Peaks: 220 nm, 300 nm
  - Em: 410 nm
  - Ex: 348 nm

- **NaI(Tl)**
  - Em: 340 nm
  - Ex: 380 nm

- **PWO**
  - Em: 424 nm
  - Ex: 310 nm

- **LYSO**
  - Em: 402 nm
  - Ex: 358 nm

- **CeF$_3$**
  - Em: 301 nm
  - Ex: 285 nm

- **CsI(Tl)**
  - Em: 540 nm
  - Ex: 322 nm

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**Wavelength (nm)**

**Intensity (a.u.)**

**Transmittance (%)**
Scintillation Light Decay Time

Recorded with an Agilent 6052A digital scope

Fast Scintillators

- $\tau = 30/6$ ns, CsI
- $\tau = 35$ ns, CeF$_3$
- $\tau = 30/10$ ns, PWO
- $\tau = 40$ ns, LSO

Slow Scintillators

- $\tau = 1250$ ns, CsI(Tl)
- $\tau = 630$ ns, CsI(Na)
- $\tau = 230$ ns, NaI(Tl)
- $\tau = 300$ ns, BGO
- $\tau = 630/0.9$ ns, BaF$_2$
Scintillation Light Output

Measured with a Philips XP2254B PMT (multi-alkali cathode)
p.e./MeV: LSO/LYSO is 6 & 230 times of BGO & PWO respectively

Fast Scintillators

Light Output (p.e./MeV)

Time (ns)

Slow Scintillators

Light Output (p.e./MeV)

Time (ns)
Emission Weighted PMT Q.E.

Taking out QE, L.O. of LSO/LYSO is 4/200 times BGO/PWO
Hamamatsu S8664-55 APD has QE 75% for LSO/LYSO

- **Hamamatsu PMT, R1306**
  - BGO: $\text{QE}=8.0 \pm 0.4\%$
  - LSO/LYSO: $\text{QE}=12.9 \pm 0.6\%$
  - CsI(Tl): $\text{QE}=5.0 \pm 0.3\%$

- **Philips PMT, XP2254-B**
  - BGO: $\text{QE}=4.7 \pm 0.2\%$
  - LSO/LYSO: $\text{QE}=7.2 \pm 0.4\%$
  - CsI(Tl): $\text{QE}=3.5 \pm 0.2\%$

- **Hamamatsu APD, S8664-55**
  - BGO: $\text{QE}=82 \pm 4\%$
  - LSO/LYSO: $\text{QE}=75 \pm 4\%$
  - CsI(Tl): $\text{QE}=84 \pm 4\%$

- **Hamamatsu PD, S2744**
  - BGO: $\text{QE}=75 \pm 4\%$
  - LSO/LYSO: $\text{QE}=59 \pm 3\%$
  - CsI(Tl): $\text{QE}=80 \pm 4\%$
BGO, LSO & LYSO Samples

2.5 x 2.5 x 20 cm (18 $X_0$)

SIC BGO
CPI LYSO
Saint-Gobain LYSO
CTI LSO
LSO/LYSO with PMT Readout

~10% FWHM resolution for $^{22}\text{Na}$ source (0.51 MeV)
1,200 p.e./MeV, 5/230 times of BGO/PWO
LSO/LYSO with APD Readout

L.O.: 1,500 p.e./MeV, 4/200 times of BGO/PWO
Readout Noise: <40 keV

Pedestal
2 × Hamamatsu S8664-55
HV = 400 V, τ = 250 ns
pedestal = 46 ADC, σ = 34 ADC
noise = 57 electrons

Fe-55 Calibration
Fe-55: 1278 electrons
pedestal = 46 ADC
peak = 814 ADC
σ = 52 ADC
1.664 electrons/ADC

SIC-BGO-L
2 × Hamamatsu S8664-55
HV = 400 V, τ = 250 ns, M = 500
ped = 43, peak = 173
L.O. = 420 p.e./MeV

CTI-LSO-L
ped = 43, peak = 698
L.O. = 2130 p.e./MeV

CPI-LYSO-L
ped = 43, peak = 450
L.O. = 1330 p.e./MeV

SG-LYSO-L
ped = 43, peak = 504
L.O. = 1500 p.e./MeV
### Crystal Calorimeters in HEP

#### Future crystal calorimeters in HEP:

**PANDA at GSI: PWO or BGO?**

**LSO/LYSO for a Super B Factory or ILC?**

<table>
<thead>
<tr>
<th>Date</th>
<th>75-85</th>
<th>80-00</th>
<th>80-00</th>
<th>80-00</th>
<th>90-10</th>
<th>94-10</th>
<th>94-10</th>
<th>95-20</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Experiment</strong></td>
<td>C. Ball</td>
<td>L3</td>
<td>CLEO II</td>
<td>C. Barrel</td>
<td>KTeV</td>
<td><em>BaBar</em></td>
<td>BELLE</td>
<td>CMS</td>
</tr>
<tr>
<td><strong>Accelerator</strong></td>
<td>SPEAR</td>
<td>LEP</td>
<td>CESR</td>
<td>LEAR</td>
<td>FNAL</td>
<td>SLAC</td>
<td>KEK</td>
<td>CERN</td>
</tr>
<tr>
<td><strong>Crystal Type</strong></td>
<td>NaI(Tl)</td>
<td>BGO</td>
<td>CsI(Tl)</td>
<td>CsI(Tl)</td>
<td>CsI</td>
<td>CsI(Tl)</td>
<td>CsI(Tl)</td>
<td>PbWO$_4$</td>
</tr>
<tr>
<td><strong>B-Field (T)</strong></td>
<td>-</td>
<td>0.5</td>
<td>1.5</td>
<td>1.5</td>
<td>-</td>
<td>1.5</td>
<td>1.0</td>
<td>4.0</td>
</tr>
<tr>
<td>$r_{inner}$ (m)</td>
<td>0.254</td>
<td>0.55</td>
<td>1.0</td>
<td>0.27</td>
<td>-</td>
<td>1.0</td>
<td>1.25</td>
<td>1.29</td>
</tr>
<tr>
<td><strong>Number of Crystals</strong></td>
<td>672</td>
<td>11,400</td>
<td>7,800</td>
<td>1,400</td>
<td>3,300</td>
<td>6,580</td>
<td>8,800</td>
<td>76,000</td>
</tr>
<tr>
<td><strong>Crystal Depth ($X_0$)</strong></td>
<td>16</td>
<td>22</td>
<td>16</td>
<td>16</td>
<td>27</td>
<td>16 to 17.5</td>
<td>16.2</td>
<td>25</td>
</tr>
<tr>
<td><strong>Crystal Volume (m$^3$)</strong></td>
<td>1</td>
<td>1.5</td>
<td>7</td>
<td>1</td>
<td>2</td>
<td>5.9</td>
<td>9.5</td>
<td>11</td>
</tr>
<tr>
<td><strong>Light Output (p.e./MeV)</strong></td>
<td>350</td>
<td>1,400</td>
<td>5,000</td>
<td>2,000</td>
<td>40</td>
<td>5,000</td>
<td>5,000</td>
<td>2</td>
</tr>
<tr>
<td><strong>Photosensor</strong></td>
<td>PMT</td>
<td>Si PD</td>
<td>Si PD</td>
<td>WS$^a$+Si PD</td>
<td>PMT</td>
<td>Si PD</td>
<td>Si PD</td>
<td>APD$^a$</td>
</tr>
<tr>
<td><strong>Gain of Photosensor</strong></td>
<td>Large</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>4,000</td>
<td>1</td>
<td>1</td>
<td>50</td>
</tr>
<tr>
<td><strong>$\sigma_N$/Channel (MeV)</strong></td>
<td>0.05</td>
<td>0.8</td>
<td>0.5</td>
<td>0.2</td>
<td>small</td>
<td>0.15</td>
<td>0.2</td>
<td>40</td>
</tr>
<tr>
<td><strong>Dynamic Range</strong></td>
<td>$10^4$</td>
<td>$10^5$</td>
<td>$10^4$</td>
<td>$10^4$</td>
<td>$10^4$</td>
<td>$10^4$</td>
<td>$10^4$</td>
<td>$10^5$</td>
</tr>
</tbody>
</table>
## L3 BGO Resolution

<table>
<thead>
<tr>
<th>Contribution</th>
<th>“Radiative”+Intrinsic</th>
<th>Temperature</th>
<th>Calibration</th>
<th>Overall</th>
</tr>
</thead>
<tbody>
<tr>
<td>Barrel</td>
<td>0.8%</td>
<td>0.5%</td>
<td>0.5%</td>
<td>1.07%</td>
</tr>
<tr>
<td>Endcaps</td>
<td>0.6%</td>
<td>0.5%</td>
<td>0.4%</td>
<td>0.88%</td>
</tr>
</tbody>
</table>

$45.6 \text{ GeV} < E_{\text{Beam}} < 94.3 \text{ GeV}$

**Barrel**

$\sigma = 1.06\%$

**Endcaps**

$\sigma = 0.86\%$

12k BGO

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Calor 2006 at Chicago, Ren-yuan Zhu, Caltech

June 5, 2006
KTeV CsI Position Resolution

Sub mm position resolution. L3 BGO & CMS PWO: 0.3 mm.

Kaons at the Tevatron

Position Resolution (mm)

Energy (GeV)
PWO Crystal ECAL Resolution

Crystal Aging & Radiation Damage?
See talks by Paramatti, Mao, Adi & Daskalakis

76k PWO

Designed Resolution

Measured Resolution
\( \sigma(E)/E < 1\% \) if \( E > 25 \) GeV
\( \sigma(E)/E \sim 0.5\% \) at \( 120 \) GeV

CMS ECAL Test Beam
Resolution in 3x3

See talks by Rumerio, Zabi and Franzoni
Crystal Degradation \textit{in situ}

L3 BGO degrades 6 – 7\% in 7 years

\textit{BaBar} CsI(Tl): 1 - 3 \% per year
Effects of Radiation Damage

- Induced absorption caused by color center formation:
  - reduced light attenuation length and thus light output, and maybe
  - degraded of light response uniformity (LRU).
- Induced phosphorescence:
  - increase readout noise.
- Reduced scintillation light yield:
  - reduce light output and degrade light response uniformity.

<table>
<thead>
<tr>
<th>Item</th>
<th>CsI(Tl)</th>
<th>CsI</th>
<th>BaF$_2$</th>
<th>BGO</th>
<th>PbWO$_4$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Color Centers</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Fluorescence</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Scintillation</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Recover @RT</td>
<td>Slow</td>
<td>Slow</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td><strong>Dose Rate Dependence</strong></td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Thermall Annealing</td>
<td>No/Yes</td>
<td>No/Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Optical Bleaching</td>
<td>No/Yes</td>
<td>No/Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
</tbody>
</table>
Radiation Induced Absorption

Measured with Hitachi U-3210 Photospectrometer

From top to bottom:
- CsI(Tl) (SIC-4)
  - After 0, 10, 40, 100 rad
  - 220, 500, 1000 rad

- CsI(Tl) (SIC-5)
  - After 0, 10, 100 rad
  - 1k, 10k rad

From top to bottom:
- PWO
  - 200°C annealing
  - 15 rad/h (65 h)
  - 100 rad/h (63 h)
  - 400 rad/h (62 h)
  - 9000 rad/h (10 h)
Secondary Ion Mass Spectroscopy revealed depth profile of oxygen contamination; Oxygen control improves CsI(Tl) quality.
TEM/EDS Study on PWO Crystals

TOPCON-002B scope, 200 kV, 10 uA, 5 to 10 nm black spots identified
JEOL JEM-2010 scope and Link ISIS EDS localized Stoichiometry Analysis

Atomic Fraction (%) in PbWO₄

As Grown Sample

<table>
<thead>
<tr>
<th>Element</th>
<th>Black Spot</th>
<th>Peripheral</th>
<th>Matrix₁</th>
<th>Matrix₂</th>
</tr>
</thead>
<tbody>
<tr>
<td>O</td>
<td>1.5</td>
<td>15.8</td>
<td>60.8</td>
<td>63.2</td>
</tr>
<tr>
<td>W</td>
<td>50.8</td>
<td>44.3</td>
<td>19.6</td>
<td>18.4</td>
</tr>
<tr>
<td>Pb</td>
<td>47.7</td>
<td>39.9</td>
<td>19.6</td>
<td>18.4</td>
</tr>
</tbody>
</table>

The Same Sample after Oxygen Compensation

<table>
<thead>
<tr>
<th>Element</th>
<th>Point₁</th>
<th>Point₂</th>
<th>Point₃</th>
<th>Point₄</th>
</tr>
</thead>
<tbody>
<tr>
<td>O</td>
<td>59.0</td>
<td>66.4</td>
<td>57.4</td>
<td>66.7</td>
</tr>
<tr>
<td>W</td>
<td>21.0</td>
<td>16.5</td>
<td>21.3</td>
<td>16.8</td>
</tr>
<tr>
<td>Pb</td>
<td>20.0</td>
<td>17.1</td>
<td>21.3</td>
<td>16.5</td>
</tr>
</tbody>
</table>

Oxygen Vacancies Identified
BGO/PWO Quality Improvement

BGO damage recovery after 2.5 krad

PWO damage at different dose rate

Eu doping: 0, 5, 30, 100 ppm

Y doping: 150 ppm

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Sample, 05/1998

Sample, 12/1998

Sample, 11/1999

Sample, 08/2000

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Nucl. Instr. and Meth. A302 (1991) 69

Nucl. Instr. and Meth. A480 (2002) 470
LYSO Transmittance Damage

LT @ 430 nm shows 6 and 3% increase under 2 rad/h, followed by 6 and 5% degradation under 9 krad/h for CPI and SG samples respectively.
LSO/LYSO ECAL Performance

- Less demanding to the environment because of small temperature coefficient.
- Radiation damage is less an issue as compared to the CMS PWO ECAL.
- A better energy resolution, $\sigma(E)/E$, at low energies than L3 BGO and CMS PWO because of its high light output and low readout noise:

$$2.0\% / \sqrt{E} \pm 0.5\% \oplus 0.001 / E$$
Summary

- Because of total absorption, precision crystal calorimetry provides the best possible energy and position resolutions for electrons and photons as well as good $e/\gamma$ identification and reconstruction efficiencies.

- Progress has been made in understanding crystal radiation damage and improving qualities of mass produced crystals.

- An LSO/LYSO crystal calorimeter will provide excellent energy resolution over a large dynamic range down to MeV level for future HEP and NP experiments.
LAL affects LRU


Ray-Tracing simulation for CMS PWO crystals shows no change in LRU if LAL is longer than 3.5 crystal length

Light collection efficiency, fit to a linear function of distance to the small end of the crystal, was determined with two parameters: the light collection efficiency at the middle of the crystal and the uniformity.

<table>
<thead>
<tr>
<th>LAL (cm)</th>
<th>20</th>
<th>40</th>
<th>60</th>
<th>80</th>
<th>200</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Large Area Photo Detector, covering 100% back face</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\eta_m$ (%)</td>
<td>9.5±.2</td>
<td>15.7±.4</td>
<td>19.2±.5</td>
<td>21.6±.6</td>
<td>26.9±.7</td>
</tr>
<tr>
<td>$\delta$ (%)</td>
<td>23±1</td>
<td>-4.6±.8</td>
<td>-11±1</td>
<td>-15±1</td>
<td>-15±1</td>
</tr>
<tr>
<td>$\phi$5 mm Photo Detector, covering 3.7% back face</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\eta_m$ (%)</td>
<td>.38±.04</td>
<td>.74±.08</td>
<td>1.1±.1</td>
<td>1.4±.2</td>
<td>3.0±.3</td>
</tr>
<tr>
<td>$\delta$ (%)</td>
<td>23±4</td>
<td>-3.5±4</td>
<td>-12±4</td>
<td>-16±4</td>
<td>-17±3</td>
</tr>
<tr>
<td>$\eta_m(\phi5mm)$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\eta_m(Full)$ (%)</td>
<td>4.0</td>
<td>4.7</td>
<td>5.7</td>
<td>6.5</td>
<td>11</td>
</tr>
</tbody>
</table>
PWO Radiation Damage

No damage in scintillation mechanism
No damage in resolution if light attenuation length > 1 m
Dose Rate Dependence


\[ dD = \sum_{i=1}^{n} \left\{ -a_i D_i dt + \left( D_{i}^{\text{all}} - D_i \right) b_i R dt \right\} \]

\[ D = \sum_{i=1}^{n} \left\{ \frac{b_i R D_{i}^{\text{all}}}{a_i + b_i R} \left[ 1 - e^{-(a_i + b_i R) t} \right] + D_{i}^{0} e^{-(a_i + b_i R) t} \right\} \]

- \( D_i \): color center density in units of \( \text{m}^{-1} \);
- \( D_{i}^{0} \): initial color center density;
- \( D_{i}^{\text{all}} \) is the total density of trap related to the color center in the crystal;
- \( a_i \): recovery constant in units of \( \text{hr}^{-1} \);
- \( b_i \): damage constant in units of \( \text{kRad}^{-1} \);
- \( R \): the radiation dose rate in units of \( \text{kRad/hr} \).

\[ D_{eq} = \sum_{i=1}^{n} \frac{b_i R D_{i}^{\text{all}}}{a_i + b_i R} \]
No Dose Rate Dependence

No/slow recovery: no/less dose rate dependence

BaF$_2$

Csl(Tl)

(a) Fast

Before Irradiation
100 rad (1 rad/s)
1 krad (11 rad/s)
10 krad (11 rad/s)

0.1 Mrad (24 rad/s)
1 Mrad (24 rad/s)

(b) Slow

Before Irradiation
100 rad (0.03 rad/s)
1 krad (0.3 rad/s)
10 krad (3 rad/s)

0.1 Mrad (20 rad/s)
1 Mrad (15 rad/s)

Normalized Light Output

Time (Day)

Wavelength (nm)
Radiation Induced Phosphorescence

Phosphorescence peaked at 430 nm with decay time constant of 2.5 h observed
**γ–ray Induced Readout Noise**

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>L.Y. p.e./MeV</th>
<th>F µ A/ rad/h</th>
<th>Q(_{15}) rad/h p.e.</th>
<th>Q(_{500}) rad/h p.e.</th>
<th>σ(_{15}) rad/h MeV</th>
<th>σ(_{500}) rad/h MeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>CPI</td>
<td>1,480</td>
<td>41</td>
<td>6.98x10(^4)</td>
<td>2.33x10(^6)</td>
<td>0.18</td>
<td>1.03</td>
</tr>
<tr>
<td>SG</td>
<td>1,580</td>
<td>42</td>
<td>7.15x10(^4)</td>
<td>2.38x10(^6)</td>
<td>0.17</td>
<td>0.97</td>
</tr>
</tbody>
</table>

γ–ray induced PMT anode current can be converted to the photoelectron numbers (Q) integrated in 100 ns gate. Its statistical fluctuation contributes to the readout noise (σ).