2nd Report on Twenty Mu2e BaF$_2$ Crystals from SIC

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Crystal Samples and Experiment

Properties measured: light output, decay kinetics and light response uniformity for Tyvek and other wrappings

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>Received Date</th>
<th>Dimension (mm³)</th>
<th>Total #</th>
<th>Polish</th>
</tr>
</thead>
<tbody>
<tr>
<td>SIC-1,20</td>
<td>4/25/2014</td>
<td>30 × 30 × 250</td>
<td>20</td>
<td>Six surfaces</td>
</tr>
</tbody>
</table>
Effect of Crystal Wrapping (I)

The highest LO is observed with 8 layer Teflon wrapping.

![Graphs showing light output vs time with different wrappings.](image)
Effect of Crystal Wrapping (II)

Adding Al foil helps if Teflon layers is less than 8.

![Graph](image)

$$L.O = A_0 + A_1(1-e^{-t/\tau})$$

<table>
<thead>
<tr>
<th>Material</th>
<th>$A_0$</th>
<th>$A_1$</th>
<th>$\tau$</th>
</tr>
</thead>
<tbody>
<tr>
<td>3×Teflon Film</td>
<td>117</td>
<td>615</td>
<td>646</td>
</tr>
<tr>
<td>3×Teflon Film +2×Al Foil</td>
<td>119</td>
<td>701</td>
<td>643</td>
</tr>
<tr>
<td>5×Teflon Film</td>
<td>123</td>
<td>736</td>
<td>632</td>
</tr>
<tr>
<td>5×Teflon Film +2×Al Foil</td>
<td>123</td>
<td>775</td>
<td>641</td>
</tr>
<tr>
<td>8×Teflon Film</td>
<td>167</td>
<td>837</td>
<td>639</td>
</tr>
<tr>
<td>8×Teflon Film +2×Al Foil</td>
<td>165</td>
<td>839</td>
<td>640</td>
</tr>
</tbody>
</table>
## Summary: Wrapping Test for SIC-1

<table>
<thead>
<tr>
<th>Material</th>
<th>Fast LO (p.e./MeV)</th>
<th>LO: 50 ns (p.e./MeV)</th>
<th>RMS 50 ns (%)</th>
<th>δF 50 ns (%/X₀)</th>
<th>R_B 50 ns (%)</th>
<th>Slow LO (p.e./MeV)</th>
<th>LO: 2.5 μs (p.e./MeV)</th>
<th>RMS 2.5 μs (%)</th>
<th>δF 2.5 μs (%/X₀)</th>
<th>R_B 2.5 μs (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al Foil (4)</td>
<td>126</td>
<td>131</td>
<td>16.8</td>
<td>-2.0</td>
<td>-44.8</td>
<td>563</td>
<td>579</td>
<td>8.5</td>
<td>-0.3</td>
<td>-25.9</td>
</tr>
<tr>
<td>Al Mylar (2)</td>
<td>129</td>
<td>148</td>
<td>10.7</td>
<td>-0.9</td>
<td>-30.4</td>
<td>597</td>
<td>644</td>
<td>5.6</td>
<td>0</td>
<td>-17.3</td>
</tr>
<tr>
<td>ESR (2)</td>
<td>119</td>
<td>130</td>
<td>11.0</td>
<td>-1.4</td>
<td>-30.2</td>
<td>467</td>
<td>525</td>
<td>5.0</td>
<td>-0.4</td>
<td>-15.1</td>
</tr>
<tr>
<td>Teflon (3)</td>
<td>117</td>
<td>117</td>
<td>21.0</td>
<td>-0.5</td>
<td>-63.5</td>
<td>615</td>
<td>567</td>
<td>12.9</td>
<td>1.2</td>
<td>-43.6</td>
</tr>
<tr>
<td>Teflon (3) + Al Foil (2)</td>
<td>119</td>
<td>125</td>
<td>20.4</td>
<td>-0.8</td>
<td>-61.9</td>
<td>701</td>
<td>645</td>
<td>12.2</td>
<td>0.3</td>
<td>-39.0</td>
</tr>
<tr>
<td>Teflon (5)</td>
<td>123</td>
<td>135</td>
<td>18.3</td>
<td>-0.9</td>
<td>-53.5</td>
<td>736</td>
<td>706</td>
<td>9.7</td>
<td>0.3</td>
<td>-32.0</td>
</tr>
<tr>
<td>Teflon (5) + Al Foil (2)</td>
<td>123</td>
<td>135</td>
<td>17.9</td>
<td>-1.1</td>
<td>-52.8</td>
<td>775</td>
<td>741</td>
<td>13.0</td>
<td>-1.2</td>
<td>-37.6</td>
</tr>
<tr>
<td>Teflon (8)</td>
<td>167</td>
<td>172</td>
<td>20.7</td>
<td>-2.0</td>
<td>-58.2</td>
<td>837</td>
<td>788</td>
<td>13.0</td>
<td>-1.2</td>
<td>-37.9</td>
</tr>
<tr>
<td>Teflon (8) + Al Foil (2)</td>
<td>165</td>
<td>178</td>
<td>20.6</td>
<td>-2.2</td>
<td>-58.6</td>
<td>839</td>
<td>788</td>
<td>13.1</td>
<td>-1.3</td>
<td>-36.8</td>
</tr>
<tr>
<td>Teflon Plate</td>
<td>118</td>
<td>125</td>
<td>18.2</td>
<td>-1.1</td>
<td>-53.1</td>
<td>614</td>
<td>574</td>
<td>12.1</td>
<td>0.5</td>
<td>-39.4</td>
</tr>
<tr>
<td>Tyvek (2)</td>
<td>119</td>
<td>130</td>
<td>14.4</td>
<td>-1.6</td>
<td>-39.8</td>
<td>591</td>
<td>586</td>
<td>9.4</td>
<td>-0.1</td>
<td>-29.6</td>
</tr>
</tbody>
</table>

Two layers of Aluminized Mylar seem providing the best uniformity.
Reflectance Measurements

Properties measured at room temperature:

Reflectance as a function of wavelength

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>Thickness (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al Foil</td>
<td>15</td>
</tr>
<tr>
<td>Al Mylar</td>
<td>10</td>
</tr>
<tr>
<td>ESR</td>
<td>65</td>
</tr>
<tr>
<td>Steel Foil</td>
<td>50</td>
</tr>
<tr>
<td>Tyvek</td>
<td>150</td>
</tr>
<tr>
<td>Teflon ×3</td>
<td>25×3</td>
</tr>
<tr>
<td>Teflon ×5</td>
<td>25×5</td>
</tr>
<tr>
<td>Teflon ×8</td>
<td>25×8</td>
</tr>
</tbody>
</table>
Setup for Reflectance Measurement

Hitachi U3210 UV/Vis Spectrophotometer Large Sample Compartment

Reference beam

Mirror

PMT at the bottom window

Integrating sphere

Measurement beam

$\theta = 10^\circ$

Film sample of 15 mm in diameter
Systematic Uncertainties

RMS values extracted from ten repeated measurements for 8 layers of Teflon films:

<1% with $\lambda$ longer than 250 nm; and Up to 15% with $\lambda$ shorter than 250 nm.
Normalized Reflectance

BaSO\textsubscript{4} is the coating material used in the integrating sphere

**EWRR**: Emission weighted relative reflectance

\[ EWRR = \frac{\int em(\lambda) \cdot \text{reflectance}(\lambda) d\lambda}{\int em(\lambda) d\lambda} \]
LO versus Reflectance for BaF$_2$ SIC-1

Positive correlations observed

Fast Component

Slow Component
Radiation Damage in Various Reflectors

Aluminum foil is the best reflector up to 100 Mrad
Radiation Damage in Wrapping Materials

Al foil is radiation hard up to 100 Mrad for BaF$_2$
Light output and FWHM energy resolution (see report dated 6/25/14) are measured at seven points along the crystal.

Crystals wrapped with two layers of Tyvek (2 x 150 μm)

One end coupled to Hamamatsu R2059 PMT
With DC-200 grease coupling

50 ns and 2.5 μs gate
Coincidence trigger from a Na-22 source
No Difference between Coupling Ends

SIC1: No difference with alternative ends coupled to the PMT

Intrinsic scintillation production is uniform
LRU and LO of No.1-10 (Tyvek)
LRU and LO of No.1-10 (Tyvek)

2.5 μs

Graphs showing normalized light output vs. distance from the end coupled to PMT for different crystals, with average LO values and gate times.
CMS Uniformity Specification

D. Graham & C. Seez, CMS Note 1996-002

Optimum slope in rear 100mm is 8% rise

Slope < 0.3%/X₀ where most of the energy is

Can tolerate almost any slope at front

Beam
First four points and last four points were fit to

\[ Y = a + b \times x \] and

\[ Y = c + d \times x \]

respectively.

\[ \delta_F = (-1.6\pm0.4)\%/X_0 \]

Back Rise = (-39.8\pm2.7)%

Average L.O. = 130 p.e./MeV (Gate=50 ns)

Distance from the end coupled to PMT (mm)
Front Slope & Back Rise: No.1-10 (Tyvek)

Back Rise = (-39.8±2.7)%
\( \delta_r = (-1.6±0.4)\% / \sqrt{X_0} \)
Average L.O. = 130 p.e./MeV (Gate=50 ns)

PMT: R2059, Grease, Tyvek wrapped

Back Rise = (-37.4±2.7)%
\( \delta_r = (-1.4±0.4)\% / \sqrt{X_0} \)
Average L.O. = 128 p.e./MeV (Gate=50 ns)

PMT: R2059, Grease, Tyvek wrapped

Back Rise = (-45.6±2.7)%
\( \delta_r = (-1.5±0.4)\% / \sqrt{X_0} \)
Average L.O. = 117 p.e./MeV (Gate=50 ns)

PMT: R2059, Grease, Tyvek wrapped

Back Rise = (-50.3±2.7)%
\( \delta_r = (-1.3±0.4)\% / \sqrt{X_0} \)
Average L.O. = 118 p.e./MeV (Gate=50 ns)

PMT: R2059, Grease, Tyvek wrapped

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Caltech HEP Crystal Laboratory
Front Slope & Back Rise: No.1-10 (Tyvek)

2.5 µs
Summary of Light Output

Consistent with LO obtained by fitting decay kinetics

<table>
<thead>
<tr>
<th>Mu2e BaF$_2$</th>
<th>Entries</th>
<th>Mean</th>
<th>RMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>SIC 30×30×250 mm$^3$</td>
<td>20</td>
<td>118.7</td>
<td>7.377</td>
</tr>
<tr>
<td>RMS/Mean = 6.2%</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- 50 ns

<table>
<thead>
<tr>
<th>Mu2e BaF$_2$</th>
<th>Entries</th>
<th>Mean</th>
<th>RMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>SIC 30×30×250 mm$^3$</td>
<td>20</td>
<td>561.8</td>
<td>38.45</td>
</tr>
<tr>
<td>RMS/Mean = 6.8%</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- 2.5 μs
Correlations between Slow & Fast Components

Positive correlations observed

CC = 0.94

CC = 0.76
Correlations between ER and LO

Negative correlations observed

CC = -0.86

CC = -0.91
Summary of RMS of LO Measured @ 7 Points

14/9% observed for 50 ns/2.5 μs gate

Mu2e BaF$_2$
SIC 30×30×250 mm$^3$
RMS/Mean = 18.4%

Mu2e BaF$_2$
SIC 30×30×250 mm$^3$
RMS/Mean = 22.2%
Summary of Light Response Uniformity

22/14% negative slope observed for 50 ns/2.5 μs gate

A consequence of UV absorption

Mu2e BaF₂
SIC 30×30×250 mm³

Entries 20
Mean 22.30
RMS 3.605

Entries 20
Mean 14.07
RMS 3.079

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Summary of Front Slope (Tyvek)

1.4% & 0.2% per $X_0$ observed for fast & slow components

Simulation is needed to understand the consequence
Summary of Back Rise (Tyvek)

38% and 28% observed for fast and slow components

Simulation is needed to understand the consequence
Crystal SIC-1 was measured with different wrappings:

- Light output of BaF$_2$ crystals depends on crystal wrapping. Eight layers of PTFE Teflon film (8 x 25 μm) show the best light output, followed by two layers of aluminized Mylar (2 x 10 μm), four layers of Al foil (4 x 15 μm) and two layers of Tyvek paper (2 x 150 μm 1056D). Additional Al foil helps if Teflon layers are less than 8.
- Positive correlations are observed between the BaF$_2$ light output and the measured reflectance of wrapping materials.
- Al foil is radiation hard up to 100 Mrad.

Light response uniformity was measured for all twenty BaF$_2$ crystals wrapped with two layers of Tyvek paper:

- No change of LRU when the crystal end coupled to PMT is altered.
- An overall negative slope of 22% & 14% (rms of 14% & 9%) was observed for 50 ns & 2.5 μs gate, indicating absorption dominance of the UV light.
- An alternative fit with two segments shows 1.4%/X$_0$ & 0.2%/X$_0$ slope in the front 13 cm and 38% & 28% rise in the back 12 cm for 50 ns & 2.5 μs gate.
No Difference between Coupling Ends

SIC2: No difference with alternative ends coupled to the PMT

**Graphs:**
- **A end coupled (50 ns):**
  - \( \delta = (-22.4 \pm 1.1)\% \)
  - Average L.O. = 128 p.e./MeV (Gate=50 ns)

- **B end coupled (50 ns):**
  - \( \delta = (-23.3 \pm 1.1)\% \)
  - Average L.O. = 131 p.e./MeV (Gate=50 ns)

- **A end coupled (2.5 \( \mu \)s):**
  - \( \delta = (-15.6 \pm 1.1)\% \)
  - Average L.O. = 607 p.e./MeV (Gate=2500 ns)

- **B end coupled (2.5 \( \mu \)s):**
  - \( \delta = (-15.6 \pm 1.1)\% \)
  - Average L.O. = 593 p.e./MeV (Gate=2500 ns)
No Difference between Coupling Ends

SIC3: No difference with alternative ends coupled to the PMT

Mu2e BaF$_2$, SIC-3 30×30×250 mm$^3$

PMT:R2059, Coincidence Trigger
Grease, Tyvek wrapped

A end coupled

\[ \delta = (-25.0 \pm 1.1)\% \]

Average L.O. = 117 p.e./MeV (Gate=50 ns)

Distance from the end coupled to PMT (mm)

50 ns

B end coupled

\[ \delta = (-27.3 \pm 1.1)\% \]

Average L.O. = 117 p.e./MeV (Gate=50 ns)

2.5 μs

B end coupled

\[ \delta = (-16.5 \pm 1.1)\% \]

Average L.O. = 564 p.e./MeV (Gate=2500 ns)

Distance from the end coupled to PMT (mm)

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LRU and LO of No.11-20 (Tyvek)

50 ns
LRU and LO of No.11-20 (Tyvek)

2.5 μs

- LRU and LO of No.11-20 crystals with Tyvek wrapping.
- Graphs showing normalized light output versus distance from the end coupled to PMT (mm).
- Crystal details: Mu2e BaF$_2$, SIC-11-15, 30x30x250 mm$^3$, PMT: R2059, Grease, Tyvek wrapped.
- Average LO: 548 p.e./MeV, (Gate=2500 ns).
- Accuracy: (-12.1±1.1)% - (-15.3±1.1)%.

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Front Slope & Back Rise: No.11-20 (Tyvek)

50 ns

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Front Slope & Back Rise: No.11-20 (Tyvek)

2.5 μs
The best LRU is observed in the crystal wrapped with Al Mylar or ESR.
LRU of Different Wrapping

The additional Al foil does not affect the LO and LRU.
Front Slope and Back Rise of Different Wrapping

50 ns

<table>
<thead>
<tr>
<th>Material</th>
<th>Back Rise</th>
<th>$\delta_F$</th>
<th>RMS</th>
<th>Average $L_O$ (p.e./MeV) (Gate=50 ns)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mu2e BaF$_2$, SiC-1 30x30x250 mm$^3$ PMT-R2059, Na-22 source Tyvek (2x150 µm)</td>
<td>(-39.8±2.7)%</td>
<td>(-1.6±0.4)%/X$_0$</td>
<td>14.4 %</td>
<td>130 p.e./MeV</td>
</tr>
<tr>
<td>Al Mylar (2x10 µm)</td>
<td>(-30.4±2.6)%</td>
<td>(-0.9±0.4)%/X$_0$</td>
<td>10.7 %</td>
<td>148 p.e./MeV</td>
</tr>
<tr>
<td>ESR (65 µm)</td>
<td>(-30.2±2.6)%</td>
<td>(-1.4±0.4)%/X$_0$</td>
<td>11.0 %</td>
<td>130 p.e./MeV</td>
</tr>
<tr>
<td>Teflon Plate (6.5 mm)</td>
<td>(-53.1±2.8)%</td>
<td>(-1.1±0.4)%/X$_0$</td>
<td>18.2 %</td>
<td>125 p.e./MeV</td>
</tr>
<tr>
<td>Al Foil (4x15 µm)</td>
<td>(-44.8±2.7)%</td>
<td>(-2.0±0.4)%/X$_0$</td>
<td>16.8 %</td>
<td>131 p.e./MeV</td>
</tr>
<tr>
<td>Teflon (3x25 µm)</td>
<td>(-63.5±2.8)%</td>
<td>(-0.5±0.4)%/X$_0$</td>
<td>21.0 %</td>
<td>117 p.e./MeV</td>
</tr>
<tr>
<td>Teflon (5x25 µm)</td>
<td>(-53.5±2.7)%</td>
<td>(-0.9±0.4)%/X$_0$</td>
<td>18.3 %</td>
<td>135 p.e./MeV</td>
</tr>
<tr>
<td>Teflon (8x25 µm)</td>
<td>(-58.2±2.8)%</td>
<td>(-2.0±0.4)%/X$_0$</td>
<td>20.7 %</td>
<td>172 p.e./MeV</td>
</tr>
</tbody>
</table>
Front Slope and Back Rise for Different Wrapping

\[
\text{Back Rise} = (-29.6 \pm 2.6)\% \\
\delta_c = (-0.1 \pm 0.4)\% / X_e \\
\text{Average } I_o = 588 \text{ p.e./MeV (Gate=2500 ns)}
\]

\[
\text{Back Rise} = (-39.4 \pm 2.6)\% \\
\delta_c = (0.5 \pm 0.4)\% / X_e \\
\text{Average } I_o = 574 \text{ p.e./MeV (Gate=2500 ns)}
\]

\[
\text{Back Rise} = (-17.3 \pm 2.6)\% \\
\delta_c = (-0.0 \pm 0.4)\% / X_e \\
\text{Average } I_o = 644 \text{ p.e./MeV (Gate=2500 ns)}
\]

\[
\text{Back Rise} = (-32.0 \pm 2.6)\% \\
\delta_c = (0.3 \pm 0.4)\% / X_e \\
\text{Average } I_o = 706 \text{ p.e./MeV (Gate=2500 ns)}
\]

\[
\text{Back Rise} = (-32.0 \pm 2.6)\% \\
\delta_c = (0.3 \pm 0.4)\% / X_e \\
\text{Average } I_o = 706 \text{ p.e./MeV (Gate=2500 ns)}
\]

\[
\text{Back Rise} = (-25.9 \pm 2.6)\% \\
\delta_c = (-0.3 \pm 0.4)\% / X_e \\
\text{Average } I_o = 579 \text{ p.e./MeV (Gate=2500 ns)}
\]

\[
\text{Back Rise} = (-37.9 \pm 2.6)\% \\
\delta_c = (-1.2 \pm 0.4)\% / X_e \\
\text{Average } I_o = 788 \text{ p.e./MeV (Gate=2500 ns)}
\]
Front Slope & Back Rise for Different Teflon Layers

Normalized Light Output

Distance from the end coupled to PMT (mm)

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