Measurements of $\text{BaF}_2$ Crystals from BGRI and SICCAS

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Following a visit to Beijing Glass Research Institute (BGRI), Beijing, on January 9, 2015, two 3 x 3 x 20 cm BaF$_2$ crystal samples were obtained.

Longitudinal transmittance (LT) was measured by using a Perkin-Elmer Lambda 950 spectrophotometer.

Pulse height spectrum (PHS), Light output (LO) and light response uniformity (LRU) were measured by using a Hamamatsu R2059 PMT with a bi-alkali cathode and a quartz window and coincidence triggers from a $^{22}$Na source for these two samples wrapped with two layers of Tyvek paper and grease coupling.

Gamma-ray irradiation was carried out up to 100 krad for these two samples with degradation in LT, LO and LRU measured, and compared to SIC samples.
**BaF₂ Crystal Samples**

Compared to 20 3 x 3 x 25 cm test beam crystals from SIC

<table>
<thead>
<tr>
<th>ID</th>
<th>Dimension (mm³)</th>
<th>Polishing</th>
</tr>
</thead>
<tbody>
<tr>
<td>BGRI-2015D</td>
<td>30x30x200</td>
<td>Six faces</td>
</tr>
<tr>
<td>BGRI-2015E</td>
<td>30x30x200</td>
<td>Six faces</td>
</tr>
</tbody>
</table>

April 15, 2015

Caltech HEP Crystal Laboratory
Initial Optical Quality (LT)

Good OQ as compared to BGRI2012 and 20 SIC samples (86%, 91%)
Comparison of Transmittance

Mu2e BaF$_2$ SIC 30×30×250 mm$^3$
Mean = 85.5%

BaF$_2$ BGRI 30×30×200 mm$^3$
Mean = 86.5%

Mu2e BaF$_2$ SIC 30×30×250 mm$^3$
Mean = 91.3%

BaF$_2$ BGRI 30×30×200 mm$^3$
Mean = 92.7%
Comparison of EWLT

![Graph comparing EWLT of fast and slow components for different materials and sizes.](image)

Mu2e BaF$_2$ SIC $30 \times 30 \times 250$ mm$^3$
Mean = 86.3%

BaF$_2$ BGRI $30 \times 30 \times 200$ mm$^3$
Mean = 88.0%

Mu2e BaF$_2$ SIC $30 \times 30 \times 250$ mm$^3$
Mean = 91.1%

BaF$_2$ BGRI $30 \times 30 \times 200$ mm$^3$
Mean = 92.4%
LT Before and After Gamma-ray Irradiation

Significant damage observed after 10 krad

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**Transmittance (%)**

**Wavelength (nm)**

![Graph showing transmittance and emission for BaF$_2$ BGRI-2015D and BGRI-2015E crystals before and after gamma-ray irradiation.](image)
Comparison: SIC2012 & BGRI2012

Much worse than SIC2012, but compatible with BGRI2012
Setup for LO & LRU Measurements

- Crystal
- BaF$_2$
- Na$^{22}$
- PMT
- PMT
- CAMAC Crate
- qvt MCA
- LeCroy 3001
- Gate generator
- LeCroy 2323A
- Discriminator
- H.V. Supply
- H.V. Supply
- PC

Crystals are wrapped with two layers of Tyvek paper.

Coincidence trigger provided by a $^{22}$Na source.
Pulse Height Spectra: BGRI-2015D

Gate: 50 ns

Ave ER = 41.7%

BaF$_2$ BGRI-2015D 30×30×200 mm$^3$
Gate = 50 ns

#1 E.R. = 40.3%
#2 E.R. = 44.4%
#3 E.R. = 42.5%
#4 E.R. = 41.6%
#5 E.R. = 42.3%
#6 E.R. = 41.2%
#7 E.R. = 39.7%

A end coupled

Ave ER = 41.1%

BaF$_2$ BGRI-2015D 30×30×200 mm$^3$
Gate = 50 ns

#1 E.R. = 42.9%
#2 E.R. = 41.3%
#3 E.R. = 41.6%
#4 E.R. = 40.3%
#5 E.R. = 40.0%
#6 E.R. = 40.6%
#7 E.R. = 41.3%

B end coupled
Pulse Height Spectra: BGRI-2015D

Gate: 2500 ns

Ave ER= 16.5%

Ave ER= 16.7%

# 1 E.R. = 19.6%
# 2 E.R. = 16.5%
# 3 E.R. = 16.2%
# 4 E.R. = 15.9%
# 5 E.R. = 16.1%
# 6 E.R. = 16.0%
# 7 E.R. = 15.4%

# 1 E.R. = 19.4%
# 2 E.R. = 17.2%
# 3 E.R. = 16.0%
# 4 E.R. = 16.1%
# 5 E.R. = 16.0%
# 6 E.R. = 16.0%
# 7 E.R. = 15.9%
Pulse Height Spectra: BGRI-2015E

Gate: 50 ns

Ave ER = 38.8%

Ave ER = 39.6%

BaF$_2$ BGRI-2015E 30×30×200 mm$^3$
Gate = 50 ns

1. E.R. = 40.0%
2. E.R. = 41.0%
3. E.R. = 39.6%
4. E.R. = 39.3%
5. E.R. = 37.2%
6. E.R. = 37.6%
7. E.R. = 36.8%

BaF$_2$ BGRI-2015E 30×30×200 mm$^3$
Gate = 50 ns

1. E.R. = 40.3%
2. E.R. = 40.5%
3. E.R. = 39.6%
4. E.R. = 40.3%
5. E.R. = 38.5%
6. E.R. = 38.6%
7. E.R. = 39.1%
Pulse Height Spectra: BGRI-2015E

Gate: 2500 ns

Ave ER = 16.2%

Ave ER = 16.8%

BaF$_2$ BGRI-2015E 30x30x200 mm$^3$

Gate = 2500 ns

# 1  E.R. = 19.2%

# 2  E.R. = 16.2%

# 3  E.R. = 15.8%

# 4  E.R. = 15.9%

# 5  E.R. = 15.5%

# 6  E.R. = 15.6%

# 7  E.R. = 15.2%

A end coupled

BaF$_2$ BGRI-2015E 30x30x200 mm$^3$

Gate = 2500 ns

# 1  E.R. = 19.4%

# 2  E.R. = 17.0%

# 3  E.R. = 16.1%

# 4  E.R. = 16.1%

# 5  E.R. = 16.2%

# 6  E.R. = 16.5%

# 7  E.R. = 16.0%

B end coupled

Channel Number

Channel Number

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Comparison of Light Output

All samples wrapped with two layers of Tyvek paper

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**Graph 1:**
- Mu2e BaF$_2$ SIC $30 \times 30 \times 250$ mm$^3$
  - Mean = 119 p.e./MeV
- BaF$_2$ BGRI $30 \times 30 \times 200$ mm$^3$
  - Mean = 124 p.e./MeV

**Graph 2:**
- Mu2e BaF$_2$ SIC $30 \times 30 \times 250$ mm$^3$
  - Mean = 559 p.e./MeV
- BaF$_2$ BGRI $30 \times 30 \times 200$ mm$^3$
  - Mean = 721 p.e./MeV

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LRU Before and After Gamma-ray Irradiation

Gate: 50 ns

Before IR

Back Rise = (-18.3±2.5)%
\( \delta_F = (0.7±0.5)\%/X_0 \)
Average \( L_O = 116 \) p.e./MeV (Gate=50 ns)

IR \( 10^3 \) rad

Back Rise = (-37.3±2.7)%
\( \delta_F = (-3.3±0.5)\%/X_0 \)
Average \( L_O = 90 \) p.e./MeV (Gate=50 ns)

IR \( 10^4 \) rad

Back Rise = (-72.5±2.9)%
\( \delta_F = (-4.0±0.5)\%/X_0 \)
Average \( L_O = 81 \) p.e./MeV (Gate=50 ns)

IR \( 10^5 \) rad

Back Rise = (-75.4±2.9)%
\( \delta_F = (-5.4±0.6)\%/X_0 \)
Average \( L_O = 54 \) p.e./MeV (Gate=50 ns)
LRU Before and After Gamma-ray Irradiation

Gate: 2,500 ns

BaF$_2$ BGR1-2015D $30\times30\times200$ mm$^3$

PMT:R2059, Grease, Tyvek wrapped

Before IR

Back Rise = (-13.2±2.5)%

δ$_F$ = (-0.0±0.5)%/X$_0$

RMS=4.2%

Average L.O. = 710 p.e./MeV (Gate=2500 ns)

IR $10^3$ rad

Back Rise = (-31.9±2.6)%

δ$_F$ = (-1.4±0.5)%/X$_0$

RMS=11.2%

Average L.O. = 528 p.e./MeV (Gate=2500 ns)

IR $10^4$ rad

Back Rise = (-44.3±2.7)%

δ$_F$ = (-1.8±0.5)%/X$_0$

RMS=15.8%

Average L.O. = 292 p.e./MeV (Gate=2500 ns)

IR $10^5$ rad

Back Rise = (-46.8±2.7)%

δ$_F$ = (-2.6±0.5)%/X$_0$

RMS=17.5%

Average L.O. = 257 p.e./MeV (Gate=2500 ns)
Comparison of Front Slope

All samples wrapped with two layers of Tyvek paper

- Mu2e BaF$_2$ SIC 30×30×250 mm$^3$
  - Mean = -1.4 \%/X_0

- BaF$_2$ BGRI 30×30×200 mm$^3$
  - Mean = 0.4 \%/X_0
Comparison of Back Rise

All samples wrapped with two layers of Tyvek paper

![Graph showing comparison of back rise for different samples.](image-url)
## Summary: Initial Properties

<table>
<thead>
<tr>
<th>ID</th>
<th>Average of 20SIC Crystals</th>
<th>BGRI2015D</th>
<th>BGRI2015E</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dimension</td>
<td>30x30x250</td>
<td>30x30x200</td>
<td>30x30x200</td>
</tr>
<tr>
<td>T@220 nm (%)</td>
<td>85.5±0.2</td>
<td>87.9±0.2</td>
<td>85.0±0.2</td>
</tr>
<tr>
<td>T@300 nm (%)</td>
<td>91.3±0.2</td>
<td>92.9±0.2</td>
<td>92.5±0.2</td>
</tr>
<tr>
<td>EWLT of Fast Component (%)</td>
<td>86.1±0.2</td>
<td>89.0±0.2</td>
<td>86.9±0.2</td>
</tr>
<tr>
<td>EWLT of Slow Component (%)</td>
<td>91.1±0.2</td>
<td>92.4±0.2</td>
<td>92.4±0.2</td>
</tr>
<tr>
<td>LO 50 ns Gate (p.e./MeV)</td>
<td>119±1</td>
<td>116±1</td>
<td>131±1</td>
</tr>
<tr>
<td>Back Rise 50 ns Gate (%)</td>
<td>-38.4±2.5</td>
<td>-18.3±2.5</td>
<td>-13.8±2.5</td>
</tr>
<tr>
<td>δ_F 50 ns Gate (%/X_0)</td>
<td>-1.4±0.5</td>
<td>0.7±0.5</td>
<td>0.1±0.5</td>
</tr>
<tr>
<td>RMS 50 ns Gate (%)</td>
<td>13.6</td>
<td>5.6</td>
<td>4.2</td>
</tr>
<tr>
<td>LO 2500 ns Gate (p.e./MeV)</td>
<td>562±6</td>
<td>710±7</td>
<td>731±7</td>
</tr>
<tr>
<td>Back Rise 2500 ns Gate (%)</td>
<td>-28.1±2.5</td>
<td>-13.2±2.5</td>
<td>-14.0±2.5</td>
</tr>
<tr>
<td>δ_F 2500 ns Gate (%/X_0)</td>
<td>-0.2±0.5</td>
<td>0±0.5</td>
<td>0.4±0.5</td>
</tr>
<tr>
<td>RMS 2500 ns Gate (%)</td>
<td>9.3</td>
<td>4.2</td>
<td>4.0</td>
</tr>
</tbody>
</table>
Radiation hardness of two new BGRI samples are compatible with BGRI2012.
Longitudinal transmittance, light output and light response uniformity of two 20 cm long BGRI samples are better than twenty 25 cm long SIC crystals, and much better than an early sample BGRI2012.

This difference seems caused by different crystal length: 20 cm versus 25 cm.

Radiation hardness of two BGRI samples was measured up to 100 krad. It is worse than SIC2012, and is compatible with BGRI2012, indicating improvement is needed by controlling oxygen contamination.

BGRI is working in two directions: test alternative raw material suppliers and improving vacuum in furnaces.

SICCAS decided to pursue non-vacuum growth in January with limited progress achieved so far.

Additional vendors are important.
SICCAS: Non-Vacuum Growth

Problems and limitations of growth in vacuum

- Complicated and expensive growth system
- Poor efficiency (6 ingots from single growth per furnace)
- No incentive to invest

New Facility to be built to meet the M2e requirements

Sealed crucible
Melt
Crystal

To build an non-oxidizing atmosphere inside Pt crucible
- No pump system
- No circulating water system
- Easier to operate

A very promising alternative method to be pursued for BaF₂ growth.

Modified multi-crucibles Bridgman Method developed in SICCAS

A general method to cost-effectively grow BGO/PWO/Ca₃Ti/PbF₂ etc.

Progress on growth BaF₂ in non-vacuum atmosphere

Before the visit

Dec. 03, 2014

Two crystal boules grown in non-vacuum atmosphere before the visit

Optical Transmittance of BaF₂ crystals

- Crack
- Fully oxidized
- No carbon and gas inclusions
- Wrong improvement direction

After the visit


- Crack-free, clear crystal boule can be grown
- Great progress, but more R&D work is needed

Three crystal boules grown in non-vacuum atmosphere at March. 26, 2015