Quality of Mass Produced PWO Crystals

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Randomly Selected PWO Samples

20 Each from BTCP, Russia, and SIC, China

BTCP: $28.5^2 \times 220 \times 30.0^2$ mm

SIC: $22^2 \times 230 \times 22^2$ mm
Experiment

- All crystals went through (1) thermal annealing at 200°C, (2) irradiations by γ-ray at 15, 400 and 9k rad/h until equilibrium and (3) recovery.
- Properties measured: Transmittance, emission and excitation spectrum, light output, decay kinetics and light response uniformity, as well as their degradation, radiation induced color center and emission weighted radiation induced absorption coefficients.
- Light output degradation was only measured at 15 rad/h because of limited light output: less than 8 p.e./MeV for BTCP samples.
Thermal Annealing

- Rigorous temperature control both in amplitude and slope:
  - From RT to 200°C: 200 minutes;
  - Maintain at 200°C: 240 minutes;
  - From 200°C to 25°C: 400 minutes.

- Crystals are kept in dark at RT (18°C) after annealing. The minimum time between annealing and the 1st measurement is 48 hours.
**Transmittance and Birefringence**

*a axis*: better longitudinal T., but non-isotropic transverse T.  
Both approaching theoretical limit

Czochralski: grown along the *a axis*  
Bridgman: grown along the *c axis*

**Detailed Diagrams**

- **BTCP-1971**
  - 200°C anniling 4 hour  
  - Transverse (x)
  - Transverse (y)
  - Longitudinal (z)

- **SIC-U517 (21.6 cm)**
  - 200°C anniling 4 hour
  - Transverse (x)
  - Transverse (y)
  - Longitudinal (z)

*Calculated longitudinal T of CMS PWO crystal*  
- // c axis, unpolarized light
- ⊥ c axis, e-polarized light

**Wavelength (nm)**

October 20, 2003
NSS03 N5-6, Liyuan Zhang, Caltech
PWO Crystals Grown along \textit{c} axis

Isotropic transverse transmittance uniformity along crystal length

\begin{itemize}
  \item SIC-U313 (18 cm)
  \item 200\degree C annealing 4 hour
  \item Seed end transverse (x, y)
  \item Tail end transverse (x, y)
  \item Longitudinal (z)

  Calculated longitudinal $T$ of CMS PWO crystal
  \begin{itemize}
    \item // \textit{c} axis,
    \item $\perp$ \textit{c} axis, unpolarized light
    \item $\perp$ \textit{c} axis, e-polarized light
  \end{itemize}

  Transmittance (%)

  Wavelength (nm)

\end{itemize}

\begin{itemize}
  \item SIC-U517 (21.6 cm)
  \item 200\degree C annealing 4 hour
  \item Seed end transverse (x, y)
  \item Tail end transverse (x, y)
  \item Longitudinal (z)

  Calculated longitudinal $T$ of CMS PWO crystal
  \begin{itemize}
    \item // \textit{c} axis,
    \item $\perp$ \textit{c} axis, unpolarized light
    \item $\perp$ \textit{c} axis, e-polarized light
  \end{itemize}

  Transmittance (%)

  Wavelength (nm)

\end{itemize}
PWO Crystals Grown along \textit{a axis}

Not isotropic transverse transmittance
Not uniform along crystal length

**BTCP-5615**

- 200°C anniling 4 hour
- Small end
- Large end
- Longitudinal

**Calculated longitudinal T of CMS PWO crystal**
- // c axis,
- \(\perp\) c axis, unpolarized light
- \(\perp\) c axis, e-polarized light

**BTCP-5658**

- 200°C anniling 4 hour
- Small end
- Large end
- Longitudinal

**Calculated longitudinal T of CMS PWO crystal**
- // c axis,
- \(\perp\) c axis, unpolarized light
- \(\perp\) c axis, e-polarized light

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Light Output and Decay Kinetics

Both are fast: 84% and 96% in 50 and 100 ns

- **BTCP-2467**
  
  with T corrections (18°C)

- **SIC-T6**
  
  with T corrections (18°C)
Comparison of L.T. and Light Output

BTCP: higher L.T., partly due to birefringence

SIC: higher light yield, the reason is unclear
Caltech $\gamma$-ray Irradiation Facilities

**Open 50 curie Co-60:**
15, 100 and 400 rad/h

**Closed 2,000 curie Cs-137:**
9k rad/h at center, up to 36k rad/h
Photoluminescence

No variation in either excitation or emission spectrum

No damage in scintillation mechanism
No Variation in Light Response Uniformity

The response \( (y) \) along the axis was fit to a linear function

\[
\frac{y}{y_{mid}} = 1 + \delta \left( \frac{x}{x_{mid}} - 1 \right)
\]
Light Output Degradation

Caused by radiation induced color center formation
Dose rate dependent: cc creation & annihilation
Damage in Longitudinal Transmittance

Radiation induced absorption caused by cc formation

From top to bottom
- 200°C annealing
- 15 rad/h (65 h)
- 100 rad/h (63 h)
- 400 rad/h (62 h)
- 9000 rad/h (10 h)
- 35000 rad/h (6.5 h)
Comparison of Radiation Damage

SIC samples seem more radiation hard

- **BTCP-PWO**
  - Mean: 16.86
  - RMS: 6.484

- **SIC-PWO**
  - Mean: 11.67
  - RMS: 2.341

- **400 rad/h**
  - $\chi^2/\text{ndf}$: 1.489 / 3
  - Constant: 4.879
  - Mean: 14.79
  - Sigma: 5.277

- **Relative L.T. loss @ 440 nm (%)**
  - $\chi^2/\text{ndf}$: 0.1179 / 1
  - Constant: 9.541
  - Mean: 11.22
  - Sigma: 3.513
Comparison of Transmittance Loss

SIC samples less diverse: Bridgman technology
Some BTCP samples are very rad hard at high doses
RIAC or radiation induced color center density can be calculated precisely by using longitudinal transmittance (0.2%)

\[
RIAC \; or \; D_{\text{Color-Center}} = \frac{1}{LAL};
\]

\[
LAL = \frac{\ell}{\ln\left\{\frac{[T(1 - T_s)^2]}{\sqrt{4T_s^4 + T^2(1 - T_s^2)^2} - 2T_s^2}}\right\}}
\]

where \( T \) is transmittance measured along crystal length \( \ell \) and \( T_s \) is the theoretical transmittance without internal absorption:

\[
T_s = (1 - R)^2 + R^2(1 - R)^2 + ... = \frac{(1 - R)}{(1 + R)}, \text{ with } R = \frac{(n_{\text{crystal}} - n_{\text{air}})^2}{(n_{\text{crystal}} + n_{\text{air}})^2}.
\]
Emission Weighted RIAC

\[ EWRIAC = \frac{\int Riac(\lambda)Em(\lambda)d\lambda}{\int Em(\lambda)d\lambda} \]

<1 m\(^{-1}\): no damage in uniformity
EWRIAC (1/m) and Normalized r.m.s

<table>
<thead>
<tr>
<th></th>
<th>Vendor</th>
<th>BTCP</th>
<th>SIC</th>
</tr>
</thead>
<tbody>
<tr>
<td>15 rad/h</td>
<td>400 rad/h</td>
<td>9.000 rad/h</td>
<td></td>
</tr>
<tr>
<td>0.16 (45%)</td>
<td>0.69 (37%)</td>
<td>1.43 (50%)</td>
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<tr>
<td>0.10 (33%)</td>
<td>0.51 (32%)</td>
<td>1.16 (48%)</td>
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**BTCP-PWO**

- Emission weighted RIAC. (m⁻¹)
- Dose rate (rad/h)

**SIC-PWO**

- Emission weighted RIAC. (m⁻¹)
- Dose rate (rad/h)
L. T. Loss versus Initial L.T. @ 360 nm

No correlation
EWRIAC versus Initial L.T. @ 440 nm

No correlation
Summary

- Investigation on 20 crystals each from two vendors shows that SIC samples are more consistent (Bridgman).

- Samples from both vendors have very good transmittance and fast light output. It is not clear why SIC samples produce more (58%) light.

- No correlations between radiation hardness and initial longitudinal transmittance was observed.

- Current mass-produced PWO crystals are radiation hard enough for an environment of up to a few hundreds rad/h. Further improvement is needed if thousands rad/h is expected (SLHC).

- Some samples are very radiation hard which should be further studied.