A Damage and Recovery Study for Lead Tungstate Crystal Samples from BTCP and SIC

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Introduction

- 54 PWO samples were studied at Caltech (32 from SIC and 22 from BTCP) for CMS.
- Properties measured: transmittance, emission and excitation spectra, light output, decay kinetics, light response uniformity and their degradation, as well as emission weighted radiation induced absorption coefficient (EWRIAC).
- Correlations between measured optical properties and their radiation damage were investigated for all samples.
- 2 SIC samples (2570 & 2572) and 2 BTCP 2003 samples (2482 & 2531) went through long term irradiation and recovery cycles @ 100 and 400 rad/h.
Initial LO versus LT @ 360 nm

Correlations observed between Initial LO & initial LT@360 nm: part of emitted light is self-absorbed.
Radiation Damage under 100 rad/h

SIC samples have longer damage time constants

Time constants: 0.6 & 57 h (BTCP), 1.1 & 107 h (SIC)

BTCP-2531

Dose rate: 100 rad/h

Normalized after 200°C annealing

\[ \text{LO}_0 = 8.3 \text{ p.e./MeV} \ (200 \text{ ns}, \ 18^\circ \text{C}) \]

\[ \text{LO}/\text{LO}_0 = 0.727 + 0.139e^{-t/0.58} + 0.134e^{-t/57.2} \]

SIC-782

Dose rate: 100 rad/h

Normalized after 200°C annealing

\[ \text{LO}_0 = 14.7 \text{ p.e./MeV} \ (200 \text{ ns}, \ 18^\circ \text{C}) \]

\[ \text{LO}/\text{LO}_0 = 0.672 + 0.169e^{-t/1.05} + 0.160e^{-t/107.0} \]
Damage Recovery after 9 krad/h

SIC samples also have longer recovery time constants
Time constants: 32 & 1360 h (BTCP), 42 & 1430 h (SIC)

BTCP-2375

\[ T_0 = 46.1\% \]
\[ T/T_0 = 0.661 + 0.135(1 - e^{-t/31.7}) + 0.076(1 - e^{-t/1363}) \]

SIC-641

\[ T_0 = 43.6\% \]
\[ T/T_0 = 0.650 + 0.088(1 - e^{-t/420}) + 0.067(1 - e^{-t/1425}) \]
EWRIAC Measured after Irradiations

\[ R_{\text{Iac}} = \frac{1}{LAL_{\text{equilibrium}}} - \frac{1}{LAL_{\text{before}}} \]

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

\[ T_s = (1 - R)^2 + R^2 (1 - R)^2 + \ldots = (1 - R)/(1 + R) \]

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

\[ EWRIAC = \frac{\int R_{\text{Iac}}(\lambda)E_m(\lambda)d\lambda}{\int E_m(\lambda)d\lambda} \]

**SIC-782**

<table>
<thead>
<tr>
<th>Wavelength (nm)</th>
<th>Transmittance (%)</th>
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<tbody>
<tr>
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<tr>
<td>400</td>
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From top to bottom
- 200°C annealing
- 15 rad/h (72 h)
- 400 rad/h (72 h)
- 9000 rad/h (48 h)

**Wavelength (nm)**

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<thead>
<tr>
<th>800</th>
<th>700</th>
<th>600</th>
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<th>400</th>
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**SIC-782**

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<th>15 rad/h</th>
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**Absorption coefficient (m⁻¹)**

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**Photon energy (eV)**

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**E.W.RIAC**

- E.W.RIAC = 0.25
- E.W.RIAC = 0.50
- E.W.RIAC = 0.77

\[ \chi^2/DOF = 0.1 \]

\[ \chi^2/DOF = 0.3 \]

\[ \chi^2/DOF = 1.3 \]
EWRIAC Measured after Irradiations

Both BTCP and SIC samples have two radiation induced color centers off emission peak, but SIC centers are deeper.
Emission Weighted RIAC

All samples: EWRIAC < 1 m⁻¹ up to 400 rad/h

Rigorous QC required to qualify endcap crystals for SLHC
Correlations is weaker at lower dose rates because of different initial status (preexisting absorption)
EWRIAC versus $\delta LT/LT$

Linear correlation exists between EWRIAC and LT loss @ 440 nm at low dose rate
EWRIAC versus $\delta$LT/LT

At high dose rate it is no longer linear. All BTCP/SIC data, however, are consistent with a 2nd order polynomial.
No correlation: preexisting absorption is not correlated with radiation induced absorption.
δLO/LO versus Initial LT and EWRIAC

No correlation between δLO/LO and Initial LT
Weak (0.48) correlation between δLO/LO and EWRIAC
δLO/LO versus δLT/LT @ 100 rad/h

Strong correlation: Slope = 4.96

BTCP-2531

Dose rate: 100 rad/h

Normalized at average value

ΔLO/LO₀ = 0.00 + 4.96 × (ΔLT/LT₀)

Normalized Light output

Transmittance @ 440 nm (%)

0 100 200 300 400 500 600 700

Time (hours)

50 55 60 65 70 75

Light Output (p.e./MeV)

-0.15 -0.1 -0.05 0 0.05 0.1 0.15 0.2

Normalized LT @ 440 nm

0 0.01 0.02 0.03

0 4 8 9 10 11

0 5 10 15 20
δLO/LO versus δLT/LT @ 400 rad/h

Strong correlation: Slope = 4.39
$\delta$LO/LO versus $\delta$LT/LT @ 100 rad/h

Strong correlation: Slope = 3.43
δLO/LO versus δLT/LT @ 400 rad/h

Strong correlation: Slope = 2.74
Summary

- A correlation between the initial LO and the initial LT @ 360 nm is observed, which may be attributed to that a part of the PWO emission spectrum is self-absorbed.

- An universal 2\textsuperscript{nd} order polynomial relation between the EWRIAC and the $\delta$LT/LT@ 440 nm is observed for all BTCP and SIC samples.

- A correlation between the EWRIAC measured at different dose rates is observed, which is weaker at lower dose rates, where the consequence of the preexisting absorption is not negligible.

- No correlation observed between the initial LT and the EWRIAC or the $\delta$LO/LO, indicating no correlation between the preexisting absorption and the radiation induced absorption.

- $\delta$LO/LO versus $\delta$LT/LT @ 440 nm follow the same slope in multiple damage and recovery cycles, indicating that the LO variation of PWO crystals can be corrected by using the variation of the LT even in a severe radiation environment with dose rate of 400 rad/h.

- The slope of $\delta$LO/LO versus $\delta$LT/LT @ 440 nm, obtained with a linear fit, however, is damage level dependent, indicating a necessity of extracting it \textit{in situ} from the data.
δLO/LO versus δLT/LT @ 100 rad/h

Strong correlation: Slope = 4.80

\[ \Delta \text{LO/LO}_0 = 0.00 + 4.80 \times (\Delta \text{LT/LT}_0) \]
δLO/LO versus δLT/LT @ 400 rad/h

Strong correlation: Slope = 3.95

BTCP-2482
Dose rate: 400 rad/h

After 2nd 15 rad/h irradiation and recovery

Transmittance @ 440 nm (%)

Time (hours)

Light Output (p.e./MeV)

Normalized Light output

Normalized LT @ 440 nm

ΔLO/LO₀ = 0.00 + 3.95 × (ΔLT/LT₀)
δLO/LO versus δLT/LT @ 100 rad/h

Strong correlation: Slope = 3.31
δLO/LO versus δLT/LT @ 400 rad/h

Strong correlation: Slope = 2.81