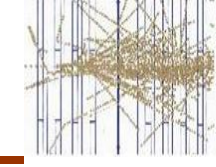

A Study on Radiation Hardness of BGO and PWO-II Crystals

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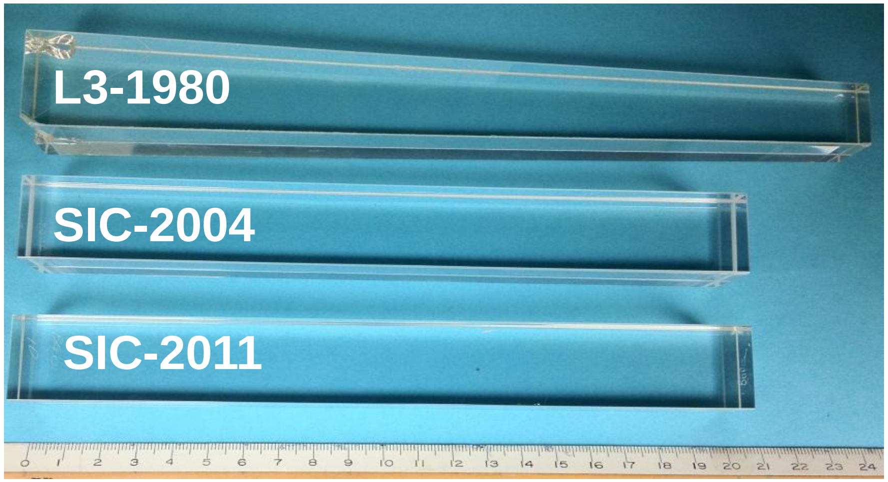
Introduction

- 20 cm long BGO crystals produced at SIC and 20 cm long PWO-II crystals produced at BTCP for the proposed PANDA experiment are investigated.
- Properties were measured before and after irradiations: Longitudinal Transmittance (LT), Light Output (LO) and Light Response Uniformity (LRU).
- The results of BGO and PWO-II crystals are compared respectively to the BGO crystal used in the L3 experiment and PWO crystals used in the CMS experiment.

Investigation on BGO Crystals



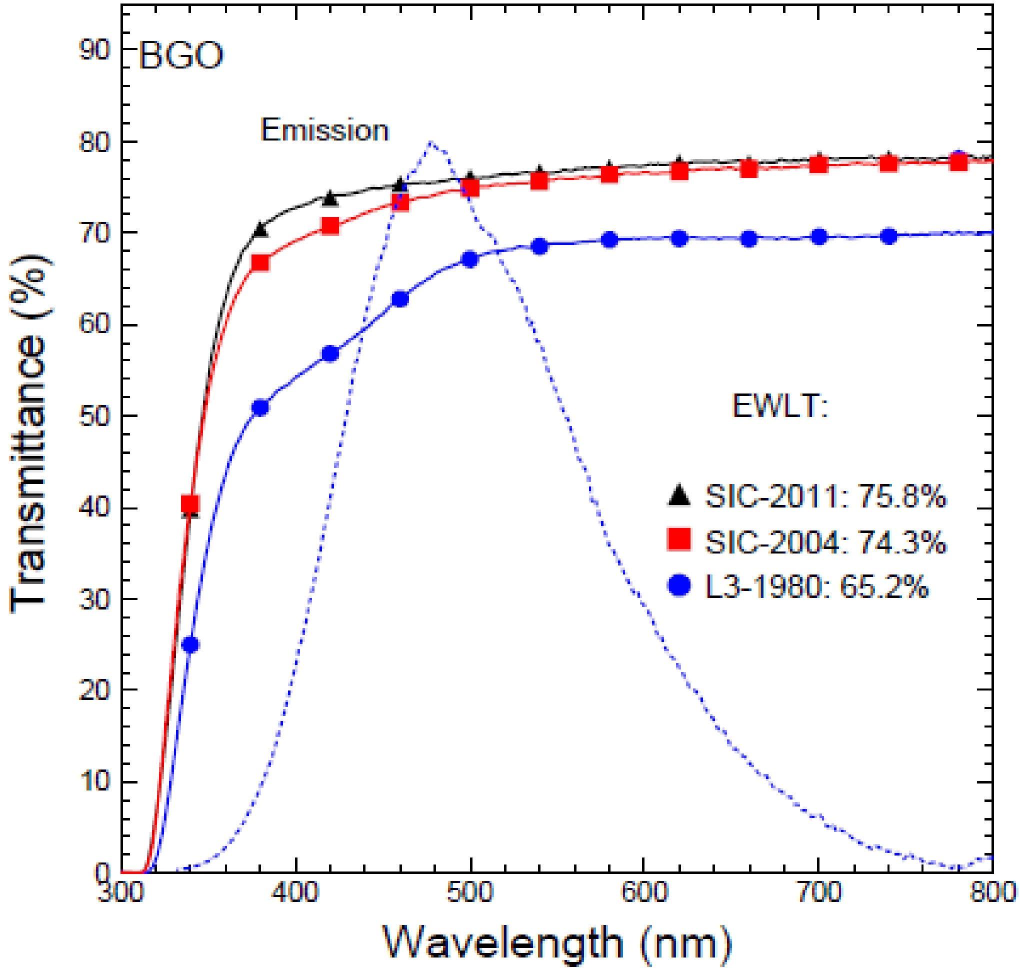
Sample ID	Dimension	Polish
L3-1980	20^2 x 30^2 x 240mm^3	Six faces
SIC-2004	25 x 25 x 200 mm^3	Six faces
SIC-2011	25 x 25 x 200 mm^3	Six faces

Radiation Damage Experiments

- Samples were annealed at 200℃ for 200 minutes to remove residual damage
- Samples went through a series of γ-ray irradiations at dose rates of 2, 8 and 30 rad/h until reaching an equilibrium

Comparison of Initial LT and EWLT

Samples 2011 and 2004 have better LT

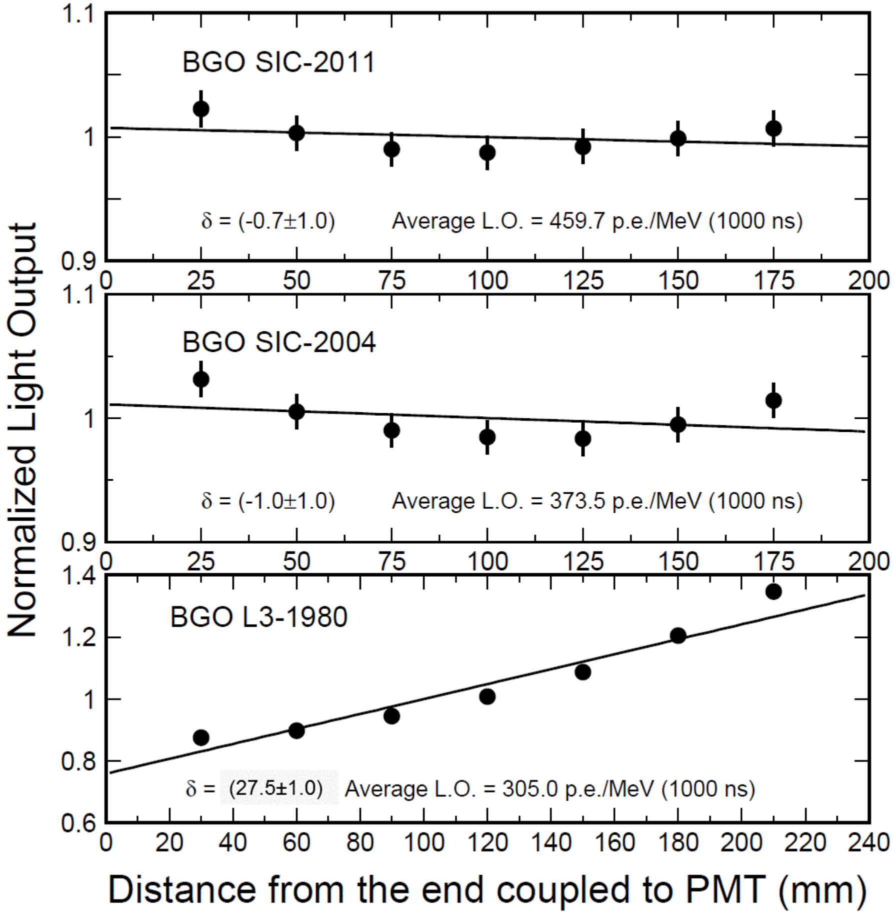


EWLT, *emission weighted longitudinal transmittance*, is defined by:

$$EWLT = \frac{\int LT(\lambda)Em(\lambda)d\lambda}{\int Em(\lambda)d\lambda}$$

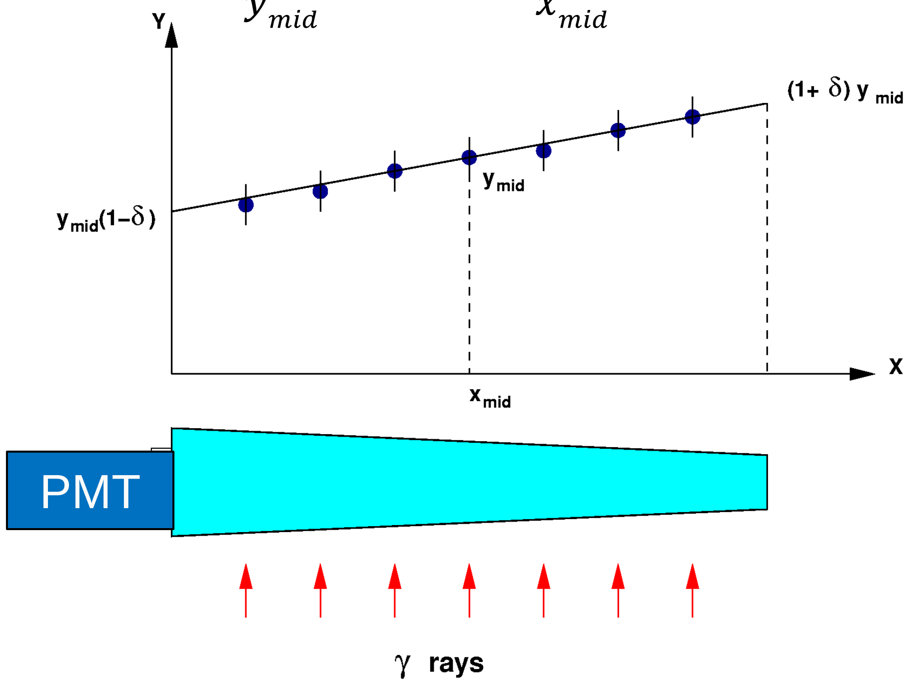
Comparison of Initial LO and LRU

Sample 2011 has high LO
δ = 0%/27% for rectangular/tapered crystal geometry



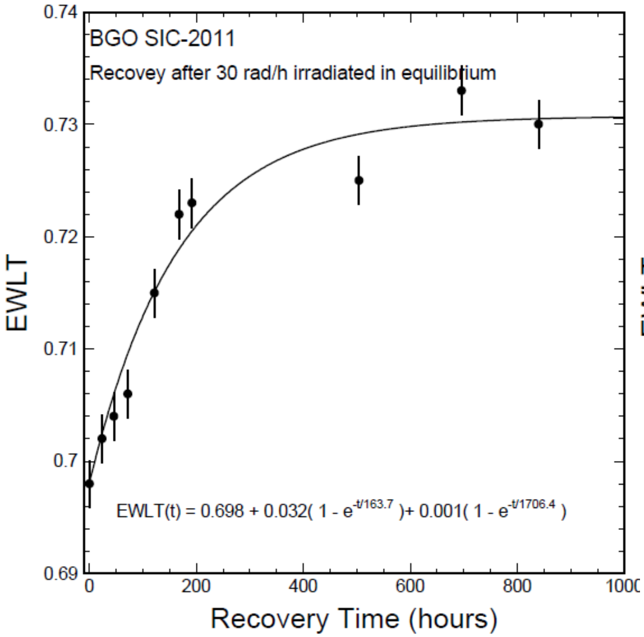
LRU, *Light Response Uniformity,* is defined as follow:

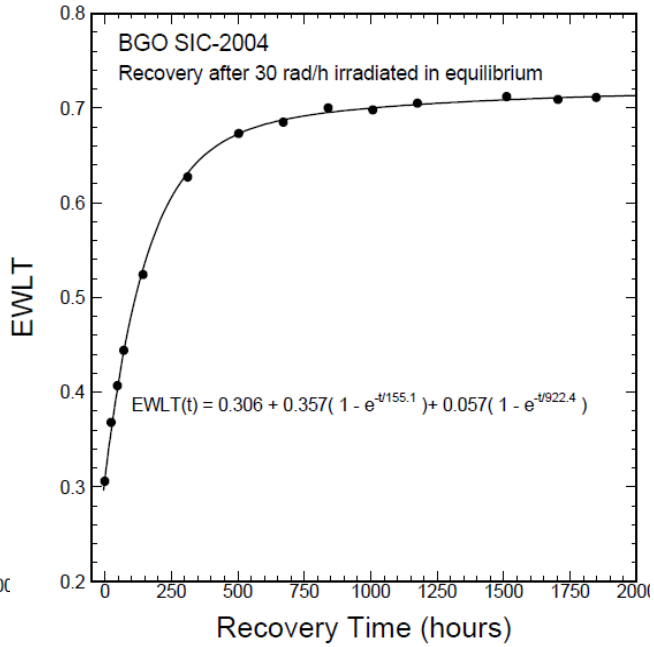
$$\frac{y}{y_{mid}} = 1 + \delta\left(\frac{x}{x_{mid}} - 1\right)$$

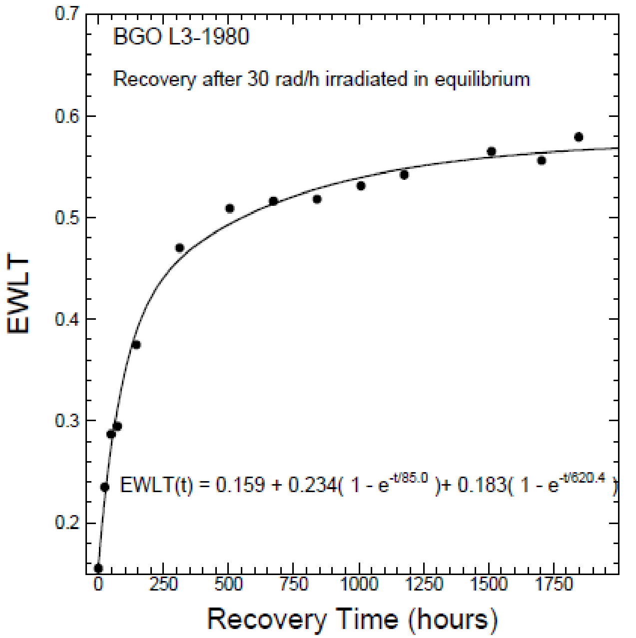


Damage Recovery of EWLT

Damage recovers with consistent time constants. Initial EWLT: 75.8%, 74.3% and 65.2% for samples 2011, 2004 and 1980 are not reached after a few thousands hours, indicating deep color centers existing



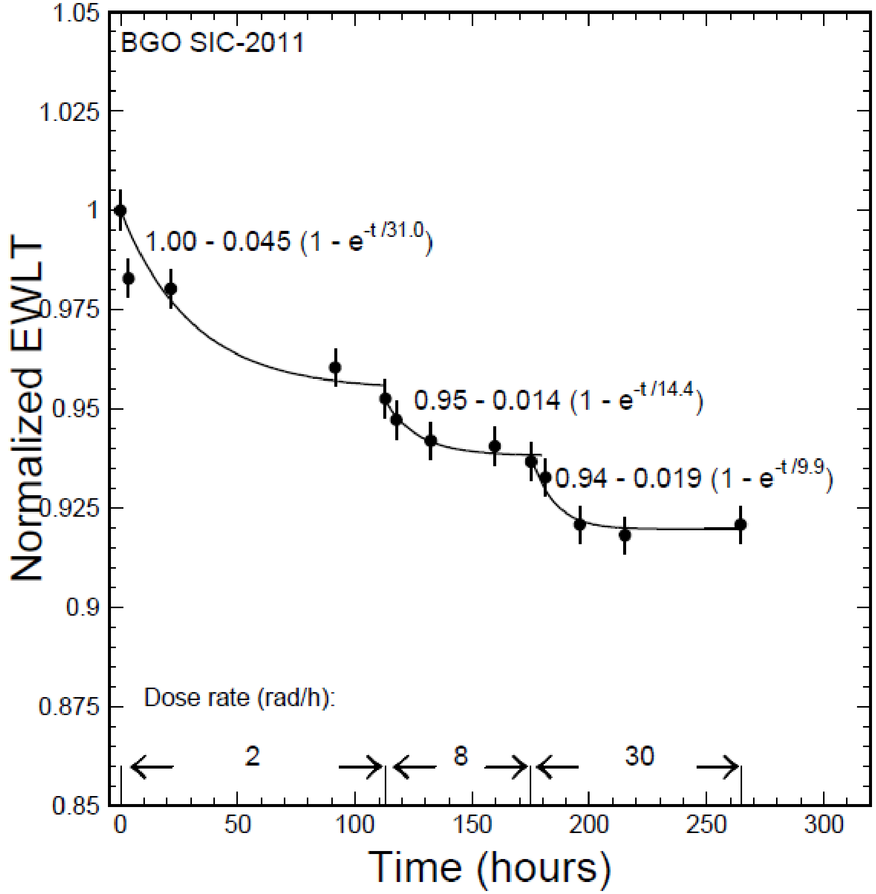


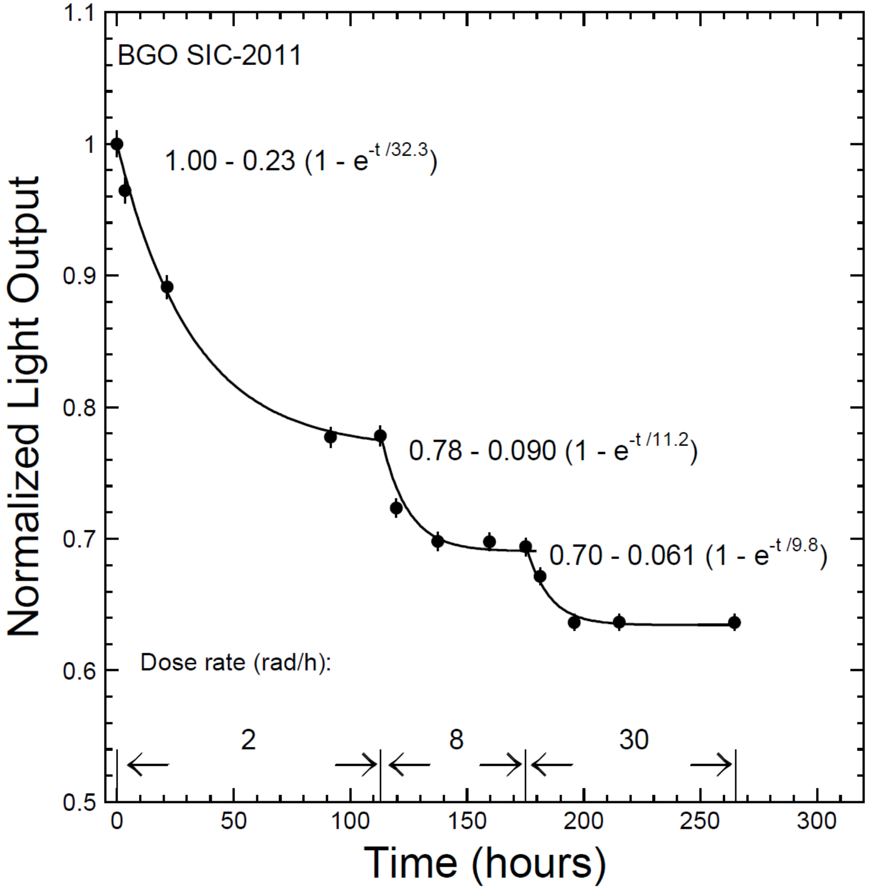


Recovery leads to a dose rate dependent damage level

Dose Rate Dependent Damage in EWLT and LO

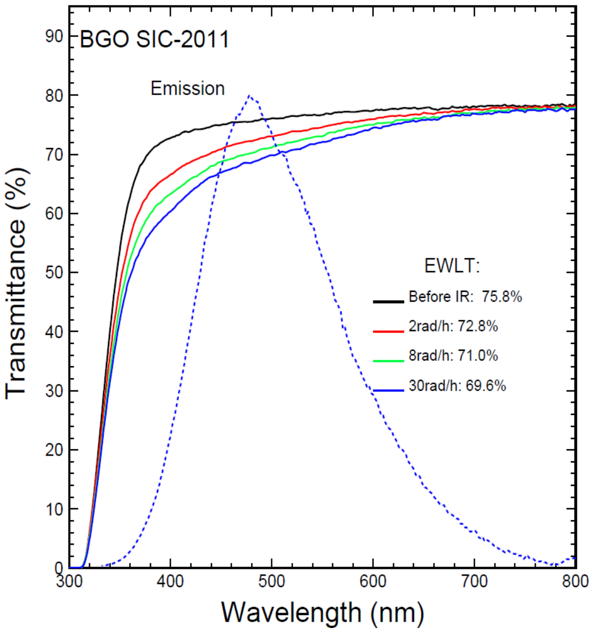
Both EWLT and LO reached equilibrium during irradiations under a defined dose rate, showing dose rate dependent radiation damage

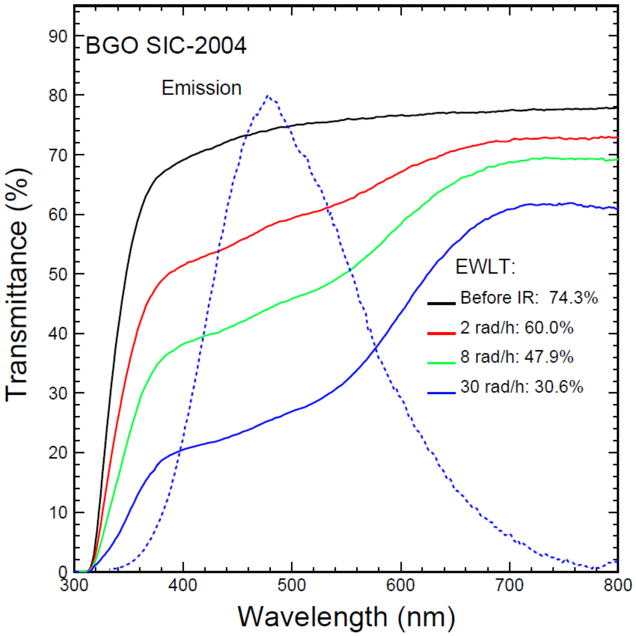


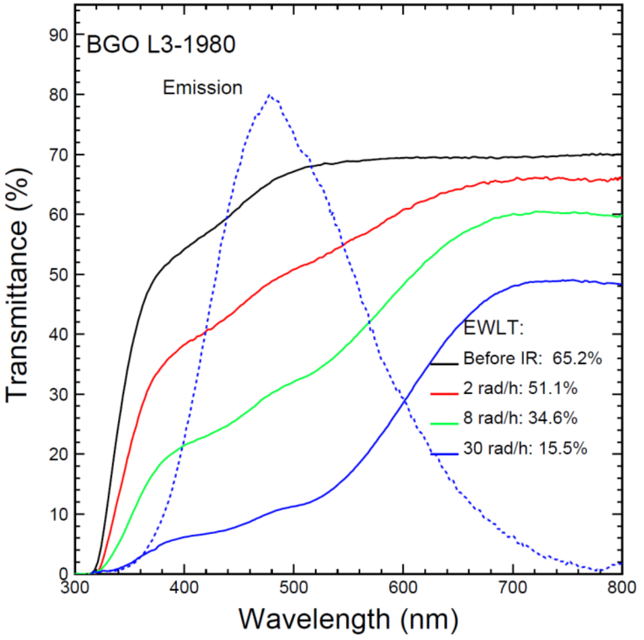


Damage in LT

Sample SIC-2011 has better initial LT and is more radiation hard than other two samples

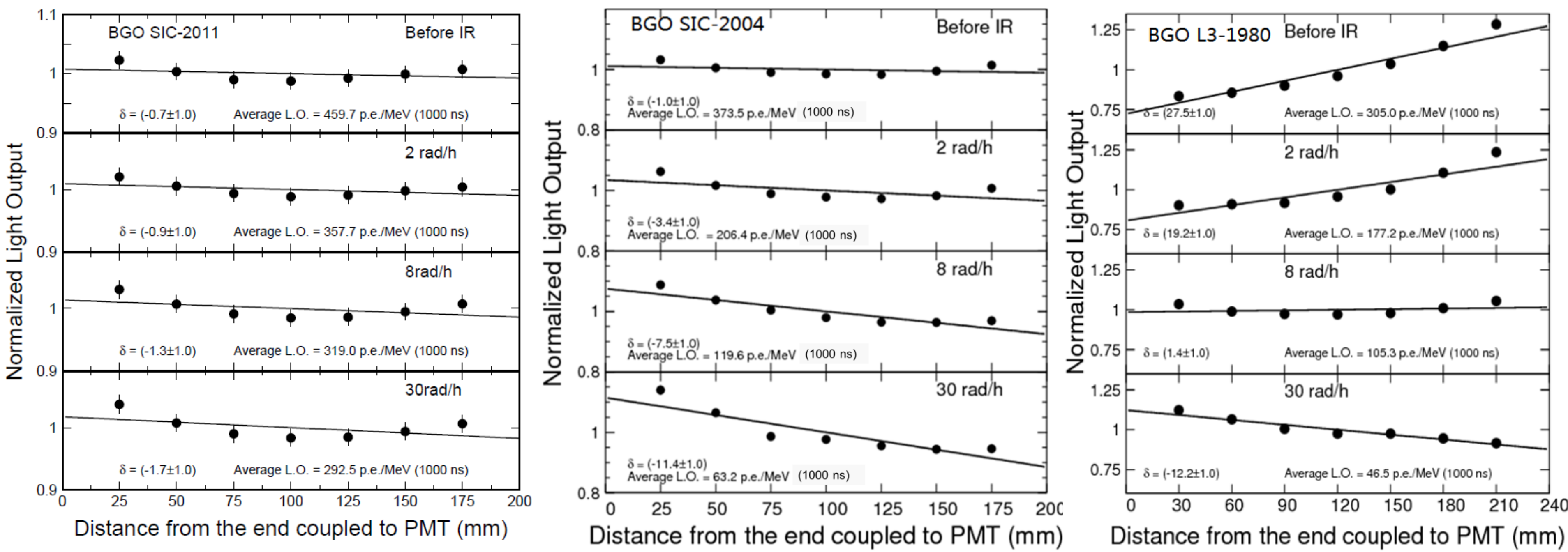




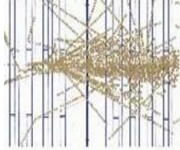


Damage in LO and LRU

Sample SIC-2011 has better initial light output and keeps its LRU during irradiations up to 30 rad/h



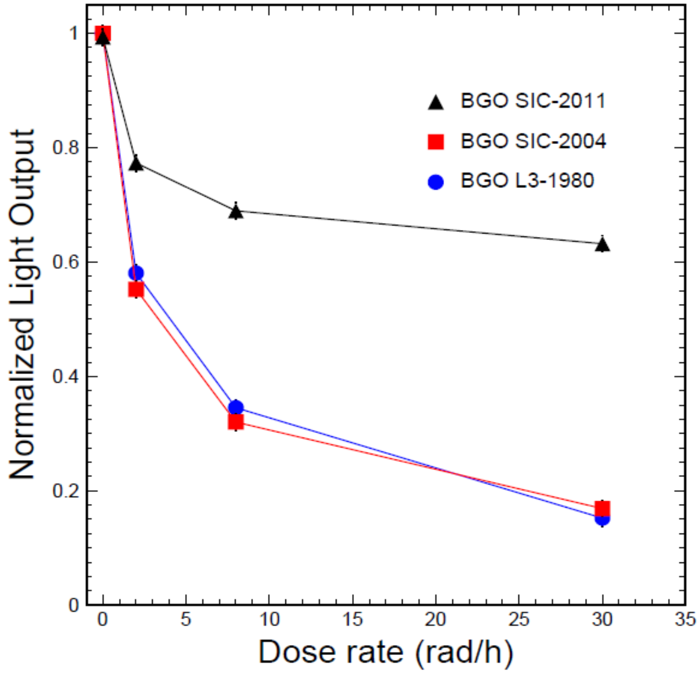
BGO Crystals with the SIC-2011 quality can be used up to 30 rad/h

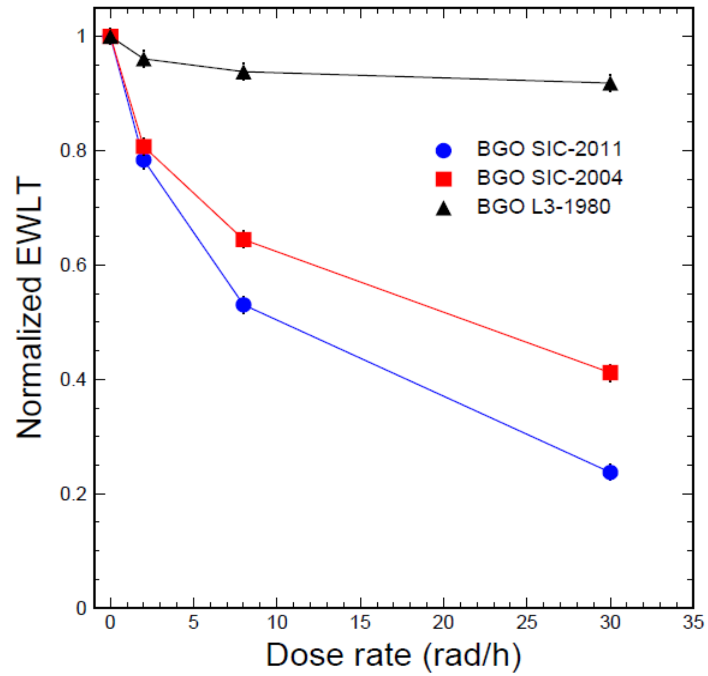


Damage as a Function of Dose Rate

Sample SIC-2011 is more radiation hard than other two samples

Samples	LO (p.e./MeV)	LO loss (%)			EWLT loss (%)		
		2 rad/h	8 rad/h	30 rad/h	2 rad/h	8 rad/h	30 rad/h
BGO SIC-2011	460	22	31	36	4	6	8
BGO SIC-2004	373	45	68	83	19	36	59
BGO L3-1980	305	42	66	85	22	47	76





Investigation on PWO-II Crystals

Sample ID	Dimension	Polish
PWO-B1757	24.5×24.5×200 mm^3	Six faces
PWO-B1782	24.5×24.5×200 mm^3	Six faces
CMS BTCP PWO	28.5^2×30.0^2×220 mm^3（20 crystals）	Six faces
CMS SIC PWO	28.5^2×30.0^2×220 mm^3（12 crystals） 22×22×230 mm^3（20 crystals）	Six faces

Radiation Damage Experiments

- Samples were annealed at 200℃ for 200 minutes to remove residual damage
- Samples went through a series of γ-ray irradiations at dose rates of 2, 8, 30 and 7,160 rad/h until reaching an equilibrium

Transmittance Cut-Off Edge and LO

PWO-II has sharper slope at the LT cut-off edge
Their LO is better than CMS BTCP, but similar to CMS SIC

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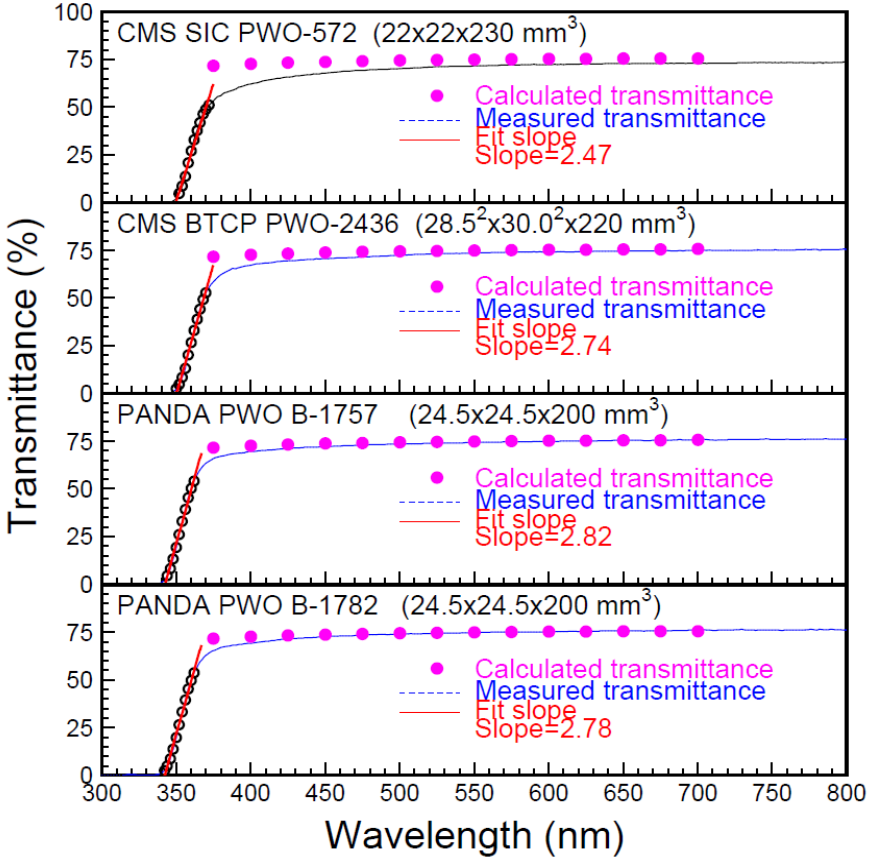

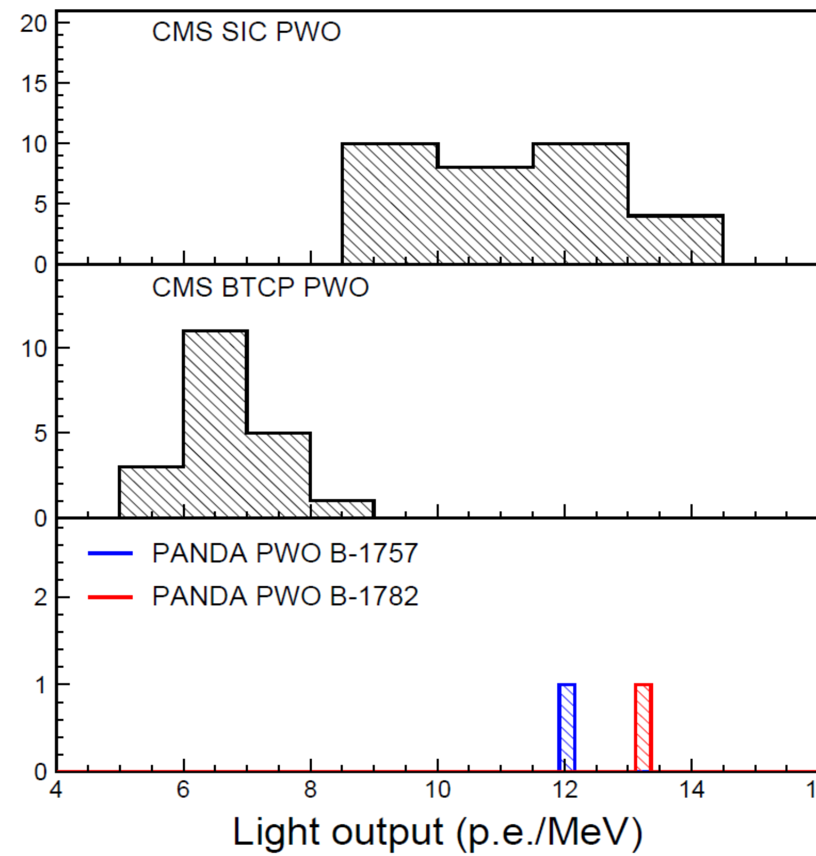

Comparison of LT @ 360, 440 & 600 nm

PWO-II has better LT, especially at 360 nm

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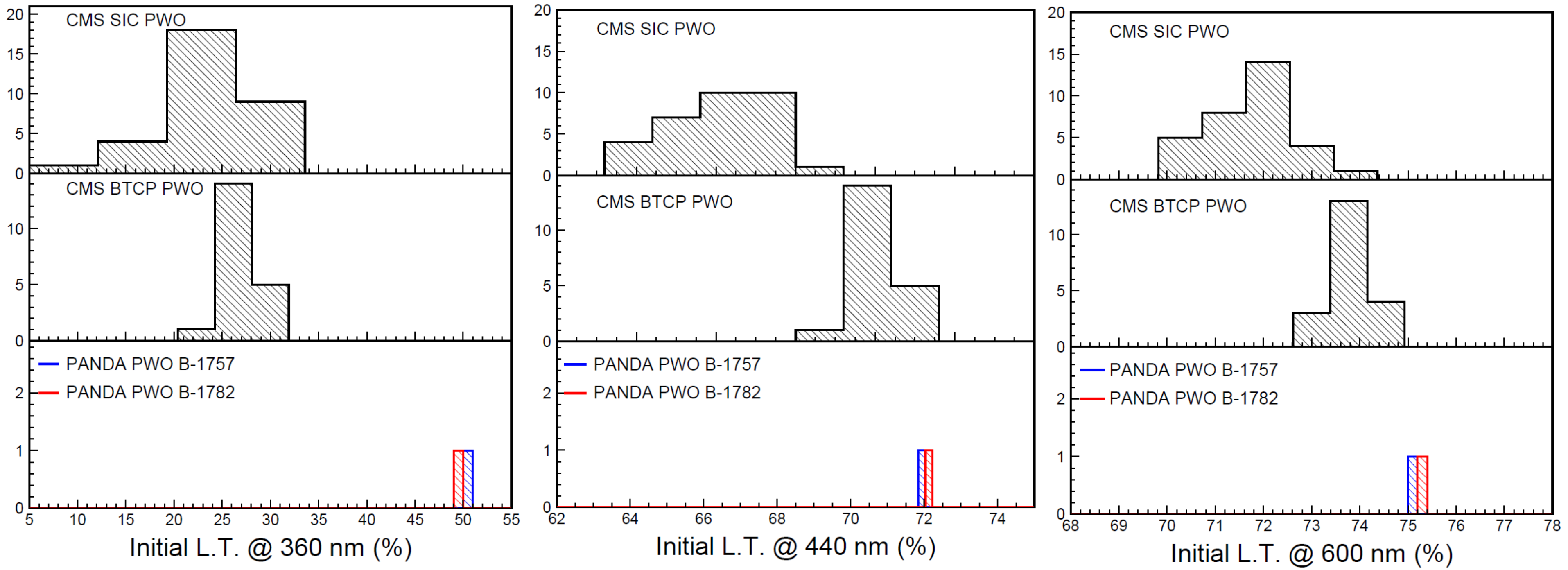
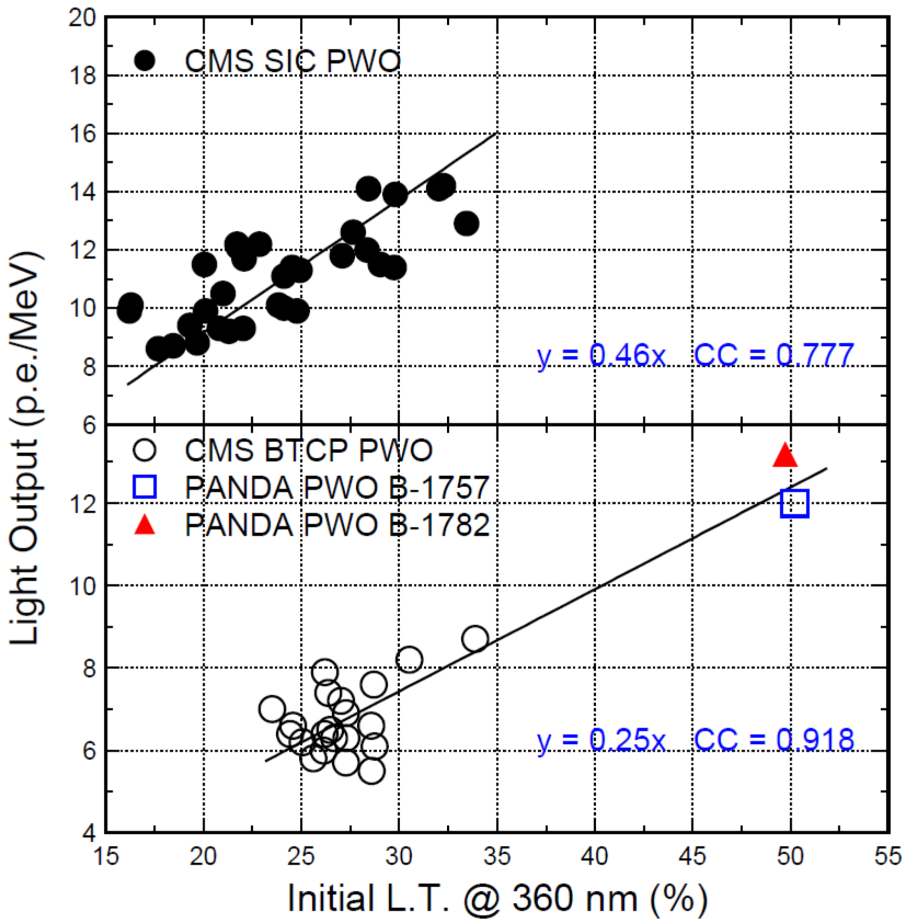


Correlation: LT @ 360 nm versus LO

Good correlation observed, indicating a partial self-absorption

IEEE Trans. Nucl. Sci., Vol. 54 (2007) 375-382

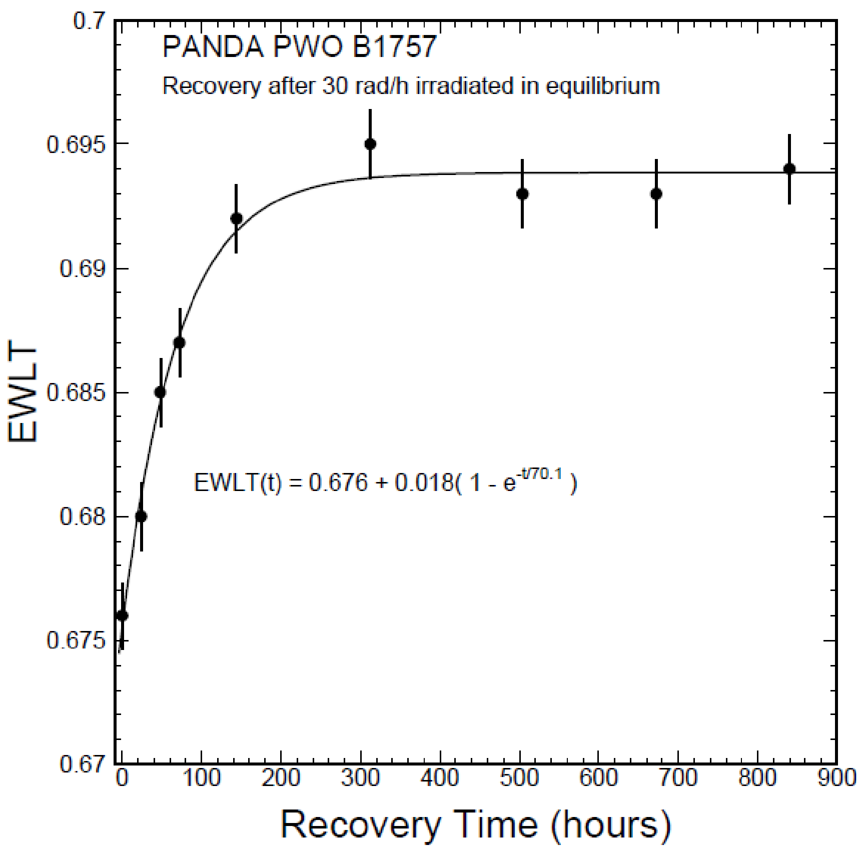


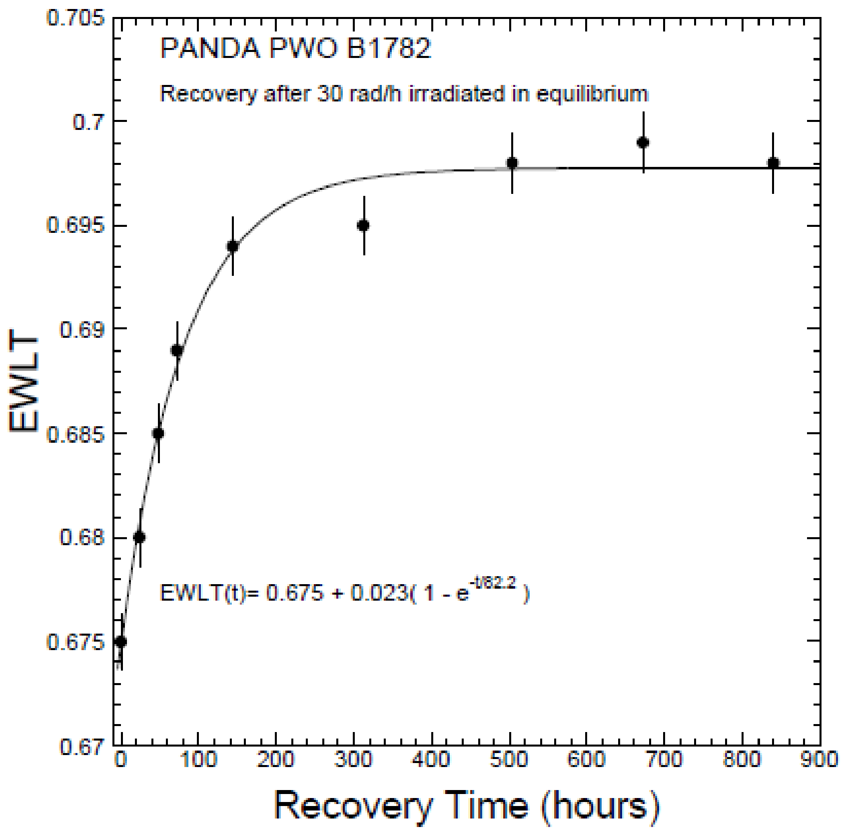
CC, *correlation coefficient*, is a measure of the correlation and defined by:

$$CC = \frac{\sum(x-\overline{x})(y-\overline{y})}{\sqrt{\sum(x-\overline{x})^2\sum(y-\overline{y})^2}}$$

Damage Recovery of EWLT

Damage recovers with consistent time constant.
Initial EWLT: 70.0%/70.1% for samples 1757/1782 are not reached after recovery for 900 h, indicating deep color centers existing

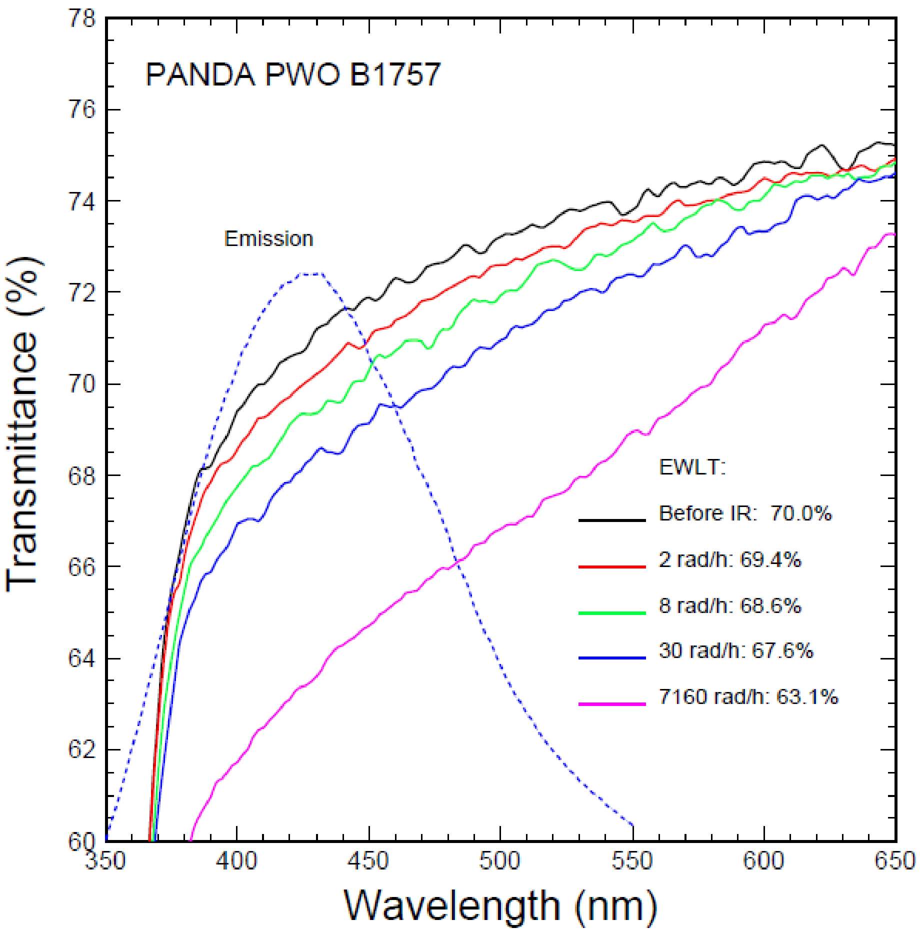


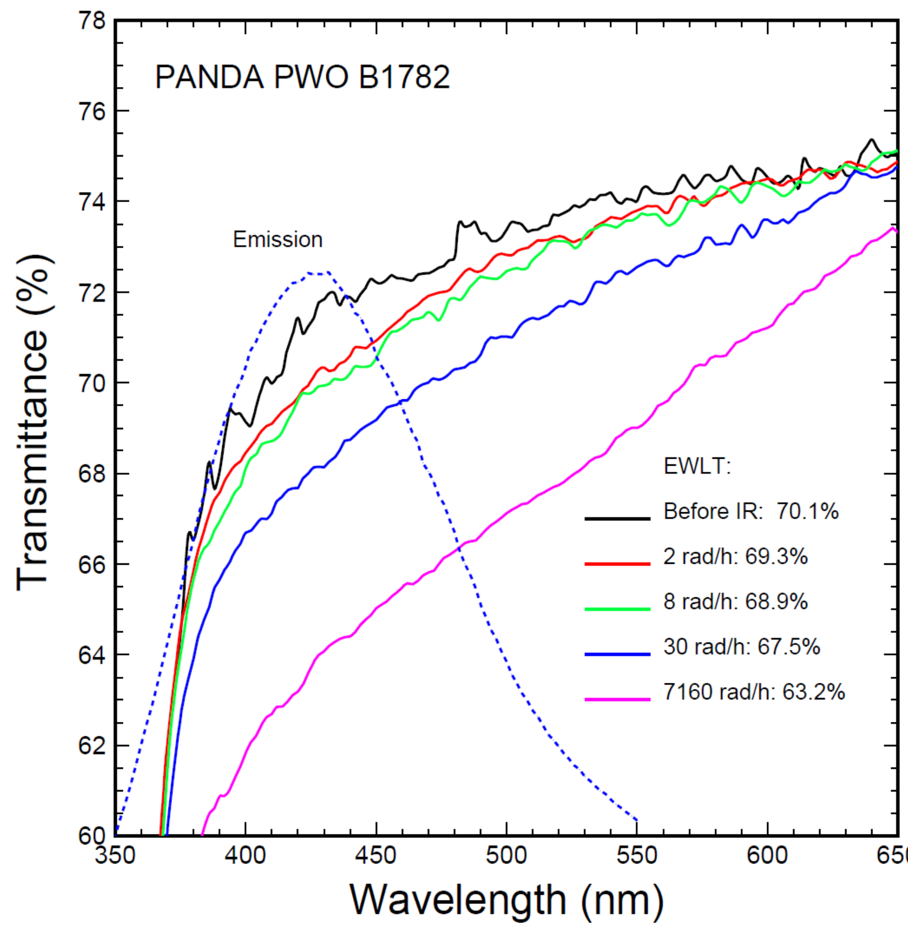


Recovery leads to a dose rate dependent damage level

Damage in LT

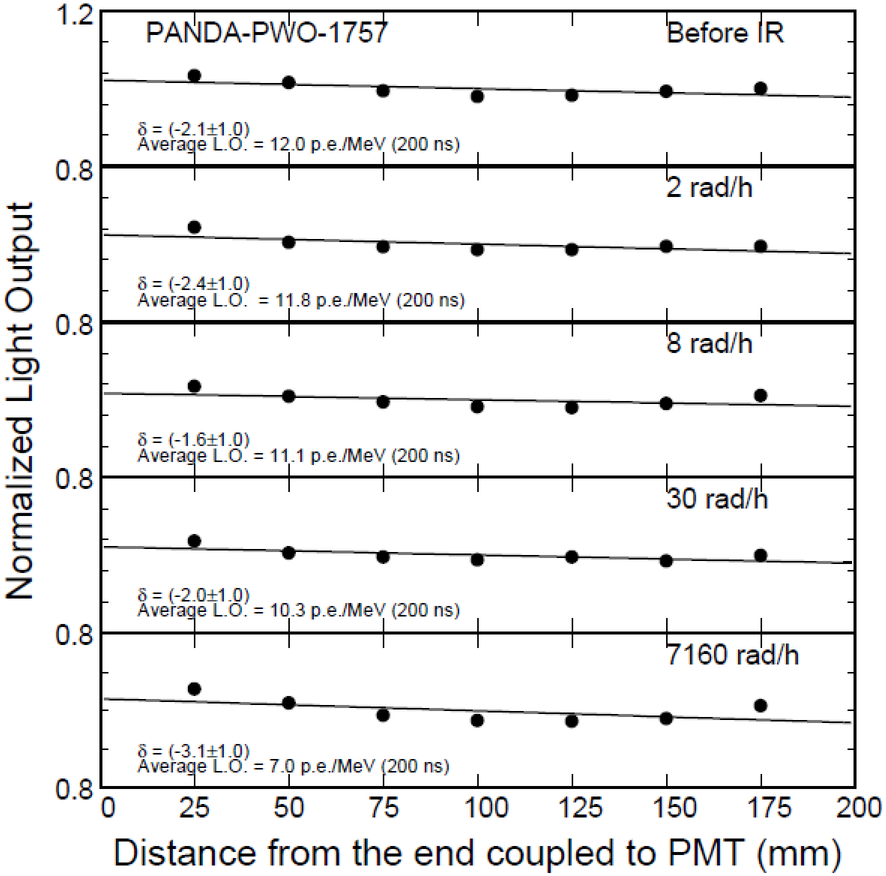
Two PWO-II samples have consistent damage level

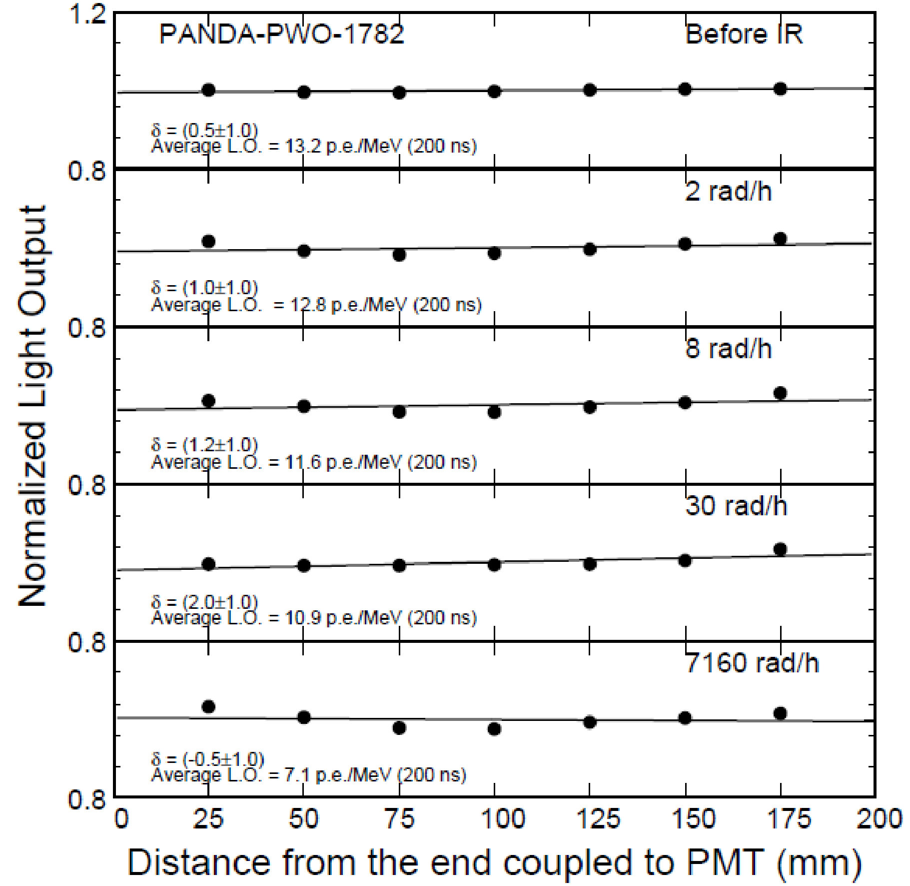




Damage in LO & LRU

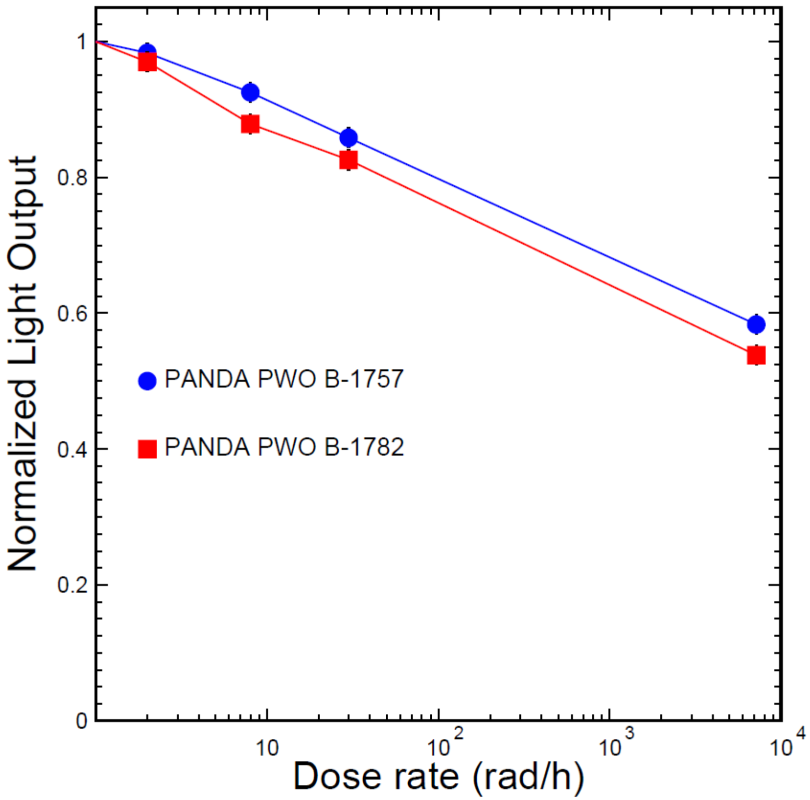
LRU is not changed up to 7,160 rad/h

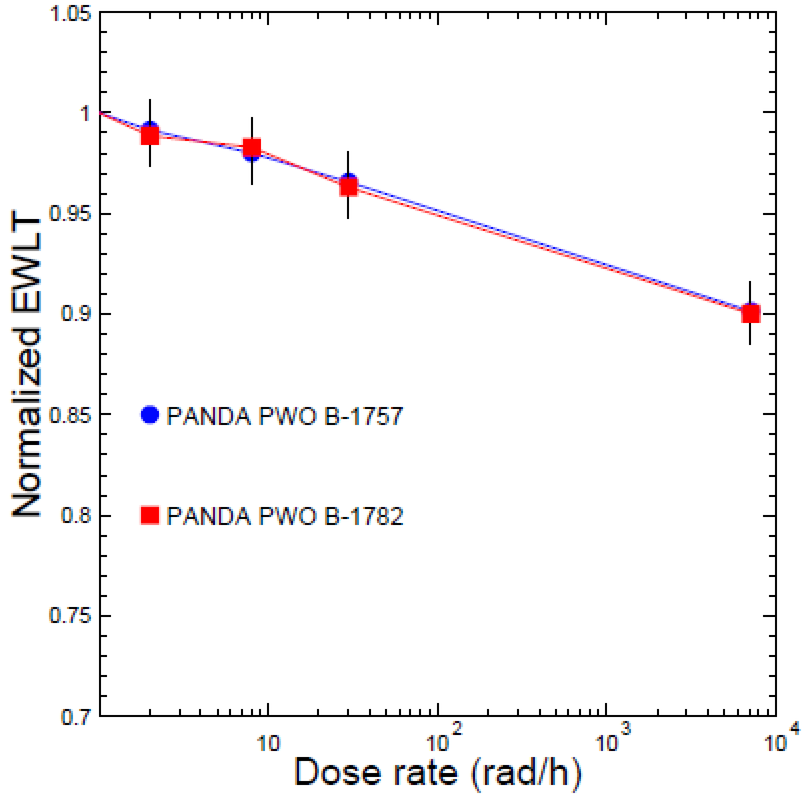




Damage as a Function of Dose Rate

Samples	LO (p.e./MeV)	LO loss (%)				EWLT loss (%)			
		2 rad/h	8 rad/h	30 rad/h	7160 rad/h	2 rad/h	8 rad/h	30 rad/h	7160 rad/h
PWO B-1757	12.0	2	8	14	42	0.8	2.0	3.4	9.9
PWO B-1782	13.2	3	12	17	46	1.1	1.7	3.7	10.0





Correlations: LO Loss versus LT loss @ 440 nm and EWRIAC

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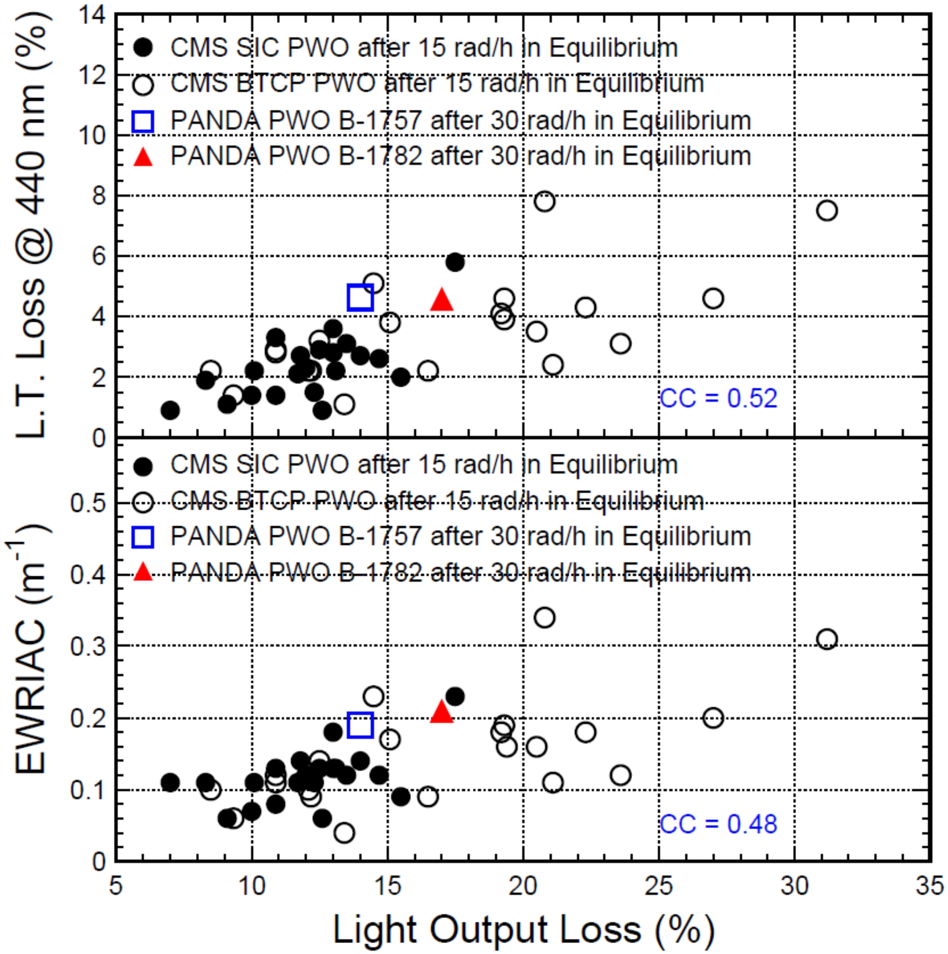

EWRIAC, *emission weighted radiation induced absorption coefficient*, is defined by:

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

$$\mathrm{Riac} = 1/\mathrm{LAL}_{\mathrm{equilibrium}} - 1/\mathrm{LAL}_{\mathrm{before}}$$

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

No Correlations: Initial LT Slope & LT @ 360nm Versus LO Loss & EWRIAC

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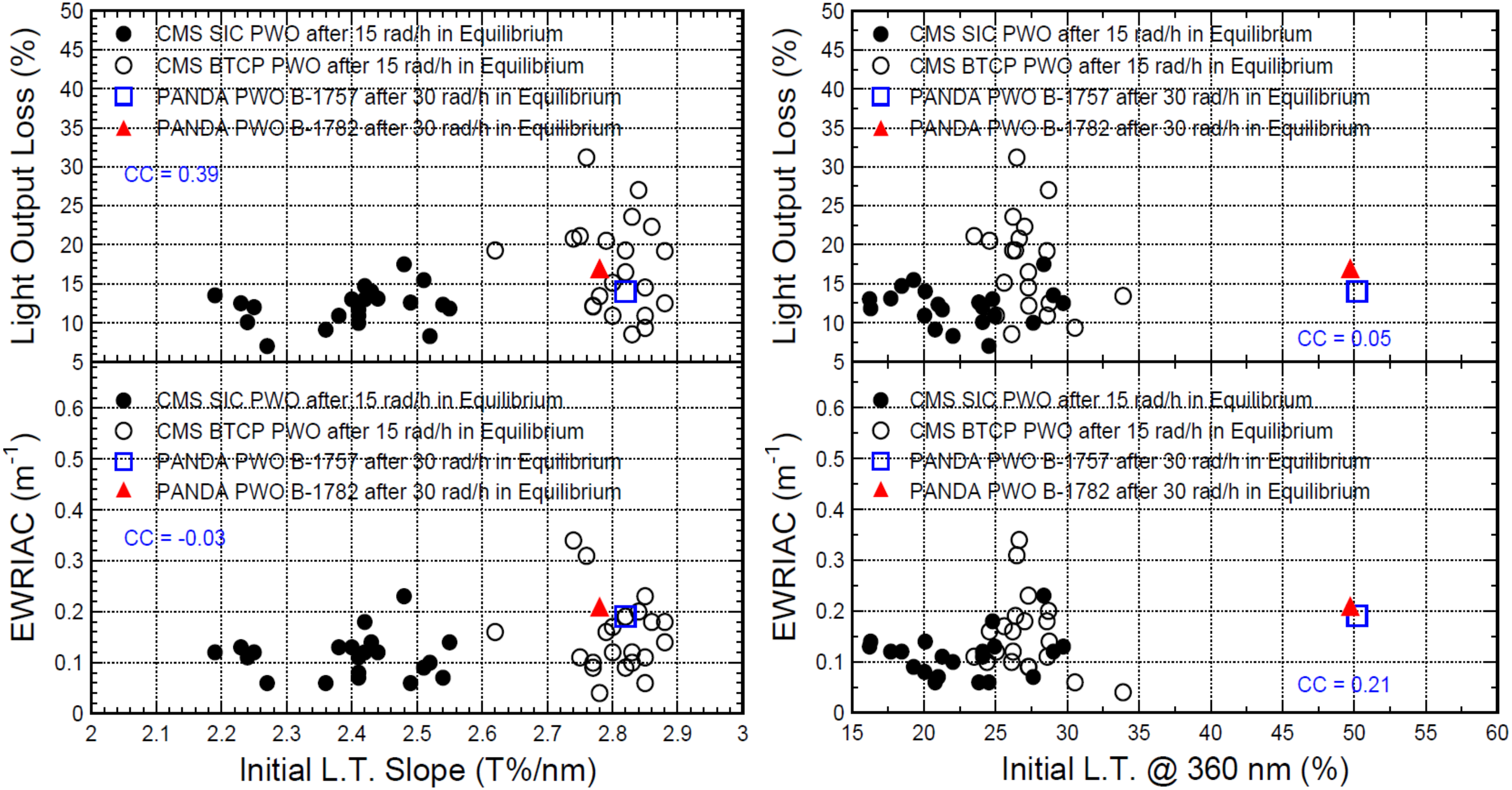
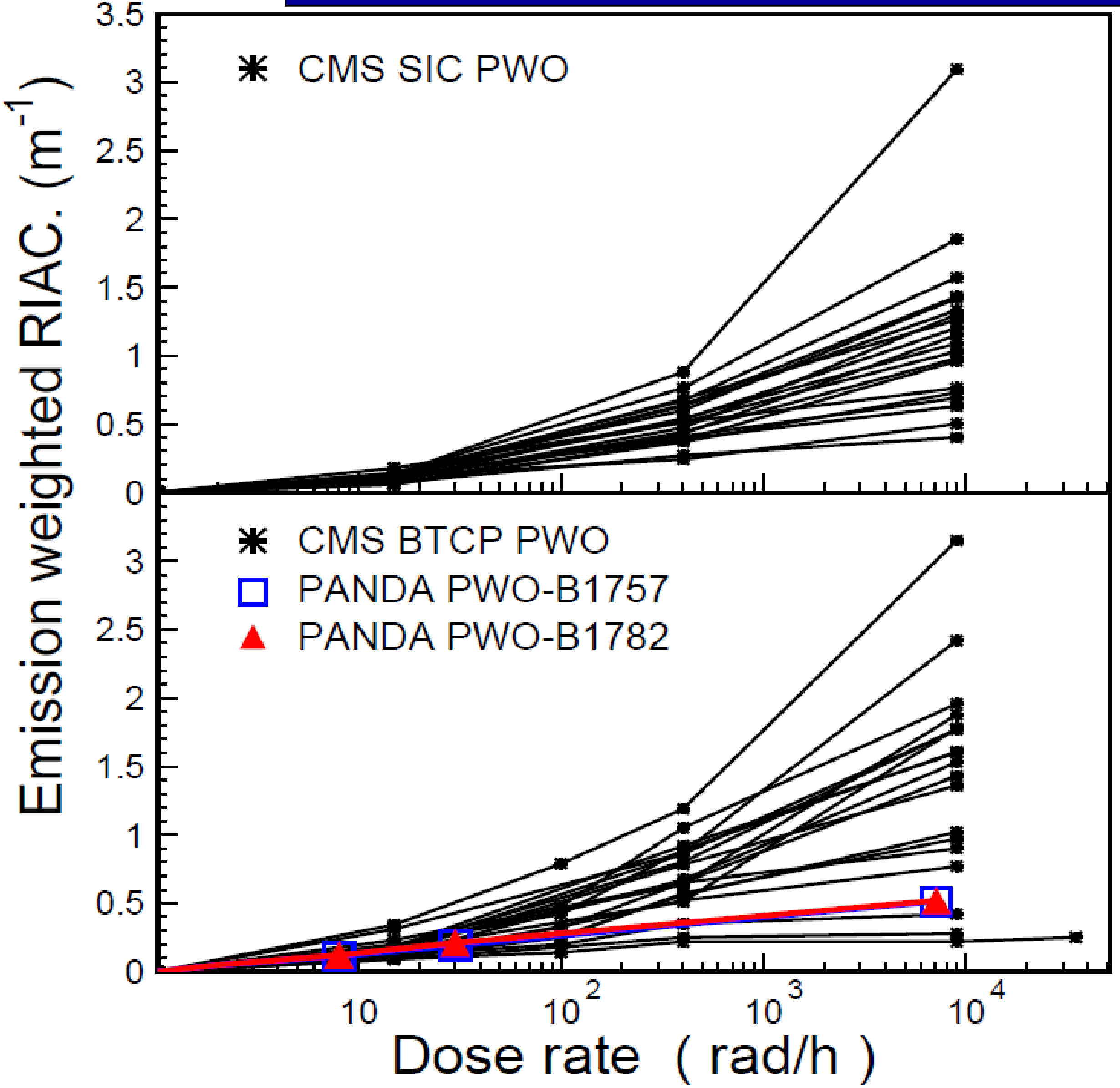


EWRIAC as a Function of Dose Rate

IEEE Trans. Nucl. Sci., Vol. 51 (2004) 1777-1783



PWO-II samples are compatible with a better portion of the CMS PWO crystals.

Summary

- The 2011 BGO sample from SIC has better initial LT and LO as well as better radiation hardness than previous BGO samples. It is radiation hard up to 30 rad/h.

- PWO-II samples have better LT @ 360 nm and LO as compared to CMS PWO crystals. Their radiation hardness is in the better portion of CMS PWO crystals. They are radiation hard up to 7,160 rad/h.

- Correlations are confirmed between (1) LO and LT @ 360 nm, (2) LO loss versus EWRIAC and (3) LO loss versus LT loss at 440 nm for PWO crystals. The last correlation indicates that radiation damage in PWO crystals can be monitored.

- Radiation damage in BGO/PWO crystals recovers under room temperature, leading to a dose rate dependent damage level. Because of the recovery, a precision light monitoring system is mandatory for a BGO/PWO crystal calorimeter to trace variations of crystal transparency *in situ*.