Results of Long Term Damage/Recovery Tests and Correlation Studies

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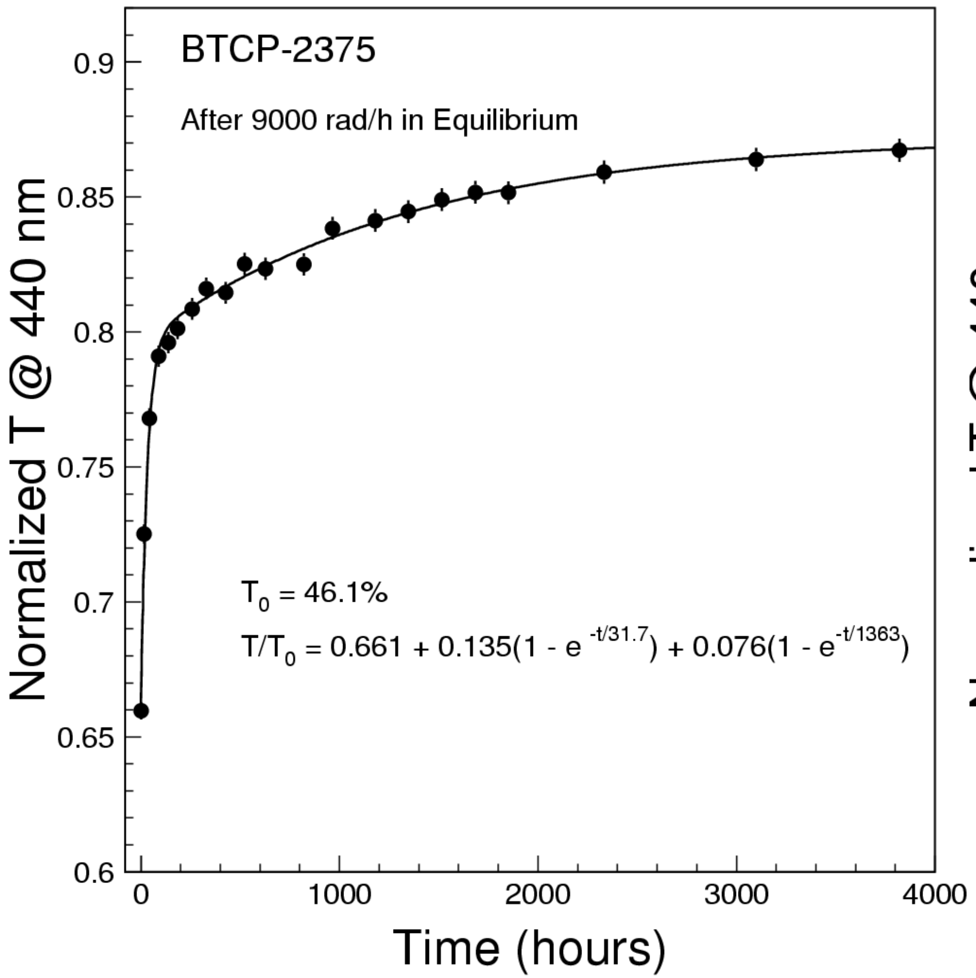
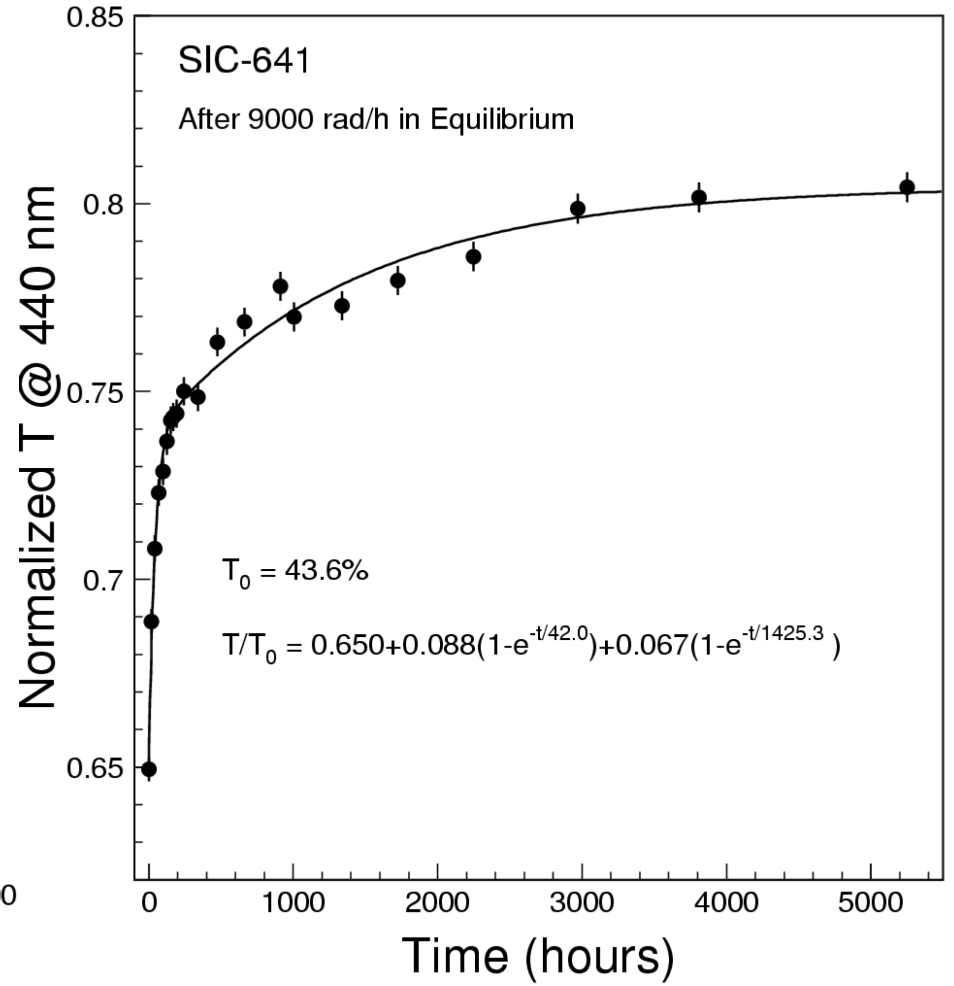
Damage Recovery after 9 krad/h

SIC samples have longer recovery time constants

Time constants: 32 h & 1360 h (BTCP), 42 h & 1430 h (SIC)

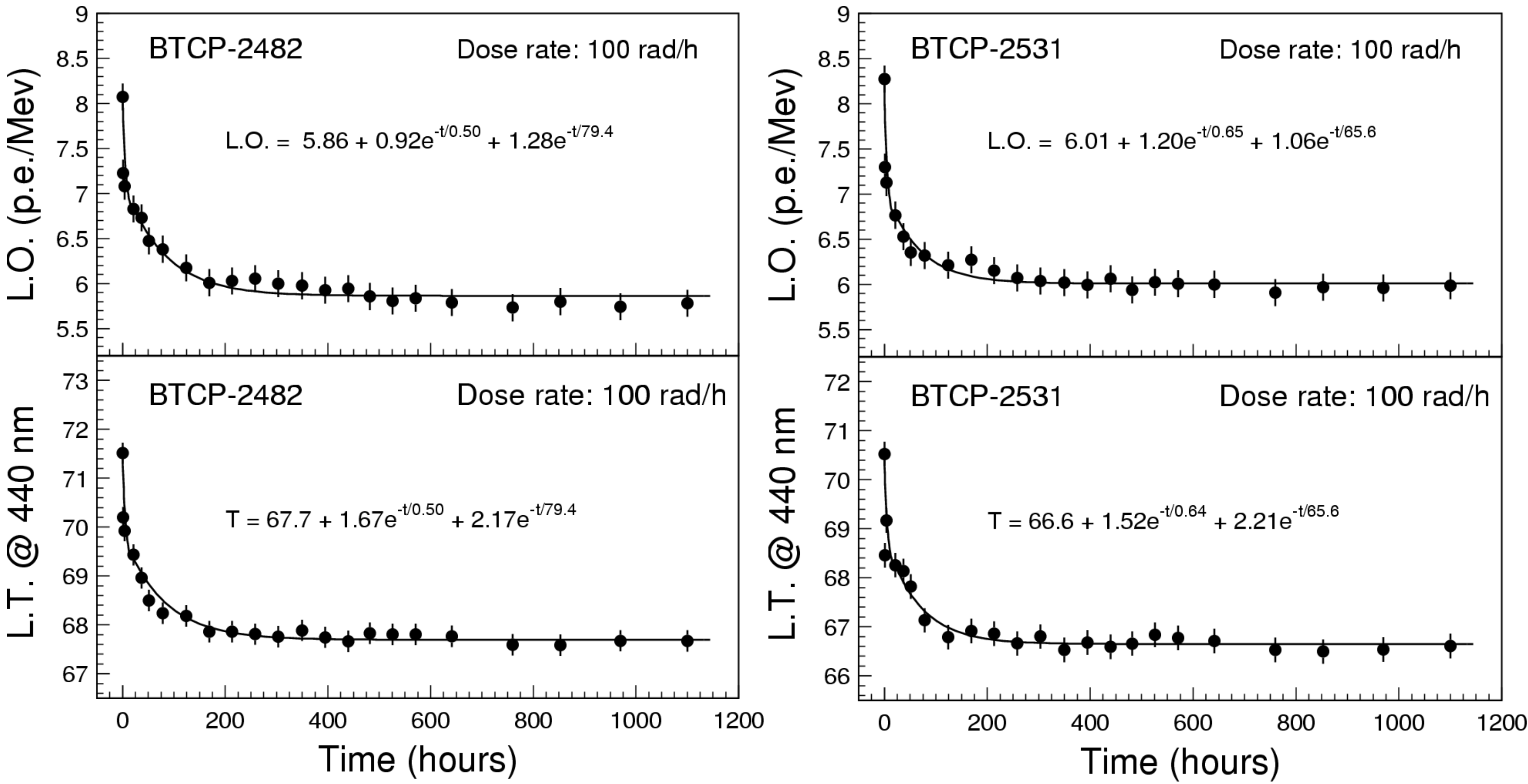




BTCP LO/LT Loss @ 100 rad/h

Time needed to reach equilibrium: 200 h

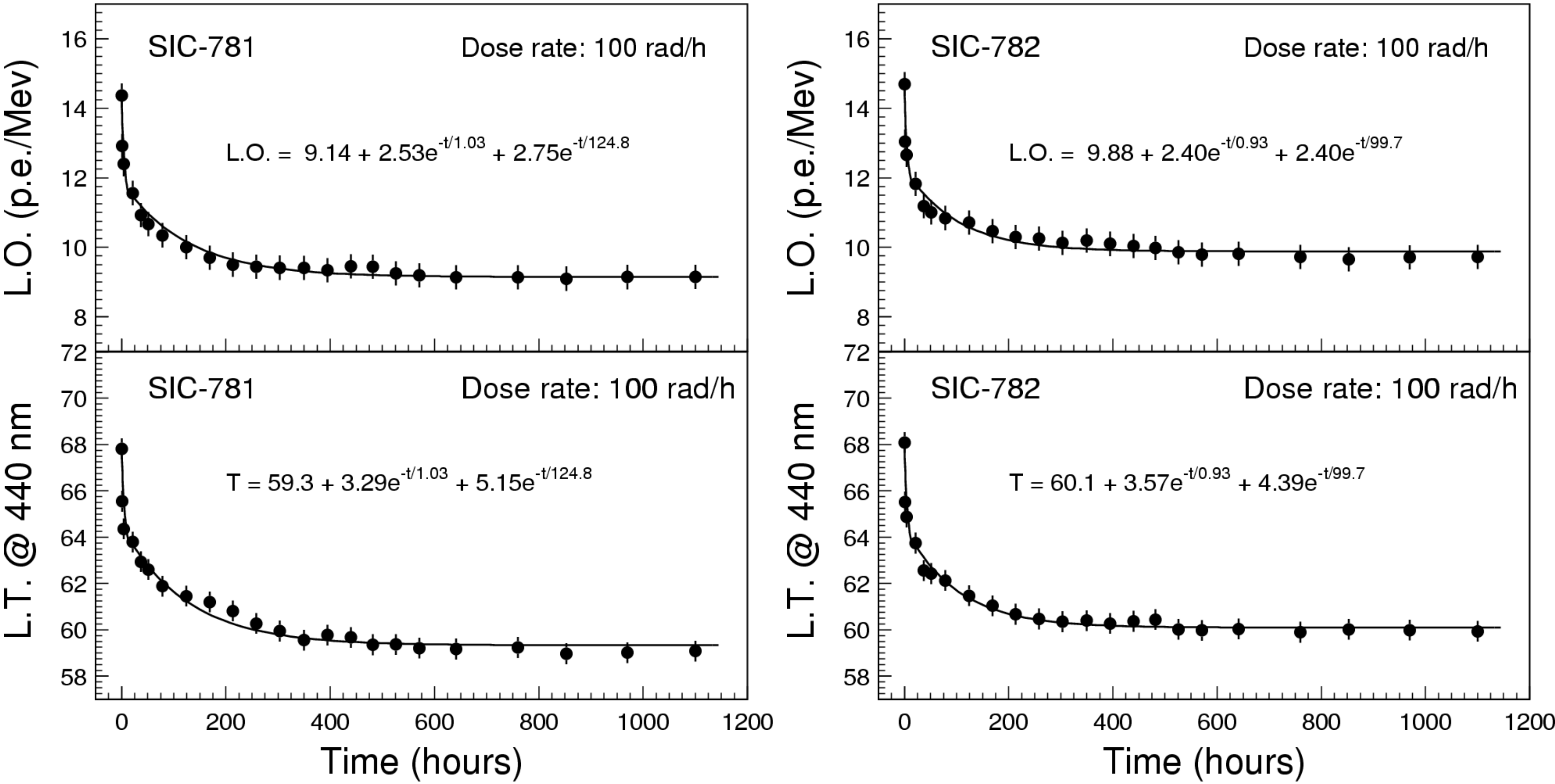
Time constants: 0.58 h and 73 h



SIC LO/LT Loss @ 100 rad/h

Time needed to reach equilibrium: 350 h

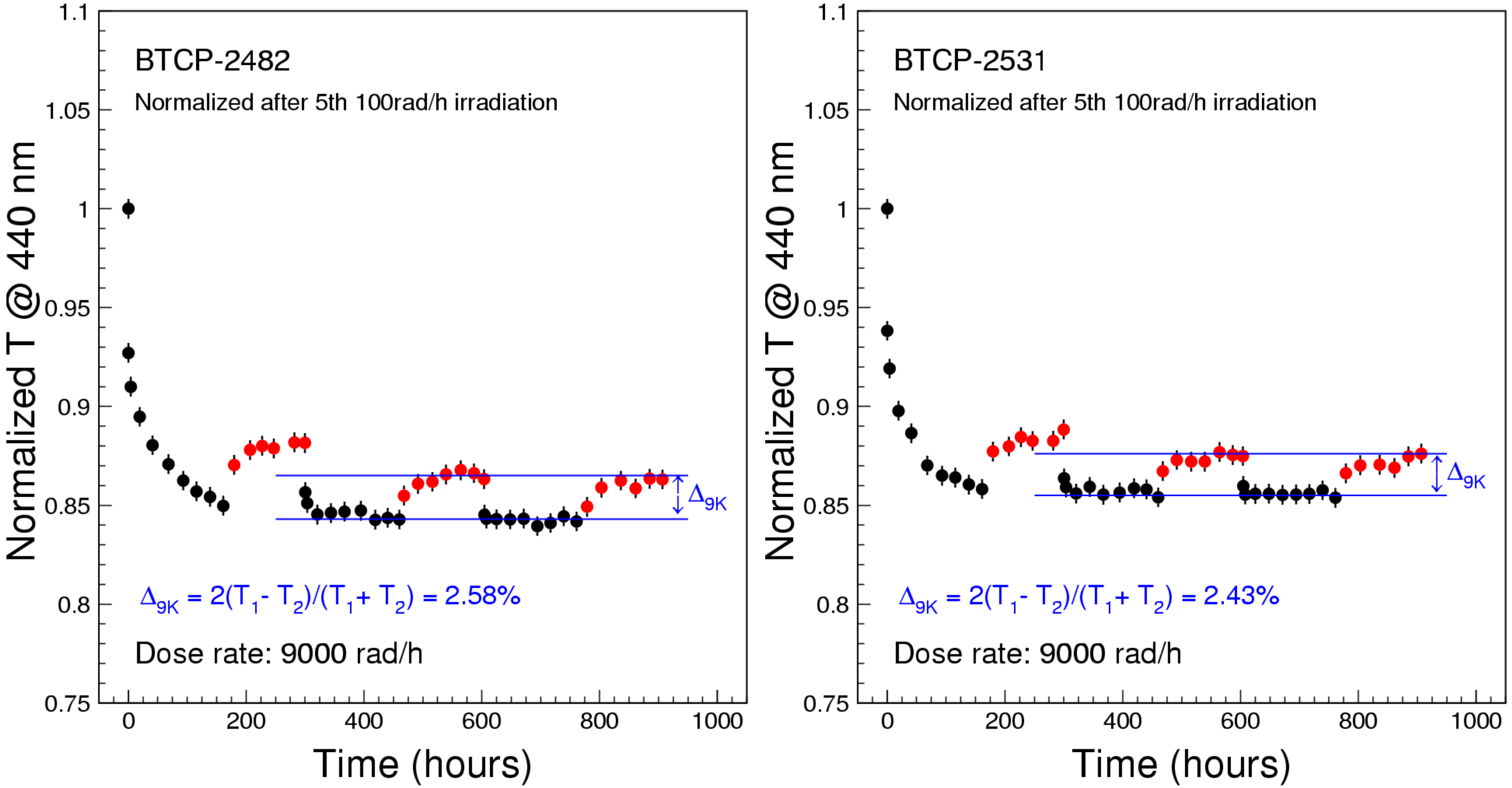
Time constants: 0.98 h and 112 h



BTCP LT Variation @ 9,000 rad/h

Time needed to reach equilibrium: 200 h

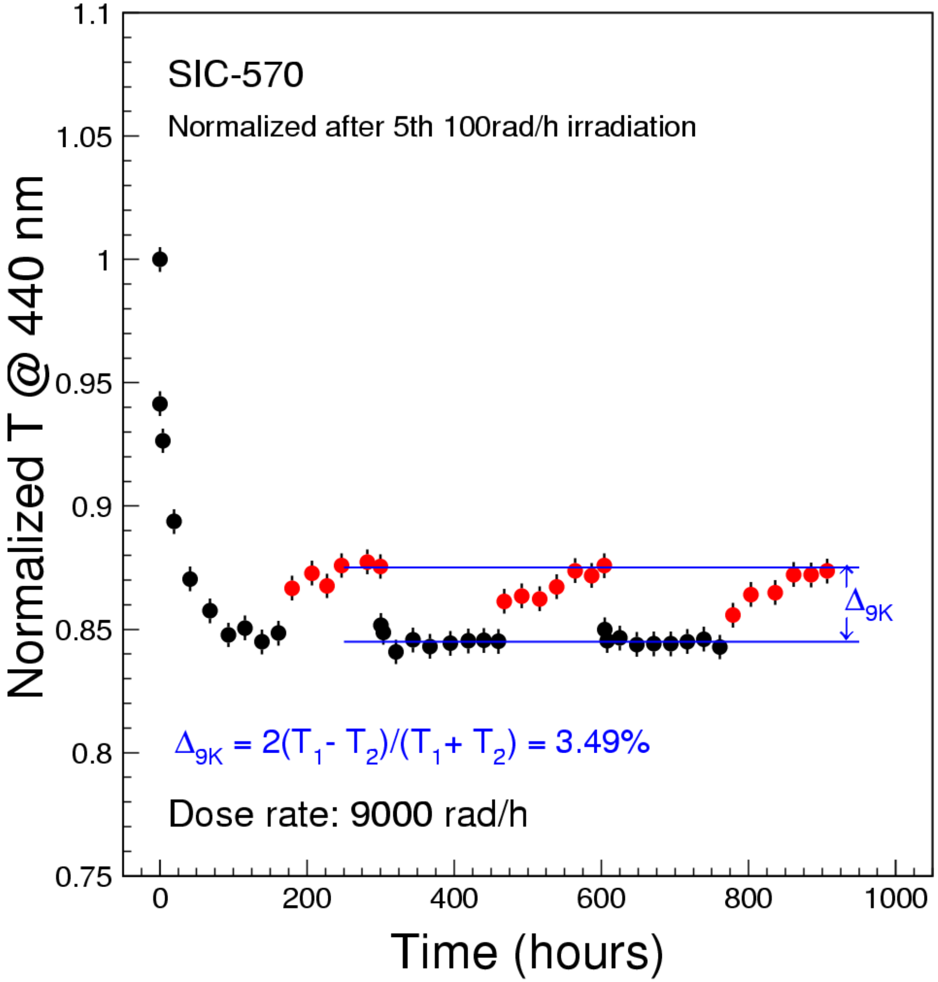
Variation Amplitude: 2.5%

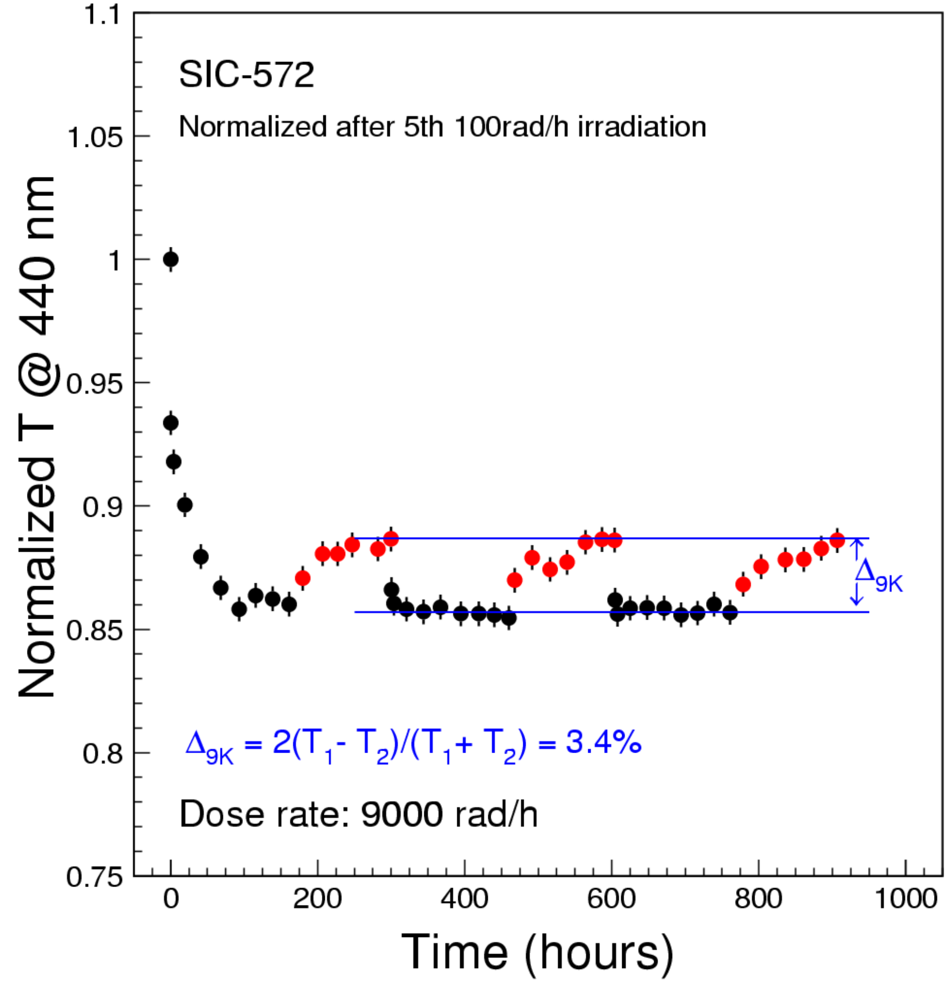


SIC LT Loss @ 9,000 rad/h

Time needed to reach equilibrium: 100 h

Variation Amplitude: 3.4%





Color Center Kinetics

IEEE Trans. Nucl. Sci., Vol. 44 (1997) 468-476

$$dD = \sum_{i=1}^{n} \{-a_i D_i dt + (D_i^{all} - D_i)\, b_i R dt\}$$

$$D = \sum_{i=1}^{n} \{\frac{b_i R D_i^{all}}{a_i + b_i R}\, [1 - e^{-(a_i + b_i R)t}] + D_i^0 e^{-(a_i + b_i R)t}\}$$

- D_i: color center density in units of m^{-1};
- D_i^0: initial color center density;
- D_i^{all} is the total density of trap related to the color center in the crystal;
- a_i: recovery costant in units of hr^{-1};
- b_i: damage contant in units of kRad^{-1};
- R: the radiation dose rate in units of kRad/hr.

$$D_{eq} = \sum_{i=1}^{n} \frac{b_i R D_i^{all}}{a_i + b_i R}$$

Recovery time constant 1/a, damage time constant: 1/(a + bR).

Longer recovery time constant: smaller “a”.

Longer damage time constant under low dose rate: smaller “a + bR”.

Shorter damage time constant under high dose rate: larger “b”.

SIC has smaller “a” and larger “b”: deeper traps.

Color Center Decomposition

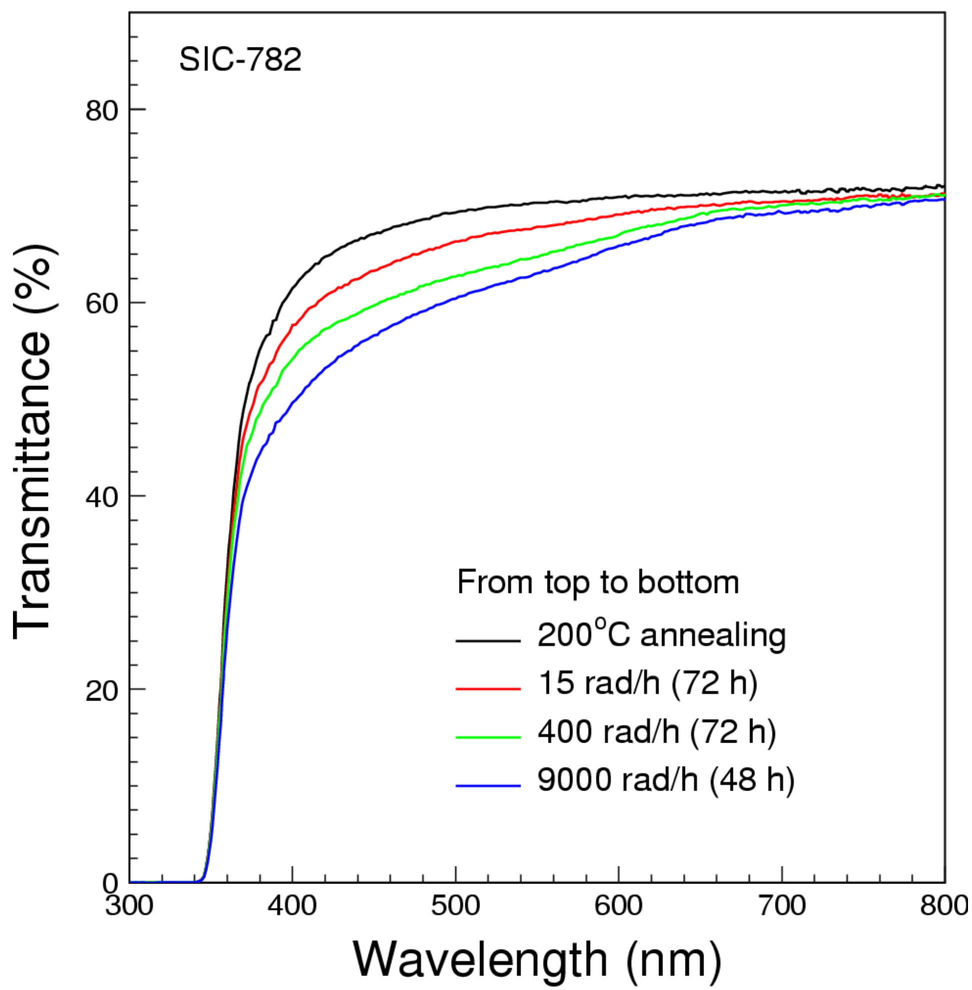
$$Riac = 1/LAL_{equilibrium} - 1/LAL_{before}$$

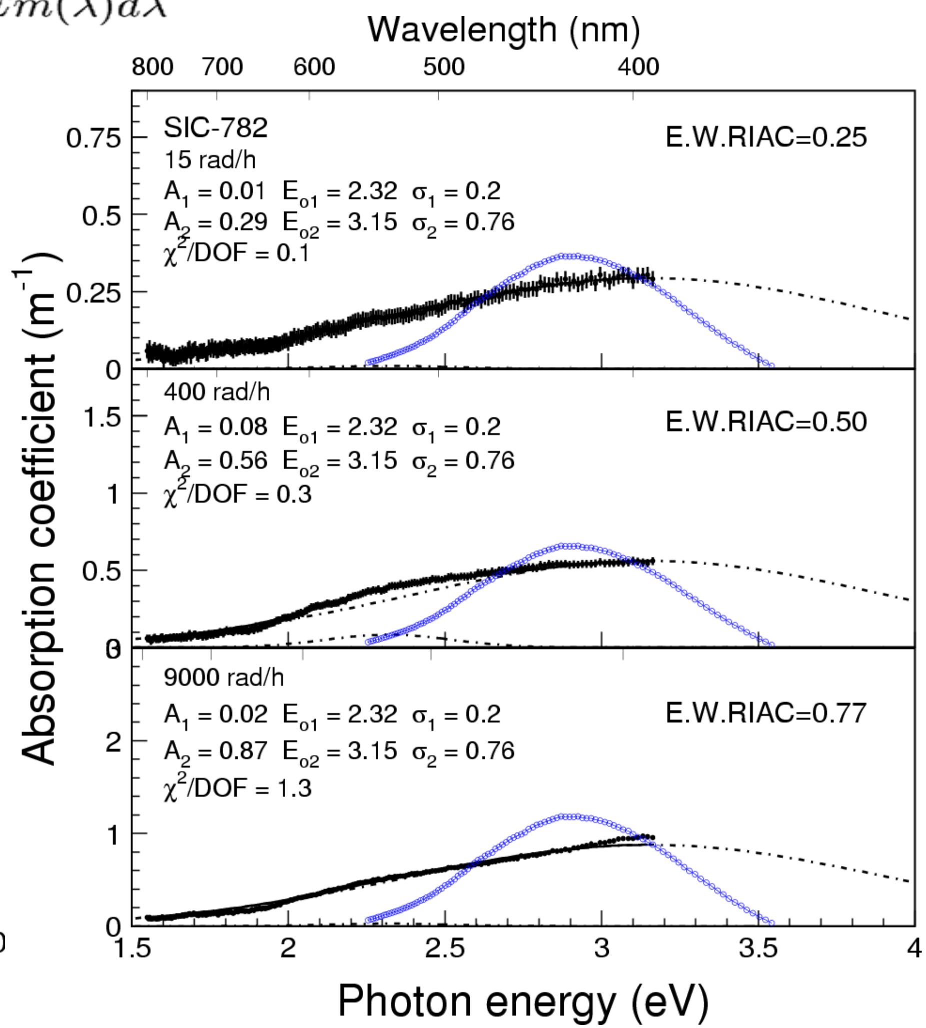
$$T_s = (1-R)^2 + R^2(1-R)^2 + \dots = (1-R)/(1+R)$$

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

$$R = \frac{(n_{crystal} - n_{air})^2}{(n_{crystal} + n_{air})^2}$$

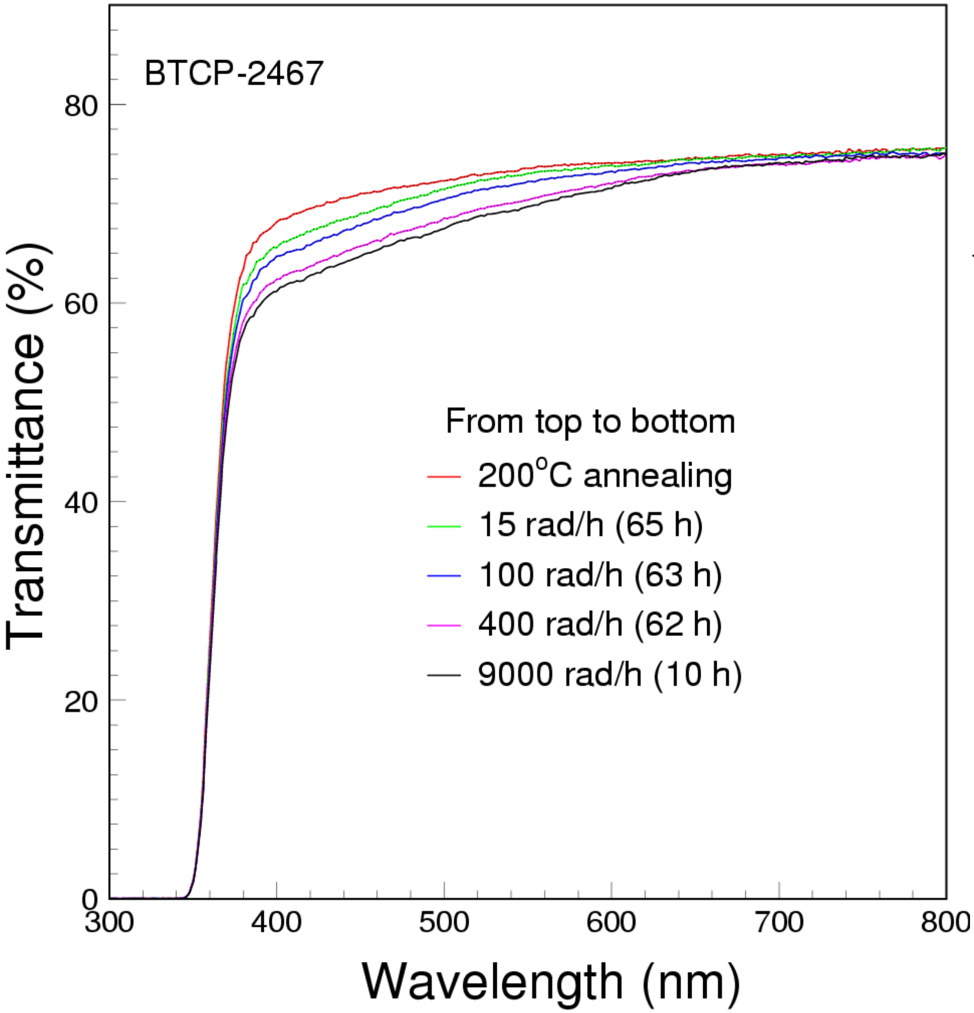
$$EWRIAC = \frac{\int Riac(\lambda)Em(\lambda)d\lambda}{\int Em(\lambda)d\lambda}$$

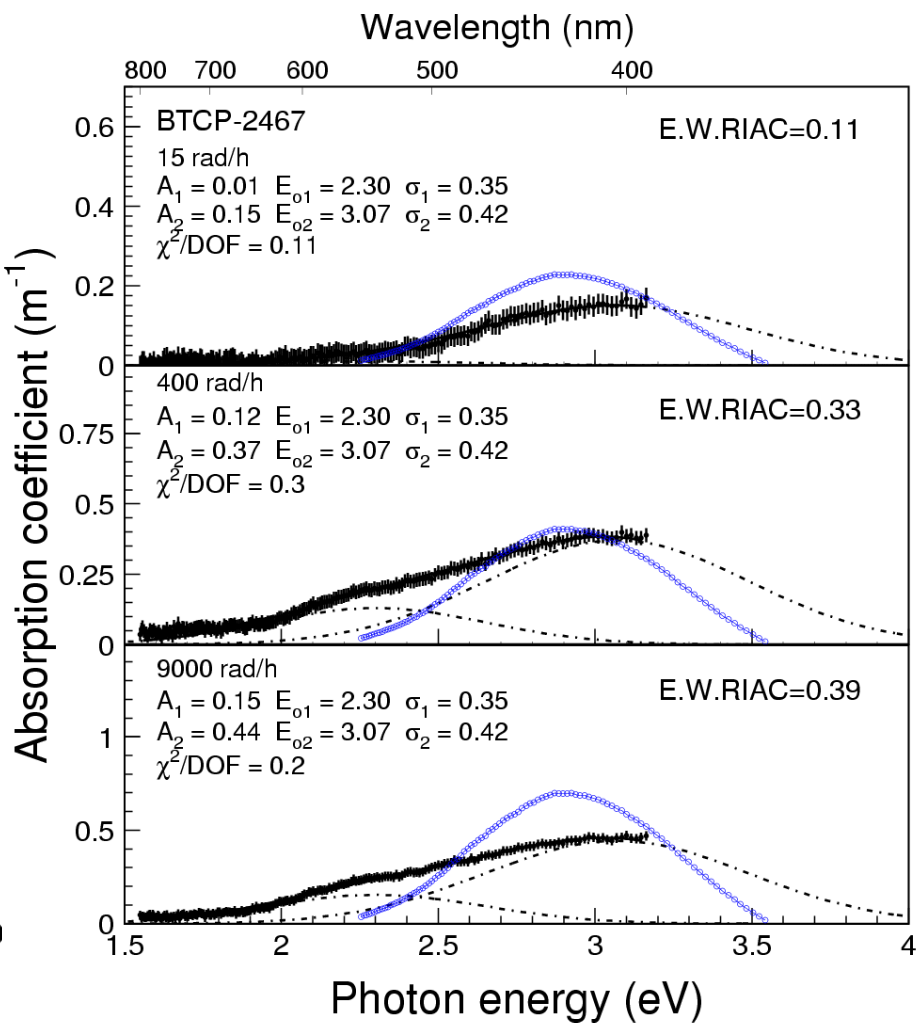




Color Center Decomposition

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



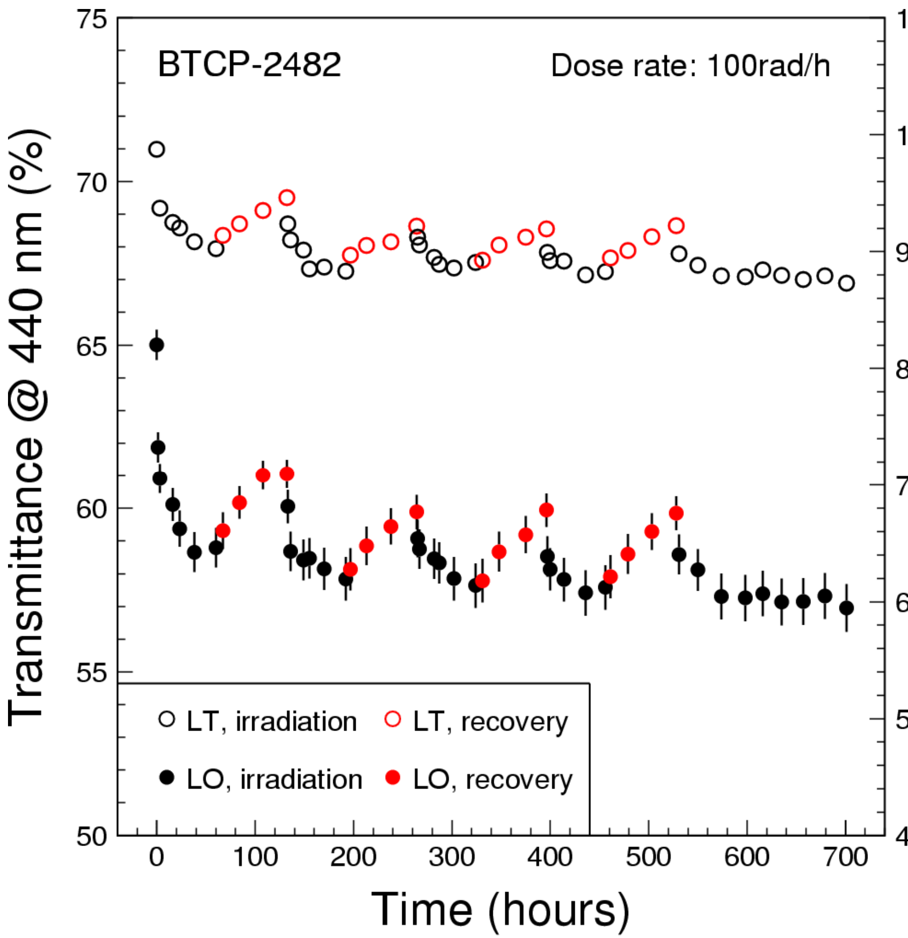


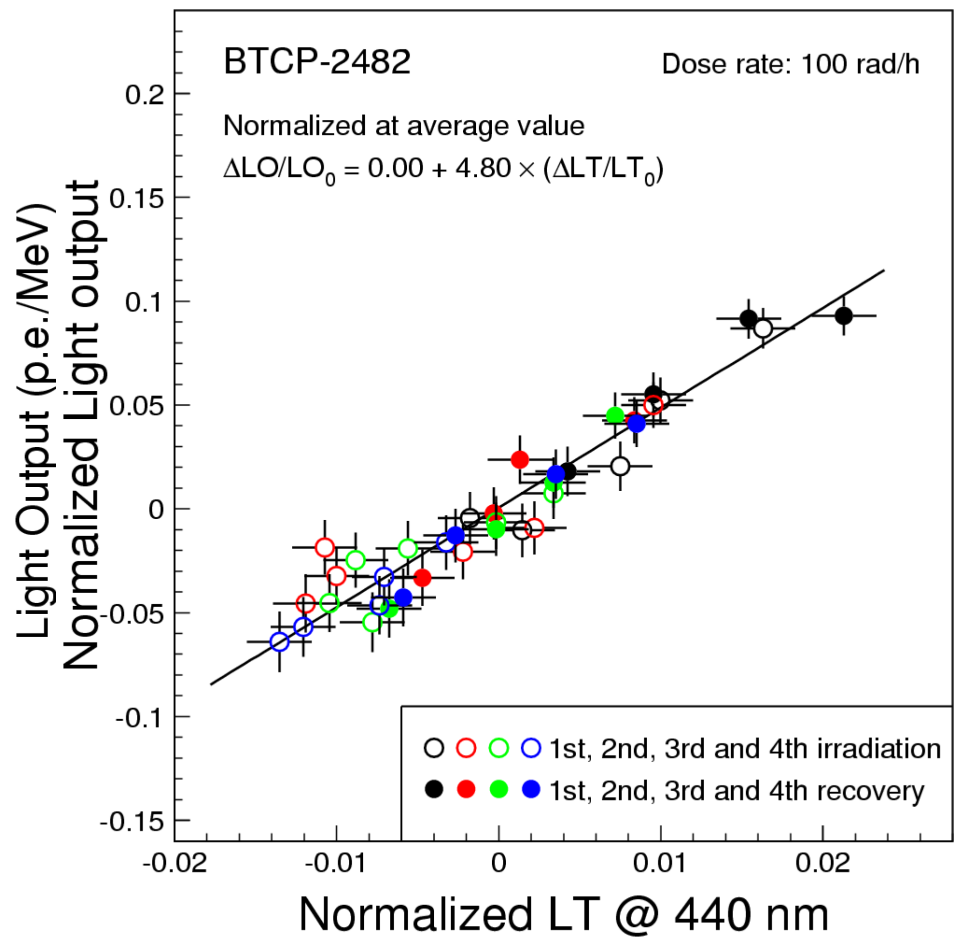
Summary I

- Long term damage and recovery processes can be fit to two time constants for all PWO samples.
- Compared to BTCP samples, SIC samples have longer recovery time constants and damage time constants under low dose rates, indicating smaller recovery (CC annihilation) constants.
- Under high dose rates, SIC samples have shorter time constants as compared to BTCP samples, indicating larger damage (CC creation) constants.
- All observations consist with our color center kinetic model and an assumption that SIC samples have deeper traps (CC) than BTCP samples, which is confirmed by color center decomposition by using the radiation induced absorption data.

δLO/LO versus δLT/LT @ 100 rad/h

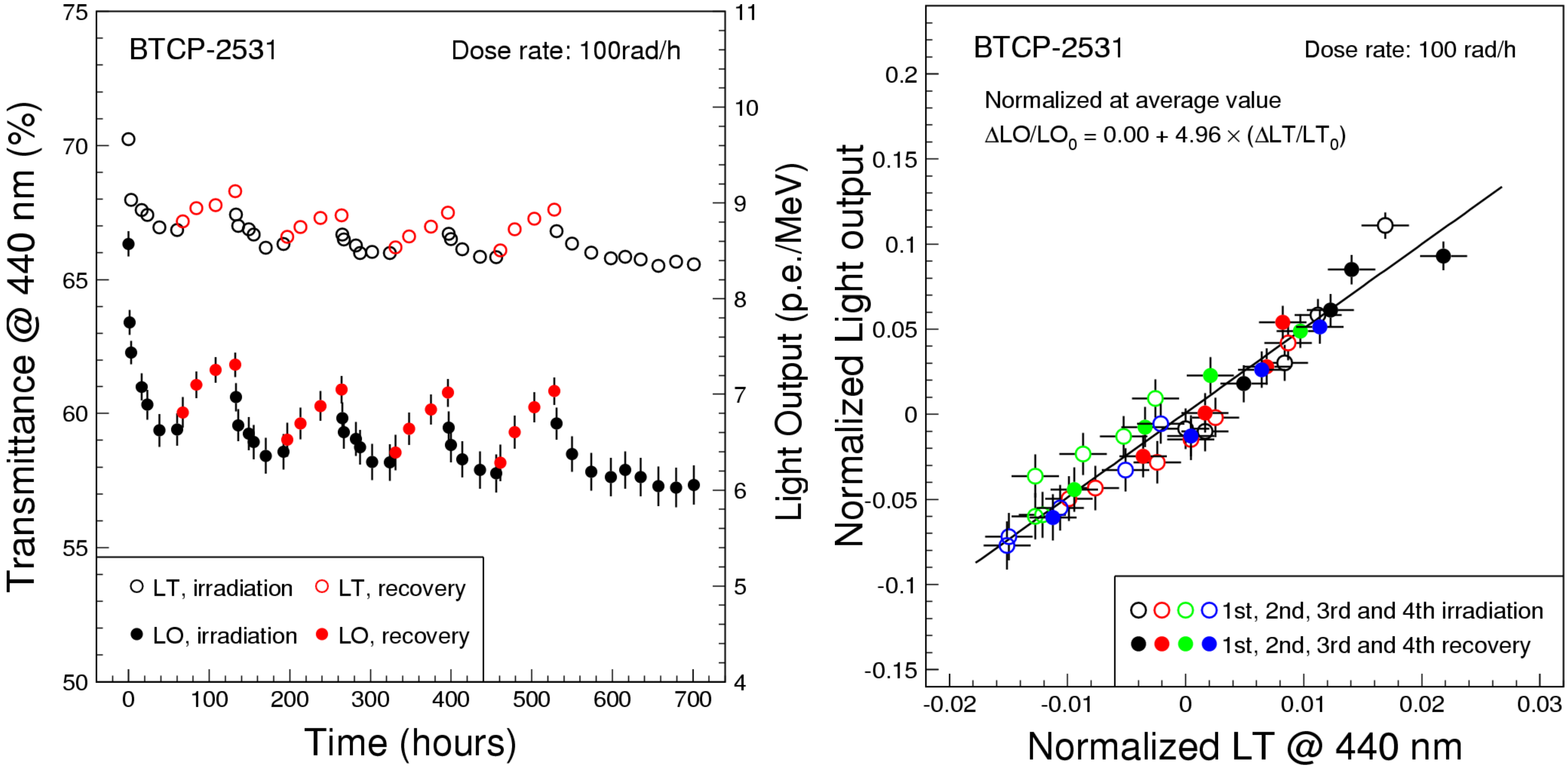
Strong correlation: Slope = 4.80





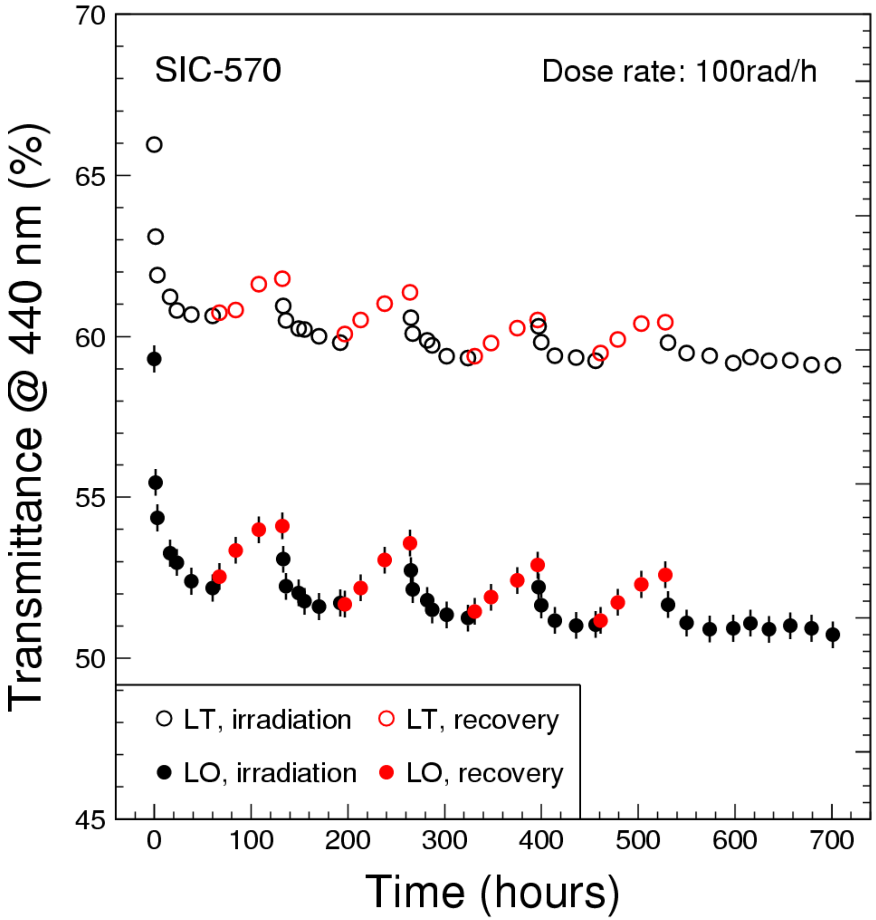
δLO/LO versus δLT/LT @ 100 rad/h

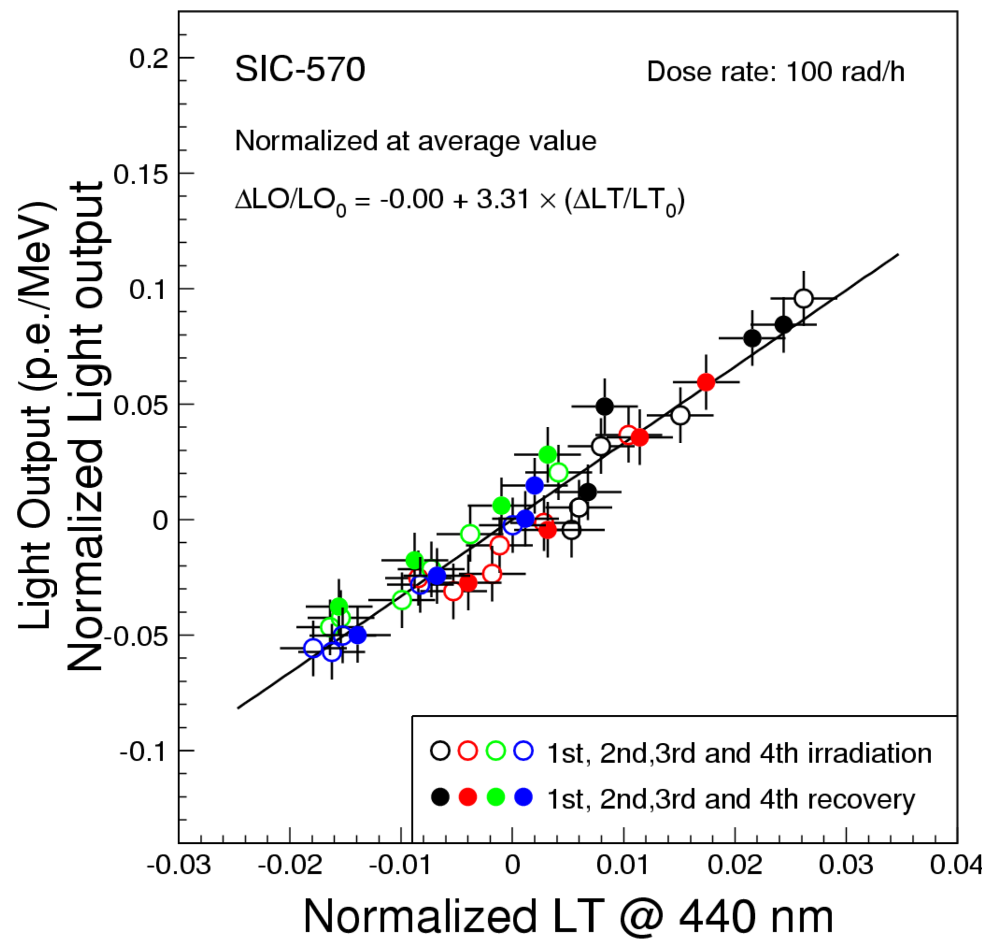
Strong correlation: Slope = 4.96



δLO/LO versus δLT/LT @ 100 rad/h

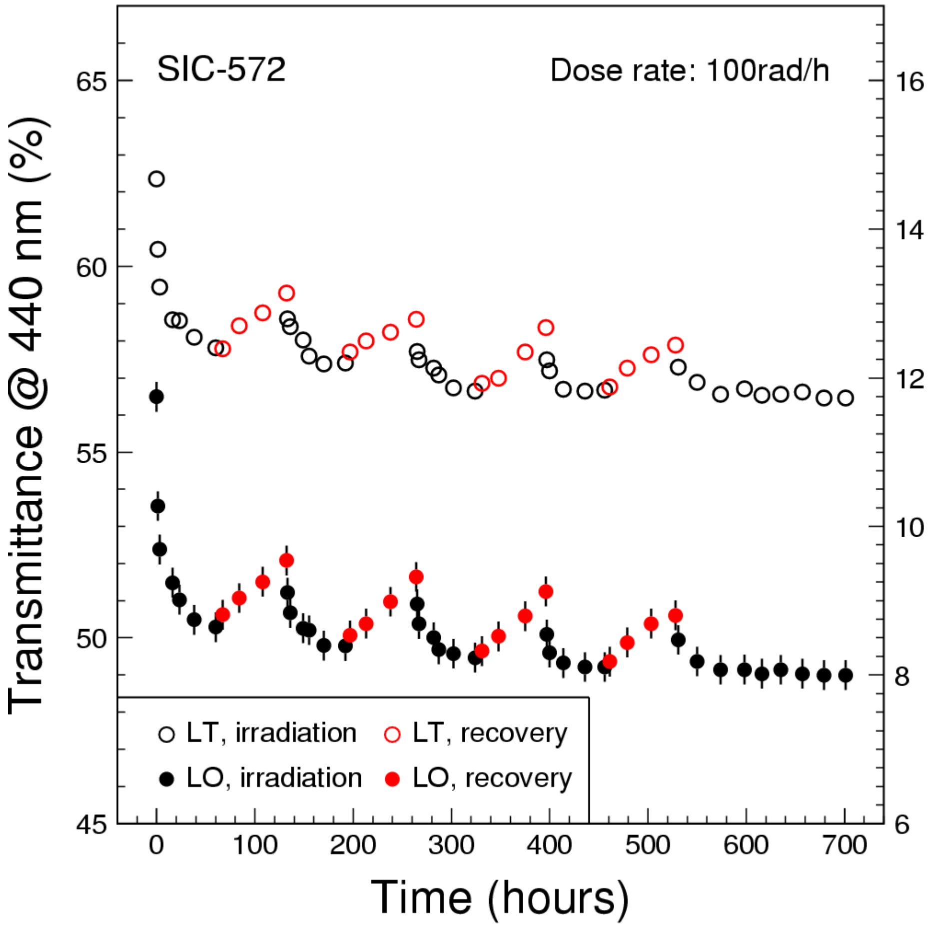
Strong correlation: Slope = 3.31

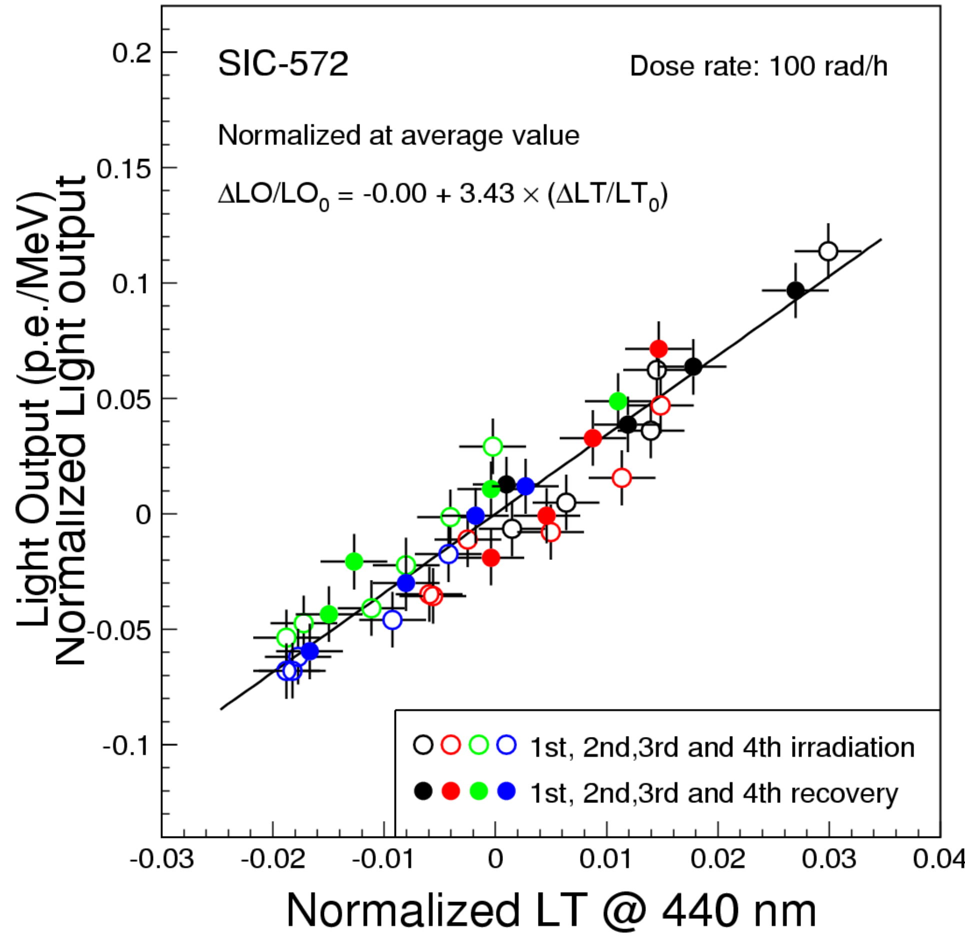




δLO/LO versus δLT/LT @ 100 rad/h

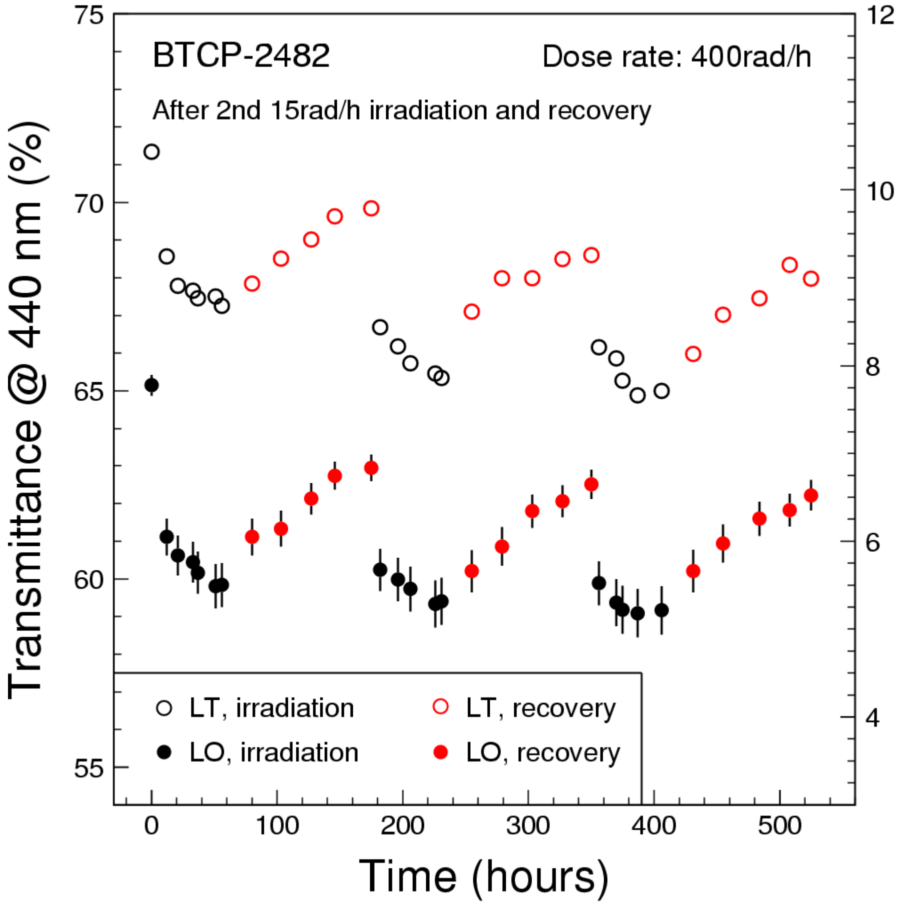
Strong correlation: Slope = 3.43

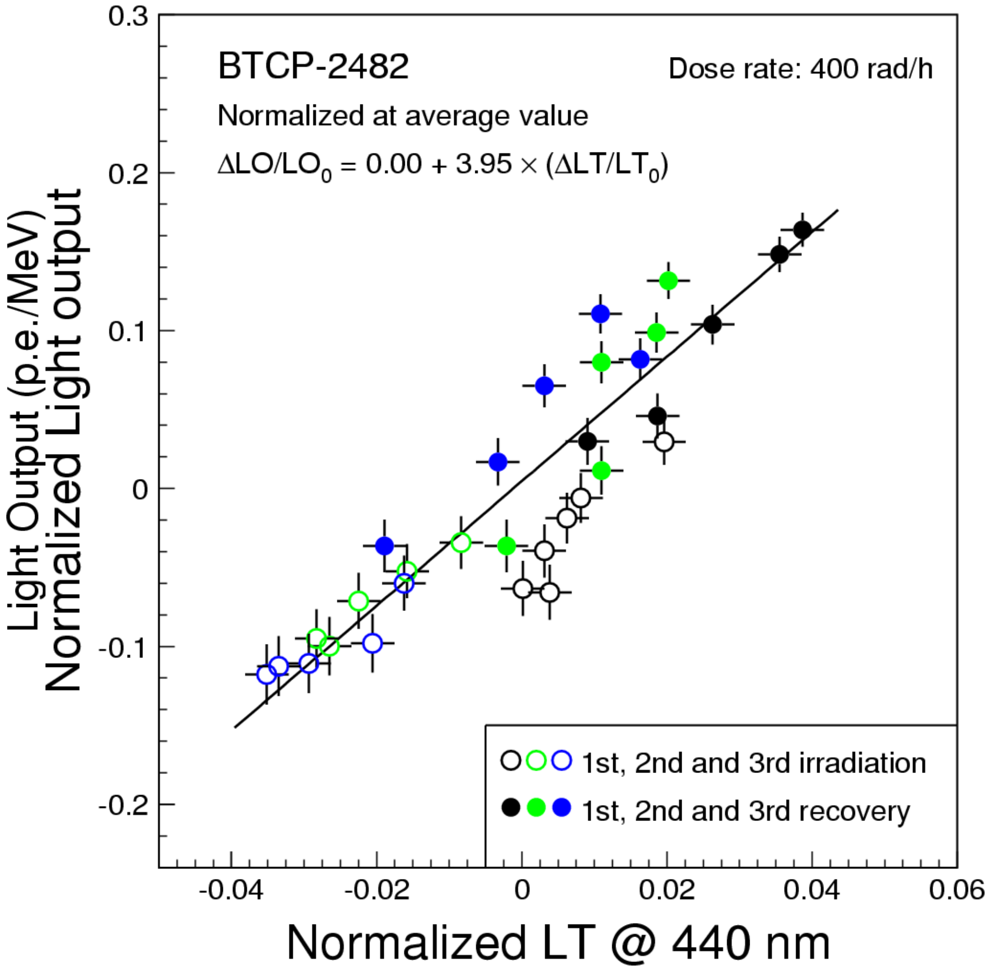




δLO/LO versus δLT/LT @ 400 rad/h

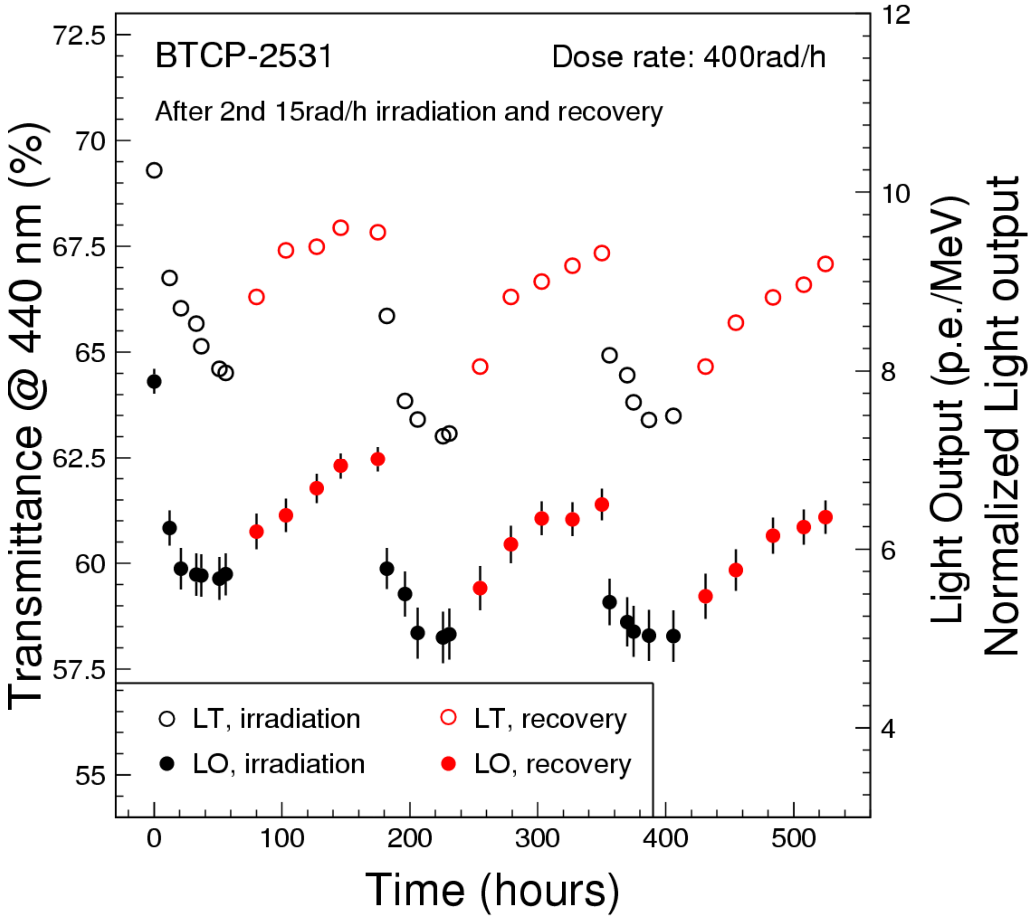
Strong correlation: Slope = 3.95

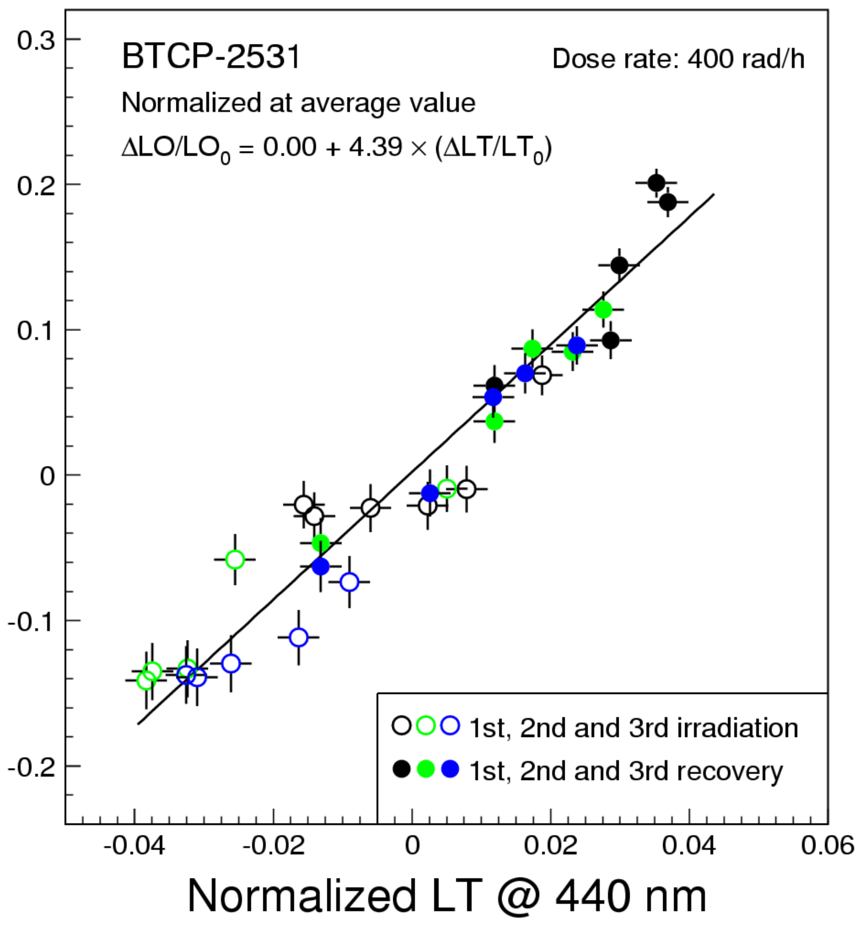




δLO/LO versus δLT/LT @ 400 rad/h

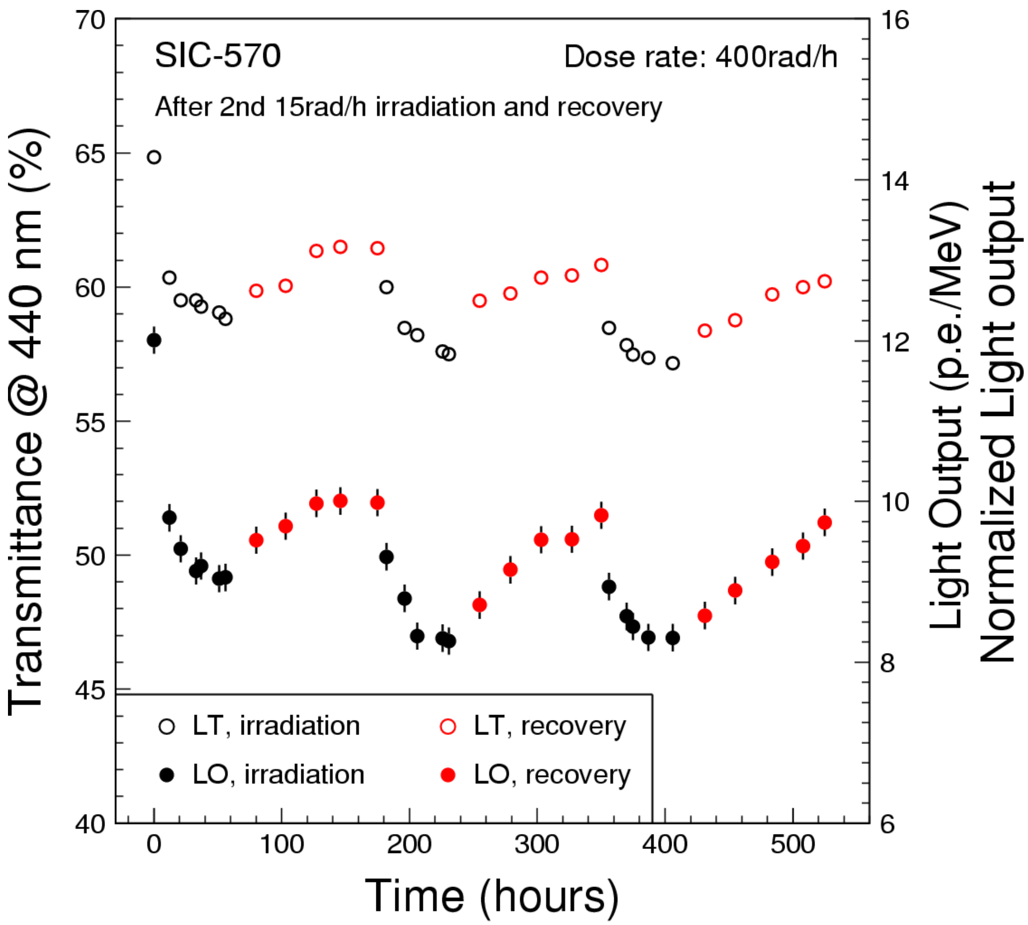
Strong correlation: Slope = 4.39

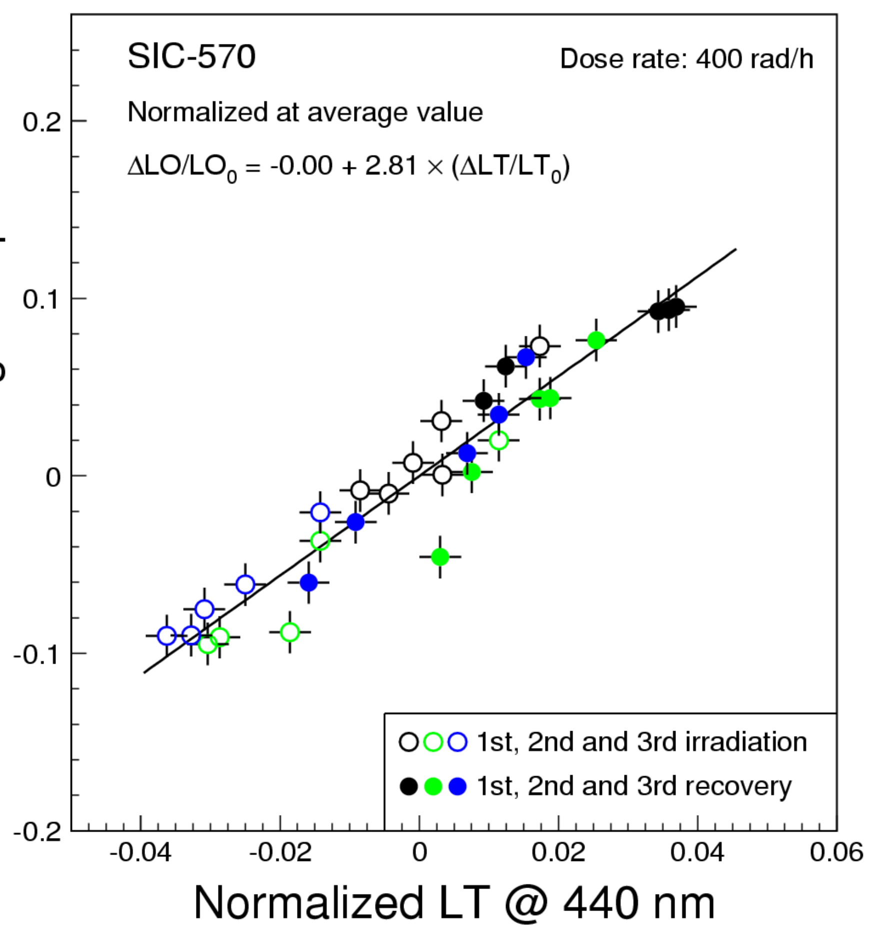




δLO/LO versus δLT/LT @ 400 rad/h

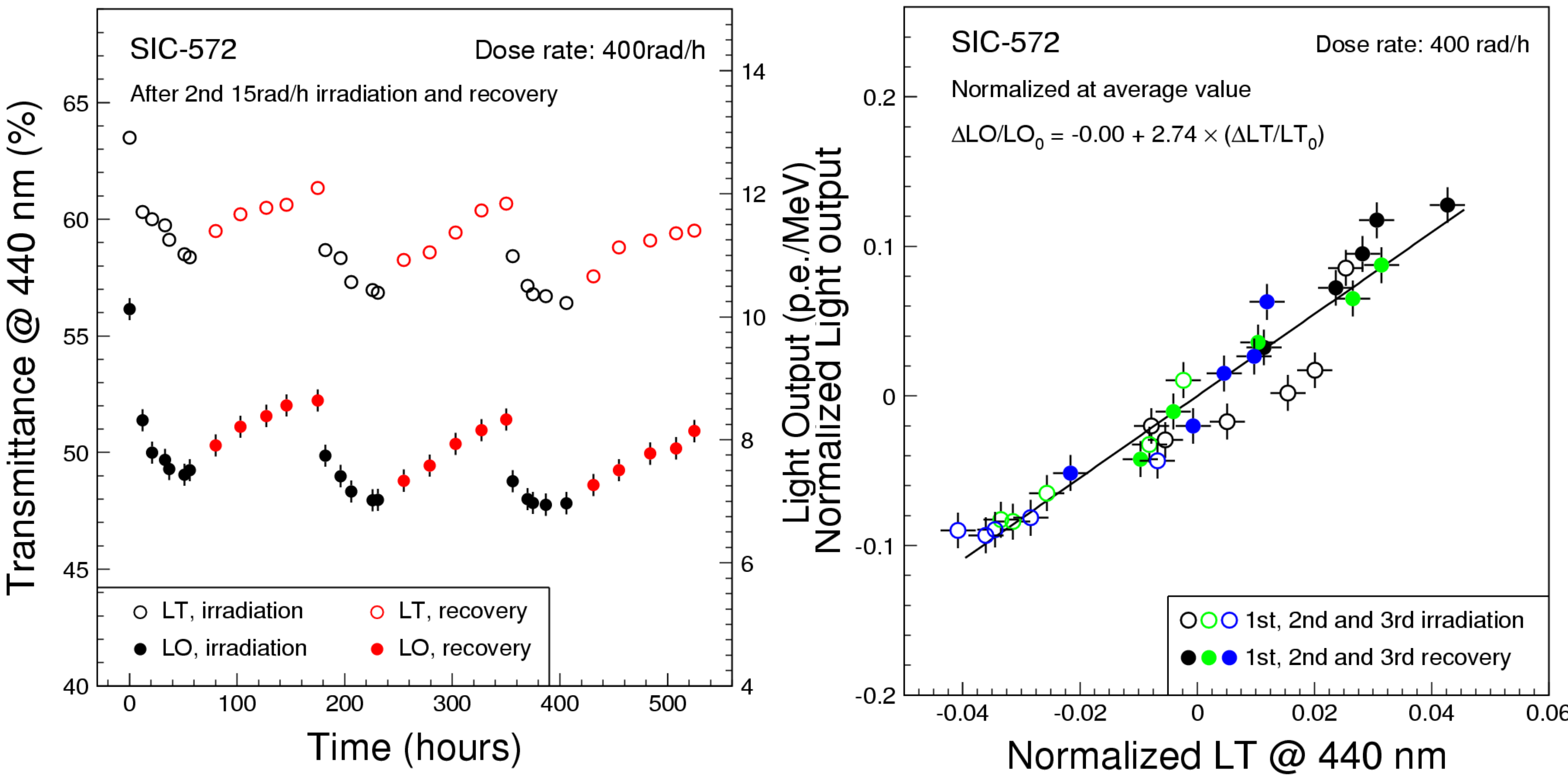
Strong correlation: Slope = 2.81





δLO/LO versus δLT/LT @ 400 rad/h

Strong correlation: Slope = 2.74



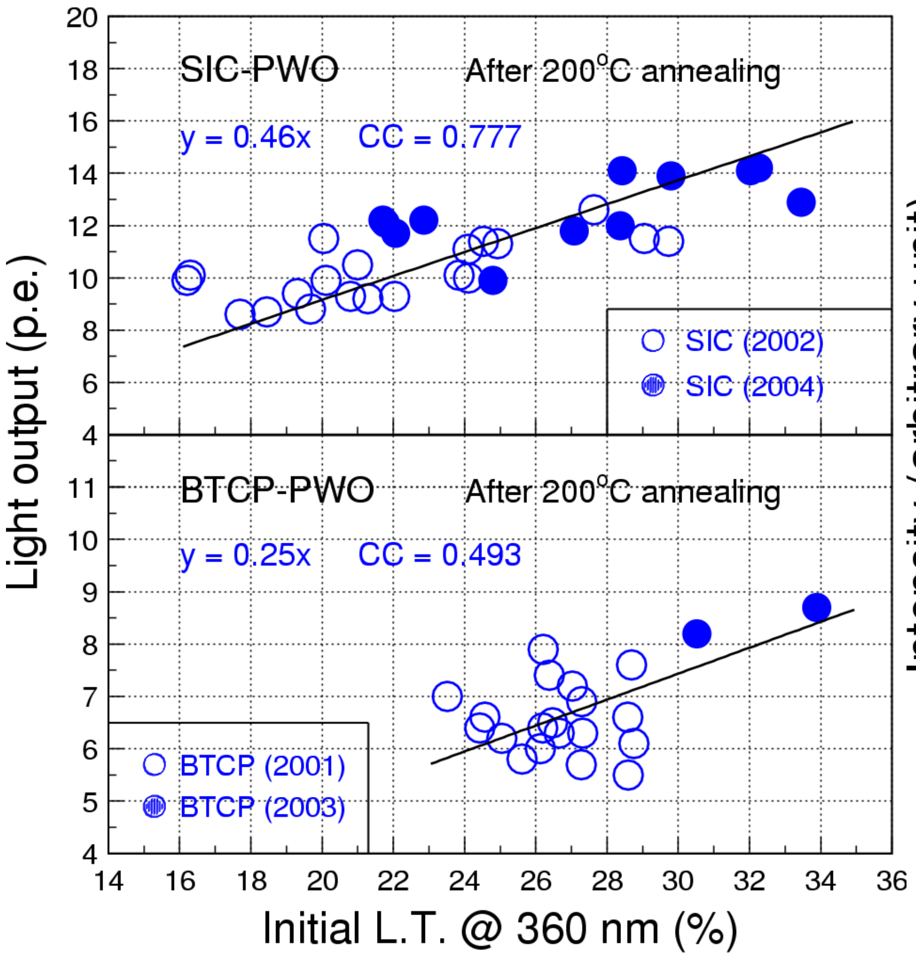
Summary II

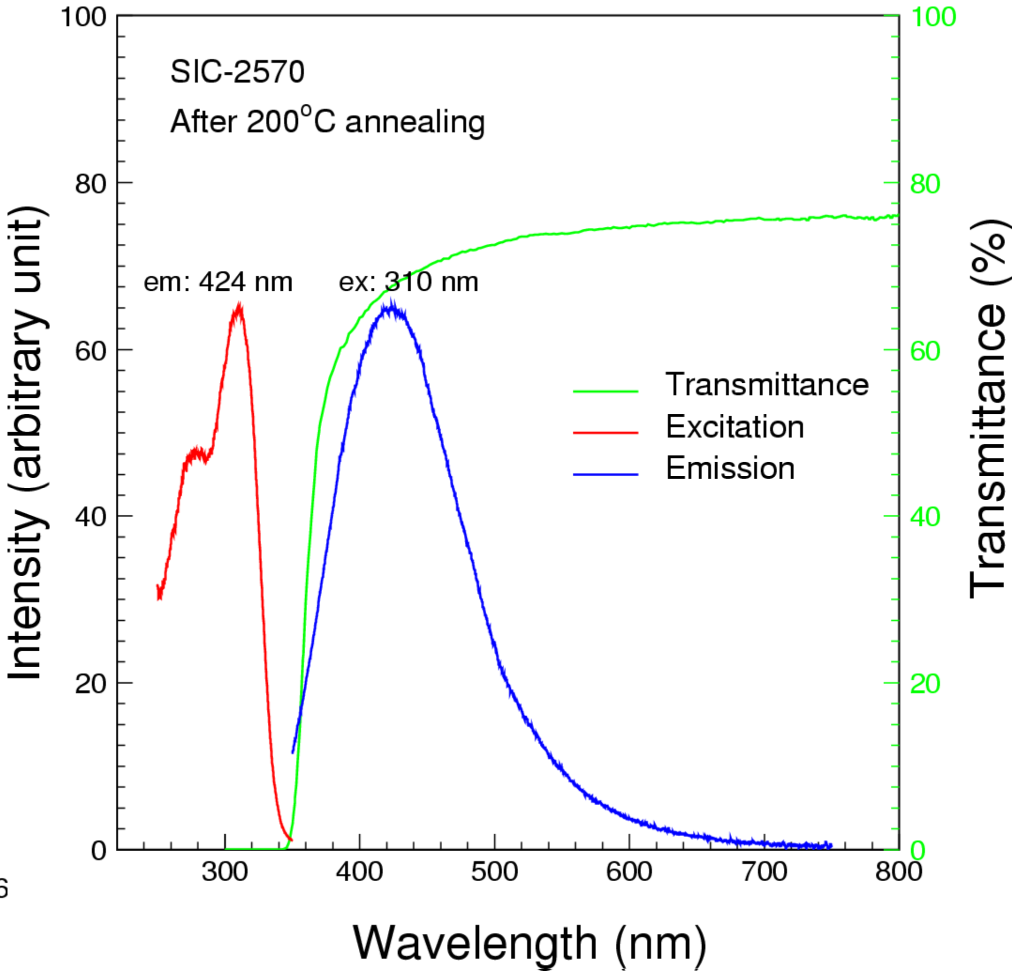
- δLO/LO versus δLT/LT @ 440 nm follow the same slope in multiple damage and recovery cycles, indicating that the LO variation of PWO crystals can be corrected by using the variations of the LT even in a severe radiation environment with dose rate of 400 rad/h.

- The slope of δLO/LO versus δLT/LT @ 440 nm, obtained with a linear fit, however, is damage level dependent, in addition to crystal dependent, indicating a necessity of extracting this parameter from physics calibration data *in situ* at LHC.

Initial LO versus LT @ 360 nm

Correlations observed between Initial LO & initial LT@360 nm: part of emitted light is self-absorbed

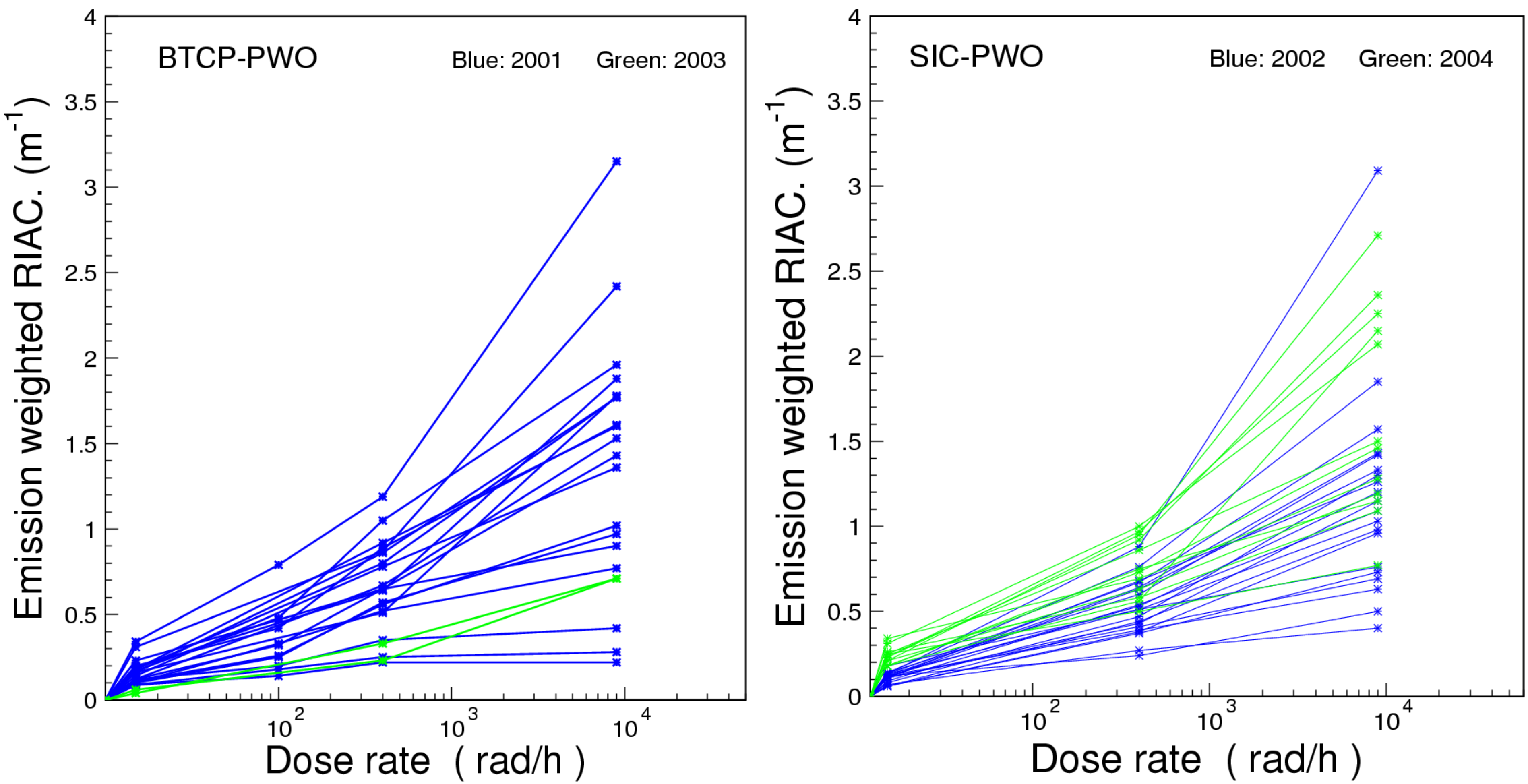




Emission Weighted RIAC

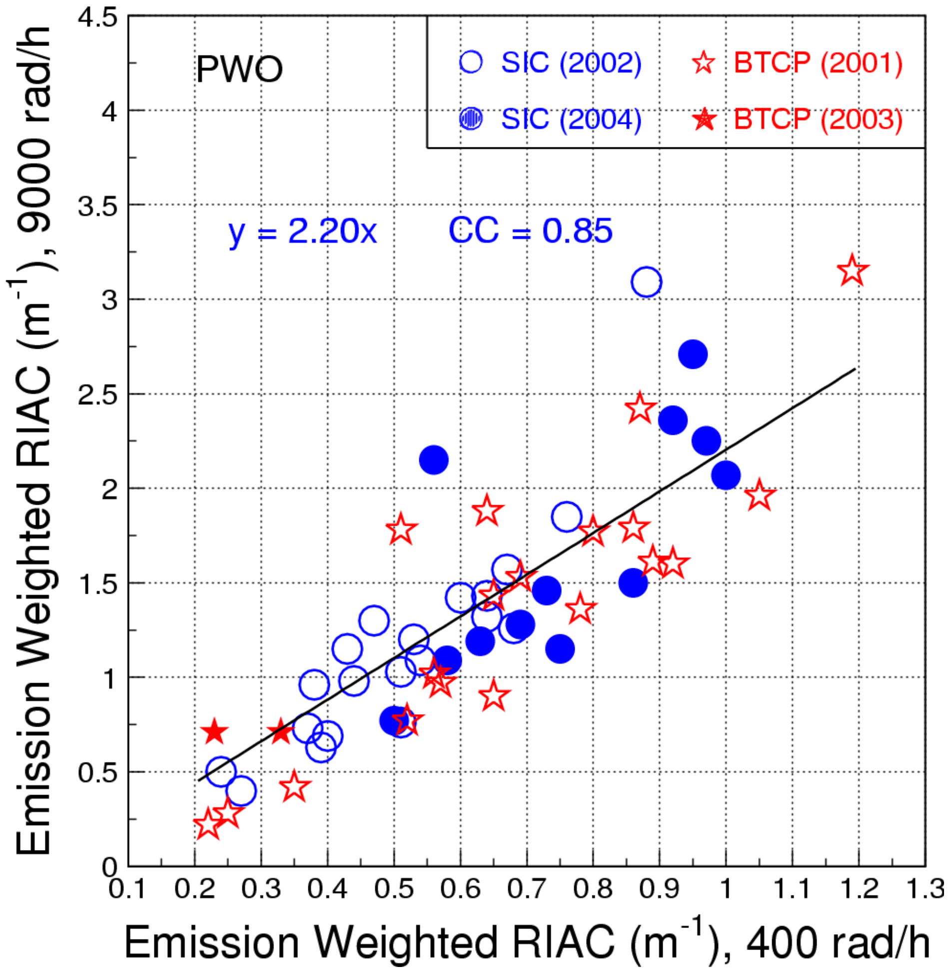
All samples: EWRIAC < 1 m^{-1} up to 400 rad/h

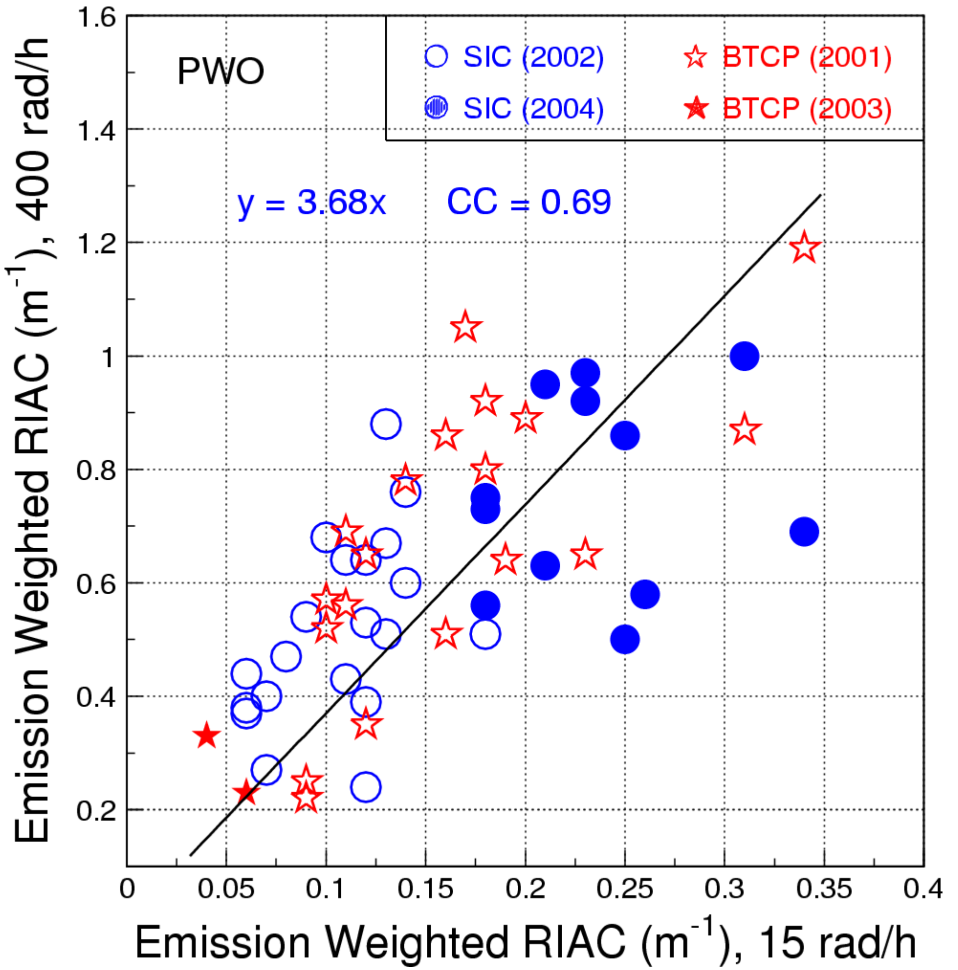
Rigorous QC required to qualify endcap crystals for SLHC



EWRIAC at Different Dose Rates

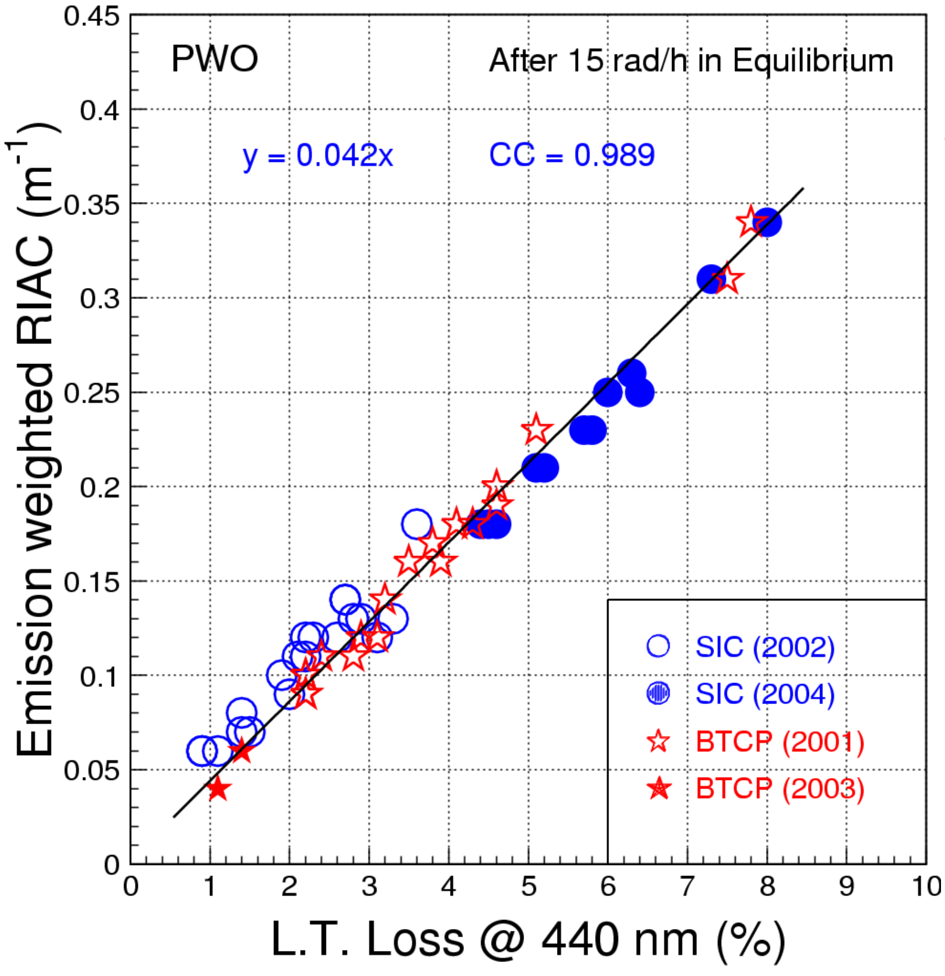
Correlations is weaker at lower dose rates because of different initial status (preexisting absorption)

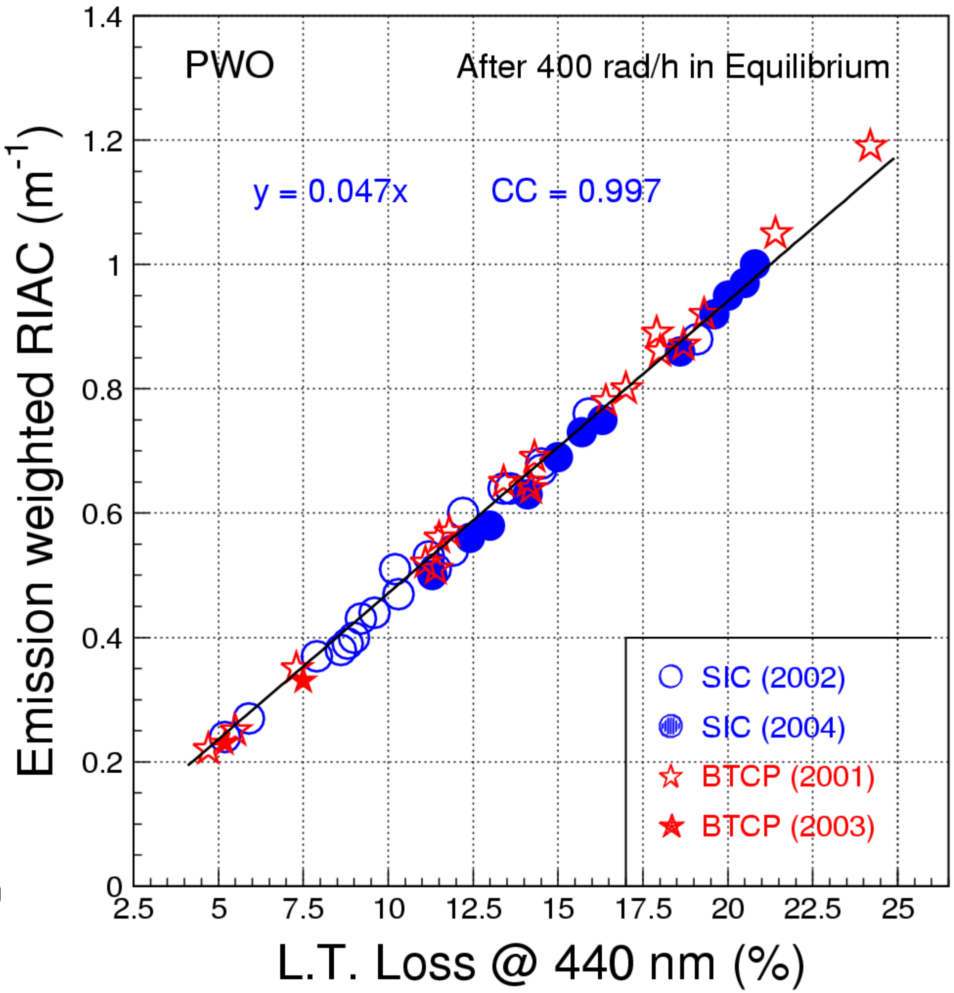




EWRIAC versus δLT/LT

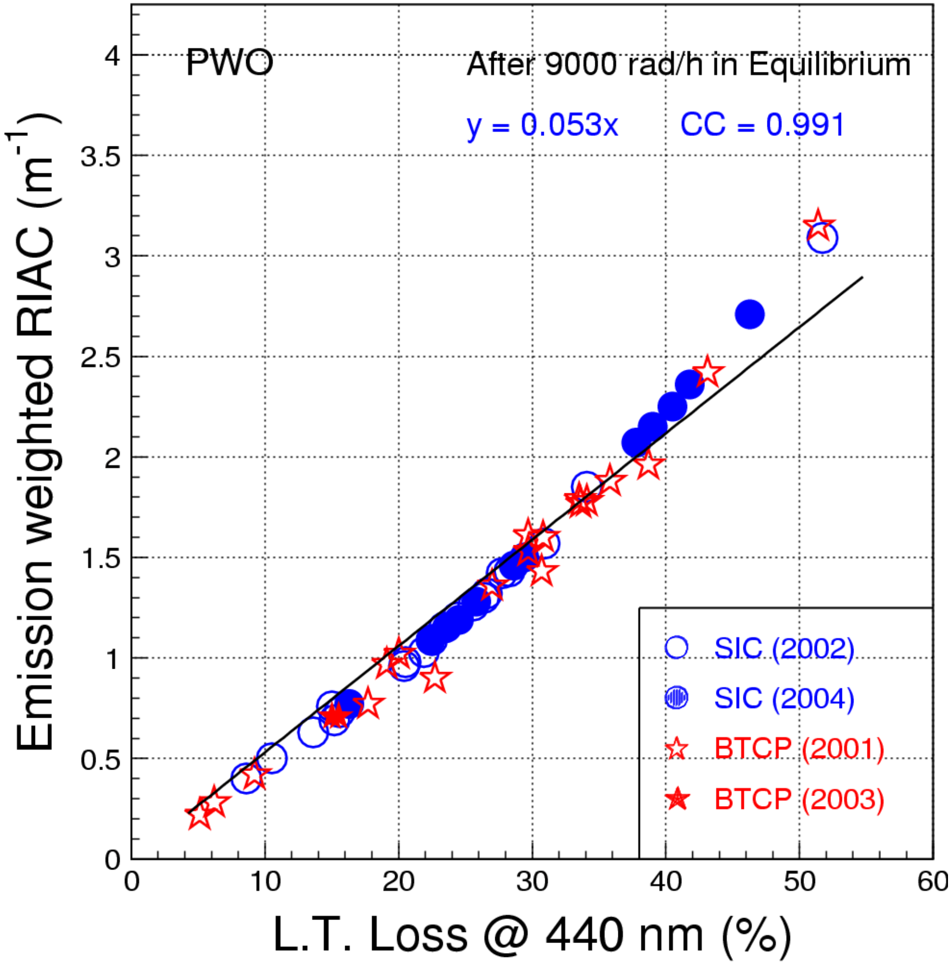
Linear correlation exists between EWRIAC and LT loss @ 440 nm at low dose rate

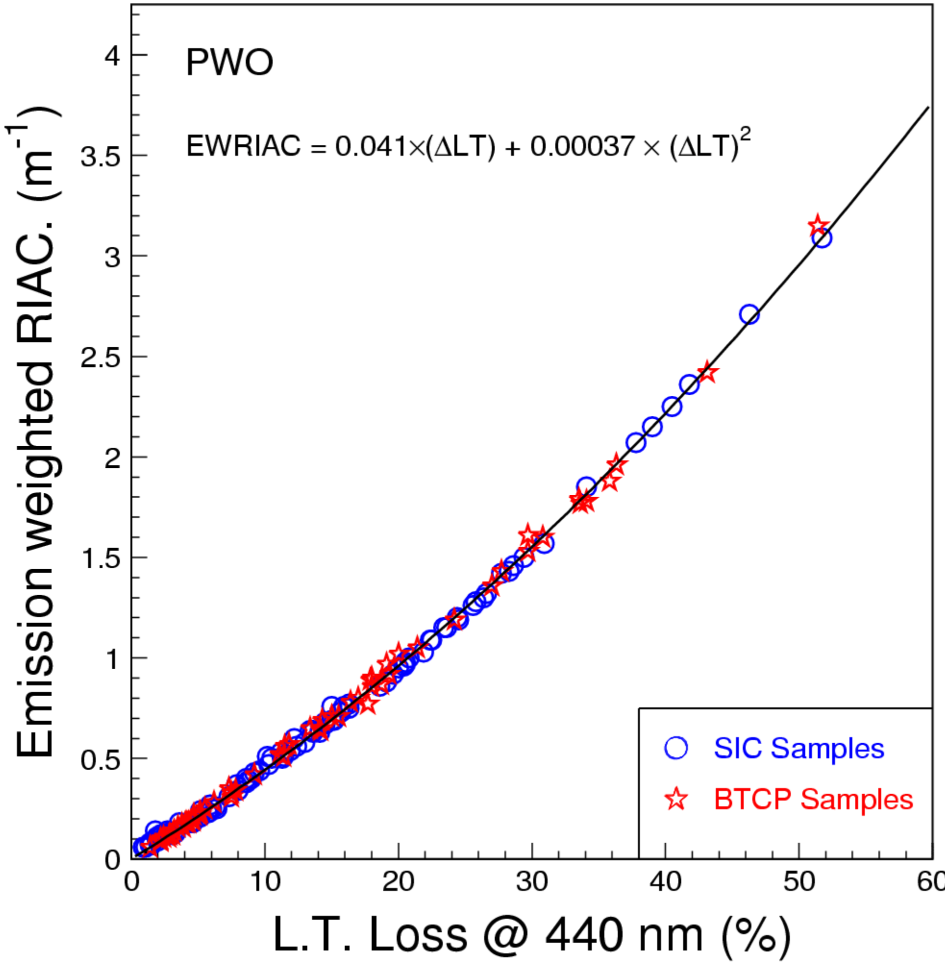




EWRIAC versus δLT/LT

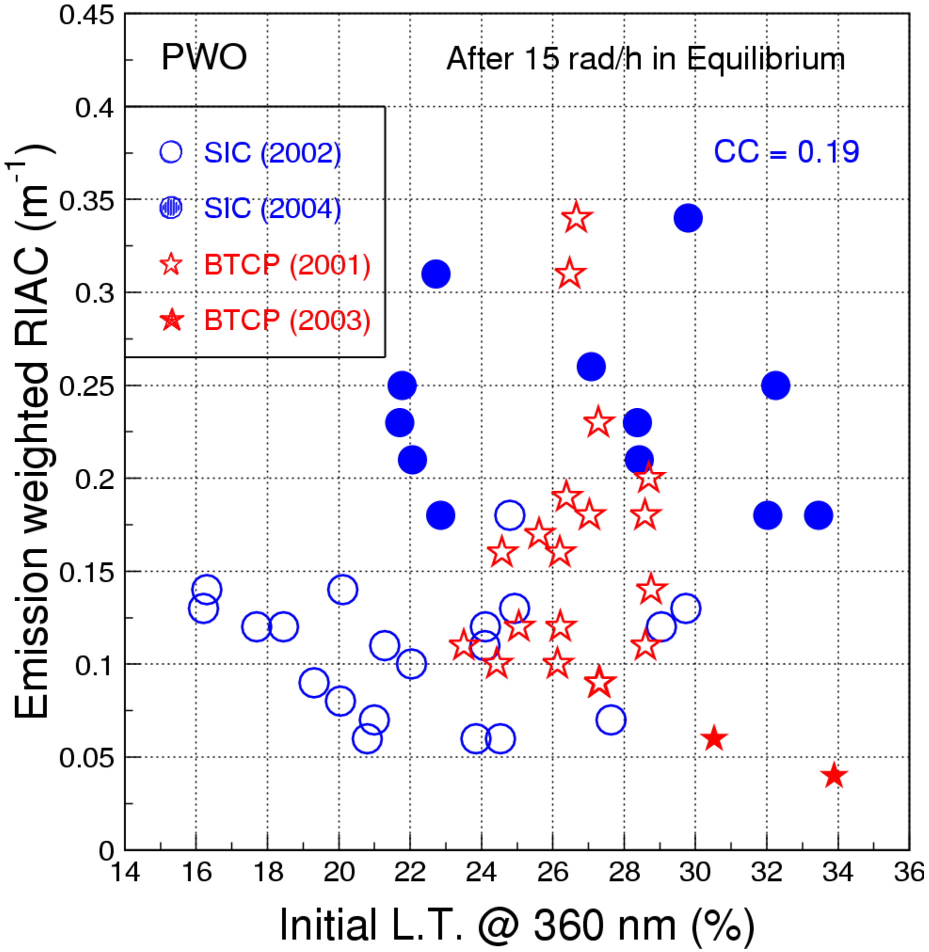
At high dose rate it is no longer linear. All BTCP/SIC data, however, are consistent with a 2^{nd} order polynomial

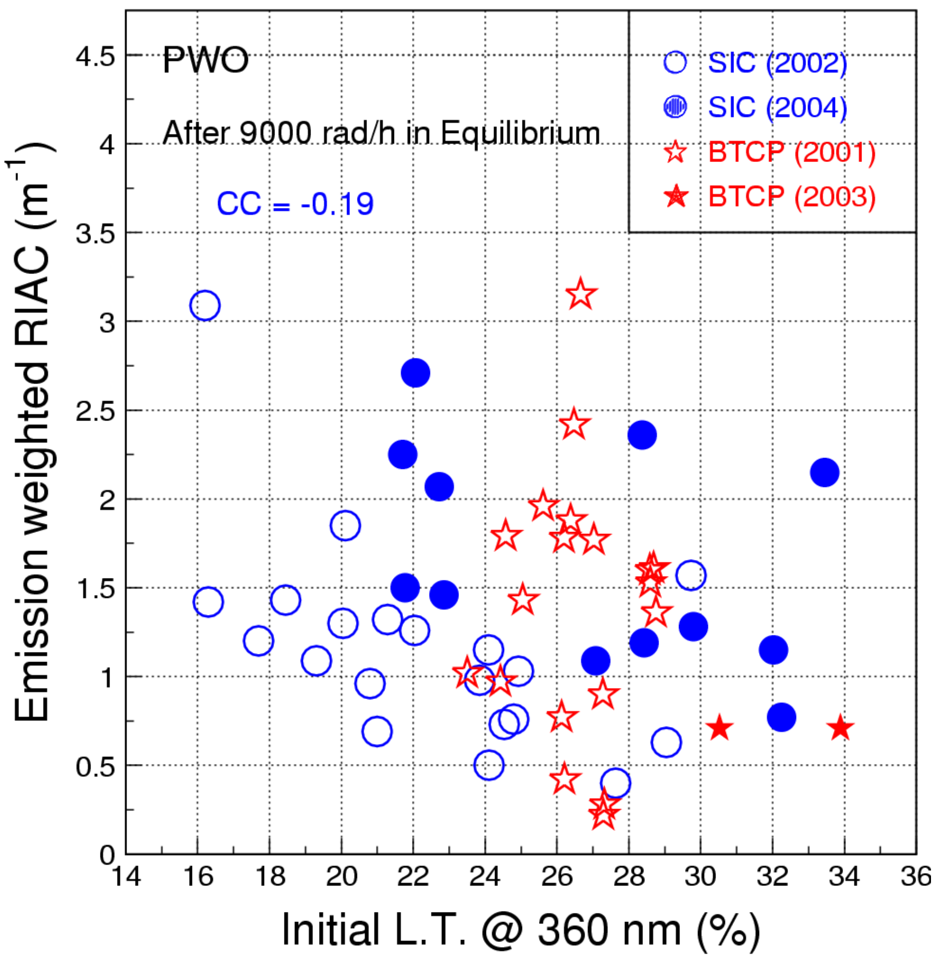




EWRIAC versus Initial LT

No correlation: preexisting absorption is not correlated with radiation induced absorption

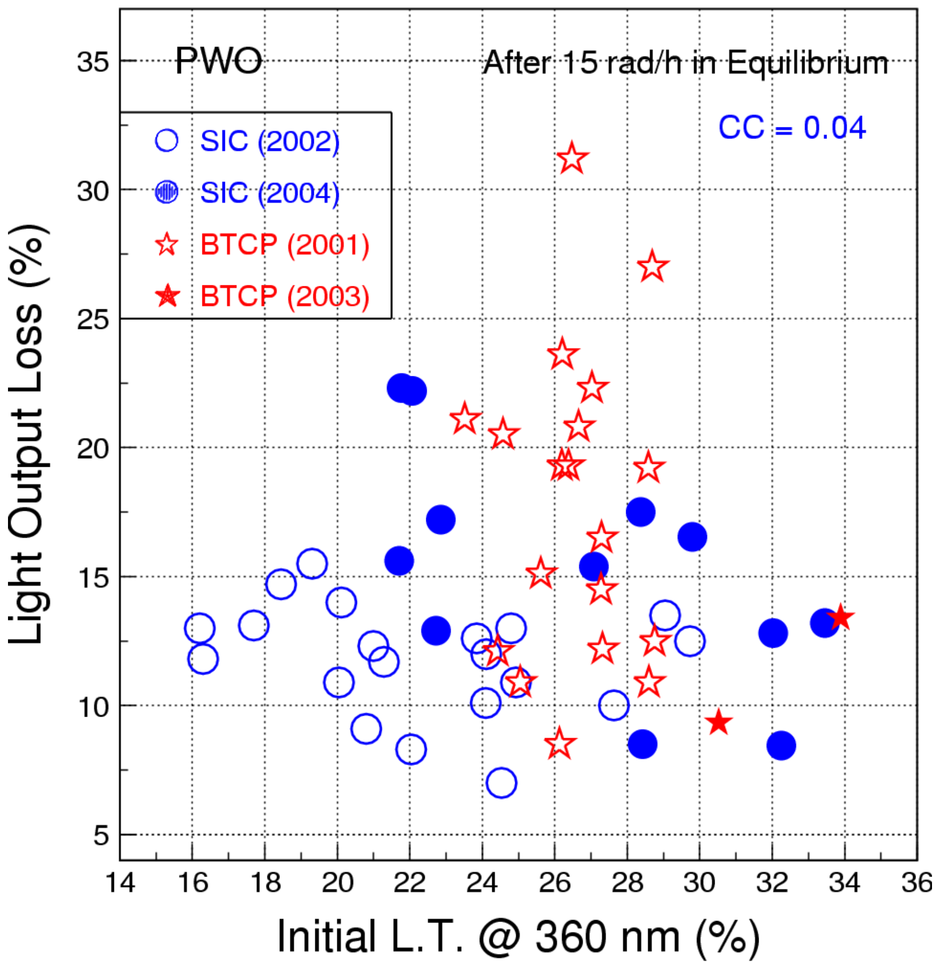


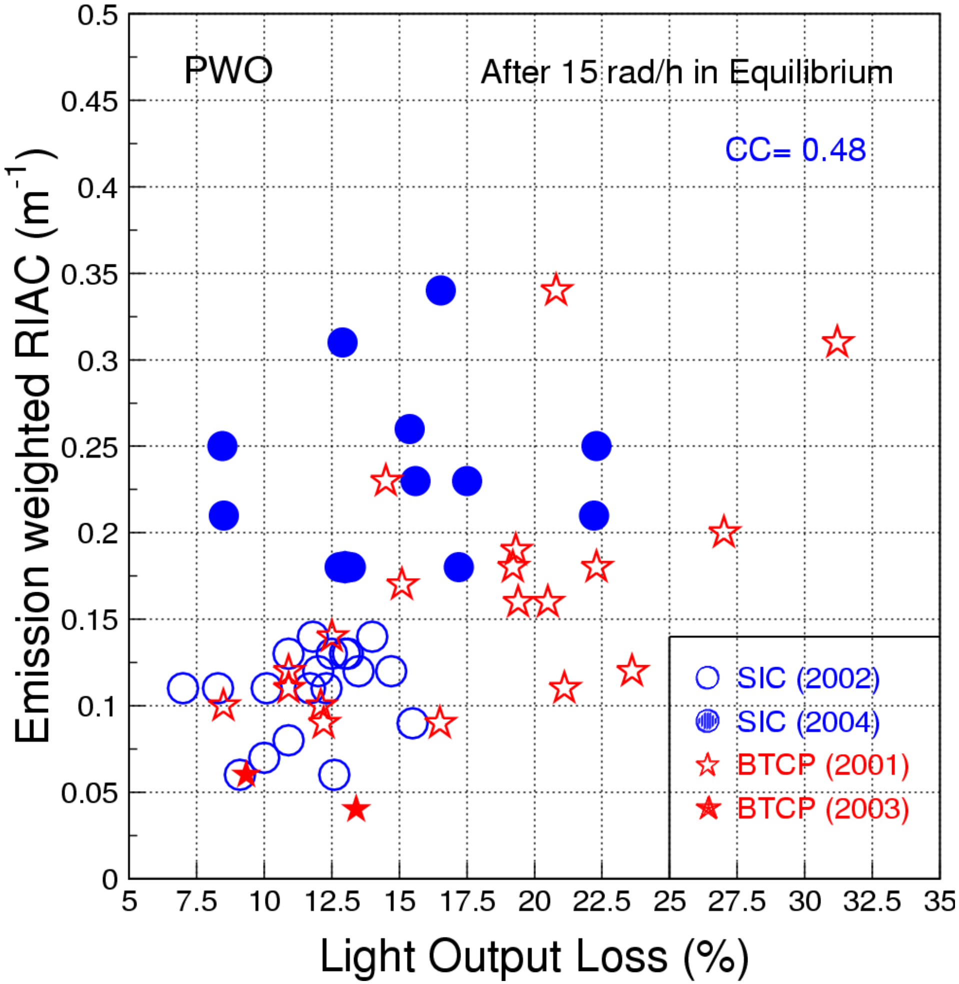


δLO/LO versus Initial LT and EWRIAC

No correlation between δLO/LO and Initial LT

Weak (0.48) correlation between δLO/LO and EWRIAC





Summary III

- 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 2nd order polynomial relation between the EWRIAC and the δLT/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 δLO/LO, indicating no correlation between the preexisting absorption and the radiation induced absorption.