



# Long Term Recovery of Seven PWO Crystals

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# Introduction

- 20 endcap and 5 barrel PWO crystals went through (1) thermal annealing at 200$^{o}$C, (2) irradiations by $\gamma$–ray at 15, 100, 400 and 9k rad/h until equilibrium and (3) short term (300 hours) recovery after 9 krad/h.
- As reported on Mar 25, 2003, 25 PWO crystals belong to three types. While type II crystals are good for the barrel dose rates (15 rad/h) , type I crystals are more radiation hard and good enough for the endcaps (500 rad/h). One type III crystal has problem for monitoring with 440 nm light, so should be rejected. All samples recover after irradiation.
- Two issues discussed during last ECAL week: (1) stability of PWO crystal after 200$^{o}$C thermal annealing, and (2) long term recovery time constant.
- 7 samples (5 type I and 2 type II) went through long term (160 days) recovery test. 15 crystals returned to CERN.

# Thermal Annealing

- Rigorous temperature control both in amplitude and slope:
  - From RT to 200$^{o}$C: 200 minutes;
  - Maintain at 200$^{o}$C: 240 minutes;
  - From 200$^{o}$C to 25$^{o}$C:  400 minutes.
- Crystals are kept in dark at RT (18$^{o}$C) after annealing. The minimum time between annealing and the 1st measurement is **48** hours.
- Question: Does the length of waiting time between the measurement and the end of annealing affect measurement result?

# Summary of Light Output

| Sample ID | L.O. (1/MeV) p.e. | L.O. (1/MeV) photon | Fraction(%) $\frac{50ns}{1\mu s}$ | Fraction(%) $\frac{100ns}{1\mu s}$ | $\Delta t^*$ (hours) | L.O.(%) | 15 rad/h $v^{dam}_{max}$(%/h) | $\tau_d$ (h) |
|---|---|---|---|---|---|---|---|---|
| B2467 | 7.9 | 53.8 | 79.7 | 96.2 | 120 | 76.4 | -6.9 | 3.3 |
| B2466 | 6.9 | 47.6 | 80.9 | 97.1 | 96 | 83.5 | -7.3 | 2.3 |
| B2456 | 6.3 | 43.4 | 77.8 | 93.6 | 240 | 87.8 | -4.8 | 2.3 |
| P7903 | 5.8 | 40.0 | 86.2 | 98.3 | 48 | 95.6 | -0.25 | 15.9 |
| P7654 | 4.8 | 33.1 | 81.3 | 93.9 | 72 | 95.4 | -0.22 | 18.4 |
| P7566 | 5.0 | 34.5 | 88.0 | 98.0 | 96 | 97.4 | -0.09 | 20.7 |
| P7557 | 4.8 | 33.1 | 89.6 | 97.9 | 120 | 94.0 | -0.35 | 17.3 |
| P7467 | 5.7 | 39.3 | 85.9 | 98.2 | 144 | 88.8 | -0.70 | 15.7 |
| B2464 | 7.6 | 52.4 | 81.8 | 97.4 | 48 | 73.0 | -6.6 | 3.9 |
| B2458 | 7.0 | 48.3 | 81.1 | 95.6 | 288 | 78.9 | -3.7 | 5.7 |
| B2457 | 6.4 | 44.1 | 81.2 | 95.3 | 264 | 87.9 | -3.9 | 2.6 |
| B2455 | 5.7 | 39.3 | 79.7 | 95.3 | 216 | 85.5 | -7.2 | 1.94 |
| B2436 | 6.3 | 43.4 | 79.7 | 95.3 | 864 | 79.2 | -3.6 | 5.5 |
| B2434 | 6.2 | 42.8 | 80.9 | 96.8 | 840 | 89.1 | -1.4 | 7.0 |
| B2433 | 6.0 | 41.4 | 81.7 | 96.7 | 816 | 91.5 | -1.3 | 6.1 |
| B2432 | 5.8 | 40.0 | 83.1 | 96.6 | 792 | 84.9 | -1.9 | 7.6 |
| B2409 | 5.5 | 37.9 | 88.7 | 98.2 | 1152 | 89.1 | -0.88 | 11.4 |
| B2408 | 6.6 | 45.5 | 83.6 | 97.0 | 1128 | 80.8 | -1.8 | 10.3 |
| B2407 | 6.1 | 42.1 | 83.1 | 96.9 | 1104 | 87.5 | -1.2 | 10.4 |
| B2406 | 6.6 | 45.5 | 82.9 | 97.1 | 1080 | 79.5 | -3.3 | 5.8 |
| B2382 | 6.5 | 44.8 | 84.8 | 93.9 | 1416 | 68.8 | -3.5 | 8.7 |
| B2381 | 7.2 | 49.7 | 86.8 | 93.4 | 1392 | 77.7 | -1.8 | 11.9 |
| B2376 | 7.4 | 51.0 | 80.0 | 94.7 | 1368 | 80.7 | -1.6 | 11.6 |
| B2375 | 6.1 | 42.1 | 73.4 | 92.2 | 1344 | 80.6 | -2.1 | 8.9 |
| B2465 | 5.4 | 37.2 | 84.9 | 96.2 | 72 | 94.9 | — | — |

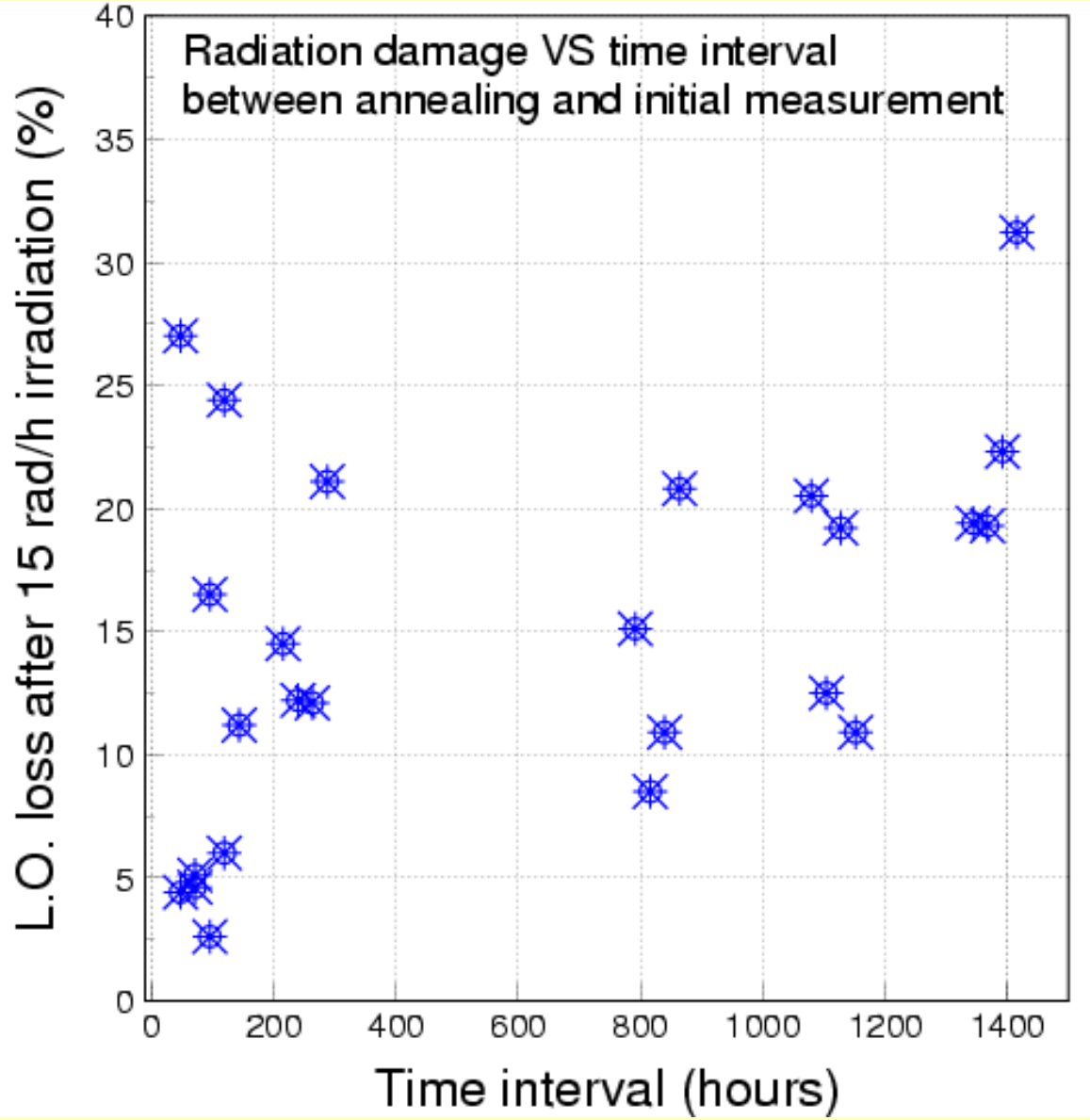
∗ time interval between annealing and initial measurement.

Type I: 5–20% loss @15 rad/h

Type II: 10–25% loss @15 rad/h

Waiting time: at least 48h

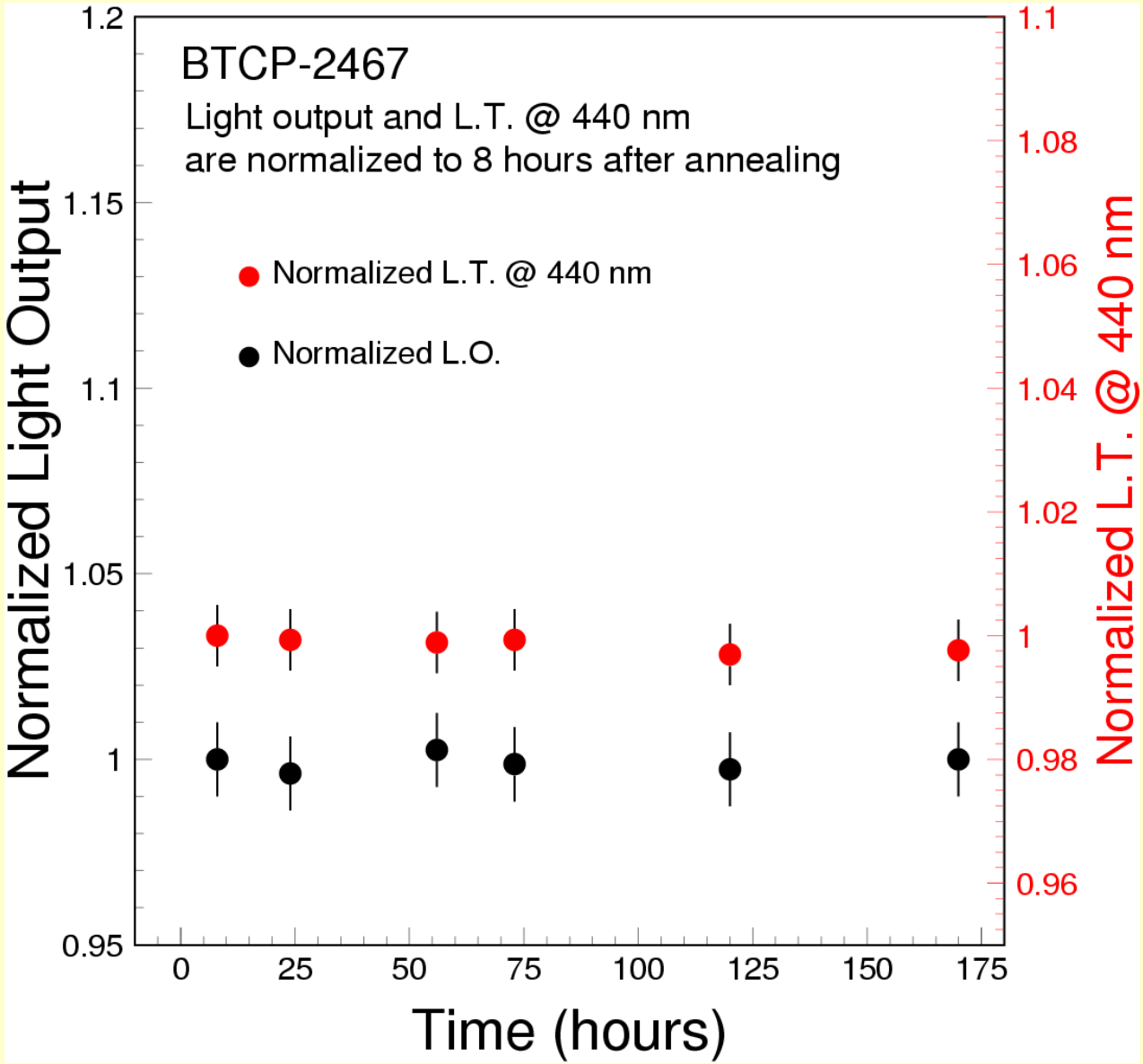
# LO loss versus Waiting Time



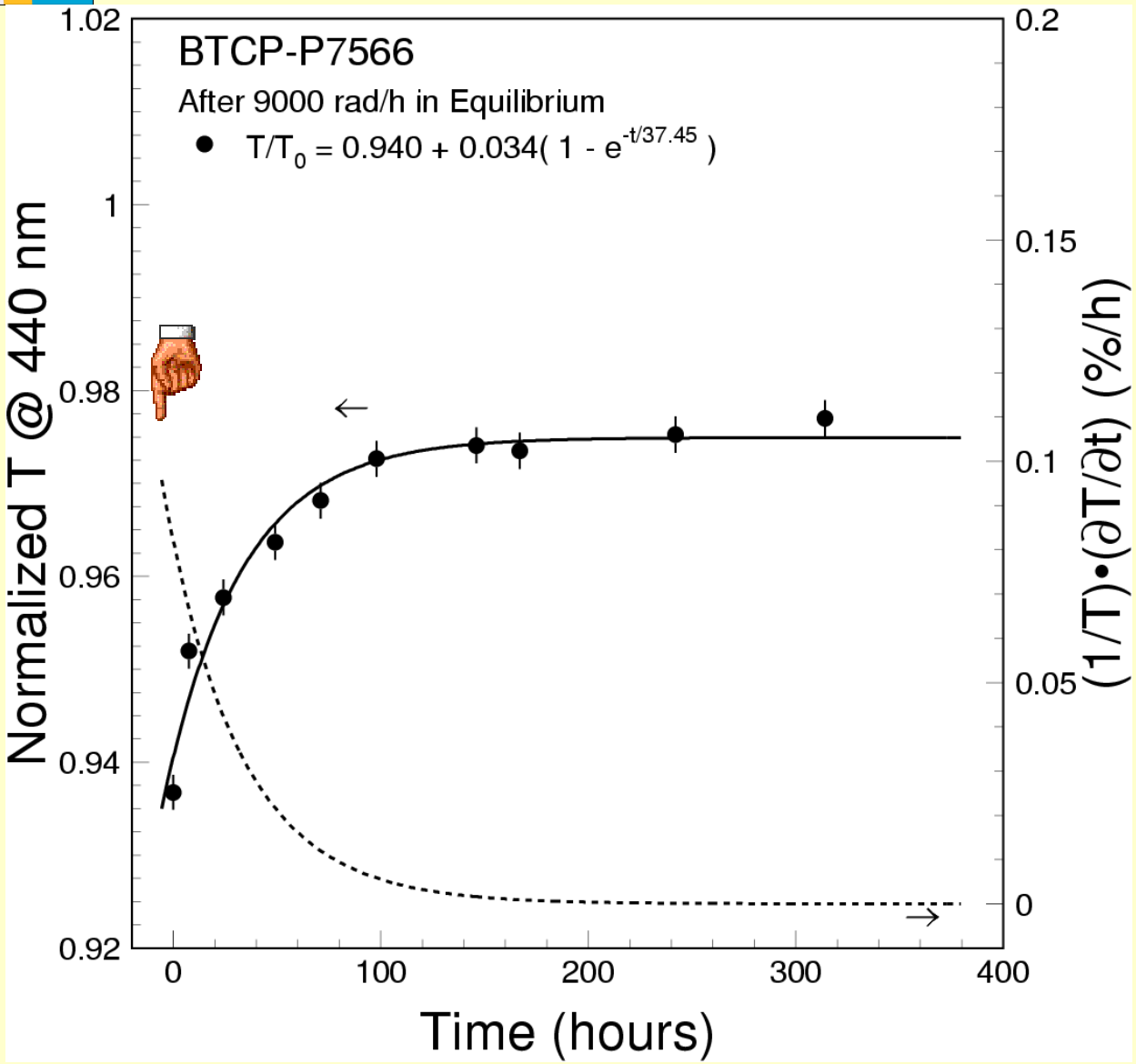

No Correlation between the LO loss and the time between the ending of the thermal annealing and the start of the initial 1st measurement.

# PWO Stable after Annealing

No variations in either light output or longitudinal transmittance was observed 8 hours after the thermal annealing procedure.



# Longitudinal Transmittance Recovery




Short Term (two weeks) Recovery

ECAL monitoring takes 30 minutes to cover entire calorimeter *in situ*.

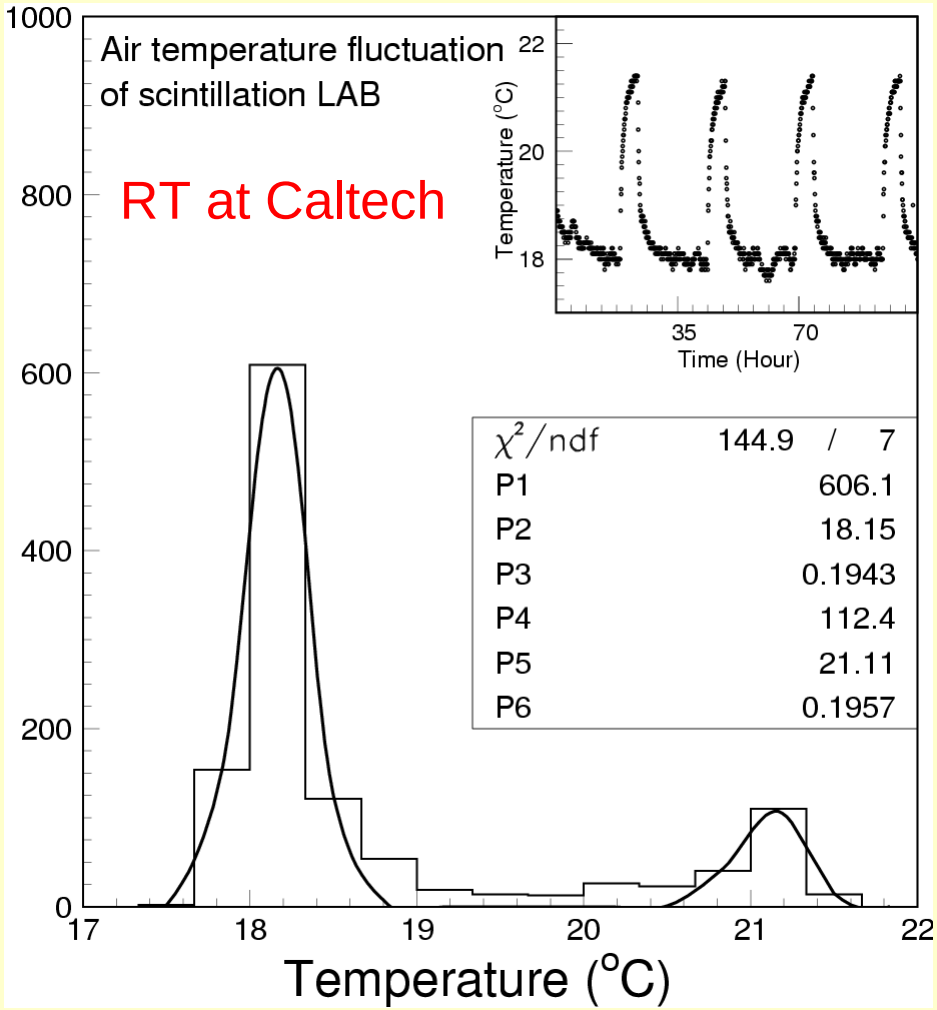
The maximum recovery speed and time constant are measures of the monitor-ability of the crystal.

# Summary: Short Term LT Recovery

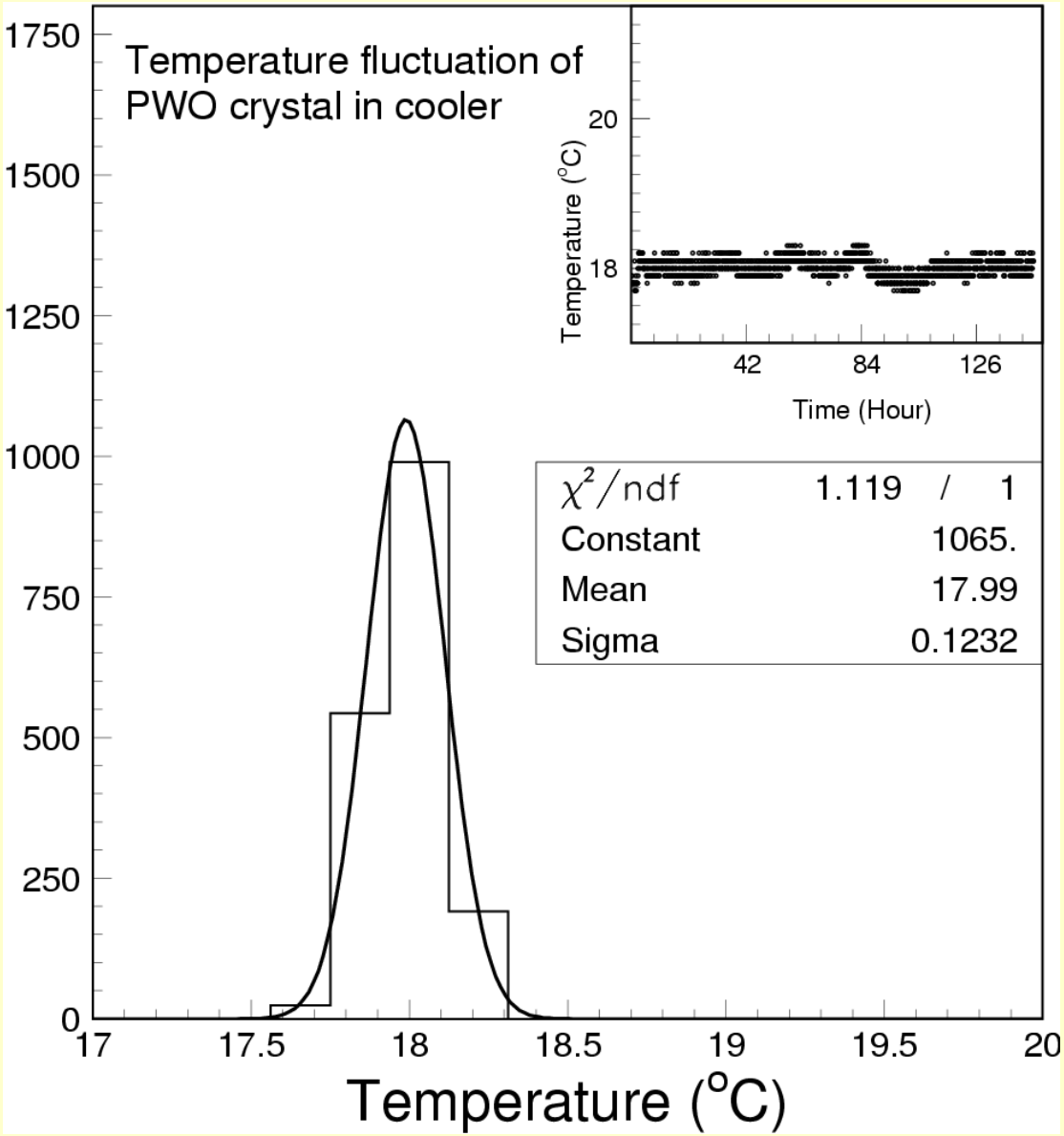
| ID | ΔT (%) | $F_{rec}$ (%) | $v_{rec}^{max}$ (%/h) | $\tau_{rec}$ (h) |
|---|---|---|---|---|
| B2467 | 9.4 | 50.0 | 0.09 | 52.6 |
| B2466* | 5.8 | 60.3 | 0.16 | 22.8 |
| B2456 | 6.4 | 54.7 | 0.07 | 47.5 |
| P7903 | 6.5 | 47.7 | 0.10 | 32.6 |
| P7654 | 8.4 | 35.7 | 0.09 | 37.1 |
| P7566 | 6.0 | 56.7 | 0.09 | 37.5 |
| P7557 | 6.5 | 50.8 | 0.06 | 51.9 |
| P7467 | 7.0 | 52.9 | 0.07 | 59.9 |
| B2464 | 29.3 | 52.2 | 0.83 | 25.9 |
| B2458 | 19.8 | 57.1 | 0.40 | 35.0 |
| B2457 | 18.9 | 52.4 | 0.41 | 30.1 |
| B2455 | 22.7 | 35.6 | 0.36 | 26.5 |
| B2436 | 51.0 | 38.4 | 0.96 | 41.5 |
| B2434 | 30.1 | 53.8 | 0.75 | 31.0 |
| B2433 | 17.6 | 57.9 | 0.95 | 29.5 |
| B2432 | 38.1 | 49.1 | 0.95 | 31.9 |
| B2409 | 29.0 | 40.7 | 0.38 | 43.8 |
| B2408 | 30.2 | 46.4 | 0.51 | 39.2 |
| B2407 | 26.5 | 47.6 | 0.49 | 34.4 |
| B2406 | 33.0 | 33.2 | 0.54 | 31.1 |
| B2382 | 42.9 | 48.7 | 0.85 | 42.8 |
| B2381 | 33.3 | 47.1 | 0.71 | 33.1 |
| B2376 | 35.5 | 43.9 | 0.79 | 30.5 |
| B2375 | 33.9 | 42.8 | 0.69 | 31.7 |

* Recovery from 35,000 rad/h, all others from 9 krad/h

All samples recover !!!

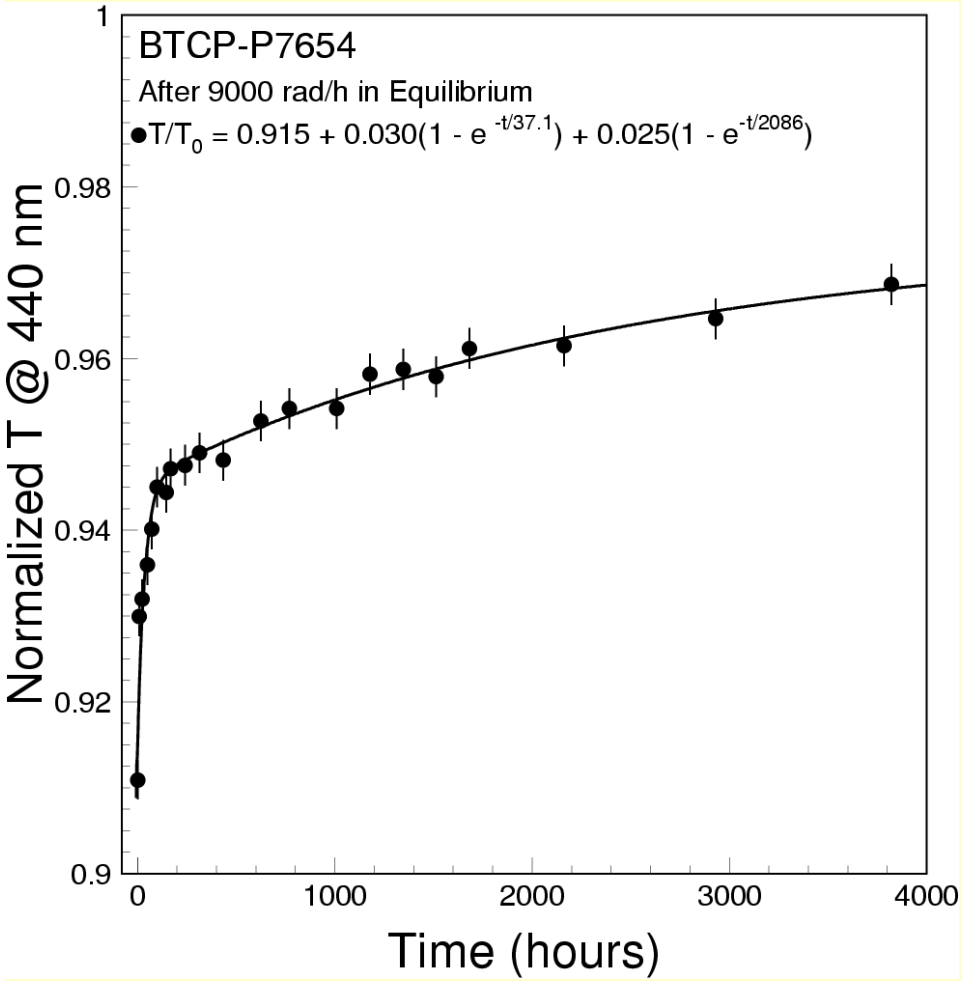


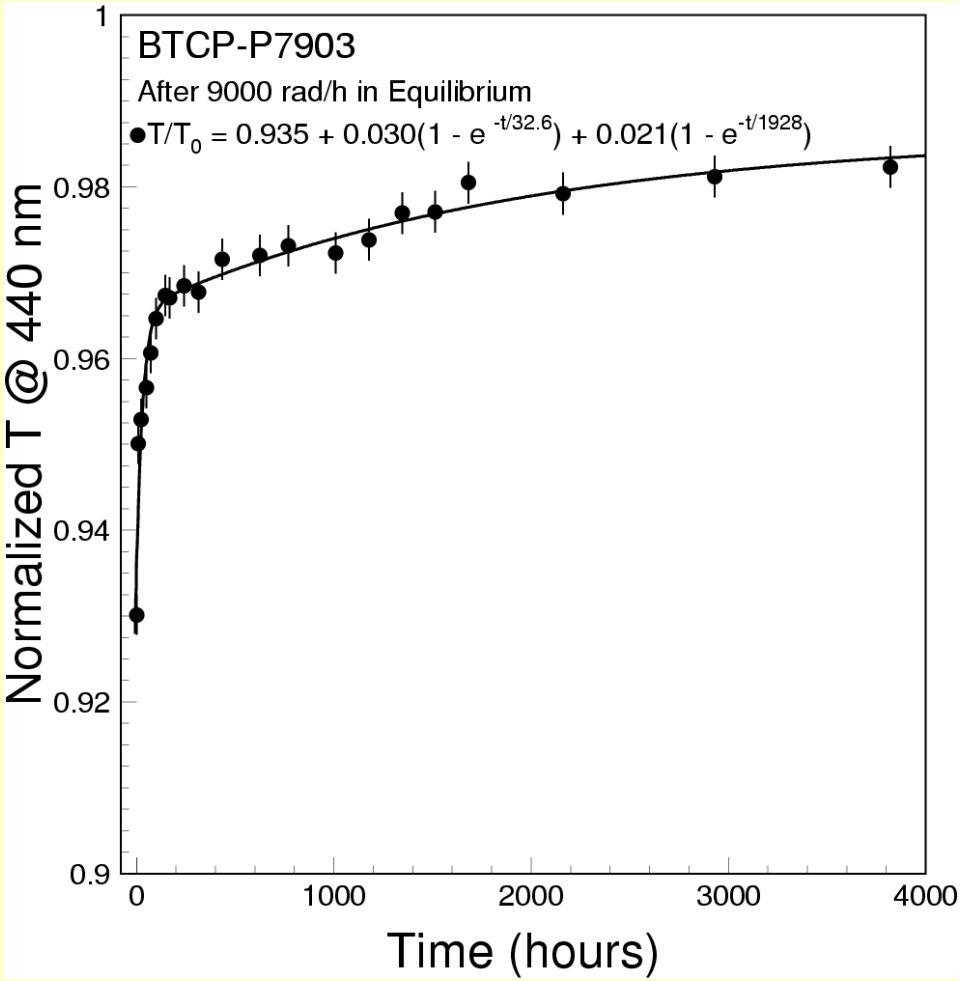
# Long Term Recovery under 18°C




Two type II samples, B2375, and B2376, and five type I samples went through a long term recovery test for 160 days. Since February, they are stored in a cooler, which keeps temperature at 18°C with 0.1°C precision.

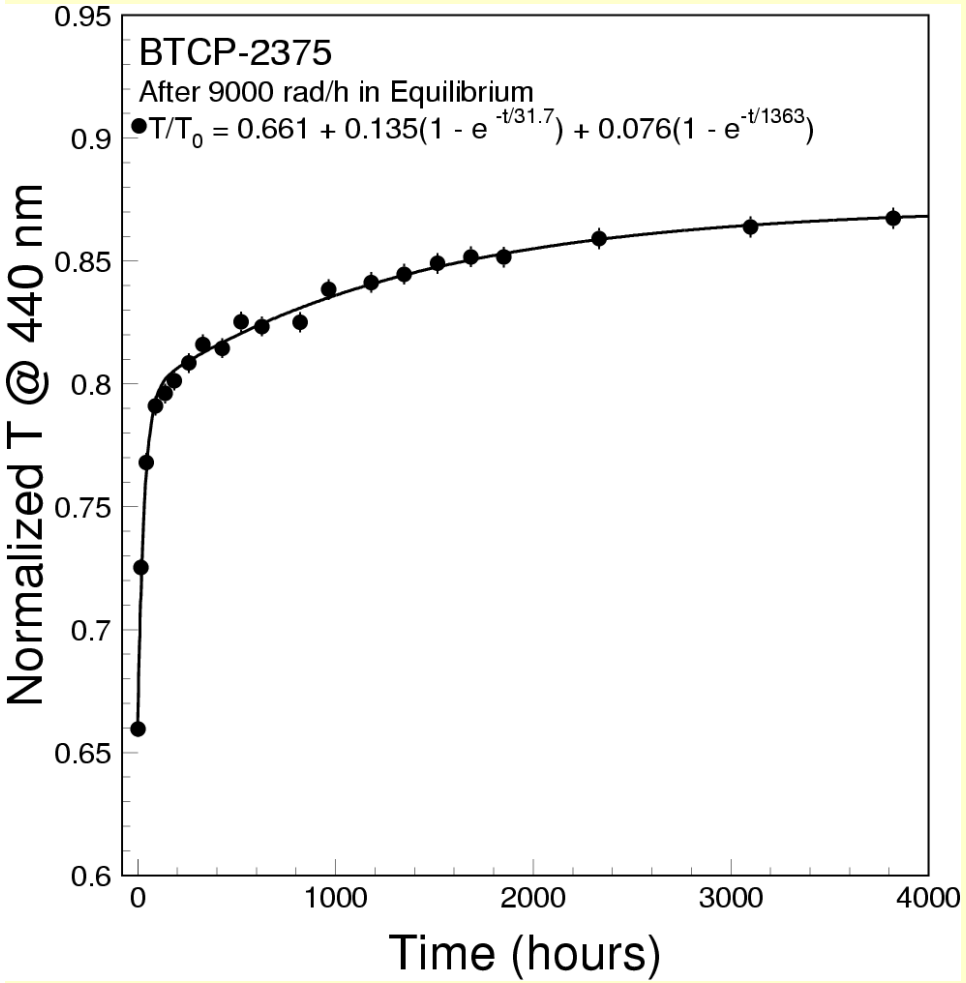
# LT Recovery: Type I

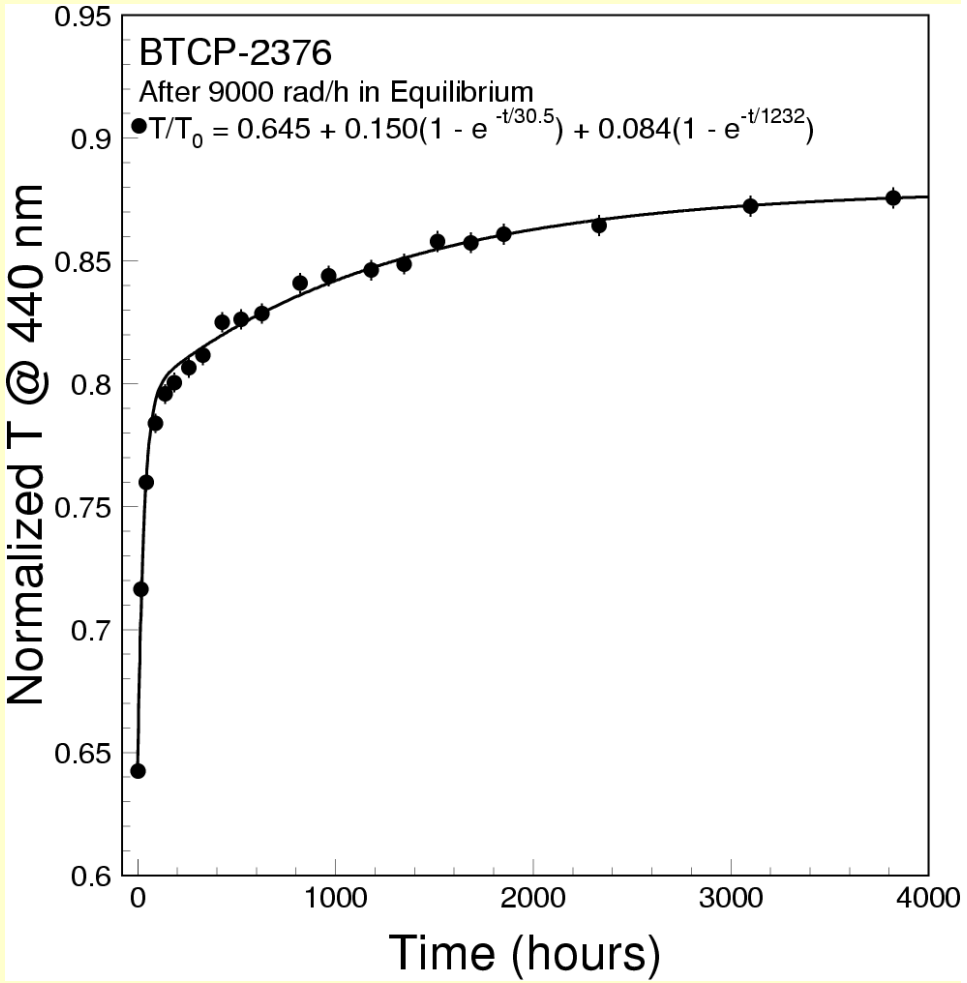



Small Damage and 2 Time Constants: ~40 h and ~1,950 h

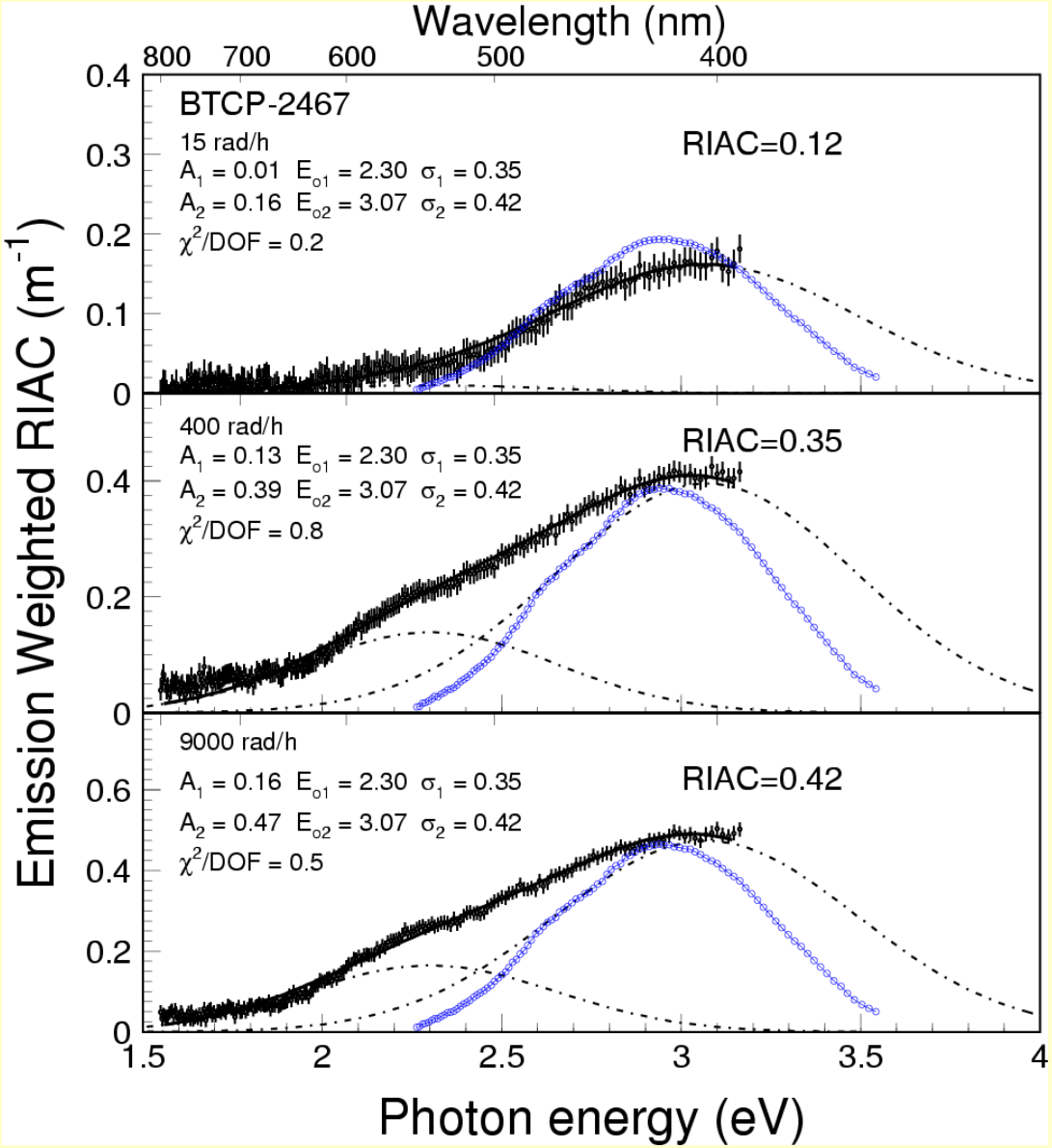
# LT Recovery: Type II



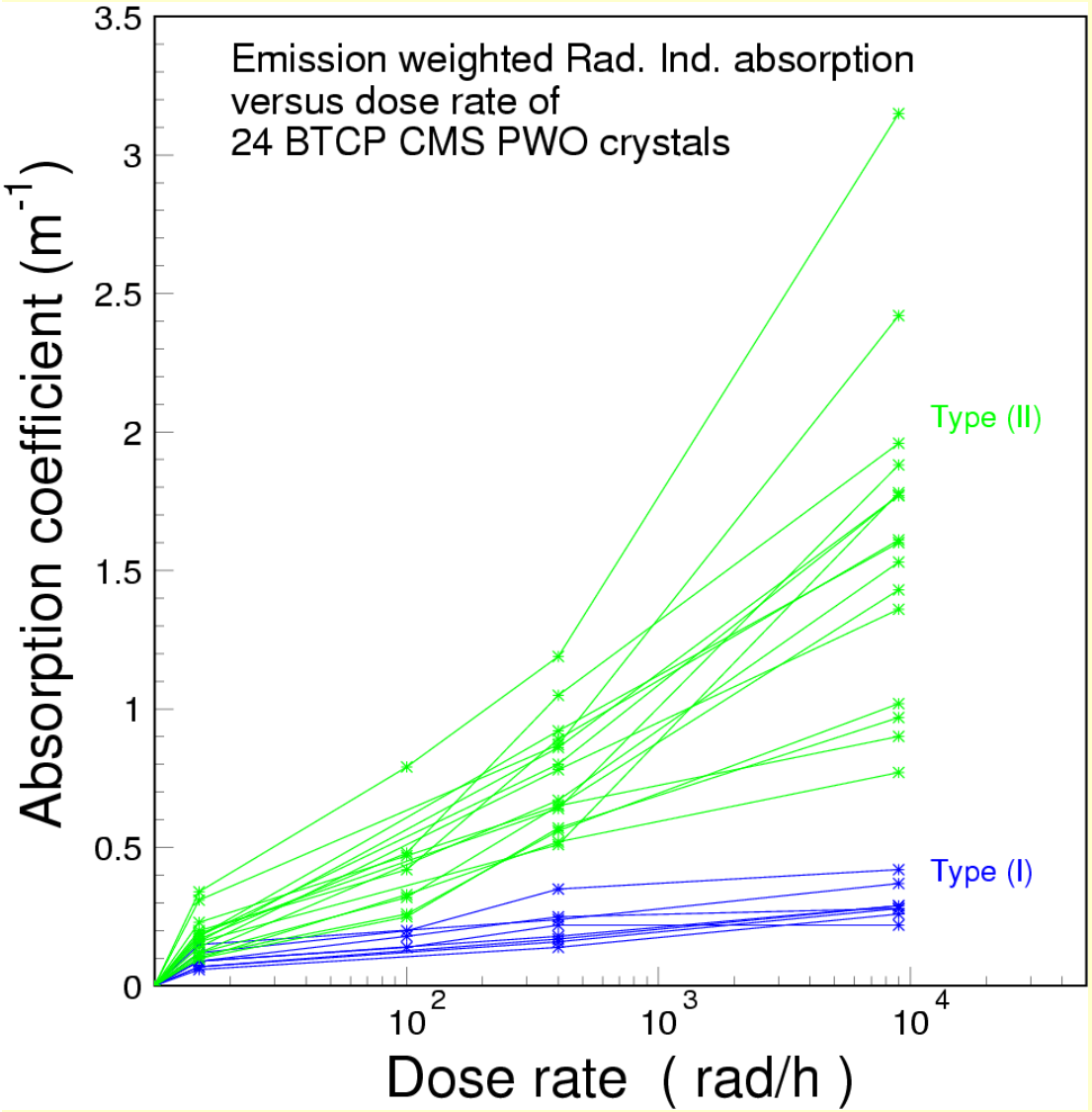

Large Damage and 2 Time Constants: ~30 h and ~1,300 h

# Emission Weighted RIAC (I)




| Sample ID | Dose Rate (rad/h) 15 | 100 | 400 | 9000 |
|---|---|---|---|---|
| B2467 | 0.12 | 0.20 | 0.35 | 0.42 |
| B2466 | 0.09 | 0.14 | 0.22 | 0.22 |
| B2456 | 0.09 | 0.18 | 0.25 | 0.28 |
| P7903 | 0.09 | — | 0.18 | 0.29 |
| P7654 | 0.15 | — | 0.24 | 0.37 |
| P7566 | 0.06 | — | 0.14 | 0.26 |
| P7557 | 0.07 | — | 0.17 | 0.29 |
| P7467 | 0.07 | — | 0.16 | 0.28 |
| B2464 | 0.20 | 0.42 | 0.89 | 1.61 |
| B2458 | 0.11 | 0.26 | 0.56 | 1.02 |
| B2457 | 0.10 | 0.25 | 0.57 | 0.97 |
| B2455 | 0.23 | 0.47 | 0.65 | 0.90 |
| B2436 | 0.34 | 0.79 | 1.19 | 3.15 |
| B2434 | 0.12 | 0.32 | 0.65 | 1.43 |
| B2433 | 0.10 | 0.33 | 0.52 | 0.77 |
| B2432 | 0.17 | 0.48 | 1.05 | 1.96 |
| B2409 | 0.12 | — | 0.69 | 1.53 |
| B2408 | 0.18 | — | 0.92 | 1.60 |
| B2407 | 0.14 | — | 0.78 | 1.36 |
| B2406 | 0.16 | — | 0.86 | 1.79 |
| B2382 | 0.31 | — | 0.87 | 2.42 |
| B2381 | 0.18 | — | 0.80 | 1.77 |
| B2376 | 0.19 | — | 0.64 | 1.88 |
| B2375 | 0.16 | — | 0.51 | 1.78 |

# Emission Weighted RIAC (II)



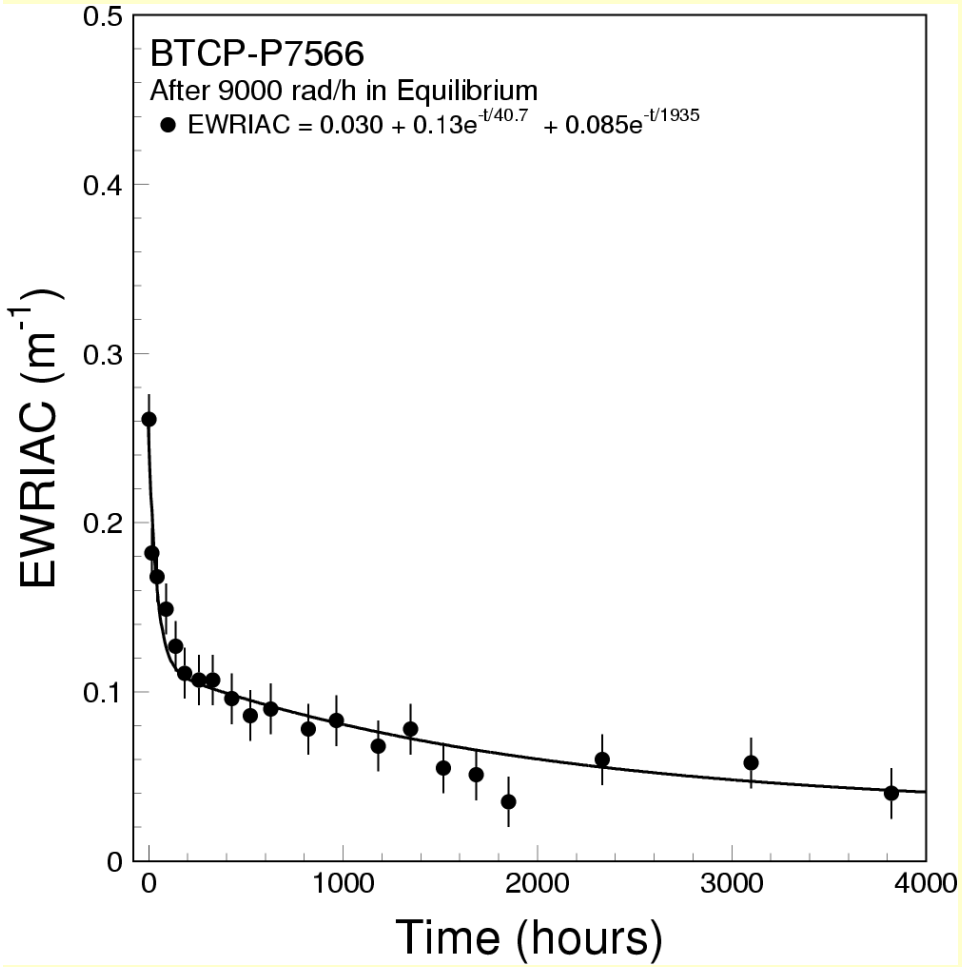

25 Crystals: 3 Types

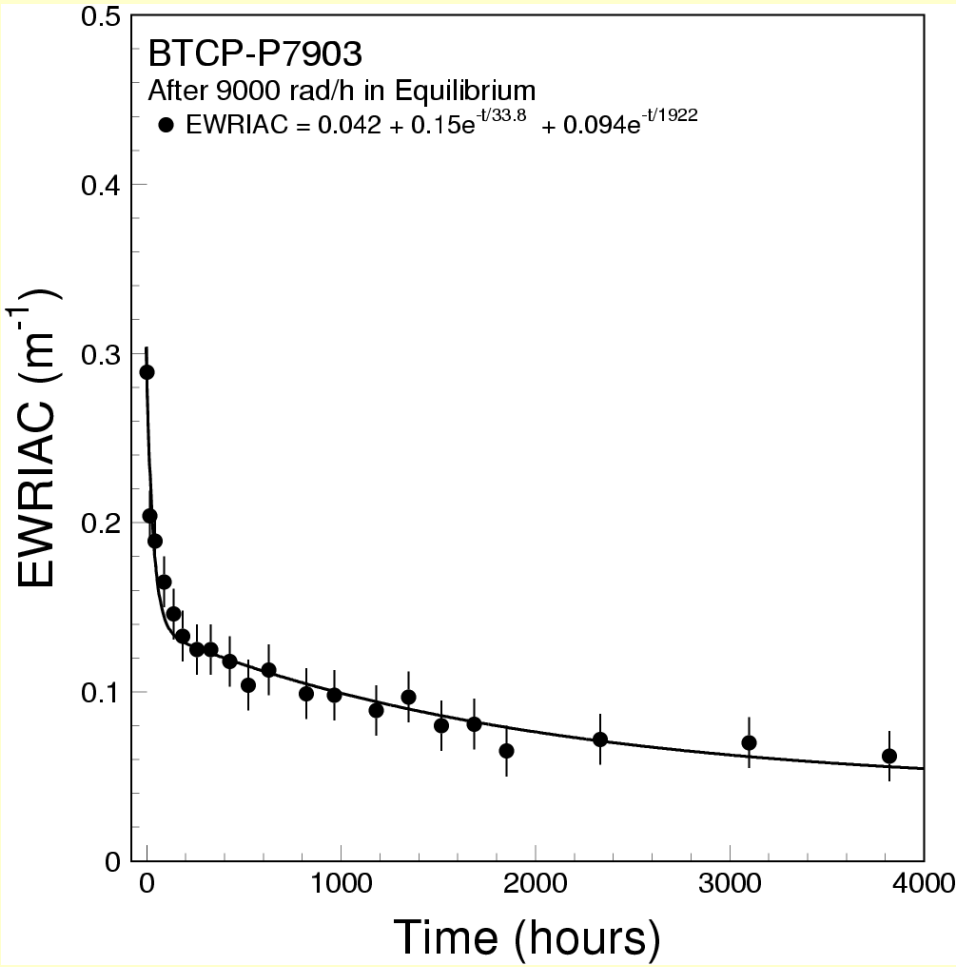
Type I: 2456, 2466 and 2467 and all 5 barrel samples: P7467, P7557, P7566, P7654, P7903.

Type II: All other endcap samples, except that in I and III;

Type III: 2465.

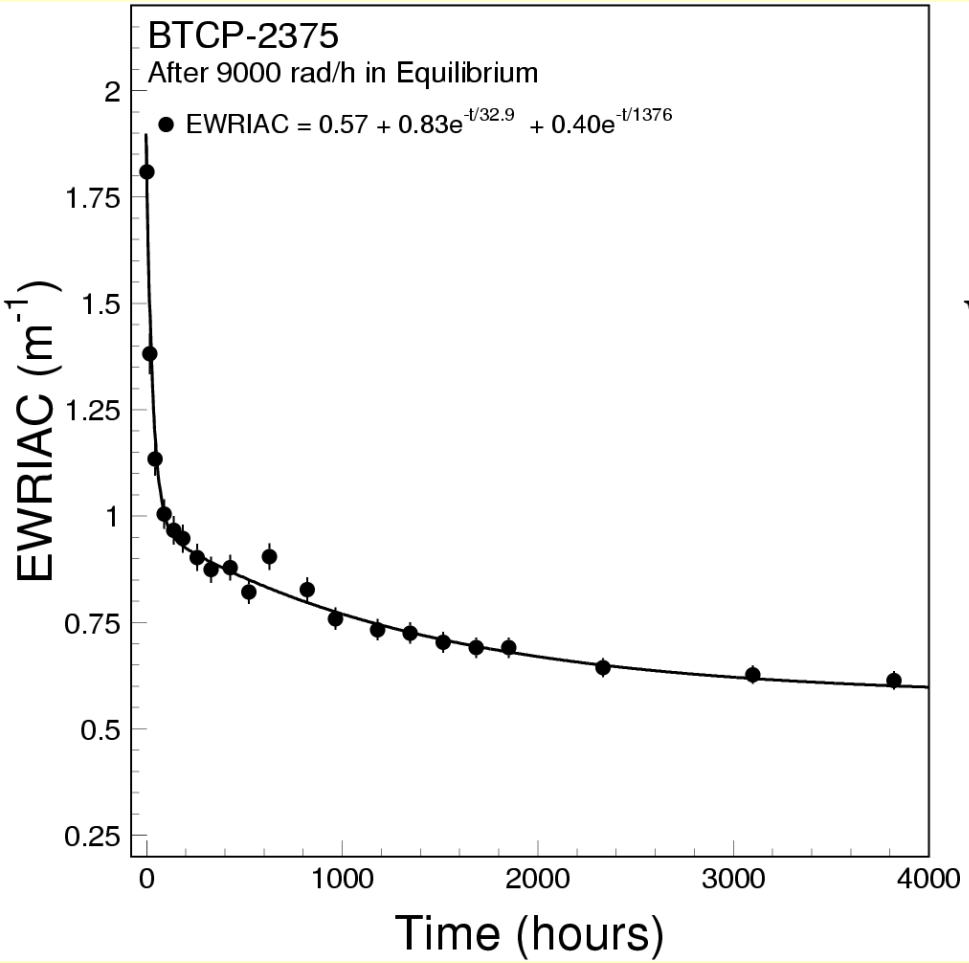
# EWRIAC Recovery: Type I

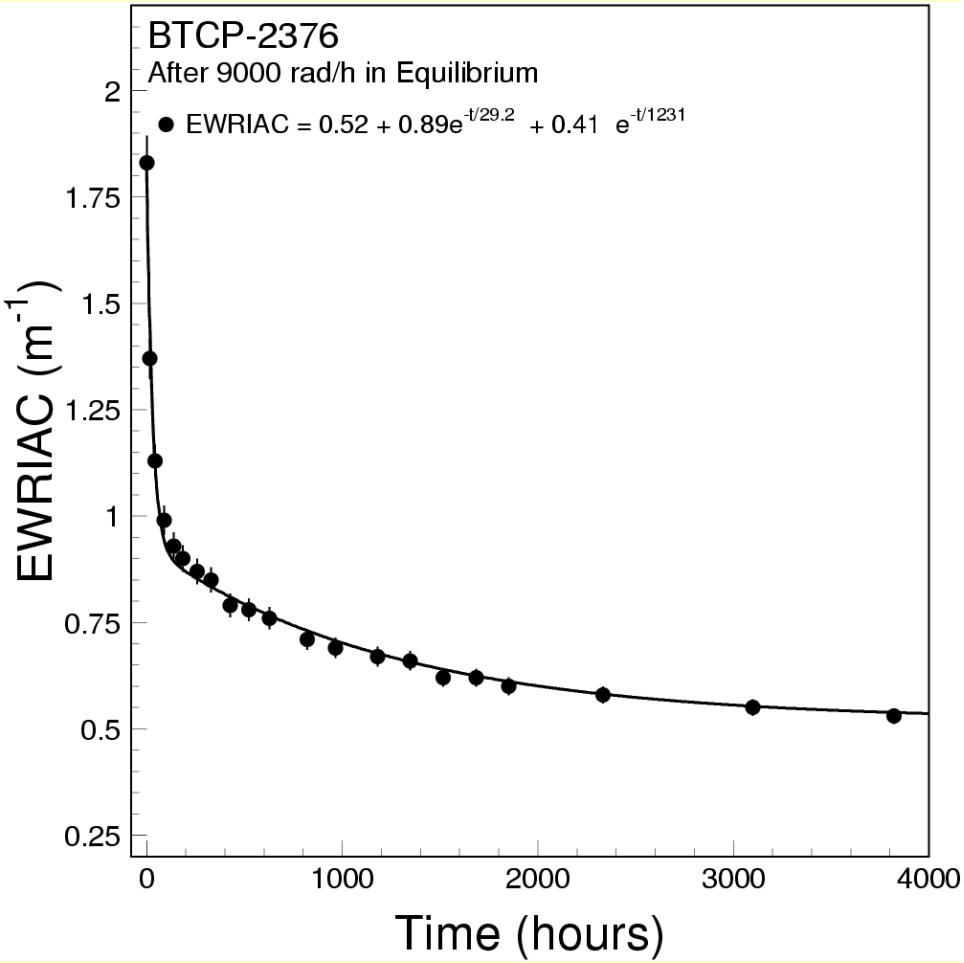



Small Damage and 2 Time Constants: ~40 h and ~1,950 h

# EWRIAC Recovery: Type II




Large Damage and 2 Time Constants: ~30 h and ~1,300 h

# Summary of Long Term Recovery

$$Fit: \frac{T}{T_o} = A_0 - A_1(1 - e^{-t/\tau_1}) - A_2(1 - e^{-t/\tau_2})$$

| Sample ID | 1-$A_0$ (%) | $F_1$ (%) | $\tau_1$ (hour) | $F_2$ (%) | $\tau_2$ (hour) | $F_\infty$ (%) |
|---|---|---|---|---|---|---|
| Type II PWO Samples | | | | | | |
| B2375 | 33.9 | 39.8 | 31.7 | 22.4 | 1,363 | 37.8 |
| B2376 | 35.5 | 42.3 | 30.5 | 23.7 | 1,232 | 34.0 |
| Average | 34.7 | 41.1 | 31.1 | 23.1 | 1,298 | 35.9 |
| Type I PWO Samples | | | | | | |
| P7467 | 7.0 | 48.6 | 59.9 | 22.9 | 1,847 | 28.5 |
| P7557 | 6.7 | 49.3 | 52.0 | 37.3 | 1,897 | 13.2 |
| P7566 | 6.1 | 54.1 | 37.5 | 39.3 | 1,926 | 6.6 |
| P7654 | 8.5 | 35.3 | 37.1 | 29.4 | 2,081 | 35.3 |
| P7903 | 6.5 | 46.2 | 32.6 | 32.3 | 1,928 | 21.5 |
| Average | 7.0 | 46.7 | 43.8 | 32.2 | 1,937 | 21.1 |

$F_i$ denotes the fraction of corresponding component.

Recovery of longitudinal transmittance at 440 nm and EWRIAC are consistent.

$$EWRIAC = A_0 + A_1 e^{-t/\tau_1} + A_2 e^{-t/\tau_2}$$

$$A_{sum} = A_0 + A_1 + A_2$$

| Sample ID | $A_{sum}$ ($m^{-1}$) | $F_1$ (%) | $\tau_1$ (hour) | $F_2$ (%) | $\tau_2$ (hour) | $F_\infty$ (%) |
|---|---|---|---|---|---|---|
| Type II PWO Samples | | | | | | |
| B2375 | 1.80 | 46.1 | 32.9 | 22.2 | 1,376 | 31.7 |
| B2376 | 1.82 | 48.9 | 29.2 | 22.5 | 1,231 | 28.6 |
| Average | 1.81 | 47.5 | 31.1 | 22.4 | 1,304 | 30.2 |
| Type I PWO Samples | | | | | | |
| P7467 | 0.29 | 52.1 | 62.3 | 25.7 | 1,836 | 22.2 |
| P7557 | 0.29 | 51.7 | 58.8 | 34.5 | 1,896 | 13.8 |
| P7566 | 0.25 | 53.1 | 40.7 | 34.7 | 1,935 | 12.2 |
| P7654 | 0.36 | 41.7 | 35.6 | 25.0 | 2,065 | 33.3 |
| P7903 | 0.29 | 52.4 | 33.8 | 32.9 | 1,922 | 14.7 |
| Average | 0.30 | 50.2 | 46.2 | 30.6 | 1,931 | 19.2 |

$F_i$ denotes the fraction of corresponding component.

A residual component with longer recovery time constant is at 20 to 30% level for type I and II crystals respectively

# Summary

- No variations in either light output or longitudinal transmittance for measurements 8 hours after the 200$^{o}$C thermal annealing.
- PWO recovery measured under 18$^{o}$C in 160 days can be described by two time constants: few tens hours and few thousands hours. Type I crystal has longer recovery time constant.
- A residual component at 20/30% level may have even longer recovery time constant.