Results on 25 PWO Crystals

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Introduction

- 20 endcap and 5 barrel PWO crystals arrived Caltech late October and December, 2002, respectively.
- All crystals went through (1) thermal annealing at 200^{o}C, (2) irradiations by γ–ray at 15, 100, 400 and 9k rad/h until equilibrium and (3) recovery.
- Transmittance, radiation induced color center, emission weighted radiation induced absorption coefficients were measured for all dose rates.
- Because of limited light output (less than 8 p.e./MeV), light output degradation was only measured at 15 rad/h for most samples.
- The 25 samples can be divided to 3 types.

Crystal Property Measured

- UV-excited photo luminescence.
- Longitudinal transmittance.
- Radiation induced color centers.
- Emission weighted radiation induced absorption coefficient.
- Recovery speed and time constant of transmittance.
- Light output and decay kinetics.
- Damage speed and time constant of light output under 15 rad/h.

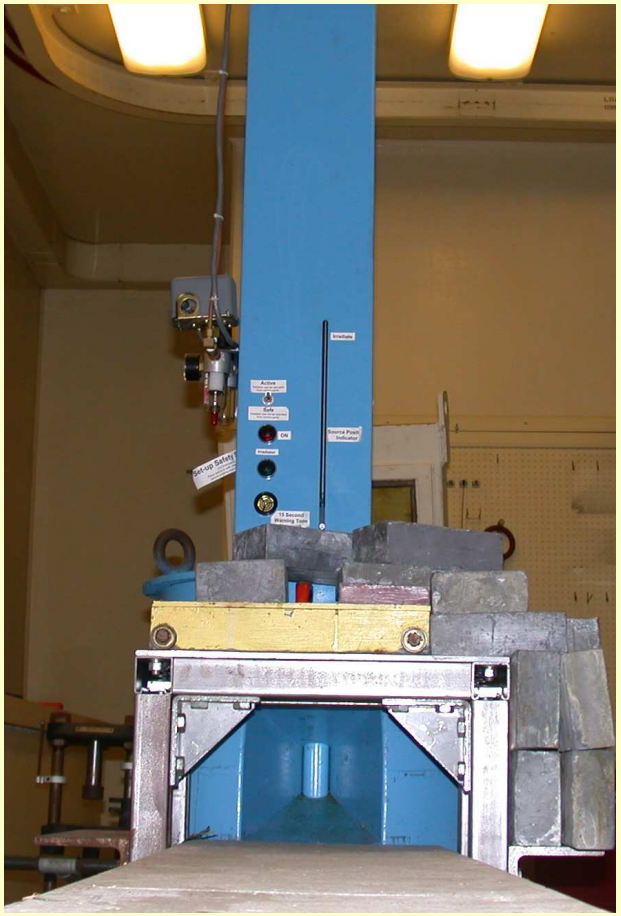
Thermal Annealing

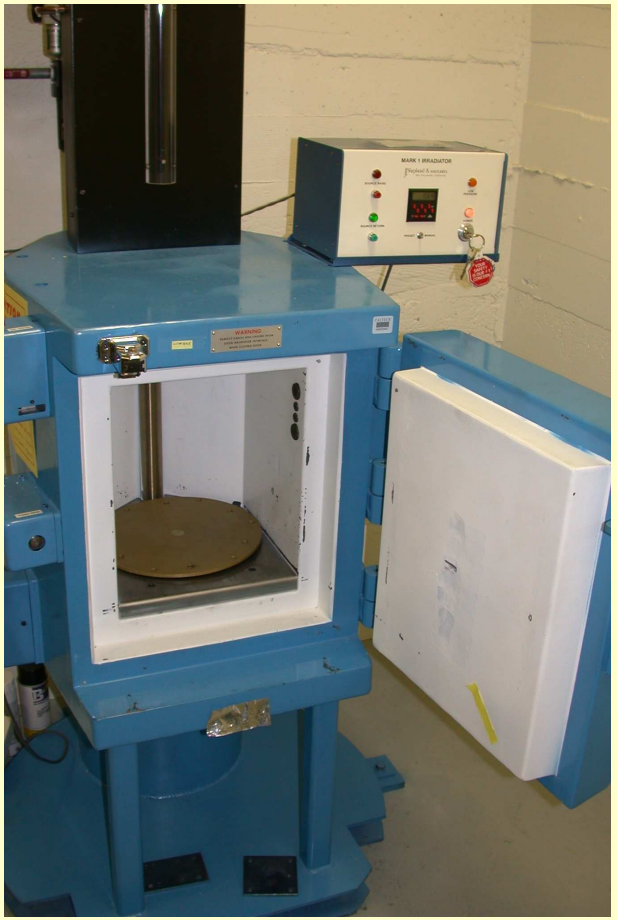
- Rigorous temperature control both in amplitude and slope:
  - From RT to 200^{o}C: 200 minutes;
  - Maintain at 200^{o}C: 240 minutes;
  - From 200^{o}C to 25^{o}C: 400 minutes.
- Crystals are kept in dark at RT (18^{o}C) after annealing. The minimum time between annealing and the 1st measurement is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

Caltech γ–ray Irradiation Facilities

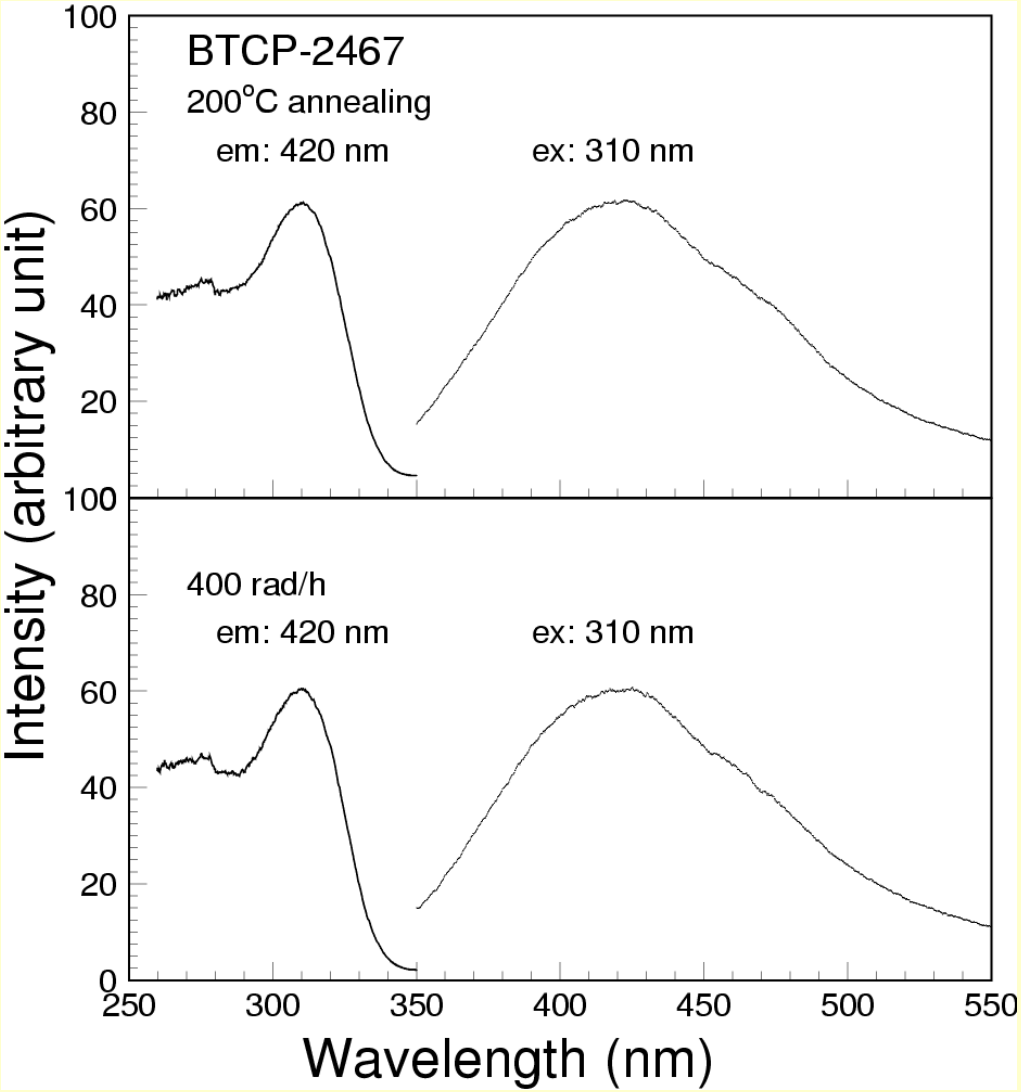
Open 50 curie Co-60:
15, 100 and 400 rad/h

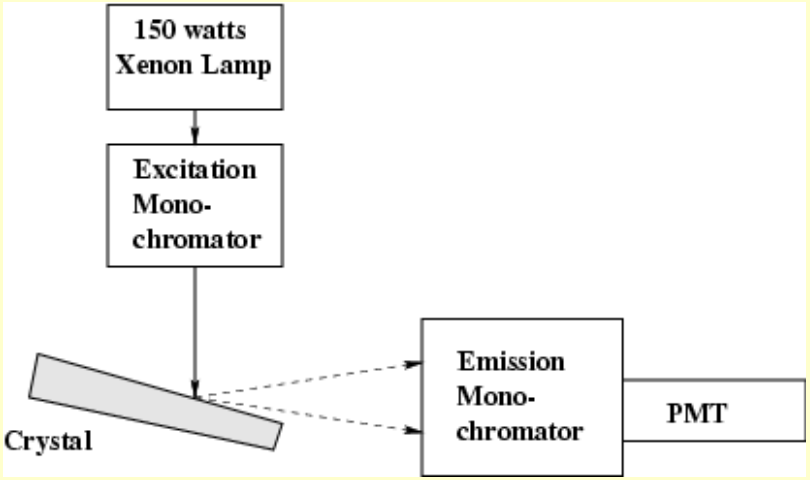
Closed 2,000 curie Cs-137:
9k rad/h at center, up to 36k rad/h





Photoluminescence

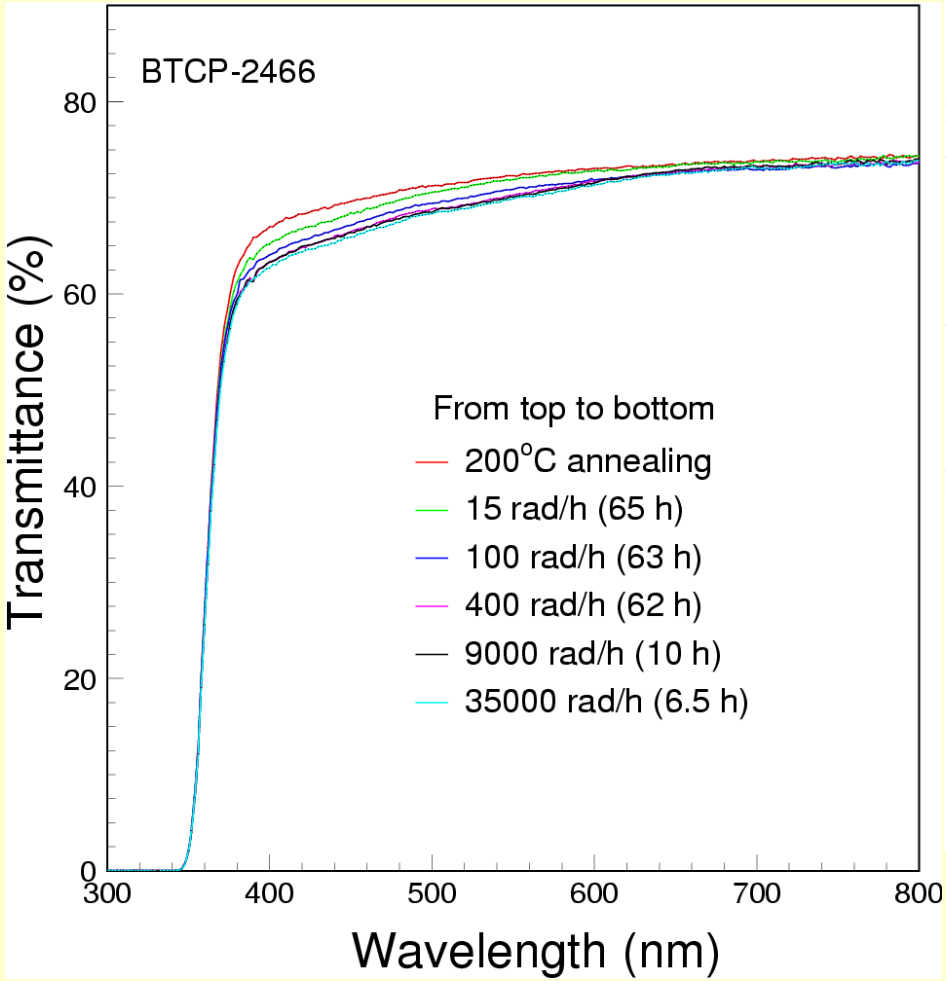


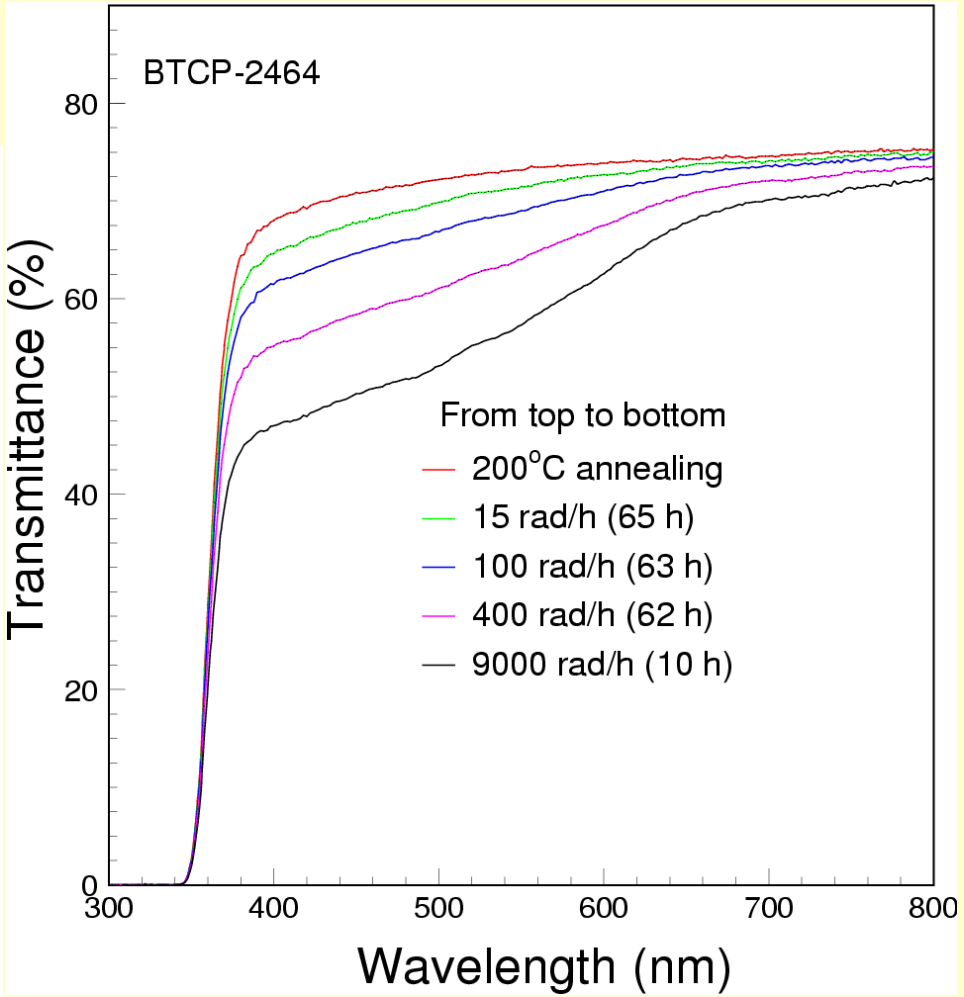


All 25 samples show no variation of either excitation or emission spectra.

Longitudinal Transmittance Loss

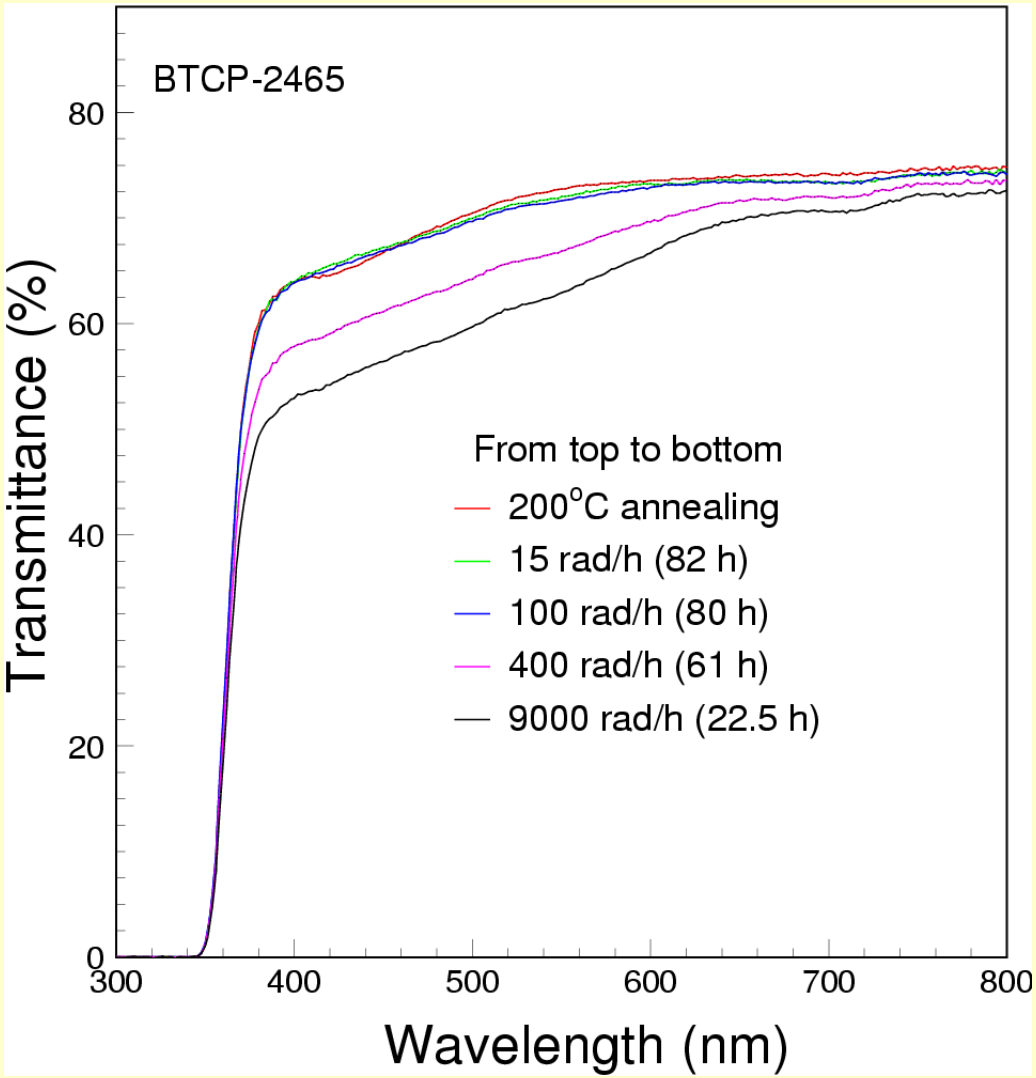
Type I sample





Type II sample

Type III Sample: LT Loss



Type III sample: preexisting intrinsic color center at 420 nm after 200 degree annealing, causing difficulty for monitoring with 440 nm light

Summary of LT Loss (I)

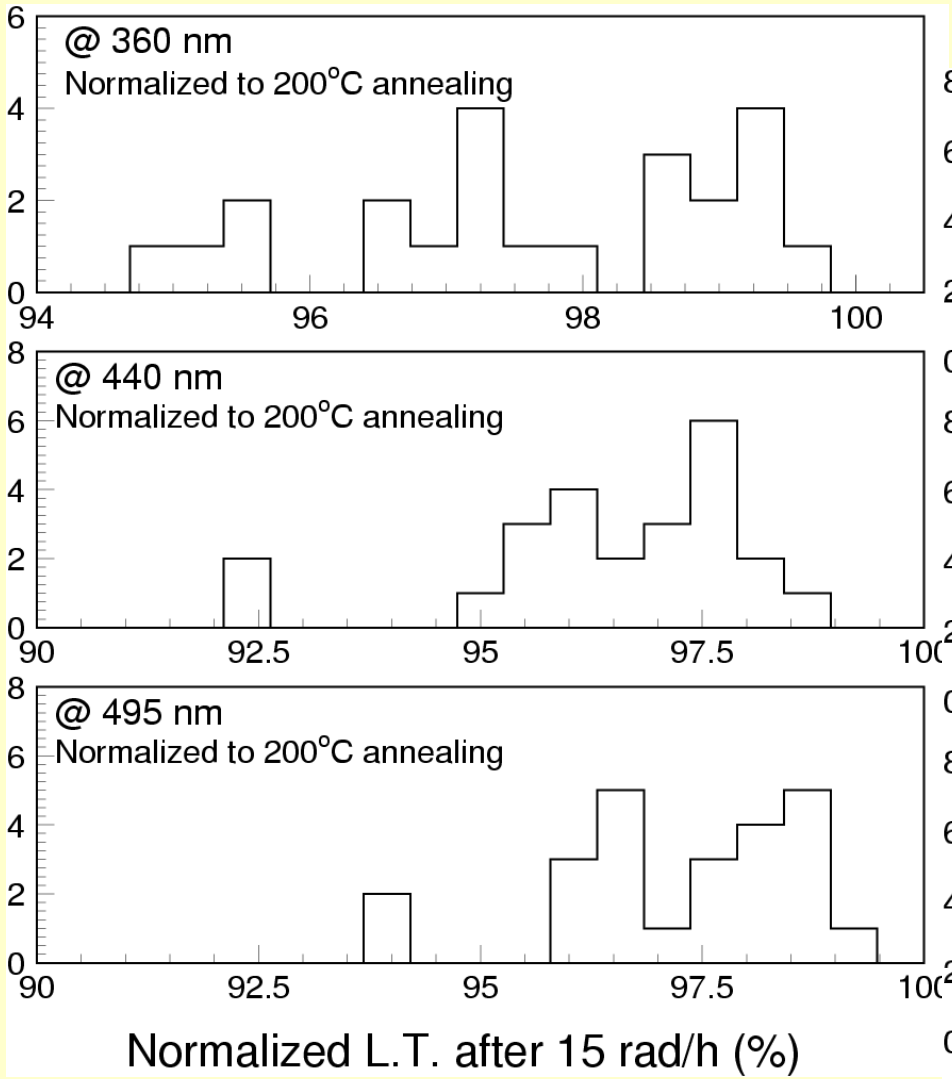
Type I

Type II

Sample ID	*I.L.T. (%) 440nm	*I.L.T. (%) 495nm	*15 rad/h 440nm	*15 rad/h 495nm	*100 rad/h 440nm	*100 rad/h 495nm	*400 rad/h 440nm	*400 rad/h 495nm	*9k rad/h 440nm	*9k rad/h 495nm
B2467	70.56	72.15	0.969	0.988	0.954	0.972	0.923	0.944	0.908	0.932
B2466	69.28	71.22	0.978	0.988	0.966	0.976	0.953	0.963	0.949	0.961
B2456	70.66	72.33	0.978	0.986	0.962	0.969	0.945	0.956	0.938	0.950
p7903	70.70	72.38	0.976	0.981	—	—	0.955	0.965	0.930	0.943
p7654	69.81	71.65	0.963	0.975	—	—	0.941	0.955	0.911	0.933
p7566	69.09	71.31	0.987	0.990	—	—	0.967	0.975	0.937	0.949
p7557	69.73	71.85	0.979	0.984	—	—	0.958	0.964	0.930	0.938
p7467	70.45	72.23	0.979	0.987	—	—	0.959	0.967	0.928	0.944
B2464	70.45	72.06	0.954	0.964	0.910	0.924	0.821	0.841	0.703	0.729
B2458	69.42	71.50	0.976	0.986	0.944	0.955	0.885	0.902	0.800	0.822
B2457	69.48	71.50	0.978	0.983	0.947	0.956	0.882	0.896	0.809	0.827
B2455	71.02	72.69	0.949	0.962	0.900	0.916	0.866	0.884	0.773	0.798
B2436	70.16	72.18	0.922	0.938	0.831	0.852	0.758	0.783	0.486	0.521
B2434	70.03	71.88	0.971	0.977	0.927	0.936	0.859	0.872	0.693	0.715
B2433	69.59	71.84	0.978	0.979	0.929	0.933	0.889	0.895	0.823	0.835
B2432	68.92	71.62	0.962	0.964	0.897	0.903	0.786	0.802	0.613	0.635
B2409	69.67	71.61	0.972	0.974	—	—	0.786	0.802	0.613	0.635
B2408	69.84	71.73	0.959	0.964	—	—	0.807	0.820	0.692	0.713
B2407	70.05	71.98	0.968	0.973	—	—	0.836	0.848	0.730	0.750
B2406	70.10	71.89	0.965	0.968	—	—	0.820	0.832	0.665	0.687
B2382	70.15	72.16	0.925	0.938	—	—	0.813	0.831	0.569	0.595
B2381	70.13	72.13	0.957	0.961	—	—	0.830	0.841	0.664	0.684
B2376	70.34	72.18	0.954	0.963	—	—	0.858	0.871	0.642	0.669
B2375	69.87	71.94	0.961	0.967	—	—	0.886	0.894	0.659	0.682

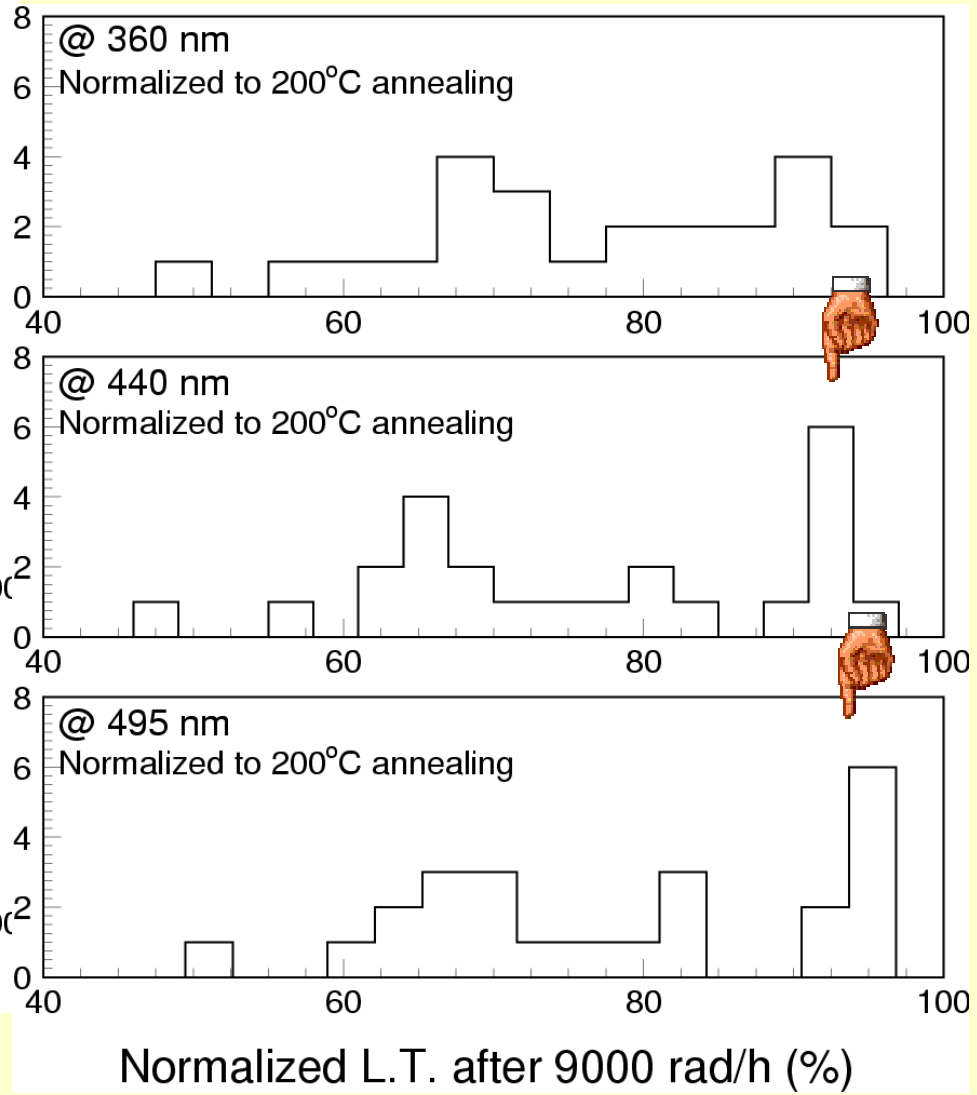
* I.L.T. represents initial longitudinal transmittance measured after 200°C annealing.
* Longitudinal transmittance, normalized to I.L.T., measured when crystal damage is in equilibrium.

Summary of LT Loss (II)

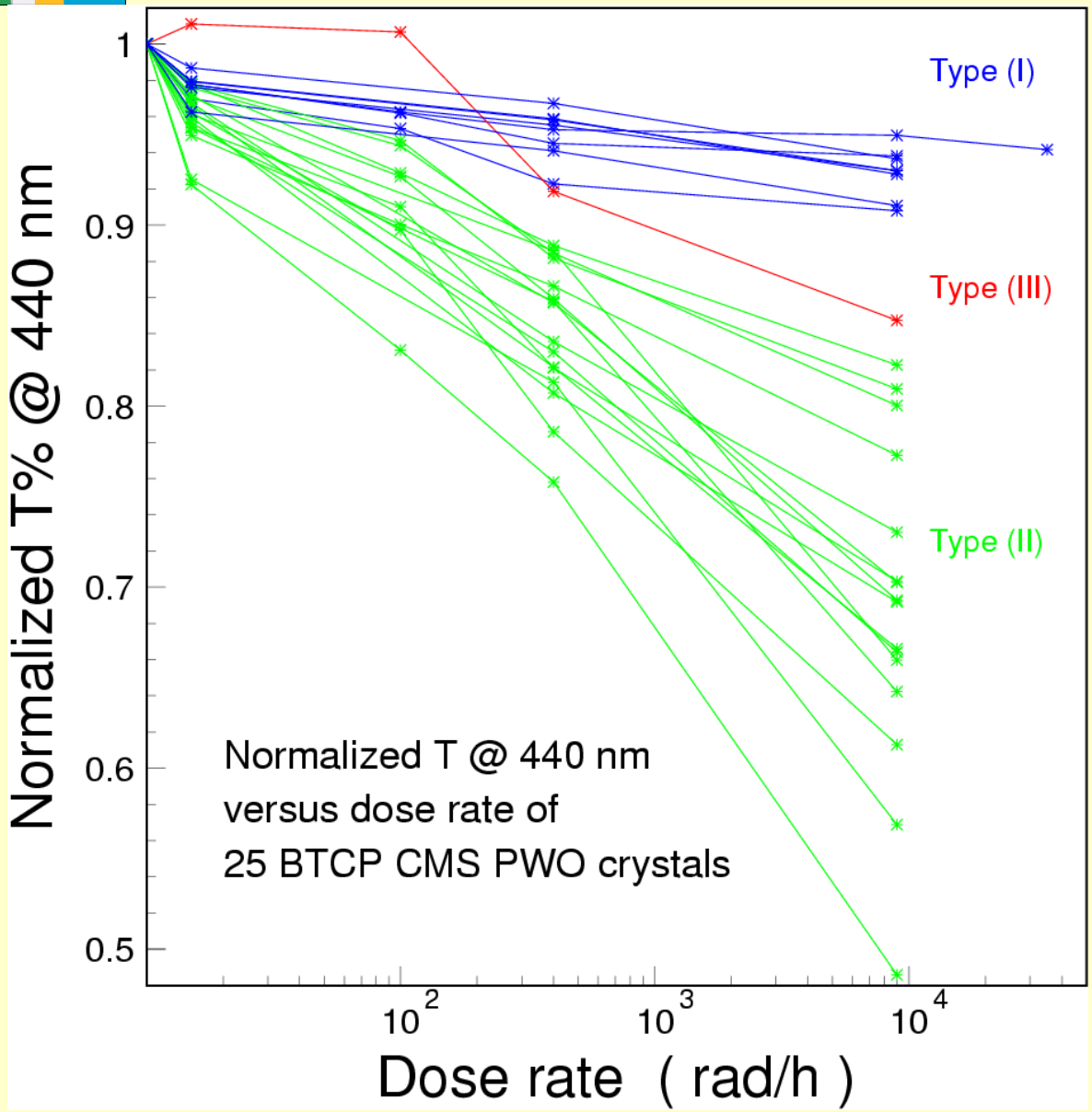


15 rad/h

9 krad/h



25 Samples in Three Types



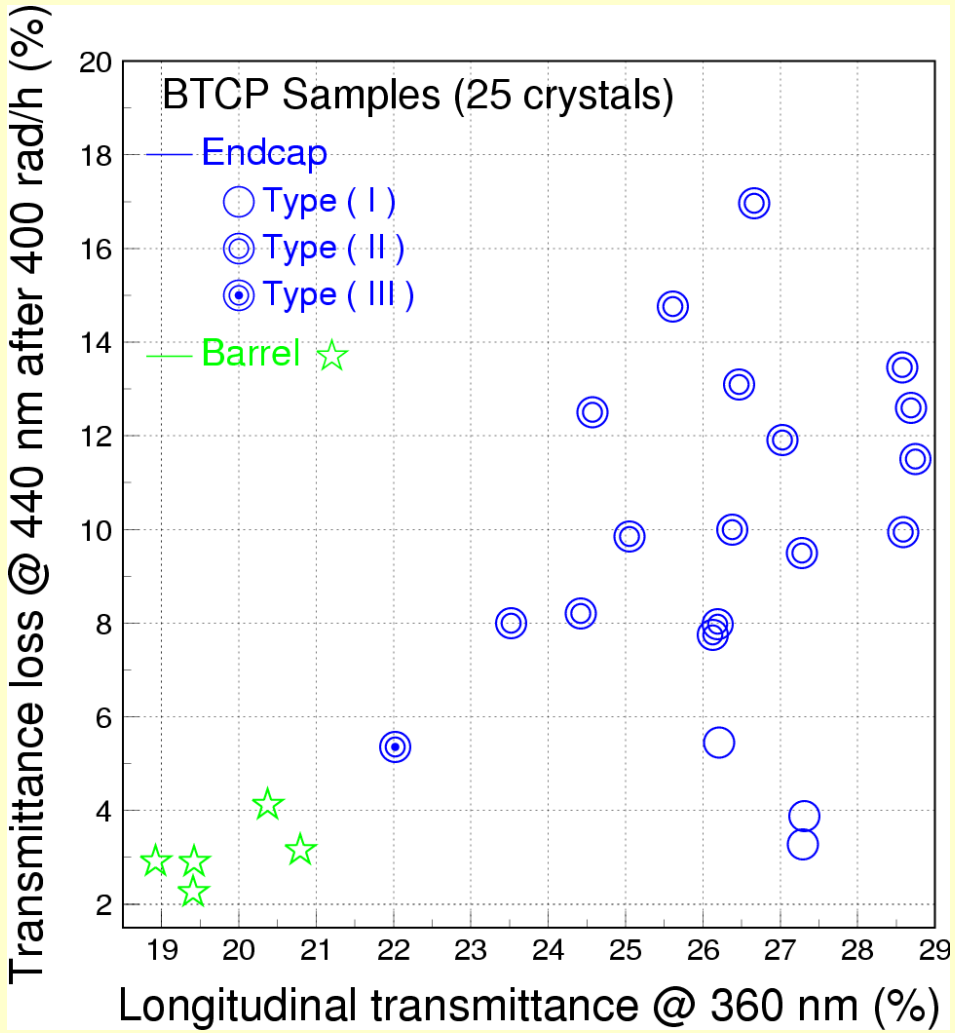
Type I: 2456, 2466 and 2467 and all 5 barrel samples: P7467, P7557, P7566, P7654, P7903.

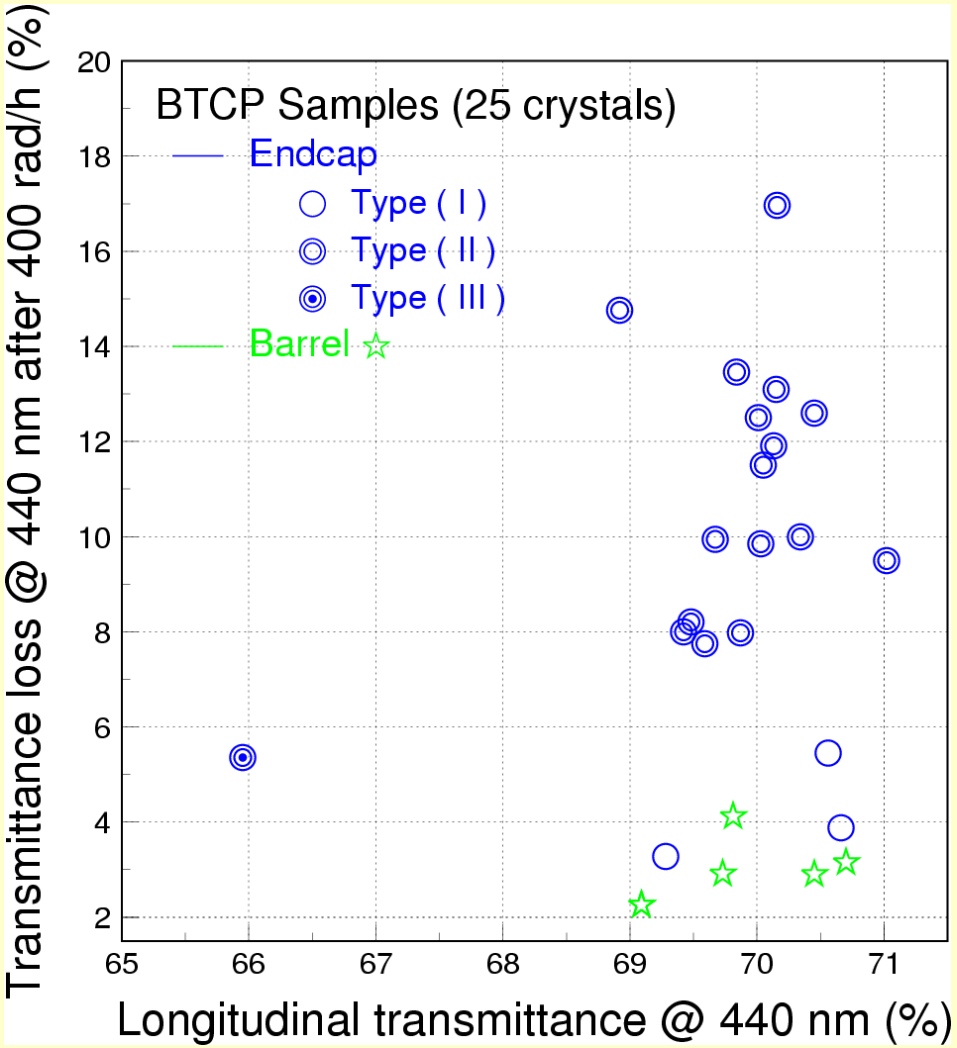
Type II: All other endcap samples, except that in I and III;

Type III: 2465.

LT Loss versus Initial LT

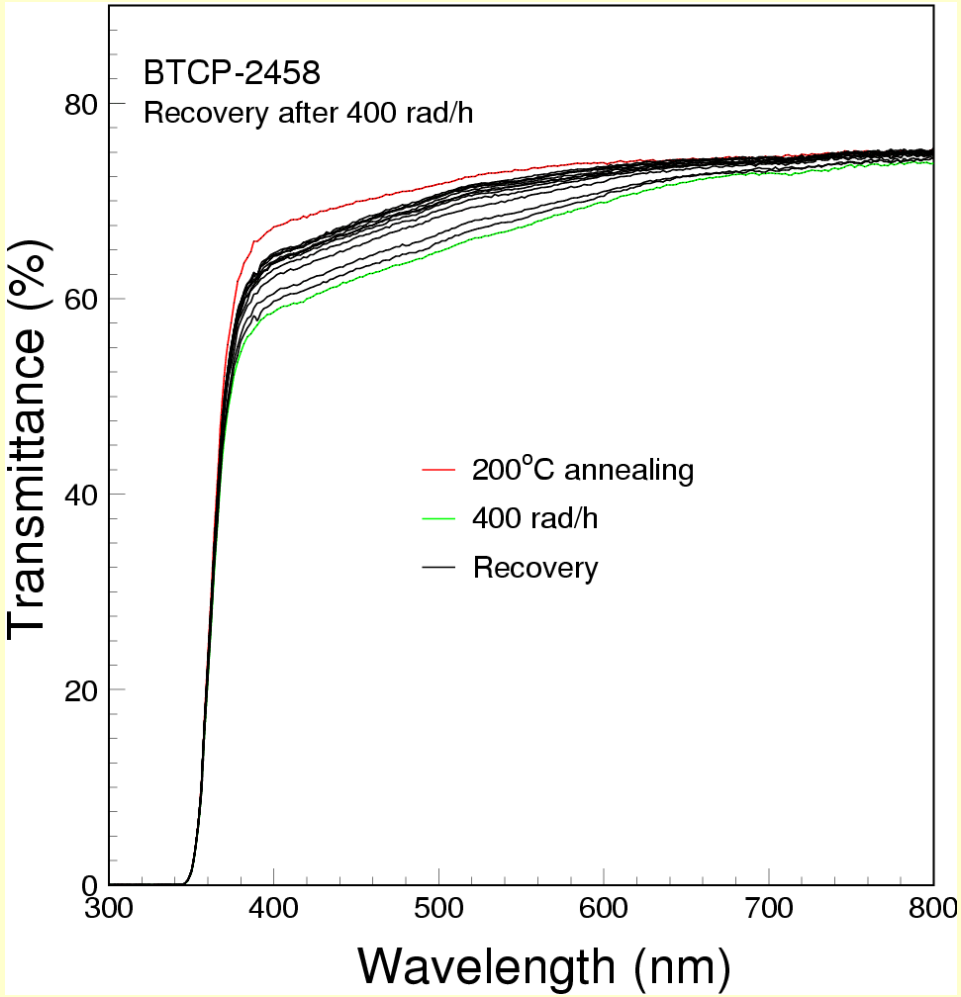
No correlation at 360 nm

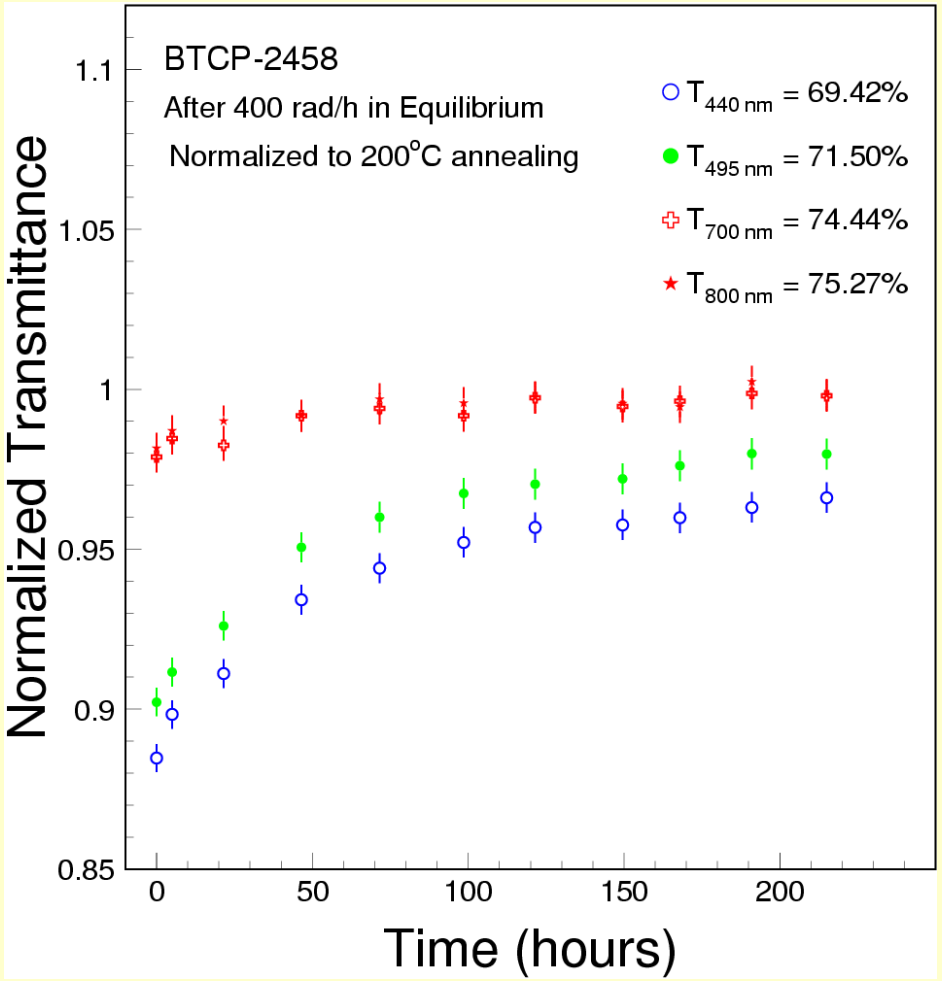




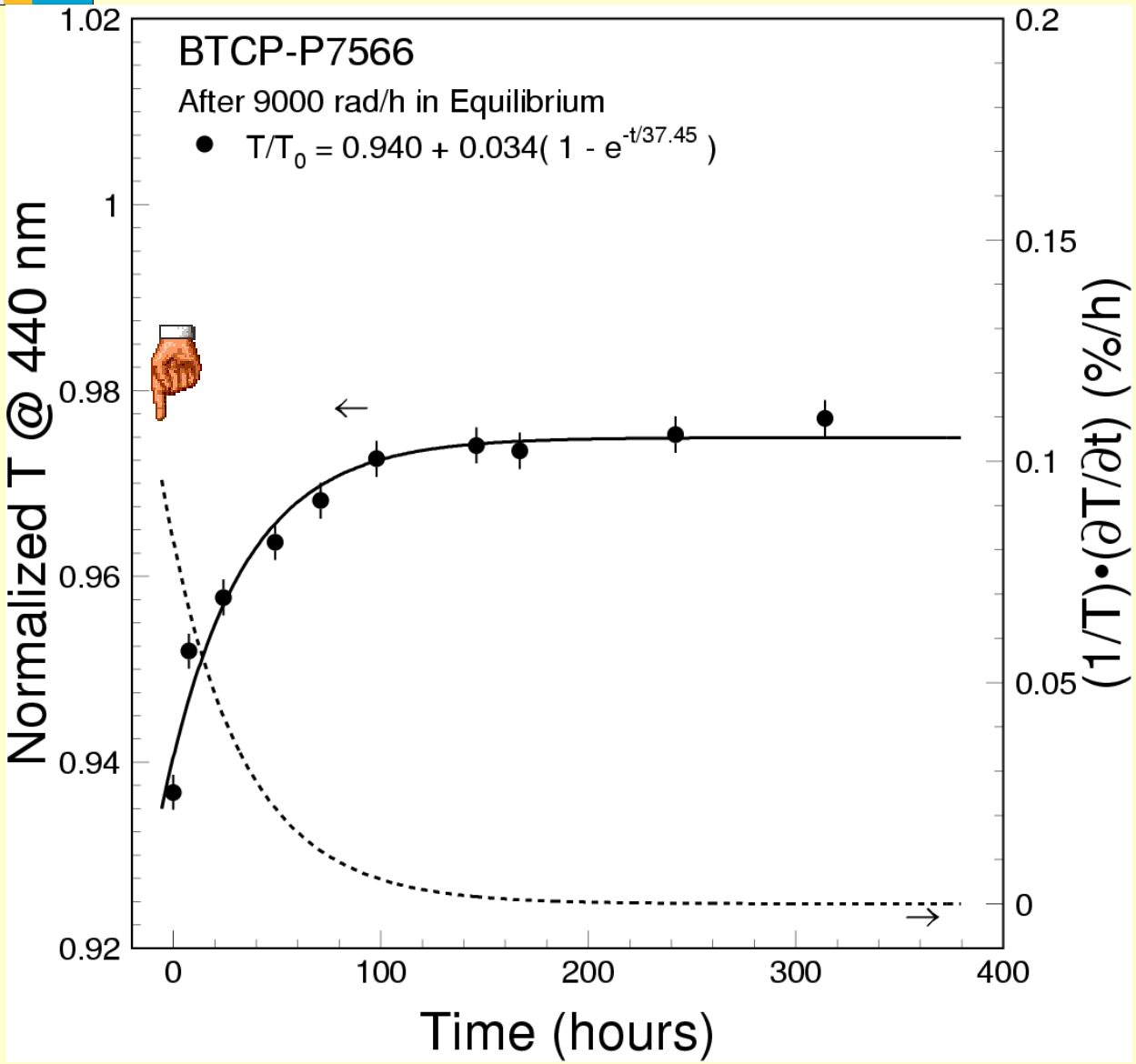
No correlation at 440 nm

2458 Recovery after 400 rad/h





Recovery Speed and Time Constant



Short Term (two weeks) Recovery

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

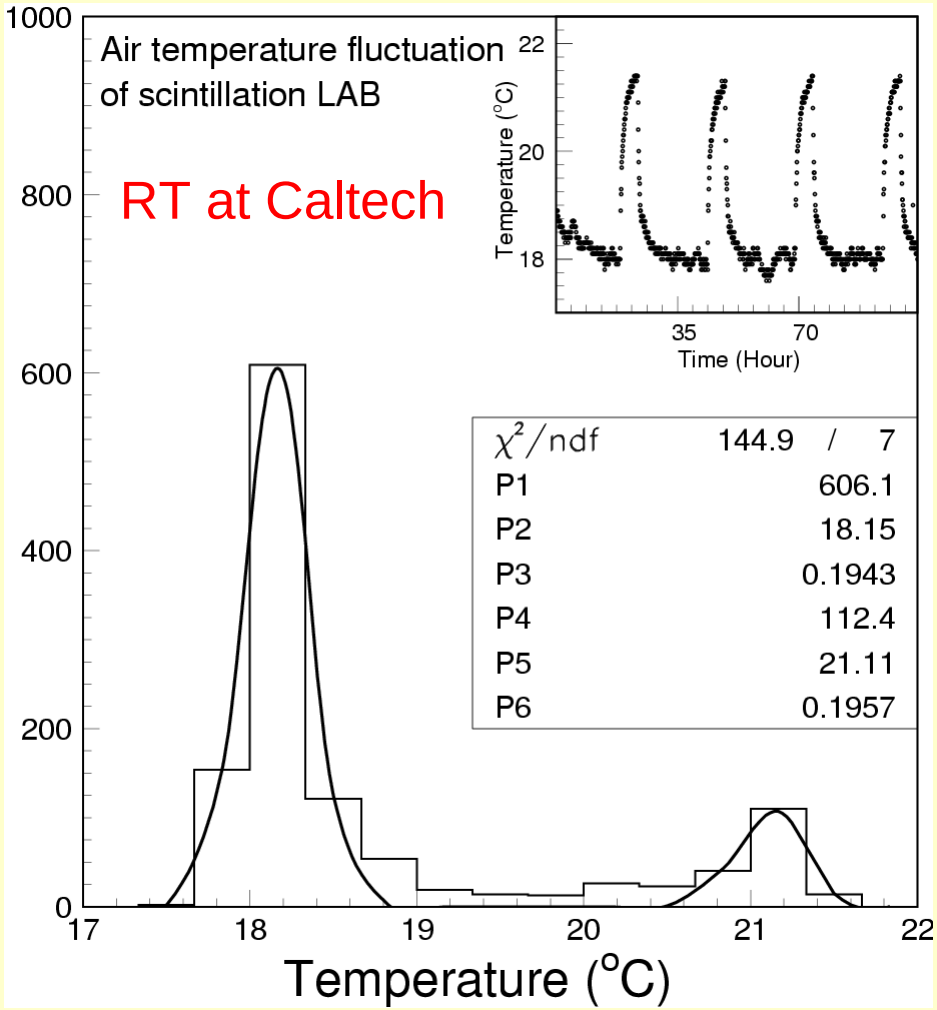
The maximum recovery speed and time constant are measures of the monitor-ability of the crystal.

Summary of Short Term Recovery

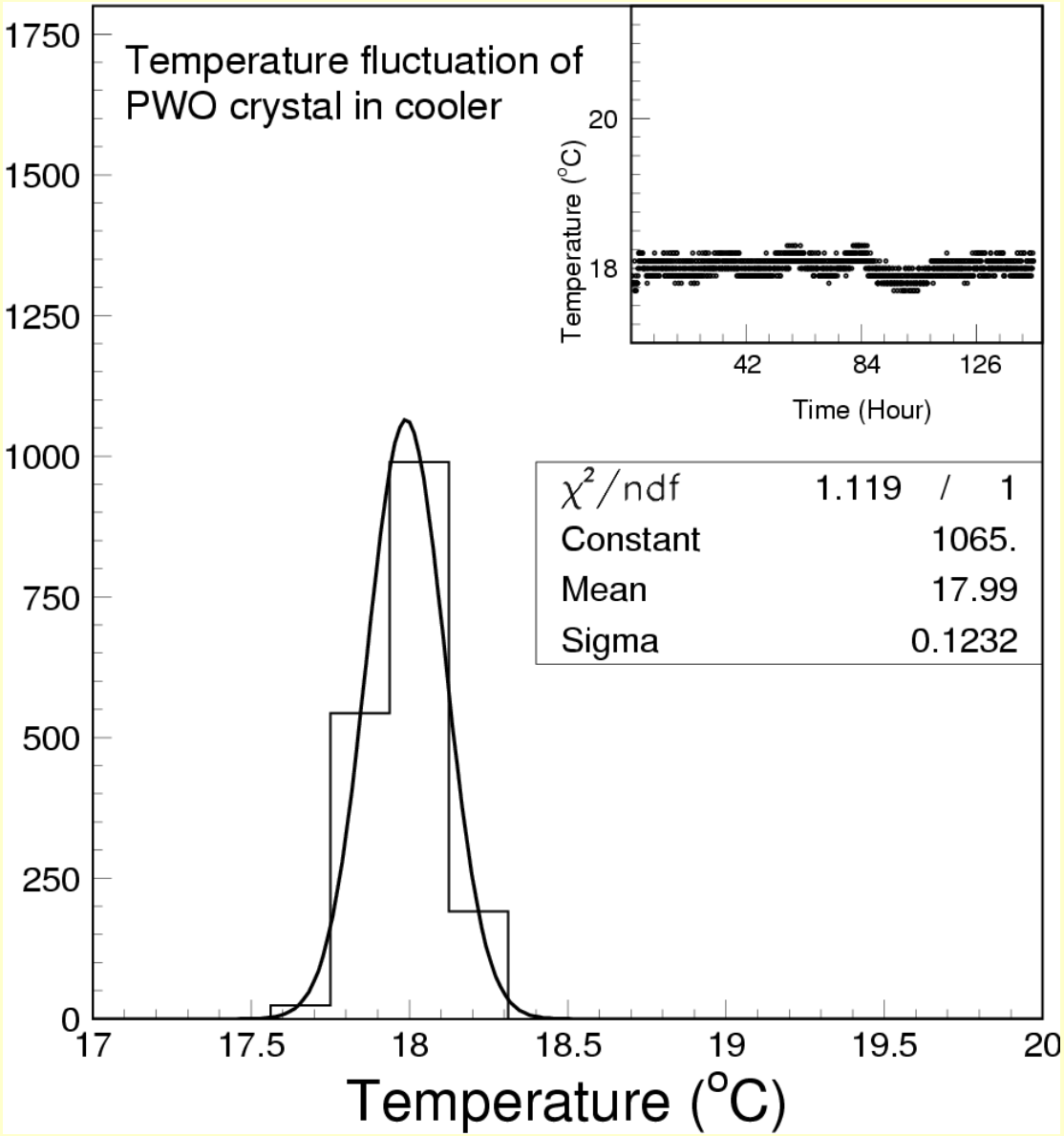
ID	ΔT (%)	F_{rec} (%)	v_{rec}^{max} (%/h)	τ_{rec} (h)
B2467	9.4	50.0	0.09	52.6
B2466*	5.8	60.3	0.16	22.8
B2456	6.4	54.7	0.07	47.5
P7903	6.5	47.7	0.10	32.6
P7654	8.4	35.7	0.09	37.1
P7566	6.0	56.7	0.09	37.5
P7557	6.5	50.8	0.06	51.9
P7467	7.0	52.9	0.07	59.9
B2464	29.3	52.2	0.83	25.9
B2458	19.8	57.1	0.40	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



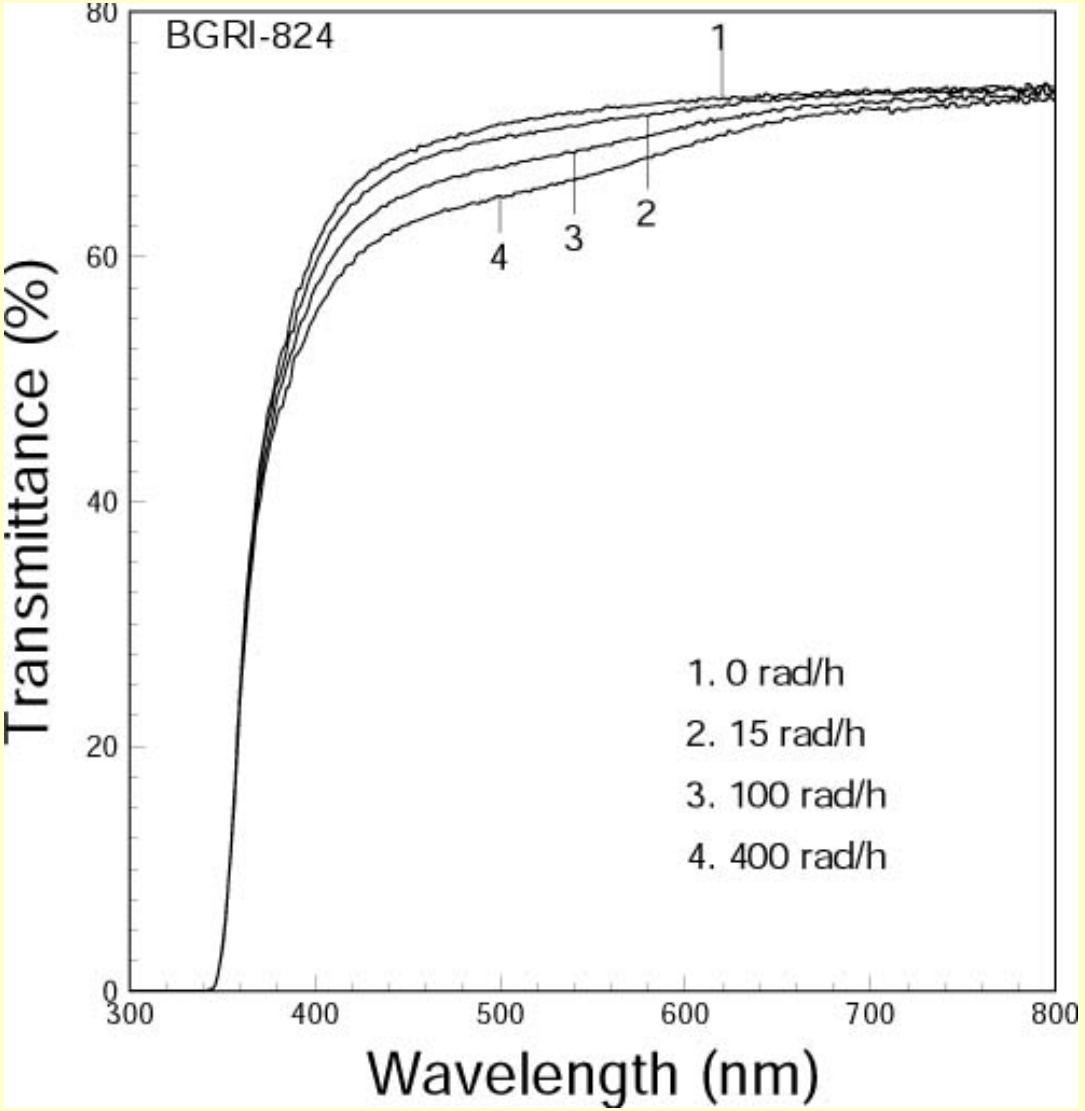
Ten samples, B2375, B2376, B2381, B2456 and B2467 and five barrel samples,are undergoing a long term recovery test. They are stored in a cooler, which keeps temperature at 18°C to 0.1°C precision.

Radiation Induced Color Center Density

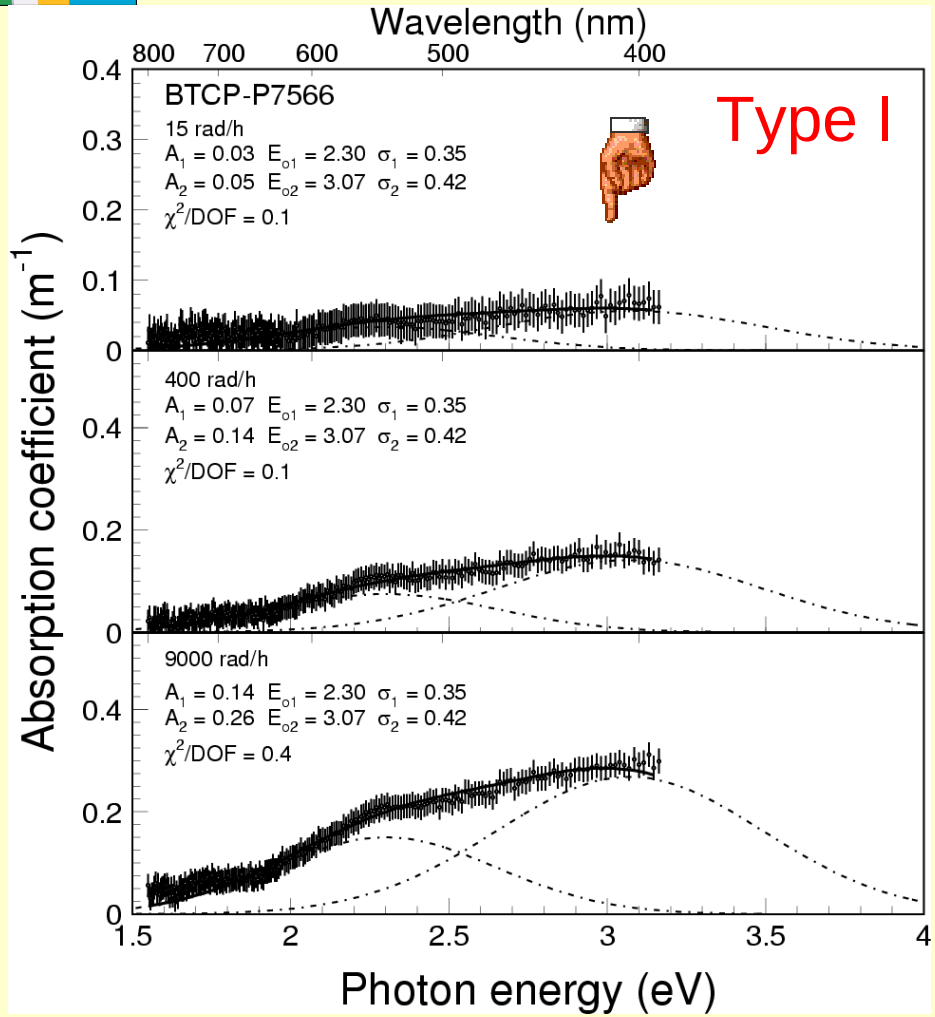
- Radiation induced color center density, or absorption coefficient:

$$D = \frac{1}{LAL_{equilibrium}} - \frac{1}{LAL_{before}}$$

LAL:
light attenuation length



Radiation Induced Color Centers



Type I

C_1: 2.30 eV (540 nm), width: 0.35 eV

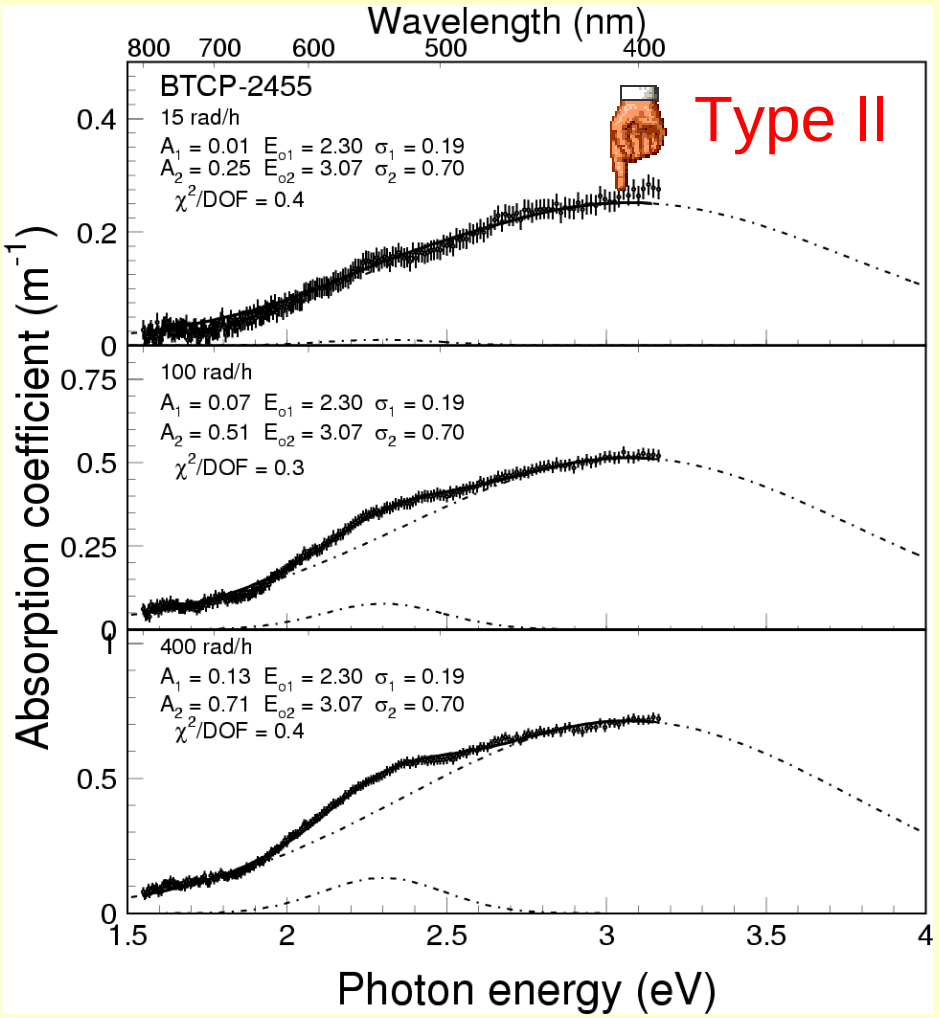
C_2: 3.07 eV (400 nm), width: 0.42 eV

Radiation induced CC density <0.4/m

C_1: 2.30 eV (540 nm),width: 0.19 eV

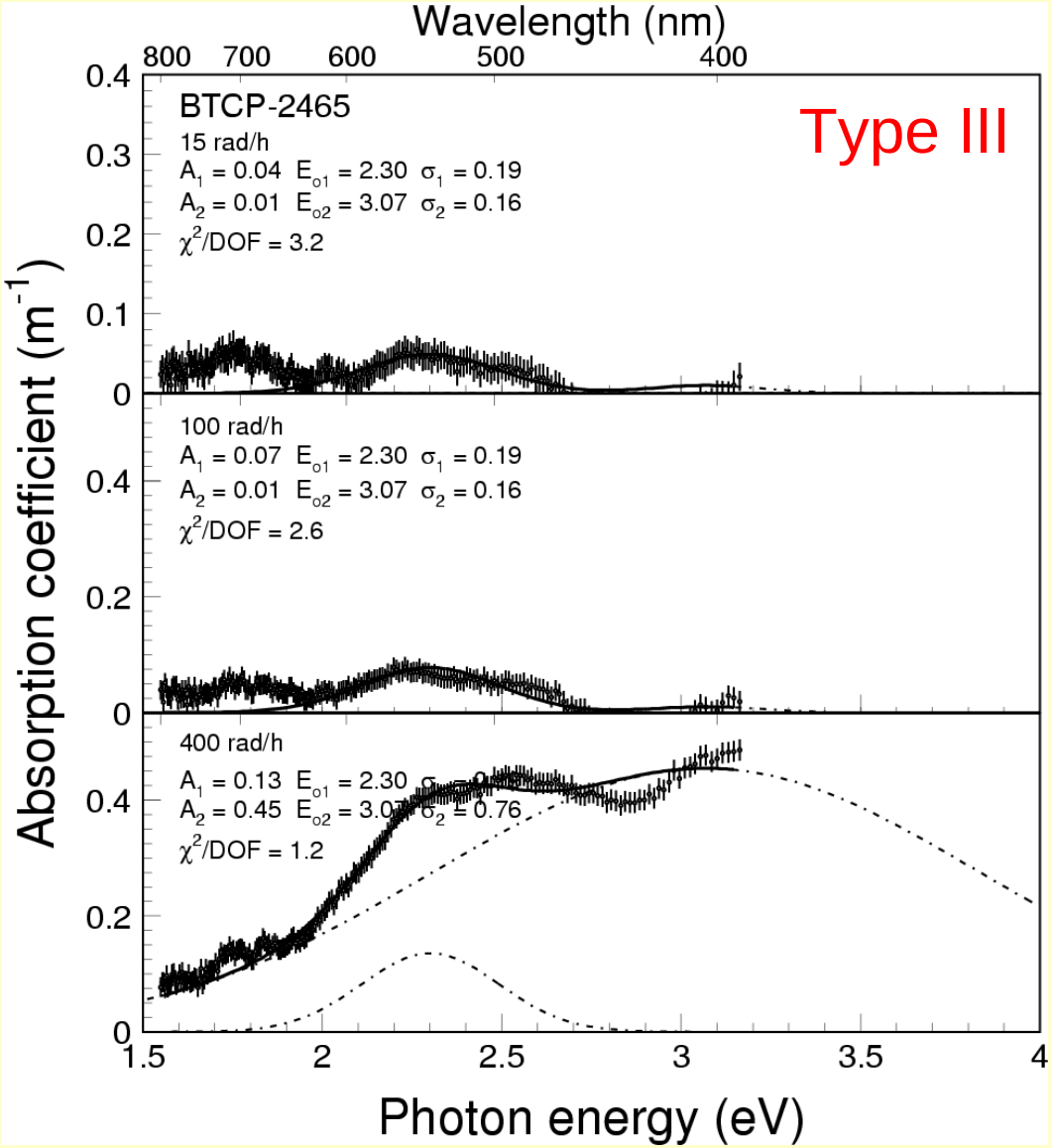
C_2: 3.07 eV (400 nm), width: 0.70 eV

Radiation induced CC density >0.5/m



Type II

Type III Sample: RICC



Different color centers under low and high dose dates: Poor Fit.

C_1: 2.30 eV (540 nm) with width of 0.19 eV

C_2: 3.07 eV (400 nm) with width of 0.16 and 0.76 eV

Summary of RICC

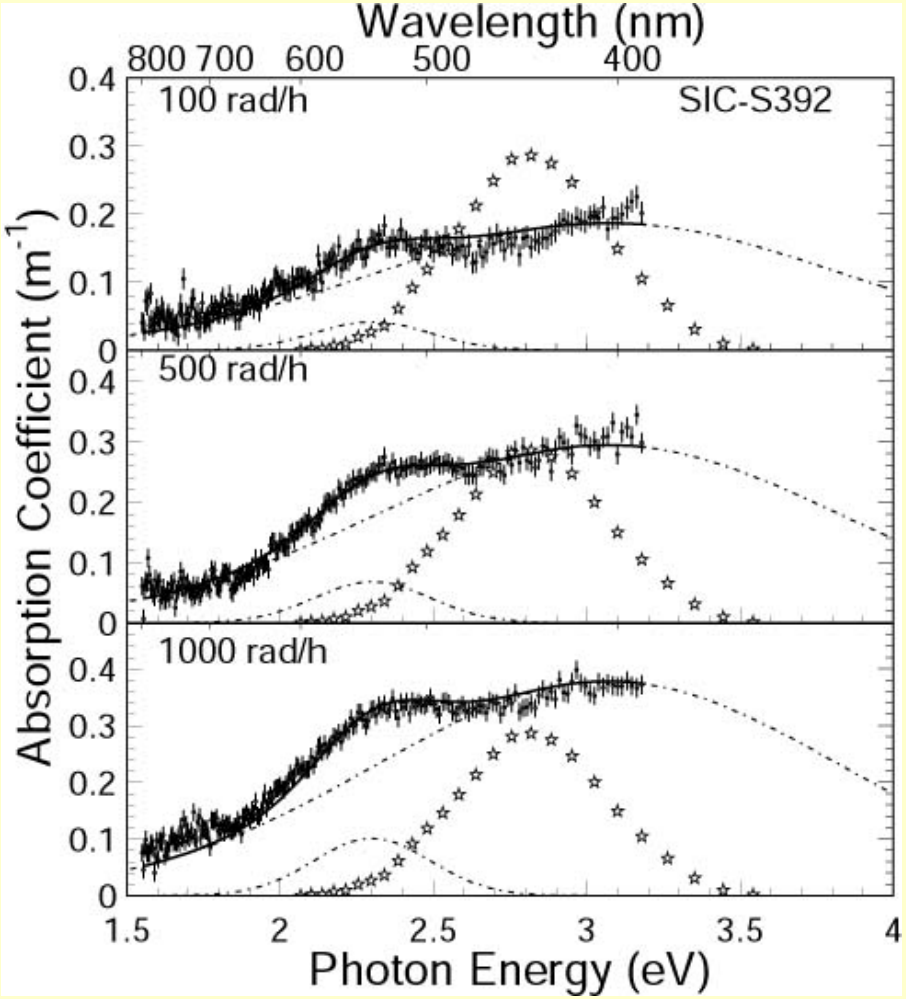
Type I

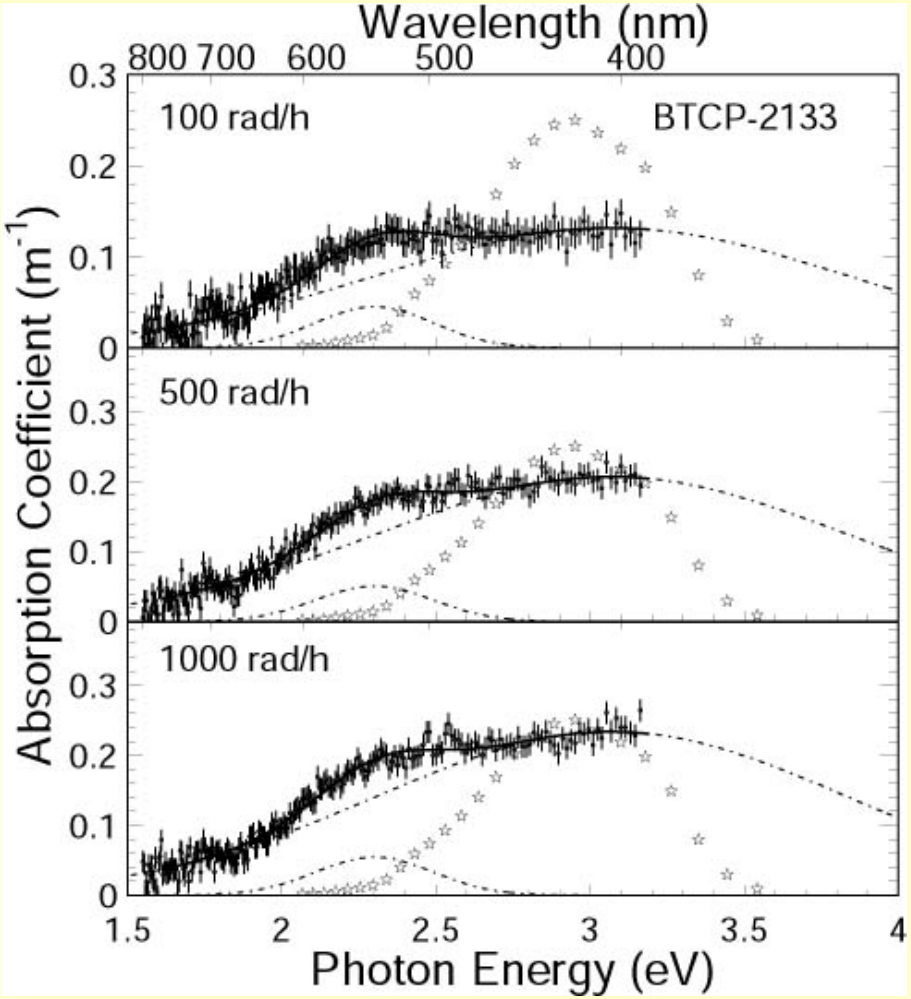
Type II

Sample ID	E_1/σ_1 (eV/eV)	A_1^a (m^{-1})	A_1^b (m^{-1})	A_1^c (m^{-1})	A_1^d (m^{-1})	E_2/σ_2 (eV/eV)	A_2^a (m^{-1})	A_2^b (m^{-1})	A_2^c (m^{-1})	A_2^d (m^{-1})
B2467	2.3/0.35	0.01	0.04	0.13	0.16	3.07/0.42	0.16	0.24	0.39	0.47
B2466	2.3/0.35	0.01	0.04	0.09	0.09	3.07/0.42	0.11	0.17	0.23	0.24
B2456	2.3/0.35	0.01	0.06	0.11	0.12	3.07/0.42	0.12	0.20	0.27	0.30
P7903	2.3/0.35	0.02	—	0.05	0.13	3.07/0.42	0.10	—	0.18	0.30
P7654	2.3/0.35	0.05	—	0.09	0.17	3.07/0.42	0.18	—	0.27	0.41
P7566	2.3/0.35	0.03	—	0.07	0.14	3.07/0.42	0.05	—	0.14	0.26
P7557	2.3/0.35	0.03	—	0.08	0.15	3.07/0.42	0.08	—	0.18	0.30
P7467	2.3/0.35	0.01	—	0.05	0.12	3.07/0.42	0.09	—	0.18	0.31
B2464	2.3/0.19	0.01	0.03	0.12	0.26	3.07/0.70	0.21	0.46	0.98	1.76
B2458	2.3/0.19	0.01	0.01	0.07	0.15	3.07/0.70	0.11	0.29	0.62	1.12
B2457	2.3/0.19	0.01	0.02	0.08	0.16	3.07/0.70	0.10	0.27	0.62	1.06
B2455	2.3/0.19	0.01	0.07	0.13	0.21	3.07/0.70	0.25	0.51	0.71	0.98
B2436	2.3/0.19	0.01	0.09	0.18	0.55	3.07/0.70	0.37	0.87	1.31	3.46
B2434	2.3/0.19	0.01	0.04	0.11	0.27	3.07/0.70	0.13	0.35	0.71	1.56
B2433	2.3/0.19	0.02	0.08	0.15	0.22	3.07/0.70	0.10	0.35	0.56	0.83
B2432	2.3/0.19	0.04	0.14	0.30	0.55	3.07/0.70	0.18	0.52	1.13	2.13
B2409	2.3/0.19	0.02	—	0.19	0.43	3.07/0.70	0.13	—	0.72	1.64
B2408	2.3/0.19	0.02	—	0.25	0.44	3.07/0.70	0.19	—	0.99	1.73
B2407	2.3/0.19	0.02	—	0.22	0.38	3.07/0.70	0.15	—	0.84	1.47
B2406	2.3/0.19	0.02	—	0.17	0.36	3.07/0.70	0.16	—	0.94	1.91
B2382	2.3/0.19	0.03	—	0.21	0.66	3.07/0.70	0.36	—	0.96	2.66
B2381	2.3/0.19	0.04	—	0.22	0.50	3.07/0.70	0.20	—	0.87	1.94
B2376	2.3/0.19	0.01	—	0.11	0.35	3.07/0.70	0.22	—	0.71	2.09
B2375	2.3/0.19	0.02	—	0.10	0.36	3.07/0.70	0.18	—	0.57	1.98

^{a,b,c} and ^{d} represent 15, 100, 400 and 9,000 rad/h respectively.

Previous Samples: Type II RICC

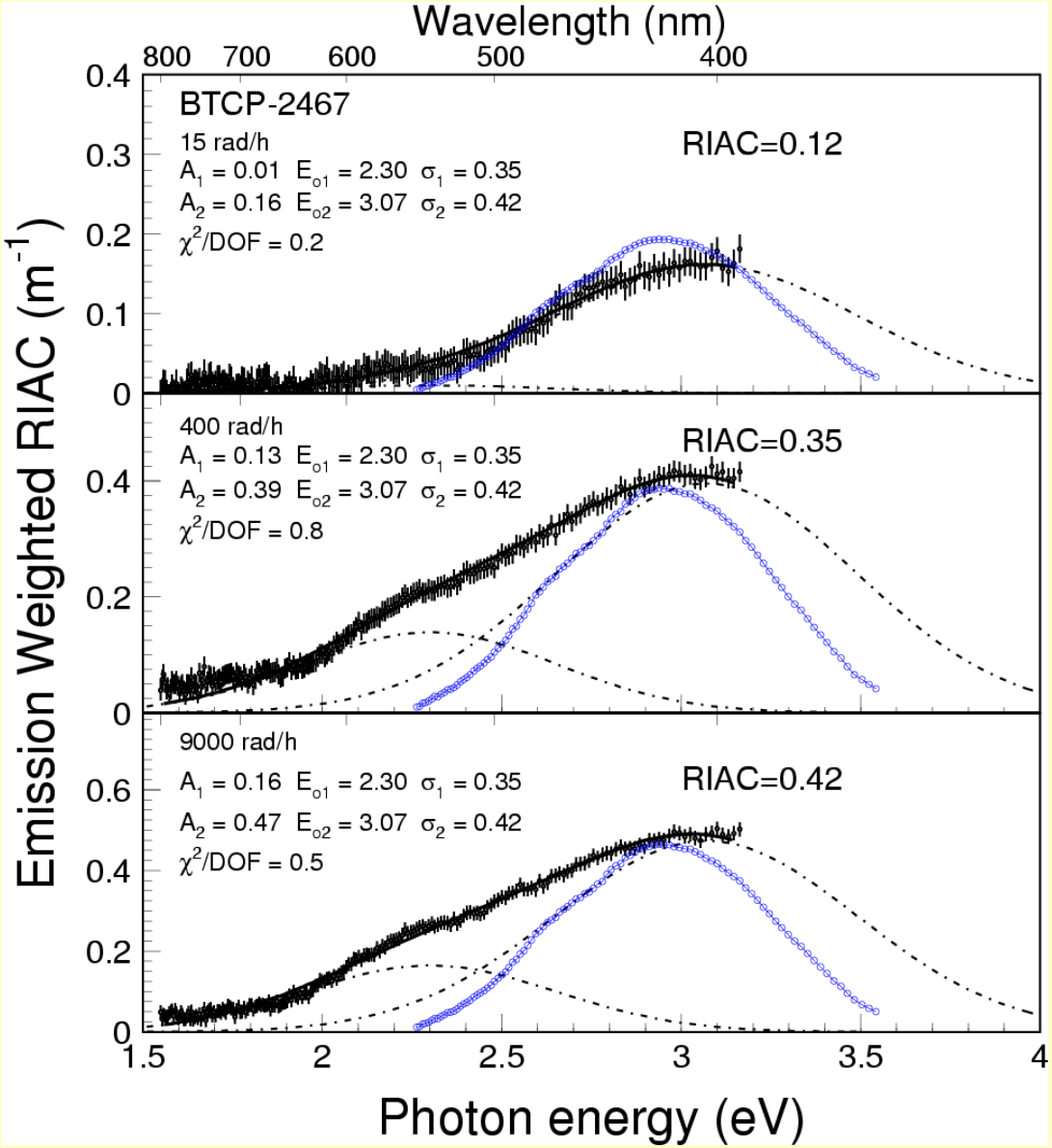




C_1: 2.30 eV (540 nm) / 0.19 eV

C_2: 3.07 eV (400 nm) / 0.76 eV

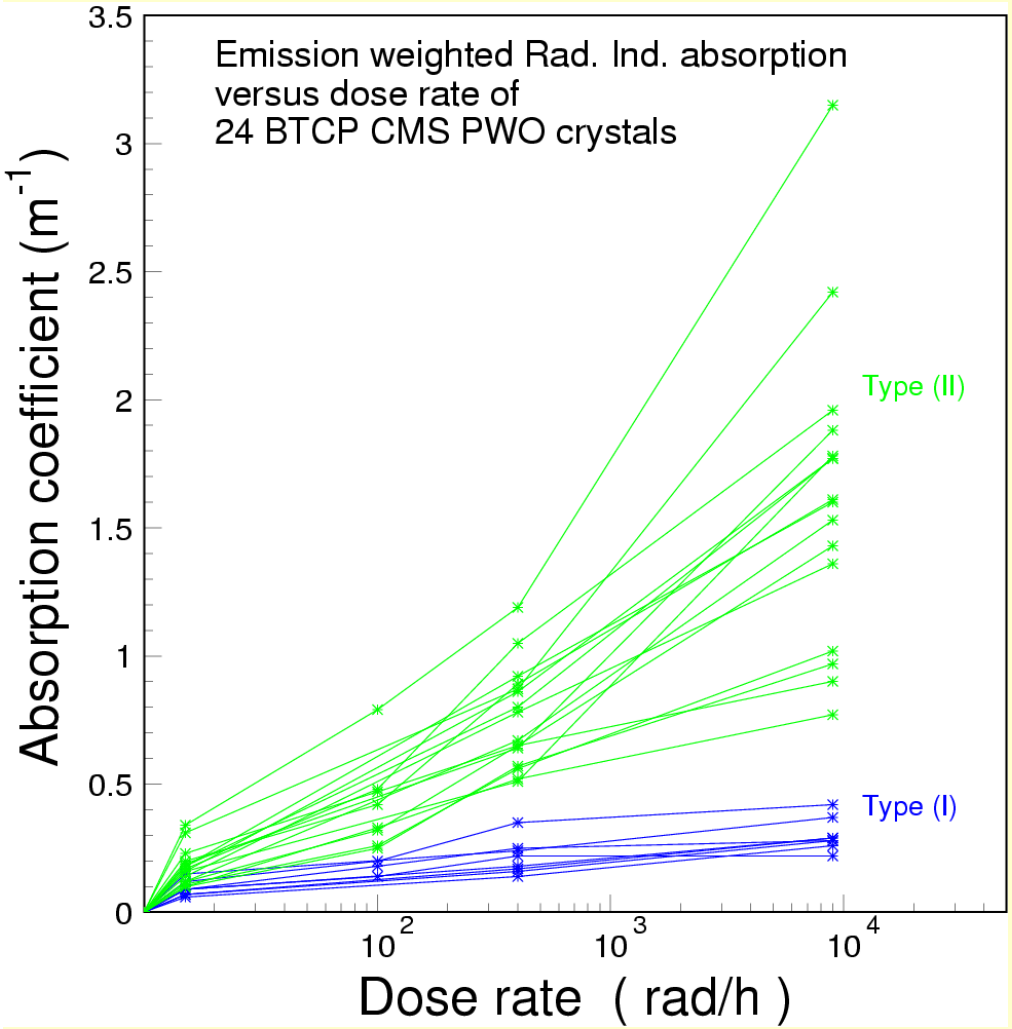
Emission Weighted RIAC (I)

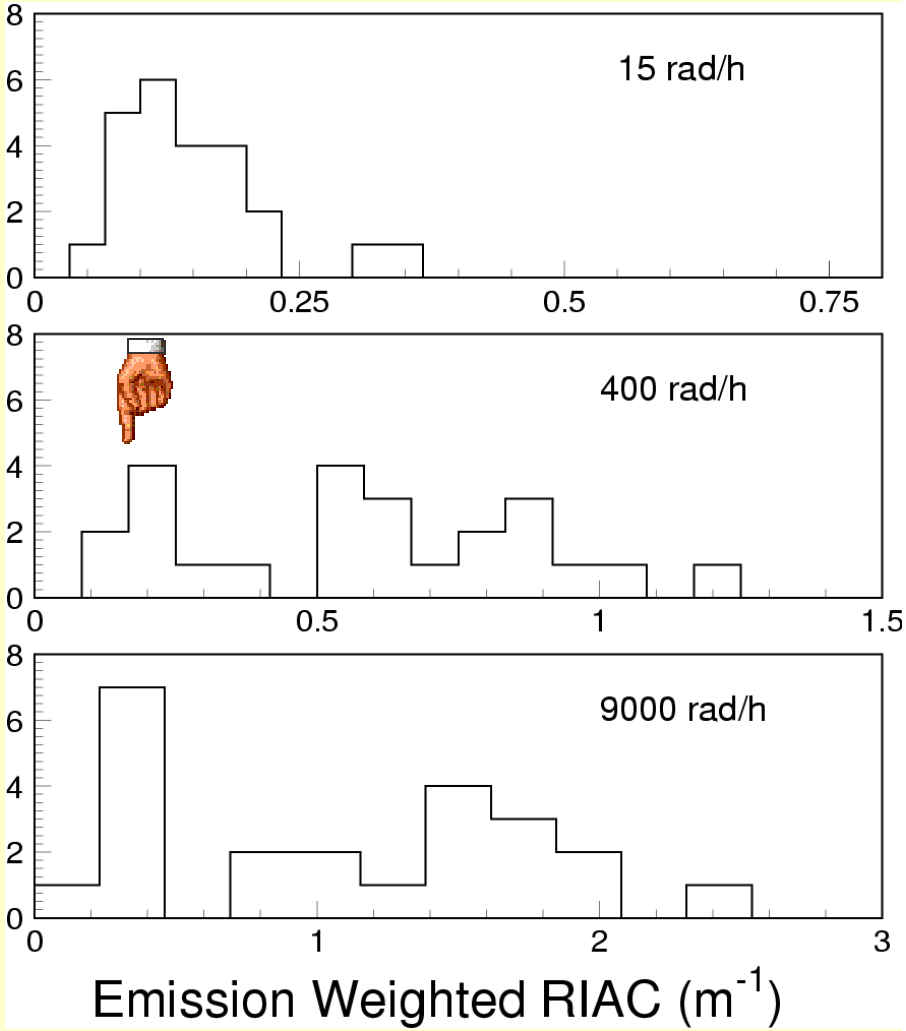


Sample ID	Dose Rate (rad/h) 15	100	400	9000
B2467	0.12	0.20	0.35	0.42
B2466	0.09	0.14	0.22	0.22
B2456	0.09	0.18	0.25	0.28
P7903	0.09	—	0.18	0.29
P7654	0.15	—	0.24	0.37
P7566	0.06	—	0.14	0.26
P7557	0.07	—	0.17	0.29
P7467	0.07	—	0.16	0.28
B2464	0.20	0.42	0.89	1.61
B2458	0.11	0.26	0.56	1.02
B2457	0.10	0.25	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

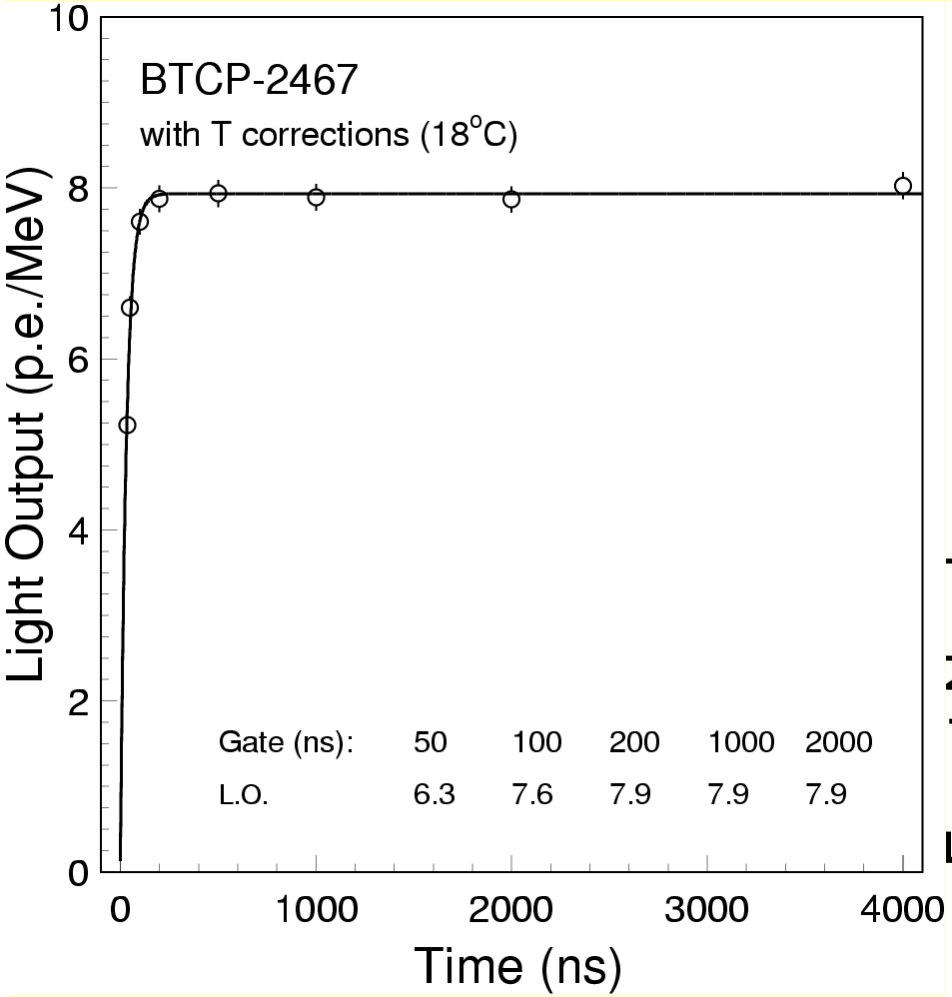
Emission Weighted RIAC (II)

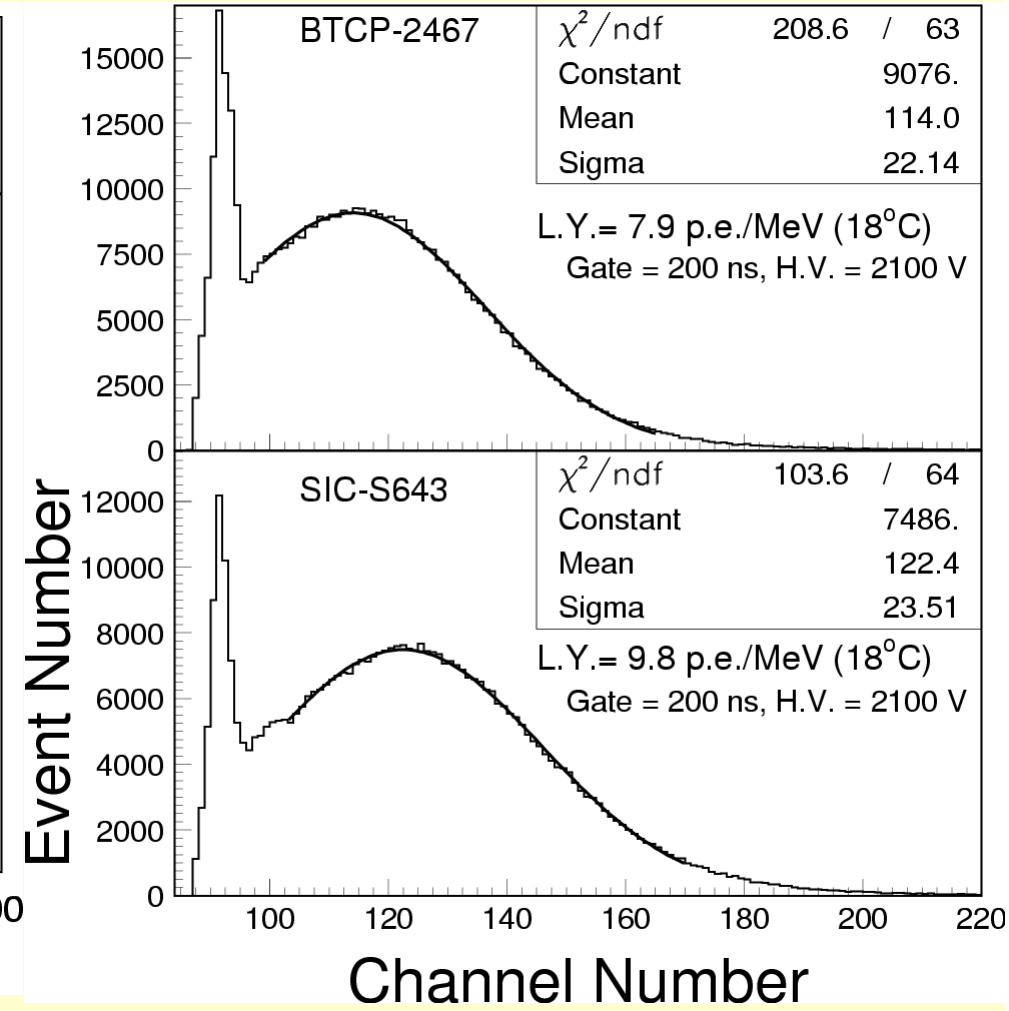
24 Crystals in Two Types





Light Output and Decay Kinetics

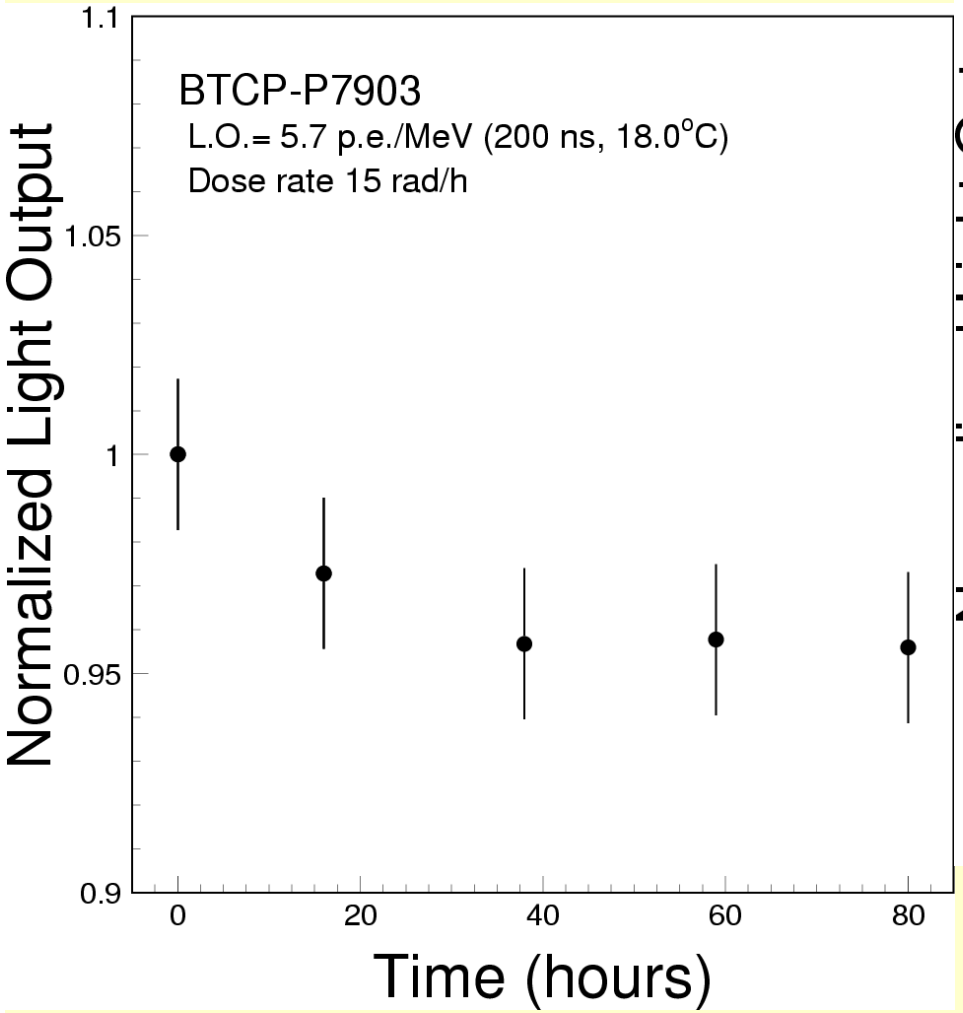


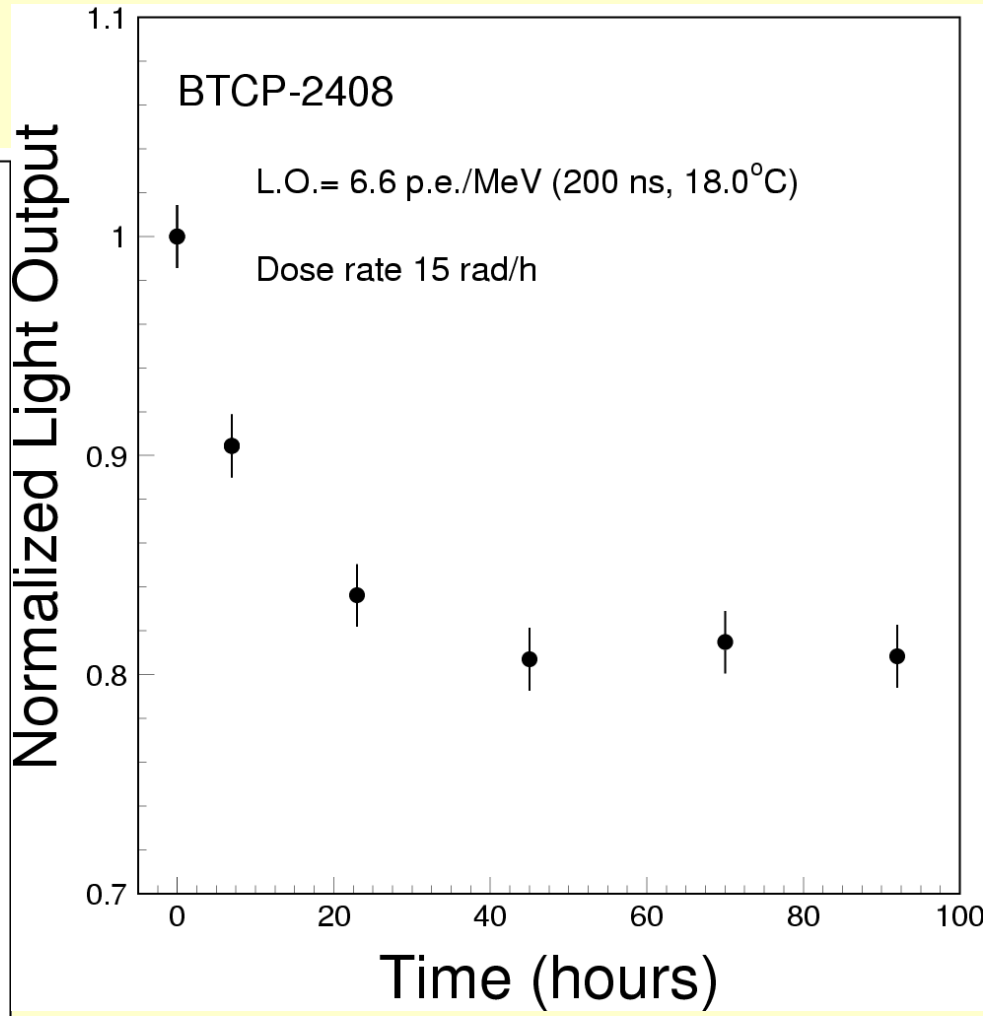


All samples have fast, but low, light output

Light Output Degradation

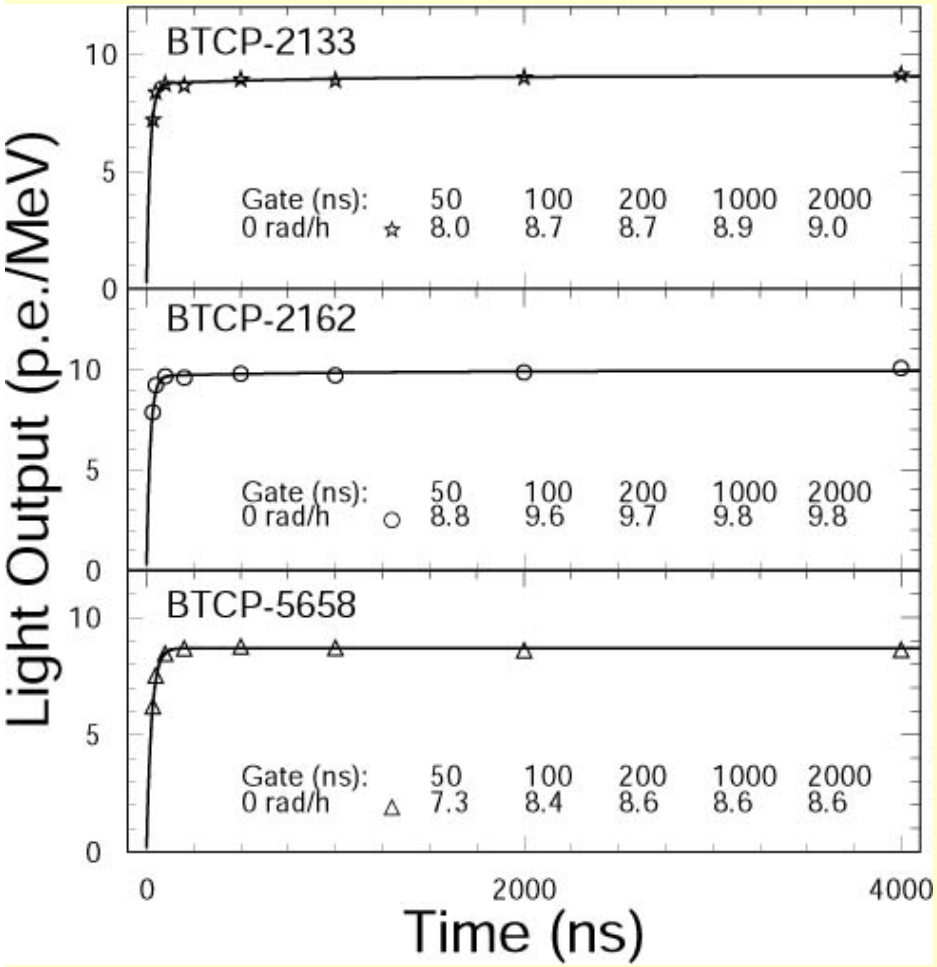
Type I sample



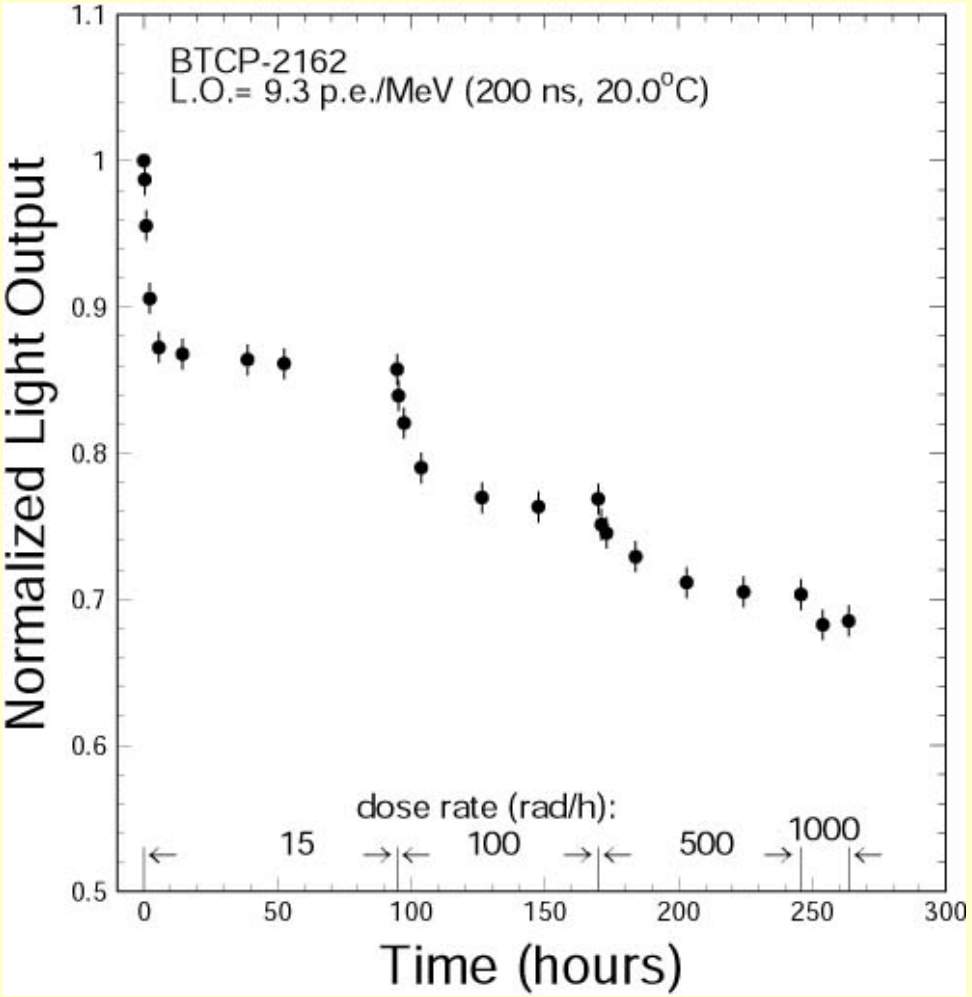


Type II sample

A Comparison with Previous Samples

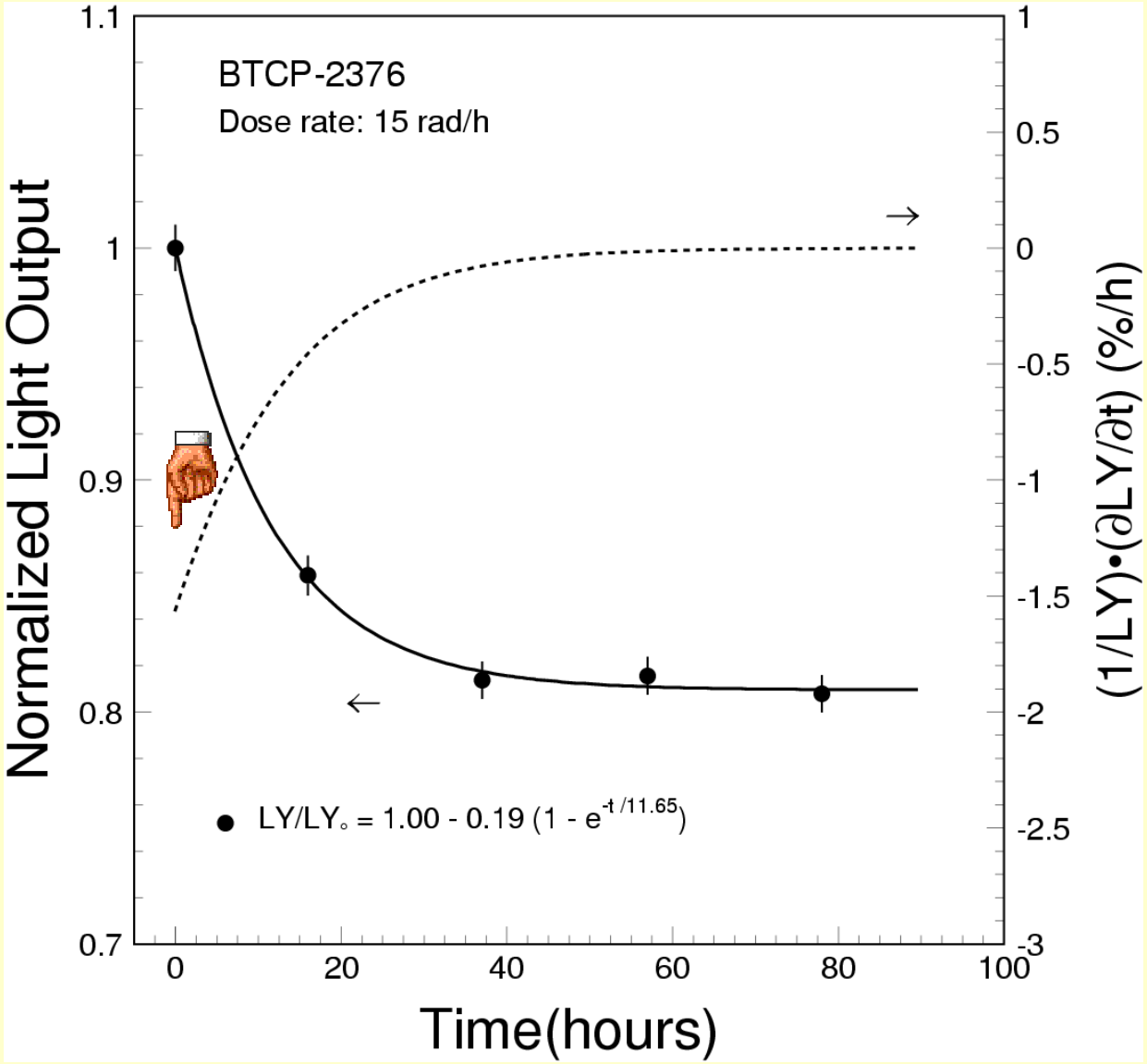


15/30% loss under 15/500 rad/h



>85/95% of light in 50/100 ns

Damage Speed and Time Constant



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

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

Summary of Light Output (I)

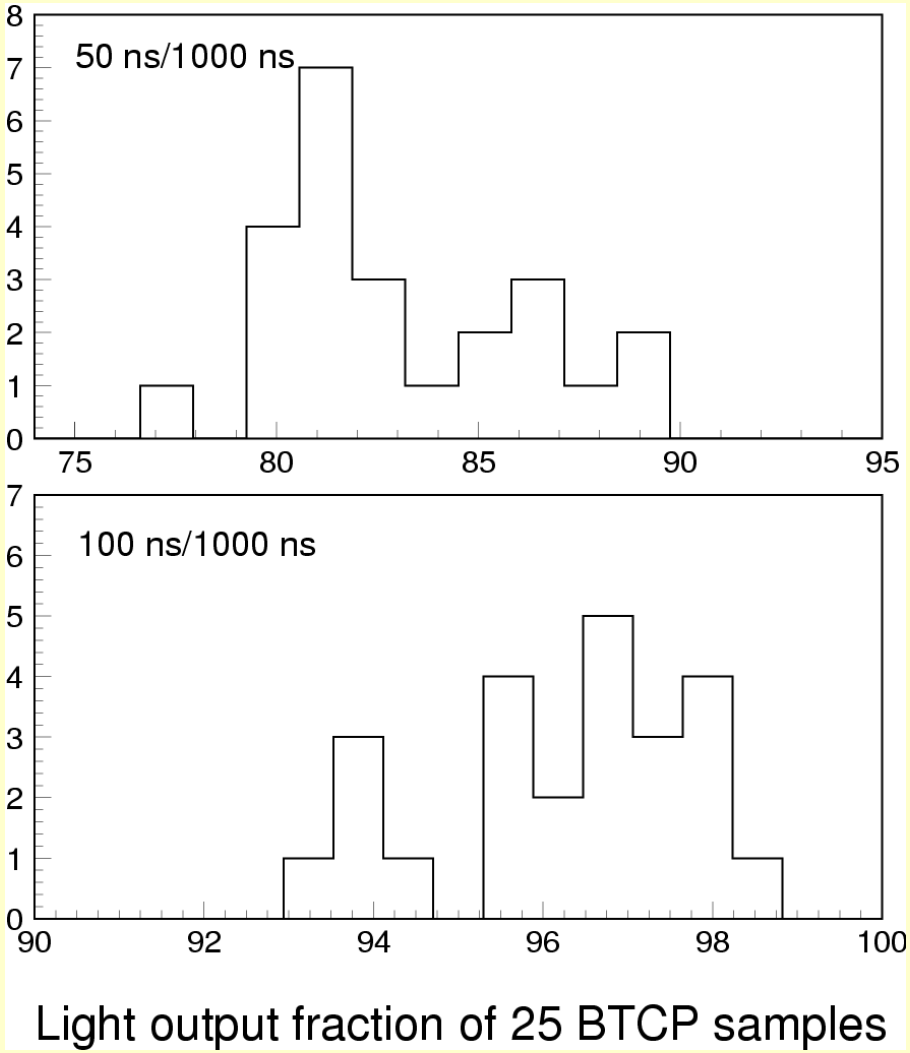
Sample ID	L.O. (1/MeV) p.e.	L.O. (1/MeV) photon	Fraction(%) $\frac{50ns}{1\mu s}$	Fraction(%) $\frac{100ns}{1\mu s}$	Δt^* (hours)	L.O.(%)	15 rad/h v_{max}^{dam}(%/h)	15 rad/h τ_d (h)
B2467	7.9	53.8	79.7	96.2	120	76.4	-6.9	3.3
B2466	6.9	47.6	80.9	97.1	96	83.5	-7.3	2.3
B2456	6.3	43.4	77.8	93.6	240	87.8	-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	—	—

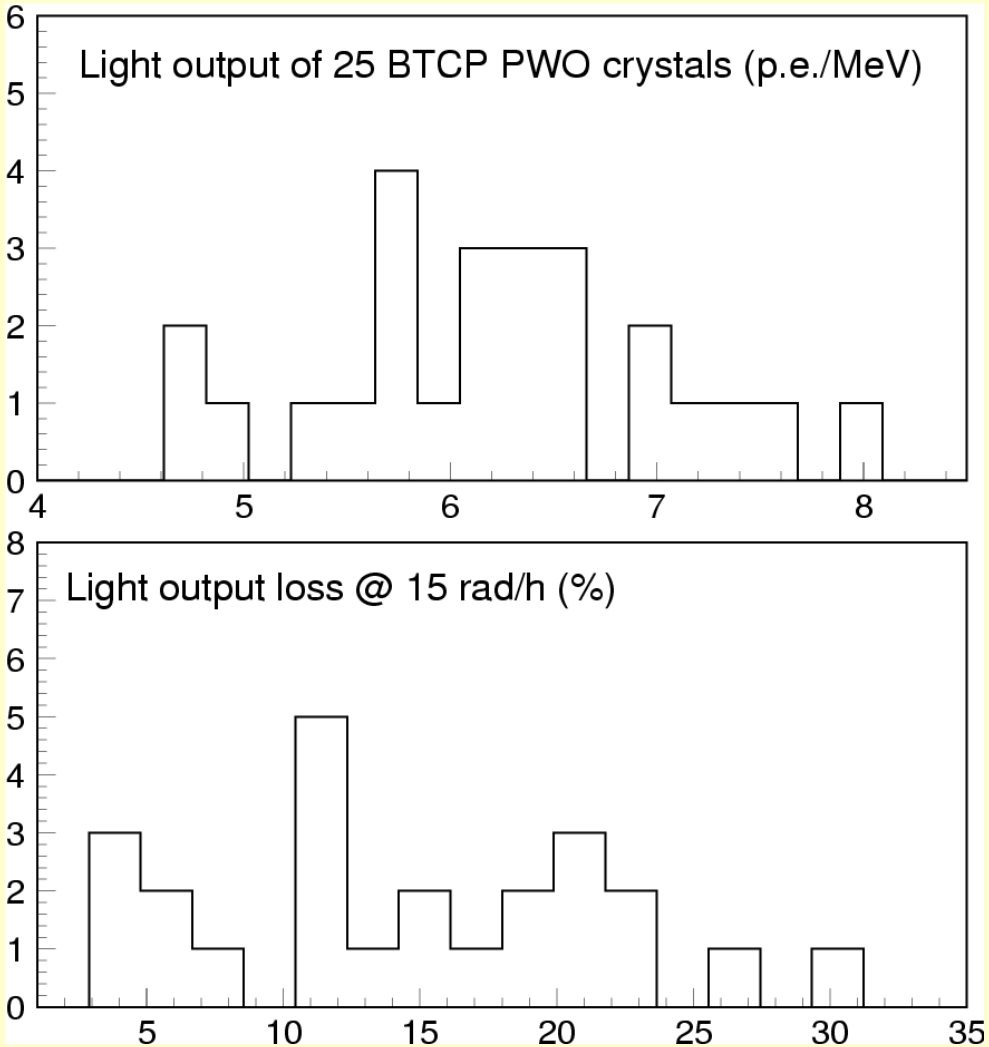
∗ time interval between annealing and initial measurement.

Type I: 5–20% loss @15 rad/h

Type II: 10–25% loss @15 rad/h

Summary of Light Output (II)





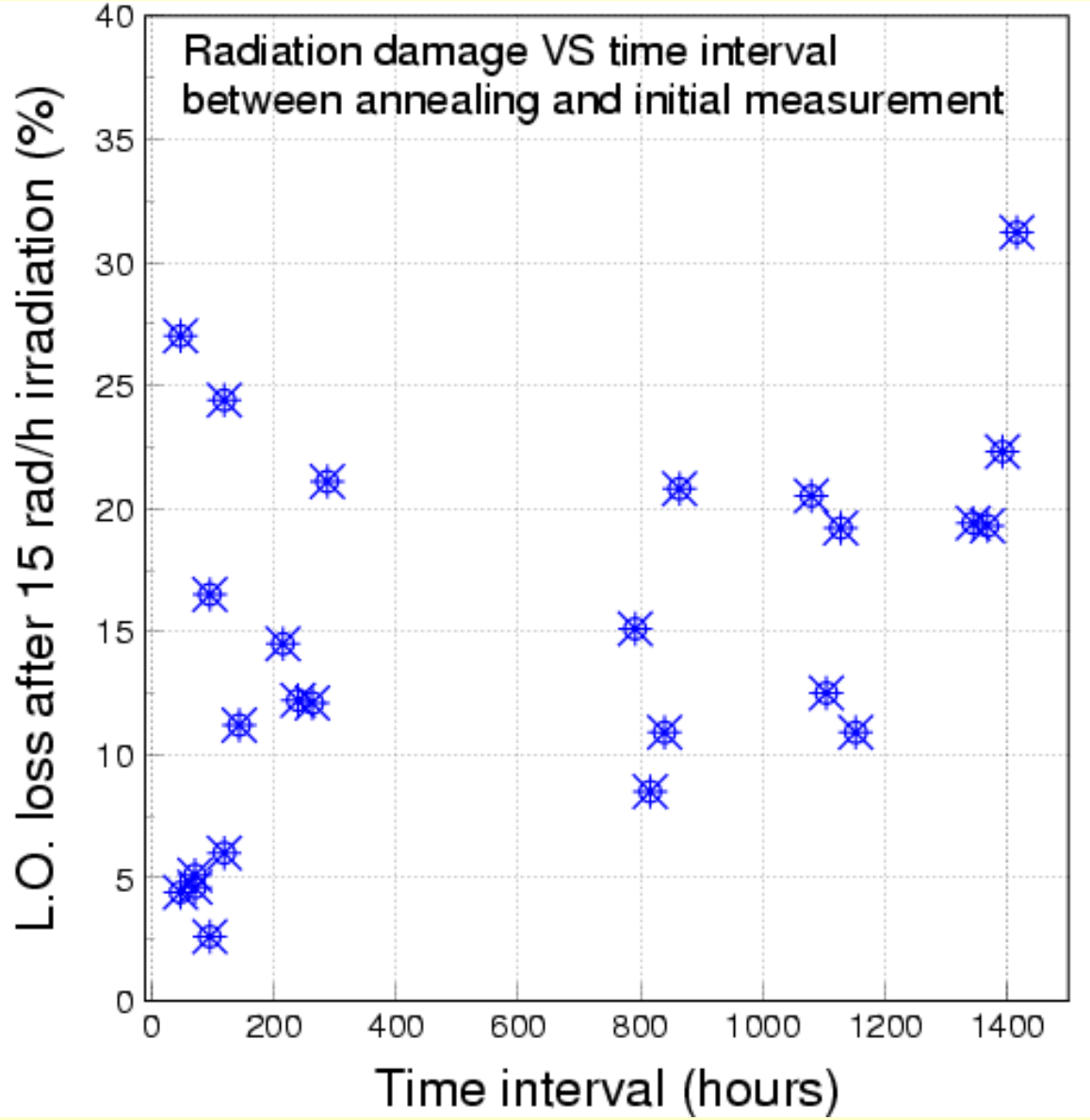
LO Summary for Previous Samples

Sample	LO (1/MeV)		Fraction (%)		LO (%) at R (rad/h)			
ID	p.e.	γ	50ns/1μs	100ns/1μs	15	100	500	1000
SIC-S301	9.4	63.5	92.0	96.6	96.6	87.3	79.5	74.3
SIC-S347	9.9	66.9	91.3	97.8	95.1	88.6	82.1	78.0
SIC-S392	8.4	56.8	92.0	97.3	98.2	91.3	83.6	80.2
SIC-S412	8.3	56.1	94.6	98.6	98.2	91.2	85.9	85.3
SIC-S643	8.9	60.1	88.8	98.9	88.3	79.8	---	---
SIC-S762	10.6	71.6	85.6	94.2	91.5	84.2	81.4	---
SIC-606	10.4	70.3	88.3	98.4	91.7	79.3	---	---
SIC-678	10.4	70.3	85.2	93.5	94.2	76.0	59.6	---
SIC-679	10.8	73.0	85.0	94.7	93.5	73.5	57.3	---
BGRI-824	11.4	77.0	83.5	95.5	89.0	78.7	69.9	---
BGRI-826	11.2	75.7	84.4	96.7	86.0	74.7	62.2	---
BTCP-2133	8.2	55.4	89.9	97.8	89.2	78.6	72.3	70.5
BTCP-2162	9.3	62.8	89.8	97.9	86.1	76.8	70.3	68.2
BTCP-5615	7.2	48.6	86.6	98.5	82.9	---	---	---
BTCP-5618	7.2	48.6	86.8	98.5	77.4	---	---	---
BTCP-5658	8.8	59.5	83.9	97.7	76.1	63.6	---	---

Summary

- 25 PWO crystals can be divided to three different types with different level of radiation damage and radiation induced color centers.
- While type II crystals are similar to previous samples, type I crystals are different and are more radiation hard: Good for the endcaps.
- Type III crystals have problem for monitoring with 440 nm light, so should be rejected.
- All samples recover after irradiation at 18^{o}C, but with at least two time constants.
- All samples have fast, but low, light output.
- No correlations between radiation hardness and initial longitudinal transmittance was observed.

LO loss versus Waiting Time



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