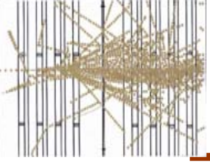

Quality of Mass Produced PWO Crystals

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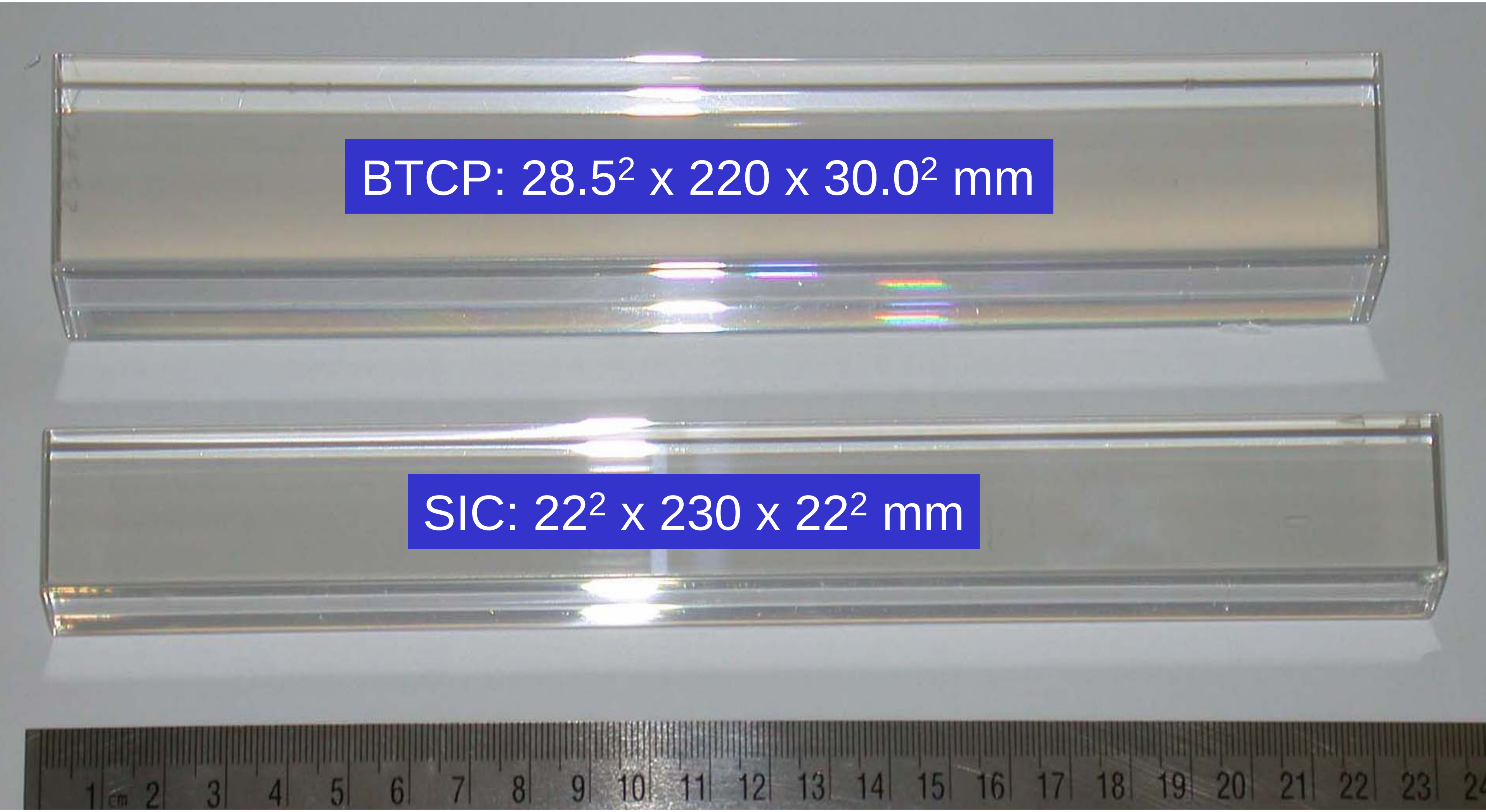
California Institute of Technology

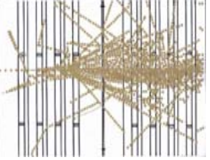
*Current address: Shanghai Institute of Ceramics, Shanghai, China

Randomly Selected PWO Samples

BTCP: 20 from 1st batch (100) for CMS endcaps

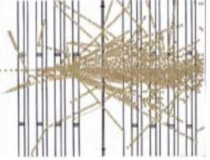
SIC: 20 from production batch for PrimEx





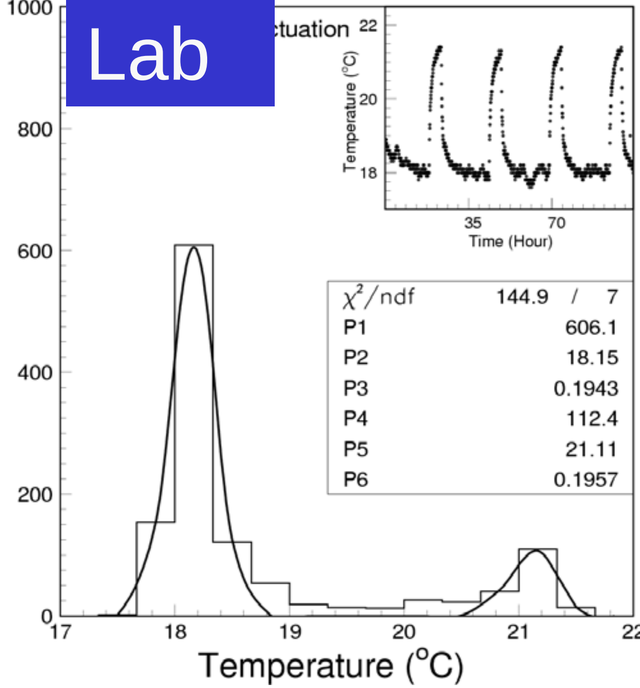
Experiment

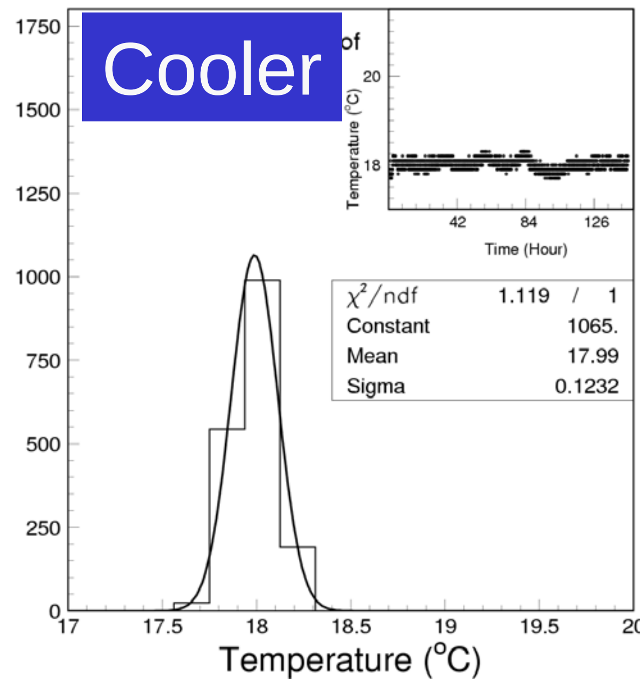
- All crystals went through (1) thermal annealing at 200^{o}C, (2) irradiations by γ–ray at 15, 400 and 9k rad/h until equilibrium and (3) recovery.
- Properties measured: Transmittance, emission and excitation spectrum, light output, decay kinetics and light response uniformity, as well as their degradation, radiation induced color center and emission weighted radiation induced absorption coefficients.
- Light output degradation was only measured at 15 rad/h because of limited light output: less than 8 p.e./MeV for BTCP samples.



Thermal Annealing

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

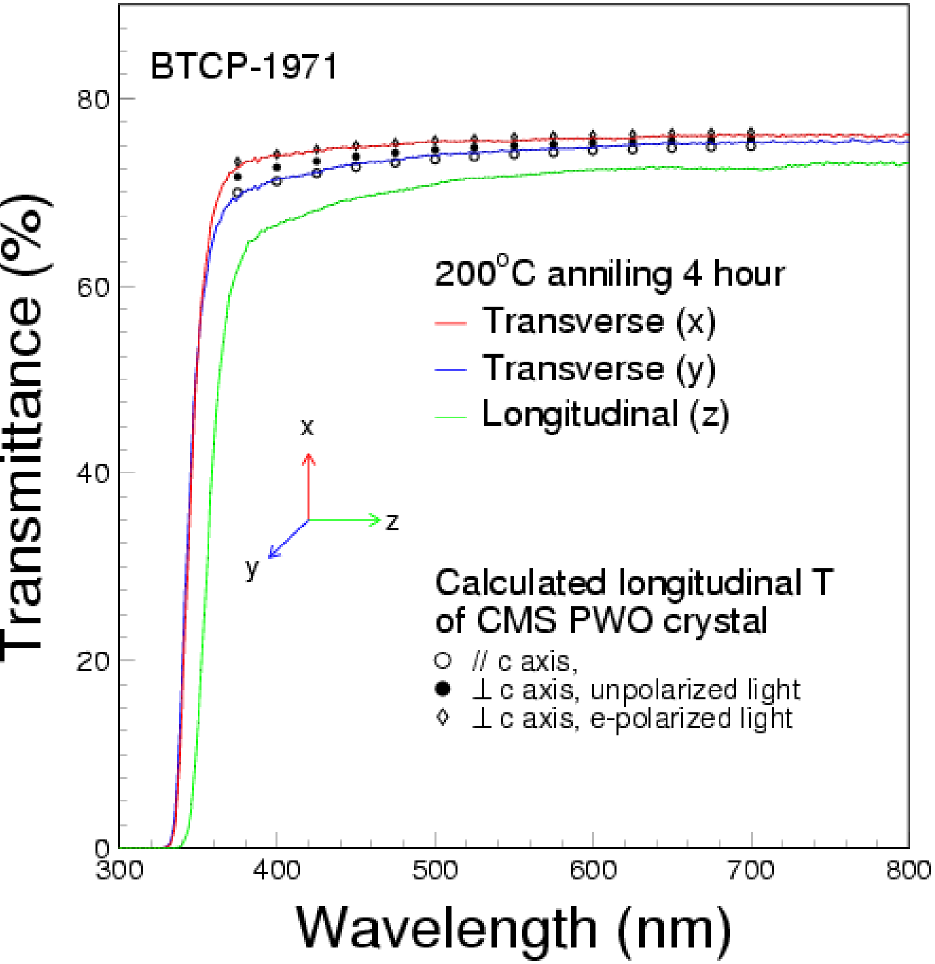




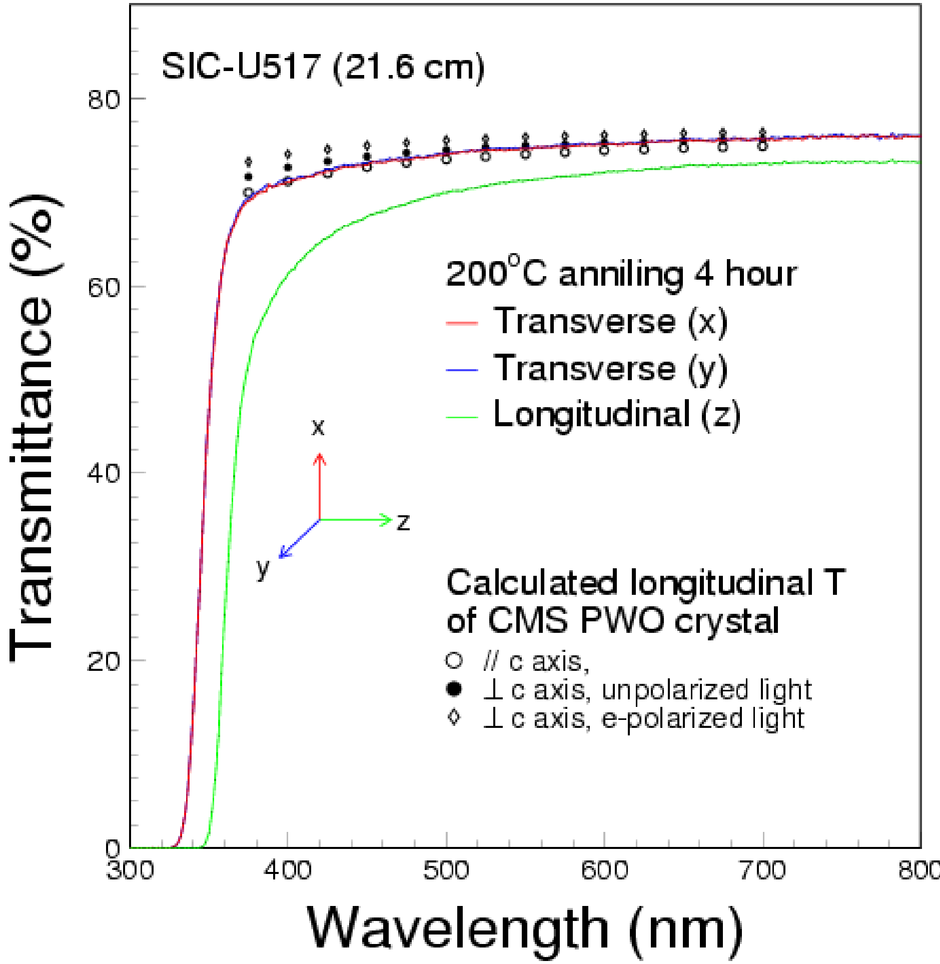
Transmittance and Birefringence

a axis: better L.T., but non-isotropic transverse T.
Both approaching theoretical limit

BTCP: grown along the ***a axis***

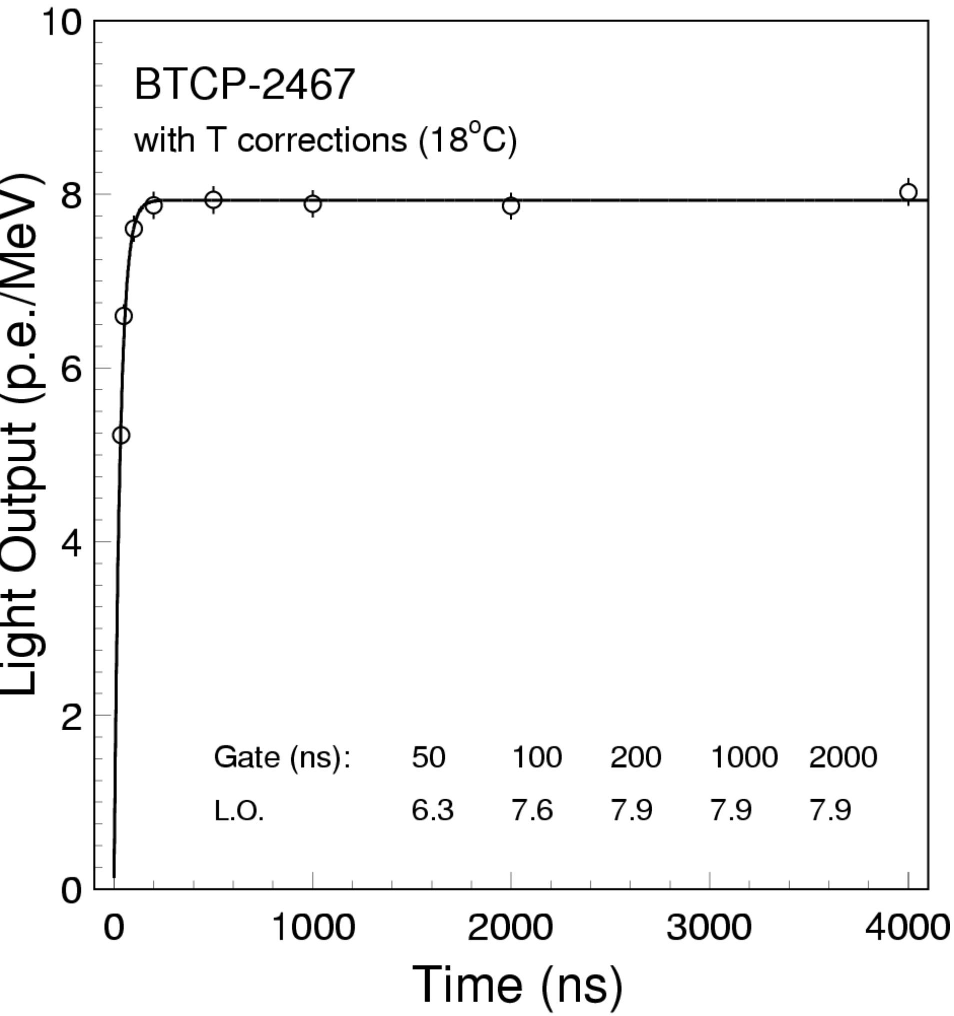


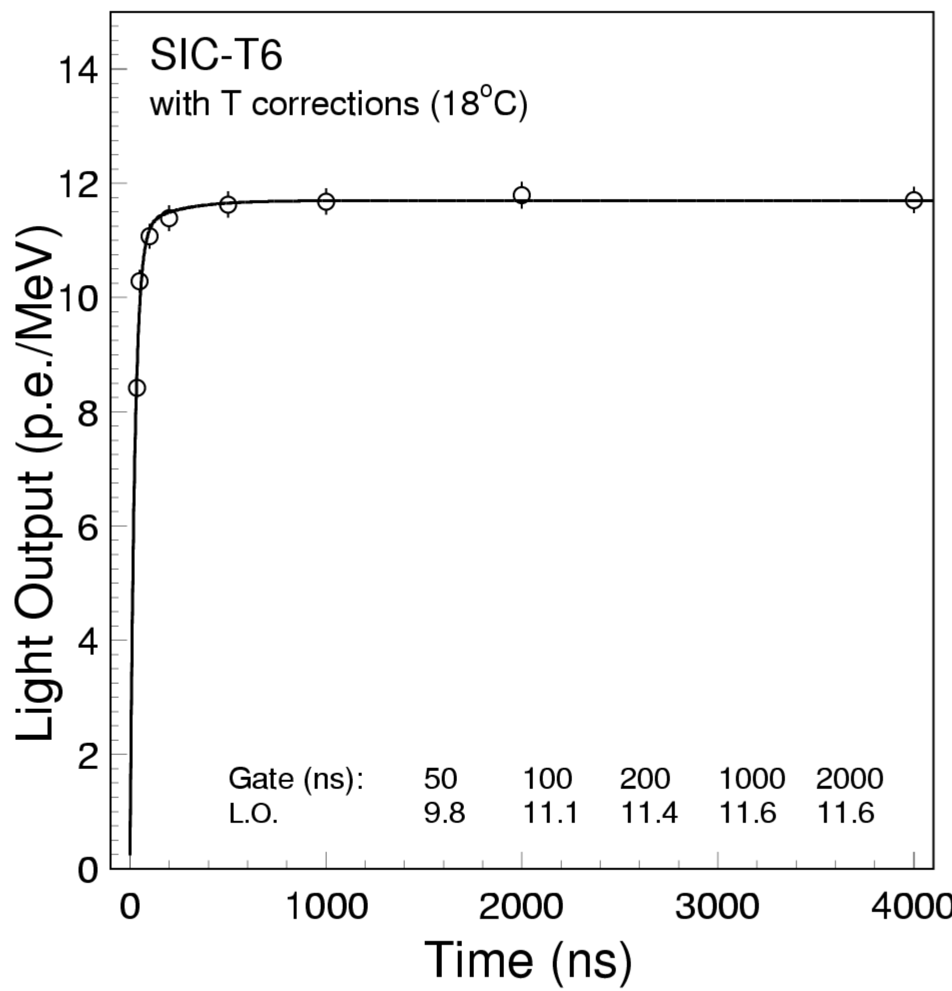
SIC: grown along the ***c axis***



Light Output and Decay Kinetics

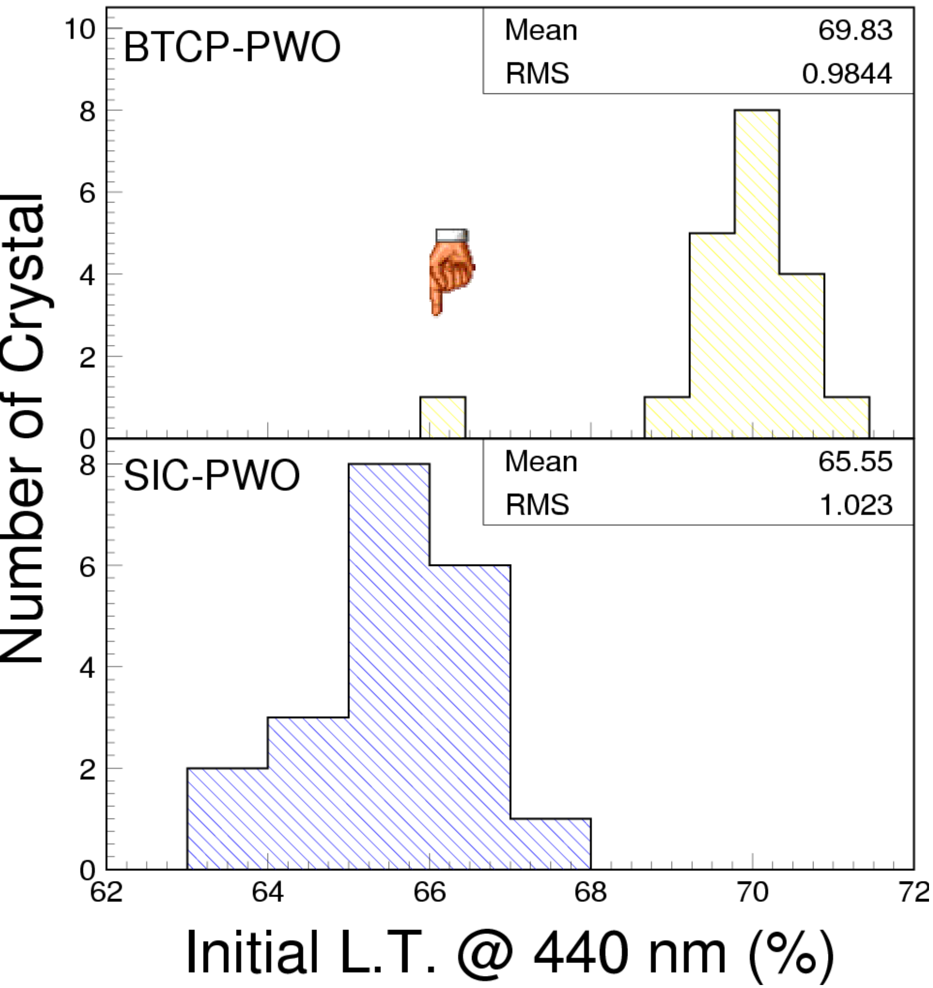
Both are fast, SIC samples have more light

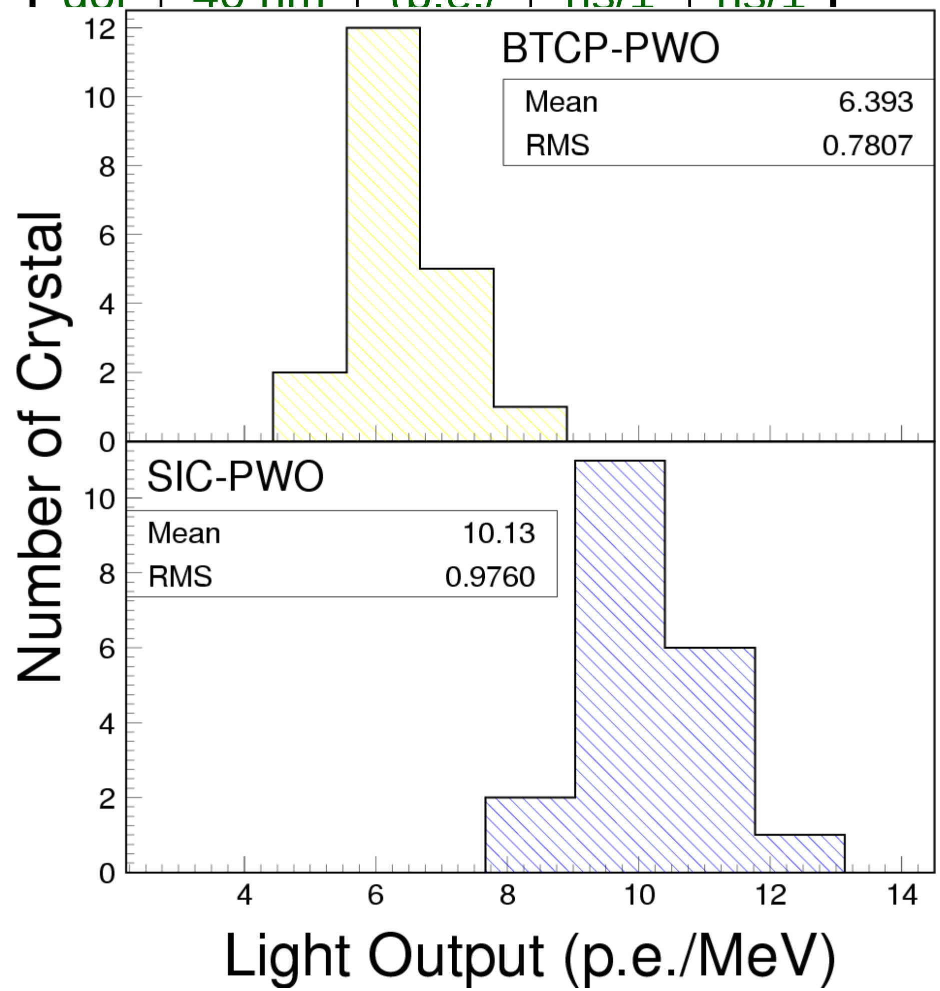




Comparison of L.T. and Light Yield

Ven dor	ILT@4 40 nm	ILO (p.e./	50 ns/1	100 ns/1

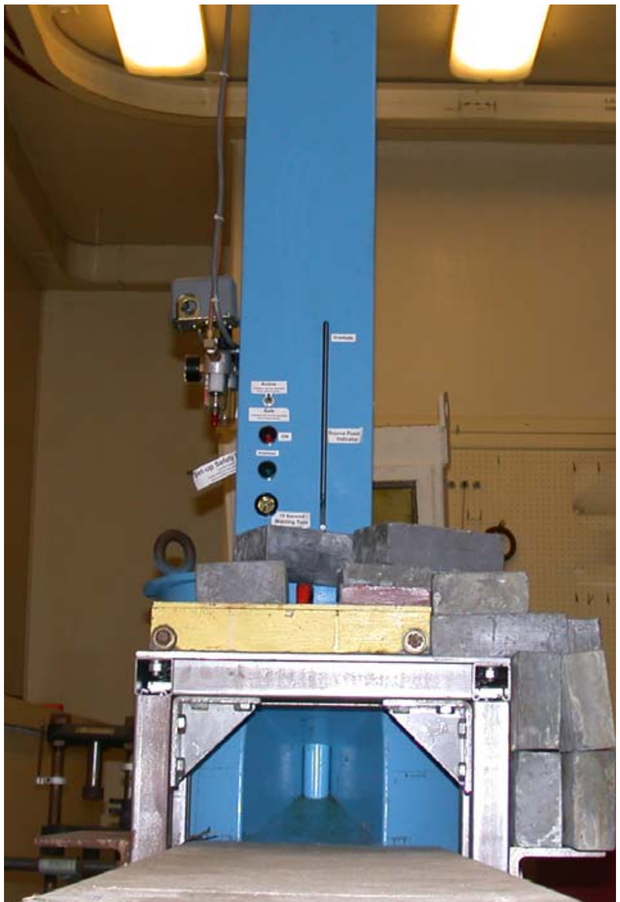


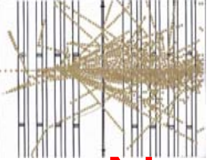


Caltech γ–ray Irradiation Facilities

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

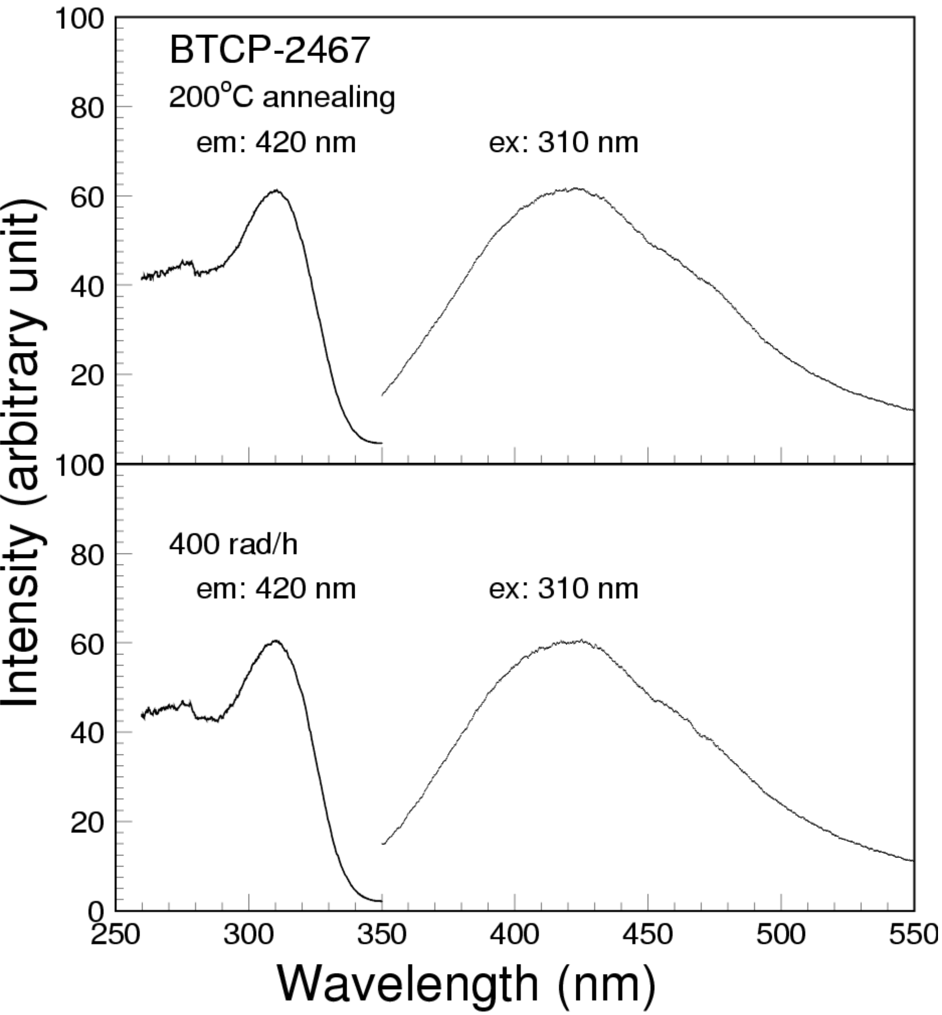


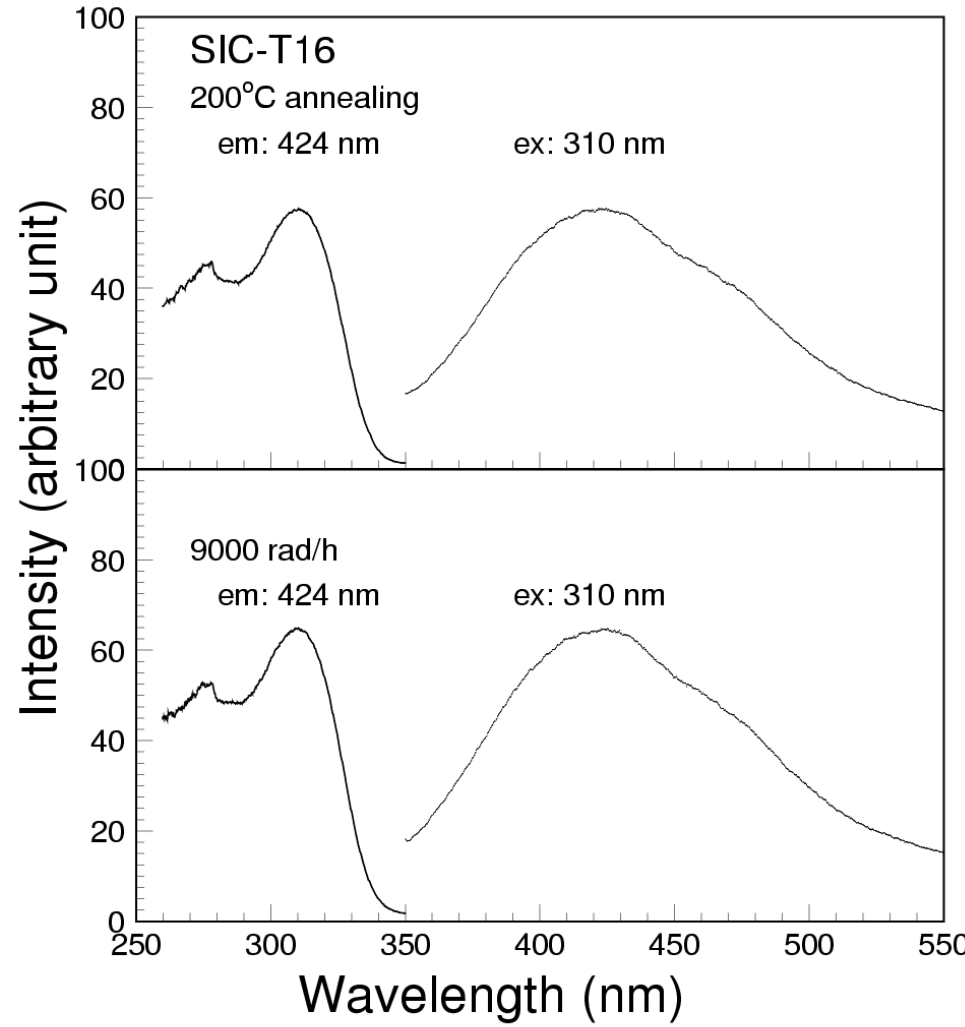


Photoluminescence

No variation in either excitation or emission spectrum

No damage in scintillation mechanism

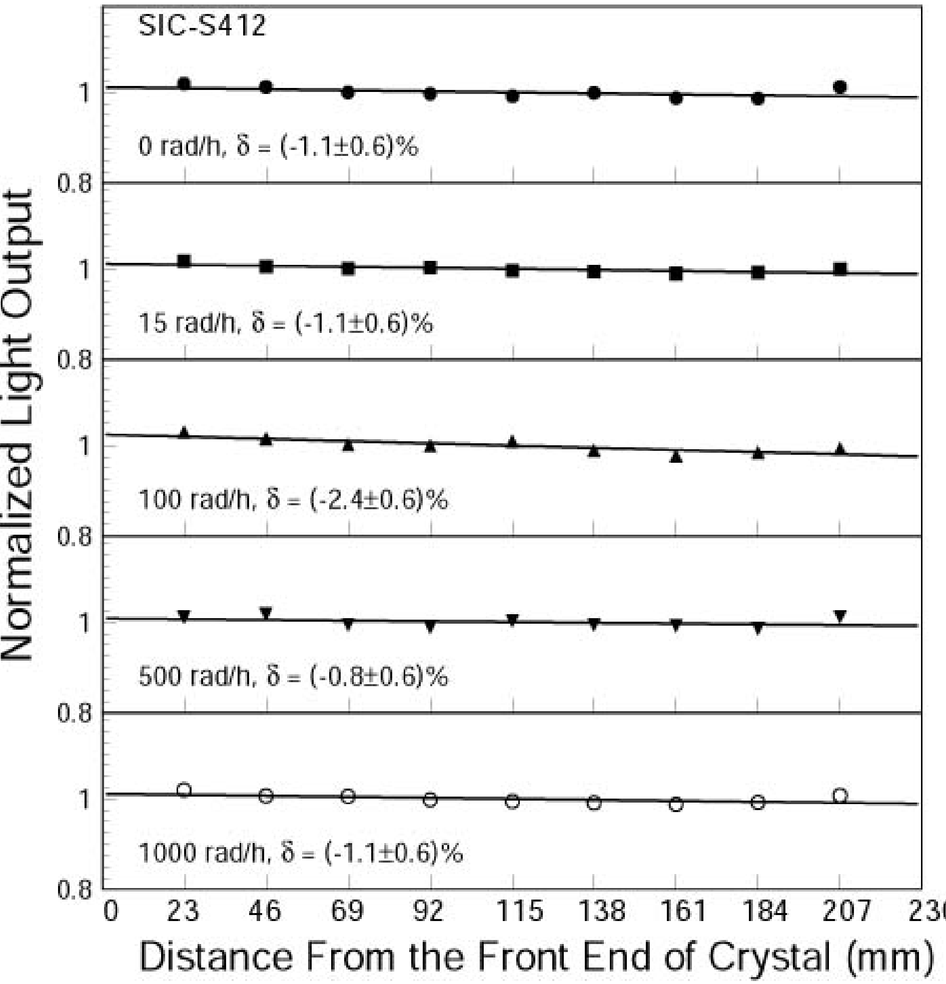


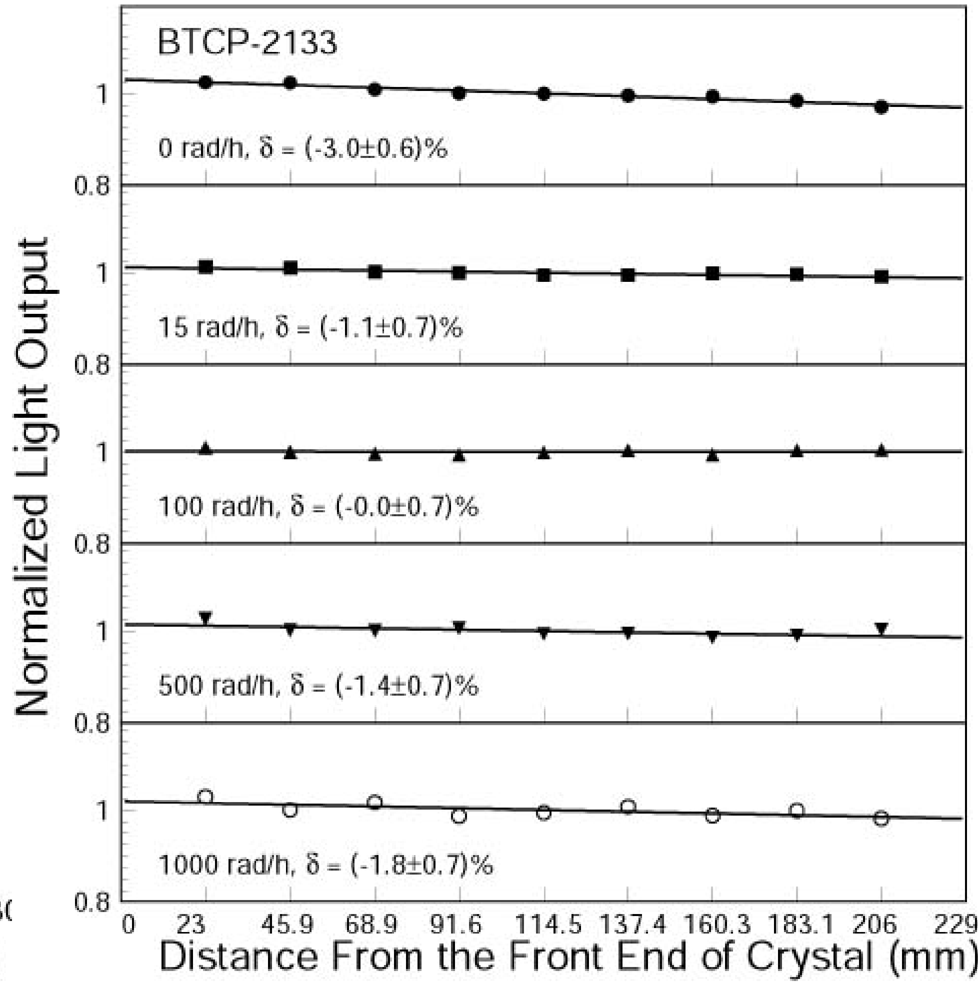


No Variation in Light Response Uniformity

The response (y) along the axis was fit to a linear function

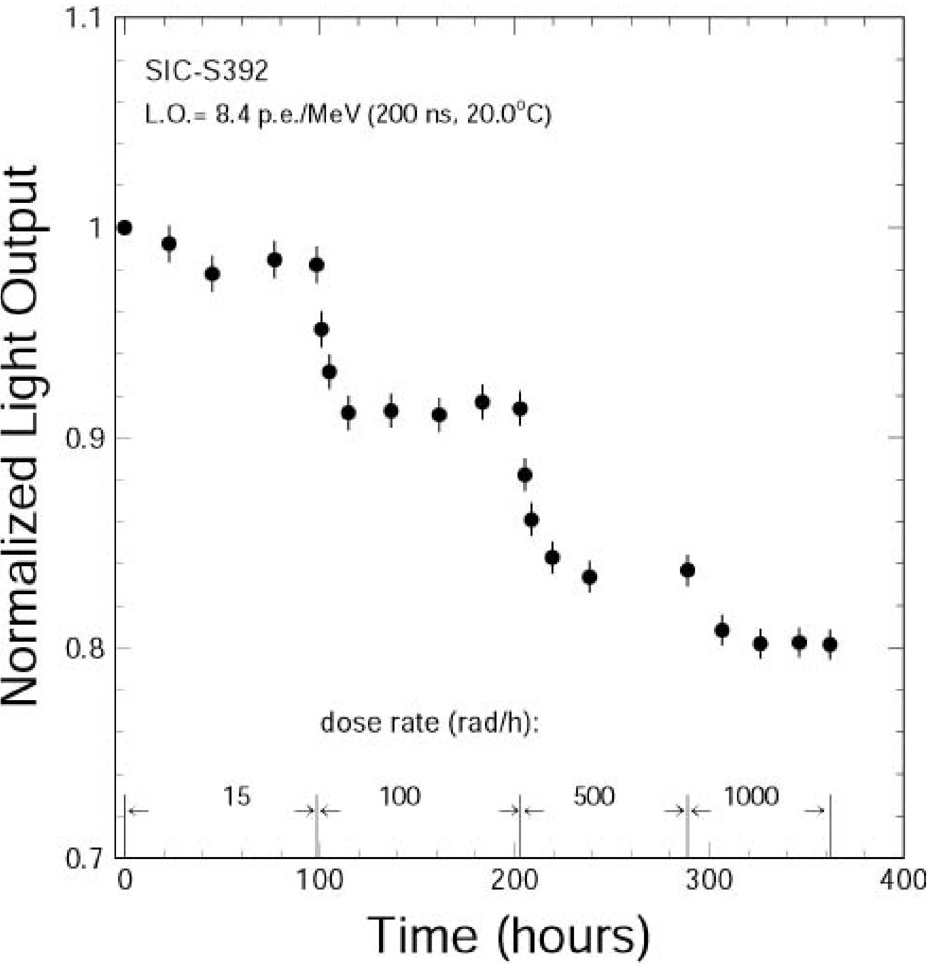
$$\frac{y}{y_{mid}} = 1 + \delta(x / x_{mid} - 1)$$

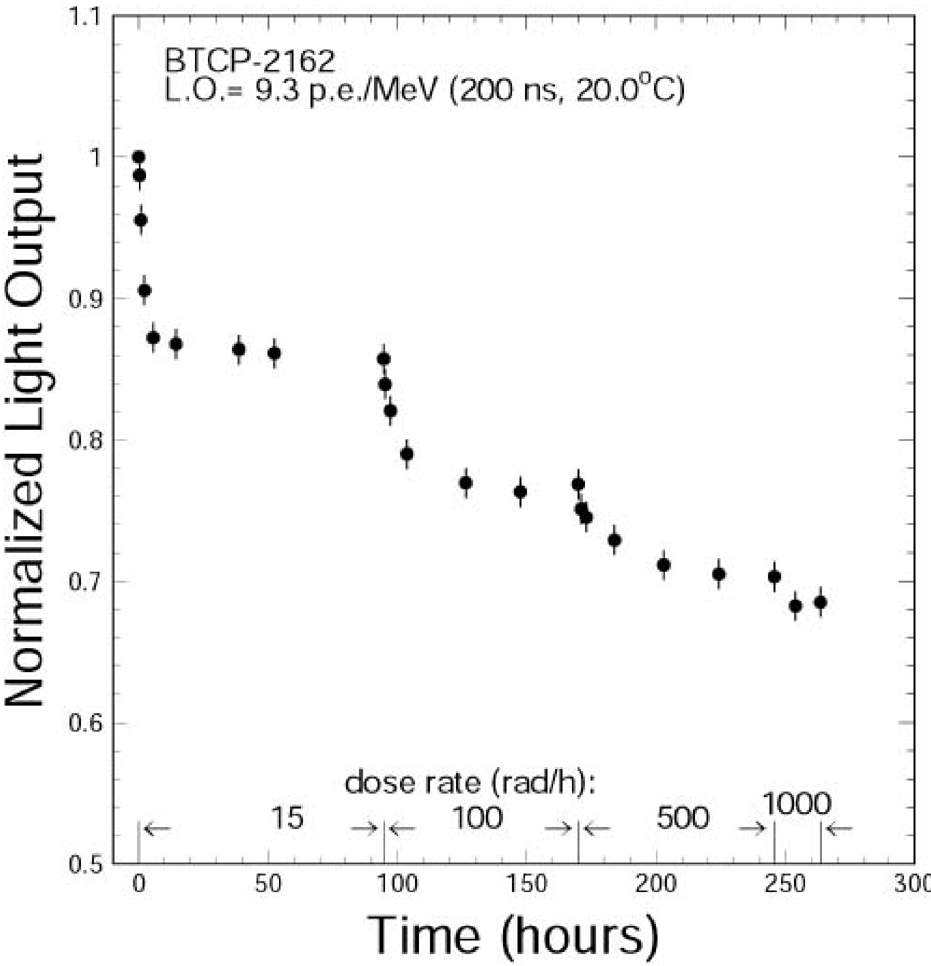




Light Output Degradation

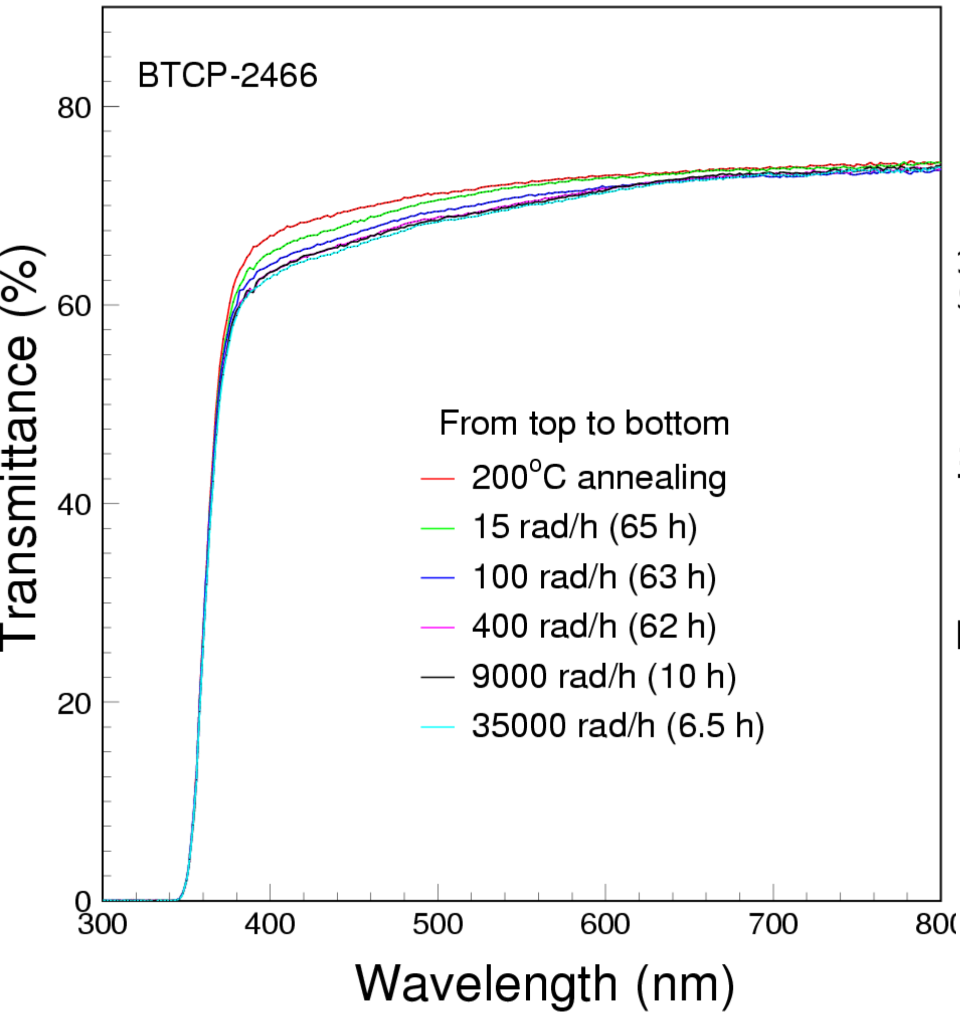
5-15% and 15-30% light output loss under 15 and 500 rad/h
Damage is dose rate dependent

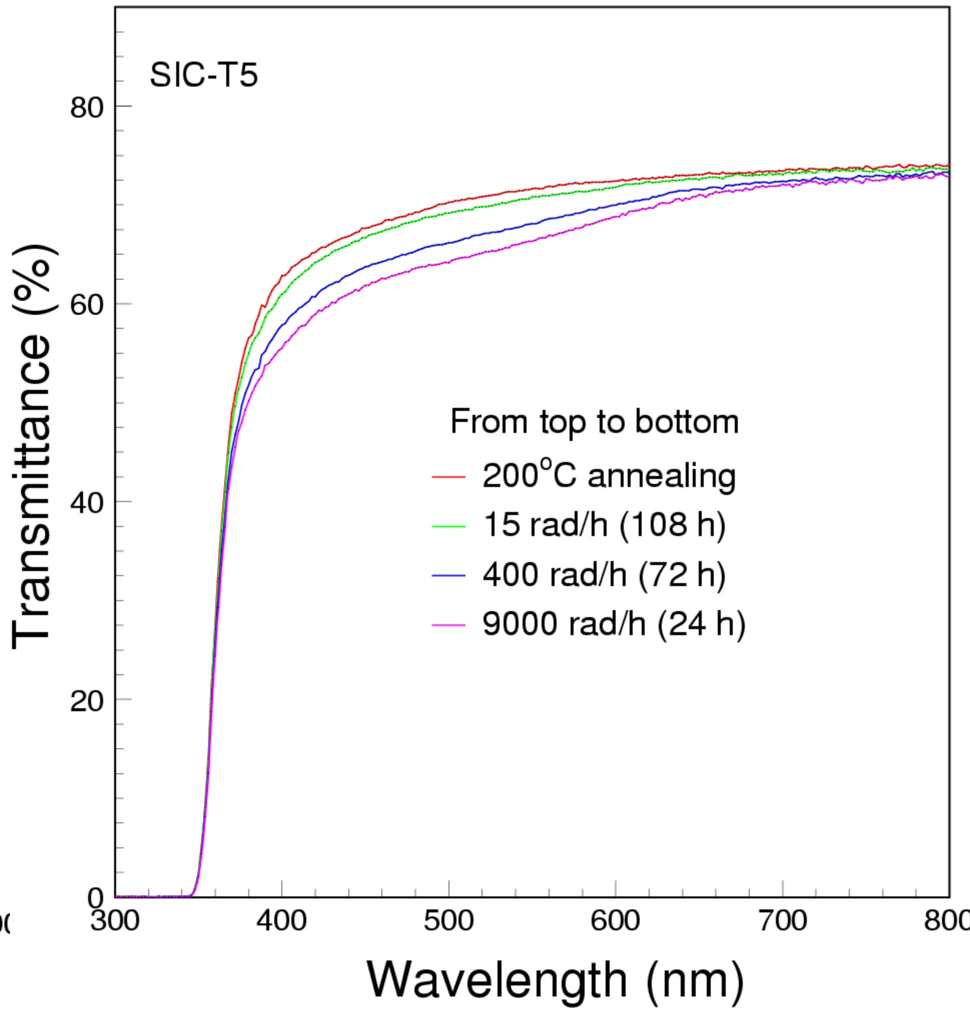




Damage in Longitudinal Transmittance

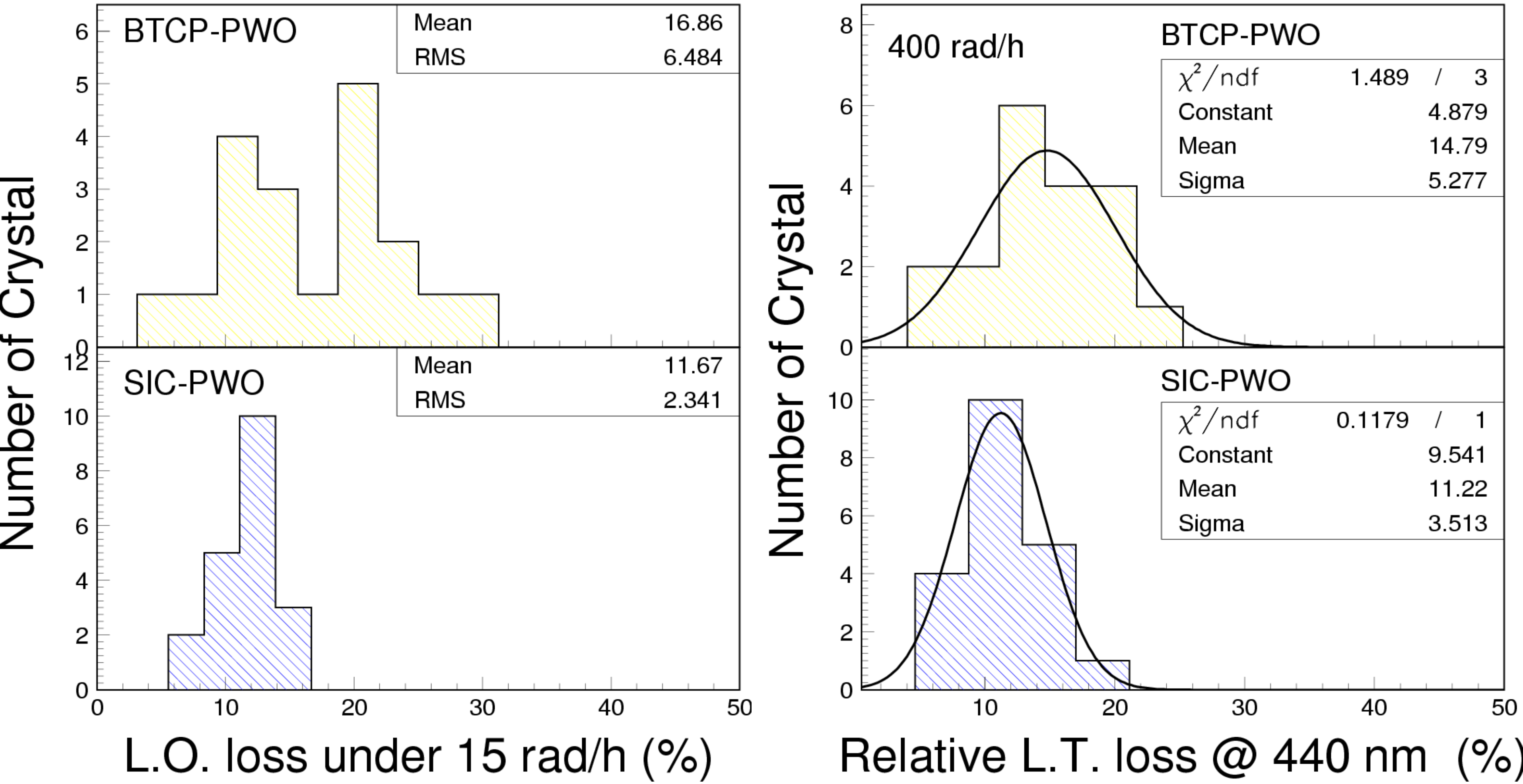
Radiation induced absorption caused by CC formation





Comparison of Radiation Damage

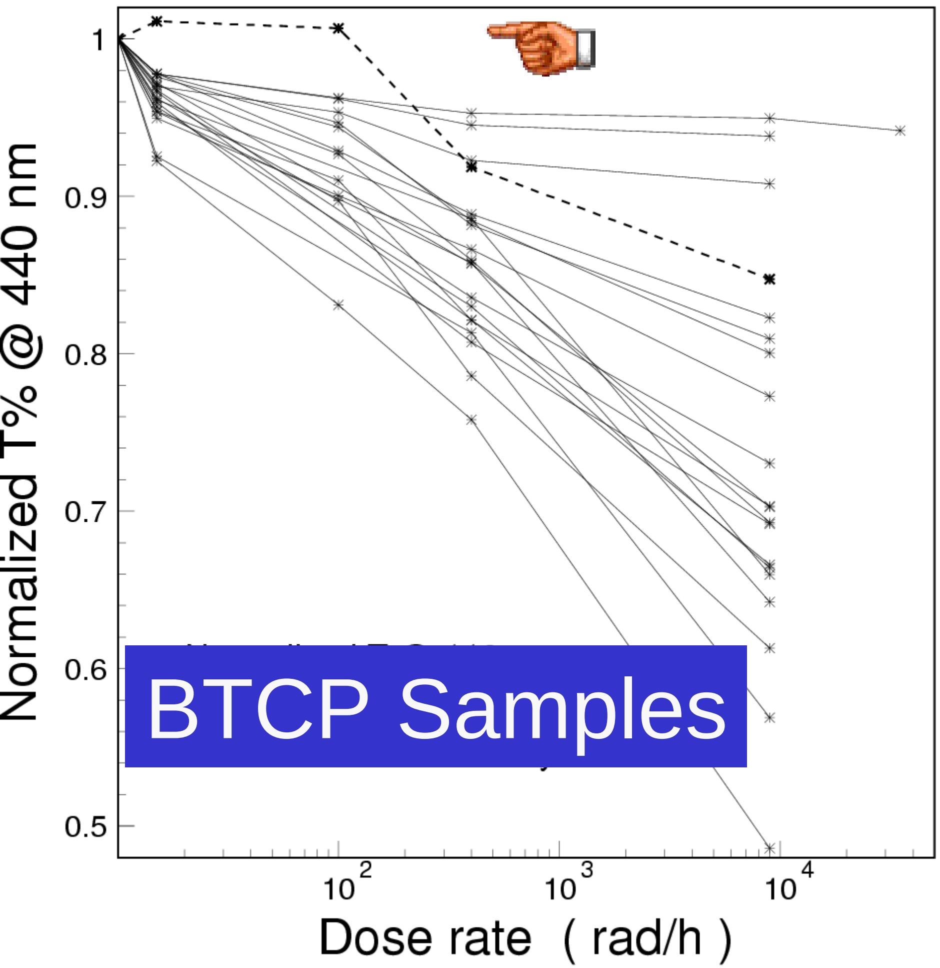
SIC samples seem more radiation hard

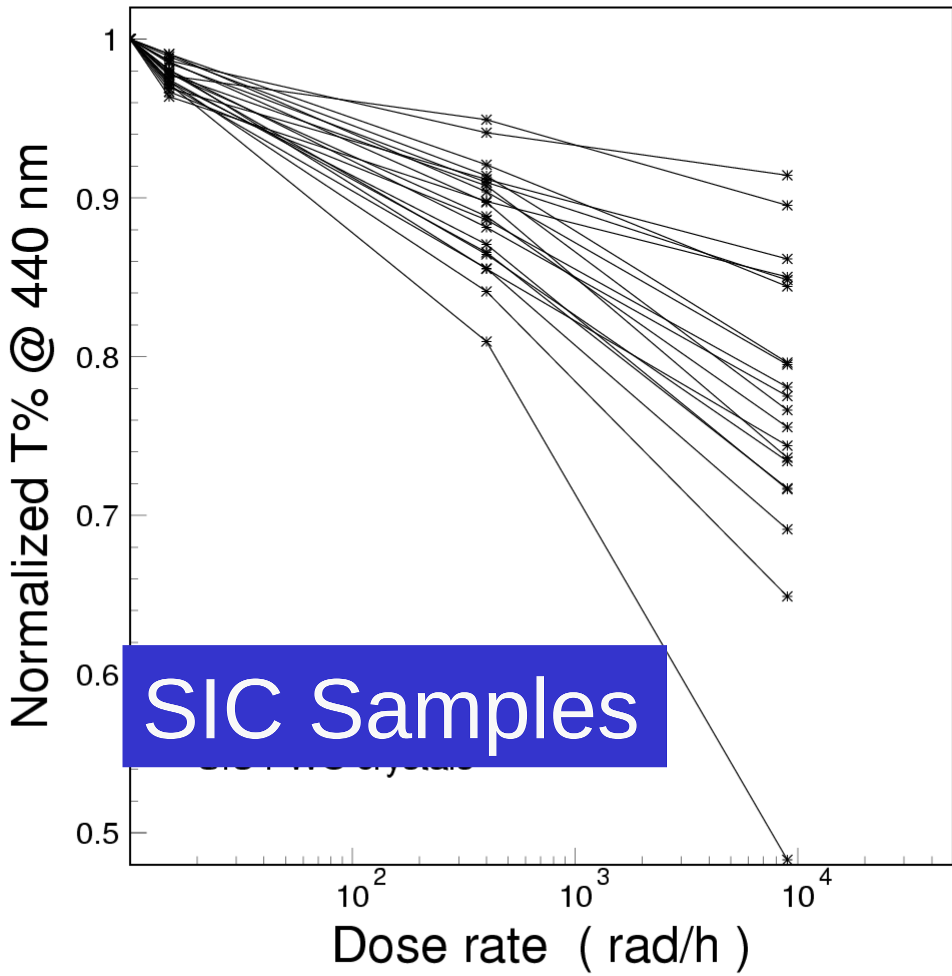


Comparison of Transmittance Loss

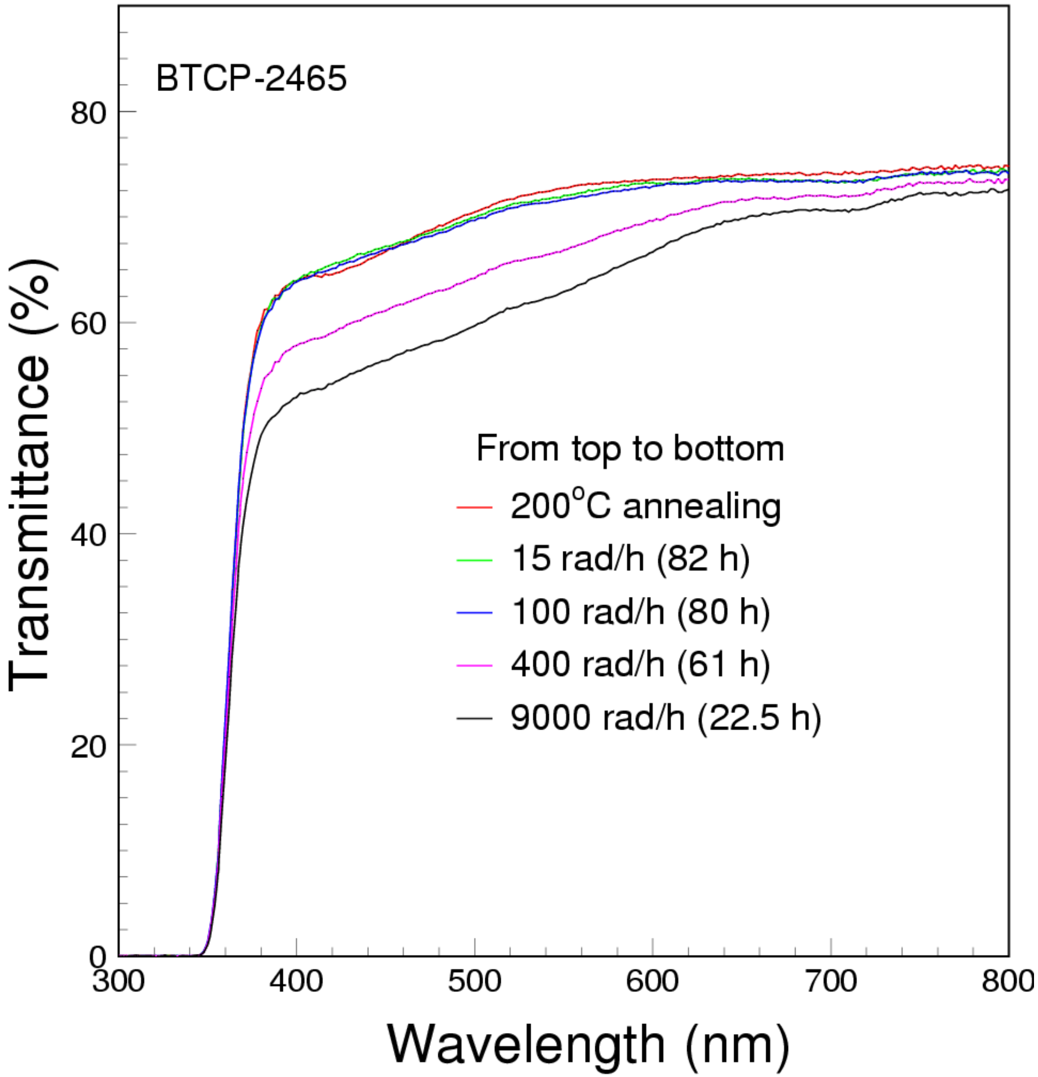
SIC samples less diverse: Bridgman technology

One BTCP sample shows LT increase under irradiation





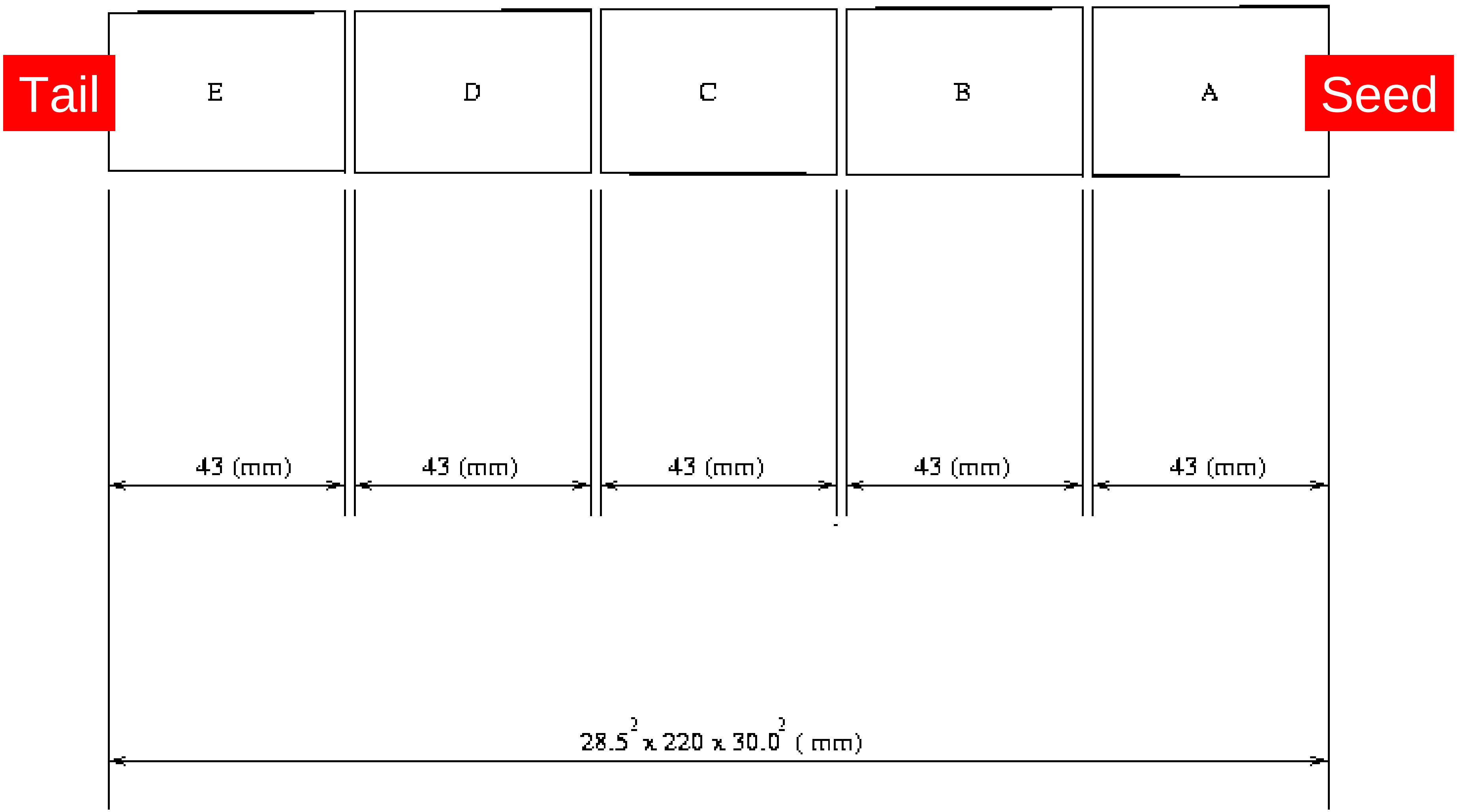
Type III Sample: Transmittance Loss



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

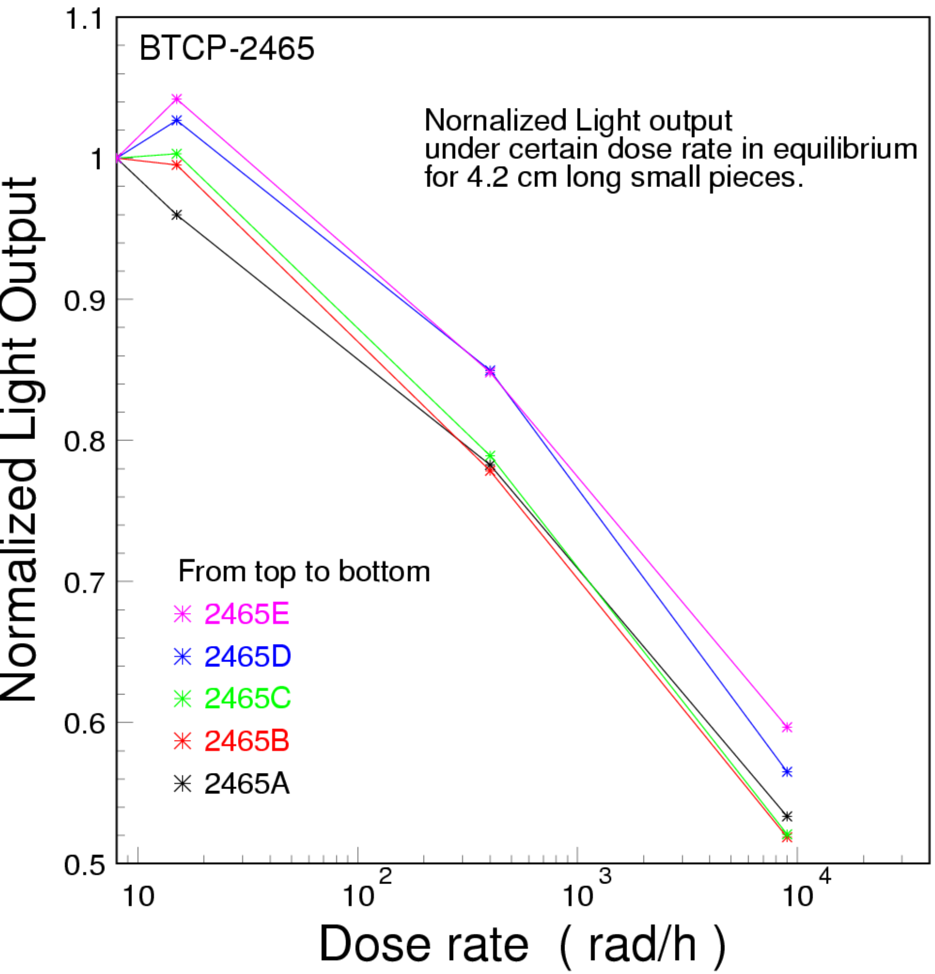
Investigation on BTCP Samples (I)

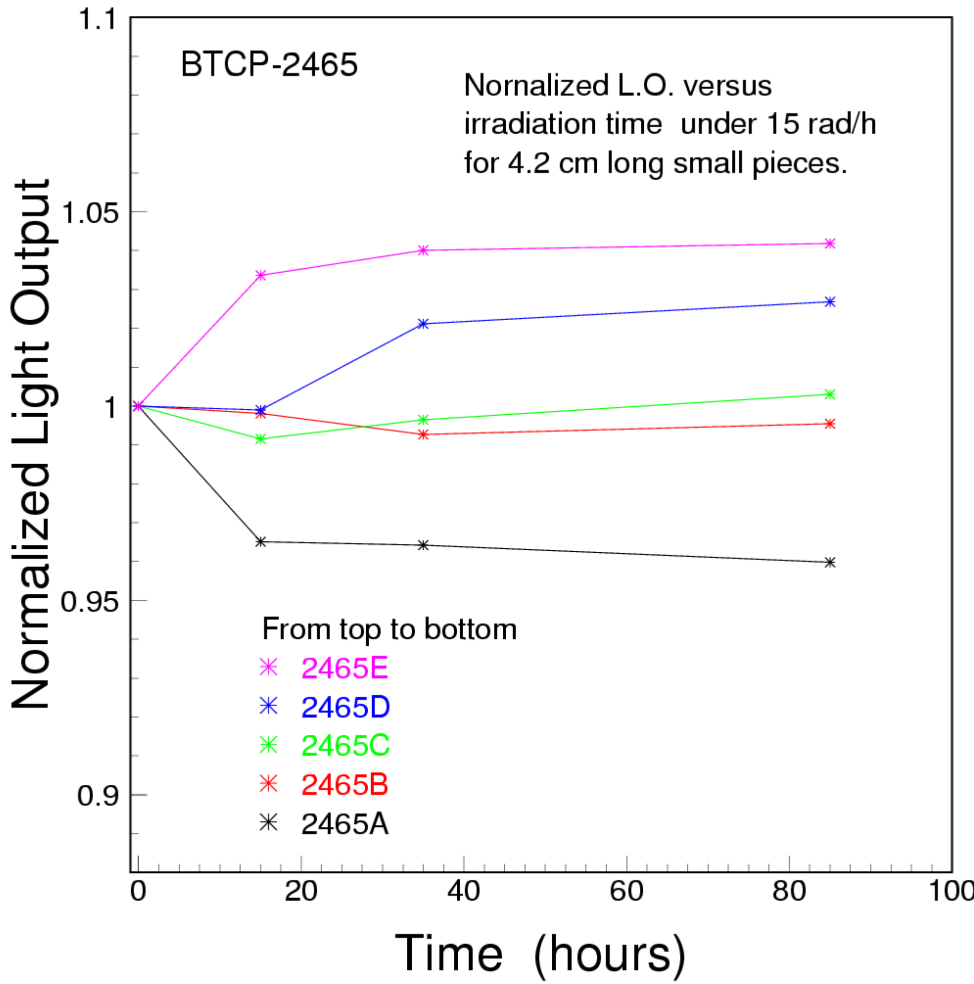
Three samples cut to 5 pieces: 4.3 cm each:
Type I: 2467, Type II: 2436, Type III: 2465



Investigation on BTCP Samples (II)

Anomaly is shown also at the Tail end (E and D)





Investigation on SIC Samples (I)

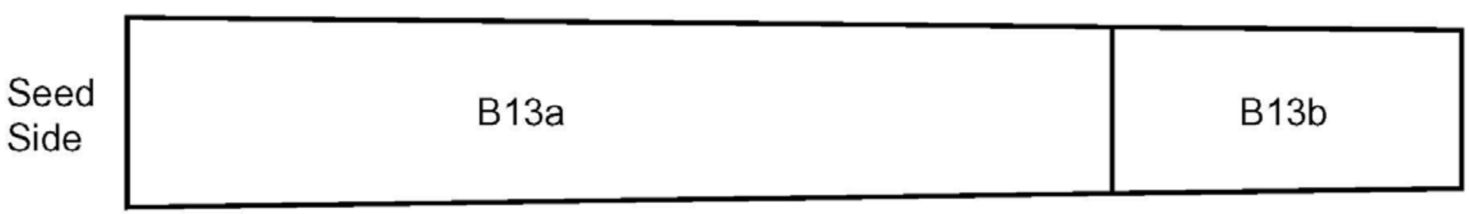
Two anomalous samples were cut to pieces

Crystal ID: NO.4-1-20 Dopant: Y/150 at ppm

The length of seed is 20.0 mm, thickness of 1, 2, 3, 4 is 5.0 mm.

Dimension of AB, CD, EF, GH and IJ is: 25.0 x 25.0 x 44.3 mm^3.

Crystal ID: B13 Dopant: Y/150 at ppm

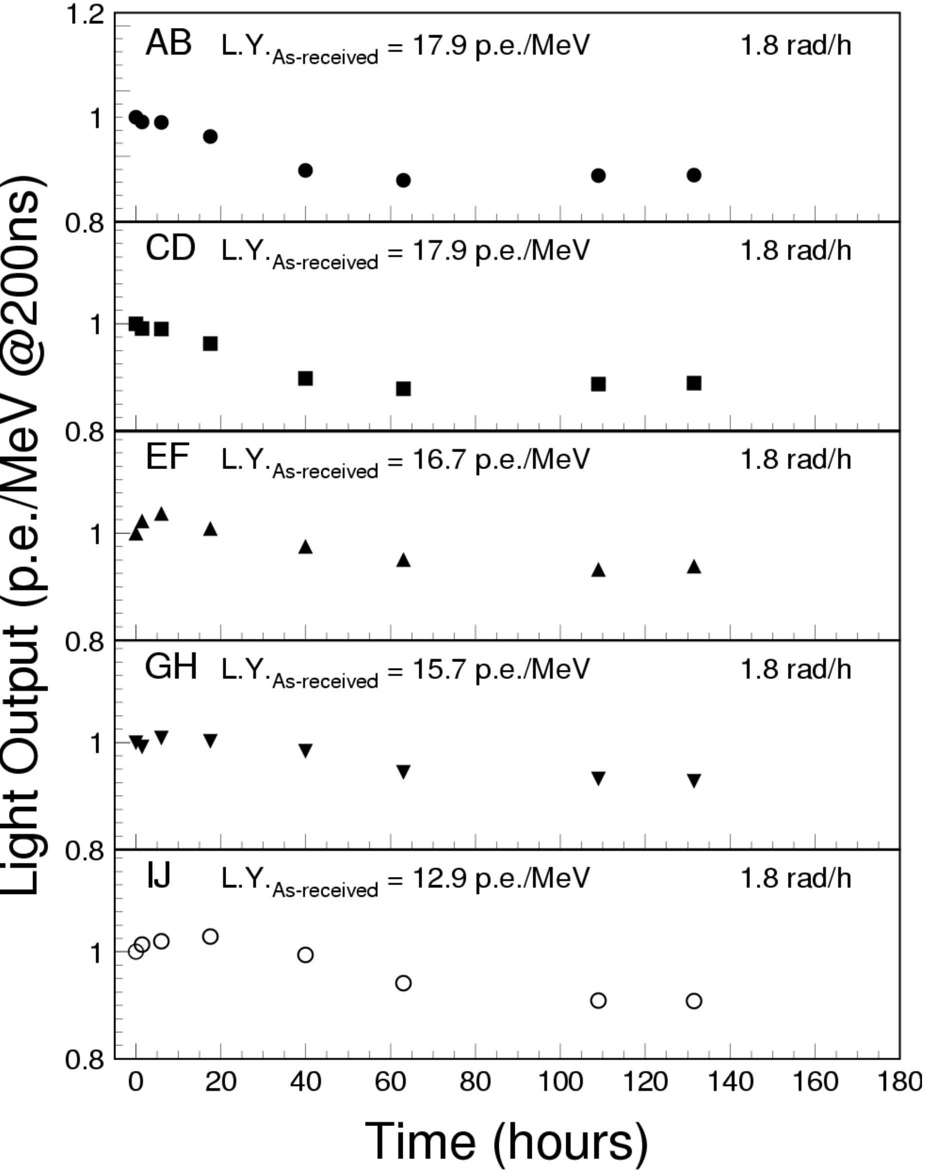


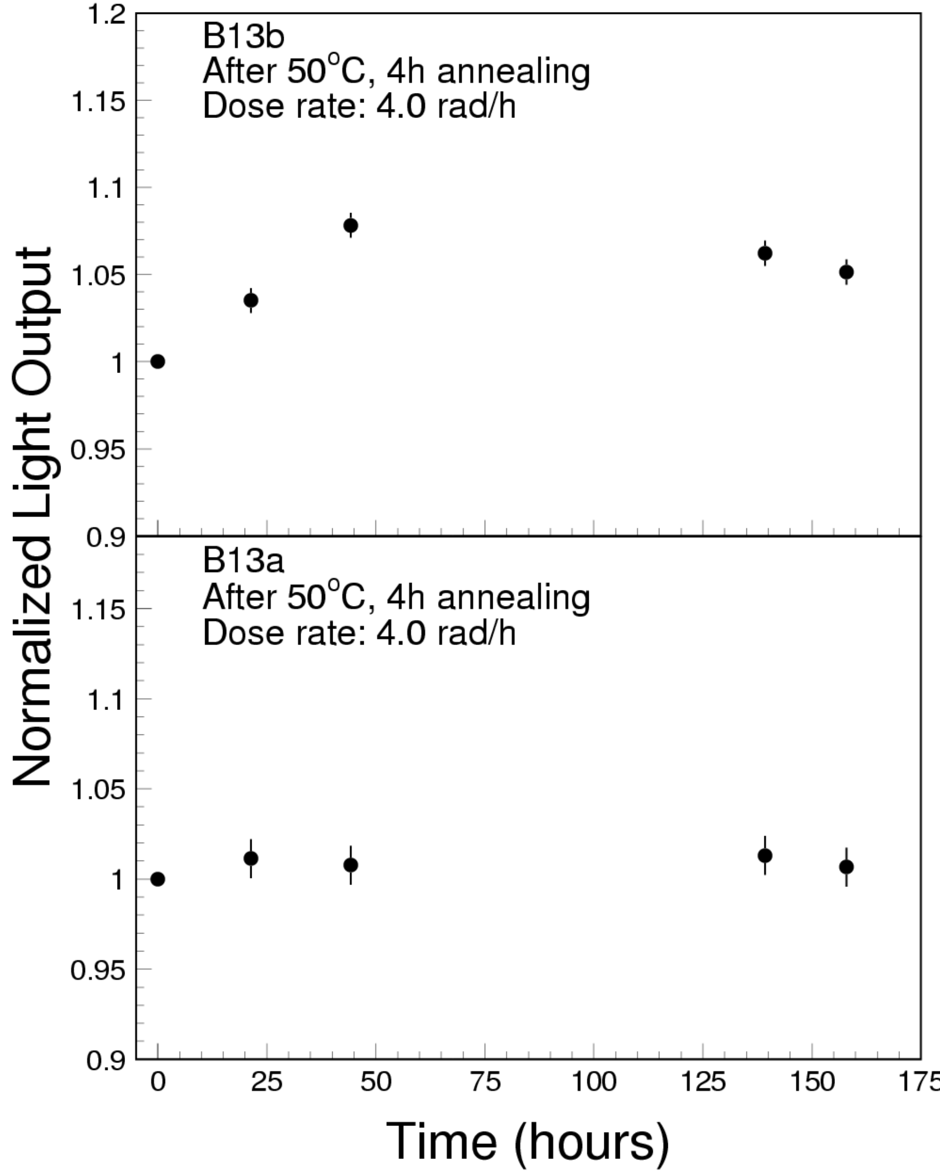
Dimension of B13a: 22.0 x 22.0 x 177.0 x 25.0 x 25.0 mm^3.

Dimension of B13b: 22.0 x 22.0 x 50.0 x 23.0 x 23.0 mm^3.

Investigation on SIC Samples (II)

Anomaly was found at the tail end: impurity related?





Trace Analysis on SIC Samples

GDMS on SIC PWO(Y) Samples (ppmw)

by Shiva Technology West (November, 1999)

		4-1-20-2/3		4-1-20-AB/EF/IJ	
Element	Seed/Tail 1	Seed/Tai 2	Seed/Tail 3	Seed/Middle/Tail 4	Tail 5
Na	0.2/0.8	0.2/2.3	0.4/0.8	0.2/0.8/1.9	0.8
Si	0.5/0.2	0.7/1.3	0.5/1.2	0.5/0.4/0.1	0.05
K	0.3/1.8	0.4/2.9	0.7/1.2	0.5/0.9/2.0	1.3
Ca	0.9/<0.05	0.6/0.08	0.12/0.15	0.8/0.6/0.2	0.15
Cu	0.04/0.2	0.04/0.4	0.3/0.35	0.08/0.1/0.54	0.23
As	0.15/0.35	0.1/0.6	0.5/0.5	0.14/0.16/0.6	0.54
Y	40/45	40/50	30/35	40/40/60	50
Nb	<0.05	<0.05	<0.05	<0.05	<0.05
Mo	0.3/0.55	0.3/0.9	0.6/0.8	0.2/0.5/0.8	1.0
Sb	<0.05	<0.05	<0.05	<0.05	<0.05
Ba	0.1/0.1	0.1/0.1	<0.05/0.06	0.3/0.15/0.07	0.1
La	<0.01	<0.01	<0.01	<0.01	<0.01
Eu	<0.05	<0.05	<0.05	<0.05	<0.05
TC†	3.8/2.1	4.9/4.6	4.4/3.4	5.3/4.0/2.5	4.3

†: Total contamination, excluding Y.

Impurity segregation:

Na, K, Cu, As, Mo: <1;

Ca, Ba: >1;

Y: slightly less, but close to 1.

SIC samples are doped with Y only.

Trace Analysis on BTCP Samples

GDMS on BTCP PWO(Y/Nb/La) Samples (ppmw)

by Shiva Technology (November, 2003)

Element	2467 Seed/Tail	2436 Seed/Tail	2465 Seed/Middle/Tail
Na	0.95/0.98	2.5/5.2	3.8/3.4/5.2
Si	<0.05	<0.05	<0.05
K	0.36/0.58	0.45/0.90	0.71/0.56/1.6
Ca	2.4/1.8	1.3/0.9	1.7/1.3/1.2
Cu	<0.05	<0.05	<0.05
As	<0.05	<0.05	<0.05
Y	71/74	94/120	98/83/100
Nb	0.06/0.11	0.07/<0.05	<0.05/0.27/0.26
Mo	0.2/0.23	0.33/0.38	0.37/0.37/0.41
Sb	<0.05	<0.05	<0.05
Ba	1.7/1.5	1.5/1.2	5.3/1.7/2.5
La	250/140	200/130	280/160/150
Eu	0.6/0.5	0.8/1.4	1.1/0.53/0.3
TC[†]	6.4/5.7	7.0/10	13/7.9/11

[†]: Total contamination, excluding Y, Nb and La.

Impurity segregation:

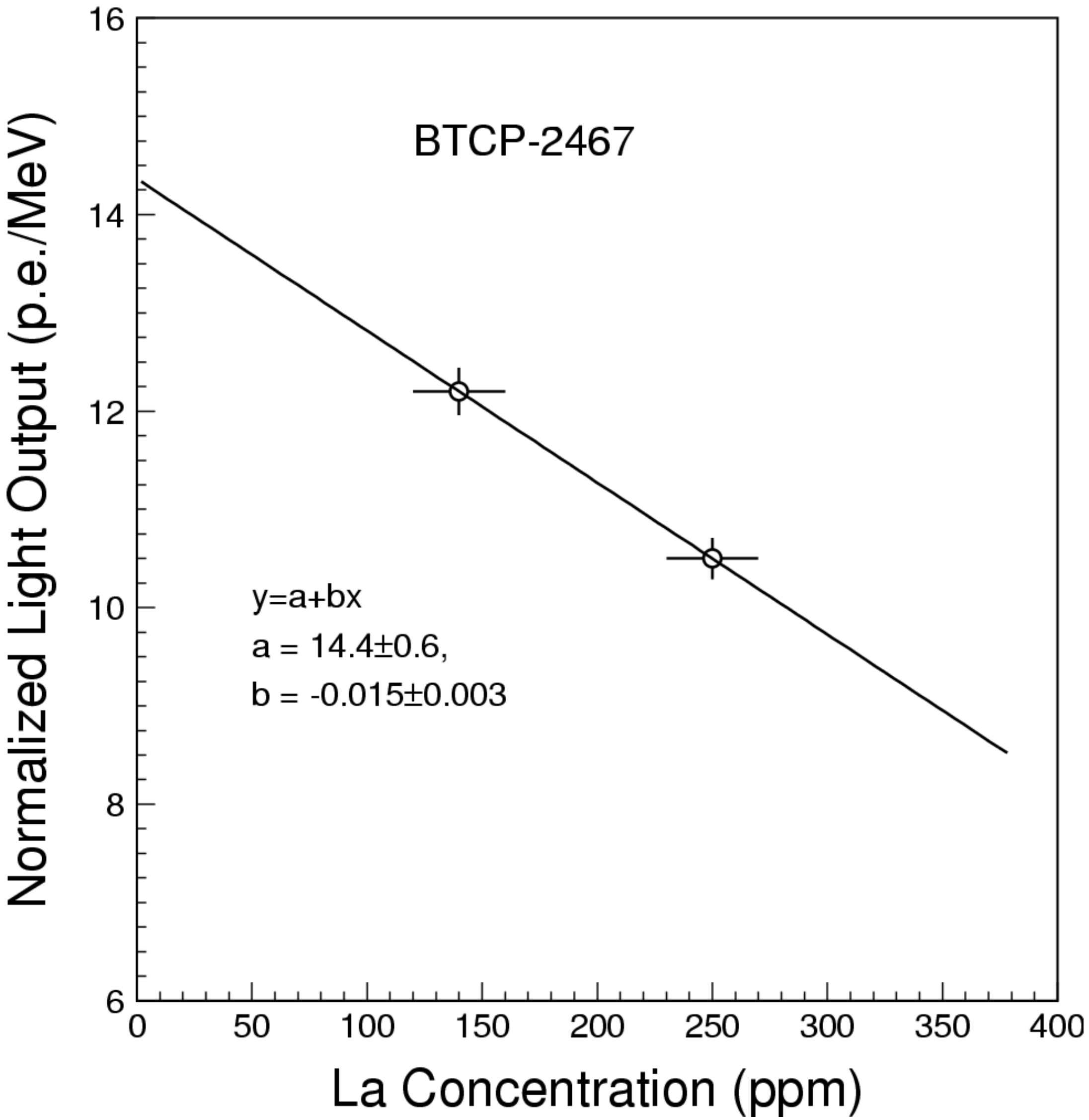
Na, K, Nb, Mo: <1;

Ca, Ba, La: >1;

Y: slightly less, but close to 1.

BTCP PWO is triple doped with Y/Nb/La!!!

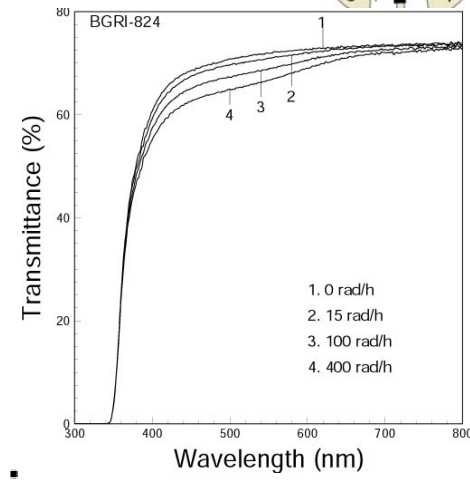
Light Output & La Concentration



- The anti-correlation between the light output of PWO and its La concentration, may explain the low light yield of BTCP PWO.
- Further study is under way to clarify this issue.

Radiation Induced Color Center Density

Nucl. Instr. And Meth. A332 (1993) 442



RIAC or radiation induced color center density can be calculated precisely by using longitudinal transmittance (0.2%)

$$RIAC \ or \ D_{Color-Center} = 1/LAL;$$

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

where T is transmittance measured along crystal length ℓ and T_s is the theoritical transmittance without internal absorption:

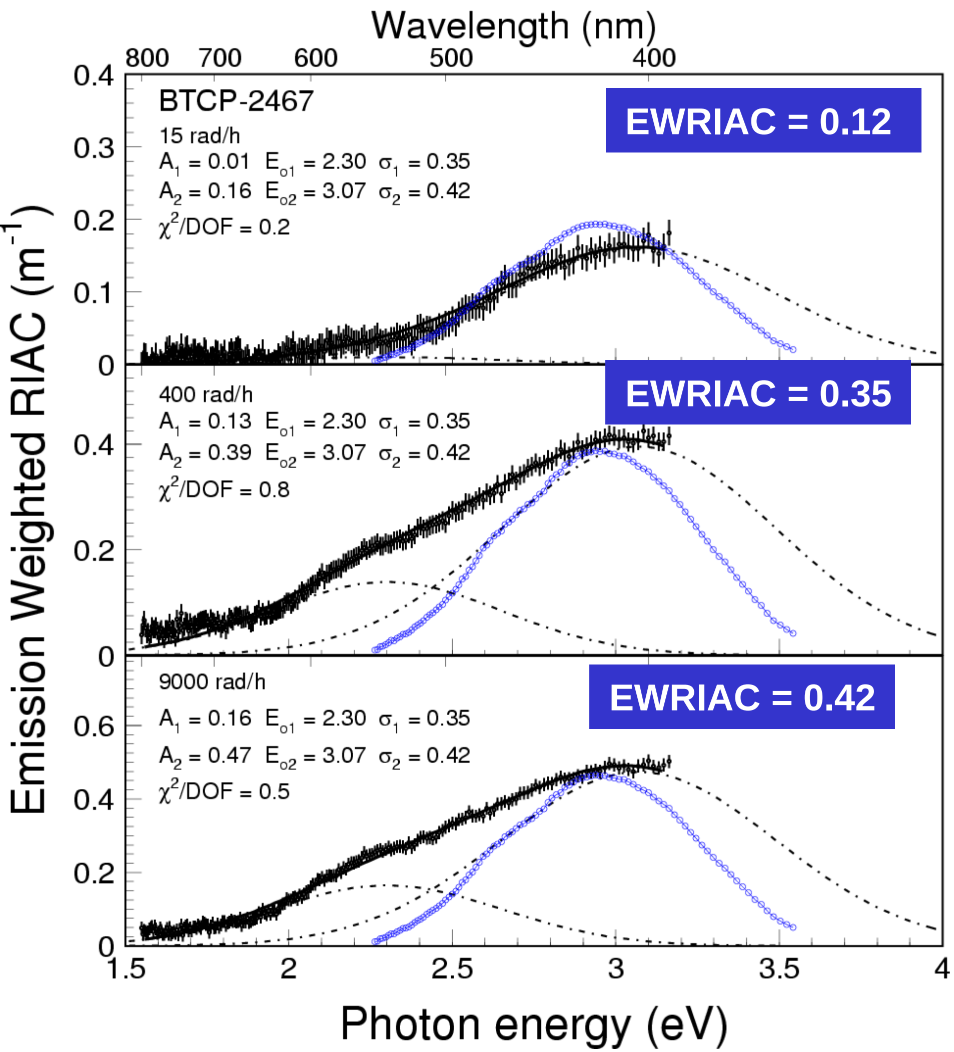
$$T_s = (1-R)^2 + R^2(1-R)^2 + ... = (1-R)/(1+R), \text{ with}$$

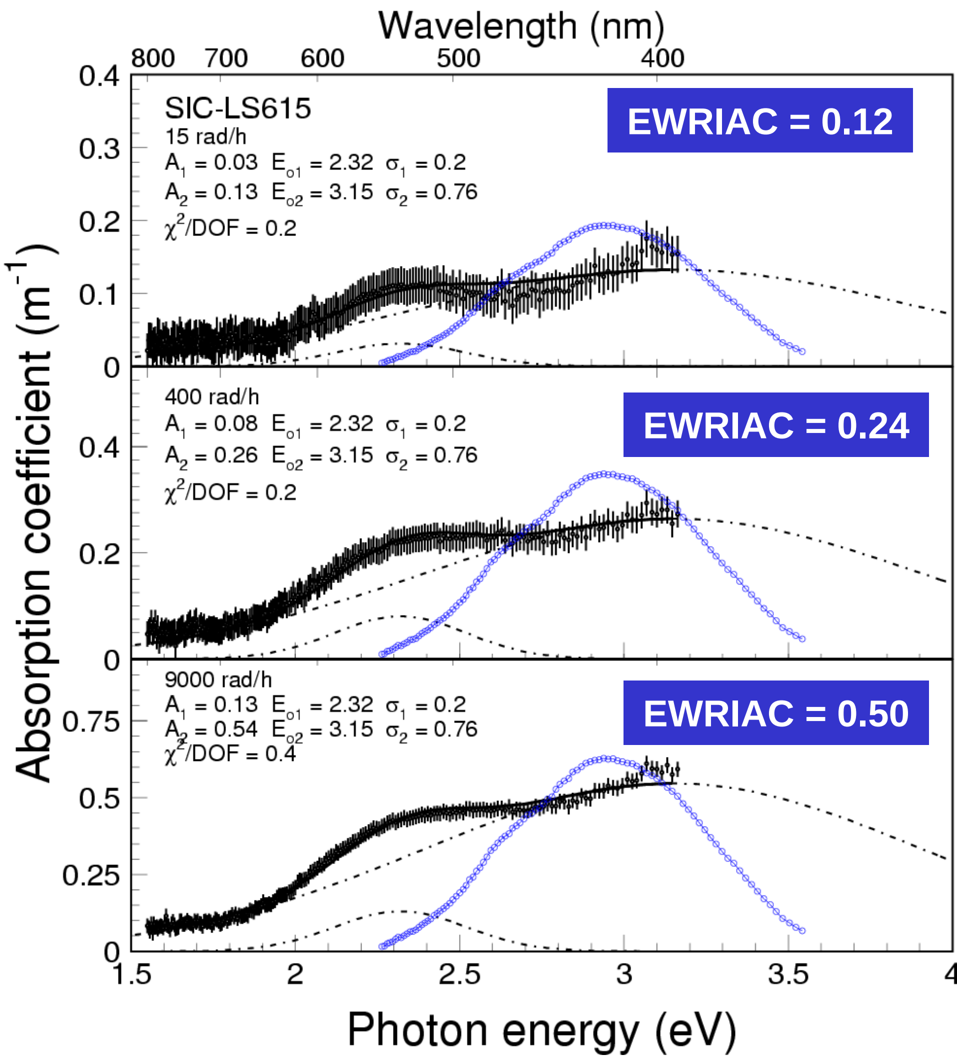
$$R = \frac{(n_{crystal} - n_{air})^2}{(n_{crystal} + n_{air})^2}.$$

Emission Weighted RIAC

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

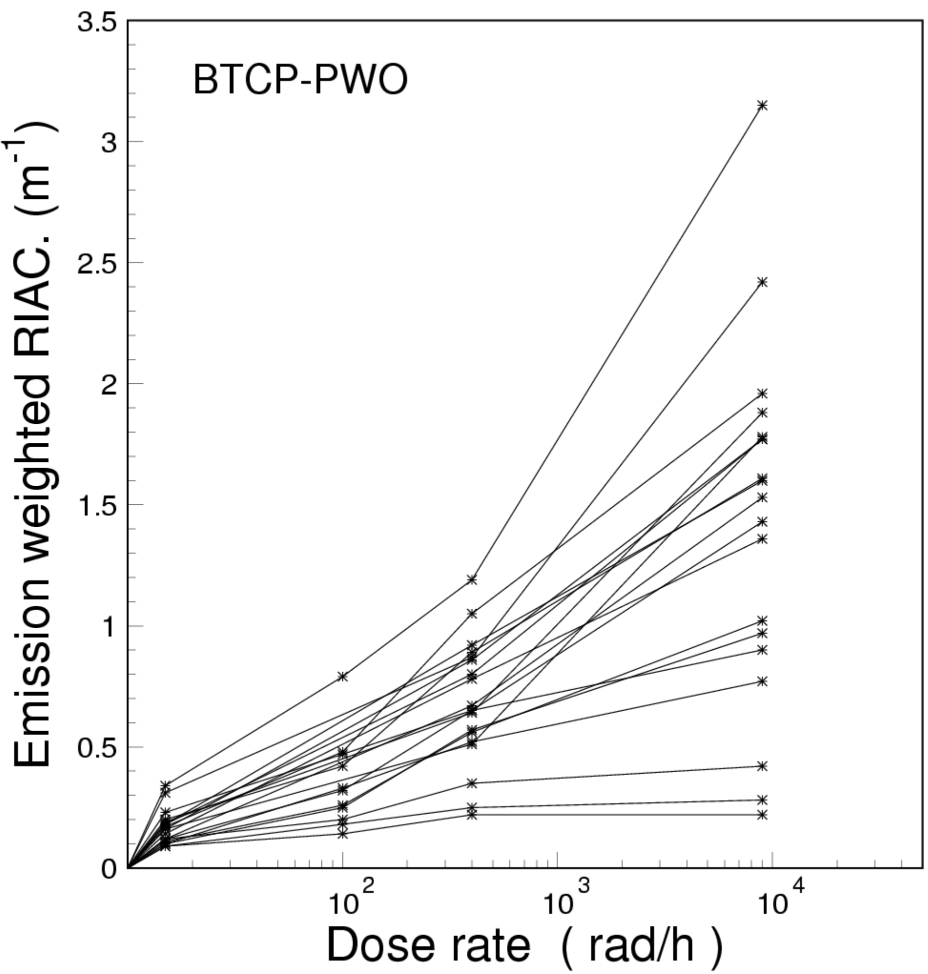
a good measure of rad. damage

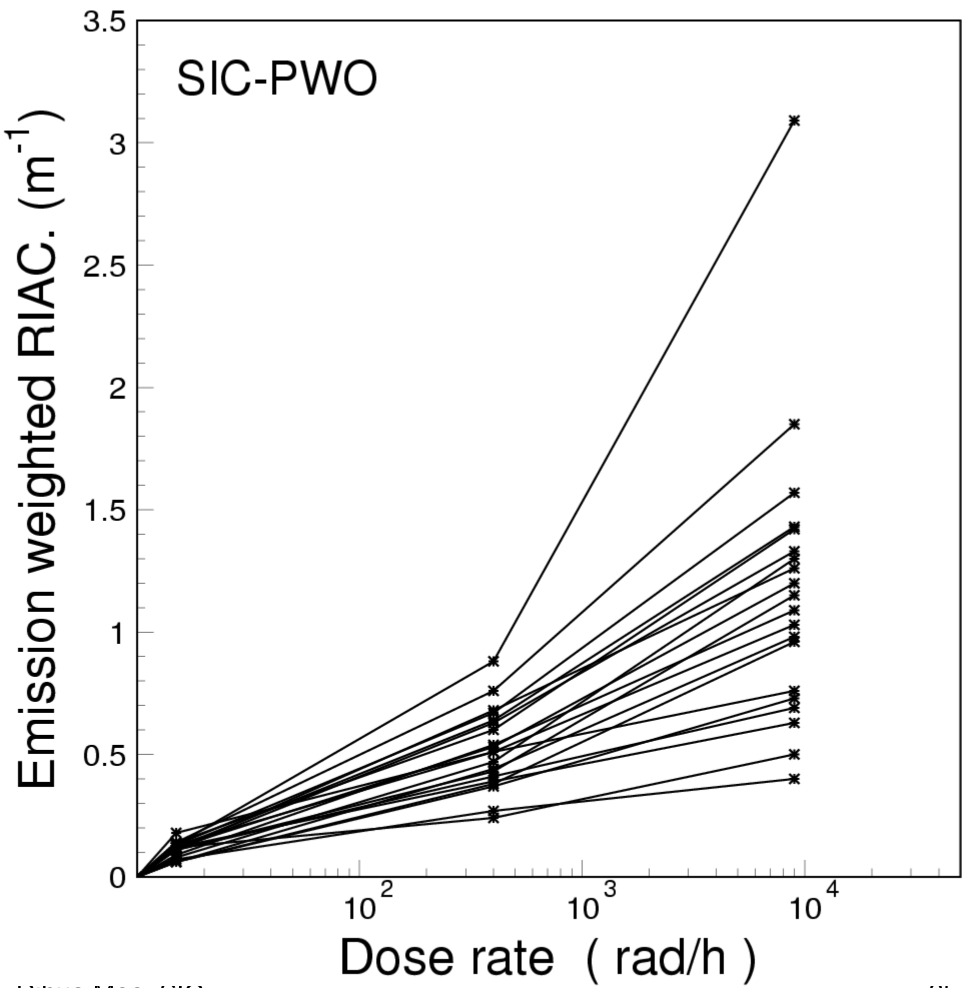




EWRIAC (1/m) and Normalized r.m.s

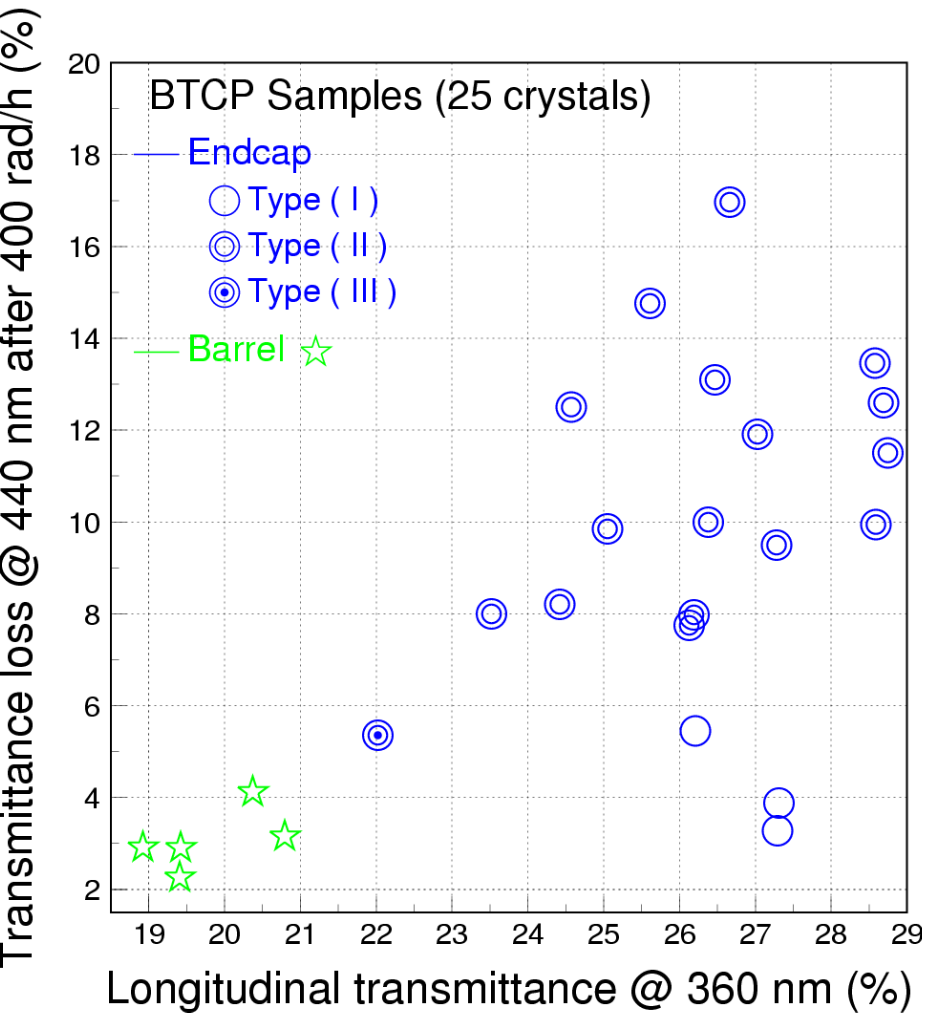
Vendor	15 rad/h	400 rad/h	9.000 rad/h
BTCP	0.16 (45%)	0.69 (37%)	1.43 (50%)
SIC	0.10 (33%)	0.51 (32%)	1.16 (48%)

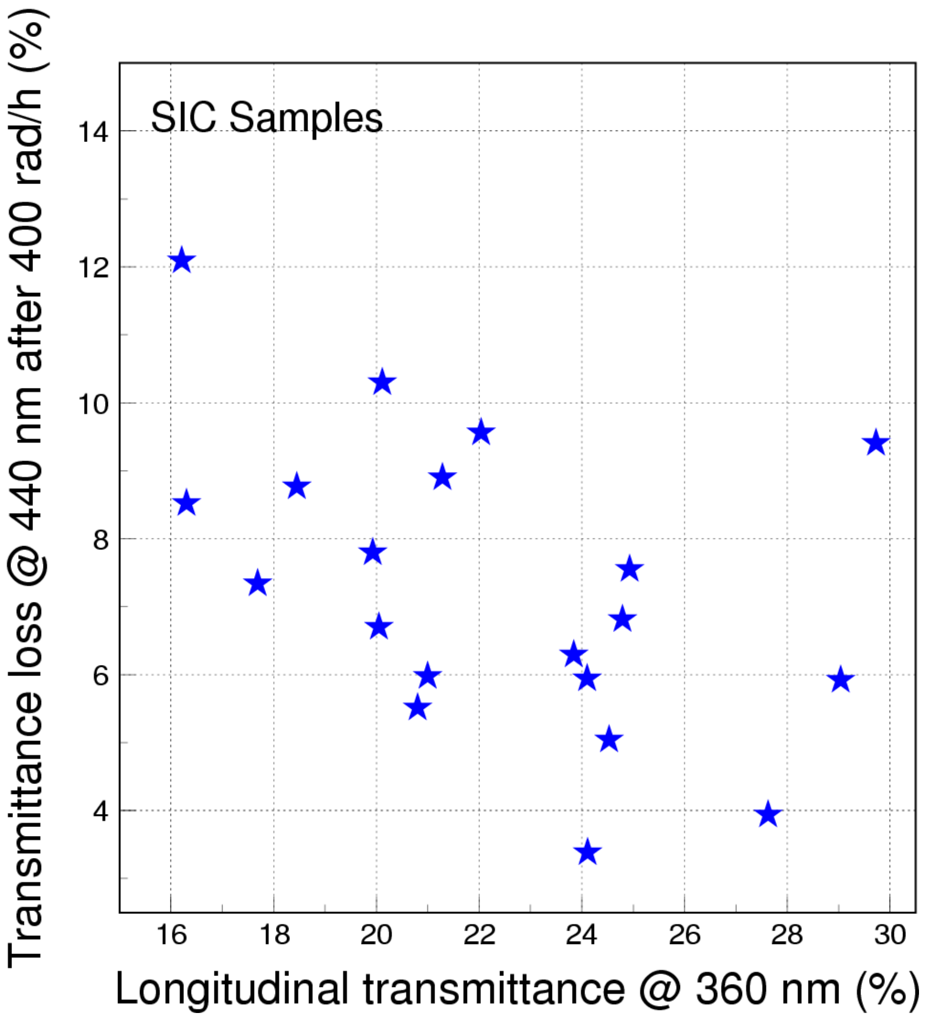




L. T. Loss versus Initial L.T. @ 360 nm

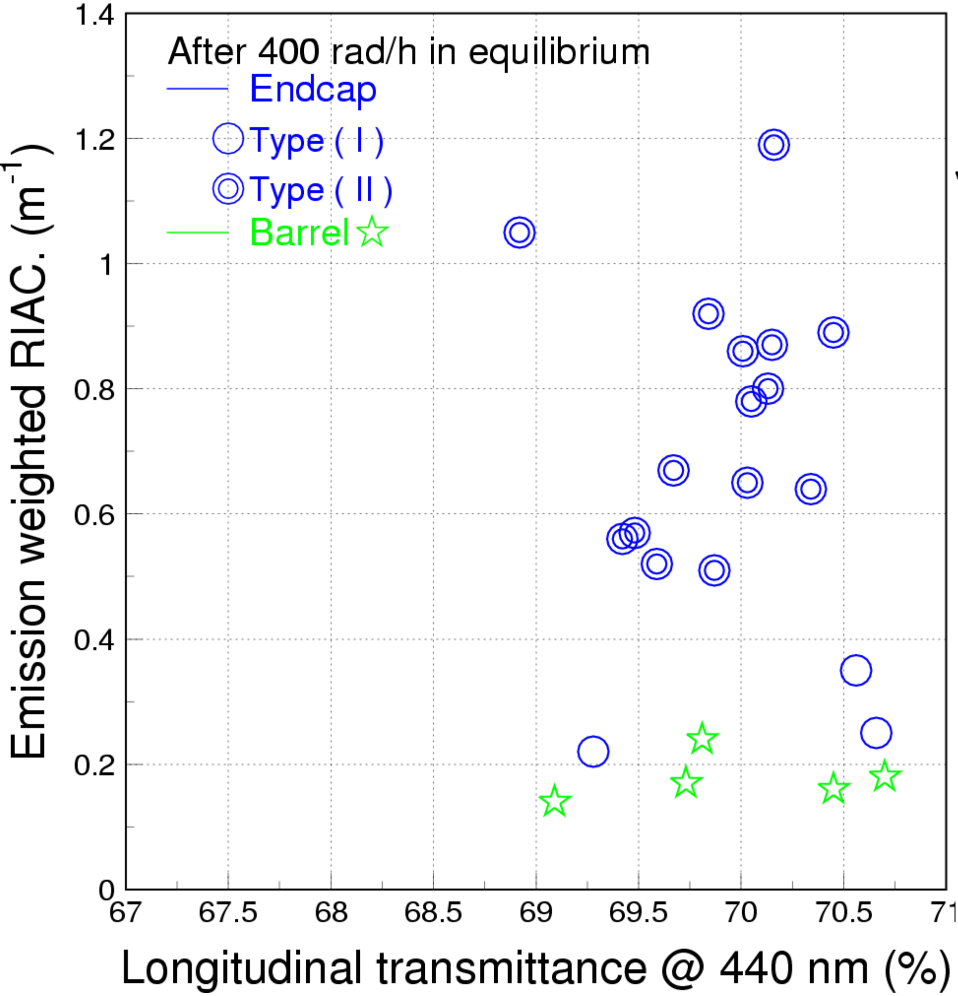
No correlation

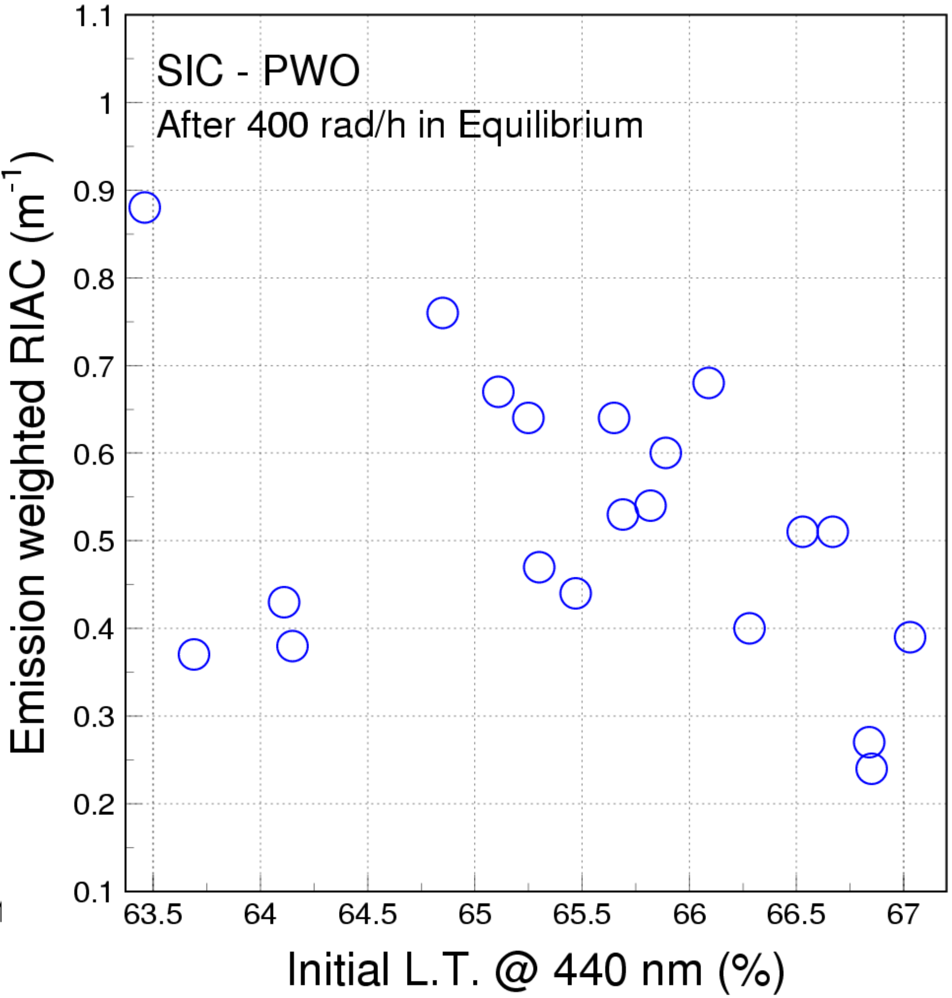




EWRIAC versus Initial L.T. @ 440 nm

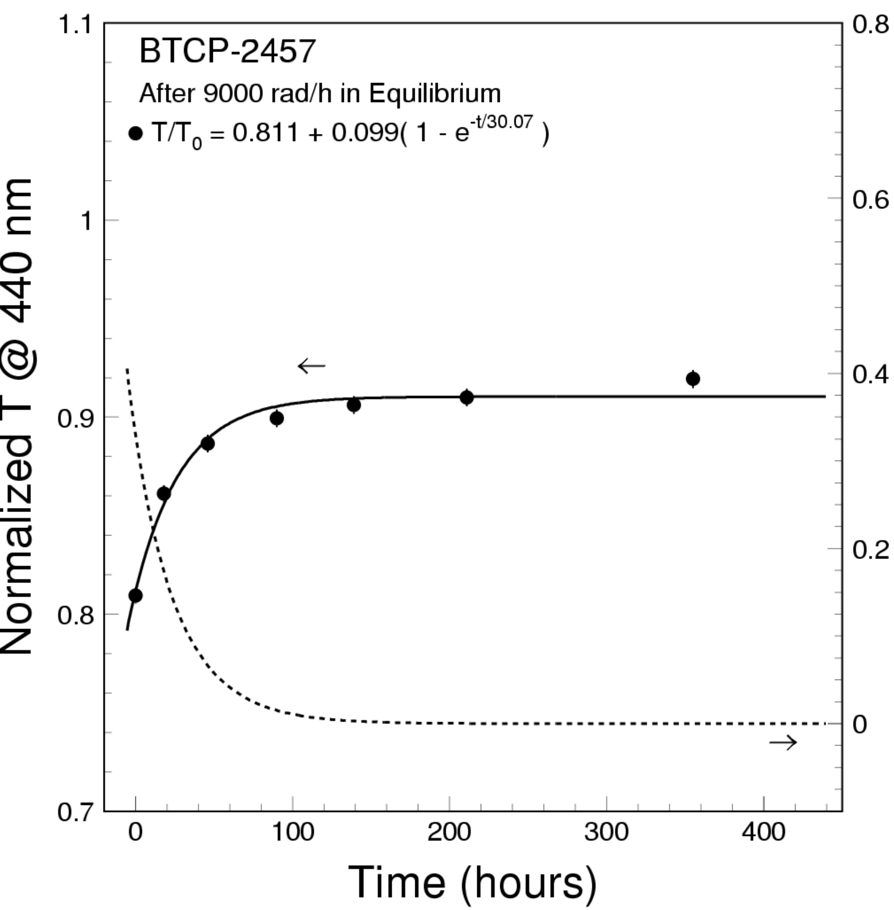
No correlation

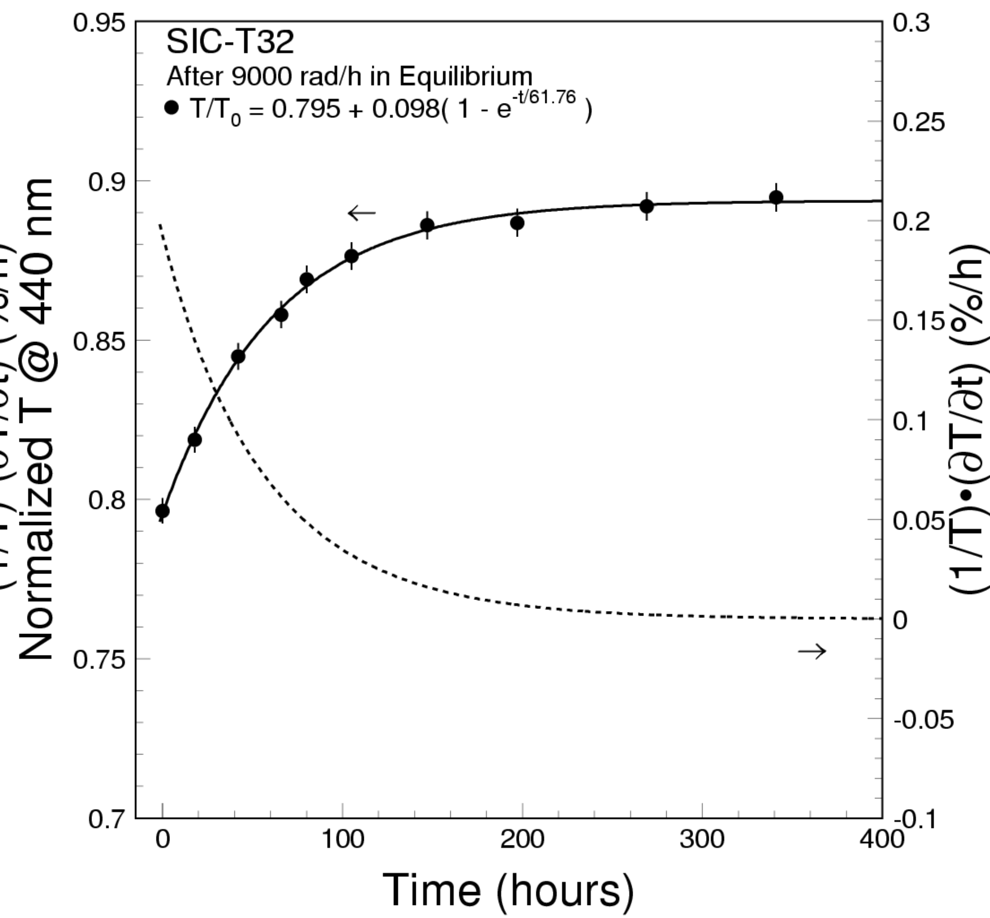


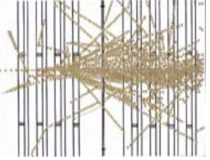


Recovery Speed and Time Constant

Recovery at 18°C in 160 days: two time constants
Short recovery: BTCP: 36.0 h (27%), SIC: 43.6 h (33%)







Summary

- PWO samples from both BTCP and SIC have very good transmittance and fast light output. SIC samples produce 58% more light, which may be explained by 130-280 ppmw La doping in BTCP samples.
- Preexisting CC, causing light output increase under irradiation, is caused by contamination of mono-valent impurities.
- No correlations between radiation hardness and initial longitudinal transmittance was observed.
- Requiring degraded LAL>1 m, current mass-produced PWO crystals are radiation hard enough for environment of up to a few hundreds rad/h --- a great achievement for HEP and MS.