Result of SIC 2004 Samples and a Damage/Recovery Study for PWO Samples from BTCP and SIC

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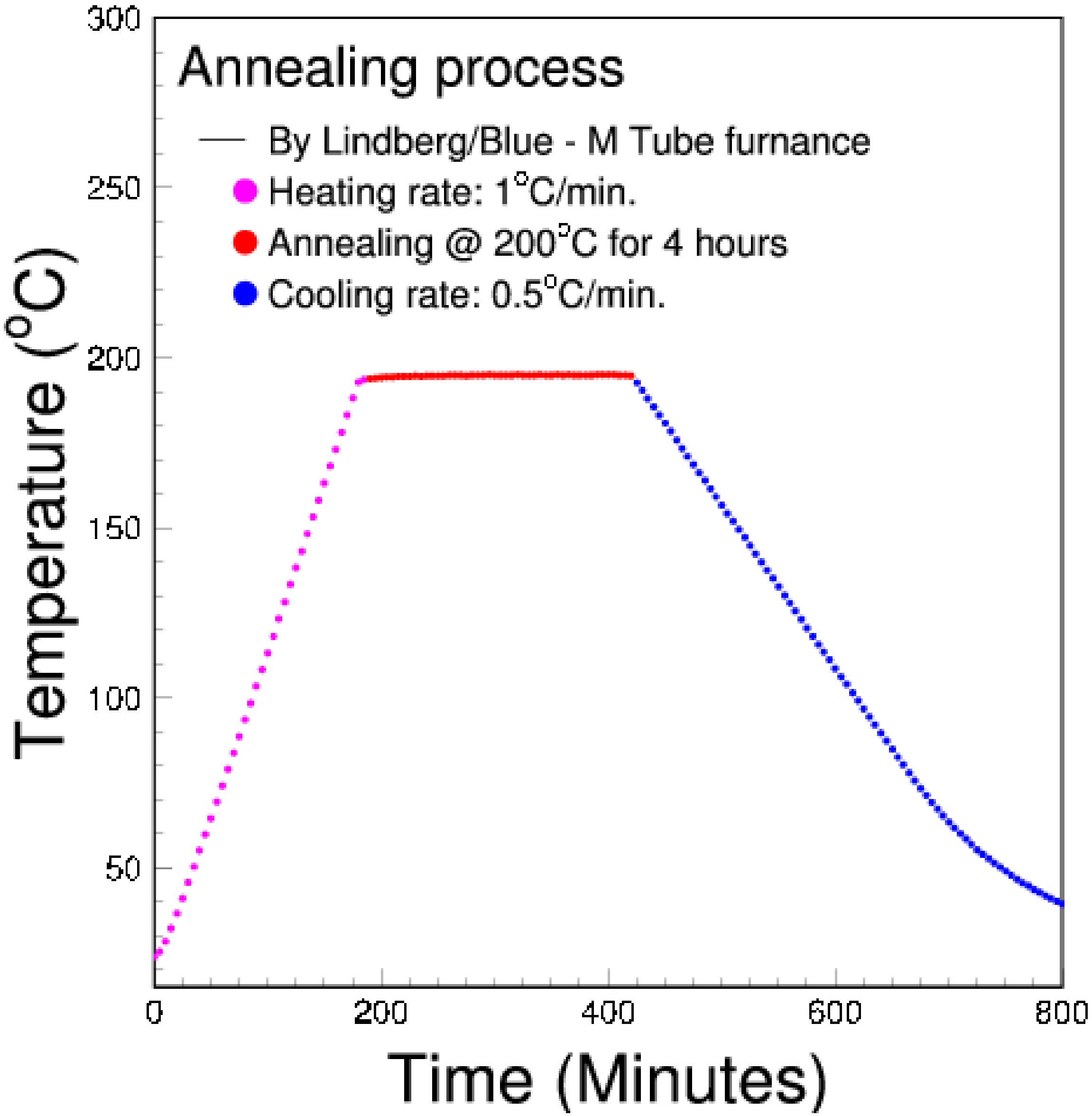
Introduction

- 12 endcap size SIC 2004 PWO samples, 570/572 (01/04), 630/641 (05/04), 686/705 (10/04), 713/747 (11/04), 781/782 (12/04) and 841/855 (01/05), went through a standard test procedure at Caltech: a thermal annealing @ 200^{o}C, followed by irradiations in three steps: **~72 h** @ 15 rad/h, **~72 h** @ 400 rad/h and **~48 h** @ 9 krad/h.
- Properties measured: transmittance, emission and excitation spectra, light output, decay kinetics, light response uniformity and their degradation, as well as emission weighted radiation induced absorption coefficient (EWRIAC).
- Results are compared to two previous batches of 20 PWO samples measured at Caltech: BTCP 2001 batch (endcap size) and SIC 2002 batch (CEBAF size).
- 2 SIC samples (570 & 572) and 2 BTCP 2003 samples (2482 & 2531) went through irradiation and recovery cycles: 2 @ 15 rad/h, 3 @ 400 rad/h, and 2 @ 9 krad/h.
- Comments on PWO quality control.

200°C Thermal Annealing

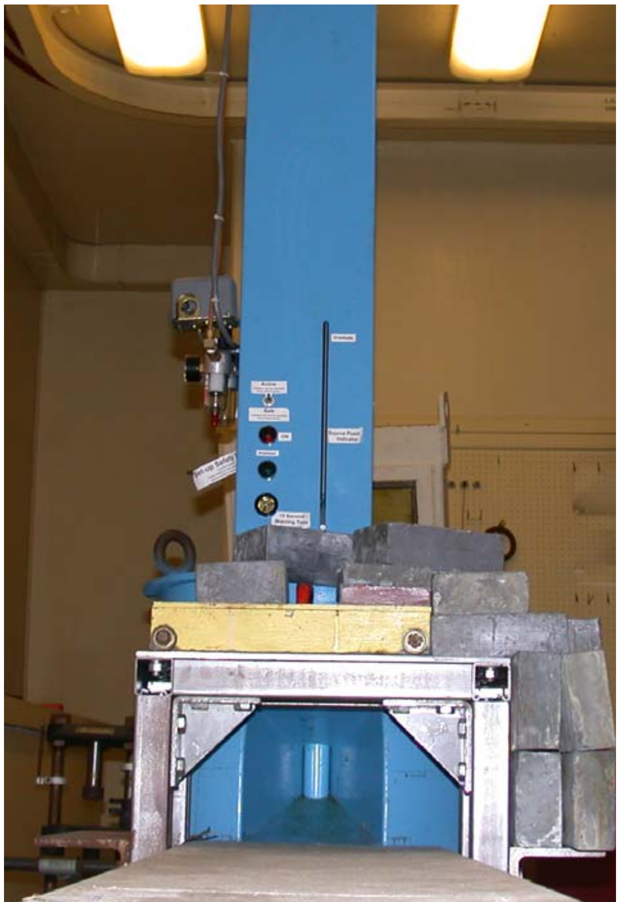


- Carried out in a Lindberg Blue-M tube furnace with automatic control.
- Removed residual absorption and restored the sample to a **"defined state"**.

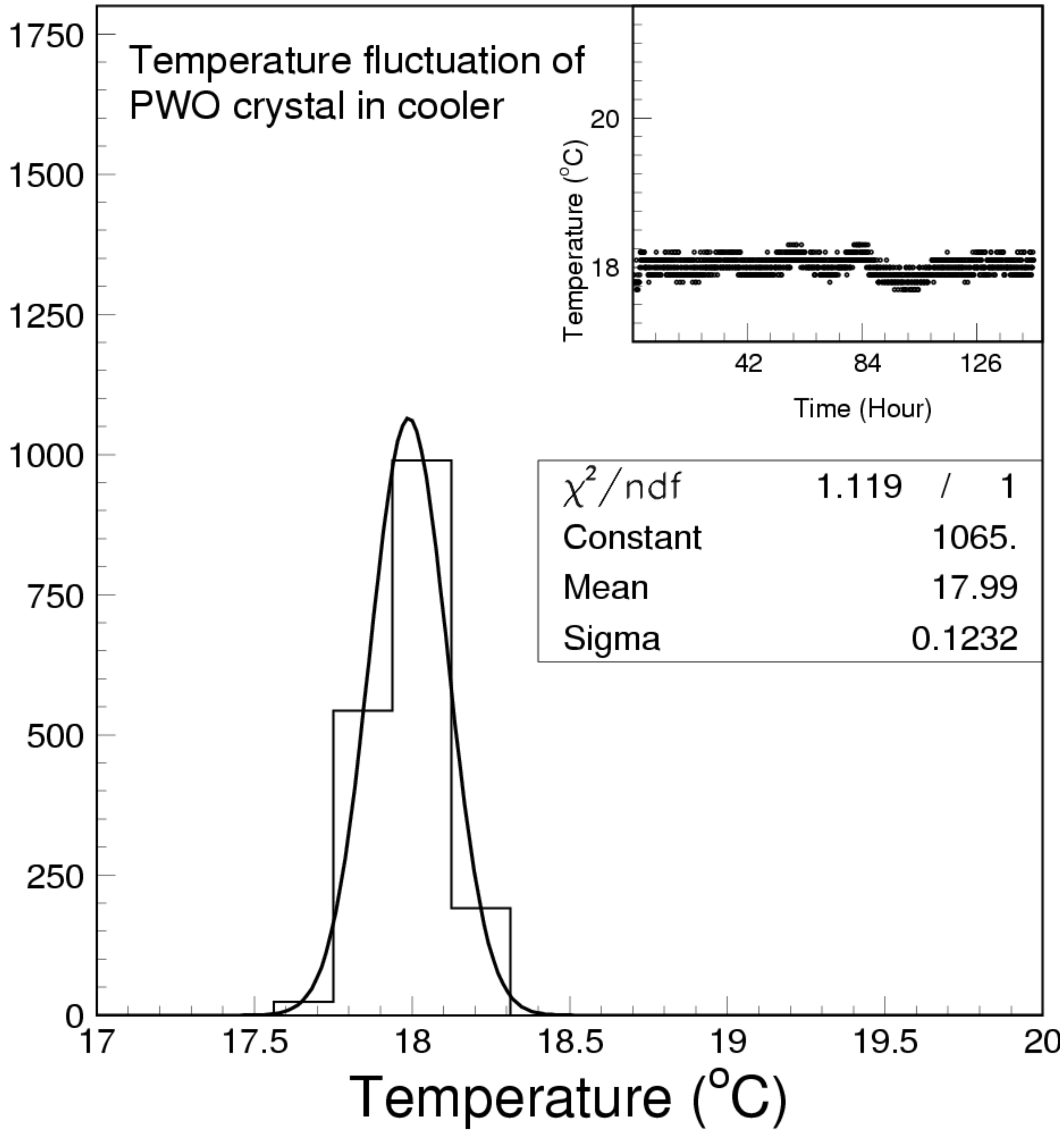
Caltech γ–ray Irradiation Facilities

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

Closed 2,000 curie Cs-137:
9k rad/h at center (10% uniformity)



Recovery Temperature Control

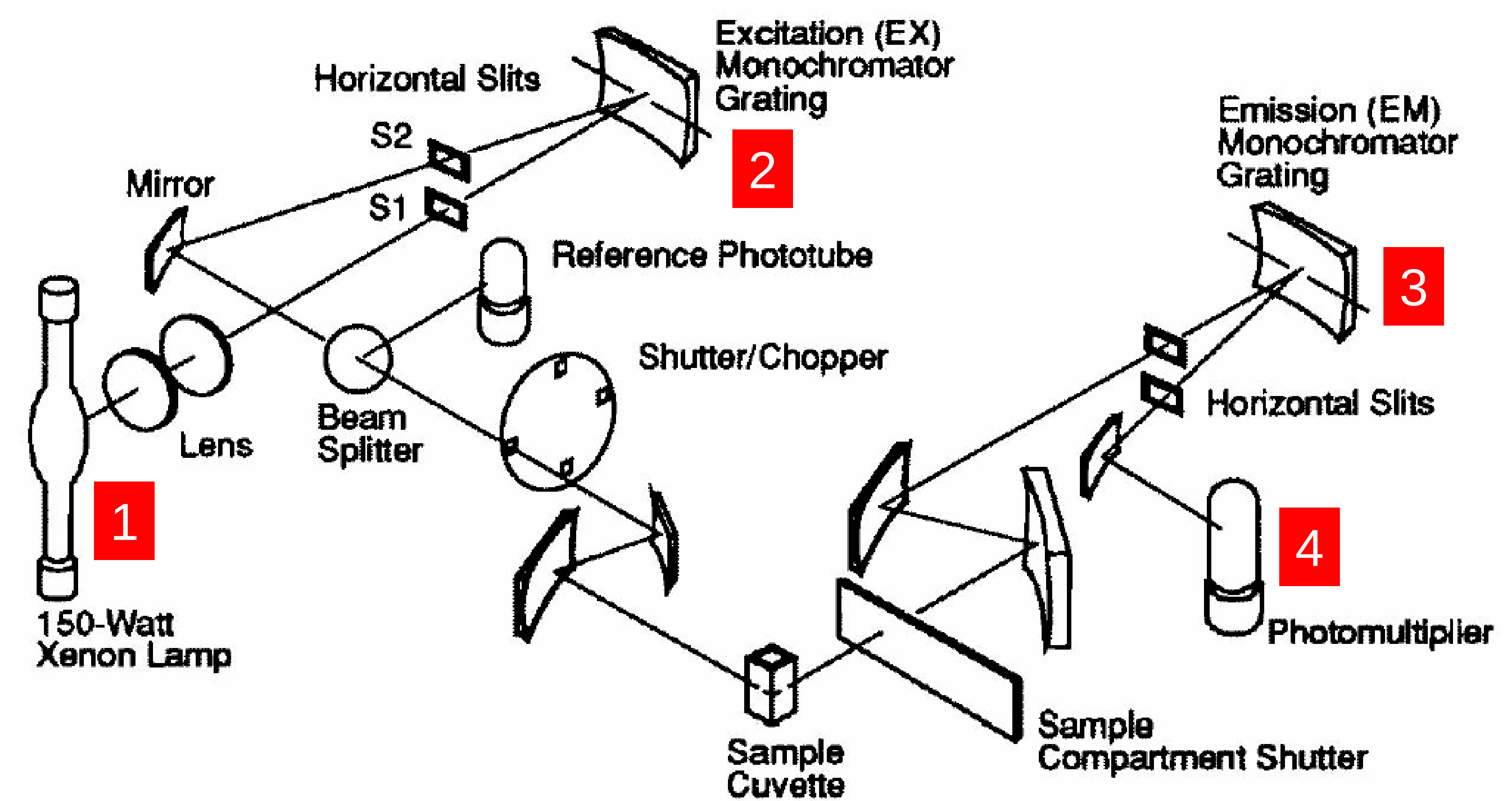


After irradiation recovery was measured when samples were kept in a cooler at 18°C with 0.12°C variation.

Photo Luminescence Measurement

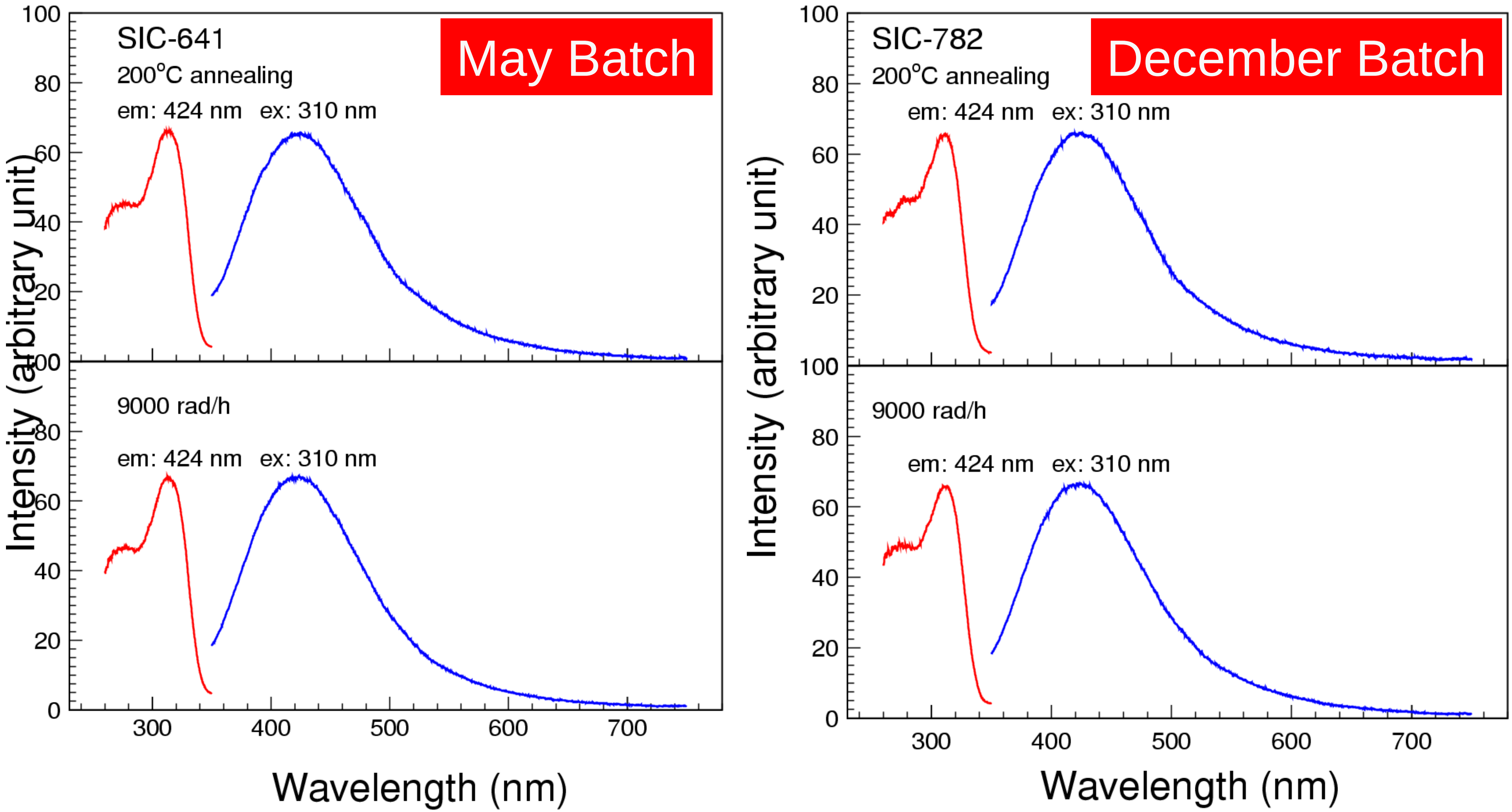
HITACHI F4500 Fluorescence Spectrophotometer

Corrections were made for light source (1), gratings efficiencies (2 & 3) & QE of the red-extended PMT (Hamamatsu R928, 4): 185 to 900 nm



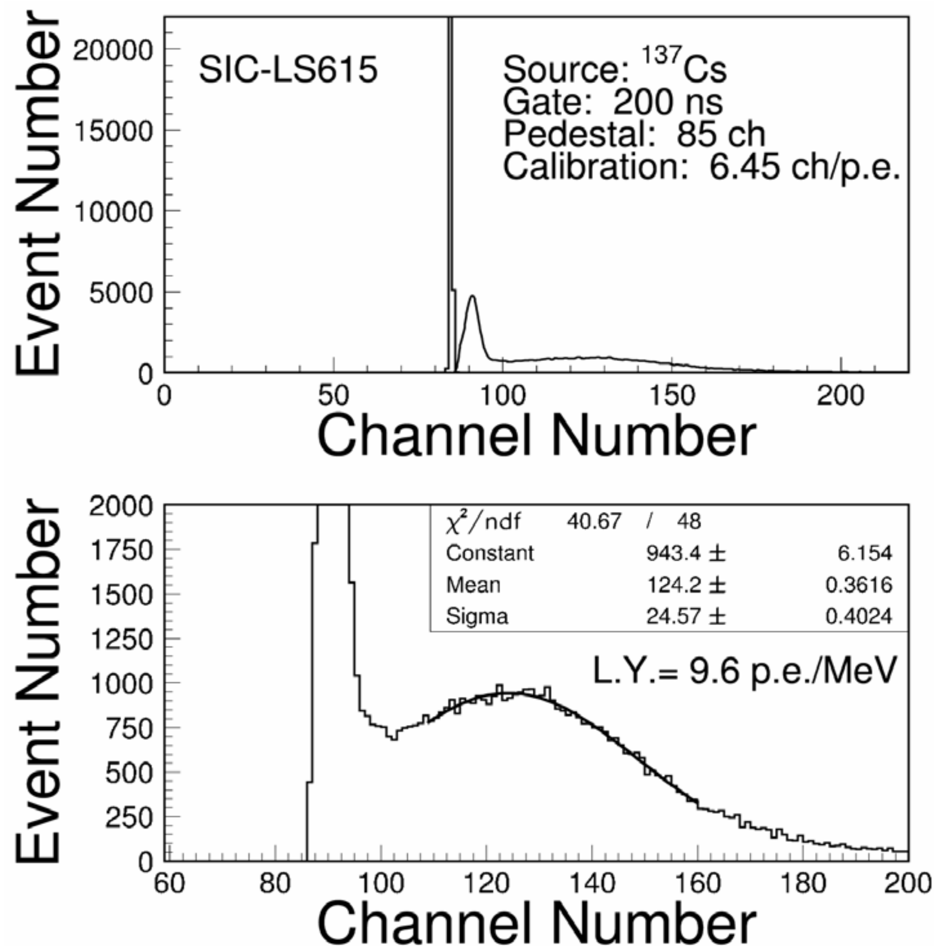
Photoluminescence

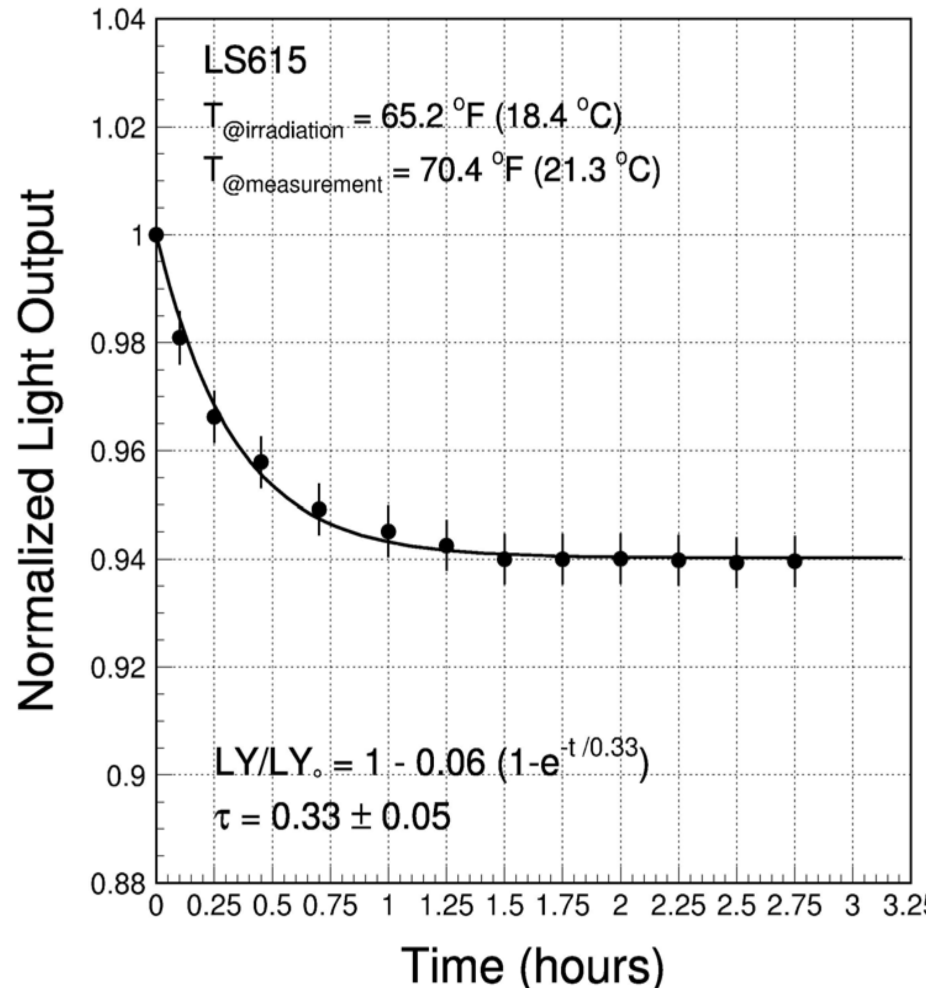
No variation in excitation and emission before and after 9000 rad/h irradiation



Light Output Measurement

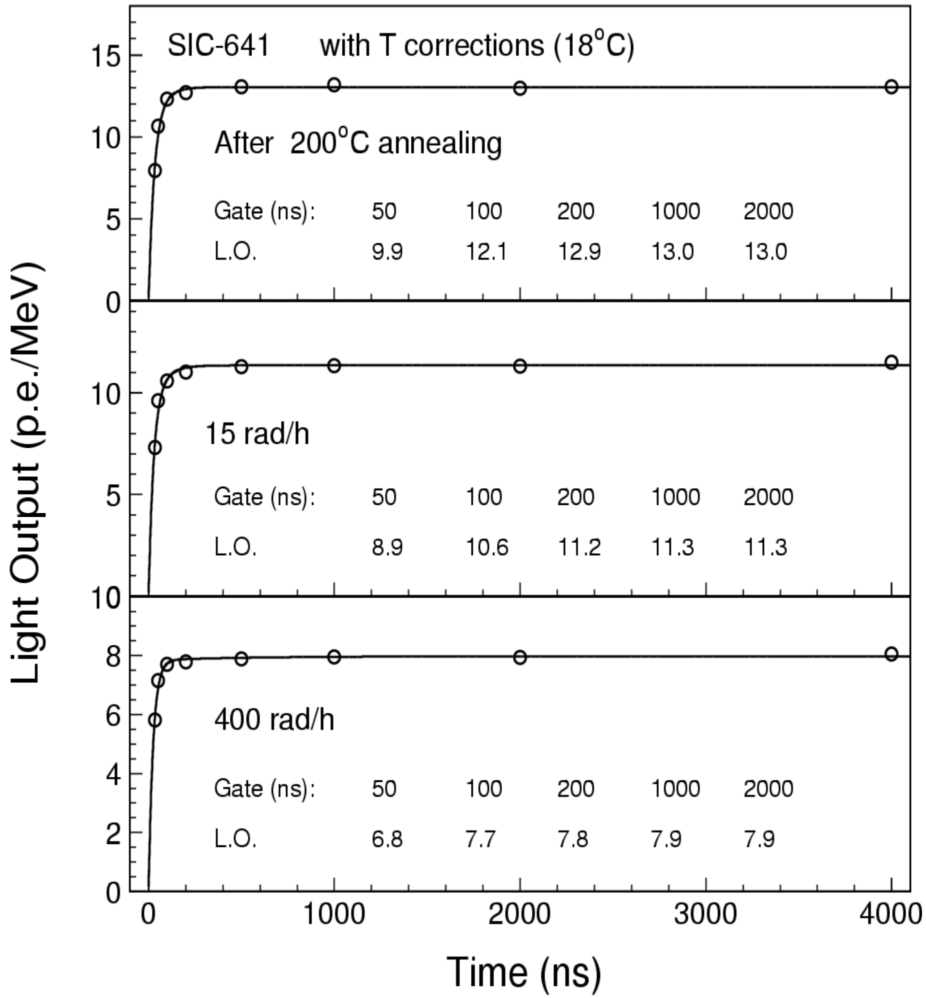
A Hamamatsu R2259 PMT, a LeCroy QVT in Q mode and a ^{137}Cs source were used for PWO samples. Temperature corrections were made to 18°C.

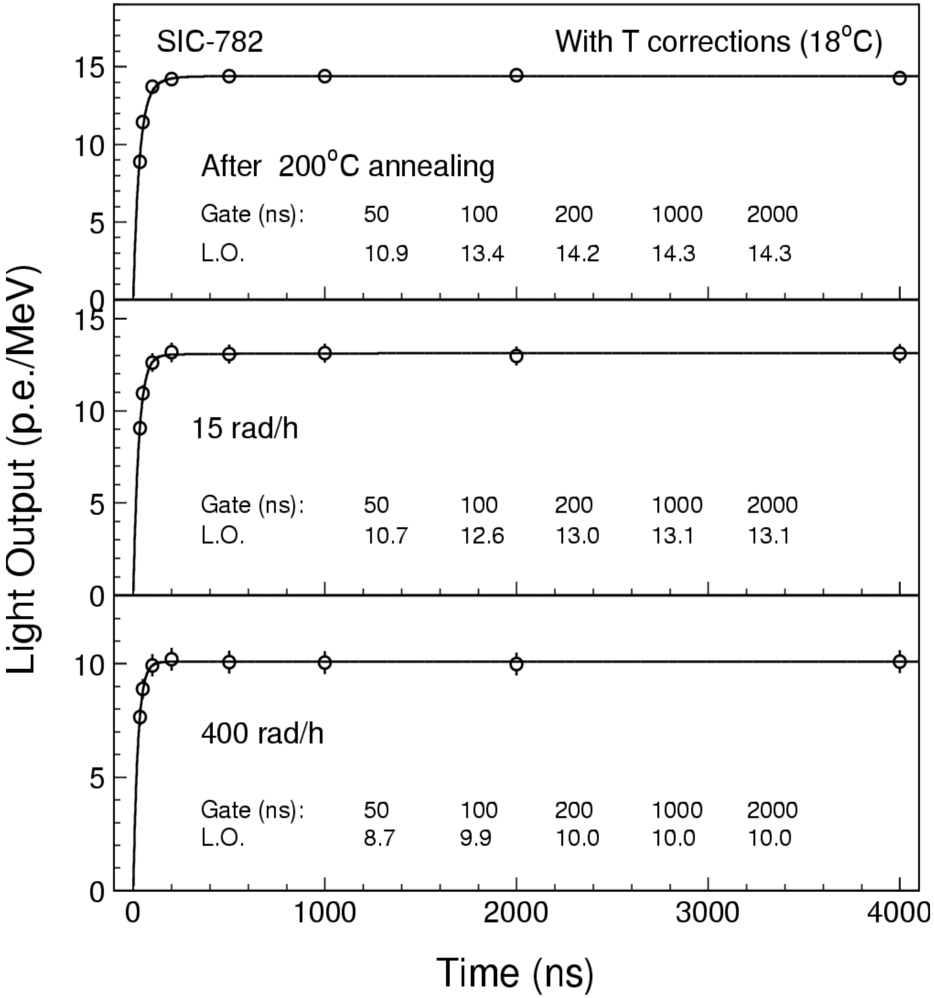




Light Output and Decay Kinetics

Fast scintillation light observed before and after 15 and 400 rad/h irradiations

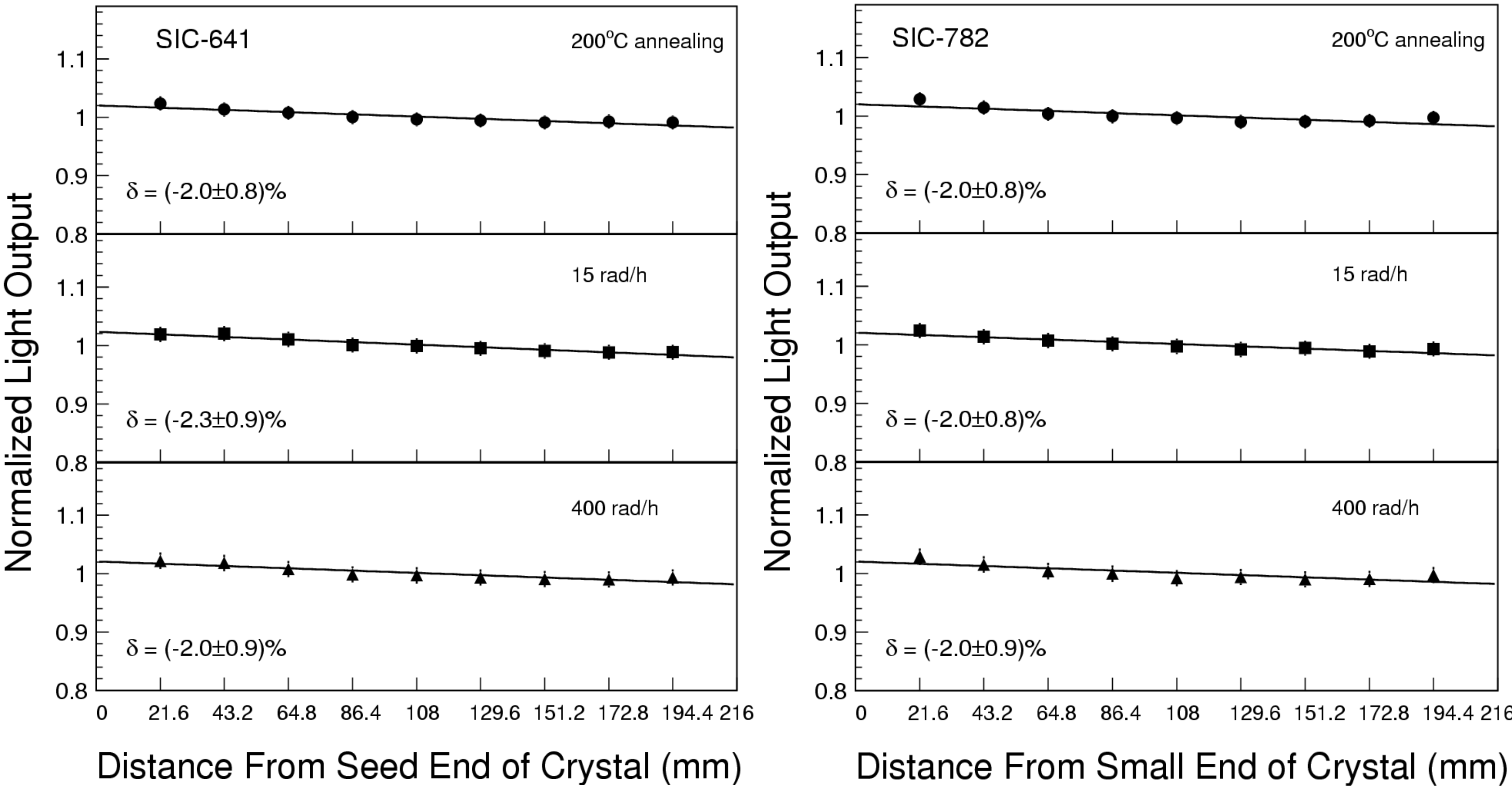




Light Response Uniformity

Fit to a linear function: $$\frac{y}{y_{mid}} = 1 + \delta(x / x_{mid} - 1)$$

No variation before and after 15 and 400 rad/h irradiations

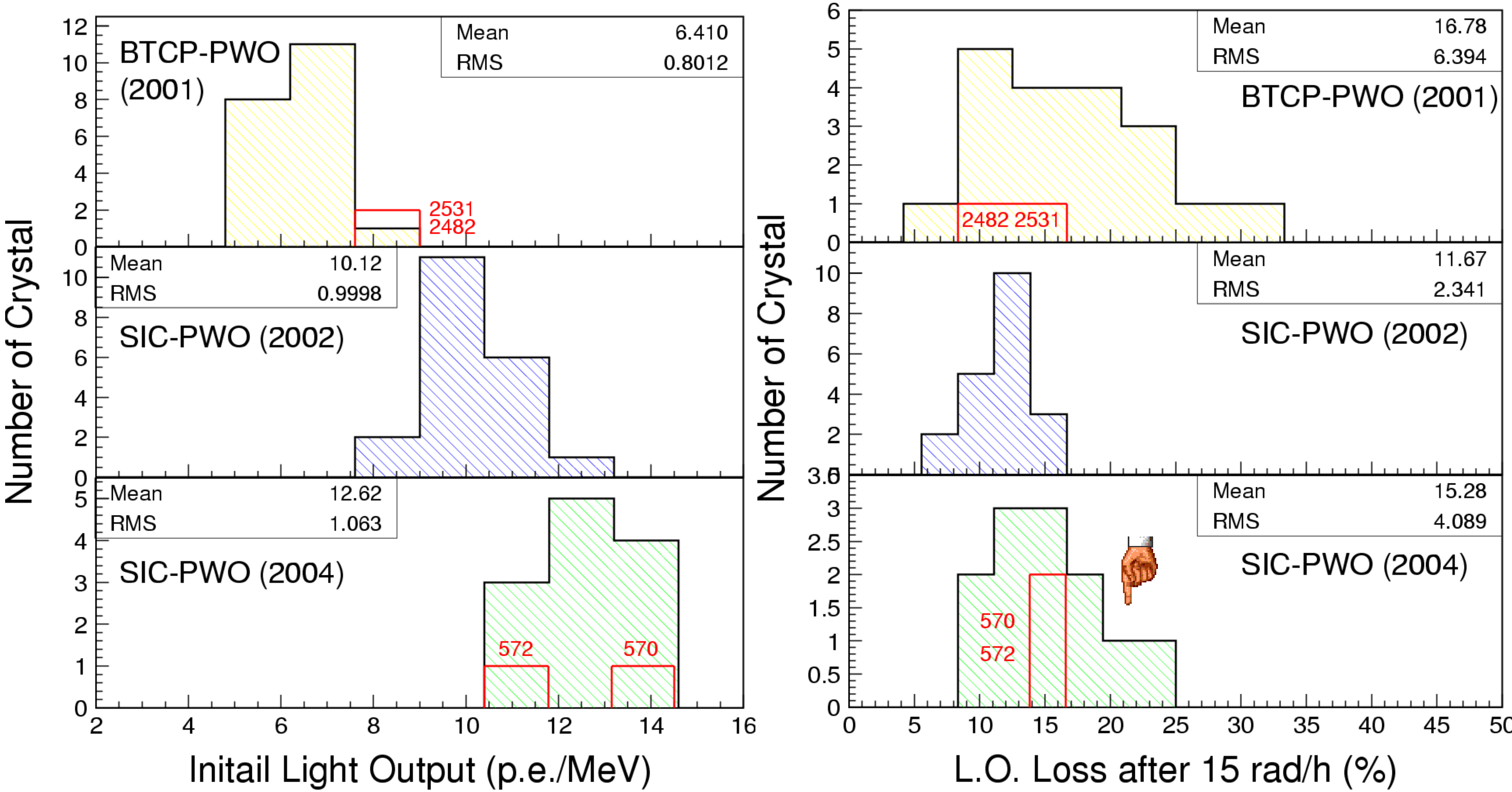


Comparison of LO & Degradation

2004 batch has more light: **geometry**

Some 2004 samples damages more: **contamination**

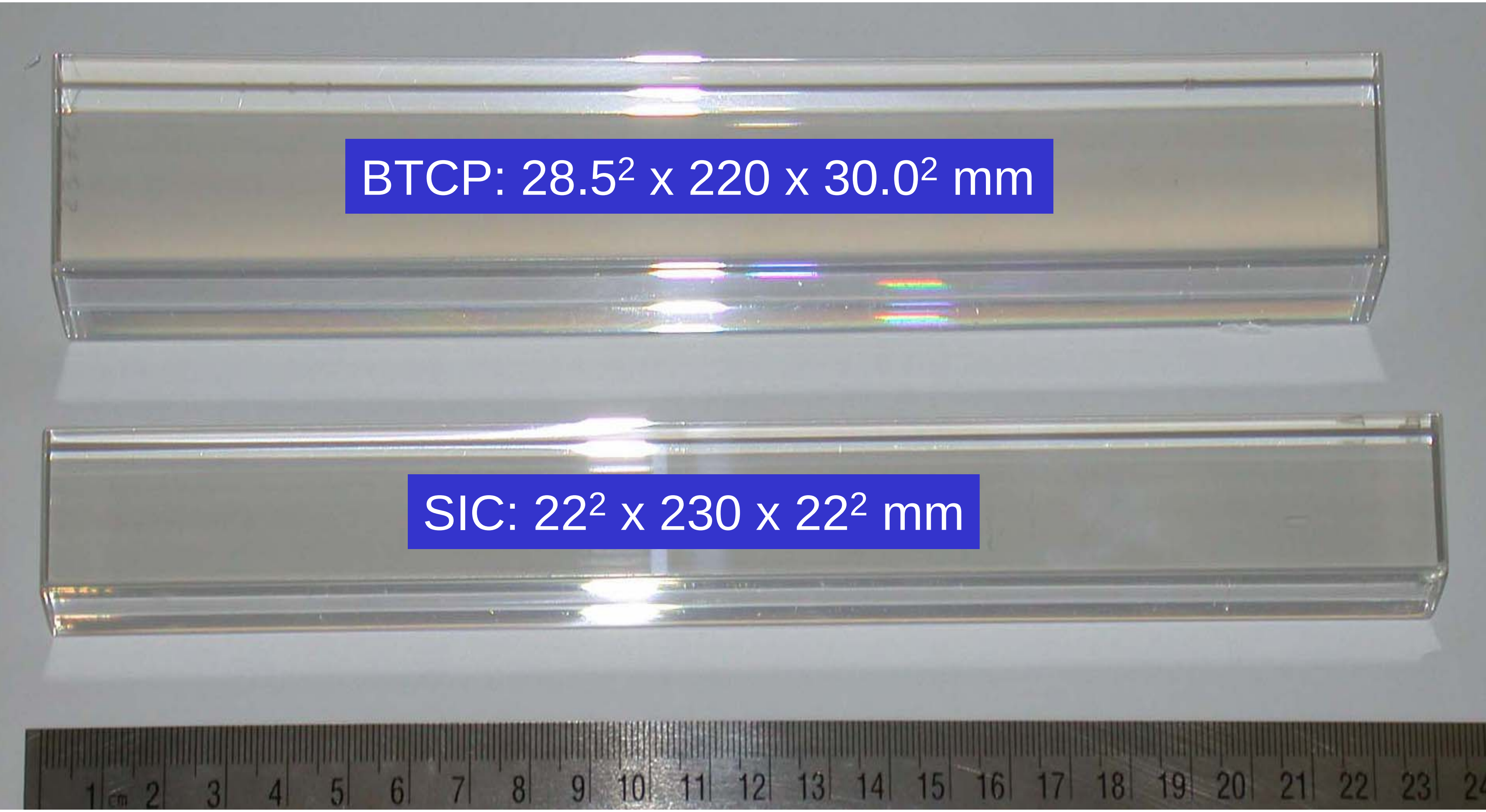
SIC samples have 50% more light than BTCP: **doping**



Randomly Selected PWO Samples

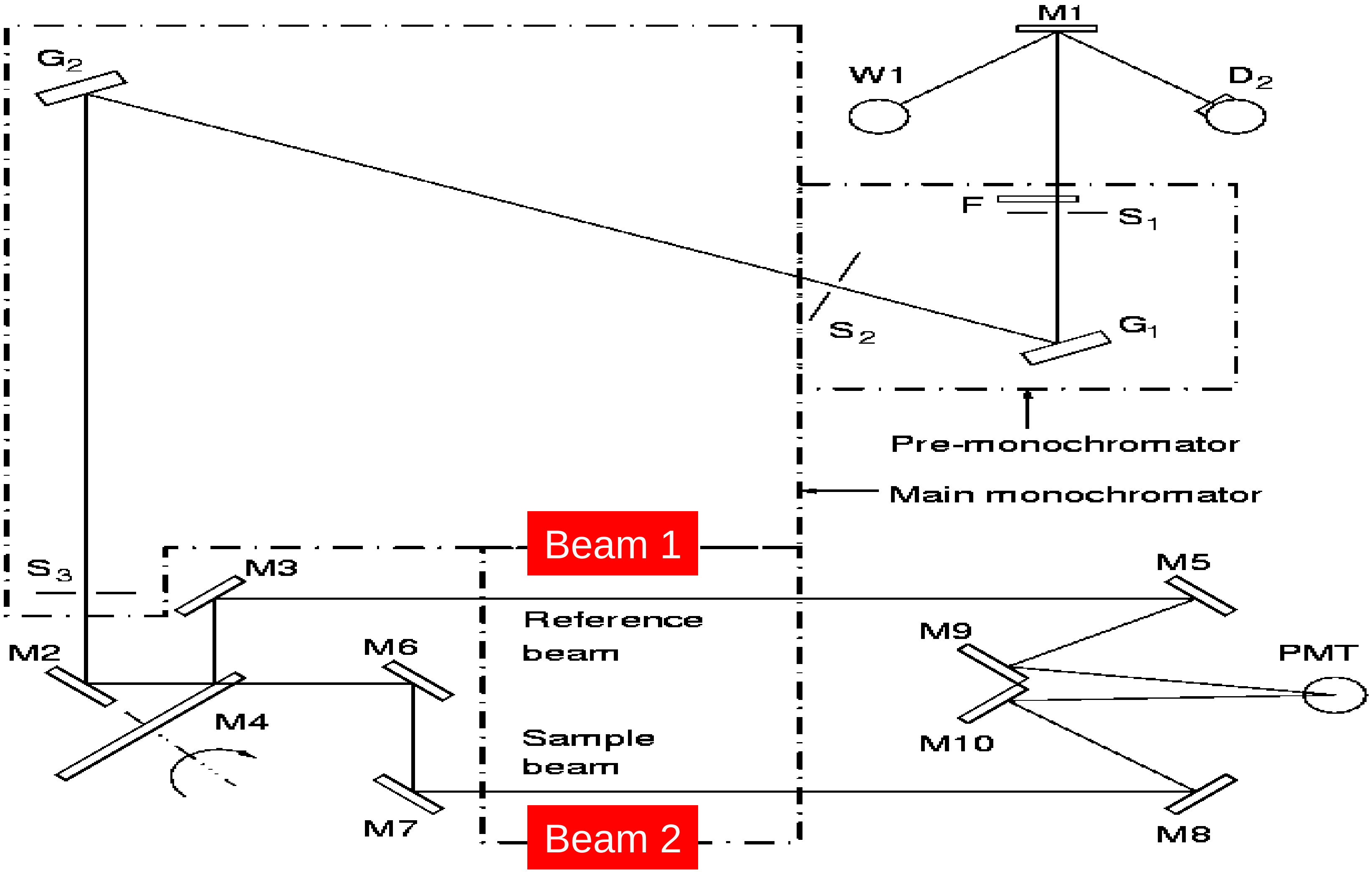
BTCP: 20 from 2001 batch for CMS endcaps

SIC: 20 from 2002 production batch for PrimEx



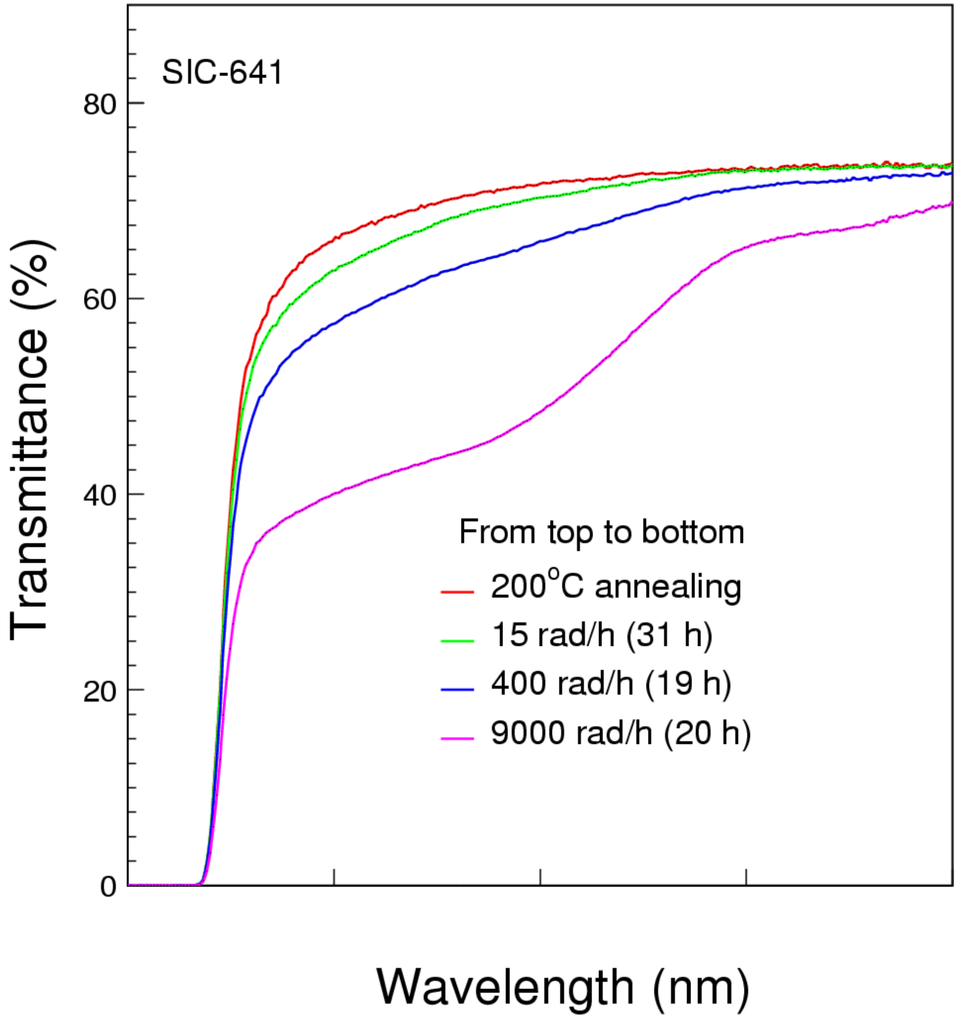
Transmittance Measurement

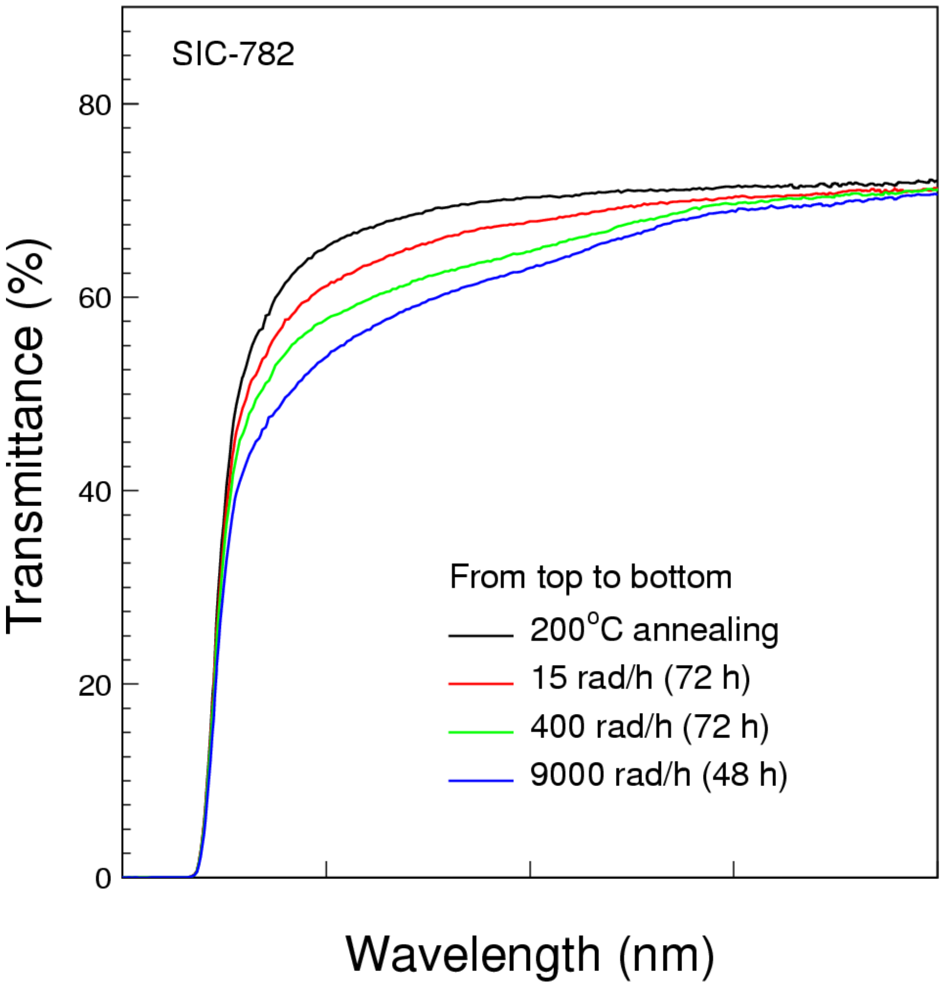
HITACHI U-3210 UV/VIS Spectrophotometer with a Large Sample Compartment



Longitudinal Transmittance

Radiation induced absorption, caused by CC formation, observed after 15, 400 and 4k rad/h





EWRIAC Measured after Irradiations

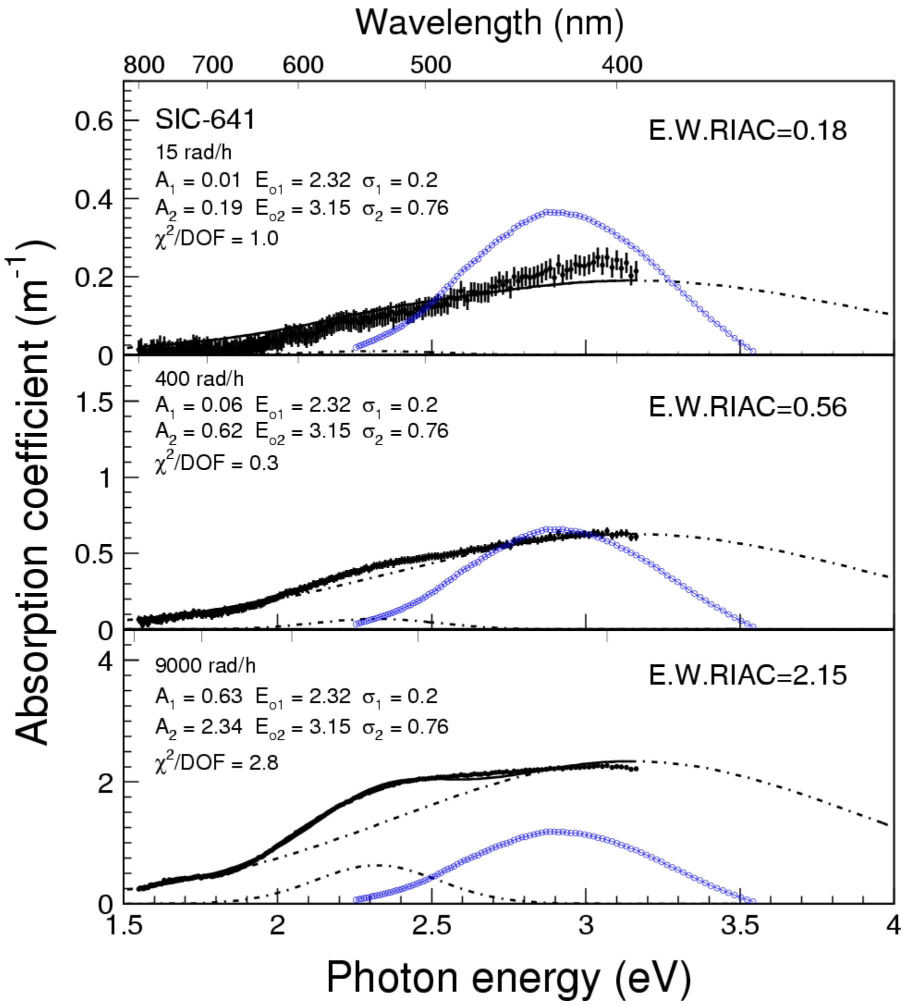
Note: emission weighted and multiple bounces

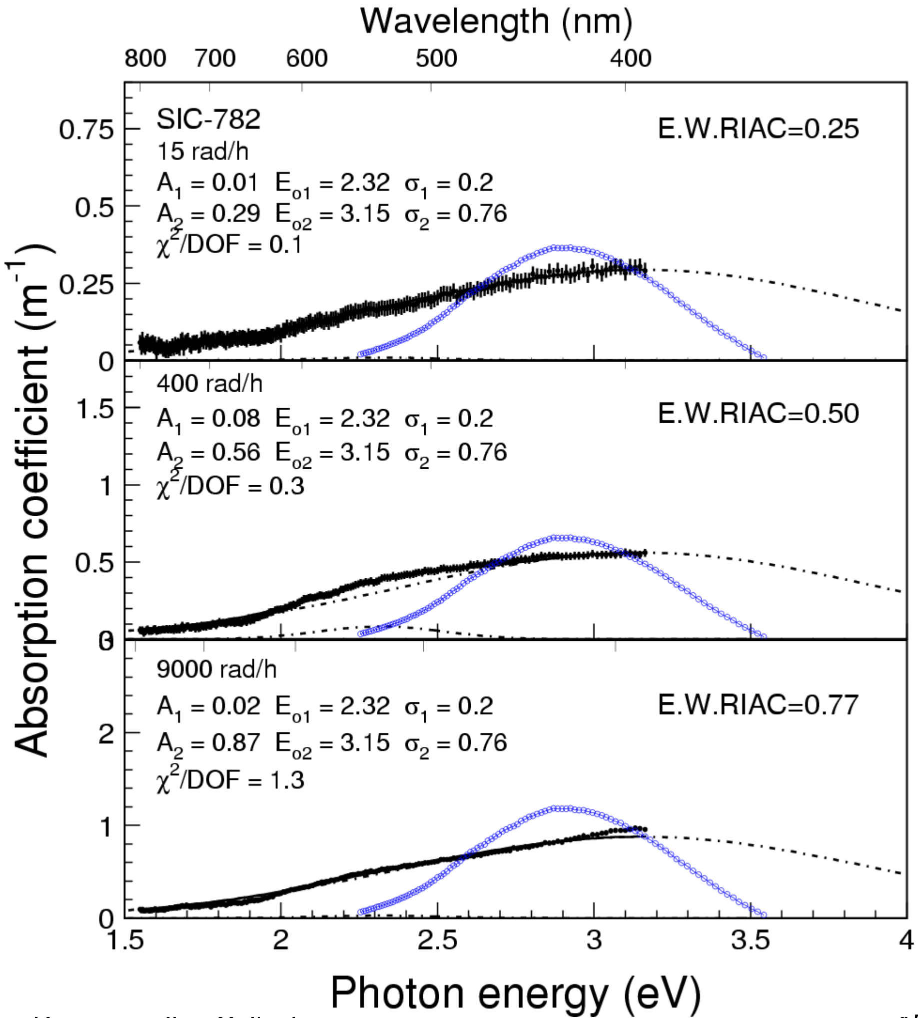
$$Riac = 1/LAL_{equilibrium} - 1/LAL_{before}$$

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

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

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

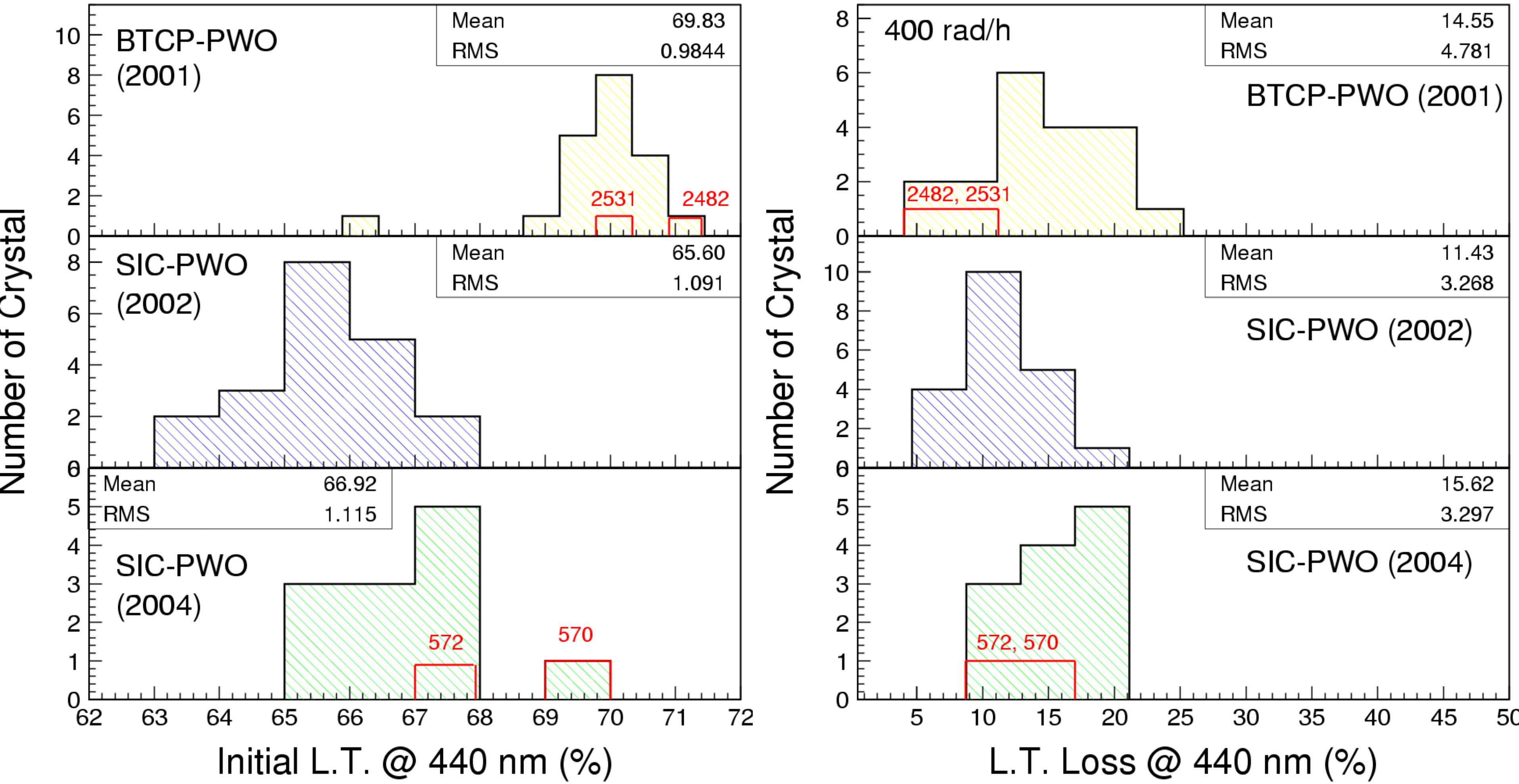




Comparison of LT and Damage

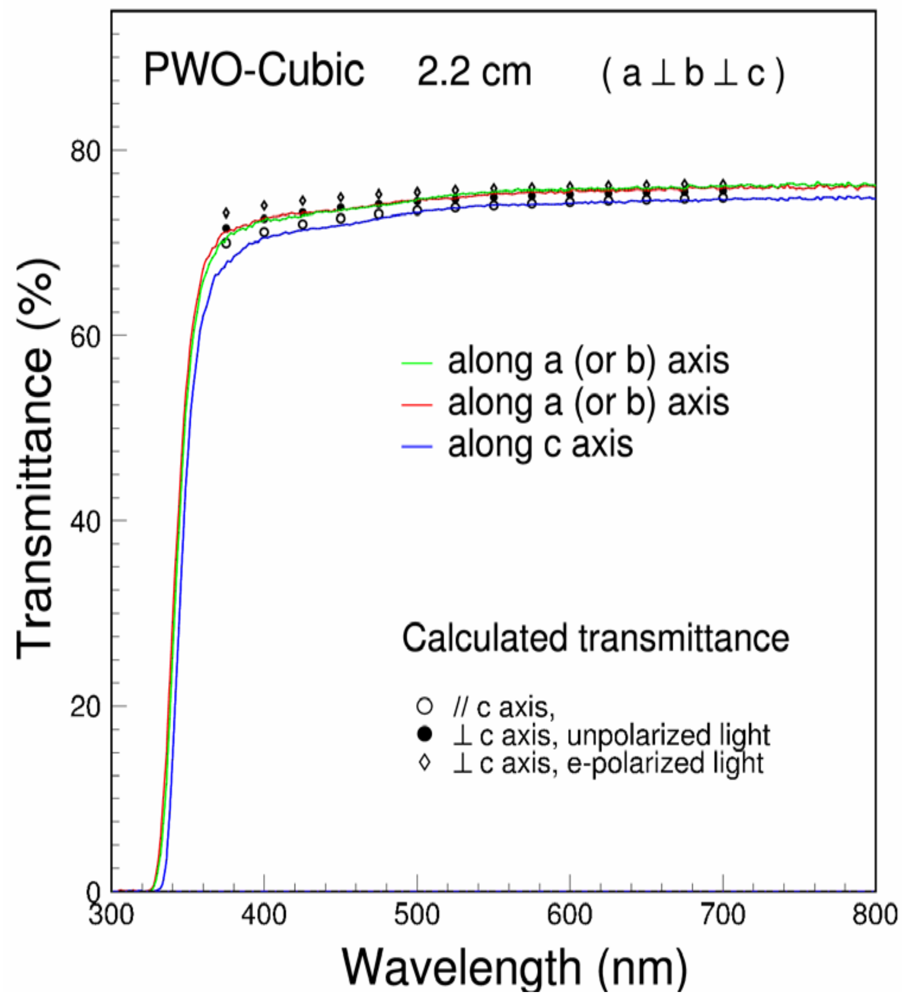
2004 batch has higher initial LT: **1 cm shorter**

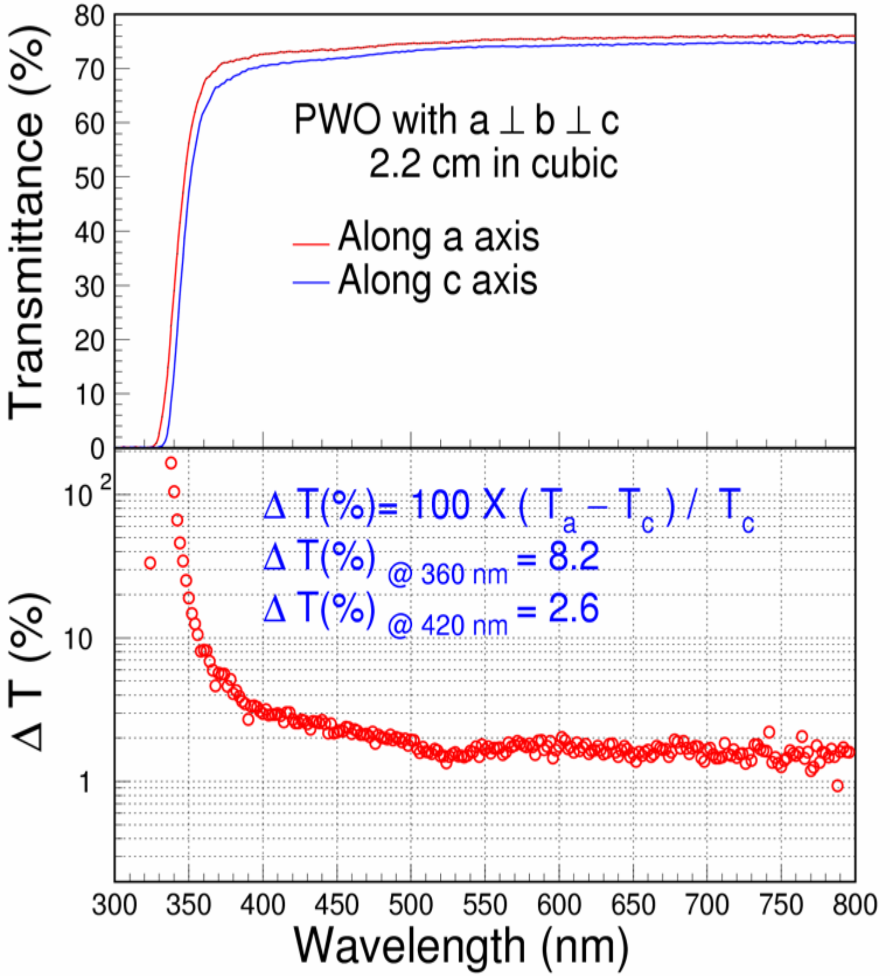
BTCP samples have 3% higher LT: **Orientation**



Transmittance of a PWO Cube

Transmittances measured along the *c* and *a* axis are **NOT** directly comparable

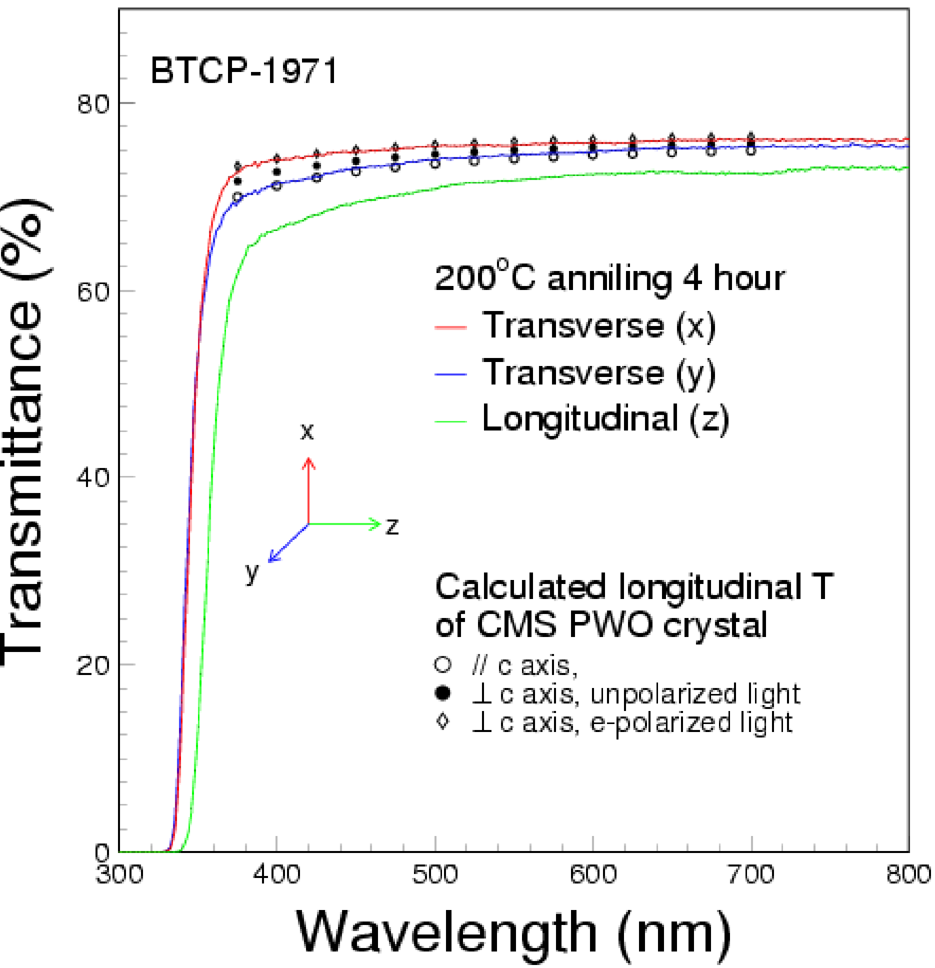




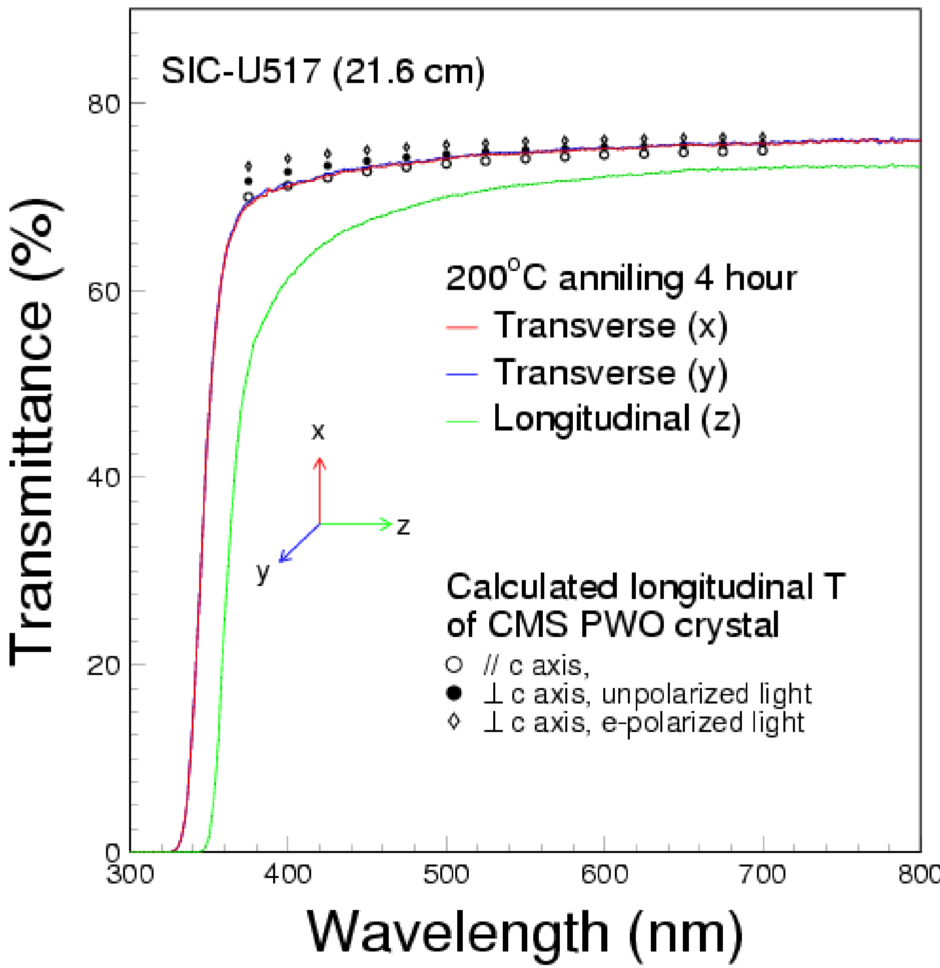
Transmittance and Birefringence

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

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

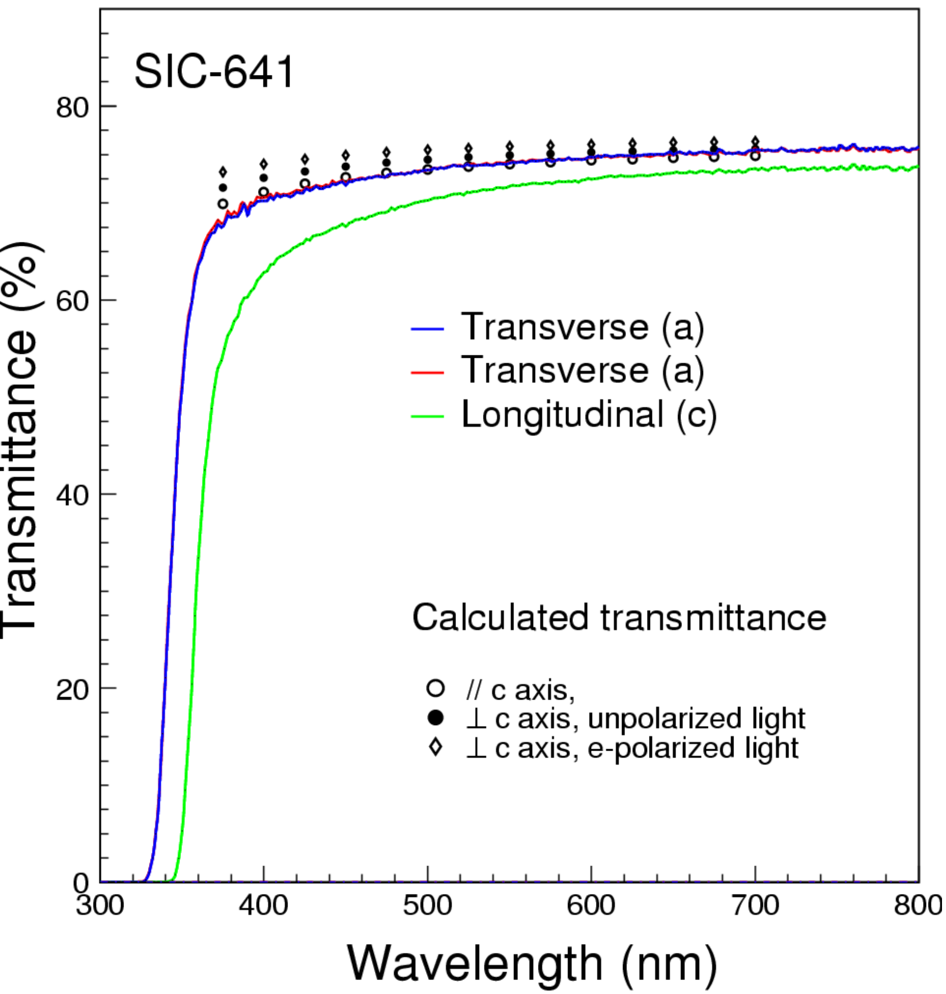


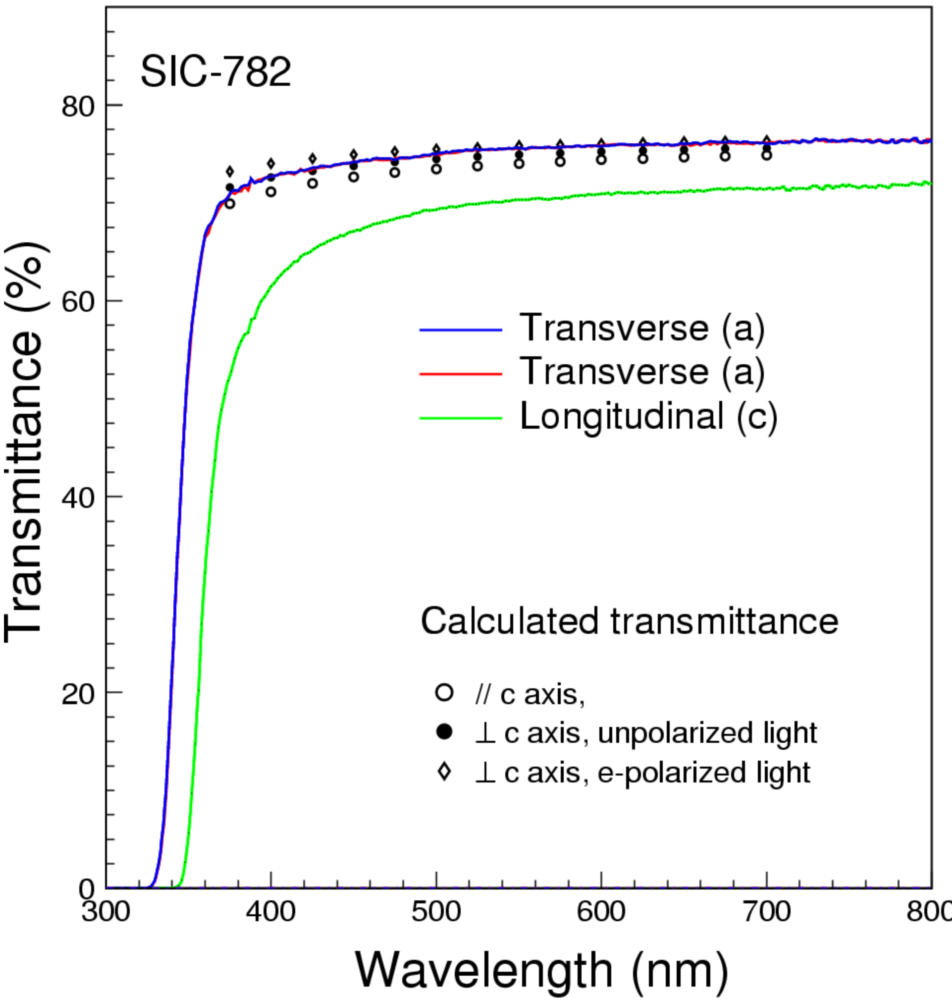
SIC: grown along the ***c axis***



Initial Transmittance

SIC samples are consistent: ***c axis*** orientation



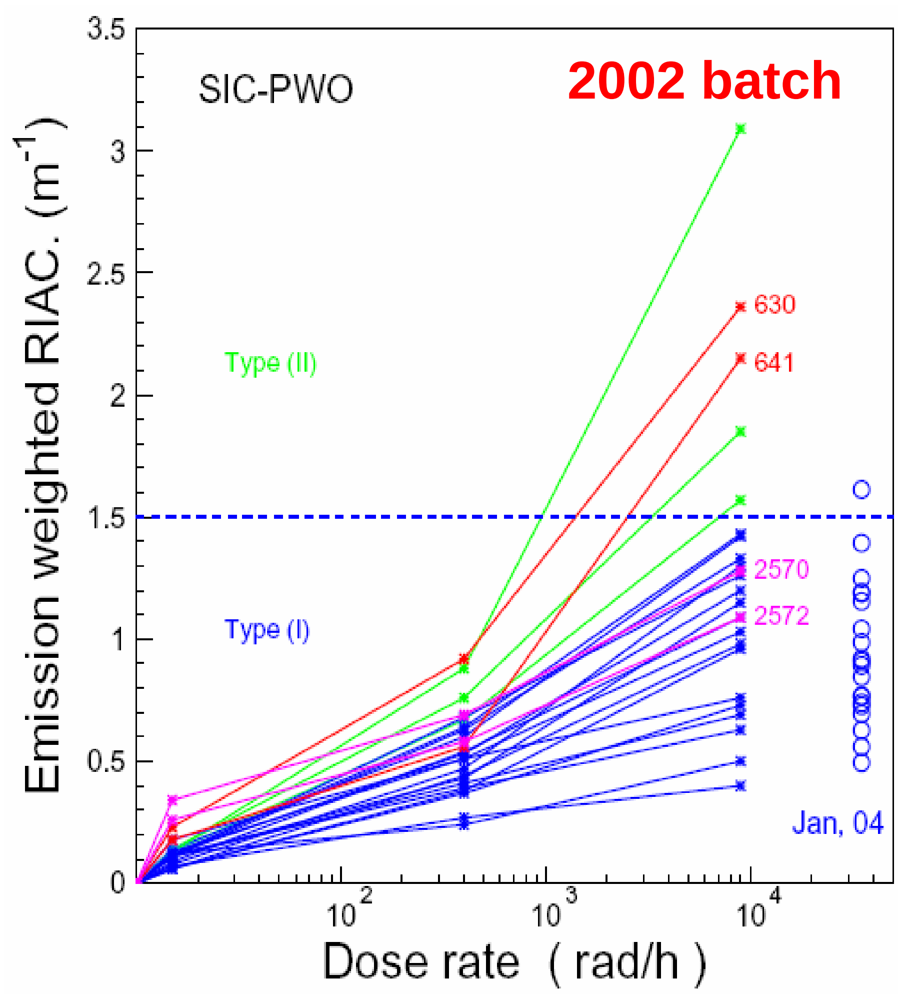


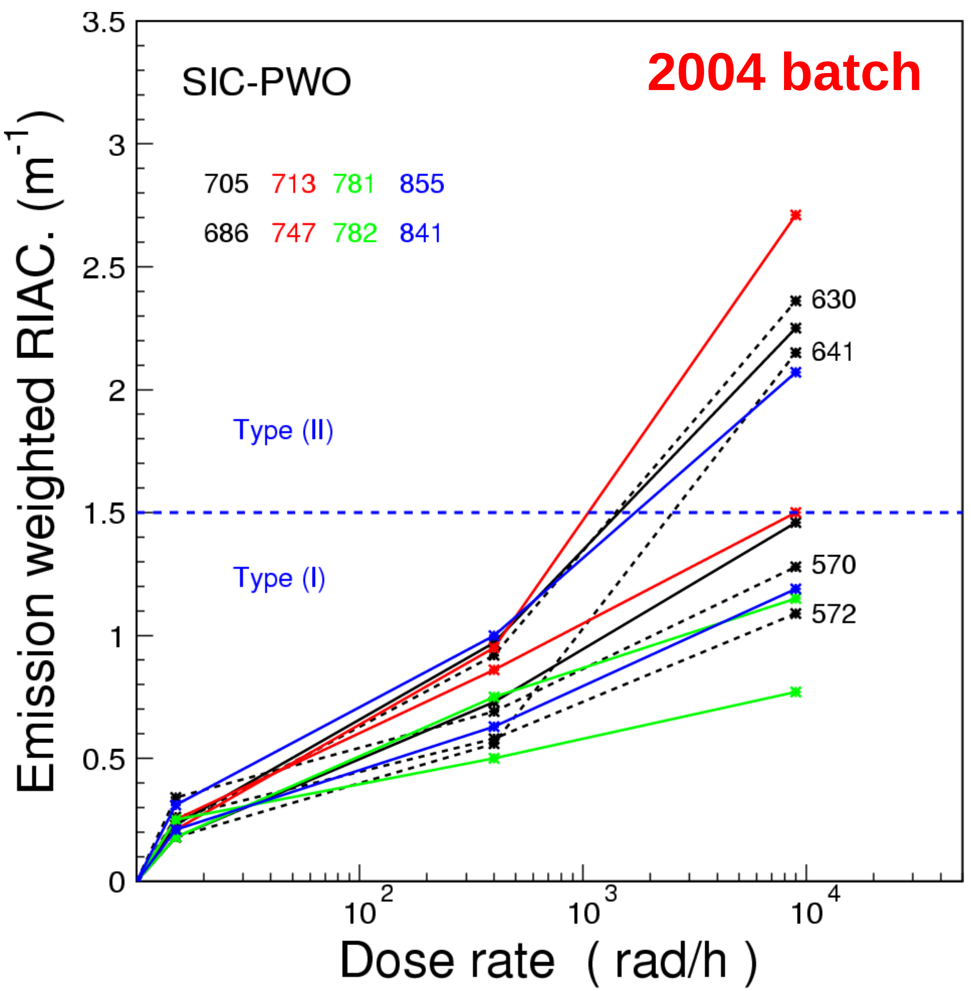
Emission Weighted RIAC

Radiation hardness is more divergent at high dose rate

01/04 and 12/04 batches are better: **need more statistics!**

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

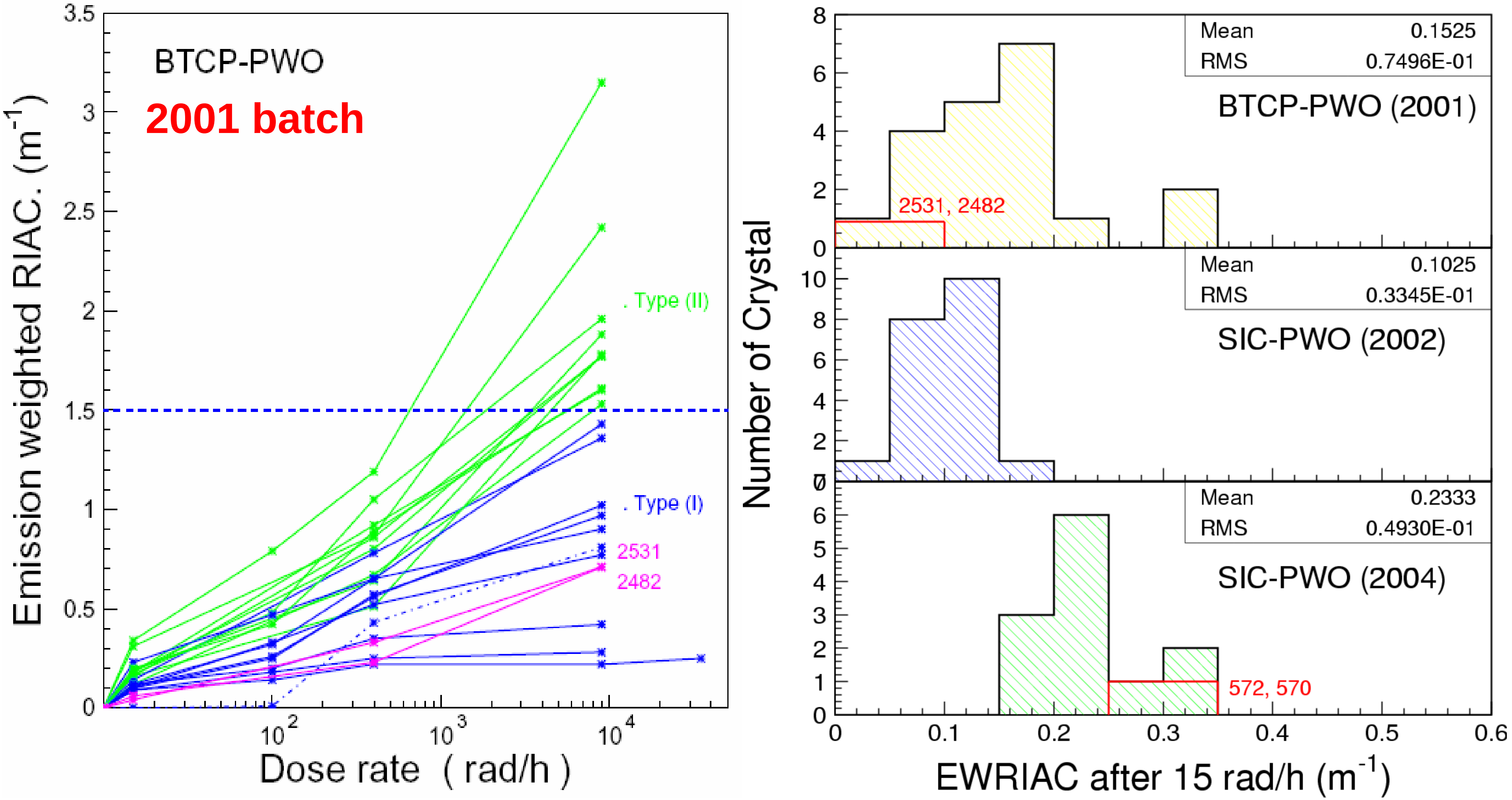




EWRIAC & Comparison

Two 2003 BTCP samples are better than the 2001 batch

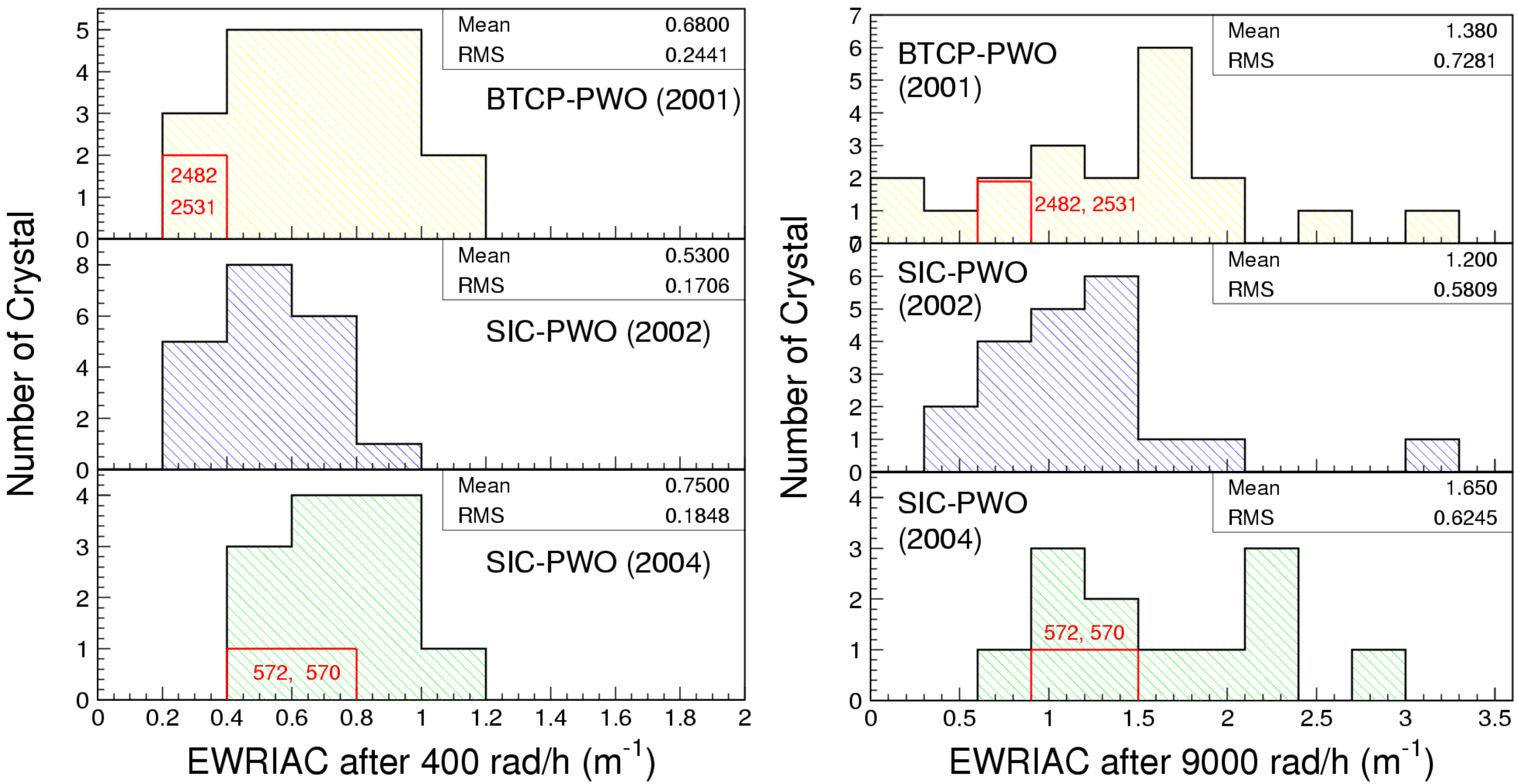
Some SIC 2004 samples are softer caused by **Contamination**



Comparison of EWRIAC

Radiation hardness is more divergent at high dose rate

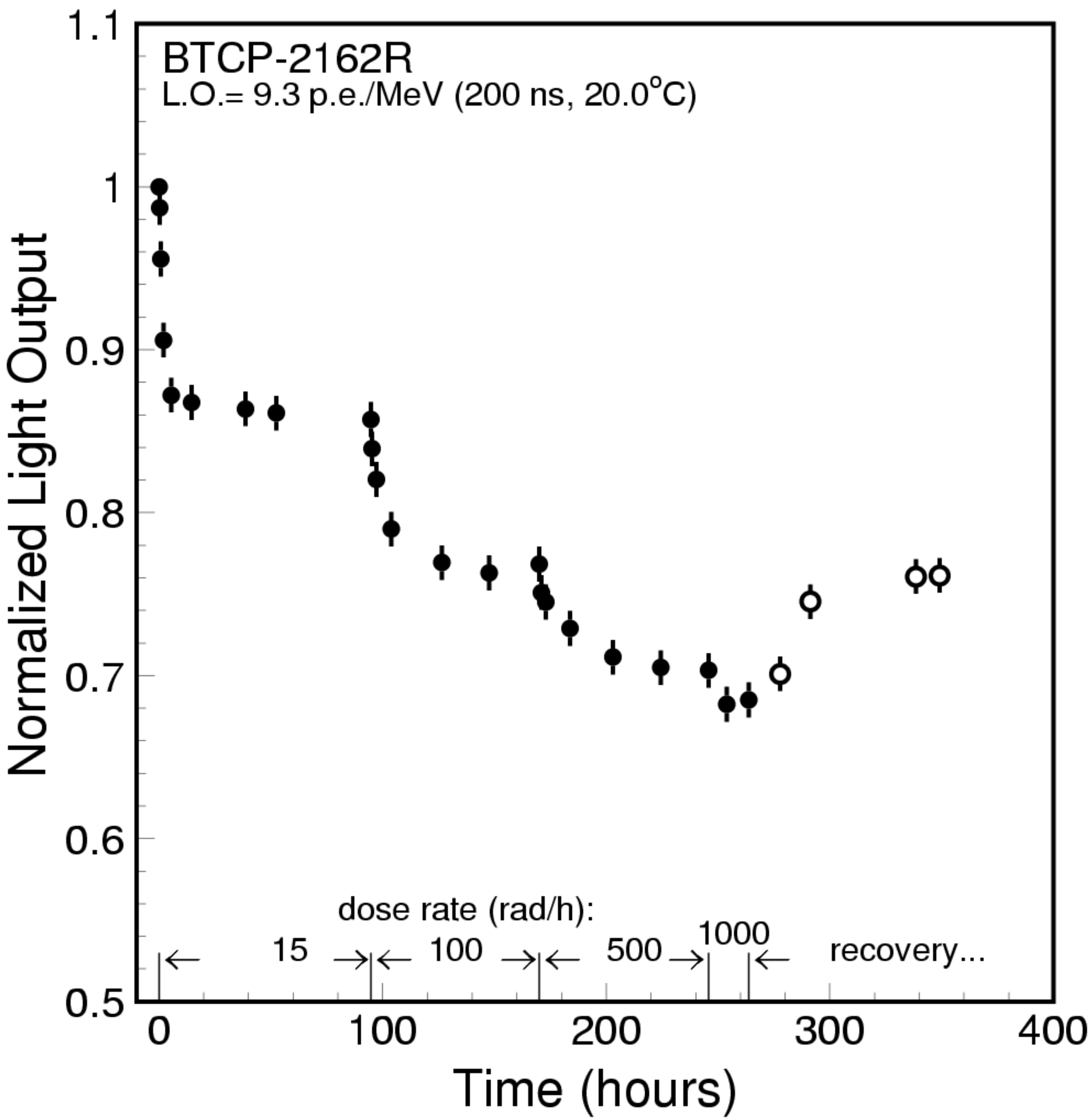
01/04 and 12/04 batches are good and two BTCP 2003 samples are better than the 2001 batch: **need more statistics!**



Summary I: 2004 SIC Samples

- SIC samples produce 50% more light than BTCP samples because of doping.
- The overall performance of SIC 2004 samples is consistent with the 2001 batch but has a batch to batch fluctuation (soft batches) caused by contamination.
- The EWRIAC data shows that all samples tested so far are qualified for CMS barrel, where dose rate is less than a few hundred rad/h even at SLHC. Stringent QC, however, is required for crystals to be used in endcaps where up to 10,000 rad/h is expected at SLHC.

Damage and Recovery Test

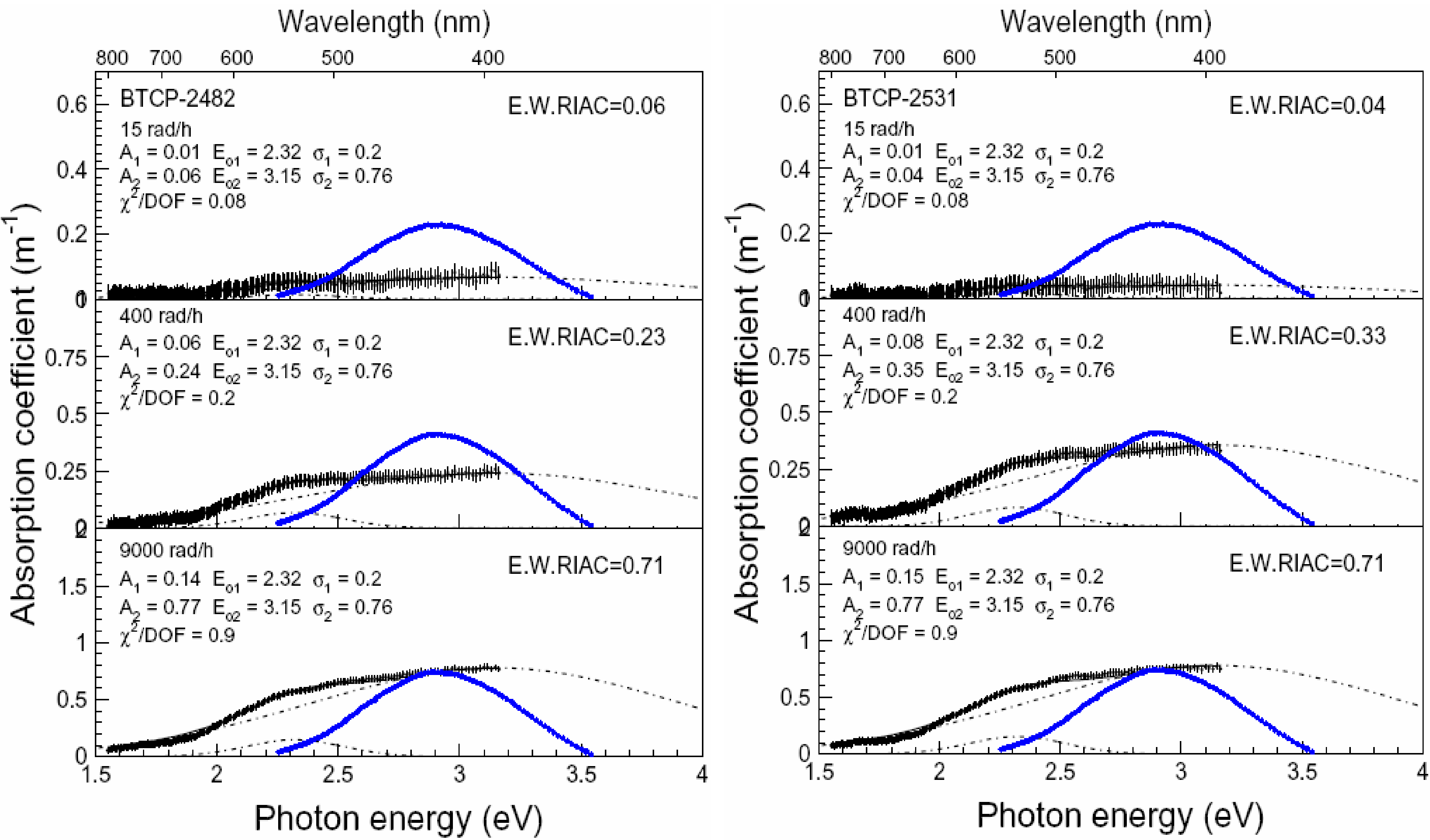


With RIAC under control we have to deal with LO variations by using knowledge of LT: monitoring.

Four PWO samples delivered around the end of 2003 (2482 & 2531 from BTCP and 2570 & 2572 from SIC) went through identical damage-recovery cycles.

EWRIAC of 2 BTCP Samples

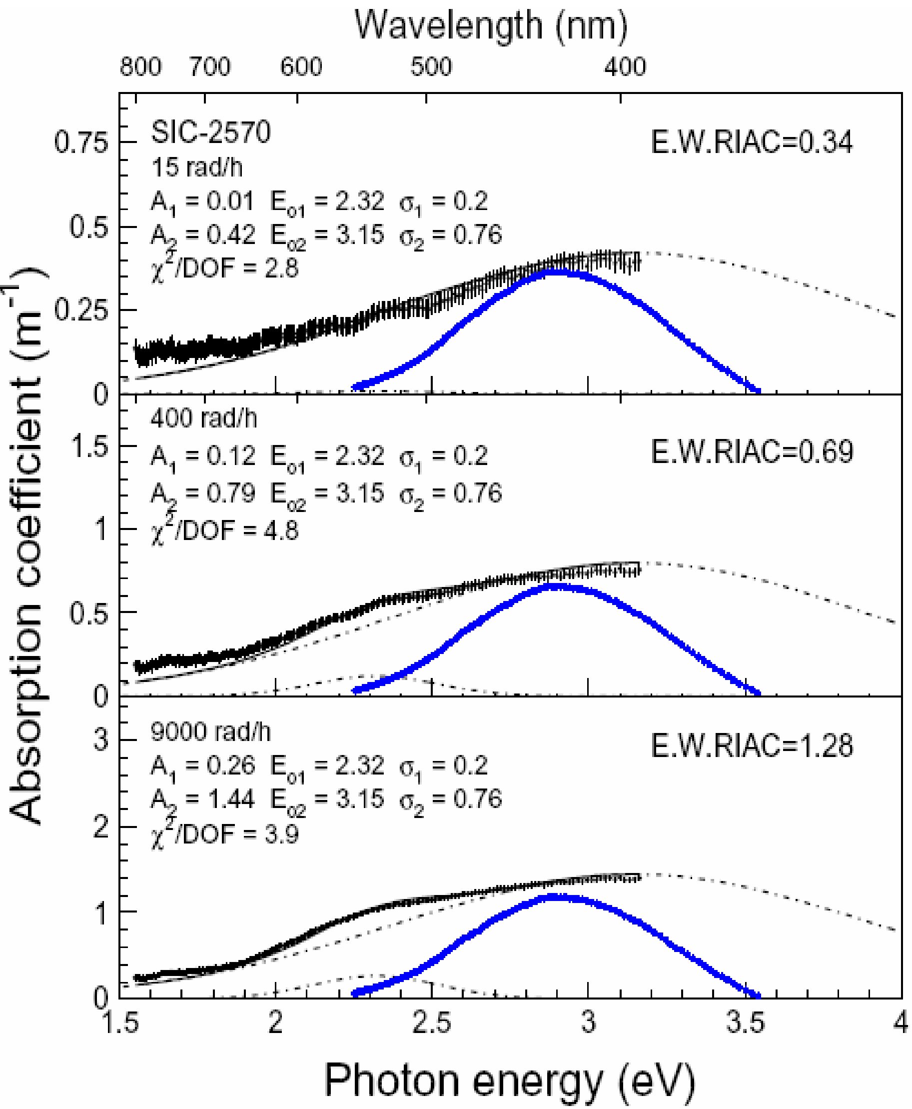
Average EWRIAC = 0.05, 0.28 & 0.71 m^{-1} @ 15, 400 and 9,000 rad/h

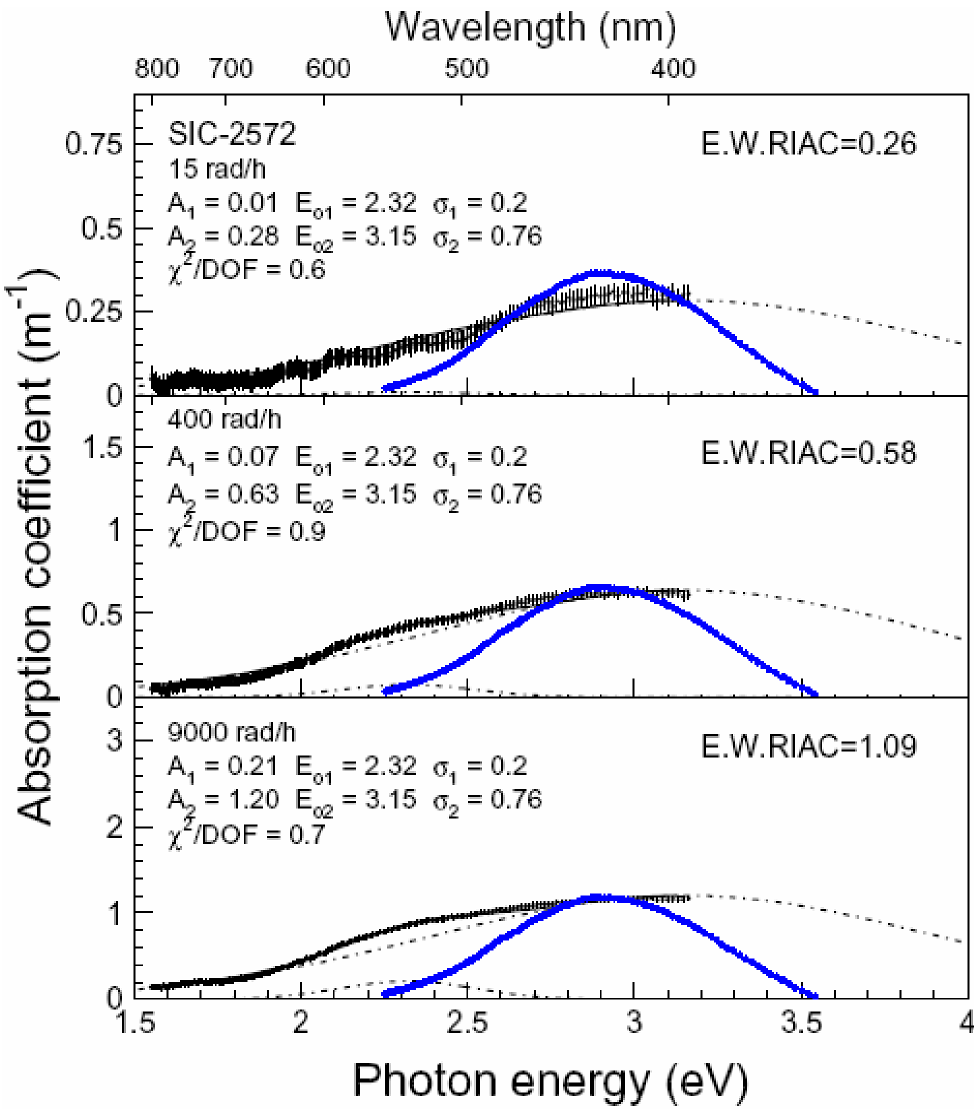


EWRIAC of 2 SIC Samples

Average EWRIAC = 0.30, 0.59 & 1.19 m^{-1} @ 15, 400 and 9,000 rad/h

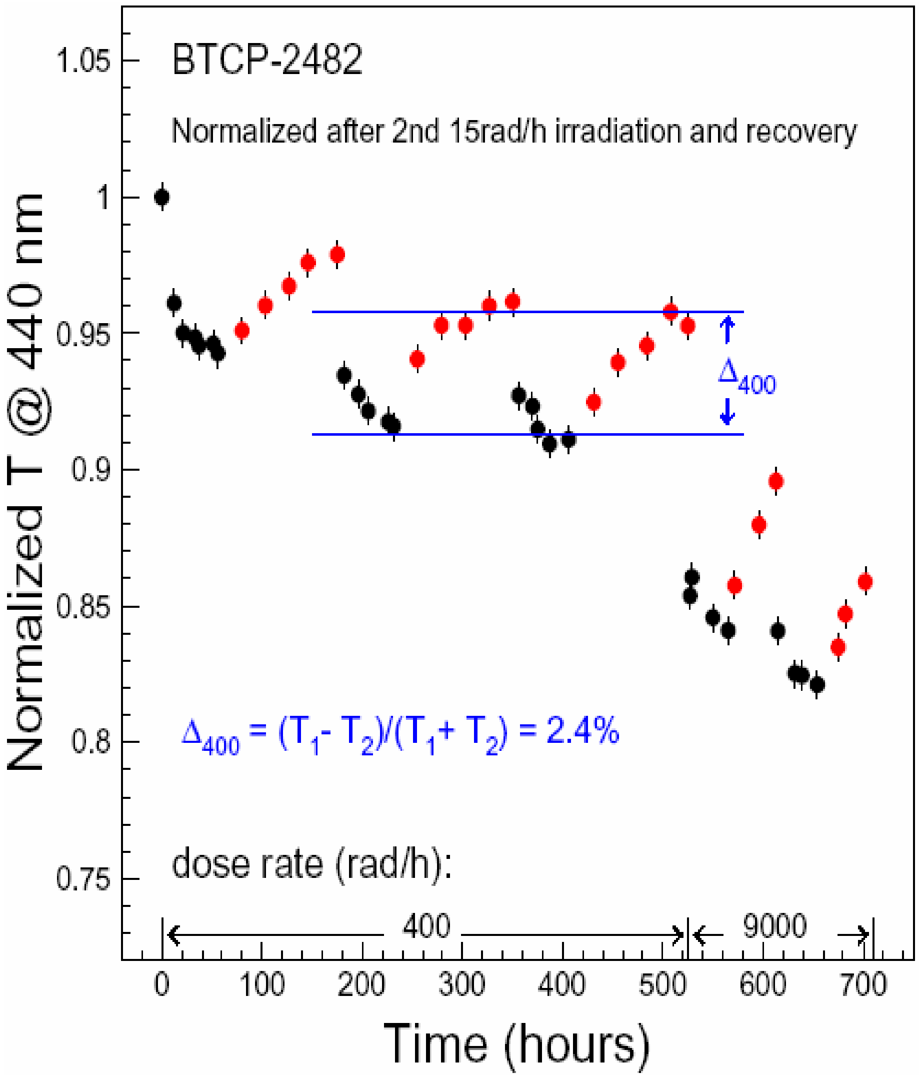
A factor of **6, 2 & 1.7** of BTCP

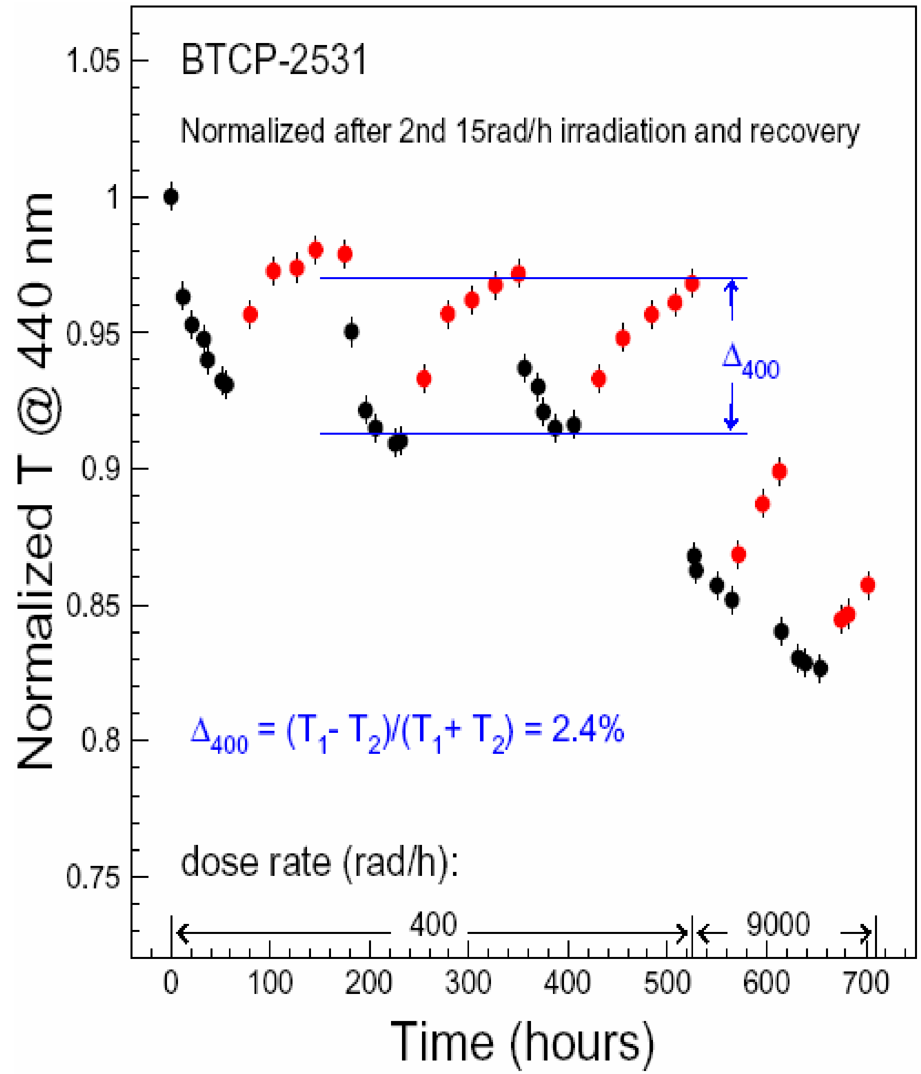




History of BTCP L.T.

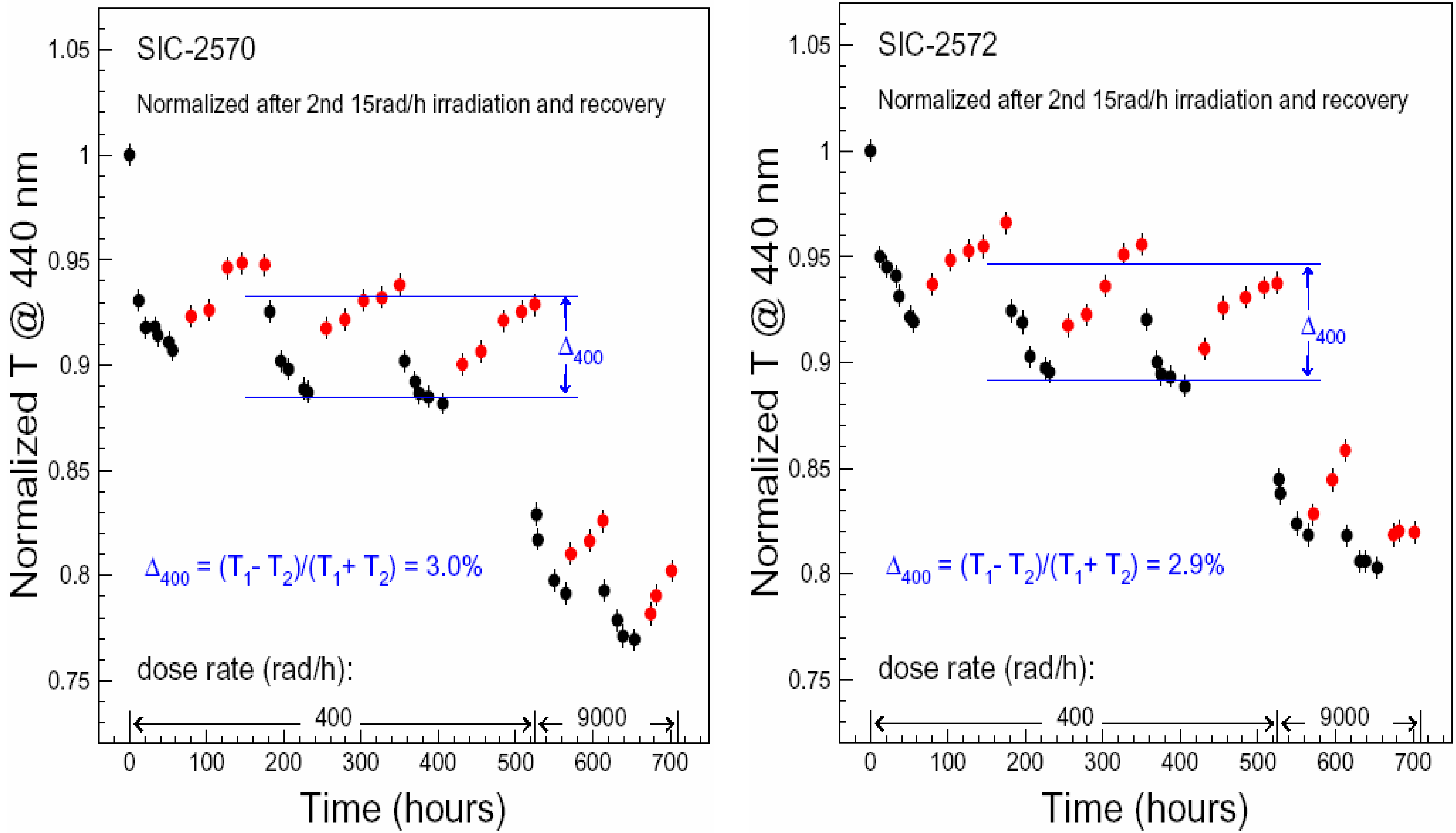
Average variation @ 400 rad/h: 2.4%





History of SIC L. T.

Average variation @ 400 rad/h: 3%
a factor of **1.3** of BTCP

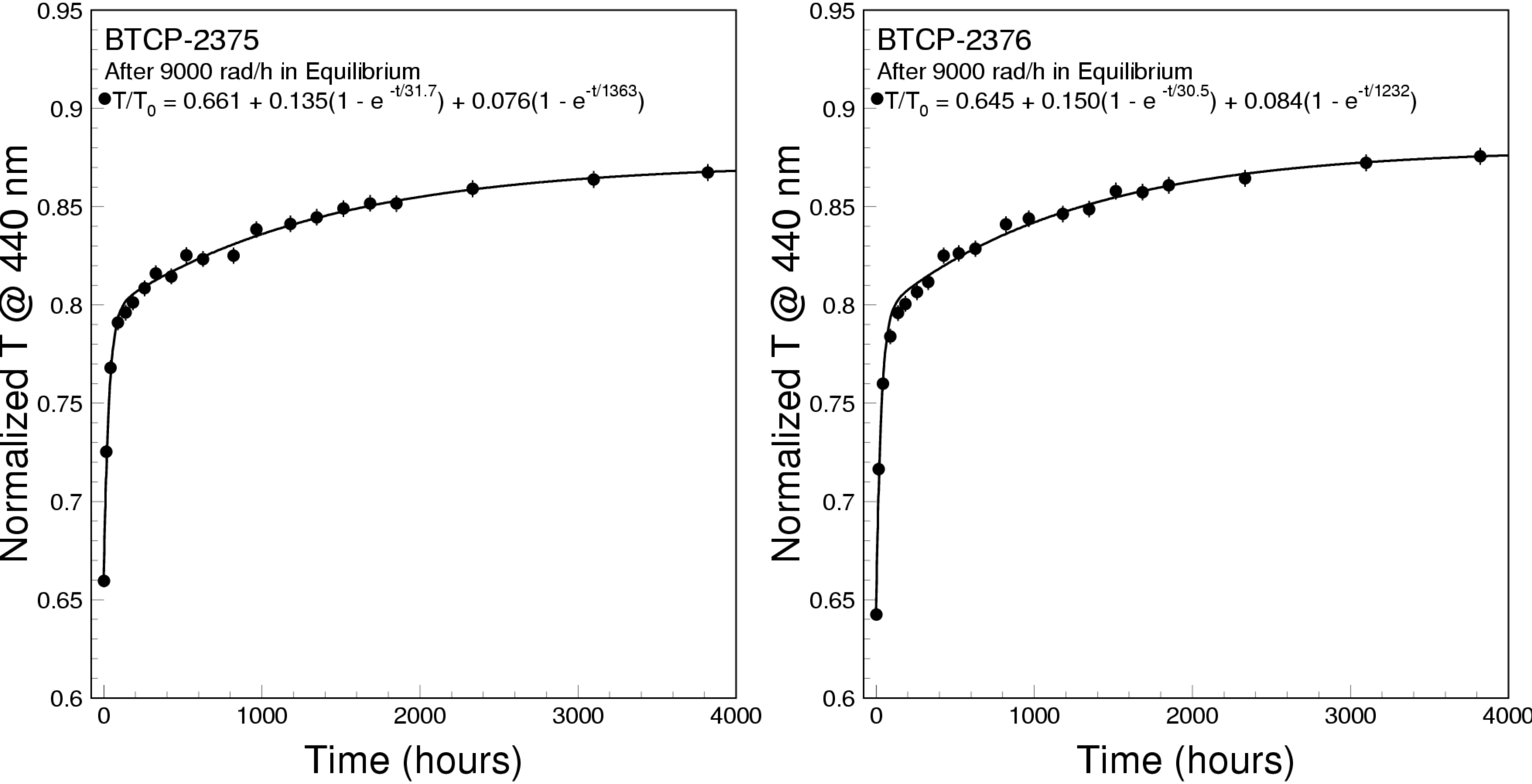


Long Term Recovery (BTCP 2001 Batch)

Fast: 40% and 42% with time constant of 31 and 31 h

Slow: 22% and 24% with time constant of 1363 and 1232 h

35% unrecoverable damage

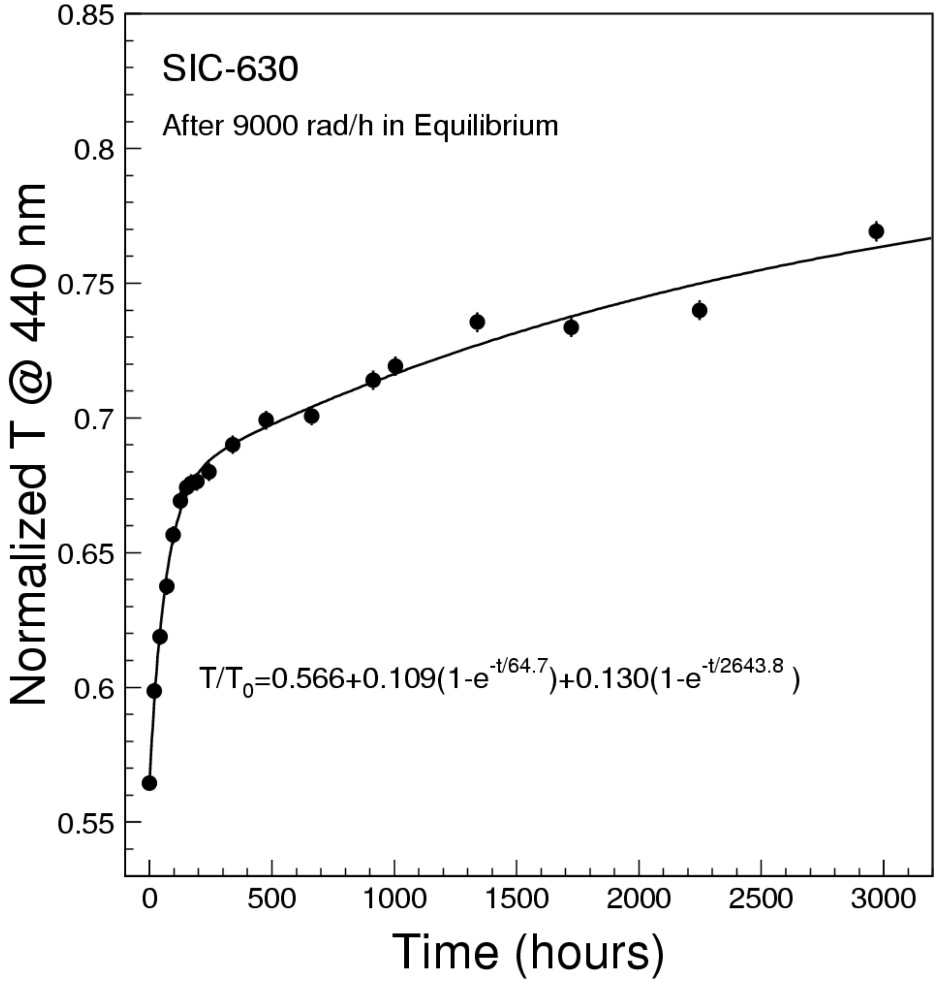


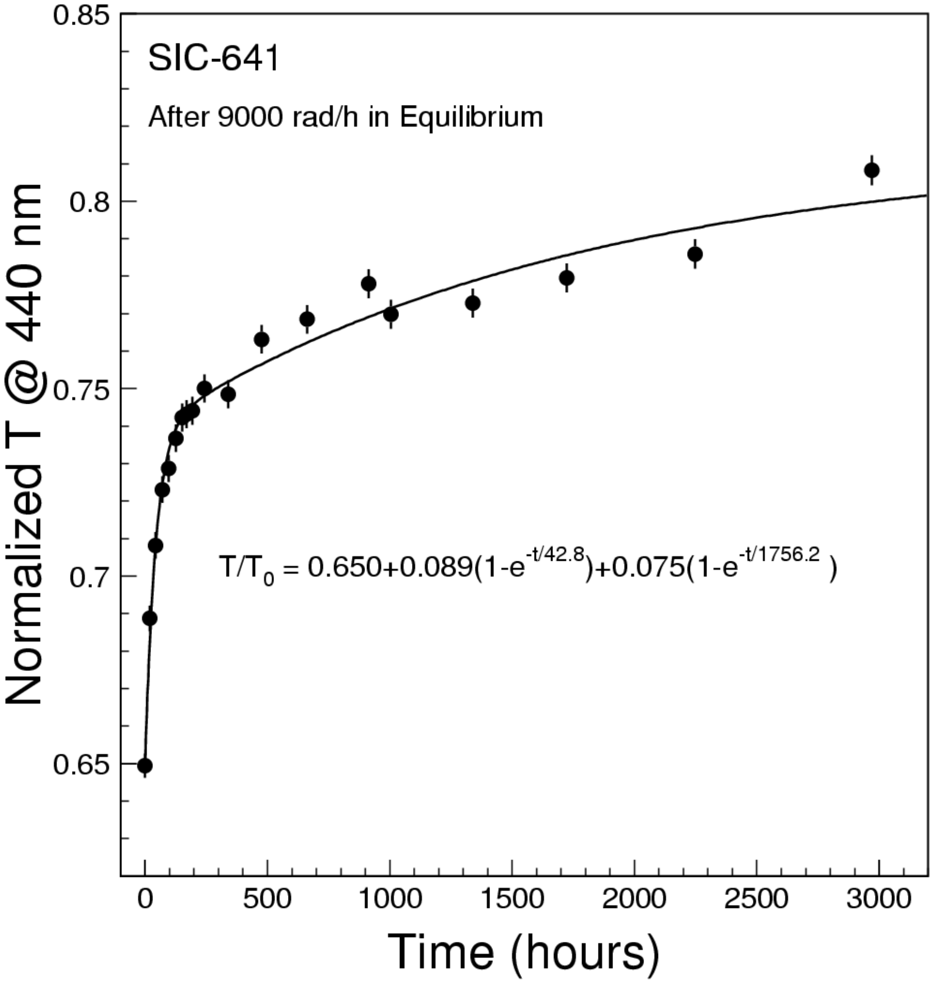
Long Term Recovery (SIC 2004 Batch)

Fast: 25% and 25% with time constant of 65 and 43 h

Slow: 30% and 21% with time constant of 2644 and 1756 h

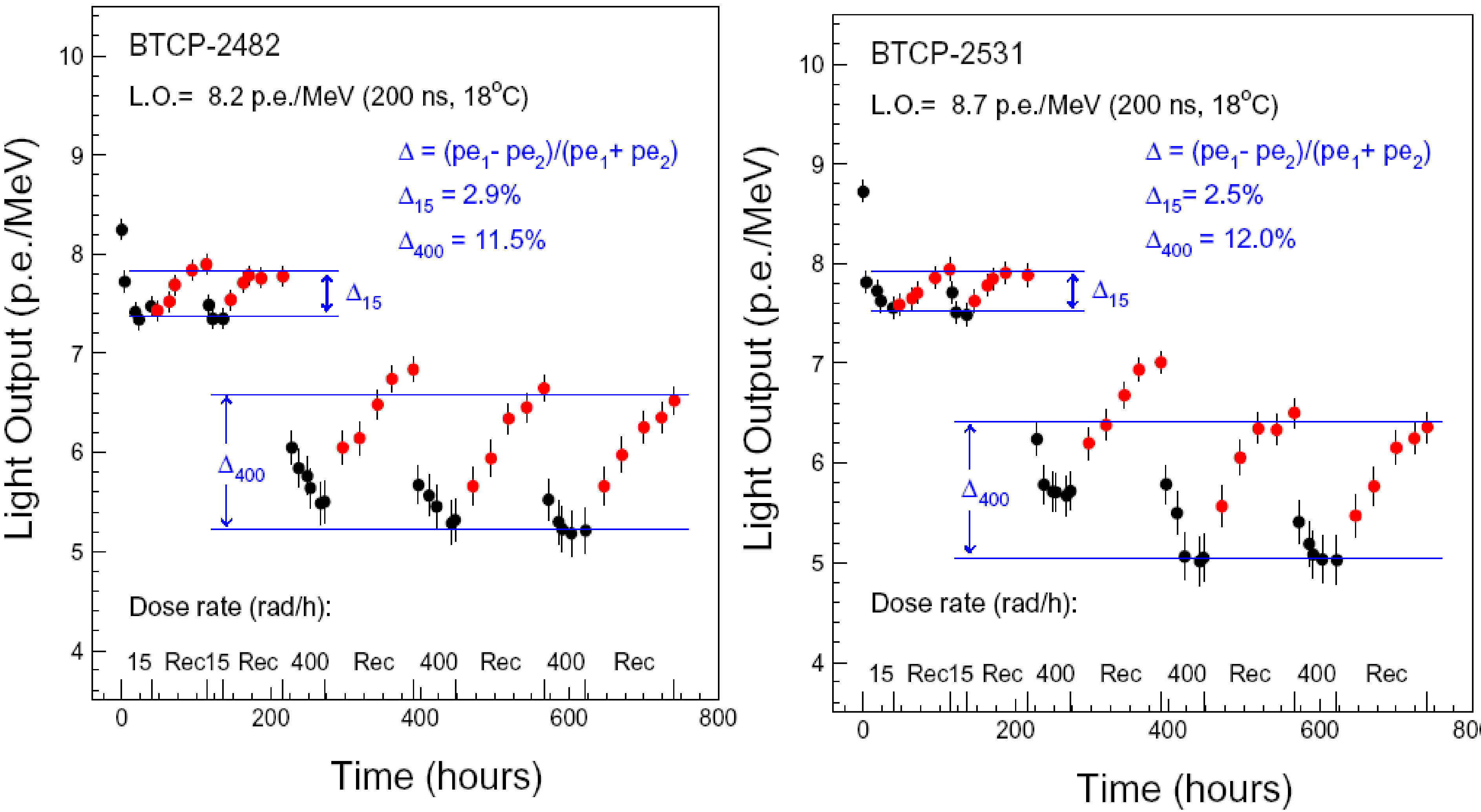
50% unrecoverable damage





History of BTCP Light Output

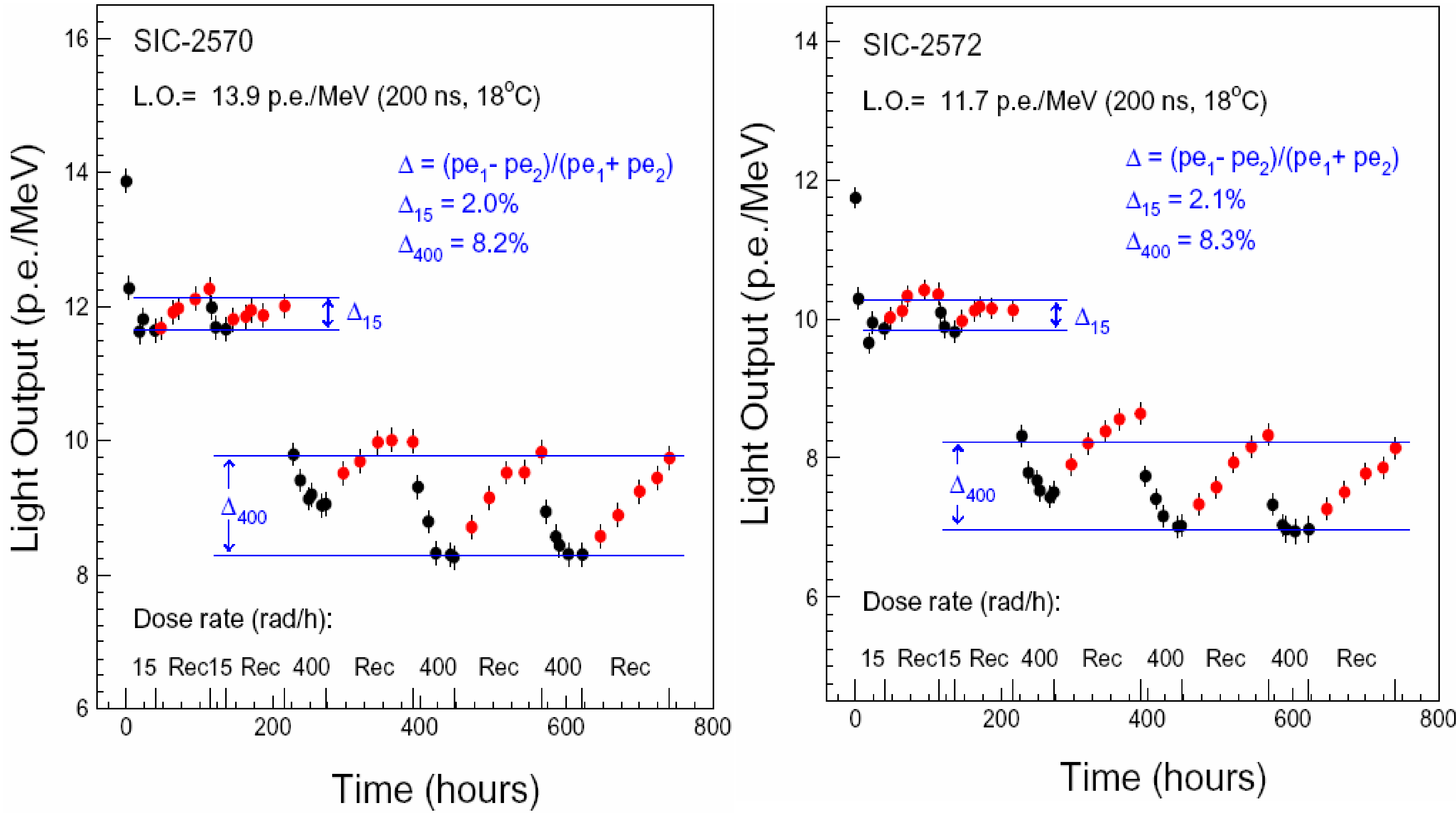
Average variations: 2.7% @ 15 rad/h, 12% @ 400 rad/h



History of SIC Light Output

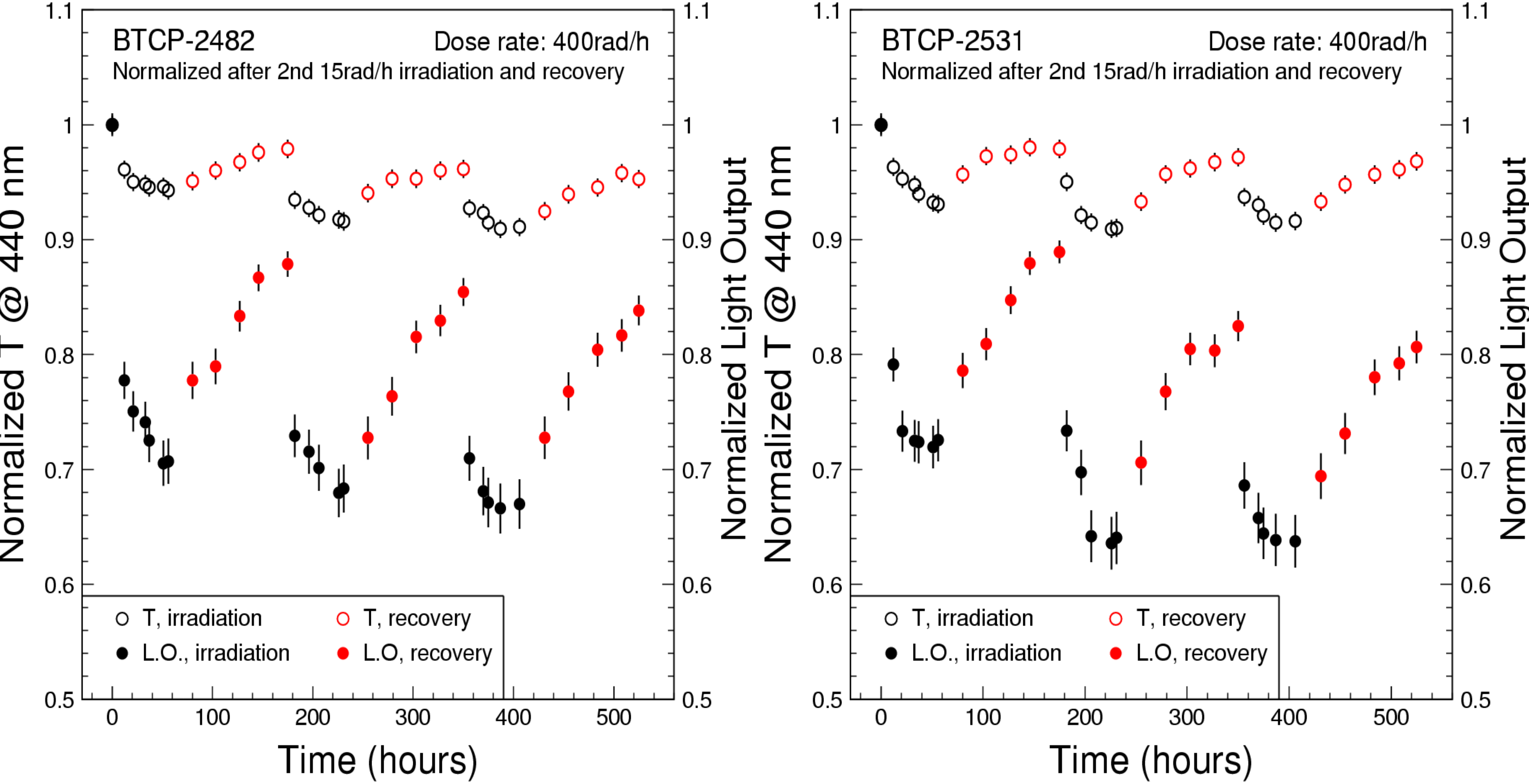
Average variations: 2.1% @ 15 rad/h, 8.3% @ 400 rad/h

A factor of **0.78 and 0.69** of BTCP



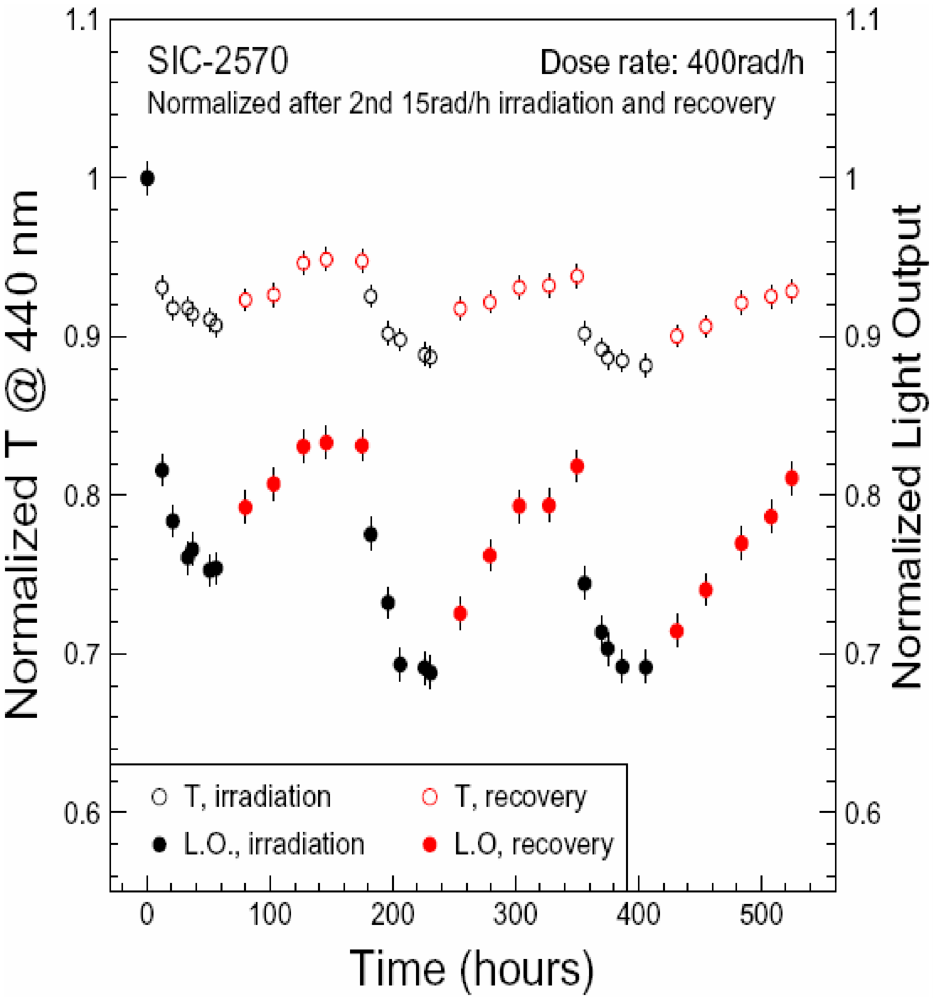
History of BTCP LT & LO @ 400 rad/h

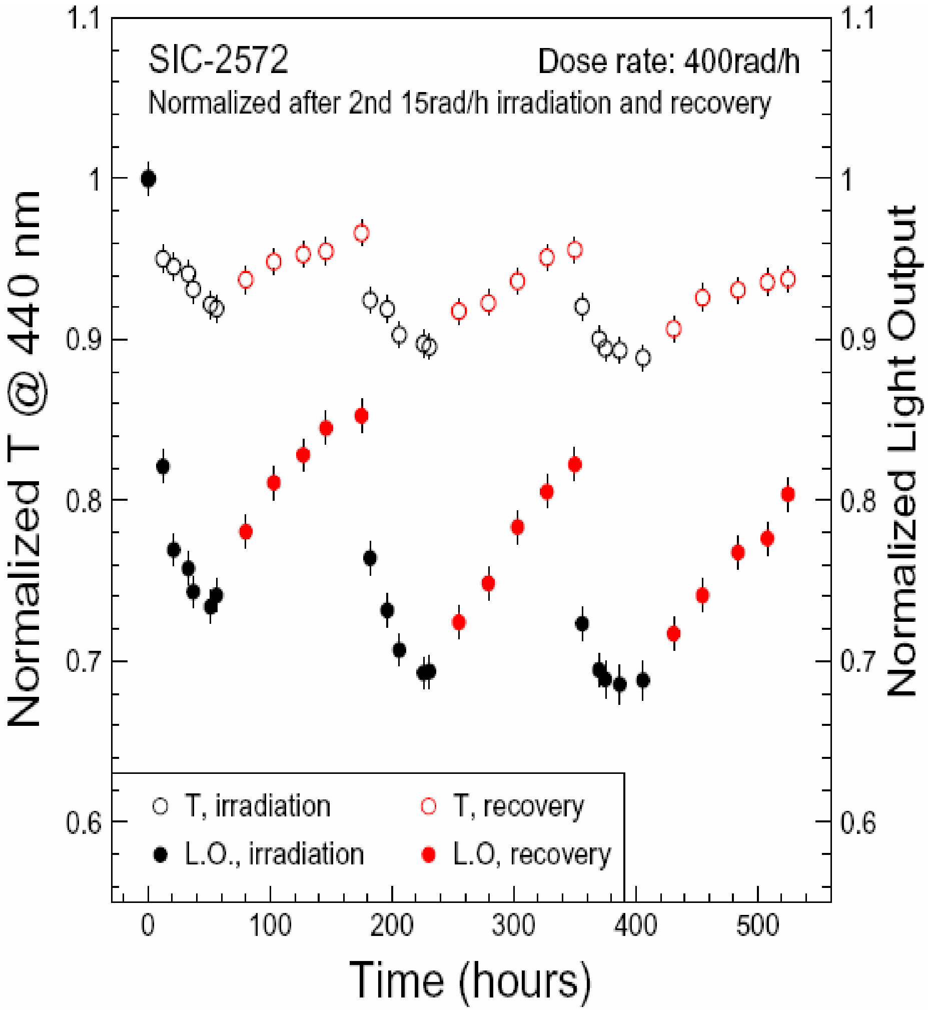
Normalization point: after 2 cycles of damage & recovery @ 15 rad/h



History of SIC LT & LO @ 400 rad/h

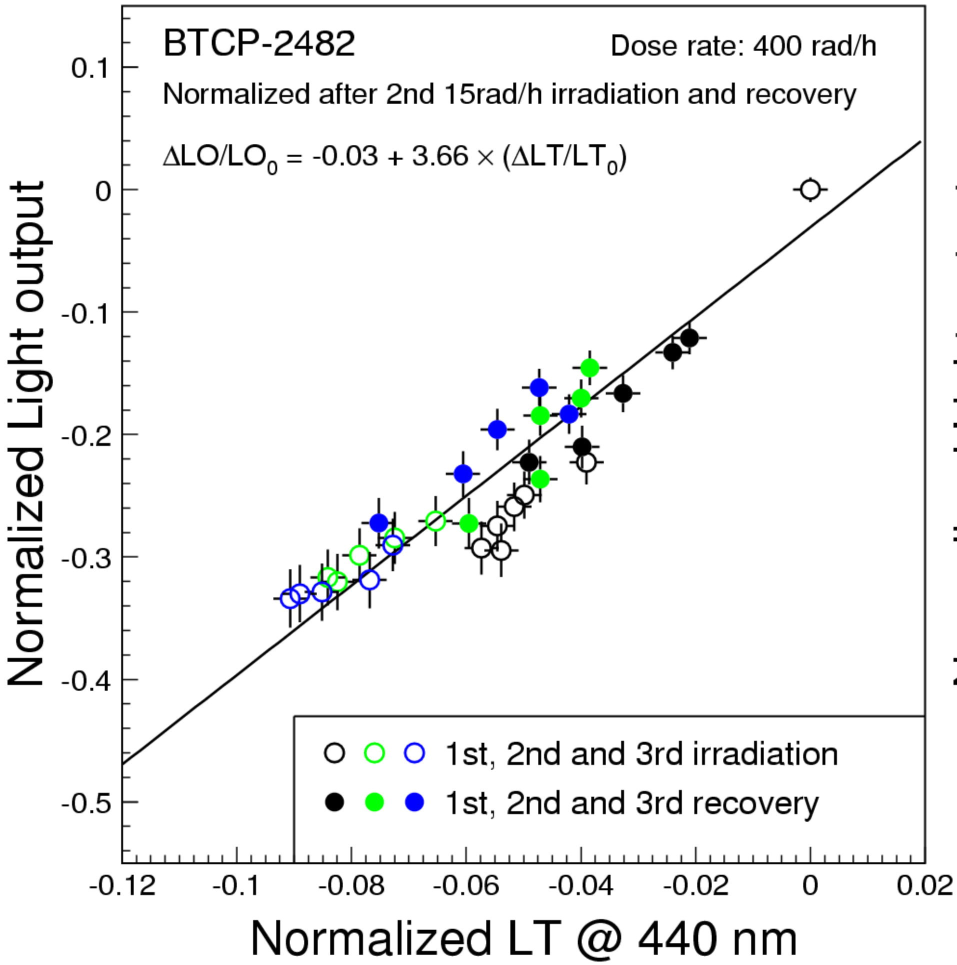
Normalized point:
after 2 cycles of damage & recovery @ 15 rad/h

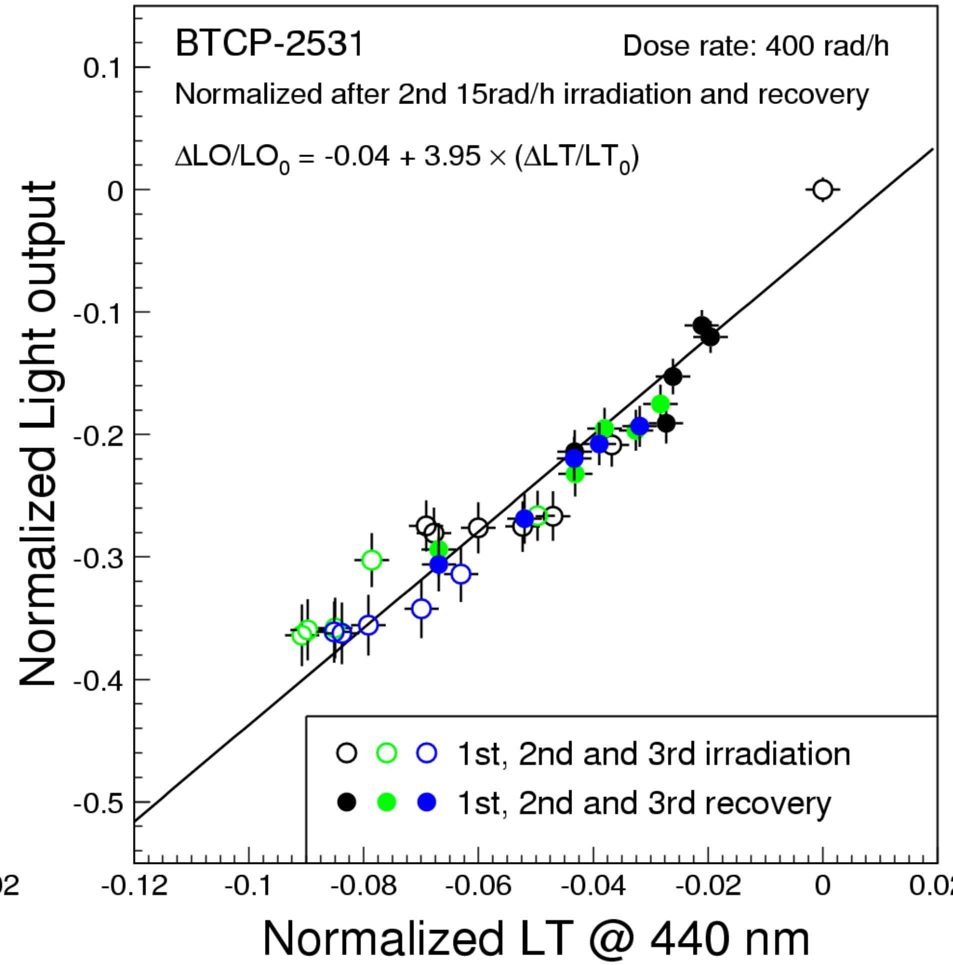




BTCP Monitoring @ 400 rad/h

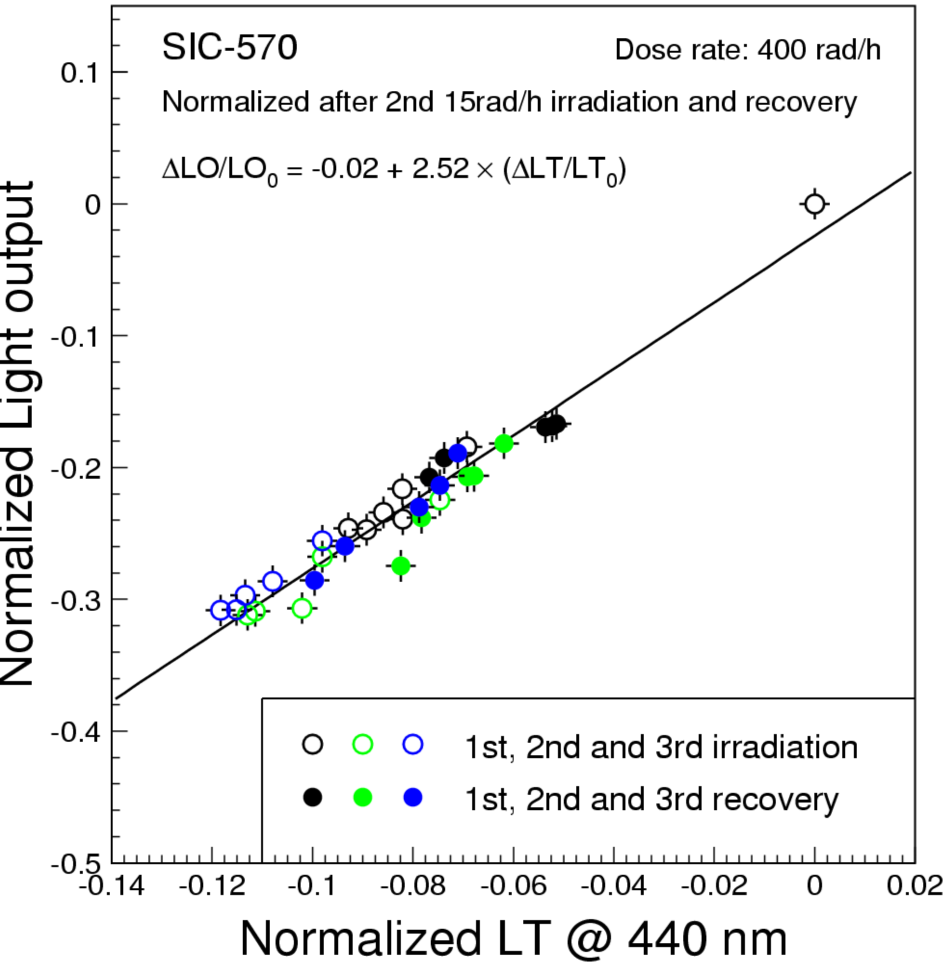
Average $Slope_{BTCP} = 3.82$

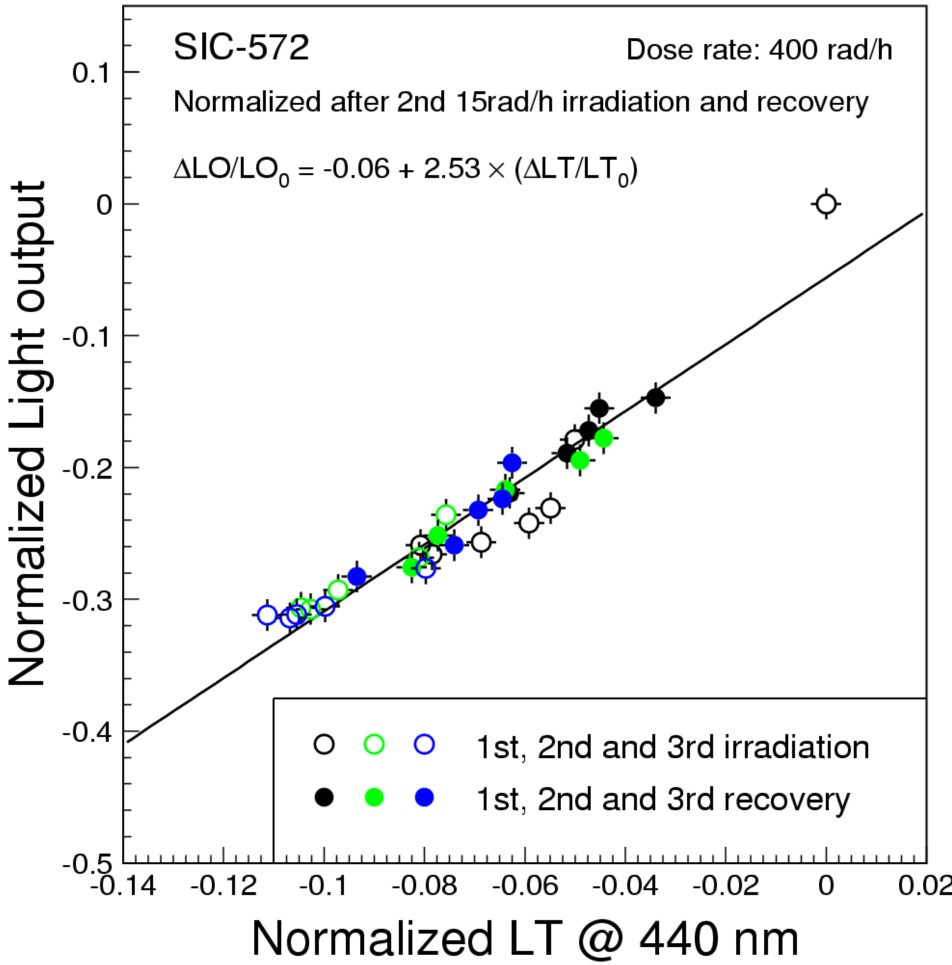




SIC Monitoring @ 400 rad/h

Average $Slope_{SIC} = 2.53 = Slope_{BTCP}/1.5$
Consistent with beam test observation





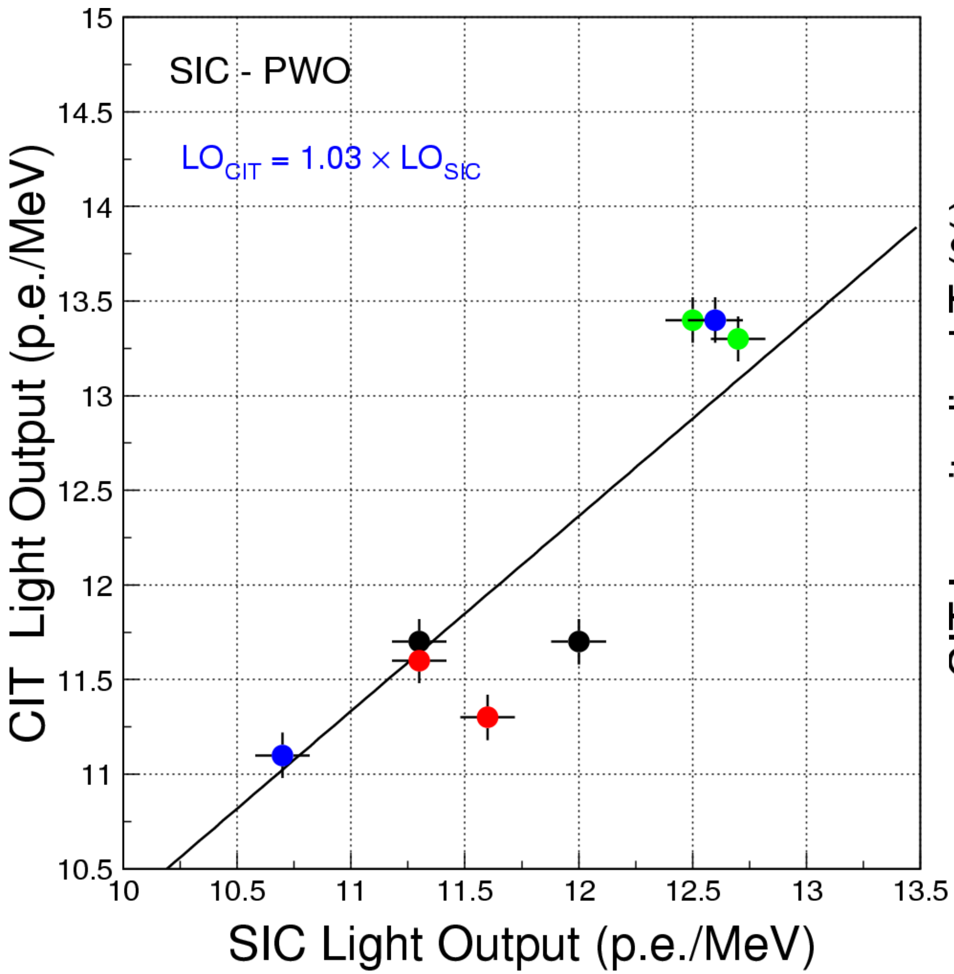
Summary II: Damage/Recovery test

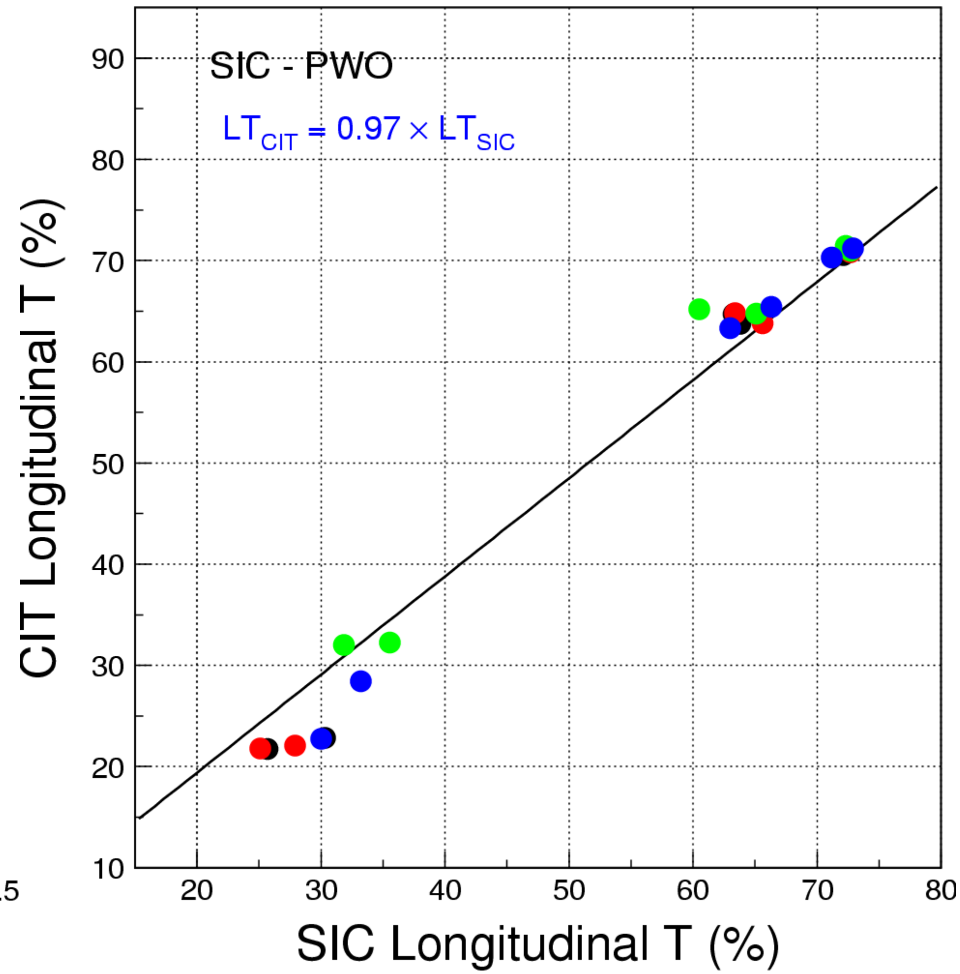
- All four samples have EWRIAC < 1.5 m^{-1} @ 9,000 rad/h.
- BTCP samples have a factor of **1.3 smaller** variation in longitudinal transmittance @ 400 rad/h, but have a factor of **1.3 and 1.4 larger** variation in light output @ 15 and 400 rad/h respectively, as compared to SIC samples, indicating more difficult in monitoring. This is caused by faster recovery and smaller unrecoverable damage fraction in BTCP samples.
- The variations of LO can be monitored (and corrected) by the variations of LT @ 400 rad/h. The slope between these two variations are **3.82** and **2.53** for BTCP and SIC samples respectively. The observed ratio (**1.5**) consists with the 2004 beam test result.
- To be studied: the nature of this difference observed.

Comparison between Caltech & SIC

Caltech LO is 3% higher: QE of PMT

Caltech LT is 3% lower: need identical QC instruments





Investigation on RIAC at SIC

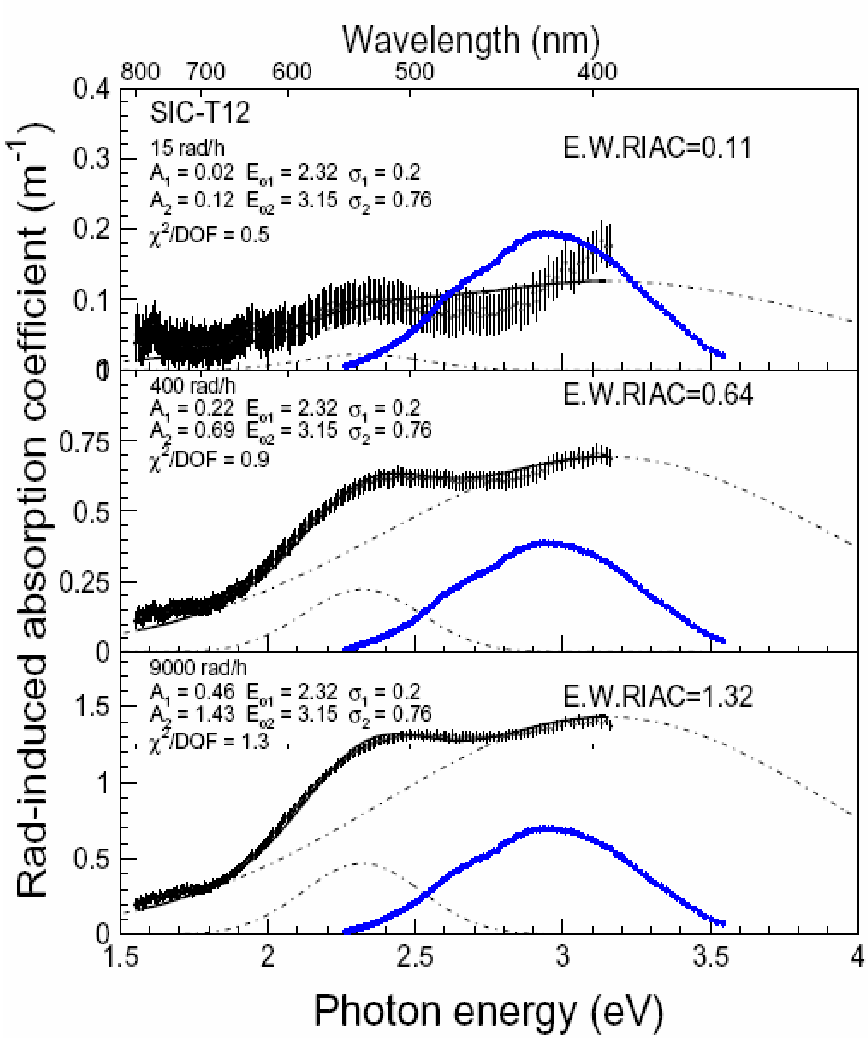
- To understand the SIC irradiation facility, Dr. Liyuan Zhang visited SIC on January 3-7, 2005.
- Two CEBAF size SIC 2002 PWO samples were irradiated for 24h at the ^{60}Co facility used by SIC. Their transmittance before and after irradiation was measured. The calculated RIAC @ 420 nm result consists with what measured at Caltech under 90 Gy/h irradiation, indicating no fundamental problem in the measurement.
- The dose rate in previous irradiations, however, has a large uncertainty.

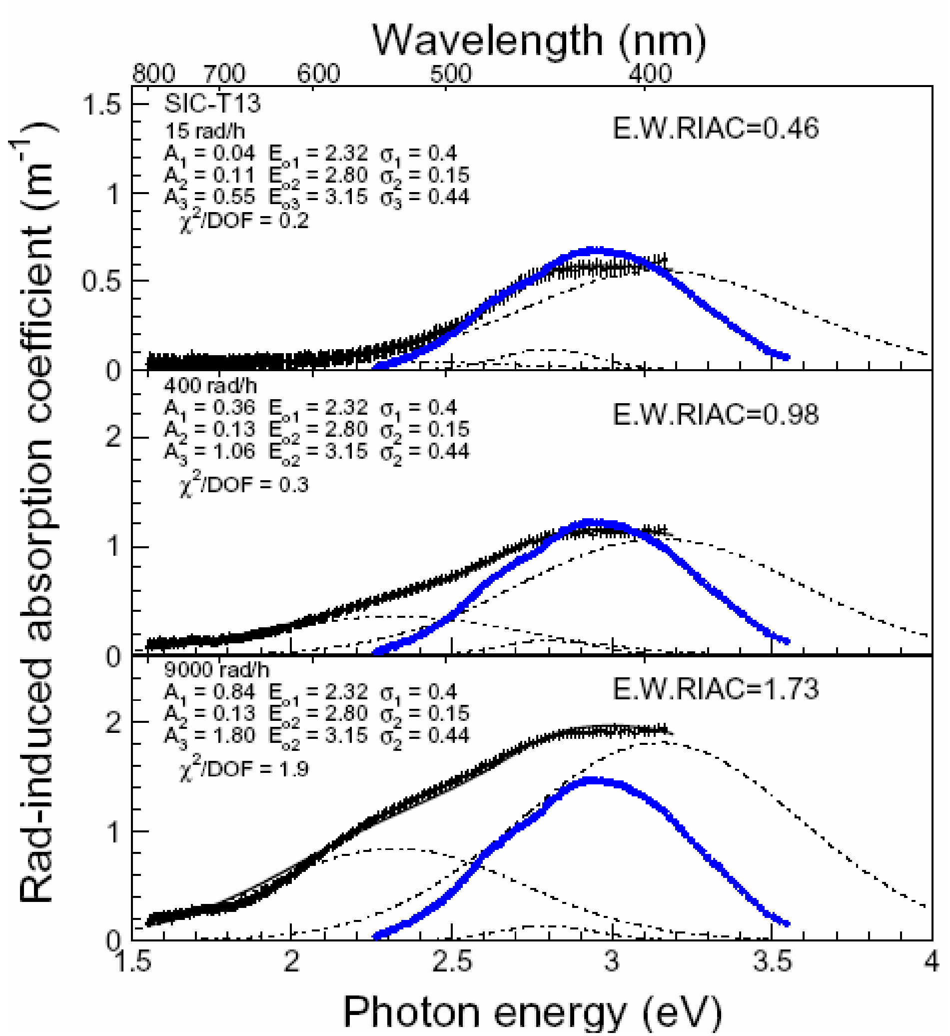
Sample	@XX Gy/h	RIAC (1/m)	@90 Gy/h	RIAC (1/m)
T12	24 h	1.7	24 h	1.4
T13	24 h	2.0	32 h	1.9

EWRIAC Measured at Caltech

Note: emission weighted and multiple bounces

EWRIAC has number to be converted to RIAC @ 420 nm



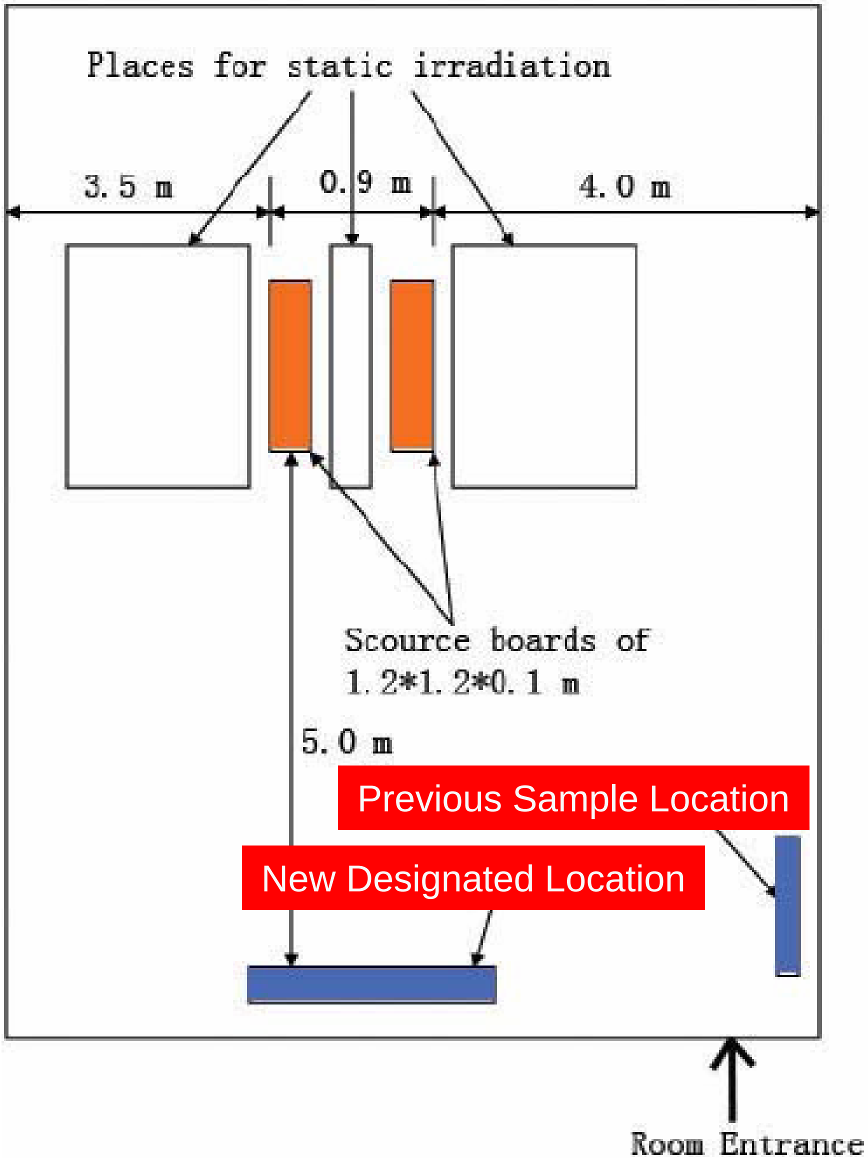


220k Curie ^{60}Co Source used by SIC

Photos by courtesy of Dr. Hui Yuan

220k Curie ^{60}Co Source used by SIC

Plot by courtesy of Dr. Hui Yuan



- The dose rate at previous sample location was affected by commercial goods being irradiated at the same time.
- Better stability of the dose rate is expected when samples are placed on a rack at the designated location.
- Attention must be paid to avoid commercial goods, including moving goods, between samples and the source during irradiations.
- Dose rate: ~80 Gy/h.

Summary III: PWO Quality Control

- Comparison between LT and LO data between Caltech and SIC indicates the importance of using **identical QC equipment.**
- There was a large uncertainty in dose rate in SIC's RIAC data, which is the origin of the discrepancy discussed in the December DPG meeting. Current sample location has a dose rate of about 80 Gy/h with uncertainty reduced.
- A well controlled irradiation facility is crucial for PWO QC, which should be used to **check every endcap crystals delivered**, and sort them out according to their radiation hardness.

Light Attenuation Length Affects LRU

Nucl. Instr. And Meth. A413 (1998) 297

Ray-Tracing simulation for CMS PWO crystals shows no change in LRU if LAL is longer than 3.5 crystal length

Light collection efficiency, fit to a linear function of distance to the small end of the crystal, was determined with two parameters: the light collection efficiency at the middle of the crystal and the uniformity.

LAL (cm)	20	40	60	80	200
Large Area Photo Detector, covering 100% back face					
η_m (%)	9.5±.2	15.7±.4	19.2±.5	21.6±.6	26.9±.7
δ (%)	23±1	-4.6±.8	-11±1	-15±1	-15±1
ϕ5 mm Photo Detector, covering 3.7% back face					
η_m (%)	.38±.04	.74±.08	1.1±.1	1.4±.2	3.0±.3
δ (%)	23±4	–3.5±4	-12±4	-16±4	-17±3
$\frac{\eta_m(\phi 5mm)}{\eta_m(Full)}$ (%)	4.0	4.7	5.7	6.5	11