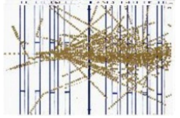

BSO Crystals for the HHCAL Detector Concept

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[1] California Institute of Technology
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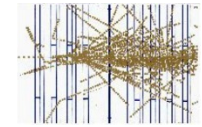
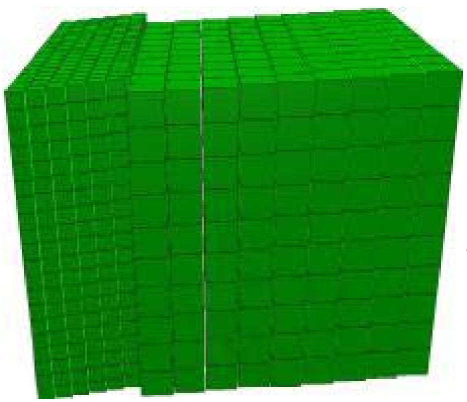
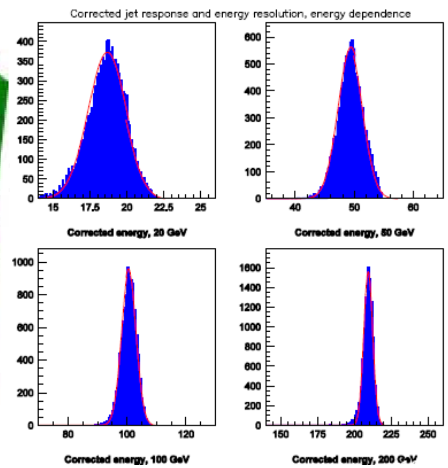
O4-19, Calor2014, April 10, 2014, Giessen, Germany

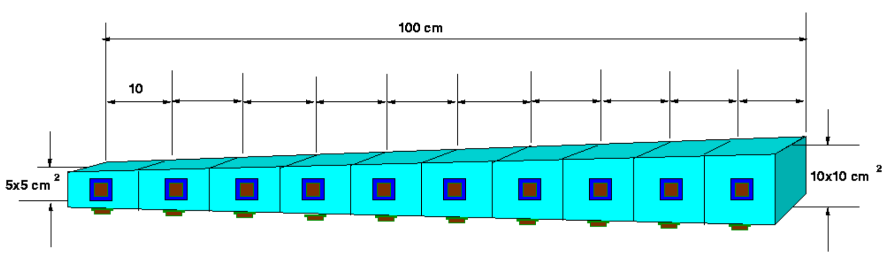


Homogeneous Hadronic Calorimeter

A Fermilab team (A. Para et al.) proposed a total absorption homogeneous hadronic calorimeter (HHCAL) detector concept to achieve good jet mass resolution at ILC/CLIC by measuring both Cherenkov and Scintillation light.



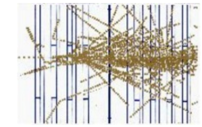




ILCWS-08, Chicago: a HHCAL cell with pointing geometry

Requirements for the Materials:

- Cost-effective material: for 70~100 m^3
- Short nuclear interaction length: ~ 20 cm.
- Good UV transmittance: UV cut-off < 350 nm, for readout of Cherenkov light.
- Some scintillation light, not necessary bright and fast.
- Discrimination between Cherenkov and scintillation lights, in spectral or temporal domain.
- Radiation hardness is not crucial at the ILC/CLIC.



Candidate Crystals for HHCAL

Cost-effective, dense, UV transparent crystals with both scintillation and Cherenkov light

Parameters	$Bi_4Ge_3O_{12}$ (BGO)	$PbWO_4$ (PWO)	PbF_2	PbFCl	$Bi_4Si_3O_{12}$ (BSO)
ρ (g/cm^3)	7.13	8.29	7.77	7.11	6.8
λ_I (cm)	22.8	20.7	21.0	24.3	23.1
n @ λ_{max}	2.15	2.20	1.82	2.15	2.06
τ_{decay} (ns)	300	30/10	?	3	**100**
λ_{max} (nm)	480	425/420	?	420	**470**
Cut-off λ (nm)	310	350	250	**280**	**300**
Light Output (%)	100	1.4/0.37	?	2	**20**
Melting point (^{o}C)	1050	1123	842	**608**	1030
Raw Material Cost (%)	100	49	**29**	**29**	47

IEEE Trans. Nucl. Sci. ***59*** *(2012) 2229-2236*

BSO Samples

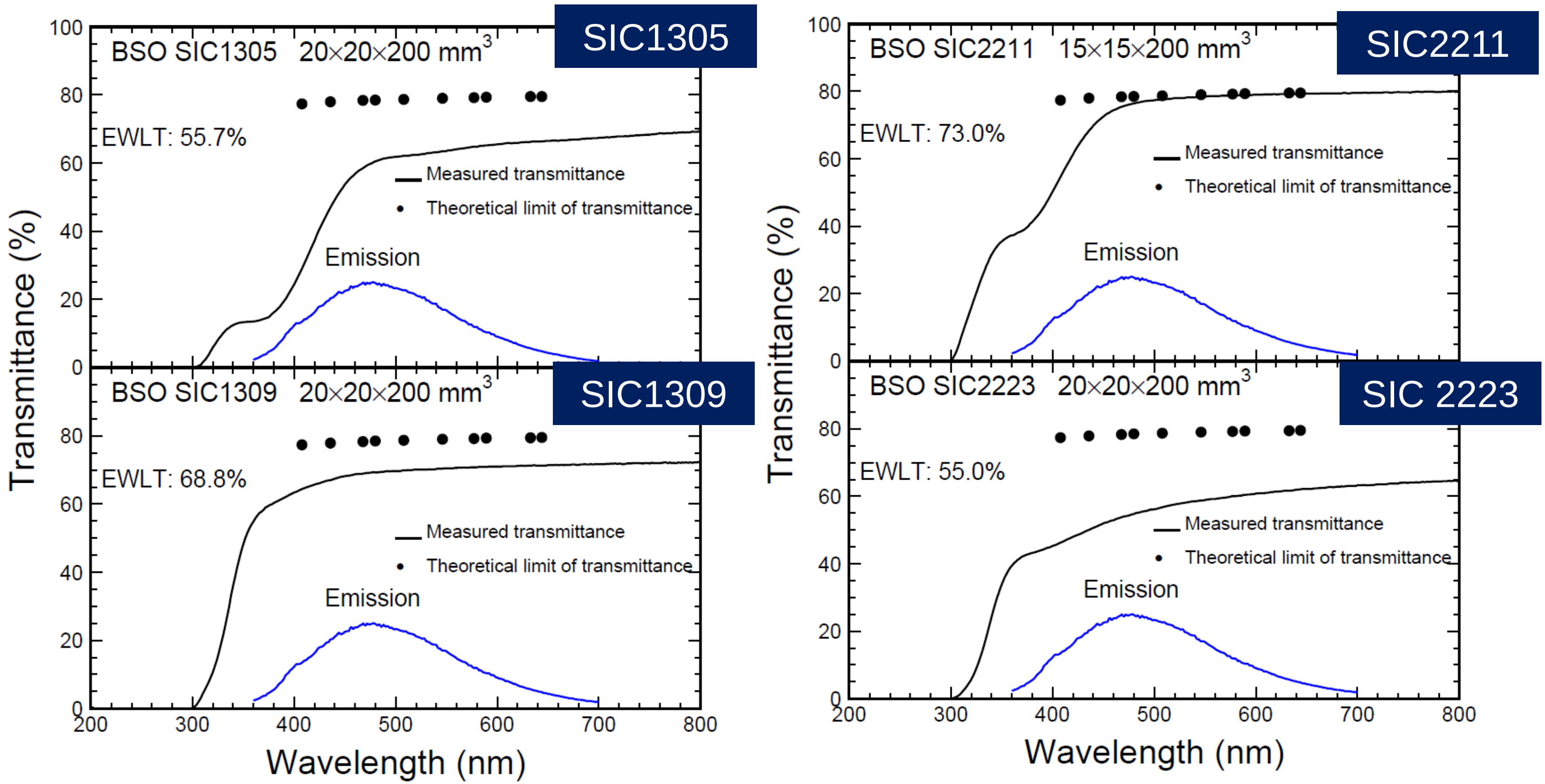
Sample ID	Received Date	Dimension (mm^3)	Polish
BSO SIC1305	2/25/2013	$20 \times 20 \times 200$	Six faces
BSO SIC1309	2/25/2013	$20 \times 20 \times 200$	Six faces
BSO SIC2211	9/26/2012	$15 \times 15 \times 200$	Six faces
BSO SIC2223	9/26/2012	$20 \times 20 \times 200$	Six faces

Experiments

- Longitudinal Transmittance (LT), Light Response Uniformity (LRU) and Light Output (LO) were measured at room temperature before, during and after the irradiation processes.

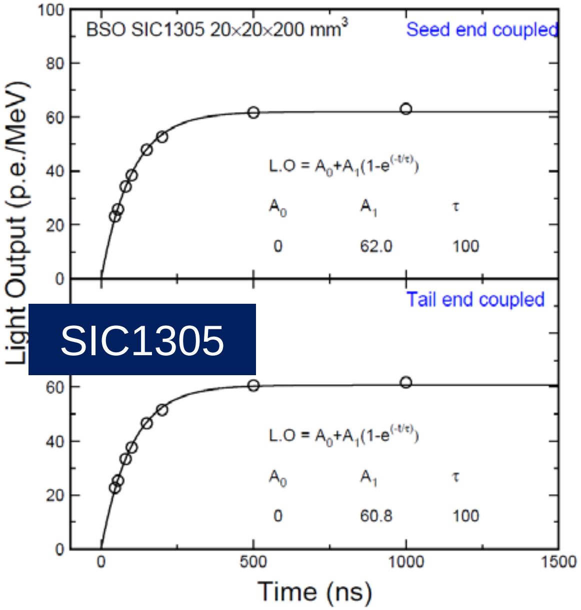
Longitudinal Transmittance

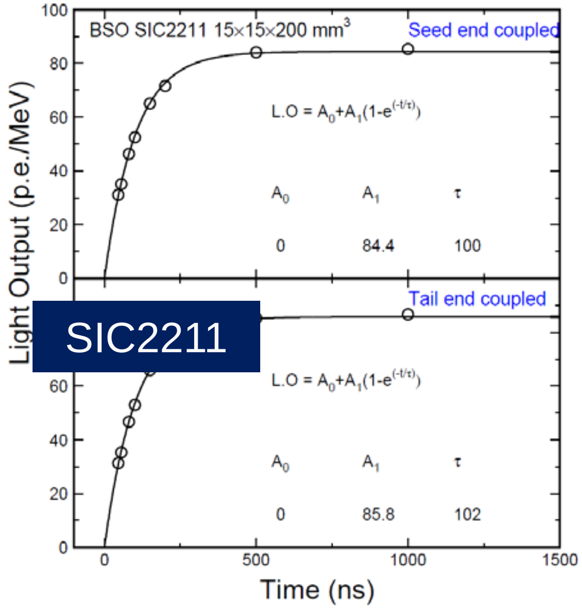
The LT of SIC2211 between 500 to 800 nm approaches the theoretical limit
There is no obvious absorption band observed in the LT of SIC1309

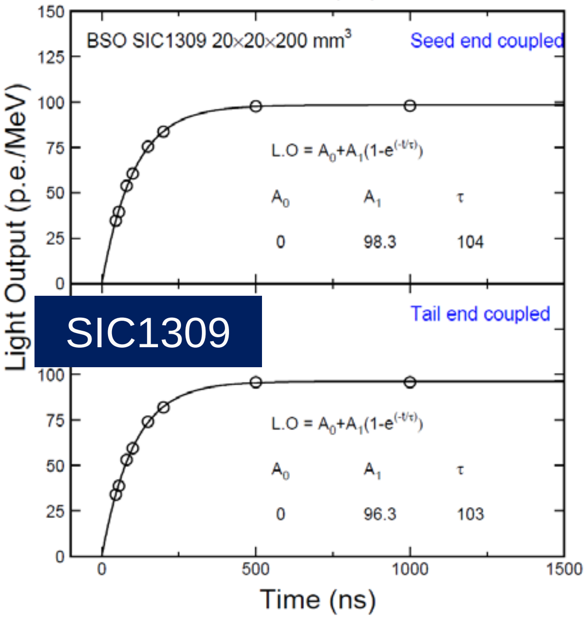


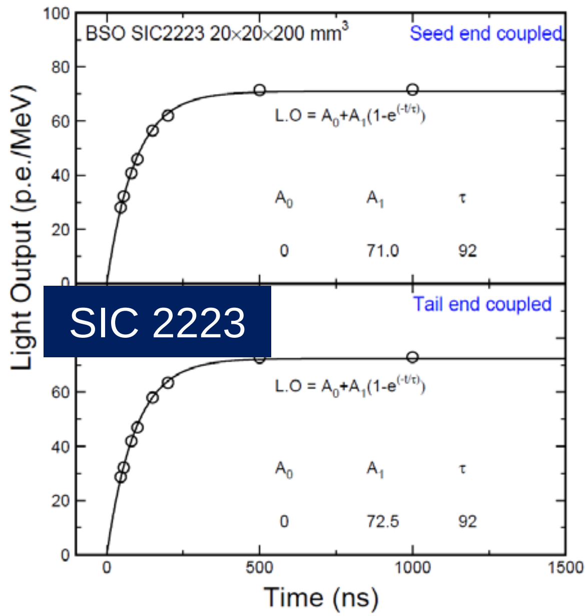
There are absorption centers or scattering centers in all the samples.
LT of SIC2211 & SIC1309 implies that the quality of BSO crystals can be improved

LO and Decay Kinetics





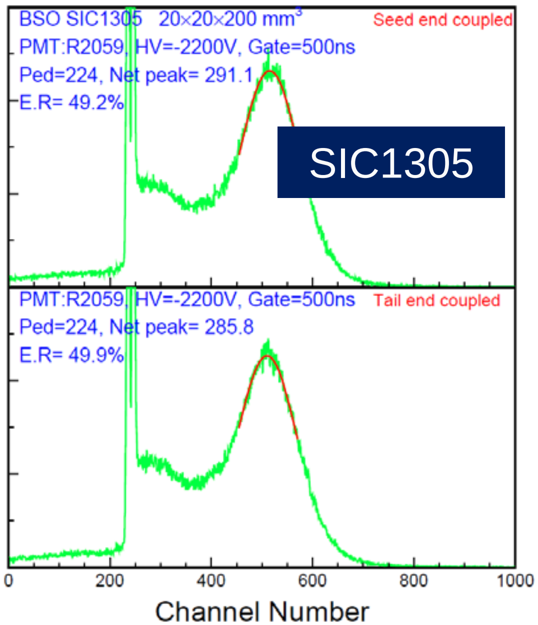


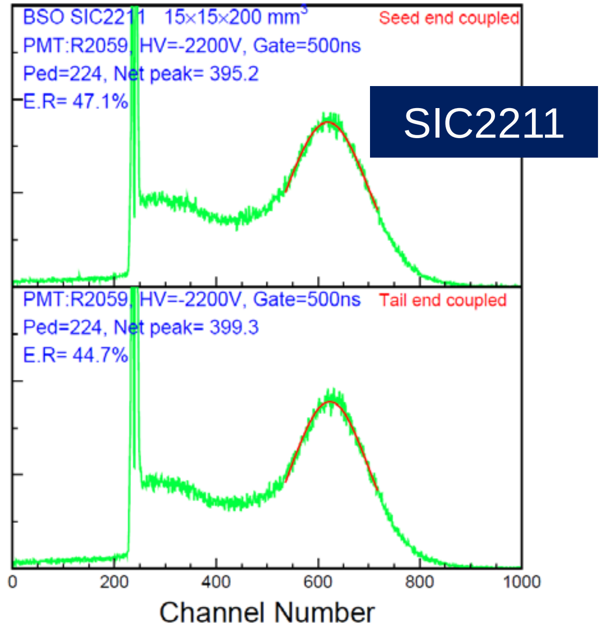


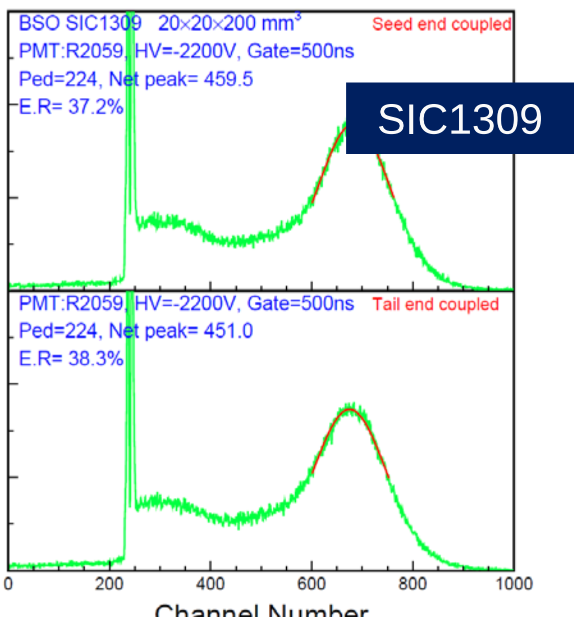
All four samples show consistent decay time of about 100 ns.

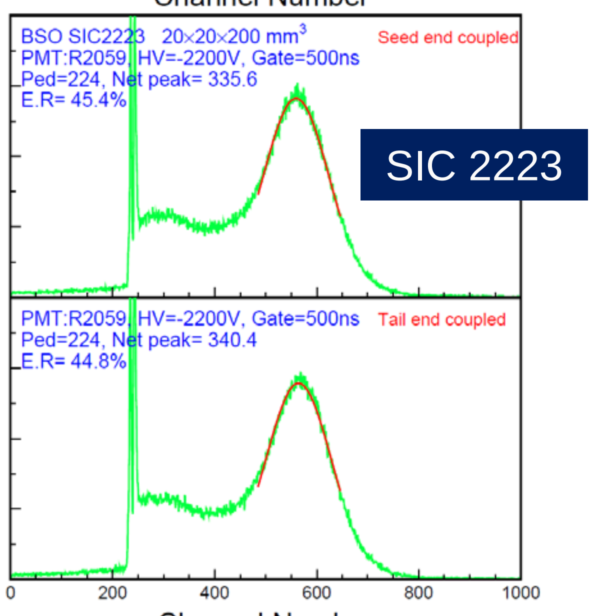
SIC1309 shows the highest LO because of its better LT.

Pulse Height Spectra





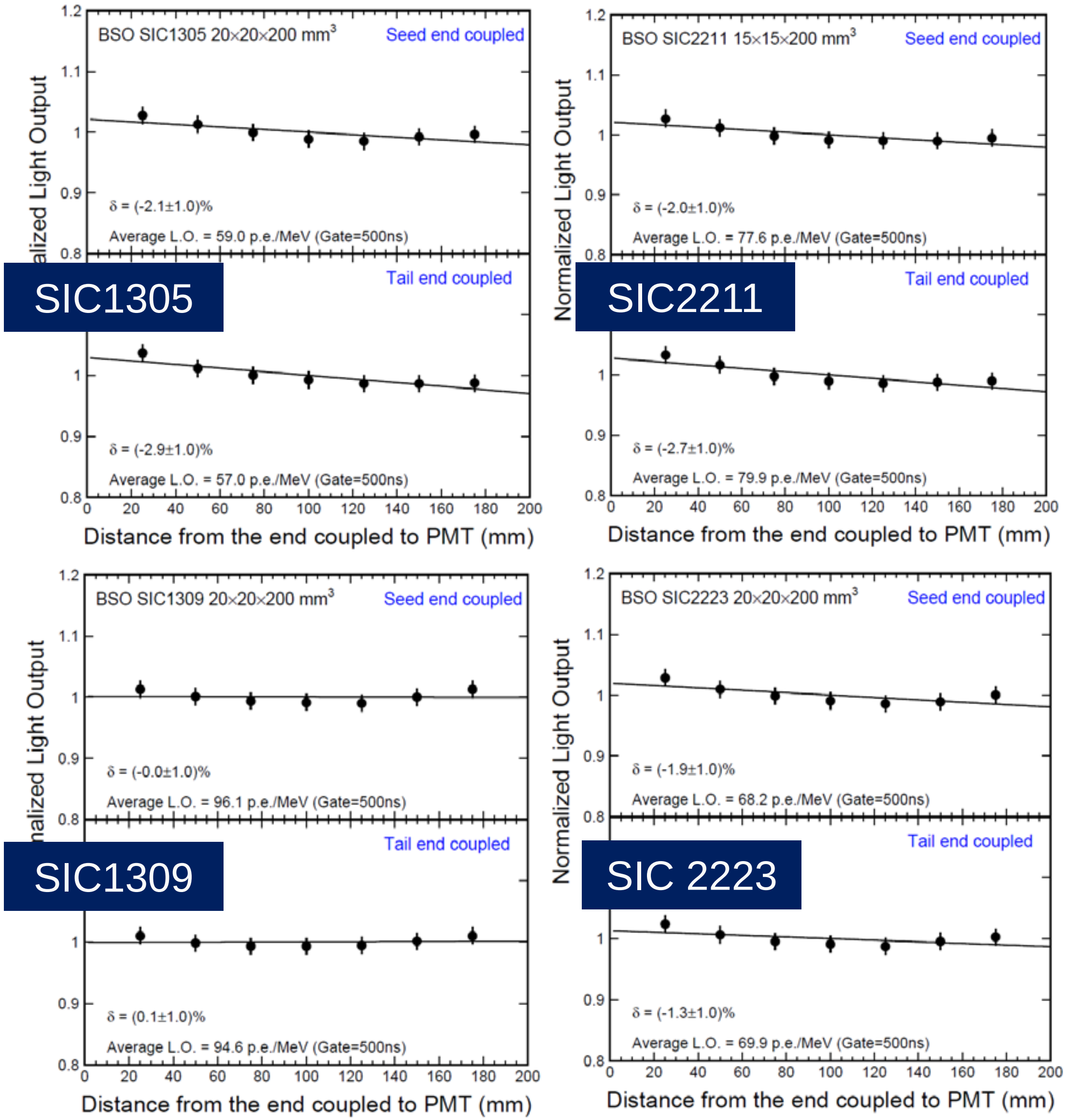




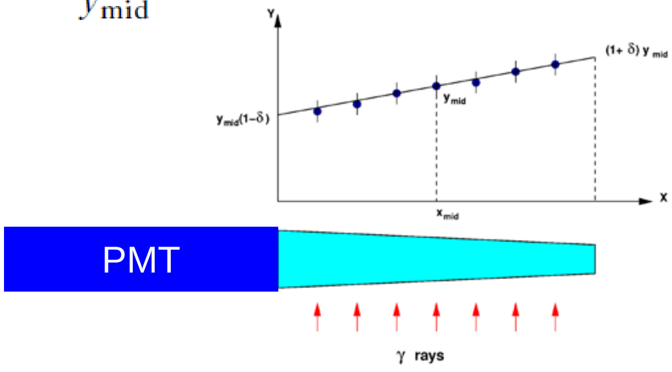
The average energy resolution (FWHM) of all samples is about 45%.

Sample SIC1309 has the best ER: 37%.

LRU with Alternative Coupling Ends



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

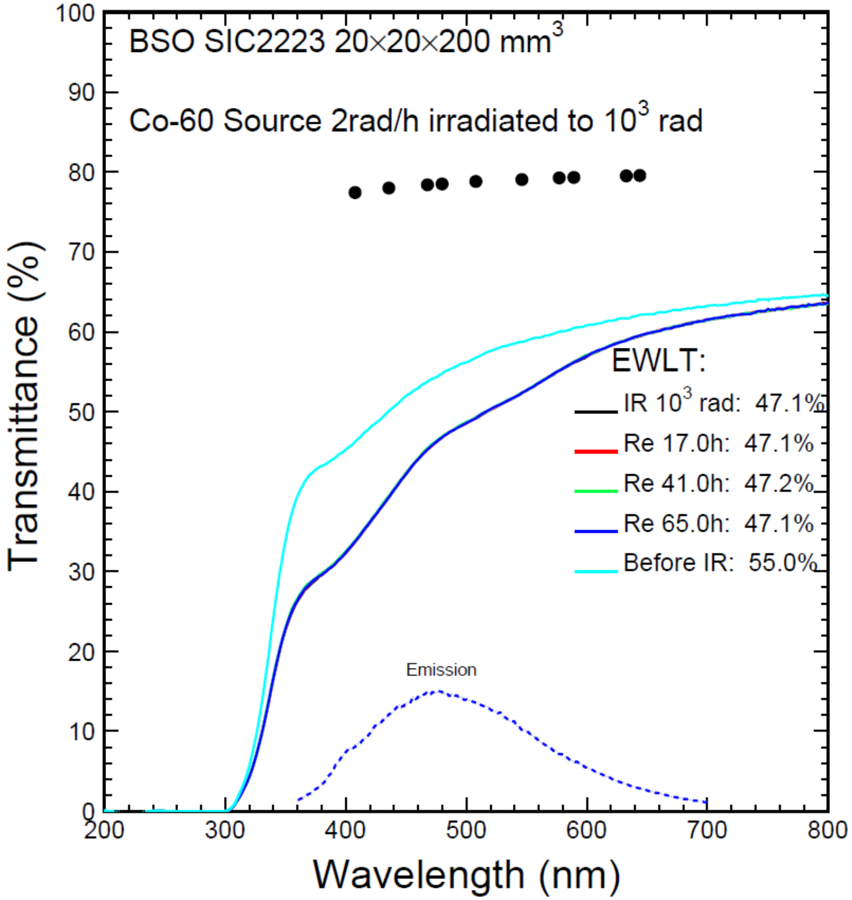


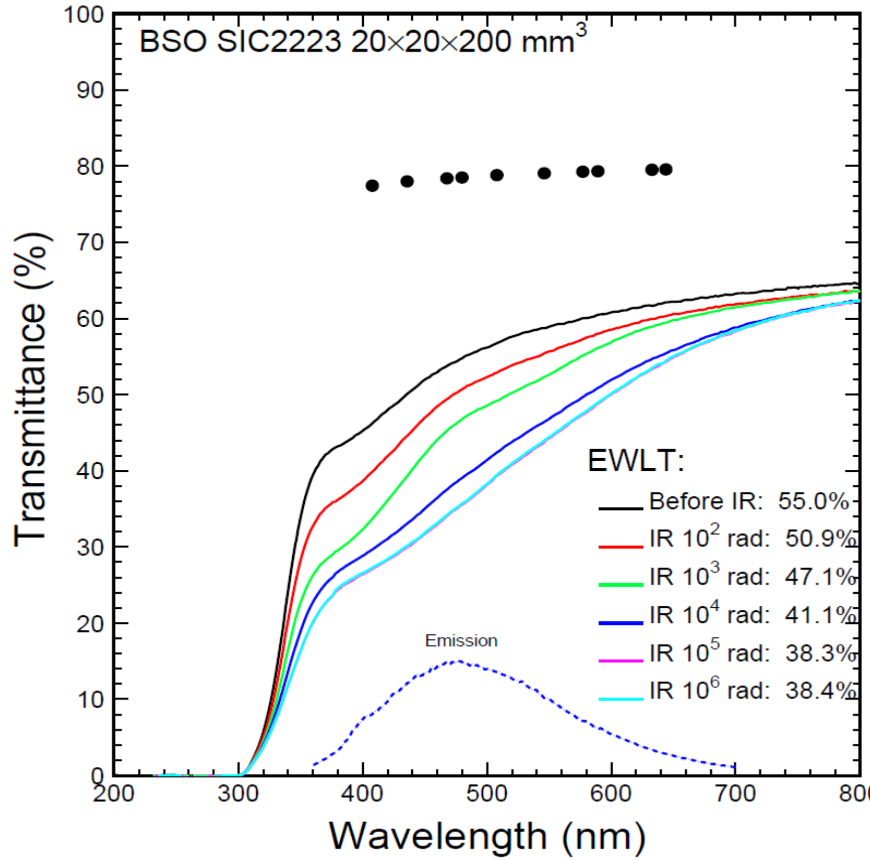
The LRUs of SIC1309 approaches 0% for both end couplings, which is the ideal LRU for a rectangular crystal with good transparency.

The negative δ values of -2% for other 3 samples indicate a significant internal absorption.

LT of SIC2223 before and after IR

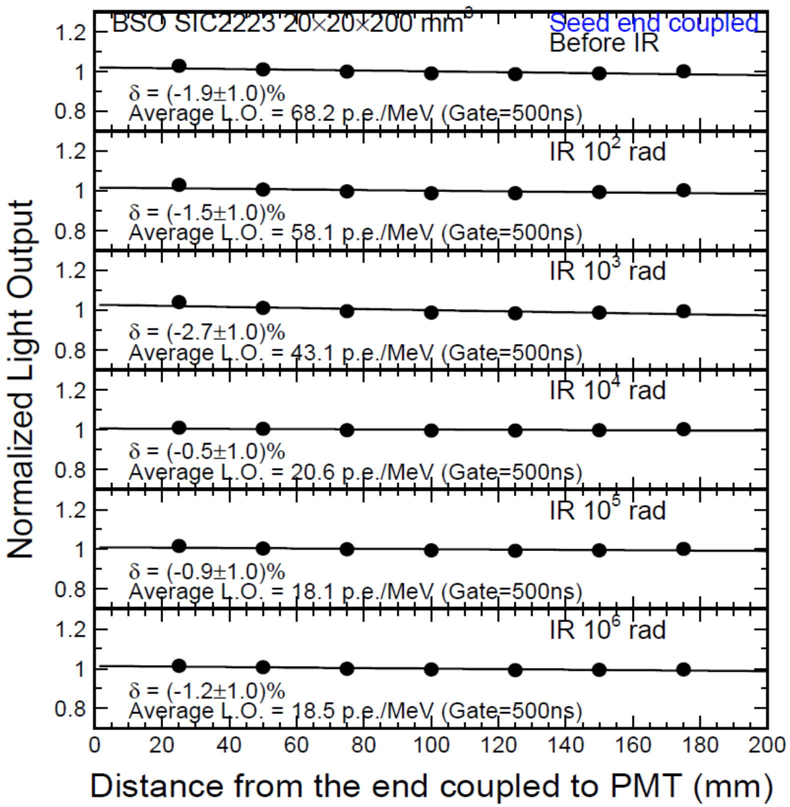
Damage in SIC2223 does not recover, so is not dose rate dependent
SIC2223 was irradiated with defined integrated dose step by step

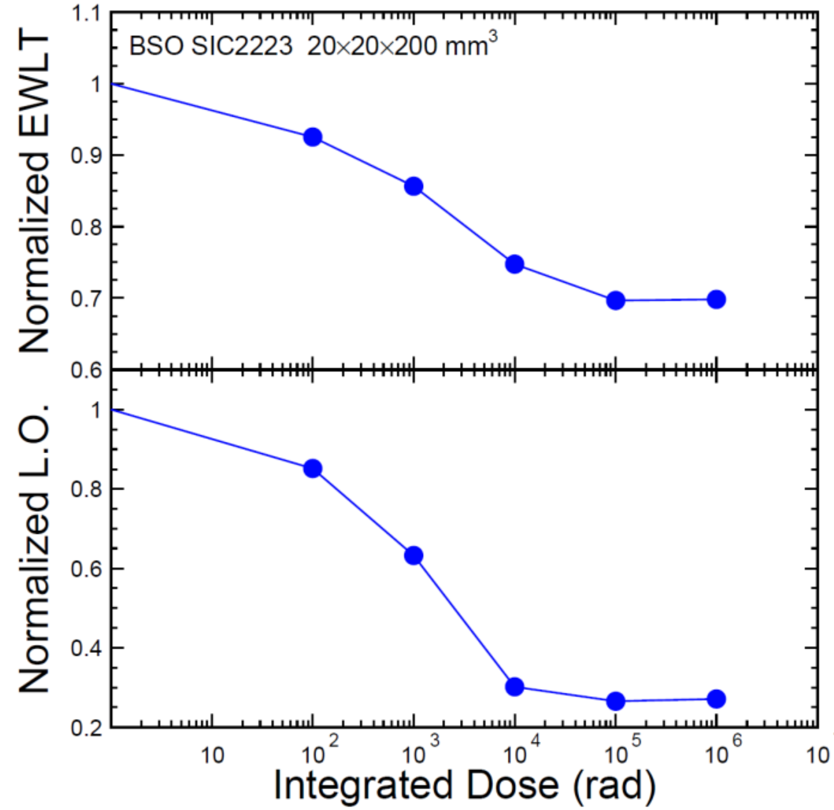




LRU and LO of SIC2223 before and after IR

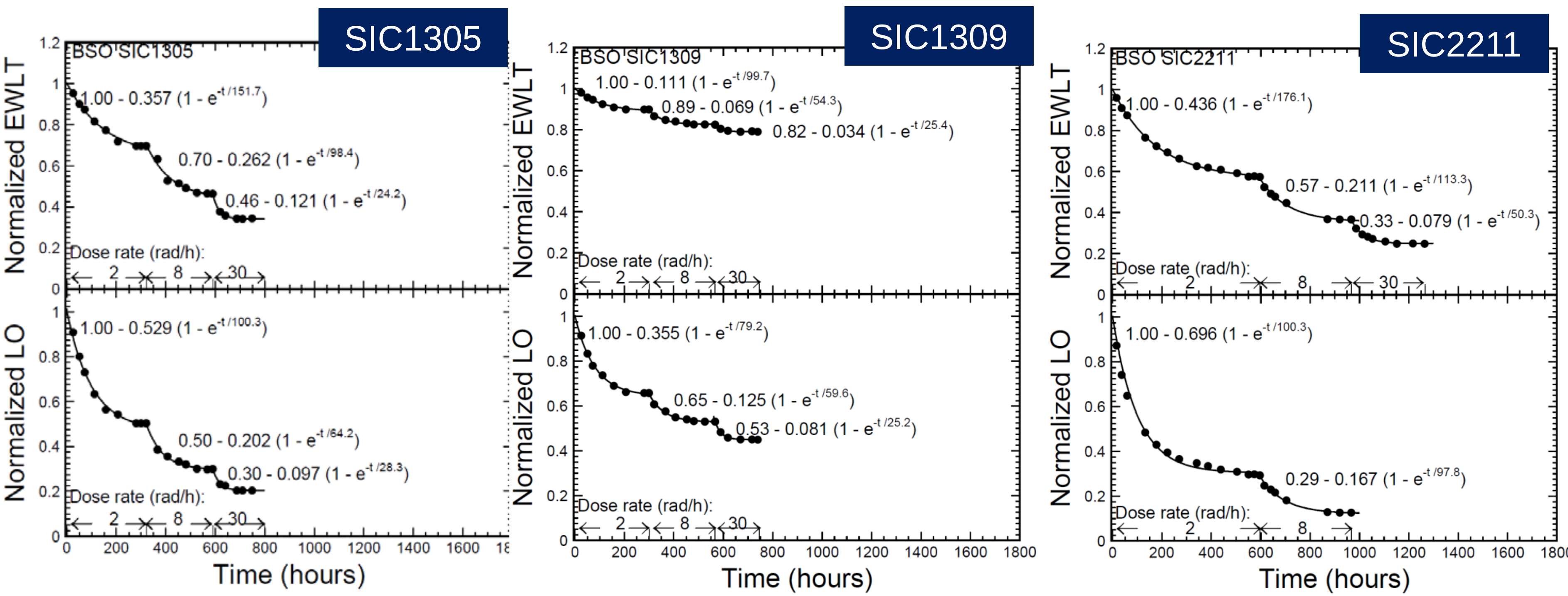
The damage in both EWLT and LO is saturated after 10^5 rad, indicating that the total defect density is limited.





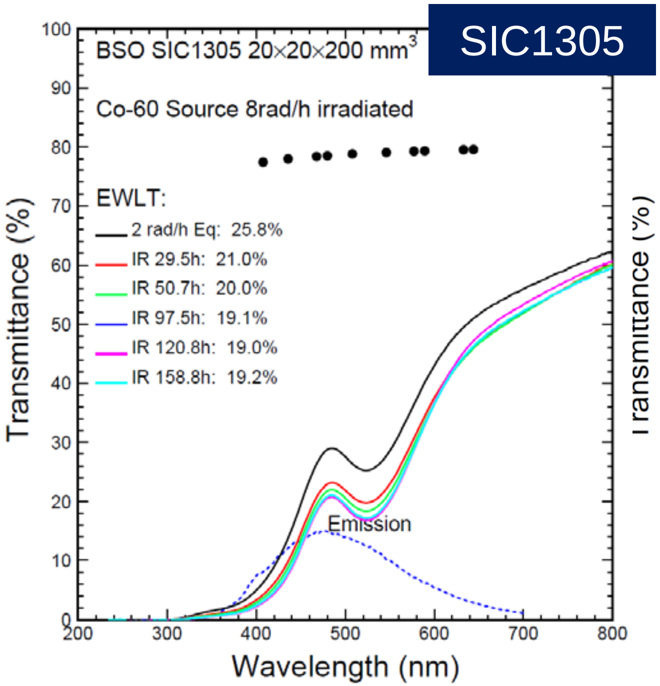
Radiation damage in EWLT & LO

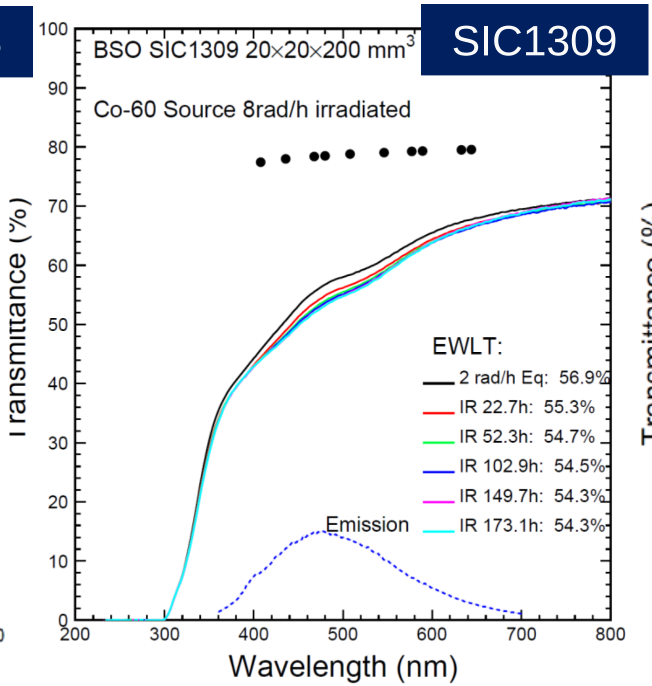
- Damage in SIC1305, 1309 and 2211 recovers, so is dose rate dependent. They were irradiated with fixed dose rate
- SIC1309 is the best in radiation hardness

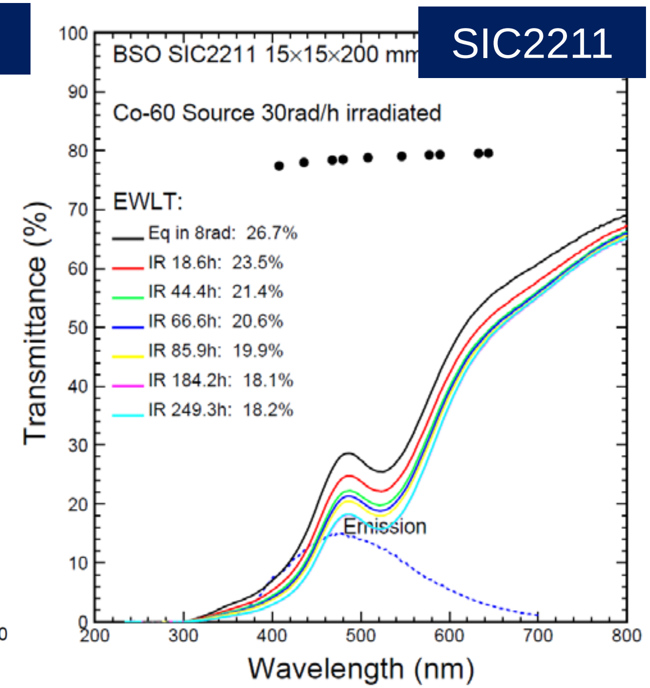


LT during Irradiation at 30 rad/h

Sample SIC1309 has the lowest degradation



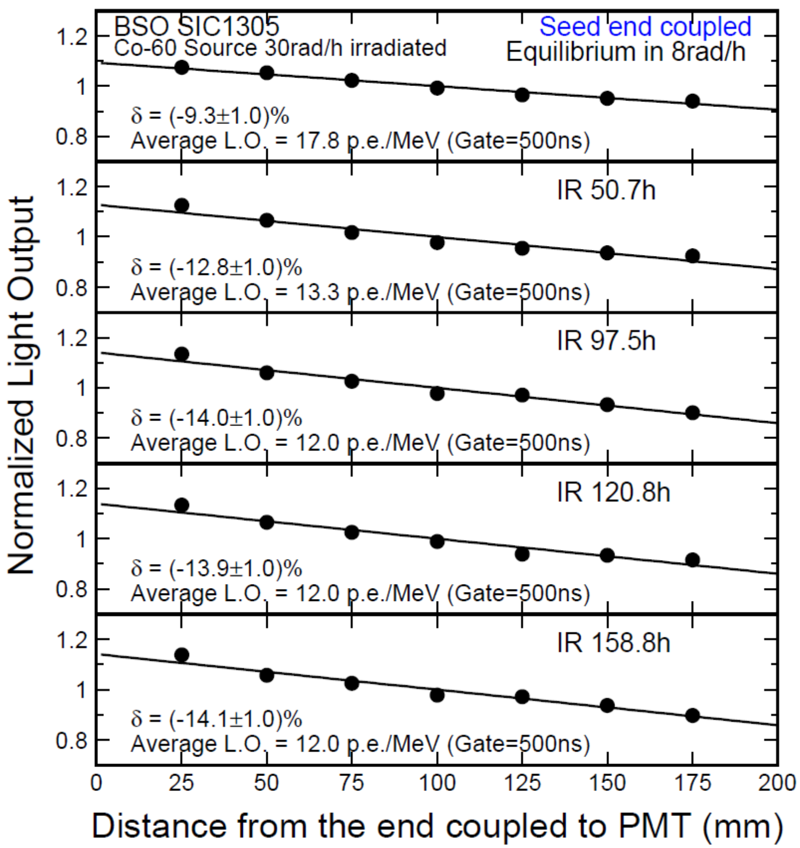




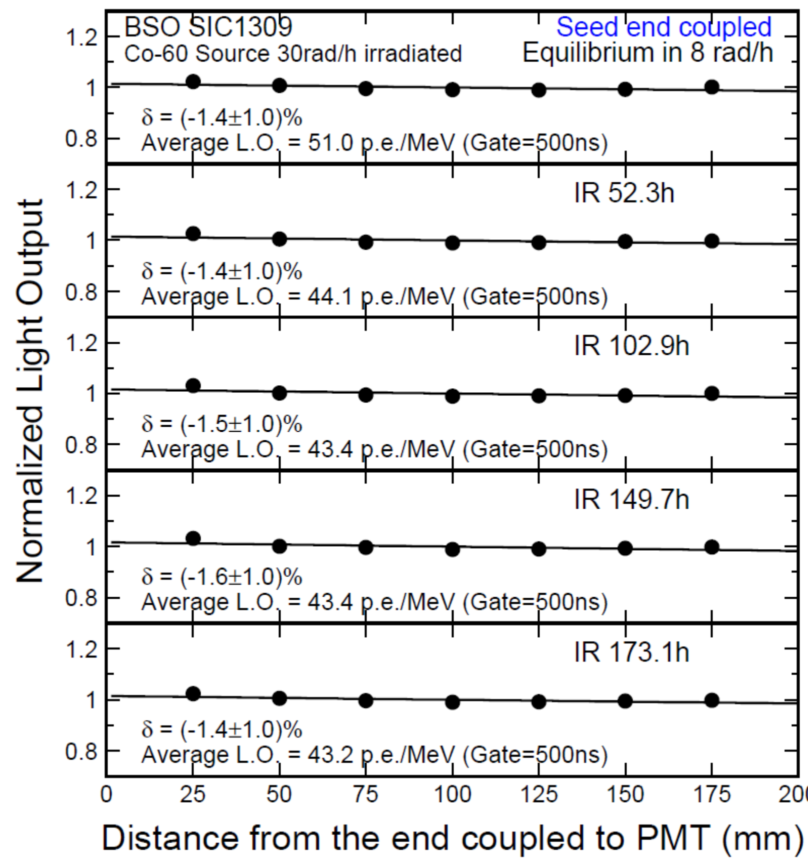
LRU During Irradiations at 30 rad/h

LRU of 1305 changed significantly while that of 1309 did not

SIC1305



SIC1309



Color Center Analysis for SIC2223 (no recovery)

$$\mathrm{Riac} = 1/\mathrm{LAL}_{\mathrm{equilibrium}} - 1/\mathrm{LAL}_{\mathrm{before}}$$

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

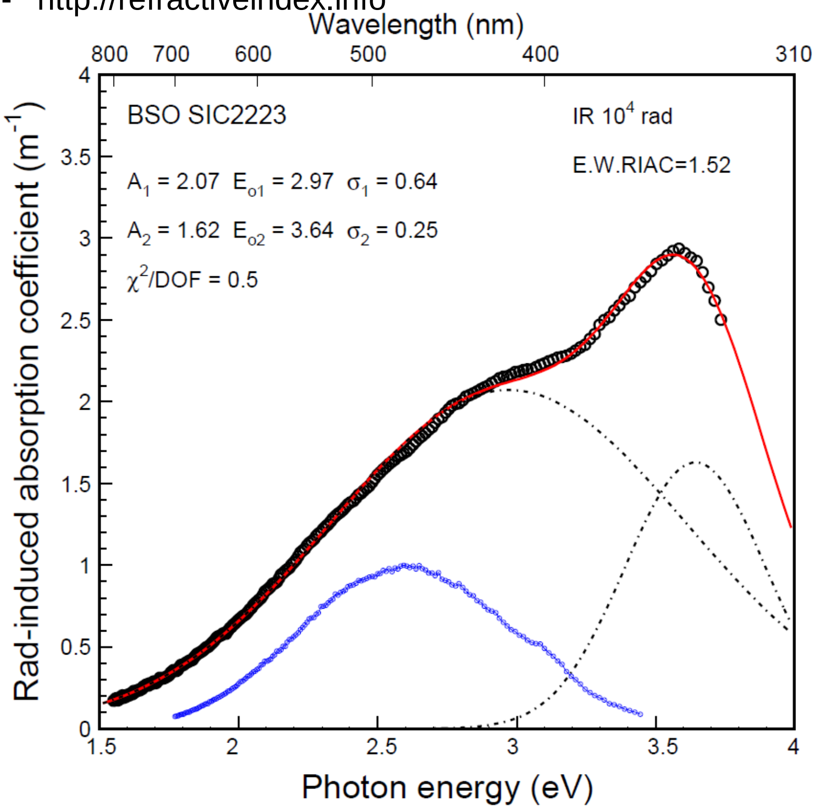
$$T_s = (1-R)^2 + R^2(1-R)^2 + \cdots = \frac{(1-R)}{(1+R)}$$

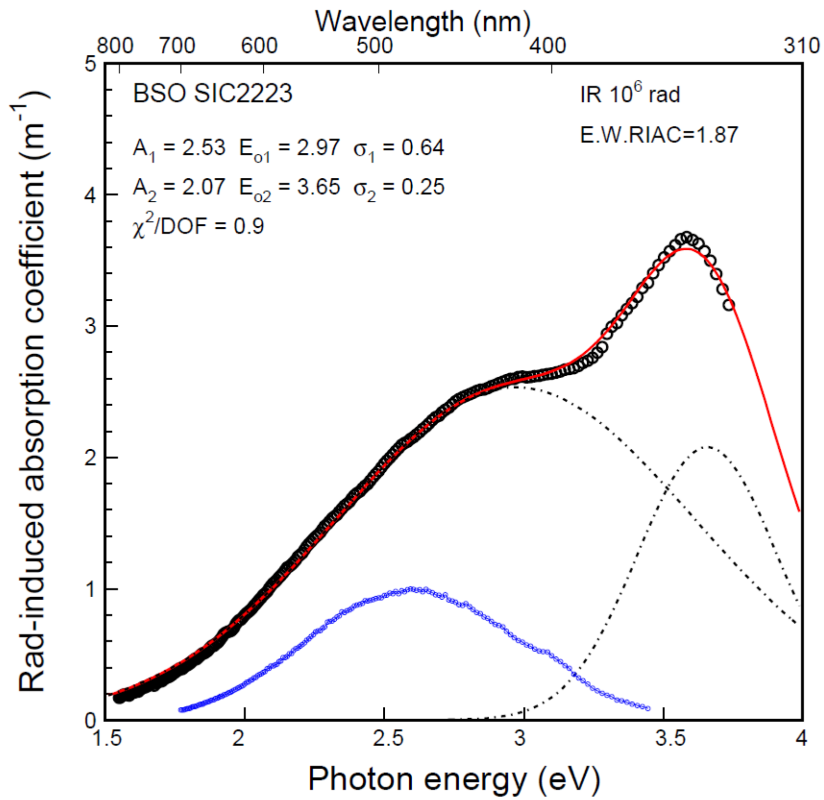
$$R = \frac{(n_{\mathrm{crystal}} - n_{\mathrm{air}})^2}{(n_{\mathrm{crystal}} + n_{\mathrm{air}})^2}.$$

$$Dispersion\ formula:\ n^2 = \frac{0.935\lambda^2}{\lambda^2 - 0.060} + 2.990$$

- *Handbook of Optics, 3rd edition, Vol. 4. McGraw-Hill 2009*
- http://refractiveindex.info

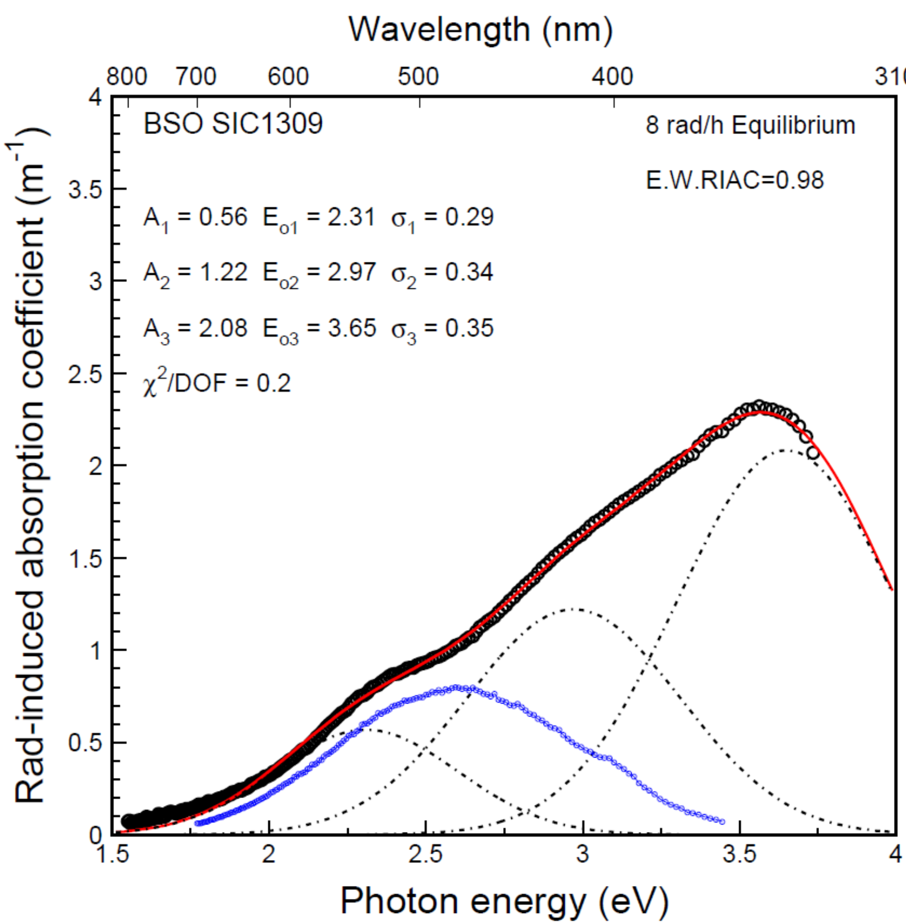
Its RIAC can be decomposed to 2 Gaussian bands.

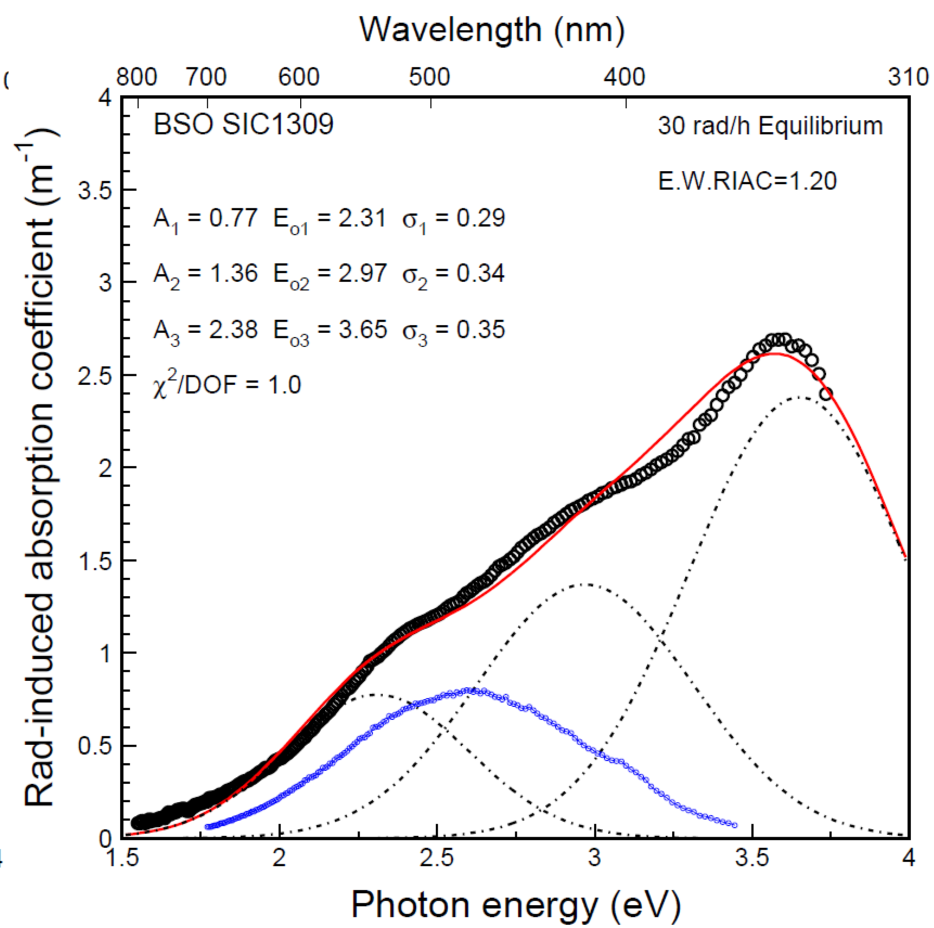




Color Center Analysis for SIC1309

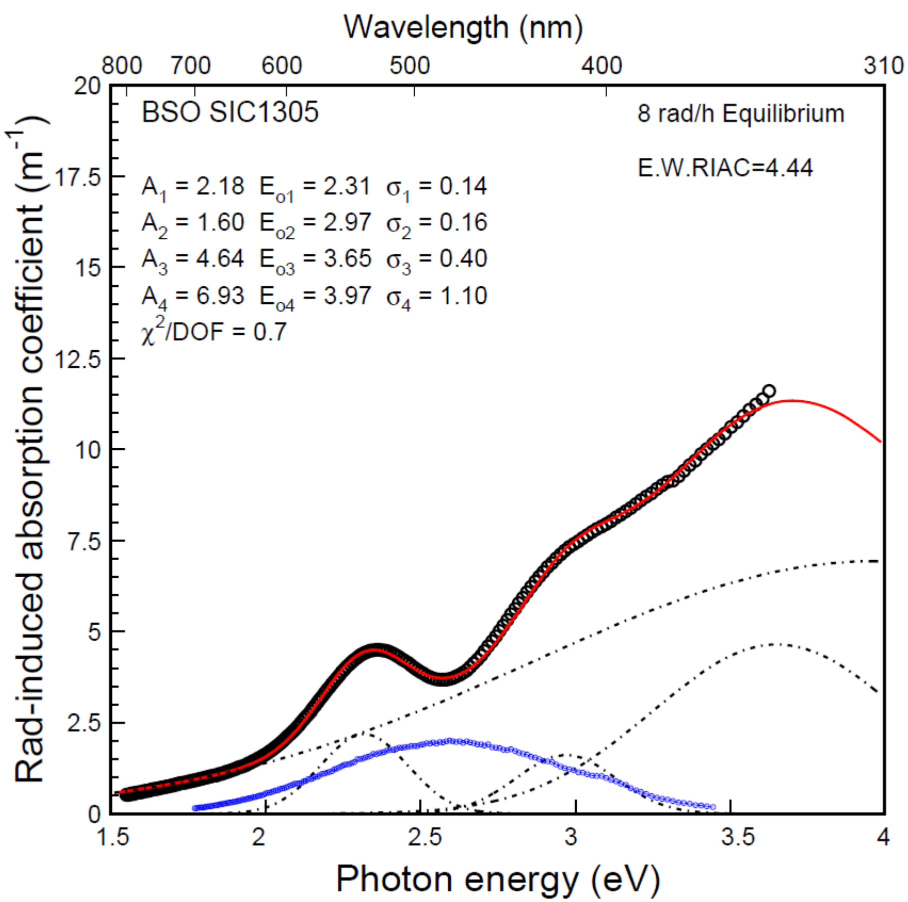
3 Gaussian bands are needed to fit RIAC in SIC1309

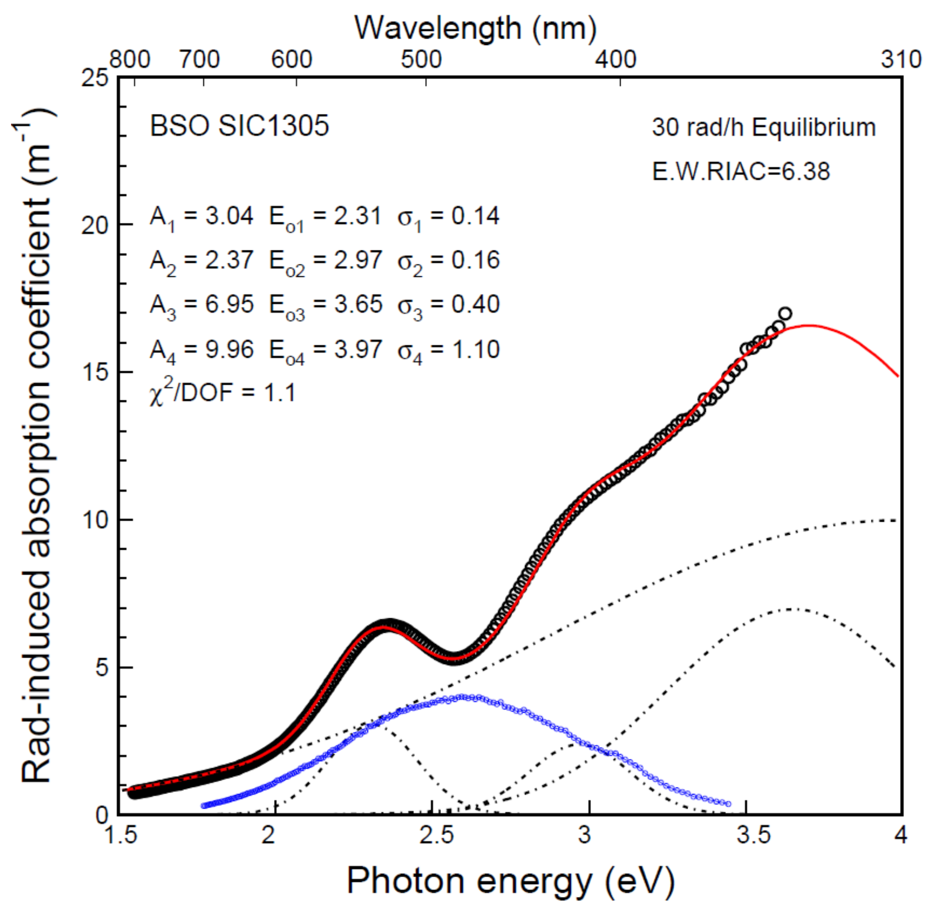




Color Center Analysis for SIC 1305/2211

4 Gaussian bands are needed for SIC1305/2211





Summary of RIAC Analysis

Measurements of recovery are under way to understand the dynamics of defect centers

		Color Center 1			Color Center 2			Color Center 3			Color Center 4		
		A_1	E_1	σ_1	A_2	E_2	σ_2	A_3	E_3	σ_3	A_4	E_4	σ_4
BSO SIC2223	10^2 rad	-	-	-	0.47	2.97	0.64	0.60	3.65	0.25	-	-	-
	10^4 rad	-	-	-	2.07	2.97	0.64	1.62	3.65	0.25	-	-	-
	10^6 rad	-	-	-	2.53	2.97	0.64	2.07	3.65	0.25	-	-	-
BSO SIC2211	2 rad/h	1.13	2.31	0.14	0.78	2.97	0.16	1.62	3.65	0.40	5.32	3.97	1.10
	8 rad/h	2.18	2.31	0.14	1.69	2.97	0.16	3.74	3.65	0.40	9.87	3.97	1.10
	30 rad/h	3.08	2.31	0.14	2.51	2.97	0.16	5.41	3.65	0.40	14.17	3.97	1.10
BSO SIC1305	2 rad/h	0.92	2.31	0.14	0.41	2.97	0.16	1.62	3.65	0.40	3.40	3.97	1.10
	8 rad/h	2.18	2.31	0.14	1.60	2.97	0.16	4.64	3.65	0.40	6.93	3.97	1.10
	30 rad/h	3.04	2.31	0.14	2.37	2.97	0.16	6.95	3.65	0.40	9.96	3.97	1.10
BSO SIC1309	2 rad/h	0.23	2.31	0.29	0.80	2.97	0.34	1.22	3.65	0.35	-	-	-
	8 rad/h	0.56	2.31	0.29	1.22	2.97	0.34	2.08	3.65	0.35	-	-	-
	30 rad/h	0.77	2.31	0.29	1.36	2.97	0.34	2.38	3.65	0.35	-	-	-

Summary

- BSO crystals are a good candidate material for the HHCAL detector concept because of (1) high density of 6.8 g/cm^3, (2) good UV cut-off edge at 300 nm, (3) emission peak at 470 nm, (4) 100 ns scintillation decay time, (5) good light output (20% of BGO) and (6) potential low cost,.
- SIC2211 shows good transmittance approaching the theoretical limit at wavelength of longer than 500 nm.
- SIC1309 shows an improvement in transmittance, light output and light response uniformity. Its radiation hardness under gamma-ray irradiations is also better than other samples.
- Progresses have been made in the crystal growth at SIC. BSO crystals satisfying HHCAL specifications, however, need to be developed after further improvement.
- Color center analysis shows BSO crystals of three types. More works are needed to further understand the origin and dynamics of these color centers.