Report on Radiation Damage in BaF_2, Pure CsI and LSO/LYSO

Ren-Yuan Zhu

California Institute of Technology

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Three Candidate Crystals for Mu2e

	LSO:Ce/LYSO:Ce	BaF_2	CsI
Density (g/cm^3)	7.40	4.89	4.51
Melting point (℃)	2050	1280	621
Radiation Length (cm)	1.14	2.03	1.86
Molière Radius (cm)	2.07	3.10	3.57
Interaction Length (cm)	20.9	30.7	39.3
Z_{eff}	64.8	51.6	54.0
dE/dX (MeV/cm)	9.55	6.52	5.56
Emission Peak[a] (nm)	420	300 220	310
Refractive Index[b]	1.82	1.50	1.95
Relative Light Yield[a]	100	42 4.8	4.2
LY in 1st ns (photons)	740	960	100
Decay Time[a] (ns)	40	650 0.9	26
d(LY)/dT [c] (%/°C)	-0.2	-1.9 0.1	-1.4

a. Top line: slow component, bottom line: fast component.
b. At the wavelength of the emission maximum.
c. At room temperature (20°C)

Radiation Damage in Three Long BaF_2 Crystals

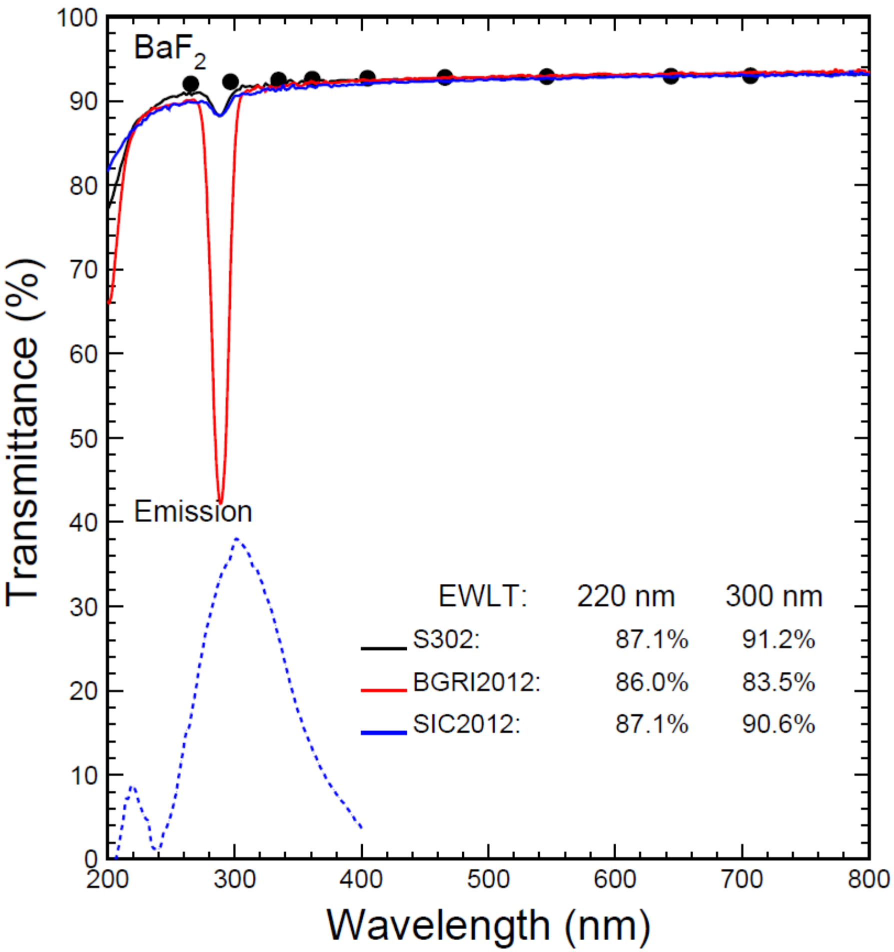
Sample ID	Received Date	Dimension (mm^3)	Polish
BaF_2-S302	1992	$30^2 \times 40^2 \times 250$	Six faces
BaF_2-BGRI2012	8/24/2012	$25 \times 25 \times 250$	Six faces
BaF_2-SIC2012	9/4/2012	$25 \times 25 \times 250$	Six faces

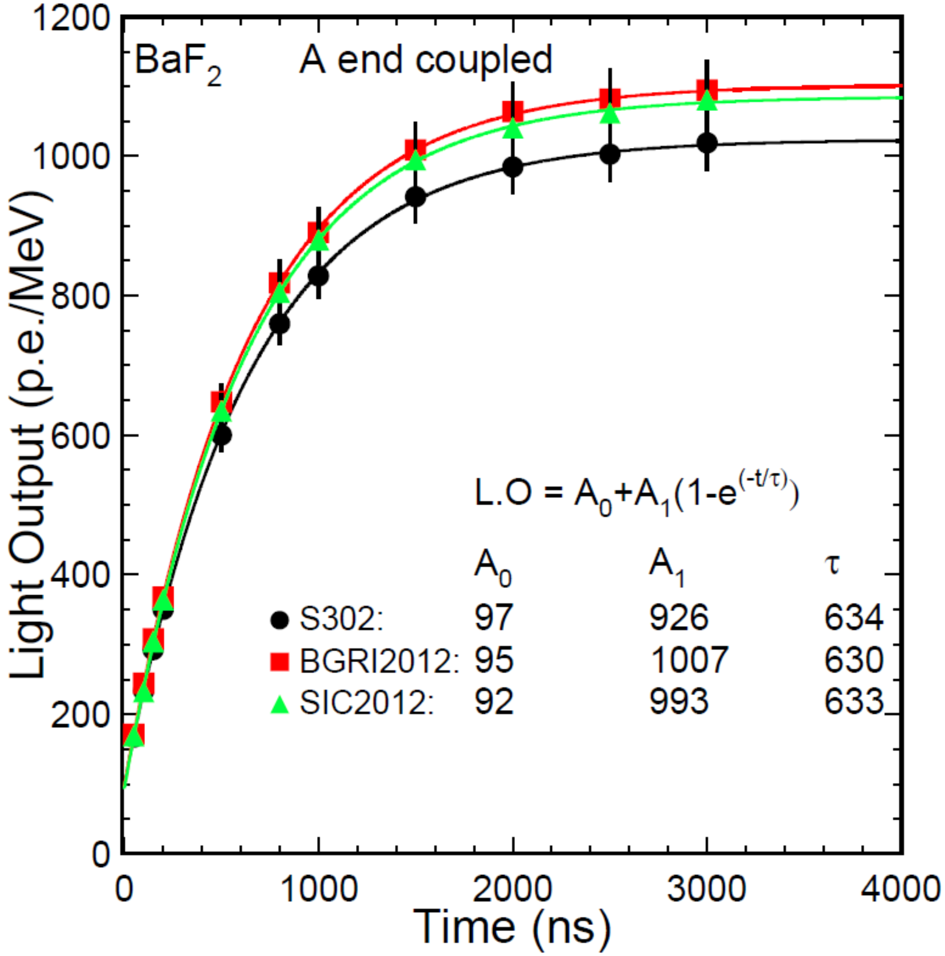
Experiments

- Three 25 cm long BaF_2 samples were investigated
- BaF_2-S302 was annealed at 500℃ for 180 minutes in N_2 flow
- All samples went through irradiations by Co-60 @ 30 rad/h and Cs-137 @ 7,062 rad/h to reach 100, 1k,10k,100k and 1M rad
- Properties measured at RT before, during and after irradiations: LT, EWLT for fast/slow components, LO & Decay Time

Initial EWLT, LO and Decay Time

All crystals have good transmittance approaching theoretical limit
A strong absorption band peaked at 290 nm observed in BGRI2012



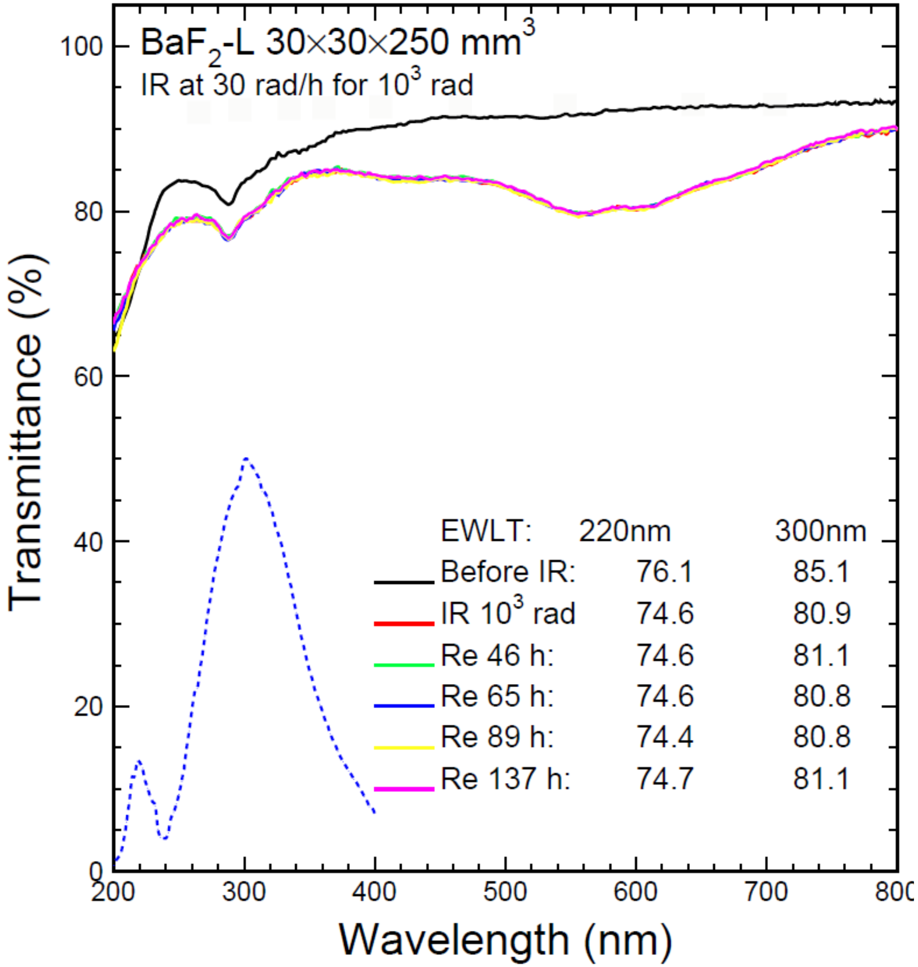


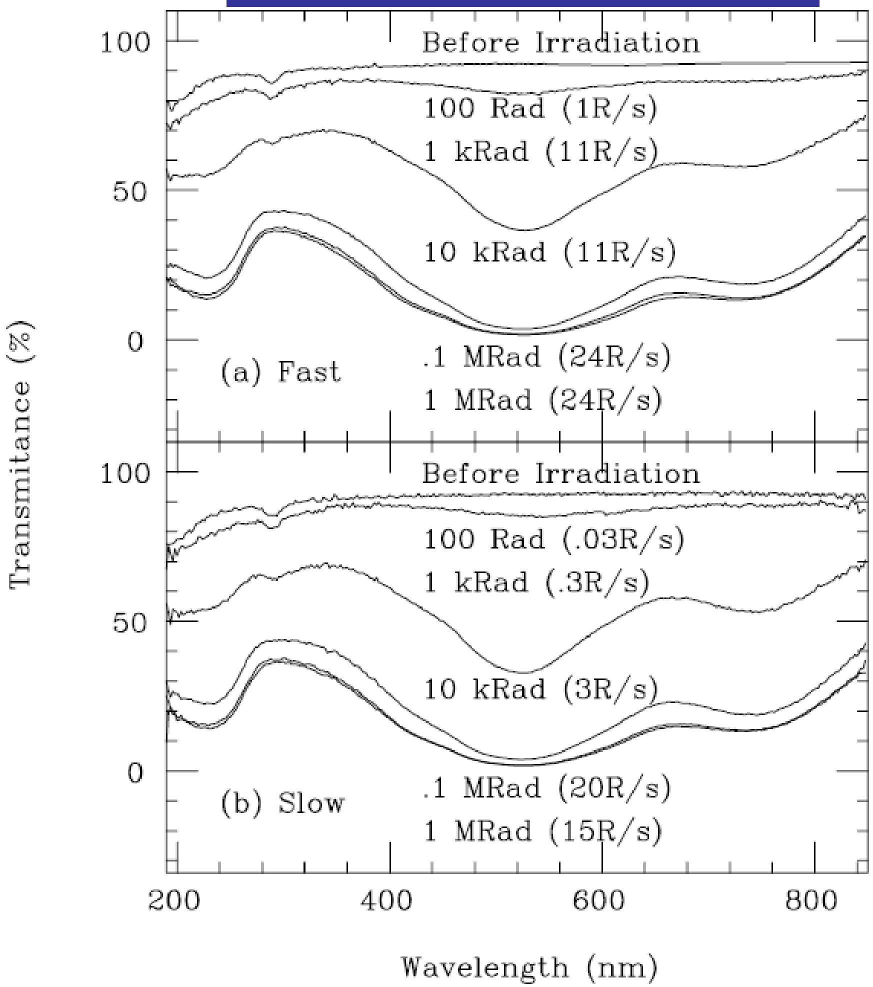
All crystals have compatible light yield

No Recovery & Dose Rate Dependence

Damage in BaF2 does not recover at RT, so is not dose rate dependent

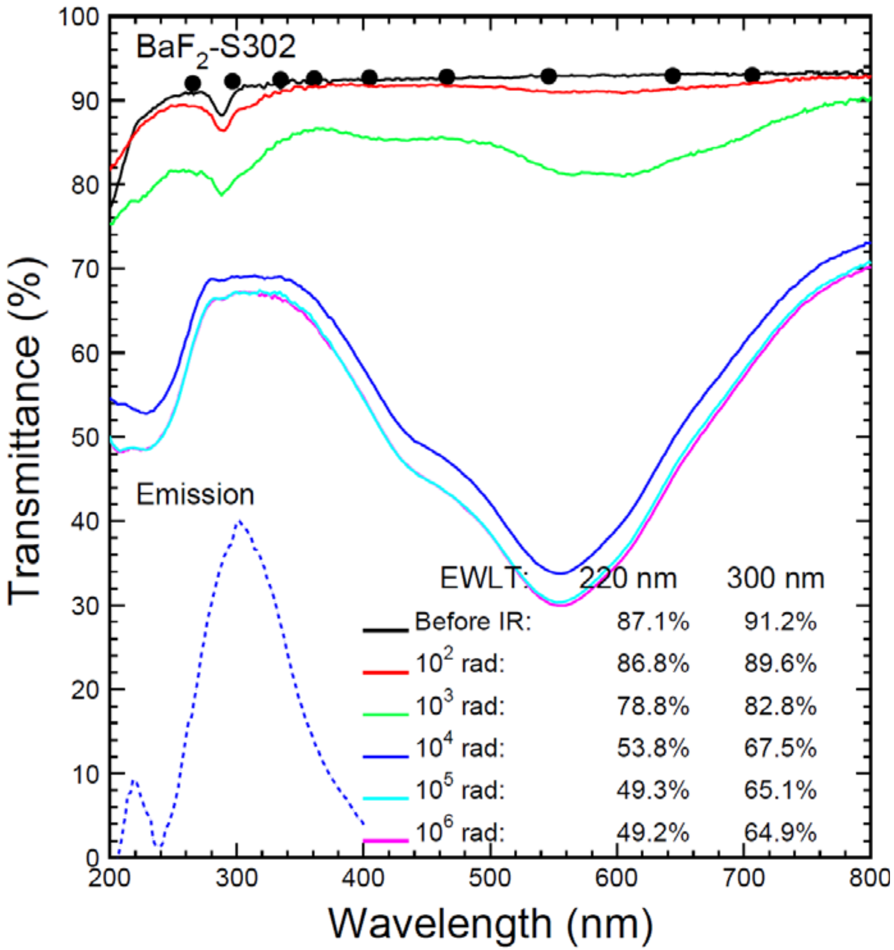
Nucl. Ins. Meth. A 340 (1994) 442-457

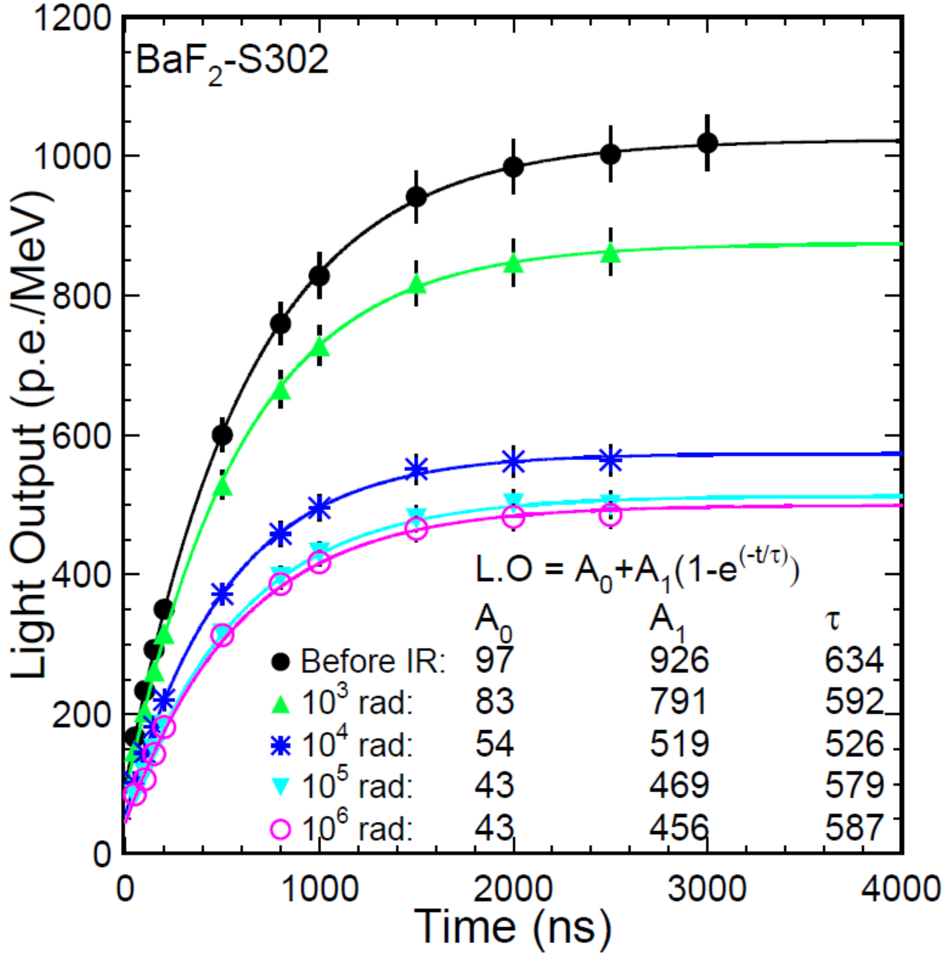




S302: EWLT, LO and Decay Time

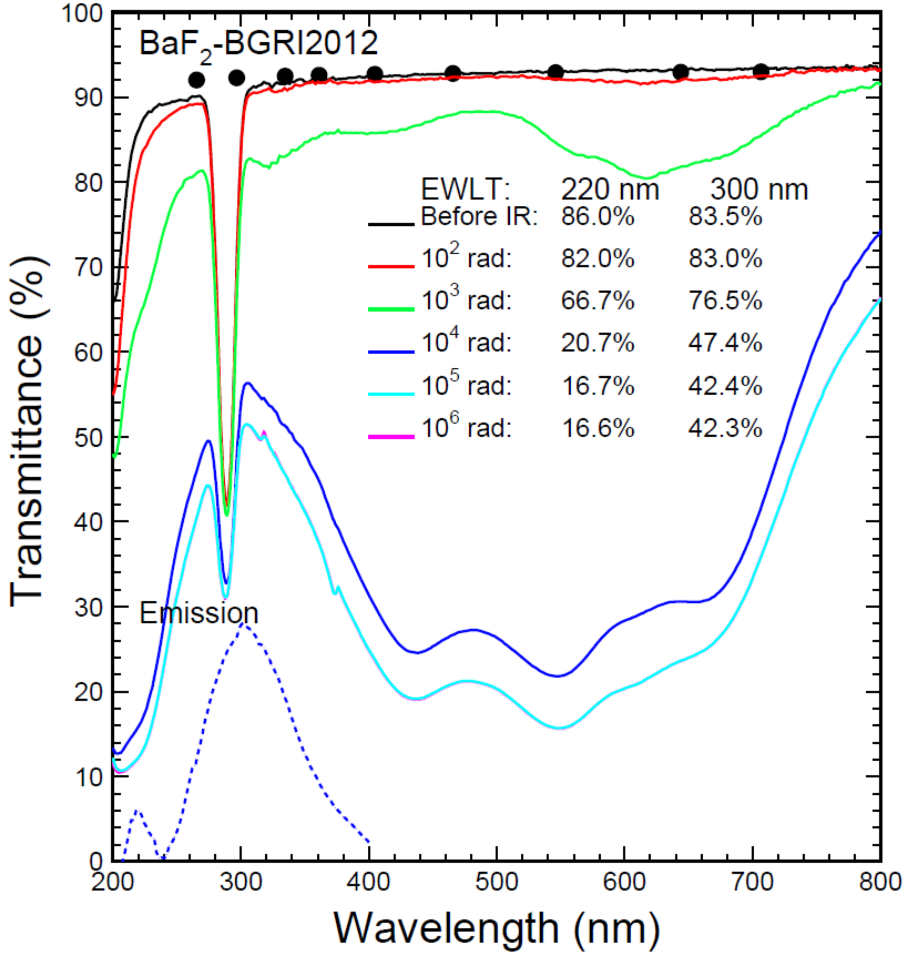
Damage in both LT and LO saturated after a few tens of krad

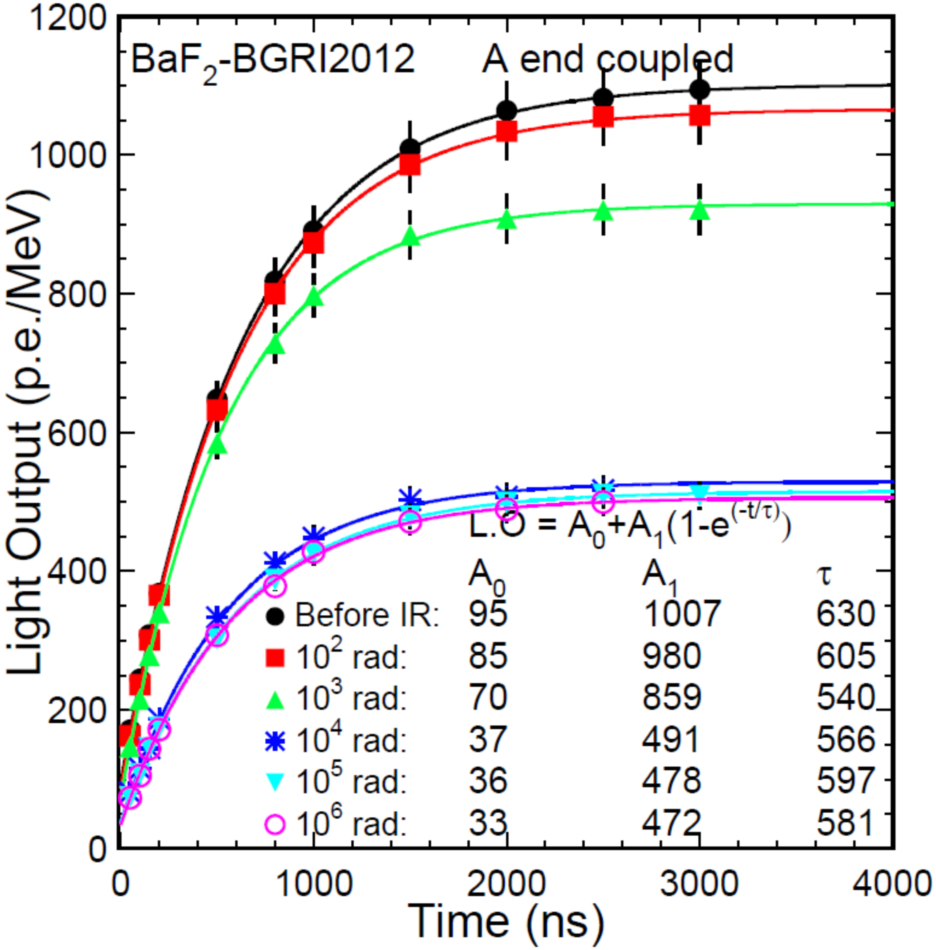




BGRI-2012: EWLT, LO and Decay Time

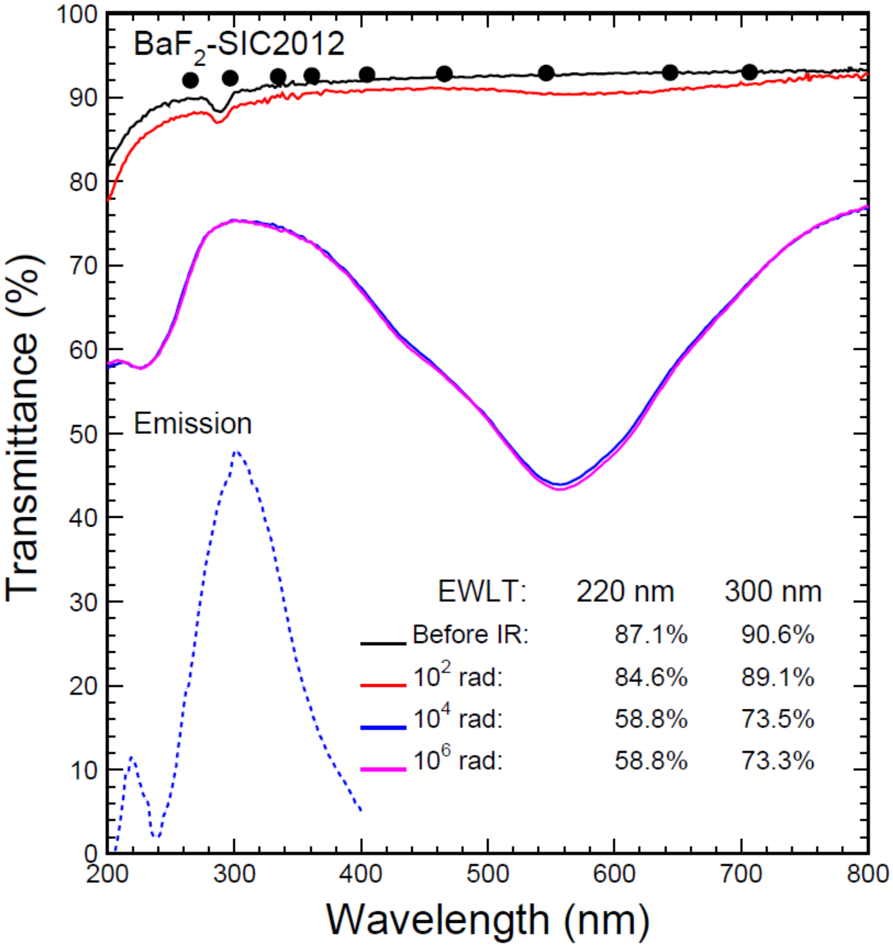
Damage in both LT and LO saturated after a few tens of krad

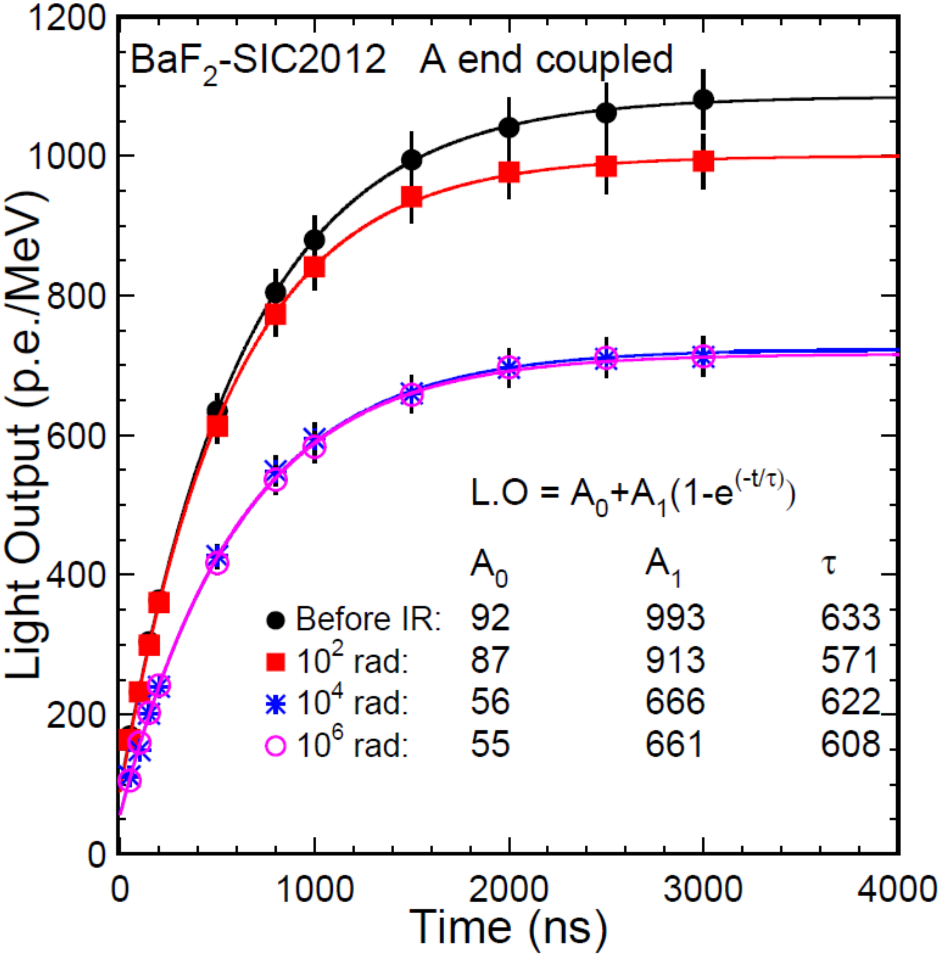




SIC-2012: EWLT, LO and Decay Time

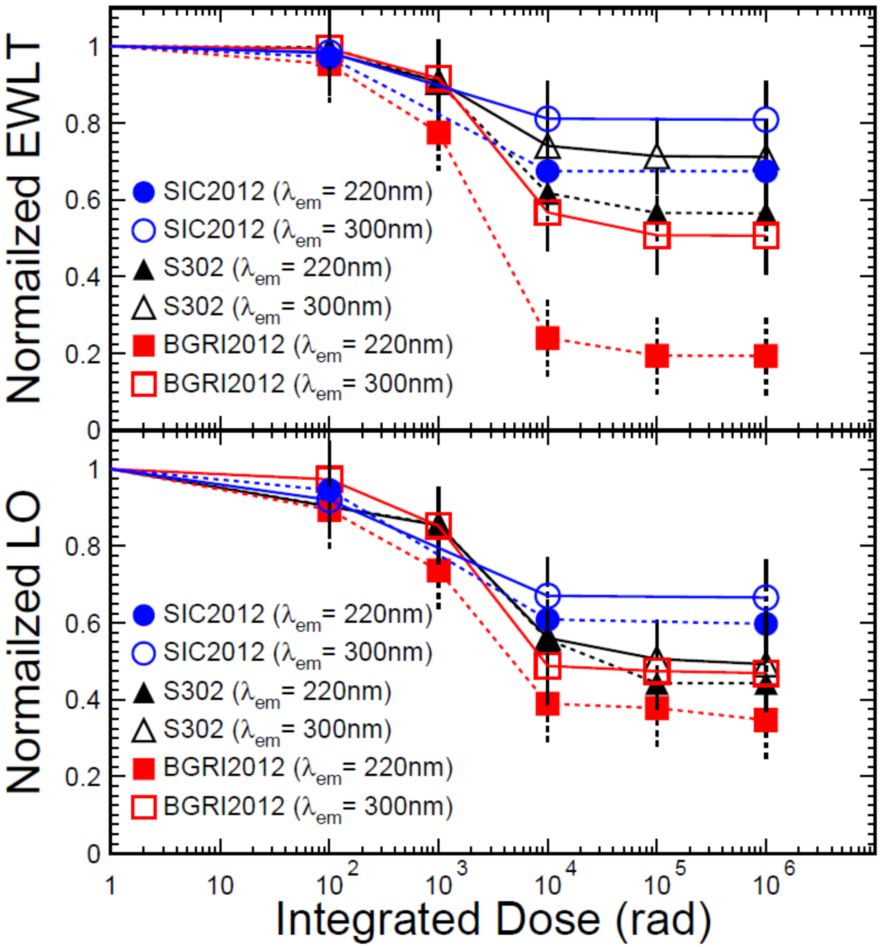
Damage in both LT and LO saturated after a few tens of krad

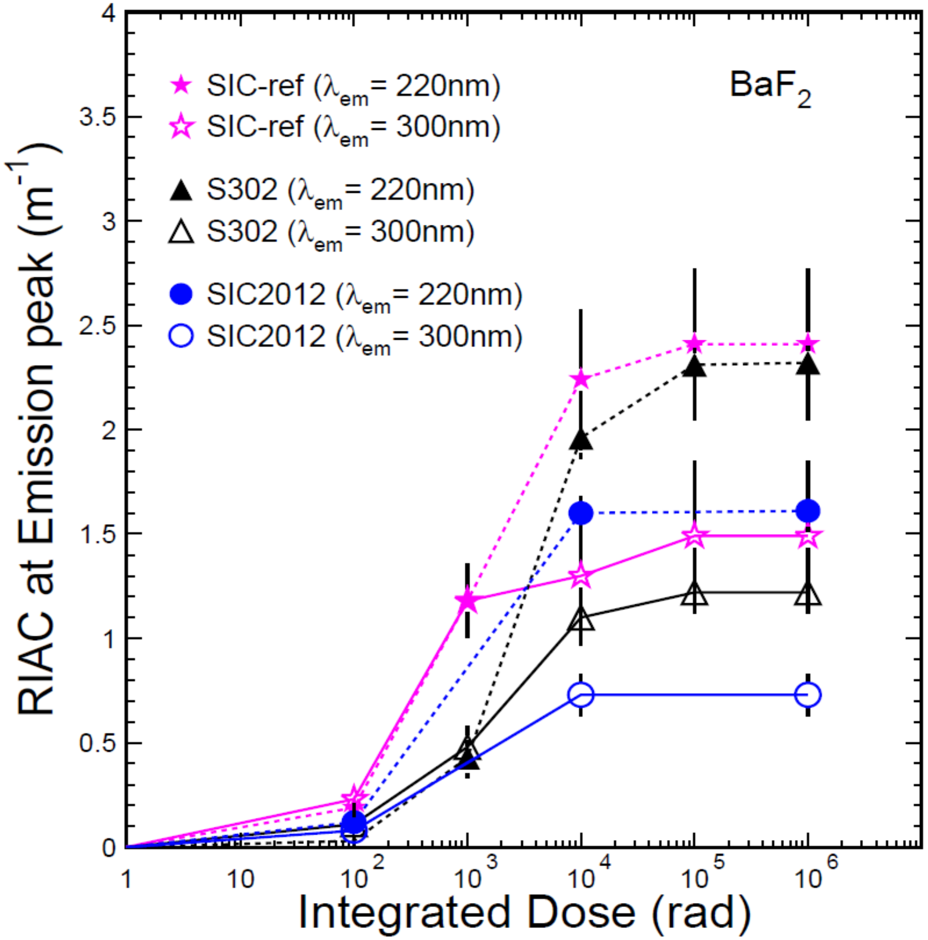




Summary: Loss of EWLT/LO and RIAC

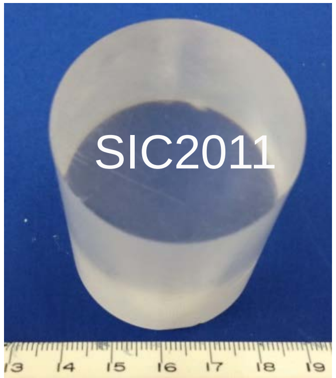
Radiation damage in BaF2 crystals saturates at a few tens of krad
SIC2012 is more radiation hard than other samples
Slow component is more radiation hard than the fast component





RIAC of mass produced BaF_2 may be controlled to less than 1.6 m^{-1}

Radiation Damage in Pure CsI Crystals



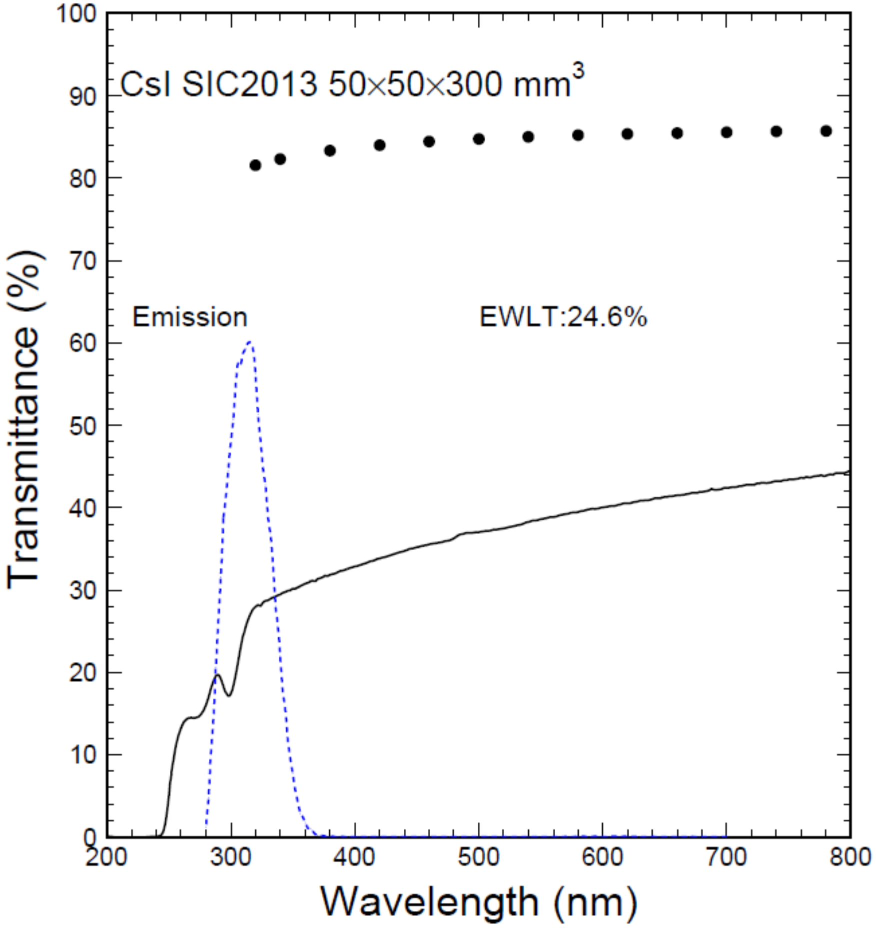
Sample ID	Received Date	Dimension (mm^3)	Polish
CsI SIC13	2/28/2013	50 × 50 × 300	Six faces
SIC2011	8/20/2011	Φ40×50	Two face (Φ40 faces)

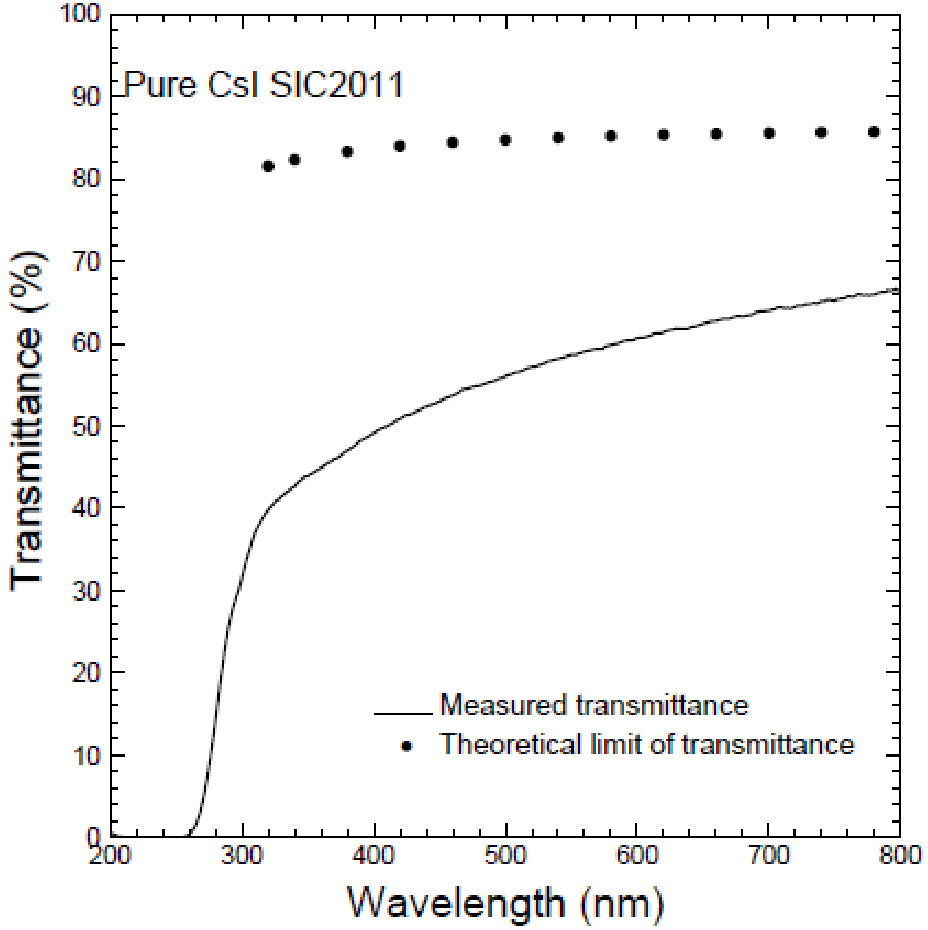
Experiments

- Two CsI sample samples were investigated
- All samples went through irradiations by Co-60 @ 30 rad/h and Cs-137 @ 7,062 rad/h to reach 100, 1k,10k,100k and 1M rad
- Properties measured at RT before, during and after irradiations: LT, EWLT, LO, Decay Time & LRU

Emission, LT and EWLT

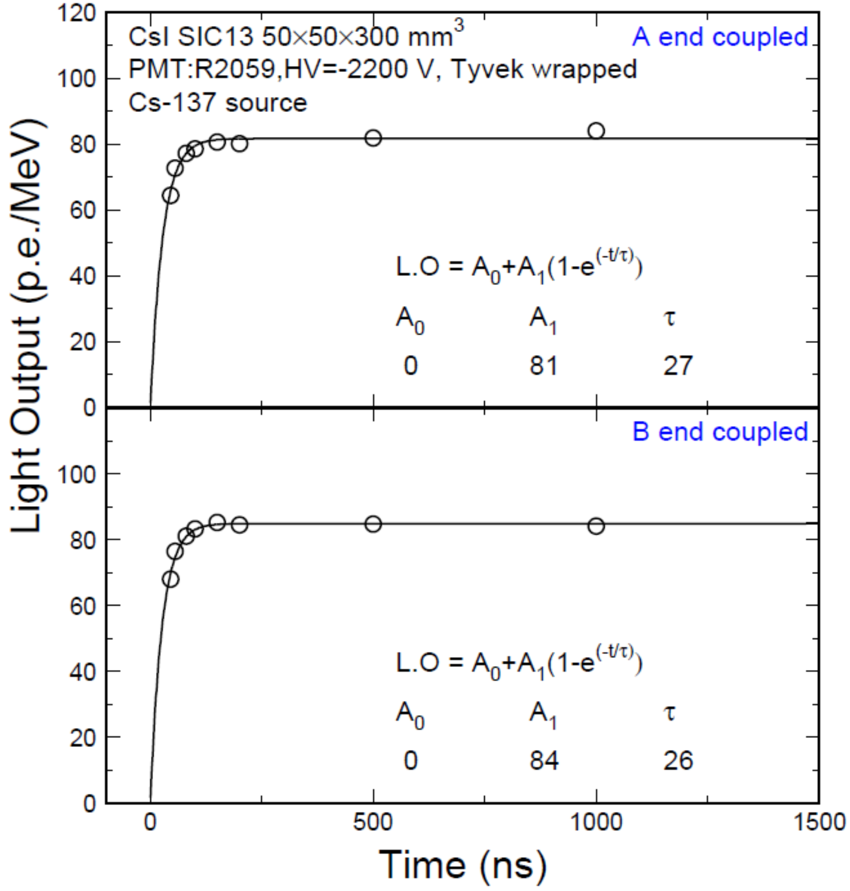
Poor surface condition makes LT much lower than theoretical limit

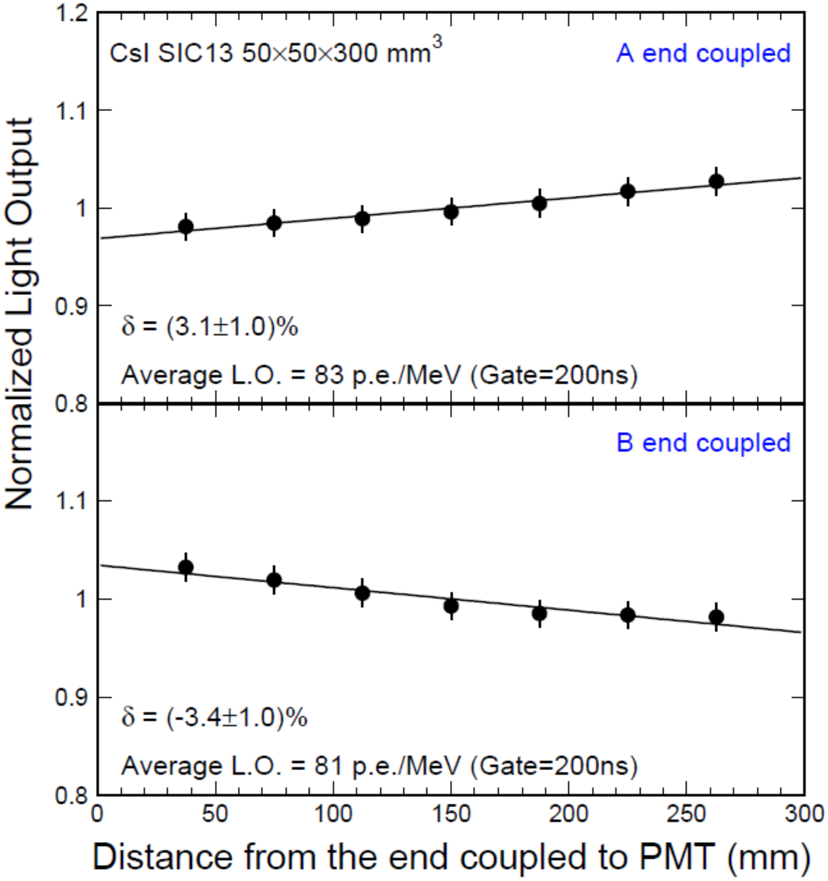




SIC-13: LO, Decay Time and LRU

82 p.e./MeV and 26 ns decay time observed

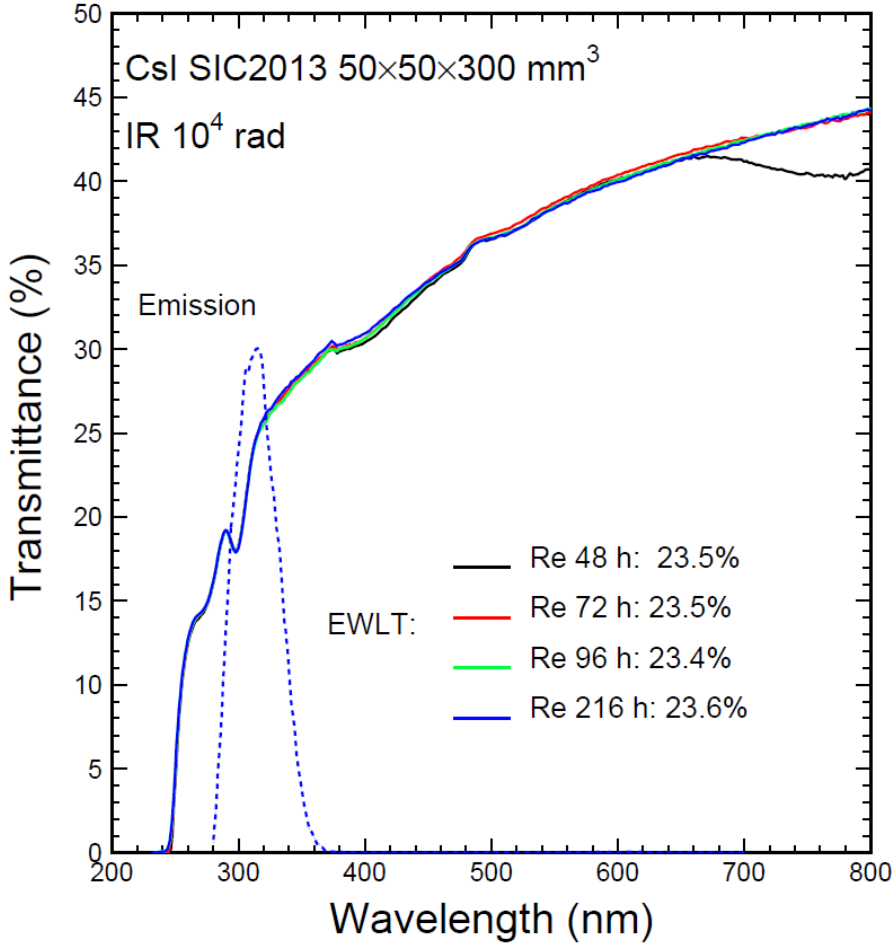


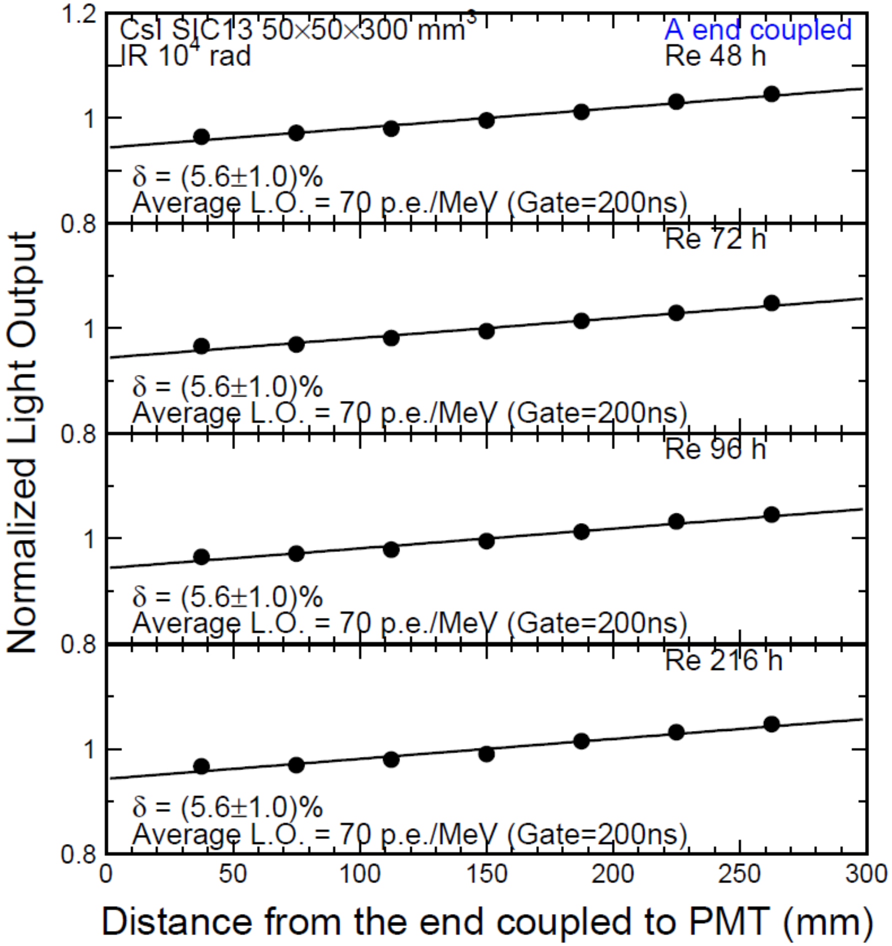


Variation of LRU for two end couplings indicates variation of LY along the crystal

No Recovery of Radiation Damage

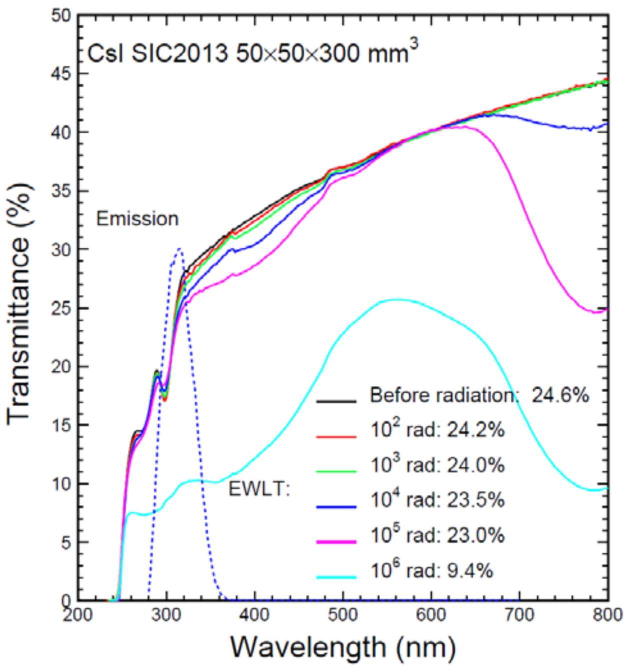
Damage does not recover under room temperature: no dose rate dependence

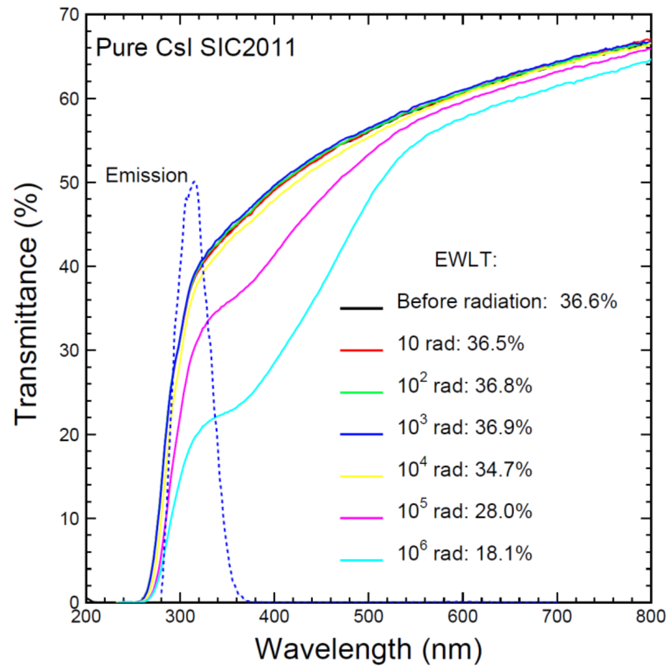


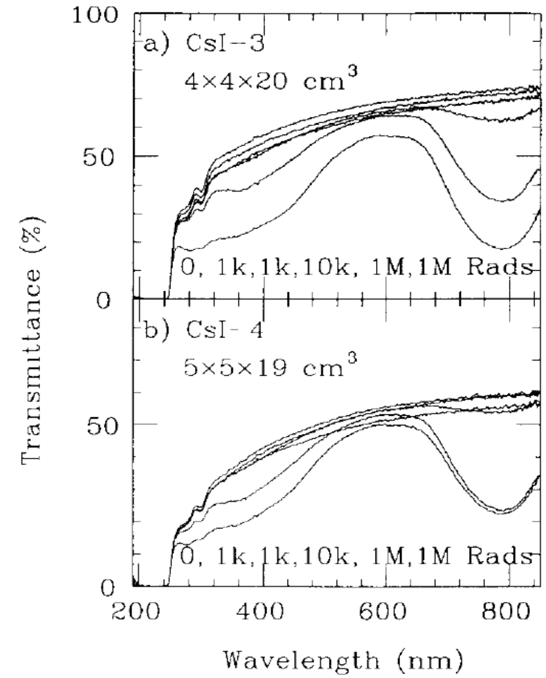


Damage on LT and EWLT

No saturation observed up to 1 Mrad, indicating high density of defects



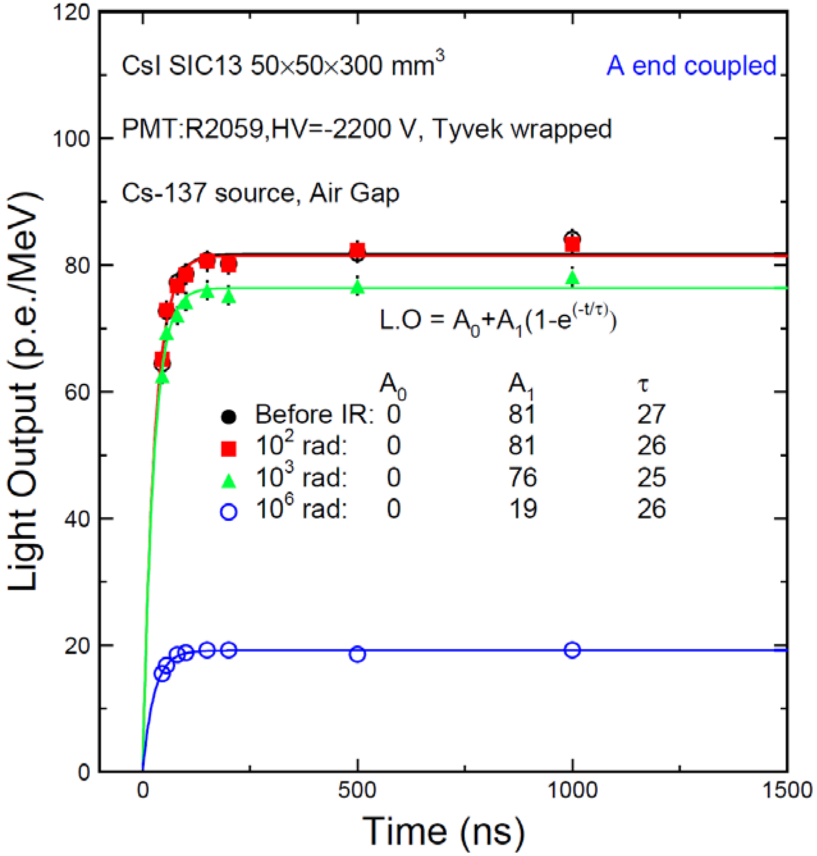


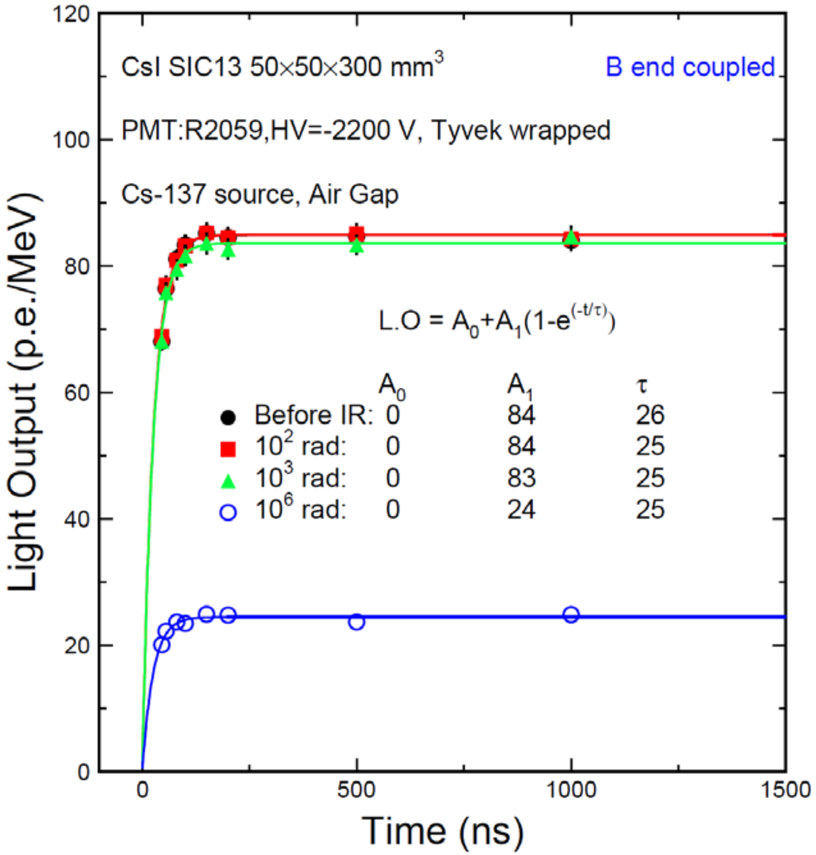


Nucl. Ins. Meth. A 326 (1993) 508-512

Light Output Damage

No saturation observed up to 1 Mrad, indicating high density of defects

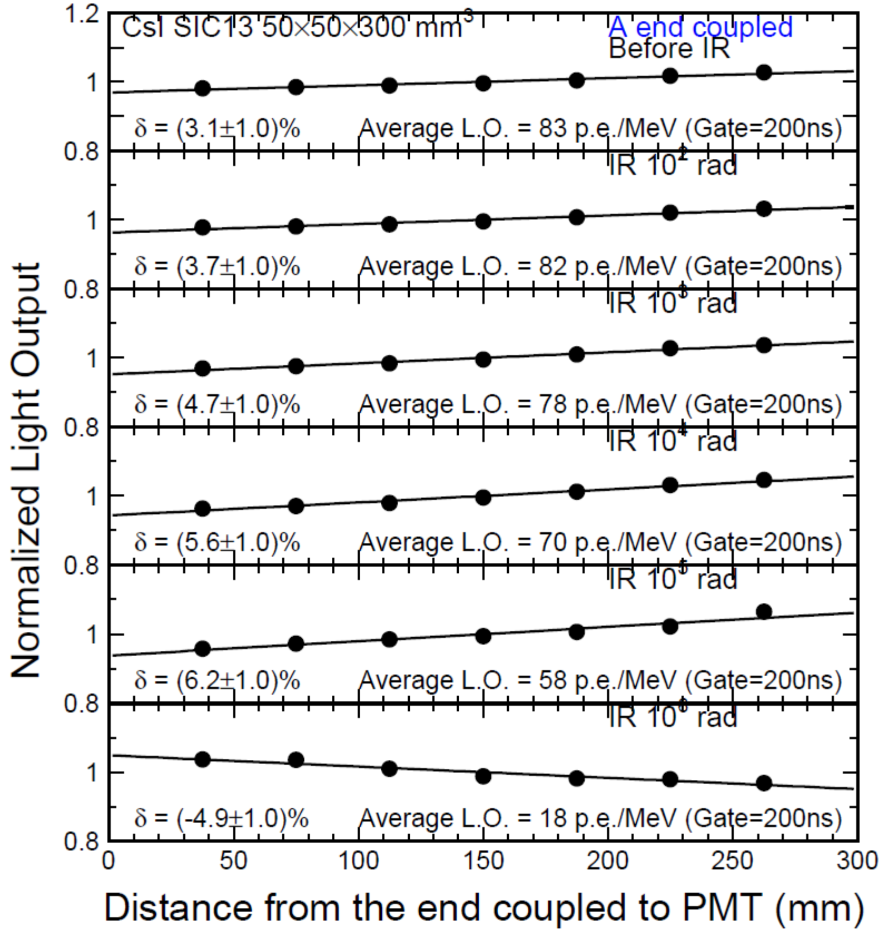


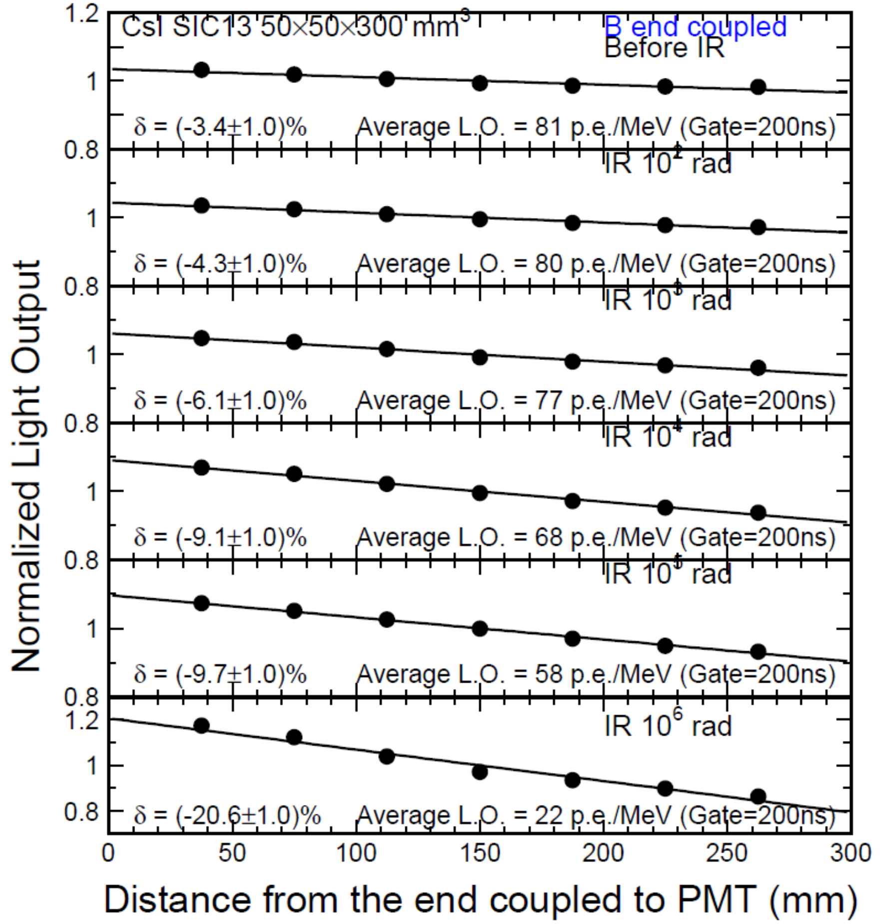


Consistent decay time indicates no damage in scintillation mechanism

Damage on LO and LRU

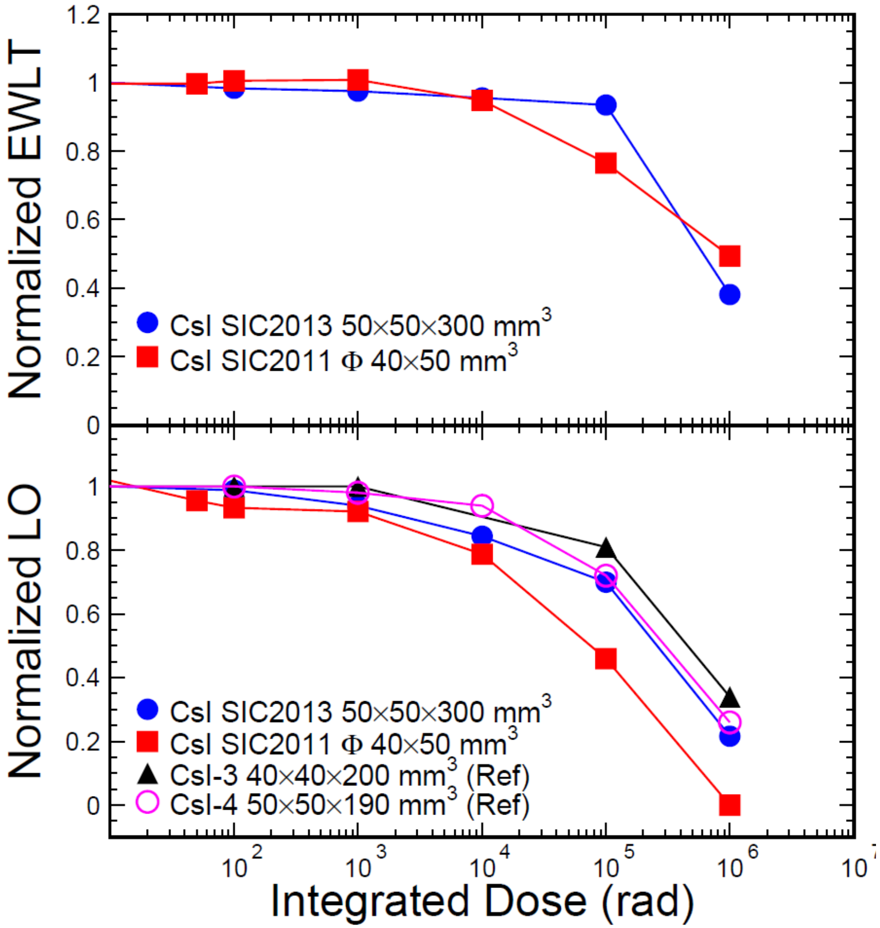
No saturation observed up to 1 Mrad, indicating high density of defects

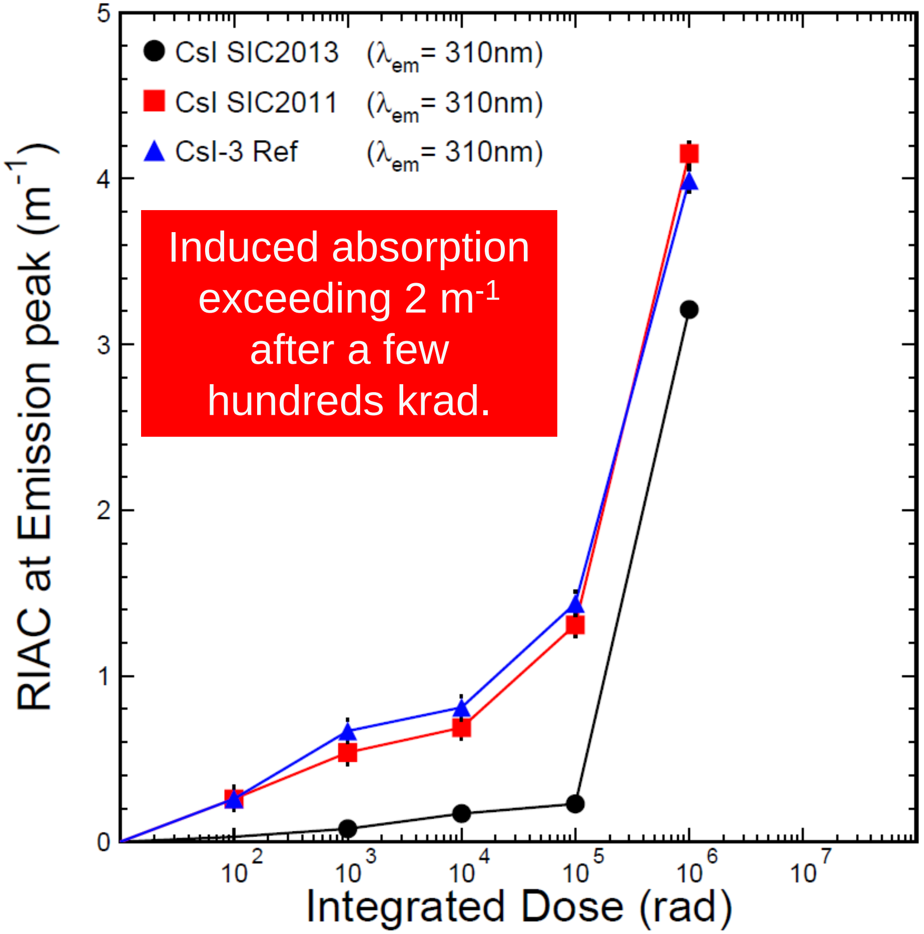




Comparison of CsI from SIC & Kharkov

Consistent damage between 30/20 cm long pure CsI from SIC/Kharkov





Data of Kharkov crystals: *Nucl. Ins. Meth. A* 326 (1993) 508-512

Radiation Damage in Long LSO/LYSO

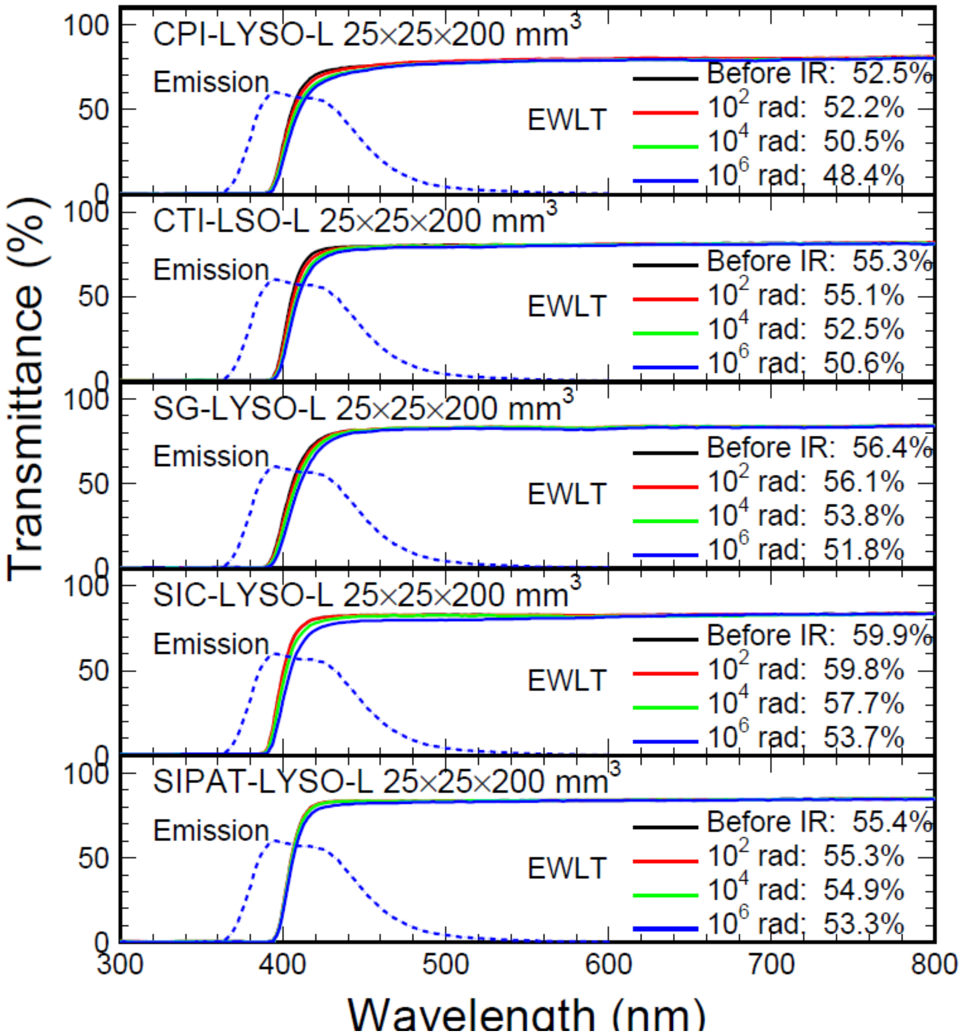
Sample ID	Dimension (mm^3)	Polish
CPI-LYSO-L	25 × 25 × 200	Six faces polished
CTI-LSO-L	25 × 25 × 200	Six faces polished
SG-LYSO-L	25 × 25 × 200	Six faces polished
SIC-LYSO-L	25 × 25 × 200	Six faces polished
SIPAT-LYSO-L	25 × 25 × 200	Six faces polished

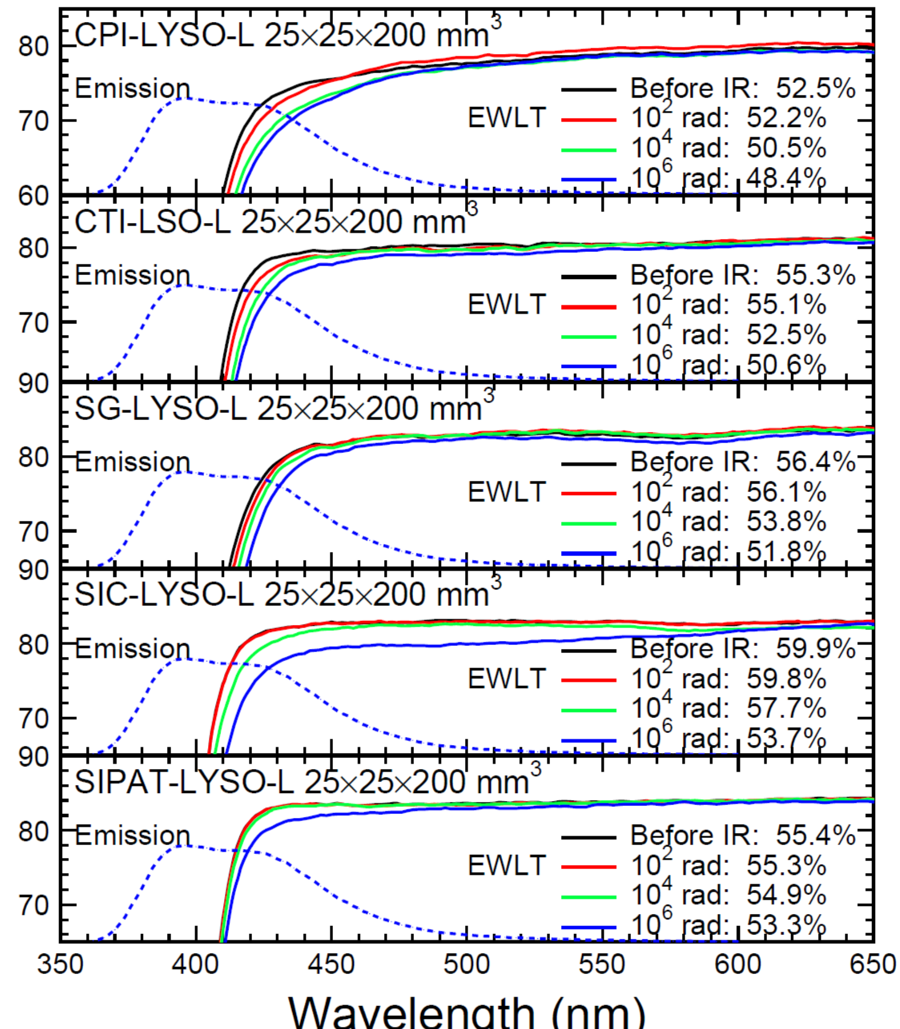
Experiments

- Properties measured at room temperature before after irradiation: longitudinal transmittance (LT) & light output (LO).
- Step by step irradiations by γ-rays: 100, 1K, 10K, 100K and 1M rad.

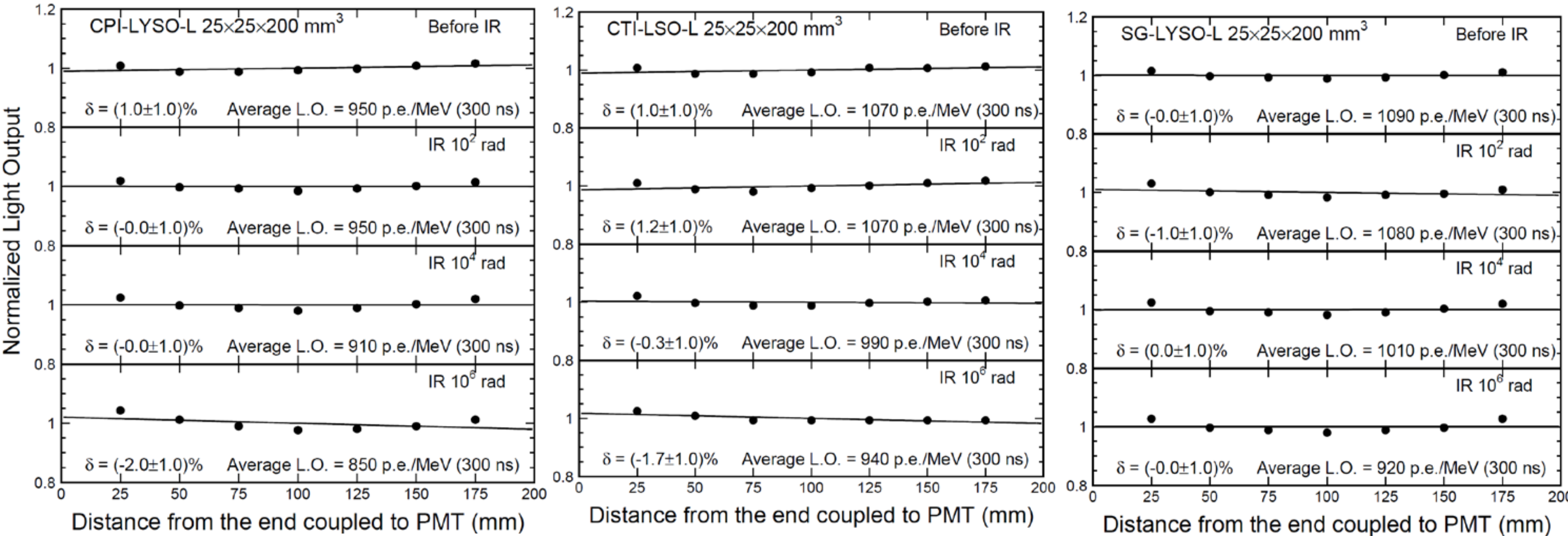
Excellent Radiation Hardness in LT

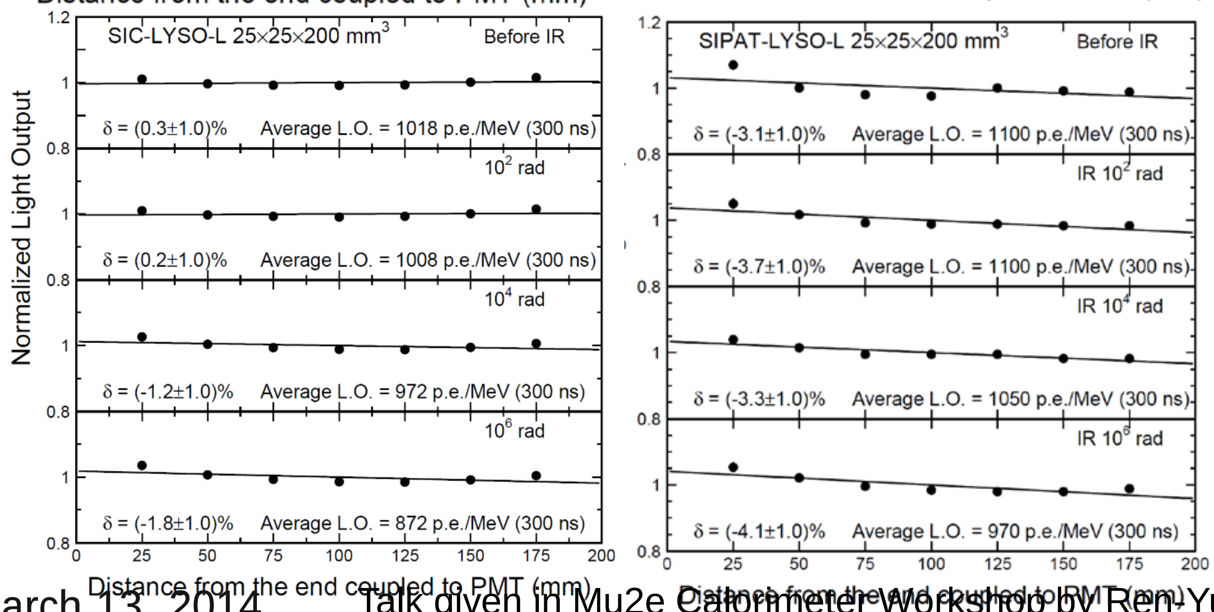
Consistent & Small Damage in LT → Larger variation @ shorter λ





Excellent Radiation Hardness in LO

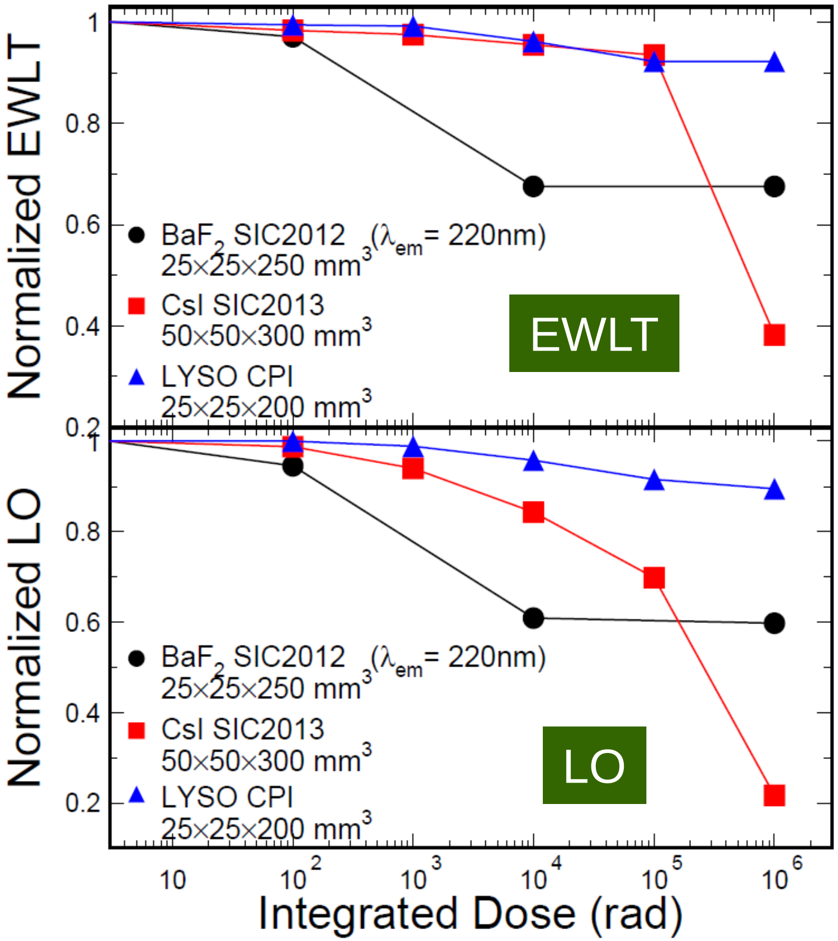


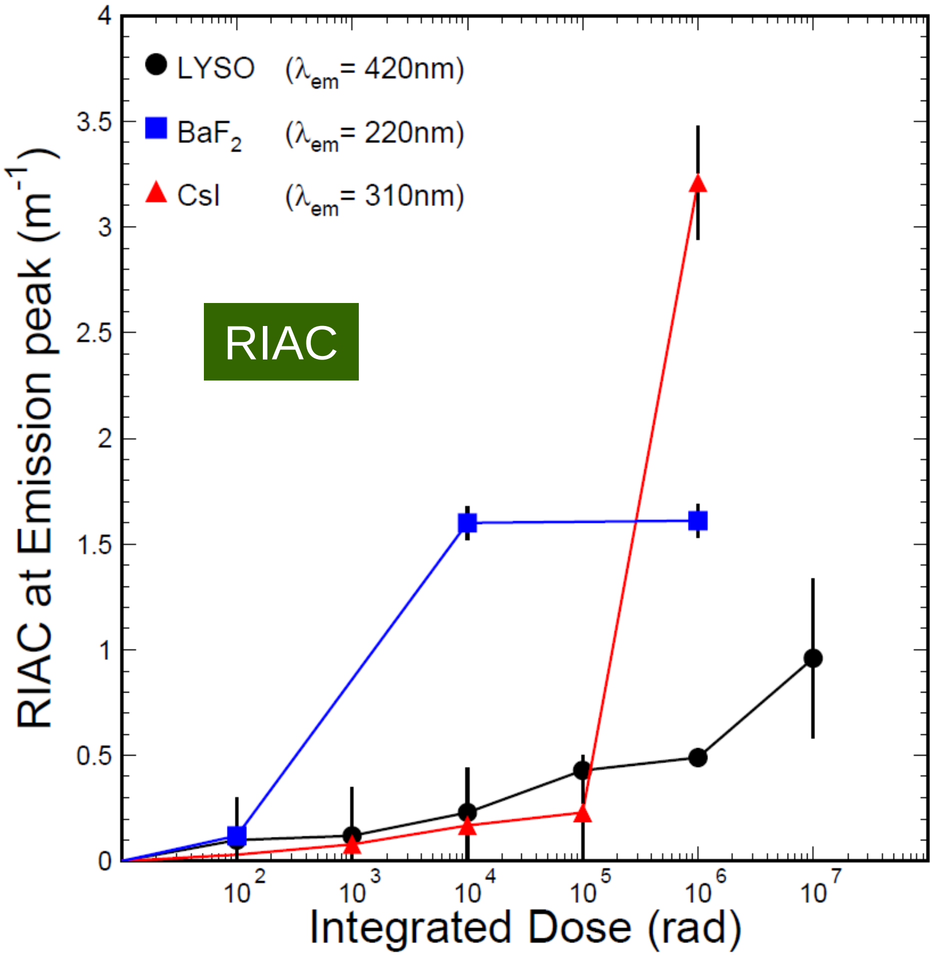


About 12% LO loss observed after 1 Mrad irradiation in all samples with LRU maintained. It can be corrected by light monitoring.

Comparison of Three Crystals

LYSO is the best in radiation hardness. BaF_2/CsI is good at high/low dose





Summary

Damage in all three crystals does not recover at room temperature, so has no dose rate dependence. LSO/LYSO crystals are the best in both brightness and radiation hardness.

Both BaF_2 and pure CsI have compatible fast light and low cost. They are, however, significantly radiation softer than LSO/LYSO.

Because of low defect density radiation damage in BaF_2 is saturated beyond 10 krad, promising a stable detector at high integrated dose.

Radiation damage in pure CsI is small at low dose, but shows no saturation at high dose.

One additional advantage of BaF_2 is that it is possible to cure radiation damage in BaF_2 through thermal annealing or optical bleaching. This feature reduces the cost for damage study and provides an additional flexibility, e.g. optical bleaching *in situ*.