γ-Ray Induced Radiation Damage in BaF_2, CeF_3, CsI and LSO/LYSO Crystals

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Candidate Fast Crystals

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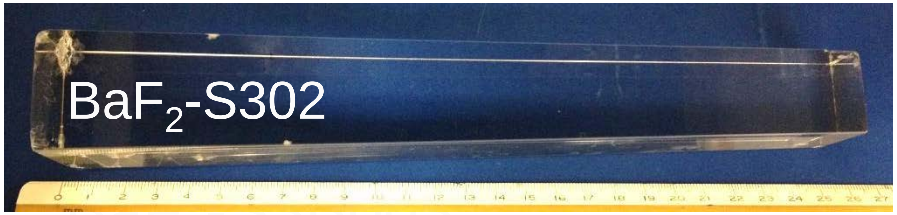
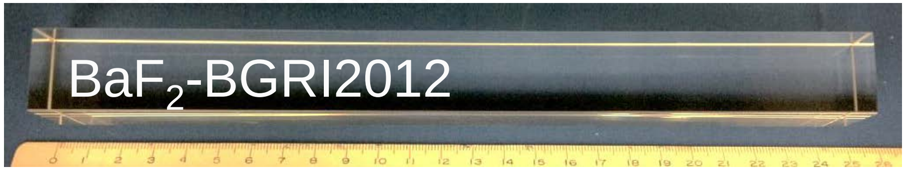
	LSO/LYSO	GSO	YSO[1]	CsI	BaF_2	CeF_3	$CeBr_3$[2]	$LaCl_3$	$LaBr_3$	Plastic scintillator (BC 404)[3]
Density (g/cm³)	7.40	6.71	4.44	4.51	4.89	6.16	5.23	3.86	5.29	1.03
Melting point (°C)	2050	1950	1980	621	1280	1460	722	858	783	70#
Radiation Length (cm)	1.14	1.38	3.11	1.86	2.03	1.70	1.96	2.81	1.88	42.54
Molière Radius (cm)	2.07	2.23	2.93	3.57	3.10	2.41	2.97	3.71	2.85	9.59
Interaction Length (cm)	20.9	22.2	27.9	39.3	30.7	23.2	31.5	37.6	30.4	78.8
Z value	64.8	57.9	33.3	54.0	51.6	50.8	45.6	47.3	45.6	-
dE/dX (MeV/cm)	9.55	8.88	6.56	5.56	6.52	8.42	6.65	5.27	6.90	2.02
Emission Peak[a] (nm)	420	430	420	420 310	300 220	340 300	371	335	356	408
Refractive Index[b]	1.82	1.85	1.80	1.95	1.50	1.62	1.9	1.9	1.9	1.58
Relative Light Yield[a,c]	100	45	76	4.2 1.3	42 4.8	8.6	141	15 49	153	35
Decay Time[a] (ns)	40	73	60	30 6	650 0.9	30	17	570 24	20	1.8
d(LY)/dT[d] (%/°C)	-0.2	-0.4	-0.3	-1.4	-1.9 0.1	~0	-0.1	0.1	0.2	~0

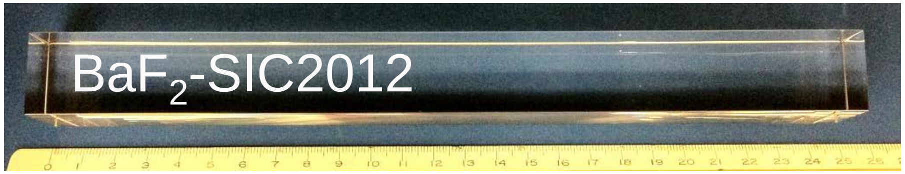
a. Top line: slow component, bottom line: fast component.
b. At the wavelength of the emission maximum.
c. Relative light yield normalized to the light yield of LSO
d. At room temperature (20°C)
#. Softening point

1. N. Tsuchida et al ***Nucl. Instrum. Methods Phys. Res. A,*** 385 (1997) 290-298 http://www.hitachi-chem.co.jp/english/products/cc/017.html
2. W. Drozdowski et al. ***IEEE TRANS. NUCL. SCI***, VOL.55, NO.3 (2008) 1391-1396 Chenliang Li et al, ***Solid State Commun***, Volume 144, Issues 5–6 (2007),220–224 http://scintillator.lbl.gov/
3. http://www.detectors.saint-gobain.com/Plastic-Scintillator.aspx http://pdg.lbl.gov/2008/AtomicNuclearProperties/HTML_PAGES/216.html

Radiation Damage in Long BaF_2 Crystals







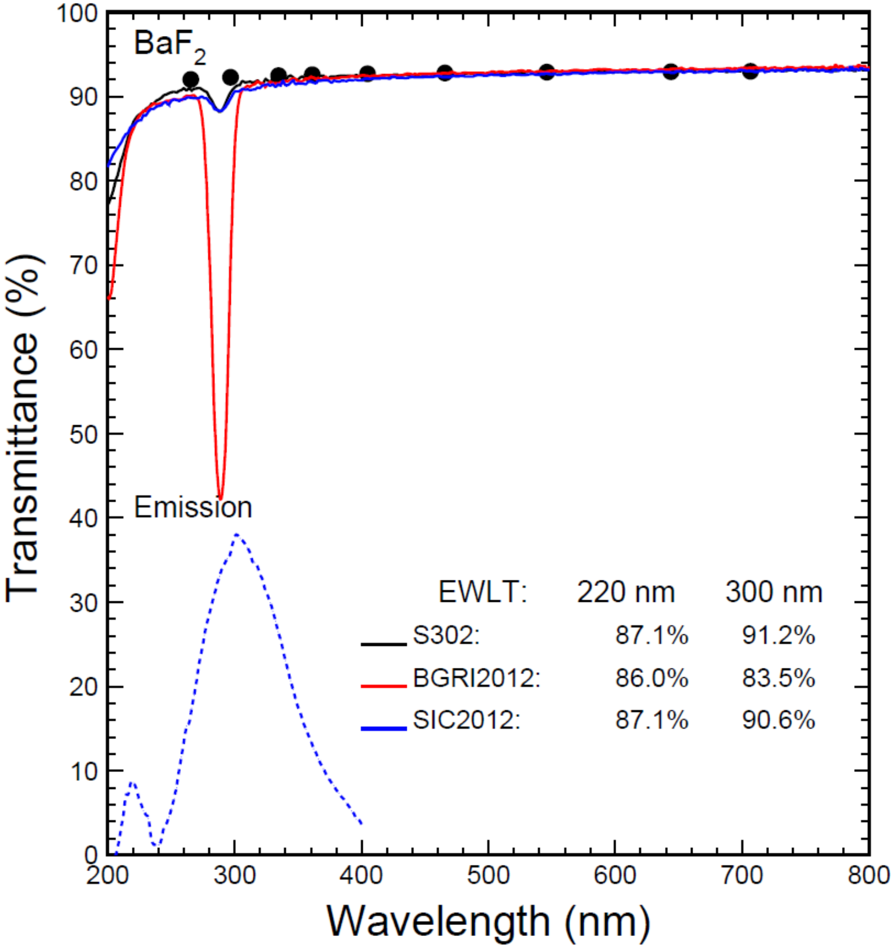
Sample ID	Received Date	Dimension (mm^3)	Polish
BaF_2-S302	1992	$30^2 \times 40^2 \times 250$	Six faces
BaF_2-BGRI2012	8/24/2012	$25 \times 25 \times 250$	Six faces
BaF_2-SIC2012	9/4/2012	$25 \times 25 \times 250$	Six faces

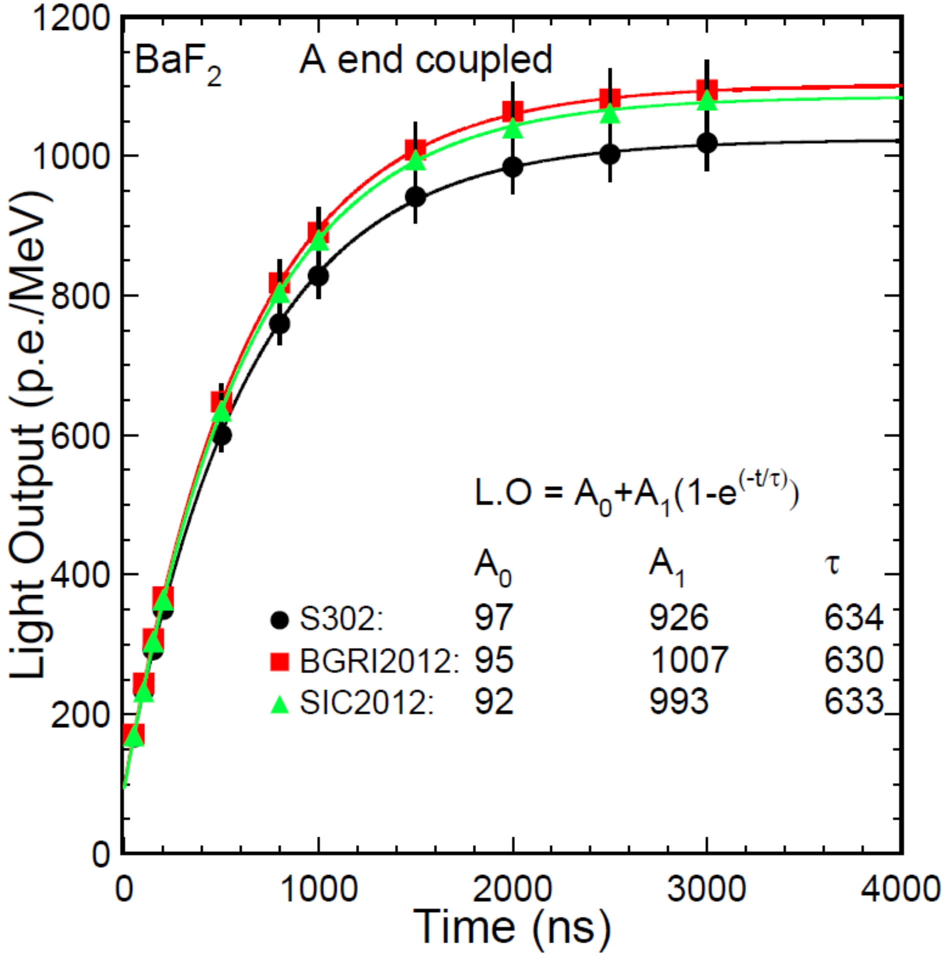
Experiments

- Three BaF_2 samples from two vendors were investigated
- Damage does not recover at room temperature
- All samples went through γ-ray irradiation @ 30 and 7k rad/h to reach 100, 1k,10k,100k and 1M rad
- Properties measured: LT, EWLT for fast/slow components, LO, decay time and LRU

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



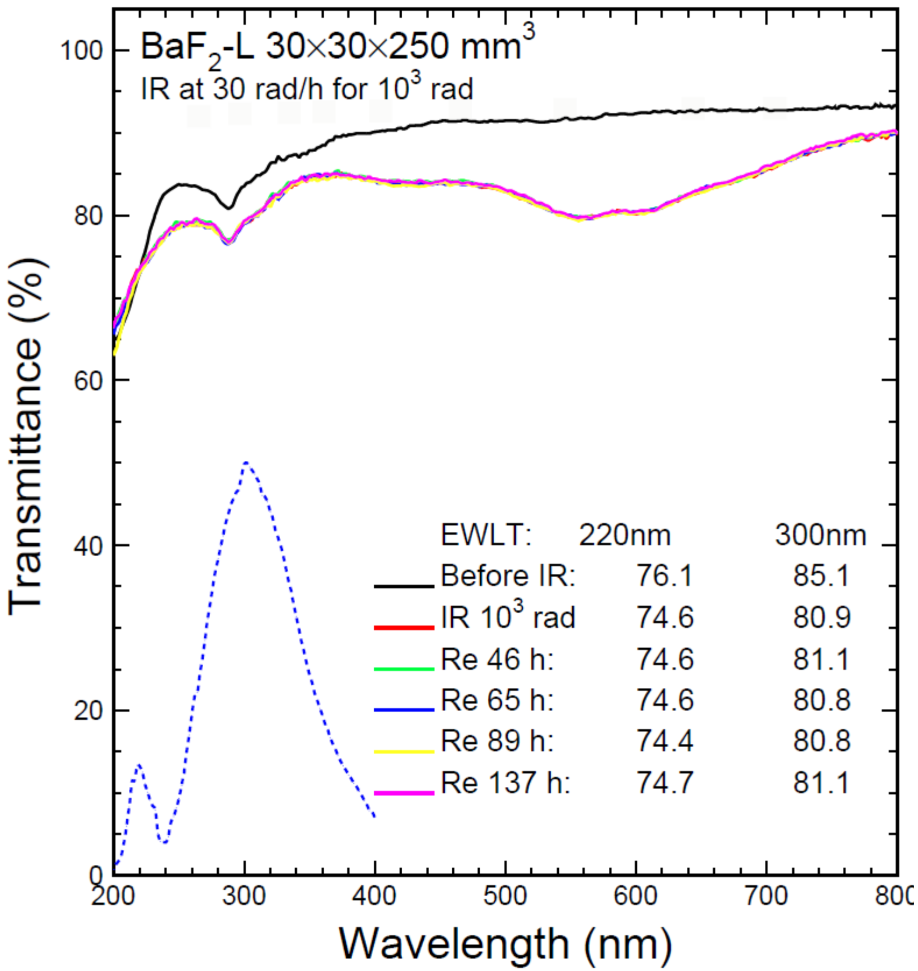


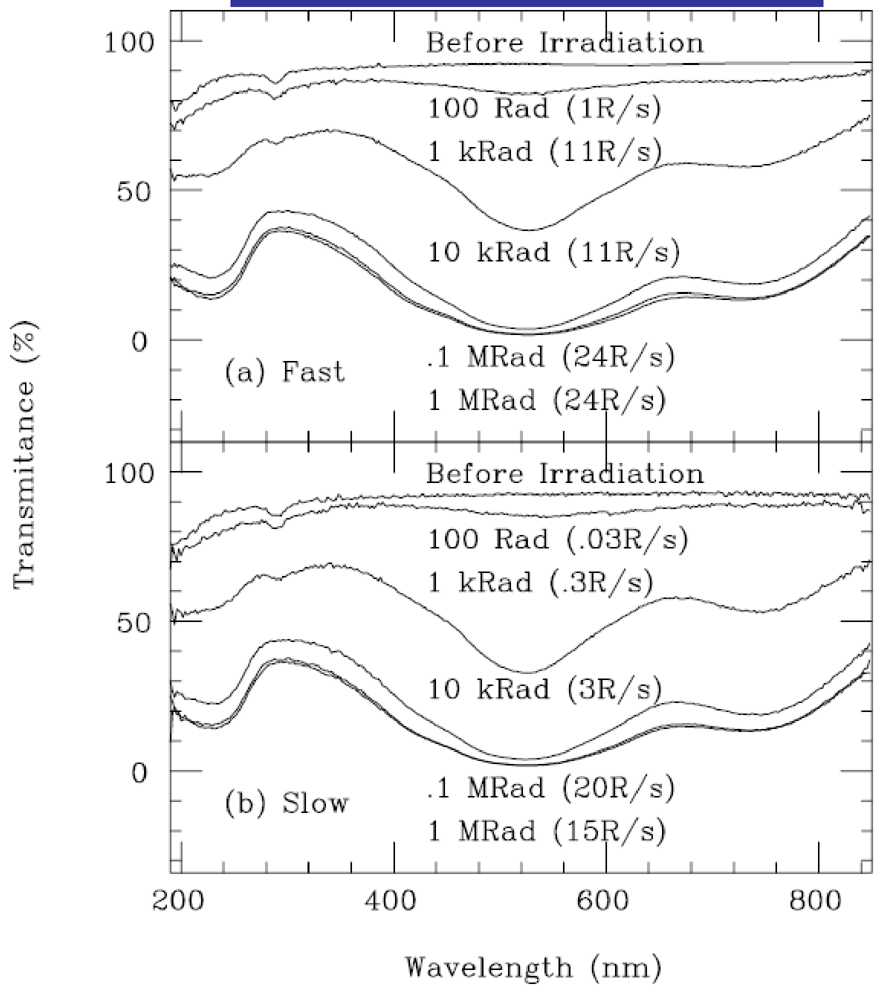
All crystals have compatible light yield

No Recovery, No Dose Rate Dependence

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

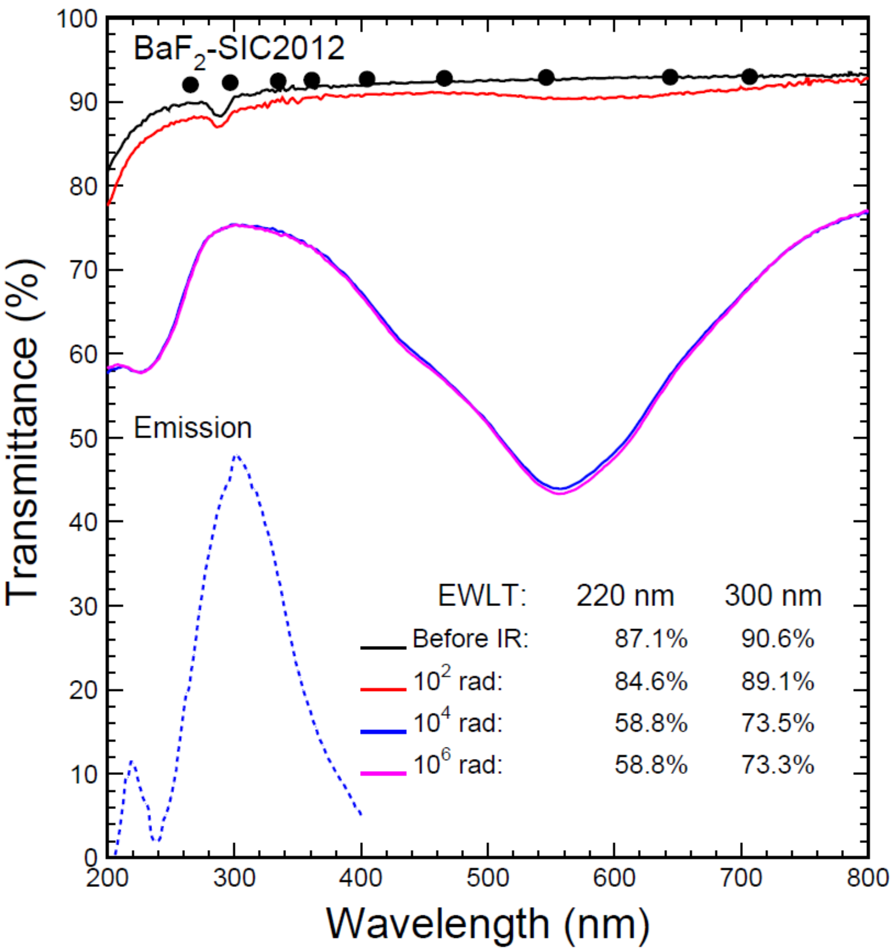
Nucl. Ins. Meth. A 340 (1994) 442-457

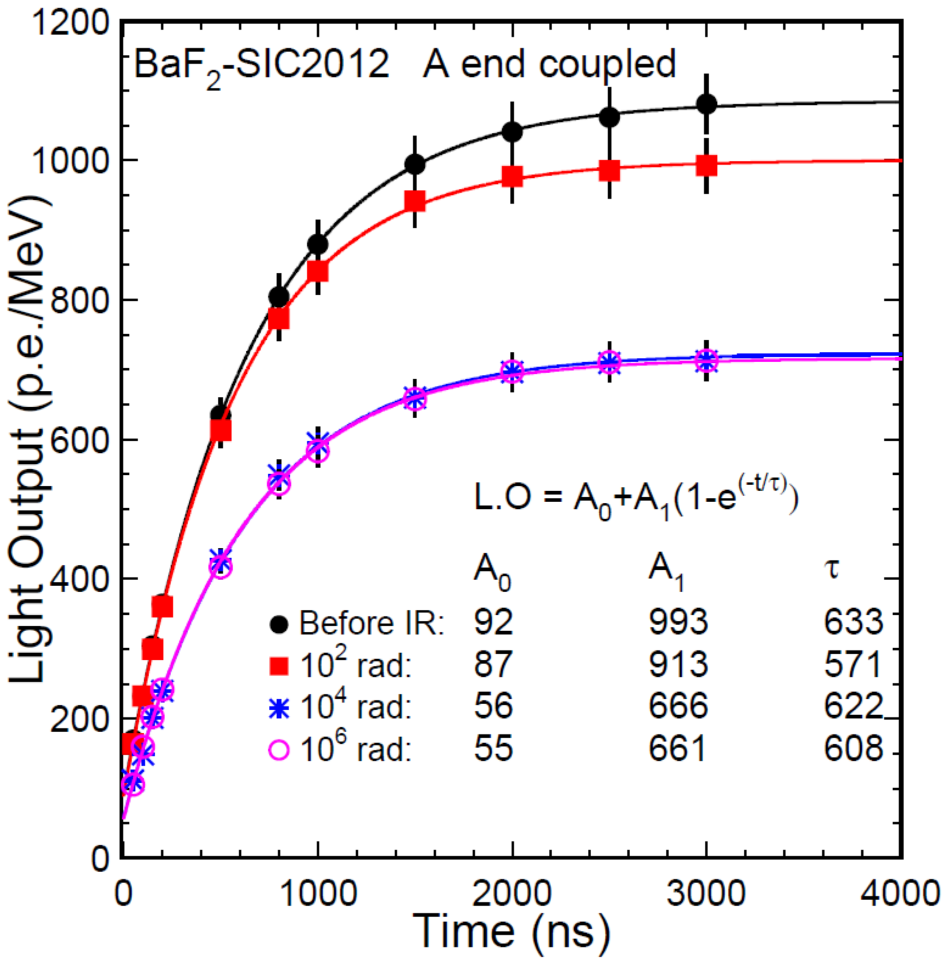




SIC-2012: EWLT, LO and Decay Time

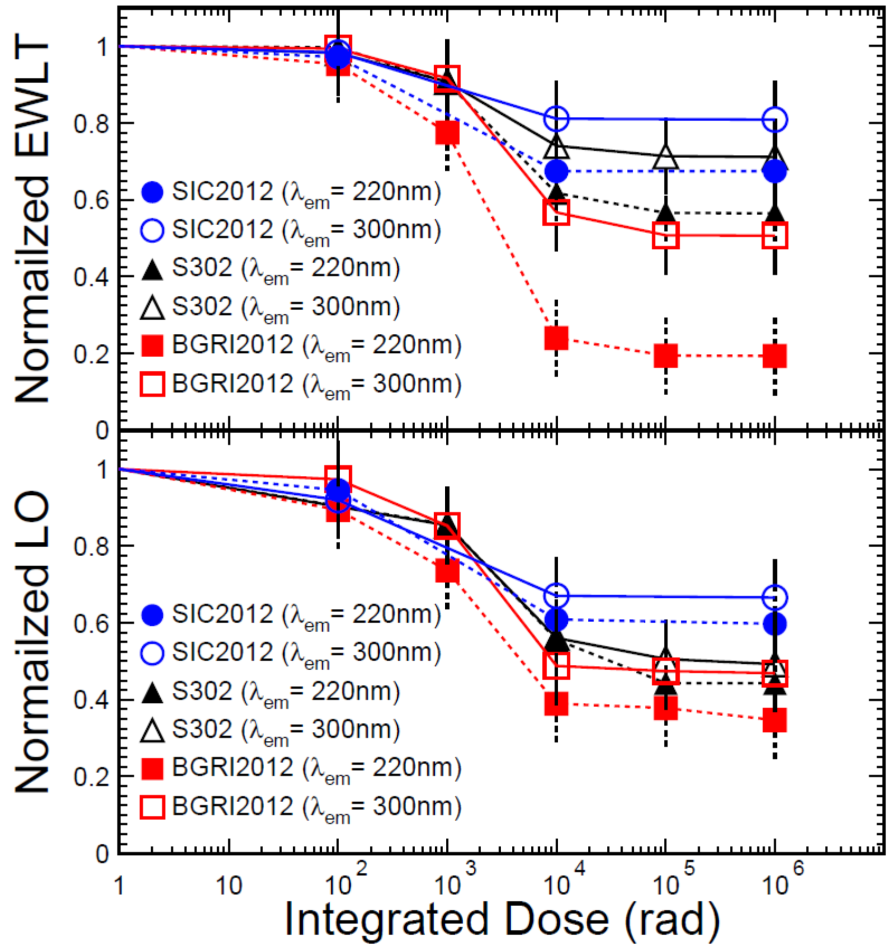
Damage in both LT and LO saturated after a few tens of krad, Indicating limited defect density in the crystal

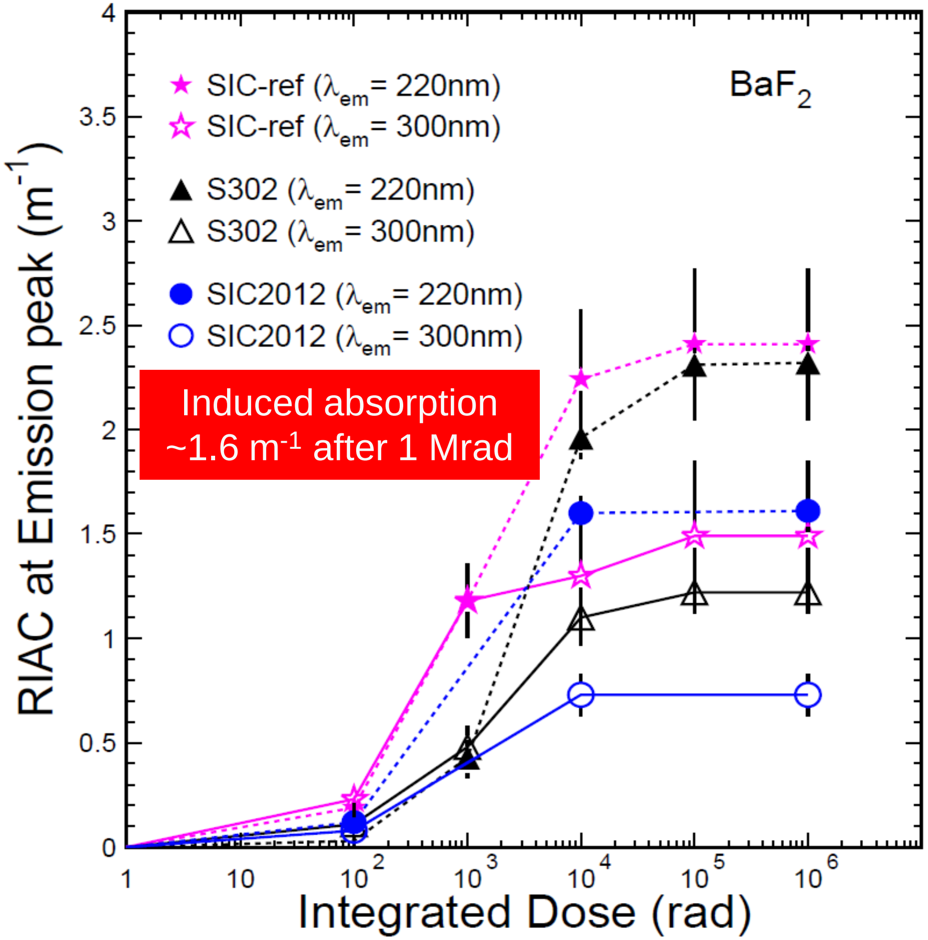




Damage in EWLT/LO and RIAC

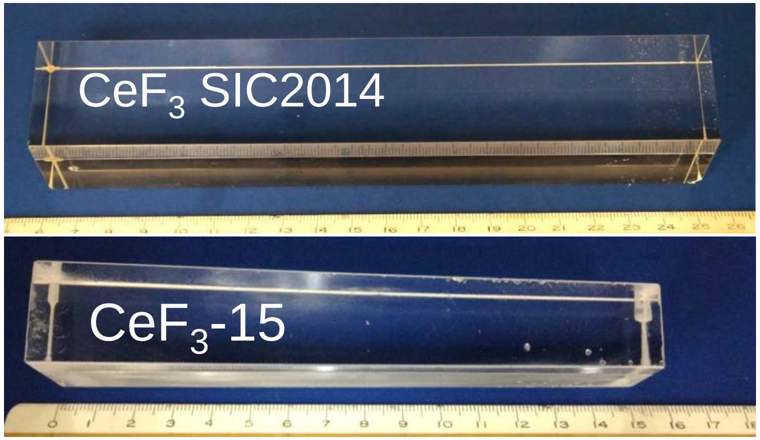
Damage in both EWLT and LO saturates after a few tens of krad at a level of less than 40% for the fast component.
Slow component is more radiation hard than the fast component





RIAC of fast component may be controlled to 1.6 m^{-1}

Radiation Damage in Long CeF_3 Crystals



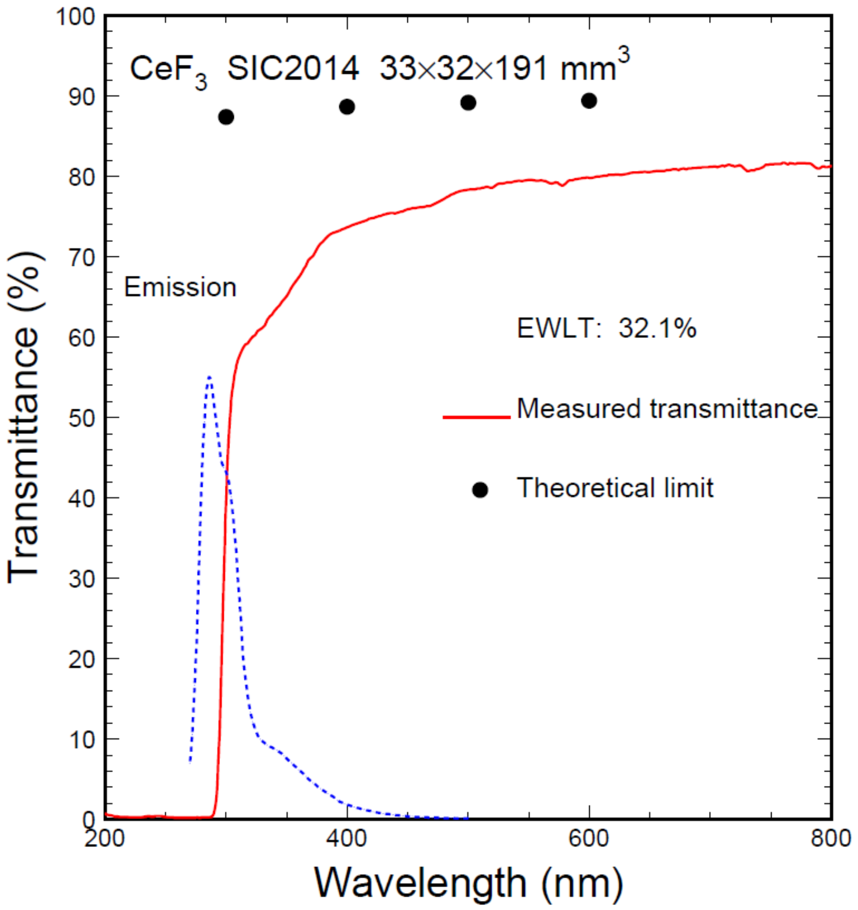
Vendor	ID	Dimension (mm^3)	Received Data	Polish
SIC	SIC2014	33 × 32 × 191	2/10/2014	All faces
Optovac	CeF_3-15	$22^2 \times 26^2 \times 150$	In nineties	All faces

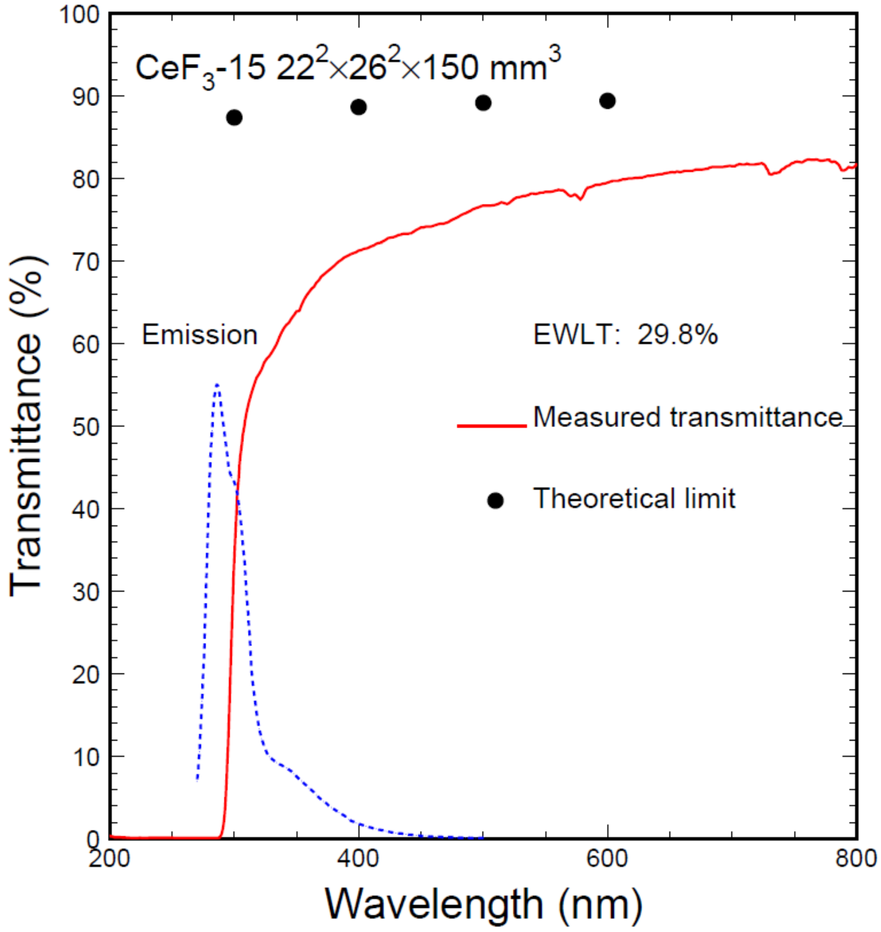
Experiments

- Two CeF_3 samples from different vendors were investigated
- Damage recovers at room temperature
- All samples went through ɣ-ray irradiation @ 2, 8, 30 and 7k rad/h step by step until equilibrium
- Properties measured: LT, EWLT, LO, decay time and LRU

Emission, LT and EWLT

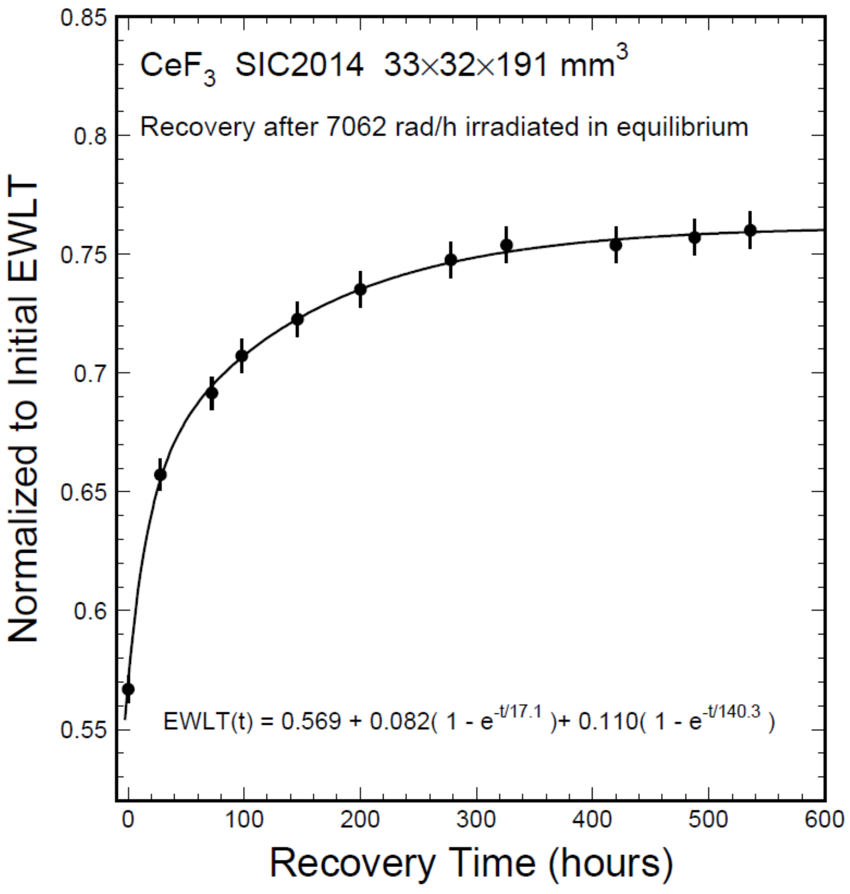
Emission spectra across absorption edge indicating strong self-absorption
Both samples have poor transmittance with absorption band & scattering centers

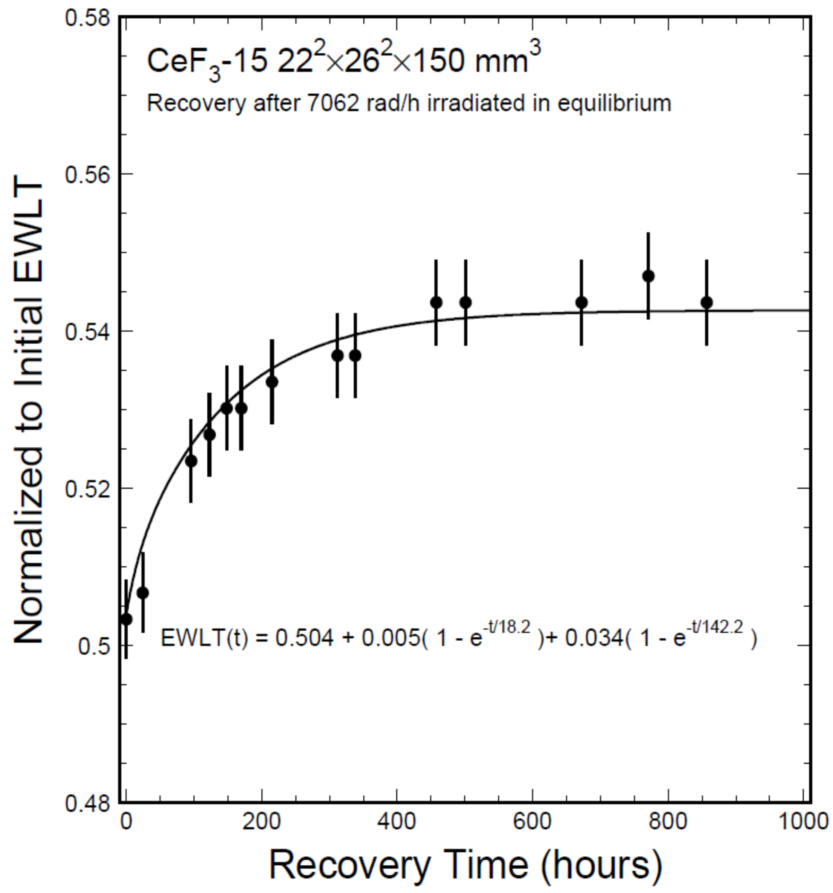




Damage Recovery Observed

Damage in CeF_3 recovers, so is dose rate dependent

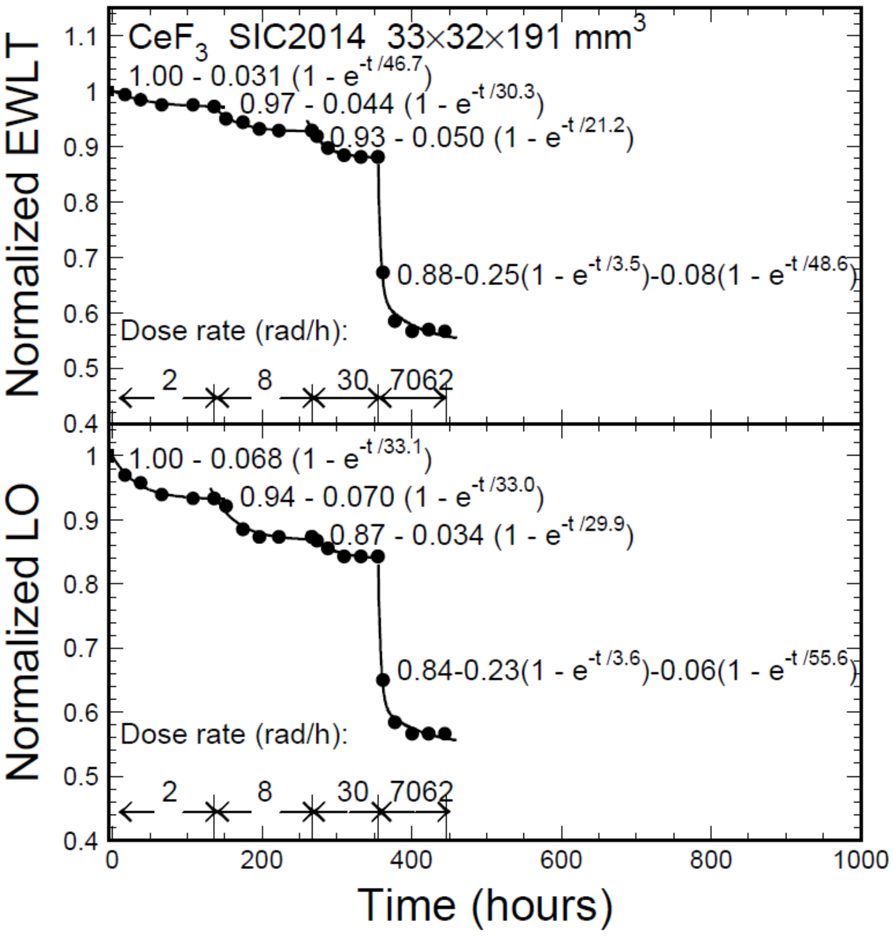


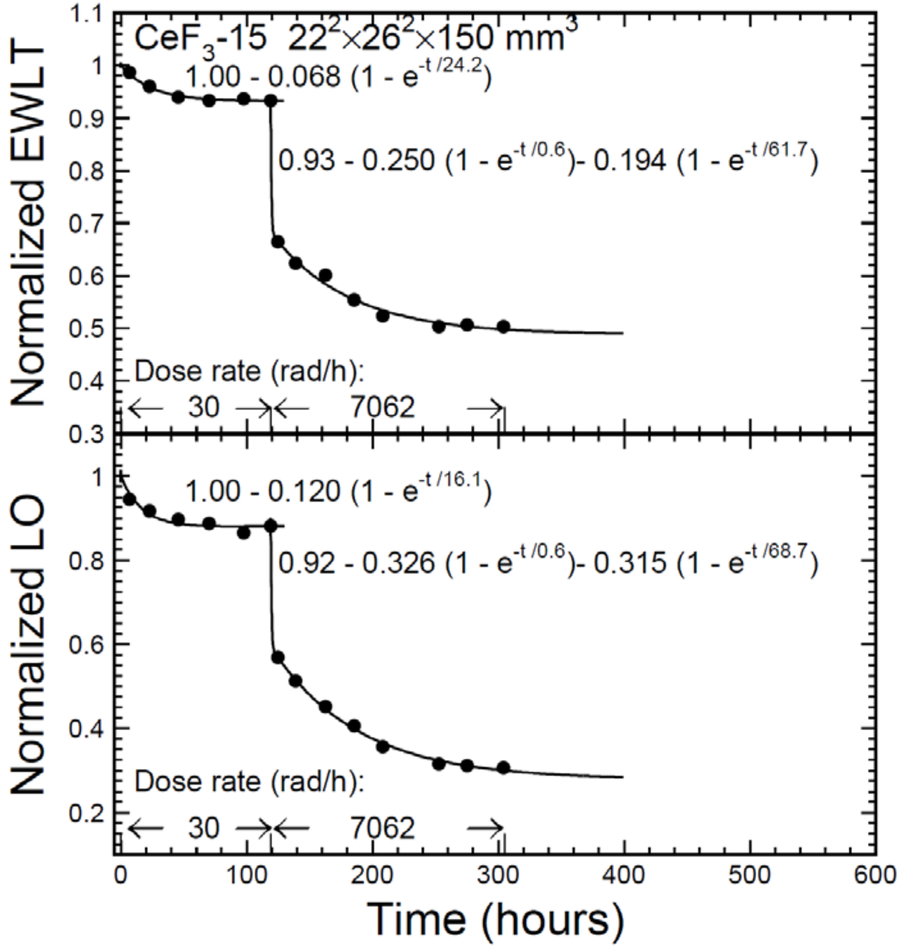


Consistent recovery time constants in two CeF_3 samples from different vendors

Normalized EWLT & LO

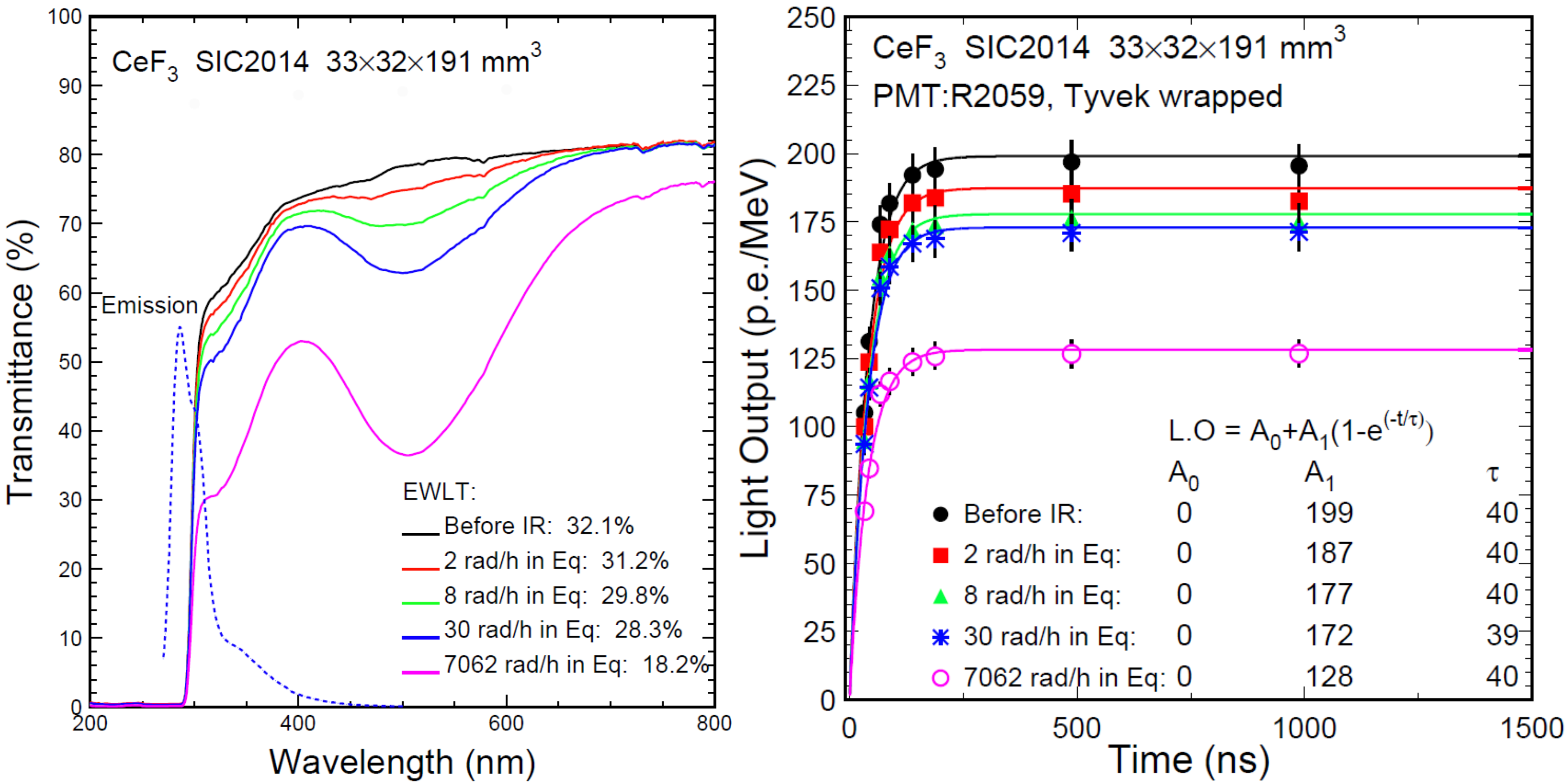
Dose rate dependent damage in both EWLT and LO observed





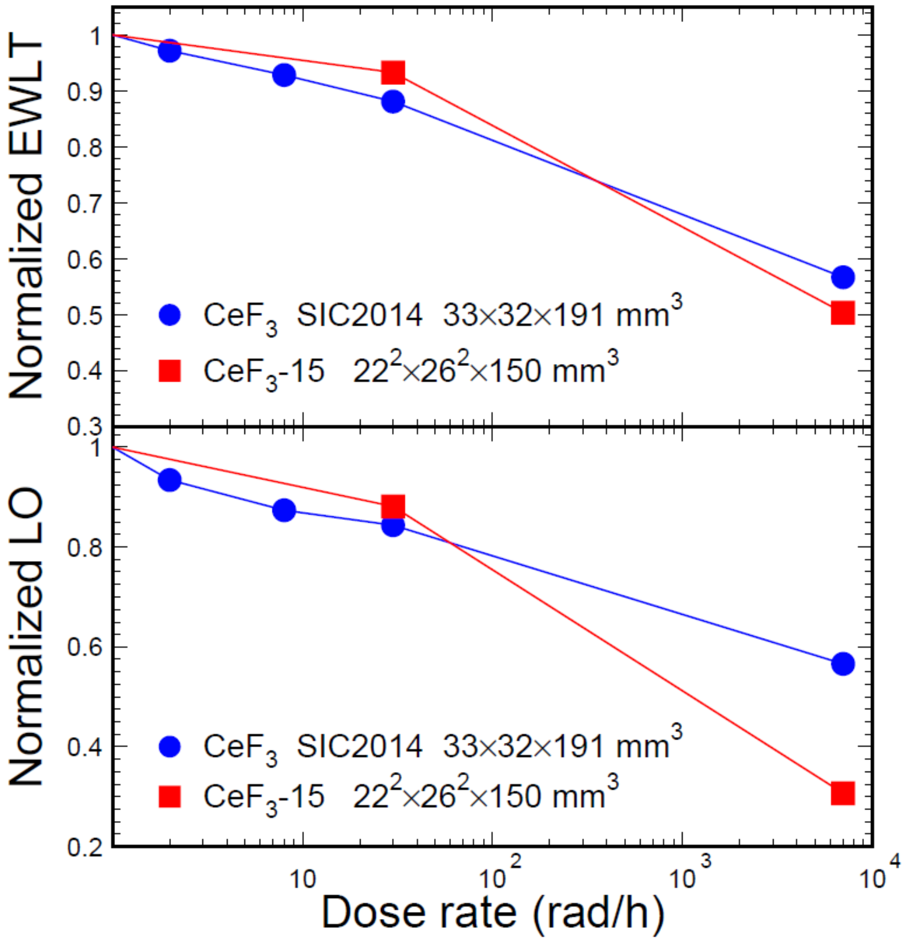
SIC2014: EWLT, LO and Decay Time

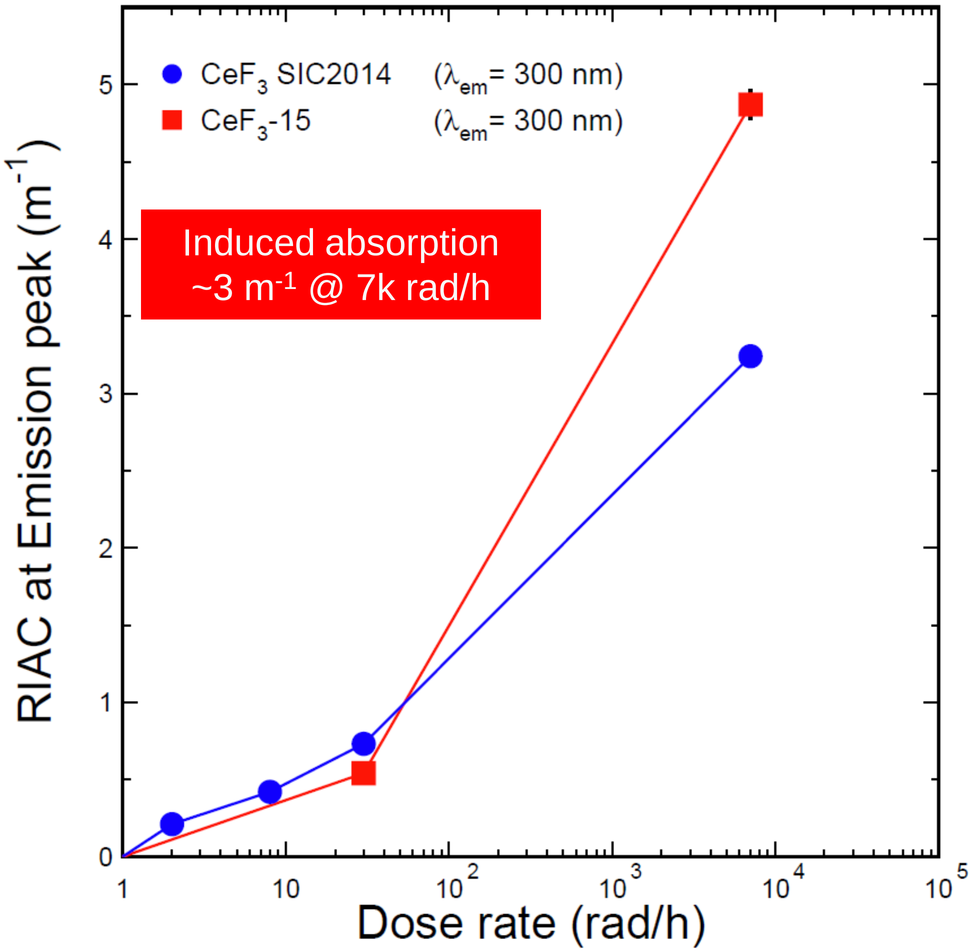
About 40% loss observed in both EWLT and light output at 7,062 rad/h



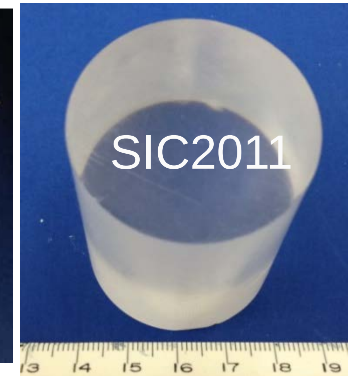
Damage in EWLT/LO and RIAC

RIAC of >3 m^{-1} observed at 7 krad/h worse than CMS PWO





Radiation Damage in Long CsI Crystals



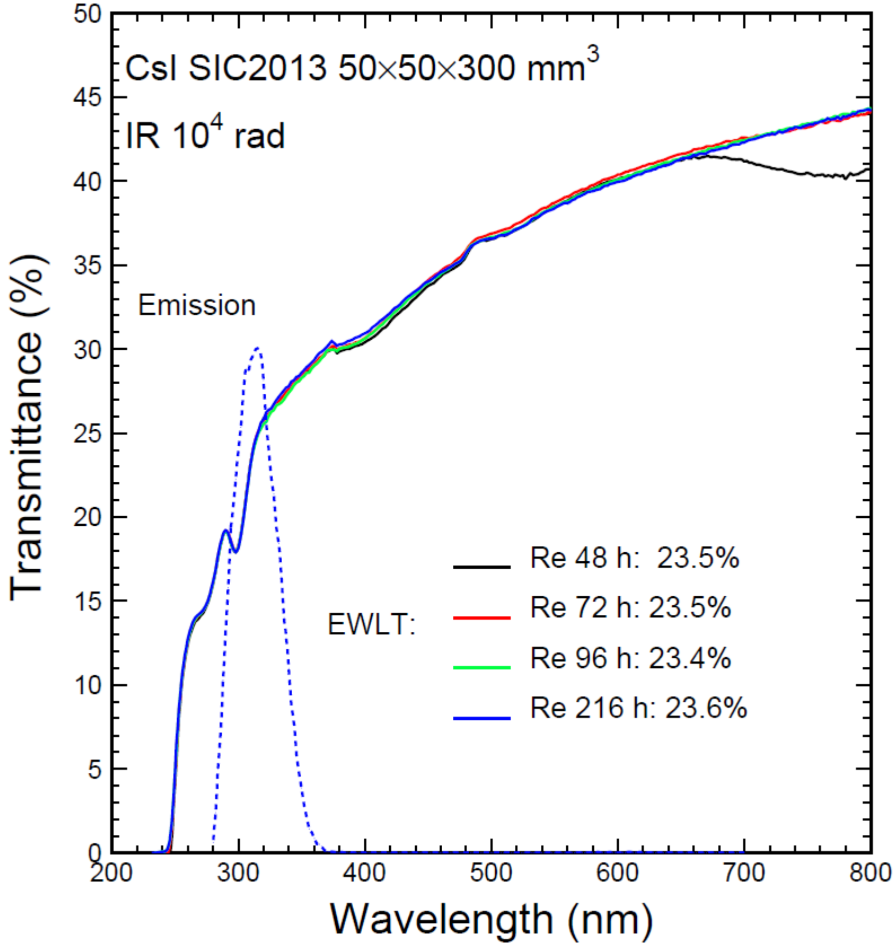
Sample ID	Received Date	Dimension (mm^3)	Polish
CsI SIC13	2/28/2013	50 × 50 × 300	Six faces
SIC2011	8/20/2011	Φ40 × 50	Two face (Φ40 faces)

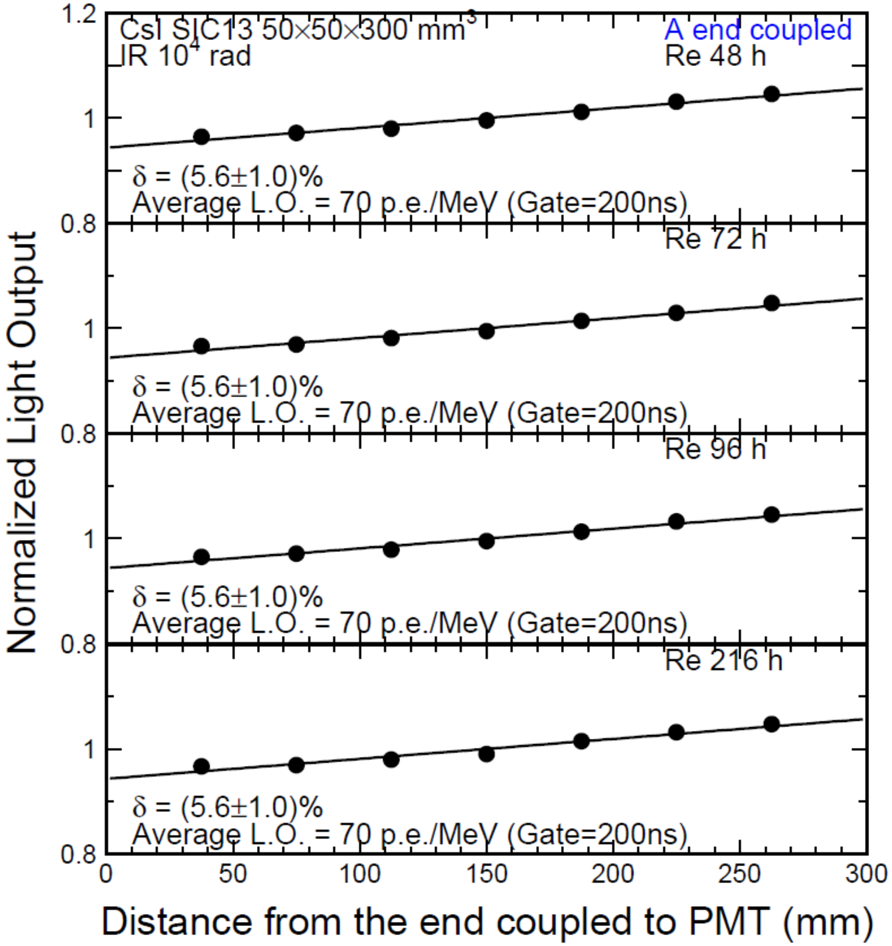
Experiments

- Two CsI samples from SIC are compared to samples from Kharkov
- Damage does not recover at room temperature
- All samples went through γ-ray irradiation @ 30 and 7k rad/h to reach 100, 1k,10k,100k and 1M rad
- Properties measured: LT, EWLT, LO, decay time and LRU

No Recovery of Radiation Damage

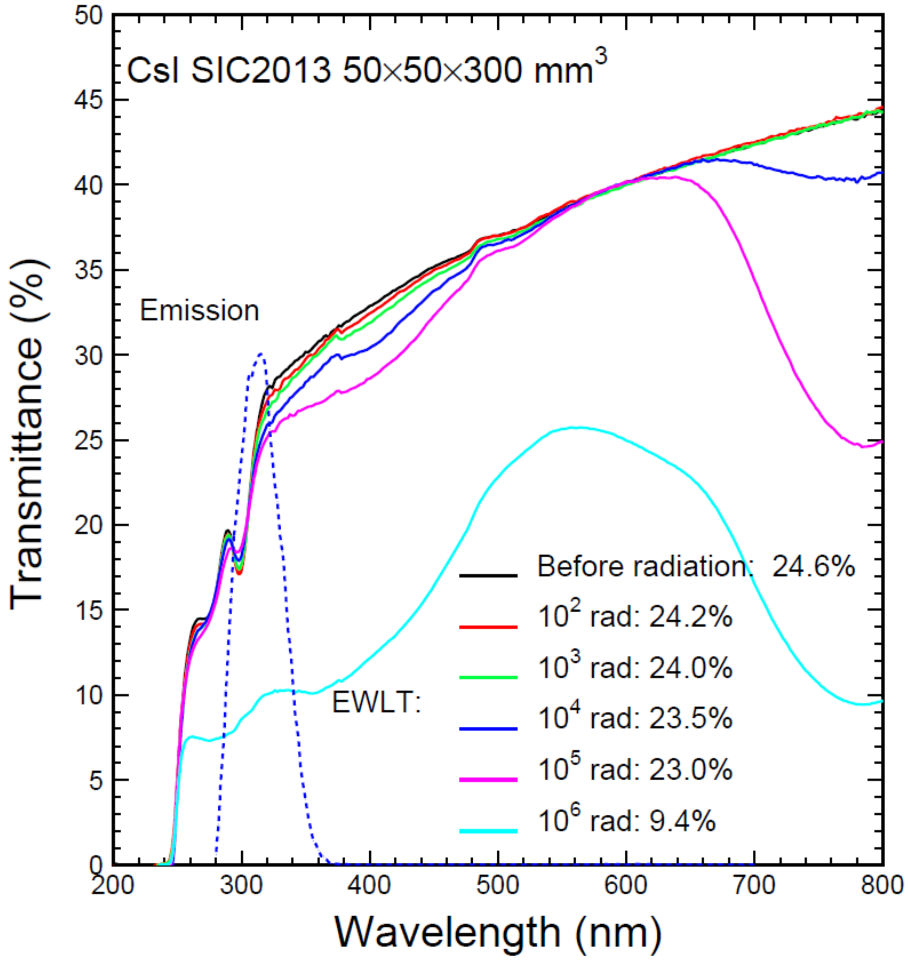
Damage does not recover, so is dose rate independent

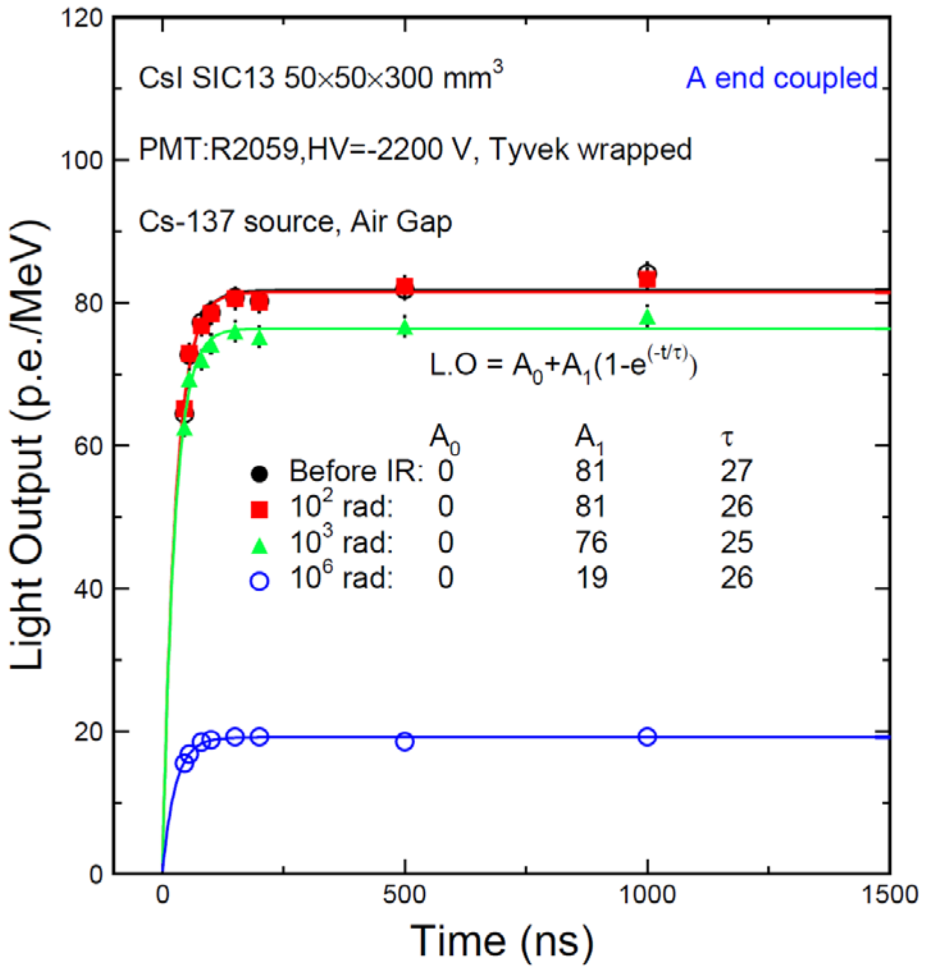




SIC2013: EWLT, LO and Decay Time

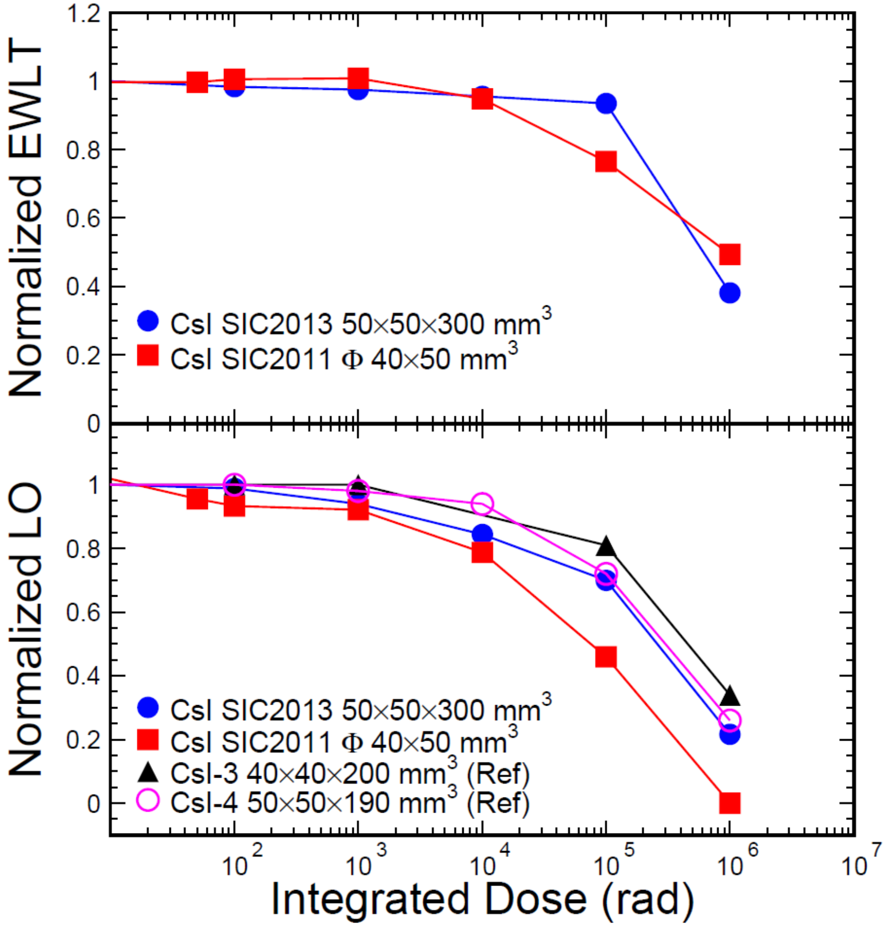
No saturation observed up to 1 Mrad, indicating high defect density in the crystal

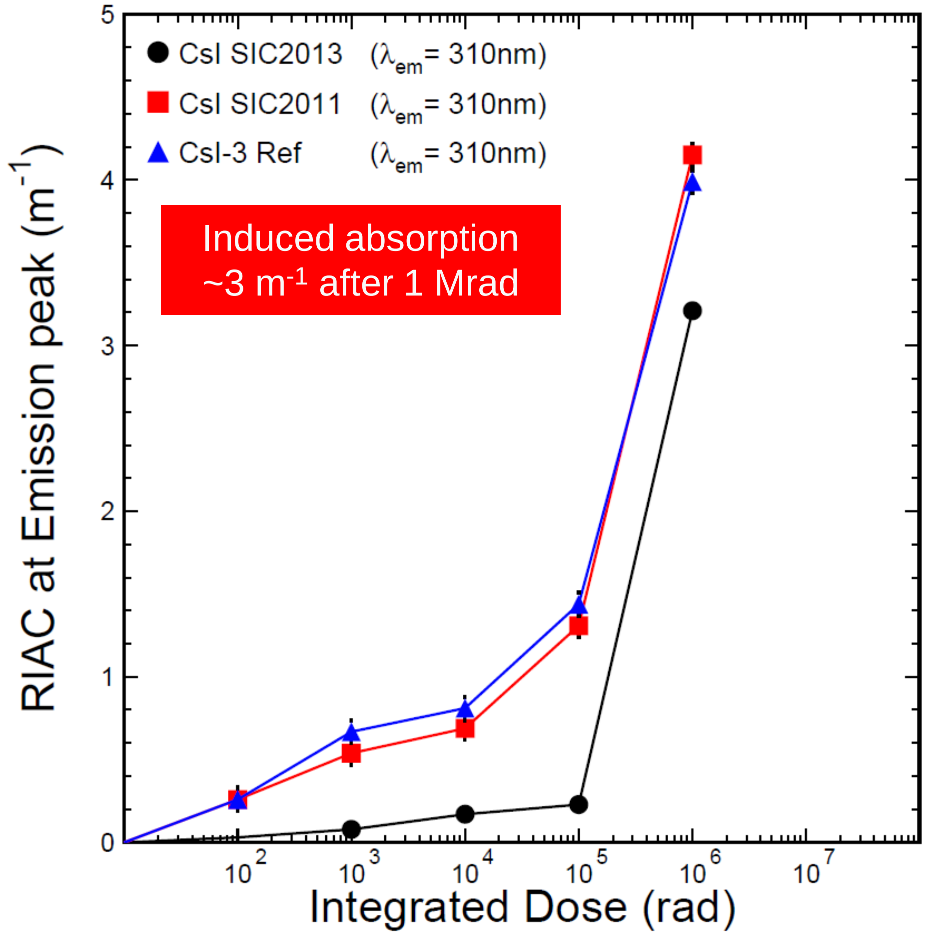




Damage in EWLT/LO and RIAC

RIAC larger than 3 m^{-1} observed after 1 Mrad
Consistent performance between CsI crystals from SIC and Kharkov





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

508-512

Radiation Damage in Long LSO/LYSO

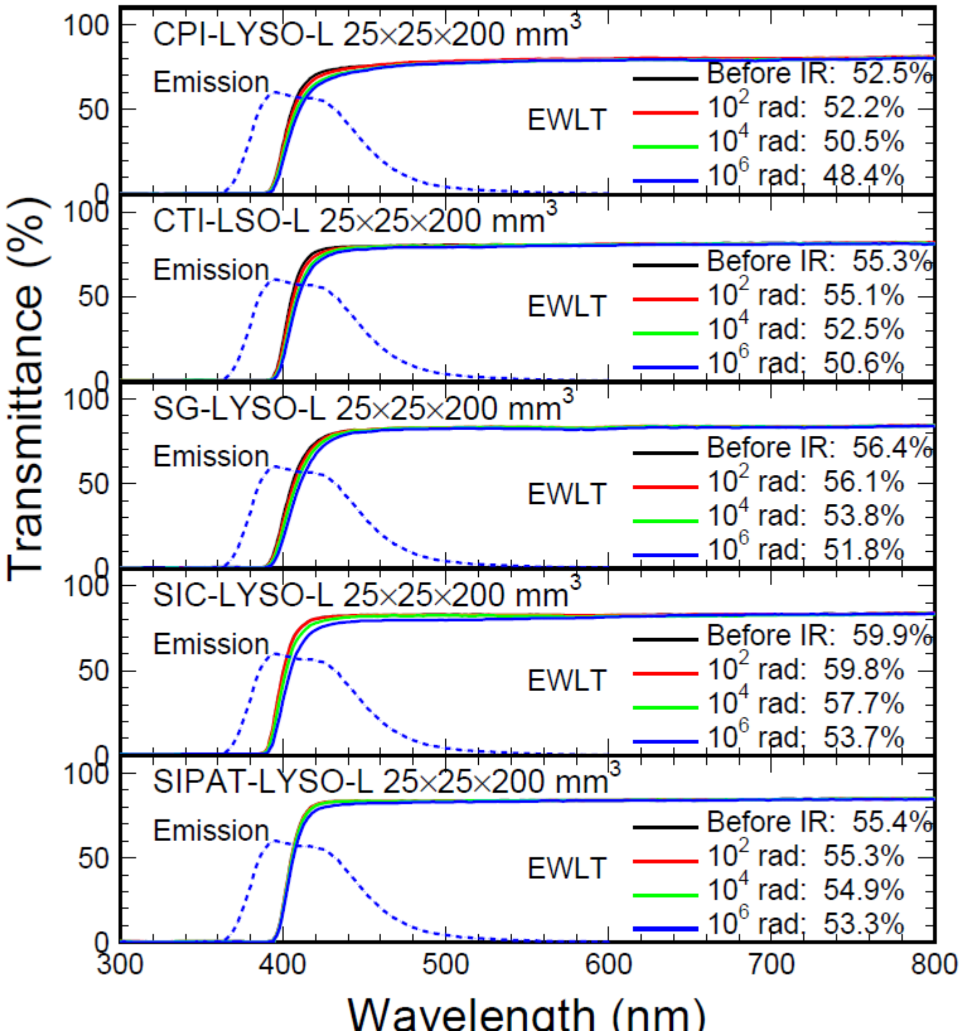
Sample ID	Dimension (mm^3)	Polish
CPI-LYSO-L	25 × 25 × 200	Six faces polished
CTI-LSO-L	25 × 25 × 200	Six faces polished
SG-LYSO-L	25 × 25 × 200	Six faces polished
SIC-LYSO-L	25 × 25 × 200	Six faces polished
SIPAT-LYSO-L	25 × 25 × 200	Six faces polished

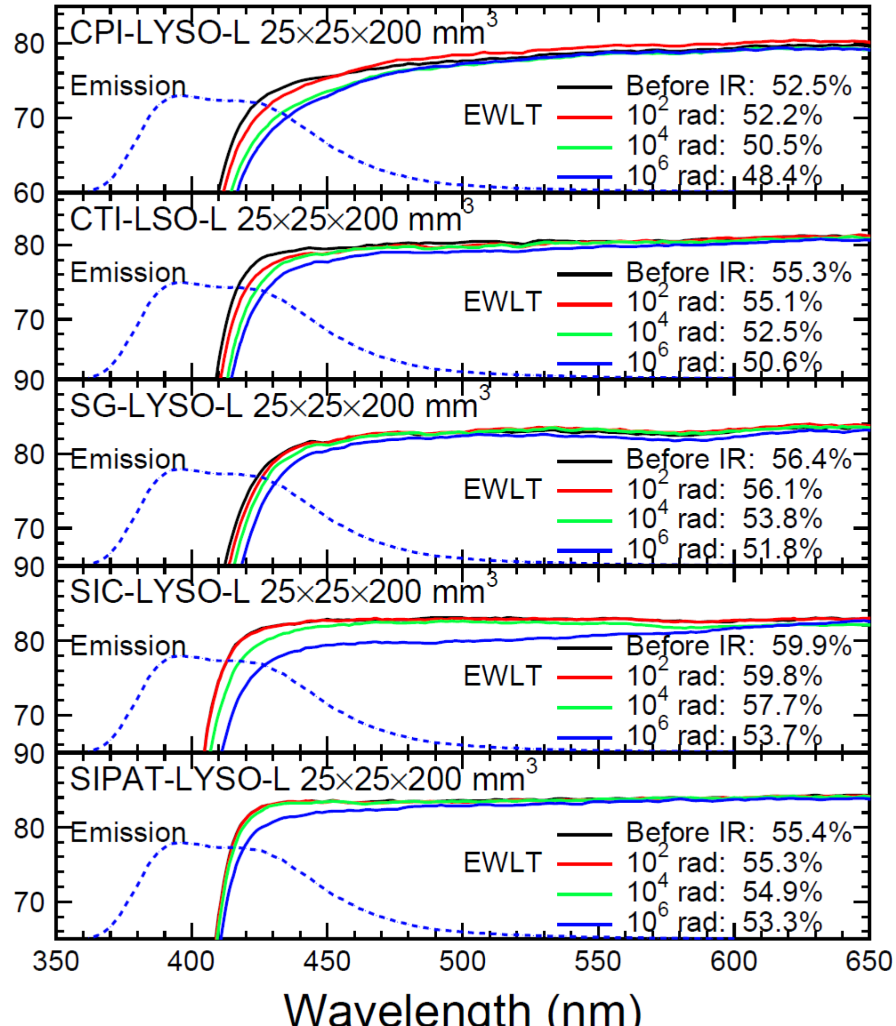
Experiments

- Five LSO/LYSO samples from five vendors were investigated
- Damage does not recover at room temperature
- All samples went through γ-ray irradiation @ 30 and 7k rad/h to reach 100, 1k,10k,100k and 1M rad
- Properties measured: LT, EWLT, LO, decay time and LRU

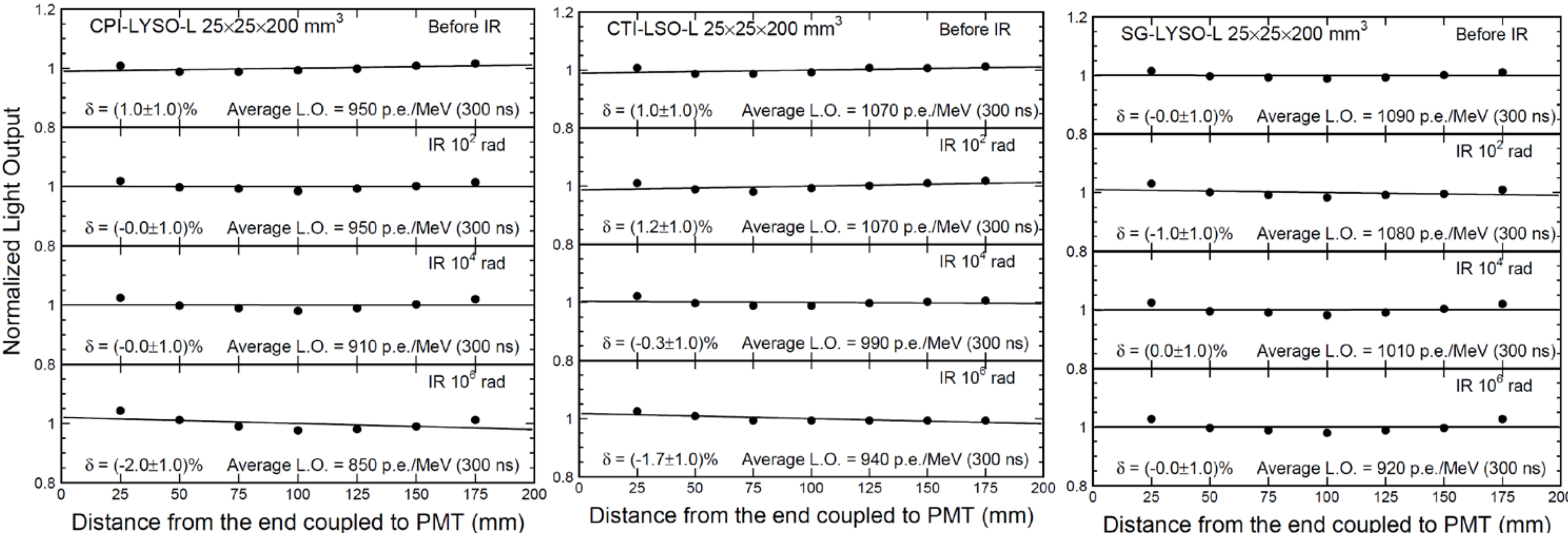
Excellent Radiation Hardness in LT

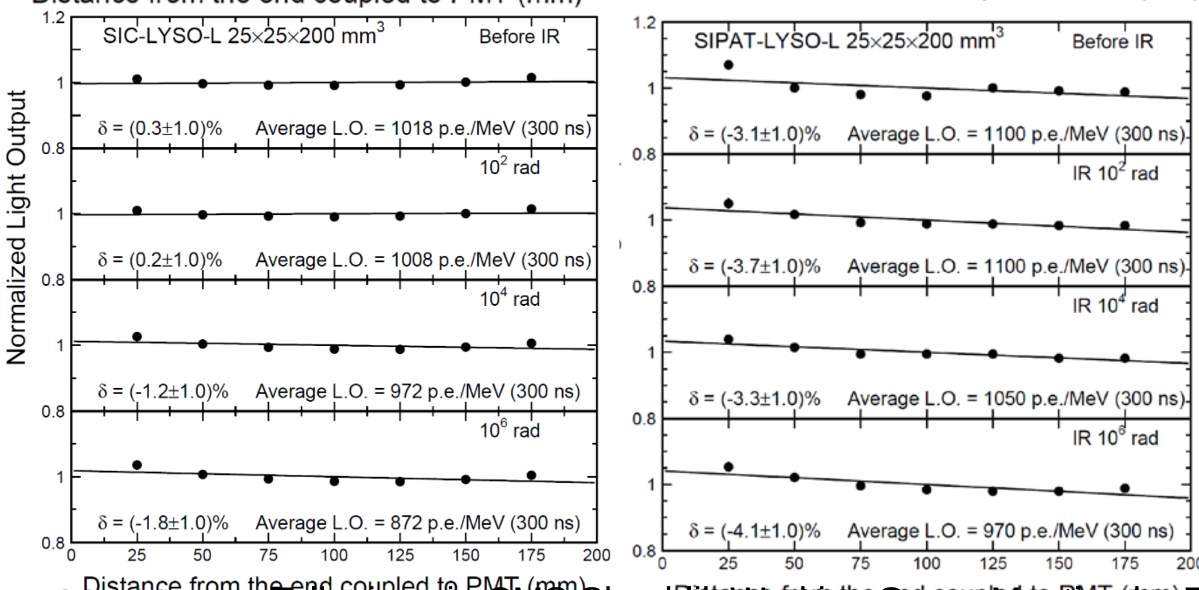
Consistent & Small Damage in LT → Larger variation @ shorter λ





Excellent Radiation Hardness in LO

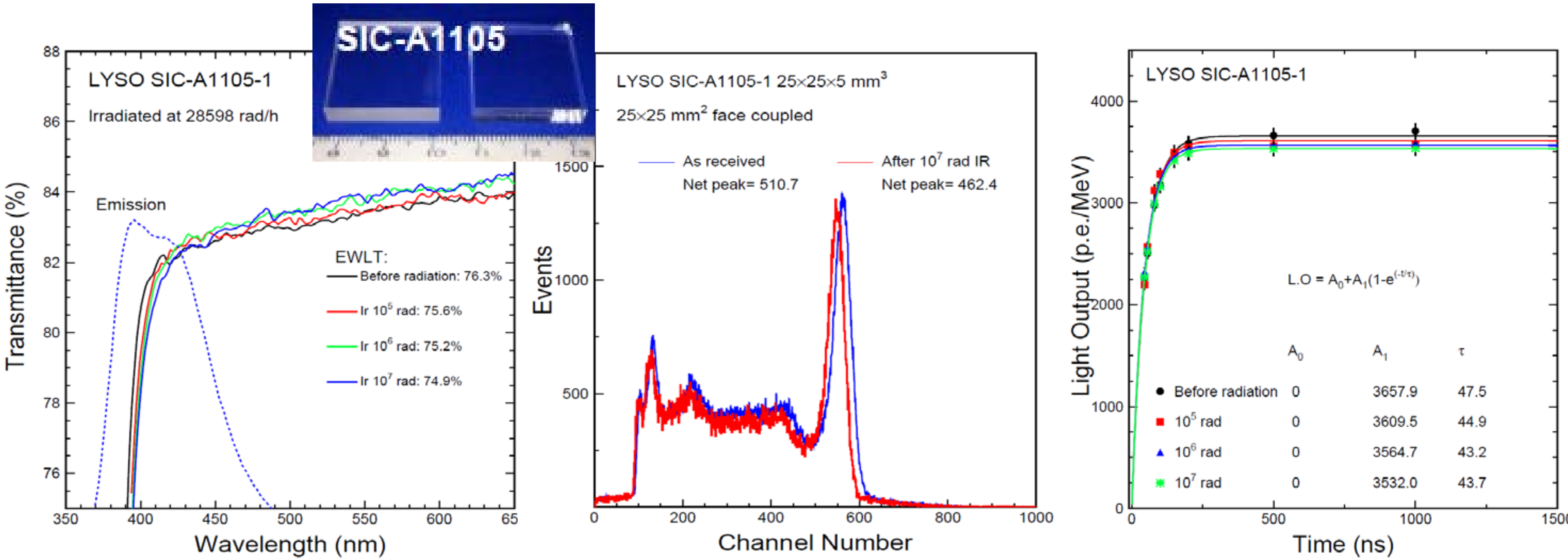




About 12% LO loss observed after 1 Mrad irradiation in all samples with LRU maintained. It can be corrected by light monitoring.

Damage in 2 x 2 x 0.5 cm Plates

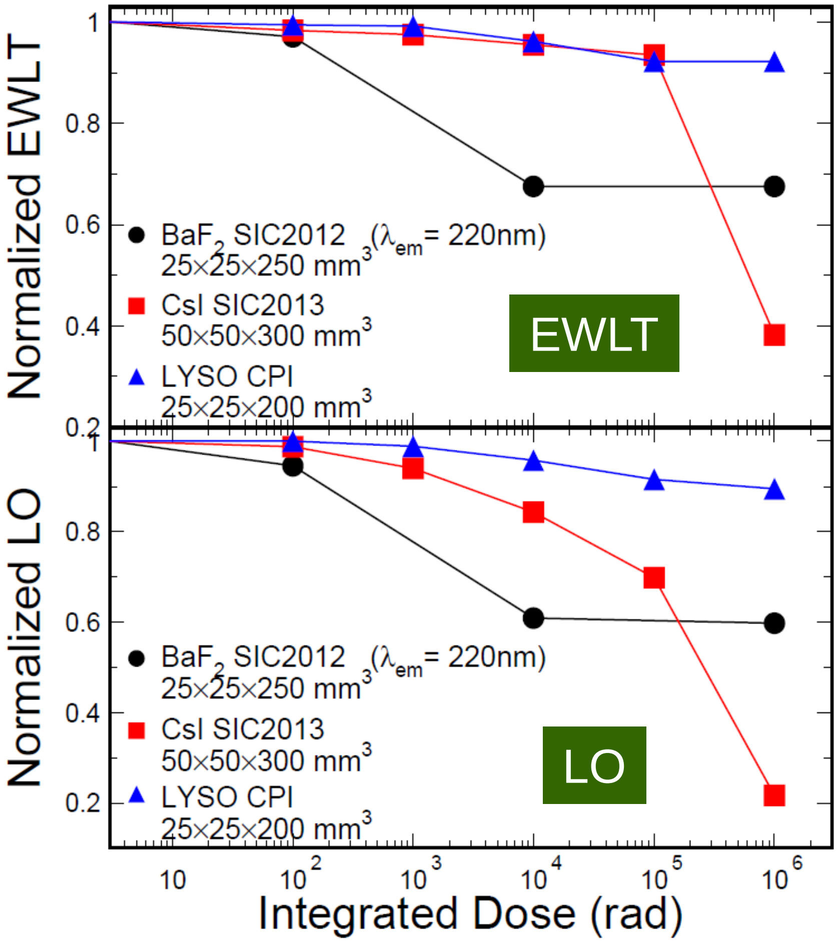
5 mm thick LYSO plates show degradation of a few percepts up to 10 Mrad

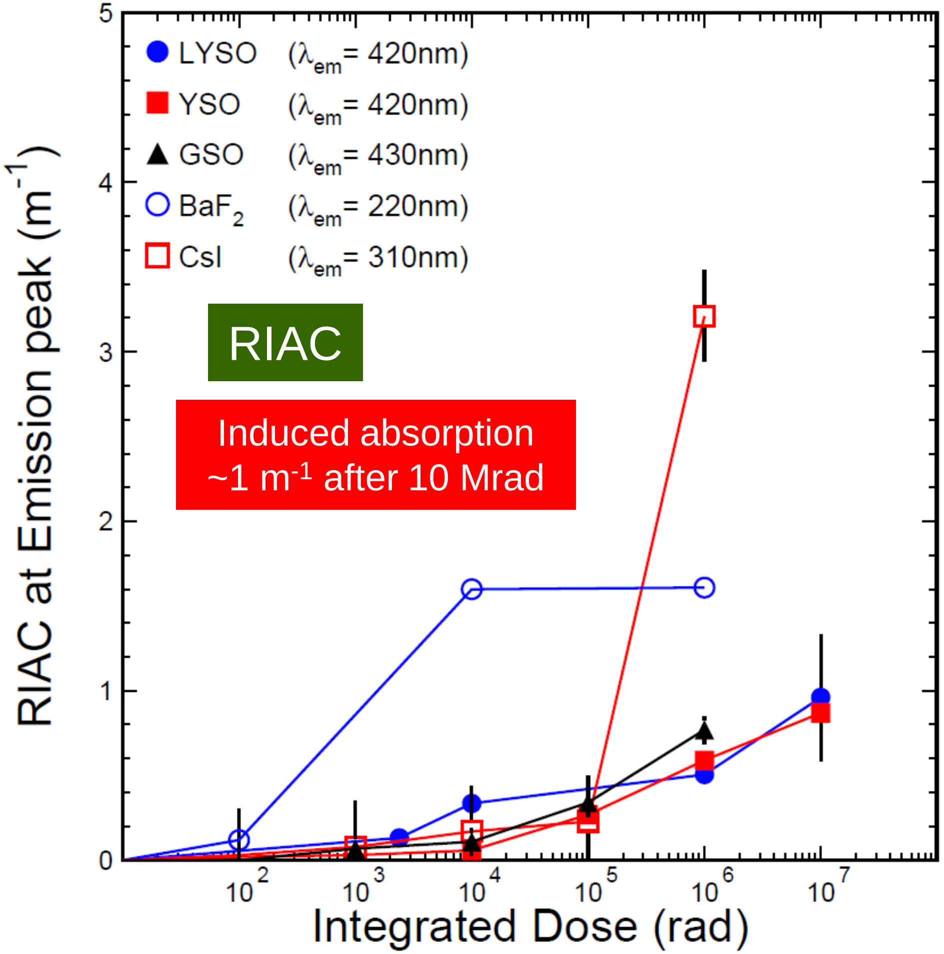


Samples	EWLT (%)	L.O. (p.e./MeV)	EWLT loss (%)			L.O. loss (%)		
			10^5 rad	10^6 rad	10^7 rad	10^5 rad	10^6 rad	10^7 rad
SIC-A1105-1	76.3	3657.9	0.9	1.4	1.8	1.3	2.5	3.4

Summary: Dose Rate Independent Crystals

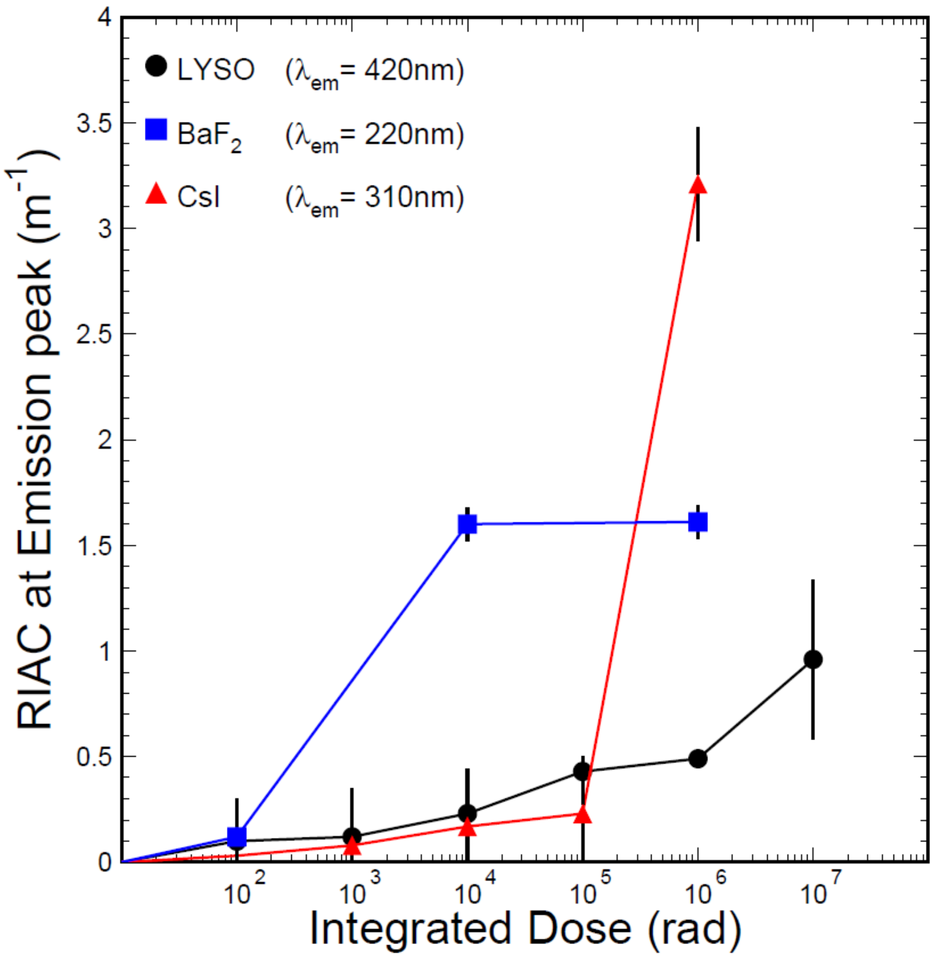
RIAC of LYSO is about 1 m^{-1} after 10 Mrad
BaF_2/CsI is good at high/low dose



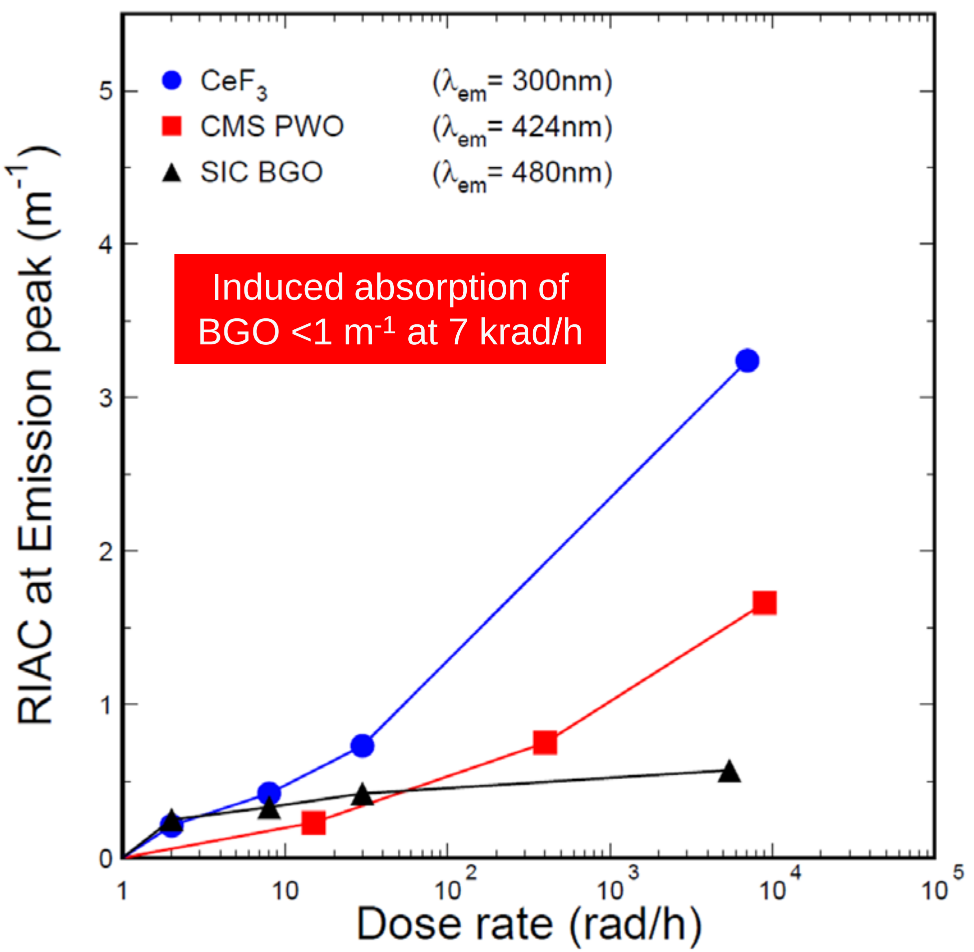


A Comparison of RIAC

Crystals with dose rate independent damage: LYSO is the best after 10 Mrad
Crystals with dose rate dependent damage: BGO is the best at 7 krad/h



Dose rate independent damage



Dose rate dependent damage

Summary

BaF_2, CeF_3 and pure CsI have fast light, but are significantly radiation softer than LSO/LYSO. RIAC of about 1 m^{-1} is observed for LYSO crystals after 10 Mrad.

Because of low defect density in crystals radiation damage in BaF_2 is saturated beyond 10 krad, promising a stable detector at high integrated dose. RIAC of the fast component may be controlled to less than 1.6 m^{-1}.

Damage in CeF_3 recovers at room temperature, so is dose rate dependent. The quality of the large size CeF_3 crystals tested is worse than PWO and much worse than BGO among crystals with dose rate dependent radiation damage. Significant R&D effort is needed for future HEP calorimeter applications.

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

Plan for Radiation Damage Study

To meet the milestones required for the CMS Phase 2 endcap calorimeter upgrade decision the following irradiation is planned in 2014.

- Test Shashlik LYSO plates of 1.4 x 1.4 x 0.15 mm by using various irradiation facilities for electrons, neutrons and protons in Brad's plan.
- Test LYSO and other fast crystals of large size by using ɣ-rays from the 26k curie Co-60 source at the JPL TID Facility up to 150 Mrad with dose rate up to 1 Mrad/h.
- Test LYSO and other fast crystals of large size by using 800 MeV proton beam at LANL up to 10^{15} p/cm^2 with flux of up to 10^{11}/cm^2/s.