Fast and Rad Hard Scintillating Ceramics as an Active Material for Shashlik Calorimeter

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Fast and Rad Hard LYSO Crystal

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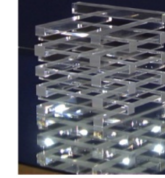
	LSO/LYSO	GSO	YSO [1]	CsI	BaF_2	CeF_3	$CeBr_3$ [2]	$LaCl_3$	$LaBr_3$	Plastic scintillator (BC 404) [3]
Density (g/cm^3)	7.40	6.71	4.44	4.51	4.89	6.16	5.23	3.86	5.29	1.03
Melting point (°C)	2050	1950	1980	621	1280	1460	722	858	783	70#
Radiation Length (cm)	1.14	1.38	3.11	1.86	2.03	1.70	1.96	2.81	1.88	42.54
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	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

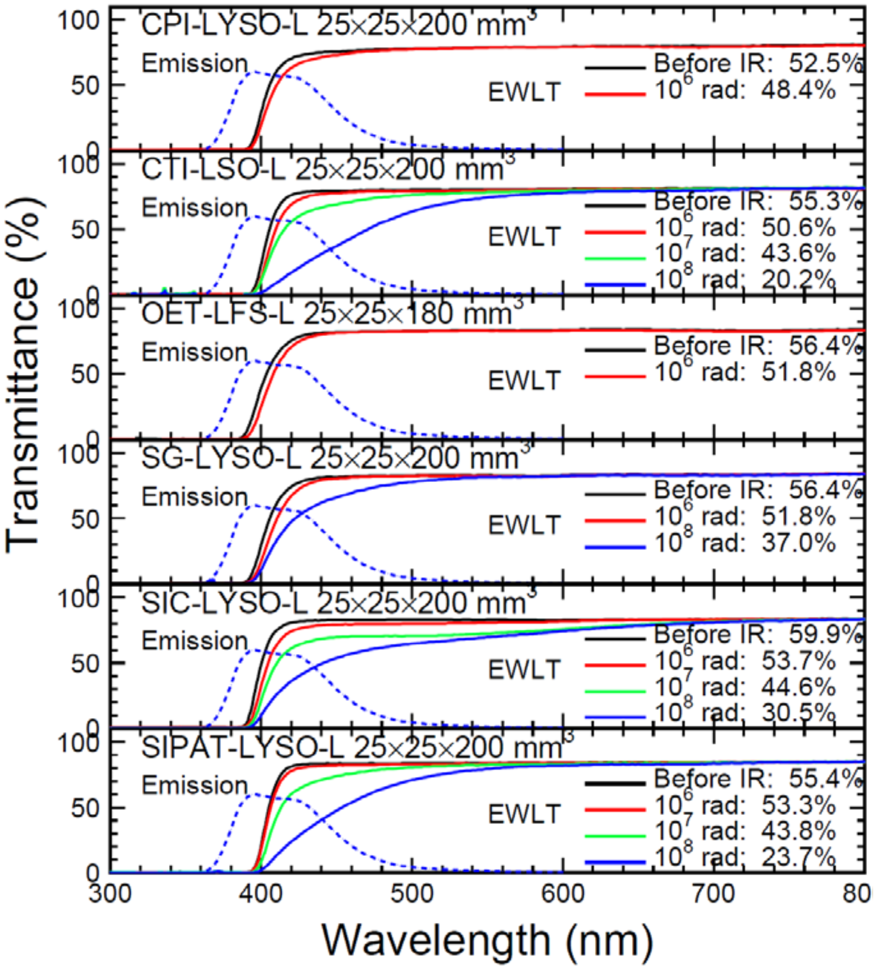
a. Top line: slow component, bottom line: fast component.
b. At the wavelength of the emission maximum.
c. Relative light yield normalized to the light yield of LSO
d. At room temperature (20°C)
#. Softening point

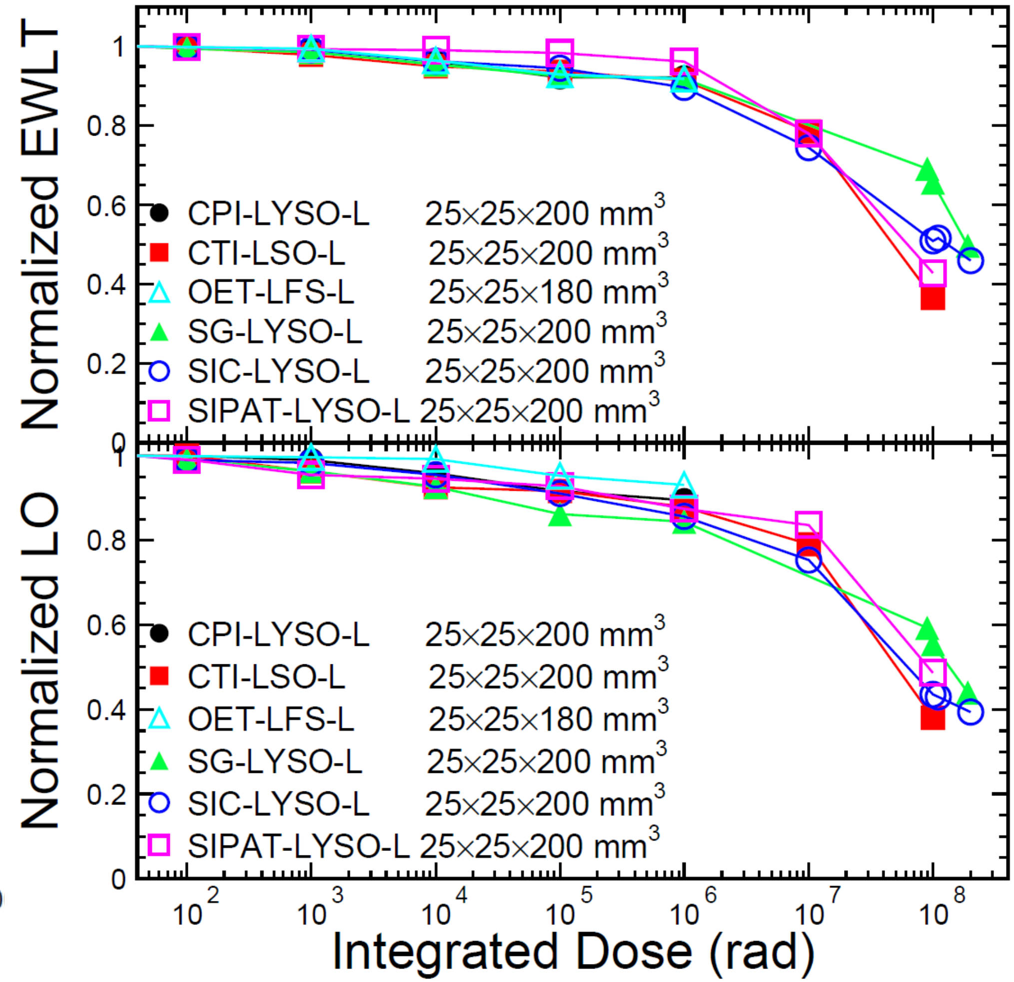
1. N. Tsuchida et al *Nucl. Instrum. Methods Phys. Res. A,* 385 (1997) 290-298
http://www.hitachi-chem.co.jp/english/products/cc/017.html
2. W. Drozdowski et al. ***IEEE TRANS. NUCL. SCI***, VOL.55, NO.3 (2008) 1391-1396
Chenliang Li et al, ***Solid State Commun***, Volume 144, Issues 5–6 (2007),220–224
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 Hardness of 20 cm LYSO

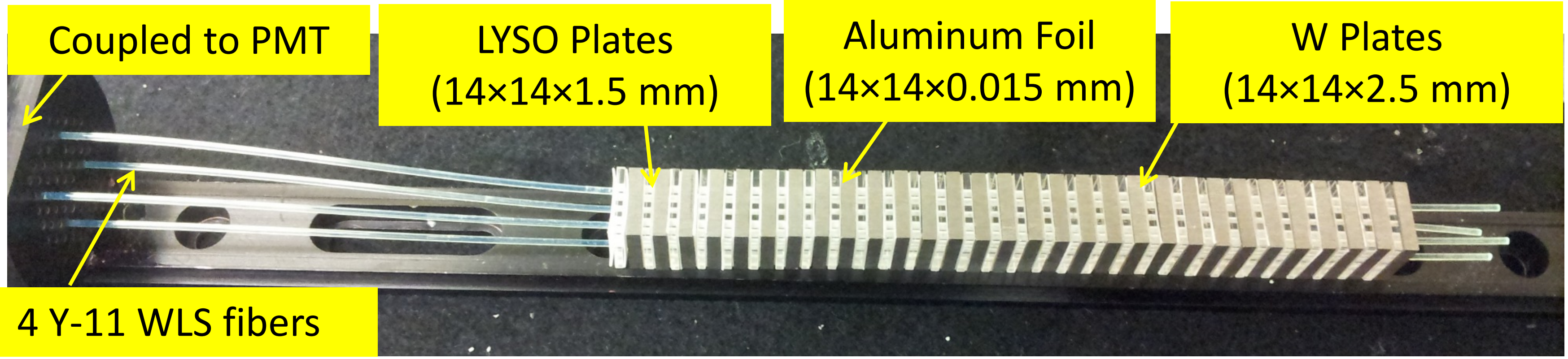


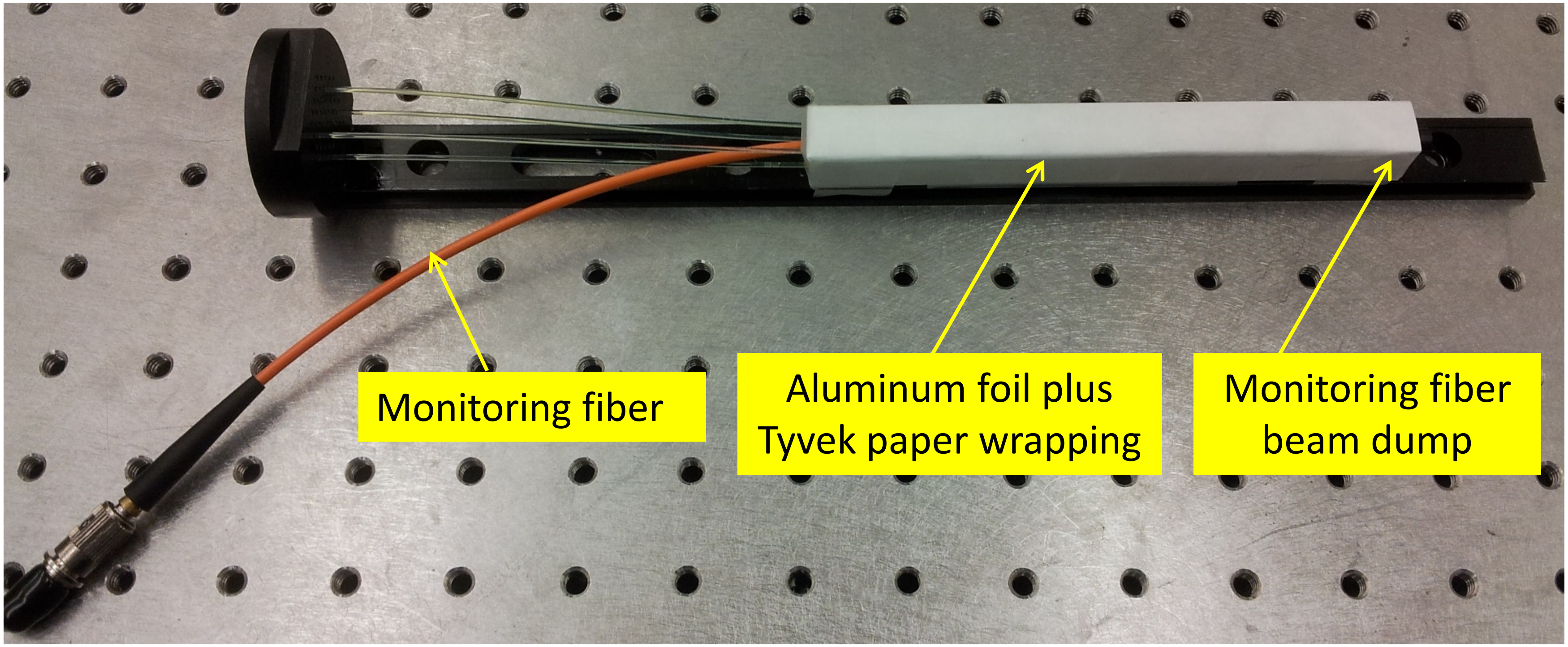
About 20% loss and <5% divergence for six vendors after 10 Mrad

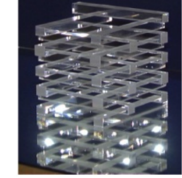




A Shashlik Cell Irradiated at JPL



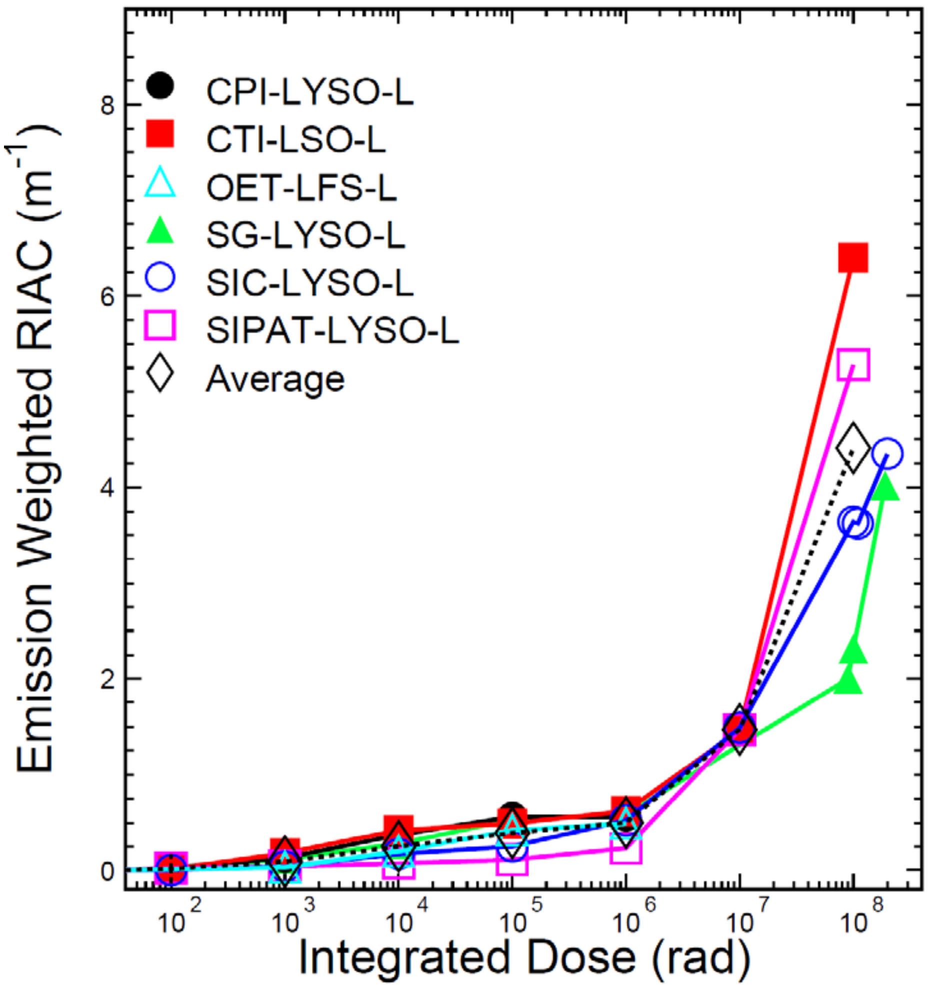


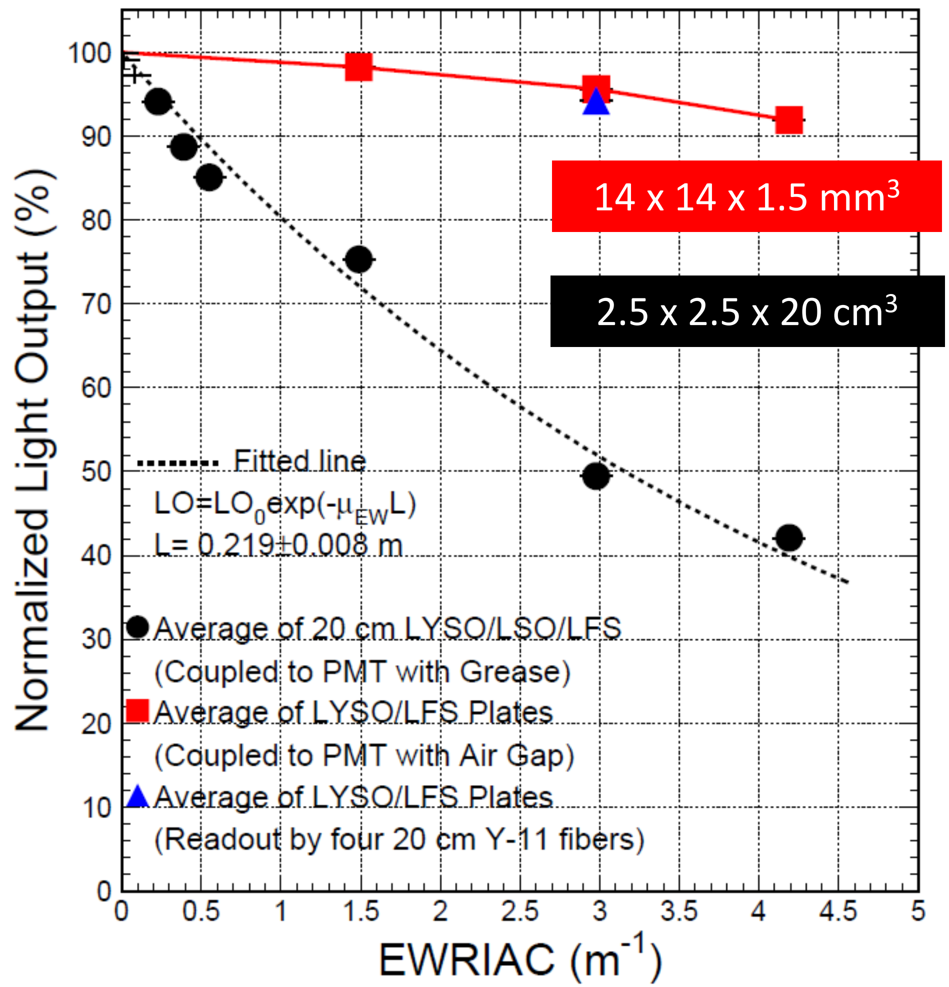


γ-ray Induced Damage in LYSO

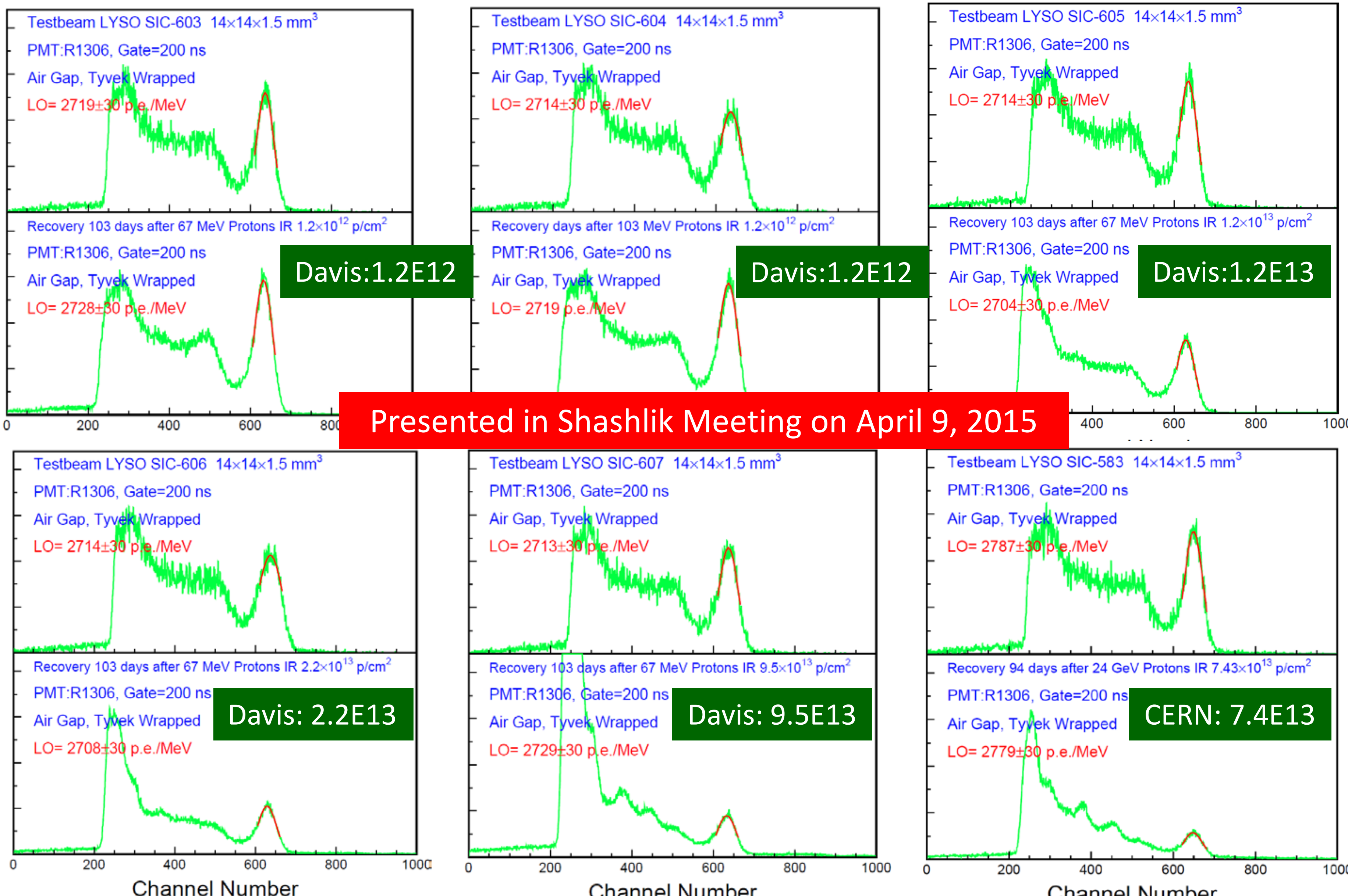
EWRIAC = 1.5, 3 and 4 m^{-1} after 10, 100 and 180 Mrad
LO loss after 100 Mrad is 4 and 6% respectively for direct and WLS readout

Presented in Shashlik Meeting on April 9, 2015

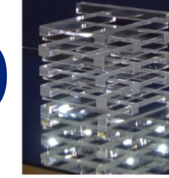




No LO Loss up to 10^{14} p/cm^2

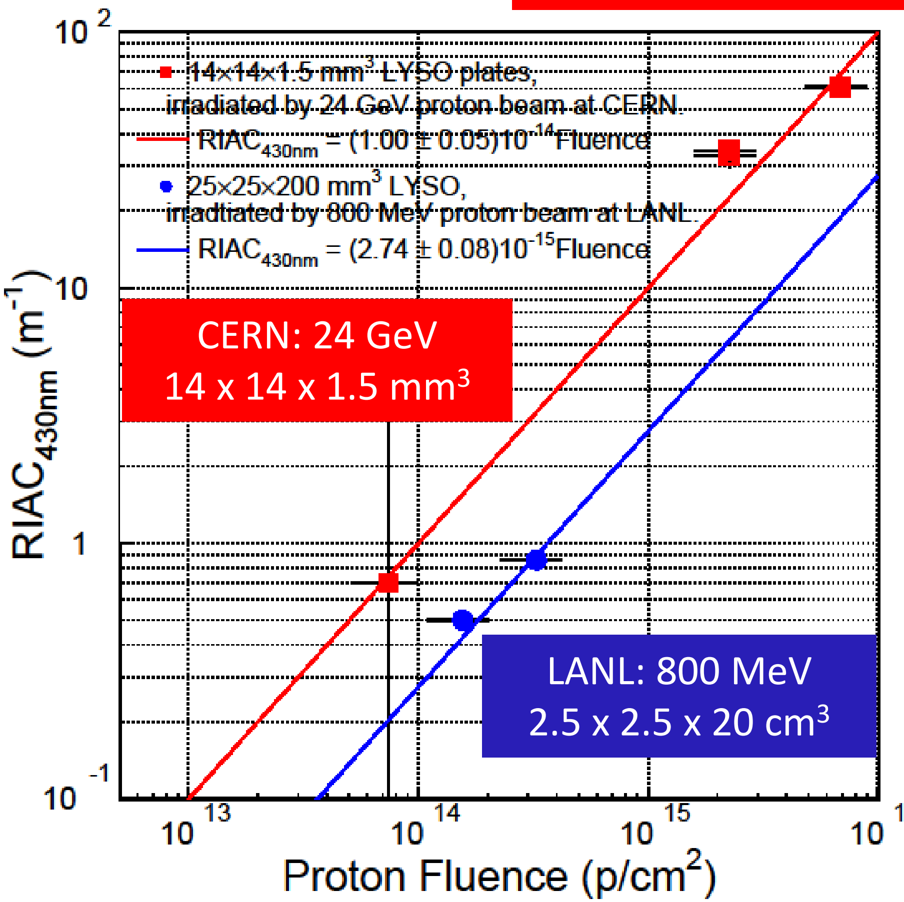


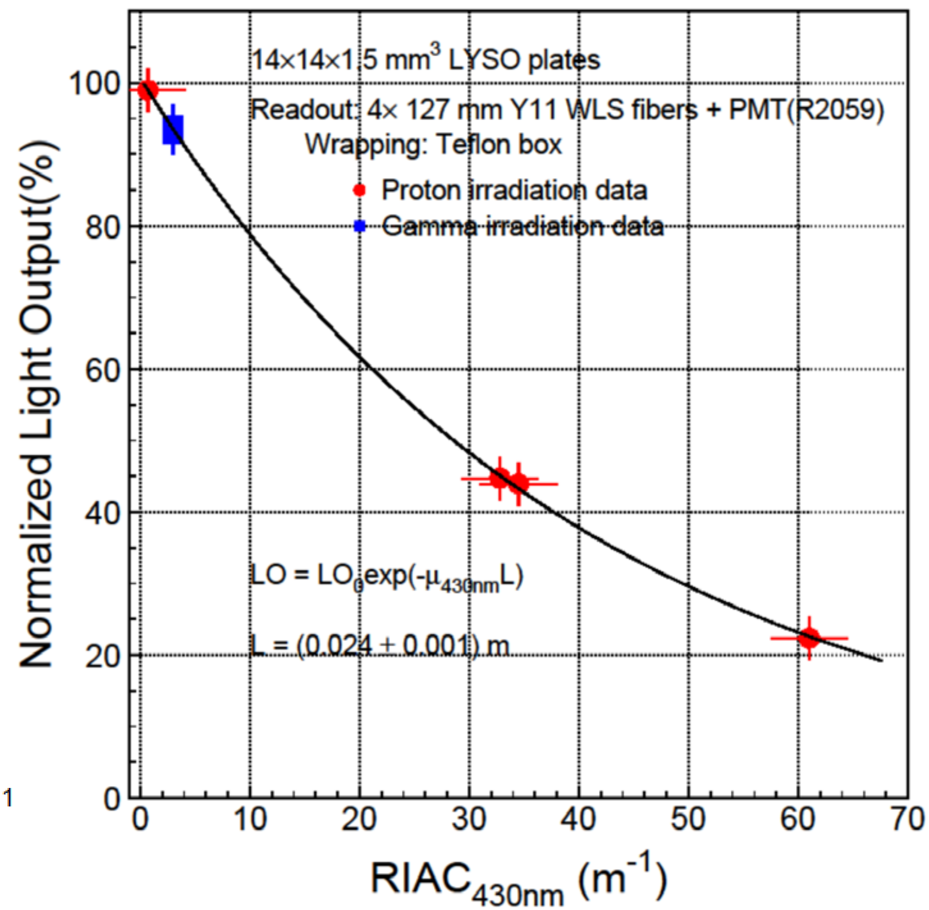
Proton Induced Damage in LYSO



A 20 cm and four 14×14×1.5 mm³ LYSO were irradiated by 800 MeV and 24 GeV protons at LANL and CERN respectively. The expected RIAC at the HL-LHC is about 3 m^{-1}, indicating a light output loss of 4 and 6% respectively for direct and WLS readout.

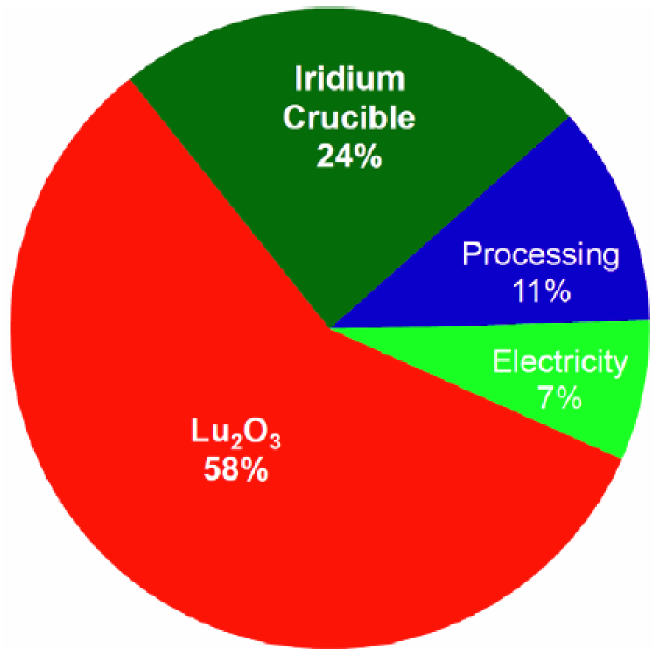
Presented in Shashlik Meeting on April 9, 2015





LYSO Crystal Cost: Lu_2O_3 Price

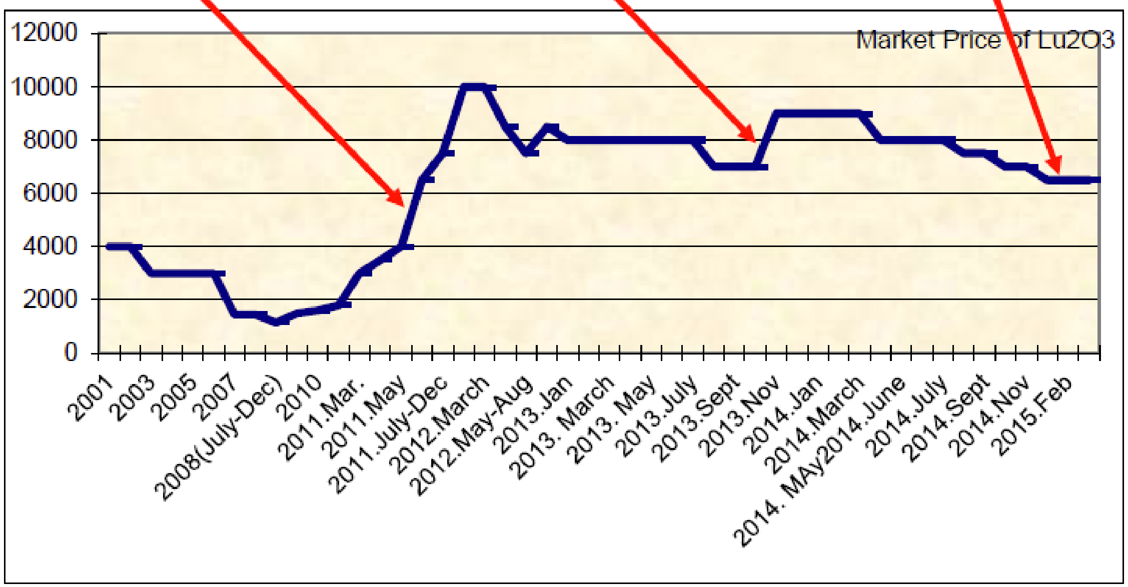
Crystal Cost Breakdown



Rare earth export control in China

Rare earth strategic reserve in China

Rare earth market going to normal



Assuming Lu_2O_3 at $400/kg and 33% yield the cost is about $18/cc. Quotations received at $22-25/cc.

Current Lu_2O_3 price indicates that LYSO price is going down from $42/cc last year

Cost of ceramics is low because of effective raw material usage and no processing waste

History of Optical Ceramics

1964—The 1st Ceramic Laser CaF_2:Dy
- Hatch et al., *Appl. Phys. Lett.* 5, 153 (1964)

1980's—The 1st Ceramic Scintillator $(Y,Gd)_2O_3$:Eu
- Greskovich C et al. *Am. Ceram. Soc. Bull.* 71, 1120 (1992)

1985—1st Ceramic YAG
- G. de With and H.J.A. van Dijk, *Meter. Sci. Bull.*, 19, 1669 (1985).

1988—The Gd_2O_2S:Pr,Ce Ceramic Scintillator
- Yukio Ito et al. *Japanese Journal of Applied Physics* . 27, 1371 (1988)

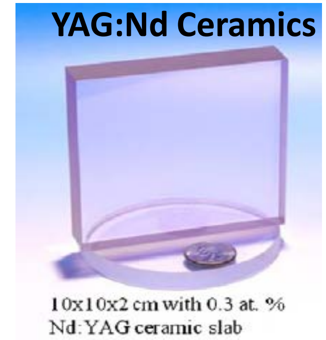
1997—Ce doped YAG scintillating ceramics
- E. Zych et al. *J. Lumin.*, 75, 193 (1997)

2002—Lu_2O_3:Eu scintillating ceramics
- A. Lempicki et al. *Nucl. Inst. Meth. A*488, 579 (2002)

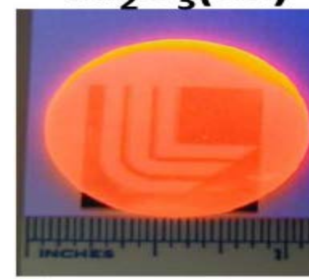
2007—LuAG:Ce scintillating ceramics
- N. J. Cherepy et al. *Nucl. Inst. Meth. A.*, 579, 38 (2007).

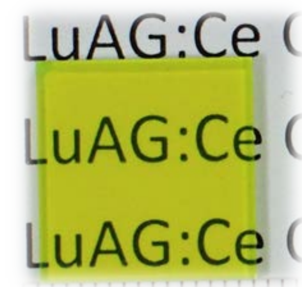
2009—LuAG:Pr scintillating ceramics
- T. Yanagida et al. *IEEE Trans. Nucl. Sci.*, 56 , 2955 (2009).

2010—GYGAG:Ce scintillating ceramics
- N. J. Cherepy et al. *Proc. SPIE*, 7805, 7805(2010).



Lu_2O_3(Eu)





GYGAG(Ce)

Properties of Scintillation Ceramics

Ceramics	$Y_{1.4}Gd_{0.6}O_3$:Eu①	Gd_2O_2S:Pr,Ce,F①	YAG:Ce②	Lu_2O_3:Eu③,④	LuAG:Ce⑤	LuAG:Pr⑥	$Gd_{1.5}Y_{1.5}Ga_2Al_3O_{12}$:Ce⑦,⑧
Density (g/cm³)*	5.92	7.34	4.57	9.42	6.76	6.76	5.80
Radiation Length (cm)*	1.73	1.16	3.53	0.81	1.45	1.45	2.11
Molière Radius (cm)*	2.44	2.13	2.76	1.72	2.15	2.15	2.43
Interaction Length (cm)*	24.5	22.3	25.2	18.1	20.6	20.6	22.4
Z value*	49.2	60.1	30.0	68.0	60.3	60.3	45.4
dE/dX (MeV/cm)*	8.02	9.30	7.01	11.6	9.22	9.22	8.32
Emission Peak (nm)	610	510	526	611	520	310	560
Light Yield (photons/MeV)	38000	43000	20000	90000	16000	22000	50000
Decay time (ns)	1000	3000	80 263 >5000	1600	37	20 770	100

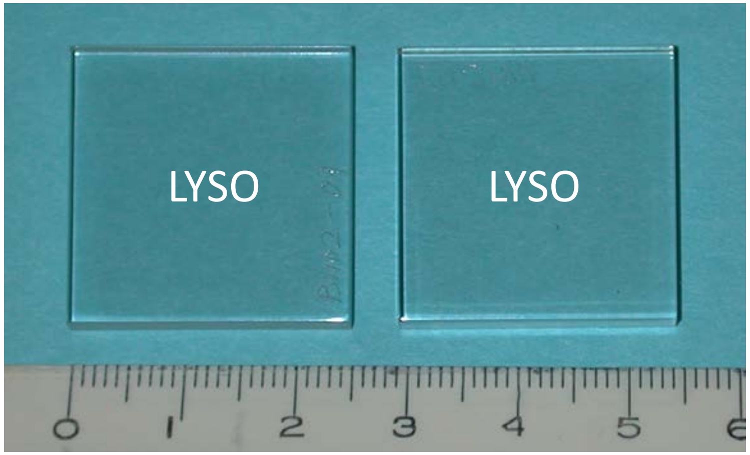
* Data based on crystals

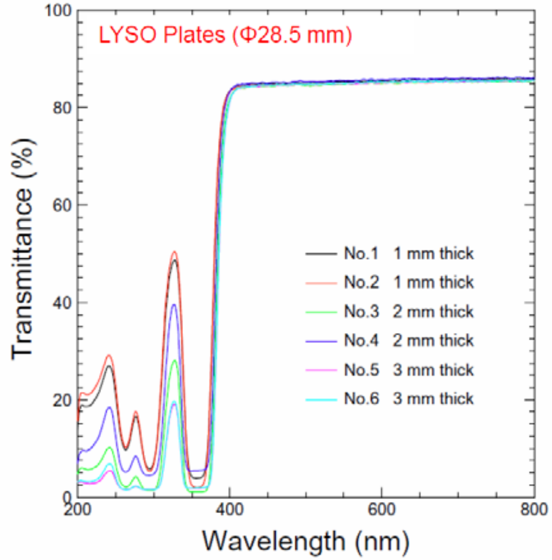
1. *C. Greskovich and S. Duclos,* **CERAMIC SCINTILLATORS**, *Annu. Rev. Mater. Sci. 27(1997)*
2. Takayuki Yanagida et al, **Evaluation of Properties of YAG (Ce) Ceramic Scintillators**, *IEEE TRANSACTIONS ON NUCLEAR SCIENCE*, 52(2005)
3. Y. Shi et al., **Processing and scintillation properties of Eu3+ doped Lu2O3 transparent ceramics**. *Opt Mater,* 31(2009)
4. Qiwei Chen et al. **Fabrication and Photoluminescence Characteristics of Eu-Doped Lu2O3 Transparent Ceramics**, *J. Am. Ceram. Soc*., 89(2006)
5. Takayuki Yanagida et al, **Scintillation properties of LuAG (Ce) ceramic and single crystalline scintillator,** *Nuclear Science Symposium Conference Record (NSS/MIC), 2010 IEEE*
6. Takayuki Yanagida et al, **Scintillation Properties of Transparent Ceramic Pr:LuAG for Different Pr Concentration**, *IEEE TRANSACTIONS ON NUCLEAR SCIENCE,* 59(2012)
7. N. J. Cherepy et al, **Development of Transparent Ceramic Ce-Doped Gadolinium Garnet Gamma Spectrometers**, *IEEE TRANSACTIONS ON NUCLEAR SCIENCE*, 60(2013)
8. N. J. Cherepy et al, **Transparent Ceramics Scintillators for Gamma Spectroscopy and MeV Imaging**, *Proc. SPIE* 9593

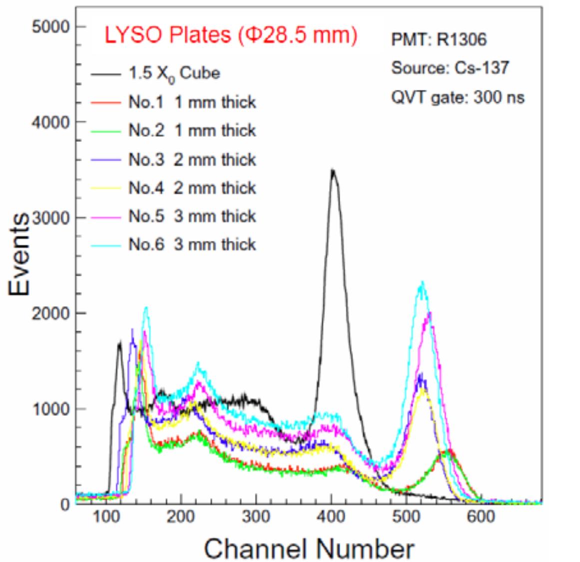
Performance of Ceramic Plates

Presented in Shashlik Meeting on Nov 8, 2011

Crystals

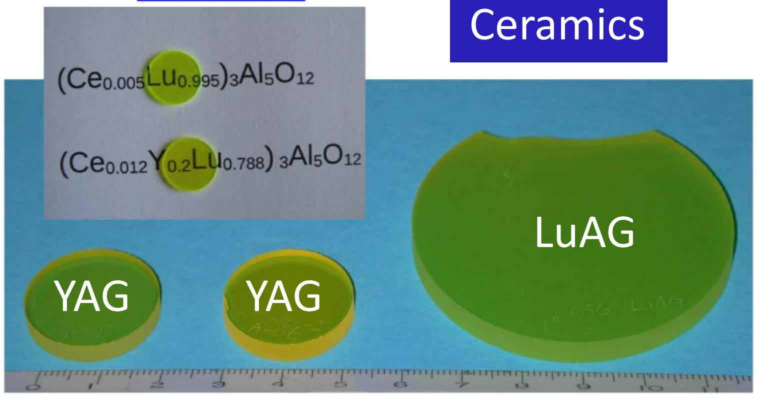






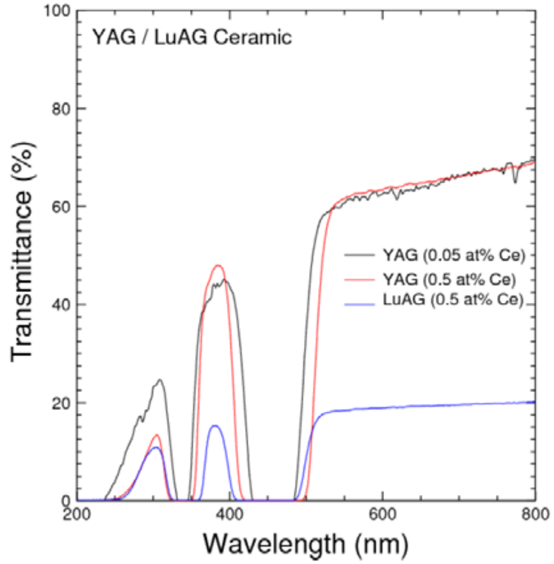
Φ20 X 3 mm

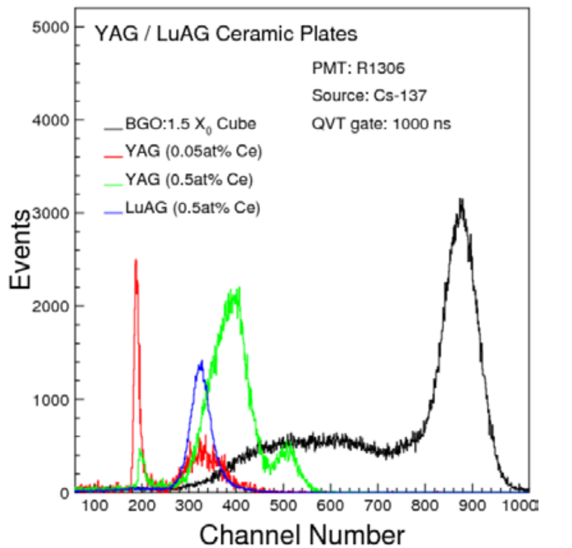
Ceramics



YAG: Φ22 x 4 mm

LuAG Φ56 x 5 mm



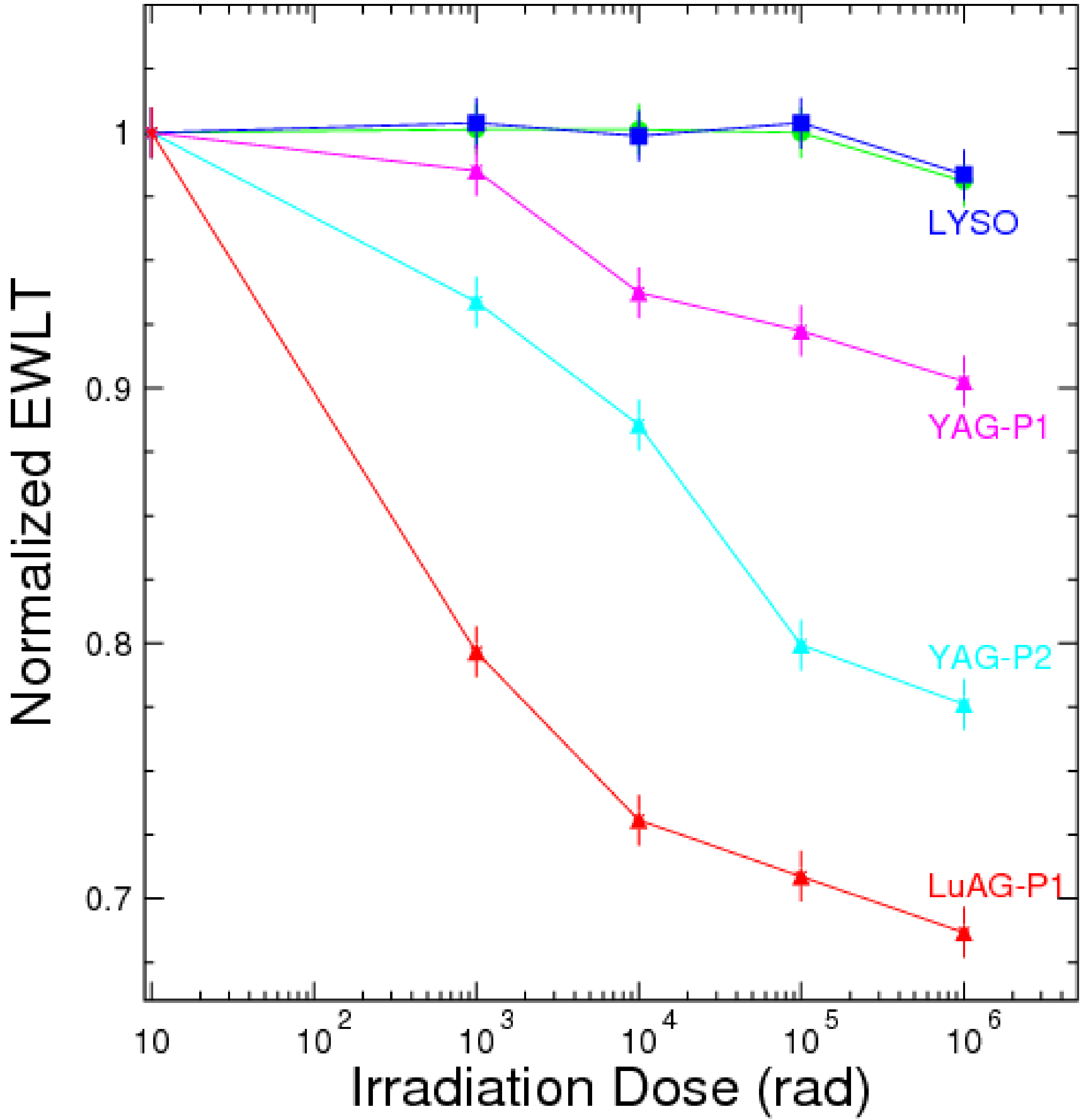


Normalized EWLT: LYSO & Ceramics

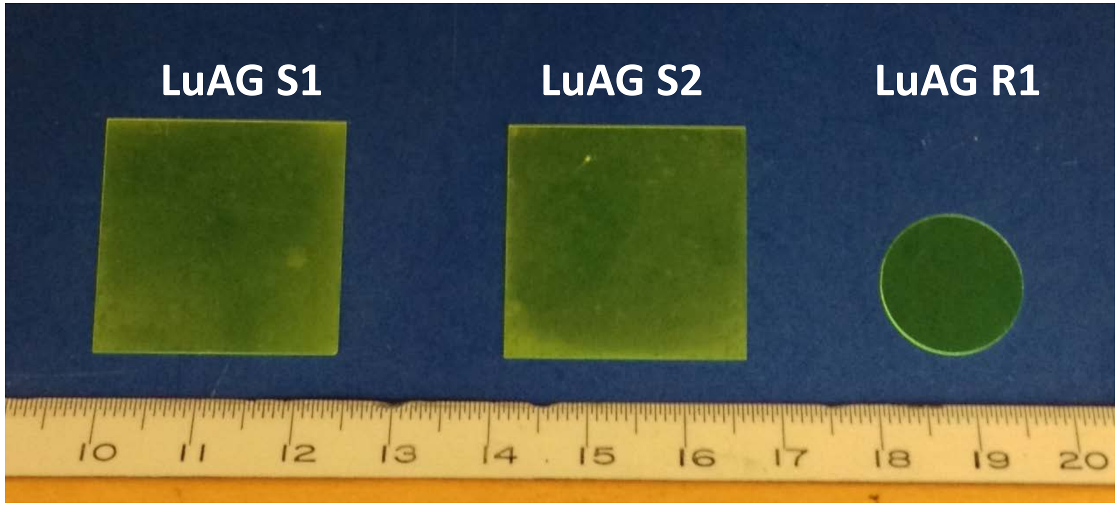
Presented in Shashlik Meeting on Nov 8, 2011

For the sampling option density of the material is no longer crucial, rather decay time and radiation hardness. Will look old and new crystal scintillators, such as BaF_2, pure CsI, CeF_3, $CeBr_3$, Ce:$LaBr_3$, Ce:$LaCl_3$, YSO and GSO, so do not miss any cost-effective solution.

As expected that LYSO is radiation hard. Ceramics, on the other hand, seem not.



Recent SIC LuAG:Ce Samples



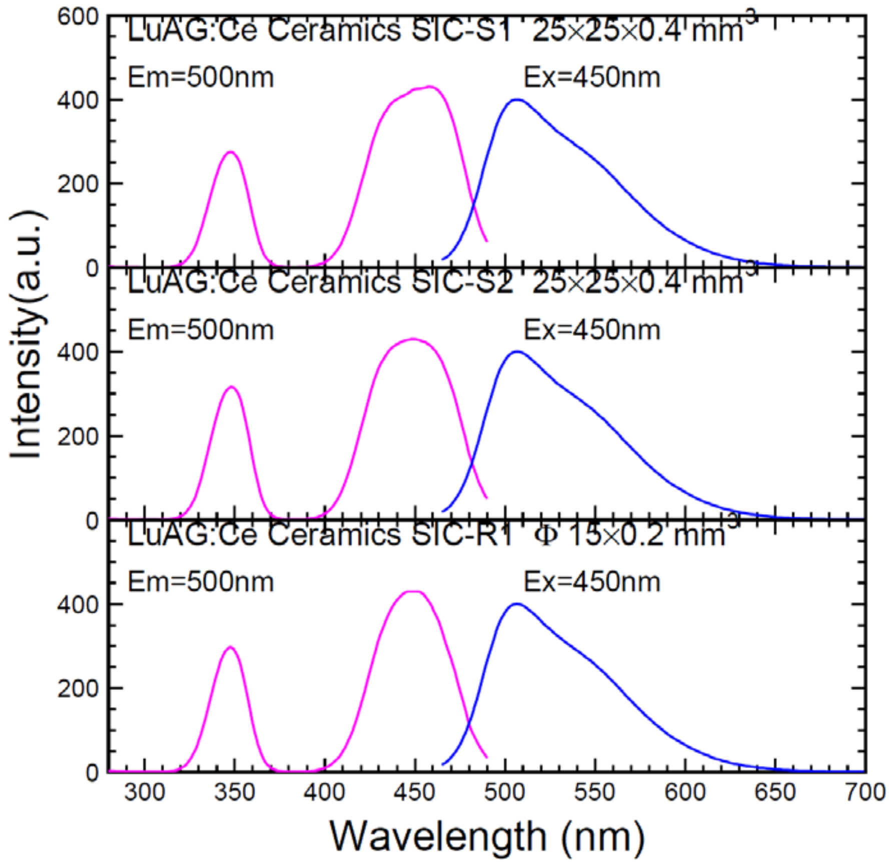
Sample ID	Dimension (mm)	Polishing
LuAG S1	25×25×0.4	Two surfaces
LuAG S2	25×25×0.4	Two surfaces
LuAG RI	Φ15×0.2	Two surfaces

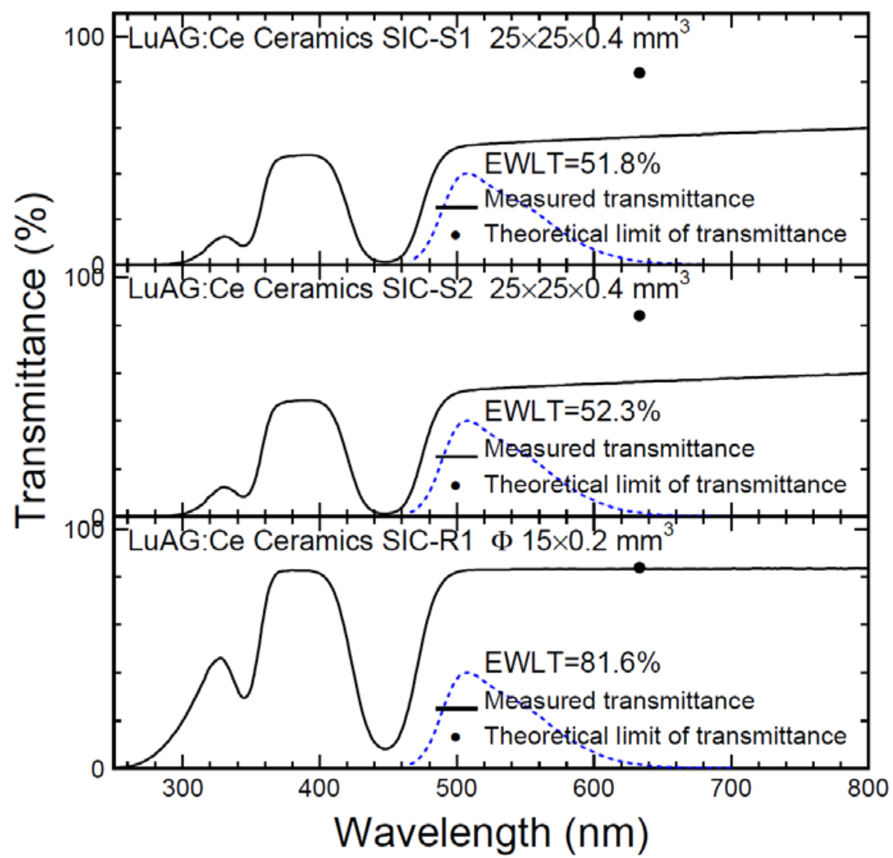
Experiments

- Properties measured at room temperature: Transmittance, Photo-luminescence, Light Output, Decay Time and Radiation Damage

PL and Transmittance

Two excitation peaks at 350 and 450 nm and one emission peak at 500 nm

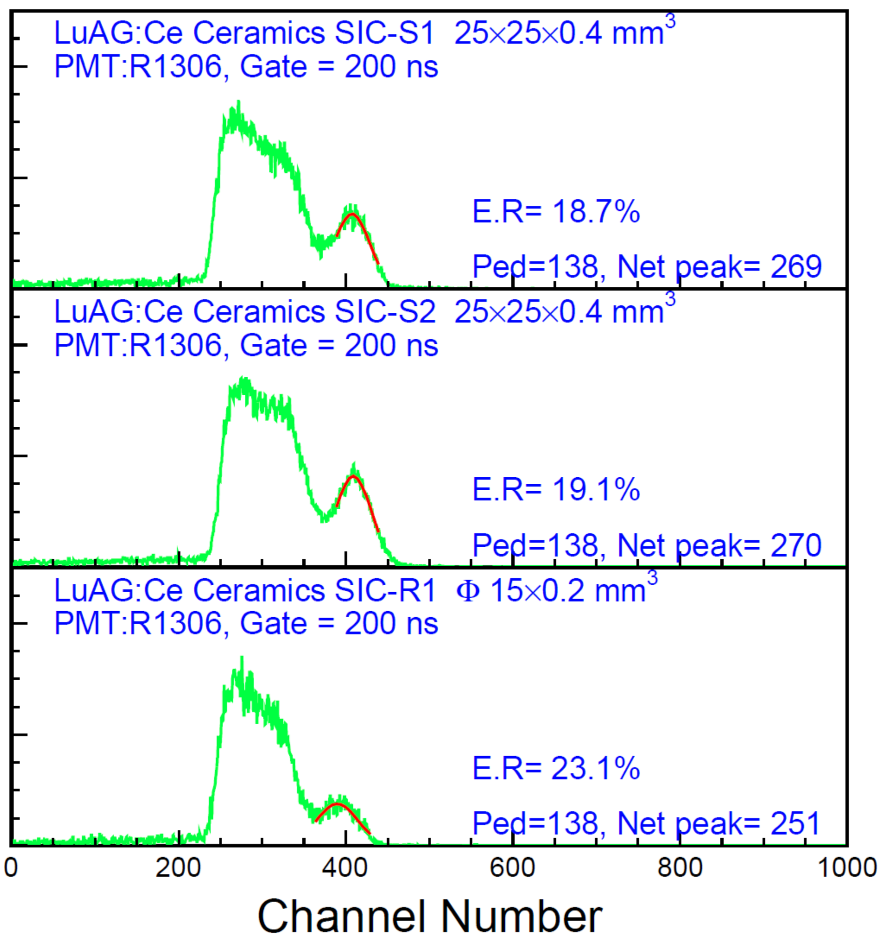


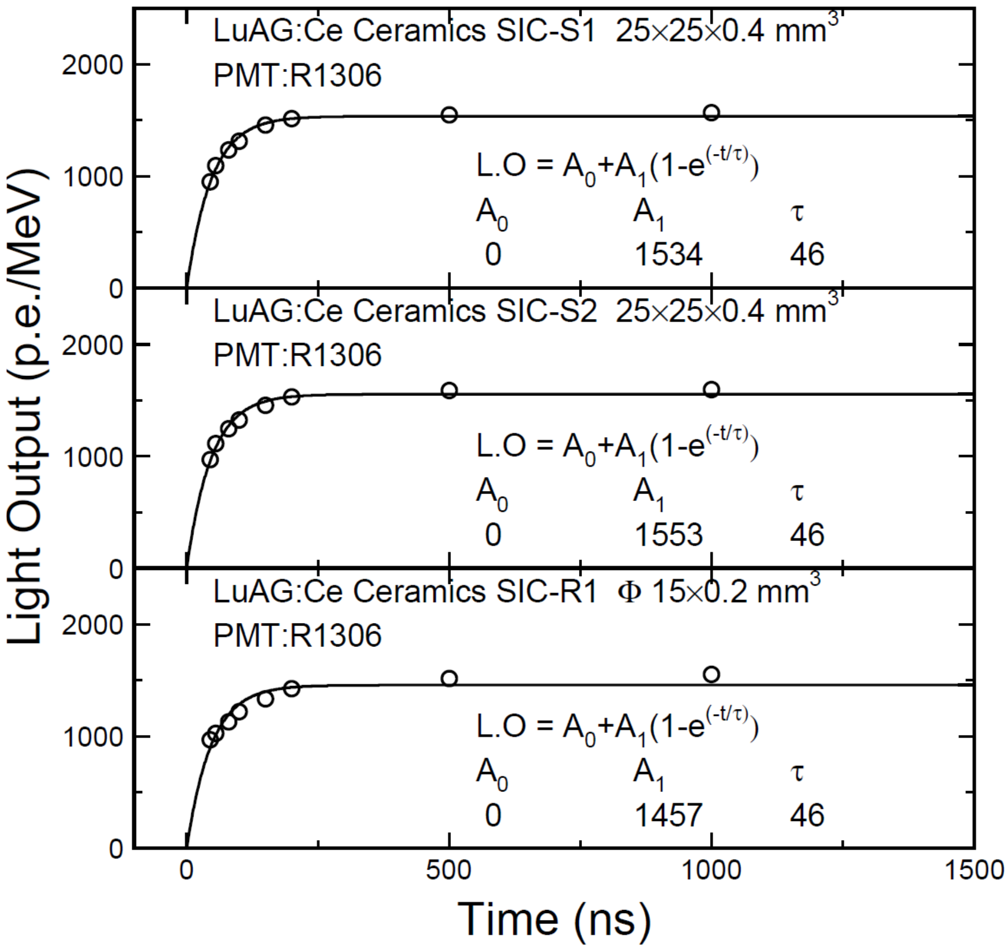


Good Optical quality of the 0.2 mm sample approaching theoretical limit
Scattering centers observed in 0.4 mm samples

PHS, Light Output and Decay Time

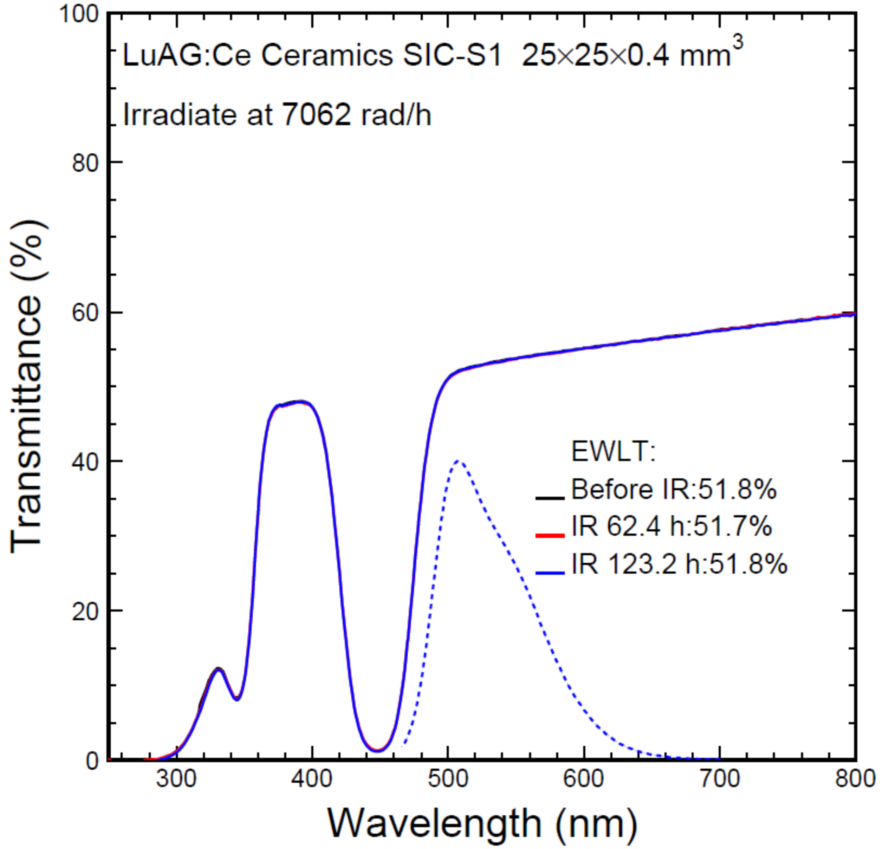
Cs-137 peaks: 20% resolution, 1,500 p.e./MeV and 46 ns decay time

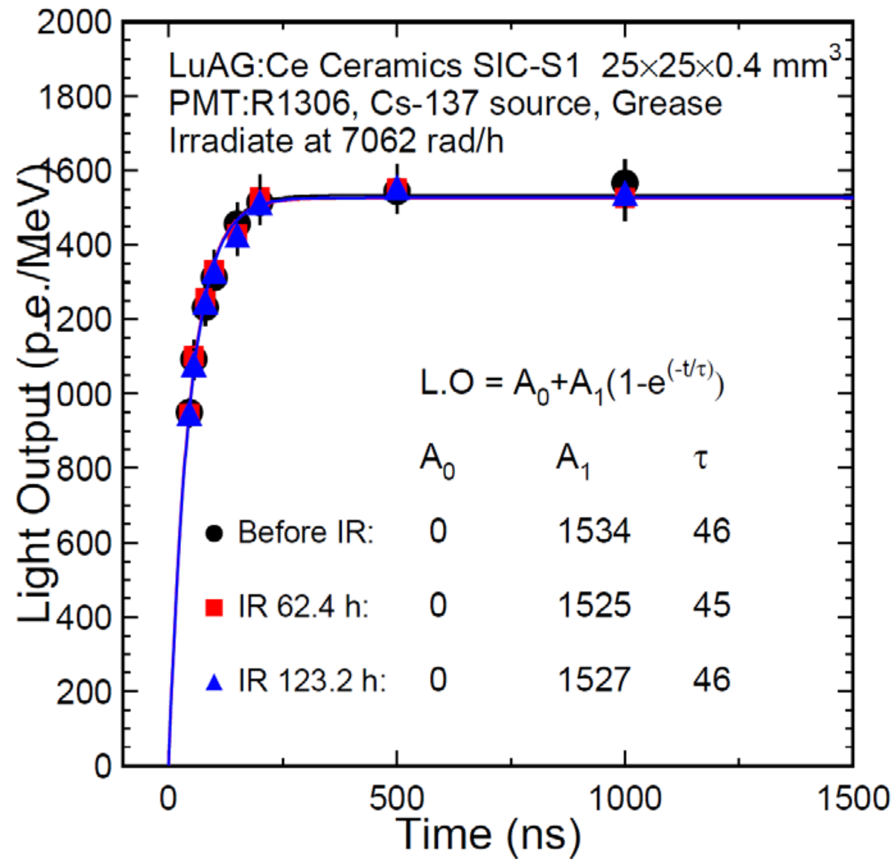




Progress in Radiation Hardness

No damage up to 0.86 Mrad in both transmittance and light output





Promising for a scintillating ceramic based sampling calorimeter

Summary

- **LYSO crystals are radiation hard against ionization dose and proton fluence. The cost of LYSO crystals, however, is high which is some times prohibitive for HEP applications.**
- **Significant progresses in quality of scintillating ceramics have been achieved, proving possible cost-effective alternatives for scintillating crystals because of effective raw material usage and no processing waste.**
- **Our plan is to continue developing inorganic scintillators for HEP applications, including cost-effective bright, fast and rad hard ceramics.**