LuAG Ceramic Scintillators for Future HEP Experiments

Chen Hu[1], Jiang Li[2], Fan Yang[1,3], Benxue Jiang[4], Liyuan Zhang[1], and Ren-Yuan Zhu[1]

1. California Institute of Technology
2. Shanghai Institute of Ceramics, CAS
3. Nankai University
4. Shanghai Institute of Optics and Fine Mechanics, CAS

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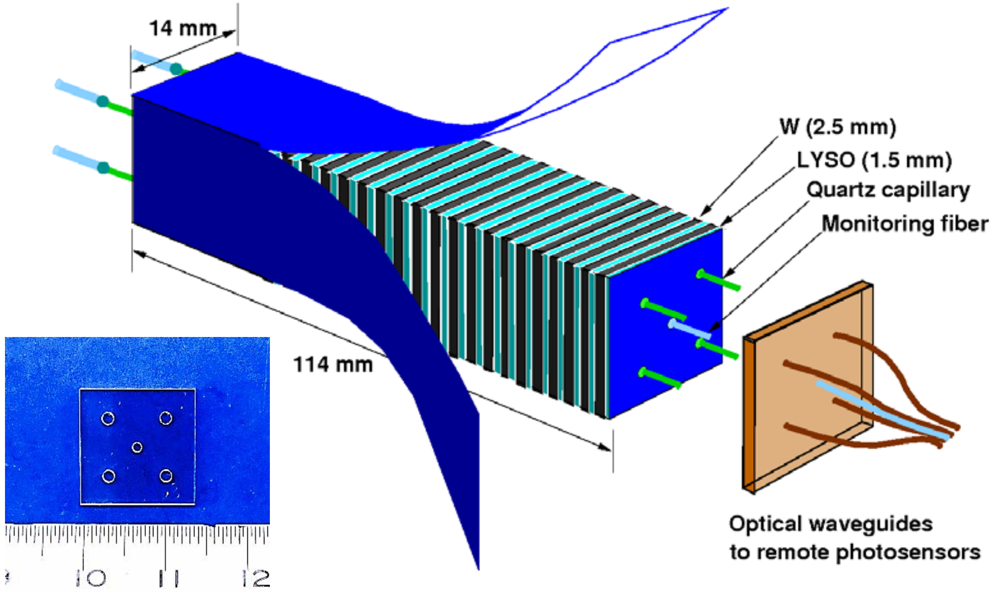
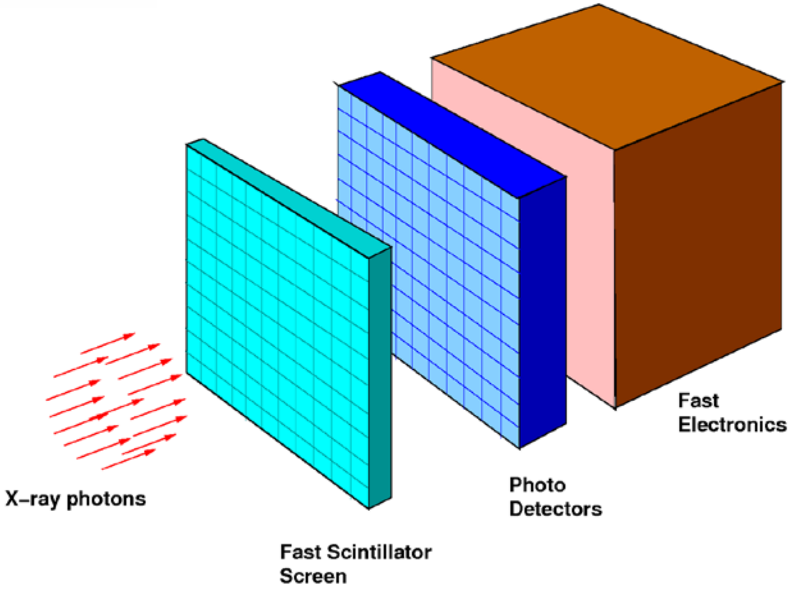
Why LuAG Ceramics for HEP Experiments

- **Challenges for future inorganic scintillators:**
    - **Ultrafast and rad hard scintillators at the energy frontier (HL-LHC);**
    - **Ultrafast scintillators at the intensity frontier (Mu2e-II);**
    - **Ultrafast scintillators for GHz hard X-ray imaging (Marie).**
- **LYSO:Ce, BaF_2:Y and LuAG:Ce survive the radiation environment expected at HL-LHC with 3000 fb^{-1}.**
    - **Absorbed dose: up to 100 Mrad,**
    - **Charged hadron fluence: up to 6×10^{14} p/cm^2,**
    - **Fast neutron fluence: up to 3×10^{15} n/cm^2.**
- **LuAG Ceramics provide a cost-effective solution for the shashlik calorimeter concept.**
    - **Simple production technology;**
    - **High raw material usage;**
    - **No after growth processing.**





Fast Inorganic Scintillators

	LYSO:Ce	LSO:Ce,Ca[a]	LuAG:Ce[b]	LuAG:Pr[c]	GGAG:Ce[d]	GLuGAG:Ce[g]	GYGAG:Ce[h]	$SrHfO_3$:Ce[i]	$BaHfO_3$:Ce[i]	$CeBr_3$[k]	$LaBr_3$:Ce[k]
Density (g/cm^3)	7.4	7.4	6.76	6.76	6.5	6.80	5.80	7.56	8.5	5.23	5.29
Melting points (°C)	2050	2050	2060	2060	1850[e]	>1900[e]	1850[e]	2730	2620	722	783
X_0 (cm)	1.14	1.14	1.45	1.45	1.63	1.38	2.11	1.17	0.98	1.96	1.88
R_M (cm)	2.07	2.07	2.15	2.15	2.20	1.57	2.43	2.03	1.87	2.97	2.85
λ_I (cm)	20.9	20.9	20.6	20.6	21.5	20.8	22.4	20.6	19.4	31.5	30.4
Z_{eff}	64.8	64.8	60.3	60.3	51.8	55.2	45.4	60.9	62.9	45.6	45.6
dE/dX	9.55	9.55	9.22	9.22	8.96	9.28	8.32	9.80	10.7	6.65	6.90
λ_{peak} (nm)	420	420	520	310	540	550	560	410	400	371	356
Refractive Index	1.82	1.82	1.84	1.84	1.92[f]	1.92[f]	1.92[f]	2.0	2.1	1.9	1.9
Normalized Light Yield	100	116	83	73	115	161	167	133	133	99	153
Total Light yield (ph/MeV)[a]	30,000	34,800	25,000	22,000	34400	48,200	50,000	5,000[j]	5,000[j]	30,000	46,000
Decay time (ns)[a]	40	31	46	20	53	84 148	100	42	25	17	20
Light Yield in 1st ns (photons/MeV)	740	950	540	1,100	640	570	500	120	200	1,700	2,200
Issues					high thermal neutron x-section			incongruent		hygroscopic	

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[a] Spurrier, et al., *IEEE T. Nucl. Sci.* 2008,55 (3): 1178-1182

[b] Liu, et al., *Adv. Opt. Mater.*, 4: 731–739. doi: 10.1002/adom.201500691

[c] Yanagida, et al., *IEEE T. Nucl. Sci.* 2012, 59(5): 2146

[d] Luo, et al., *Ceram. Int.* 2016, 41(1): 873

[e] The melting point of these materials various with different composition from 1800 to 1980 °C. The data is based on reported values.

[f] Kuwano, et al., *J. Cryst. Growth.* 1988, 92: 17

[g] Wu, et al., *NIMA* 2015, 780: 45

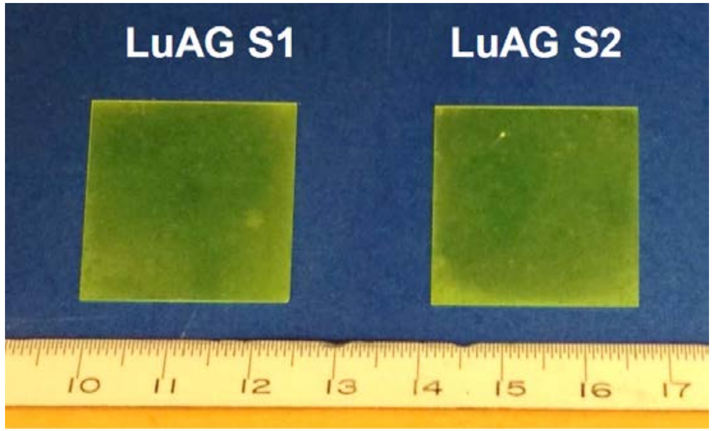
[h] Cherepy, et al., *IEEE T. Nucl. Sci.* 2013, 60(3): 2330

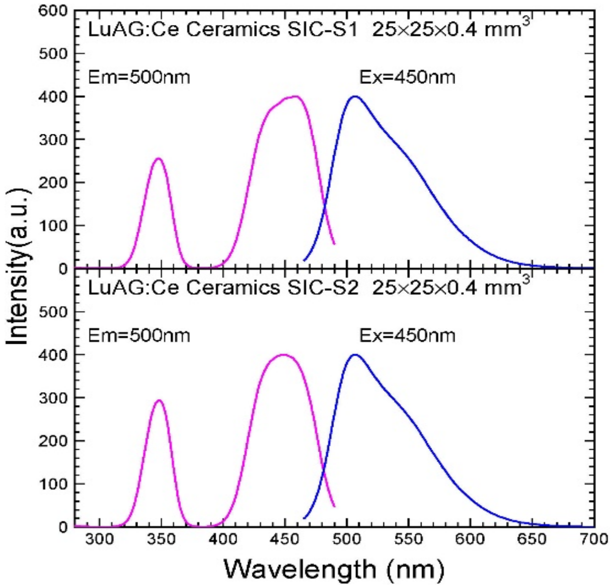
[i] van Loef, et al., *IEEE T. Nucl. Sci.* 2007, 54(3):741

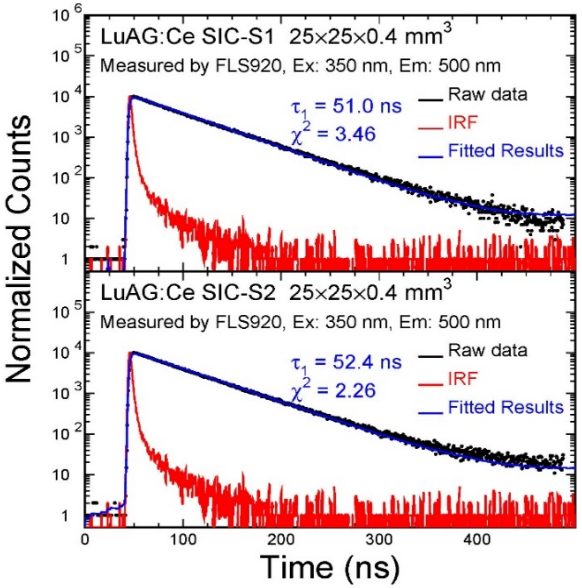
[j] Based on ^{137}Cs gamma-ray excitation (shaping time of 4 µs) light yield result in ref. i

[k] Data based on single crystals

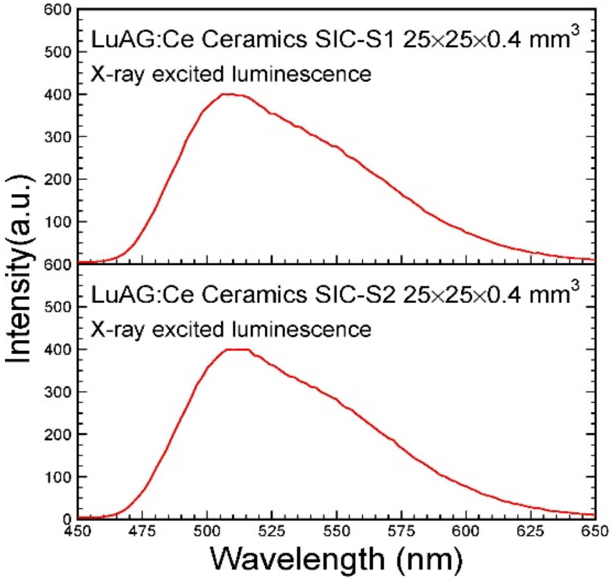
LuAG:Ce Ceramic Plates

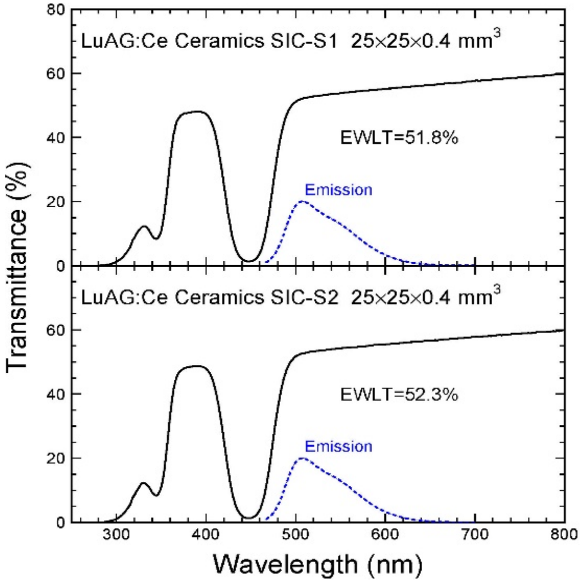






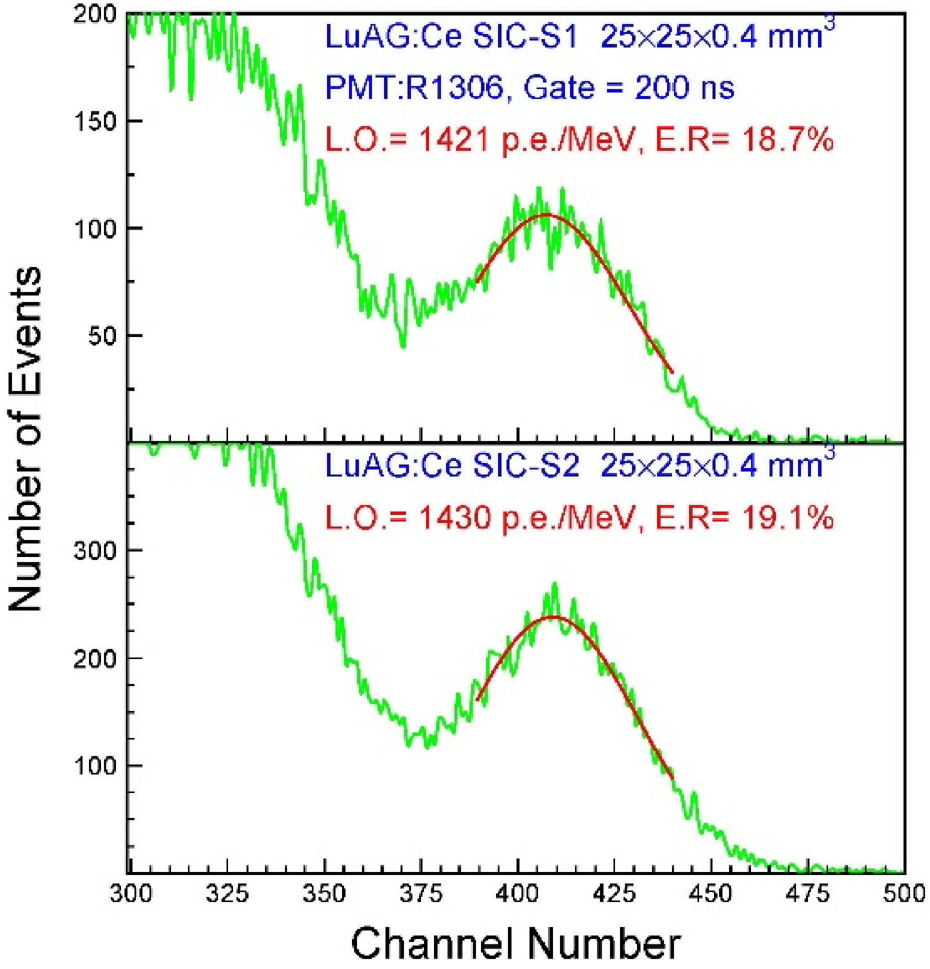
LuAG ceramic scintillators S1 and S2 prepared by SIC show consistent emission peak at 500 nm with a PL decay time of ~50 ns and no self absorption

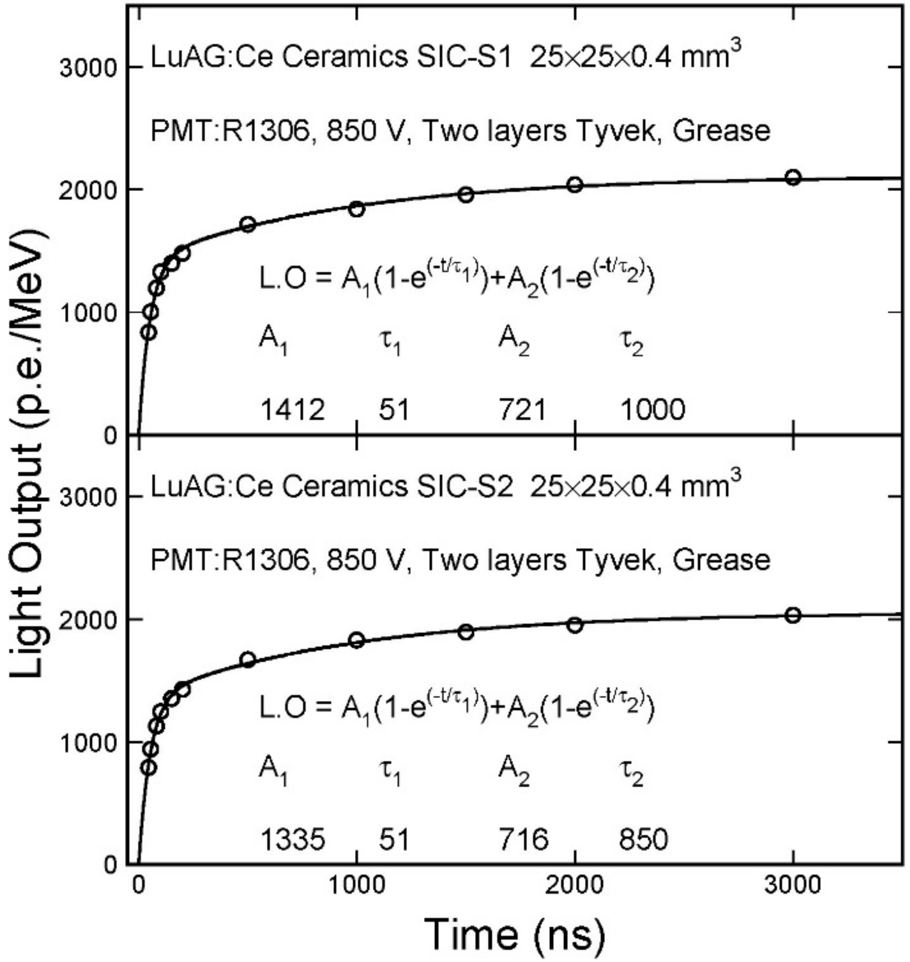




Scintillation Performance for LuAG:Ce Ceramics

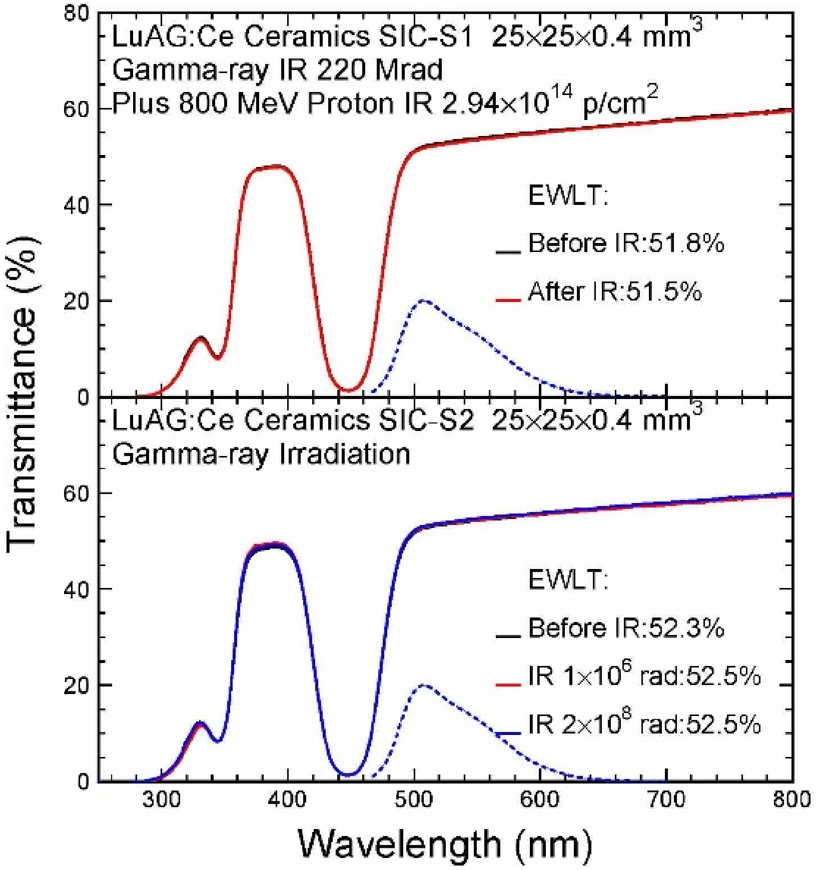
Light output is about 1,400 p.e./MeV. In addition to the ~50 ns decay time, a slow component was observed with a F/T ratio, defined as LO(200)/LO(3000), of 60%

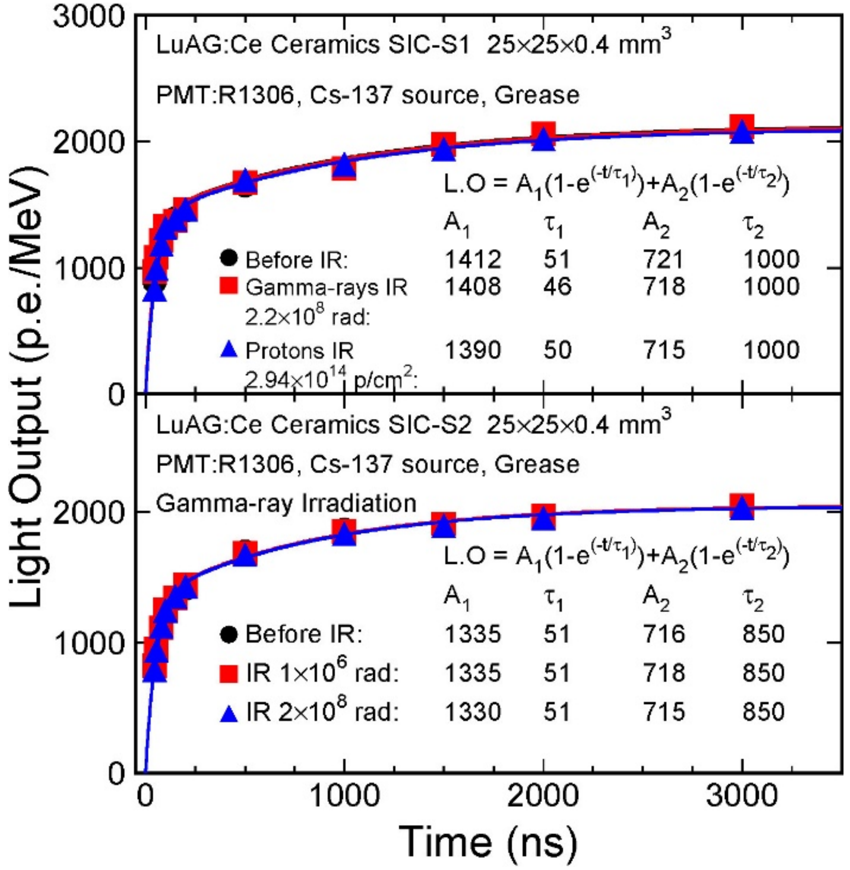




Excellent Radiation Hardness: γ-ray & Protons

No damage was observed in both transmittance and light output after 220 Mrad gamma radiation and 2.9 × 10^{14} p/cm^2 of 800 MeV





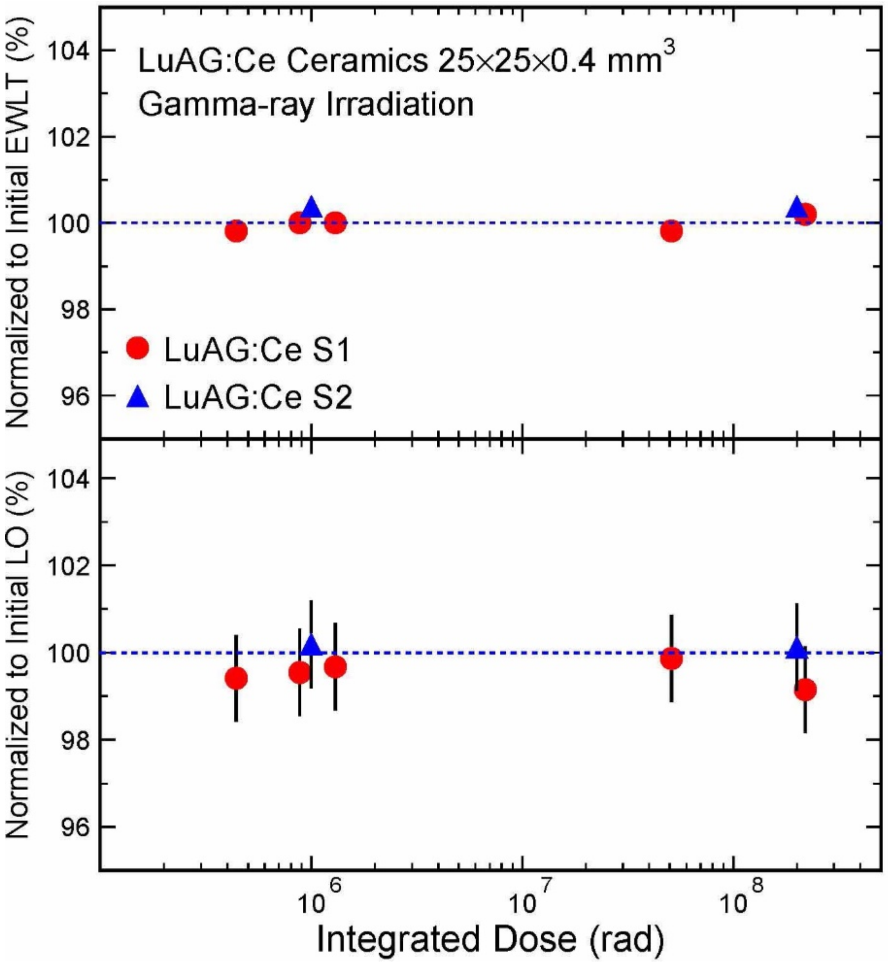
	A_1	τ_1	A_2	τ_2
● Before IR:	1412	51	721	1000
🟥 Gamma-rays IR 2.2×10^8 rad:	1408	46	718	1000
▲ Protons IR 2.94×10^{14} p/cm^2:	1390	50	715	1000

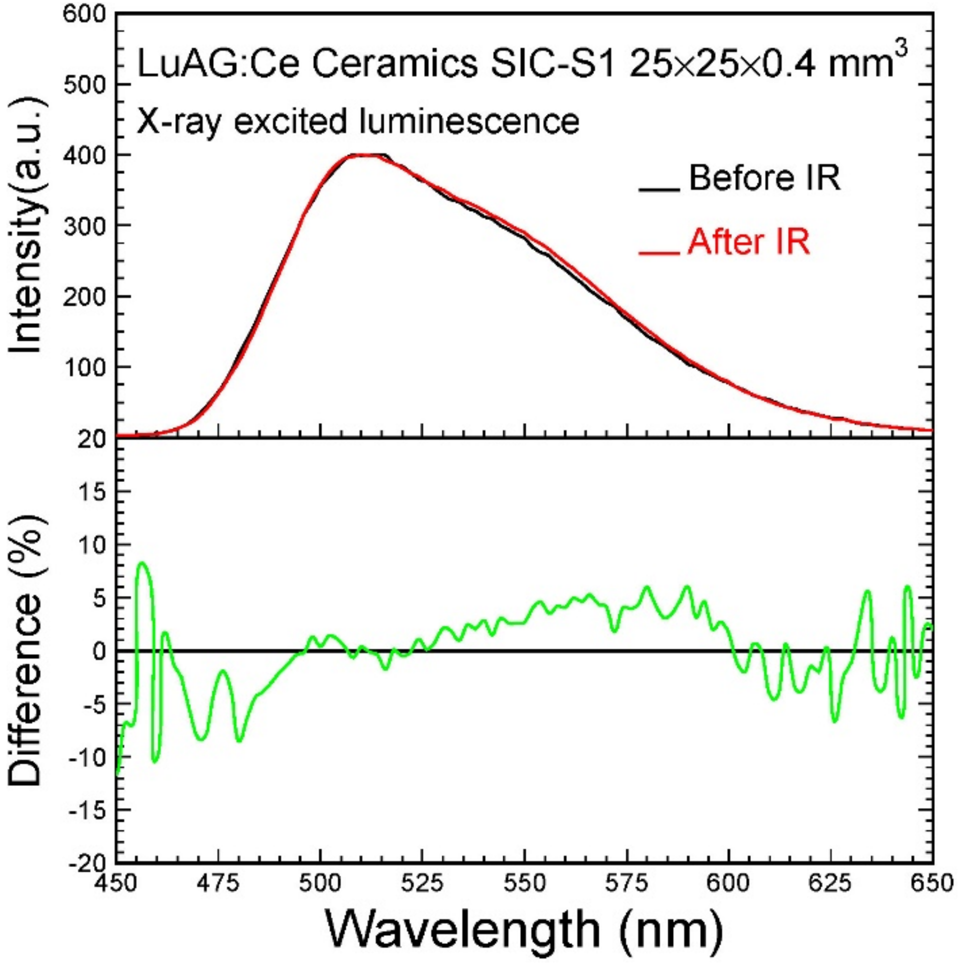
	A_1	τ_1	A_2	τ_2
● Before IR:	1335	51	716	850
🟥 IR 1×10^6 rad:	1335	51	718	850
▲ IR 2×10^8 rad:	1330	51	715	850

Very promising for a LuAG ceramics-based calorimeter for future HEP experiments

Excellent Radiation Hardness: γ-ray & proton IR

No damage was observed in EWLT, LO and XEL spectrum

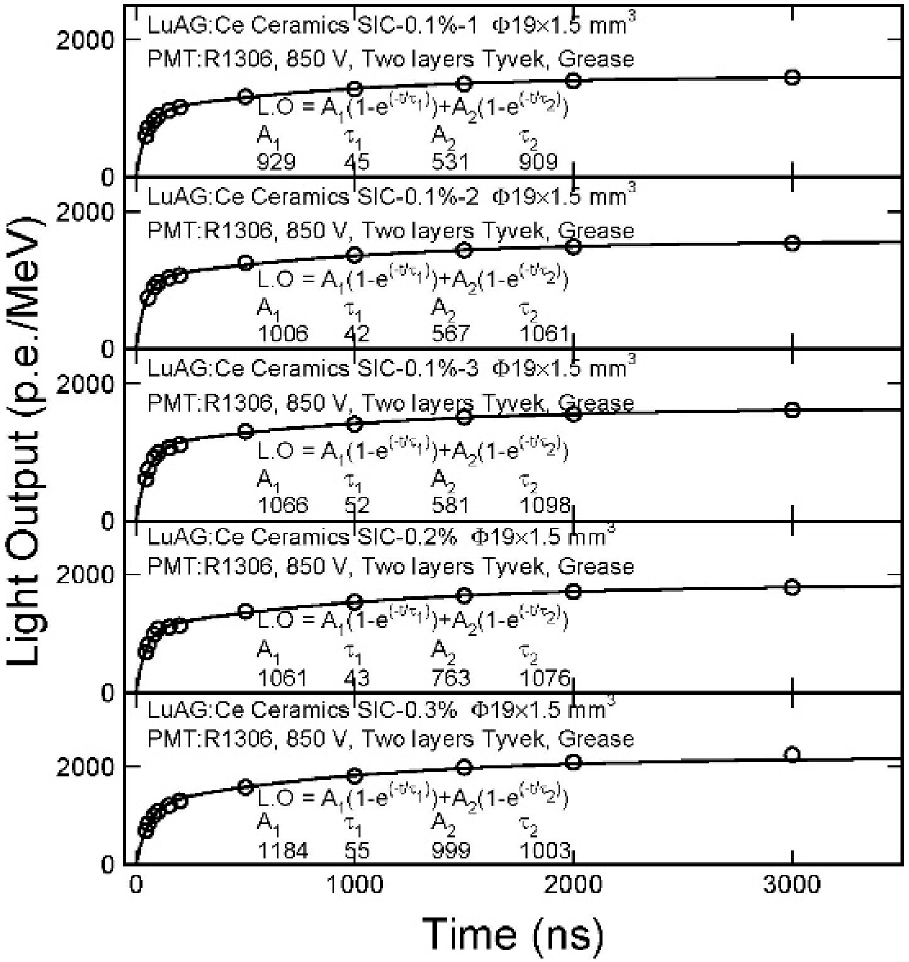


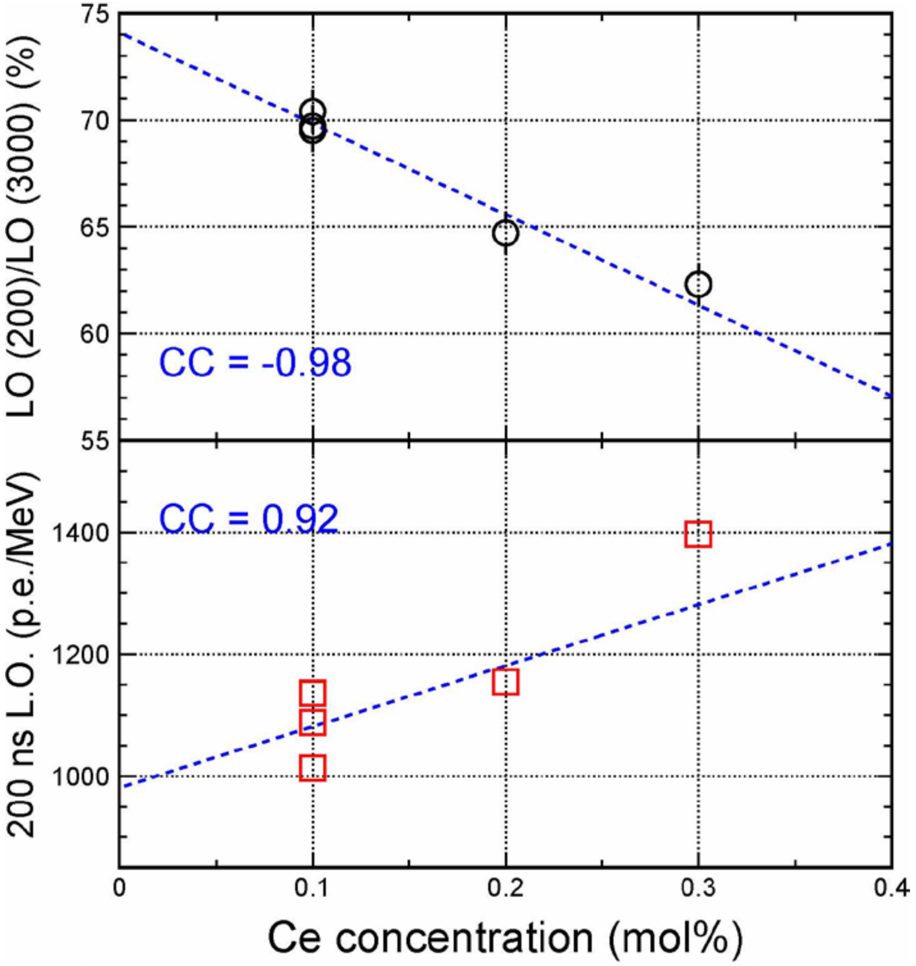


The slow component issue, however, needs to be addressed

LO & F/T Ratio vs Ce Concentration

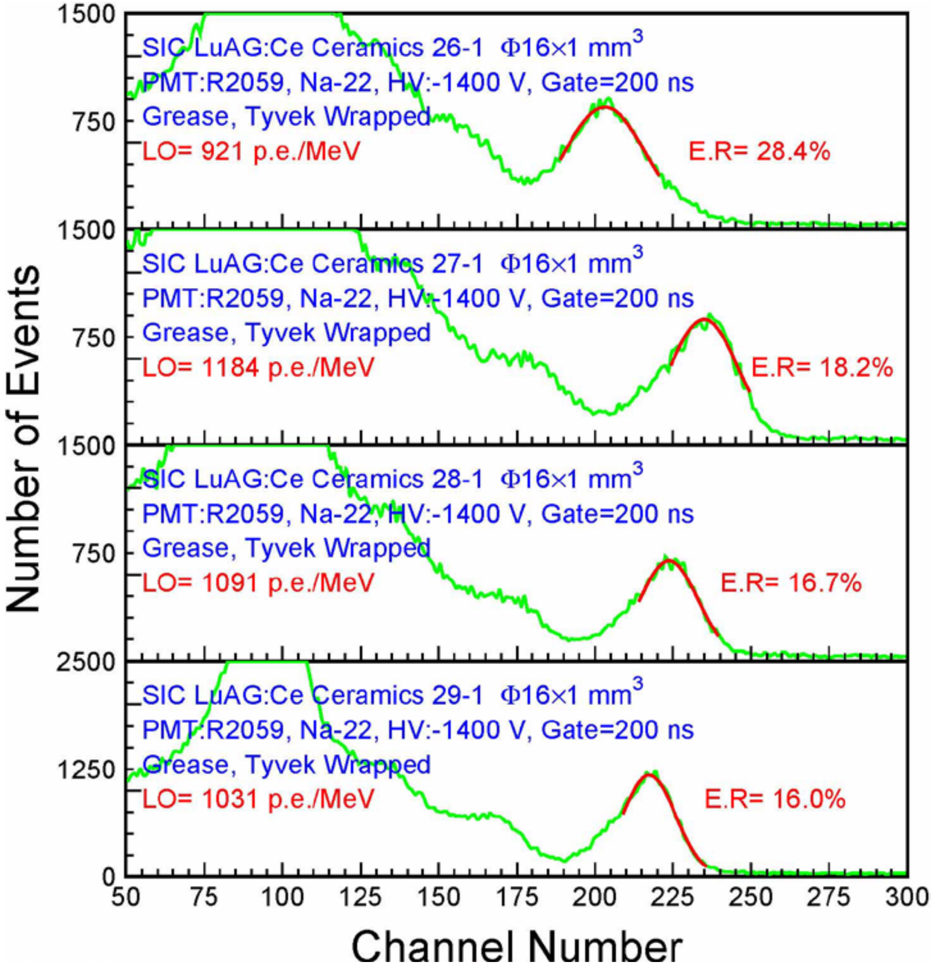
1. The F/T ratio decreases from 70% to 62% as the Ce concentration increases;
2. LO of 200 ns gate increases as the Ce concentration increases.

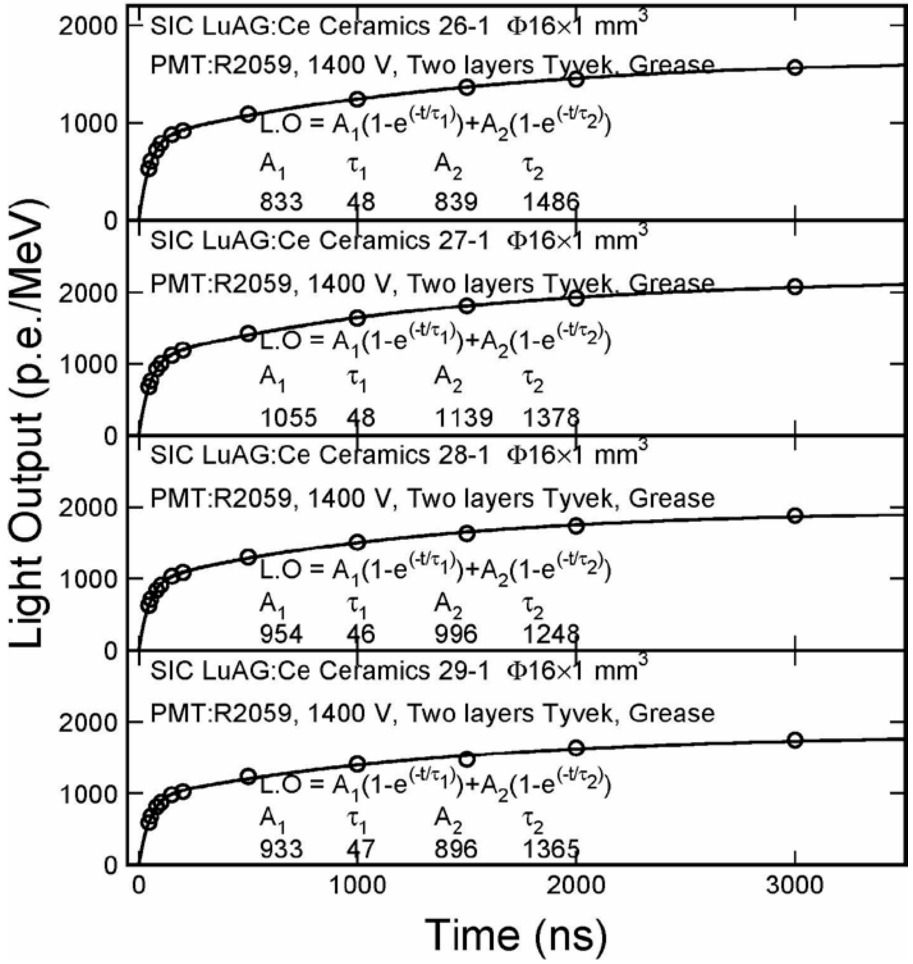




Effect of Co-doping: Li$^+$

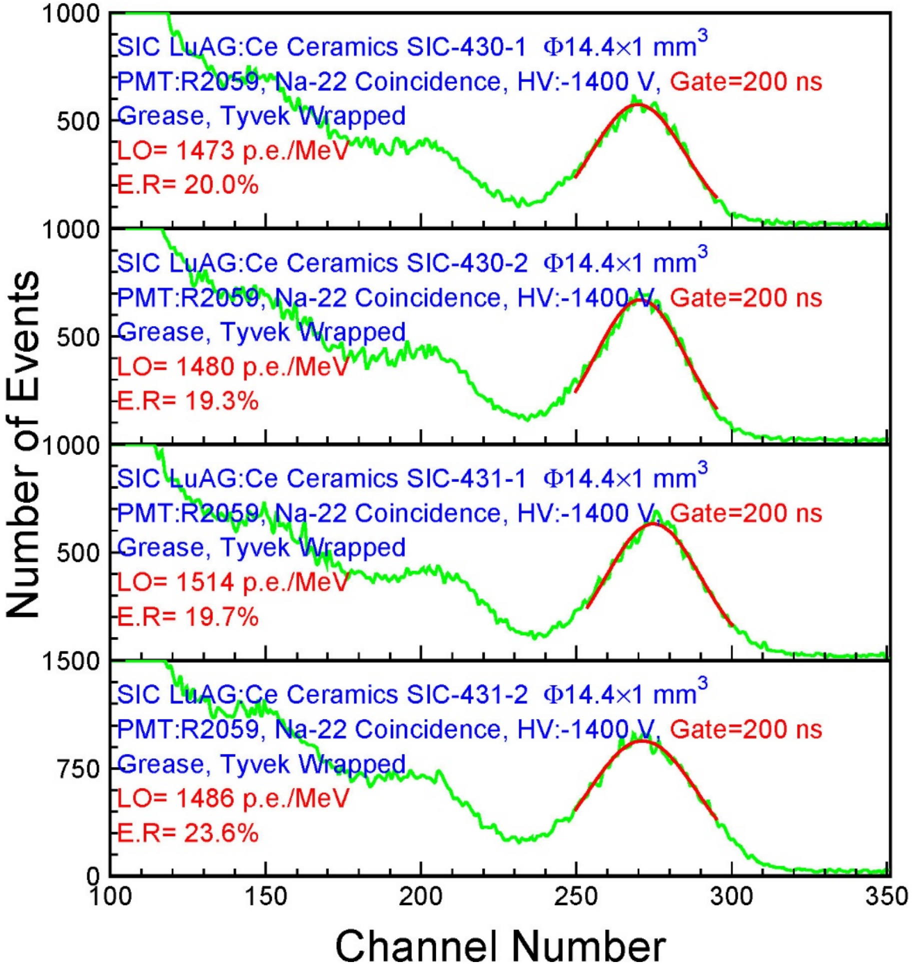
1. Li$^+$ co-doping degrades the F/T ratio to less than 60%.
2. The LO of 200 ns gate is reduced to ~1,100 p.e./MeV.

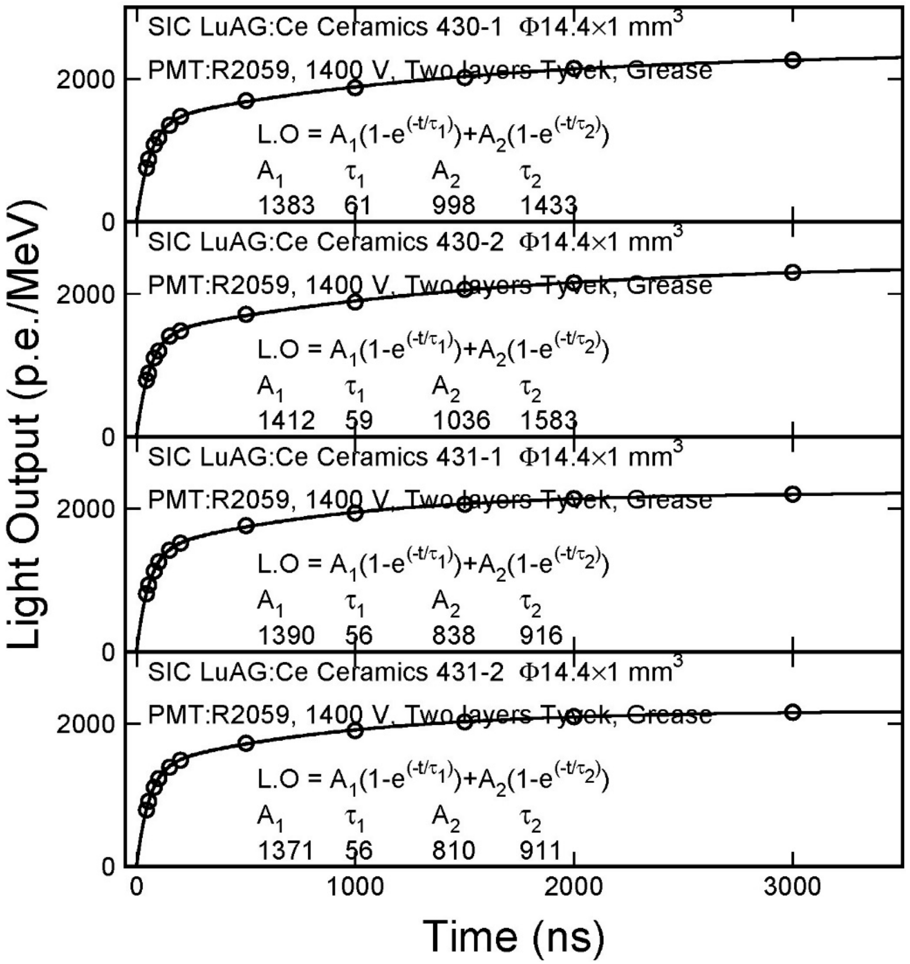




Effect of Co-doping: Mg^{2+}

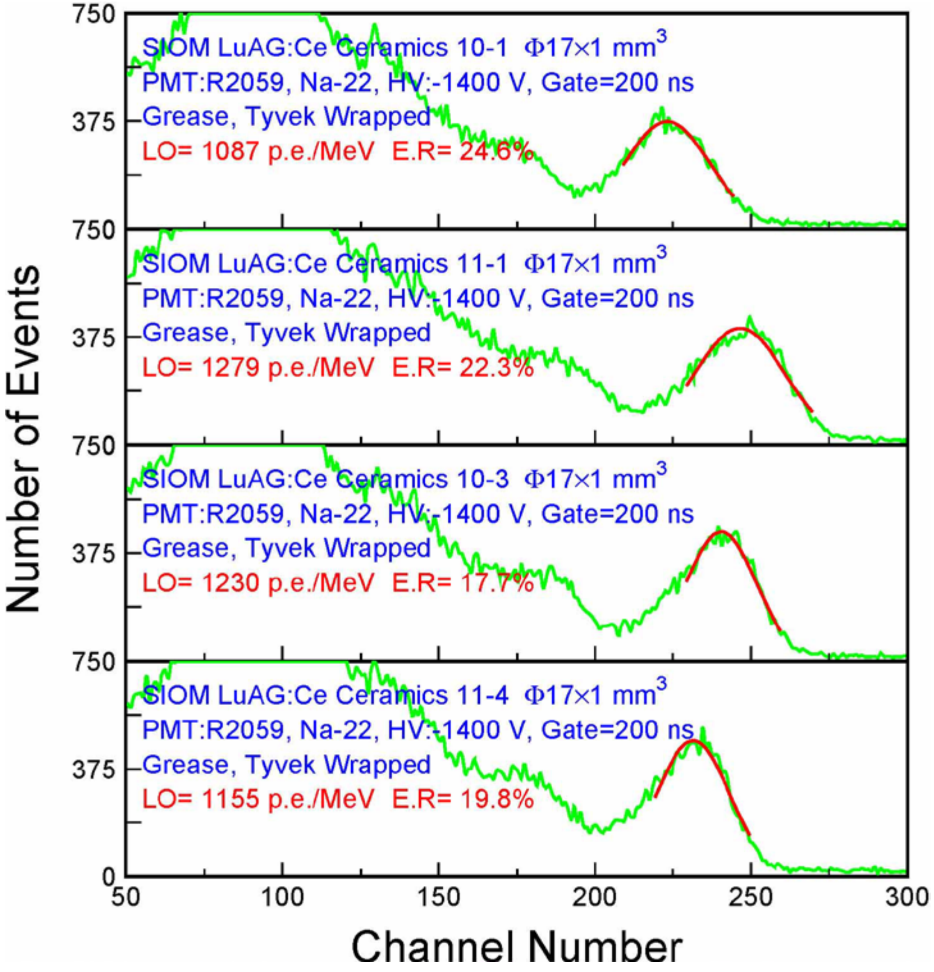
1. Mg^{2+} co-doping improves the F/T ratio to 74%.
2. The LO of 200 ns gate is increased to 1,500 p.e./MeV.

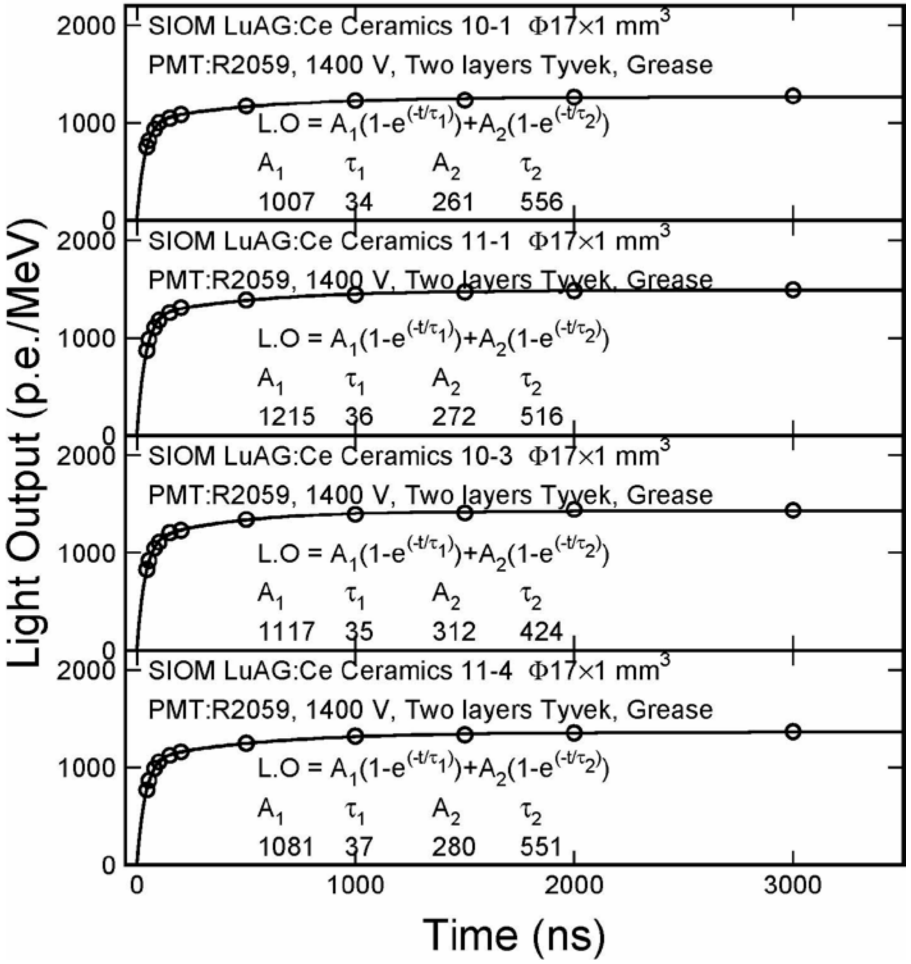




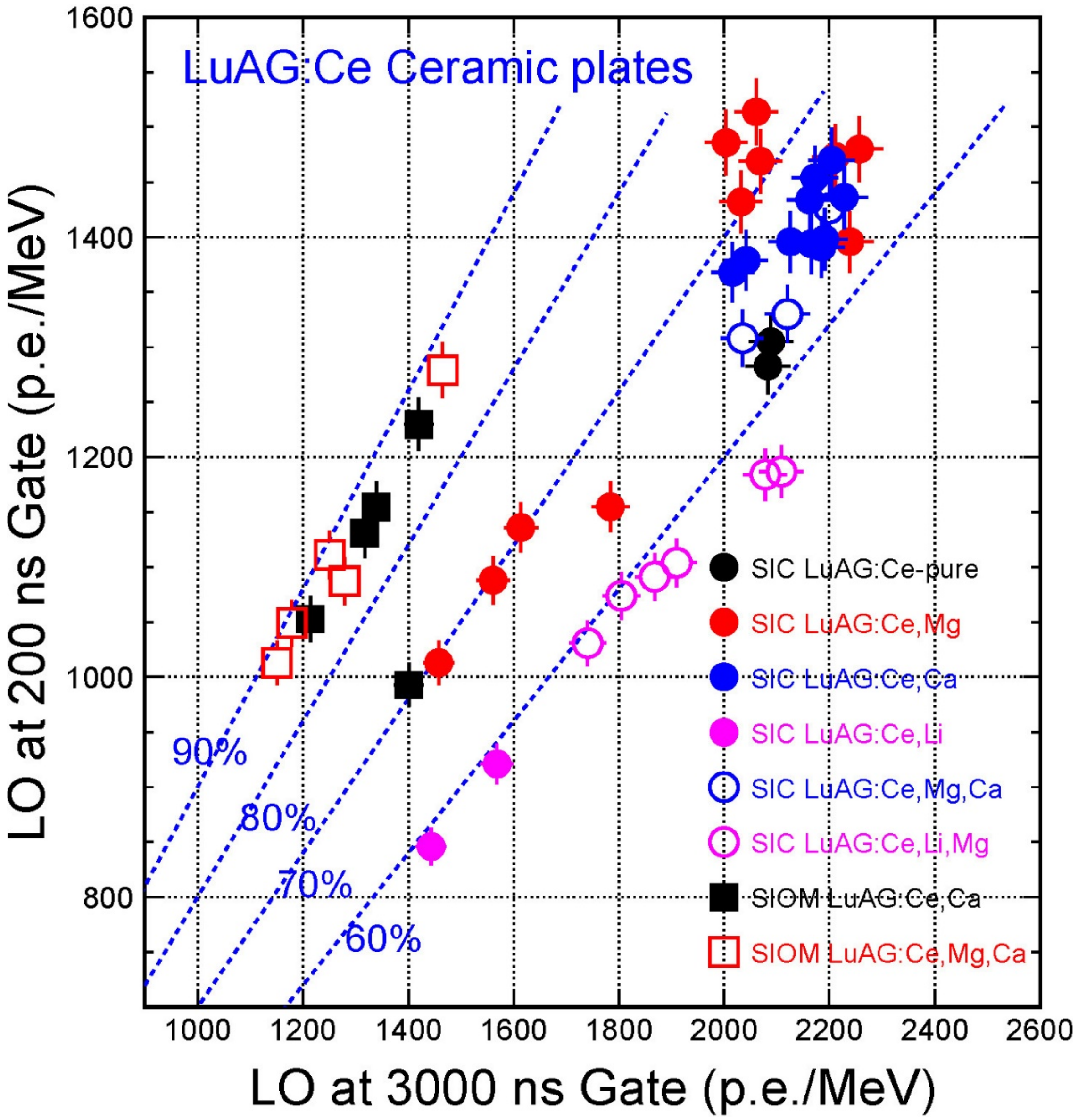
Effect of Co-doping: Ca^{2+}

1. Ca^{2+} co-doping improves the F/T ratio to 90%.
2. The LO of 200 ns gate is reduced to ~1,200 p.e./MeV.





Summary: Li, Mg and Ca Co-doping

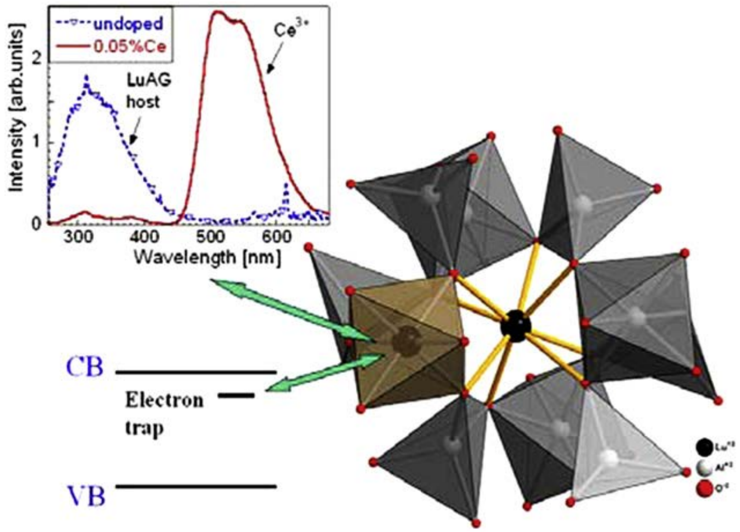


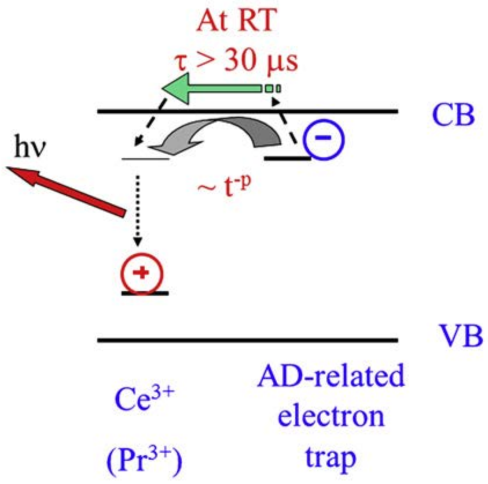
1. Li^+ co-doping decreases the F/T ratio and the LO of 200 ns gate;
2. Mg^{2+} co-doping improves the F/T ratio, and shows the highest LO of 200 ns gate;
3. Ca^{2+} co-doping shows the highest F/T ratio ~90%.

Summary

- **LuAG:Ce ceramics shows an emission peaked at 500 nm with no self-absorption. Its emission has a 50 ns decay time and a slow scintillation component with a decay time of ~1 μs. Its light output of 200 ns gate is about 1,400 p.e./MeV.**
- **LuAG:Ce ceramics are found to have excellent radiation hardness against an ionization dose up to 220 Mrad and a proton fluence up to 3×10^{14} p/cm^2. This material is very promising for future HEP calorimeters to be operated in a severe radiation environment, such as the HL-LHC.**
- **Correlations are observed between the Ce concentration, the F/T ratio and the light output of 200 ns gate.**
- **Mono- and divalent co-dopants are investigated to reduce the slow component in LuAG:Ce. While the Mg^{2+} co-doping shows the highest LO of 200 ns gate, the F/T ratio reaches 90% for Ca^{2+} co-doped LuAG:Ce ceramics.**
- **R&D will continue to develop Ca co-doped LuAG:Ce ceramics and LuAG:Pr ceramics.**

Origin of the Slow Component in LuAG:Ce





Nikl, M., et al. (2013). *Prog. Cryst. Growth Charact. Mater.* **59**(2): 47-72.

Delayed combination process around the **antisite defect (AD) & Ce^{3+} complex defects** accomplished through the above and below CB pathway

The intrinsic AD-related defects are hard to be eliminated. Possible means for the slow component suppression are:

1. Reduce the AD&Ce^{3+} complex defect by reducing Ce^{3+} concentration.
2. Mono- and divalent ions (Me^{+}, Me^{2+}) co-doping to convert Ce^{3+} to Ce^{4+} to avoid the combination process.