LYSO Crystals for SLHC

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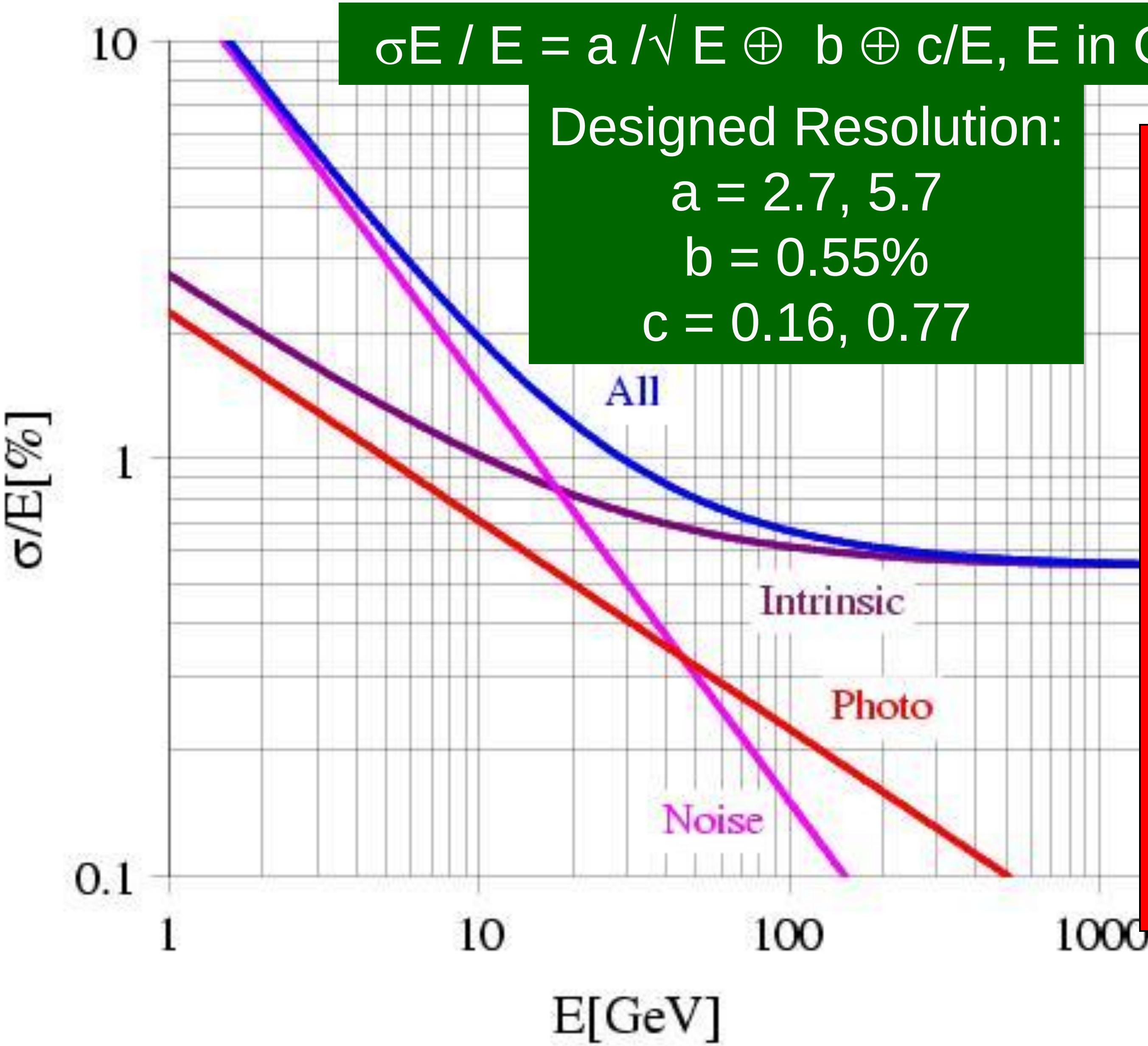
CMS PWO Energy Resolution

$\sigma E / E = a / \sqrt{E} \oplus b \oplus c/E$, E in GeV

Designed Resolution:
a = 2.7, 5.7
b = 0.55%
c = 0.16, 0.77



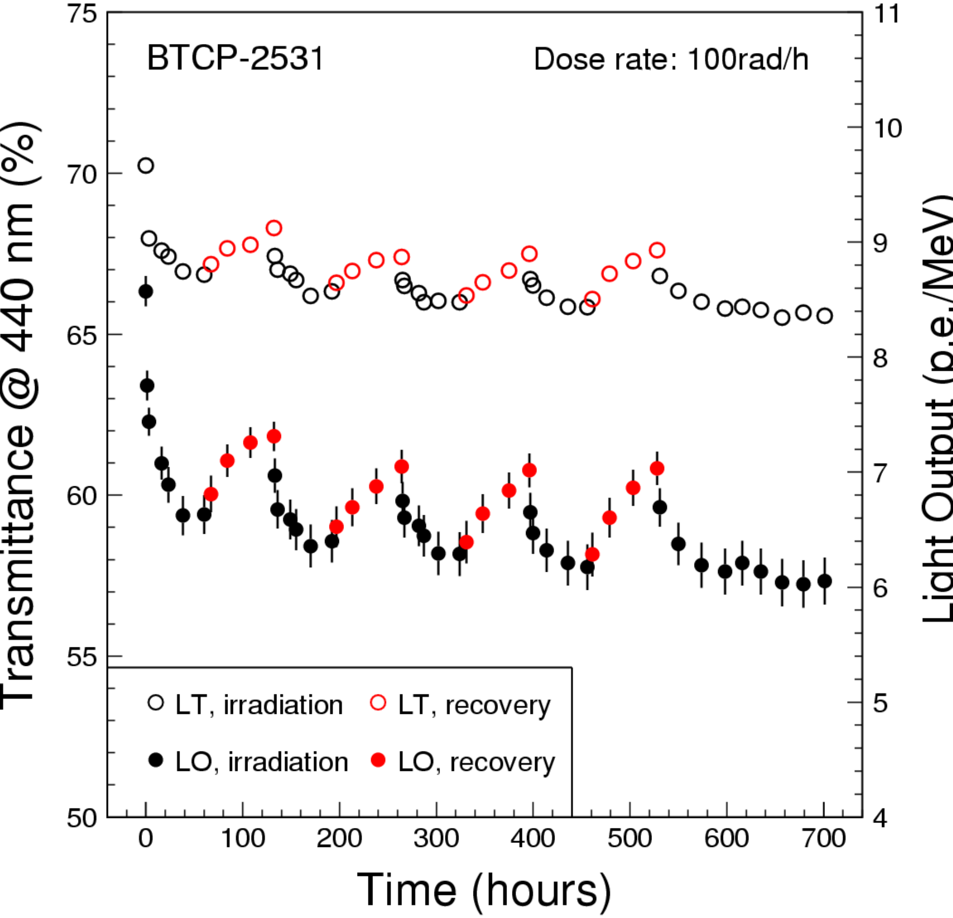
Any degradation of transmittance leads to a degraded light output & energy resolution, but how much?

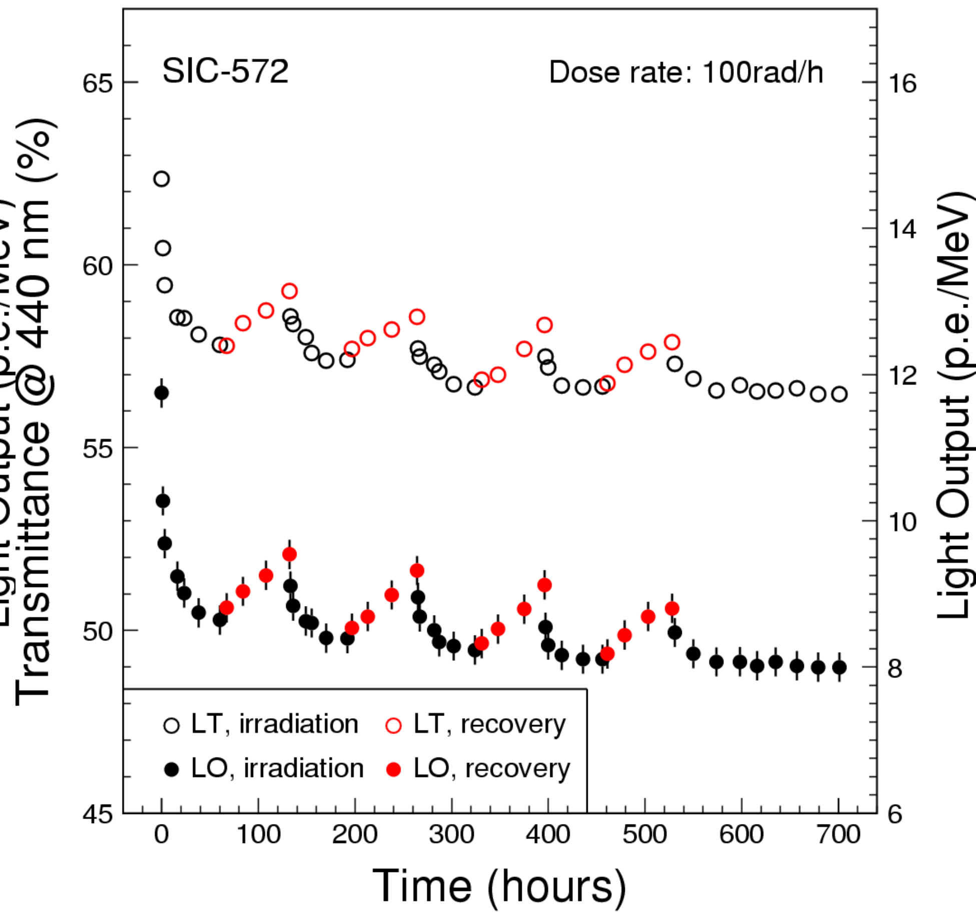
This estimation is made by using published data and RIAC.

Losses of L.O. & L.T. @ 440 nm

Monitoring data for 2 samples each from BTCP and SIC under 100 and 400 rad/h & recovery

R. Mao et al., in Calor2006 Proceedings

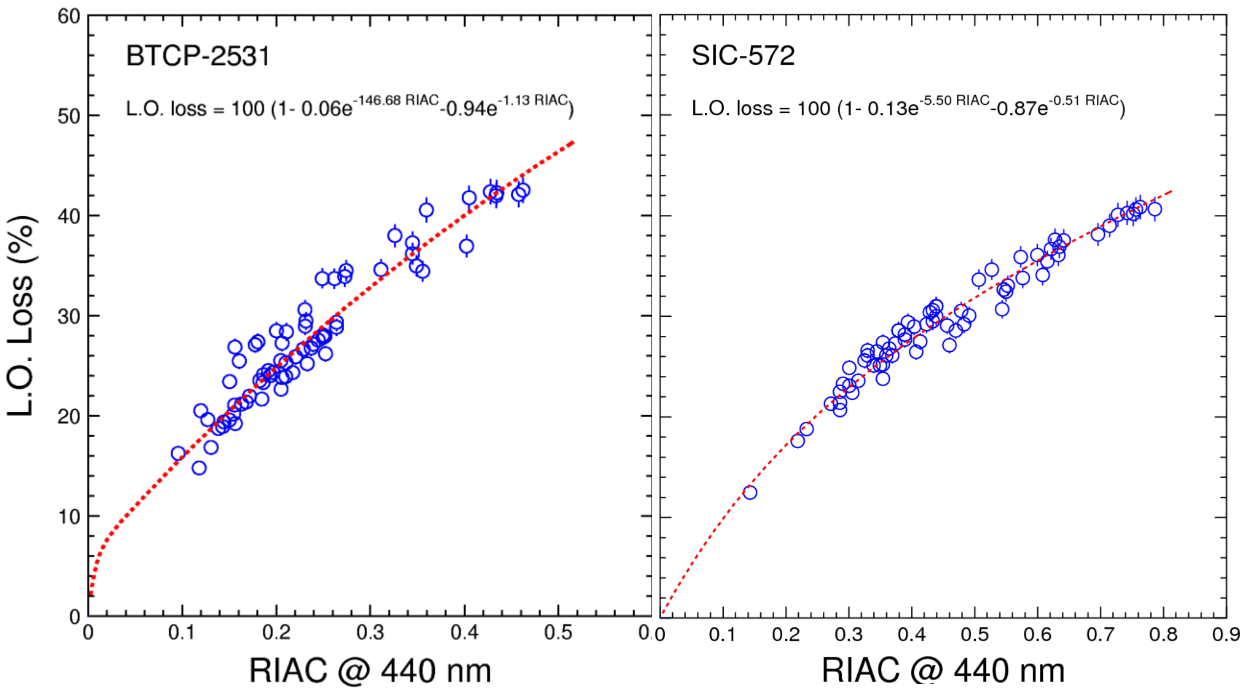




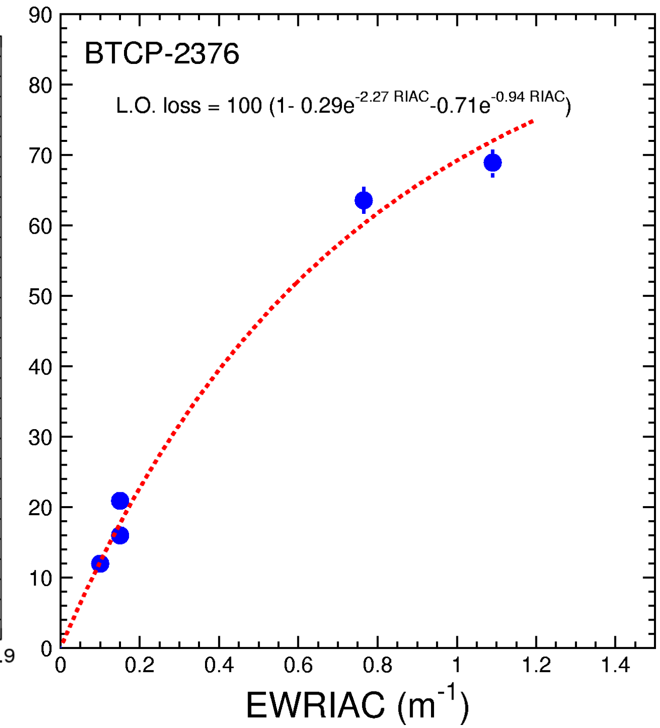
LO Loss versus RIAC

Two exponentials are needed to fit data

Measured with Cs Source



Cosmic Ray Data



Summary of LO Loss vs. RIAC

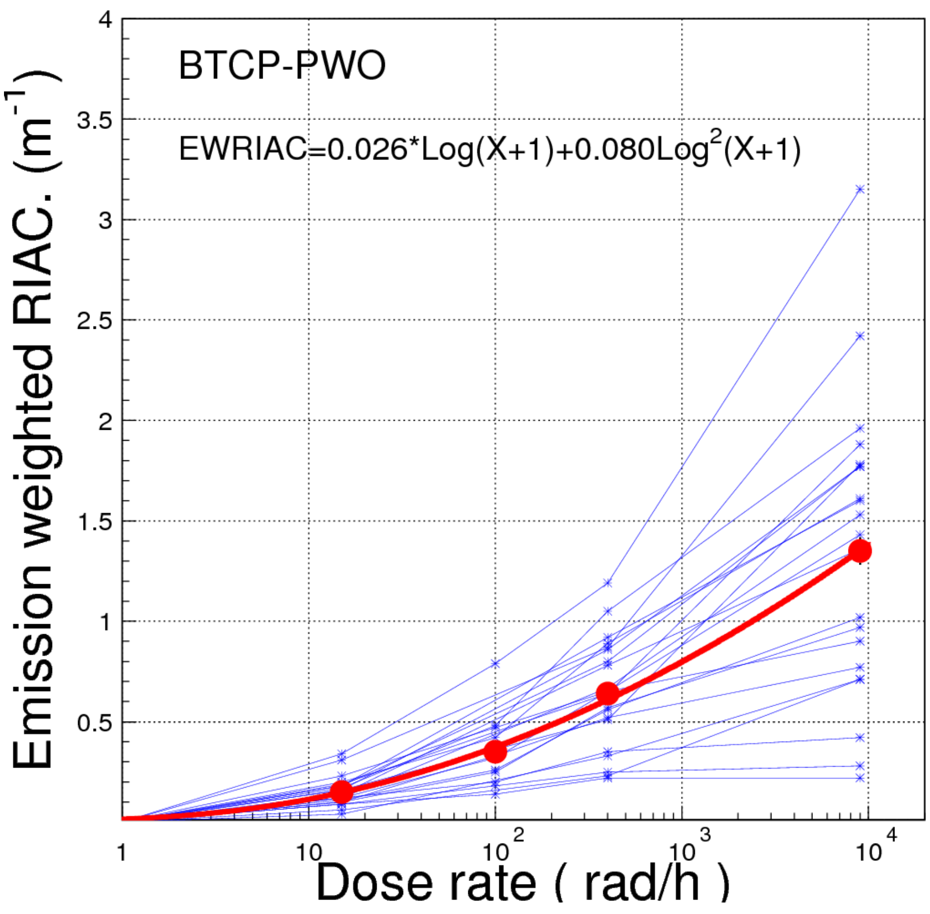
BTCP and SIC crystals self-consistent, but behave differently as observed in monitoring beam tests

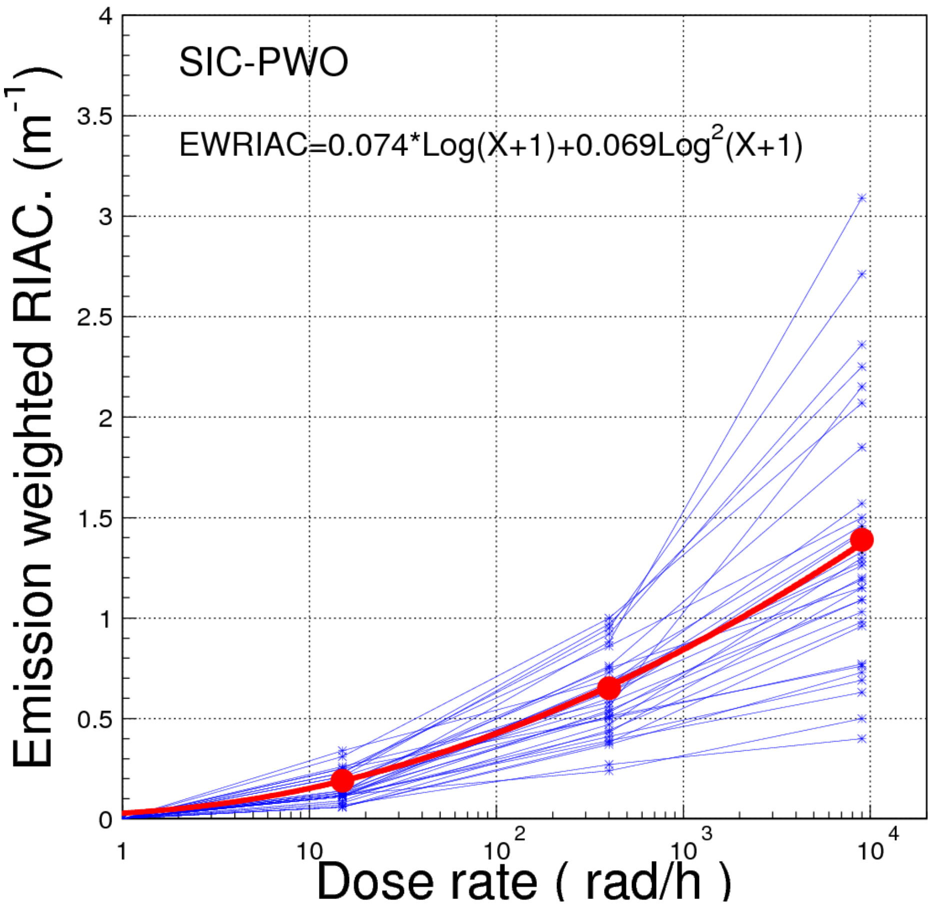
μ (m^{-1})	0.2	0.5	1.0	2.0	5.0	10.0
BTCP-2482	23.7%	43.3%	65.4%	87.2%	99.3%	100.0%
BTCP-2531	25.0%	46.6%	69.6%	90.2%	96.7%	100.0%
BTCP-2376	22.4%	44.8%	66.3%	85.9%	98.8%	100.0%
SIC-570	13.8%	31.1%	52.5%	77.4%	97.6%	99.9%
SIC-572	17.1%	31.8%	47.7%	68.6%	93.2%	99.5%

Result more or less consistent with FN's data

RIAC of Mass Produced Crystals

Average RIAC fits to 2nd order polynomials of log dose rate
Large spread of RIAC under high dose rate is noticed



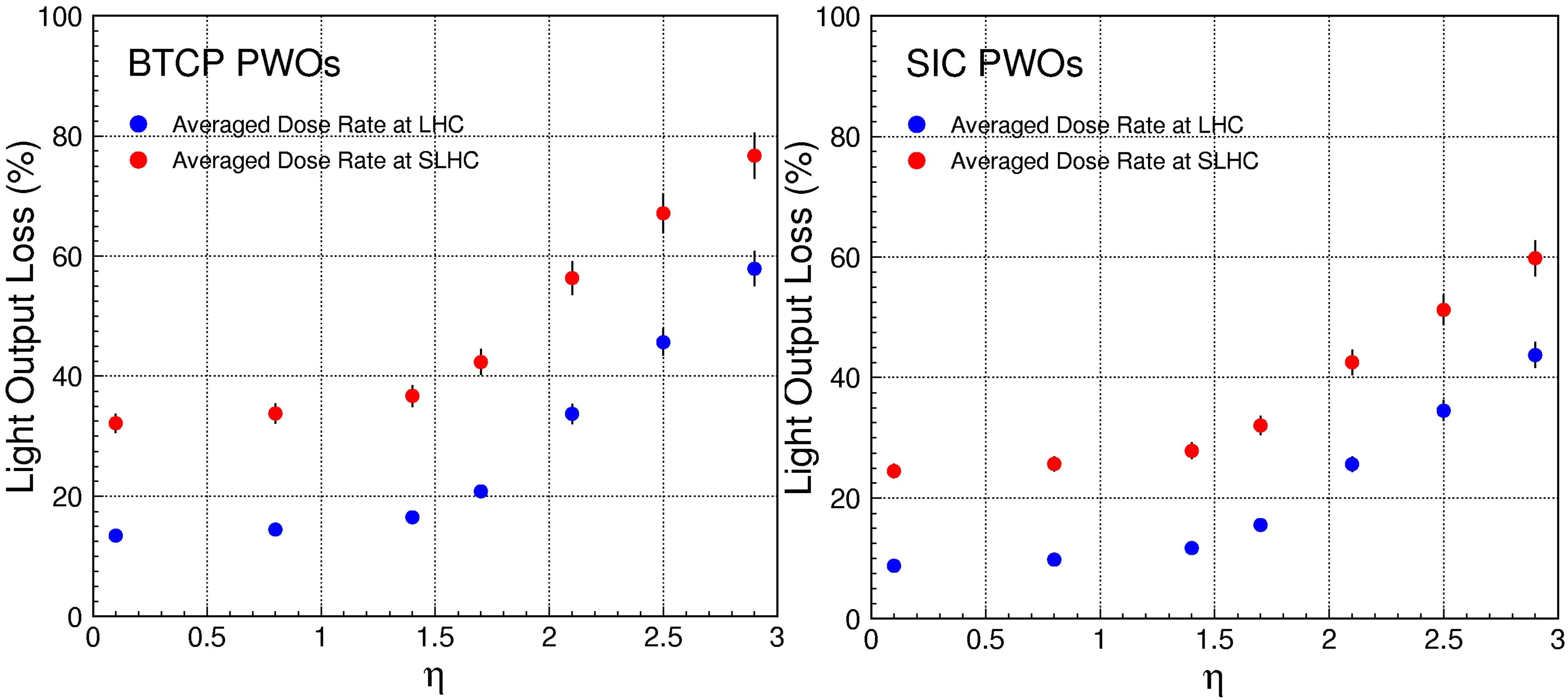


EM Dose Rate Used in Estimation

Pseudo rapidity (η)		0.1	0.8	1.4	1.7	2.1	2.5	2.9
LHC (rad/h)	Ave	6	7	10	17	70	234	826
	Peak	17	19	25	41	160	478	1193
SLHC (rad/h)	Ave	60	70	100	170	700	2340	8260
	Peak	170	190	250	410	1600	4780	11930

Expected LO Loss by EM Dose

Up to 80 and 60% light output loss is expected due to EM dose for BTCP and SIC crystals respectively, which is not as serious as charged hadron damage. Note, this is average.



Why LYSO?

LYSO is a bright (200 times of PWO), fast (40 ns) crystal, and is an intrinsically radiation-hard scintillator. The light output loss of 20 cm long crystals is about 10% after 1 Mrad γ–ray irradiation, so it is expected to survive SLHC. LYSO is preferred than LSO because of its stability in radio luminescence. (See *IEEE Trans. Nucl. Sci.* NS-55 (2008) 1759-1766)

The longitudinal non-uniformity issue caused by the cerium segregation is resolved by optimizing the cerium doping.

Mass production capability exists in industry. Emerging growers in China would help in reducing the crystal cost.

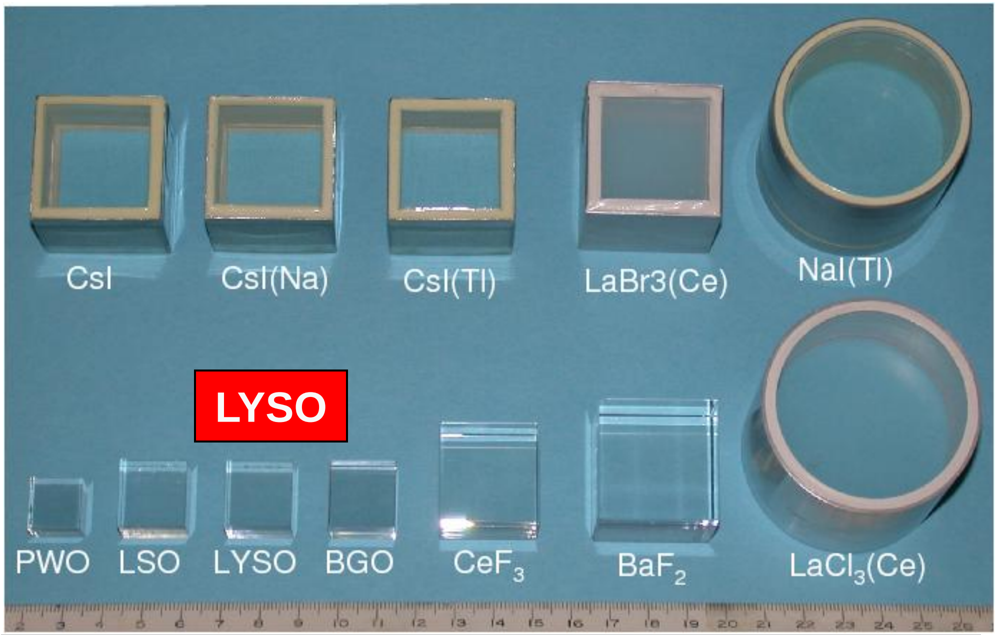
References: *IEEE Trans. Nucl. Sci.* NS-52 (2005) 3133-3140, *Nucl. Instrum. Meth.* A572 (2007) 218-224, *IEEE Trans. Nucl. Sci.* NS-54 (2007) 718-724, *IEEE Trans. Nucl. Sci.* NS-54 (2007) 1319-1326, *IEEE Trans. Nucl. Sci.* NS-55 (2008) 1759-1766 and *IEEE Trans. Nucl. Sci.* NS-55 (2008) 2425-2341, and NSS N69-8 @ NSS08, Dresden.

Crystals for HEP Calorimeters

Crystal	NaI(Tl)	CsI(Tl)	CsI(Na)	CsI	BaF_2	CeF_3	BGO	PWO(Y)	LYSO(Ce)
Density (g/cm^3)	3.67	4.51	4.51	4.51	4.89	6.16	7.13	8.3	7.40
Melting Point (ºC)	651	621	621	621	1280	1460	1050	1123	2050
Radiation Length (cm)	2.59	1.86	1.86	1.86	2.03	1.70	1.12	0.89	1.14
Molière Radius (cm)	4.13	3.57	3.57	3.57	3.10	2.41	2.23	2.00	2.07
Interaction Length (cm)	42.9	39.3	39.3	39.3	30.7	23.2	22.8	20.7	20.9
Refractive Index [a]	1.85	1.79	1.95	1.95	1.50	1.62	2.15	2.20	1.82
Hygroscopicity	Yes	Slight	Slight	Sligh t	No	No	No	No	No
Luminescence [b] (nm) (at peak)	410	550	420	420 310	300 220	340 300	480	425 420	402
Decay Time [b] (ns)	245	1220	690	30 6	650 0.9	30	300	30 10	40
Light Yield [b,c] (%)	100	165	88	3.6 1.1	36 4.1	7.3	21	0.3 0.1	85
d(LY)/dT [b] (%/ ºC)	-0.2	0.4	0.4	-1.4	-1.9 0.1	0	-0.9	-2.5	-0.2
Experiment	Crystal Ball	BaBar BELLE BES III	-	KTeV	(L*) (GEM) TAPS	-	L3 BELLE	CMS ALICE PANDA	SuperB? CMS?

a. at peak of emission; b. up/low row: slow/fast component; c. QE of readout device taken out.

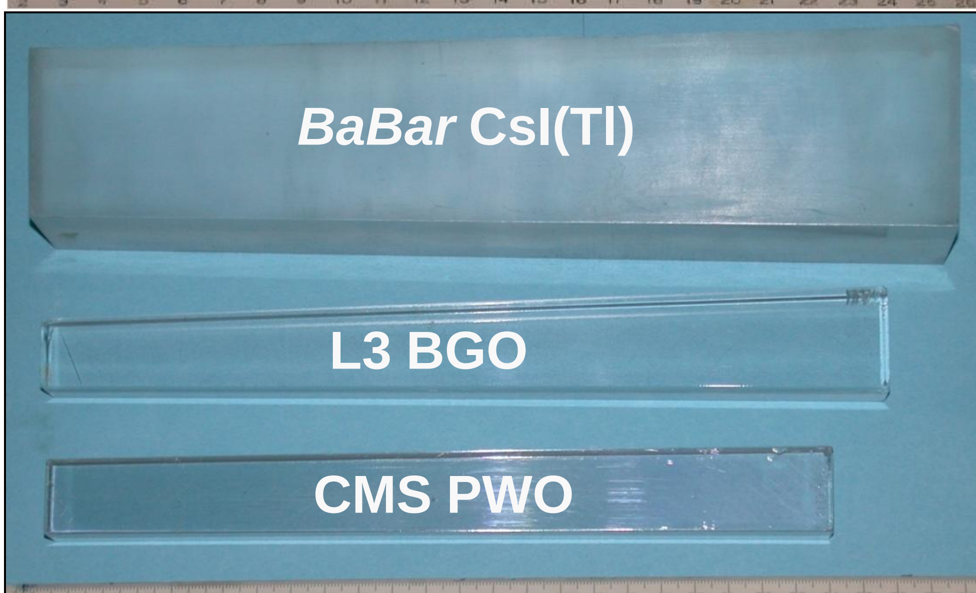
Crystal Density: Radiation Length



$1.5\ X_0$ Samples:

Hygroscopic: Sealed

Non-hygro: Polished



Full Size Crystals:

BaBar CsI(Tl): $16\ X_0$

L3 BGO: $22\ X_0$

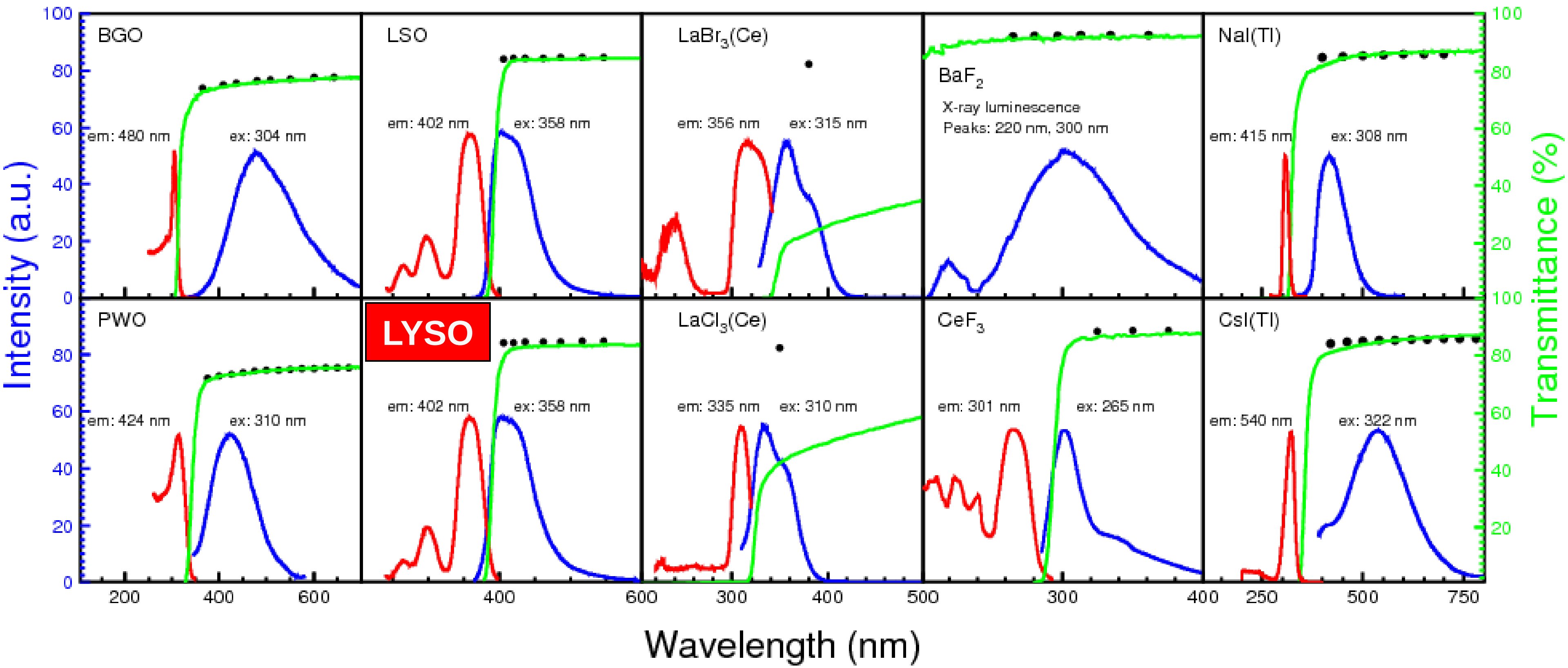
CMS PWO(Y): $25\ X_0$

Excitation, Emission, Transmission

$$T_s = (1-R)^2 + R^2(1-R)^2 + \ldots = (1-R)/(1+R), \text{ with}$$

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

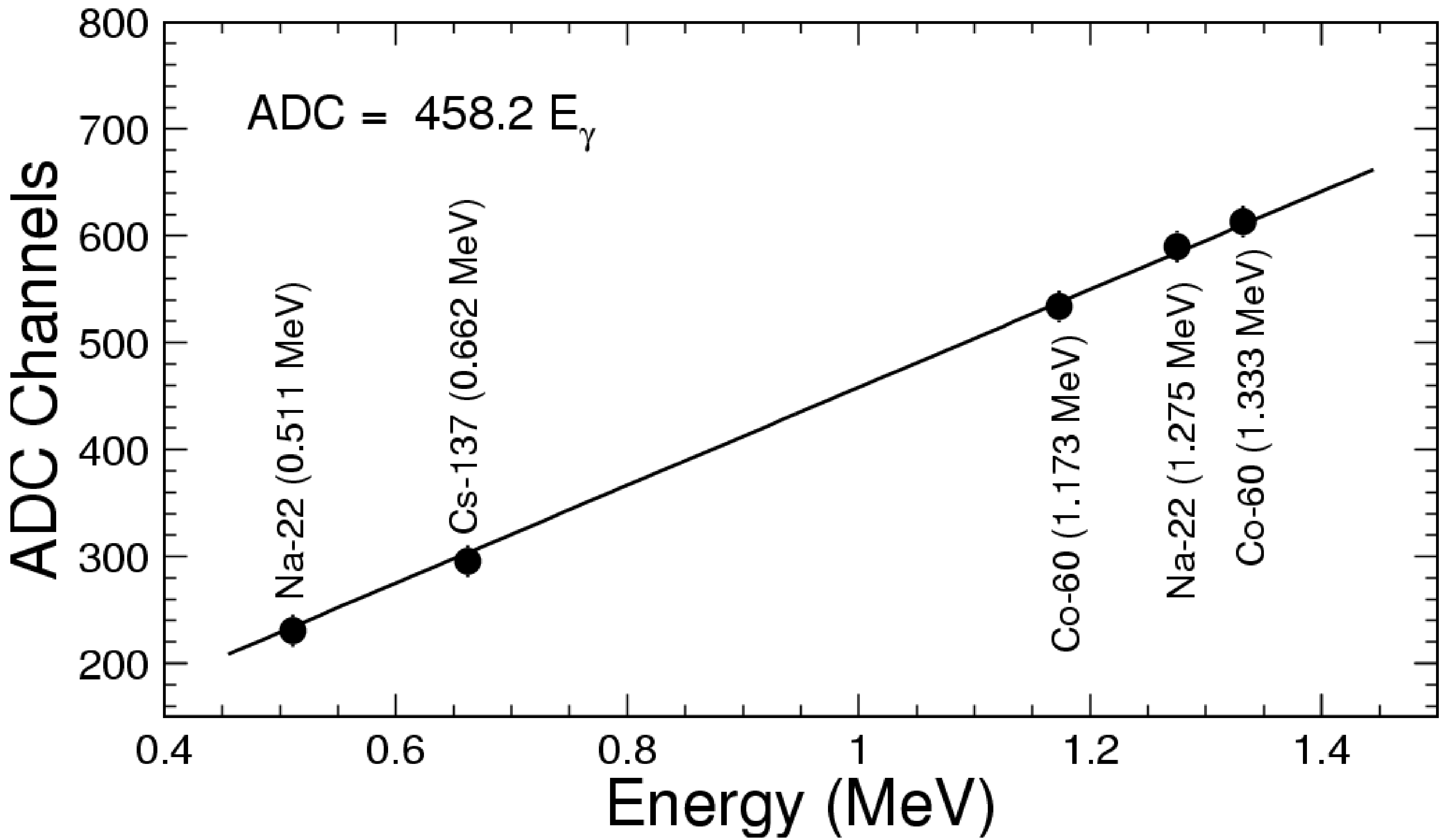
Black Dots: Theoretical limit of transmittance: NIM A333 (1993) 422



No Self-absorption: BGO, PWO, BaF$_2$, NaI(Tl) and CsI(Tl)

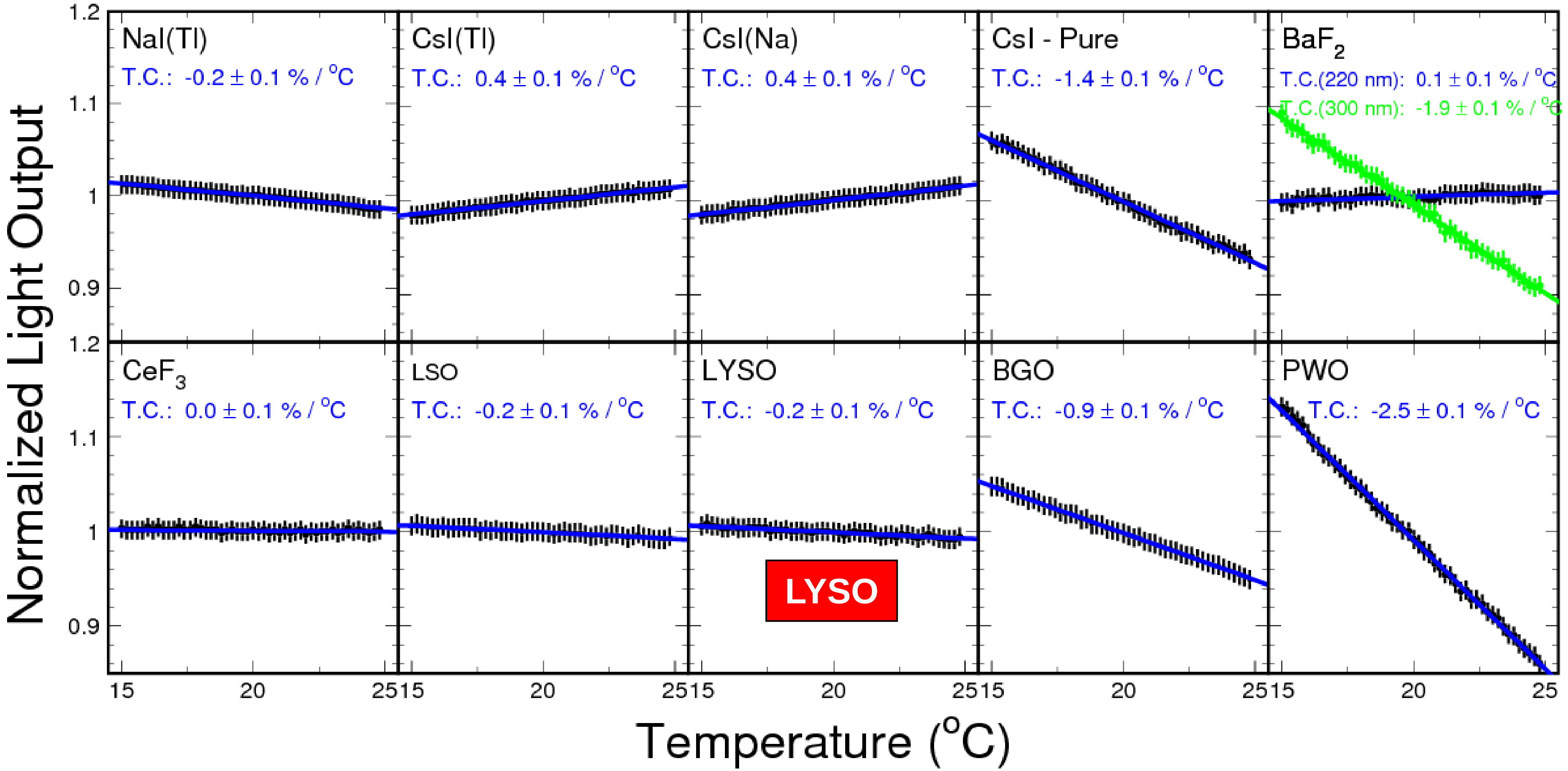
Excellent Linearity: > 0.51 MeV

Observed with APD readout



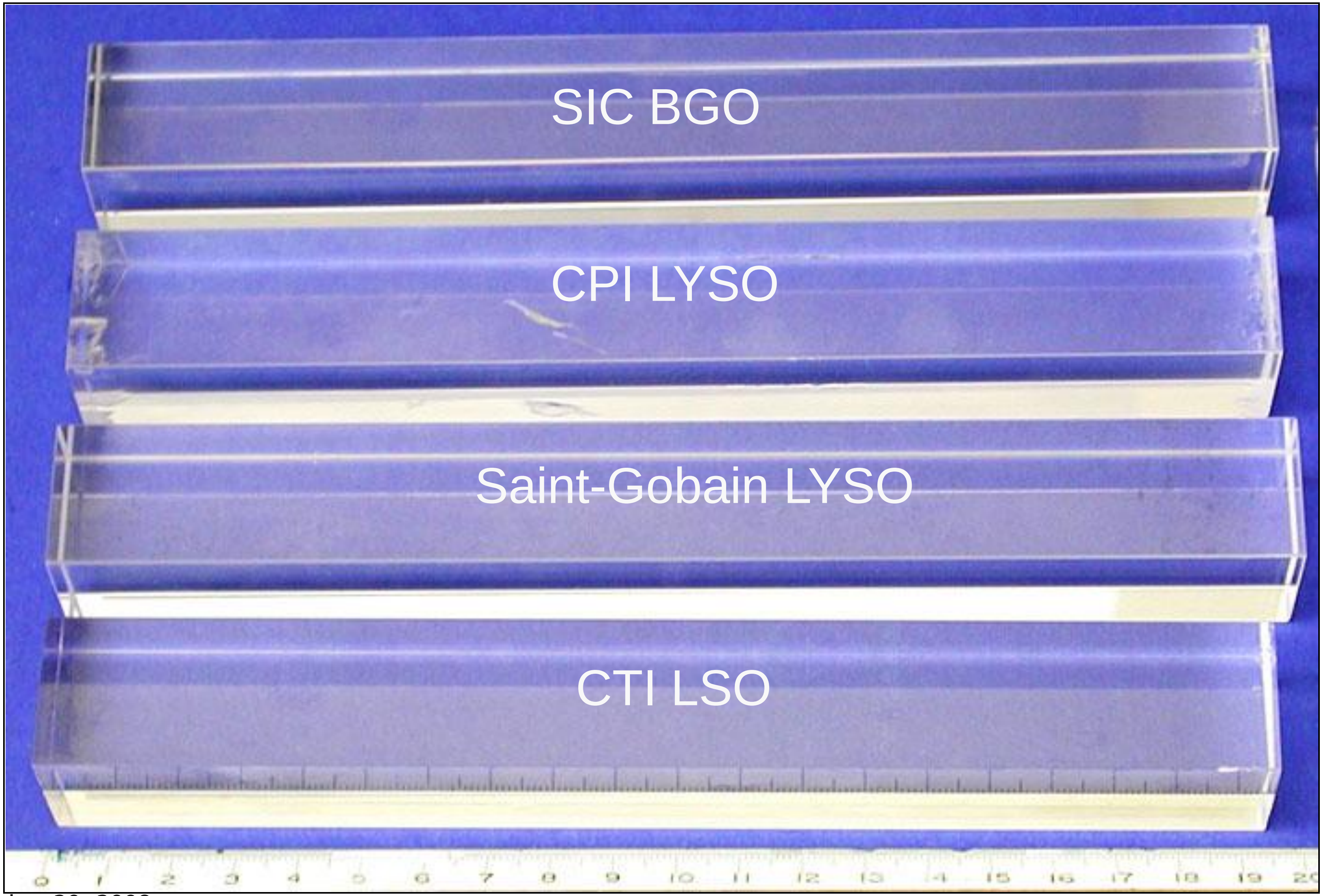
Light Output Temperature Coefficient

Temperature Range: 15ºC ~ 25ºC
Good crystals: CeF_3, LSO, LYSO and NaI(Tl)



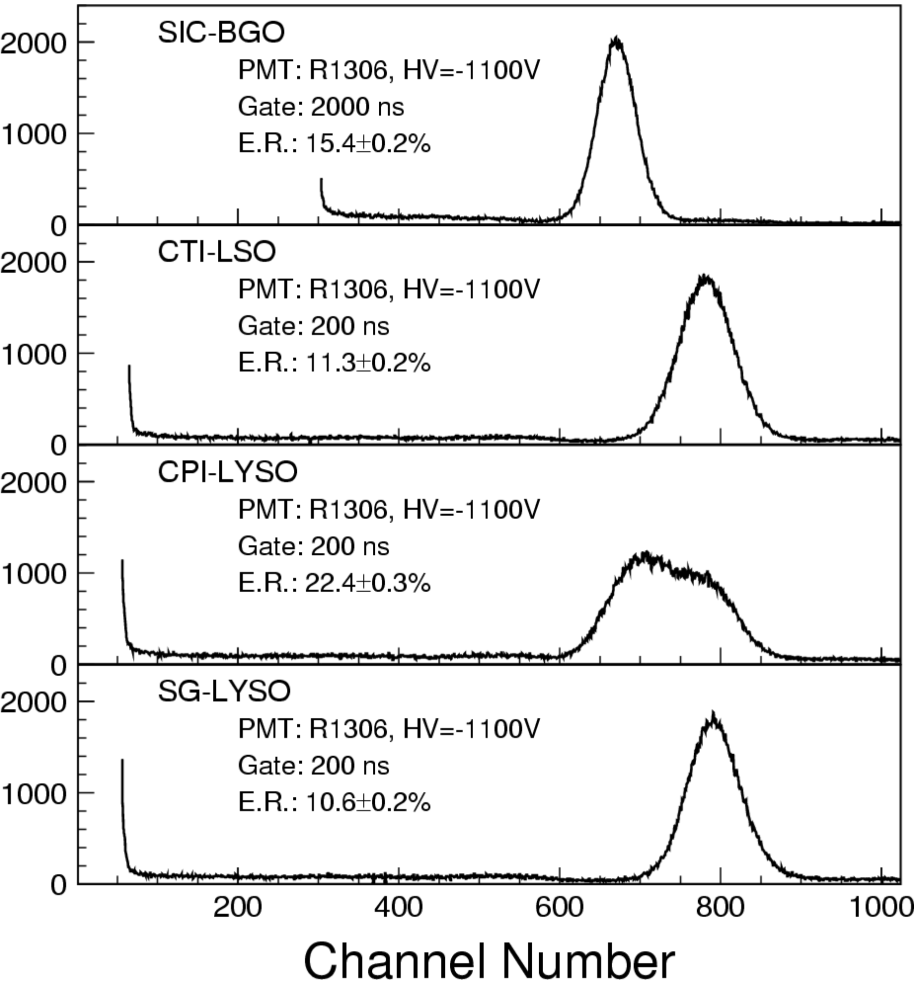
BGO, LSO & LYSO Samples

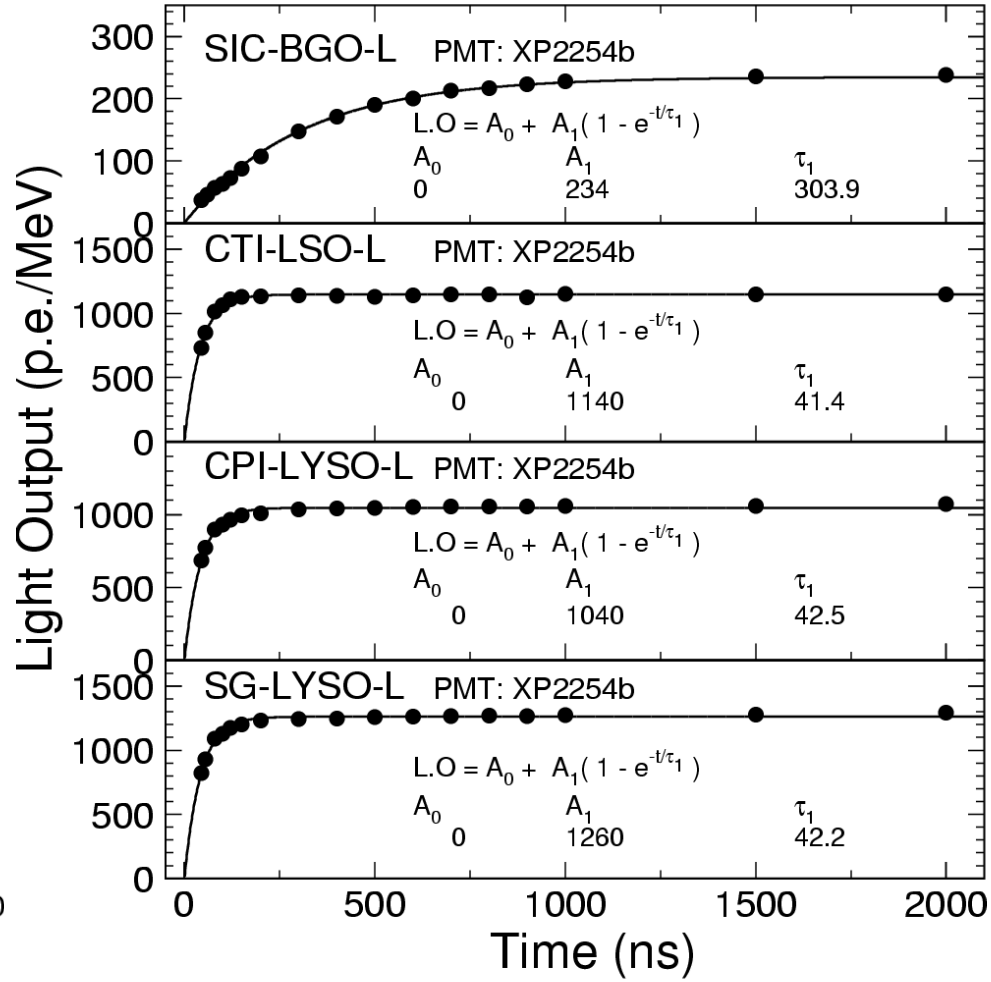
2.5 x 2.5 x 20 cm (18 X_0)



LSO/LYSO with PMT Readout

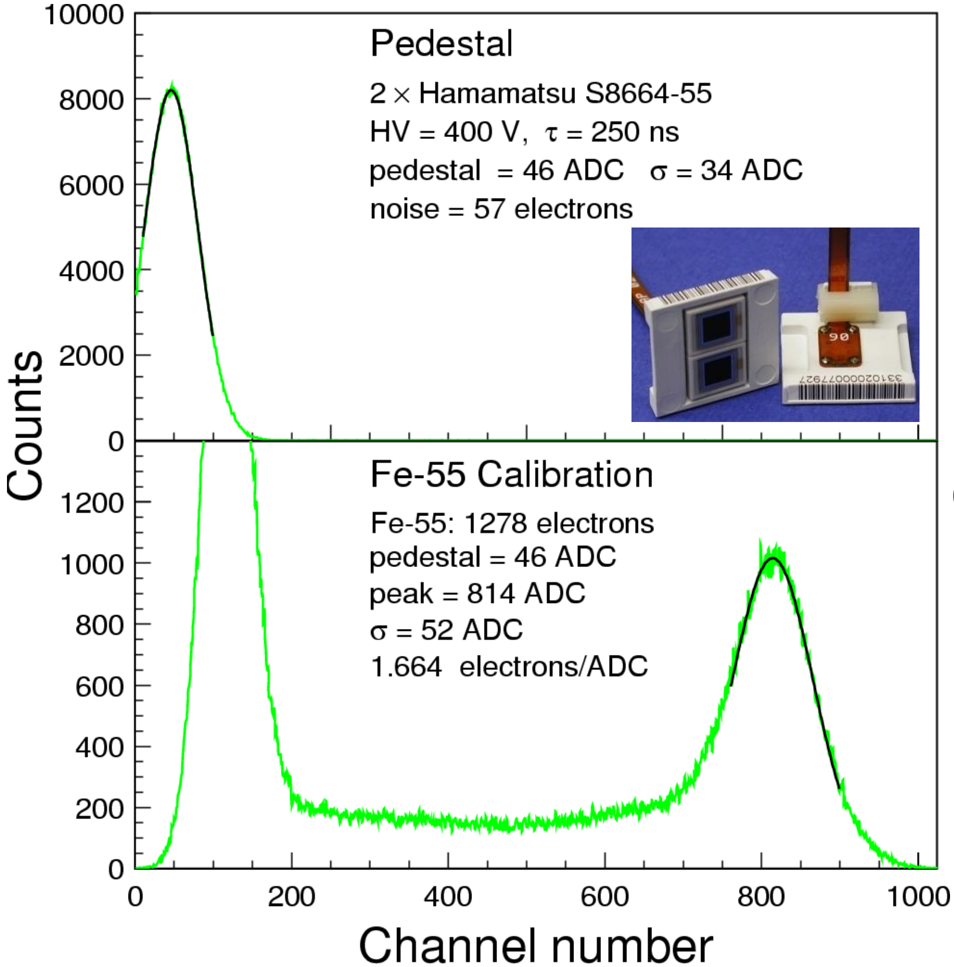
~10% FWHM resolution for ^{22}Na source (0.51 MeV)
40 ns, 1,200 p.e./MeV, 5/230 times of BGO/PWO

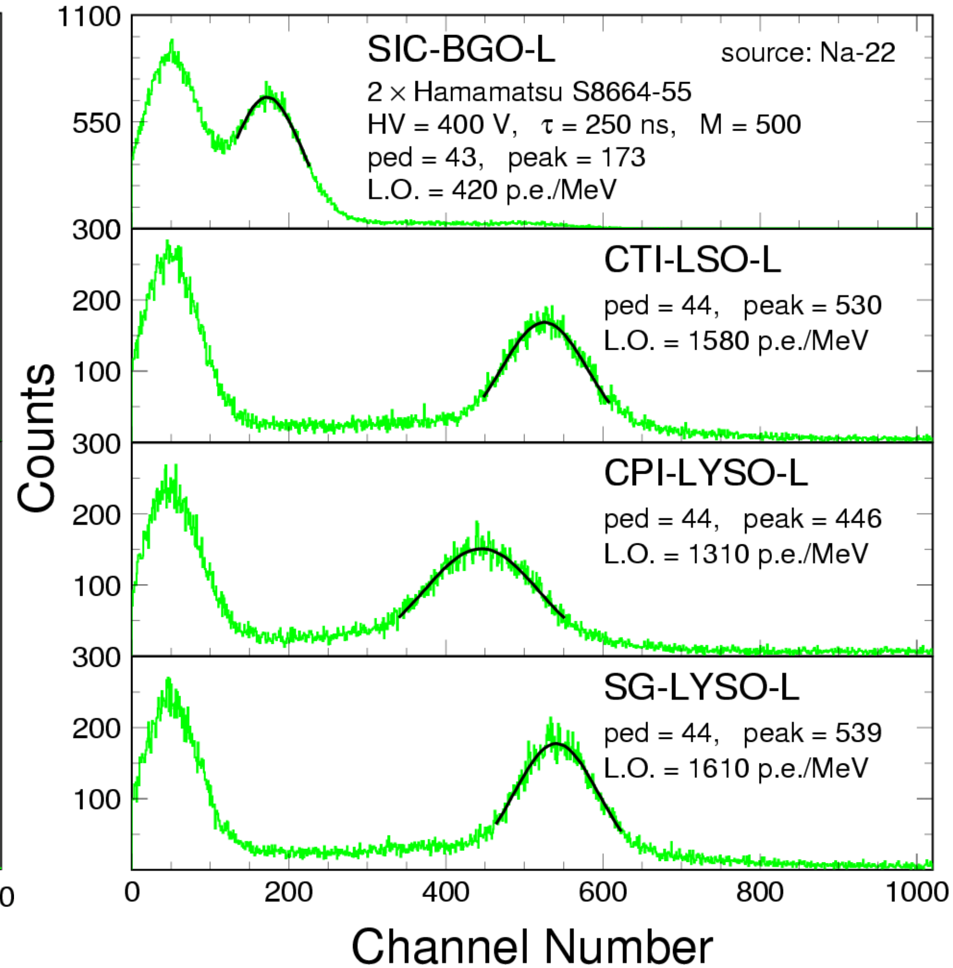




LSO/LYSO with APD Readout

L.O.: 1,500 p.e./MeV, 4/200 times of BGO/PWO
Readout Noise: < 40 keV

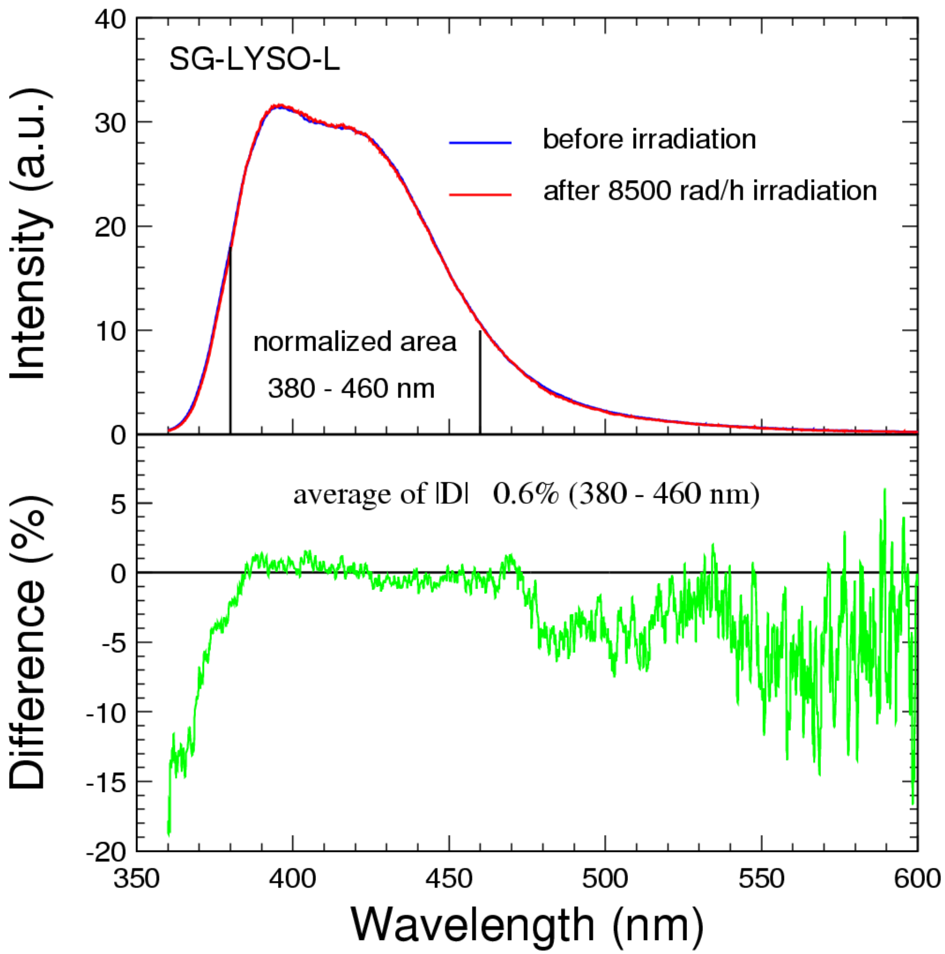


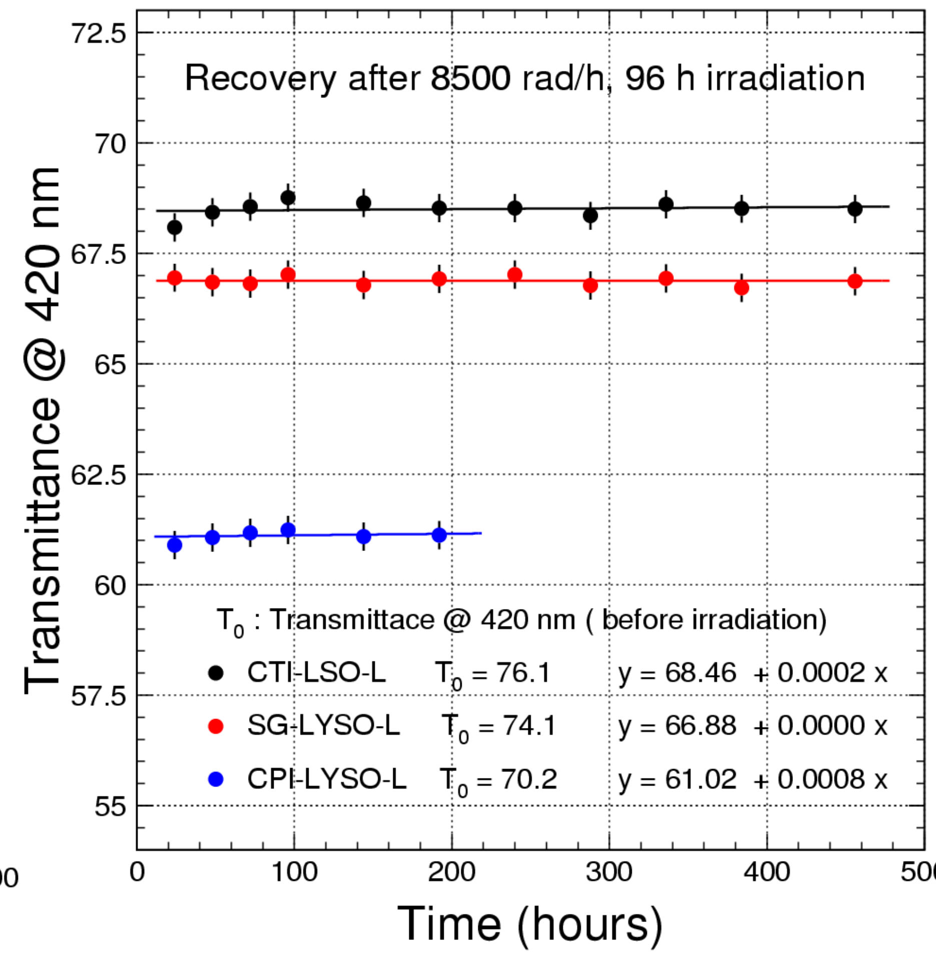


γ-Rays Induced Damage

No damage in photo-luminescence

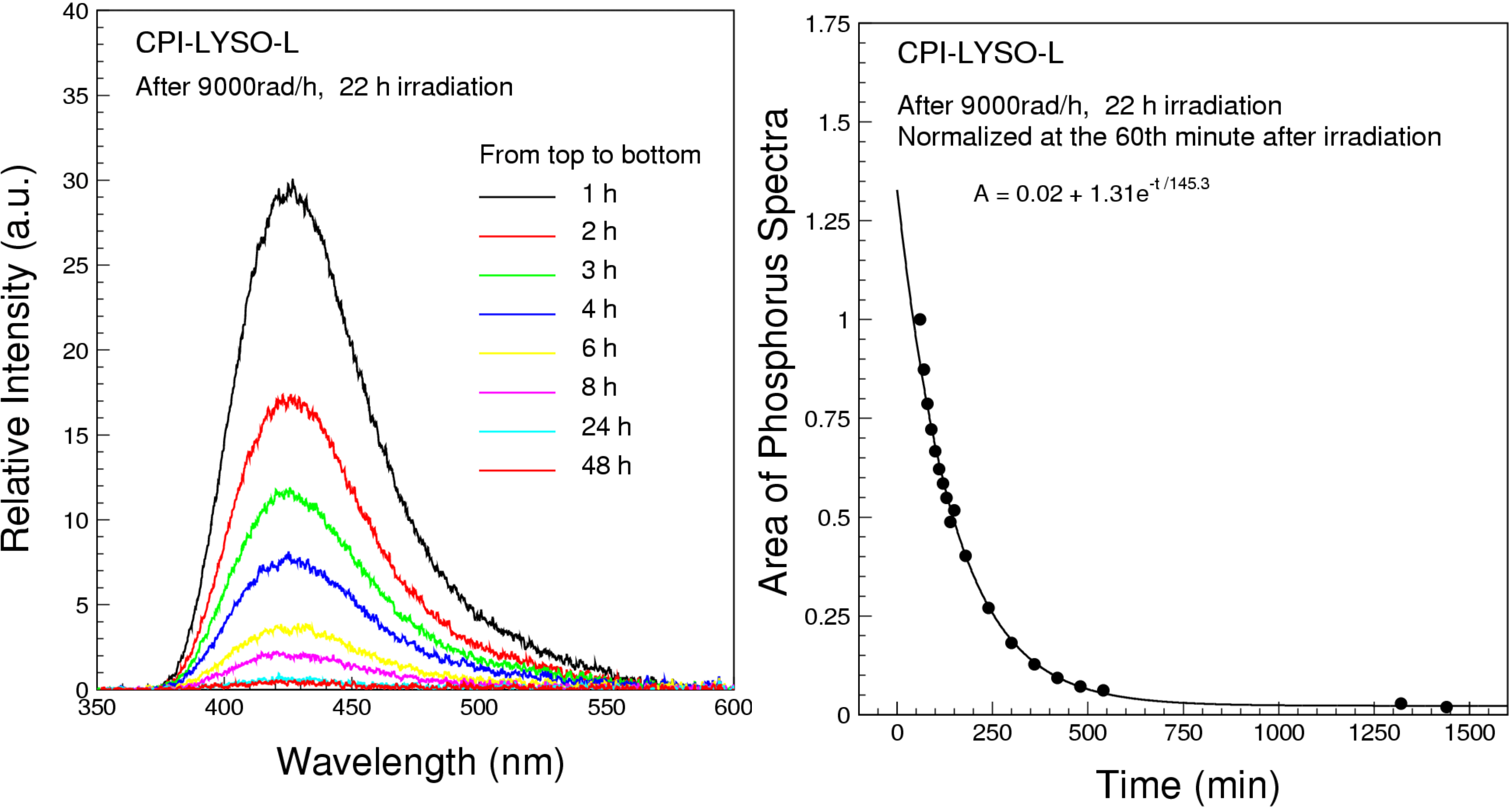
Transmittance recovery slow





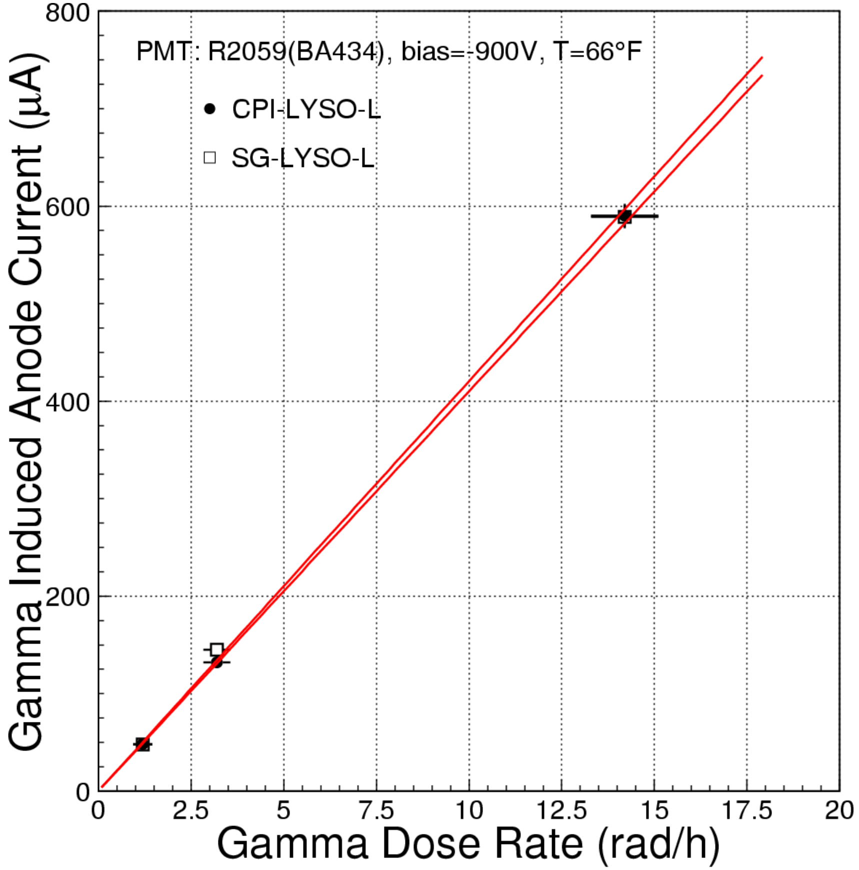
γ–Ray Induced Phosphorescence

Phosphorescence peaked at 430 nm with decay time constant of 2.5 h observed



γ–Ray Induced Readout Noise

Sample ID	L.Y. p.e./MeV	F μA/rad/h	$Q_{15\ rad/h}$ p.e.	$Q_{500\ rad/h}$ p.e.	$\sigma_{15\ rad/h}$ MeV	$\sigma_{500\ rad/h}$ MeV
CPI	1,480	41	6.98×10^4	2.33×10^6	0.18	1.03
SG	1,580	42	7.15×10^4	2.38×10^6	0.17	0.97

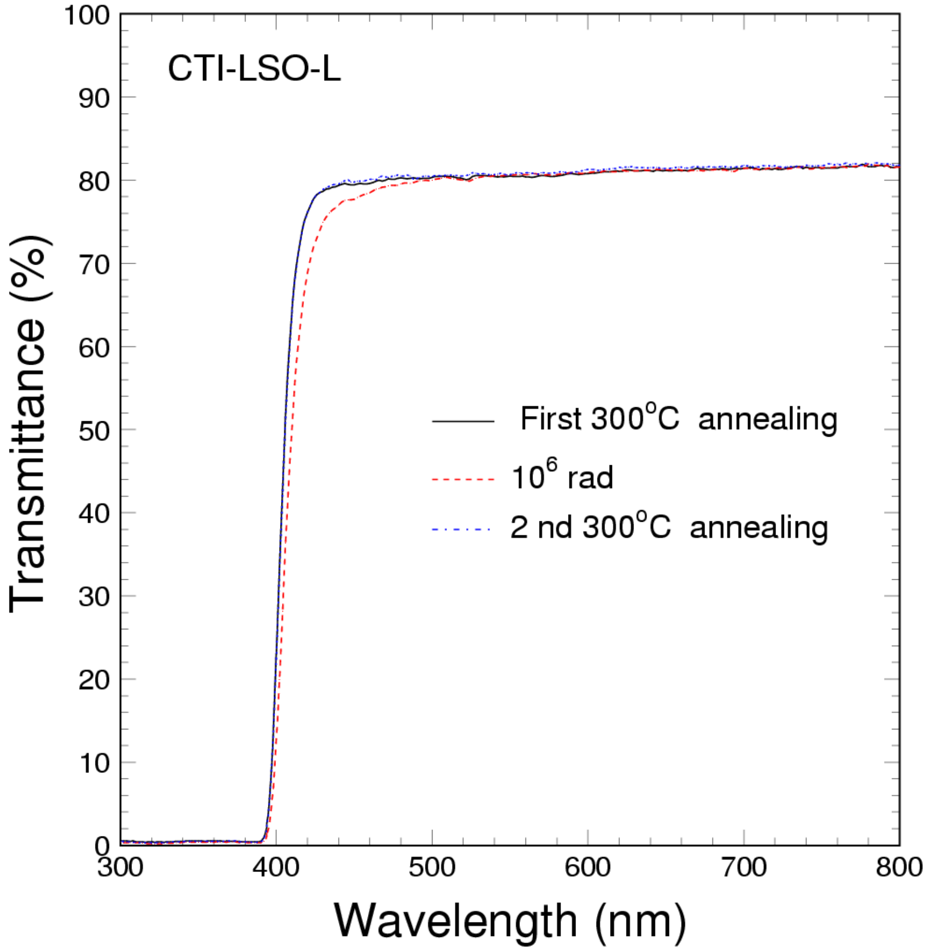


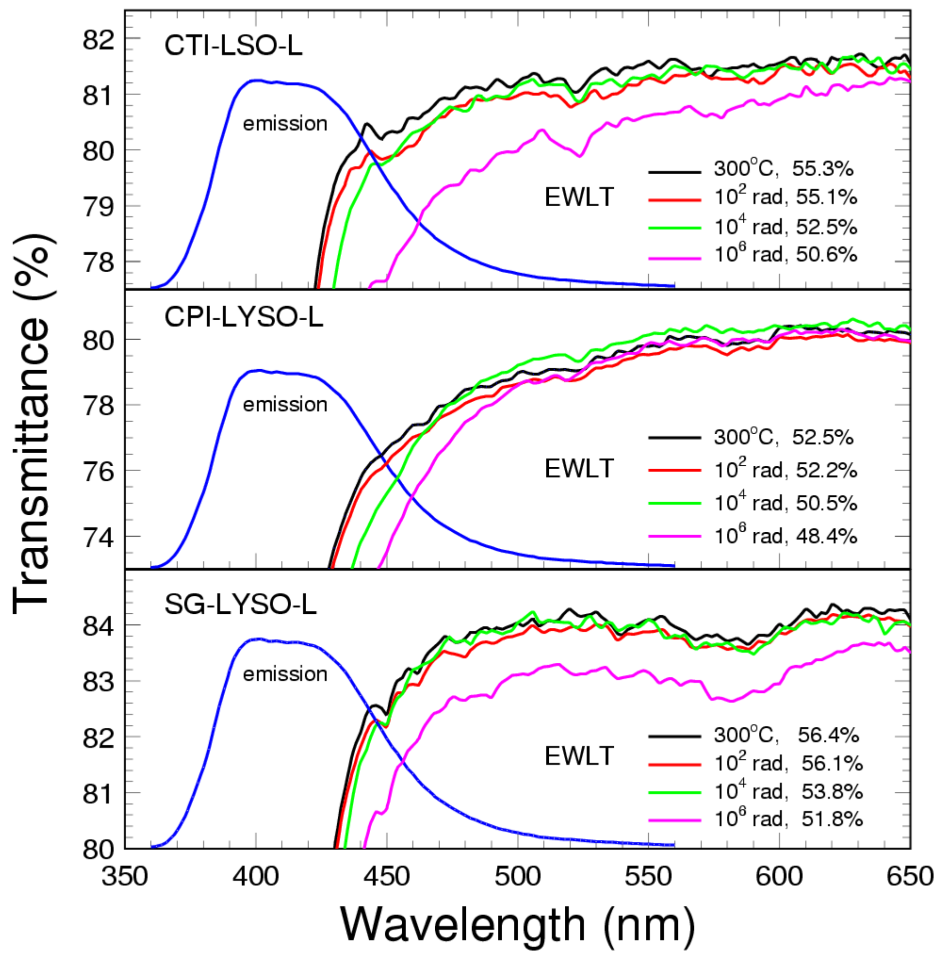
γ–ray induced PMT anode current can be converted to the photoelectron numbers (Q) integrated in 100 ns gate. Its statistical fluctuation contributes to the readout noise (σ): 0.2 & 1 MeV @ 15 & 500 rad/h.

γ-Rays Induced Transmittance Damage

300ºC thermal annealing effective

LT damage: 8% @ 1 Mrad

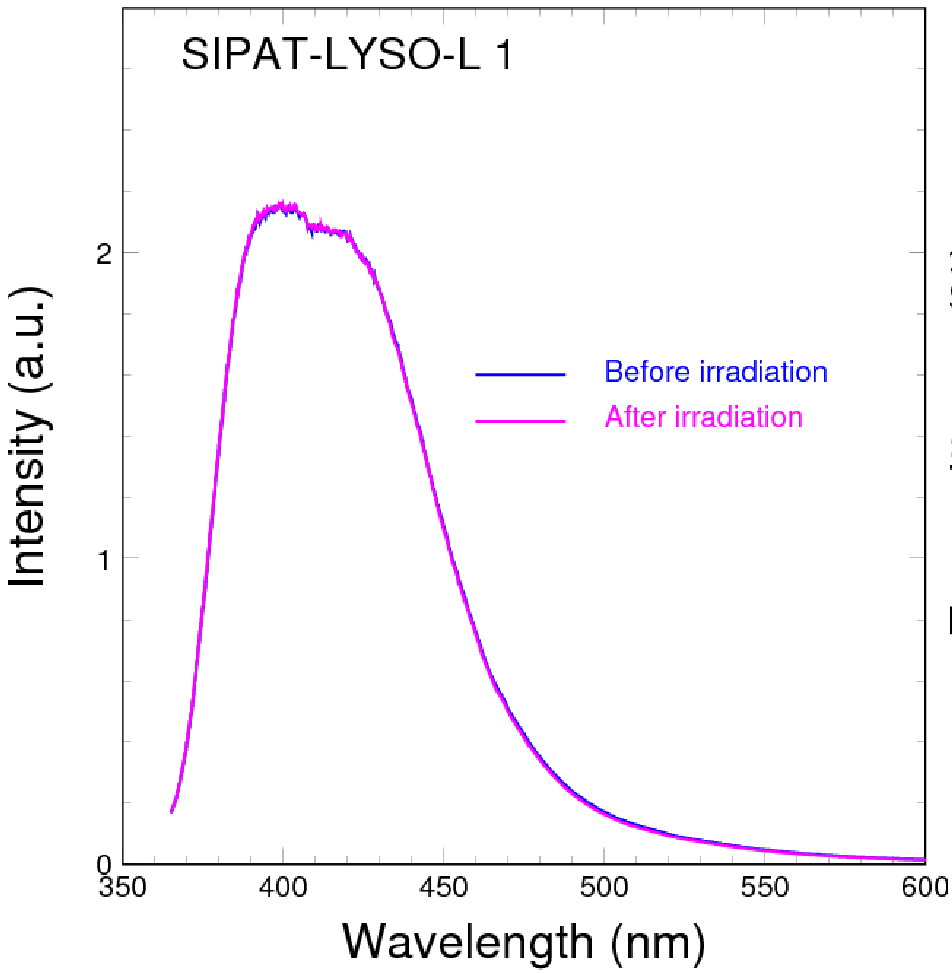


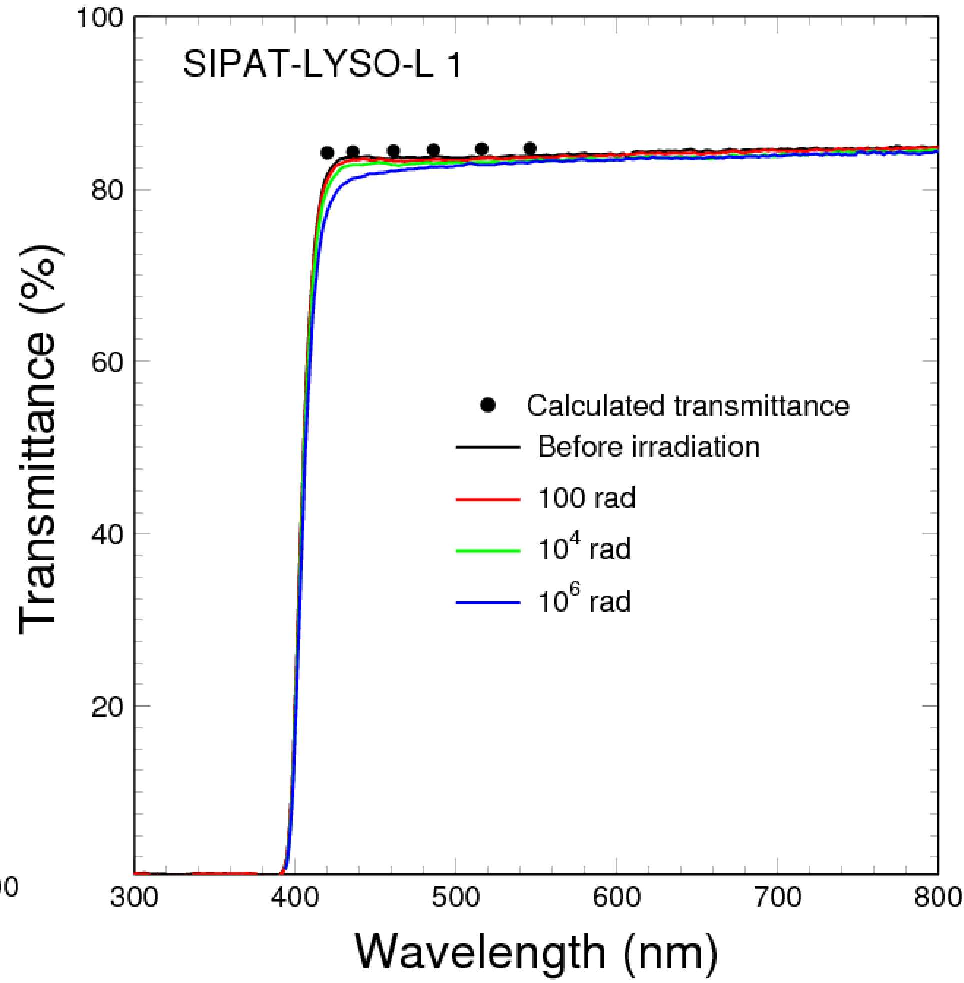


Similar γ-Ray Damage in SIPAT LYSO

Scintillation spectrum not affected by irradiation

~8% damage @ 420 nm after 1 Mrad irradiation



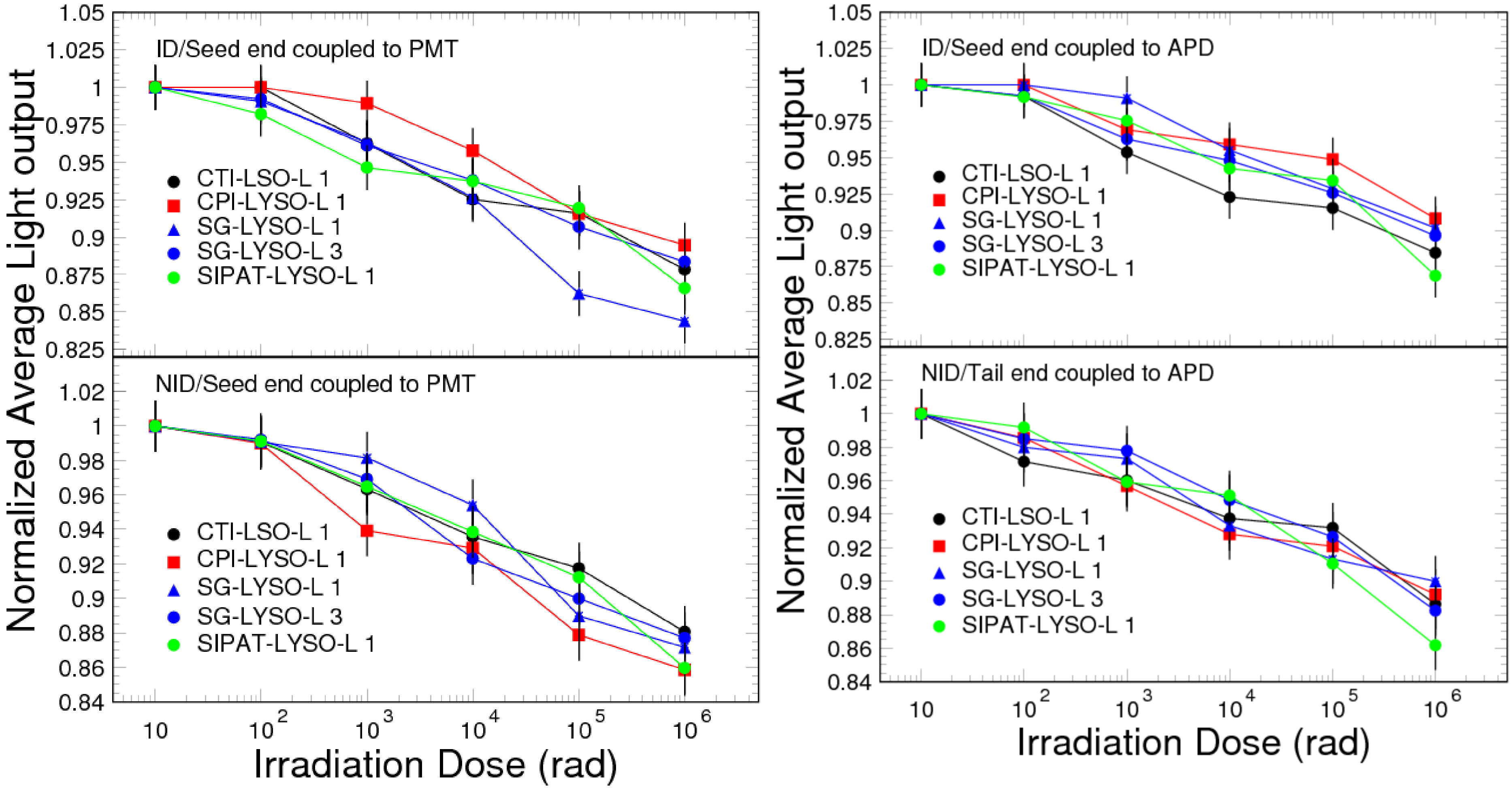


About 10% L.O. Loss after 1 Mrad

All samples show consistent radiation resistance

10% - 15% loss by PMT

9% - 14% loss by APD



LSO/LYSO ECAL Performance

- Less demanding to the environment because of small temperature coefficient.
- Radiation damage is less an issue as compared to other crystals.
- A better energy resolution, $\sigma(E)/E$, at low energies than L3 BGO and CMS PWO because of its high light output and low readout noise:

$$2.0\%/\sqrt{E} \oplus 0.5\% \oplus .001/E$$

LSO/LYSO Mass Production

CTI: LSO

CPI: LYSO

Saint-Gobain LYSO

Additional Capability: SIPAT @ Sichuan and SICCAS @ Shanghai, China

Sichuan Institute of Piezoelectric and Acousto-optic Technology (SIPAT)

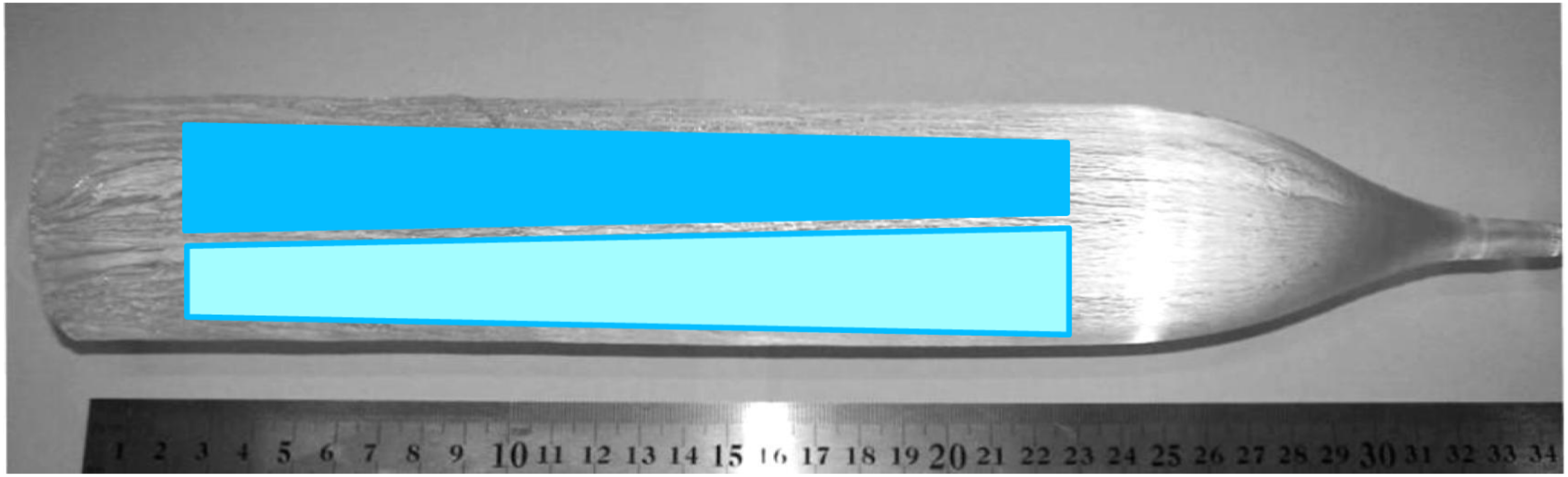
China Electronics Technology Corporation (CETC)
No. 26 Research Institute, www.sipat.com

SIPAT Czochralski Furnaces

SIPAT Ø60 x 250 mm LYSO Ingots

LYSO Longitudinal Uniformity

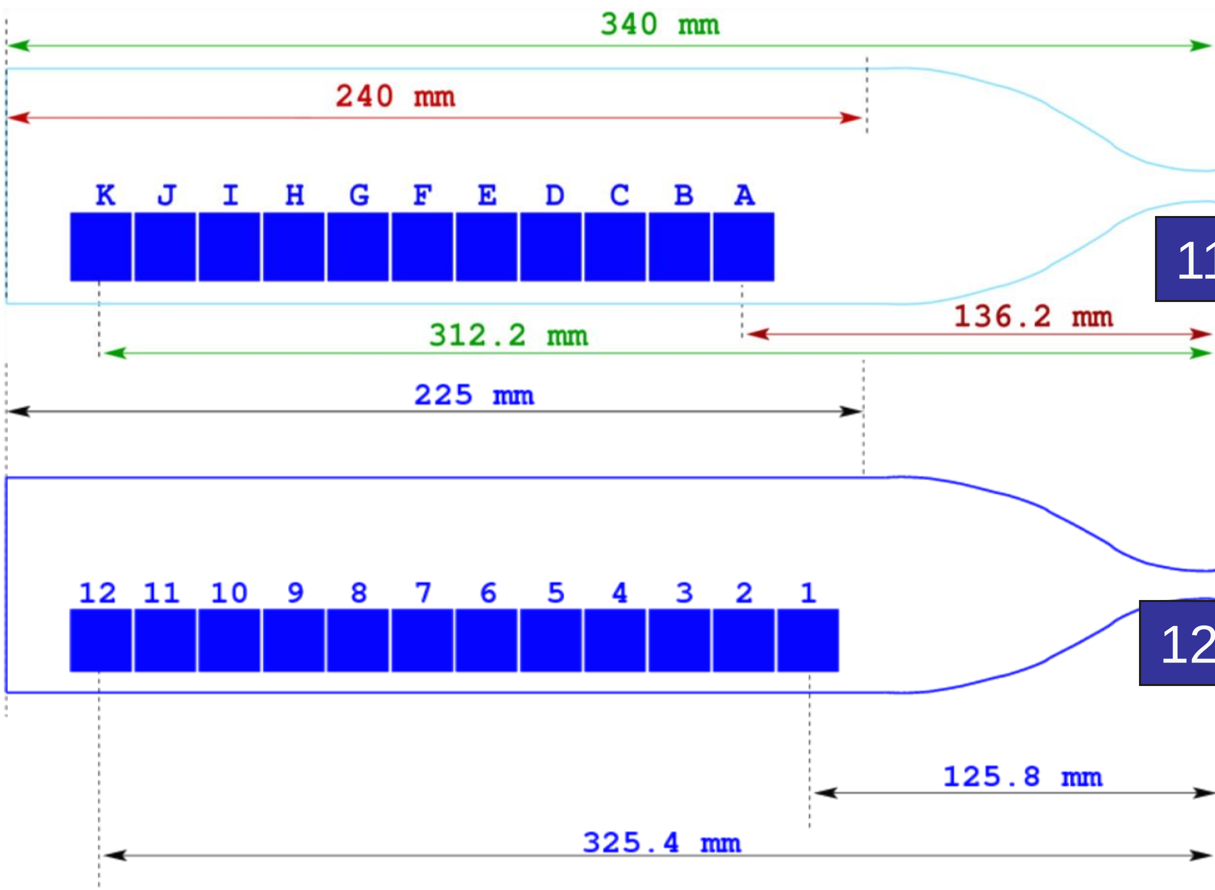
➢ Good light response uniformity is crucial for a crystal calorimeter to achieve its designed energy resolution. The distribution of the cerium activator, however, is not uniform along the crystal.



➢ Sipat's Φ60 x 250 mm ingot may be cut to two SuperB crystals, significantly increasing the ingot usage. The key issue: longitudinally uniformity.

Ingots Grown at SIPAT

Ingots grown by Czochralski method at Sichuan Institute of Piezoelectric and Acousto-optic Technology (SIPAT), China.



1st ingot with high cerium

11 cubes of 17 (1.5 X_0) mm^3

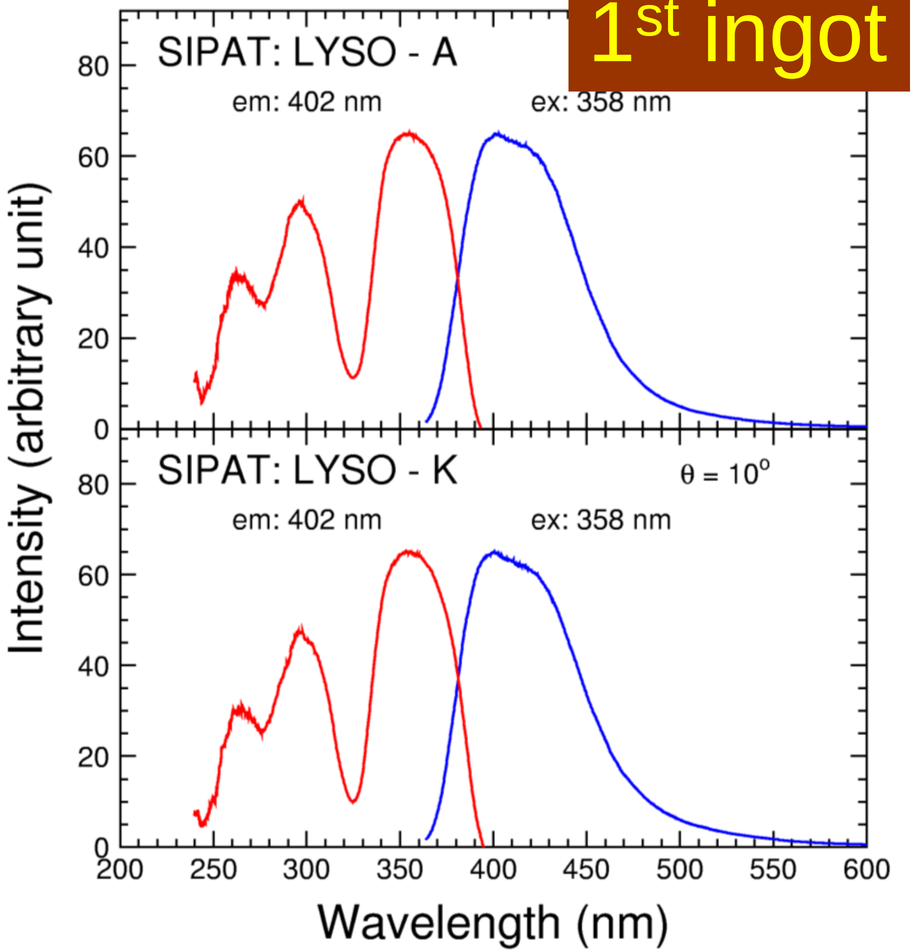
2nd ingot with low cerium

12 cubes of 17 (1.5 X_0) mm^3

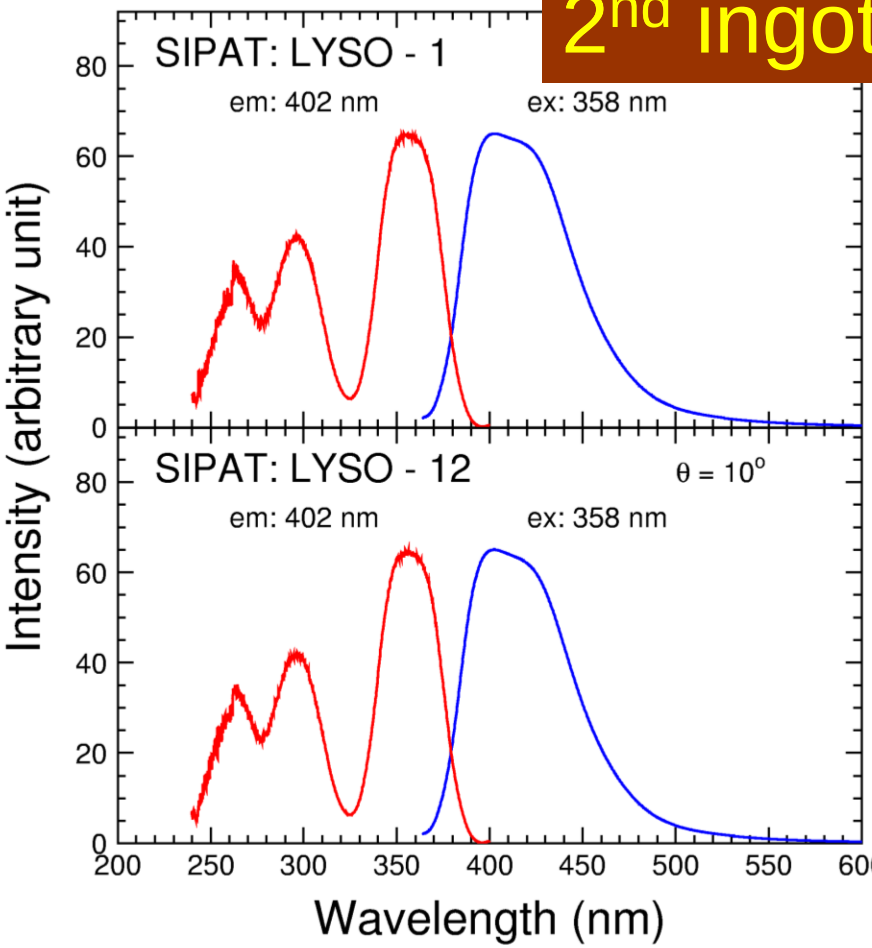
UV Excitation & Emission Spectra

Consistent excitation (red) and emission (blue) spectra observed from seed to tail for both ingots.

1st ingot



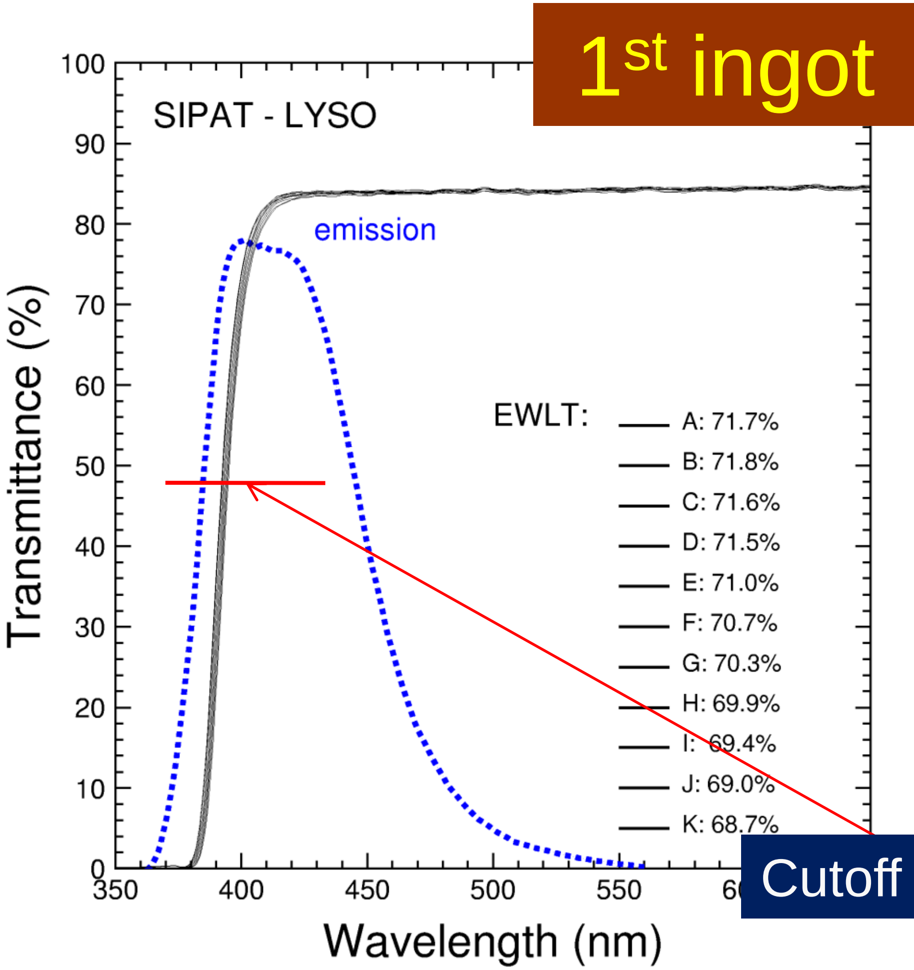
2nd ingot

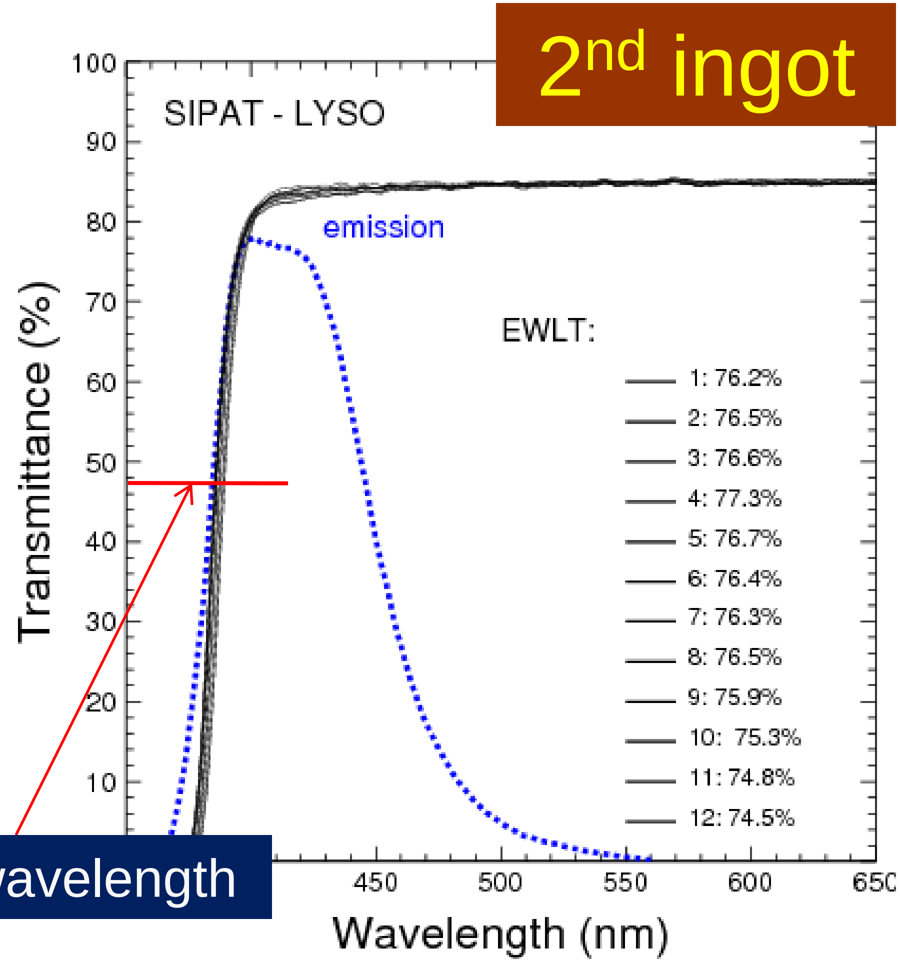


Transmission Spectra

Transmissions are position dependent:

$$EWLT = \frac{\int LT(\lambda)Em(\lambda)d\lambda}{\int Em(\lambda)d\lambda}$$

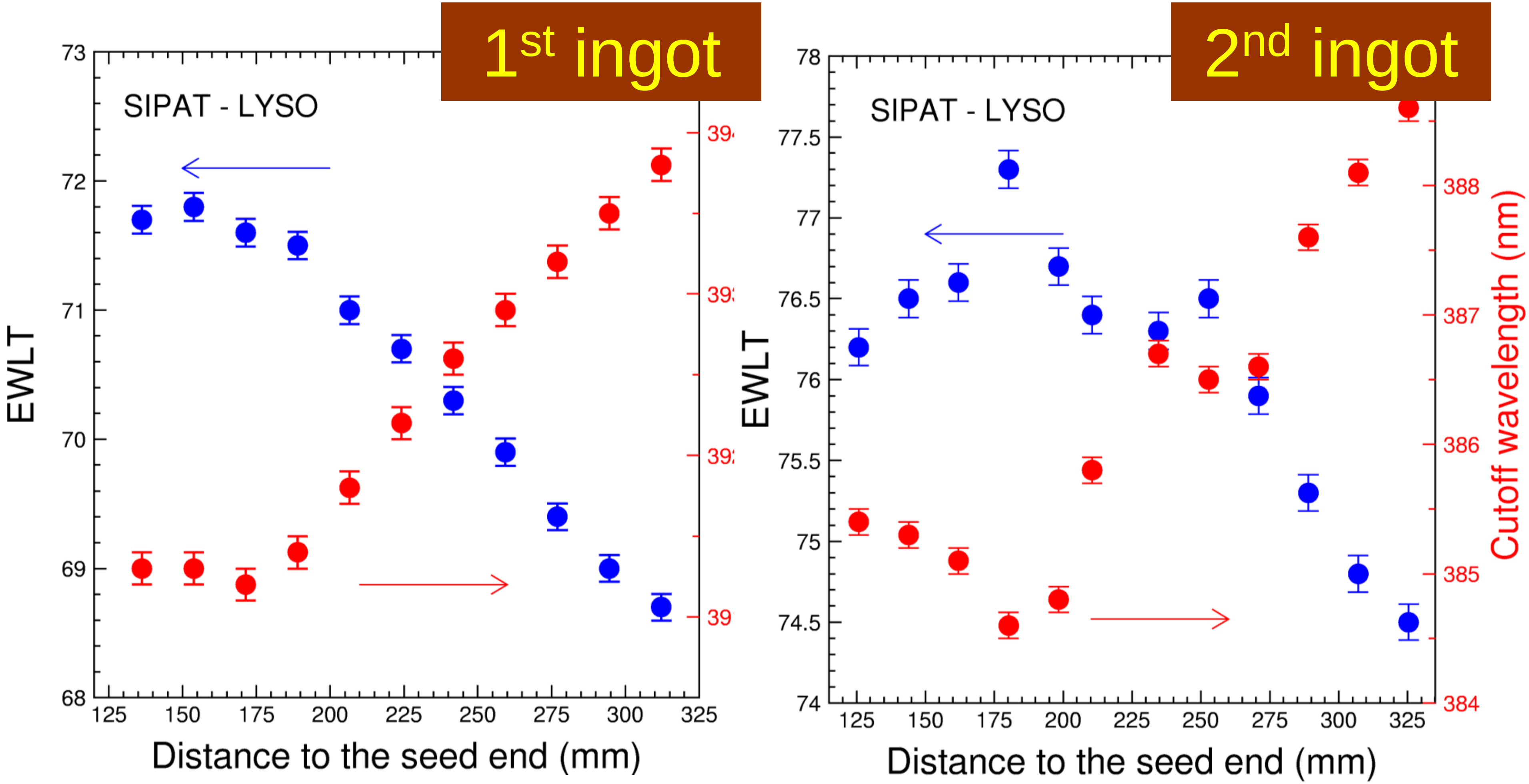




Cutoff wavelength

EWLT and Cut-off versus Position

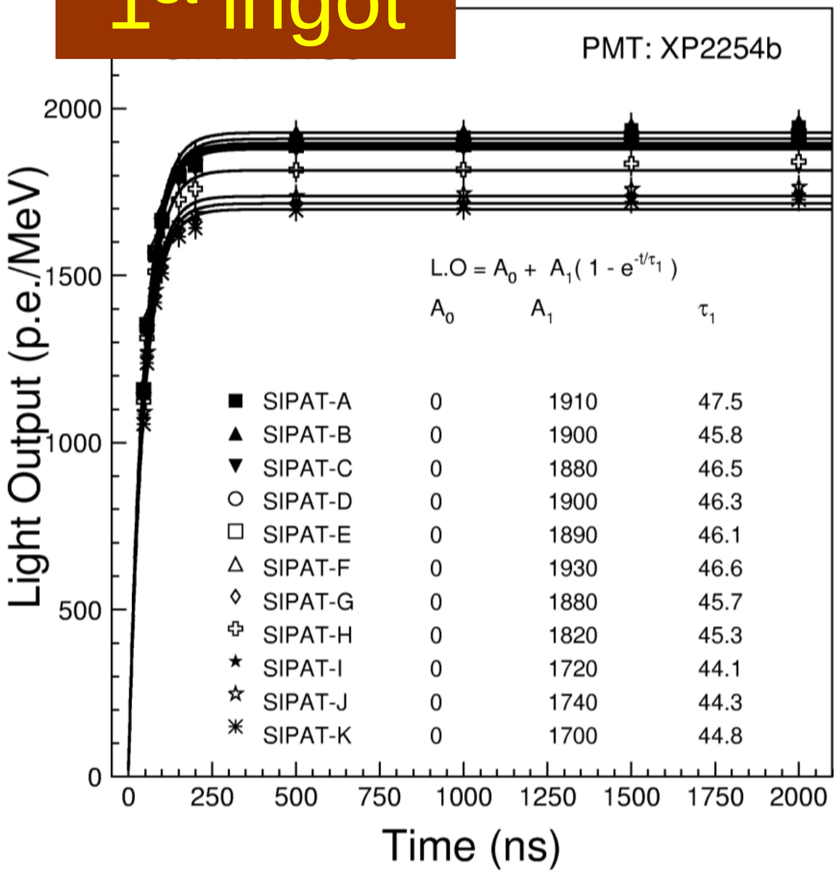
Correlations exist between EWLT/cut-off and cube position, indicating possible correlation with dopant concentrations.



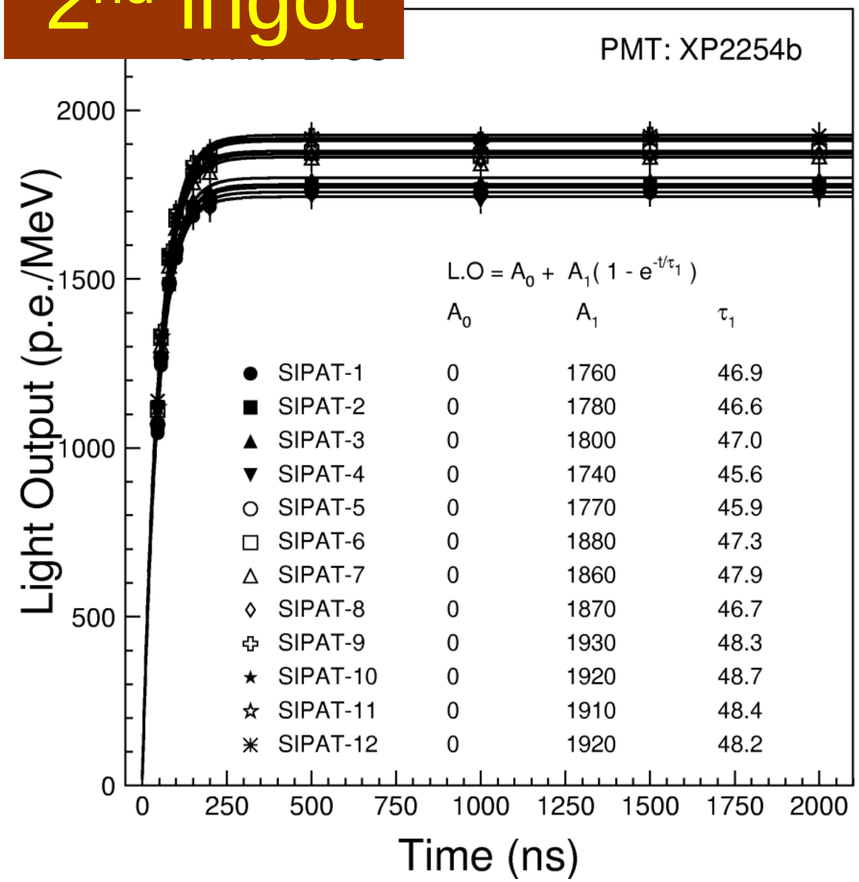
Light Output

Light Outputs are position dependent, indicating possible correlation with dopant concentrations.

1st ingot

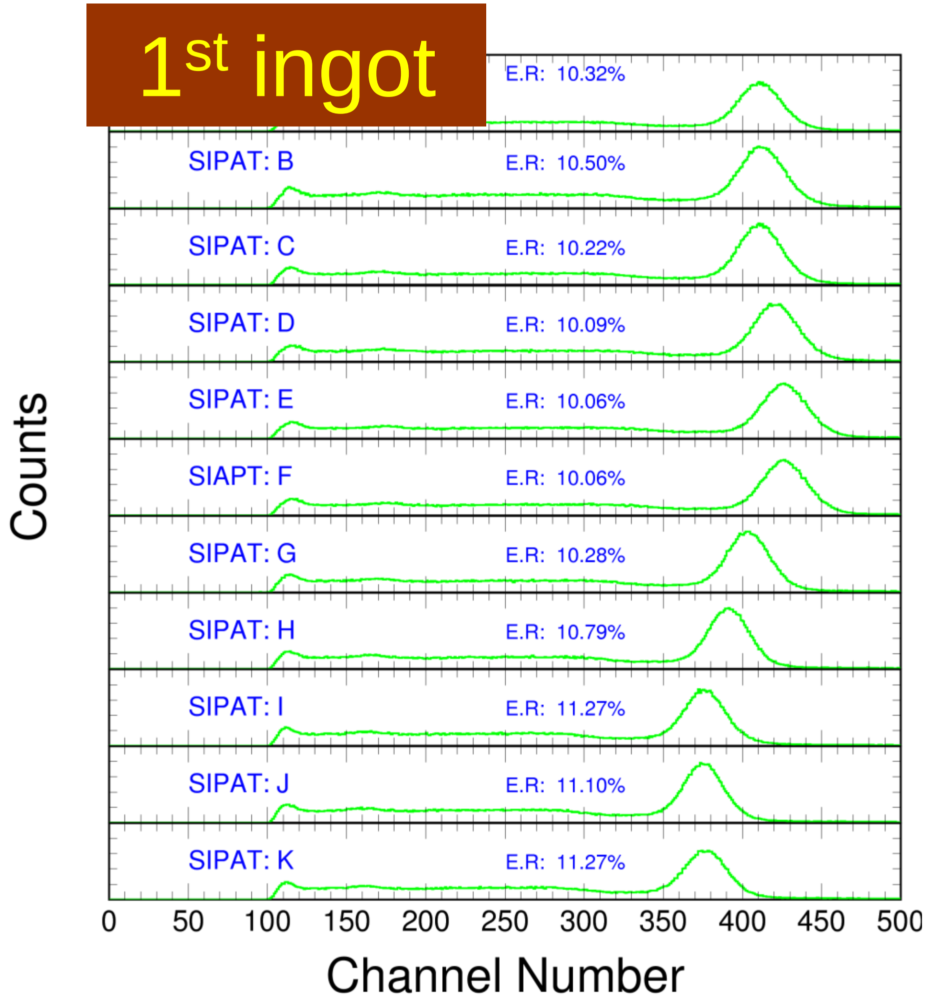


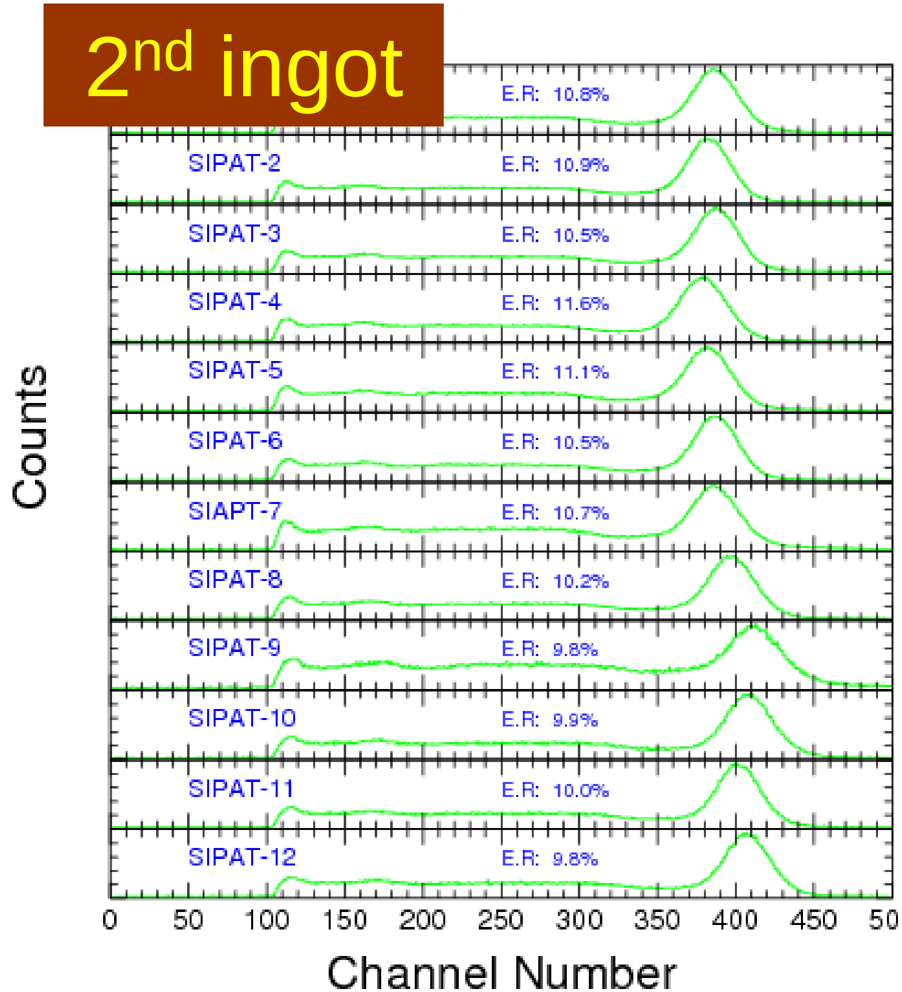
2nd ingot



FWHM Energy Resolution

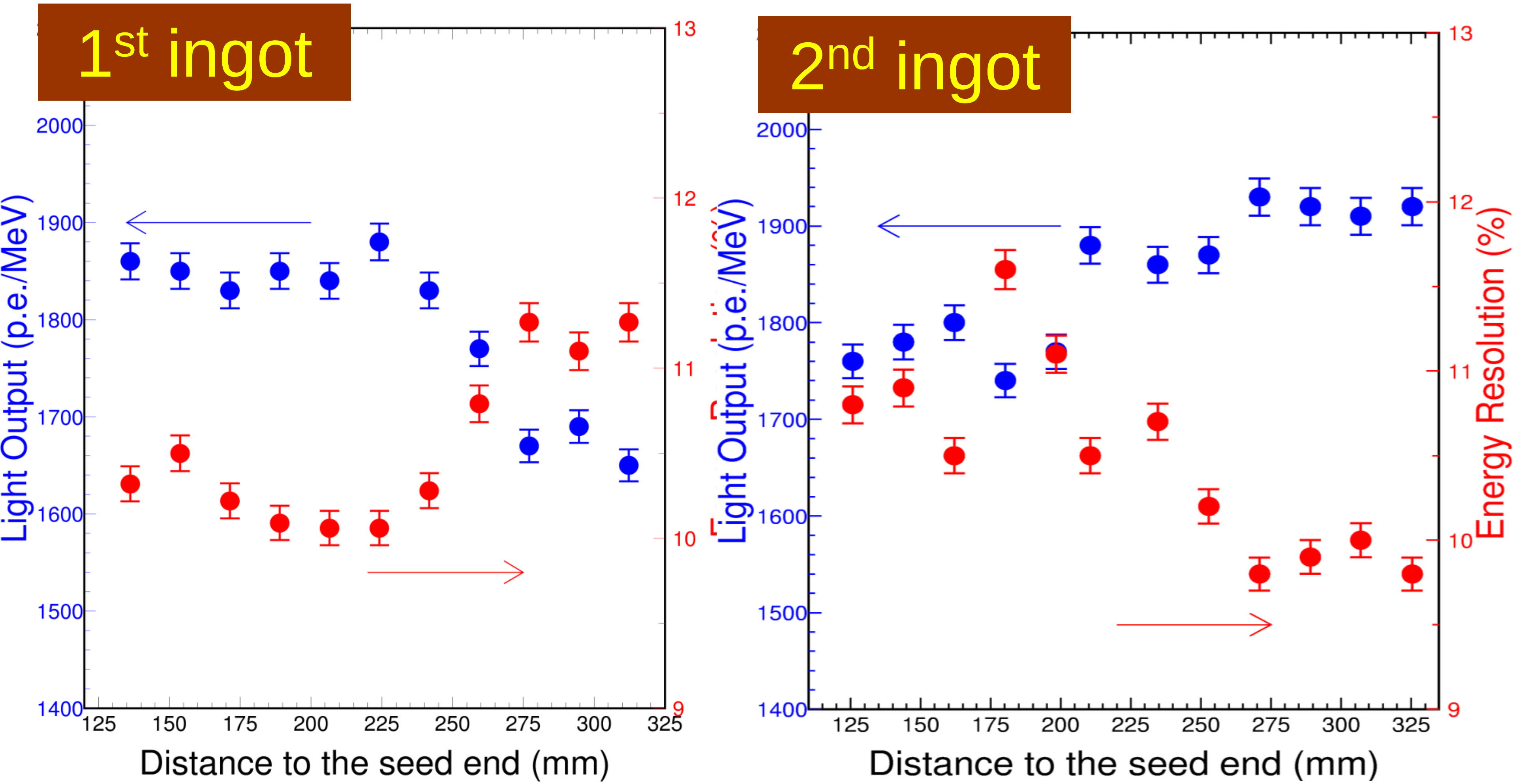
Energy resolutions are position dependent, indicating possible correlation with dopant concentrations.





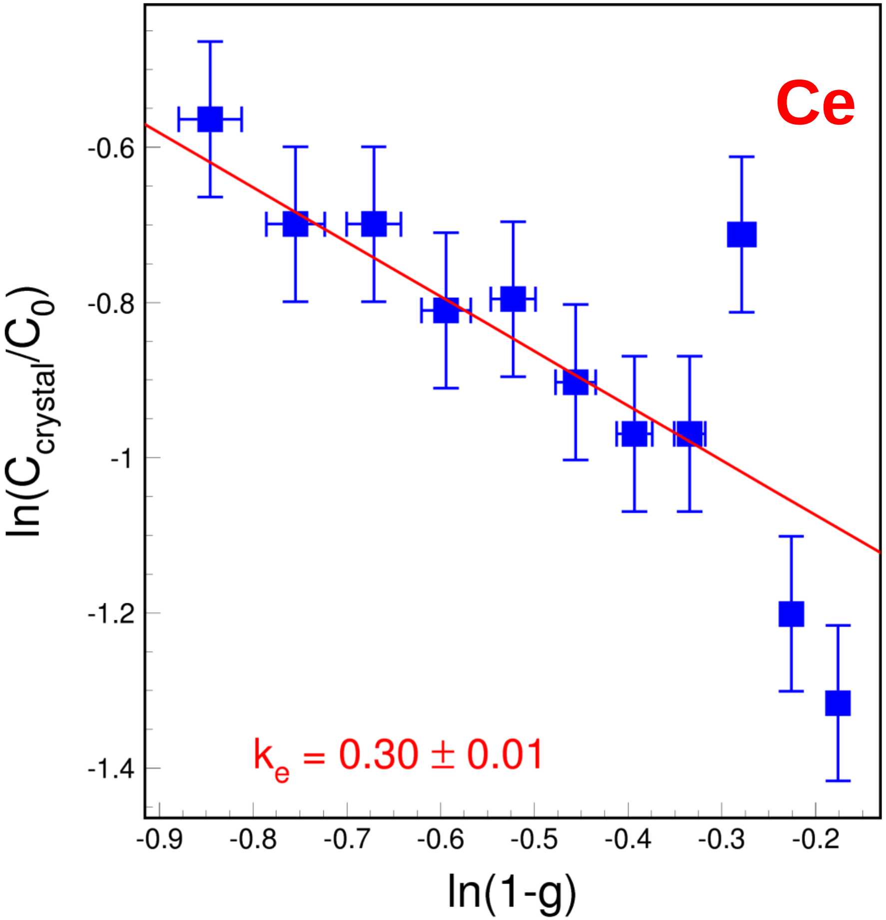
L.O. and E.R. versus Position

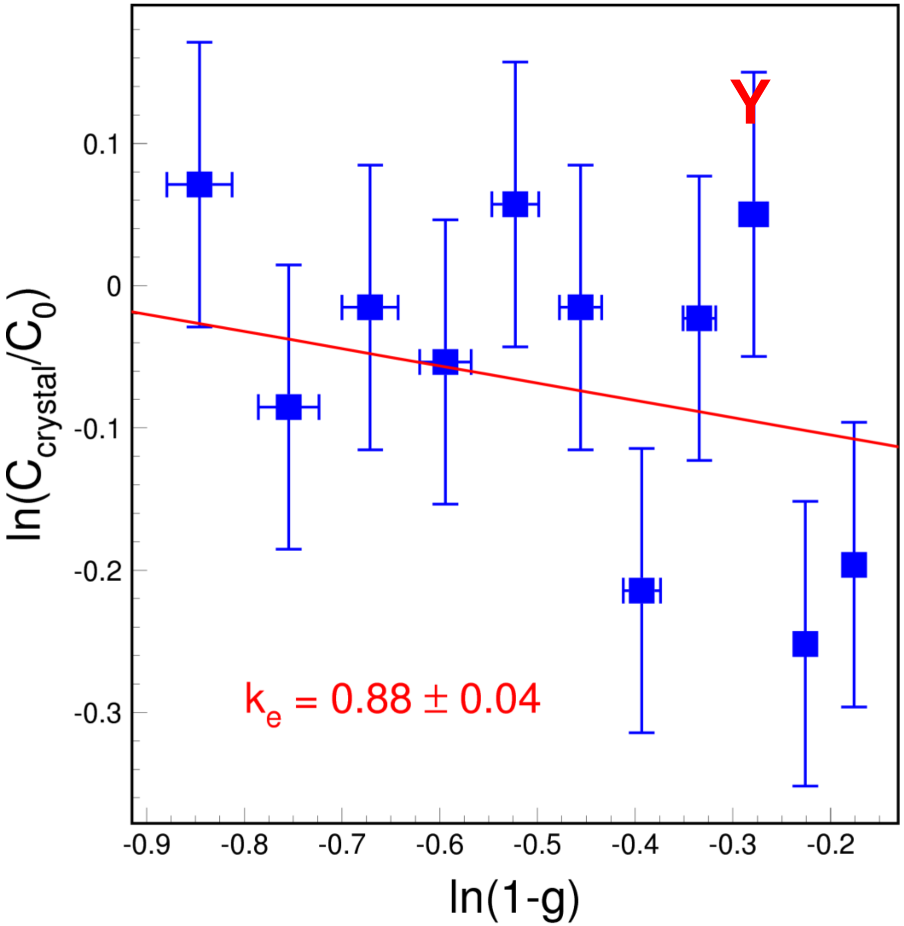
Correlations exist between L.O./E.R. and cube position



Cerium & Yttrium Segregation Coefficient

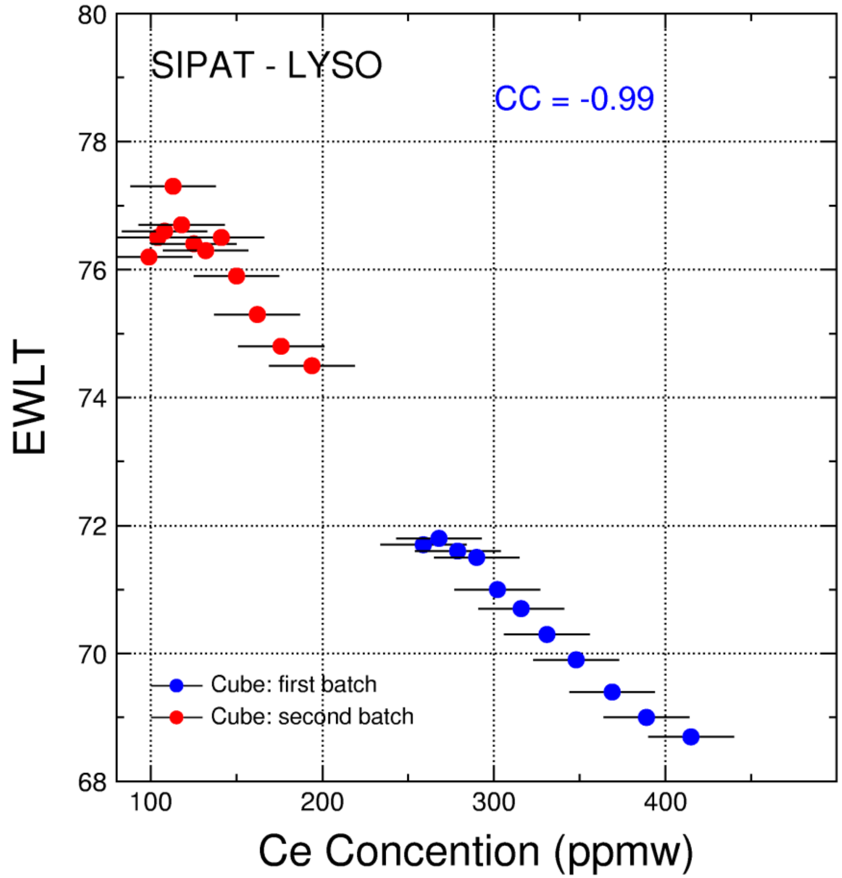
- Concentrations of cerium and yttrium were measured by using Glow Discharge Mass Spectrometry (GDMS) analysis.
- Segregation coefficients of cerium and yttrium in LSO were fitted to be 0.30 and 0.88 respectively: $ln\frac{C_{Crystal}}{C_0} = lnk_e + (k_e - 1)\ln(1-g)$

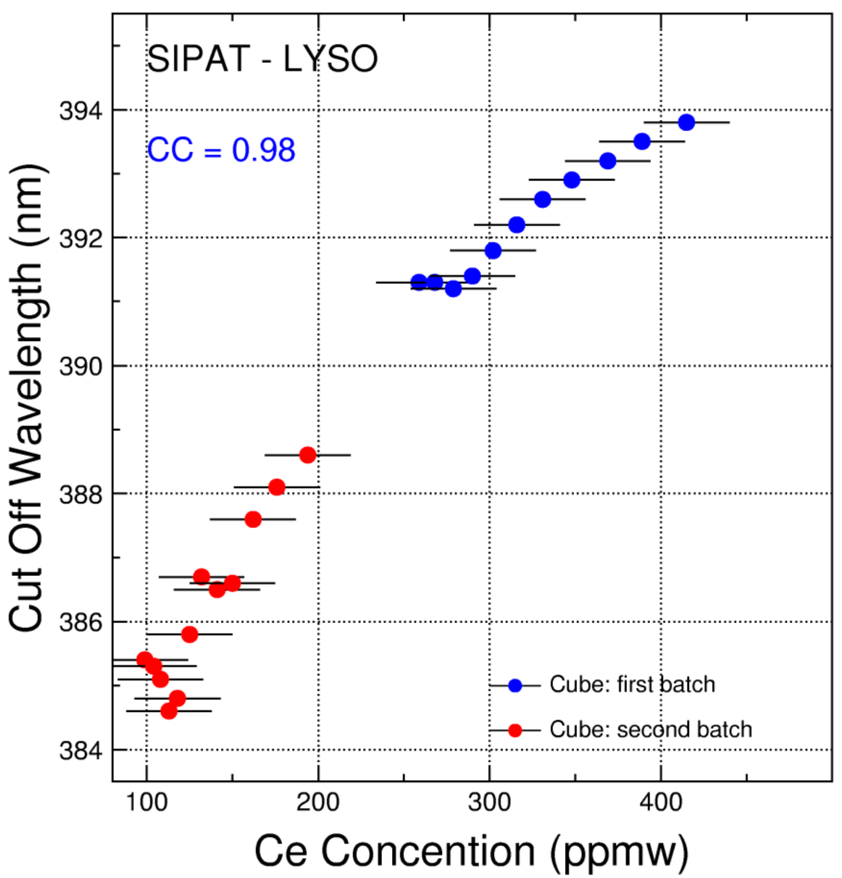




EWLT & Cut-off vs. Ce Concentration

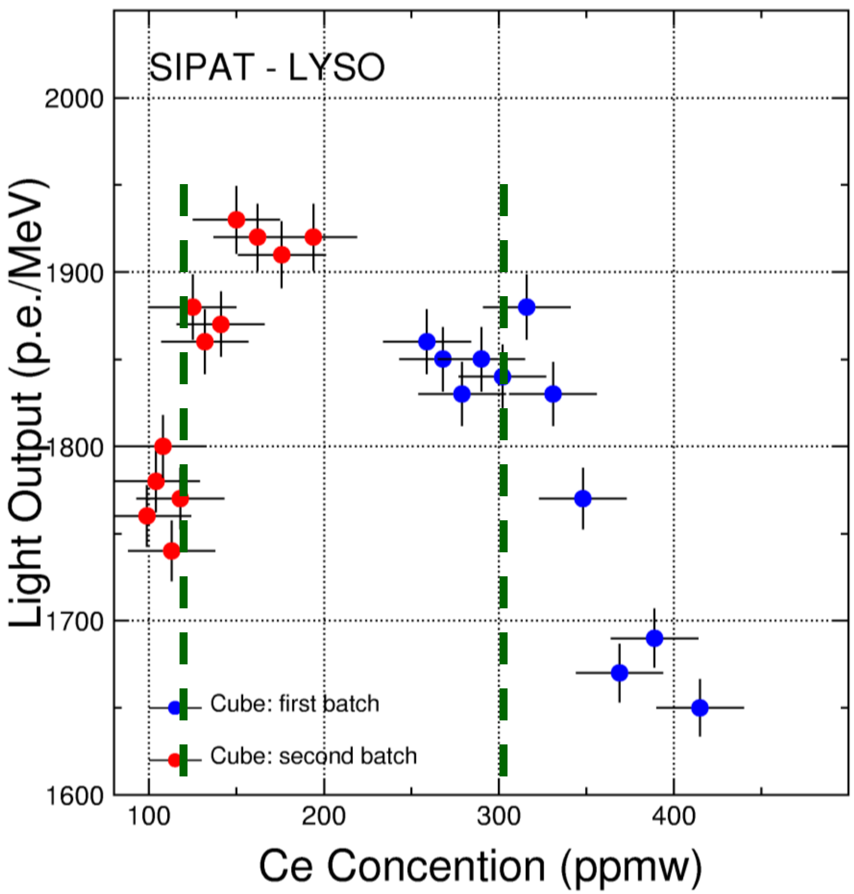
Strong correlations observed between EWLT and the cut-off wavelength versus the Ce concentration.

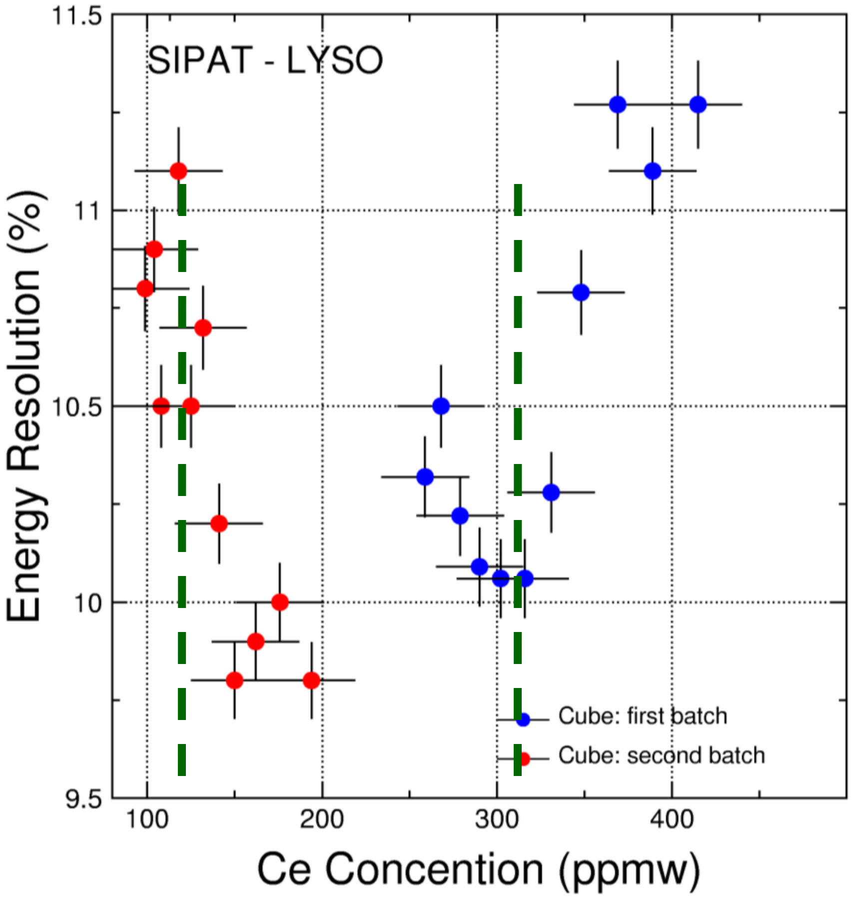




L.O. and E.R. versus Ce Concentration

A 'plateau' observed between 125 ~ 325 ppm, indicating a possibility to grow uniform crystal with optimized Ce doping. This observation consists with private data from C. Melcher.

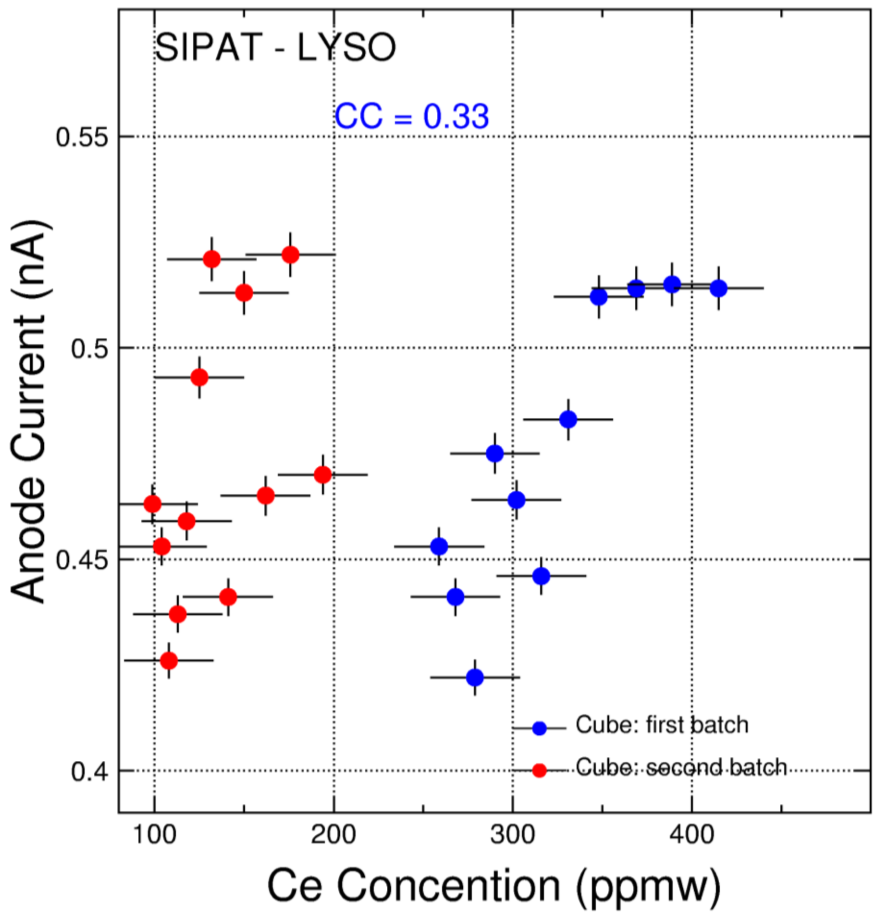




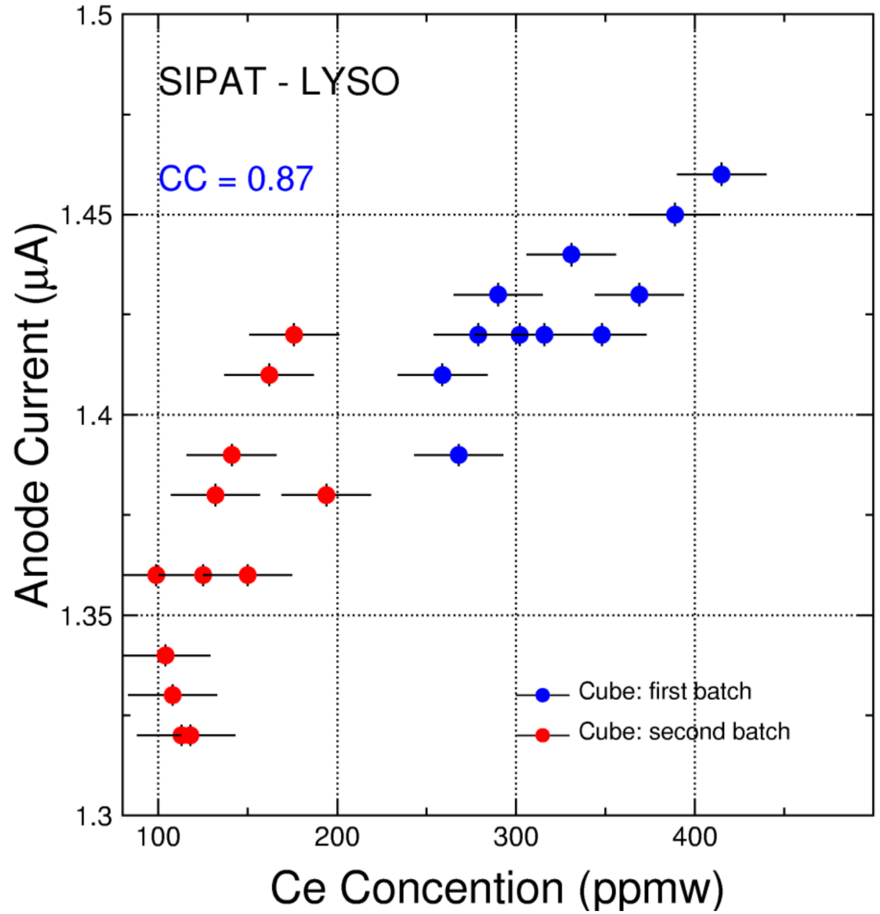
Phosphorescence vs. Ce Concentration

Correlation observed between radiation induced phosphorescence and the Ce concentration, but not before gamma-ray irradiation.

Before irradiation

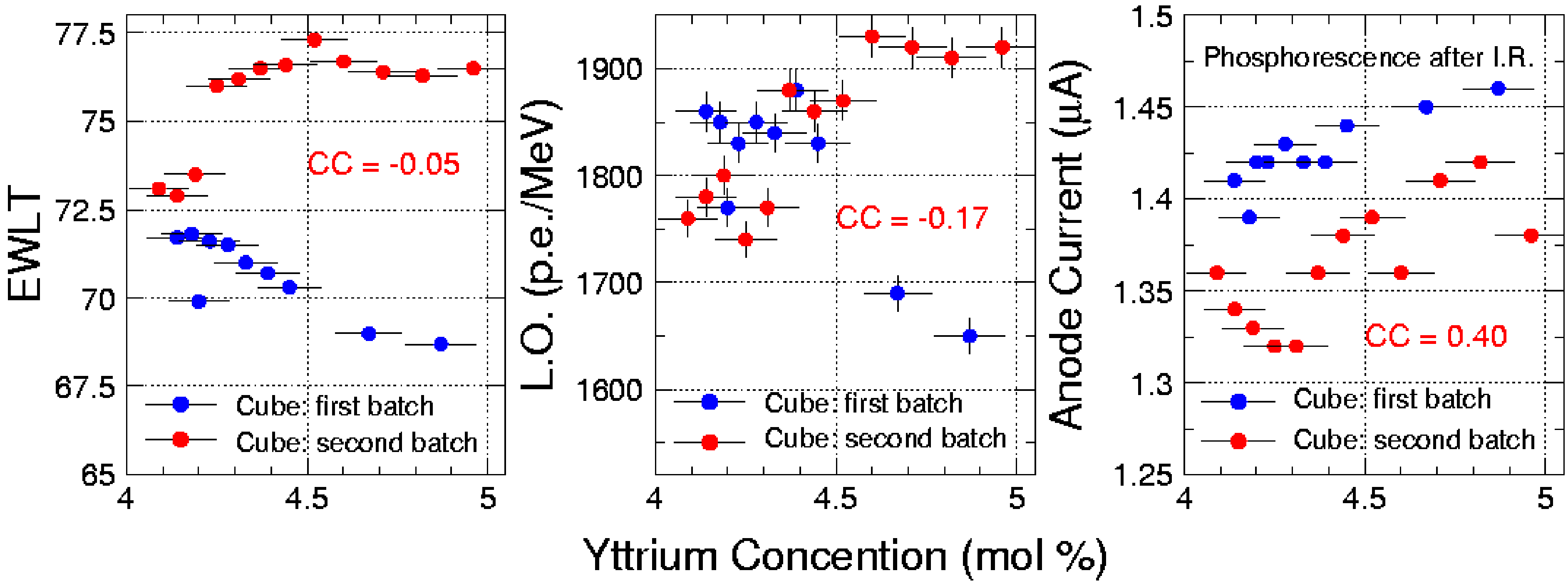


After irradiation

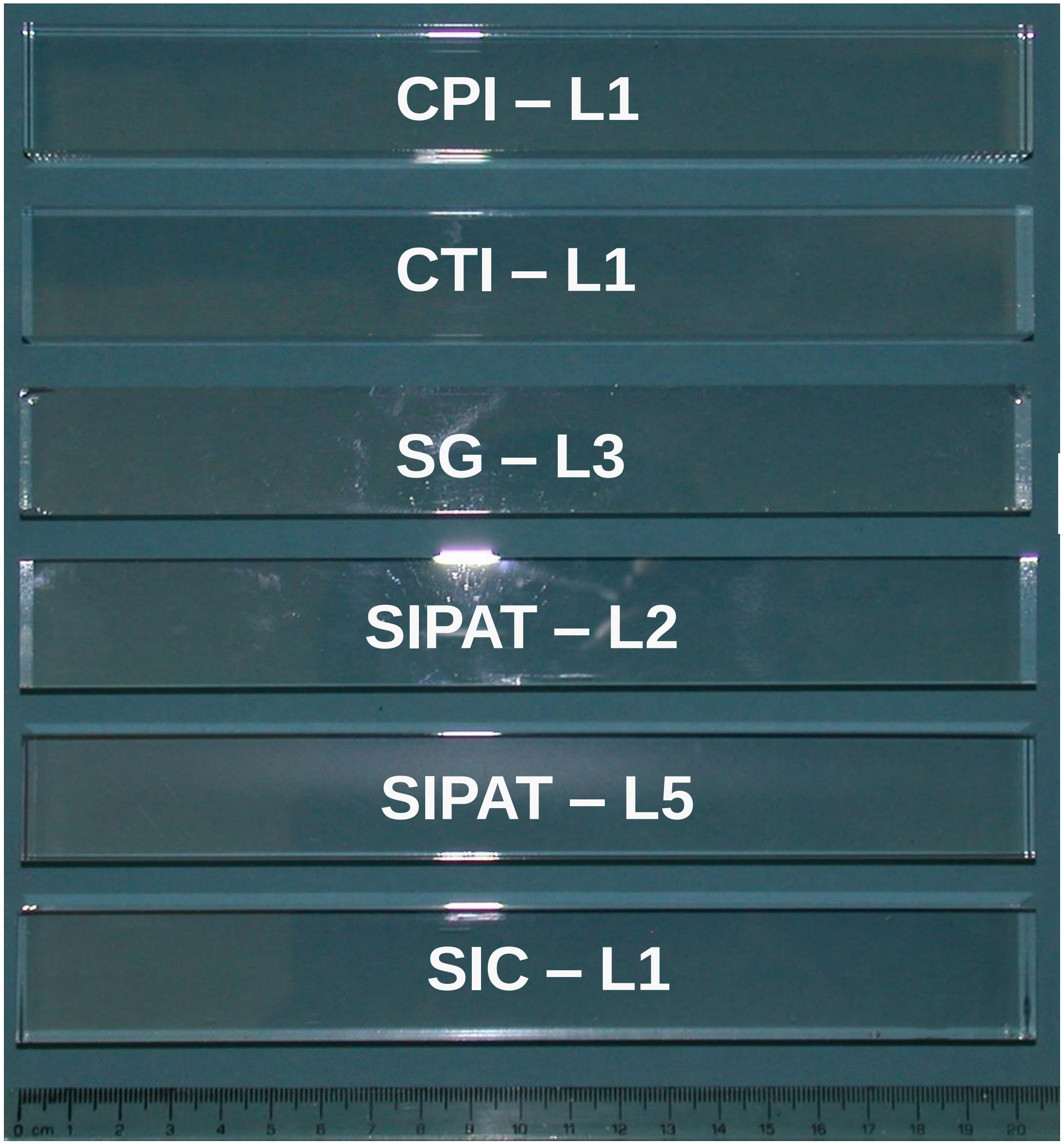


EWLT, L.O. and Phosphorescence after irradiation vs. the Yttrium Concentration

No correlations were observed between the yttrium concentrations and EWLT, the light output and the intensity of phosphorescence after gamma-ray irradiations.

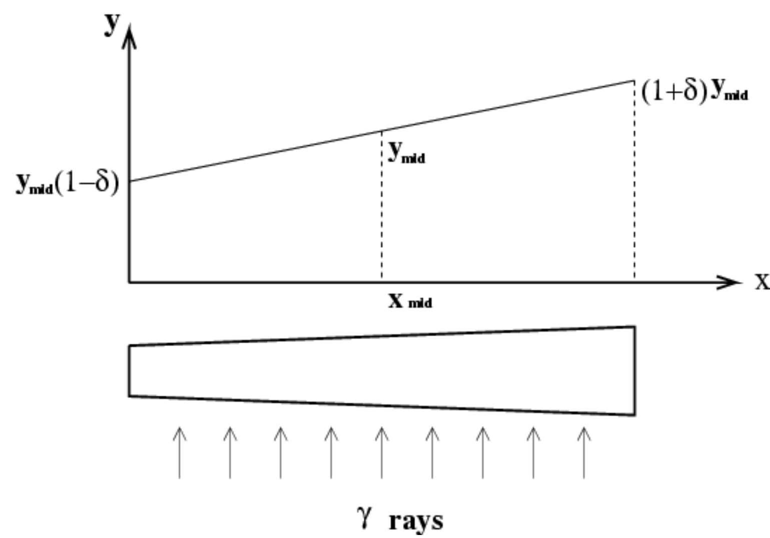


Light Response Uniformity



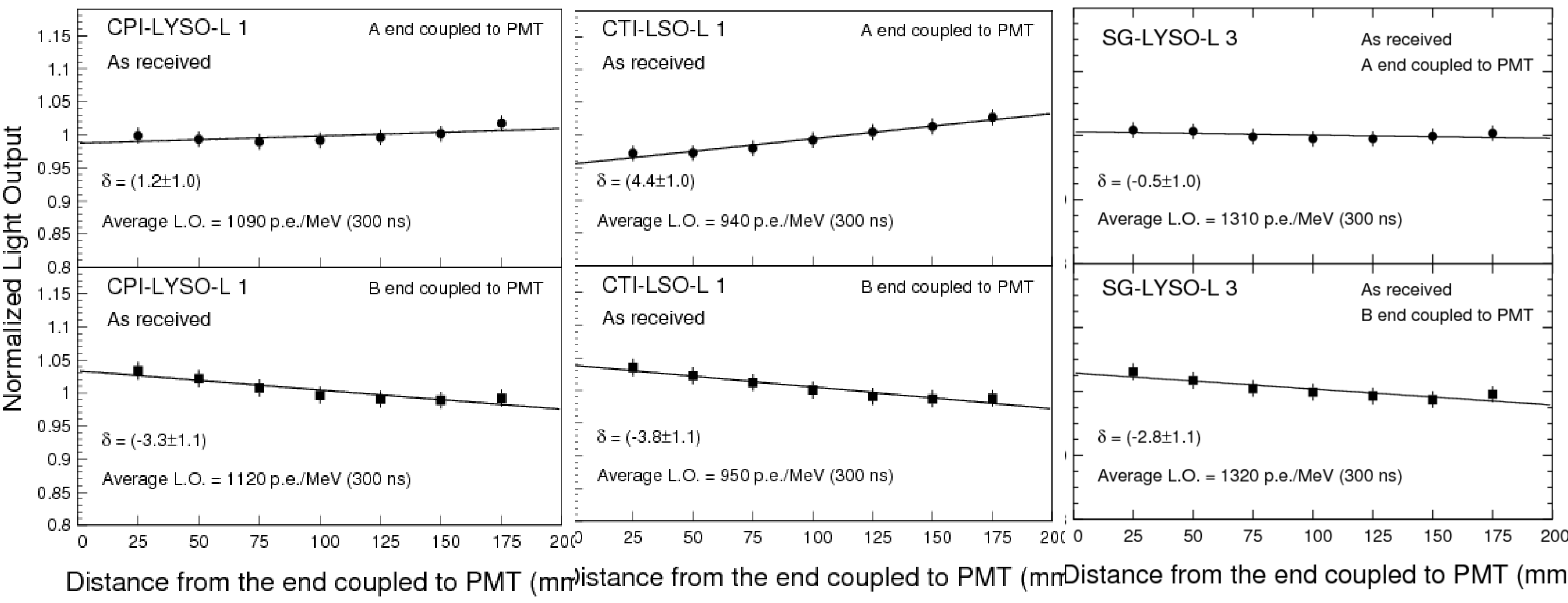
2.5 x 2.5 x 20 cm Samples tested for their light response uniformity

$$Y = Y_{mid}\left[1 + \delta(x/x_{mid} - 1)\right]$$



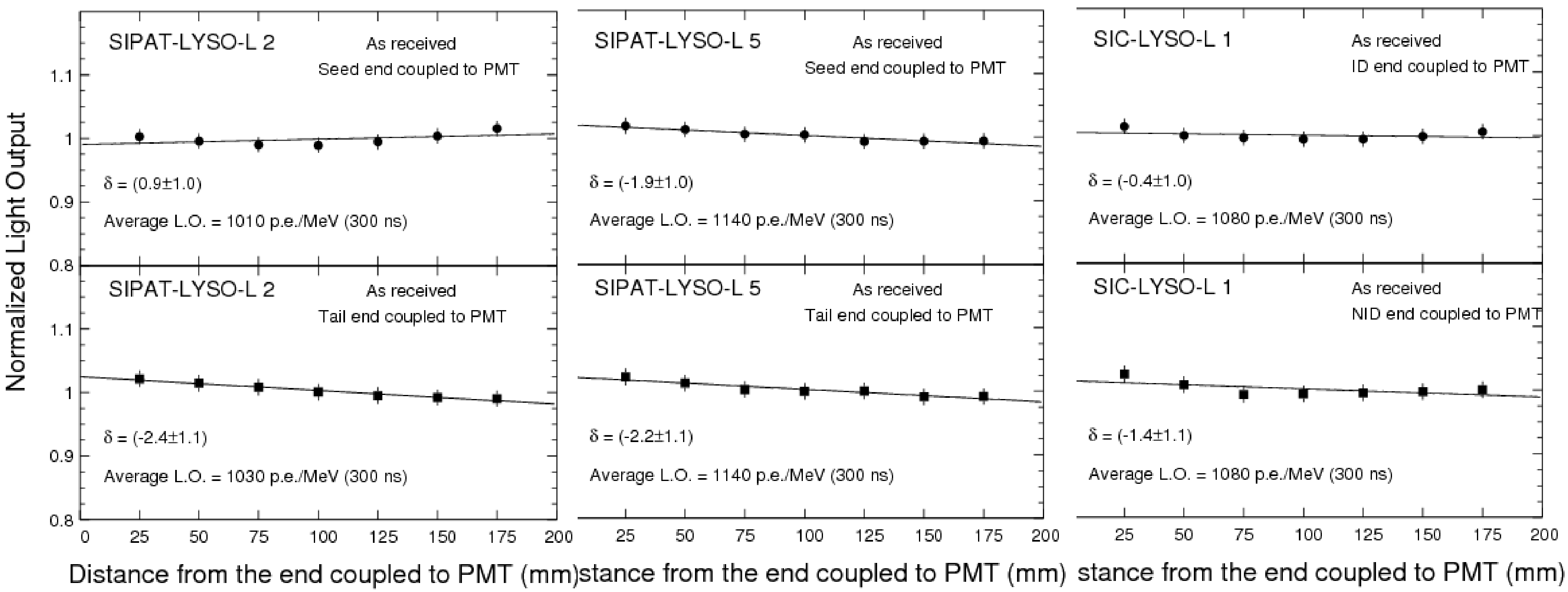
L.R.U. of 20 cm Long LYSO

Diverse light response uniformities observed with δ = 1.2/-3.3, 4.4/-3.9, -0.5/-2.8 for CPI, CTI & SG respectively



Progress Achieved in L.R.U.

The L.R.U. of SIPAT samples is improved from 0.9/-2.4 to -1.9/-2.2. SIC sample also shows good L.R.U.: -0.4/-1.4



Before Optimization | After Optimization | 1st SIC Sample

Summary

- Lead tungstate crystals suffer from radiation damge originated from photons/electrons and hadrons. While the real consequence will only be measured *in situ* when LHC starts collision, existing data indicate that light output loss and energy resolution degradation are expected.
- LYSO crystals with blight, fast scintillation and excellent radiation resistance is an excellent candidate for the ECAL endcap upgrade at SLHC.
- While the quality of LYSO crystals is adequate for SuperB, work is needed to develop LYSO crystals of CMS size (28 cm long) and to learn radiation damage effect by hadrons.