LSO/LYSO/LFS Crystals for Precision Timing

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Fast Crystal Scintillators

Talk in CMS Forward Calorimetry Task Force Meeting, CERN, June 27, 2012

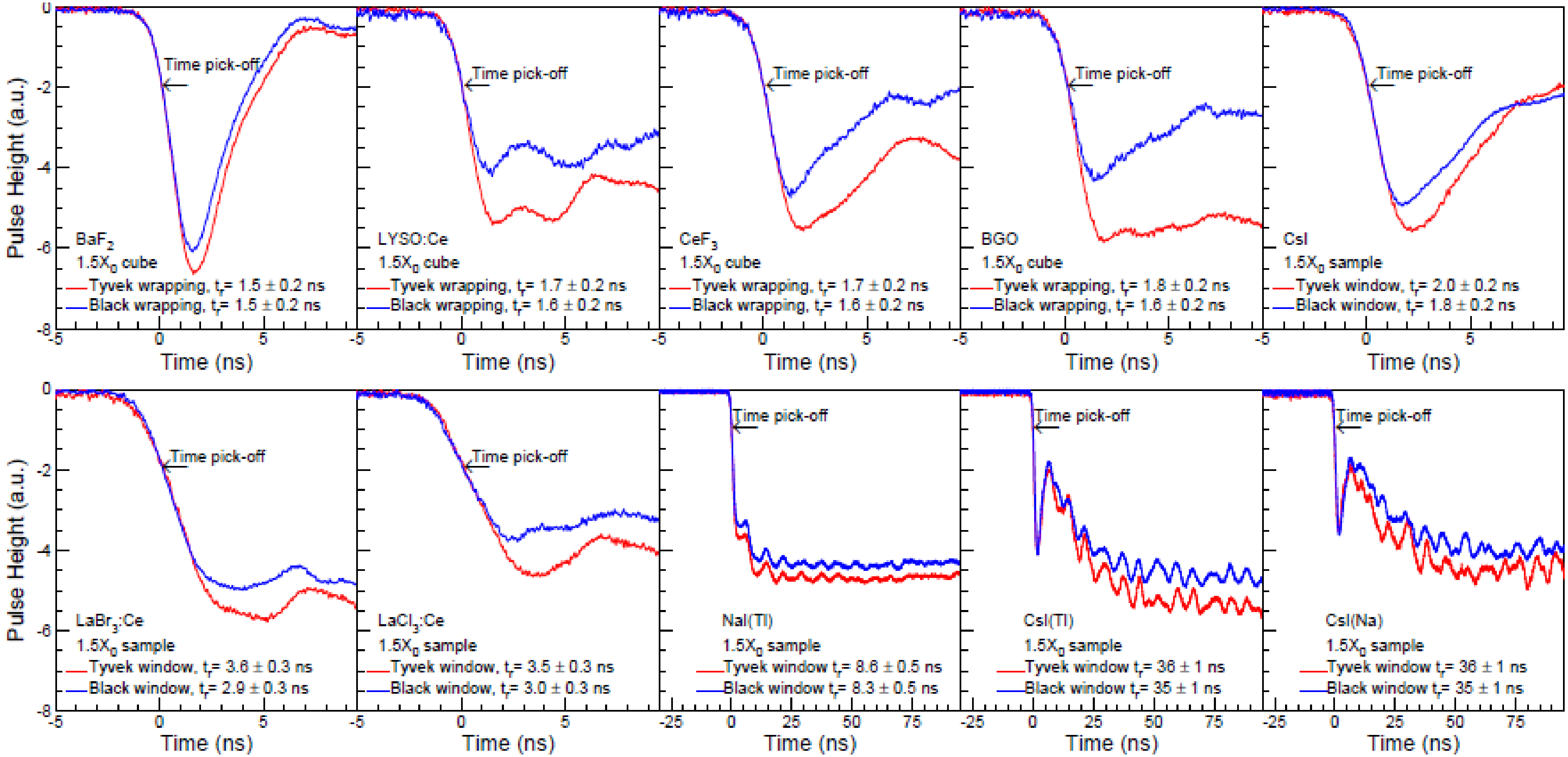
	LSO/LYSO	GSO	YSO [1]	CsI	BaF_2	CeF_3	$CeBr_3$ [2]	$LaCl_3$	$LaBr_3$	Plastic scintillator (BC 404) [3]
Density (g/cm³)	7.40	6.71	4.44	4.51	4.89	6.16	5.23	3.86	5.29	1.03
Melting point (°C)	2050	1950	1980	621	1280	1460	722	858	783	70#
Radiation Length (cm)	1.14	1.38	3.11	1.86	2.03	1.70	1.96	2.81	1.88	42.54
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	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

Rising Time for 1.5 X_0 Samples

Talk in the time resolution workshop at U. Chicago, 4/28/2011: Agilent MSO9254A (2.5 GHz) DSO with 0.14 ns rise time Hamamatsu R2059 PMT (2500 V) with rise time 1.3 ns



Measured rising time is dominated by photo-detector response, and is affected by light propagation in crystal.

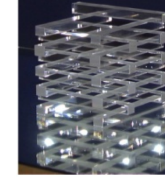
Figure of Merit for Timing

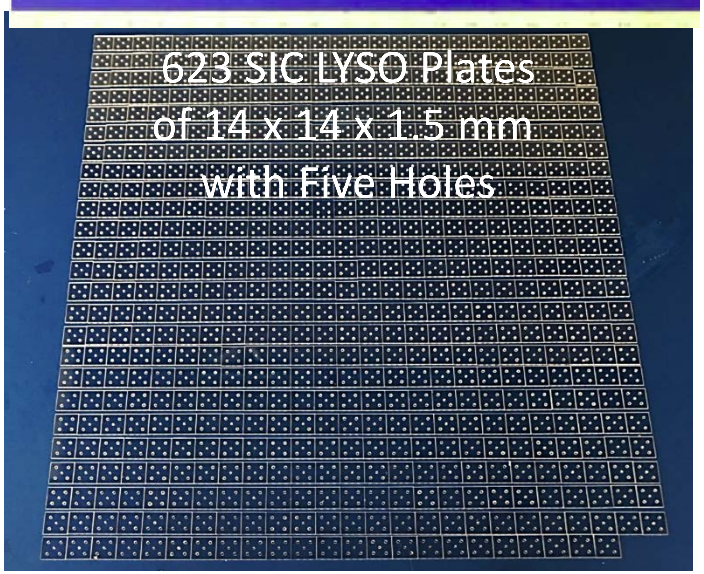
FoM is calculated as the LY in 1st ns obtained by using light output and decay time data measured for 1.5 X_0 crystal samples.

Crystal Scintillators	Relative LY (%)	A_1 (%)	τ_1 (ns)	A_2 (%)	τ_2 (ns)	Total LO (p.e./MeV, XP2254B)	LO in 1ns (p.e./MeV, XP2254B)	LO in 0.1ns (p.e./MeV, XP2254B)	LY in 0.1ns (photons/MeV)
BaF_2	40.1	91	650	9	0.9	1149	71.0	11.0	136.6
LSO:Ca,Ce	94	100	30			2400	78.7	8.0	110.9
LSO/LYSO:Ce	85	100	40			2180	53.8	5.4	75.3
CeF_3	7.3	100	30			208	6.8	0.7	8.6
BGO	21	100	300			350	1.2	0.1	2.5
PWO	0.377	80	30	20	10	9.2	0.42	0.04	0.4
$LaBr_3$:Ce	130	100	20			3810	185.8	19.0	229.9
$LaCl_3$:Ce	55	24	570	76	24	1570	49.36	5.03	62.5
NaI:Tl	100	100	245			2604	10.6	1.1	14.5
CsI	4.7	77	30	23	6	131	7.9	0.8	10.6
CsI:Tl	165	100	1220			2093	1.7	0.2	4.8
CsI:Na	88	100	690			2274	3.3	0.3	4.5

The best crystal scintillator for ultra-fast timing is BaF_2 and LSO(Ce/Ca) and LYSO(Ce). $LaBr_3$ is a material with high potential. One necessary condition to be used at HL-LHC is rad hardness.

Bright, Fast & Rad Hard Crystal





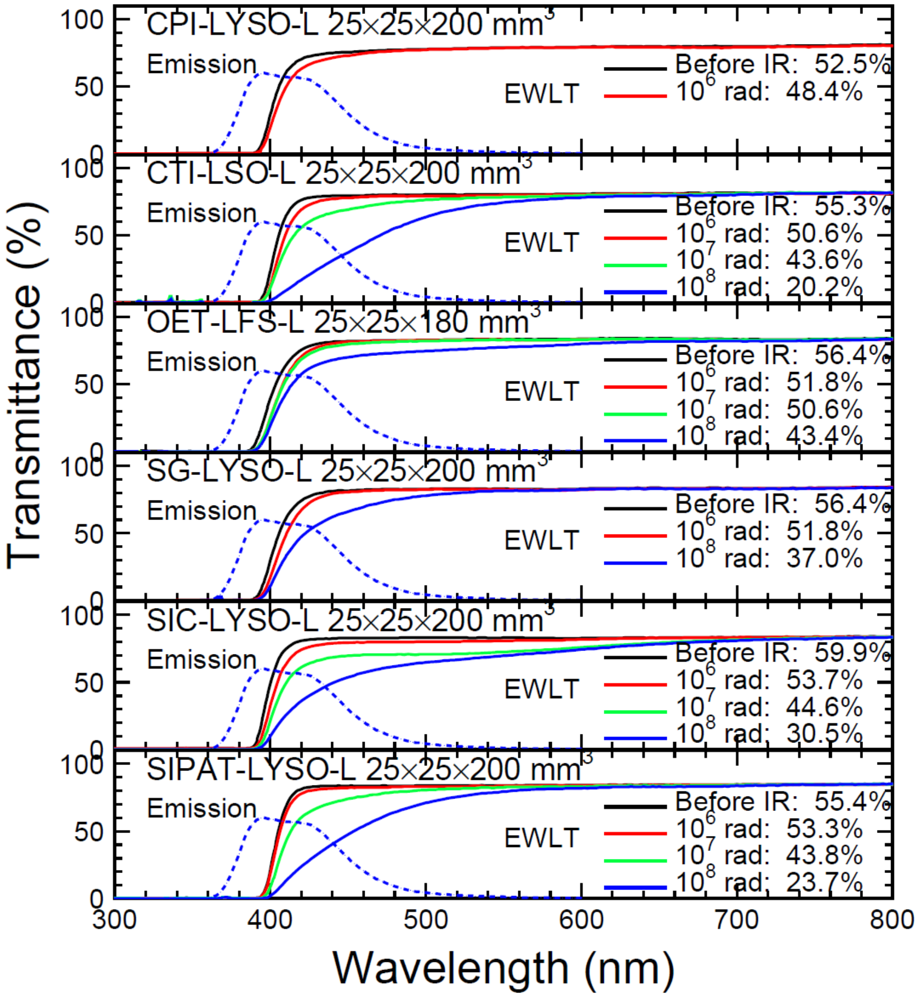
- LSO/LYSO/LFS is a bright (200 times of PWO), fast (40 ns) crystal scintillator widely used in the medical industry with mass production capability.

- Radiation hardness of LSO/LYSO/LFS has been scrutinized for samples of 20 cm long and 1.5 mm thick.

- γ-ray and proton induced absorption coefficient is ~3 m^{-1} after 150 Mrad or 3 x 10^{14} p/cm^2, corresponding to a few percent LO loss for crystals of 14 x 14 x 1.5 mm at the HL-LHC.

Ionization Dose Induced Damage Longitudinal Transmittance (LT)

The best sample: 77% EWLT after 100 Mrad



EWLT or emission weighted longitudinal transmittance is defined as:

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

RIAC or radiation induced absorption coefficient is defined as:

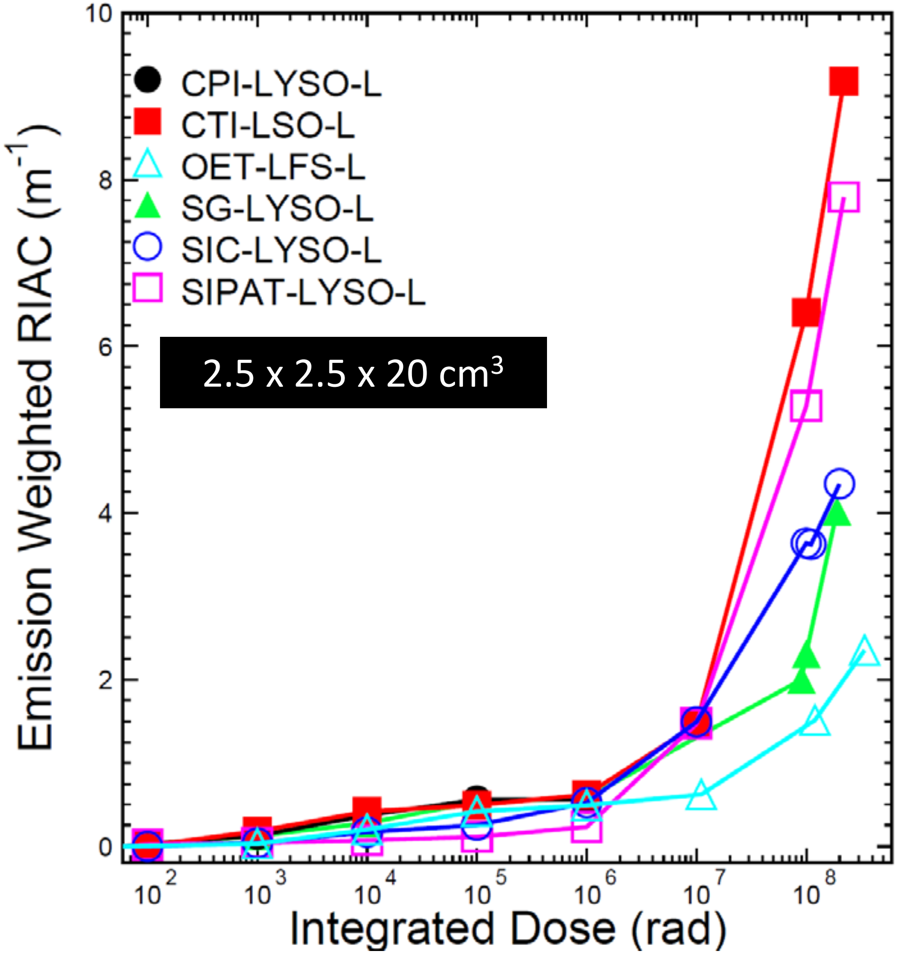
$$\mathrm{RIAC} = \frac{1}{l}\ln\frac{T_0(\lambda)}{\mathrm{T}(\lambda)}$$

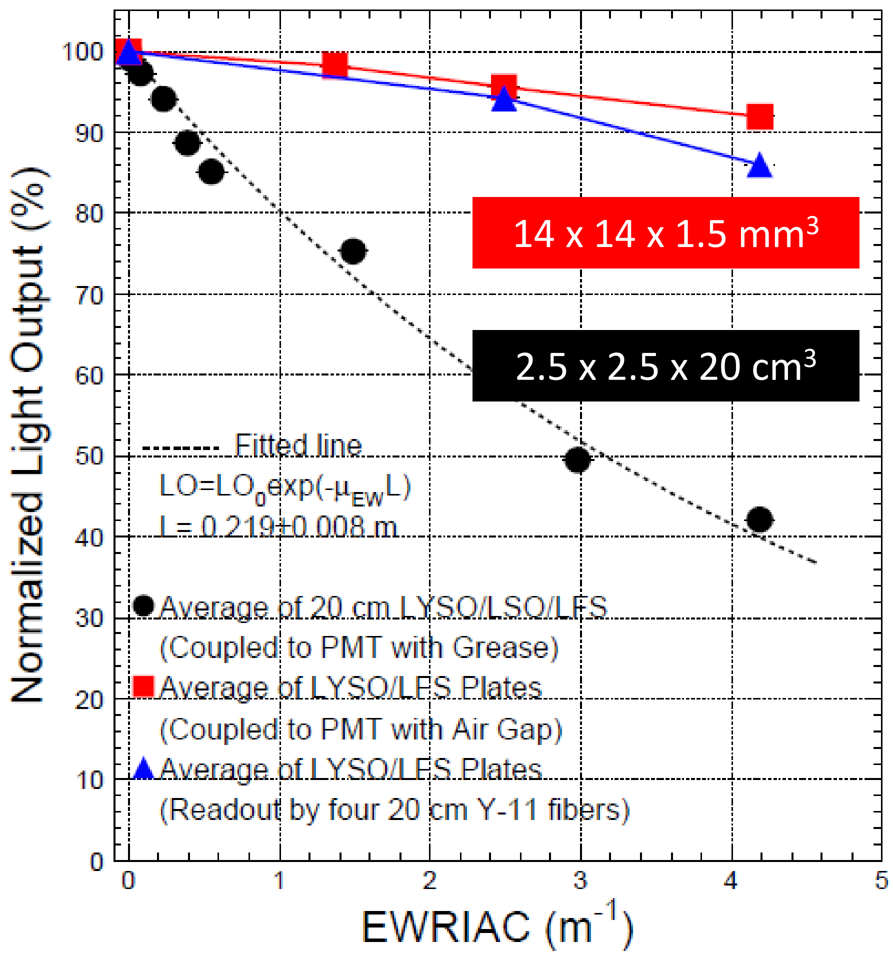
EWRIAC or emission weighted radiation induced absorption coefficient is defined as:

$$\mathrm{EW}RIAC = \frac{\int RIAC(\lambda)\mathrm{Em}(\lambda)d\lambda}{\int \mathrm{Em}(\lambda)d\lambda}$$

EWRIAC vs. Dose and Normalized LO vs. EWRIAC

EWRIAC in the best sample is 0.62, 1.5 and 2.4 m^{-1} after 10, 120 and 340 Mrad

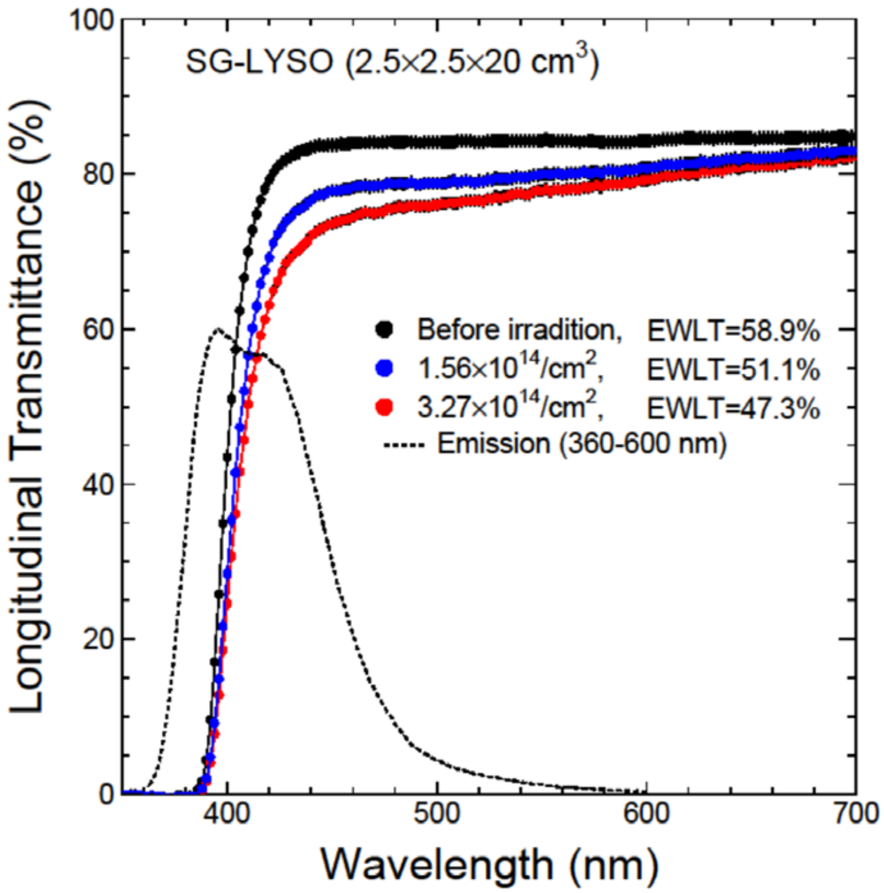


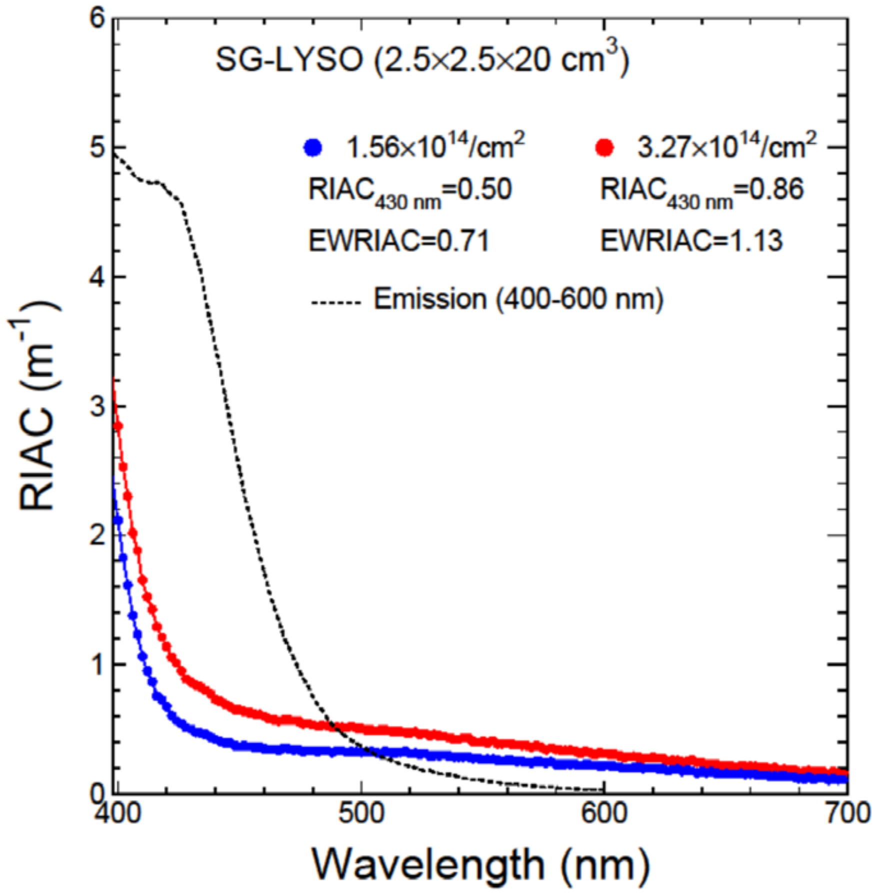


LO losses of 5% in 14x14x1.5 mm plates with EWRIAC of 3 m^{-1}

800 MeV Proton Induced Damage Transmittance and RIAC

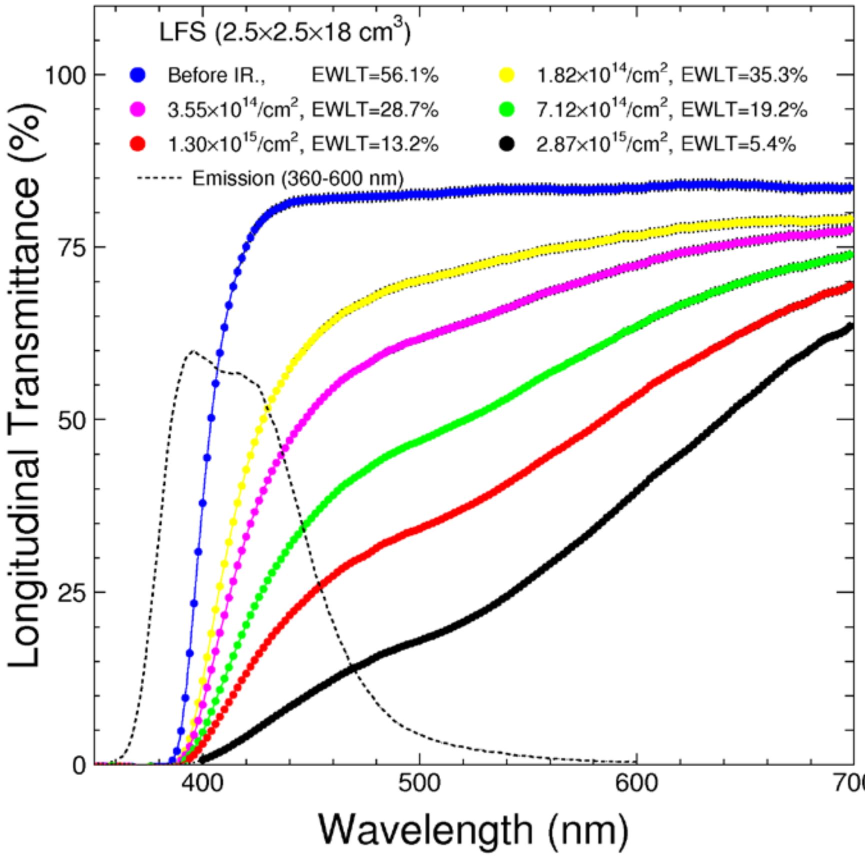
RIAC at 430 nm of 0.86 m^{-1} for an LYSO after 3×10^{14} p/cm^2

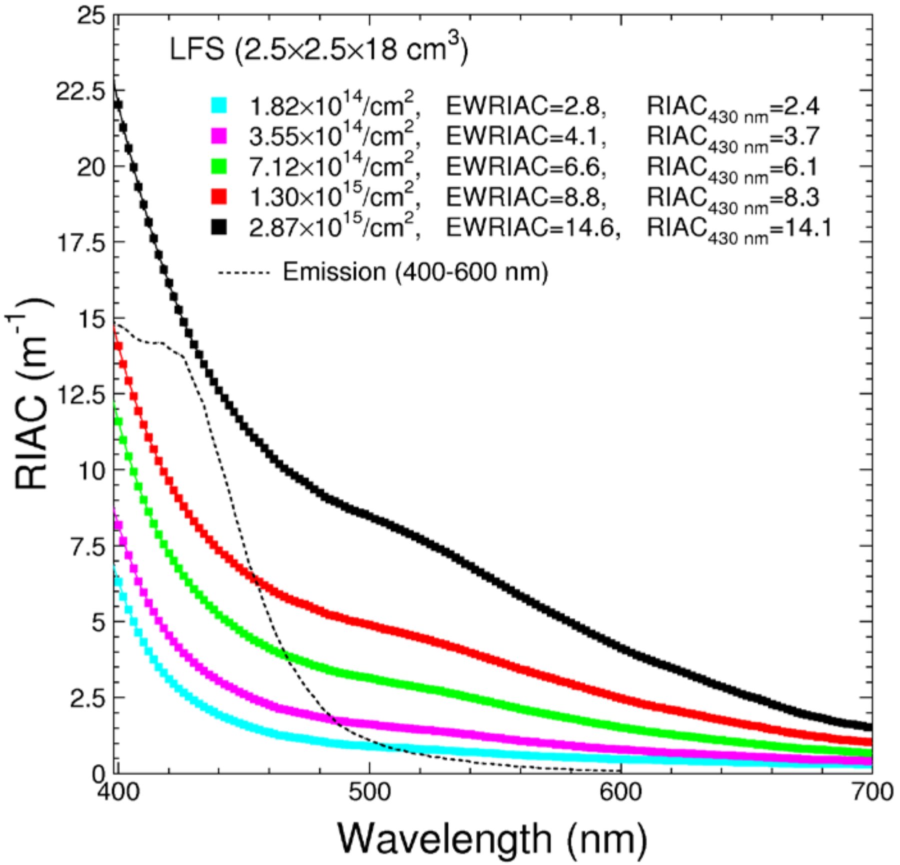




800 MeV Proton Induced Damage Transmittance and RIAC

RIAC at 430 nm of 3.7 m^{-1} for an LFS crystal after 3.6×10^{14} p/cm^2





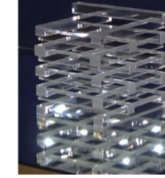
RIAC at the Emission Peak by 800 MeV Protons

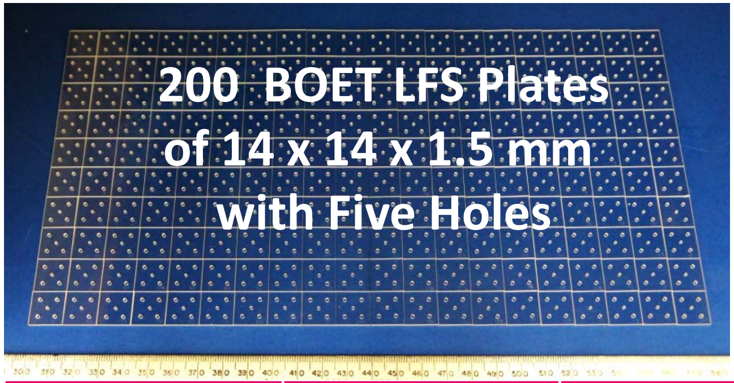
Measured Values at about E14, and extracted to 3E14 p/cm^2

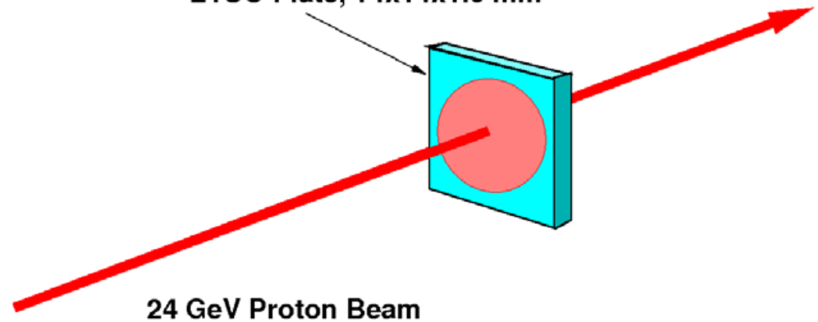
Crystal	Dimensions (mm^3)	ID	Emission Peak (nm)	Fluence (p/cm^2)	RIAC at EP (1/m)	@ 3E+14
BGO	25×25×200	SIC-BGO	480	1.77E+14	14.7	24.9
CeF_3	22^2×26^2×150	SIC-CeF	340	1.40E+14	17.4	37.3
LYSO	**25×25×200**	**SG-LYSO**	**430**	**3.27E+14**	**0.86**	**0.8**
LFS	**25×25×180**	**OET-LFS**	**430**	**3.55E+14**	**3.7**	**3.1**
PWO*	28.5^2×30^2×220	SIC-PWO	420	1.80E+14	> 36	> 60

LSO/LYSO/LFS is radiation hard against protons

Irradiation by 24 GeV Protons



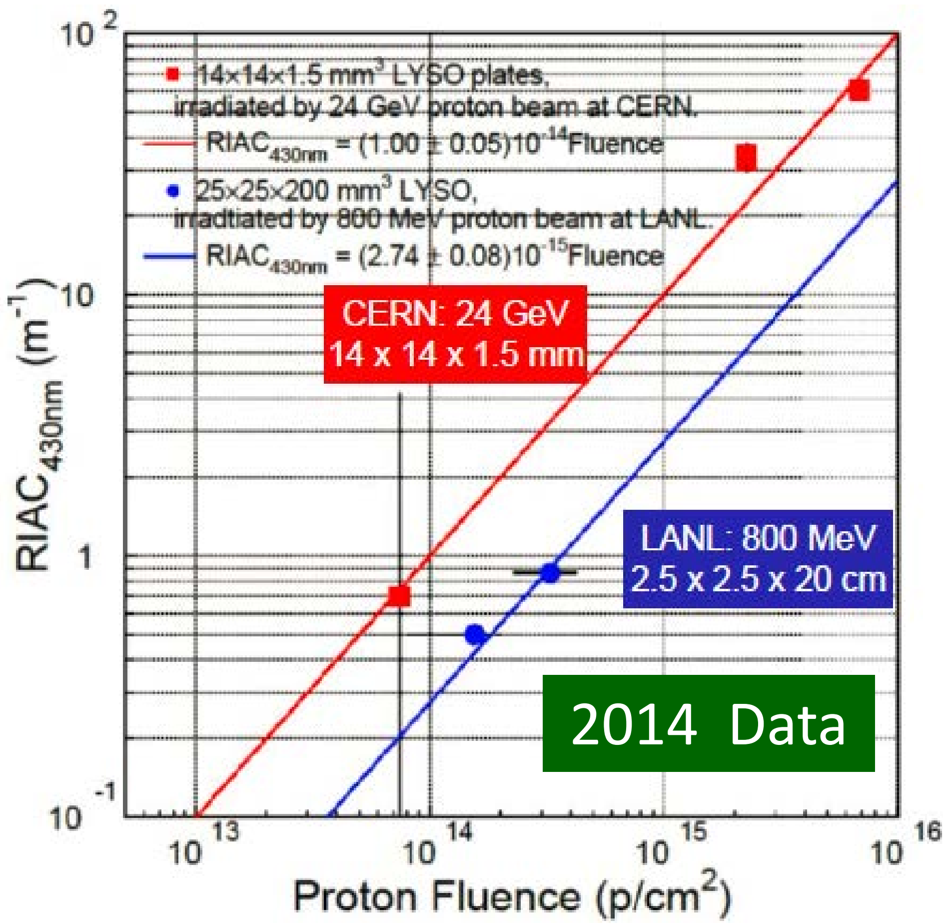


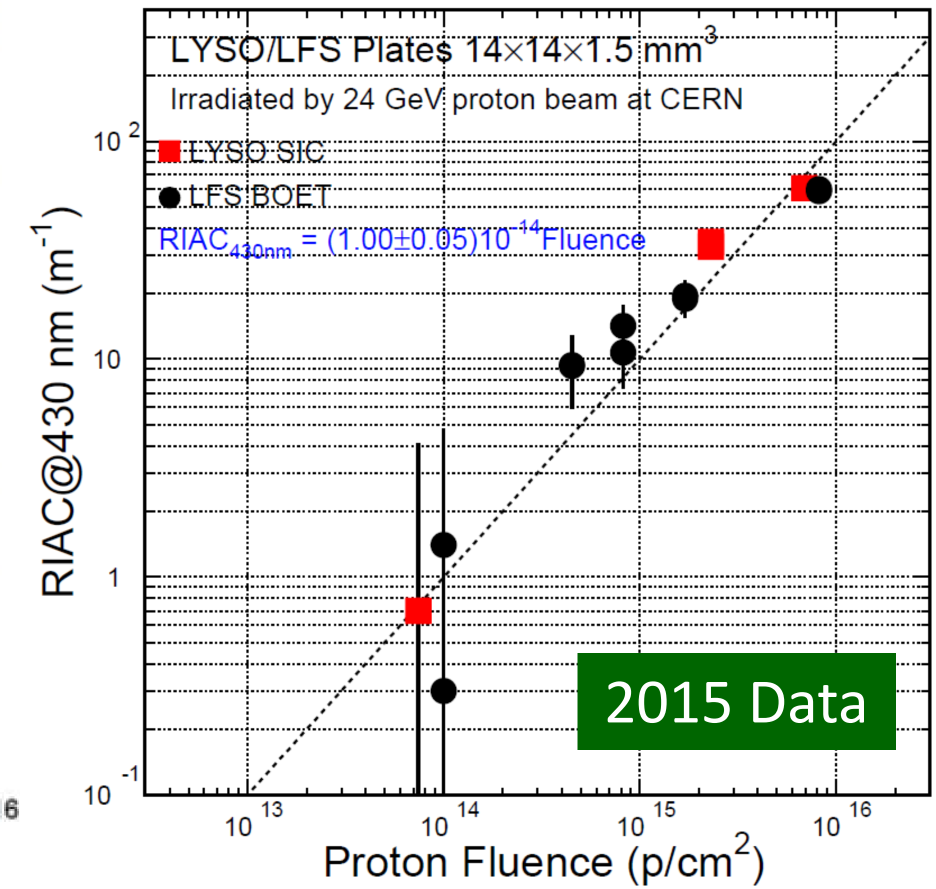


ID	Dimension (mm^3)	Facility	Protons (GeV)	Irradiation Set	Fluence (p/cm^2)	Error (+/- %)
LFS BOET-6	14×14×1.5	CERN	24	2045	9.97×10^{13}	7.0
LFS BOET-7	14×14×1.5	CERN	24	2045	9.97×10^{13}	7.0
LFS BOET-8	14×14×1.5	CERN	24	2046	4.48×10^{14}	8.4
LFS BOET-9	14×14×1.5	CERN	24	2046	4.48×10^{14}	8.4
LFS BOET-10	14×14×1.5	CERN	24	2047	8.21×10^{14}	7.6
LFS BOET-11	14×14×1.5	CERN	24	2047	8.21×10^{14}	7.6
LFS BOET-12	14×14×1.5	CERN	24	2048	1.65×10^{15}	7.5
LFS BOET-13	14×14×1.5	CERN	24	2048	1.65×10^{15}	7.5
LFS BOET-14	14×14×1.5	CERN	24	2049	8.19×10^{15}	7.3
LFS BOET-15	14×14×1.5	CERN	24	2049	8.19×10^{15}	7.3

24 GeV Protons: RIAC@ 430 nm

Consistent damage in LFS and LYSO Plates

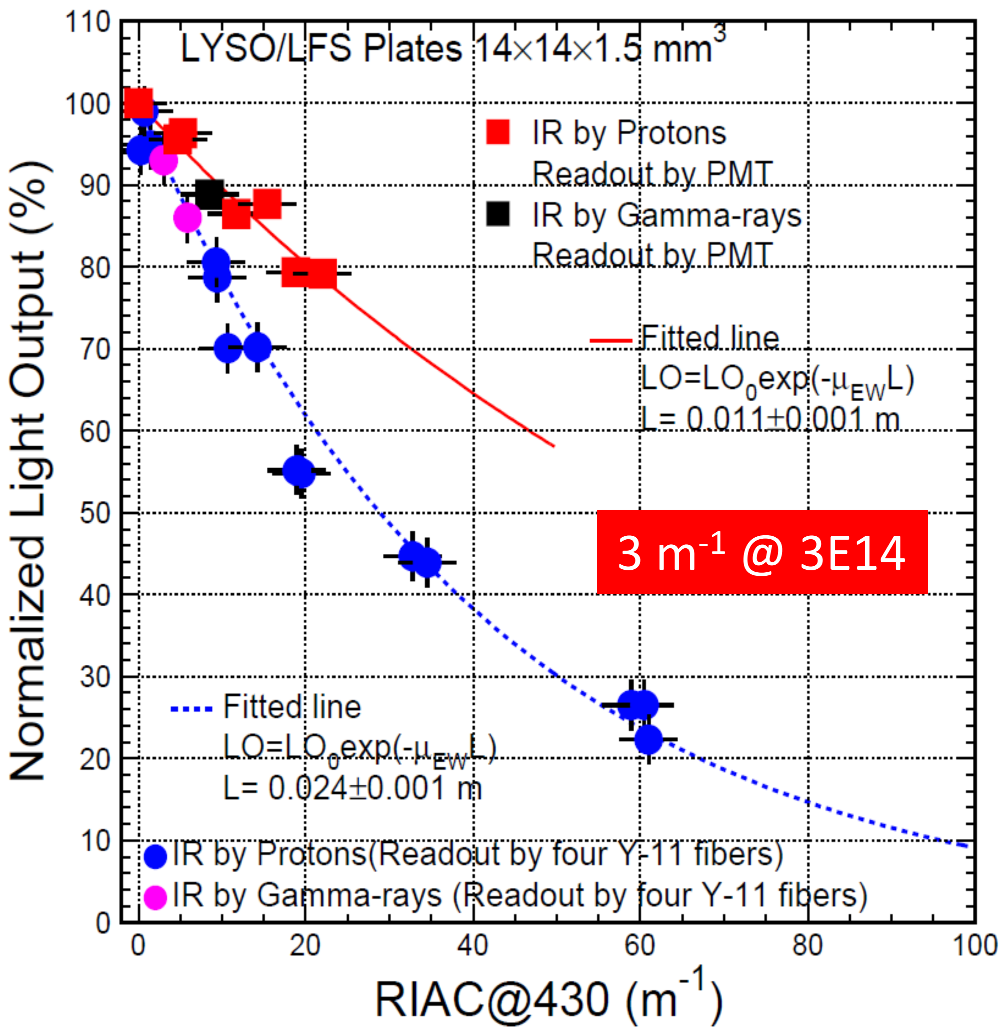




RIAC at 430 nm of 3 m^{-1} after 3×10^{14} p/cm^2

LO by γ-Rays & Protons

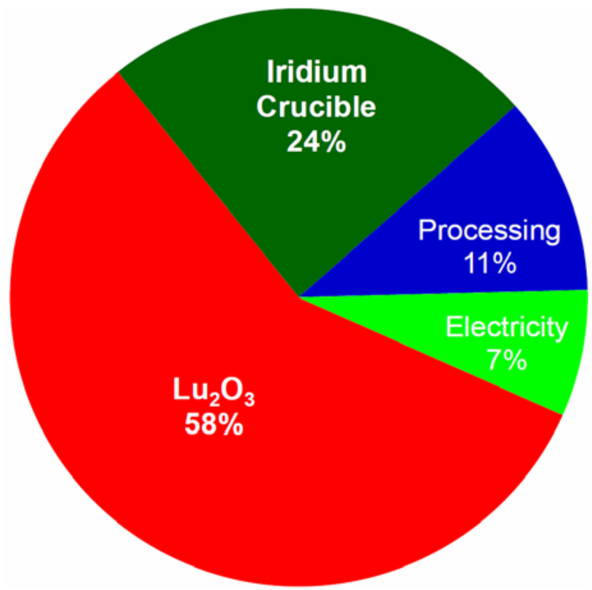
Consist damage by γ-rays and protons in LYSO and LFS plates with average light path length of 1.1 and 2.4 cm at 430 nm for direct and Y-11 readout respectively.



LO losses of 5% in 14x14x1.5 mm plates after 3×10^{14} p/cm^2

LSO/LYSO/LFS Crystal Cost

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 to \$25/cc

A Report on Lu_2O_3 Price

Asian Metal (http://www.asianmetal.cn/) and Ruidow website (http://www.ruidow.com/)

The rare earth market has been weak for the past 4 years. The price of Lutetium Oxide was high in the beginning of 2015, which was around 6,000-6,200 RMB/Kg, and decreased with time. At the beginning of 2016, the price was around 4,000 RMB/Kg. Some transaction was carried out even at 3,800-3,900 RMB/Kg if the volume was large. In early March 2016 and time after that, the price increased a little. There was a news on street that the Chinese central government was taking actions to buy all critical and valuable rare earth products to secure the supply and to stabilize the market. So sellers were not willing to sell for a while. The price reached 4,600-4,800 RMB/Kg for a short time with very limited deal done. Shortly in May the negotiation between the sellers and the government broke down with no real action of procurement from the government. The price decreased to the current level of about 4,500 RMB/Kg.

Crystal Thickness

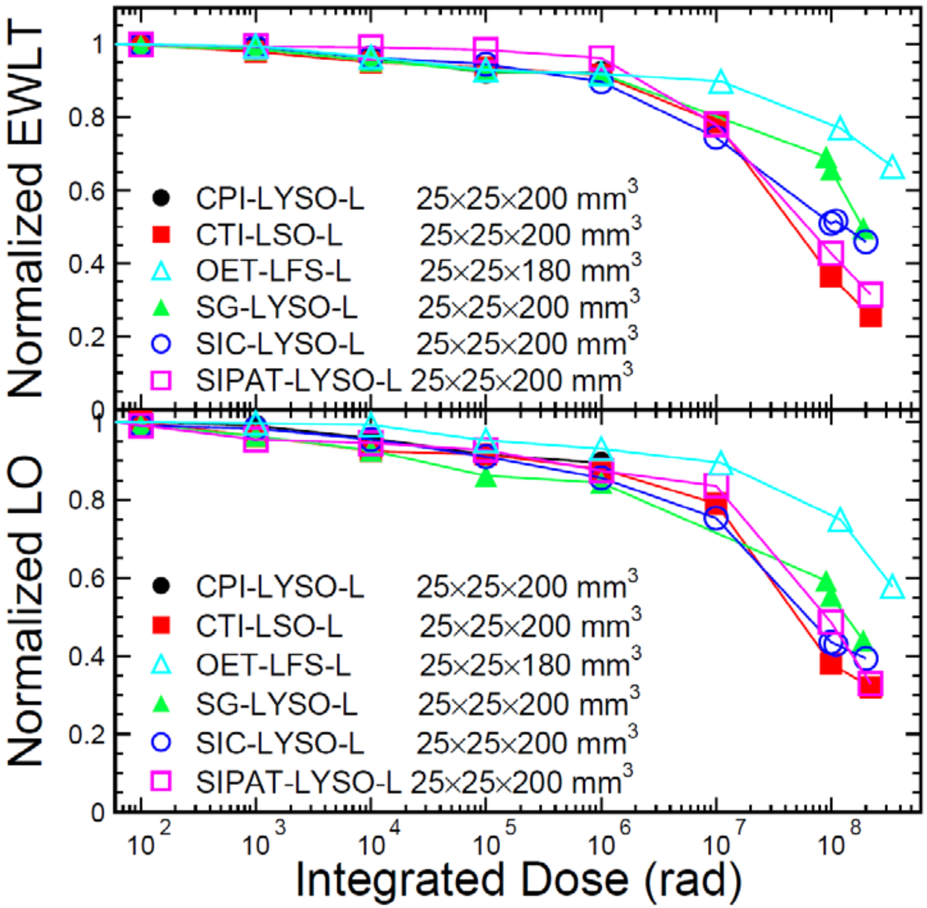
- LSO/LYSO/LFS crystals have high light yield: 30,000 photons/MeV, leading to 3,000 p.e./MeV for an overall efficiency of 10%.
- dE/dx in LSO/LYSO/LFS is about 9.6 MeV/cm for a MIP. 1 mm plate would provide 3,000 p.e., which is sufficient for MIP timing.
- A crucial issue to be understood is the readout noise caused by both increased leakage current and radiation induced phosphorescence. Quantitative measurements under expected dose rate and neutron fluence are needed.

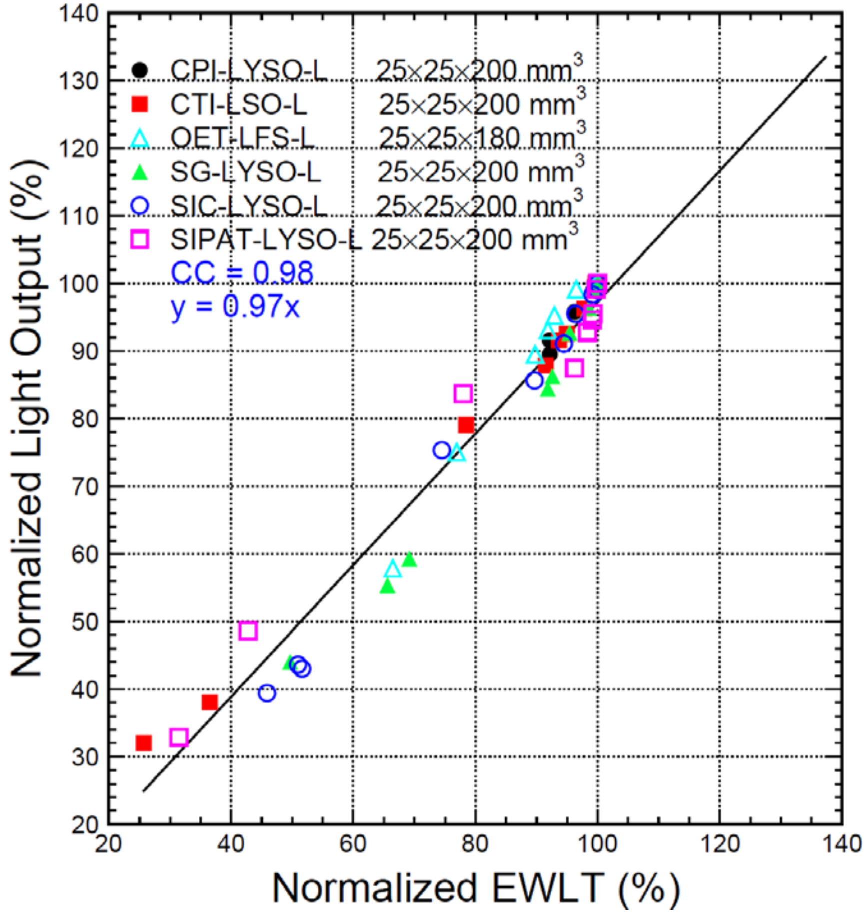
Summary

- Bright and fast LSO/LYSO/LFS is in one of the best crystal choices for precision timing. Its radiation hardness has been scrutinize for HL-LHC: about 5% LO loss is observed for 14 x 14 x 1.5 mm plates after 150 Mrad and 3×10^{14} p/cm^2 fluence.
- Current price of LSO/LYSO/LFS crystals is about $25/cc with 1 cm dimension.
- A thick crystal layer may provide both timing and energy measurements for charged particles and photons, and would enhance discovery potential for CMS. A top down budget would help to define what we can afford for crystals and its thickness within the budgetary constraints.

Normalized EWLT and LO vs. Dose and LO vs. EWLT

The best sample: 58% light output after 340 Mrad

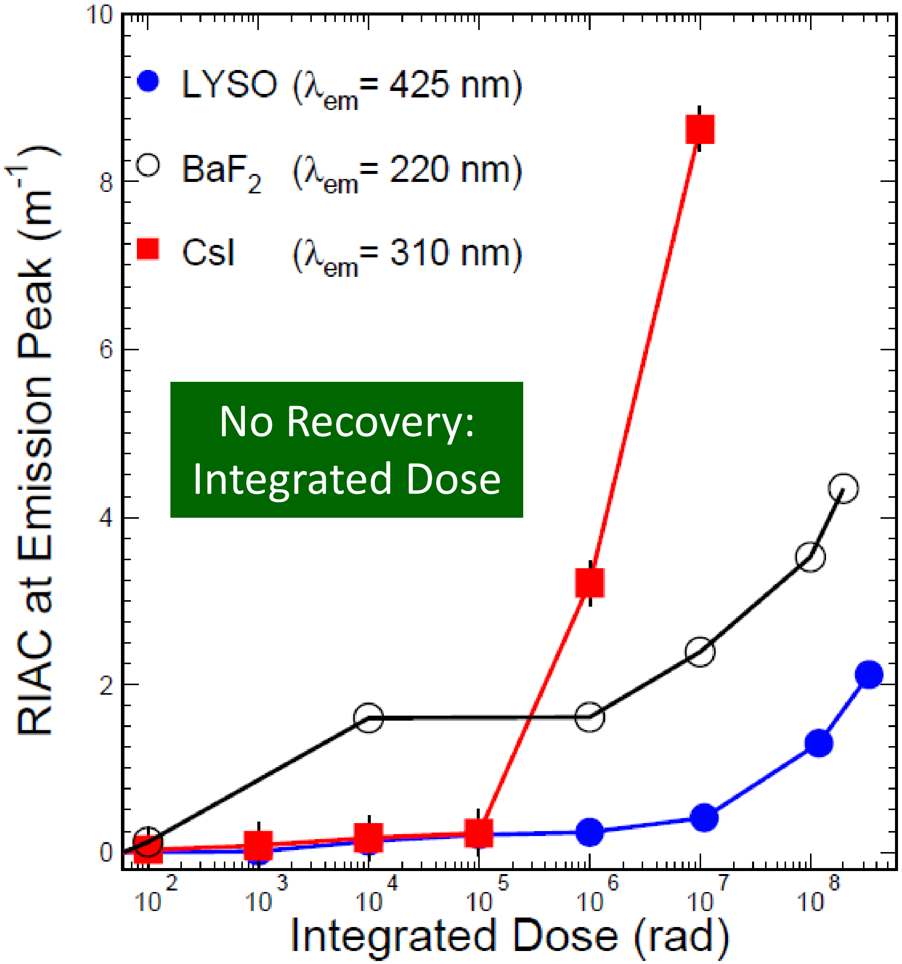


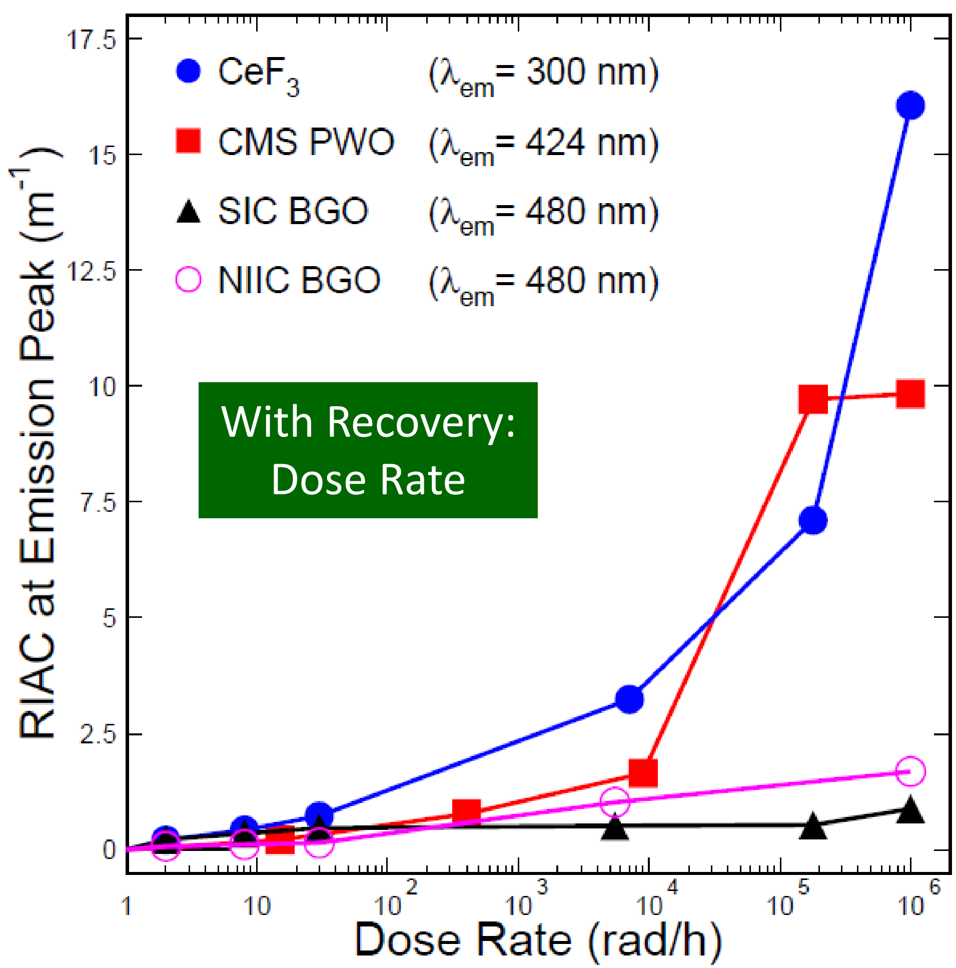


Good correlation between LO and EWLT: LO loss is caused by absorption

All Crystals: RIAC @ Emission Peak

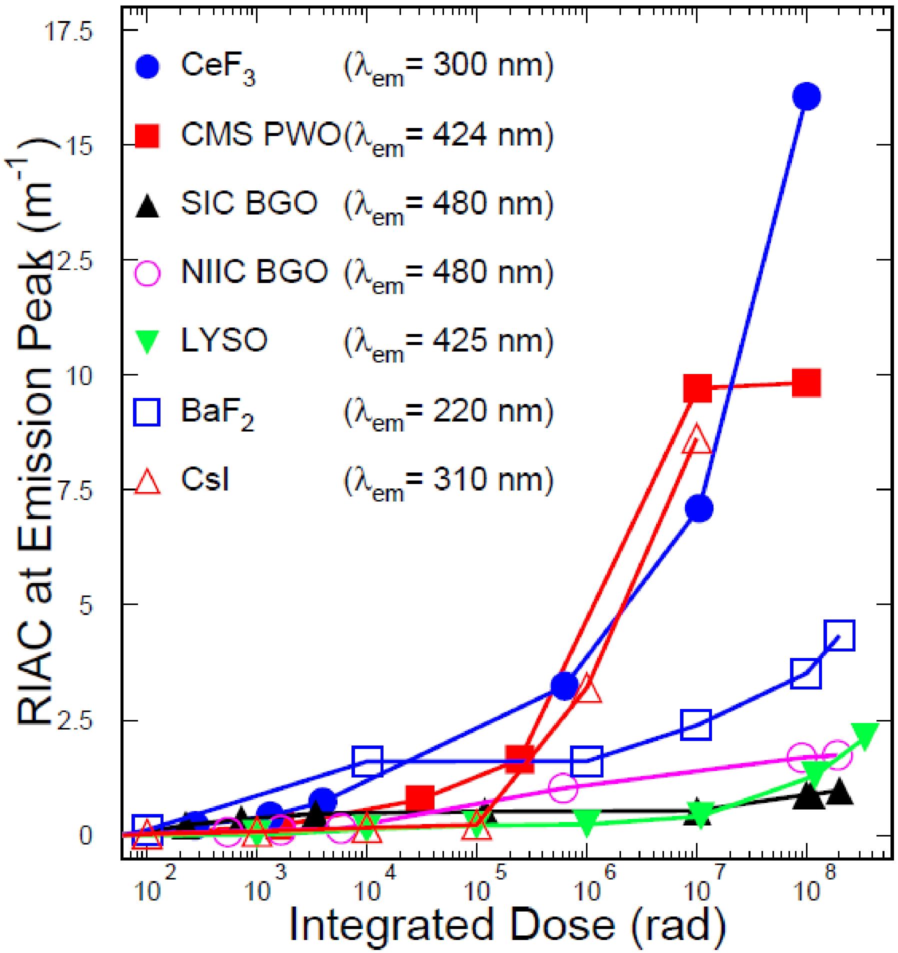
Pure CsI is good below 100 krad; LYSO and BaF_2 are good beyond 1 Mrad
BGO shows small radiation induced absorption up to 1 Mrad/h

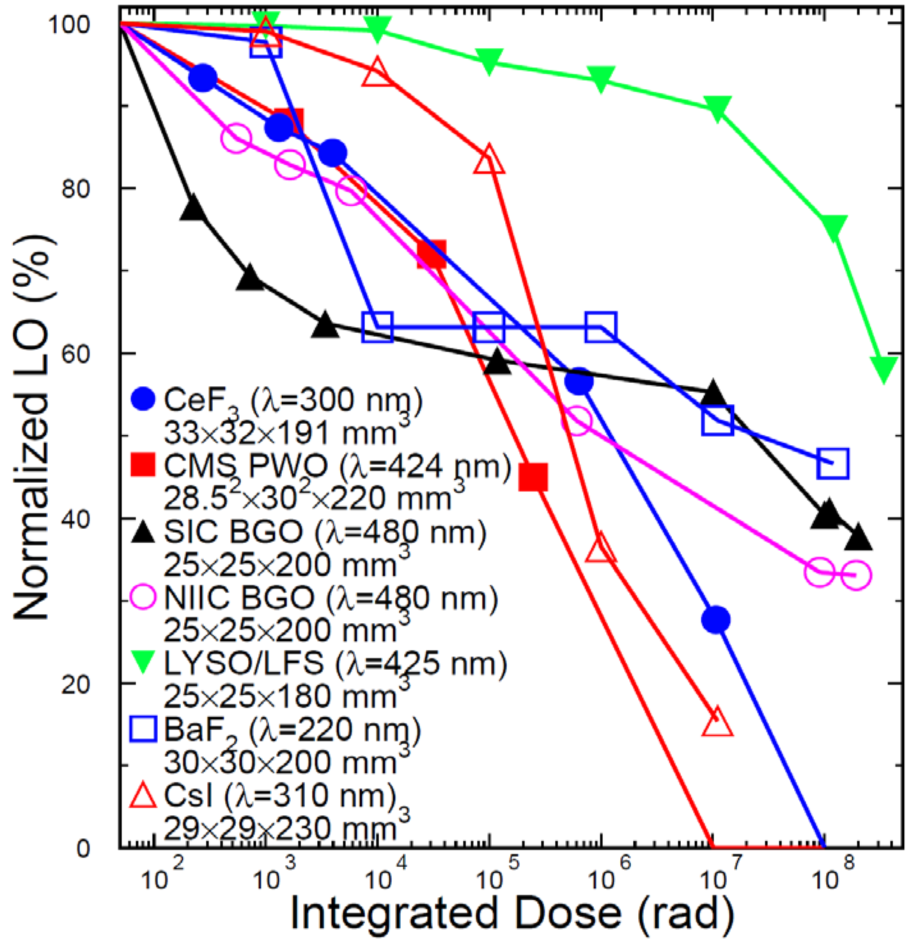




All Crystals: RIAC and LO

Ignoring dose rate dependence, the values of RIAC at the emission peak and normalized LO shown as a function of the integrated dose





LYSO crystals show the best radiation hardness up to 340 Mrad

PbF_2 Radiation Hardness

Damage by ionization dose checked up to 1 Mrad