LYSO Crystal Based Shashlik Calorimeter Cell Design

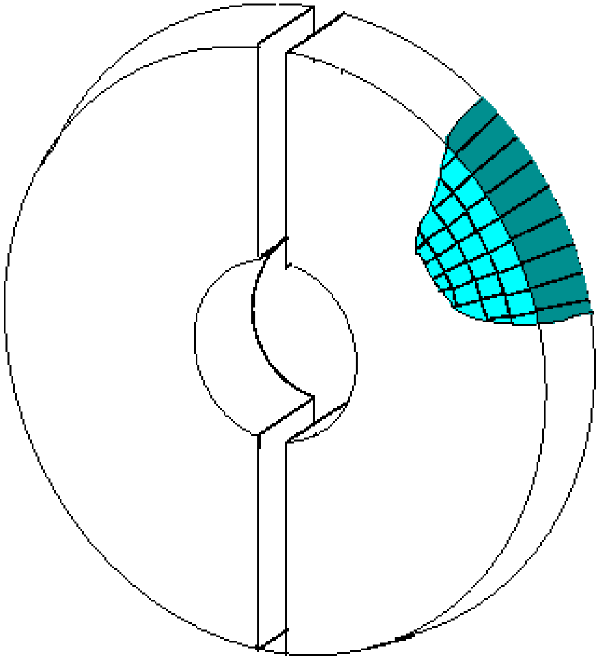
Ren-Yuan Zhu

California Institute of Technology

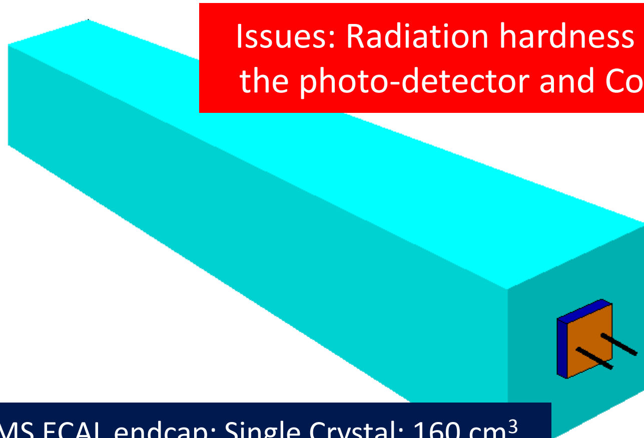
August 30, 2012

Talk given at CMS Forward Calorimetry Taskforce Meeting

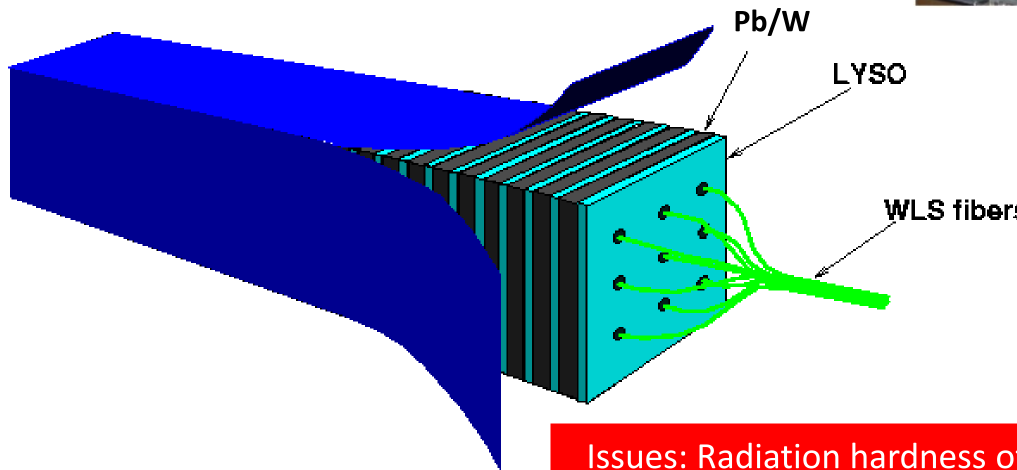
Options for CMS FCAL Upgrade



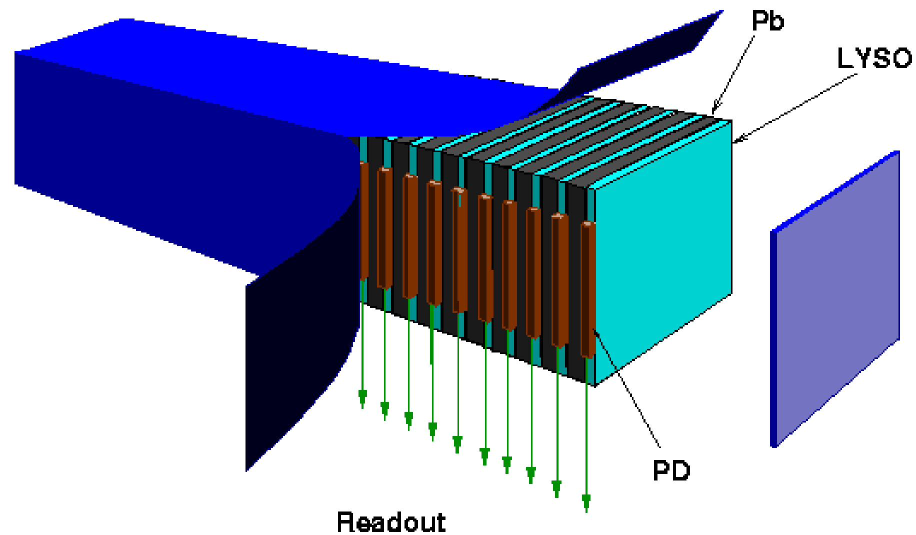
Issues: Radiation hardness of the photo-detector and Cost



CMS ECAL endcap: Single Crystal: 160 cm^3
Total number: 16,000 Total Volume: 2.5 m^3
Expected Crystal Cost: ~$60M@$25/cc



Issues: Radiation hardness of photo-detector and WLS fiber



Crystal Cost: <$10M

Issue: Radiation hardness of the photo-detector

LYSO Based Shashlik Cell Design

- Square geometry: Hexagonal geometry may be considered if needed.
- Since LYSO is relatively expansive the crystal plate thickness, sampling fraction and total cell length (25 X_0) drive the crystal cost:
  - Thickness of LYSO plates 2 mm: < 2 mm is less cost-effective;
  - LYSO crystal volume < 20% of that needed for the total absorption option (25 X_0 LYSO of 28.5 cm): total LYSO length < 5.8 cm.
- Lateral cell dimension about $R_{Moliere}$ for good shower separation.
- WLS Fiber density ~ 1/cm^2. Higher density does not help much [4]. Light yield is estimated by using the LHCb data [1].
- Readout can also be at the front allowing longitudinal segmentation.
- We have a cost-effective compact (17/13 cm cell length) Shashlik design with fine granularity (1.9/1.4 cm) for Pb/W absorbers respectively.

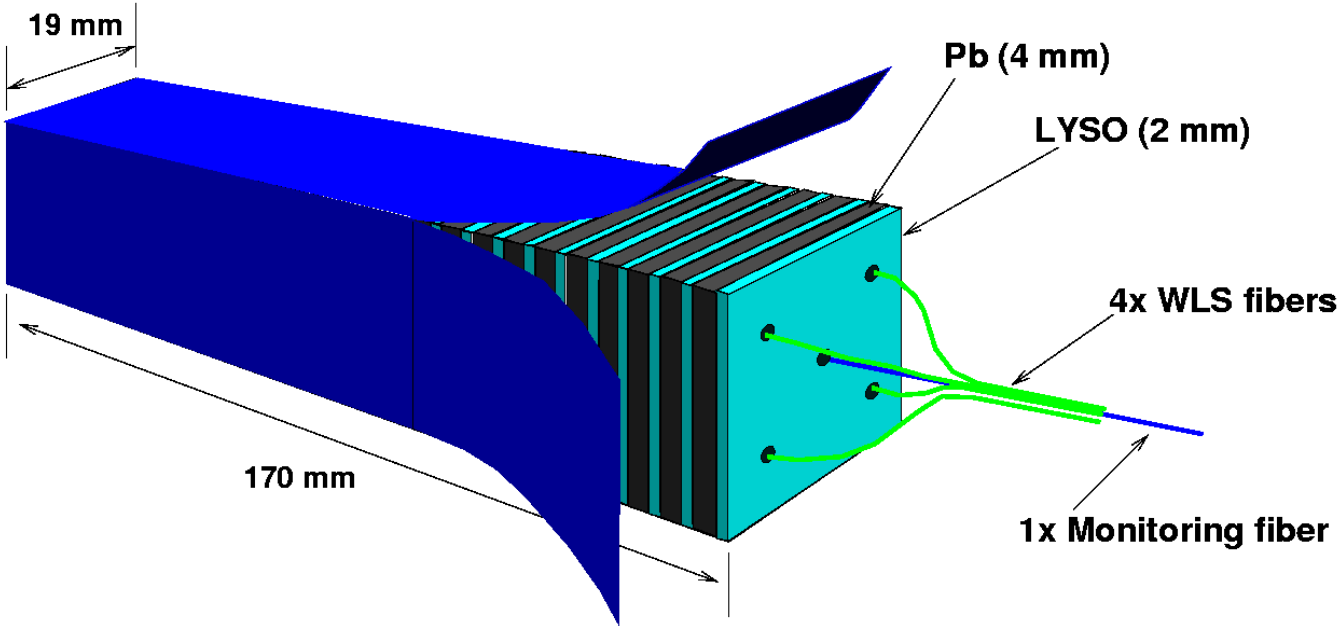
[1] Irina Machikhiliyan for the LHCb calorimeter group, "The LHCb electromagnetic calorimeter", XIII International Conference on Calorimetry in High Energy Physics (Calor2008).
[2] A. Bamberger et al., "The ZEUS forward plug calorimeter with lead-scintillator plates and WLS fiber readout", NIM A450 (2000), p 235-252.
[3] C.S. Atoyan et al., "Lead-scintillator electromagnetic calorimeter with wavelength shifting fiber readout", NIM A320 (1992), p 144-154.
[4] L. labarga and E. Ros, "Mont Carlo study of the light yield, uniformity and energy resolution of electromagnetic calorimeter with a fiber readout system", NIM A249 (1986), p. 228-234.

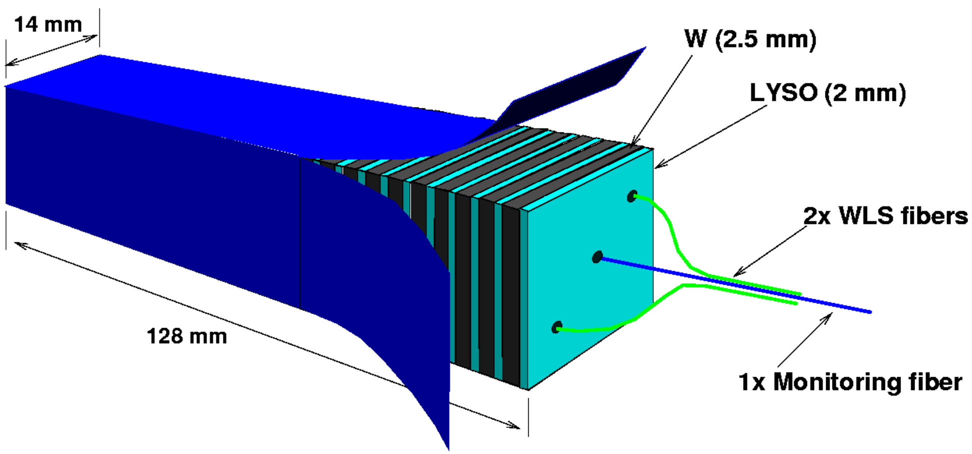
LSO/LYSO Shashlik Cell Design

Cost constraints: 2 mm think crystal plates and 20% crystal volume

		LHCb	Plan-1	Plan-2
Absorber		Lead (Pb)	Lead (Pb)	Tungsten (W)
	Density (g/cm3)	11.4	11.4	19.3
	Radiation Length (cm)	0.56	0.56	0.35
	Moliere Radius (cm)	1.60	1.60	0.93
	dE/dX (MeV/cm)	12.74	12.74	22.1
	Thickness (mm)	2	4	2.5
Scintillation Plate		BASF-165 Polystyrene (Sc)	LYSO	LYSO
	Density (g/cm3)	1.06	7.4	7.4
	Light Yield (photons/MeV)	5200	20000	20000
	Radiation length (cm)	41.31	1.14	1.14
	Moliere Radius (cm)	9.59	2.07	2.07
	dE/dX (MeV/cm)	2.05	9.55	9.55
	Thickness(mm)	4	2	2
Plates number	Absorber	66	28	28
	Scintillator	67	29	29
WLS Fiber		Kurarray Y-11(250)	Kurarray Y-11(250)	Kurarray Y-11(250)
	Diameter (mm)	1.2	1.2	1.2
	Number /Cell	16	4	2
Cell Properties	Total Depth (X0)	24.22	25.09	25.09
	Sampling Fraction	0.25	0.28	0.26
	Total Physical Length (cm)	40	17	12.8
	Total Sc Length (cm)	26.8	5.8	5.8
	Absorber Weight Ratio	0.84	0.75	0.76
	Scintillator Weight Ratio	0.16	0.25	0.24
	Average Density (g/cm3)	4.47	10.04	13.91
	Average Radiation Length (cm)	1.65	0.68	0.51
	Average Moliere Radius (cm)	3.6	1.7	1.2
	Transverse Dimension (cm)	4.1	1.9	1.4
	Sc-depth/Total-depth in X0	0.0268	0.2028	0.2028
	WLS Fiber Density (N/cm2)	0.97	1.06	1.03
MIPs Energy Deposition	Sc plates (MeV)	54.94	55.39	55.39
Light Yield using MIPs	Photon Electrons/GeV	3077	11932	11932
Signal of MIPs	Photon Electrons / MIP	169	720	702

Shashlik Cells with Pb/W Absorbers

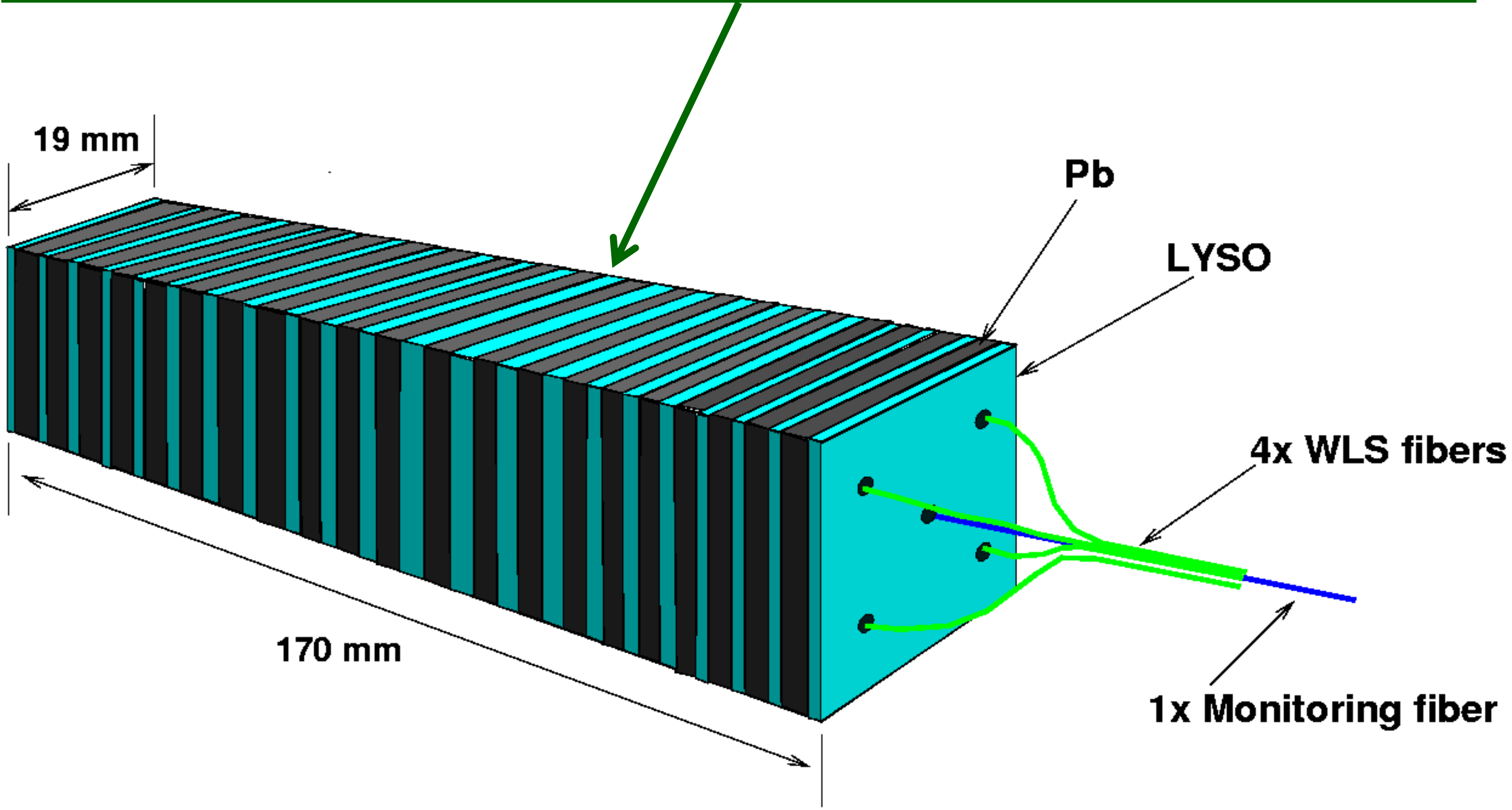




It is interesting to see what is the energy resolution and the photon angular resolution with longitudinal segmentation.

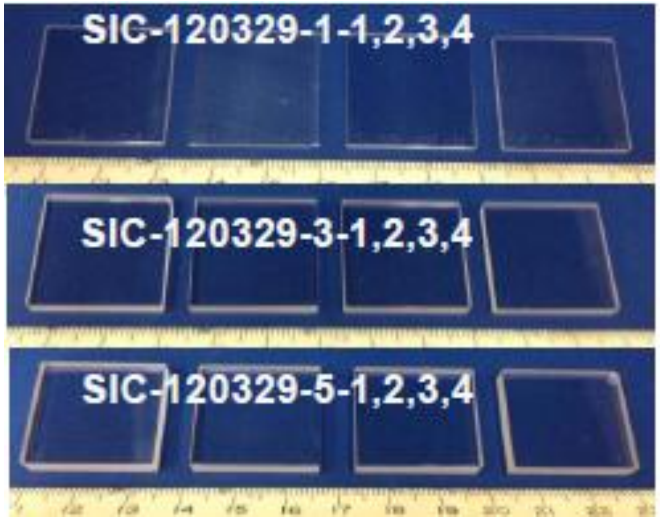
Another Option: Varied Sampling

The thickness of crystal plates may be adjusted according to the longitudinal shower profile without cost increase. An optimized sampling with varied crystal plate thickness may provide a better resolution for photons and electrons, but...



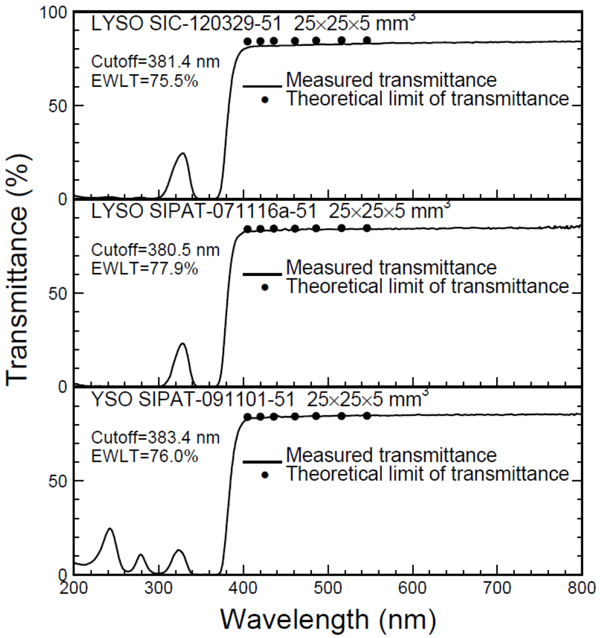
20/4 LYSO/YSO Plates from SIC/SIPAT

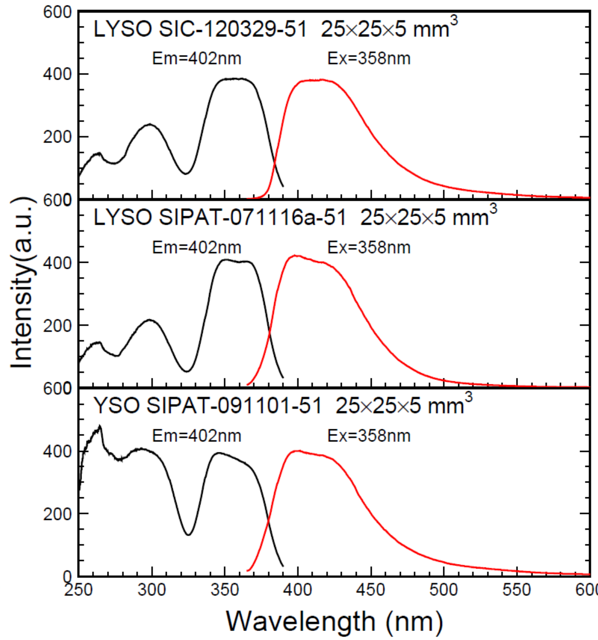
1.5 mm, 3 mm and 5 mm thick

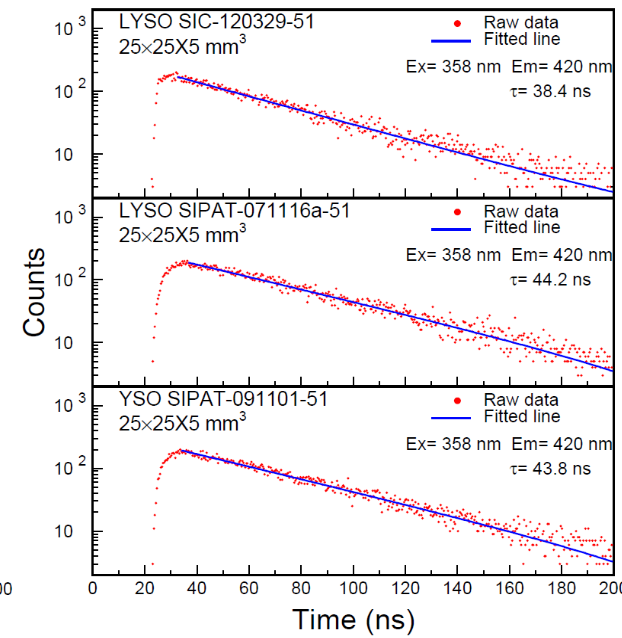


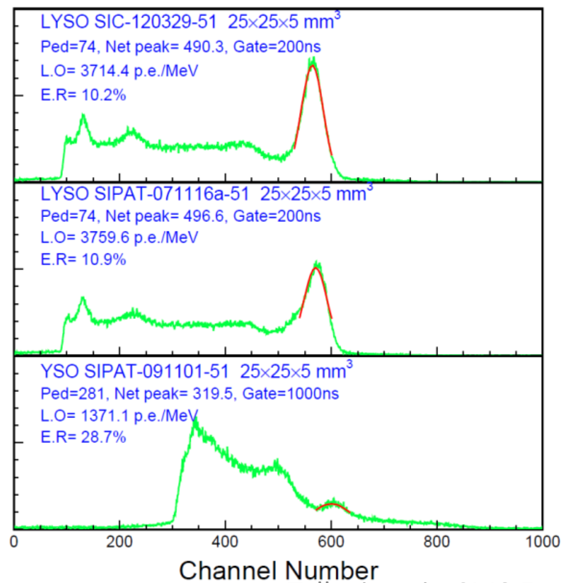
Sample ID	Crystal	Received Date	Dimension (mm³)	Polish
SIC-120329-1-1,2,3,4	LYSO	3/29/2012	25×25×1.5	Two faces (25×25 mm² faces)
SIC-120329-3-1,2,3,4		3/29/2012	25×25×3	Two faces (25×25 mm² faces)
SIC-120329-5-1,2,3,4		3/29/2012	25×25×5	Two faces (25×25 mm² faces)
SIC-A1105-1		11/11/2011	25×25×5	Two faces (25×25 mm² faces)
SIC-A1105-2		11/11/2011	25×25×5	Six faces
SIPAT-071116a-11,12		4/17/2012	25×25×1.5	Six faces
SIPAT-071116a-31,32		4/17/2012	25×25×3	Six faces
SIPAT-071116a-51,52		4/17/2012	25×25×5	Six faces
SIPAT-091101-31,32	YSO	4/17/2012	25×25×3	Six faces
SIPAT-091101-51,52		4/17/2012	25×25×5	Six faces

Optical and Scintillation Properties







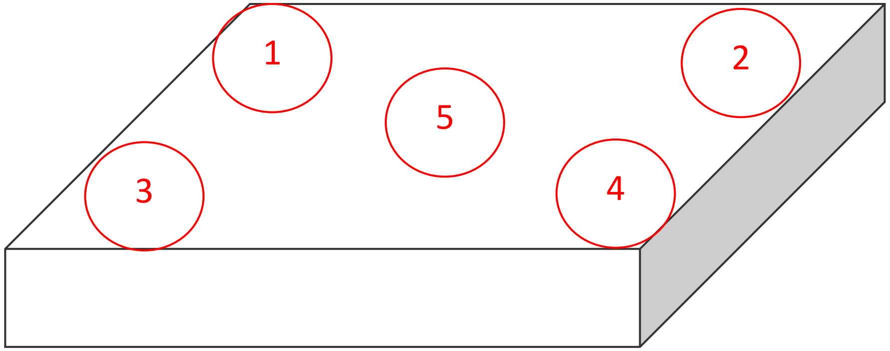


Consistent optical properties observed in transmittance, excitation and photo-luminescence.

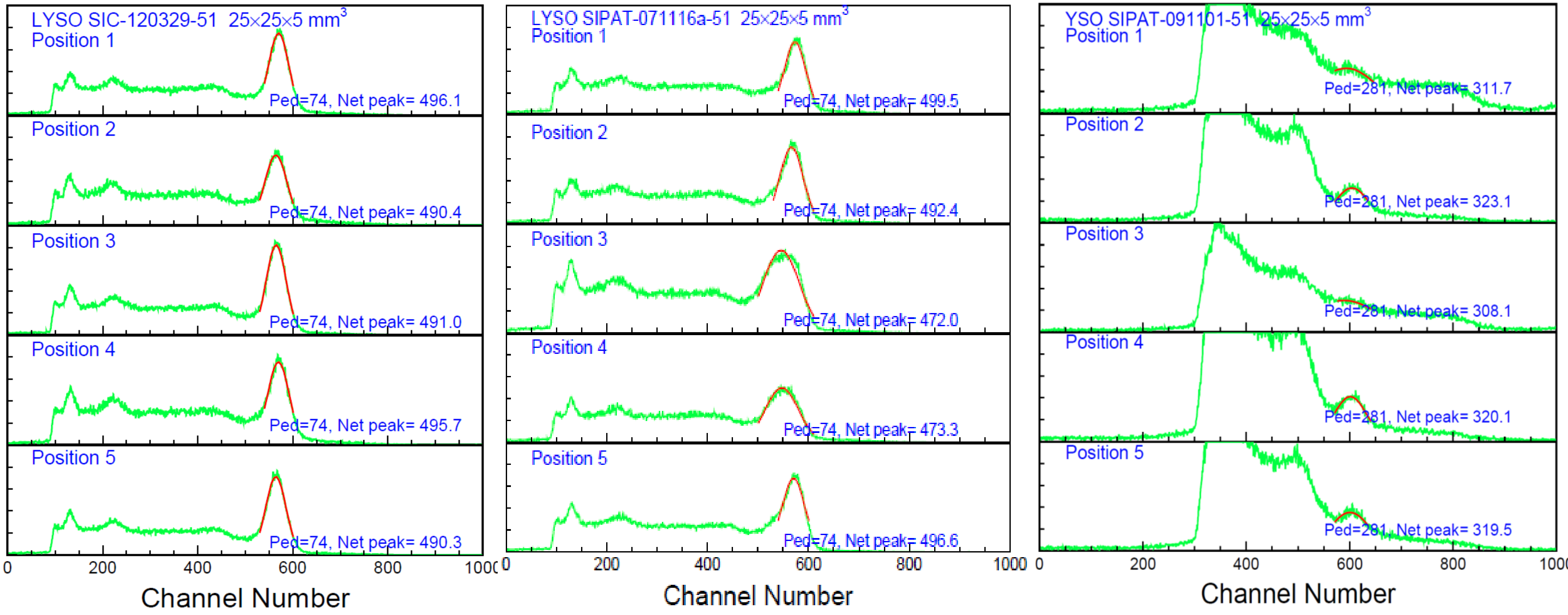
Consistent decay time observed.

YSO crystals, however, have less light output as compared to LYSO, and poorer energy resolution as measured with ^{137}Cs source.

Light Response Uniformity of Plates

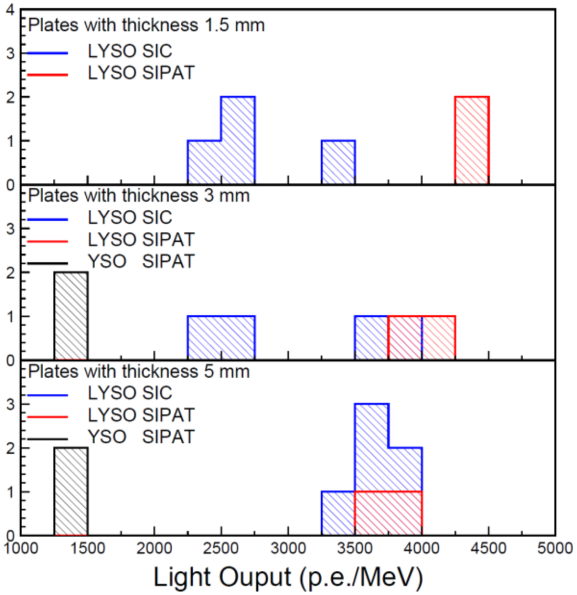


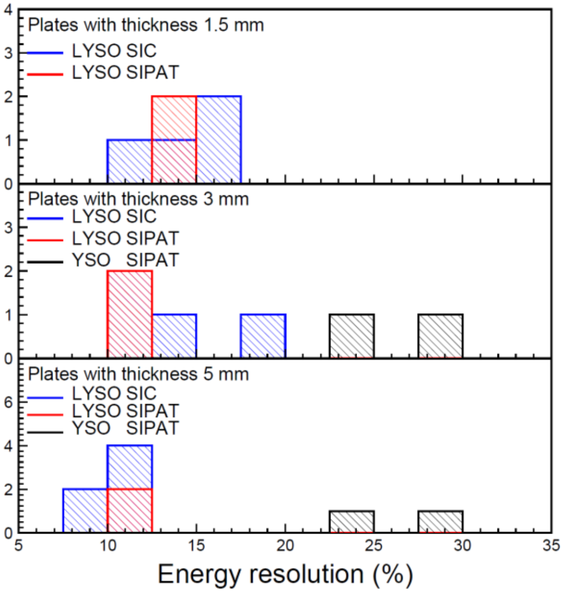
Good light response uniformity at a few percent level observed by injecting collimated ^{137}Cs source at five positions of the plate.

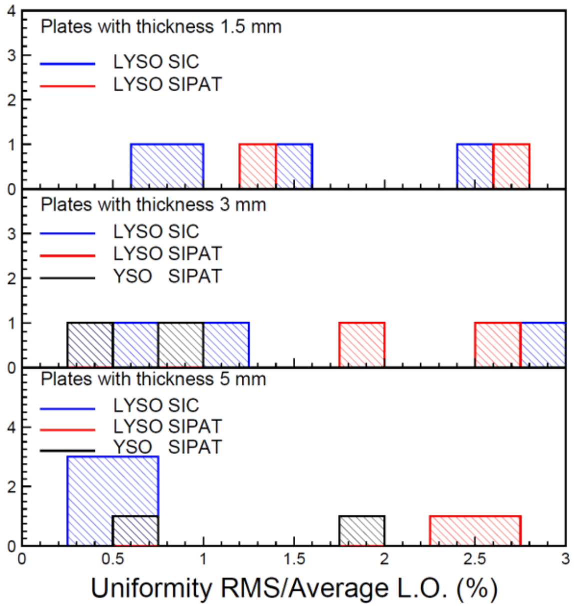


Summary of Plate Performance

Vender	Crystal	Thickness (mm)	Ave. Cutoff (nm)	Ave. EWLT (%)	Ave. τ (ns)	Ave. LO (p.e./MeV)	Ave. E.R. (%)	Ave.Uniformity RMS/L.O. (%)
SIC	LYSO	1.5	376.2	78.7	36.9	2776.2	14.0	1.38
		3.0	379.0	77.9	38.2	3117.1	13.2	1.25
		5.0	381.0	75.8	39.8	3669.7	9.9	0.44
SIPAT	LYSO	1.5	375.1	80.3	40.4	4363.5	13.8	2.02
		3.0	377.9	79.3	43.1	4009.4	11.7	2.32
		5.0	380.5	78.1	43.5	3734.2	11.5	2.52
SIPAT	YSO	3.0	380.5	79.2	42.7	1440.0	27.0	0.59
		5.0	383.3	78.1	44.0	1363.0	26.7	1.28

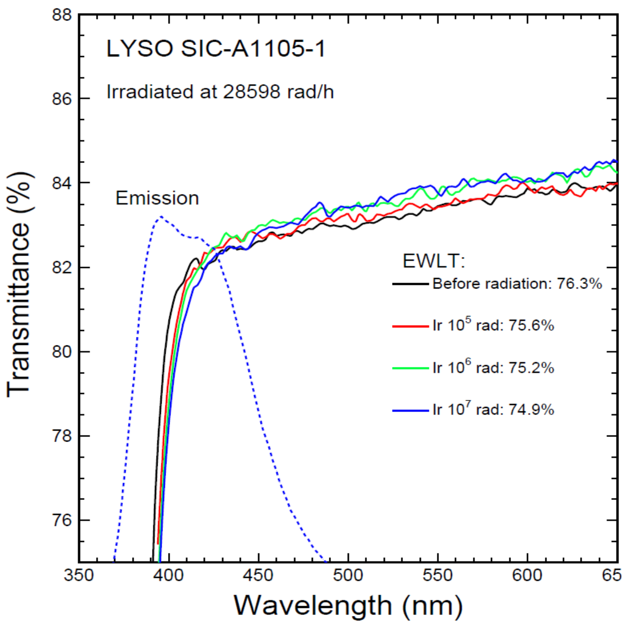


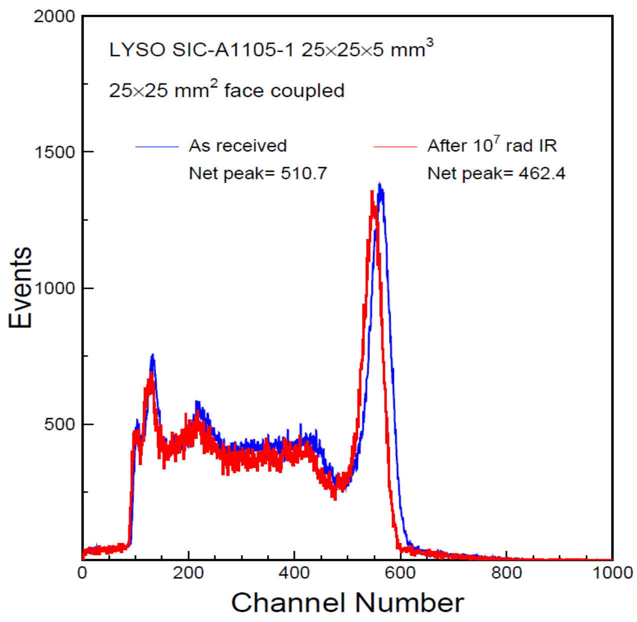


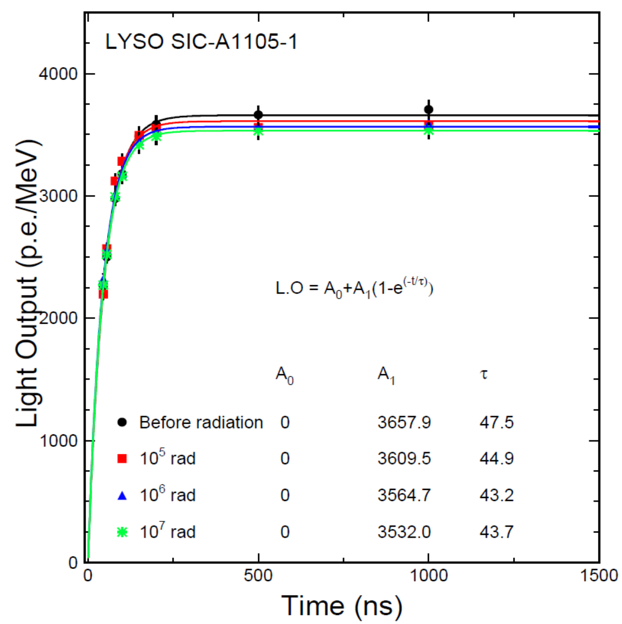


LYSO Plate Radiation Hardness

Two 5 mm thick LYSO plates went through γ-ray irradiation to 10 Mrad with degradation in both EWLT and LO less than 10%. Since damage does not recover, so is easy to be monitored.



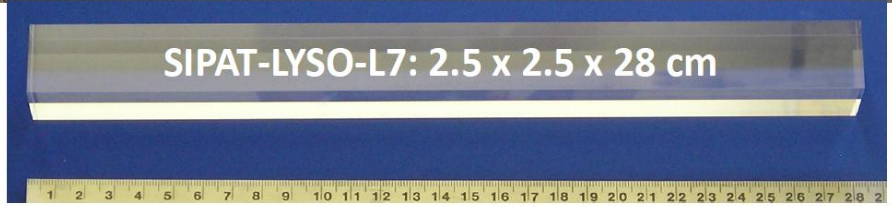


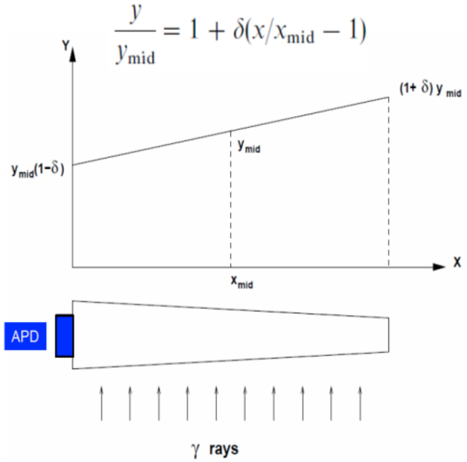


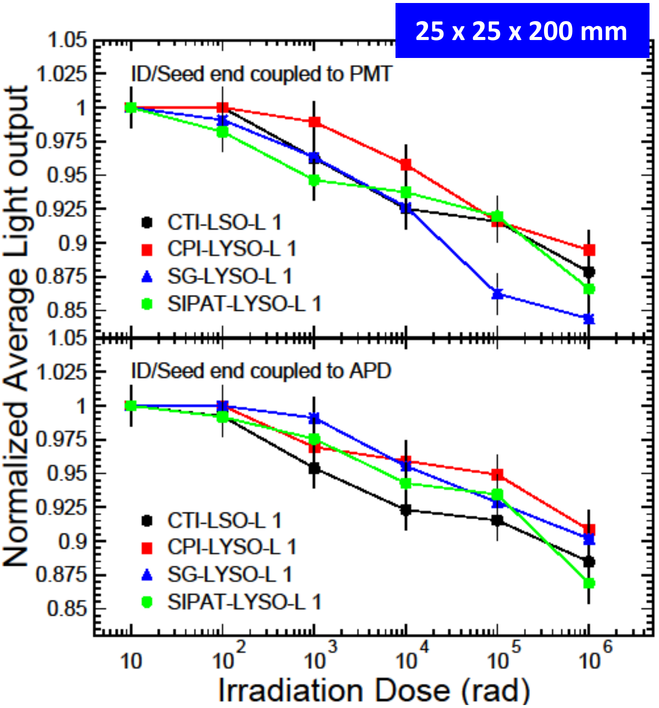
Samples	EWLT (%)	L.O. (p.e./MeV)	EWLT loss (%)			L.O. loss (%)		
			10^5 rad	10^6 rad	10^7 rad	10^5 rad	10^6 rad	10^7 rad
SIC-A1105-1	76.3	3657.9	0.9	1.4	1.8	1.3	2.5	3.4
SIC-A1105-2	77.2	3846.1	2.3	2.5	2.6	4.4	7.7	9.1

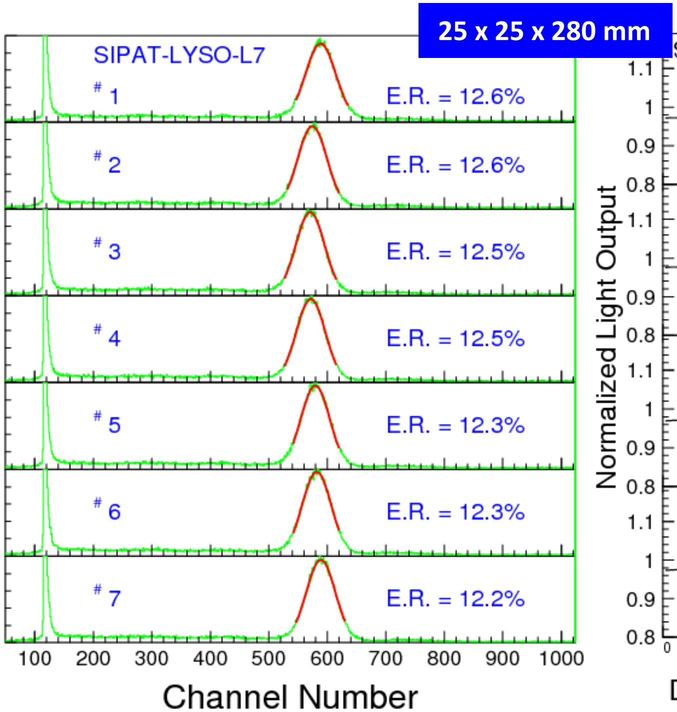
Rad-Hard Long LYSO Crystals

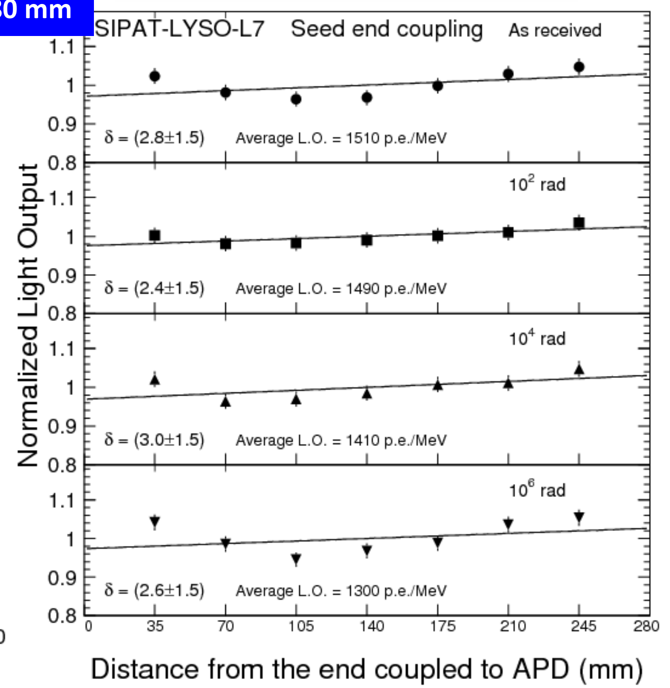
R.H. Mao, L.Y. Zhang and R.-Y. Zhu, ``Quality of a 28 cm Long LYSO Crystal and Progress on Optical and Scintillation Properties”, *IEEE Trans. Nucl. Sci.* **NS-59** (2012)











Other Fast Crystal Candidates

R.-Y. Zhu, Talk in CMS Forward Calorimetry Task Force Meeting, CERN, June 27, 2012

	LSO/LYSO	GSO [1]	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	4.54	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	3.04	1.86	2.03	1.70	1.96	2.81	1.88	42.54
Molière Radius (cm)	2.07	2.23	2.87	3.57	3.10	2.41	2.97	3.71	2.85	9.59
Interaction Length (cm)	20.9	22.2	27.3	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	6.70	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	35	40	4.2 1.3	42 4.8	8.6	141	15 49	153	35
Decay Time[a] (ns)	40	65	70	30 6	650 0.9	30	17	570 24	20	1.8
d(LY)/dT[d] (%/°C)	-0.2	-0.7	-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

Caltech Plan for FCAL R&D

- The LYSO R&D was supported by an Advanced Detector R&D award from DOE.
- The R&D at Caltech includes studies for fast crystal scintillators to be used for the CMS FCAL upgrade, including long LYSO crystals for the total absorption option and crystal plates for the sampling option with materials ranged from fast crystals, such as BaF_2, CeF_3, CsI, GSO, LSO, LYSO and YSO, to ceramics, such as YAG, LuAG and others. Samples will be procured from various vendors. Their optical and scintillation properties will be characterized at Caltech Crystal Laboratory.
- The R&D program for FCAL at Caltech also includes design of sampling calorimeter cells and prototype construction. Sampling calorimeter cells will be characterized with a cosmic-ray based test stand, and may be used to construct a test beam matrix for a beam test.
- Following this R&D program and further design studies, if successful, the Caltech group would be interested in implementing an LYSO-based forward ECAL for the CMS Upgrade, in partnership with other interested CMS groups.

Caltech Crystal Laboratory

- Overall Goal: develop novel detector concept.
- Investigation of new crystal scintillators, such as CeF_3, $LaBr_3$, $LaCr_3$, BSO, PbFCl and Doped PbF_2 etc.
- Investigation of various photo-detectors.
- Radiation hardness study for crystal and ceramic scintillators: BaF_2, BGO, CeF_3, CsI, CsI(Tl), GSO, LSO, LYSO, PbF_2, PWO, YSO, YAG, LuAG…
- Prototype building and evaluation at single cell level.

Recent Published Papers

1. R.H. Mao, L.Y. Zhang and R.-Y. Zhu, ``Quality of a 28 cm Long LYSO Crystal and Progress on Optical and Scintillation Properties", *IEEE Trans. Nucl. Sci*. NS-59 (2012).
2. R.-Y. Zhu, ``Radiation damage effects". In Handbook of particle detection and imaging, ed. Grupen, Claus et al. vol. 1 535-555 (2012).
3. R.H. Mao, L.Y. Zhang and R.-Y. Zhu, ``Fast Neutron Induced Nuclear Counter Effect in Hamamatsu Silicon PIN Diodes and APDs,'' *IEEE Trans. Nucl. Sci*. NS-58, 1249-1256 (2011).
4. R.H. Mao, L.Y. Zhang and R.-Y. Zhu, ``LSO/LYSO Crystals for Future High Energy Physics Experiments,'' 2011 J. Phys.: Conf. Ser. 293 012004
5. R.H. Mao, L.Y. Zhang and R.-Y. Zhu, ``A Search for Scintillation in Doped Cubic Lead Fluoride Crystals,'' *IEEE Trans. Nucl. Sci*. NS-57, 3841-3845 (2010).
6. R.H. Mao, L.Y. Zhang and R.-Y. Zhu, ``Effects of Neutron Irradiations in Various Crystal Samples of Large Size for Future Crystal Calorimeter,'' Paper N32-4 in IEEE NSS/MIC Conference Record (2009).
7. R.H. Mao, L.Y. Zhang and R.-Y. Zhu, ``Gamma-ray Induced Radiation Damage in PWO and LSO/LYSO Crystals,'' Paper N32-5, in IEEE NSS/MIC Conference Record (2009).
8. R.-Y. Zhu, ``Crystal Calorimeters in the Next Decade,'' JOP Conference Series 160 (2009) 012017.
9. R.-Y. Zhu, ``Precision Crystal Calorimeters in High Energy Physics: Past, Present and Future,'' Invited Paper, Proc. of SPIE Vol. 7079 70790W-1 (2008).
10. R.H. Mao, L.Y. Zhang and R.-Y. Zhu, ``Emission Spectra of LSO and LYSO Crystals Excited by UV Light, X-Ray and Gamma-ray,'' *IEEE Trans. Nucl. Sci*. NS-55, 1759--1766 (2008).
11. R.H. Mao, L.Y. Zhang and R.-Y. Zhu, ``Optical and Scintillation Properties of Inorganic Scintillators in High Energy Physics,'' *IEEE Trans. Nucl. Sci*. NS-55 2425--2431 (2008).
12. J.M. Chen, R.H. Mao, L.Y. Zhang and R.-Y. Zhu, ``Gamma-Ray Induced Radiation Damage in Large Size LSO and LYSO Crystal Samples,'' *IEEE Trans. Nucl. Sci.* NS-54 1319--1326 (2007).
13. J.M. Chen, R.H. Mao, L.Y. Zhang and R.-Y. Zhu, ``Large Size LSO and LYSO Crystals for Future High Energy Physics Experiments,'' *IEEE Trans. Nucl. Sci.* NS-54 718--724 (2007).
14. J.M. Chen, L.Y. Zhang and R.-Y. Zhu, ``Large Size LSO and LYSO Crystal Scintillators for Future High Energy Physics and Nuclear Physics Experiments,'' *Nucl. Instr. and Meth*. A572 218--224 (2007).
15. J.M. Chen, R.H. Mao, L.Y. Zhang and R.-Y. Zhu, ``A Study on Correlations between the Initial Optical and Scintillation Properties and their Radiation Damage for Lead Tungstate Crystals,'' *IEEE Trans. Nucl. Sci*. NS-54 375--382 (2007).