LSO/LYSO Crystals for HEP Applications

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Why LSO/LYSO for HEP?

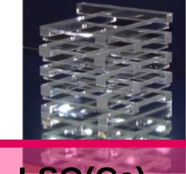
LSO/LYSO is a bright (200 times of PWO), fast (40 ns) crystal, and is a radiation-hard scintillator. The light output loss of 20 to 28 cm long crystals is at a level of 10% after 1 Mrad γ–ray irradiations, much better than all other crystal scintillators.

The longitudinal non-uniformity issue caused by crystal geometry, self-absorption and cerium segregation is addressed by roughening one side surface for uniformization.

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, N32-4 & N32-5 @ NSS09, Orlando, N38-2 @ NSS10, Knoxville.

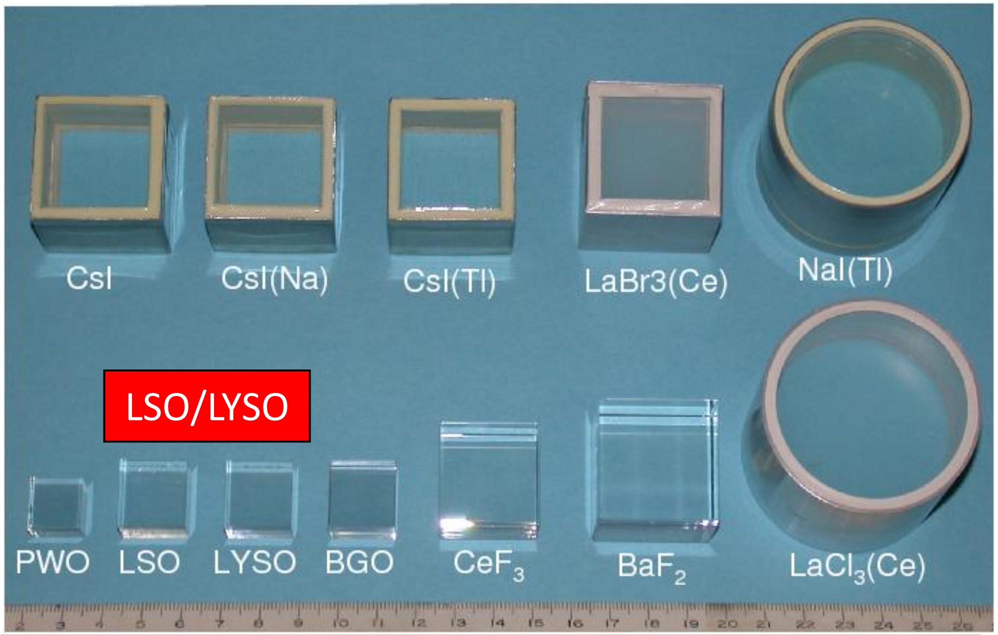
Crystals for HEP Calorimeters

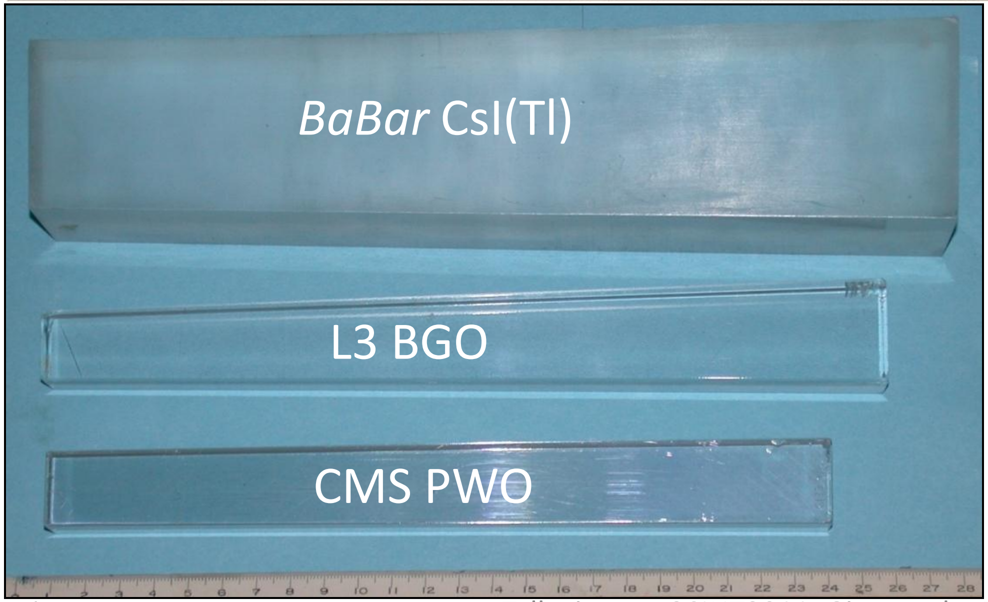


Crystal	NaI(Tl)	CsI(Tl)	CsI(Na)	CsI	BaF_2	CeF_3	BGO	PWO(Y)	LSO(Ce)
Density (g/cm^3)	3.67	4.51	4.51	4.51	4.89	6.16	7.13	8.3	7.40
Melting Point (°C)	651	621	621	621	1280	1460	1050	1123	2050
Radiation Length (cm)	2.59	1.86	1.86	1.86	2.03	1.70	1.12	0.89	1.14
Molière Radius (cm)	4.13	3.57	3.57	3.57	3.10	2.41	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	Slight	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] (%/ °C)	-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	Mu2e 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

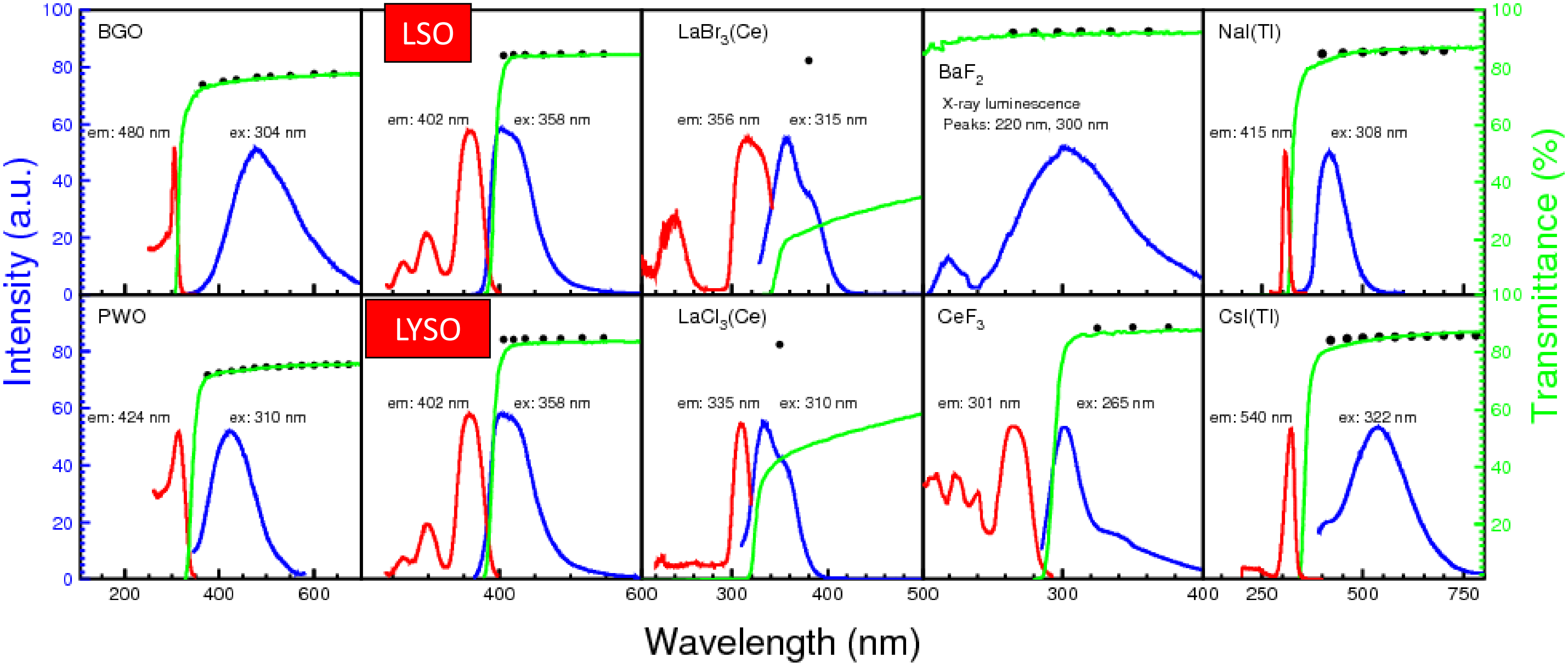
CMS PWO(Y): 25 X_0

Excitation, Emission, Transmission

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

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

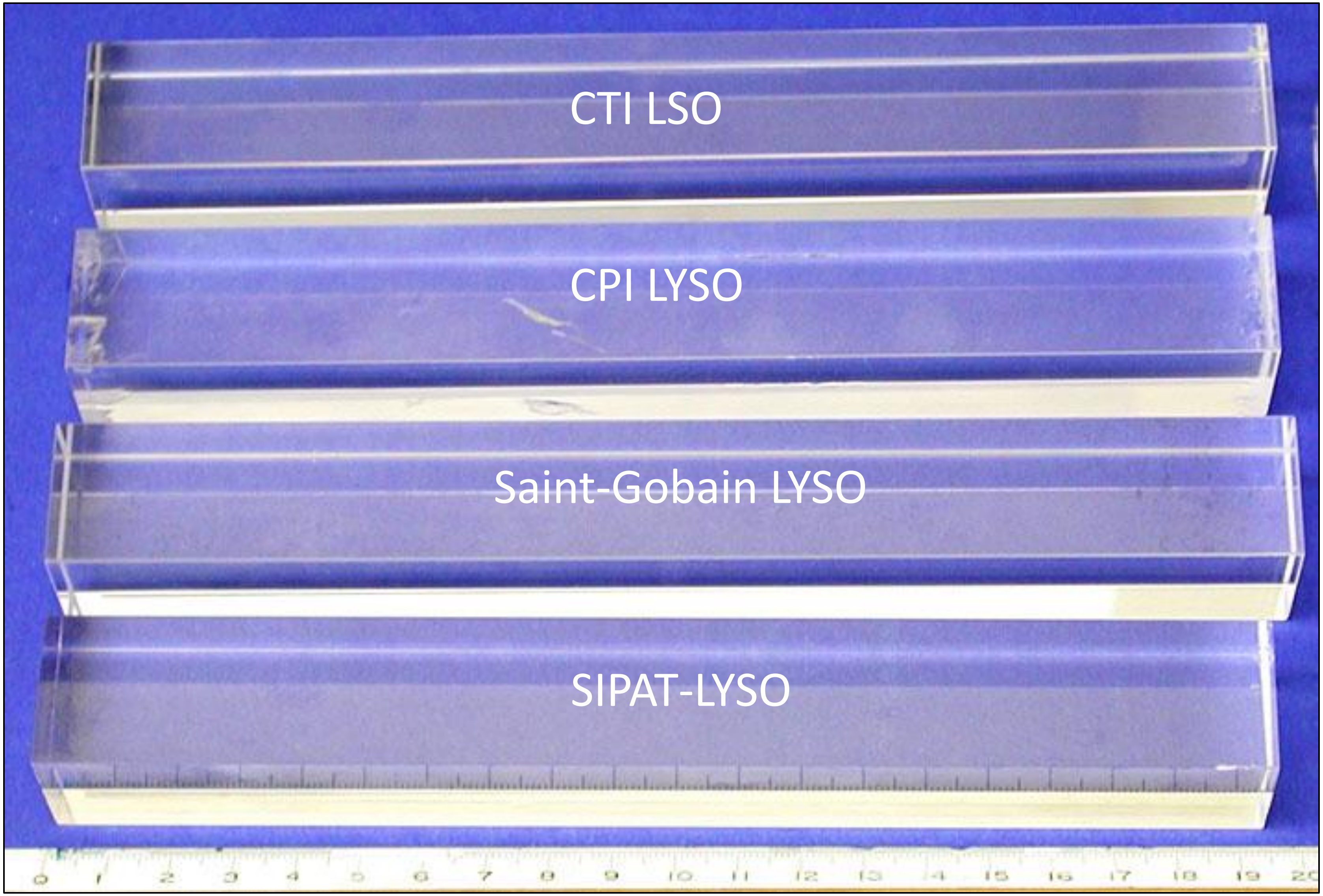
Black Dots: Theoretical limit of transmittance: NIM A333 (1993) 422



No Self-absorption: BGO, PWO, BaF_2, NaI(Tl) and CsI(Tl)

LSO & LYSO Crystal Samples

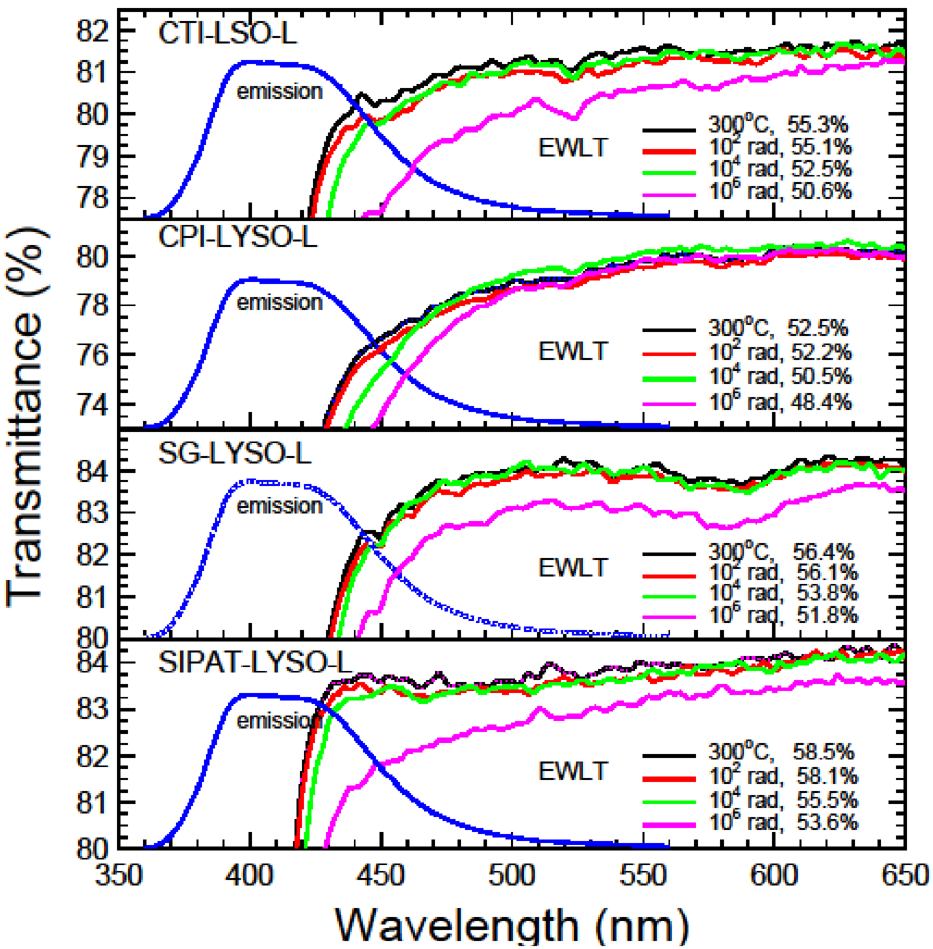
2.5 x 2.5 x 20 cm (18 X_0)



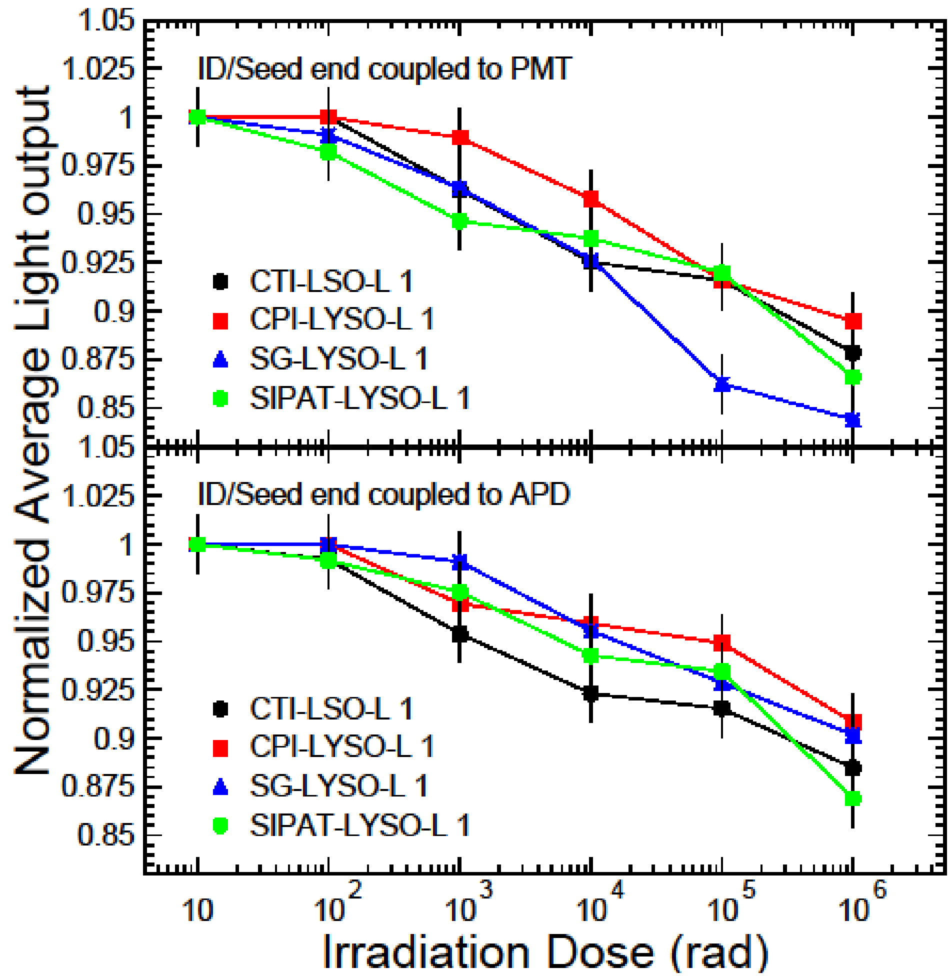
20 cm Long LSO/LYSO under γ-Rays

Consistent radiation hardness better than other crystals

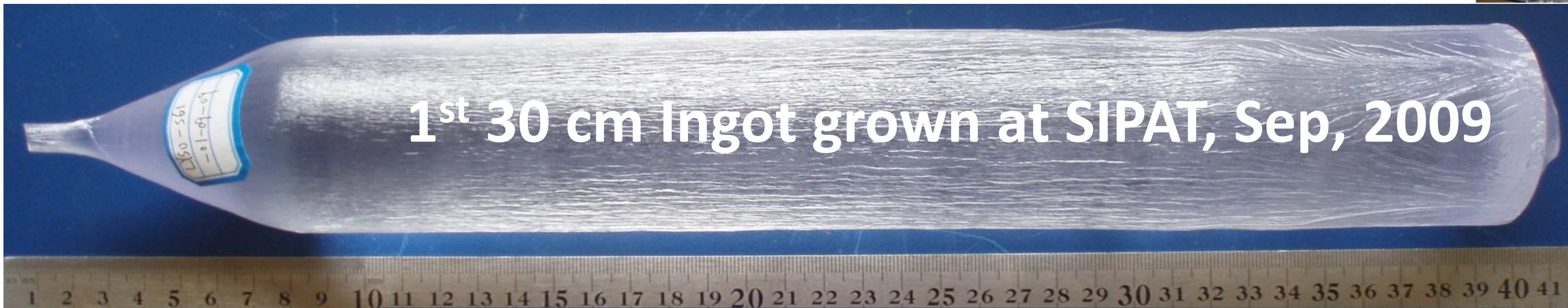
EWLT damage: 8% @ 1 Mrad

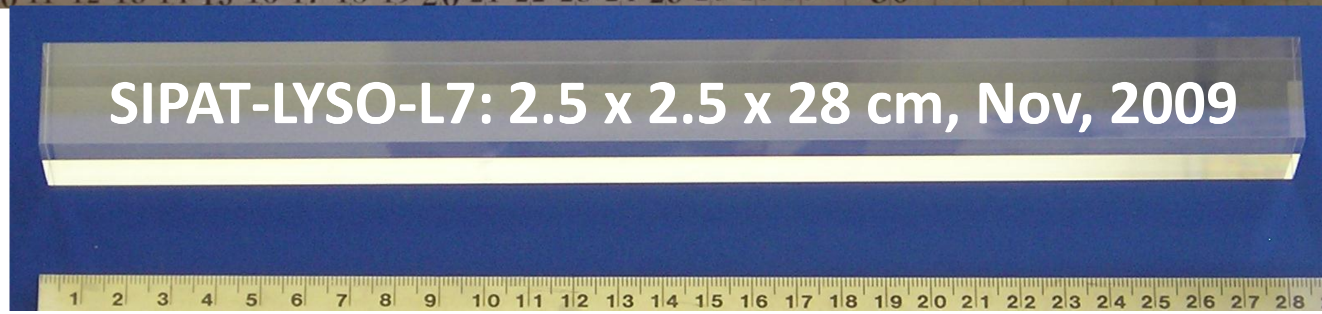


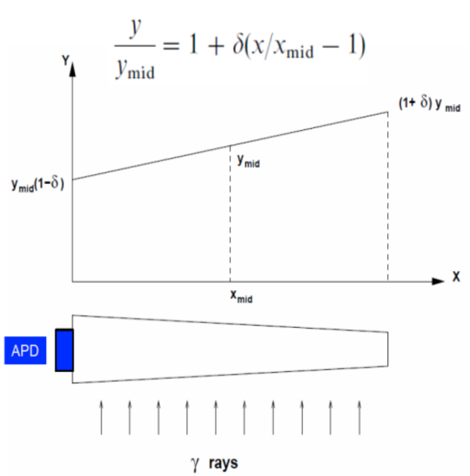
10% - 15% loss by PMT & APD

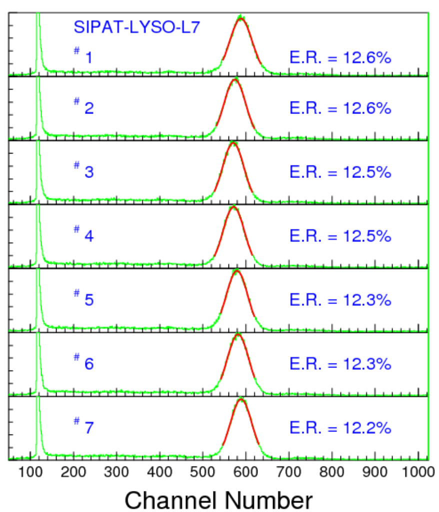


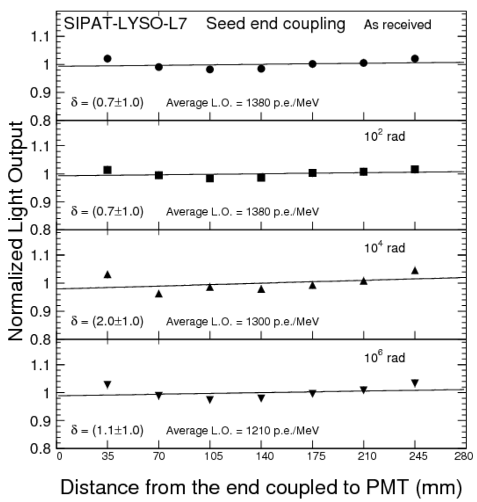
Excellent Radiation Hardness

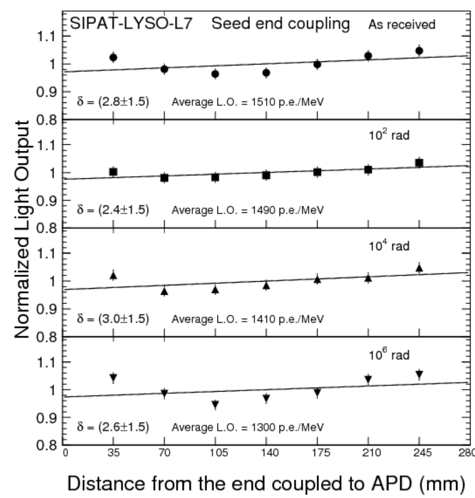






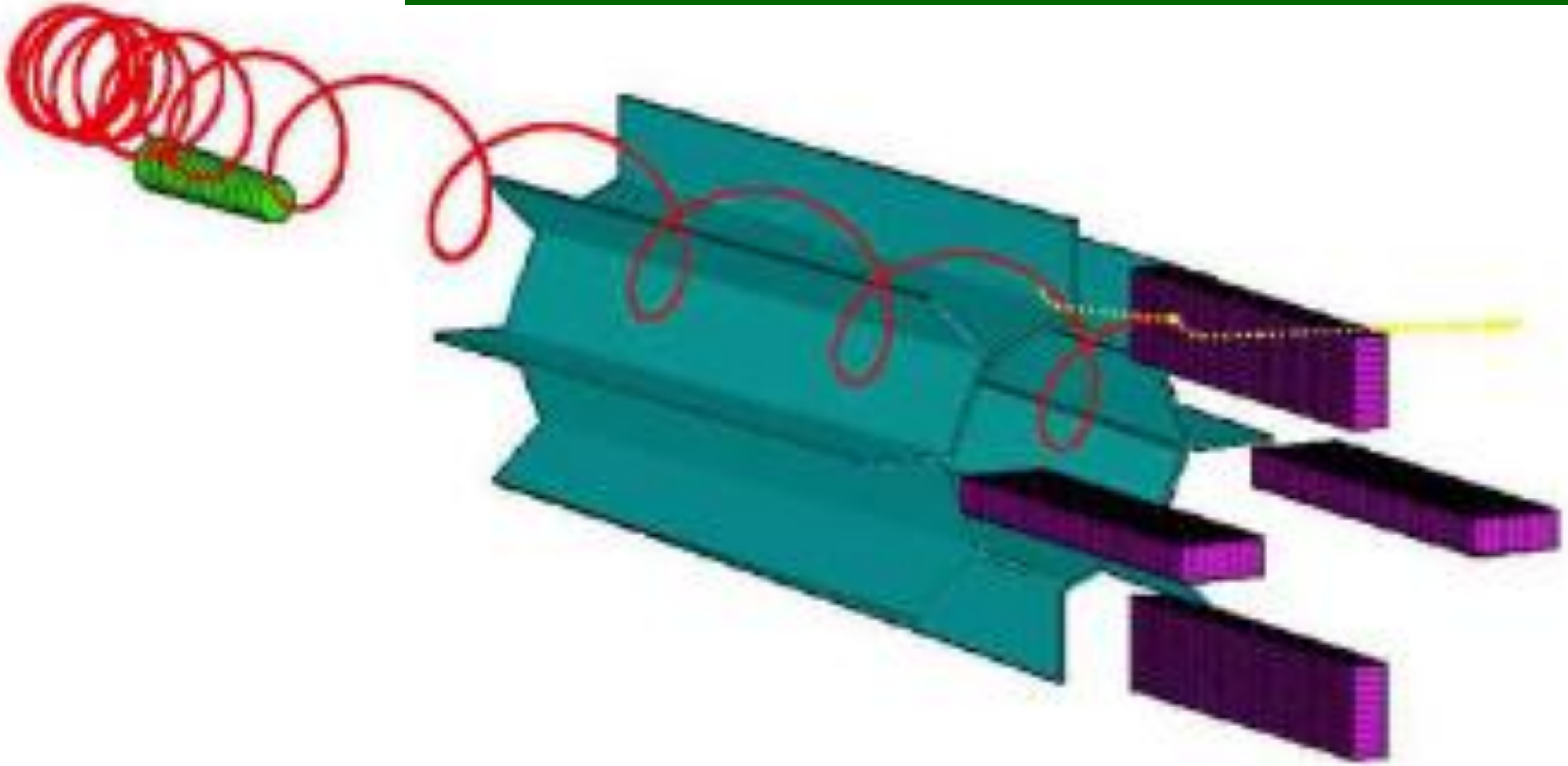






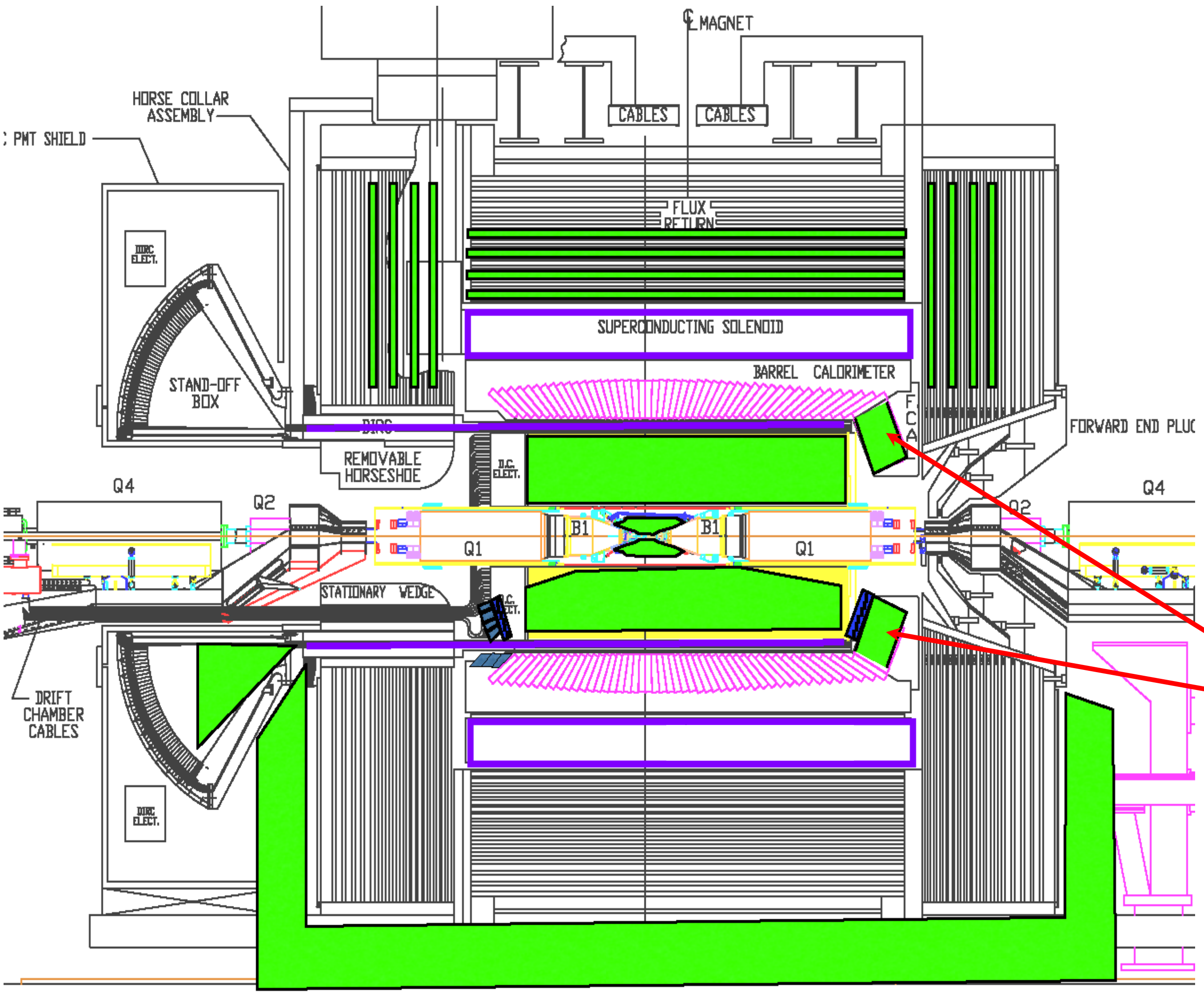
LSO/LYSO ECAL for Mu2e

Four-vane calorimeter, comprised of 2,400 LSO/LYSO crystals of 30 x 30 x 130 mm



LYSO Endcap for Super*B*

SuperB Conceptual Design Report, INFN/AE-07/2, March (2007)

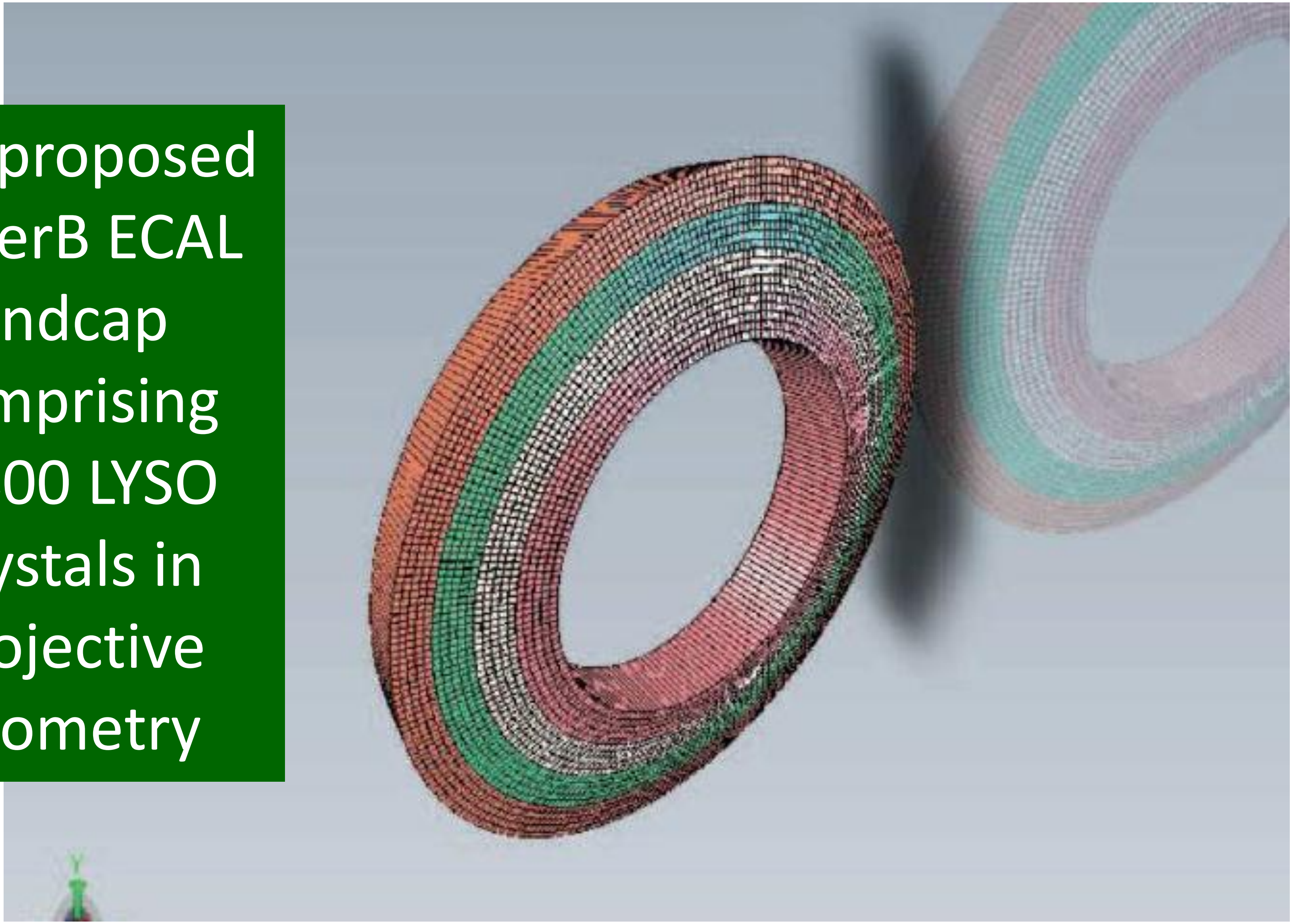


Aiming at $10^{36}/cm^2/s$ luminosity for rare B decays

Need a fast detector with low noise at the endcap

Need cost effective crystals

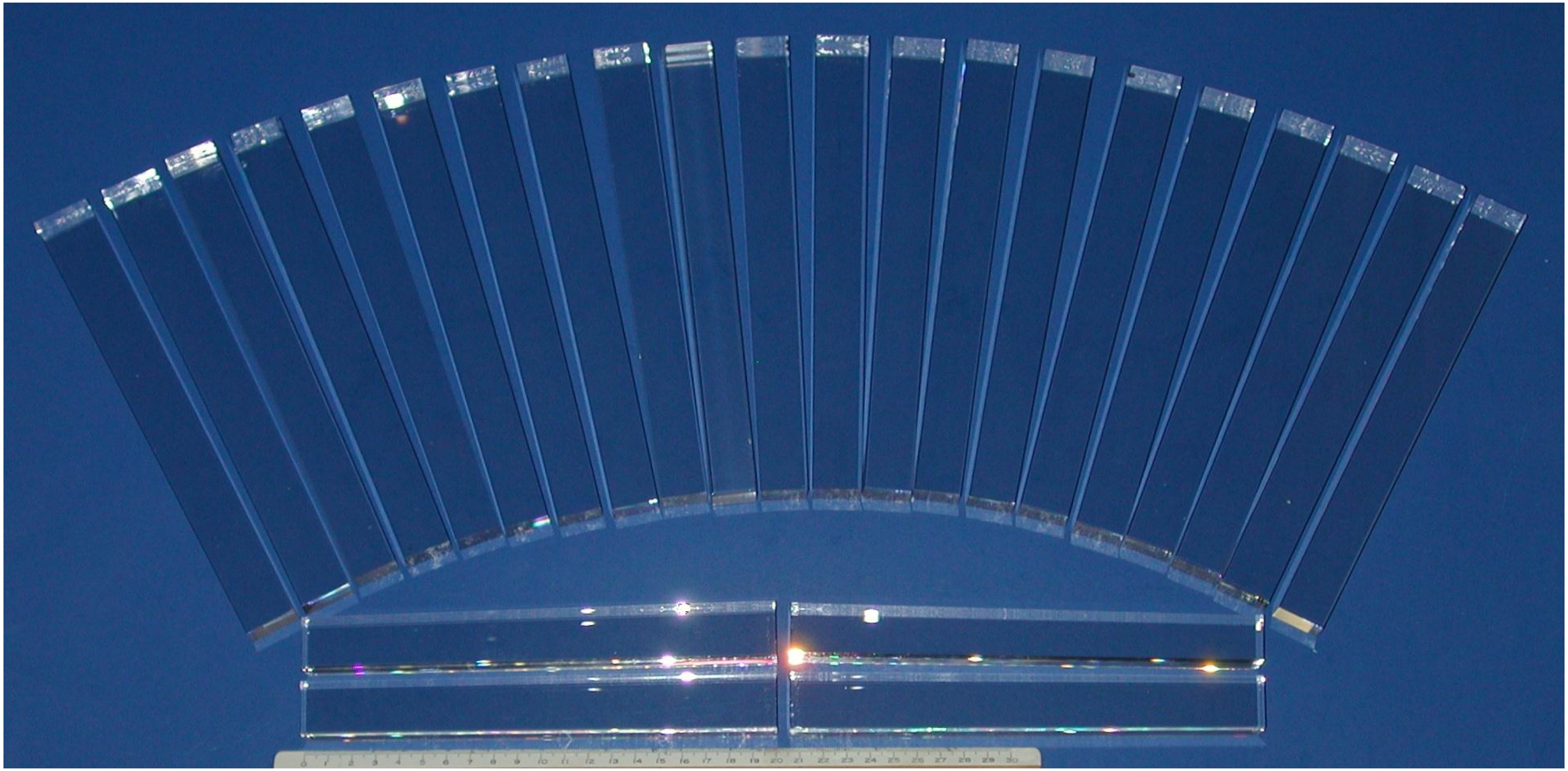
LSO/LYSO Endcap for SuperB



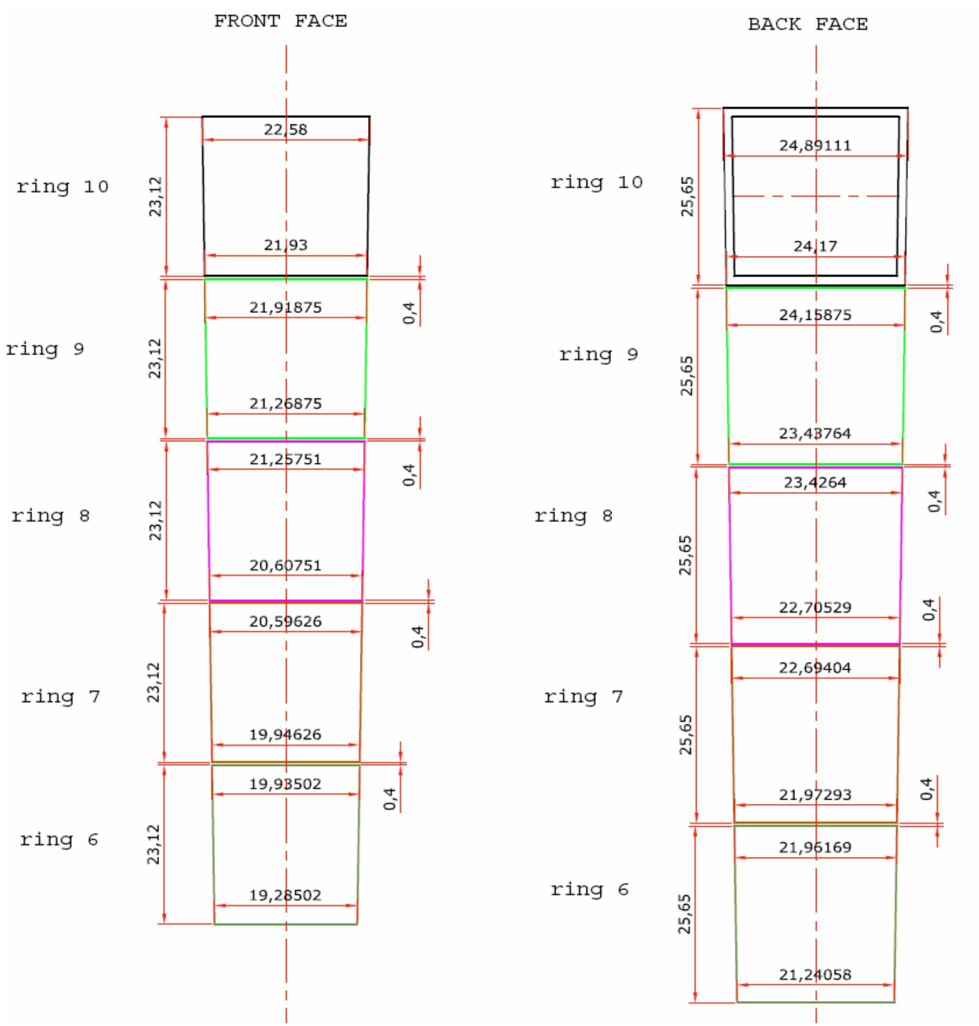
The proposed SuperB ECAL endcap comprising 4,400 LYSO crystals in projective geometry

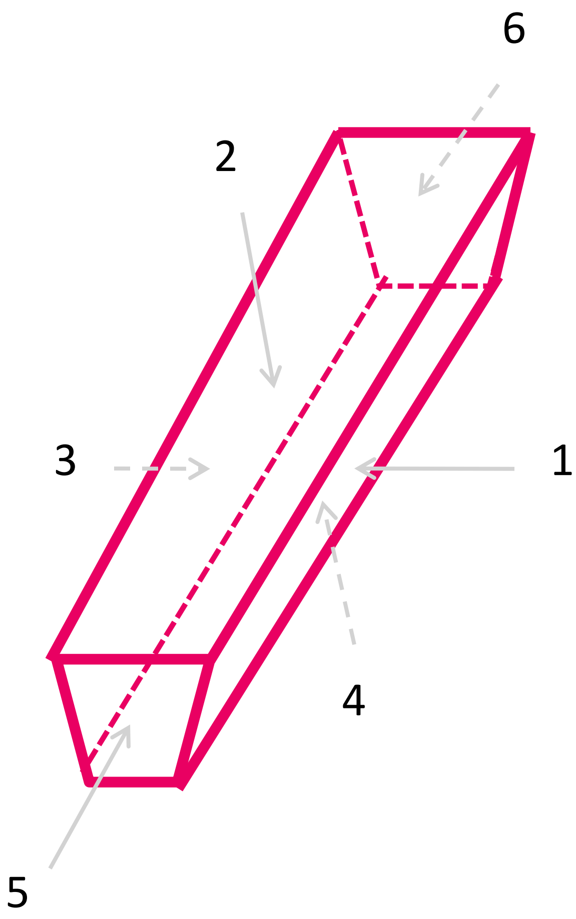
Twenty Five Test Beam Crystals

All crystals are characterized in Caltech Crystal Laboratory
Two beam tests were carried out at CERN and Frascati



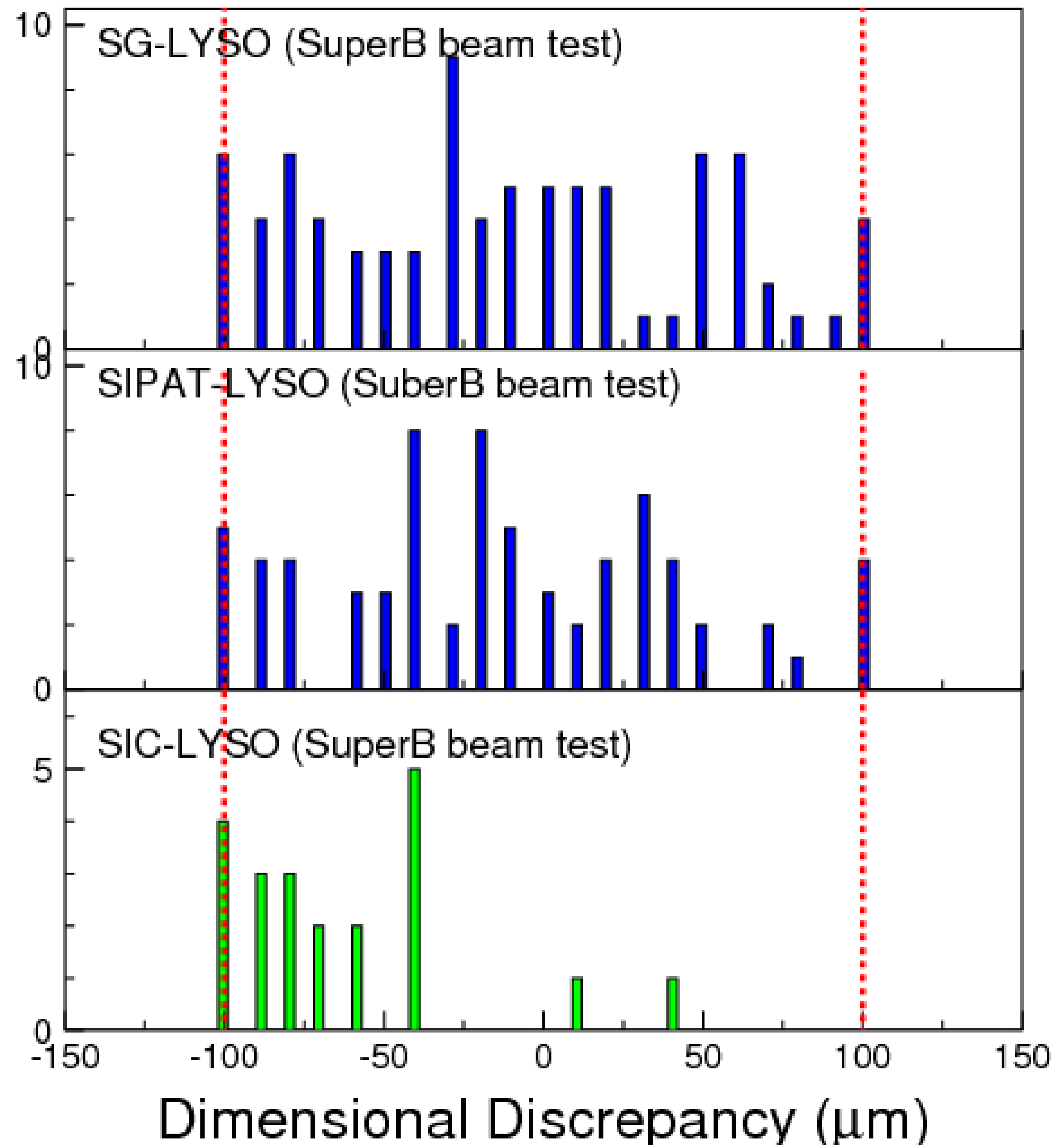
Dimensions and Surface Definition





Summary: Dimension

All dimensions satisfy the tolerance specification: ±100 μm. Will move to +0/-100 μm for mass production.



Summary of SuperB Test Beam Crystals

Caltech-ID	Vendor-ID	Test-Beam-Position	Type	LT @ 420 nm (%)	LY, ER & Uniformity by PMT* (% of cancel 1), (FWHM, %), (δ, %)	LY, ER & Uniformity by APD (As)* (p.e./MeV), (σ, %), (δ, %) (rms, %)	LY, ER & Uniformity by APD (Uni)* (p.e./MeV), (σ, %), (δ, %) (rms, %)	LO Loss %
SIPAT-11	02_08_08	ring 8-3	8	82.3	47.6, 10.7, 5.3	1420, 15.5, 12.9, 6.5	1190, 21.4, 7.2, 3.8	16.2
SIPAT-12	02_08_08	ring 8-1	8	82.2	46.5, 10.4, 3.9	1440, 15.1, 14.2, 7.1	1210, 20.7, 10.0, 5.1	15.9
SIPAT-13		ring 6-1	6	82.6	52.5, 11.5, 2.7	1440, 14.9, 6.8, 3.6	1220, 20.4, 3.4, 2.0	15.3
SIPAT-14		ring 6-2	6	82.7	53.7, 10.9, 3.2	1500, 14.9, 14.4, 7.4	1200, 20.4, 9.0, 4.6	20.0
SIPAT-15		ring 6-4	6	80.7	52.8, 10.5, 3.4	1580, 13.7, 11.9, 6.0	1310, 19.1, 6.1, 3.4	17.1
SIPAT-16		ring 6-5	6	81.1	51.8, 10.1, -0.8	1570, 13.5, 9.7, 5.0	1100, 19.6, 5.3, 2.7	29.9
SIPAT-17		ring 6-3	6	82.1	53.0, 12.2, 3.5	1260, 17.1, 9.8, 4.9	1080, 24.1, 4.9, 2.7	14.3
SIPAT-20	07_10_02	ring 7-2	7	79.8	56.4, 10.0, 5.6	1670, 14.6, 8.7, 4.4	1340, 18.2, 5.1, 2.6	19.8
SIPAT-21	02_10_23	ring 7-5	7	81.6	48.8, 10.9, 3.0	1550, 15.8, 10.7, 5.6	1190, 20.7, 6.1,3.2	23.2
SIPAT-22	07_10_02	ring 7-1	7	81.4	52.6, 11.0, 2.7	1600, 15.2, 9.2, 4.8	1180, 20.3, 5.2, 3.0	26.3
Average				81.7	51.5, 10.8, 3.3	1500, 15.0, 10.8, 5.5	1200, 20.5, 6.2, 3.3	19.8
SG-S1			8	80.5	52.2, 9.8, 1.0	1370,14.5,9.6,5.0	1040,19.7,5.4,2.8	24.1
SG-S2			8	79.5	54.2, 9.6, 1.4	1400,14.3,9.0,4.7	1040,19.5,6.6,3.4	25.7
SG-S3			9	79.1	56.0, 9.8, 1.0	1370,14.7,8.0,4.2	1000,19.7,6.1,3.2	27.0
SG-S4			9	80.1	56.5, 9.7, 0.1	1310,15.4,9.6,5.0	970,20.5,7.0,3.6	26.0
SG-S5			9	80.9	54.5, 9.9, 3.6	1330,15.0,11.4,5.9	961,20.8,9.8,5.0	27.8
SG-S6			9	79.7	57.6, 9.7, 1.8	1290,15.5,8.3,4.6	980,20.3,5.9,3.1	24.0
SG-S7			9	79.3	55.2, 9.7, 0.5	1350,14.7,5.9,3.5	970,20.7,3.9,2.1	28.1
SG-S8			10	80.7	54.3, 9.8, 1.9	1350,15.2,8.1,4.3	1040,19.6,5.6,2.8	23.0
SG-S9			10	81.4	54.1, 9.8, -1.4	1320,15.0,6.3,3.3	960,20.0,4.9,2.5	27.3
SG-S10			10	79.5	54.3, 9.6, 3.4	1350,14.8,10.8,5.7	990,20.3,5.5,2.8	26.7
SG-S11			10	80.6	51.6, 10.0, 1.4	1330,15.0,6.9,3.7	980,20.4,5.6,2.9	26.3
SG-S12			10	81.2	53.4, 10.0, 0.6	1350,14.7,9.3,4.9	930,20.8,6.0,3.2	31.1
Average				80.2	54.5, 9.8, 1.3	1340,14.9,8.6,4.6	1000, 20.2,6.0,3.1	26.4
SIC-3			8	80.5	54.8, 10.9, 6.6	1380, 18.0, 15.1, 7.8	1020, 23.8, 10.9, 5.6	26.1
SIC-4			7	77.5	58.7, 11.9, -2.1	1170, 16.8, 9.3, 5.1	880, 23.2, 5.4, 2.9	24.8
SIC-5			7	78.6	59.4, 10.6, -1.8	1290, 15.5, 10.9, 6.1	910, 20.1, 5.4, 2.9	29.5
Average				78.9	57.6, 11.1, 0.9	1280, 16.8, 11.8, 6.3	940, 22.4, 7.2, 3.8	26.8

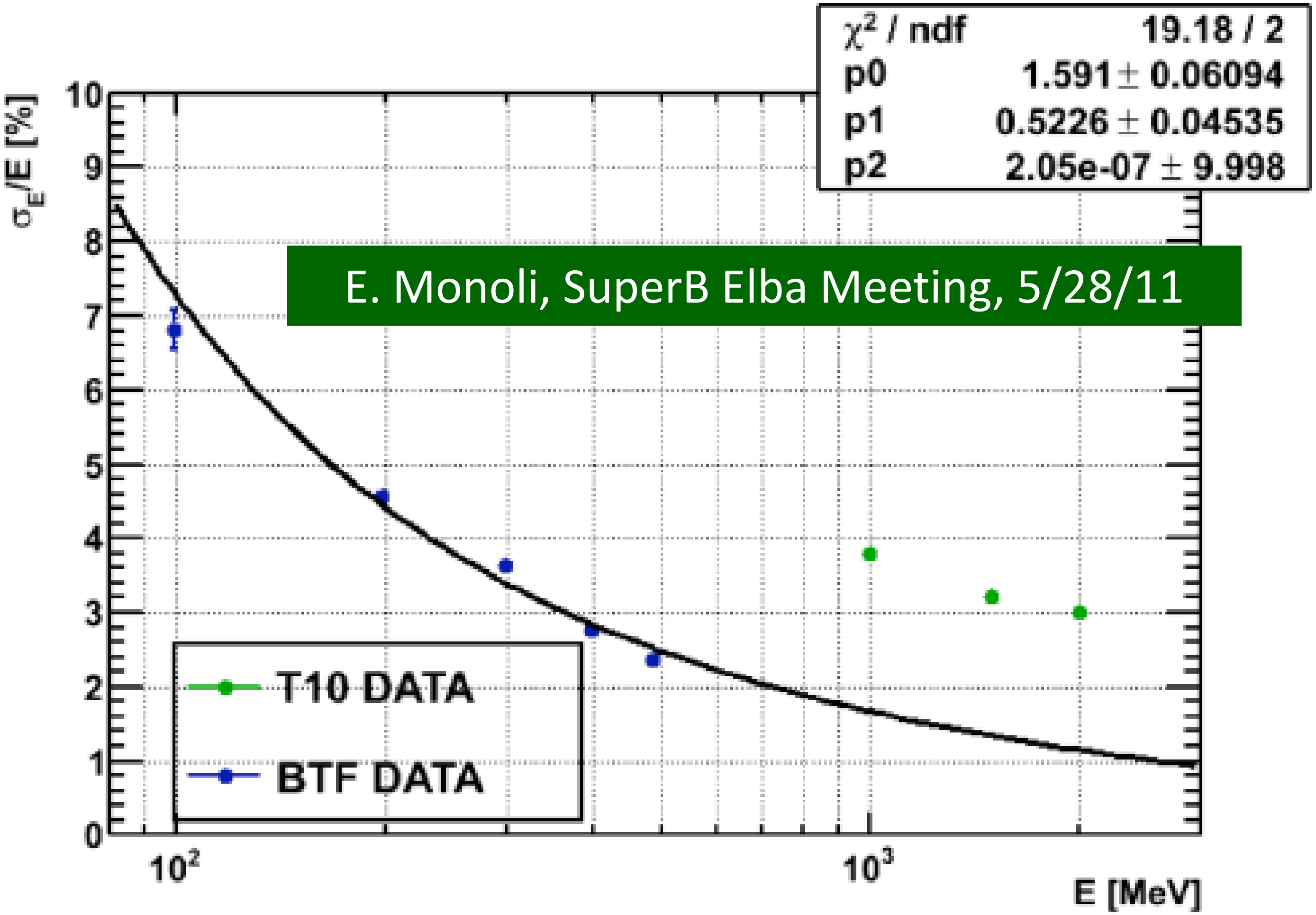
* Light Yield (LY) and Energy Resolution (ER) are the average of the seven points measured along the crysals.

Note 1 Light Yield (LY) for the APD readout is measured with a quartz plate between the crystal and the APDs.

Note 2 Width of the black band at the small end on the smallest side surface: 15 mm

SuperB LYSO Test Beam Result

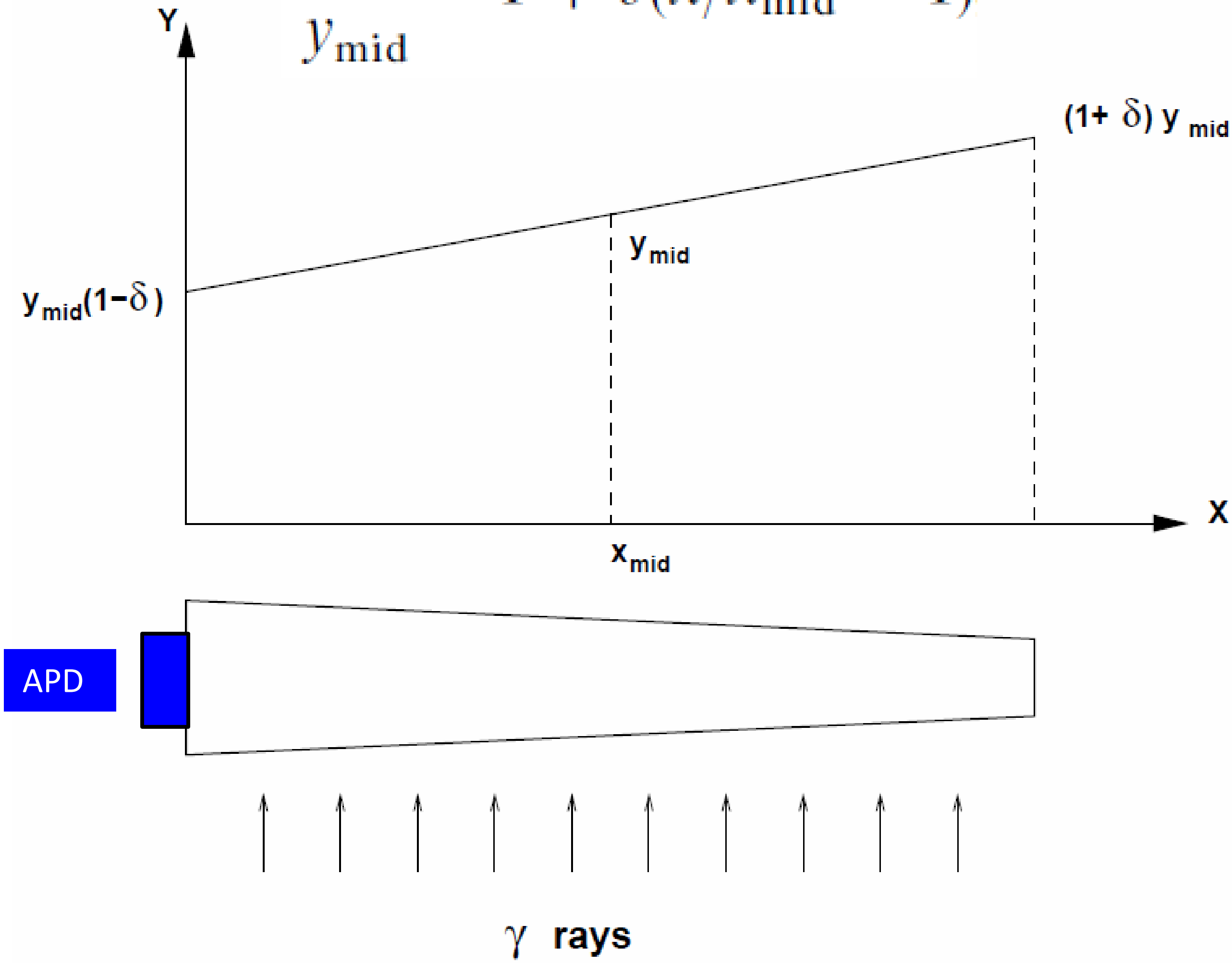
Encouraging resolution measured at BTF, Frascati, with non uniformized crystals. Another test is planned in this Fall with uniformized crystals.



E. Monoli, SuperB Elba Meeting, 5/28/11

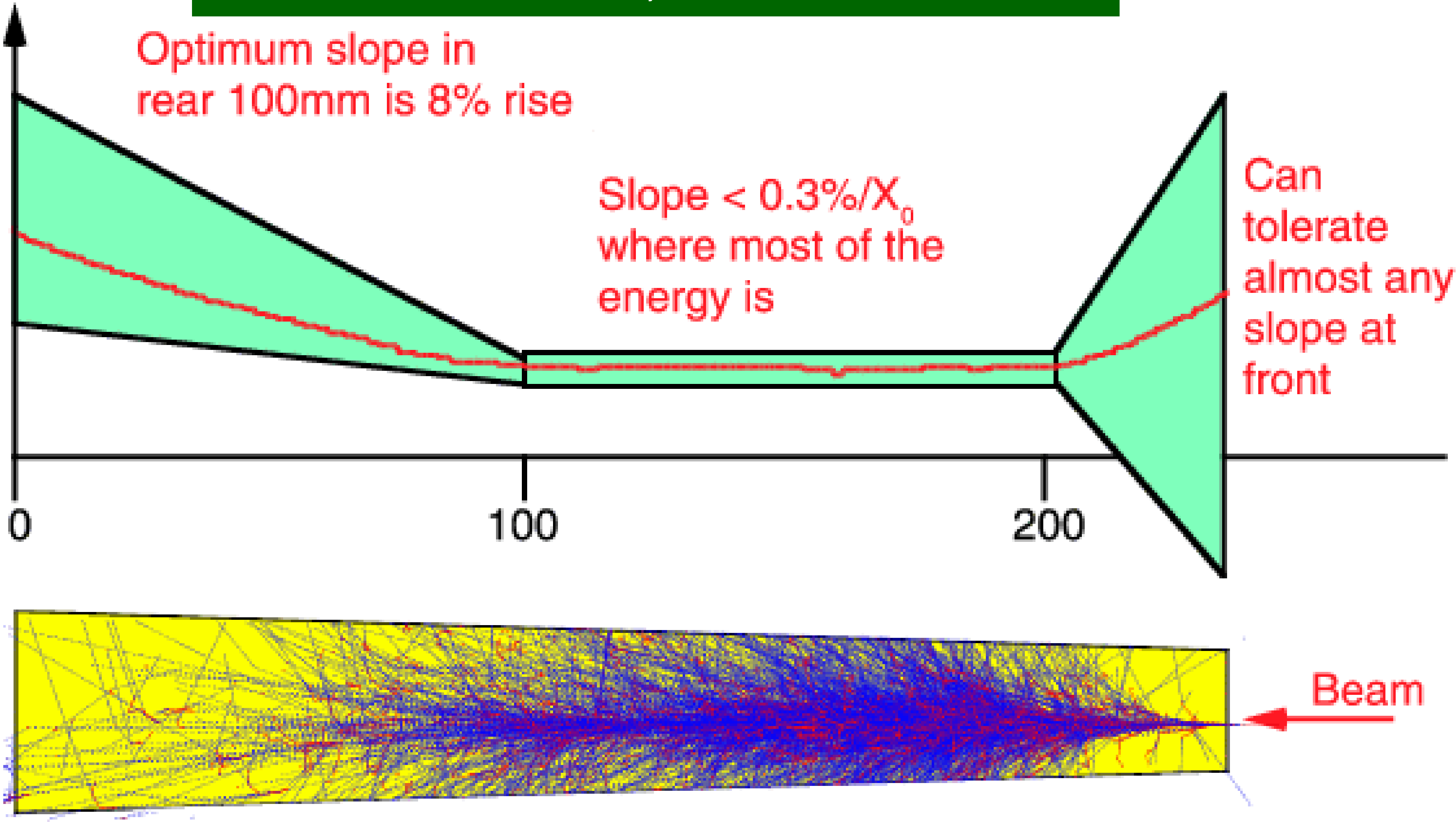
Light Response Non-Uniformity: δ

$$\frac{y}{y_{\mathrm{mid}}} = 1 + \delta(x/x_{\mathrm{mid}} - 1)$$



CMS Specification for Uniformity

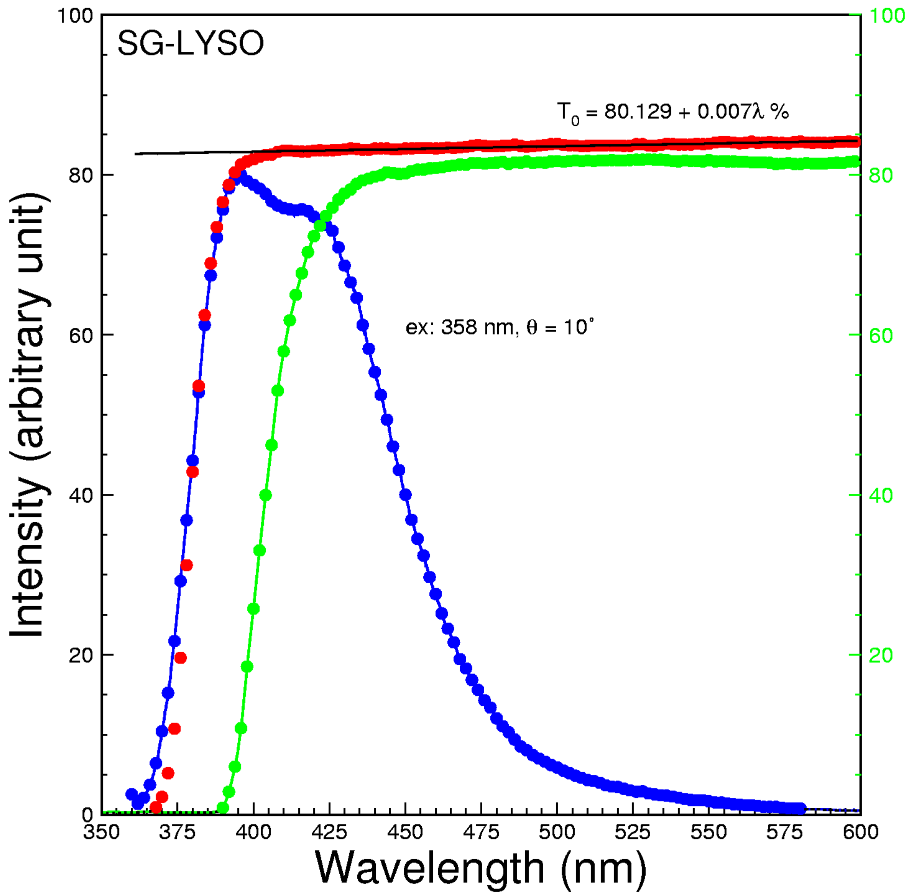
D. Graham & C. Seez, CMS Note 1996-002

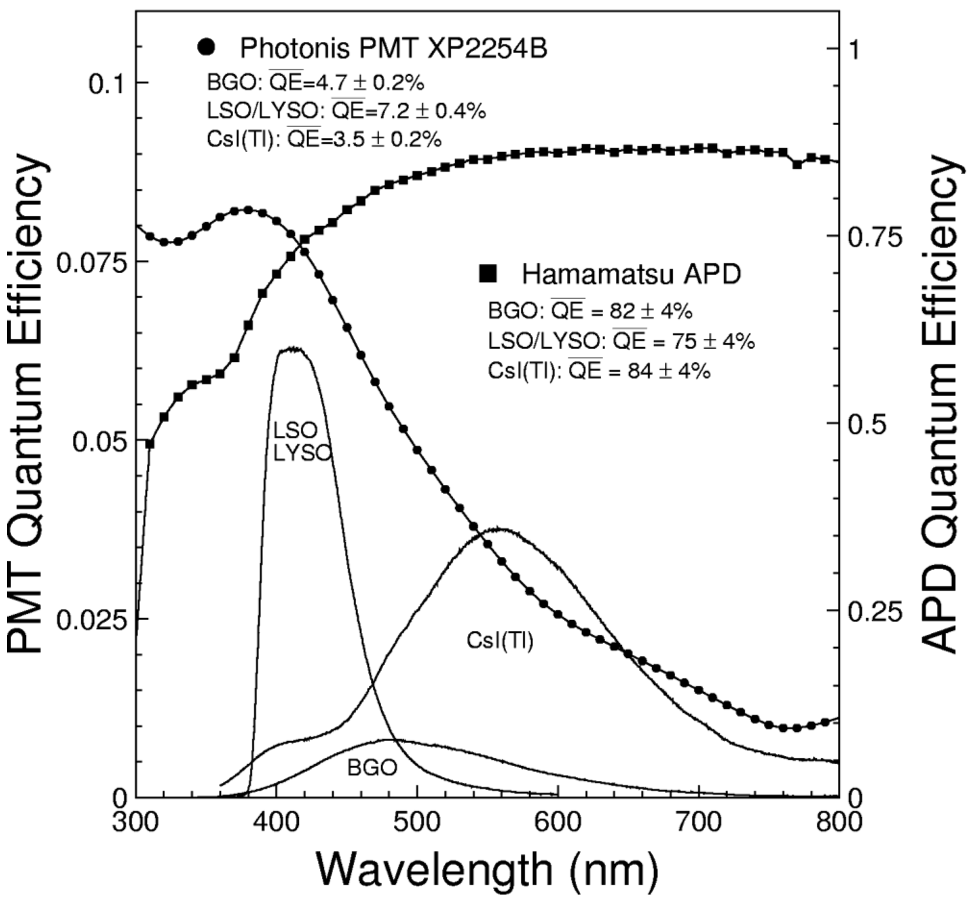


$|\delta| < 3\%$ & 4% for 18 X_0 (SuperB) & 25X_0 (CMS)

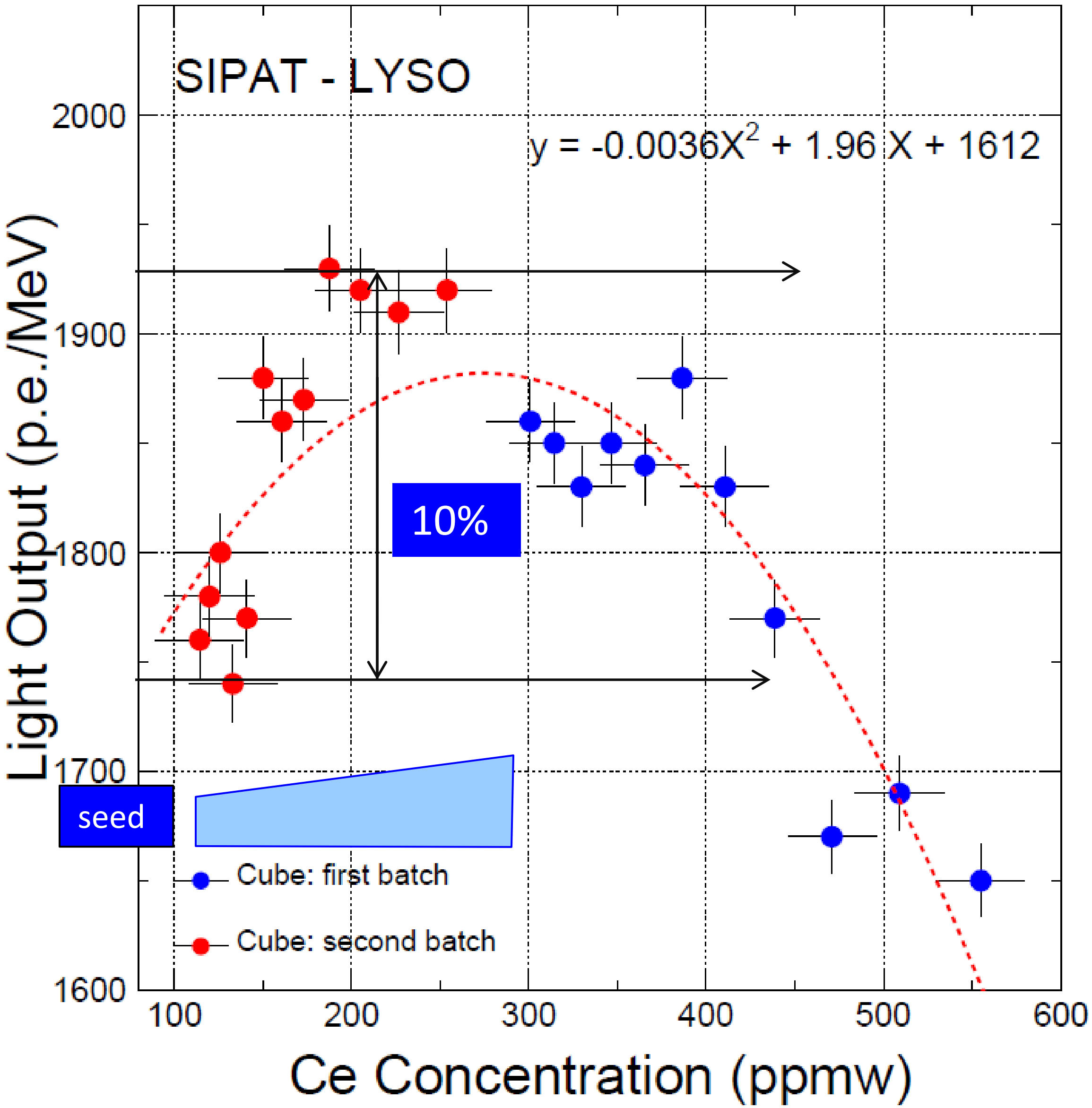
Effect of Self-absorption

It is well known that part of the emission light is absorbed in the crystal: self-absorption.





Effect of Cerium Segregation

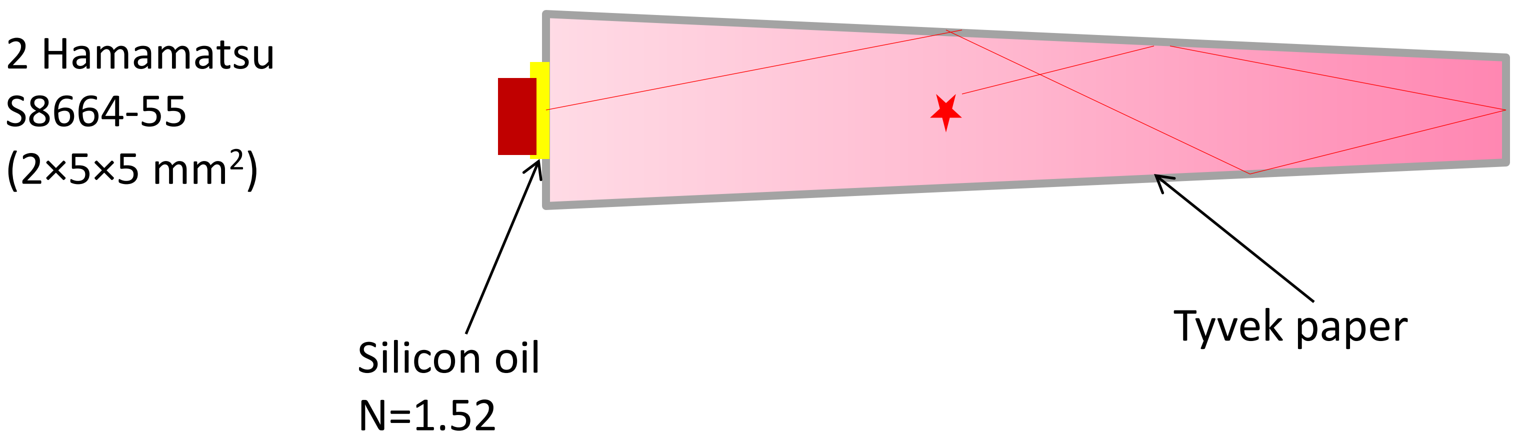


It is also known that cerium concentration along long LYSO crystals is not uniform, causing non-uniformity up to 10% at two ends, indicating up to 5% variation in δ is possible because of cerium segregation.

Ray-Tracing Simulation "set-up"

The simulation package was developed in early eighties, and was used for the L3 BGO and CMS PWO crystals.

SuperB LYSO crystals

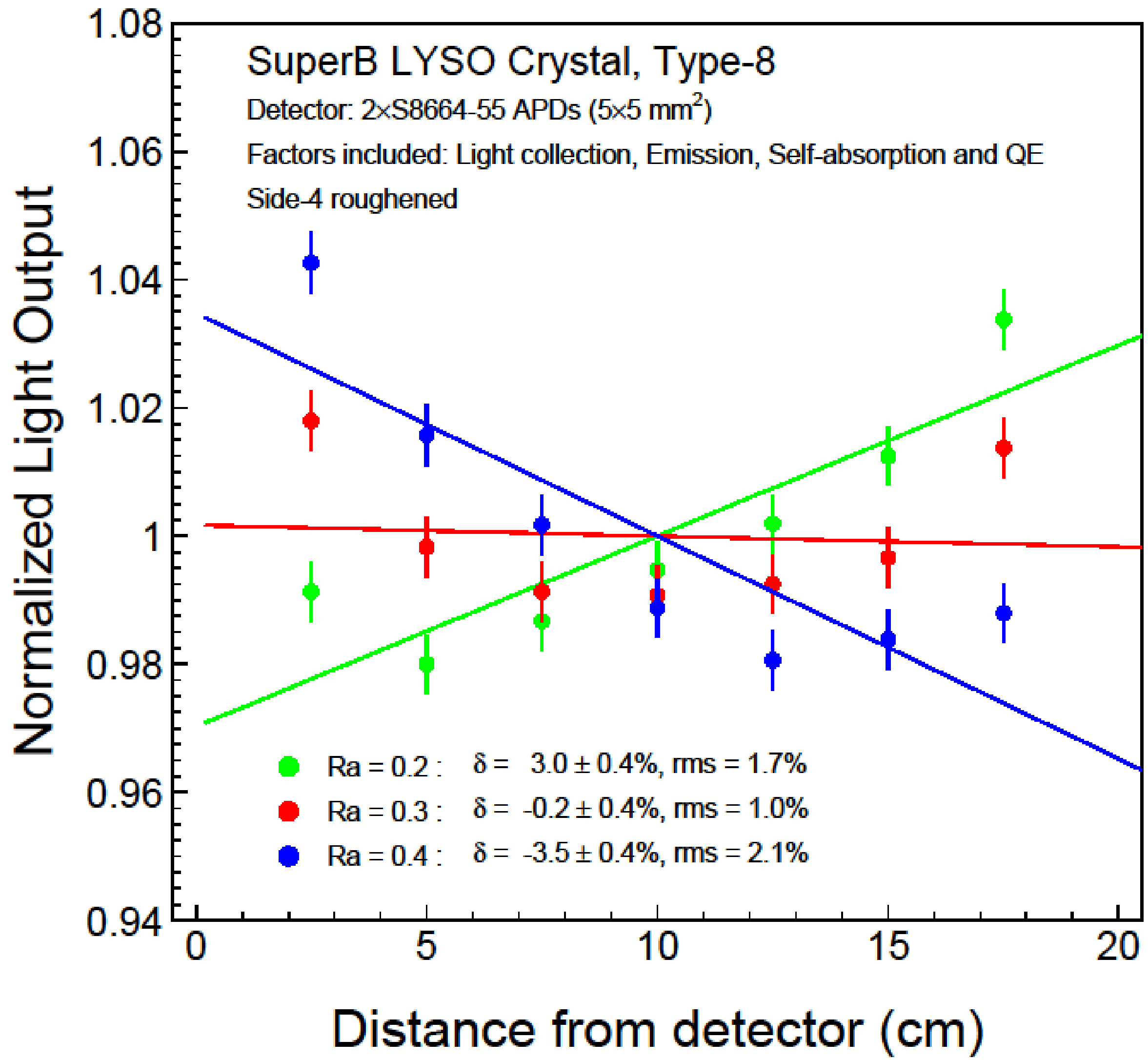


$$LO(z) = LY(z)\int Em(\lambda)LCE(\lambda,z)QE(\lambda)d\lambda$$

How Rough it Should Be?

The R_a matters.

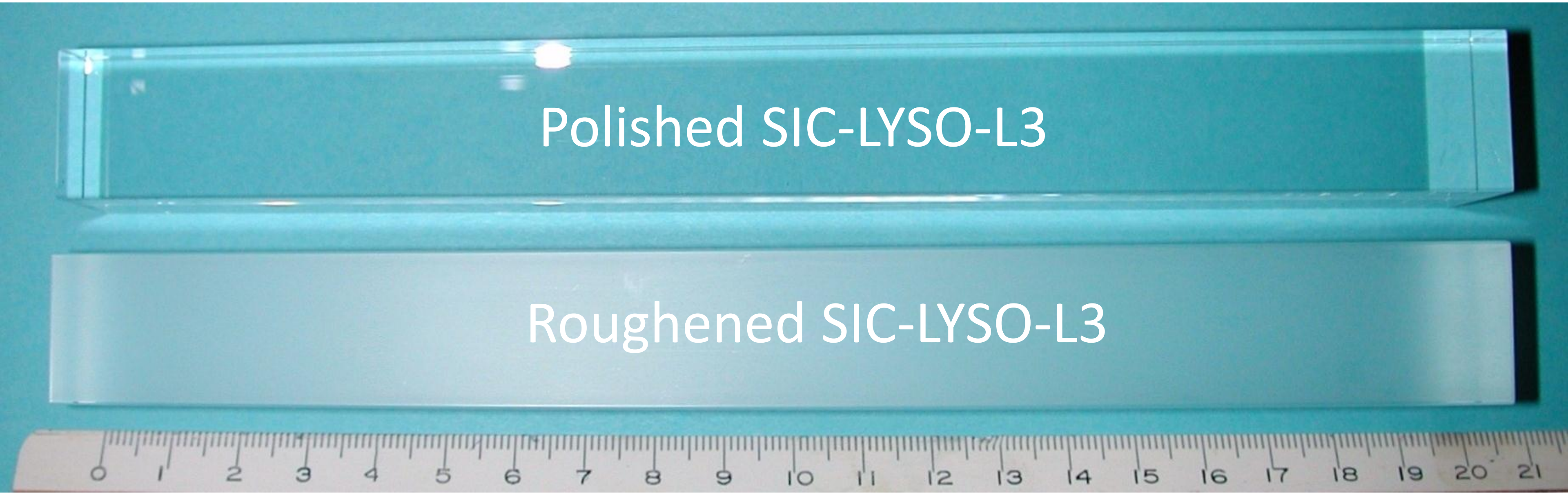
A variation of 0.1 in R_a causes a 3% variation in δ.



Real Exercise: Roughening SIC-LYSO-L3

The smallest side surface of SIC-LYSO-L3 was roughened to Ra = 0.3 at SIC via a two step process

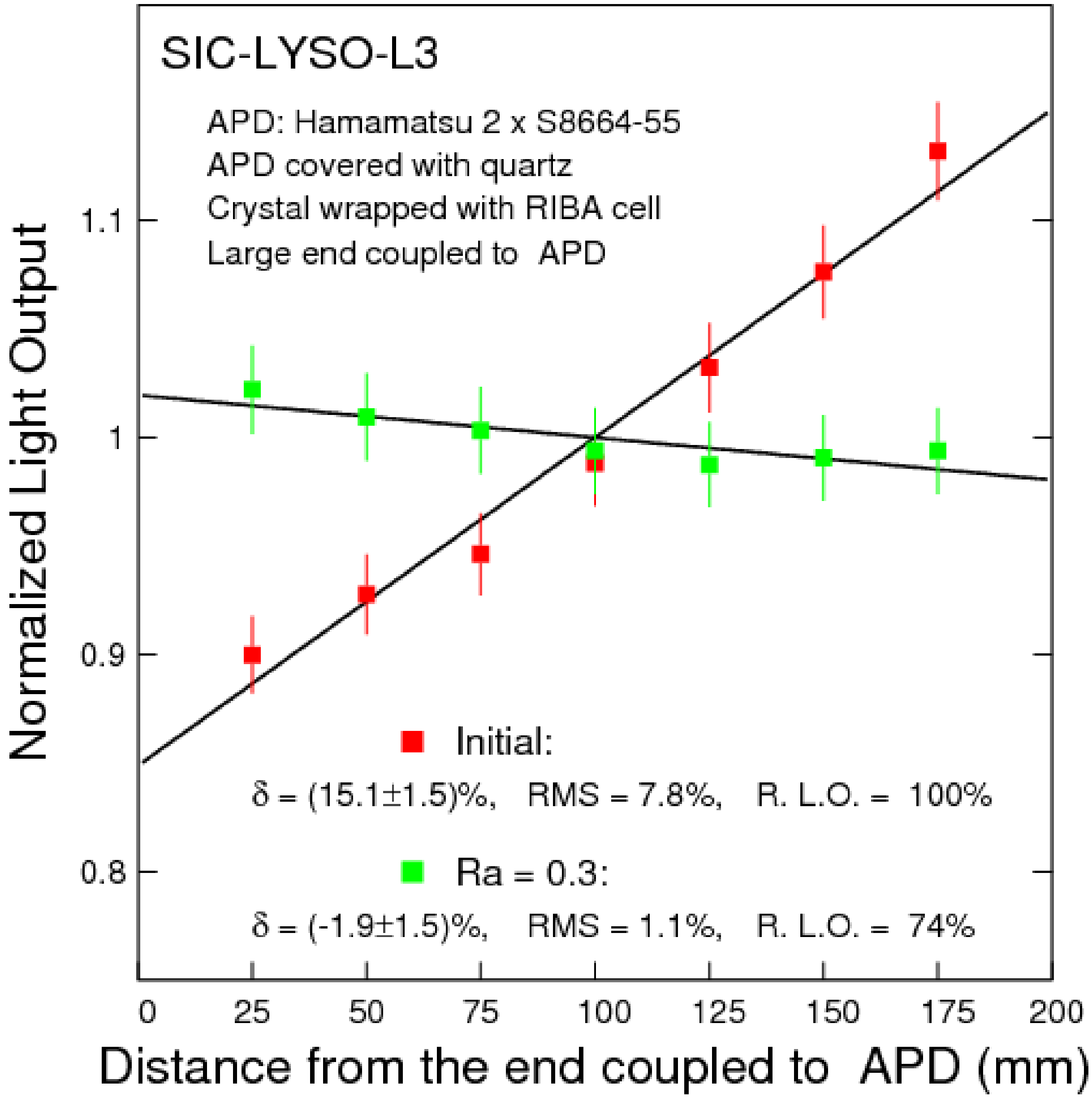
Thanks to SICCAS for roughening this crystal



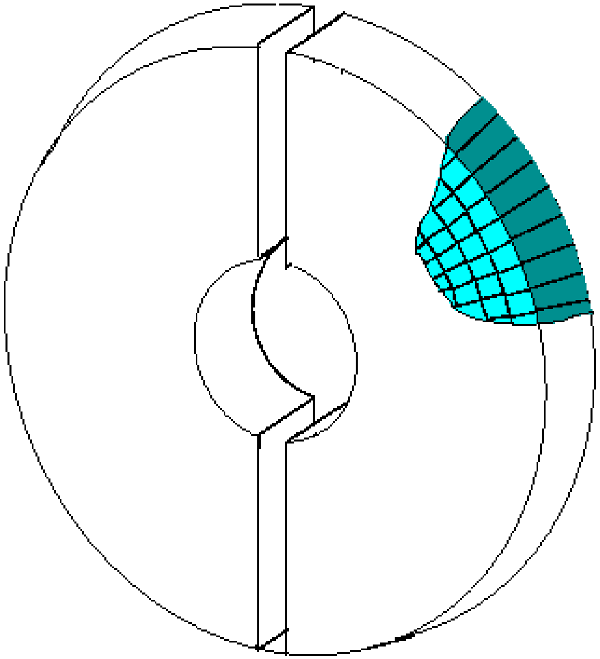
1st: lapped to Ra = 0.5 by using 11 μm Al_2O_3 powder for 10 min with 2.5 kg weight.
2nd: lapped to Ra = 0.3 by using 6.5 μm SiC powder for 3 min with 1.5 kg weight.

Relative Light Output & Uniformity

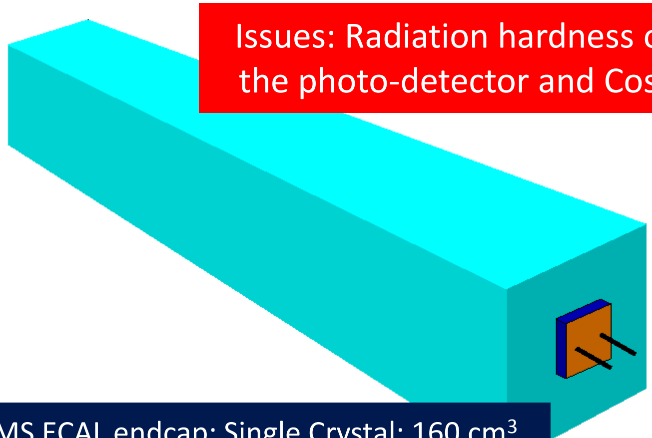
Ra = 0.3 uniformize this crystal to < 2%. Ra = 0.25 seems the best for this sample.



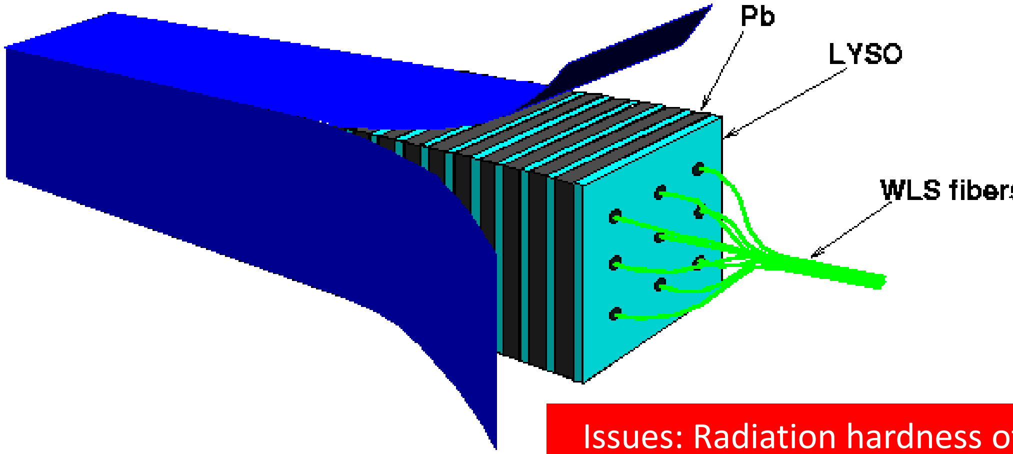
CMS Forward Calorimeter Upgrade



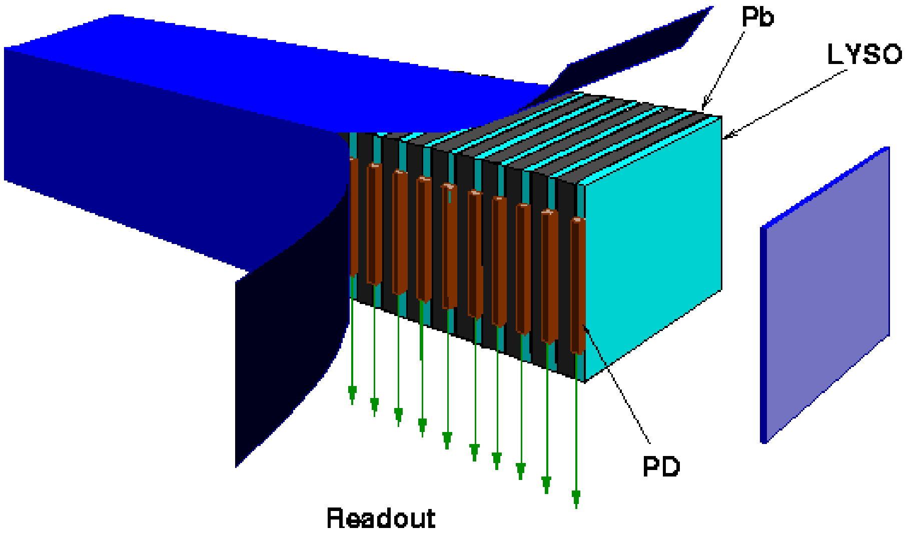
Issues: Radiation hardness of the photo-detector and Cost



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

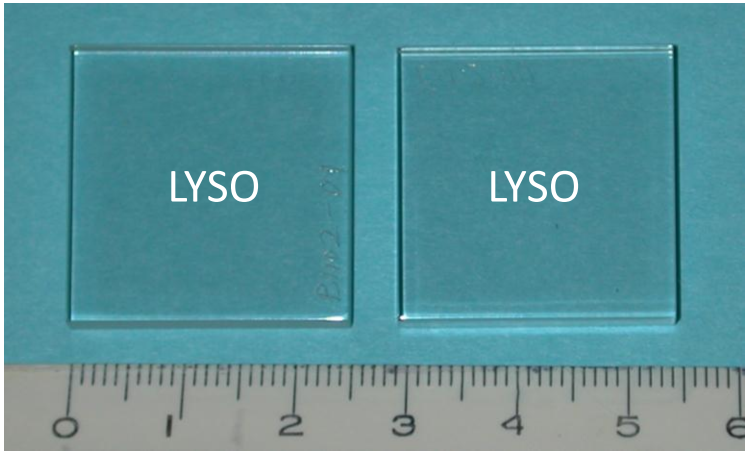


Crystal Cost: <$10M

Issue: Radiation hardness of the photo-detector

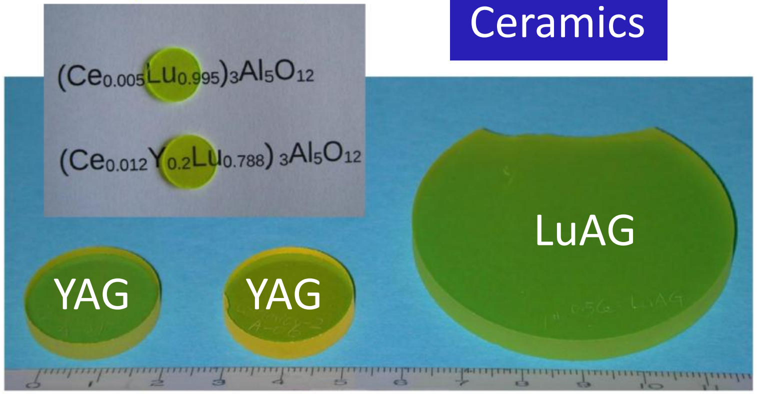
Performance of Scintillator Plates

Crystals



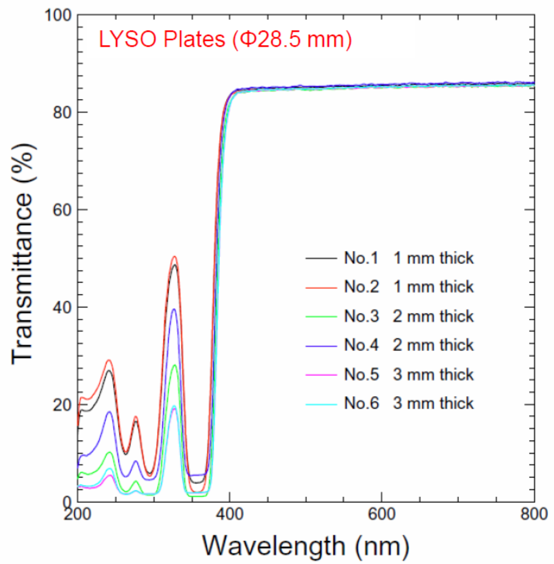
Φ20 X 3 mm

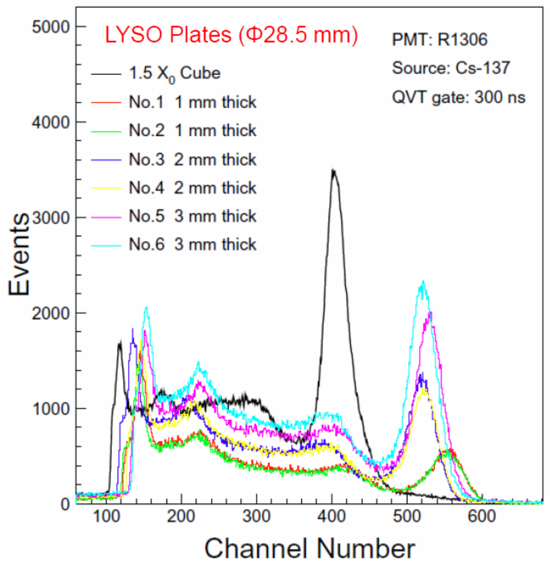
Ceramics

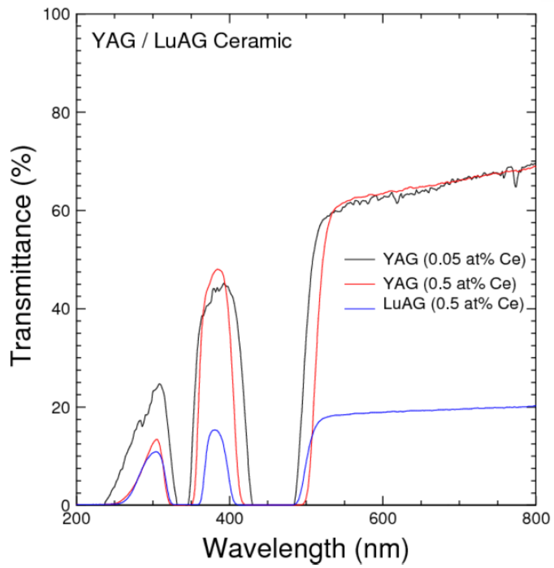


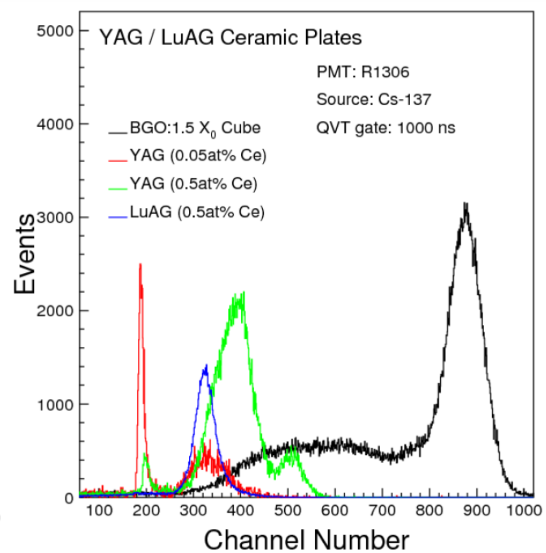
YAG: Φ22 x 4 mm

LuAG Φ56 x 5 mm







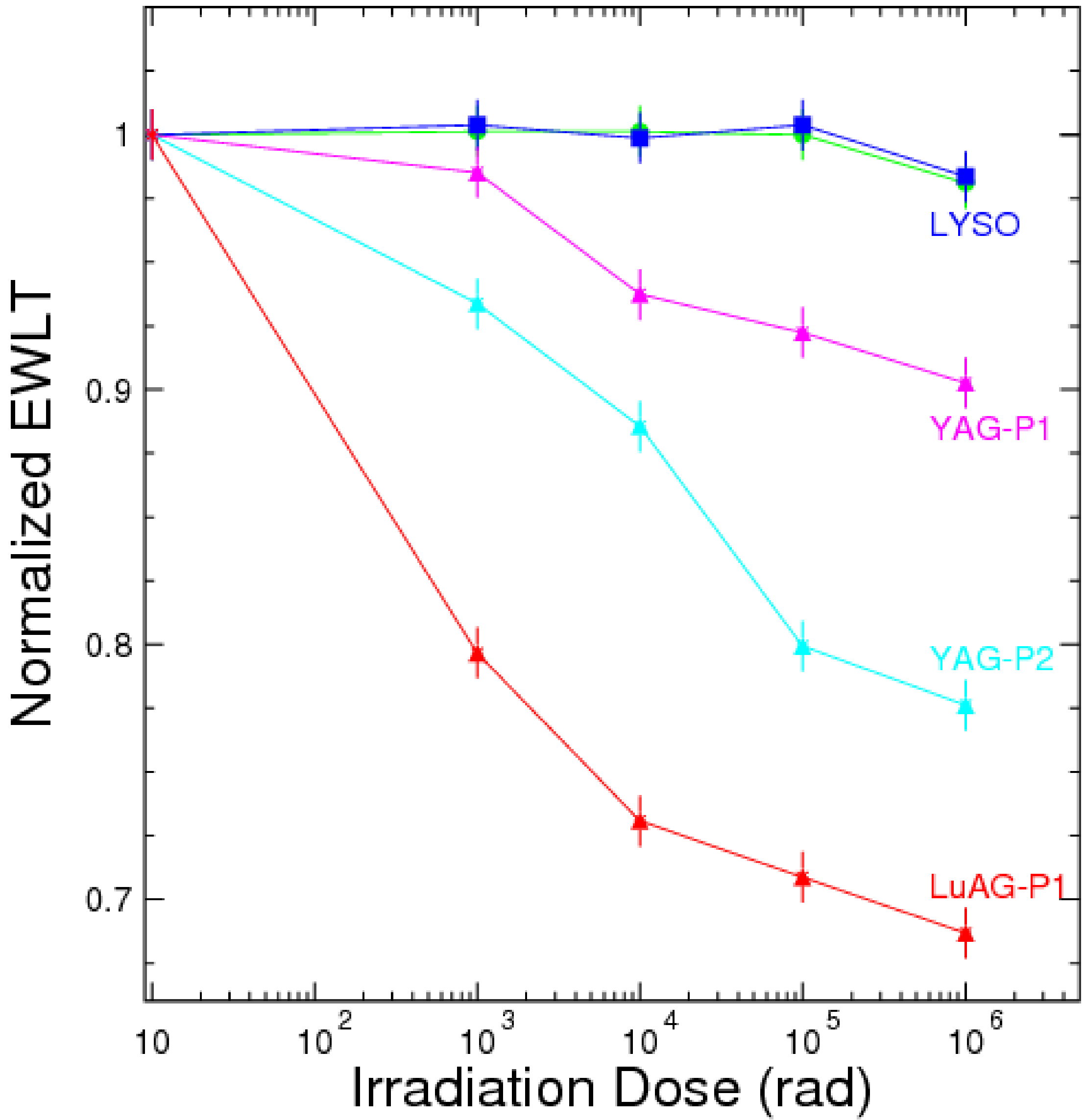


Normalized EWLT: LYSO & Ceramic

As expected that LYSO is radiation hard.

Ceramics, on the other hand, seem not.

Need to investigate further to see position dependence.



Summary

- LSO/LYSO crystals with bright, fast scintillation and excellent radiation hardness is a good candidate material for HEP & NP experiments, especially those experiments in a severe radiation environment.
- The R&D work for SuperB is now concentrated on the optimization of the light response uniformity for the APD readout, which is affected by (1) the optical focusing, (2) the self-absorption and (3) the non-uniformity of the cerium concentration. Will roughen all 25 test beam crystals.
- For applications in a severe radiation environment, such as the high luminosity LHC, R&D work concentrates on two directions:
  - Growth of crystals of adequate length/size cost-effectively; and
  - Looking into LSO/LYSO plates for a sampling option. Initial test with YAG and LuAG ceramics indicates they are not radiation hard.