Update on LYSO Development

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November 8, 2011

Introduction

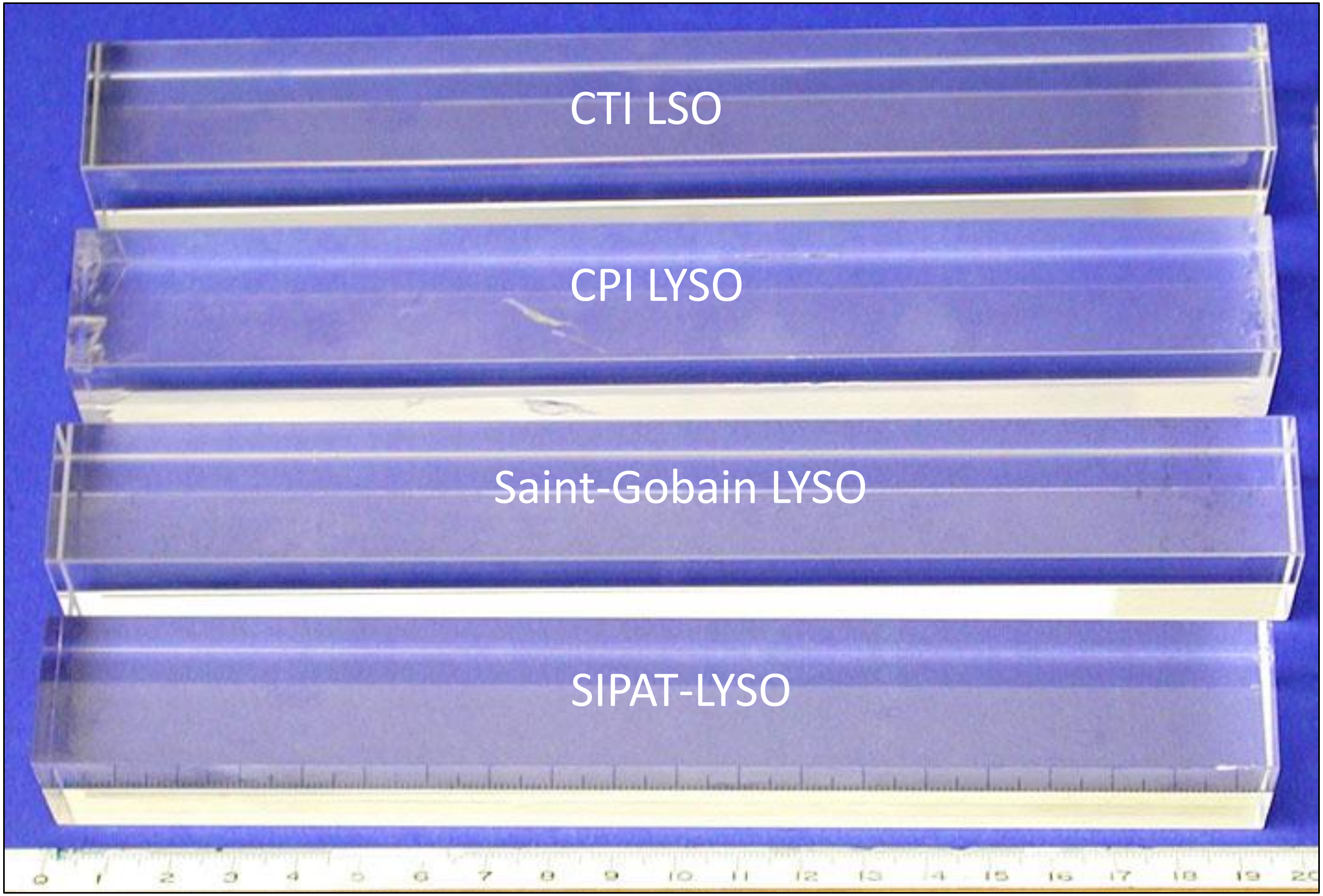
LSO/LYSO is a bright (200 times of PWO) and fast (40 ns) crystal scintillator. It has been widely used in medical industry. Its mechanical characteristics allows it be used in various forms for different calorimeter designs.

Supported by DOE ADR and US CMS Upgrade Effort the Caltech group has been investigating this material for HEP applications since 2005. It was found that its radiation hardness is excellent against γ–ray, neutrons and high energy protons (ETH data). No recovery, so calibration is less complicated. As a result, LYSO is now base-lined for the Mu2e and SuperB experiments.

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, paper N69-8 @ NSS08, Dresden, paper N32-3, N32-4 and N32-5 @ NSS09, Orlando, paper N38-2 @ NSS10, Knoxville, and paper N29-6 @ NSS11, Valencia .

LSO & LYSO Crystal Samples

2.5 x 2.5 x 20 cm (18 X_0)

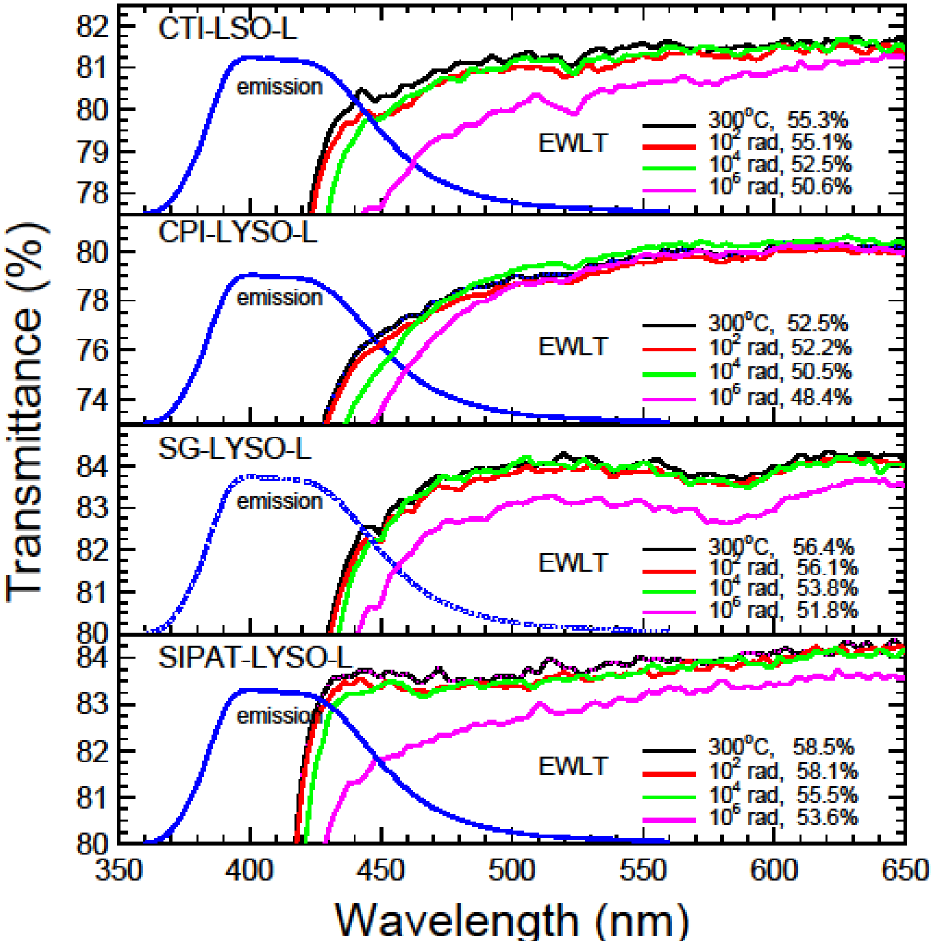


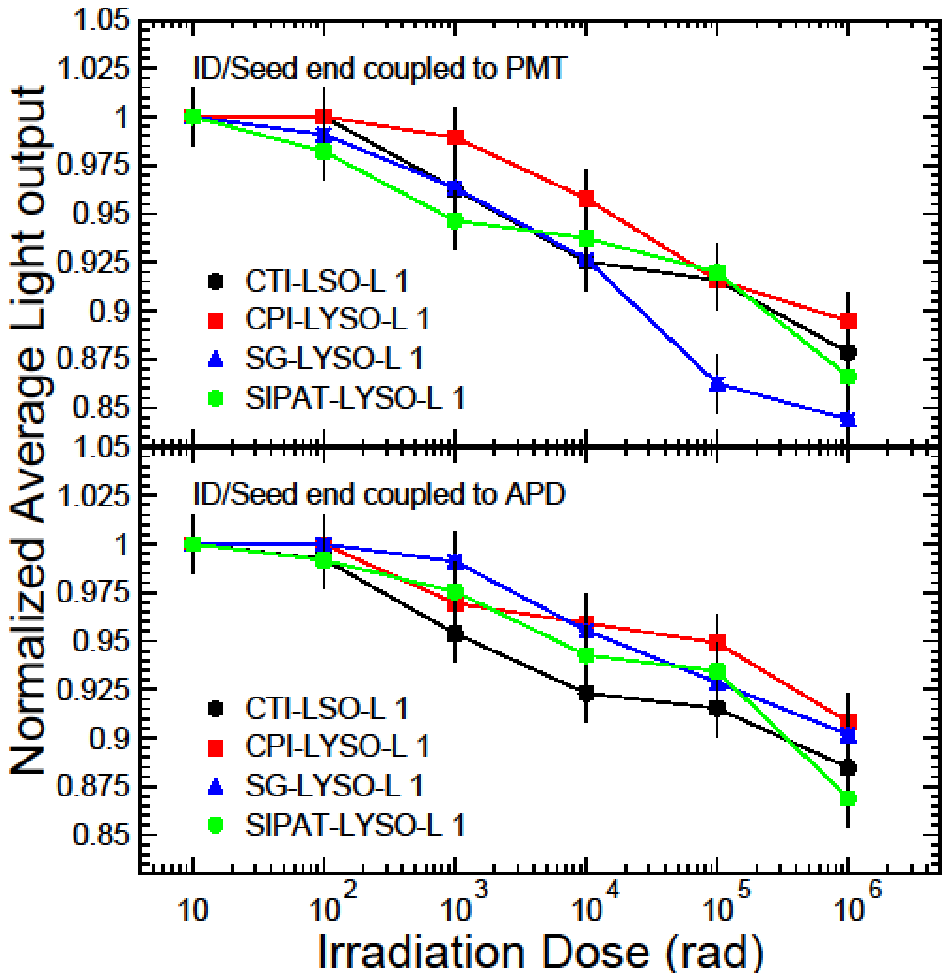
20 cm Long LSO/LYSO under γ-Rays

Consistent radiation hardness better than other crystals

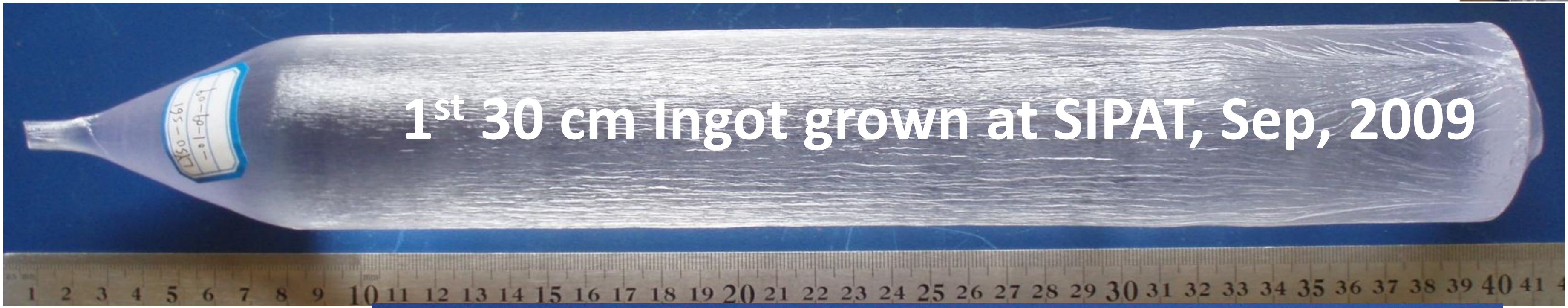
EWLT damage: 8% @ 1 Mrad

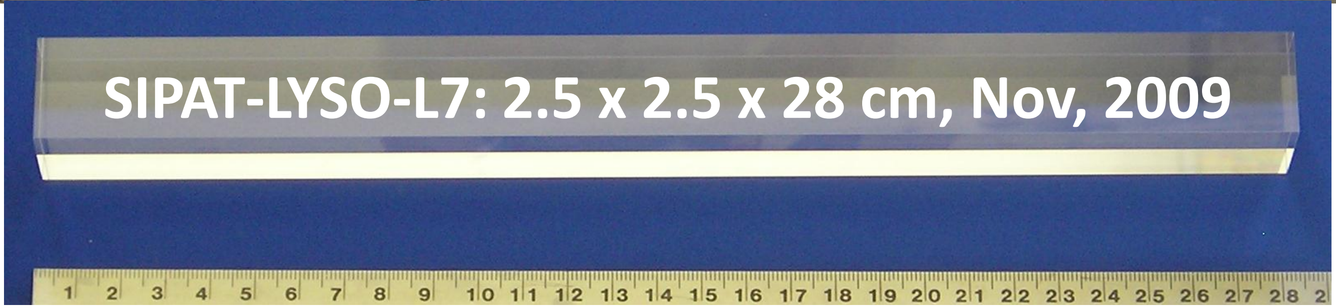
10% - 15% loss by PMT & APD

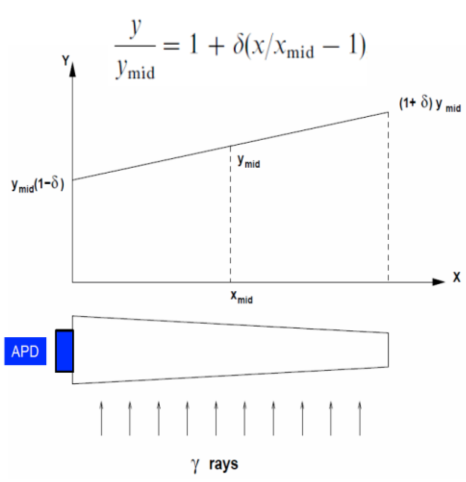


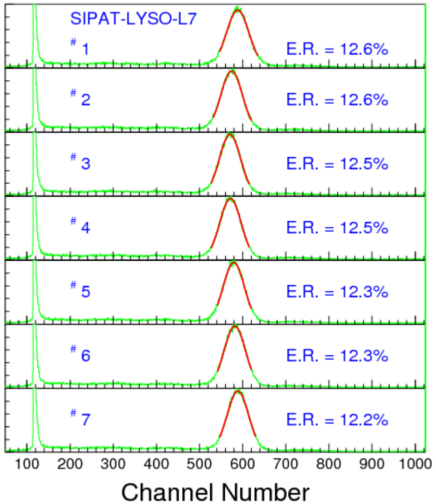


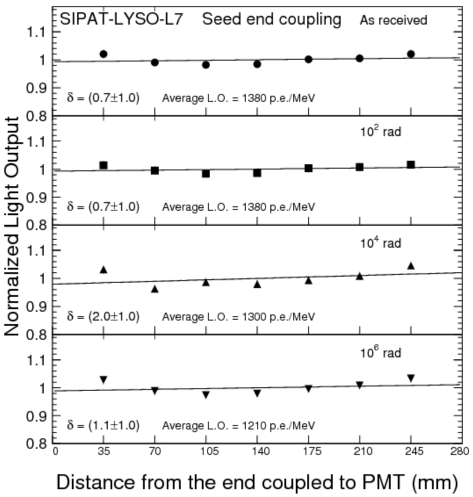
Excellent Radiation Hardness

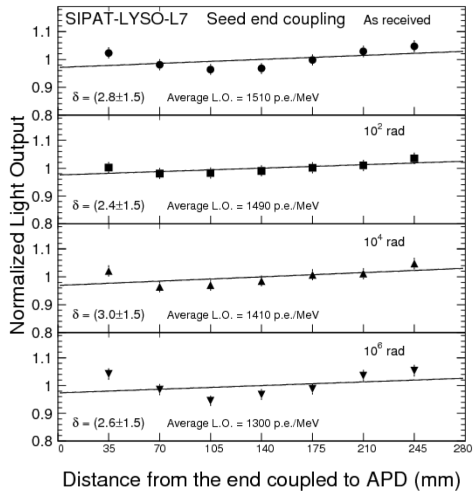






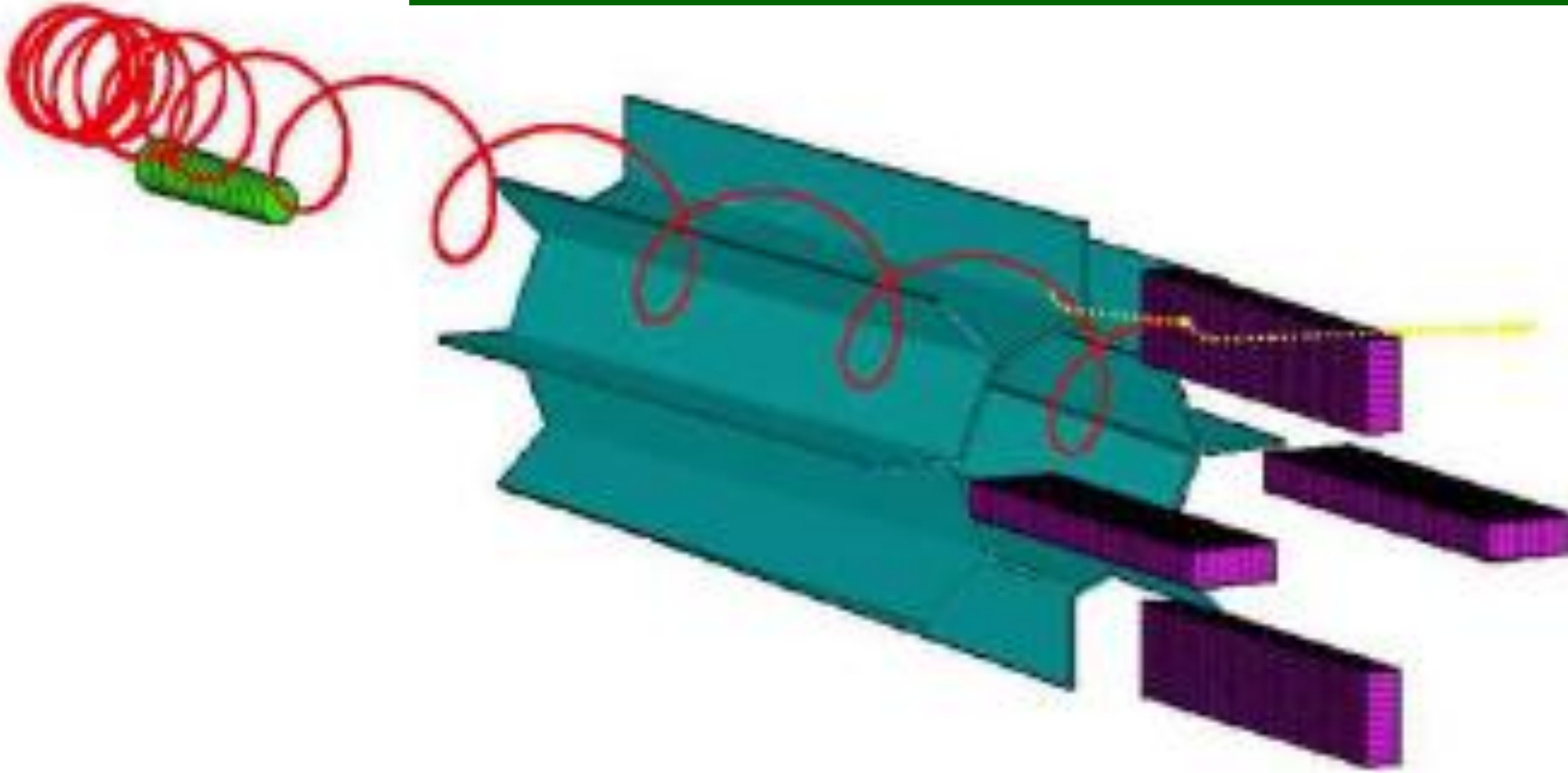






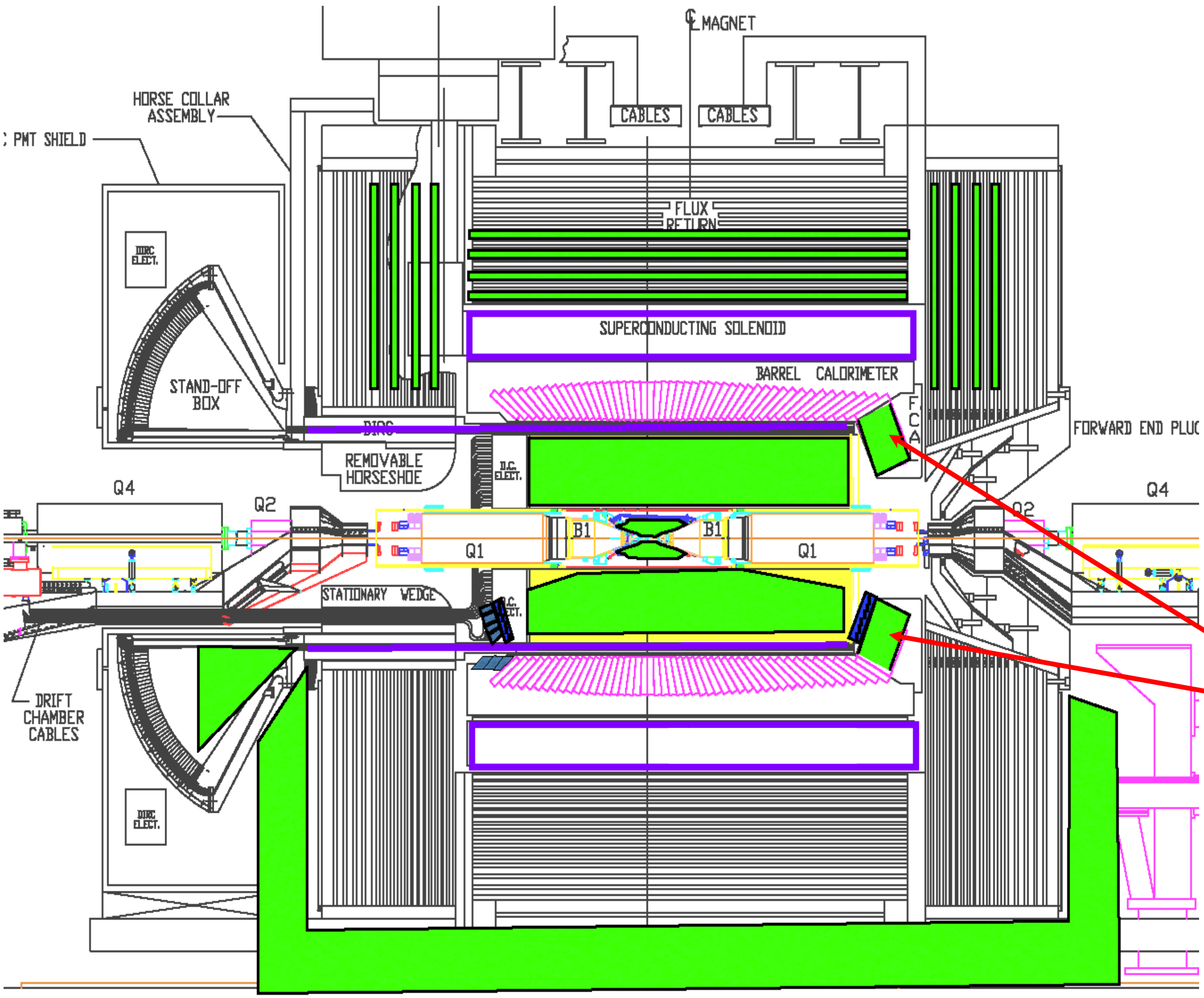
LSO/LYSO ECAL for Mu2e

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)



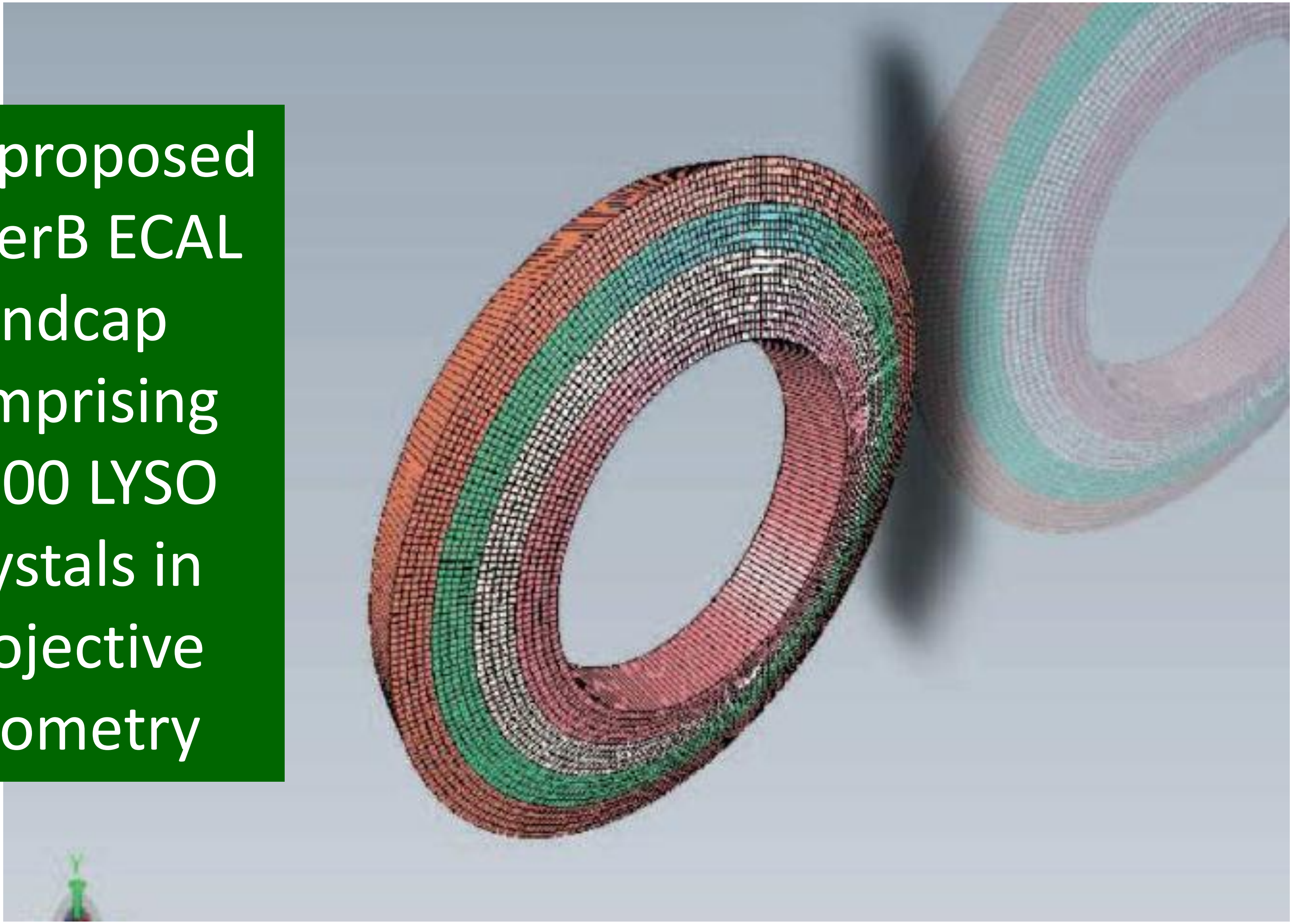
Aiming at 10^{36}/cm^2/s luminosity for rare B decays

Need a fast detector with low noise at the endcap

LSO/LYSO

Need cost effective crystals

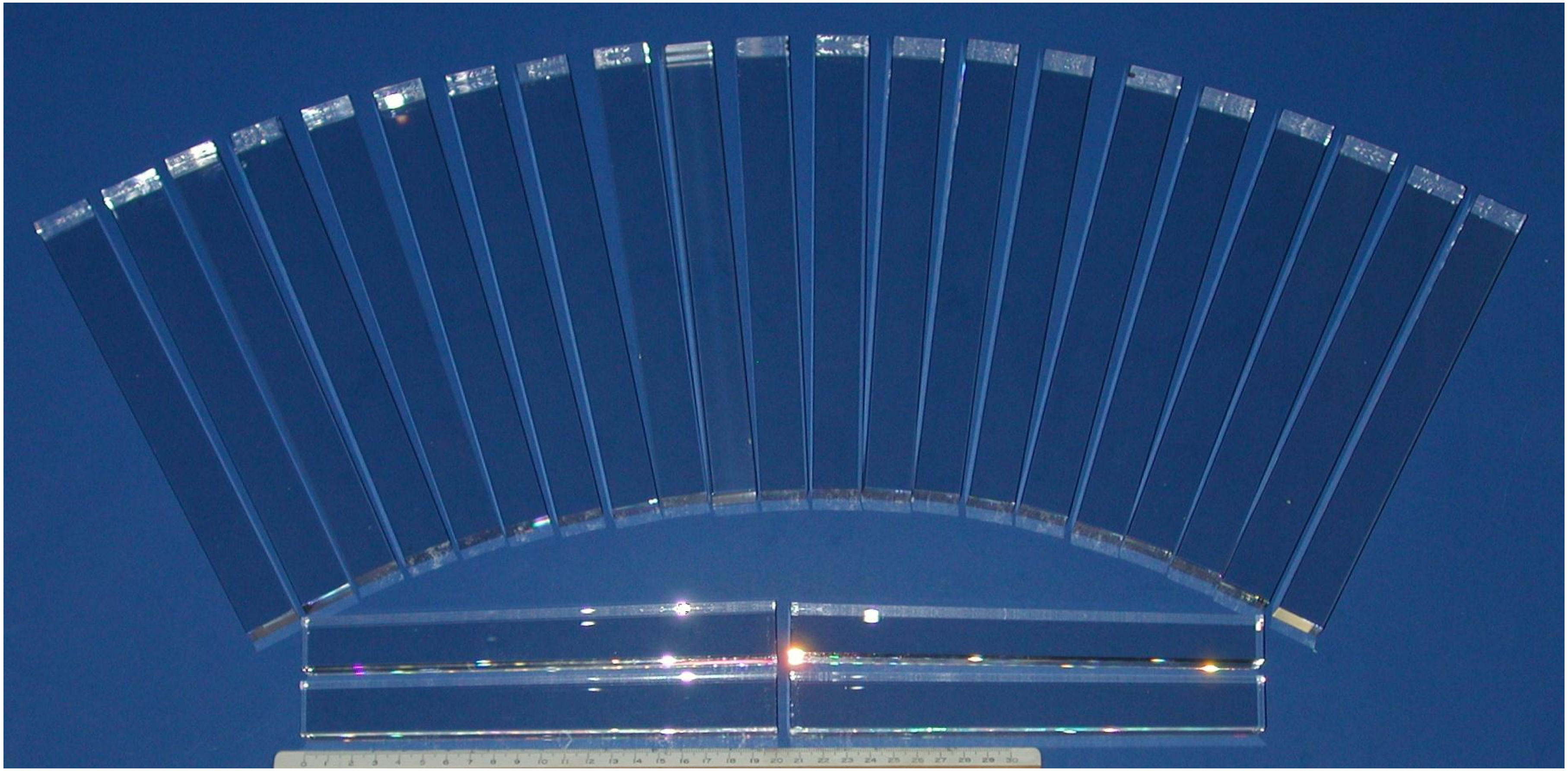
LSO/LYSO Endcap for SuperB



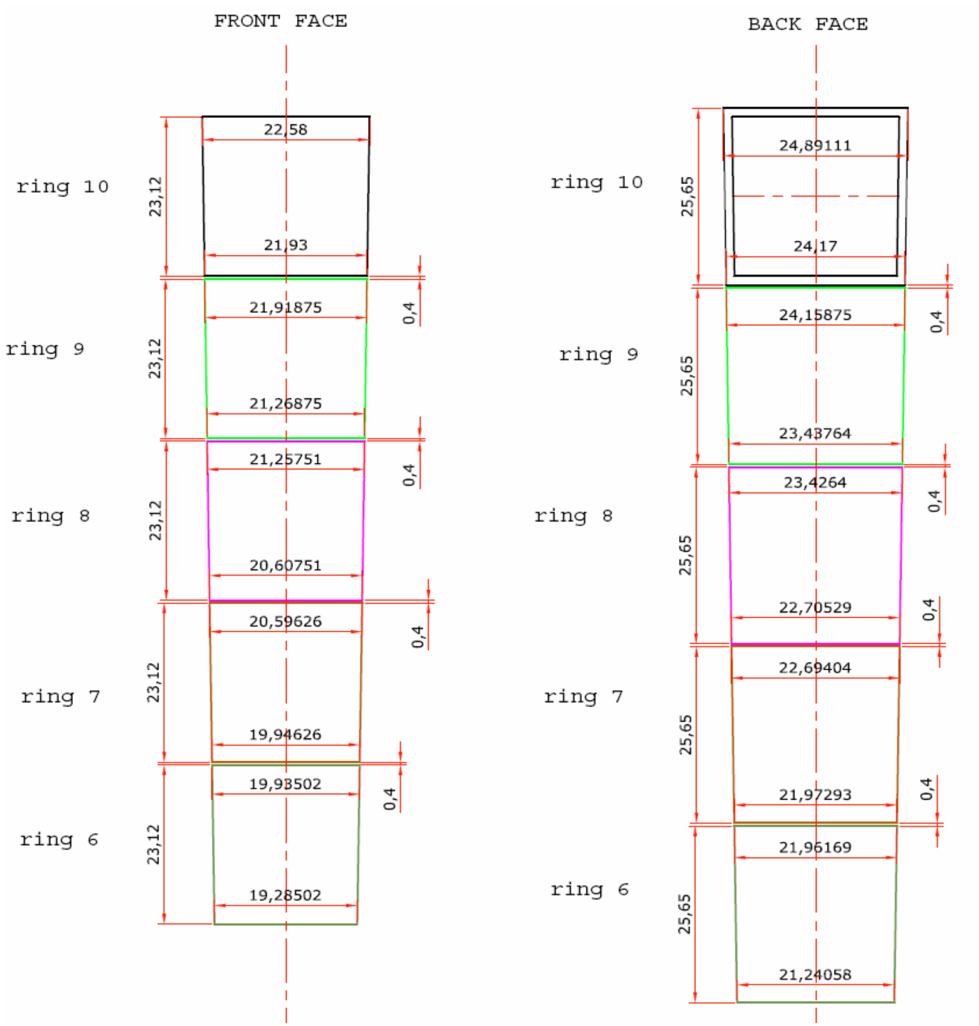
The proposed SuperB ECAL endcap comprising 4,400 LYSO crystals in projective geometry

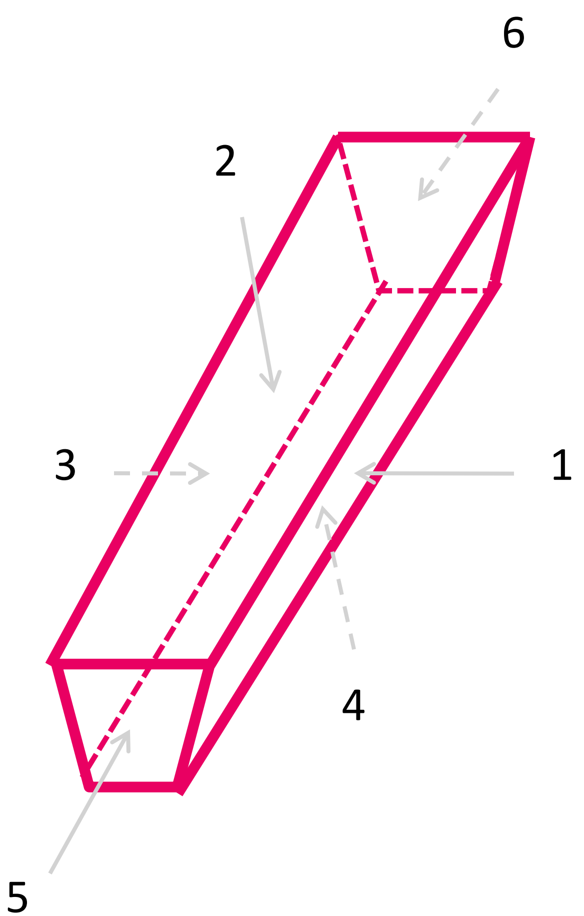
Twenty Five Test Beam Crystals

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



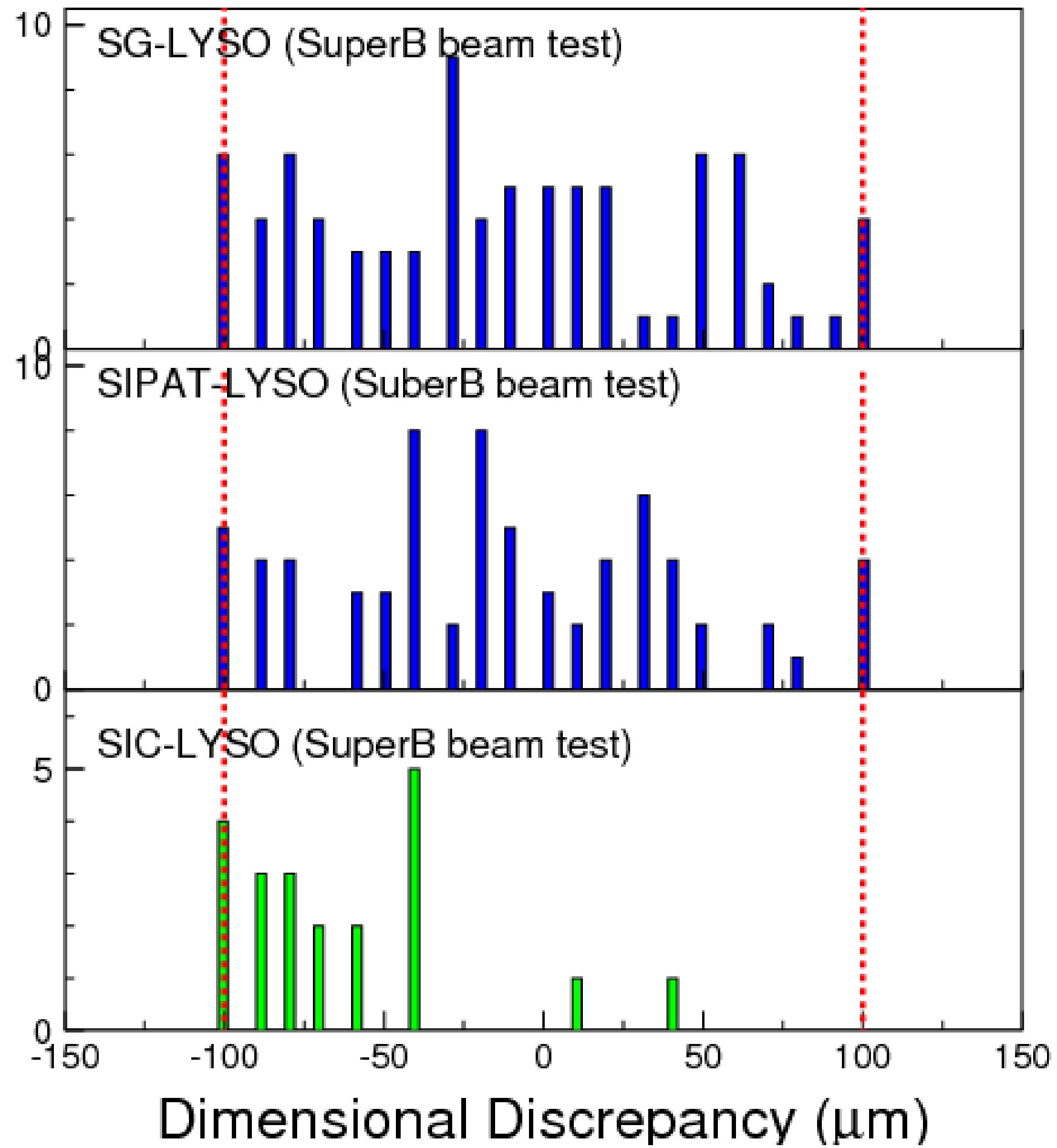
Dimensions and Surface Definition



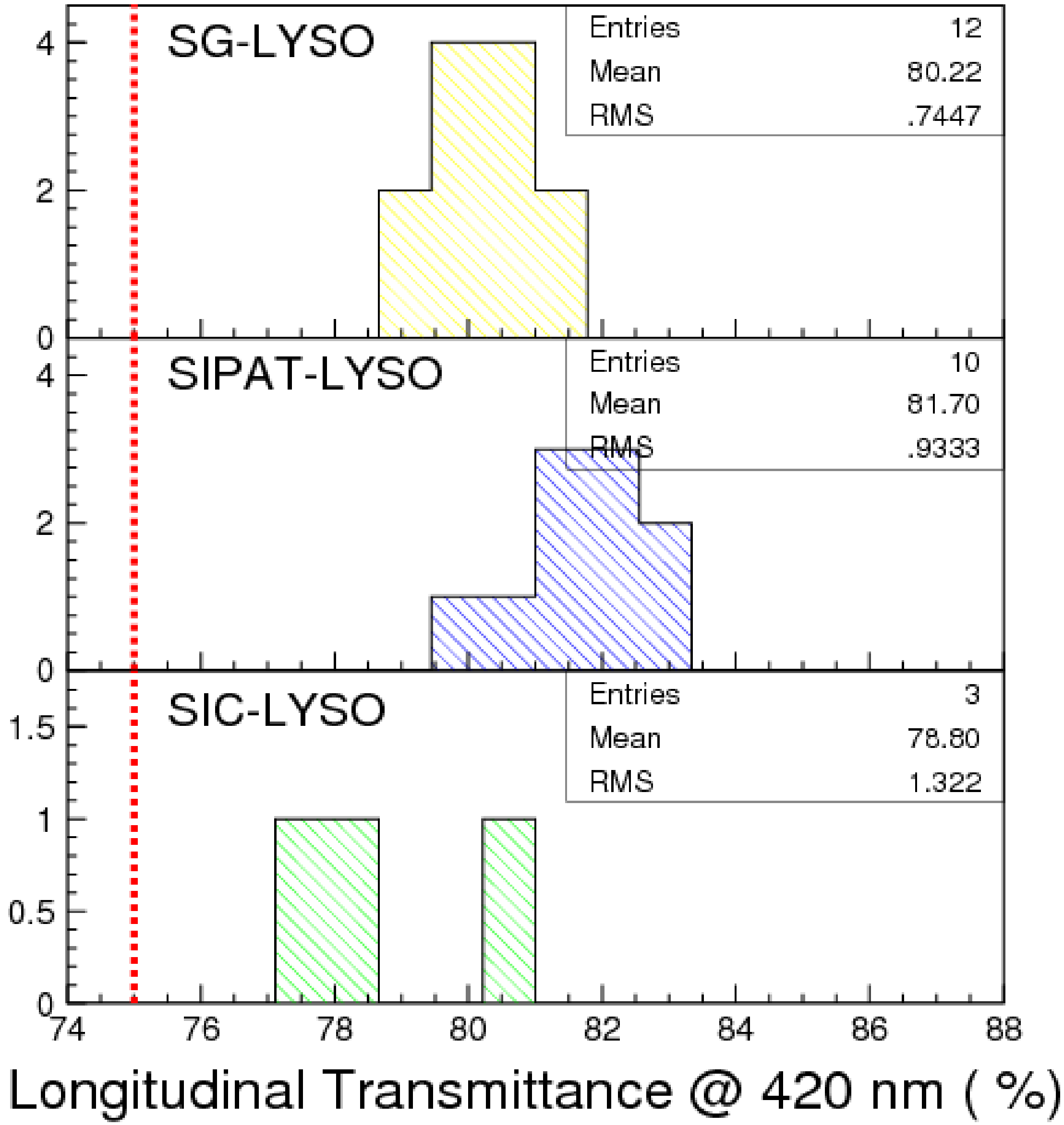


Summary: Dimension

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



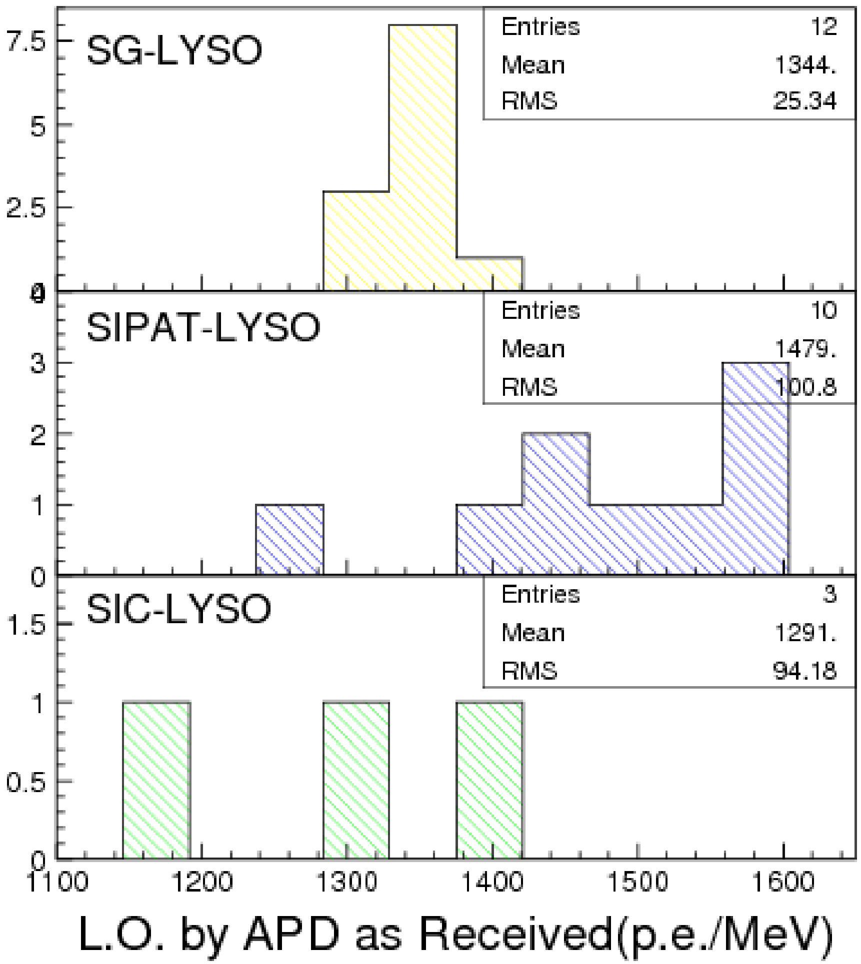
Summary: LT% @ 420 nm

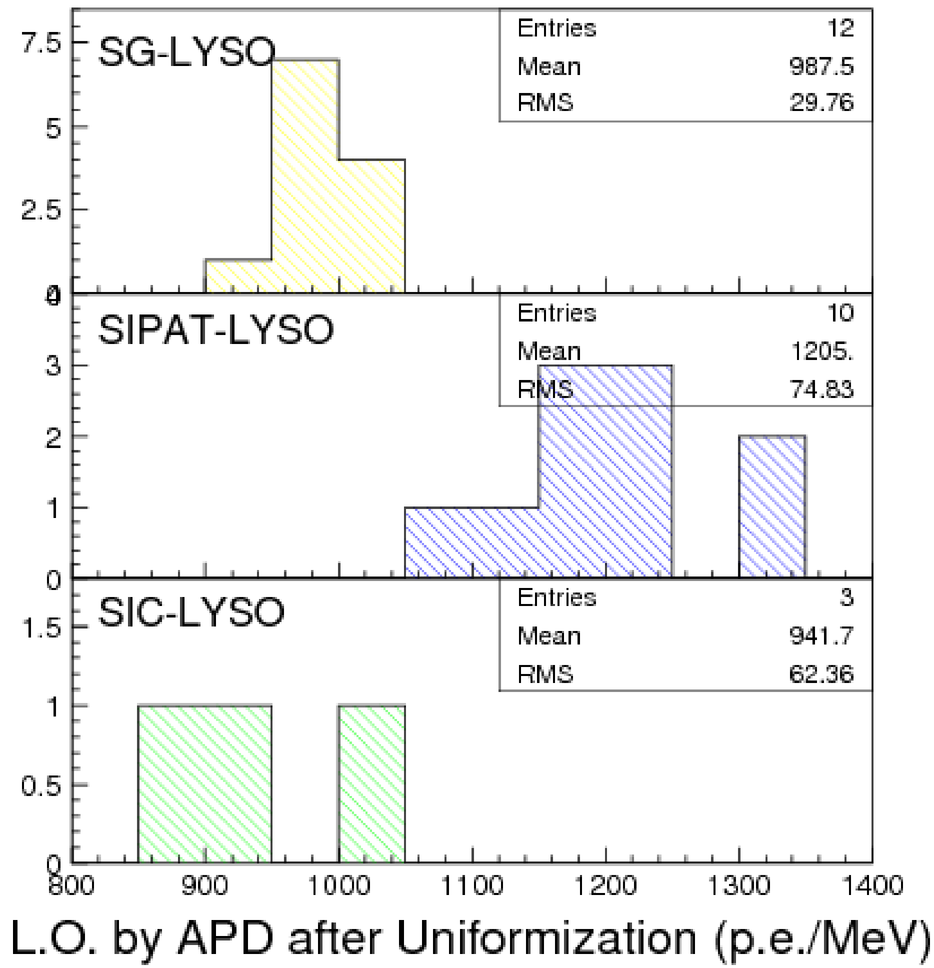


Orders: SIPAT, SG and SIC. All crystals satisfy the transmittance specification: 75%@420nm. Will keep this for mass production.

Summary: L.O. by APD

Orders: SIPAT, SG and SIC, caused by emission?





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

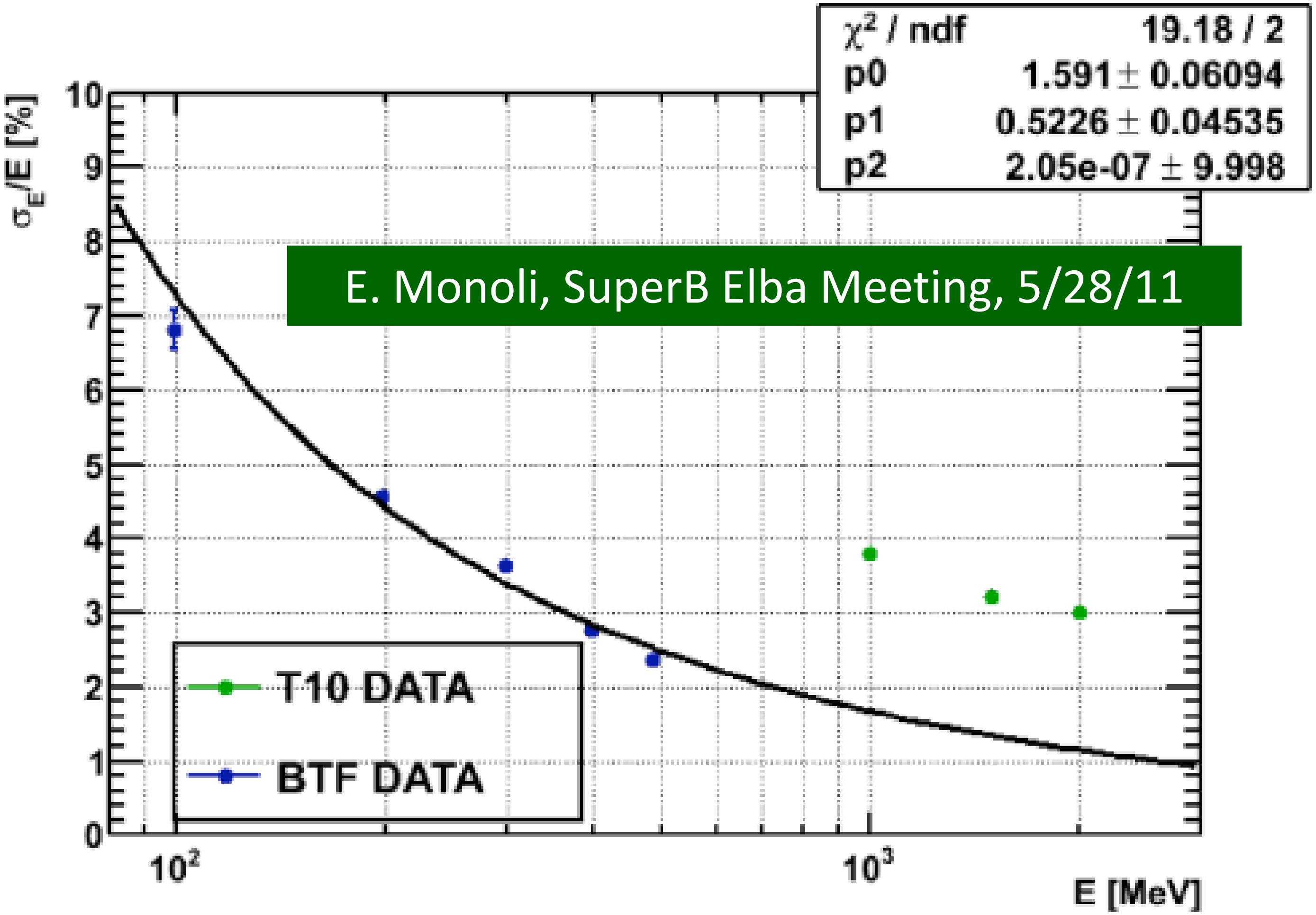
* Light Yield (LY) and Energy Resolution (ER) are the average of the seven points measured along the crysals.

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

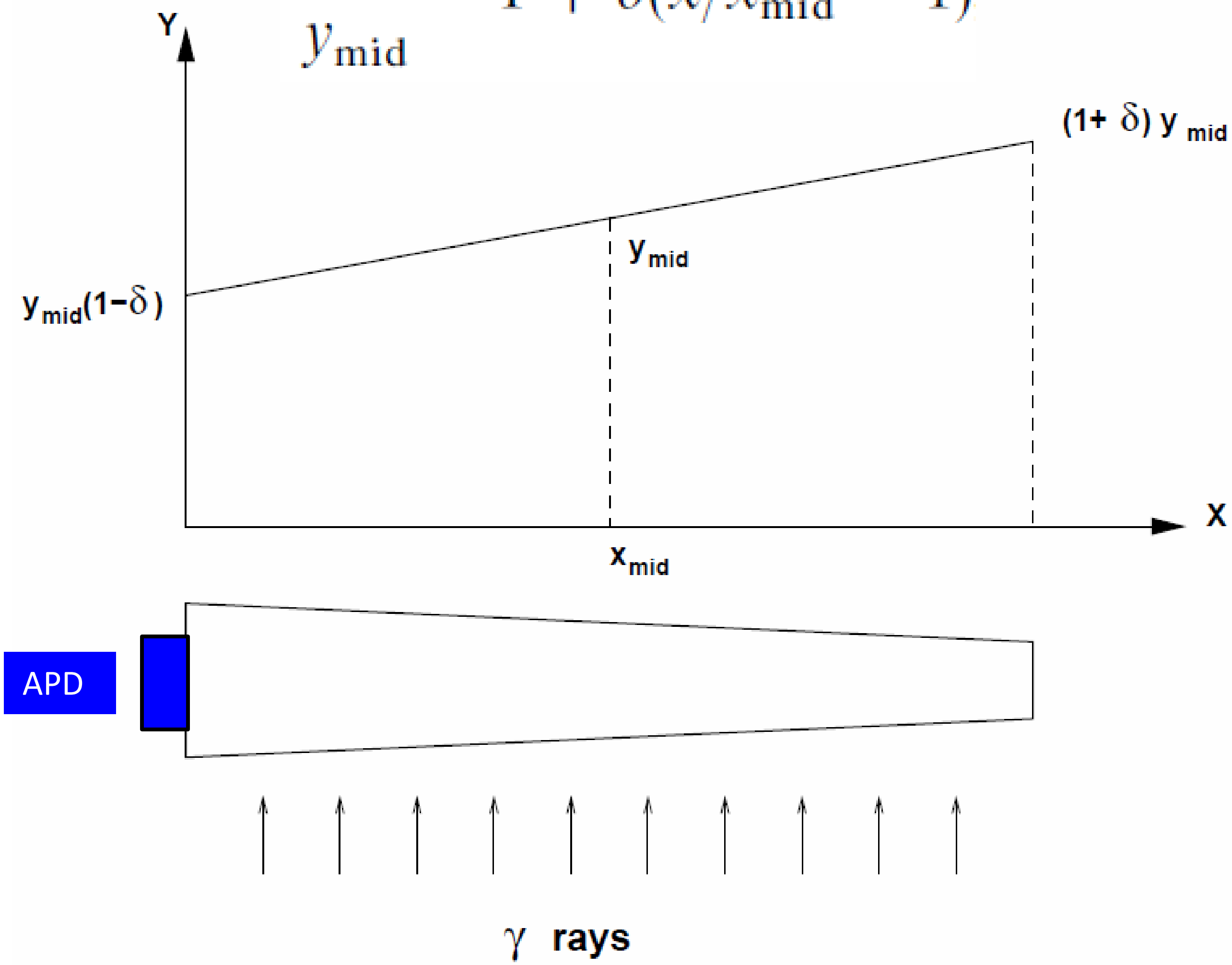
Encouraging resolution measured at BTF, Frascati, with non uniformized crystals. Another test is planned in this Fall with uniformized crystals.



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

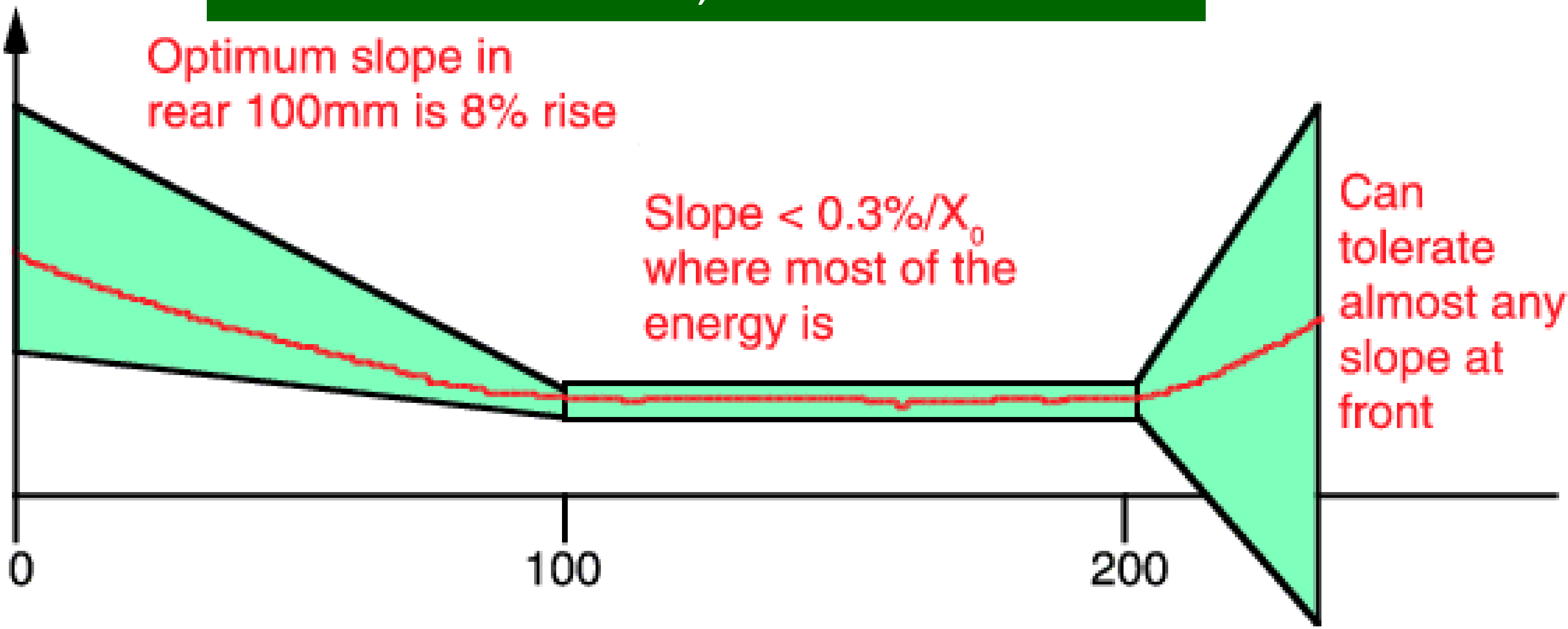
Light Response Non-Uniformity: δ

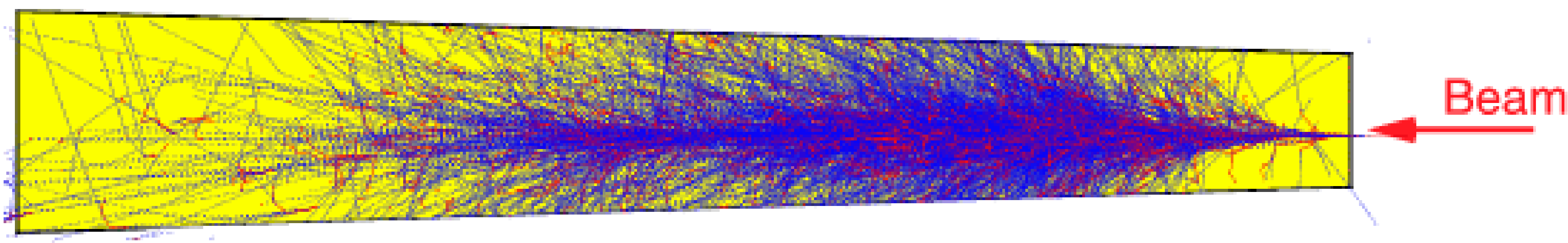
$$\frac{y}{y_{\mathrm{mid}}} = 1 + \delta(x/x_{\mathrm{mid}} - 1)$$



CMS Specification for Uniformity

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



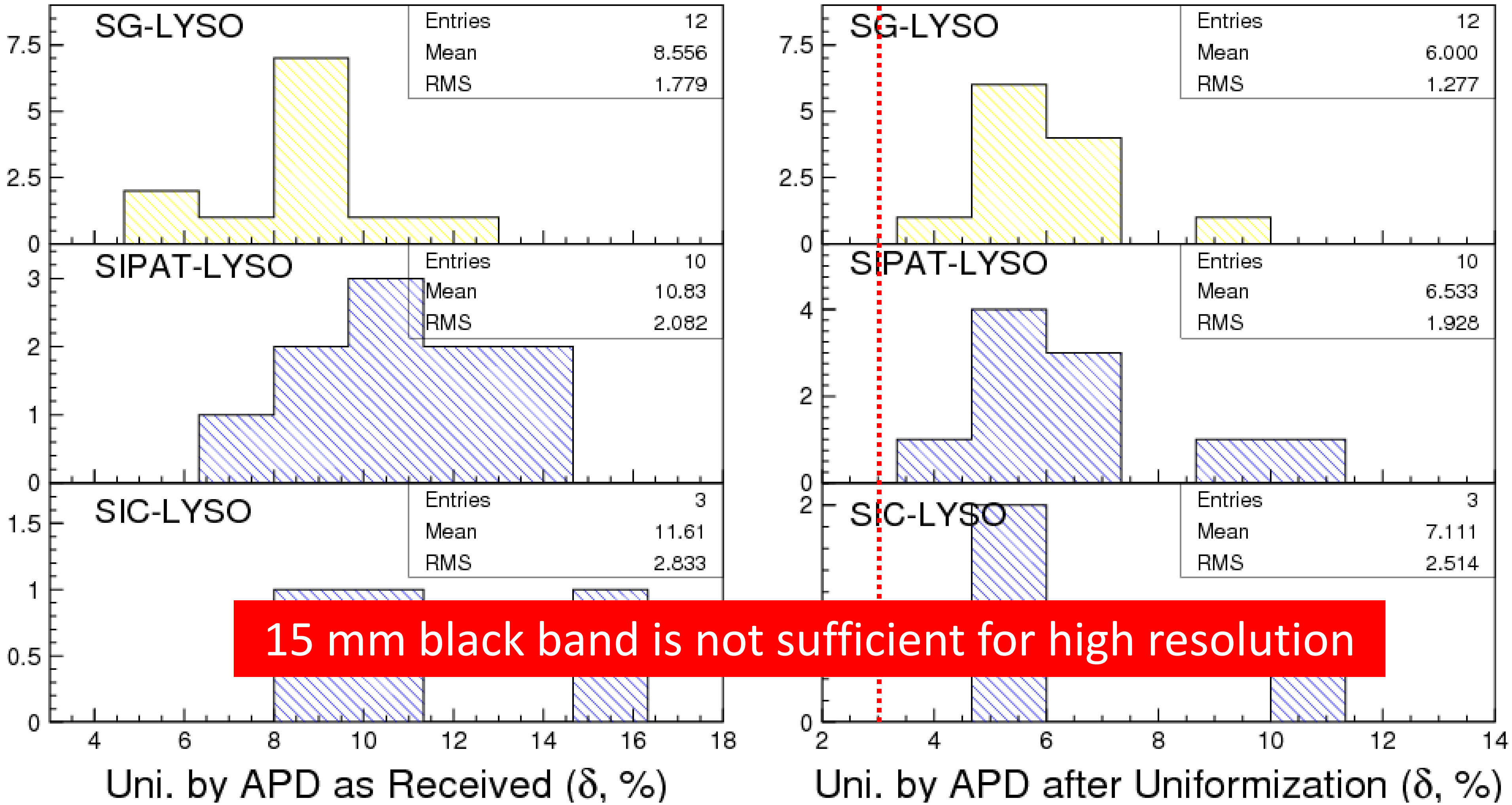


|δ| < 3% & 4% for 18 X_0 (SuperB) & 25X_0 (CMS)

Summary: Uniformity (δ) by APD

Diverse but consistent between vendors

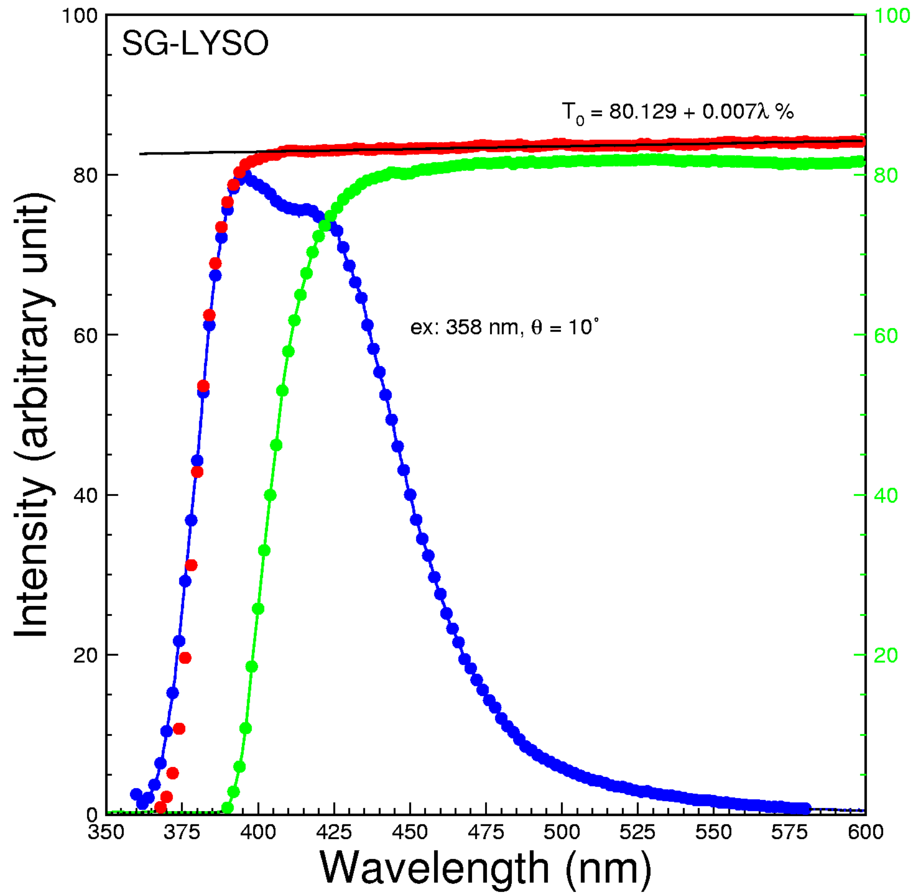
15 mm black paint is not sufficient for |δ| < 3%

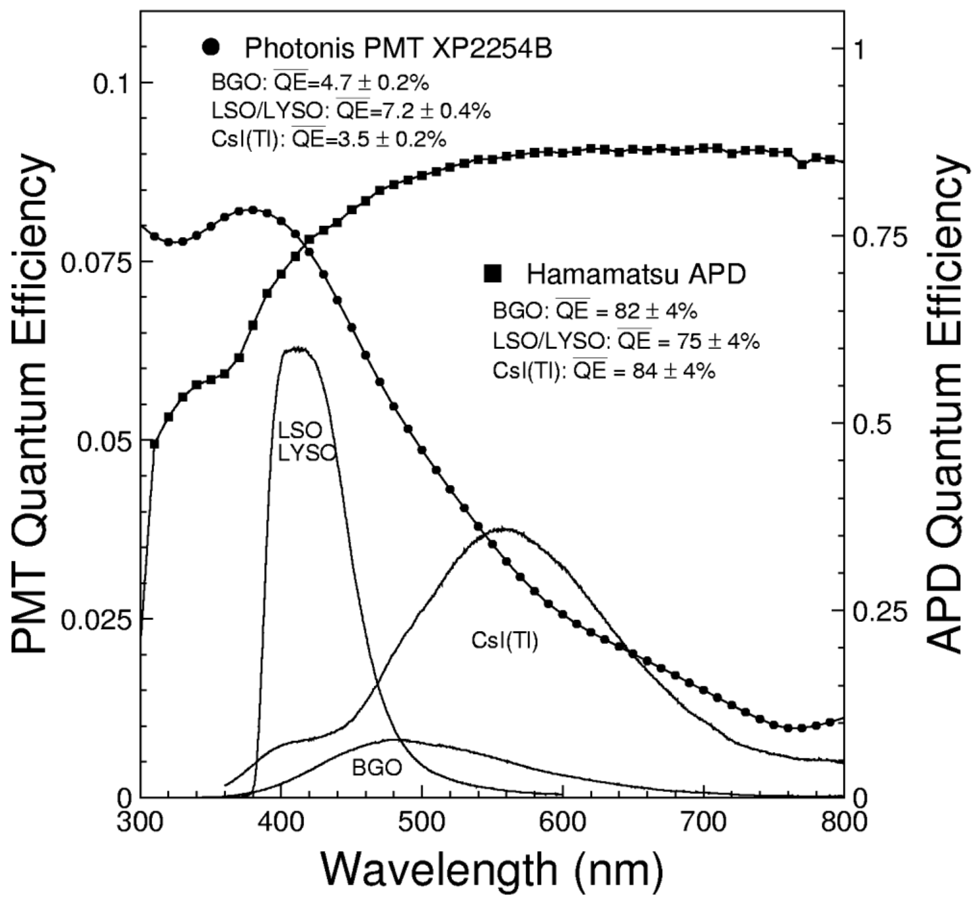


15 mm black band is not sufficient for high resolution

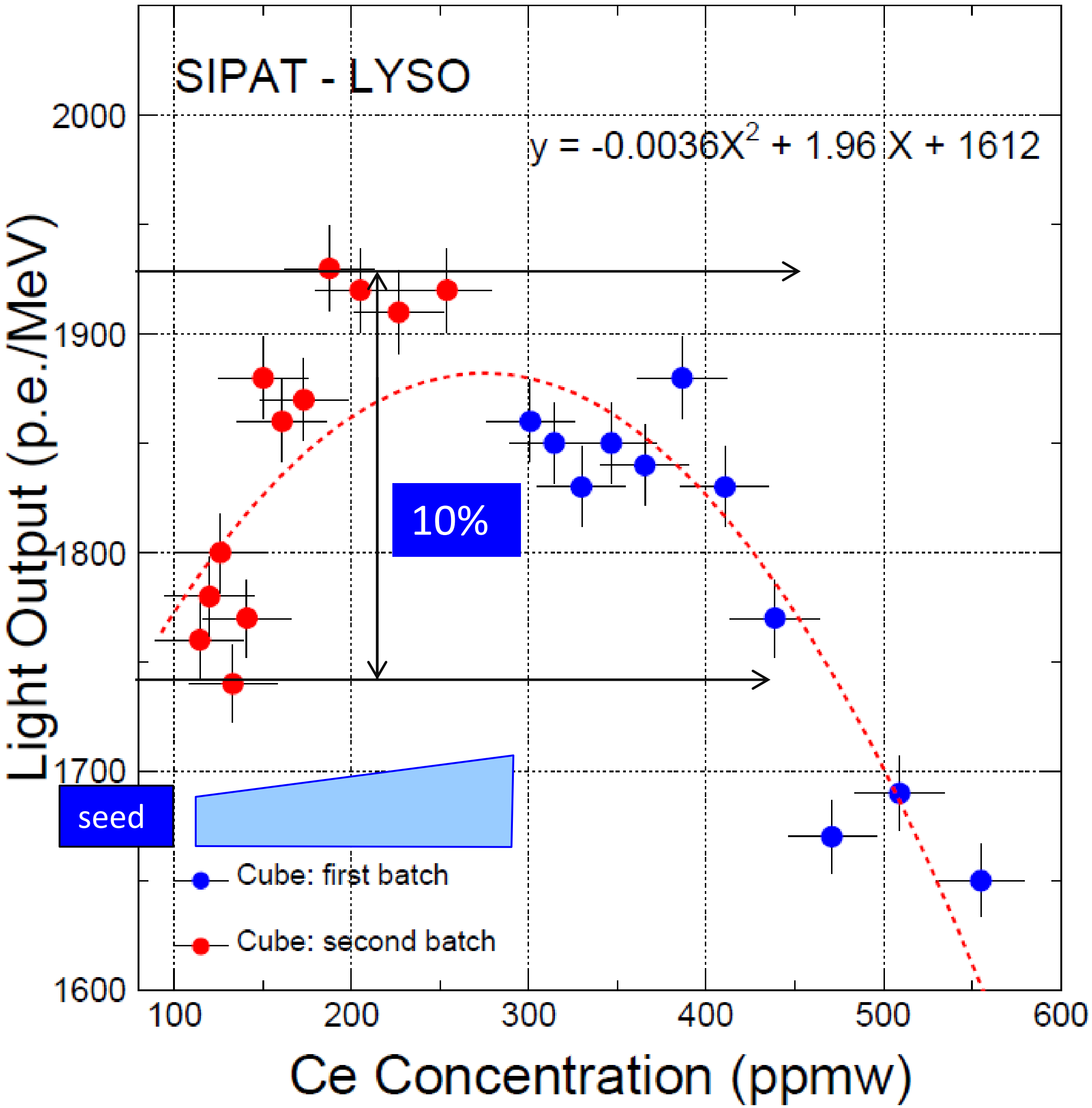
Effect of Self-absorption

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





Effect of Cerium Segregation

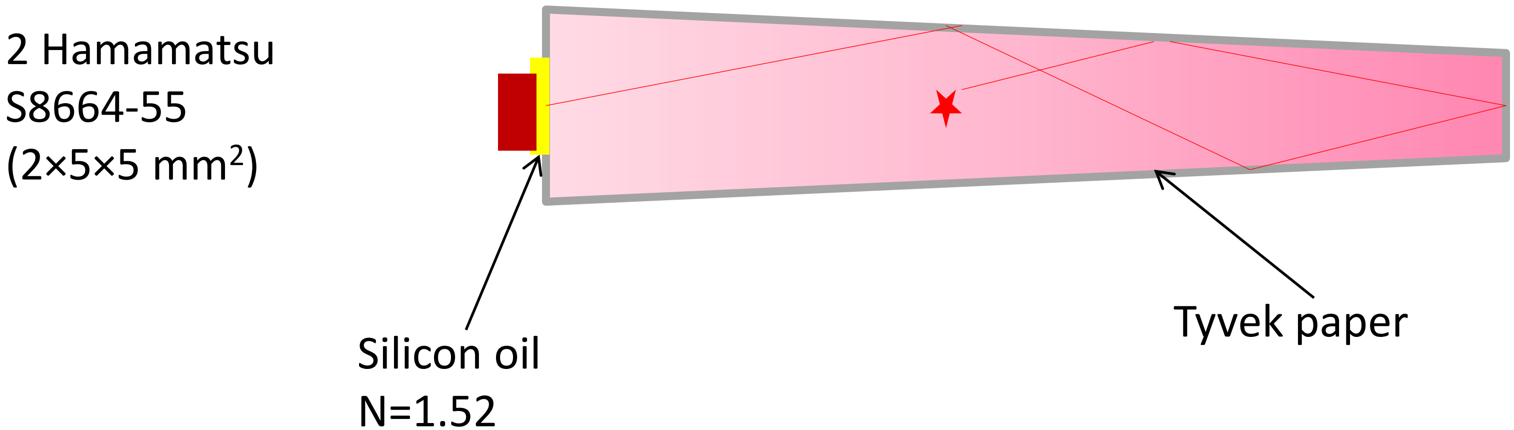


It is also known that cerium concentration along long LYSO crystals is not uniform, causing non-uniformity up to 10% at two ends, indicating up to 5% variation in δ is possible because of cerium segregation.

Ray-Tracing Simulation "set-up"

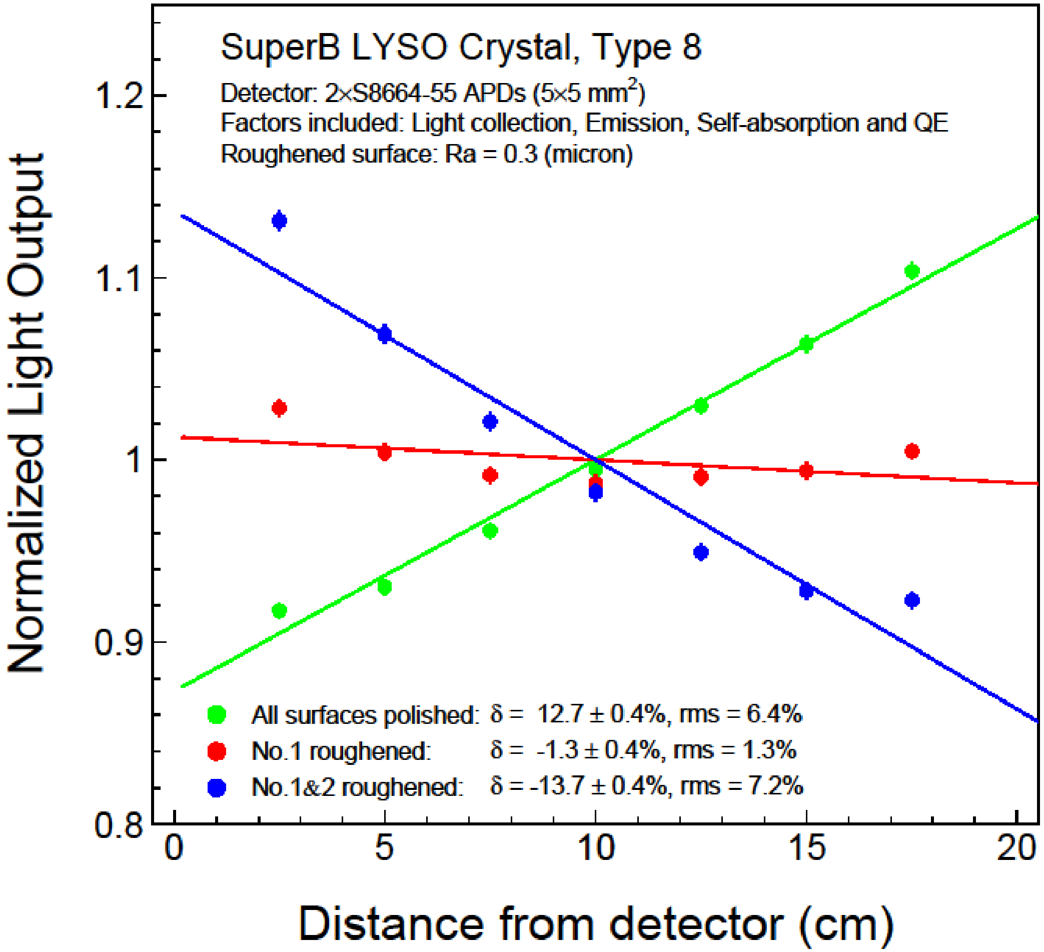
The simulation package was developed in early eighties, and was used for the L3 BGO and CMS PWO crystals.

SuperB LYSO crystals



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

Polished and Roughened Surfaces

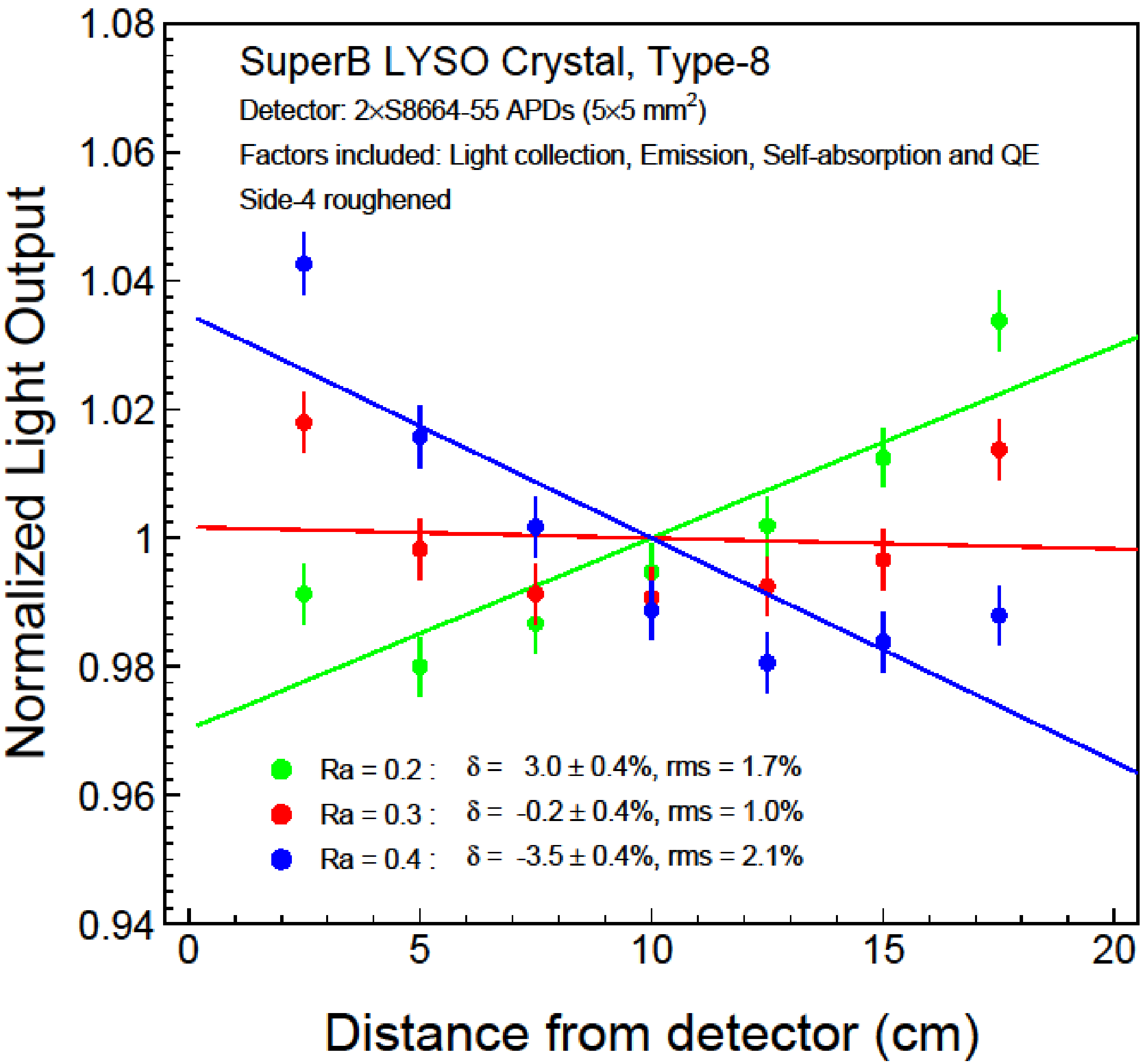


- The optical focusing, effect dominates non-uniformity: δ is about 13% for all polished surfaces.
- Roughened surface(s) can compensate the optical focusing effect.
- The best result is achieved by roughening only one side surface.

How Rough it Should Be?

The R_a matters.

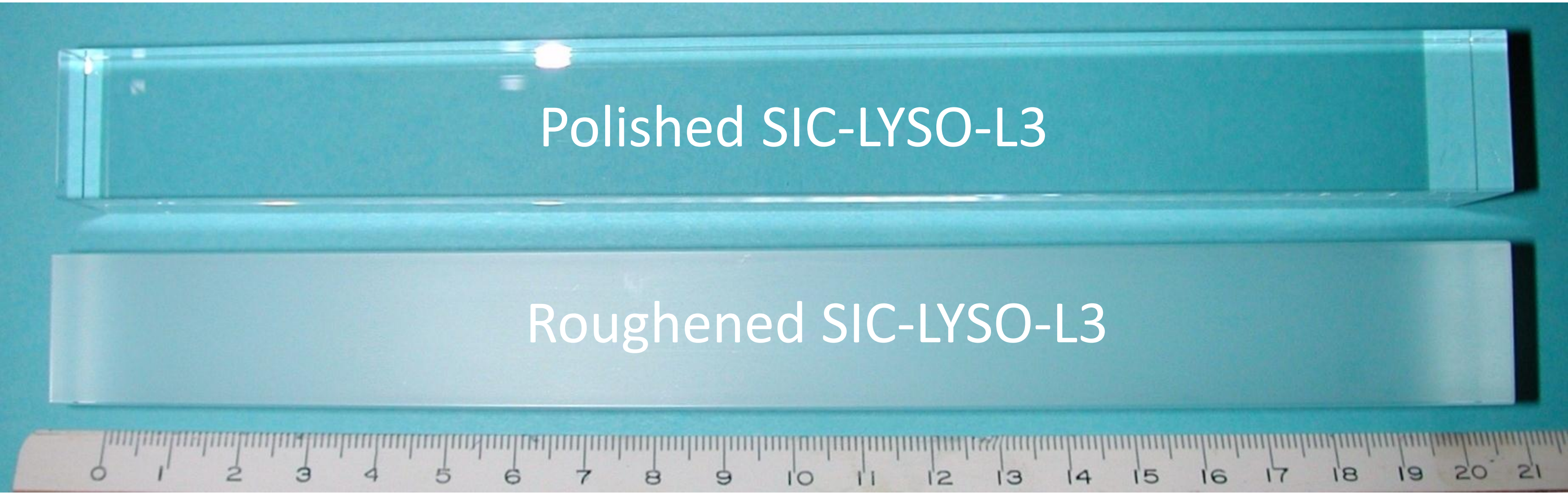
A variation of 0.1 in R_a causes a 3% variation in δ.



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

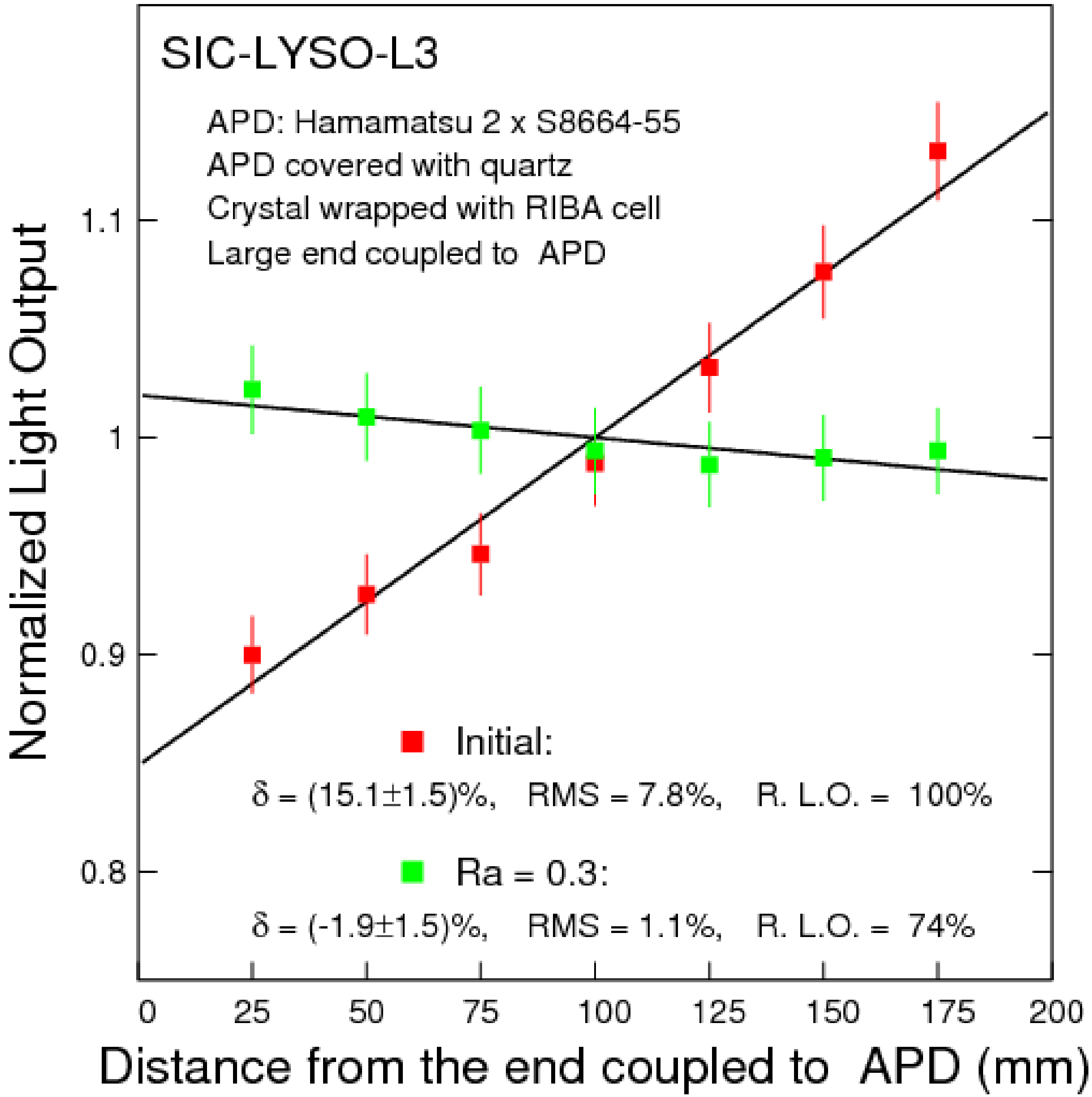
Thanks to SICCAS for roughening this crystal



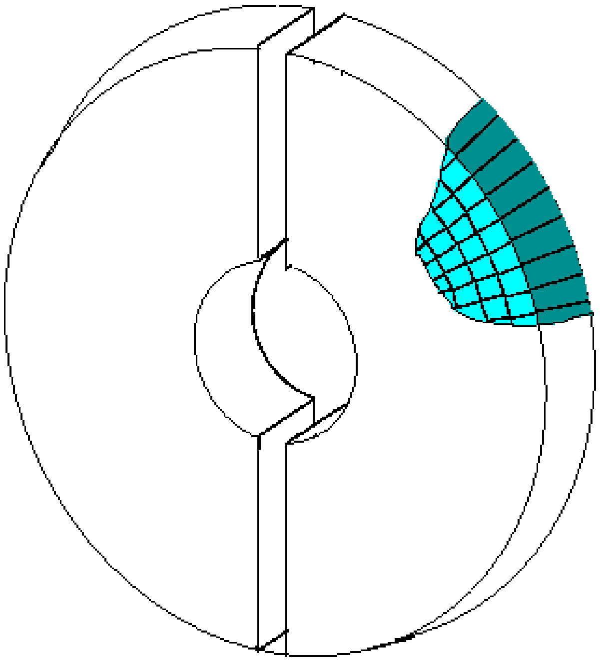
1st: lapped to Ra = 0.5 by using 11 μm Al_2O_3 powder for 10 min with 2.5 kg weight.
2nd: lapped to Ra = 0.3 by using 6.5 μm SiC powder for 3 min with 1.5 kg weight.

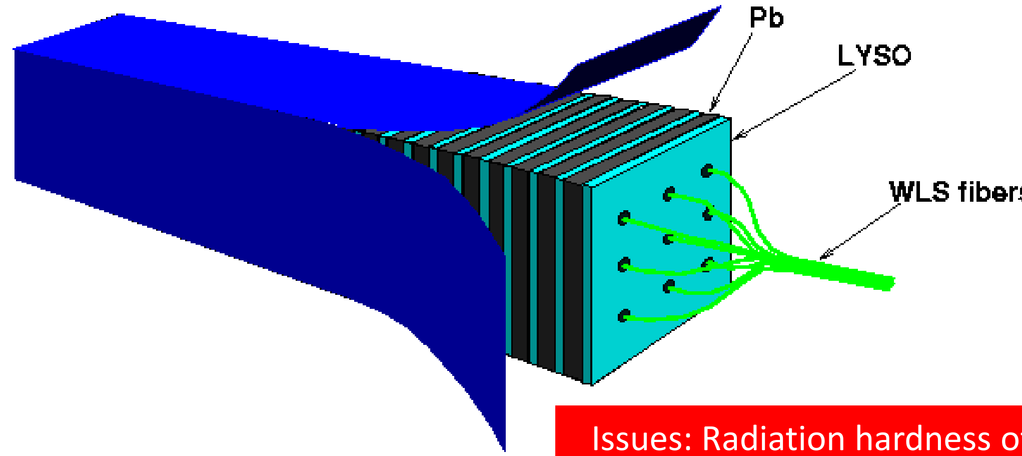
Relative Light Output & Uniformity

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



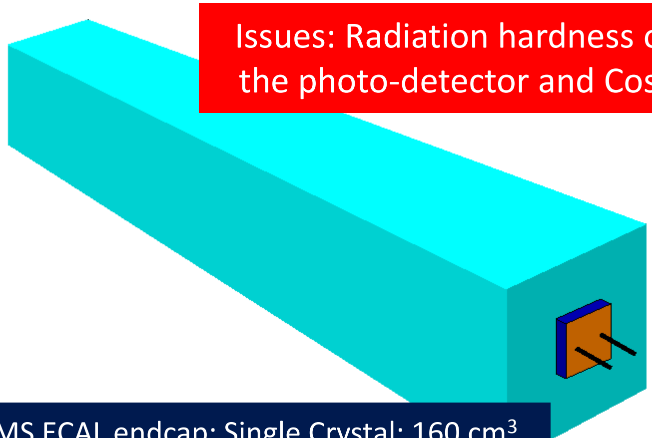
CMS Forward Calorimeter Upgrade

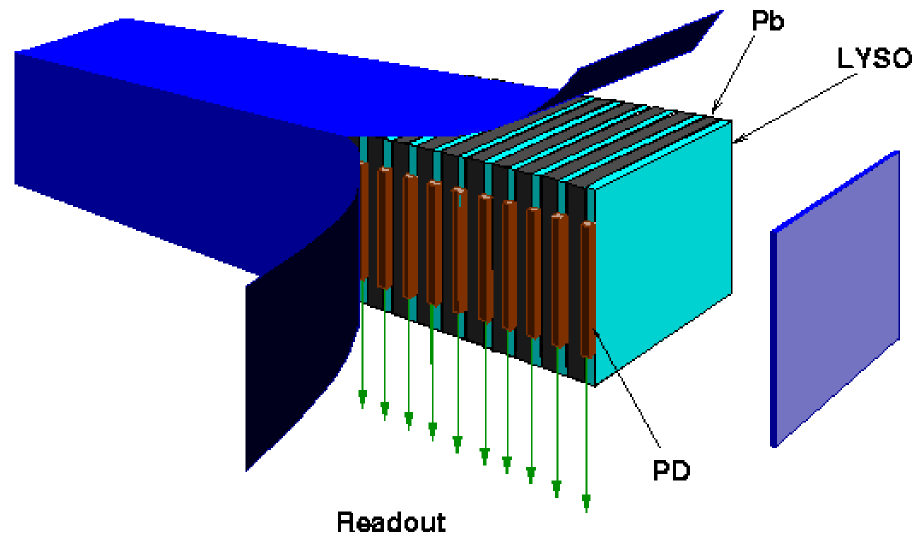




Issues: Radiation hardness of photo-detector and WLS fiber

Issues: Radiation hardness of the photo-detector and Cost





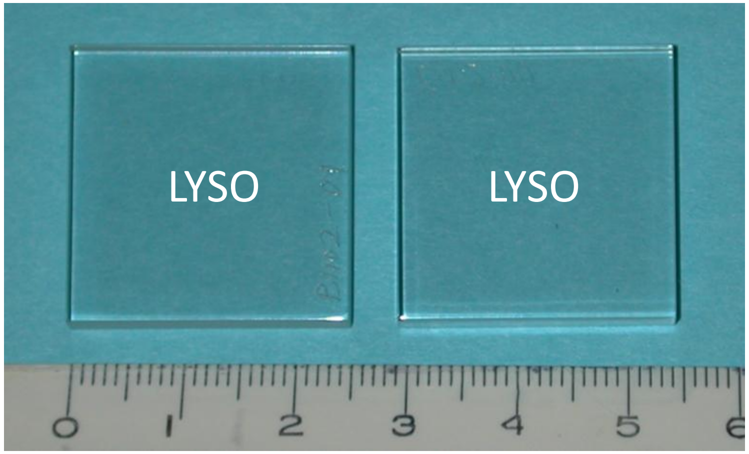
CMS ECAL endcap: Single Crystal: 160 cm^3
Total number: 16,000 Total Volume: 2.5 m^3
Expected Crystal Cost: ~$60M@$25/cc

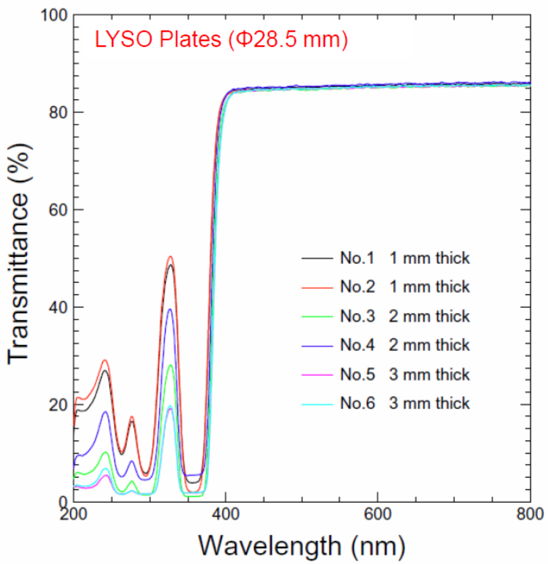
Crystal Cost: <$10M

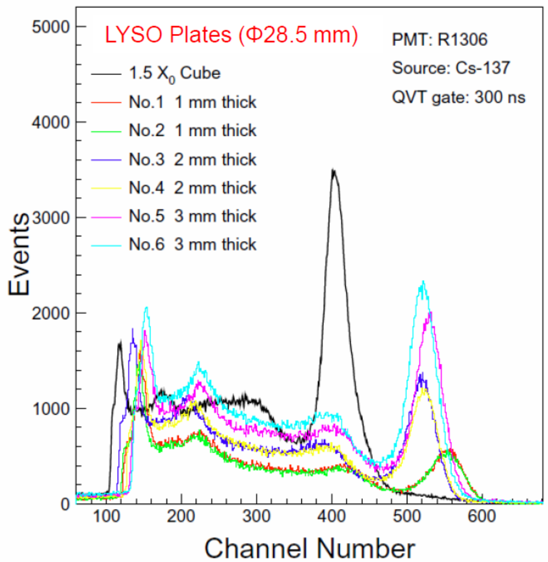
Issue: Radiation hardness of the photo-detector

Performance of Scintillator Plates

Crystals

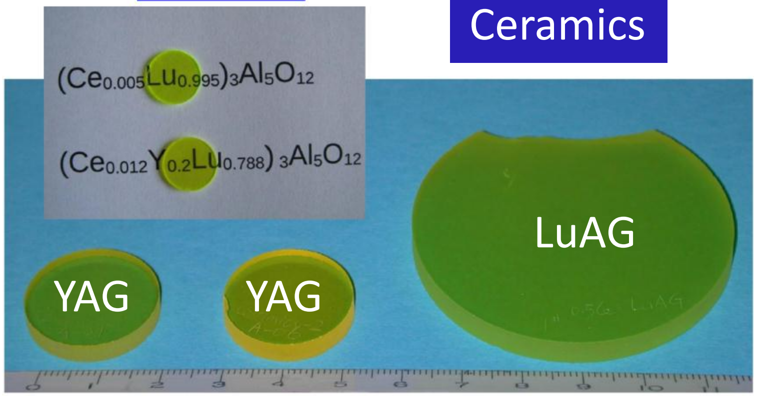






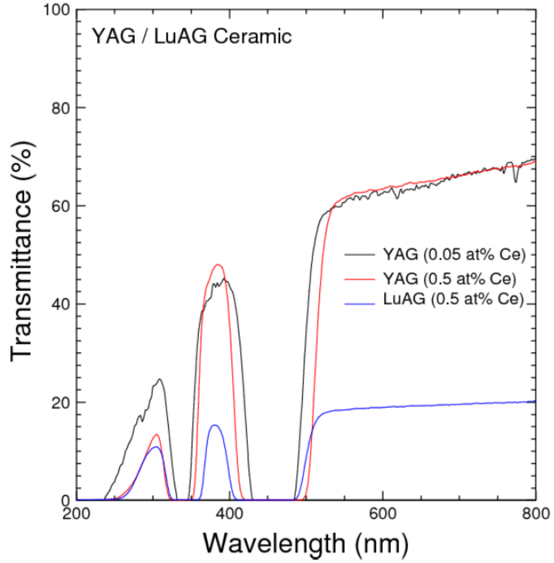
Φ20 X 3 mm

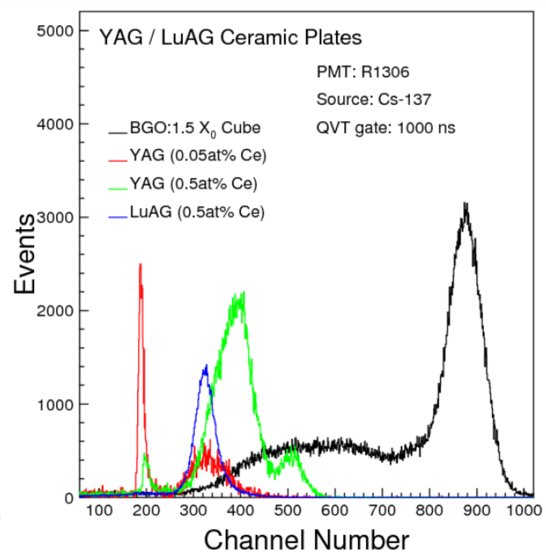
Ceramics



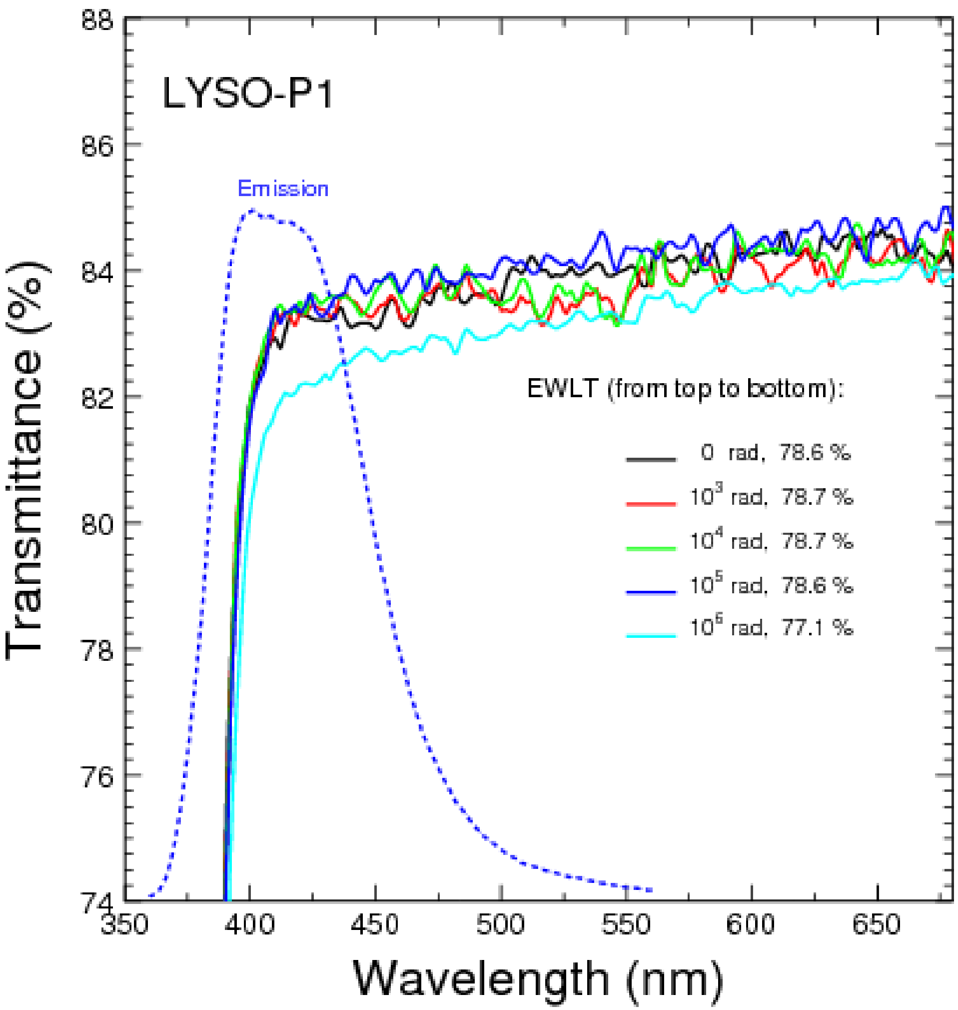
YAG: Φ22 x 4 mm

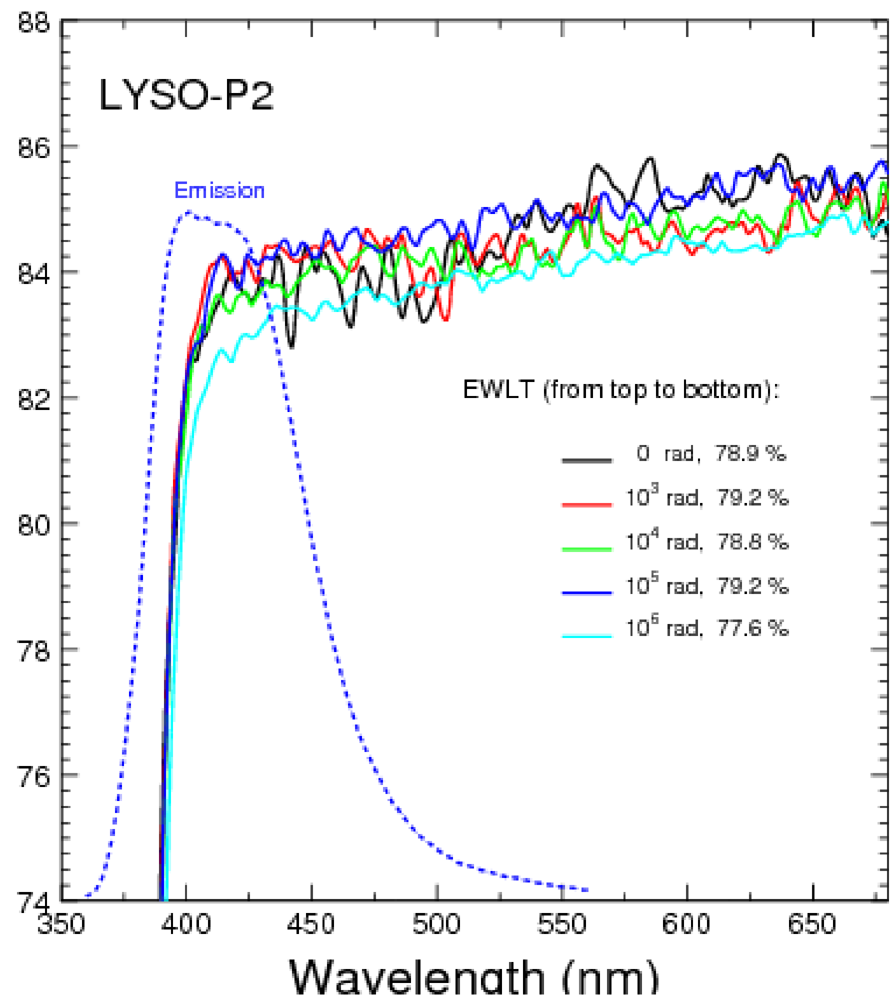
LuAG Φ56 x 5 mm



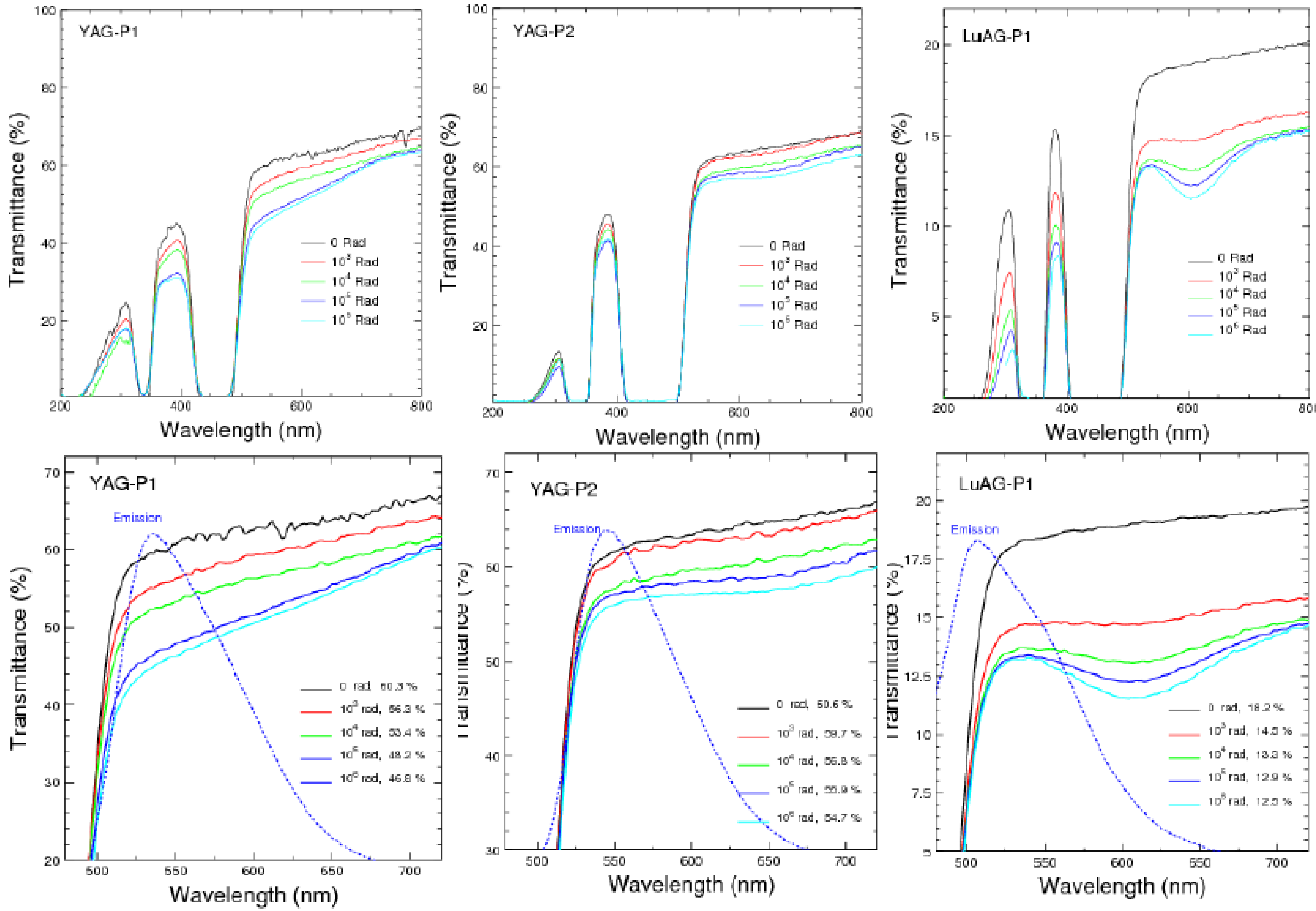


Radiation Hard LYSO Plates





Radiation Hardness of Ceramics

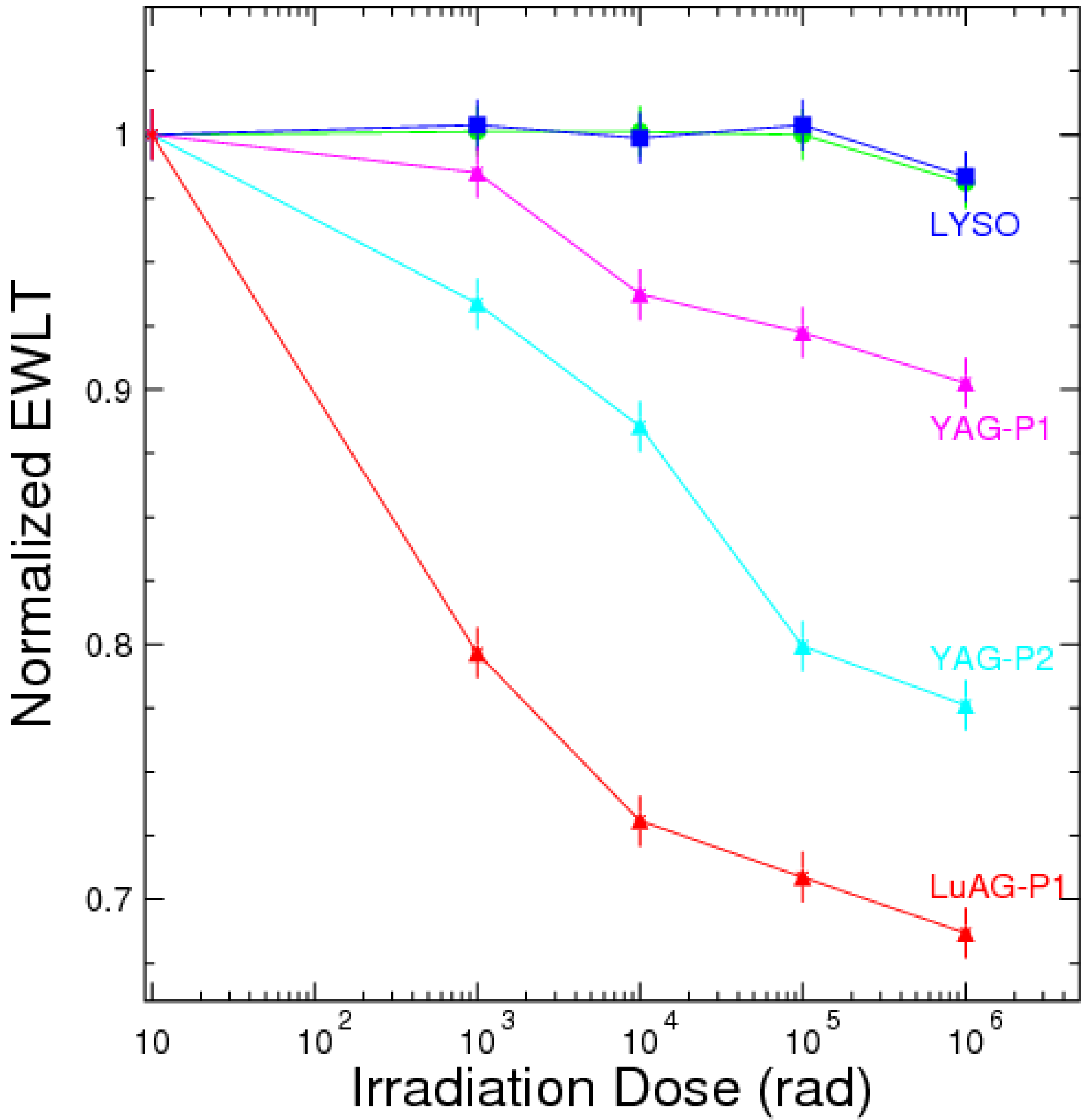


Normalized EWLT: LYSO & Ceramic

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 CMS forward calorimeter upgrade.
- The light response uniformity of tapered LYSO long crystals is affected by (1) optical focusing, (2) self-absorption and (3) non-uniformity of the cerium concentration, and may be optimized by appropriate roughening to a side surface.
- For CMS forward calorimeter upgrade R&D works are concentrated on two directions:
  - Growth of crystals of adequate length/size cost-effectively; and
  - LSO/LYSO plates for sampling options. Initial test with YAG and LuAG ceramics indicates that they are not radiation hard.