LSO/LYSO Crystals and their Applications for Future HEP Experiments

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Why LSO/LYSO for HEP?

LSO/LYSO is a bright (200 times of PWO), fast (40 ns) and radiation hard crystal 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 tapered crystal geometry, self-absorption and cerium segregation can be addressed by roughening one side surface.

The material is widely used in the medical industry. Existing mass production capability would help in crystal cost control.

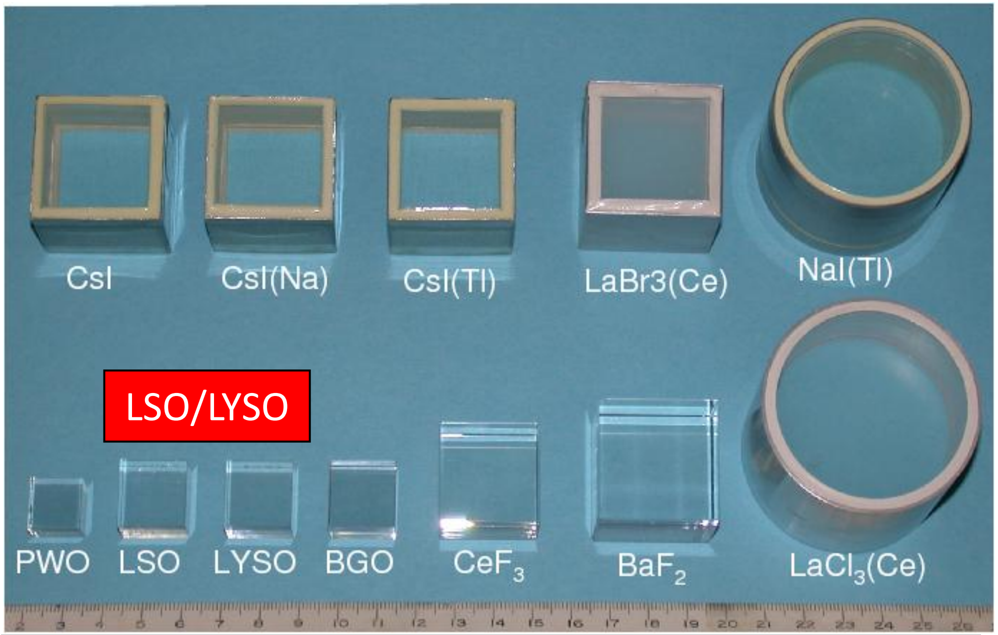
References: *IEEE Trans. Nucl. Sci.* NS-52 (2005) 3133-3140, *Nucl. Instrum. Meth.* A572 (2007) 218-224, *IEEE Trans. Nucl. Sci.* NS-54 (2007) 718-724, *IEEE Trans. Nucl. Sci.* NS-54 (2007) 1319-1326, *IEEE Trans. Nucl. Sci.* NS-55 (2008) 1759-1766 and *IEEE Trans. Nucl. Sci.* NS-55 (2008) 2425-2341, N32-4 & N32-5 @ NSS09, Orlando, N38-2 @ NSS10, Knoxville, N29-6 @ NSS11, Valencia.

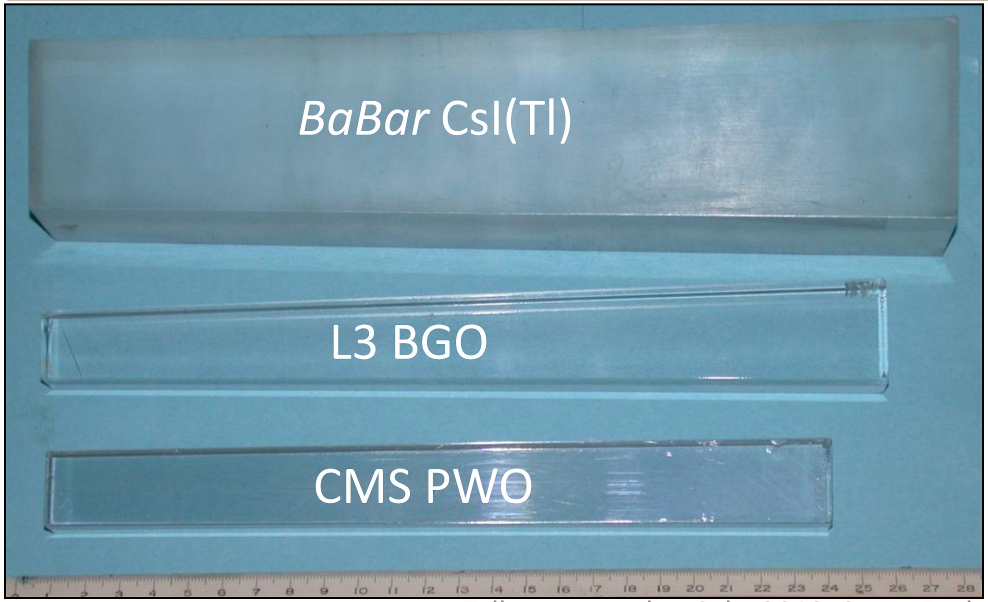
Crystals for HEP Calorimeters

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 (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	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

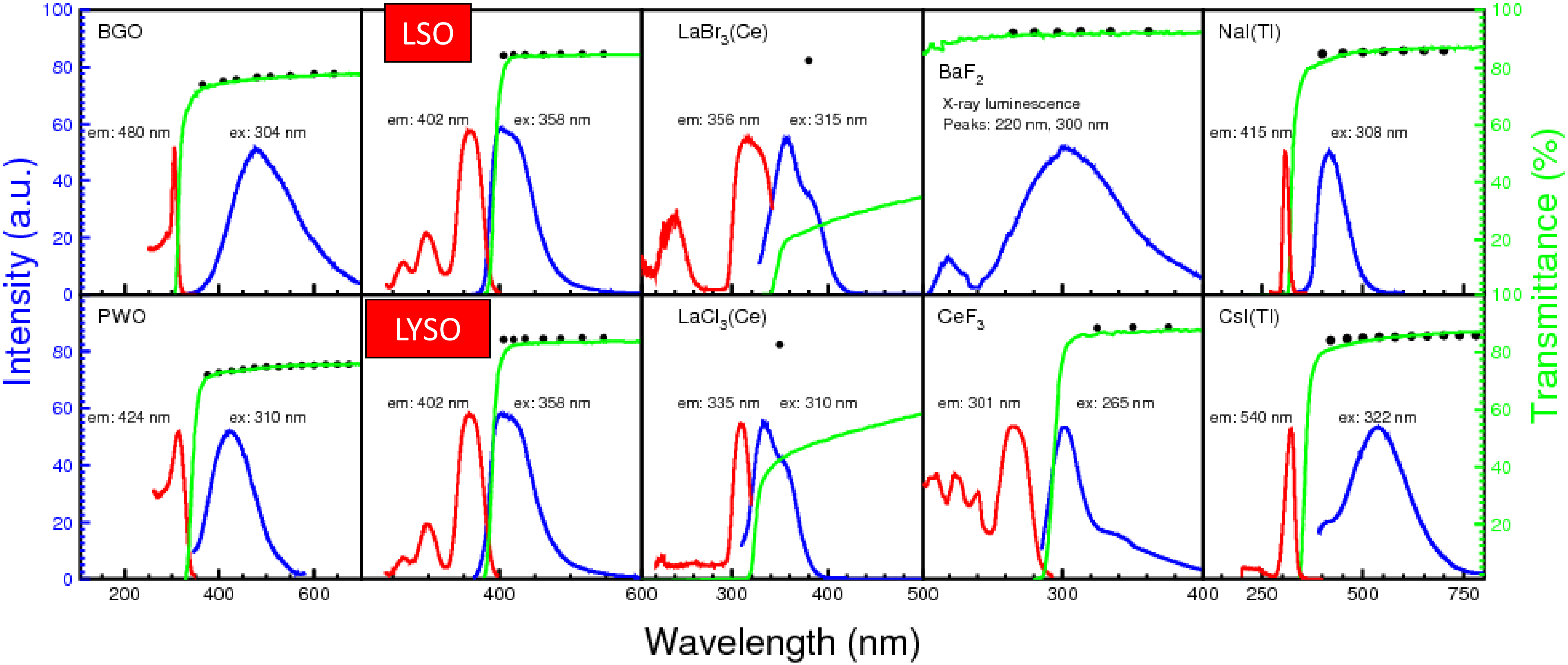
L3 BGO: 22 X_0

CMS PWO(Y): 25 X_0

Excitation, Emission, Transmission

$$T_s = (1-R)^2 + R^2(1-R)^2 + \ldots = (1-R)/(1+R), \text{ with}$$
$$R = \frac{(n_{crystal} - n_{air})^2}{(n_{crystal} + n_{air})^2}.$$

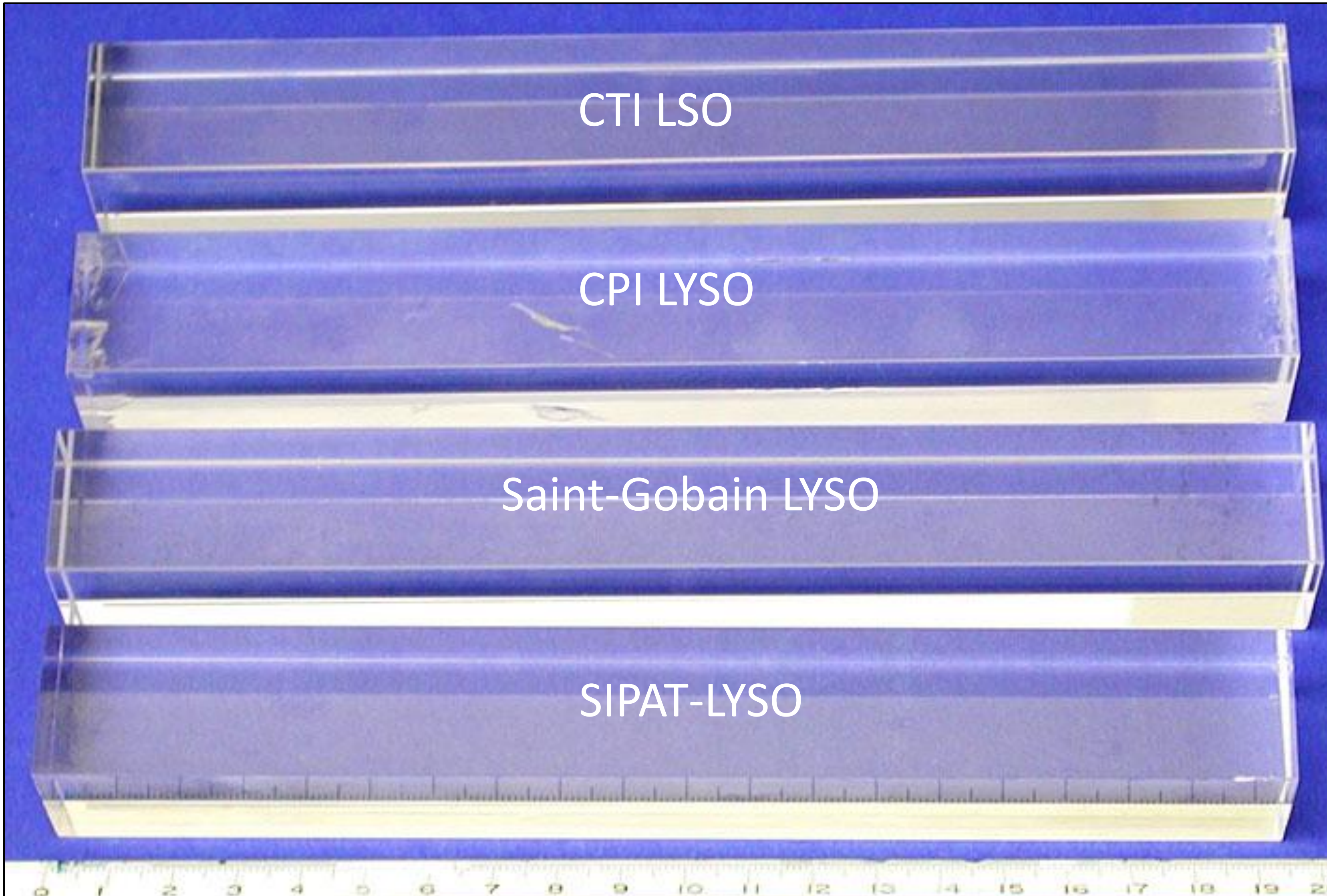
Black Dots: Theoretical limit of transmittance: NIM A333 (1993) 422



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

LSO & LYSO Crystal Samples

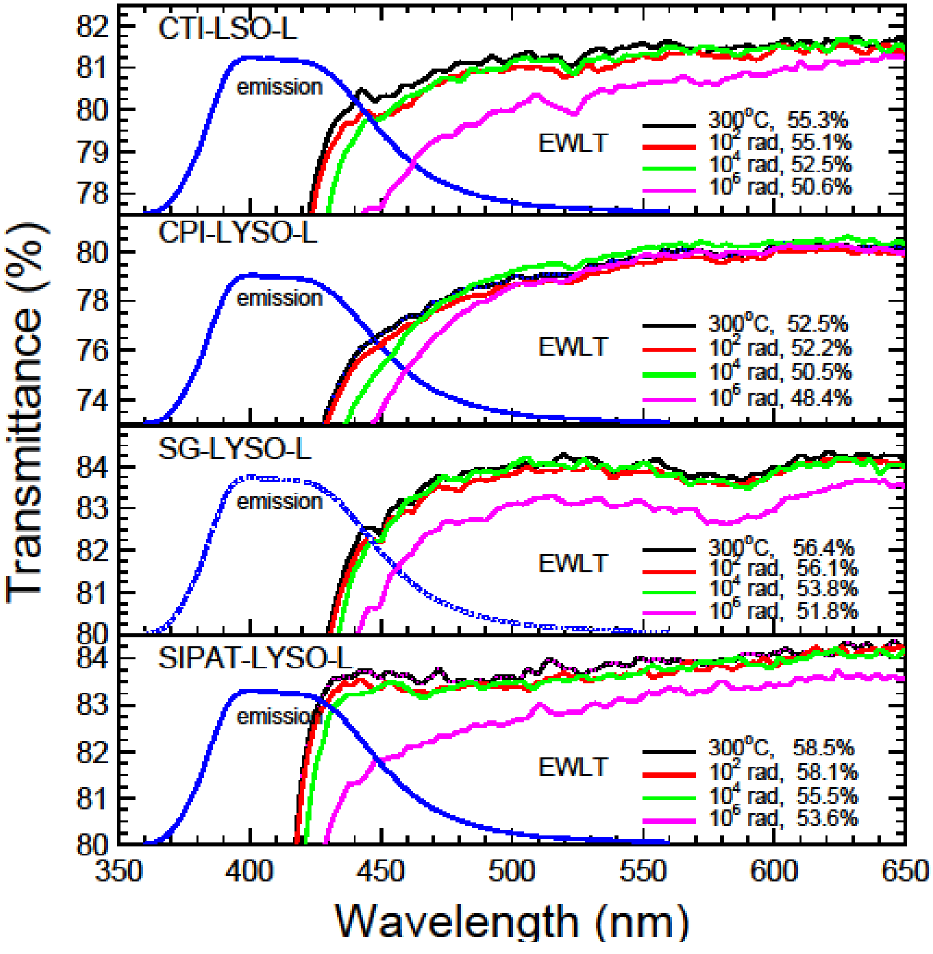
2.5 x 2.5 x 20 cm (18 X_0)



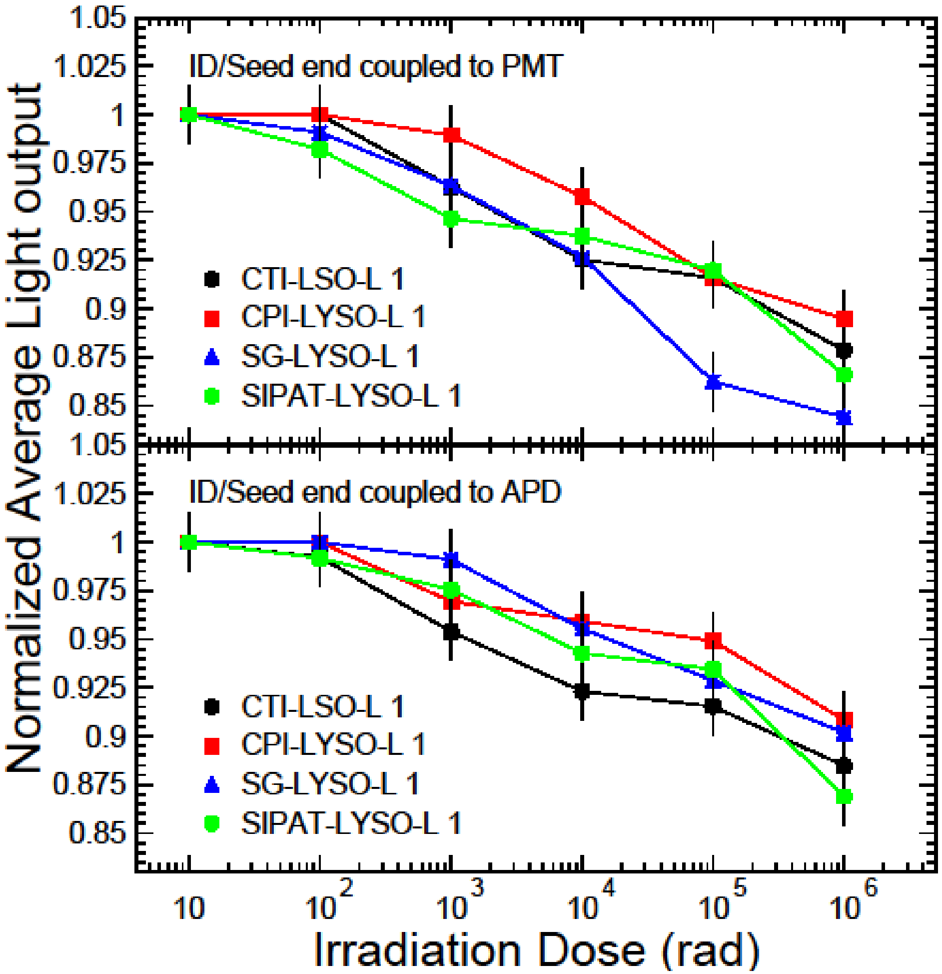
20 cm Long LSO/LYSO under γ-Rays

Consistent radiation hardness better than other crystals

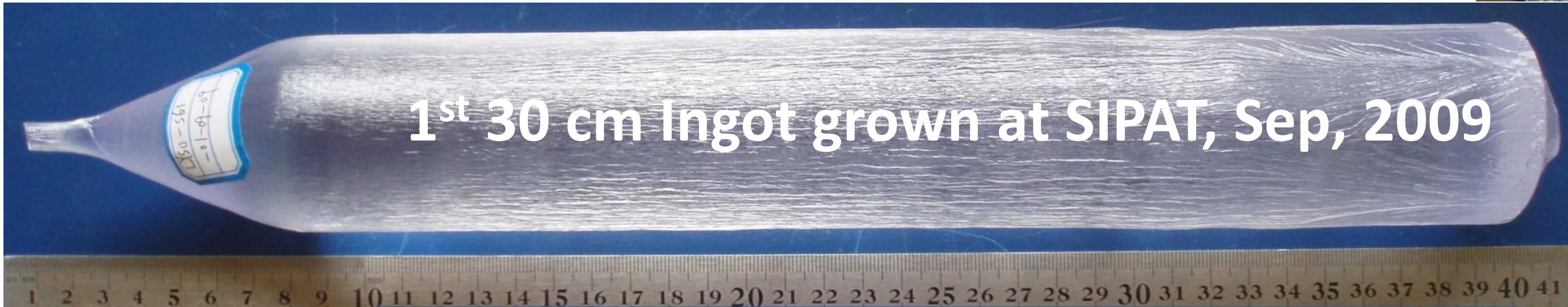
EWLT damage: 8% @ 1 Mrad

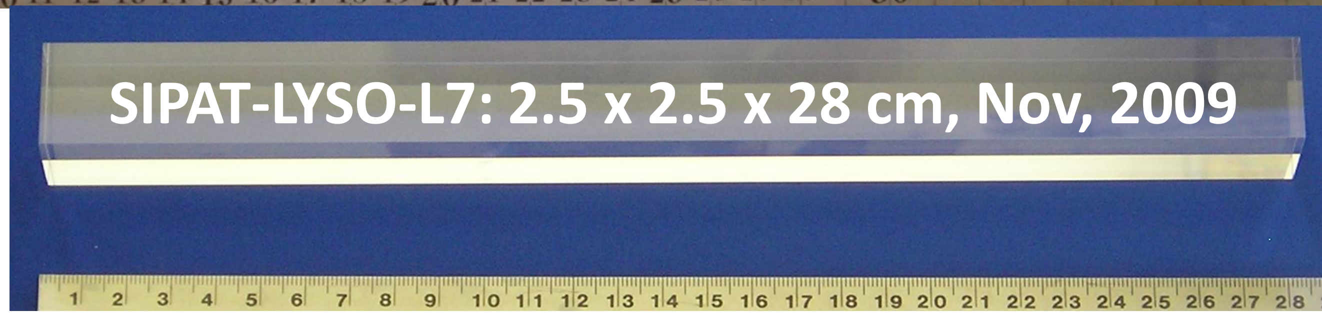


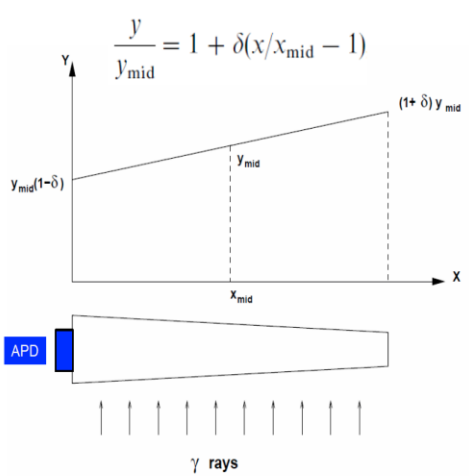
10% - 15% loss by PMT & APD

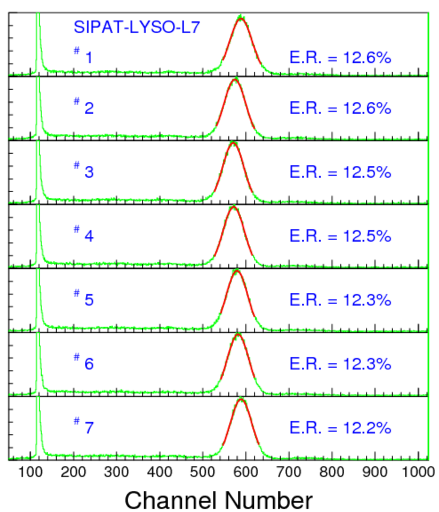


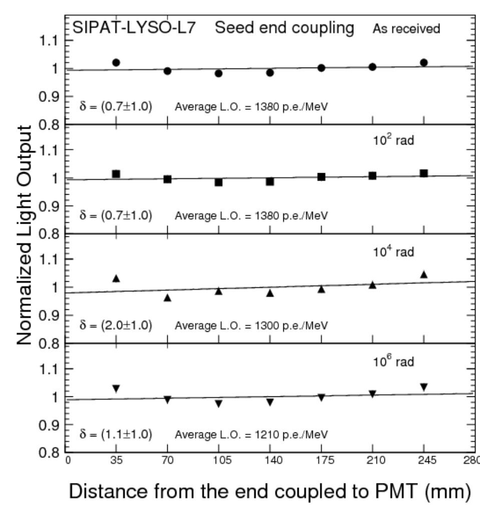
Excellent Radiation Hardness

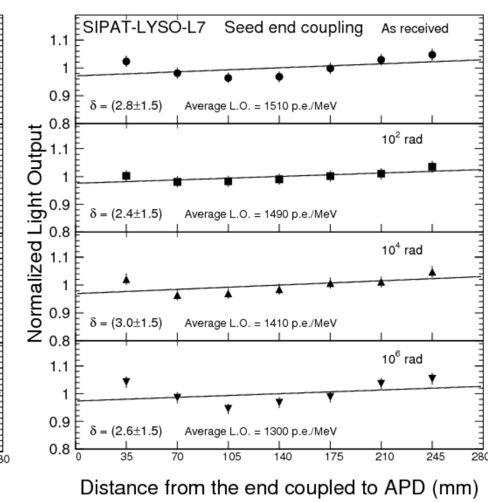












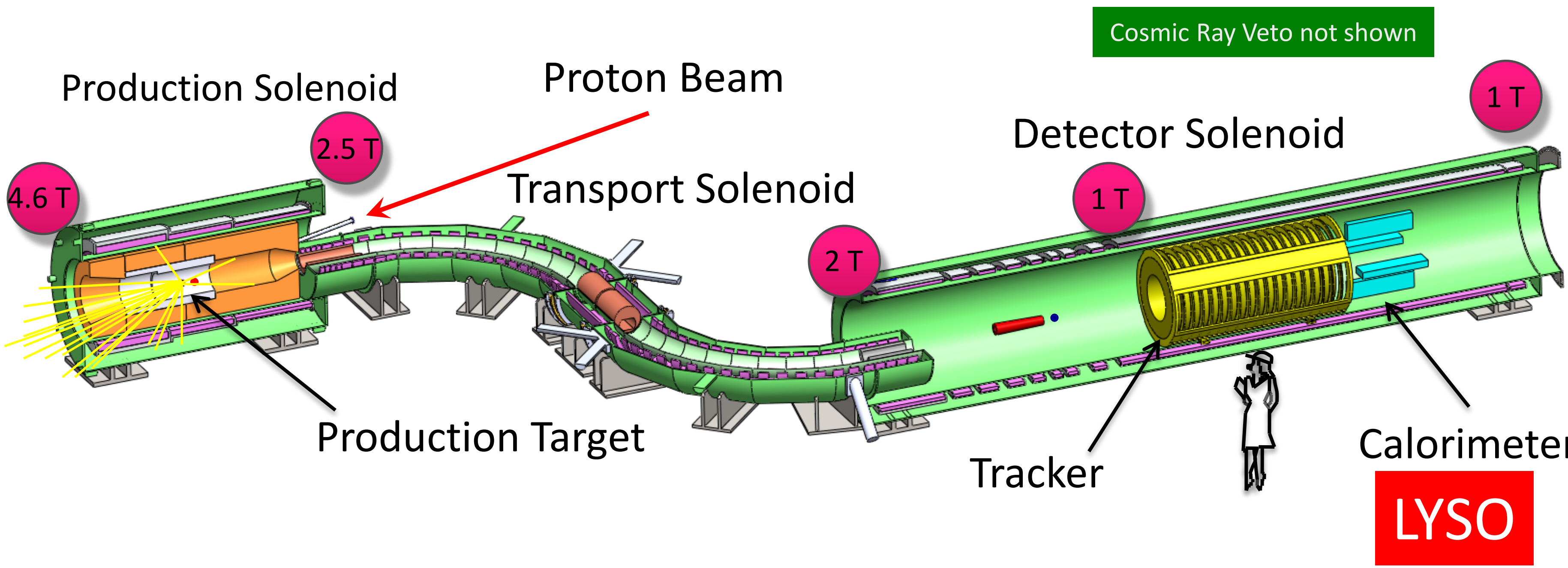
Mu2e Experiment at Fermilab

Production Solenoid
- Production target
- Graded field

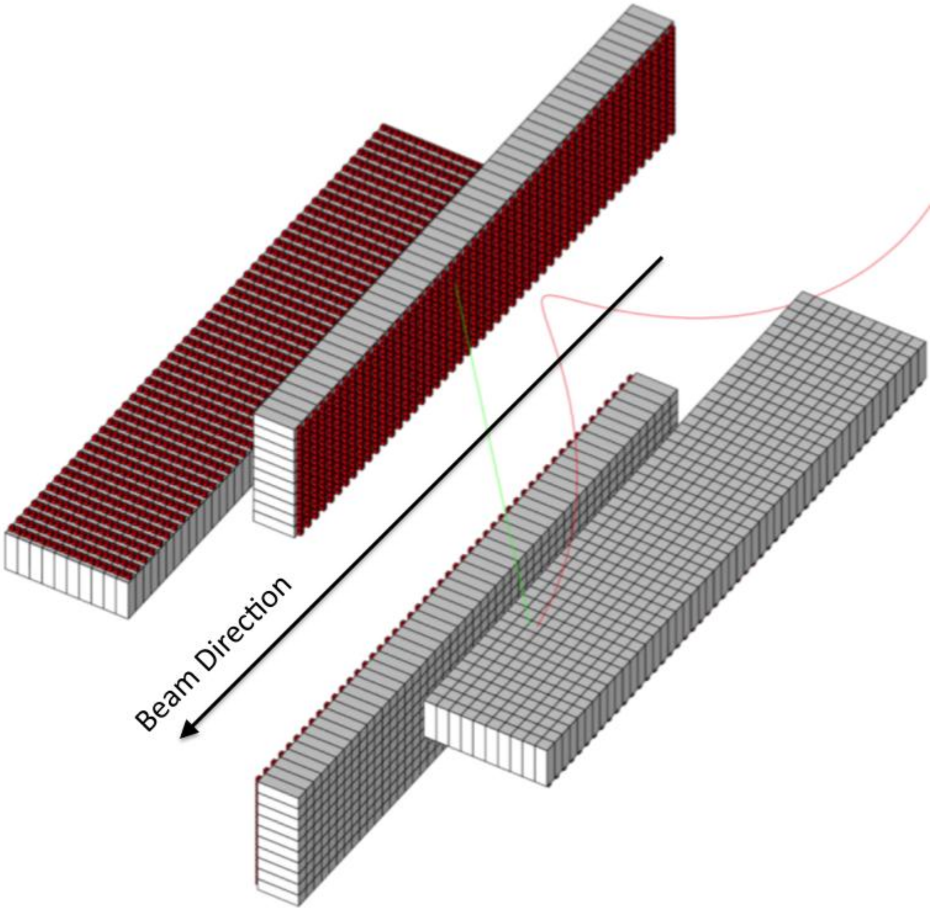
- Delivers ~ 0.0015 stopped μ^- per incident proton
- 5×10^{10} Hz of stopped muons

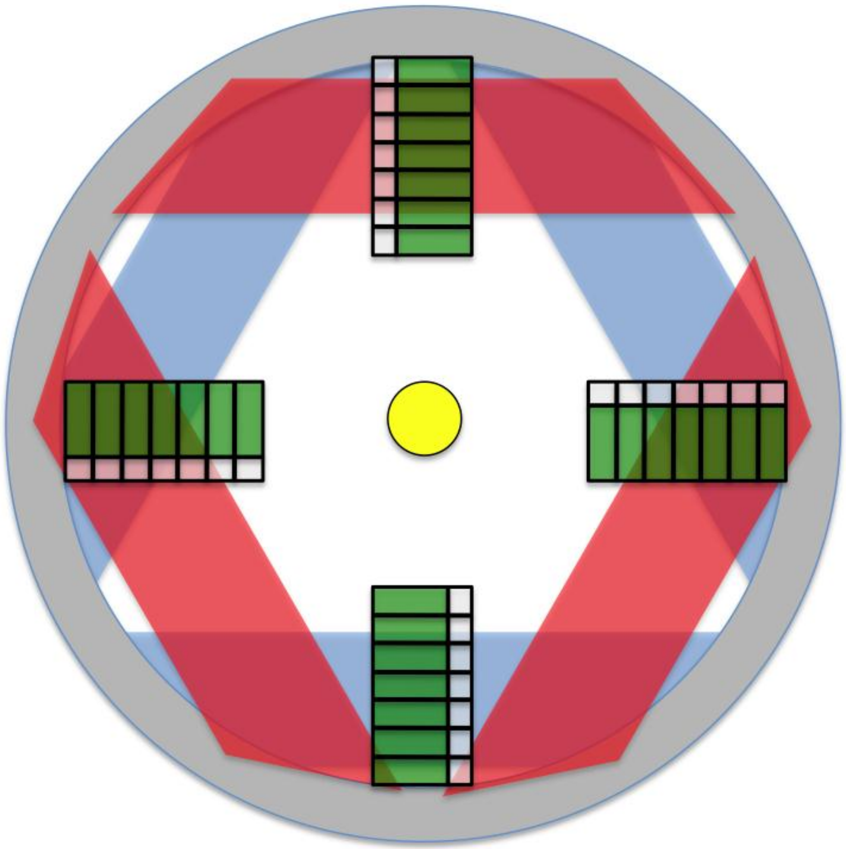
Detector Solenoid
- Muon stopping target
- Tracker
- Calorimeter
- Warm bore evacuated to 10^{-4} Torr

Transport Solenoid
- Collimation system selects muon charge and momentum range
- Pbar window in middle of central collimator



Mu2e LYSO Crystal Calorimeter

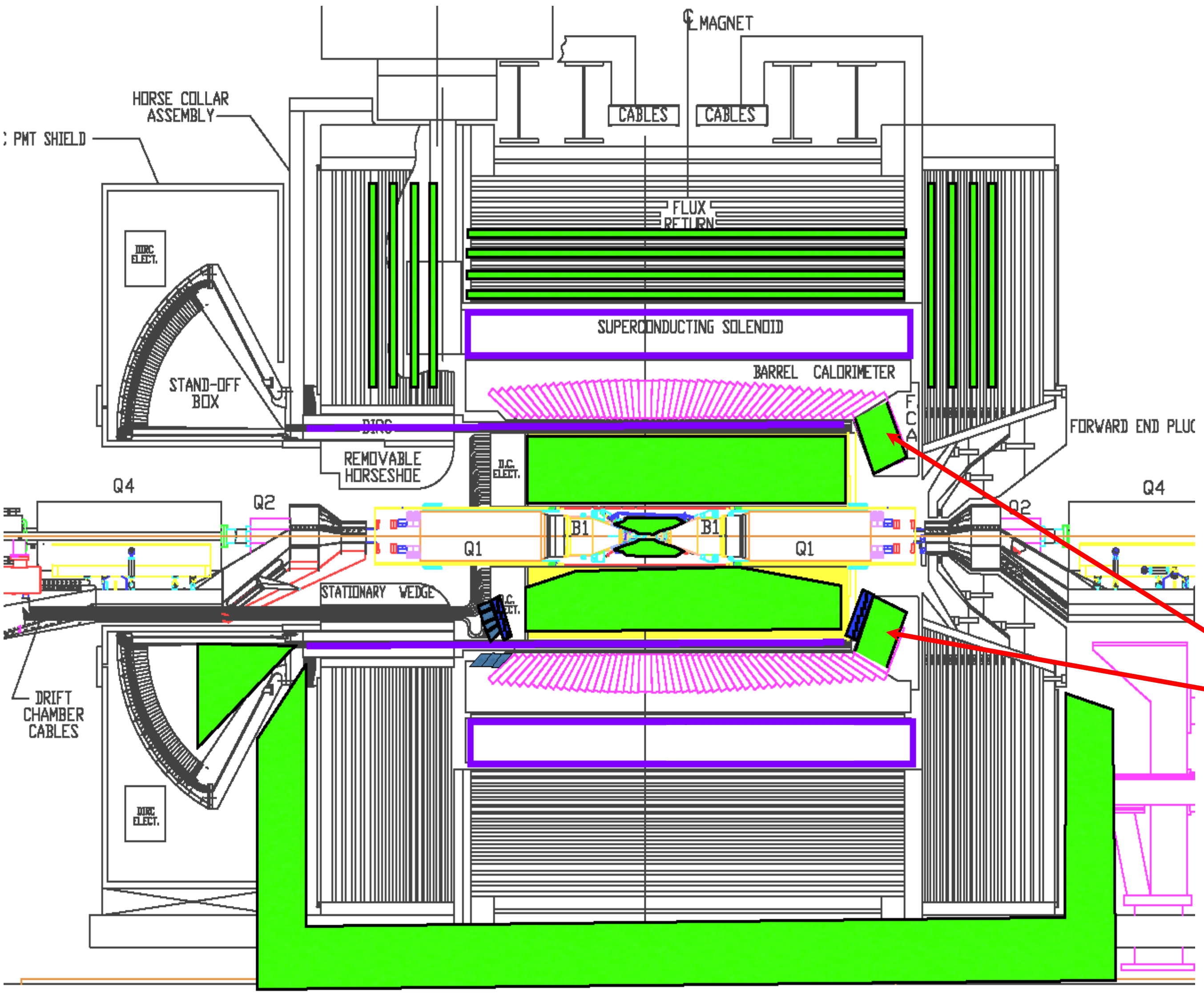




1952 LYSO crystals 3 × 3× 11 cm^3 arranged in four vanes with a total crystal volume 0.2 m^3

Crystal Forward Calorimeter 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

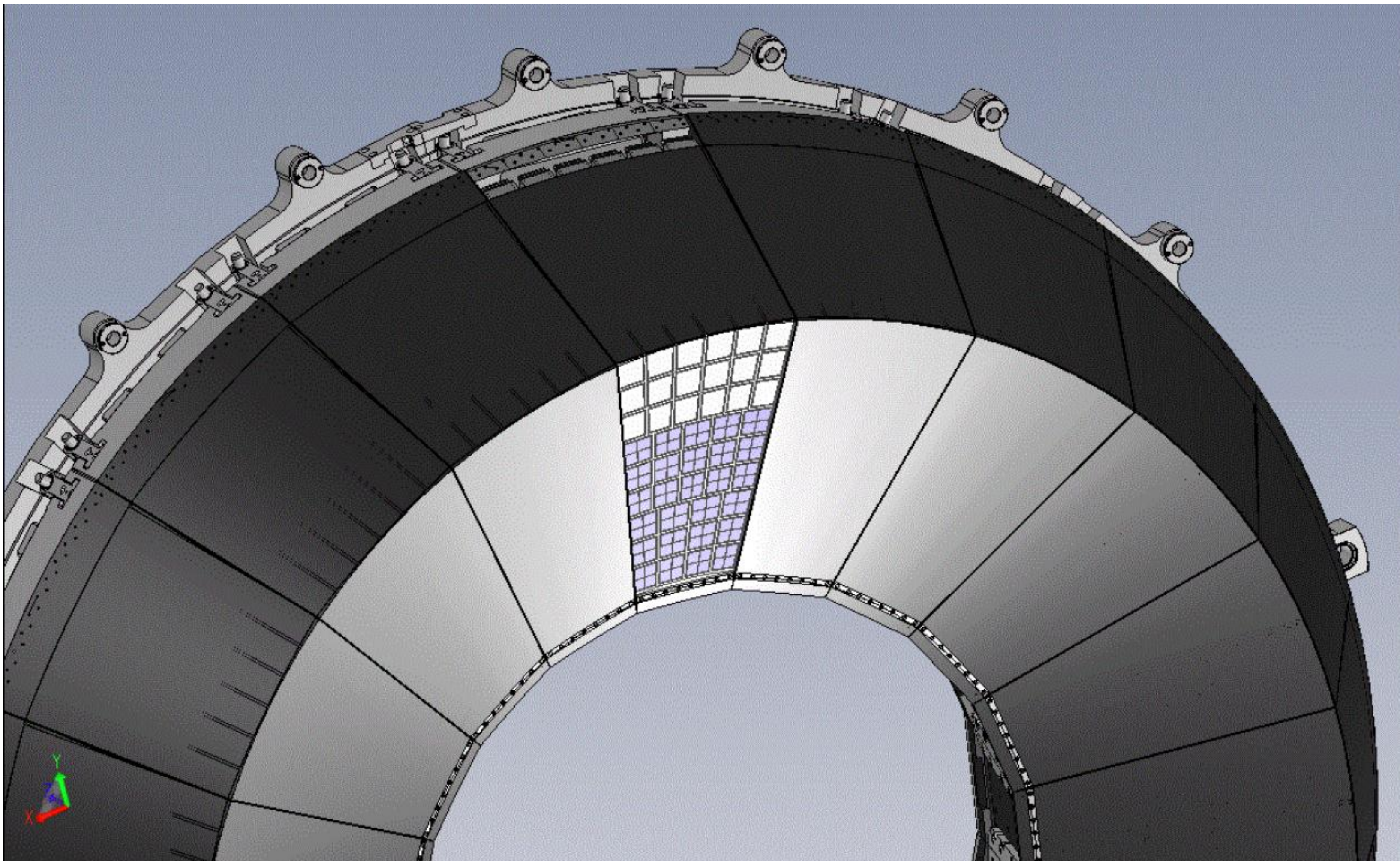
Need a fast detector with low noise at the endcap

LSO/LYSO

Need cost effective crystals

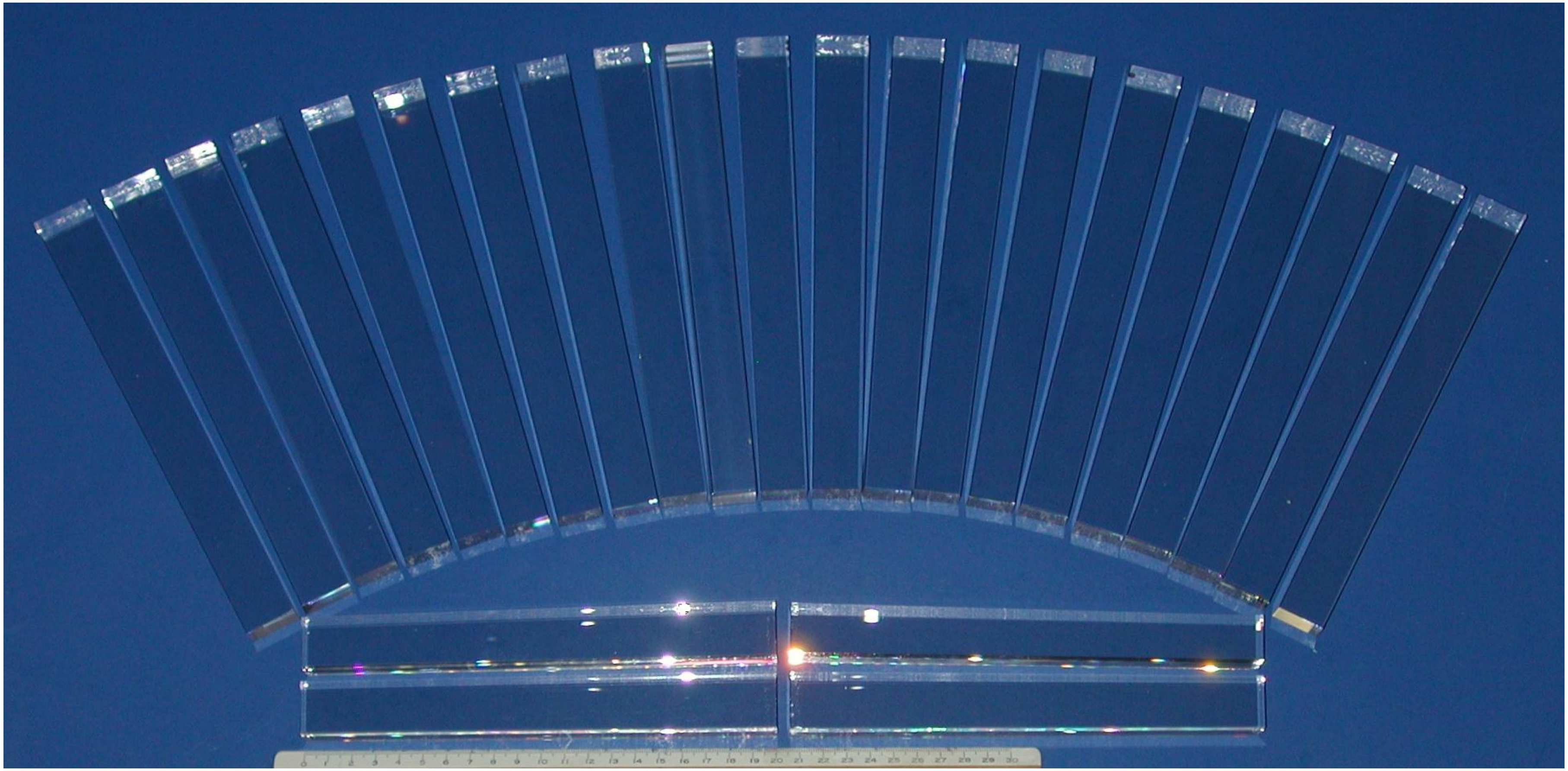
Super*B* Forward Calorimeter

BaBar endcap structure with CsI(Tl) and LYSO crystals

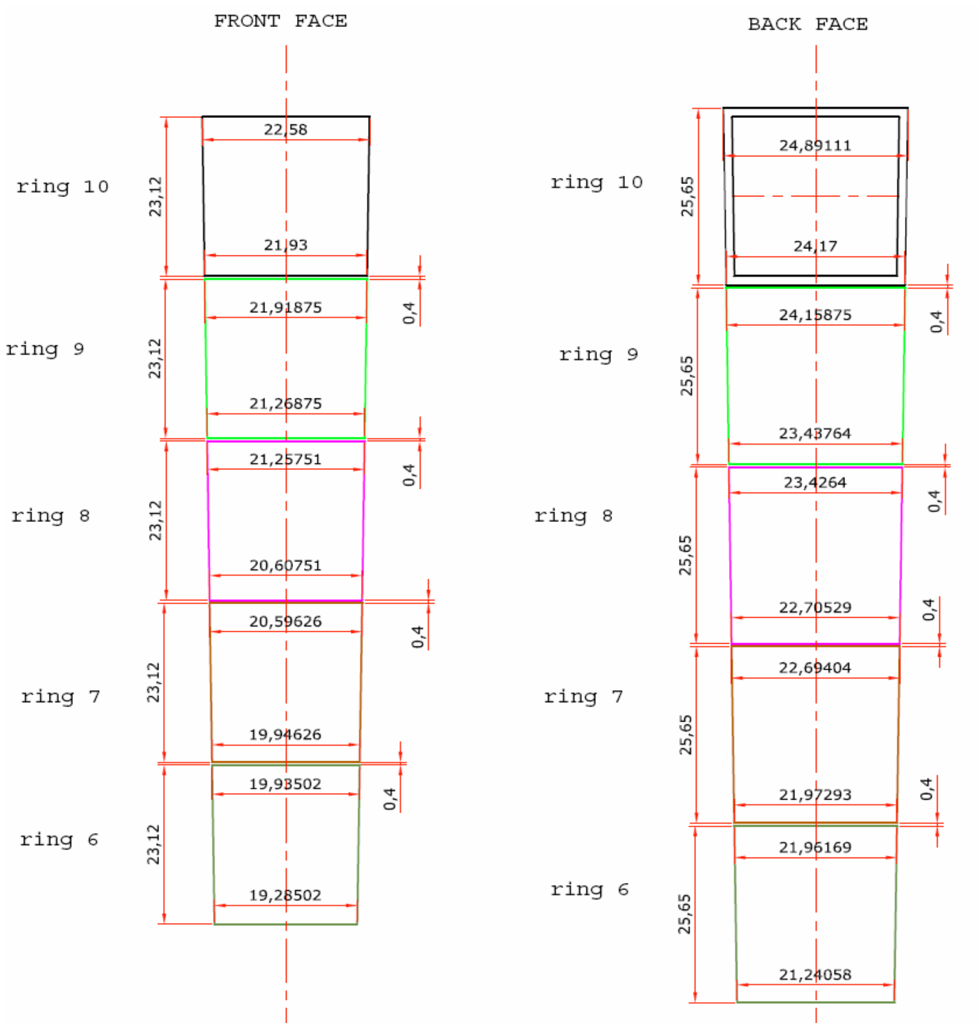


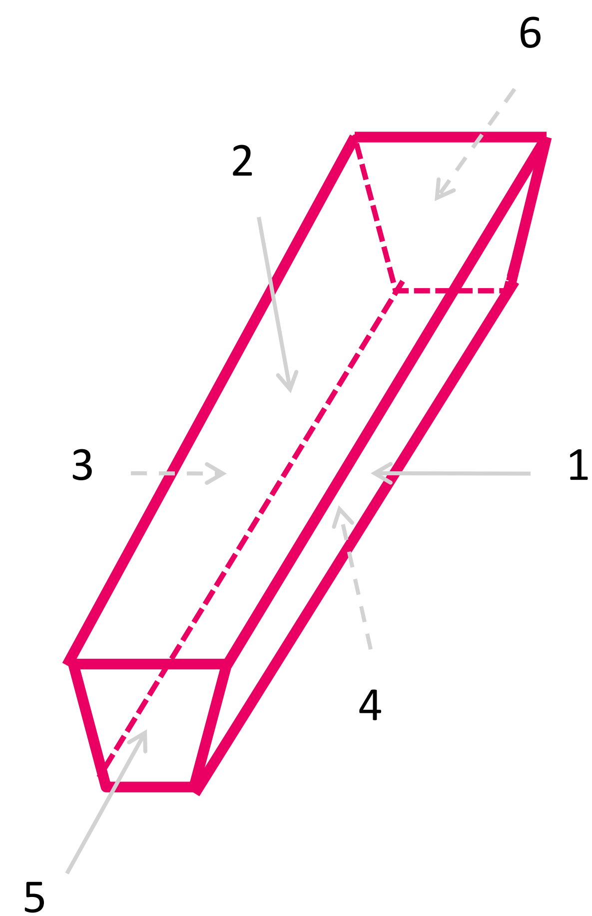
Twenty Five Super*B* Crystals

All crystals are characterized in Caltech Crystal Laboratory
See report of S. Germani on June 8 for test beam result



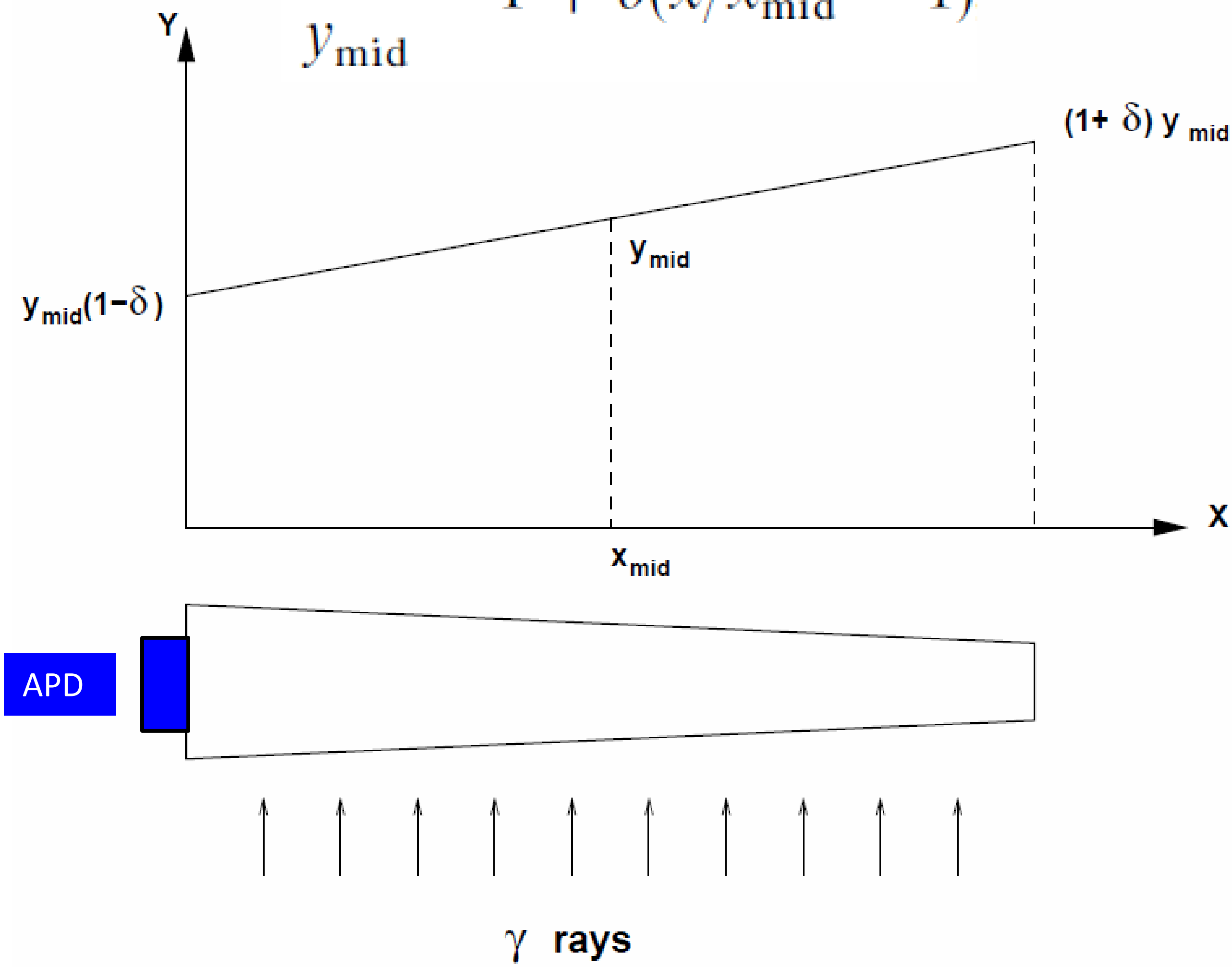
Dimensions and Surface Definition





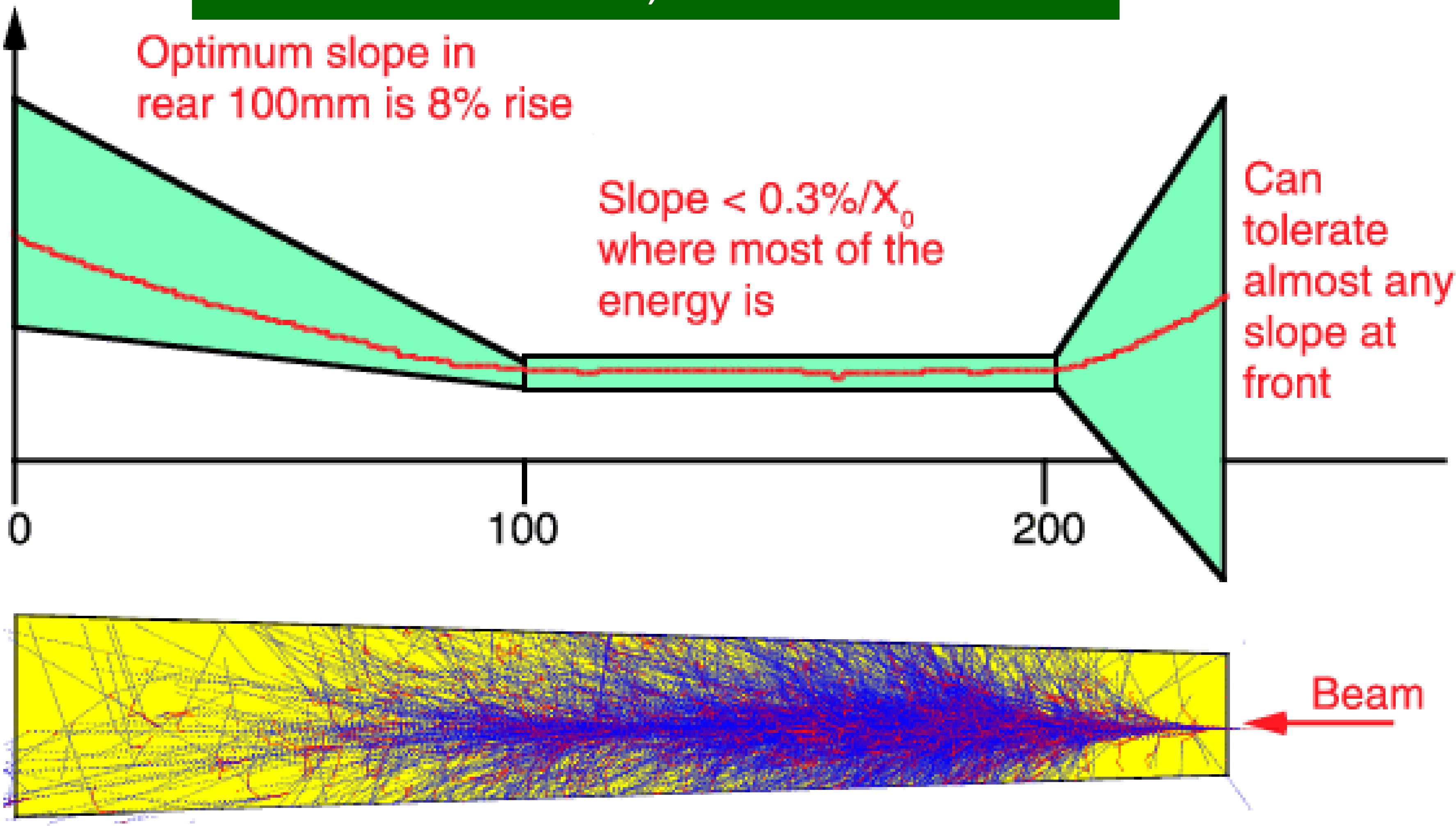
Light Response Non-Uniformity: δ

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



CMS Specification for Uniformity

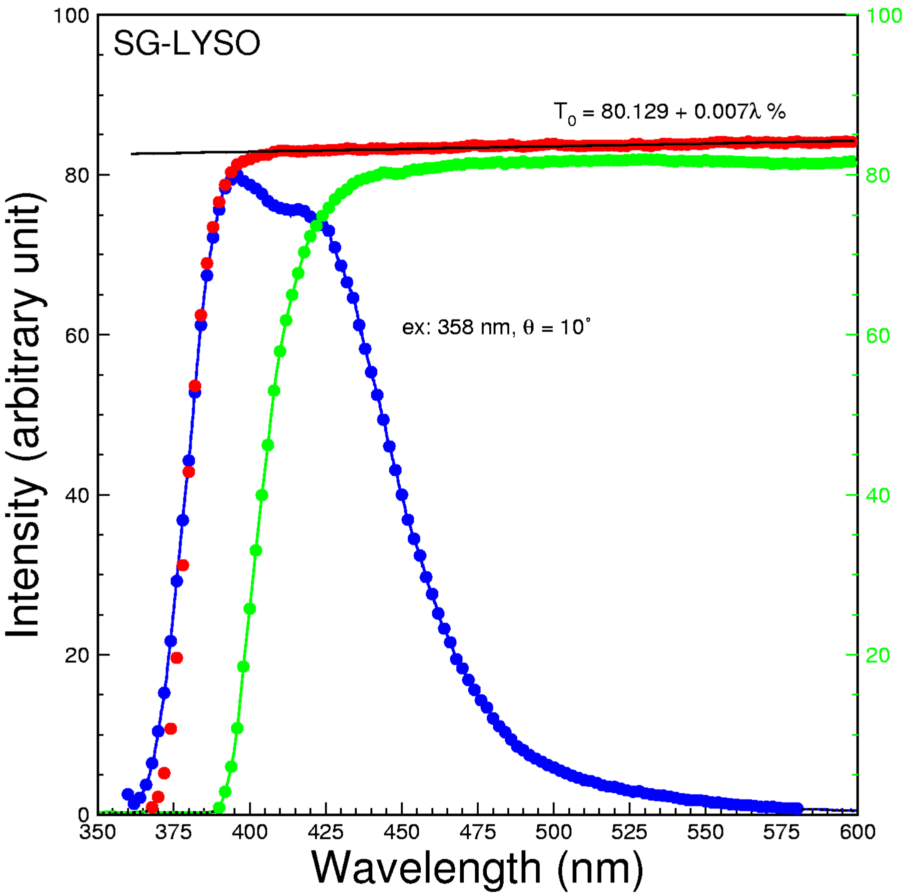
D. Graham & C. Seez, CMS Note 1996-002

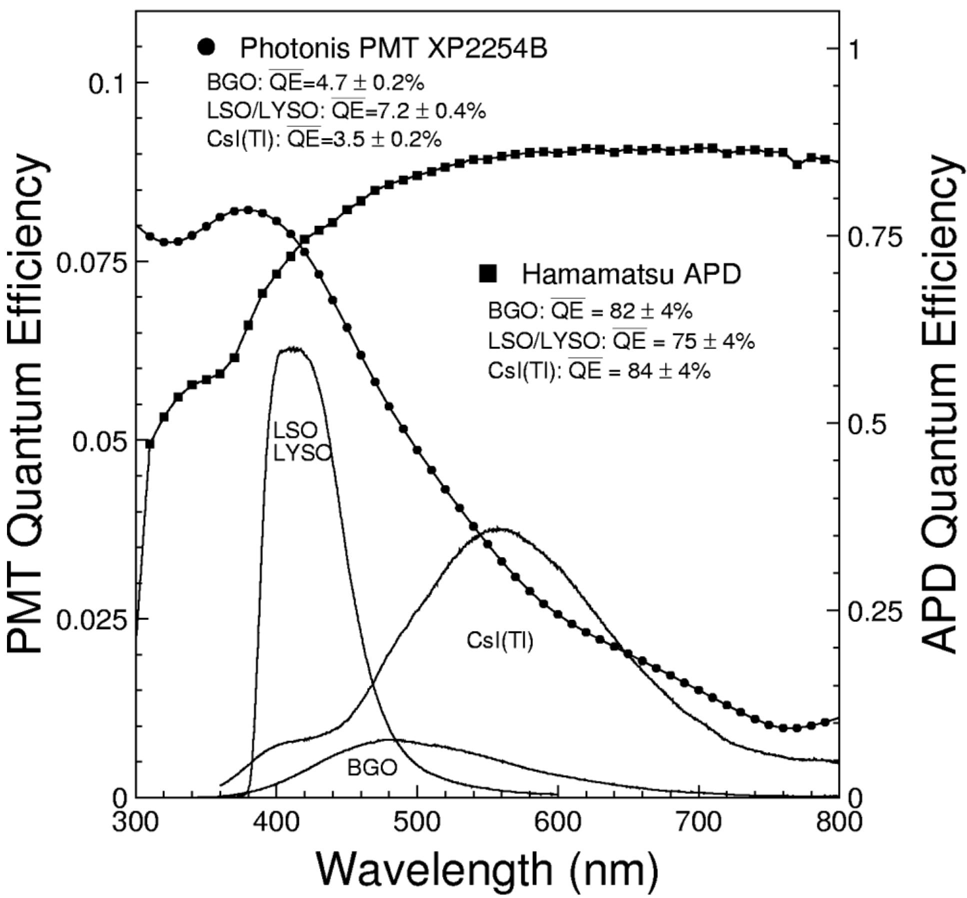


|δ| < 3% & 4% for 18 X_0 (SuperB) & 25X_0 (CMS)

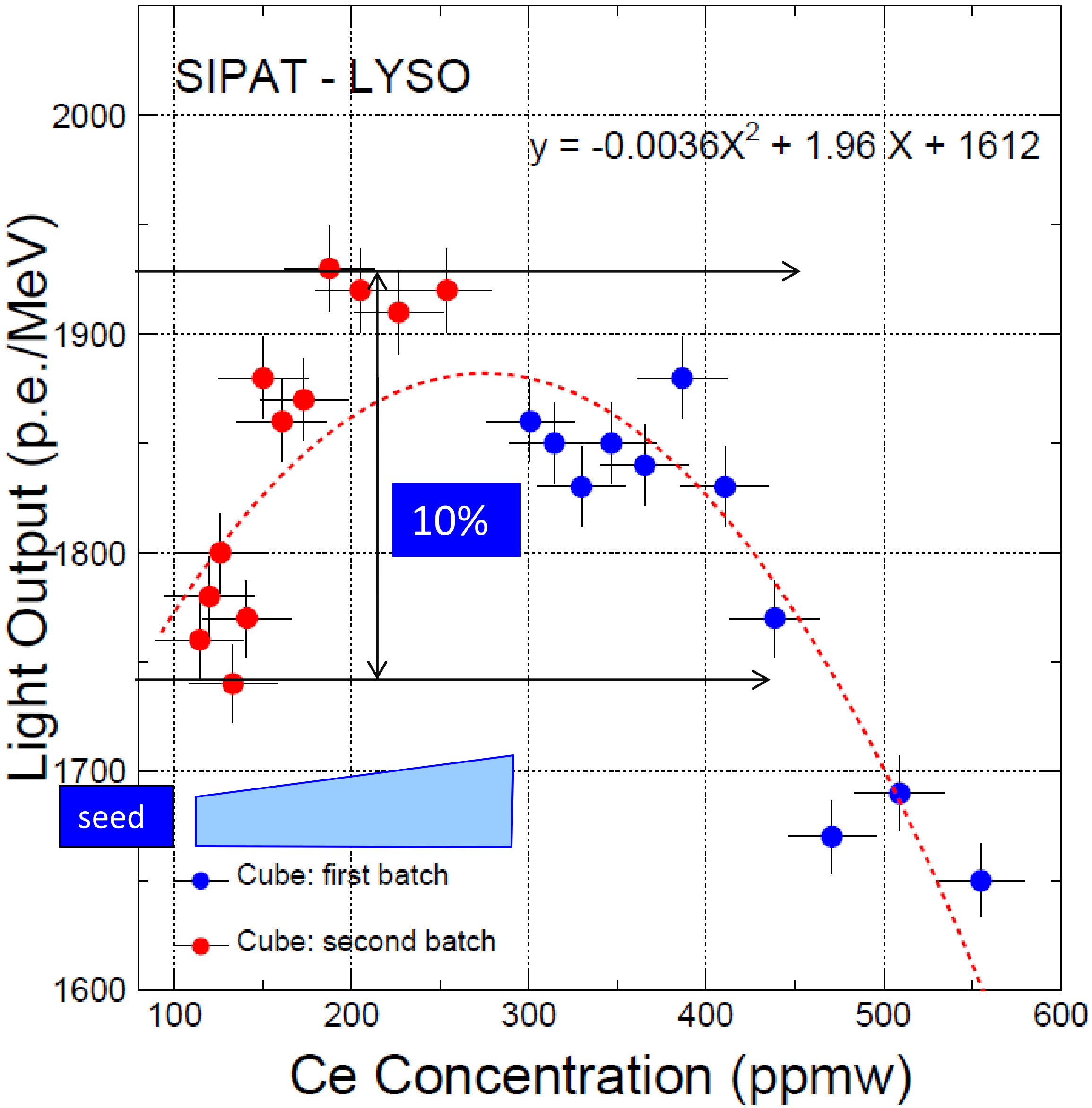
Effect of Self-absorption

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





Effect of Cerium Segregation

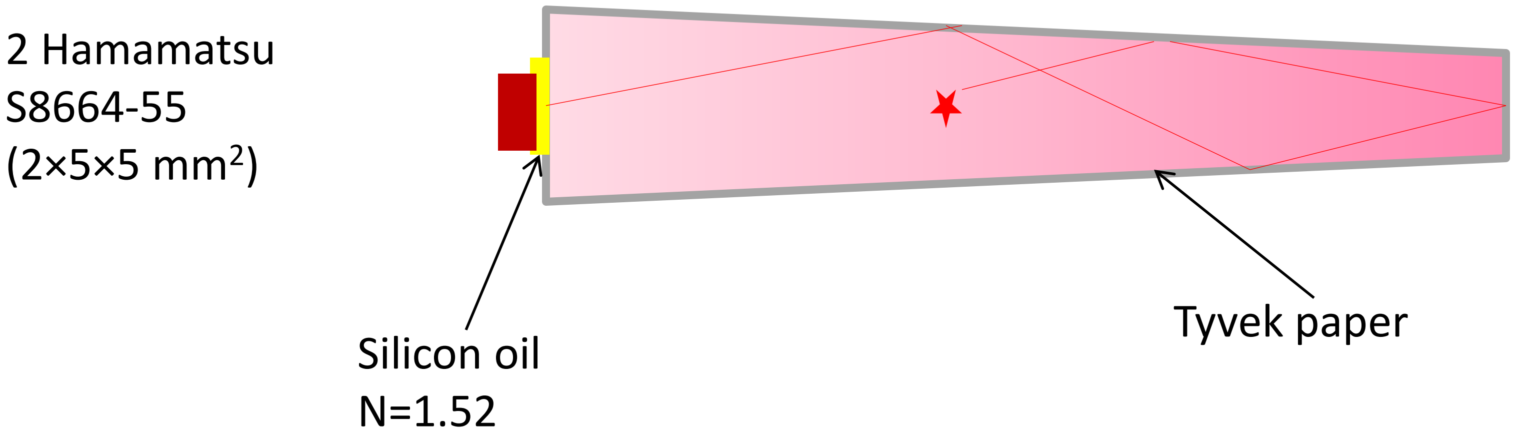


It is also known that cerium concentration along long LYSO crystals is not uniform, causing non-uniformity up to 10% at two ends, indicating up to 5% variation in δ is possible because of cerium segregation.

Ray-Tracing Simulation "set-up"

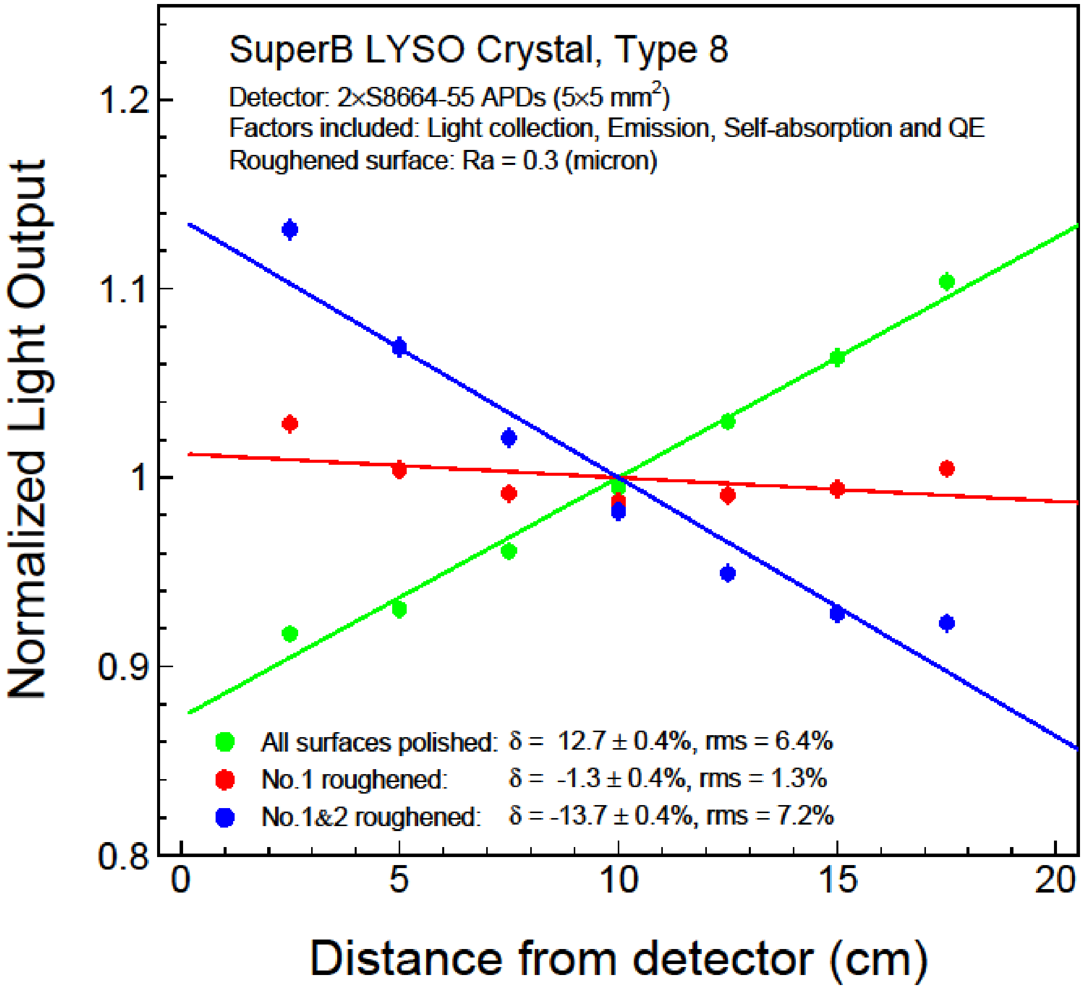
The simulation package was developed in early eighties, and was used for the L3 BGO and CMS PWO crystals.

SuperB LYSO crystals



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

Polished and Roughened Surfaces

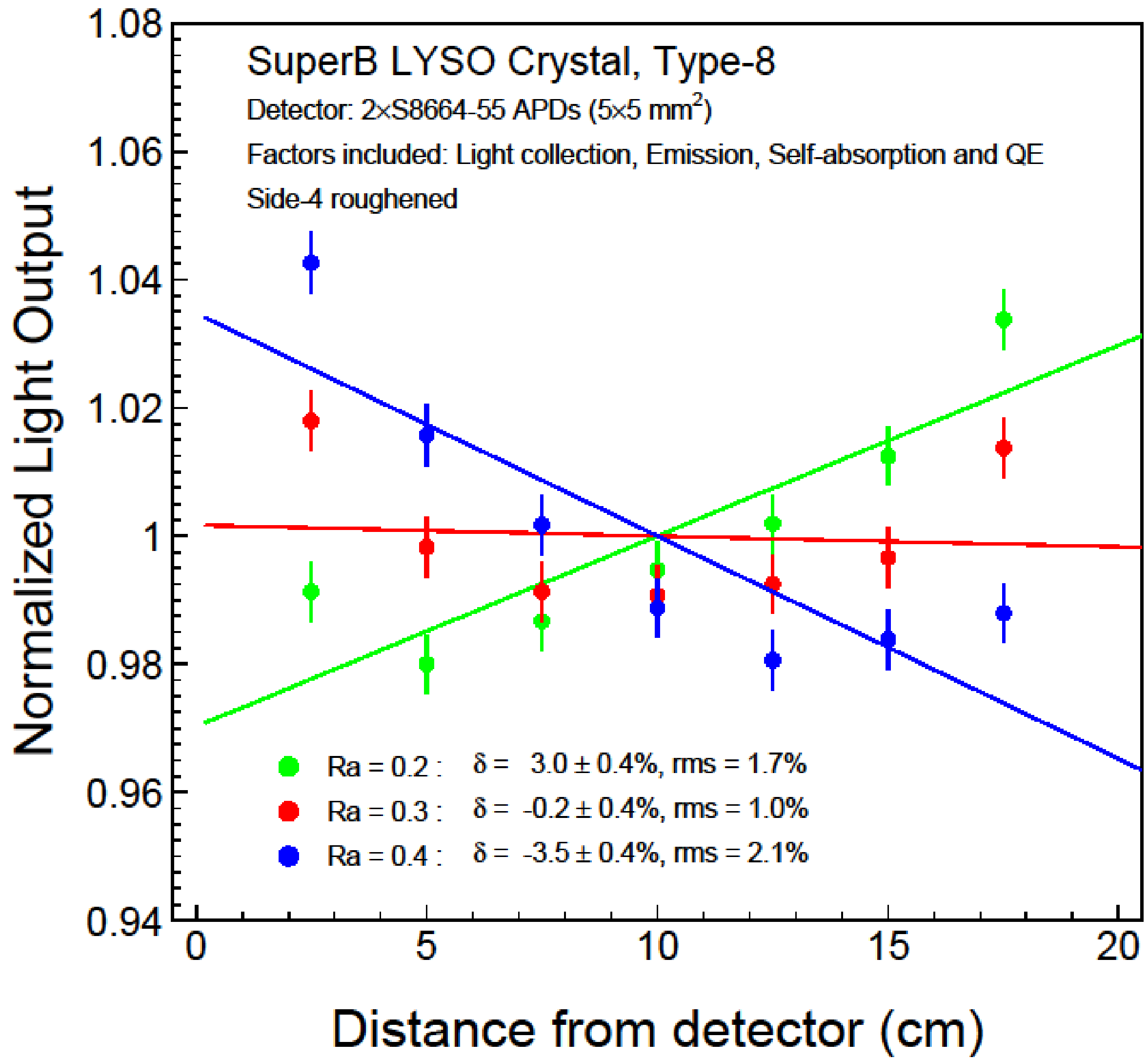


- The optical focusing, effect dominates non-uniformity: δ is about 13% for all polished surfaces.
- Roughened surface(s) can compensate the optical focusing effect.
- The best result is achieved by roughening only one side surface.

How Rough it Should Be?

The R_a matters.

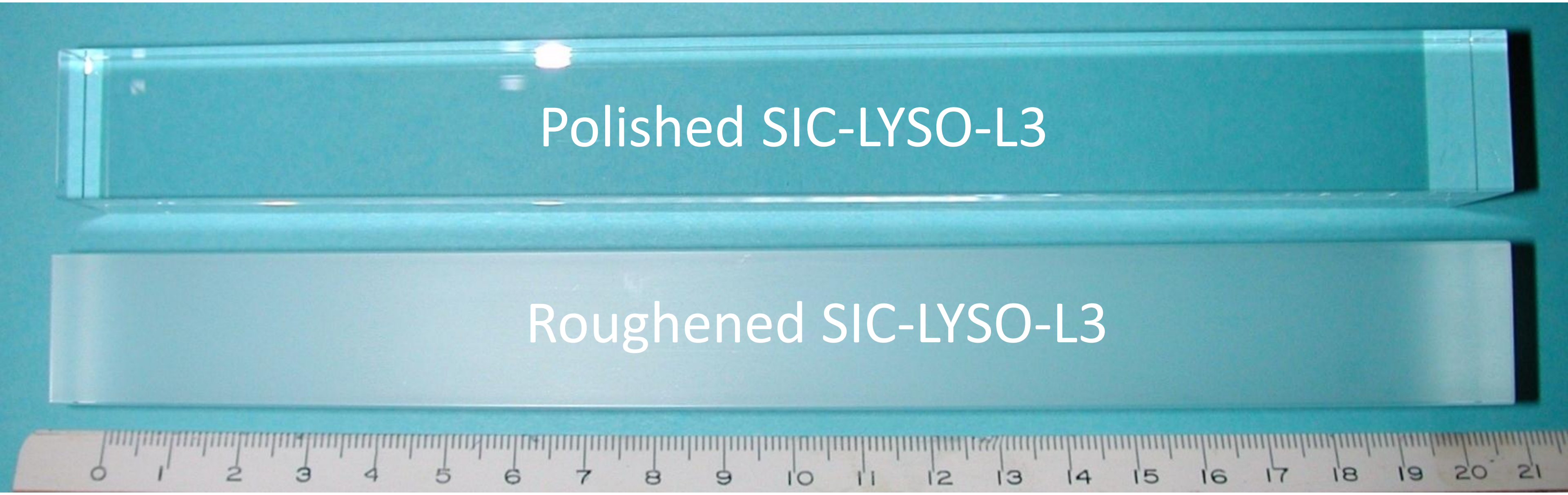
A variation of 0.1 in R_a causes a 3% variation in δ.



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

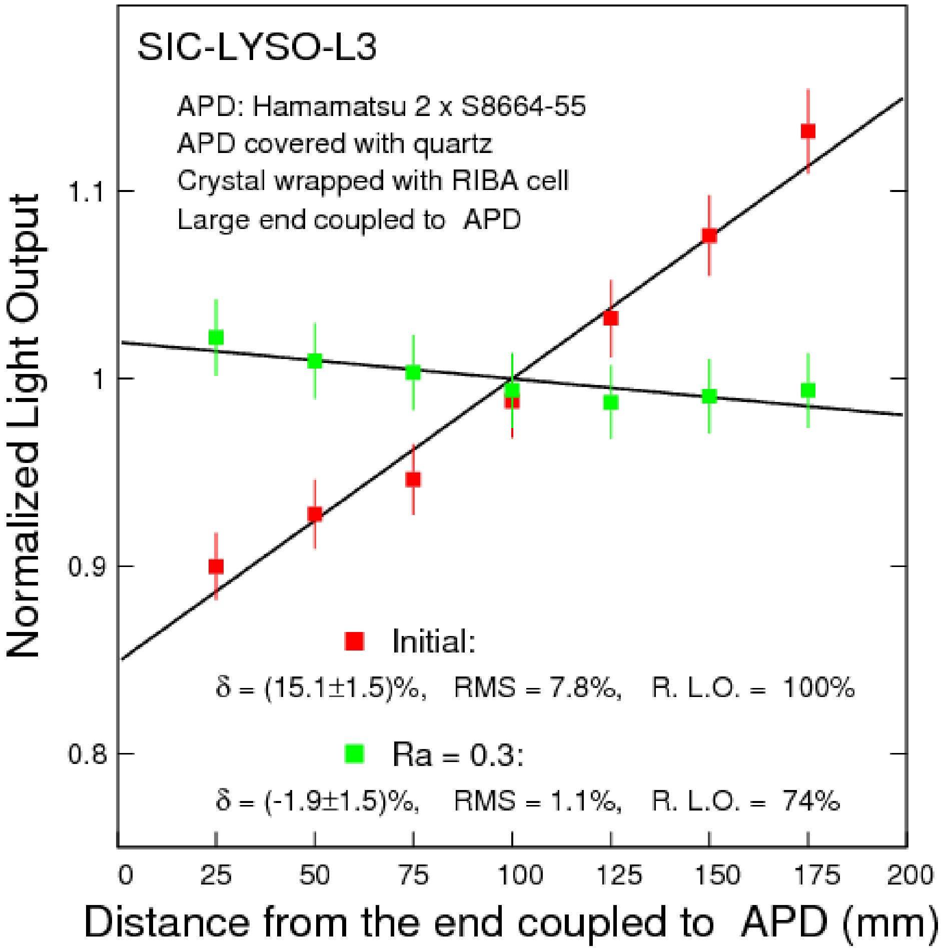
Thanks to SICCAS for roughening this crystal

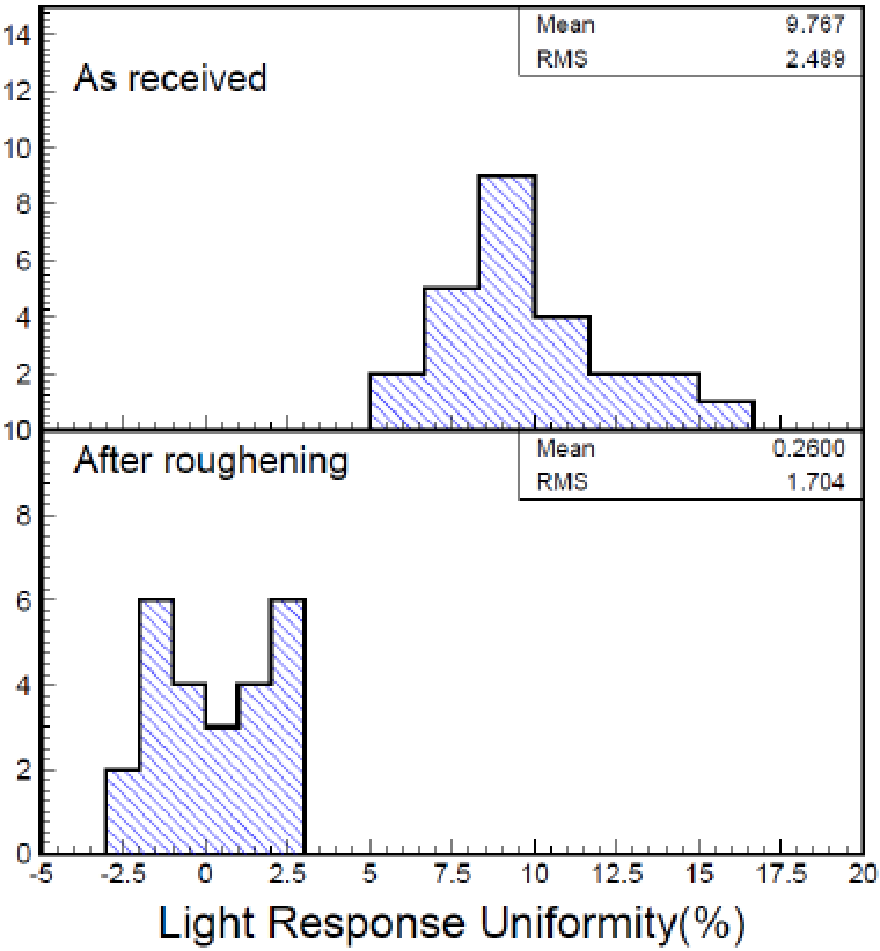


1st: lapped to Ra = 0.5 by using 11 µm Al_2O_3 powder for 10 min with 2.5 kg weight
2nd: lapped to Ra = 0.3 by using 6.5 µm SiC powder for 3 min with 1.5 kg weight

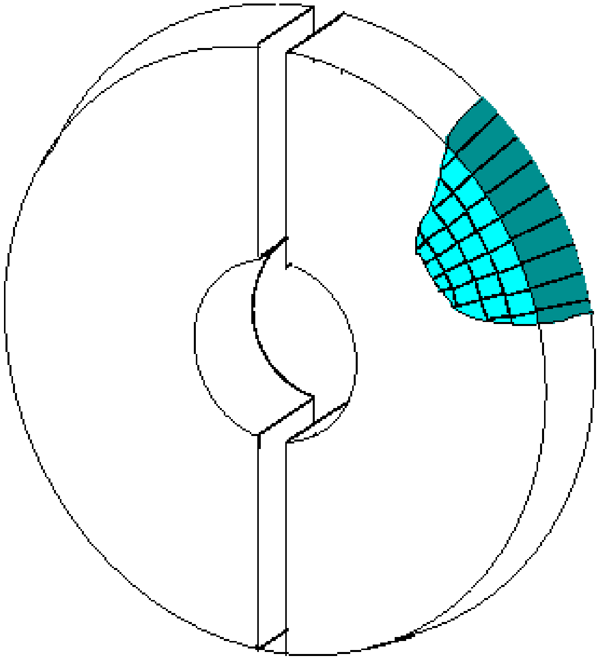
Relative Light Output & Uniformity

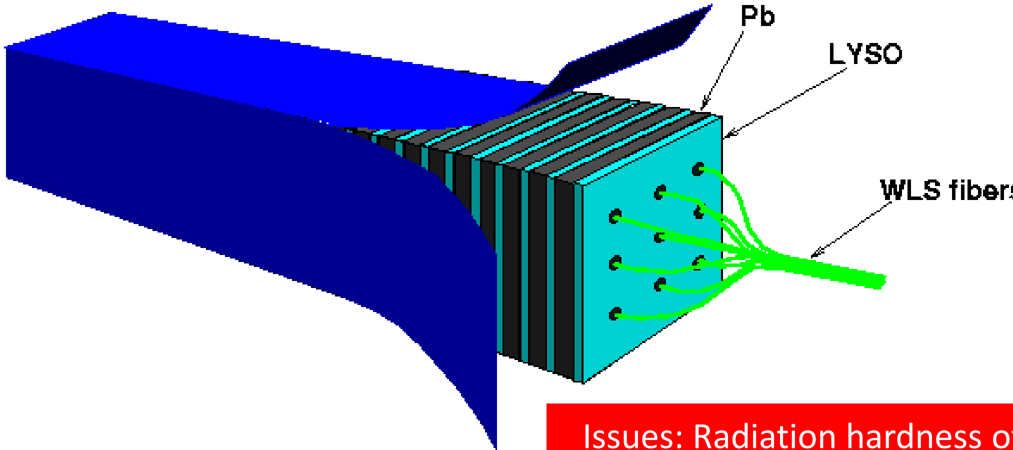
Ra = 0.3 uniformizes SIC-L3 to < 2%
All 25 crystals are uniformized to |δ| < 3%





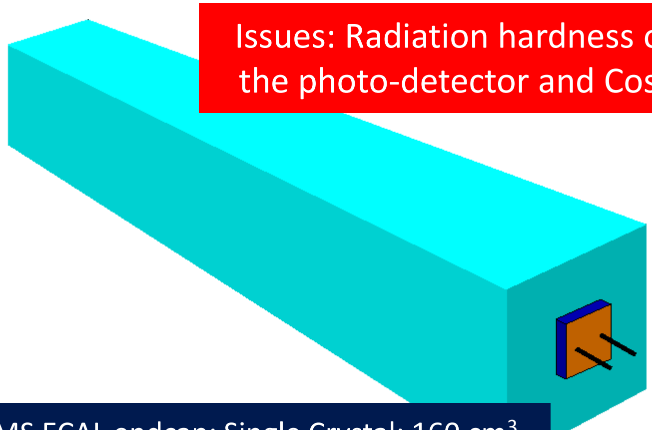
CMS Forward Calorimeter Upgrade

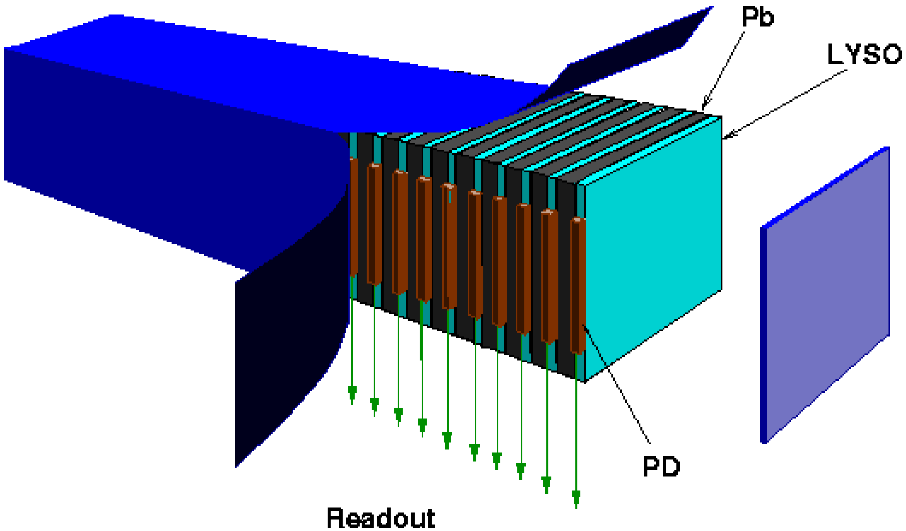




Issues: Radiation hardness of photo-detector and WLS fiber

Issues: Radiation hardness of the photo-detector and Cost





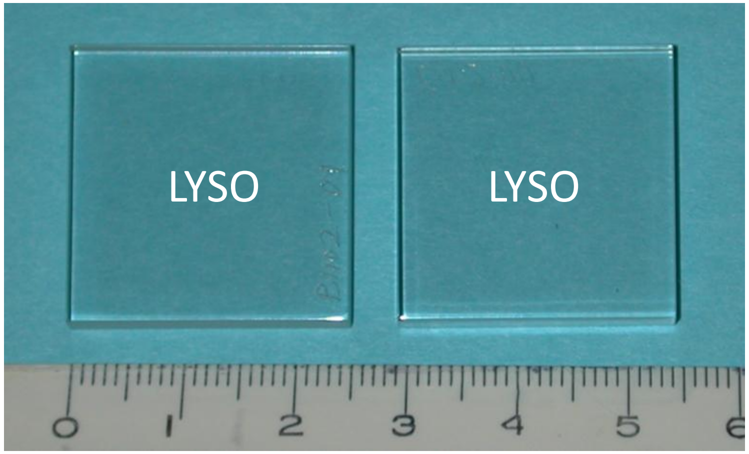
CMS ECAL endcap: Single Crystal: 160 cm^3
Total number: 16,000 Total Volume: 2.5 m^3
Expected Crystal Cost: ~$60M@$25/cc

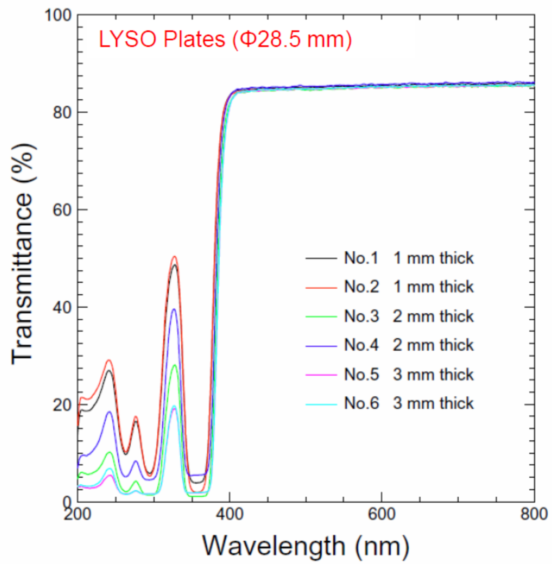
Crystal Cost: <$10M

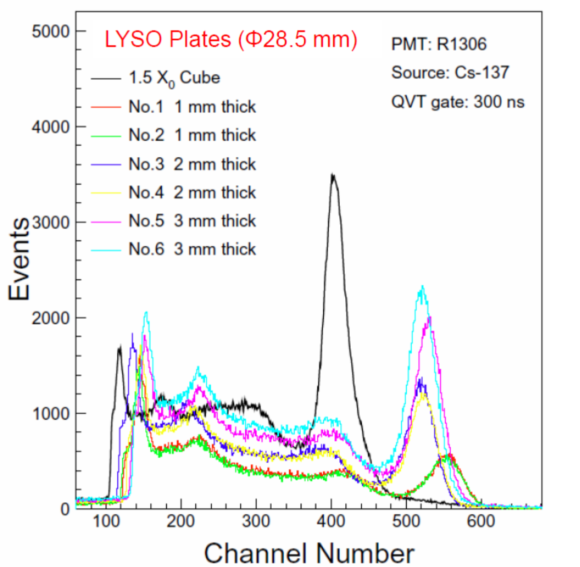
Issue: Radiation hardness of the photo-detector

Performance of Scintillator Plates

Crystals

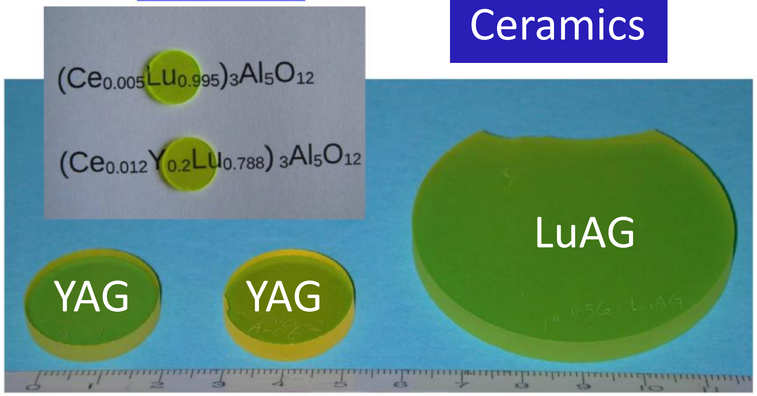






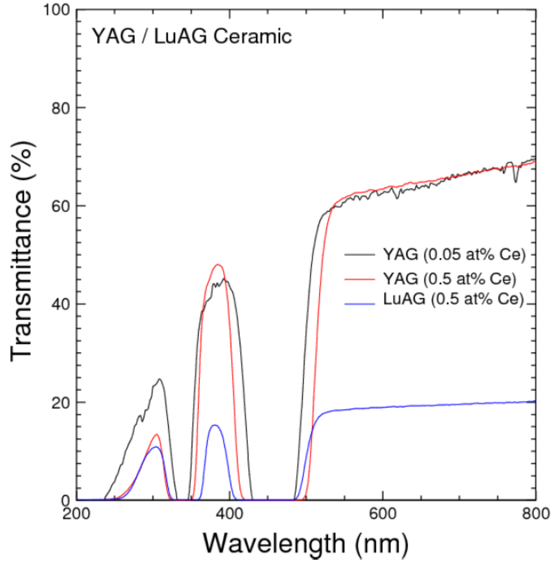
Φ20 X 3 mm

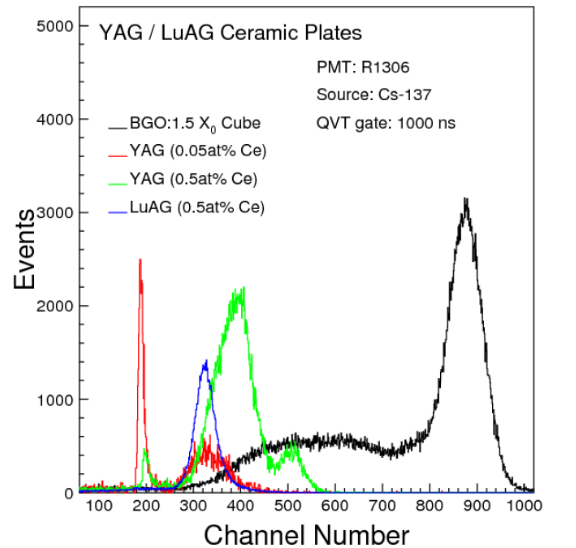
Ceramics



YAG: Φ22 x 4 mm

LuAG Φ56 x 5 mm



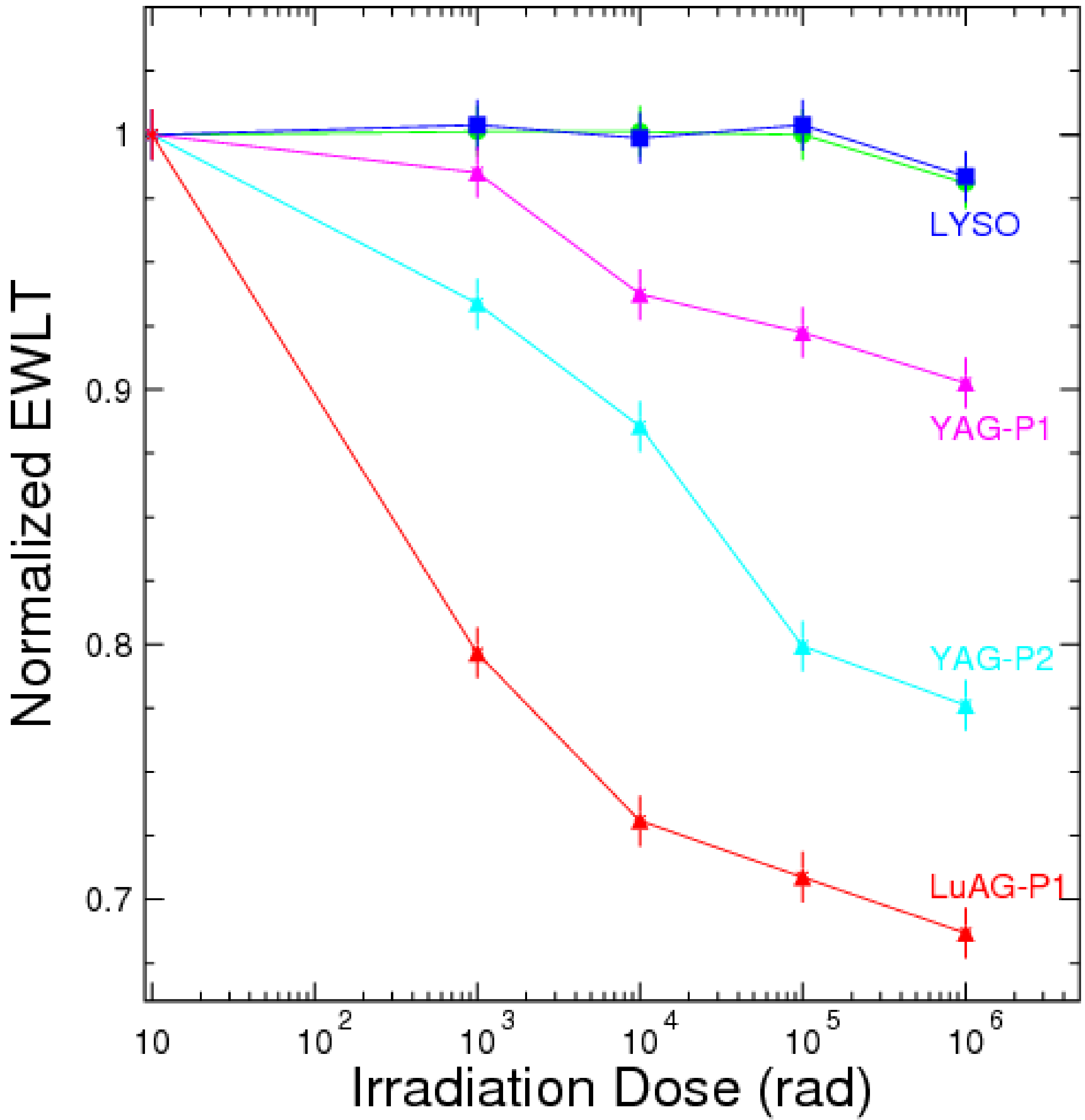


Normalized EWLT: LYSO & Ceramic

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 light response uniformity of Super*B* crystals is affected by (1) the optical focusing effect, (2) the self-absorption and (3) the non-uniformity of the cerium concentration. All 25 crystals are uniformized to $|\delta|<3\%$ by roughening the smallest side surface.

- For applications in a severe radiation environment, such as the CMS forward calorimeter at the HL-LHC, R&D works concentrate 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.