# Crystal Calorimetry for Lepton Factories


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# Why Crystal Calorimeter in HEP?

- **Photons and electrons are fundamental particles. Precision e/γ measurements enhance physics discovery potential.**
- **Performance of homogeneous crystal calorimeter in e/γ measurements is well understood:**
  - **The best possible energy resolution;**
  - **Good position resolution;**
  - **Good e/ γ identification and reconstruction efficiency.**
- **Challenges at future lepton colliders: bright, fast crystal scintillators with better radiation hardness than CsI(Tl).**
- **Crystals are being considered for sampling calorimeters as well as homogeneous hadron calorimeter with dual readout for good jet mass resolution.**

# Crystal Calorimeters in HEP

| Date | 75-85 | 80-00 | 80-00 | 80-00 | 90-10 | 94-10 | 94-10 | 95-20 |
|---|---|---|---|---|---|---|---|---|
| Experiment | C. Ball | L3 | CLEO II | C. Barrel | KTeV | *BaBar* | BELLE | CMS |
| Accelerator | SPEAR | LEP | CESR | LEAR | FNAL | SLAC | KEK | CERN |
| Crystal Type | NaI(Tl) | BGO | CsI(Tl) | CsI(Tl) | CsI | CsI(Tl) | CsI(Tl) | $PbWO_4$ |
| B-Field (T) | - | 0.5 | 1.5 | 1.5 | - | 1.5 | 1.0 | 4.0 |
| $r_{inner}$ (m) | 0.254 | 0.55 | 1.0 | 0.27 | - | 1.0 | 1.25 | 1.29 |
| Number of Crystals | 672 | 11,400 | 7,800 | 1,400 | 3,300 | 6,580 | 8,800 | 76,000 |
| Crystal Depth ($X_0$) | 16 | 22 | 16 | 16 | 27 | 16 to 17.5 | 16.2 | 25 |
| Crystal Volume ($m^3$) | 1 | 1.5 | 7 | 1 | 2 | 5.9 | 9.5 | 11 |
| Light Output (p.e./MeV) | 350 | 1,400 | 5,000 | 2,000 | 40 | 5,000 | 5,000 | 2 |
| Photosensor | PMT | Si PD | Si PD | WS[a]+Si PD | PMT | Si PD | Si PD | APD[a] |
| Gain of Photosensor | Large | 1 | 1 | 1 | 4,000 | 1 | 1 | 50 |
| $\sigma_N$/Channel (MeV) | 0.05 | 0.8 | 0.5 | 0.2 | small | 0.15 | 0.2 | 40 |
| Dynamic Range | $10^4$ | $10^5$ | $10^4$ | $10^4$ | $10^4$ | $10^4$ | $10^4$ | $10^5$ |

**Future crystal calorimeters in HEP:**

PWO for PANDA at GSI

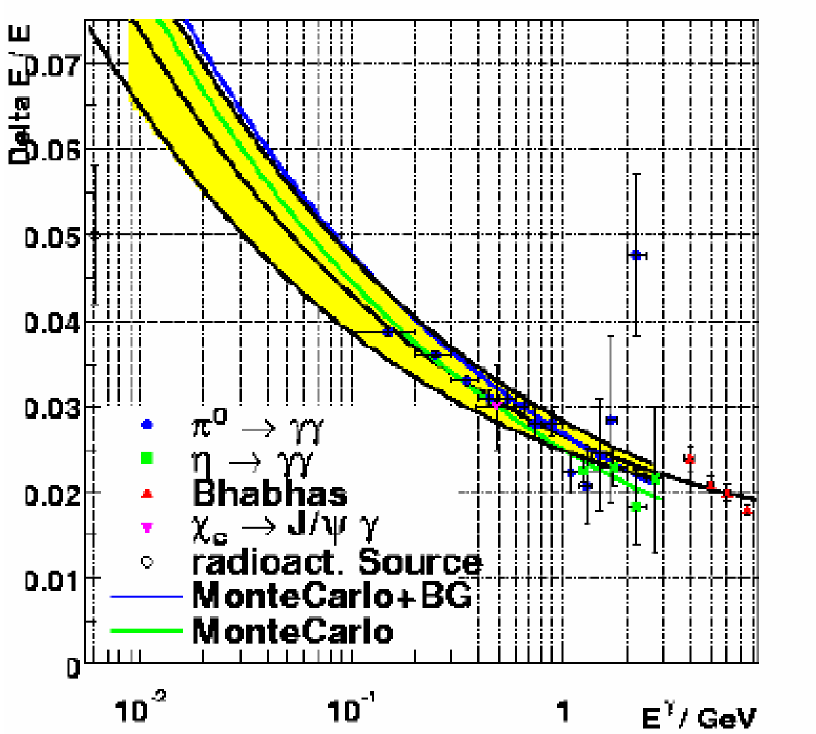
LSO/LYSO for Mu2e, Super B and HL-LHC, also a Shashlic

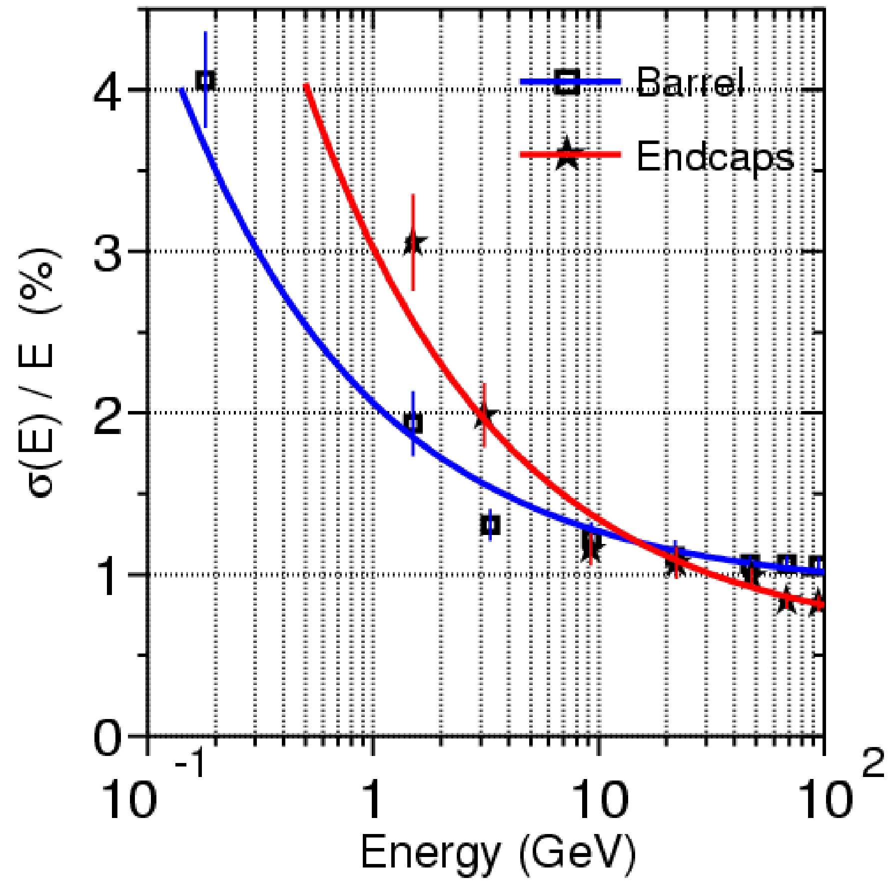
$PbF_2$, PbFCl, BSO for Homogeneous HCAL

# Crystal Calorimeter Resolution

**BaBar: 6.6k CsI(Tl)**

**L3: 12k BGO**




$$\frac{\sigma_E}{E} = \frac{\sigma_1}{\sqrt[4]{E}} \oplus \sigma_2$$

$$\sigma_1 = (2.30 \pm 0.03 \pm 0.3)\%$$

$$\sigma_2 = (1.35 \pm 0.08 \pm 0.2)\%$$

2%/√E + 0.5%

# Why LSO/LYSO?

LSO/LYSO is a bright (200 times of PWO), fast (40 ns) and radiation hard crystal scintillator. The light output loss of 28 cm long crystal is at a level of 10% after 1 Mrad $\gamma$–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.

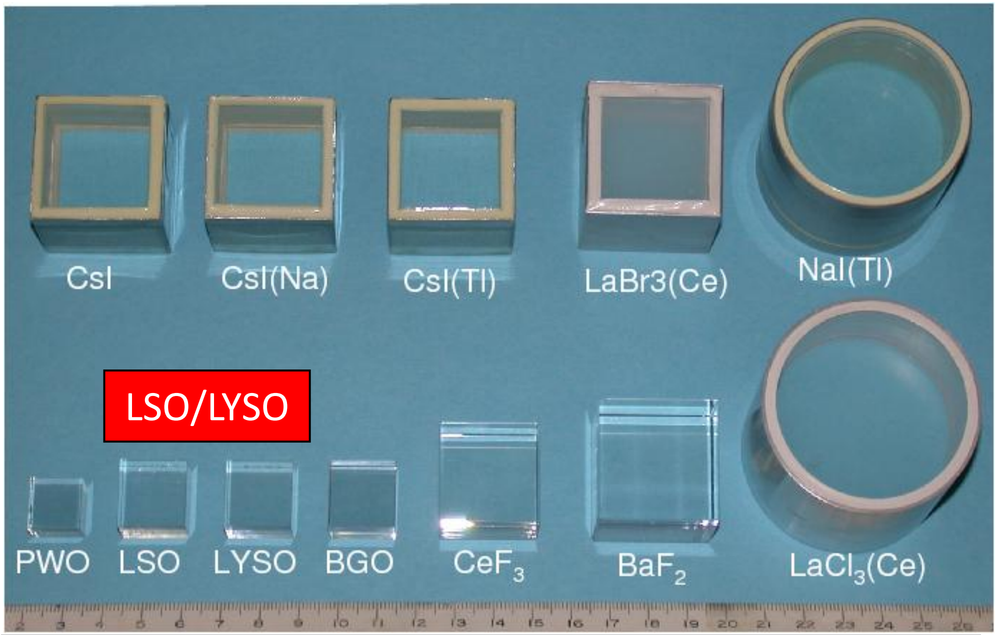
References: *IEEE Trans. Nucl. Sci.* NS-52 (2005) 3133-3140, *IEEE Trans. Nucl. Sci.* NS-54 (2007) 718-724, *IEEE Trans. Nucl. Sci.* NS-54 (2007) 1319-1326, *IEEE Trans. Nucl. Sci.* NS-55 (2008) 1759-1766, *IEEE Trans. Nucl. Sci.* NS-55 (2008) 2425-2341, *IEEE Trans. Nucl. Sci.* NS-59 (2012) 2224-2228, N32-4 & N32-5 @ NSS09, Orlando, N38-2 @ NSS10, Knoxville, N29-6 @ NSS11, Valencia.

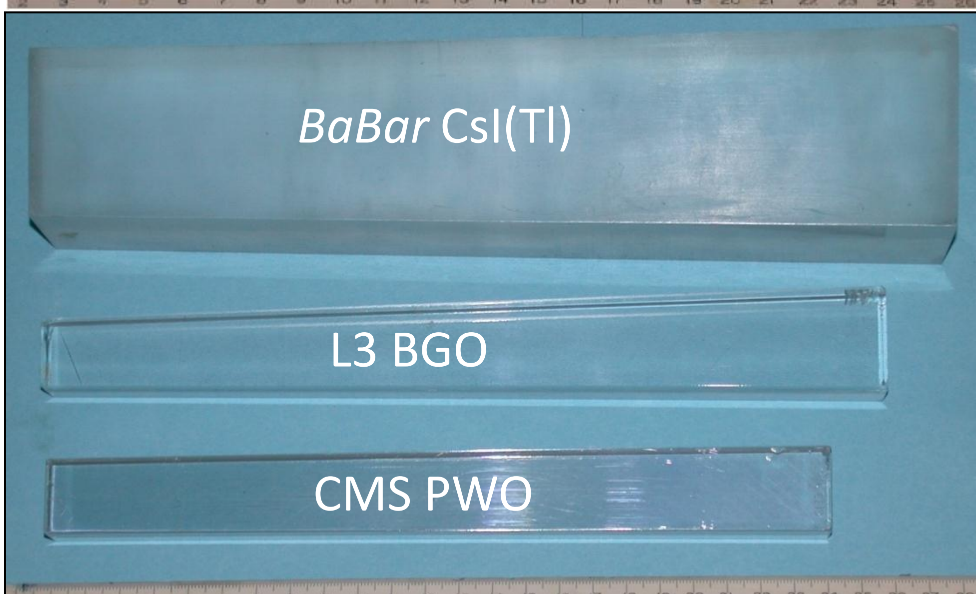
# Crystals for HEP Calorimeters

| 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 | Slight | No | No | No | No | No |
| Luminescence [b] (nm) (at peak) | 410 | 550 | 420 | 420<br>310 | 300<br>220 | 340<br>300 | 480 | 425<br>420 | 402 |
| Decay Time [b] (ns) | 245 | 1220 | 690 | 30<br>6 | 650<br>0.9 | 30 | 300 | 30<br>10 | 40 |
| Light Yield [b,c] (%) | 100 | 165 | 88 | 3.6<br>1.1 | 36<br>4.1 | 7.3 | 21 | 0.3<br>0.1 | 85 |
| d(LY)/dT [b] (%/ ºC) | -0.2 | 0.4 | 0.4 | -1.4 | -1.9<br>0.1 | 0 | -0.9 | -2.5 | -0.2 |
| Experiment | Crystal Ball | BaBar<br>BELLE<br>BES III | - | KTeV | (L*)<br>(GEM)<br>TAPS | - | L3<br>BELLE | CMS<br>ALICE<br>PANDA | Mu2e<br>(SuperB)<br>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 $X_0$

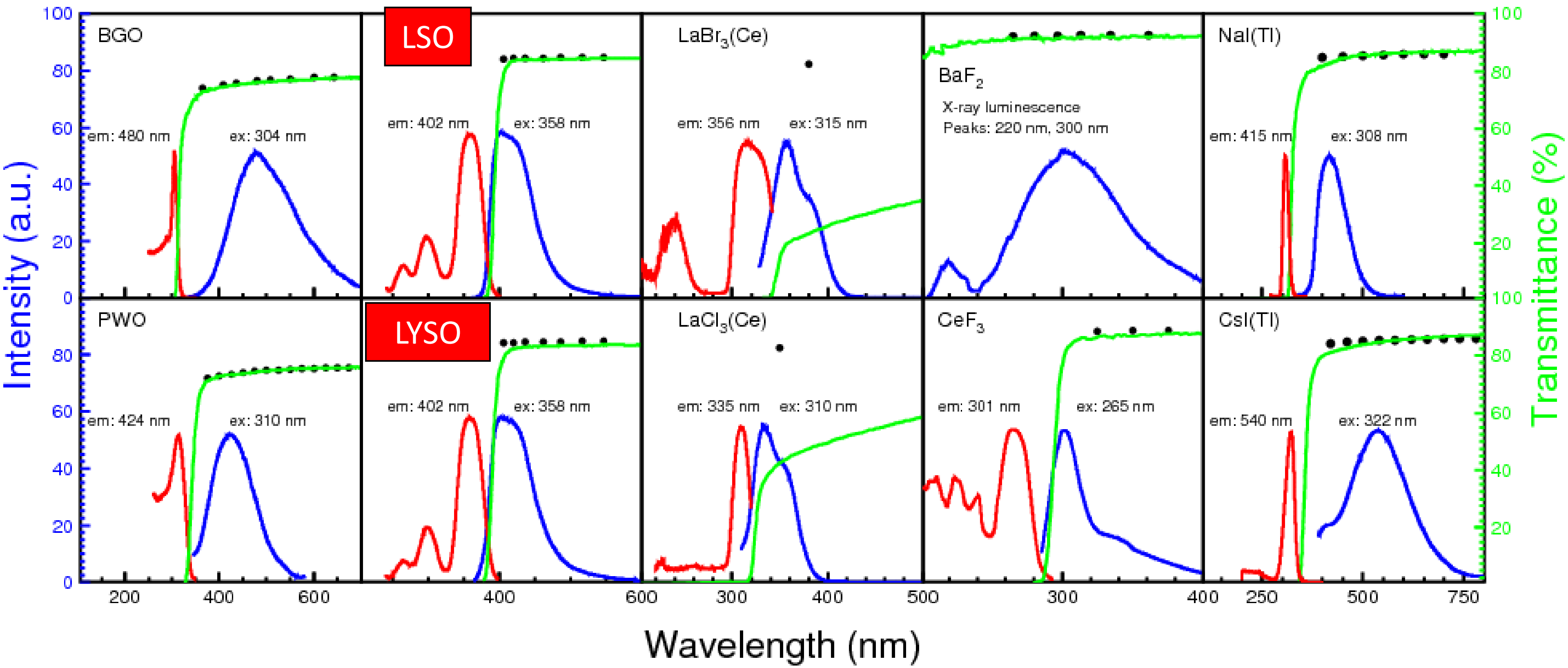
CMS PWO(Y): 25 $X_0$

# 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

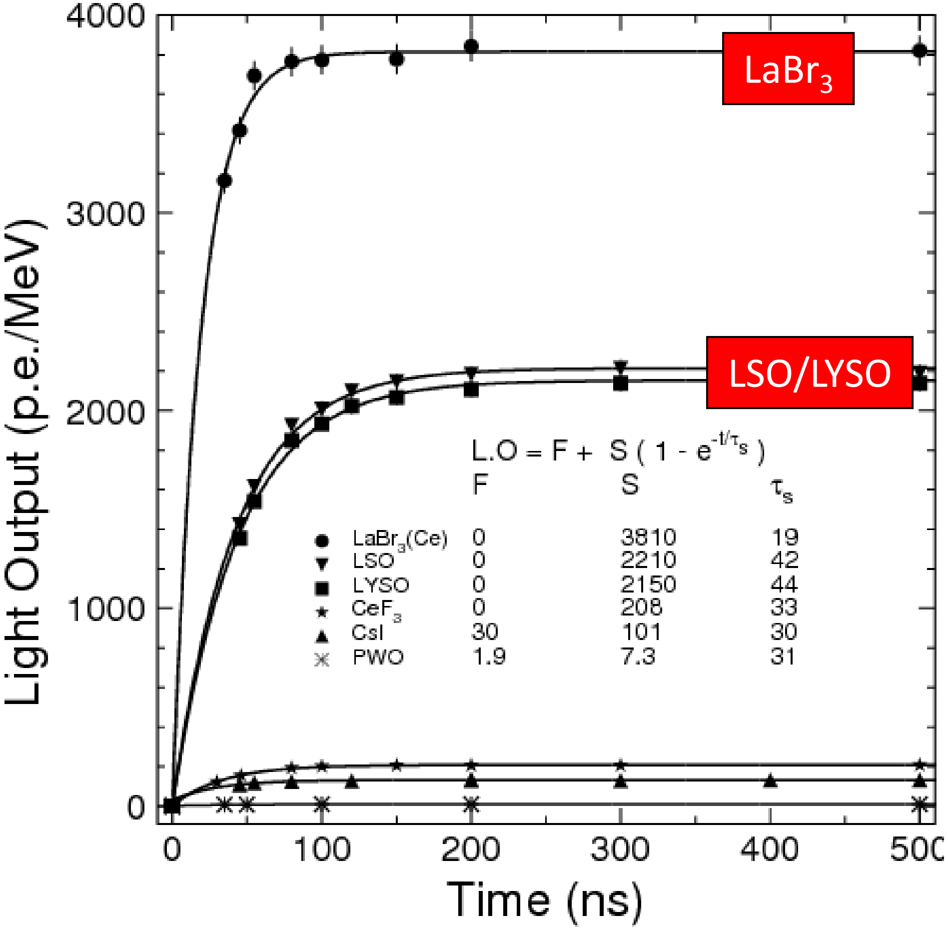



No Self-absorption: BGO, PWO, $BaF_2$, NaI(Tl) and CsI(Tl)

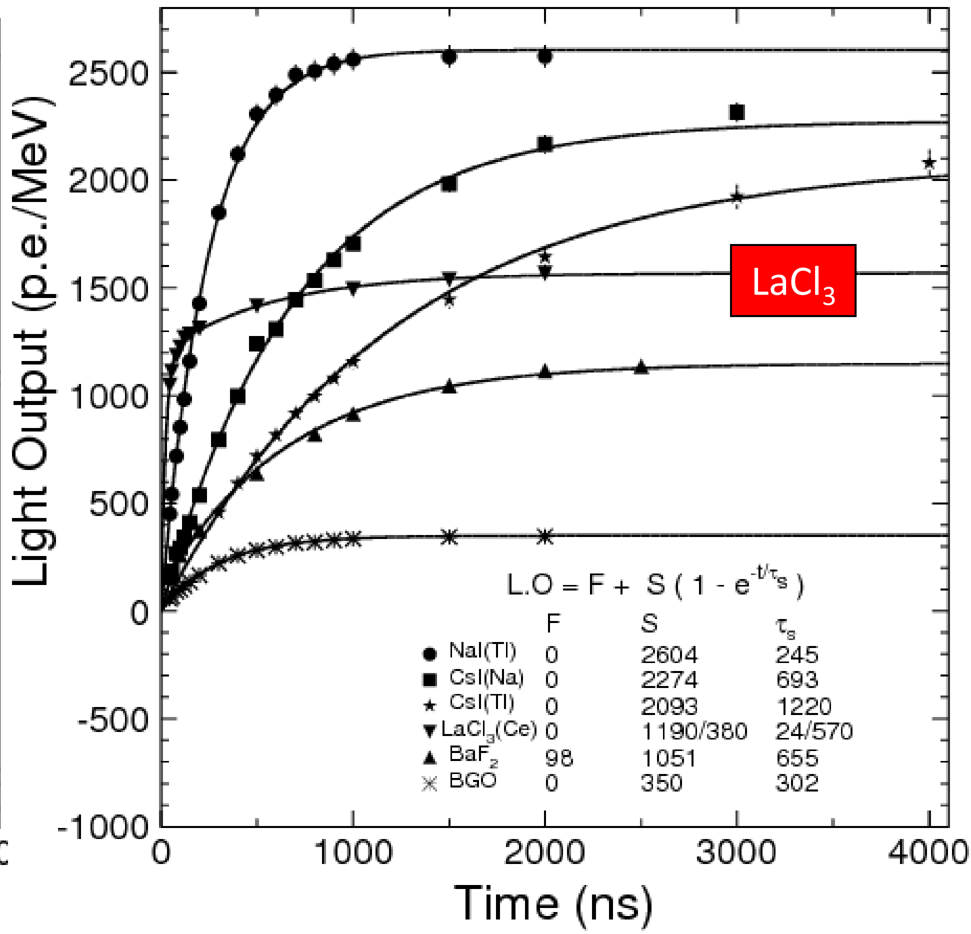
# Light Output & Decay Kinetics

Measured with Philips XP2254B PMT (multi-alkali cathode)
p.e./MeV: LSO/LYSO is 6 & 230 times of BGO & PWO respectively

**Fast Crystal Scintillators**

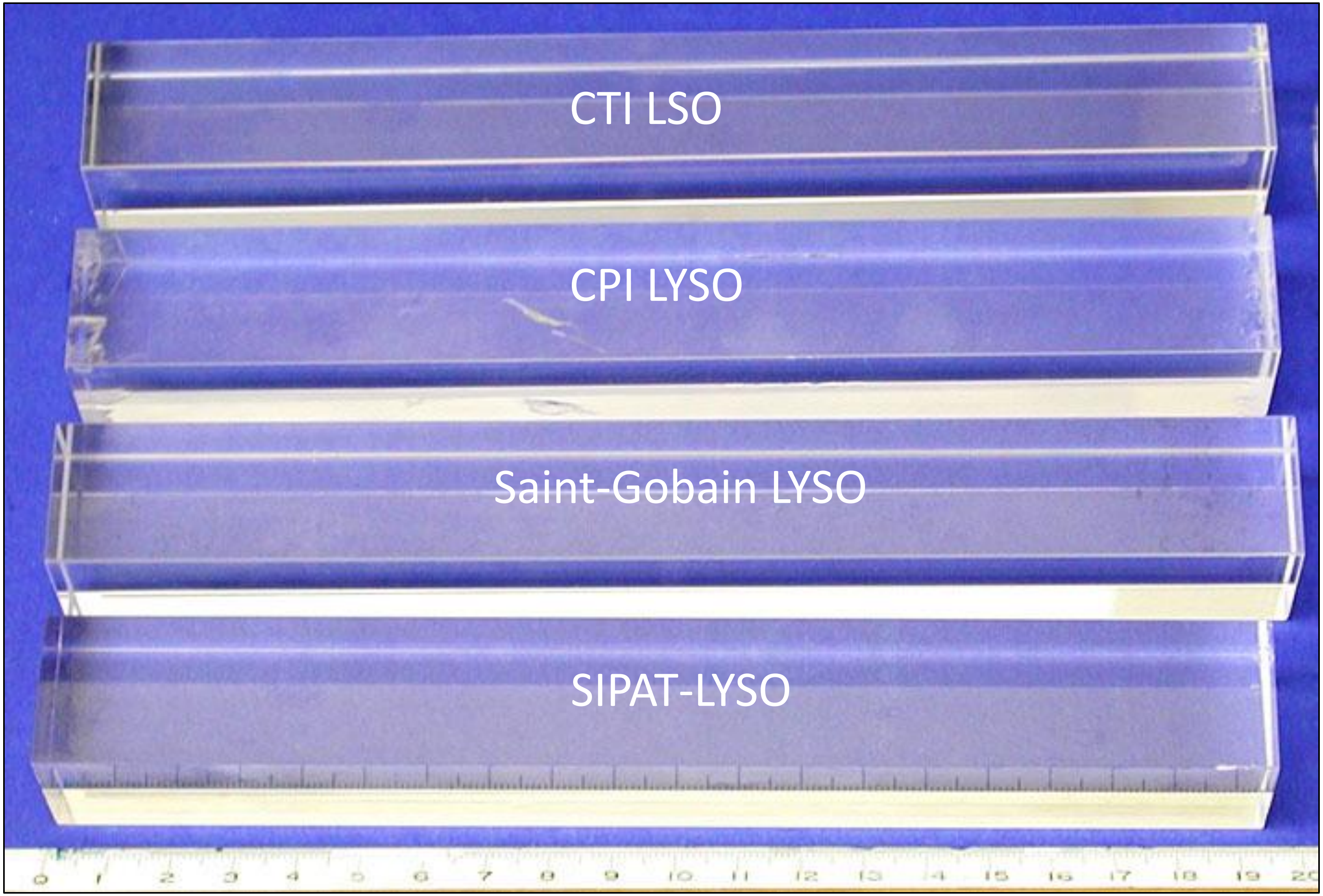



**Slow Crystal Scintillators**



# Long LSO & LYSO Crystal Samples

2.5 x 2.5 x 20 cm (18 $X_0$)

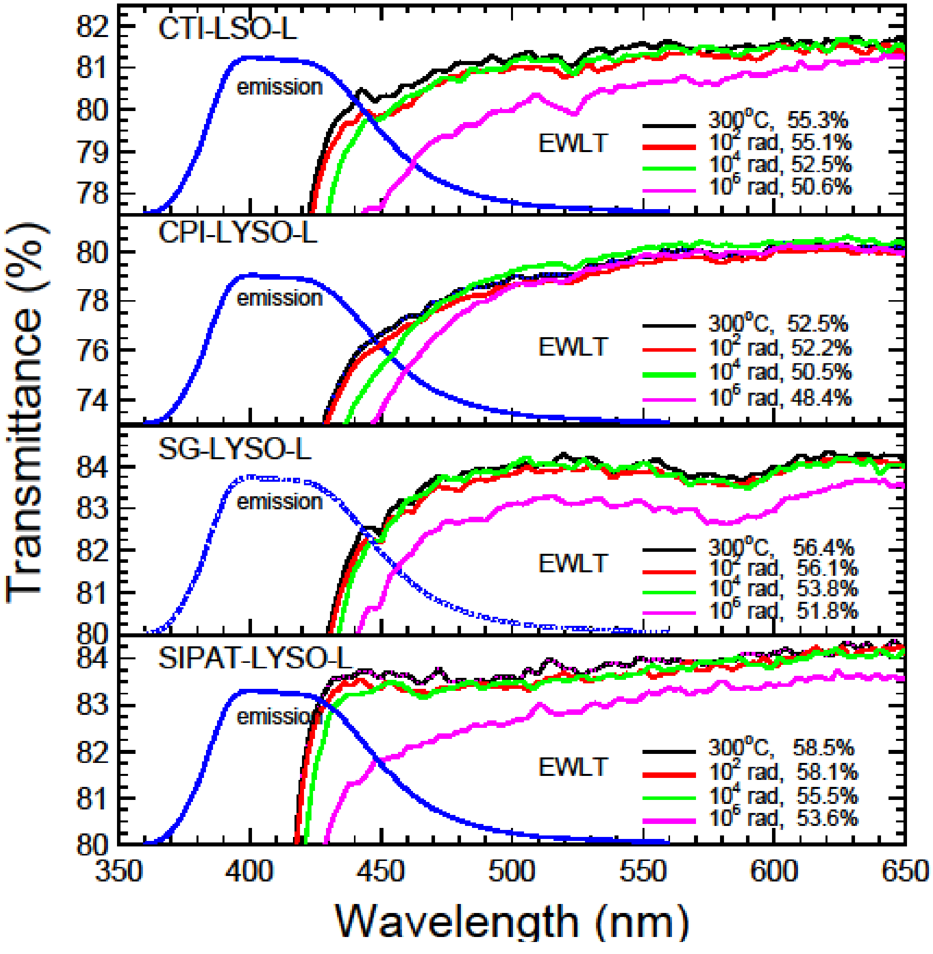


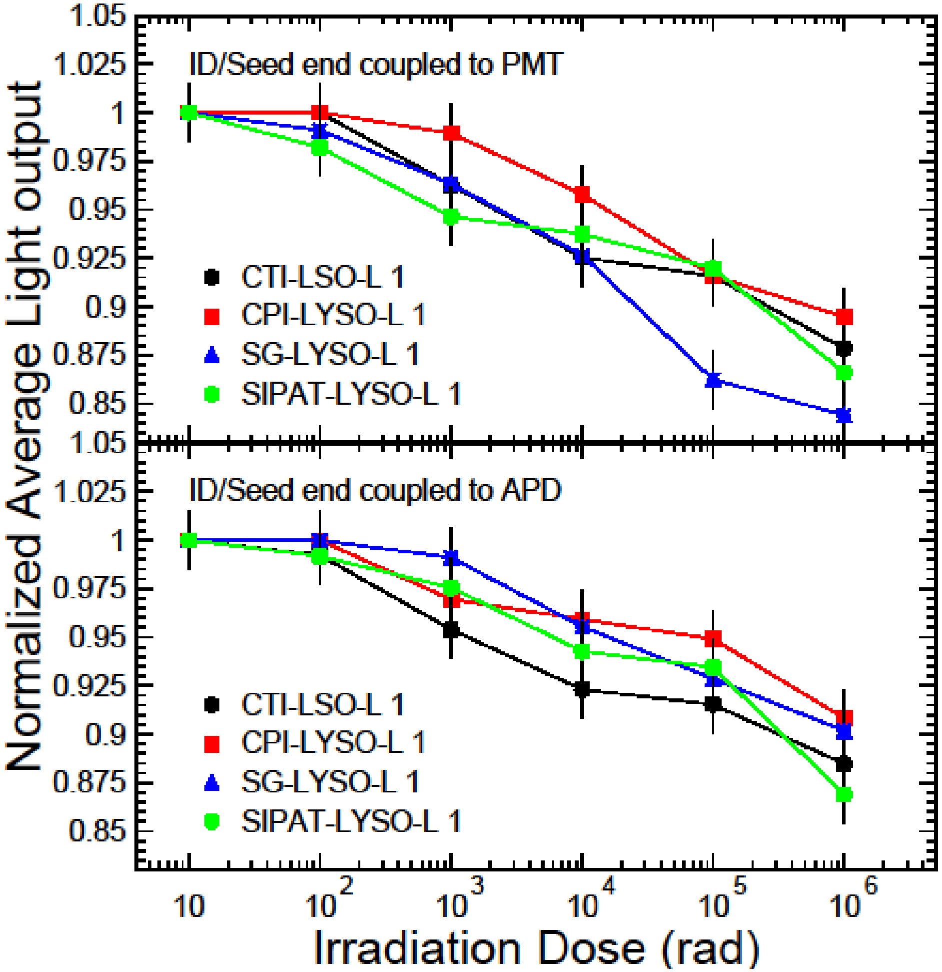
# 20 cm Long LSO/LYSO under γ-Rays

## Consistent radiation hardness better than other crystals

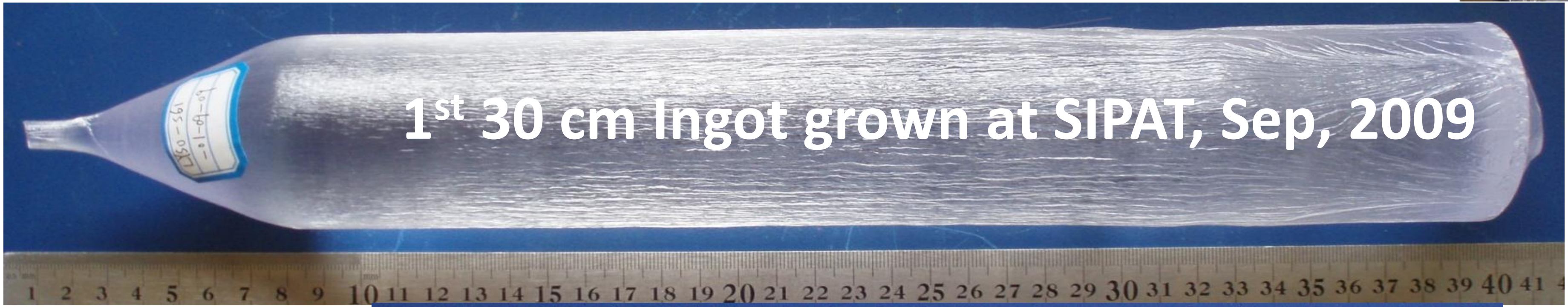
EWLT damage: 8% @ 1 Mrad

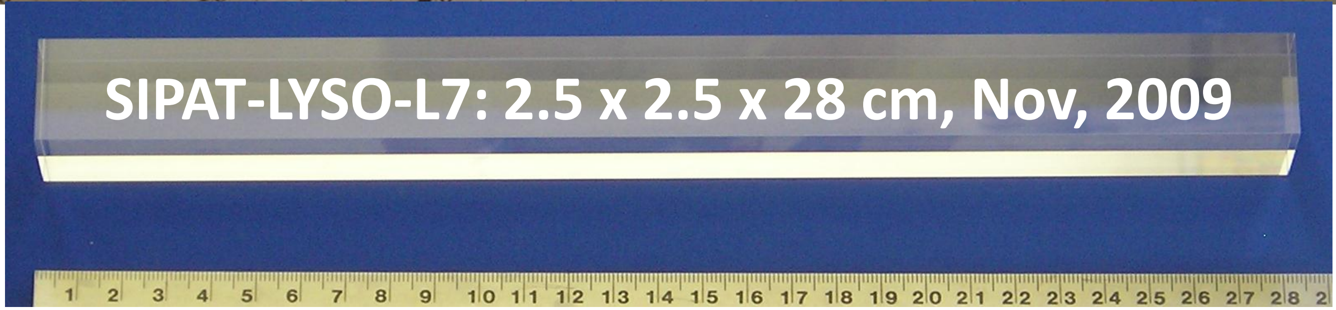
10% - 15% loss by PMT & APD



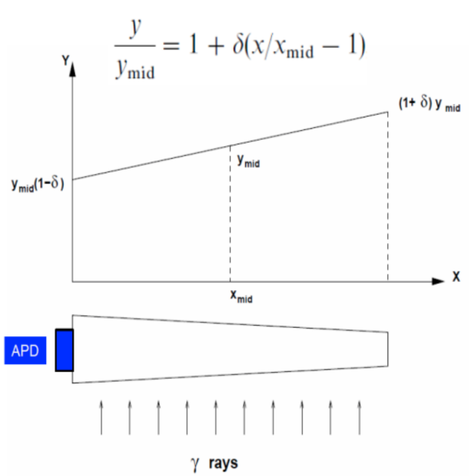



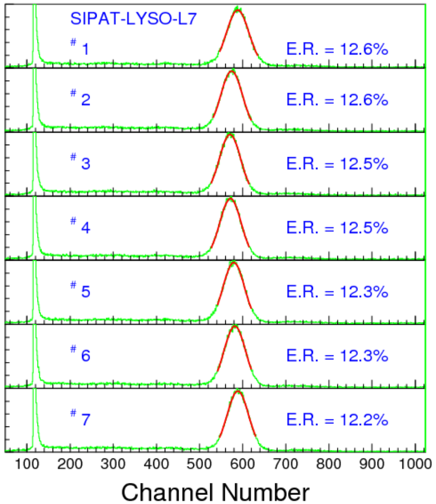
# Excellent Radiation Hardness

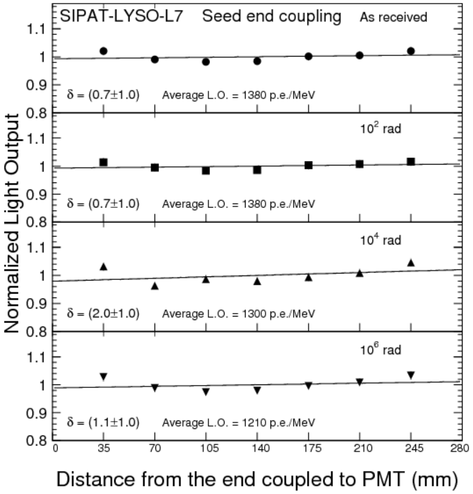


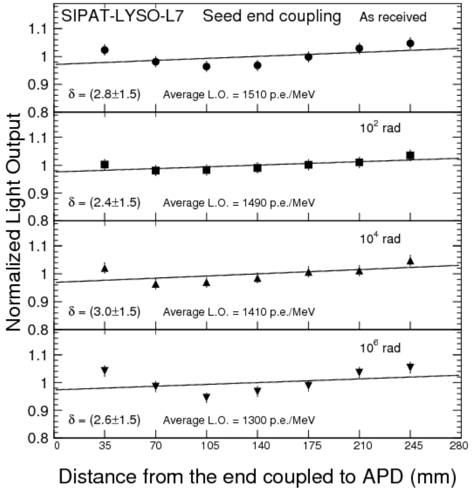




$$\frac{y}{y_{\mathrm{mid}}} = 1 + \delta(x/x_{\mathrm{mid}} - 1)$$



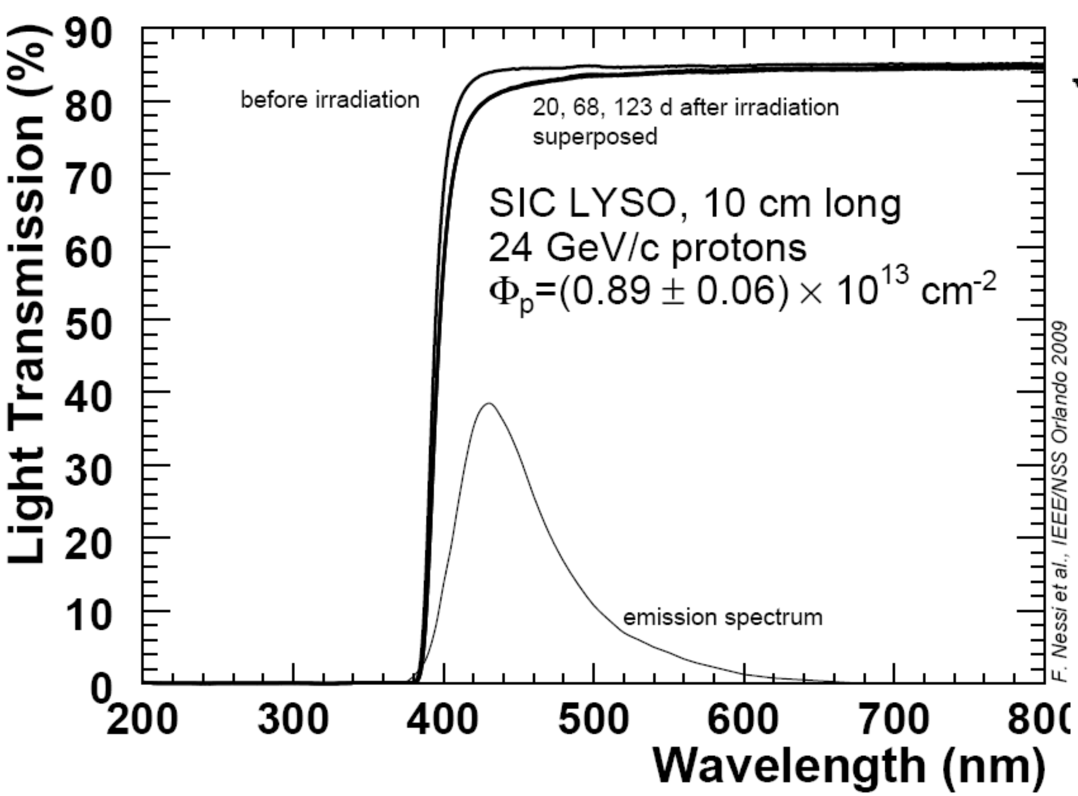



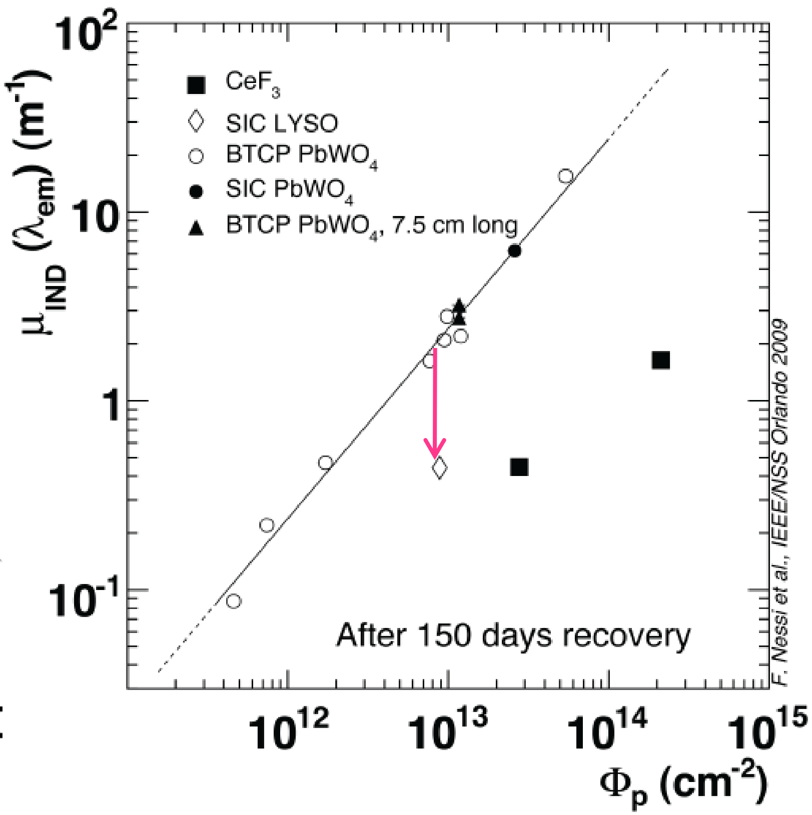



# Radiation Hardness aginst Hadrons

G. Dissertori, D. Luckey, P. Lecomte, Francesca Nessi-Tedaldi, F. Pauss, IEEE NSS09, N32-3

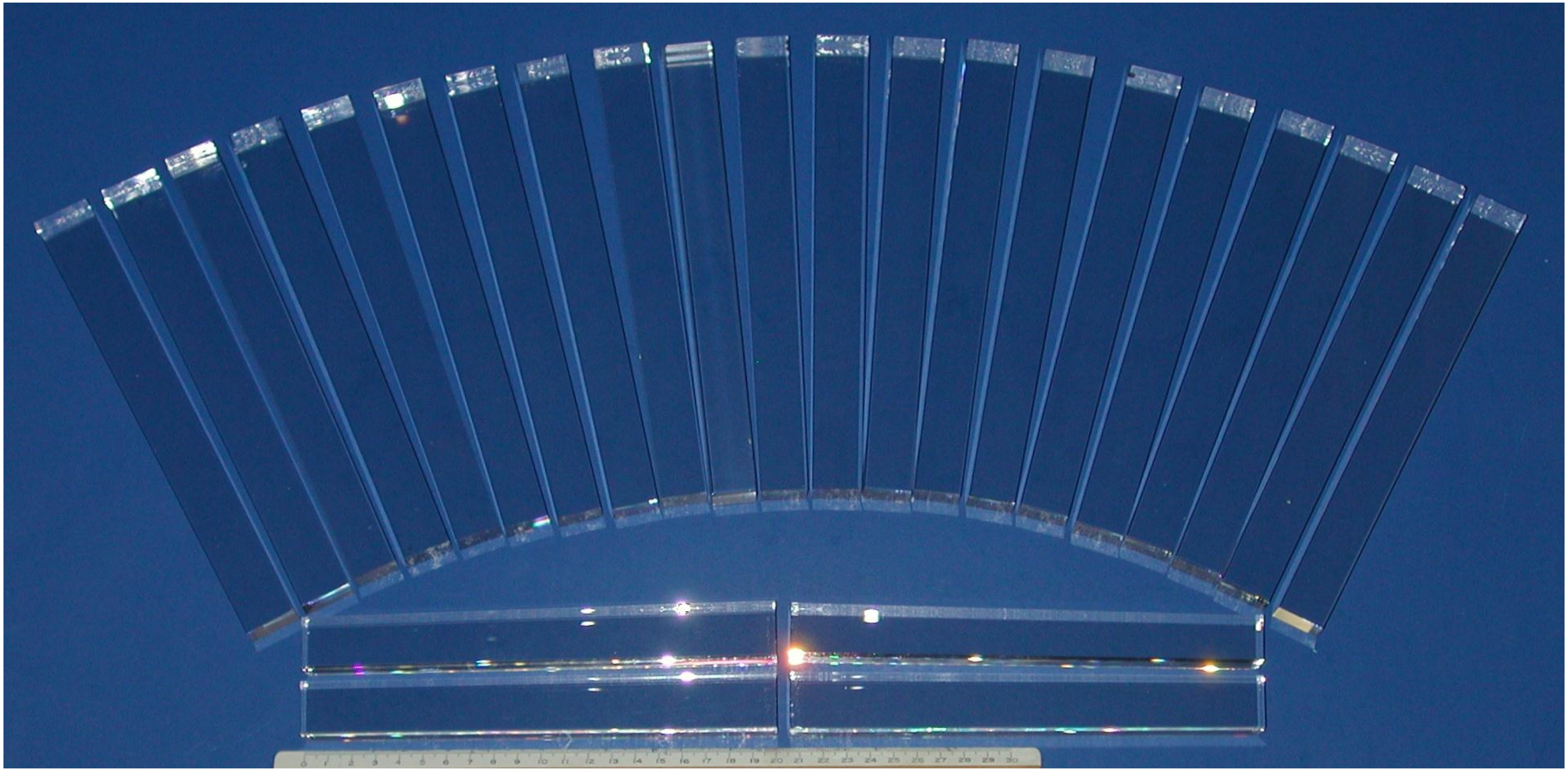


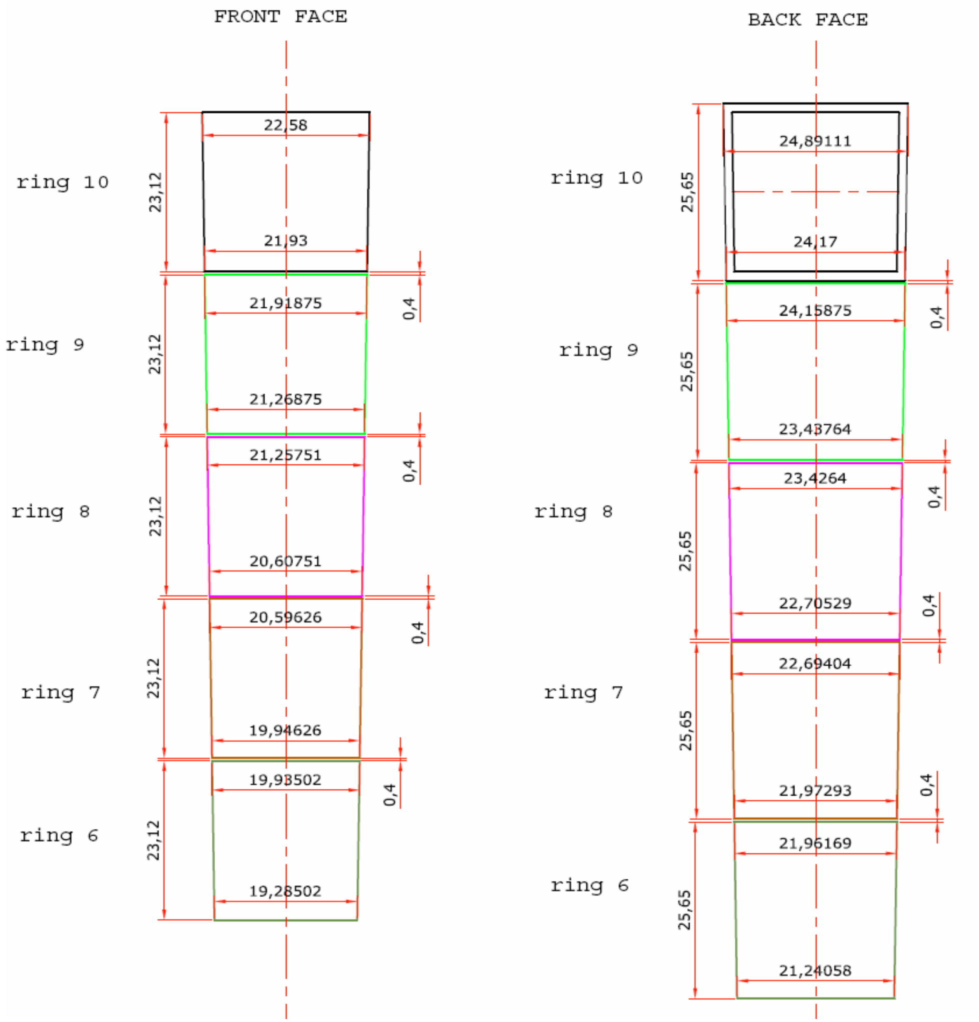

**The induced absorption of LYSO is 1/5 of PWO.**

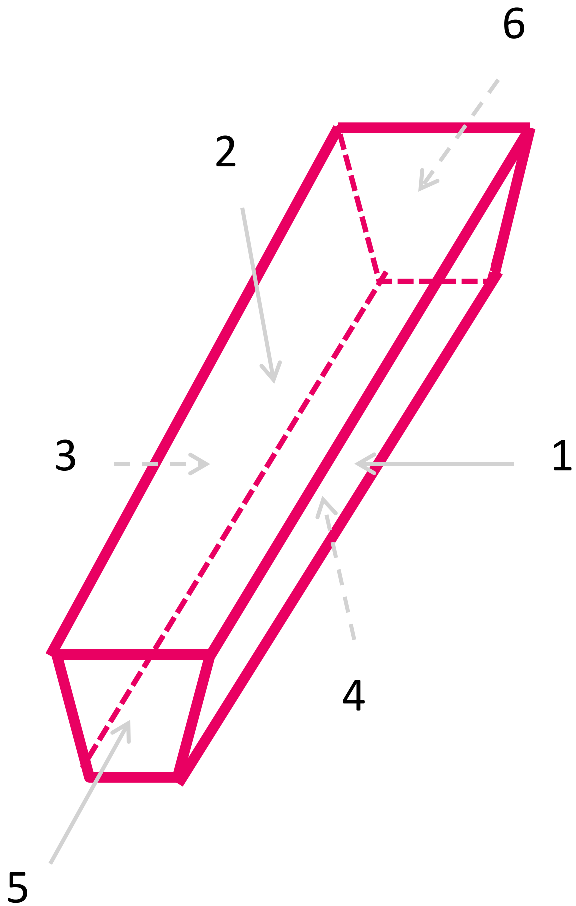
# Twenty Five Super*B* Crystals

All crystals are characterized in Caltech Crystal Laboratory



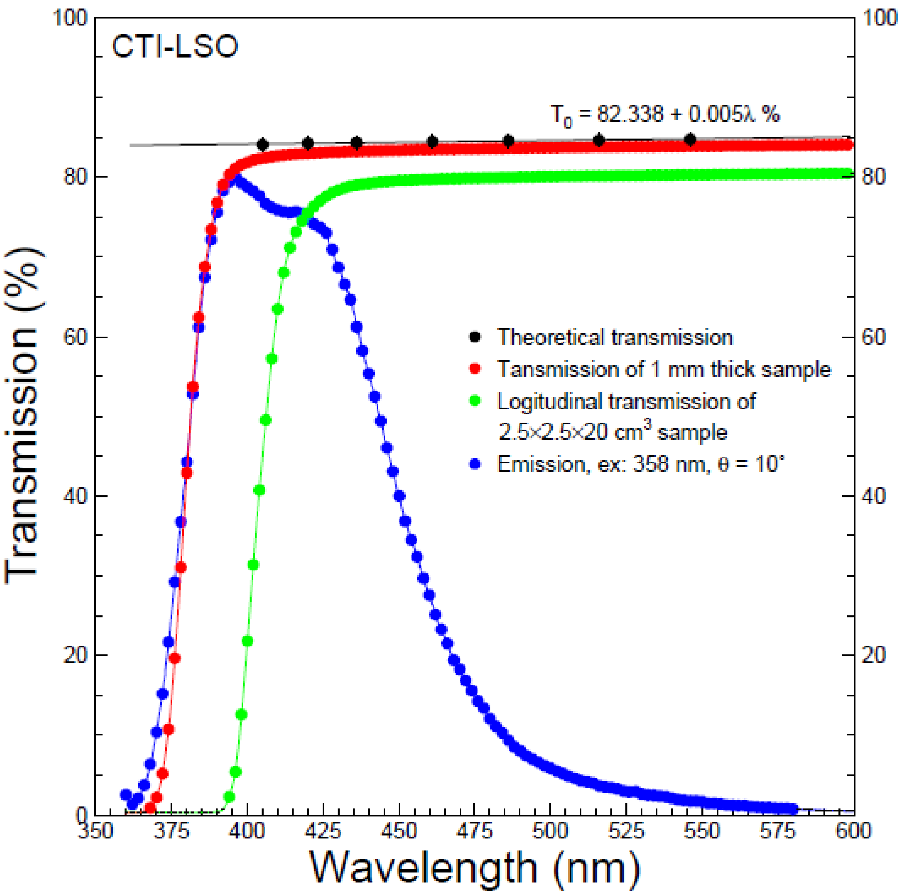
# Dimensions and Surface Definition

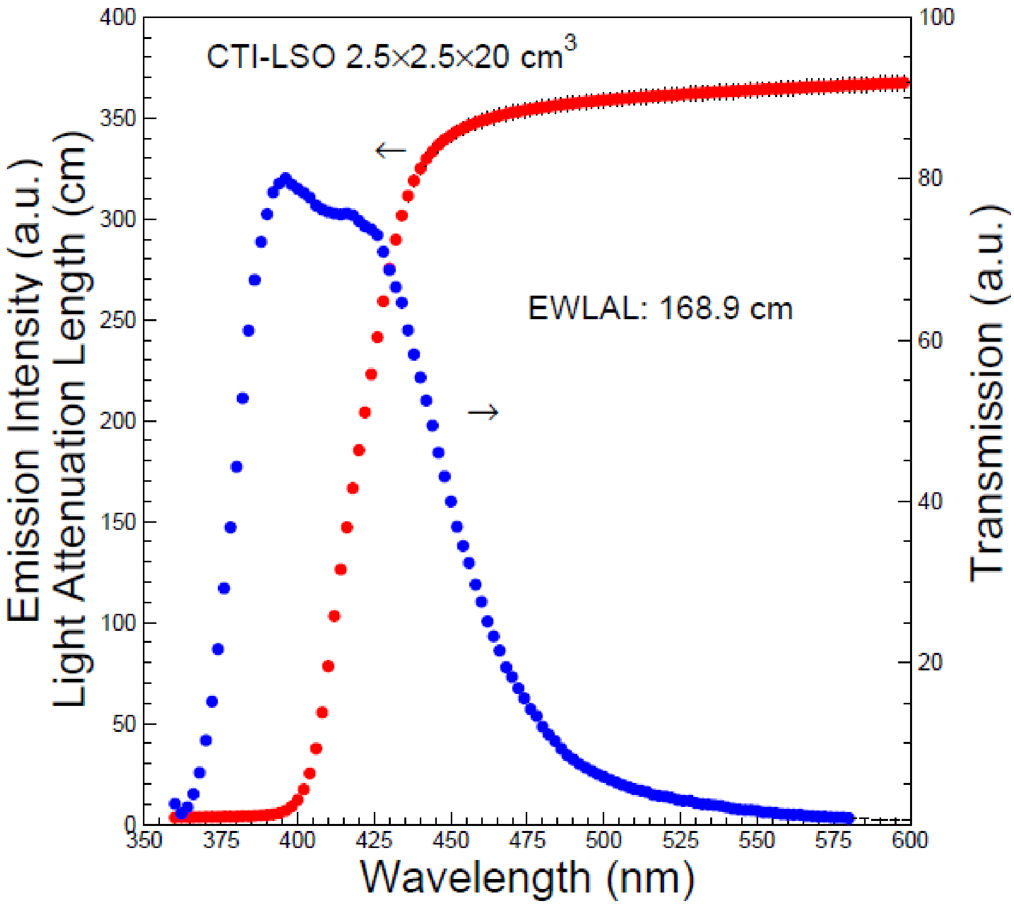


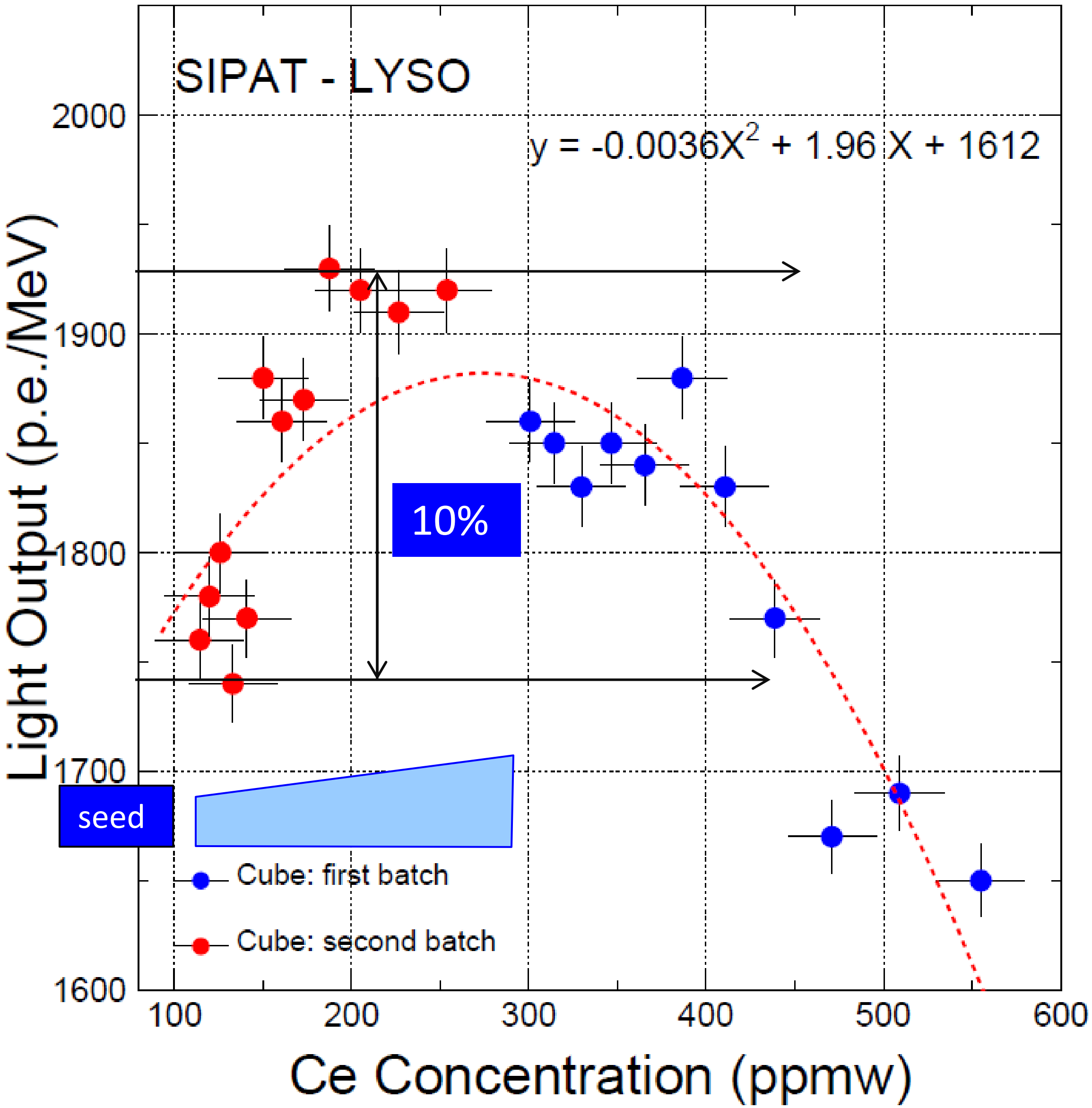
# Effect of Self-Absorption

Part of the emission light is absorbed in the crystal (self-absorption), leading to a strong wavelength dependent light attenuation length



# Effect of Cerium Segregation

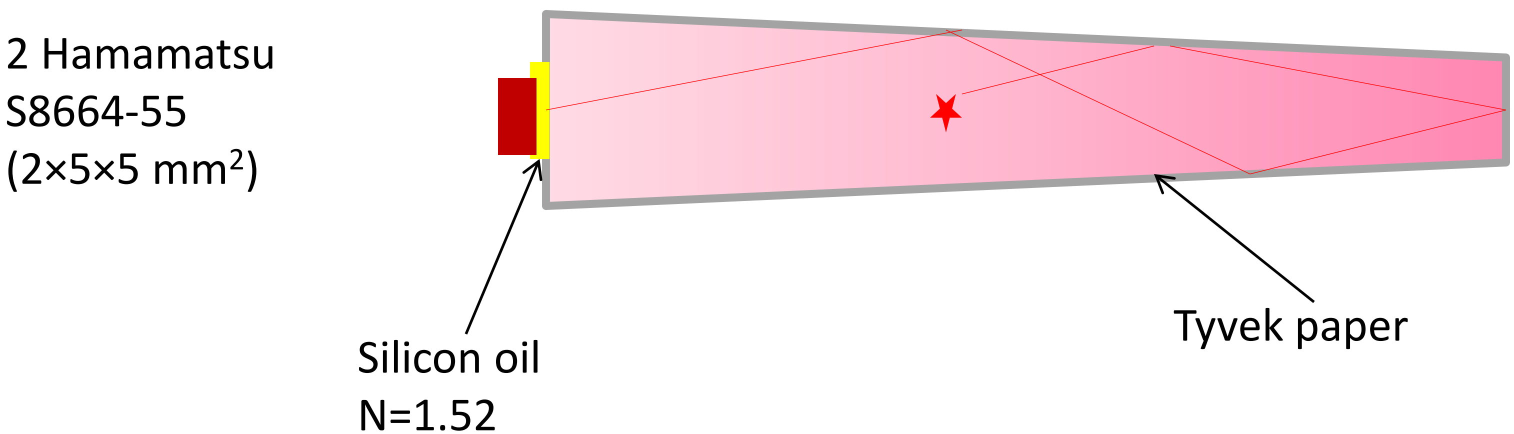



It is also known that cerium concentration along long LYSO crystals is not uniform, causing non-uniformity up to 10% at two ends, indicating up to 5% variation in δ is possible because of cerium segregation.

# Ray-Tracing Simulation "set-up"

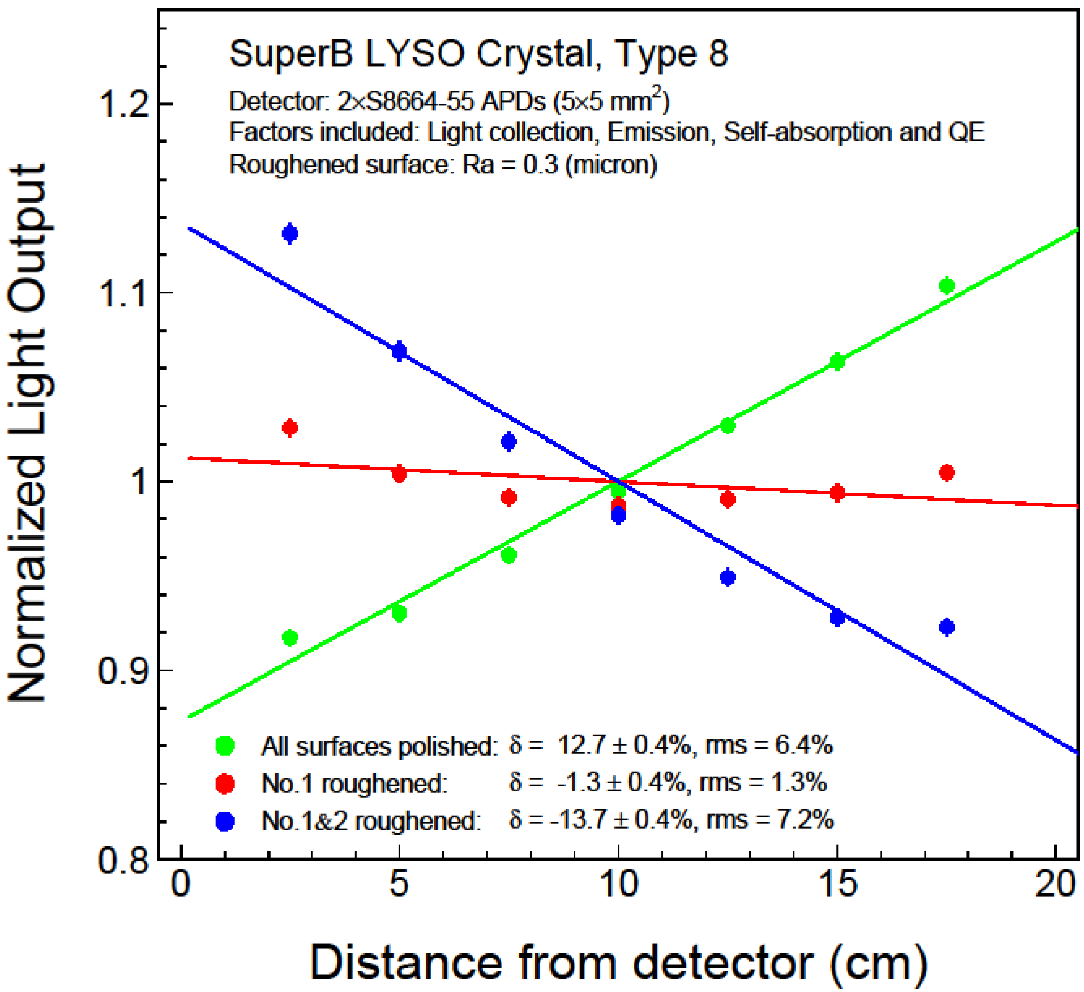
The simulation package was developed in early eighties, and was used for the L3 BGO and CMS PWO crystals.

SuperB LYSO crystals




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

# Polished and Roughened Surfaces

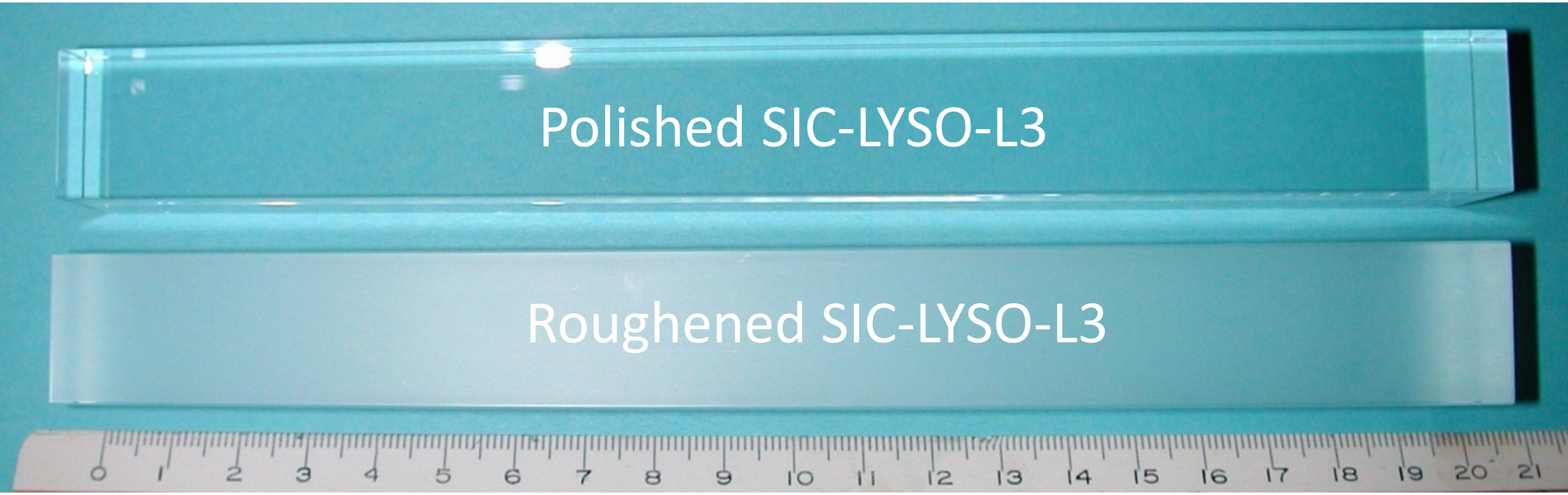



- The optical focusing, effect dominates non-uniformity: δ is about 13% for all polished surfaces.
- Roughened surface(s) can compensate the optical focusing effect.
- The best result is achieved by roughening only one side surface.

# 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

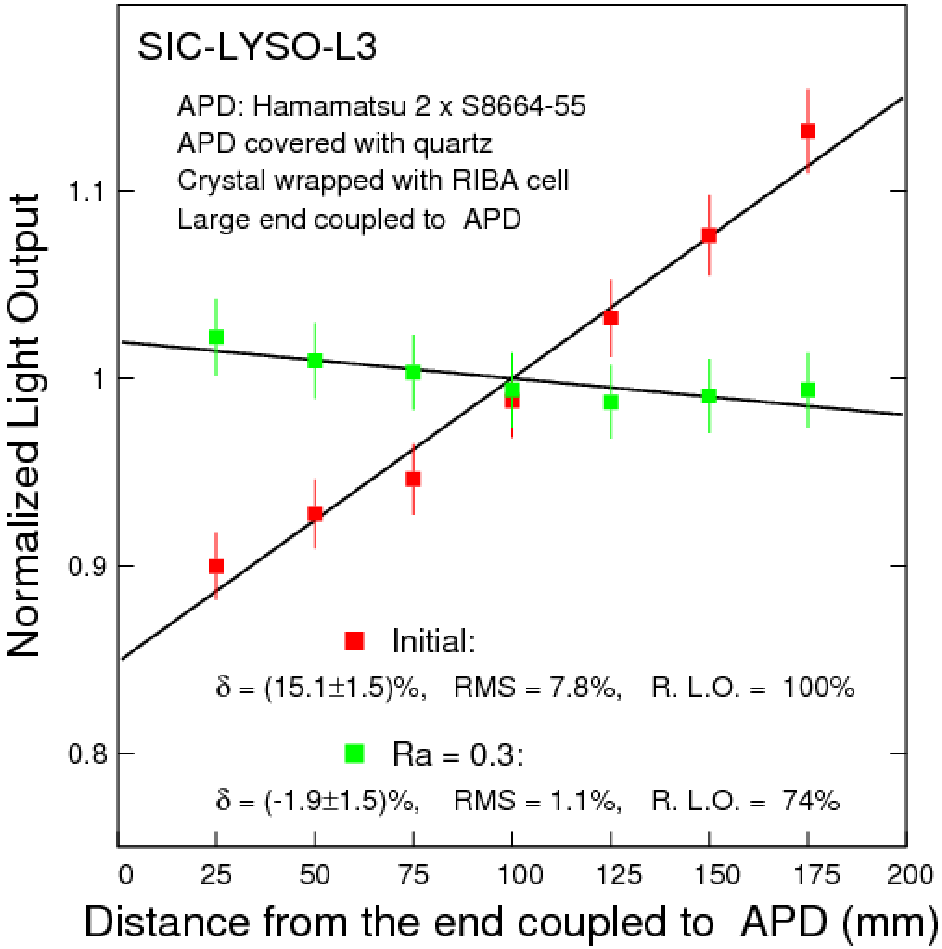


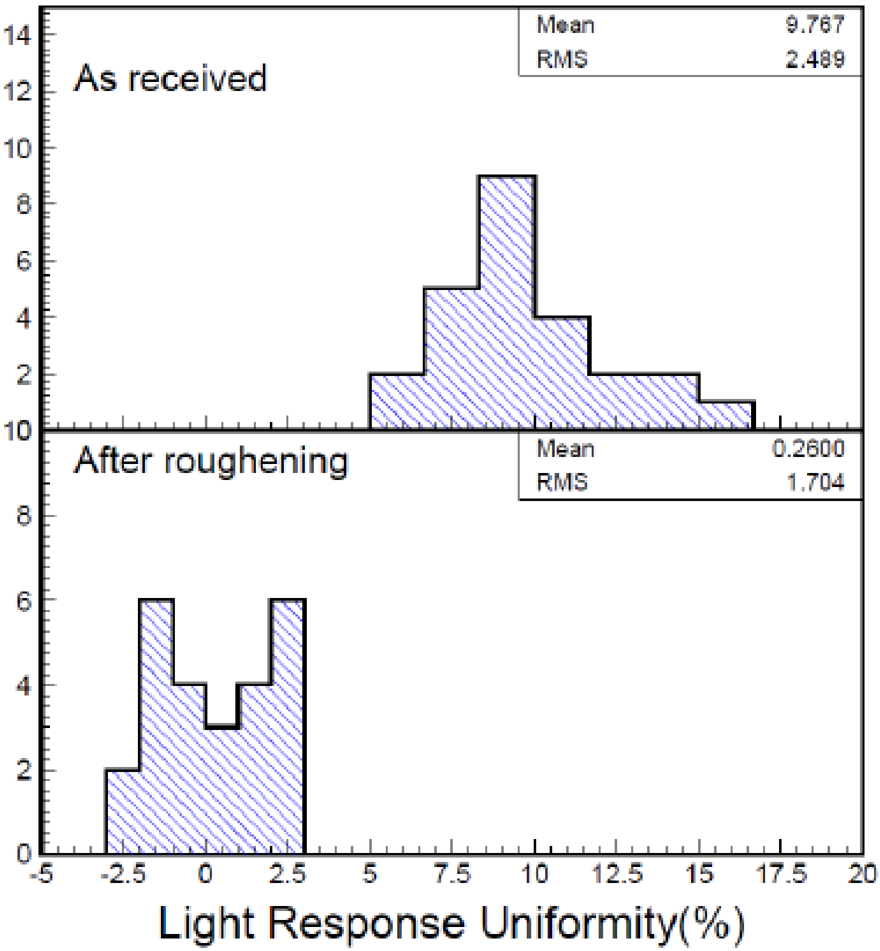

1st: lapped to Ra = 0.5 by using 11 µm $Al_2O_3$ powder for 10 min with 2.5 kg weight
2nd: lapped to Ra = 0.3 by using 6.5 µm SiC powder for 3 min with 1.5 kg weight

# Relative Light Output & Uniformity

Ra = 0.3 uniformizes SIC-L3 to < 2%

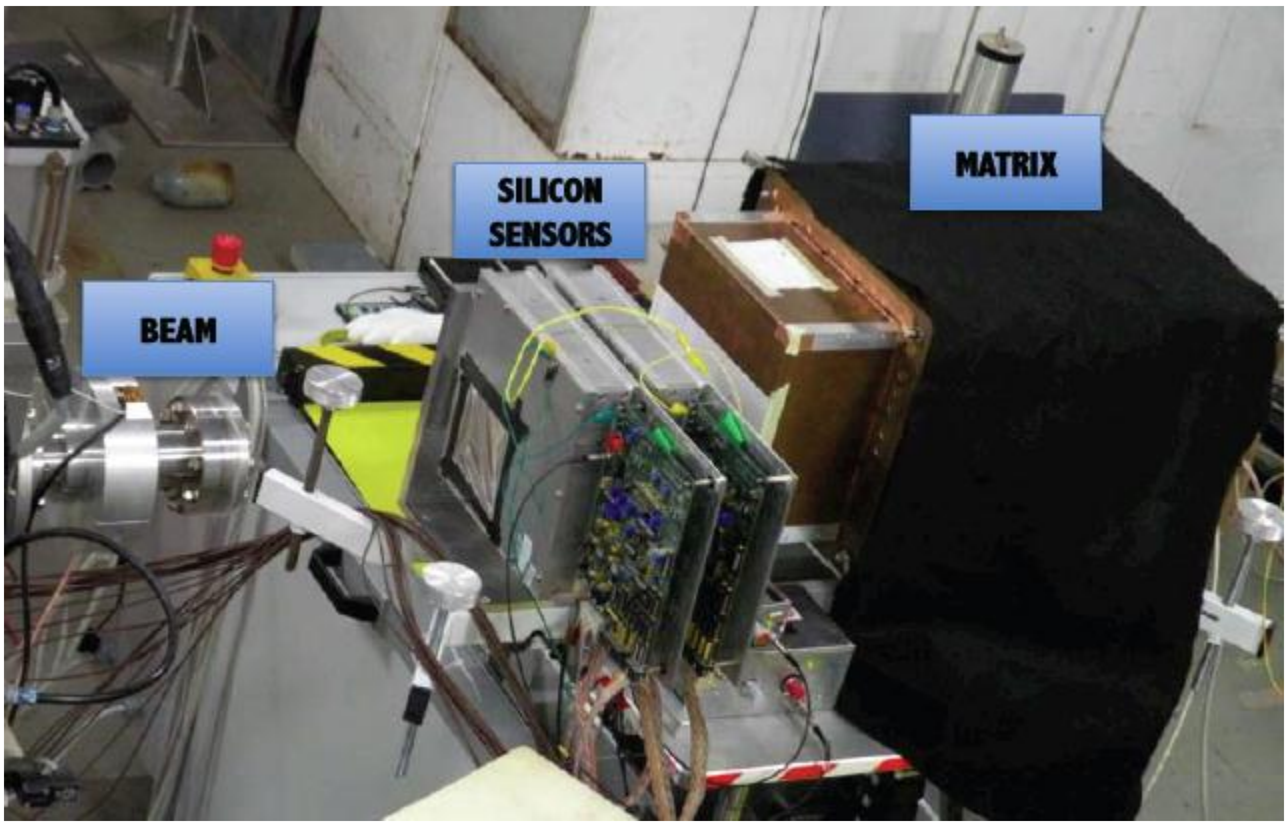
All 25 crystals are uniformized to |δ| < 3%

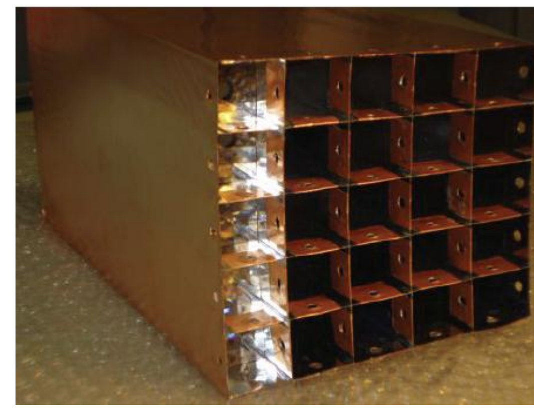


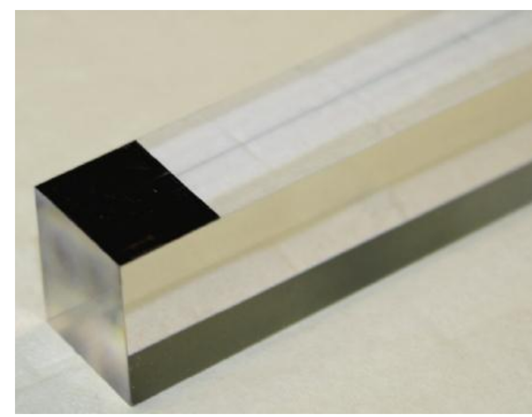



# SuperB Test Beam at BTF, Frascati

A LYSO matrix of 25 crystals was tested in May, 2011 at the beam test facility in Frascati. Crystals were uniformized by black painting of 15 mm at the small end of the smallest side surface

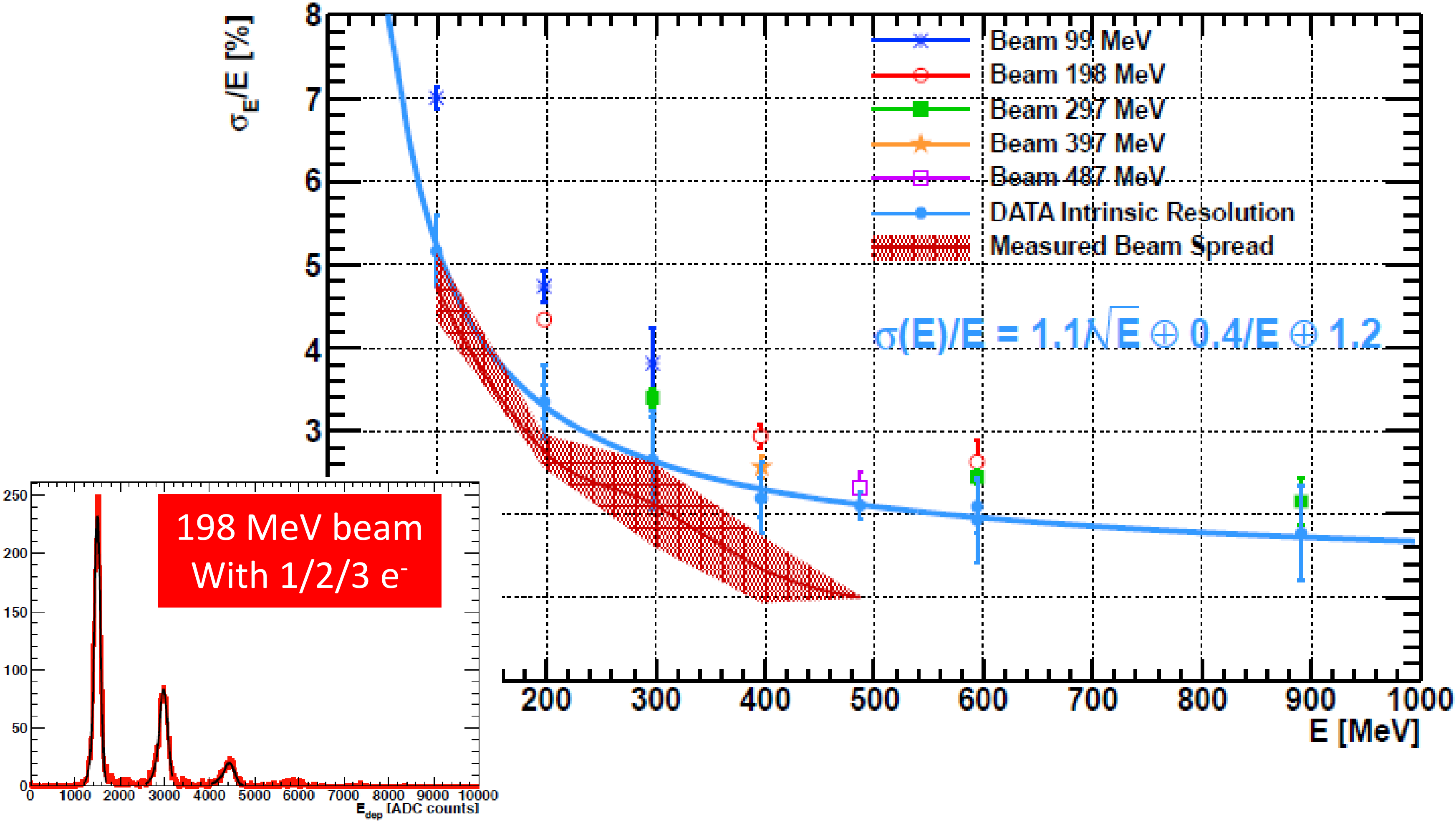




# Test Beam Result

$$\frac{\sigma(E)}{E} = \frac{1.1}{\sqrt{E[GeV]}} \oplus \frac{0.4}{E[GeV]} \oplus 1.2\ \%$$



# Summary

- Because of its excellent resolution crystal calorimetry will play an important role in future lepton factories.
- LSO/LYSO crystals with bright, fast scintillation and excellent radiation hardness is a good candidate for crystal calorimetry in future lepton factories.
- The light response uniformity of tapered Super*B* crystals is affected by (1) the crystal geometry related optical focusing, (2) the self-absorption and (3) the non-uniformity of the cerium concentration. All 25 SuperB test beam crystals are uniformized to |δ|<3% by roughening the smallest side surface.
- For applications in a severe radiation environment, such as the CMS forward calorimetry at the HL-LHC, R&D works concentrate on LSO/LYSO based sampling calorimeters. See crystal calorimeter talk in Session G.