Monitoring LSO/LYSO Based Crystal Calorimeters

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June 11, 2015

See also papers O6-5, O7-2, O12-2, O12-3 and O12-4

Introduction

- Because of the severe radiation environment expected by the future HEP experiments a light monitoring system is important for keeping intrinsic precision of the proposed LYSO crystal calorimeter. The required monitoring precision is 0.5%.
- LYSO crystal has the best radiation hardness among all crystal scintillators with small variations in transparency. Long crystals were studied to understand LYSO monitoring.
- The required monitoring frequency is much relaxed as compared to the **half hour** for the CMS PWO ECAL:
    - The radiation damage effect in LYSO crystals is much smaller than that in PWO crystals.
    - There is no need to monitor the calorimeter when the beam is off since radiation damage in LYSO crystals does not recover.
- Progress has been made in monitoring the proposed LYSO/W Shashlik calorimeter. Prototype LYSO/W/Al Shashlik cells were built and tested at JPL. An OPO laser based monitoring system was used in the LYSO/W Shashlik test beam at Fermilab.

LYSO Samples Investigated

Sample ID	Dimension (mm^3)	Polish
CPI-LYSO-L	25 × 25 × 200	Six faces polished
CTI-LSO-L	25 × 25 × 200	Six faces polished
SG-LYSO-L	25 × 25 × 200	Six faces polished
SIC-LYSO-L	25 × 25 × 200	Six faces polished
SIPAT-LYSO-L	25 × 25 × 200	Six faces polished

Experiments

- Properties measured at room temperature before after irradiation: longitudinal transmittance (LT) & light output (LO).
- Step by step irradiations by γ-rays: 100, 1K, 10K, 100K and 1M rad.

Excitation, Emission & Transmittance

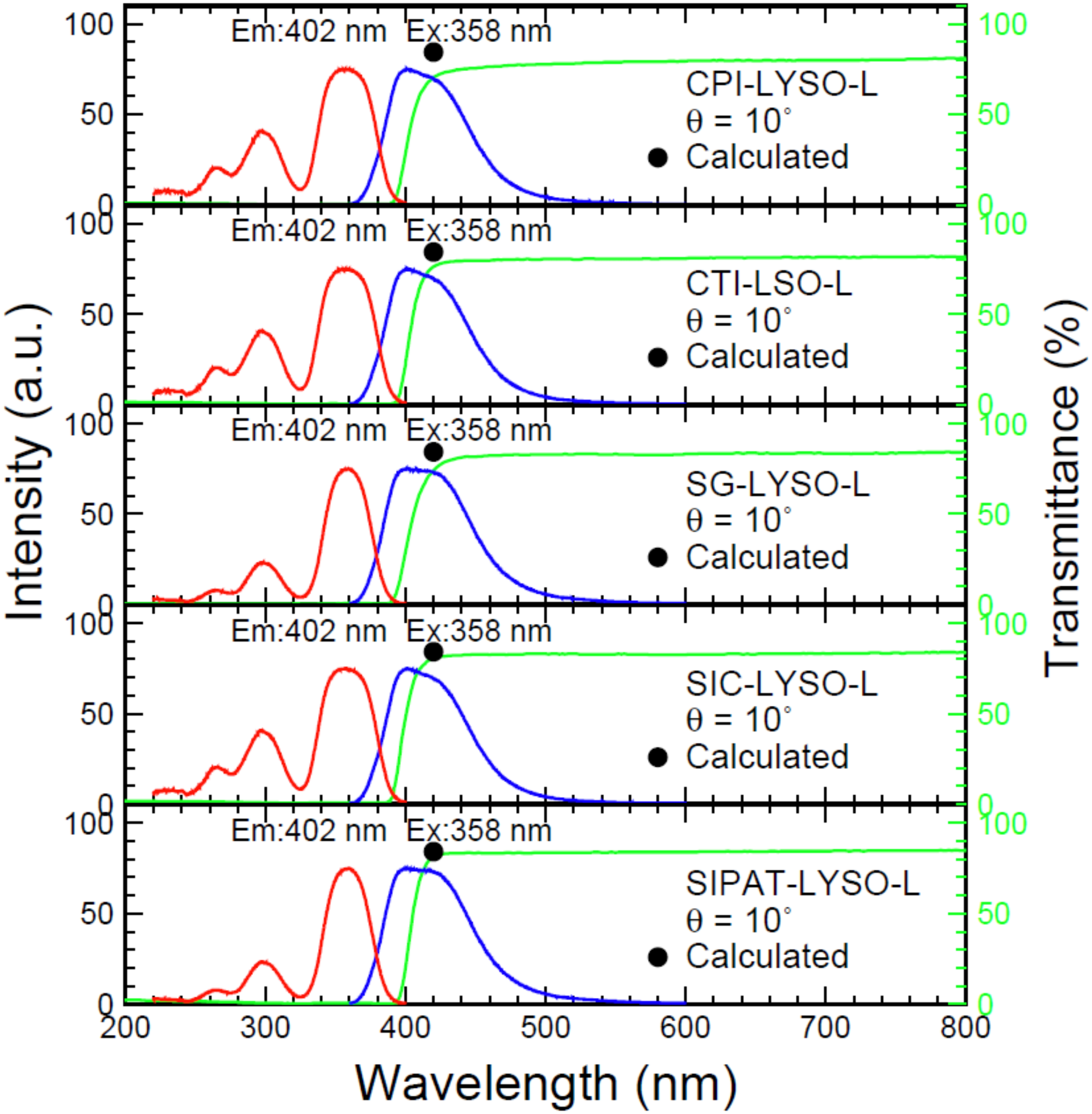


Photo-luminescence spectra for 20 cm samples with peaks:

Excitation: 358 nm

Emission: 402 nm

The cut-off wavelength of the transmittance is red-shifted because of self-absorption.

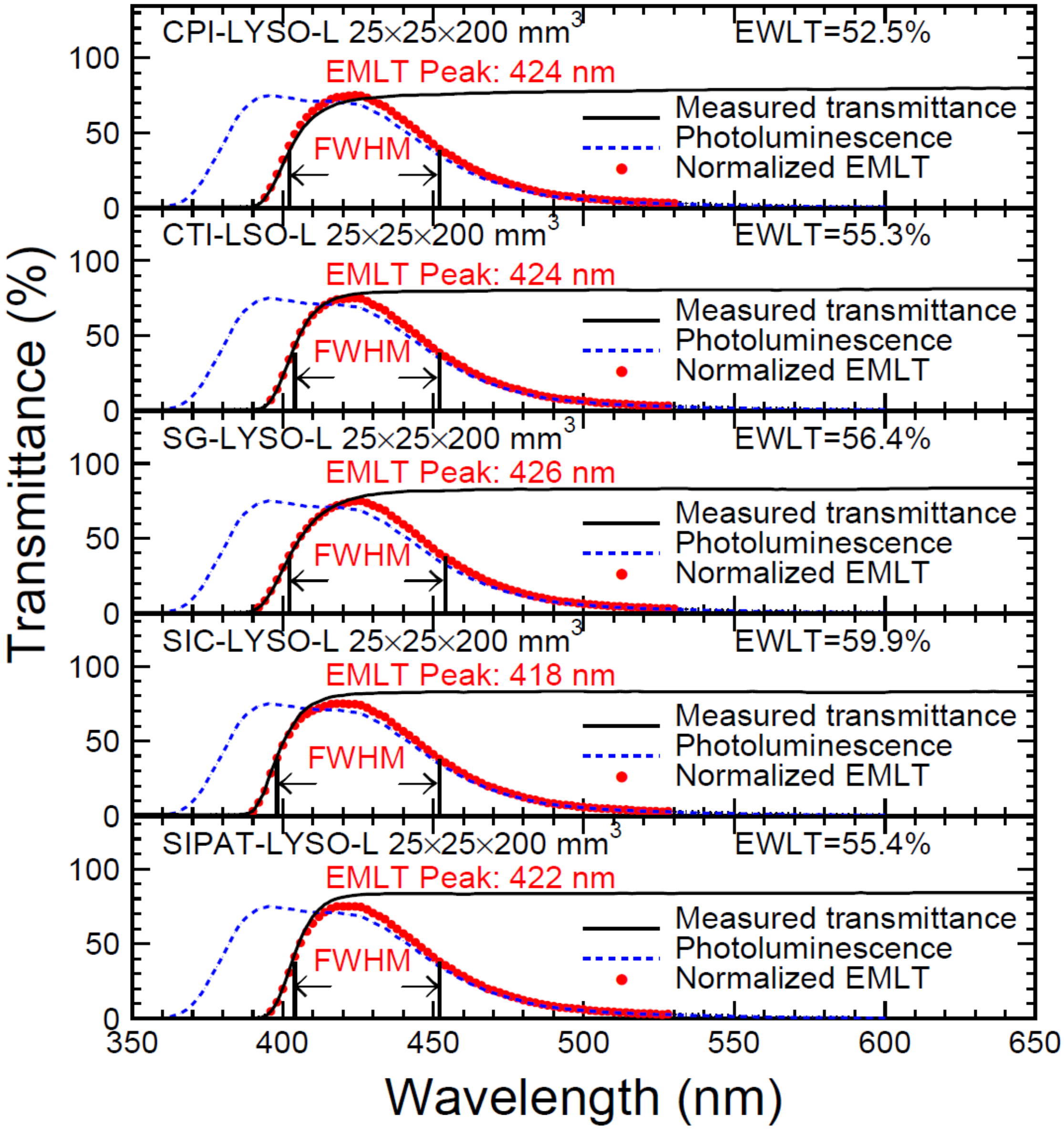
Emission (PL), LT and EMLT

EMLT (Emission Multiplied Longitudinal Transmittance): $EMLT(\lambda) = Em(\lambda) \times LT(\lambda)$.

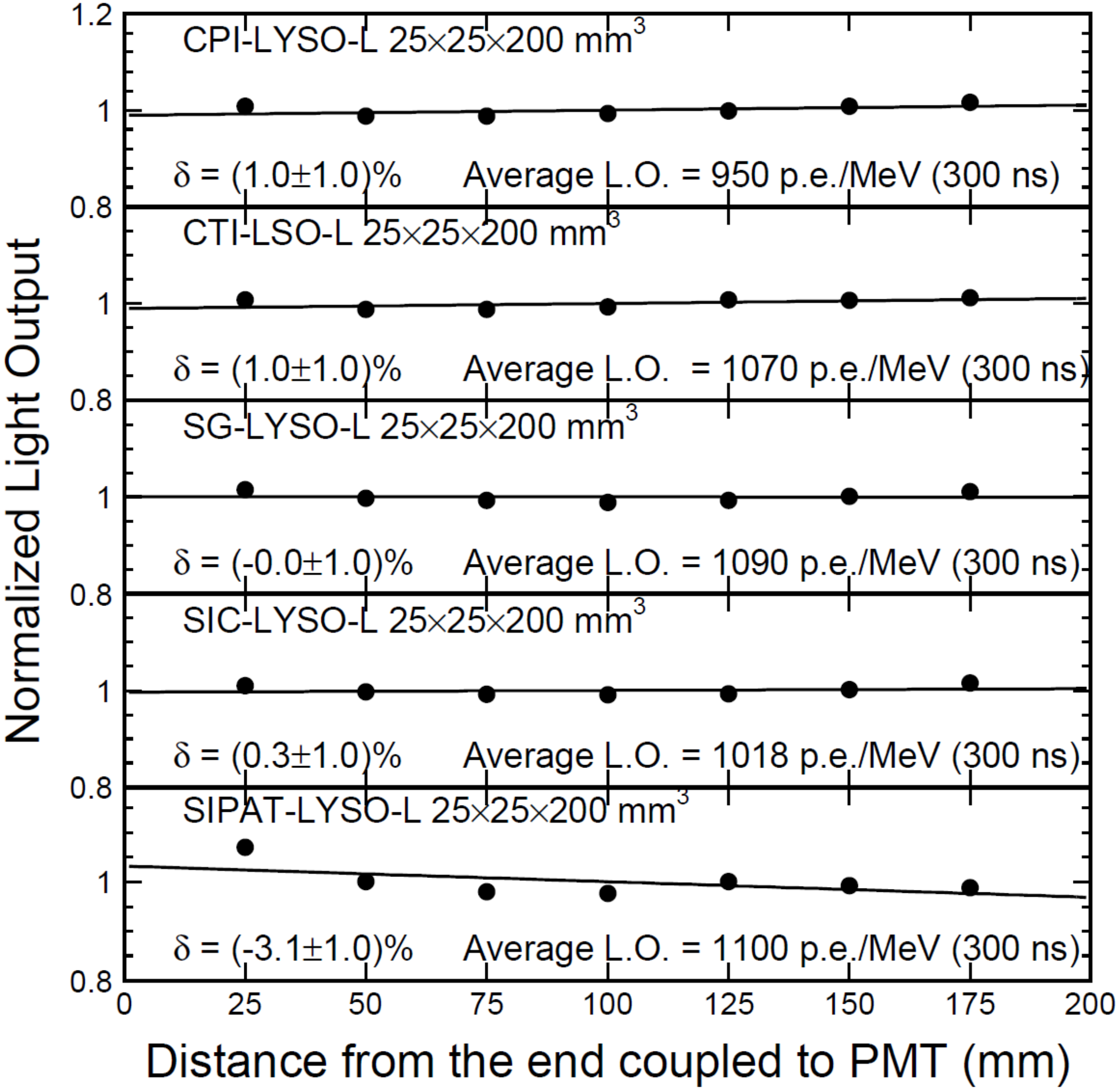
The average peak position of EMLT is at 423 nm.

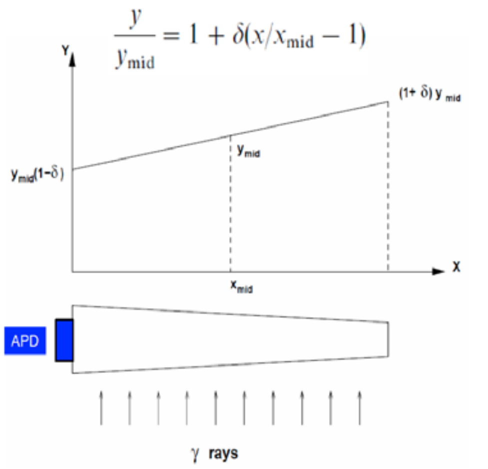
The average FWHM of EMLT is 48 nm:
from 404 nm to 452 nm.

EWLT (Emission Weighted Longitudinal Transmittance), $EWLT = \int Em(\lambda) LT(\lambda) d\lambda$, represents the transparency for the entire emission spectrum.



Initial LO and LRU



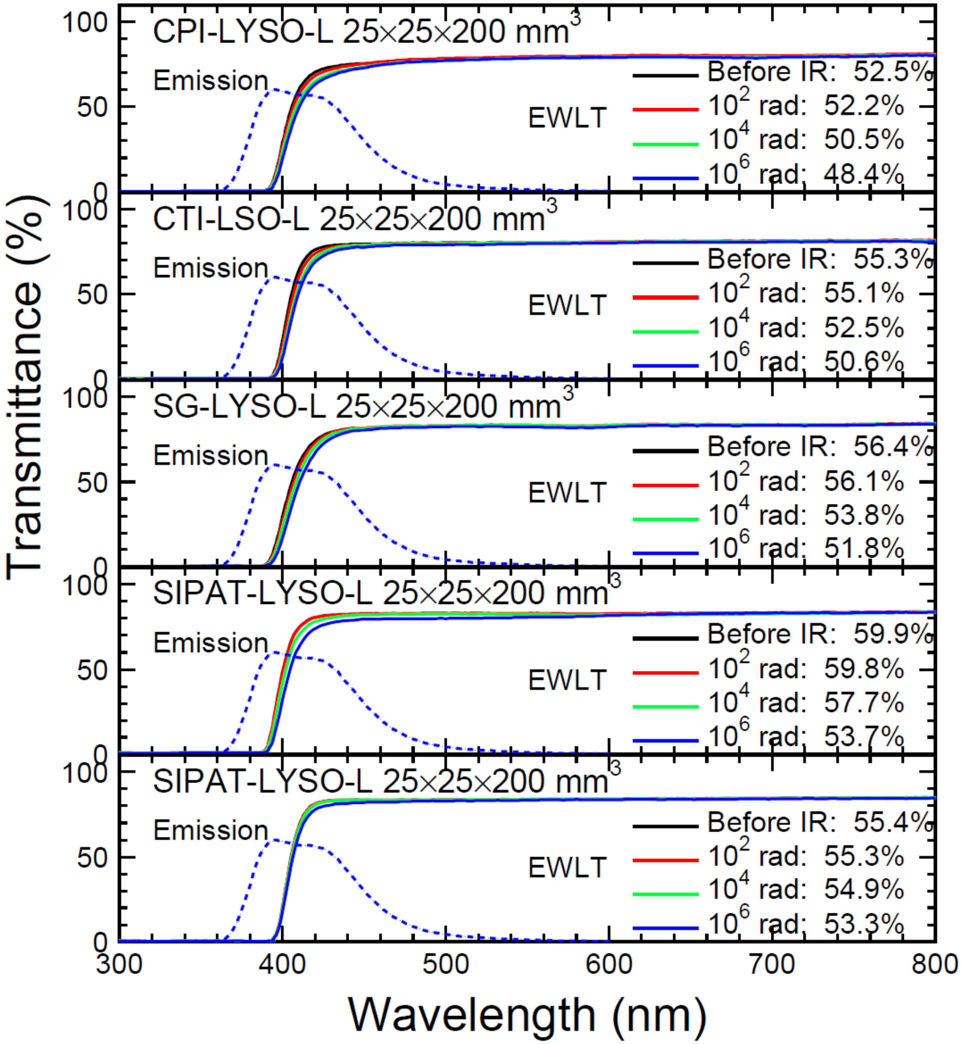


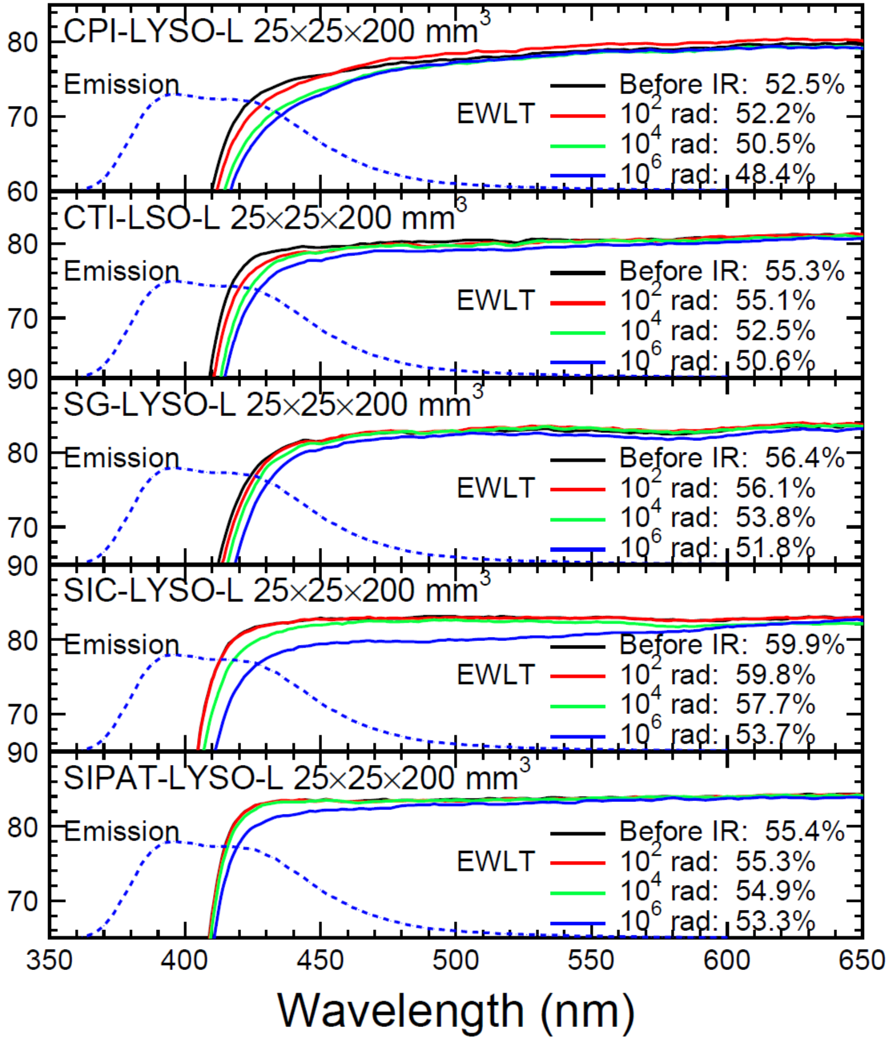
Light output (LO) is defined as the average of seven measurements uniformly distributed along the sample.

All samples have good LO with light response uniformity (LRU) of better than 3%: the self-absorption effect is compensated by [Ce].

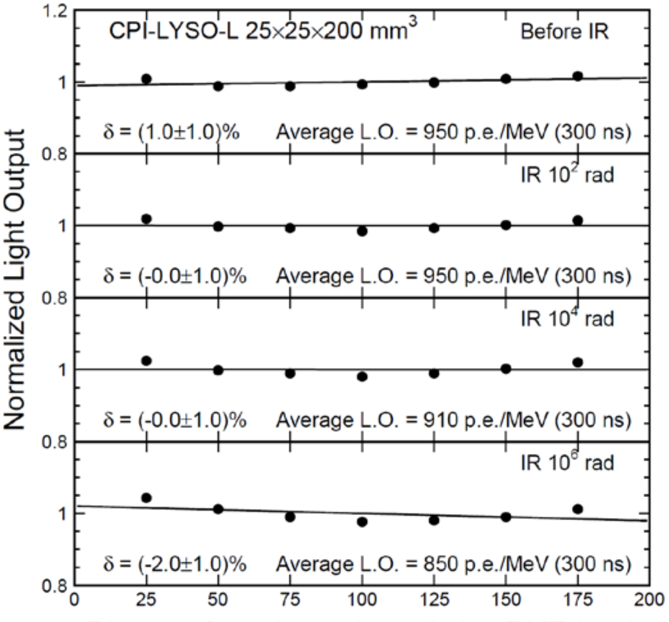
Excellent Radiation Hardness in LT

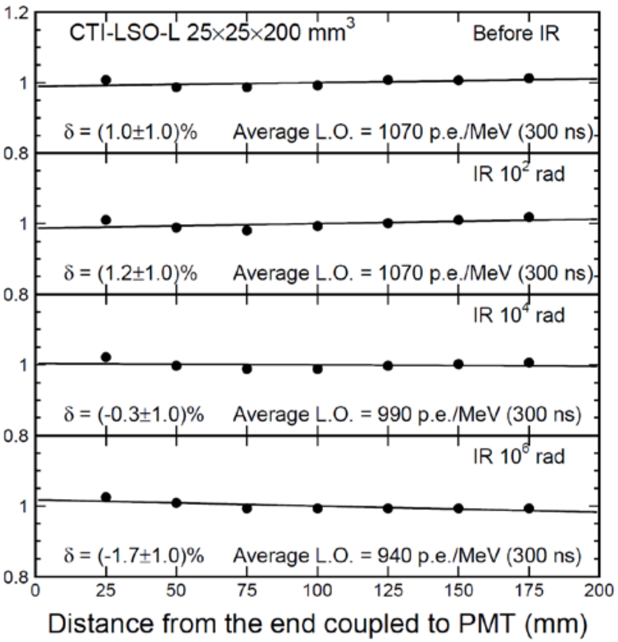
Consistent & Small Damage in LT → Larger variation @ shorter λ

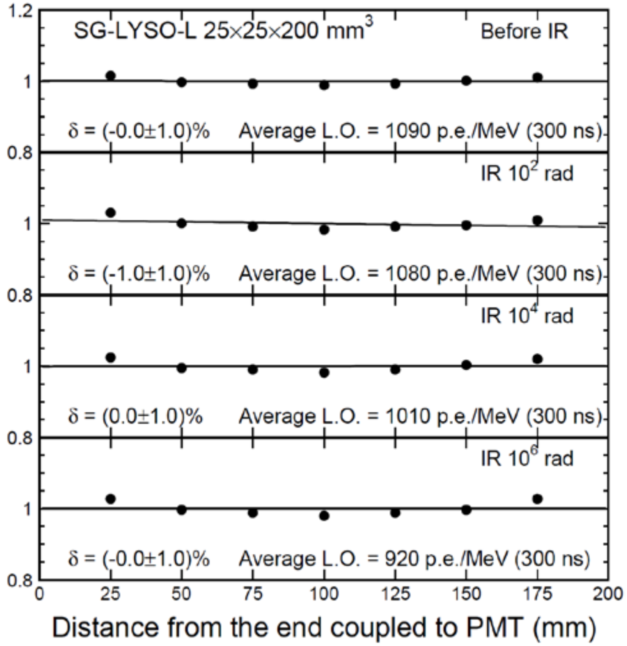


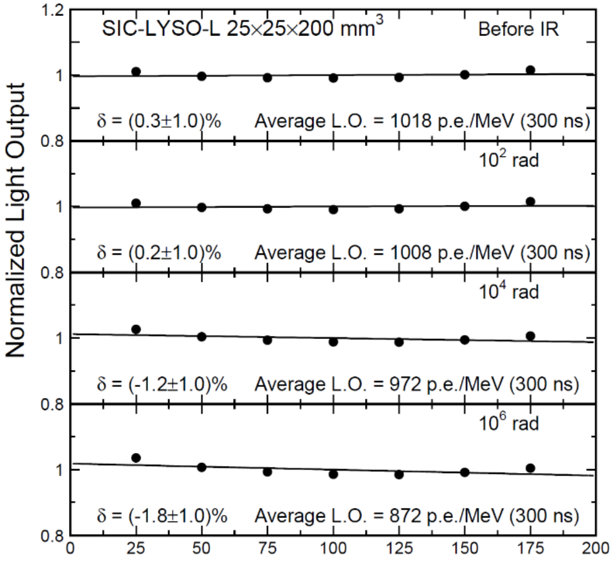


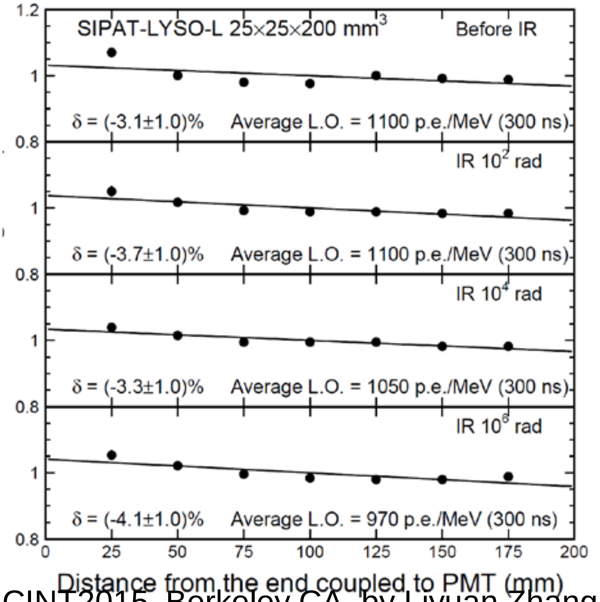
Excellent Radiation Hardness in LO





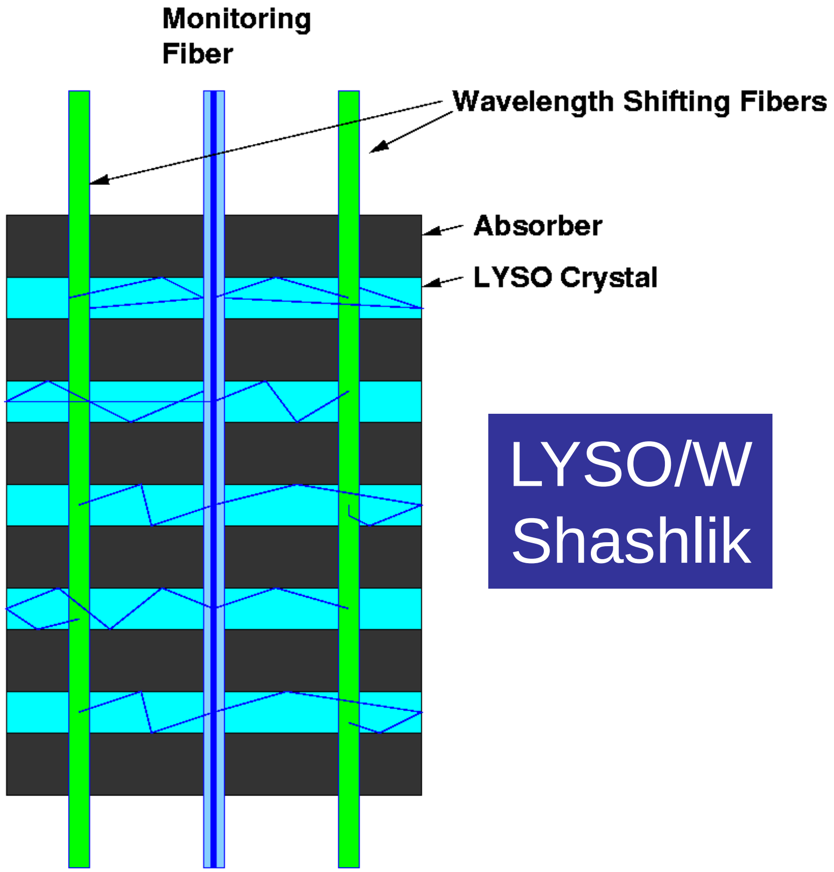




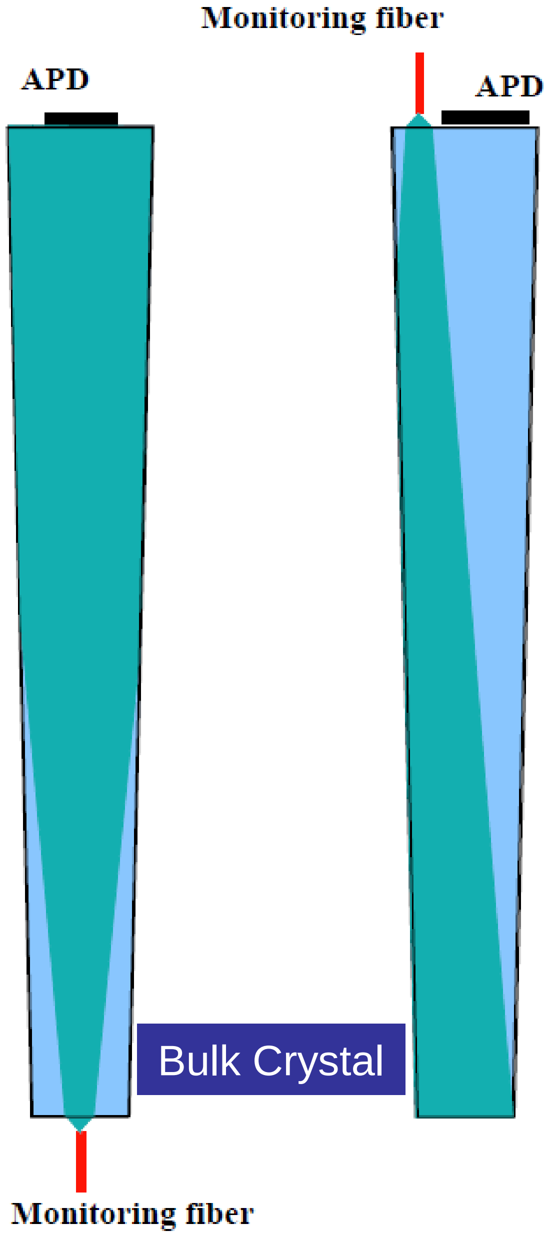


About 12% LO loss observed after 1 Mrad irradiation in all samples with LRU maintained. It can be corrected by light monitoring.

Monitoring with Scintillation Light



LYSO/W Shashlik



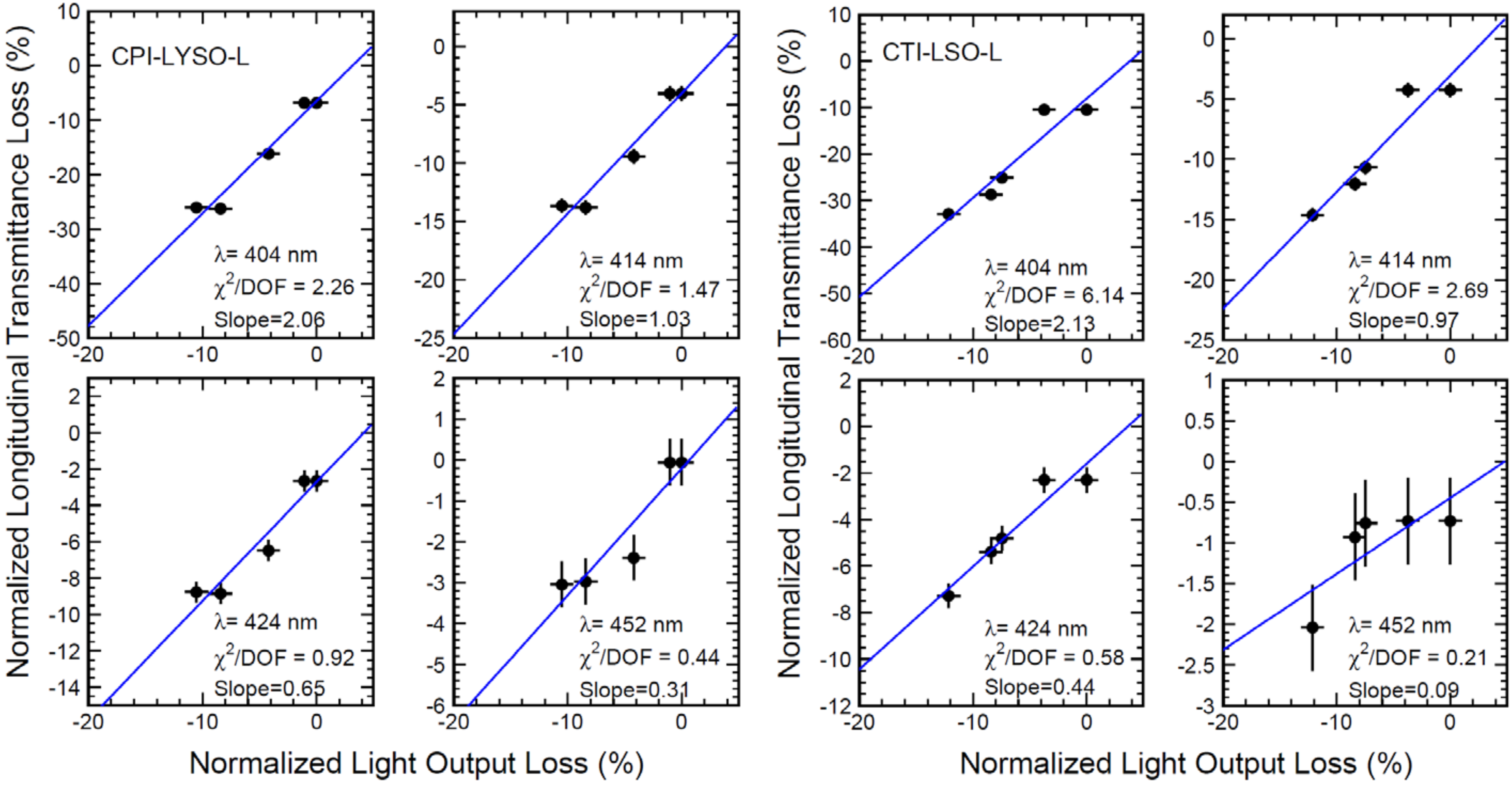
Bulk Crystal

If scintillation mechanism is not damaged, light pulses with a wavelength close to the emission peak would be effective to monitor variations of crystal transparency. CMS at LHC, for example, selects ~440 nm for PWO crystal monitoring.

X.D. Qu *et al*., IEEE TNS VOL. 47, NO. *6*, DECEMBER (2000) 1741-1747

LT Loss vs. LO Loss after Irradiation

Fitting function: $\frac{LT_{IR}-LT_0}{LT_0} = \mathit{Slope} \times \frac{LO_{IR}-LO_0}{LO_0}$



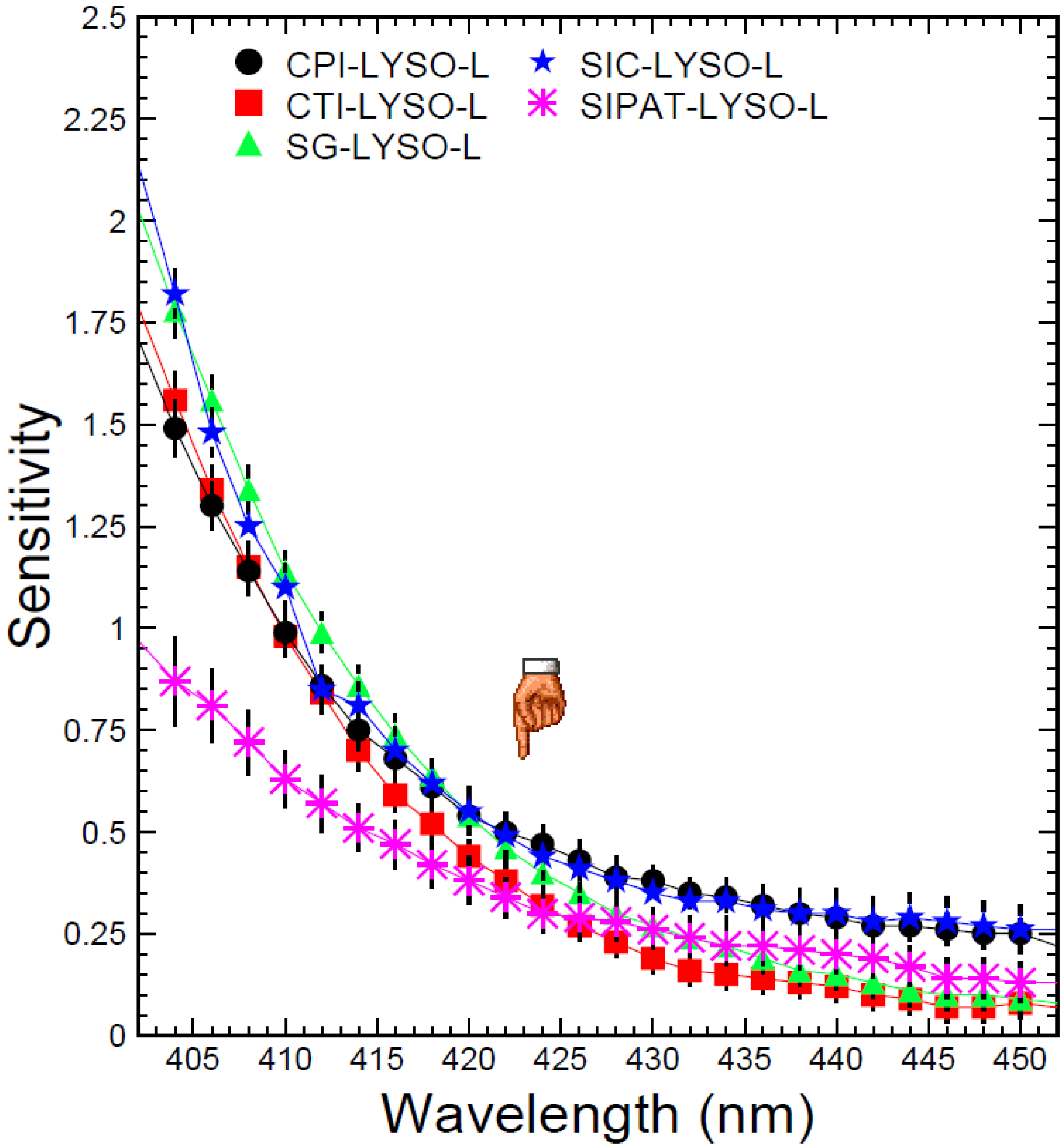
The slope represents the **monitoring sensitivity** at a particular wavelength

Monitoring Sensitivity vs. Wavelength

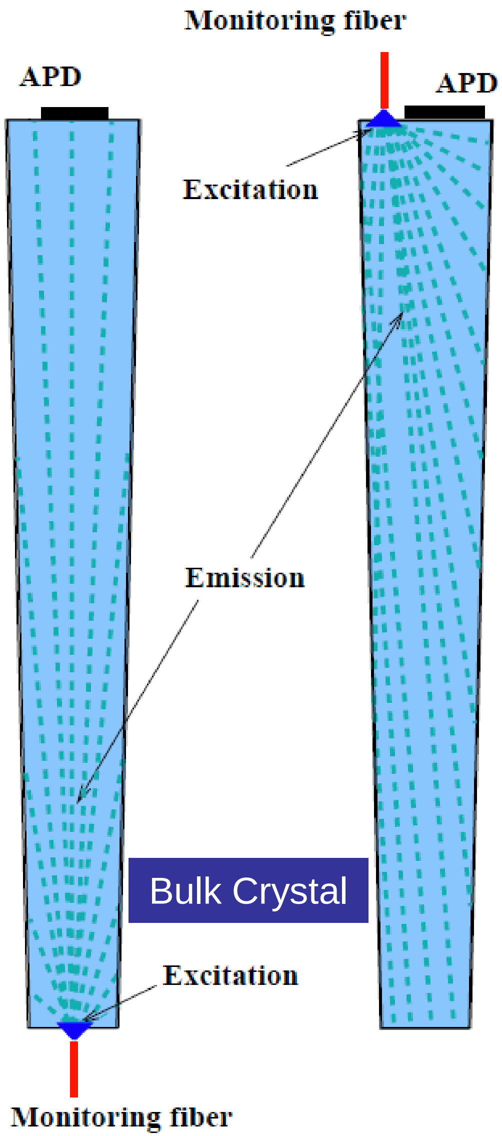
The monitoring sensitivity increases at shorter wavelengths because of larger variation in transparency.

A shorter wavelength is preferred for a better sensitivity. A longer wavelength is preferred for a larger monitoring light signal.

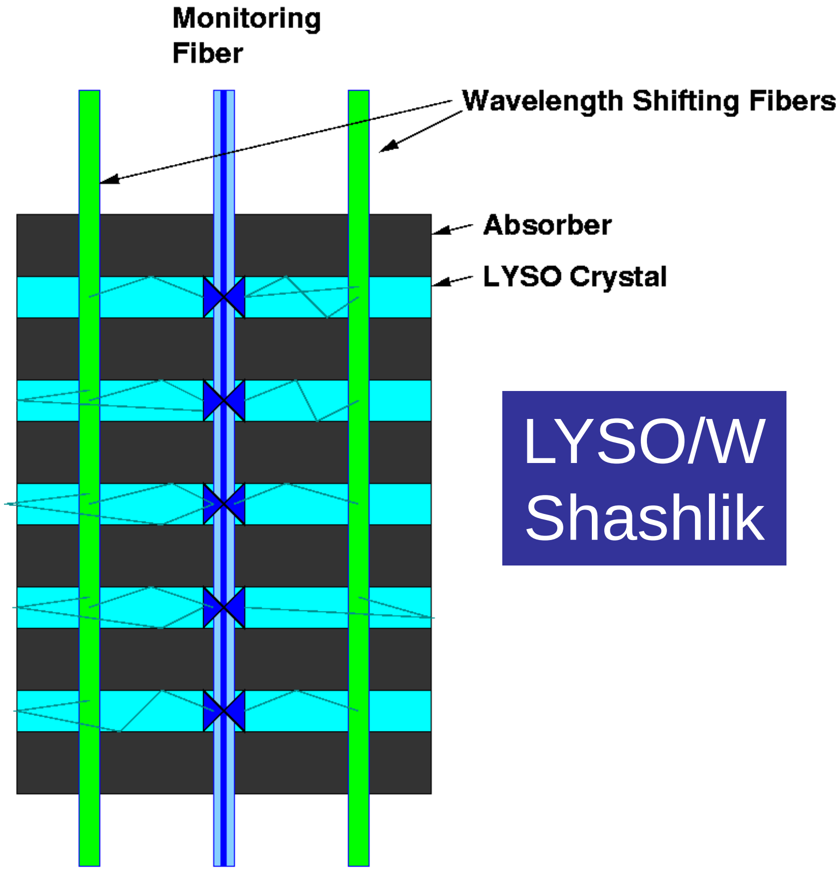
The EMLT peak position at ~423 nm would be the choice. Blue DPSS lasers, however, are expensive.



Monitoring with Excitation Light



Bulk Crystal

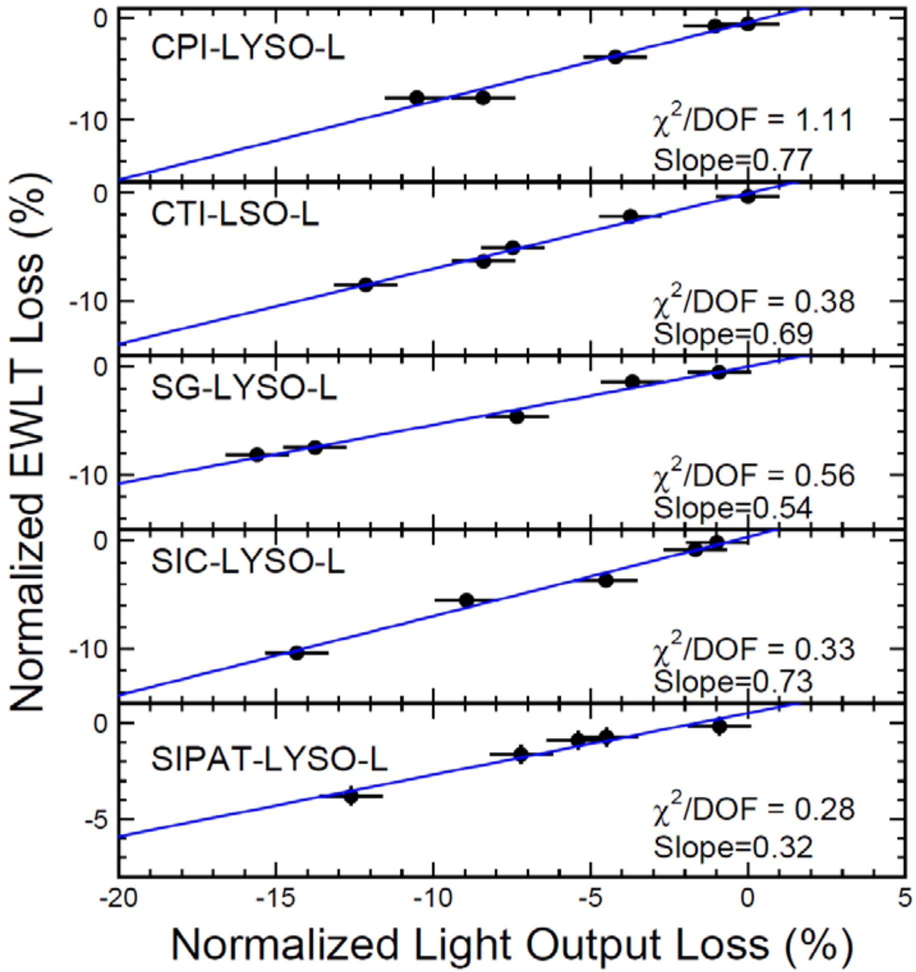


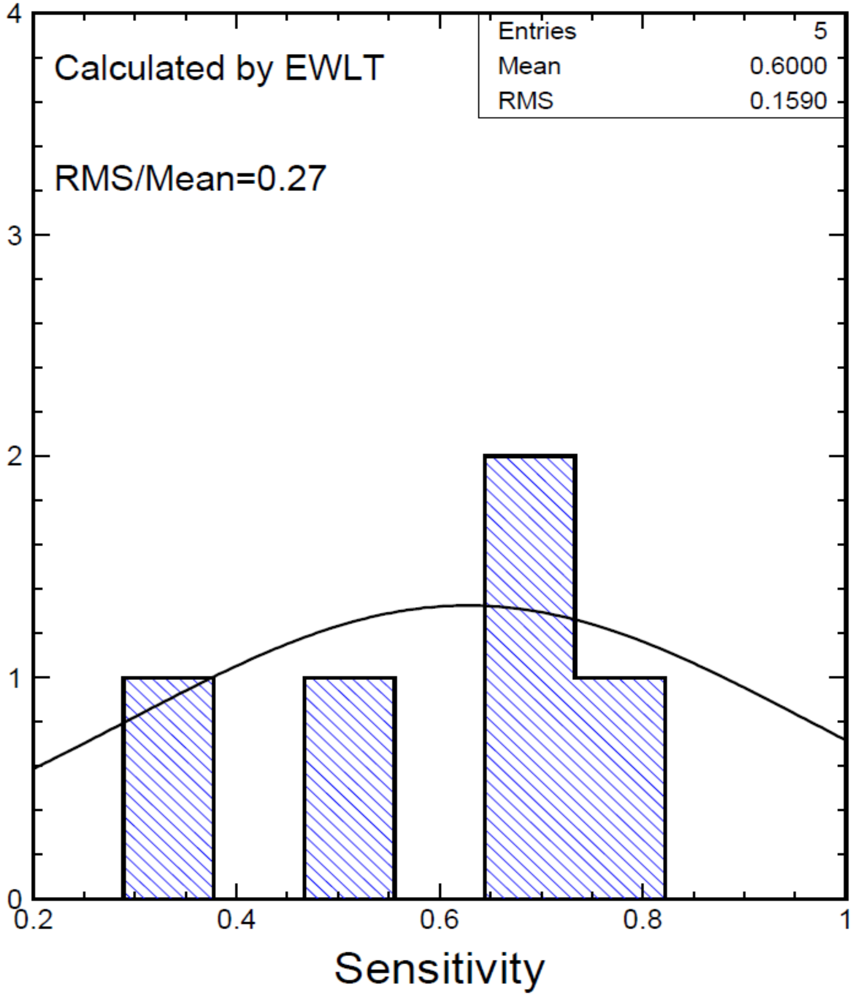
LYSO/W Shashlik

Light pulses with a wavelength at an excitation peak, e.g. 358 nm for LYSO, monitor crystal transparency and photo-luminescence production. PHENIX at RHIC selects 355 nm from an Nd:YAG laser for plastic scintillators. See IEEE Trans. Nucl. Sci.Vol.45, 705-709, 1998.

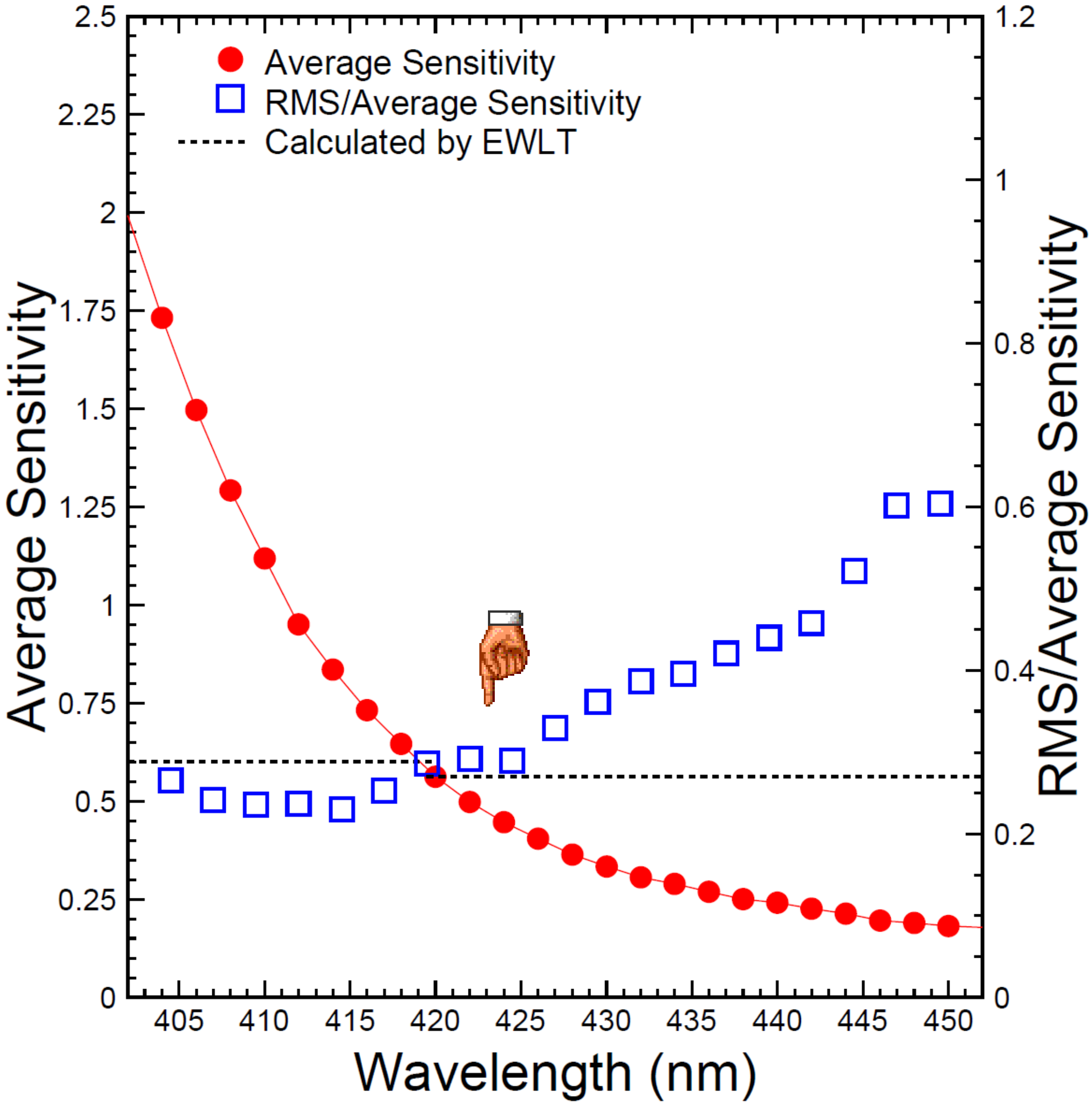
Monitoring Sensitivity with EWLT

RMS/Mean represents the divergence between 5 vendors





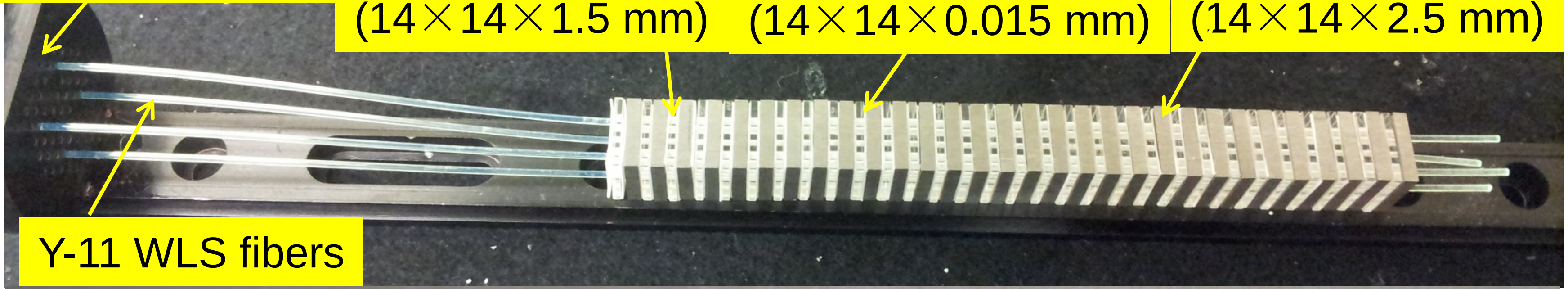
Choice of Monitoring Wavelength



Consistent monitoring sensitivity is observed for both the EWLT for the entire emission spectrum and the wavelength close to the emission peak: 423 nm.

A divergence at 25% level for crystals from five different vendors is observed for both the EWLT and the wavelength close or shorter than the emission peak, which will be improved in mass-production.

A LYSO/W/Al Shashlik Cell



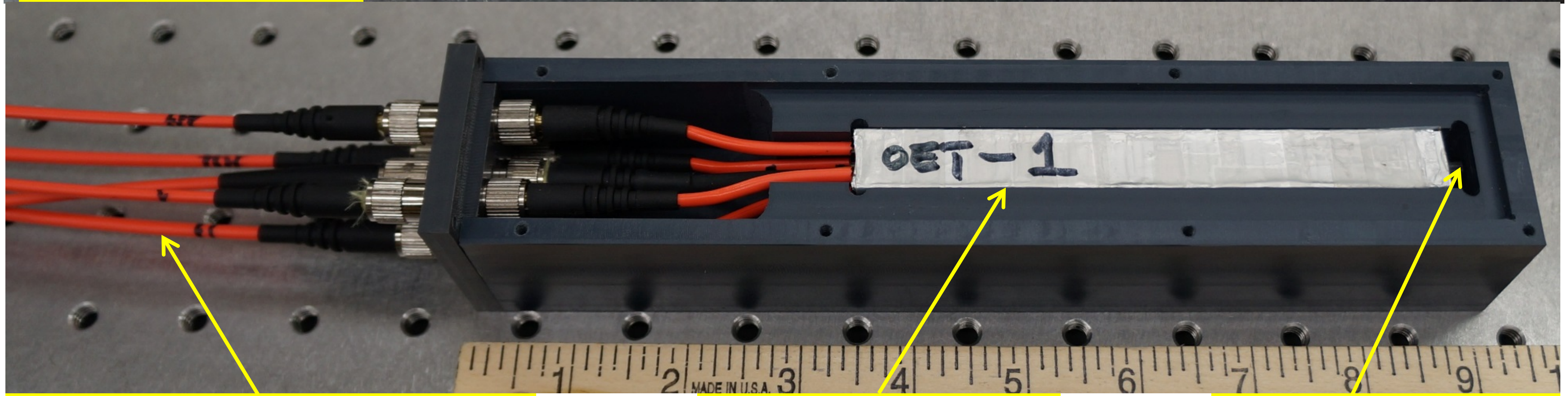
Coupled to PMT

LYSO Plates (14×14×1.5 mm)

Aluminum Foil (14×14×0.015 mm)

W Plates (14×14×2.5 mm)

Y-11 WLS fibers



Monitoring & Y-11 fibers

Al foil wrapping

Monitoring fiber beam dump

Aluminum foil is used because of its excellent radiation hardness

See: https://indico.cern.ch/event/341217/contribution/7/material/slides/0.pdf

LYSO/W Shashlik Cell Radiation Damage

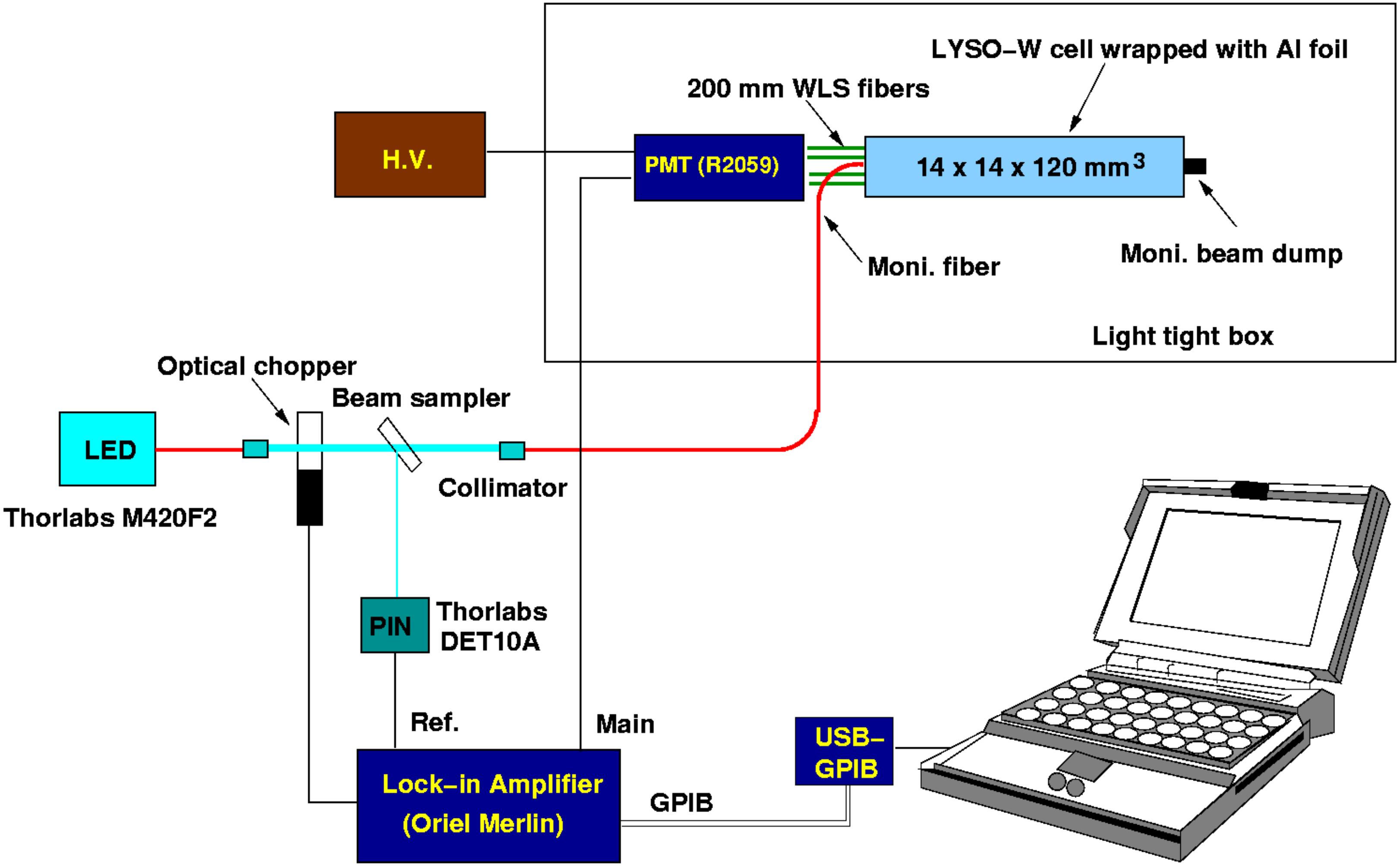
Two LYSO/W/Al Shashlik cells with thirty LYSO plates of 14 x 14 x 1.5 mm were irradiated by Co-60 ɣ-rays at JPL to 90 Mrad with radiation damage measured by a 420 nm LED based monitoring system.

90 Mrad @ 1 Mrad/h

ID	Dimension (mm)
Shashlik (LYSO/W)	14x14x150
LYSO SIC Plate	14x14x1.5
LYSO SIC Plate	14x14x2
LYSO CPI Plate	14x14x2
CeF_3 SIC	33x32x191
BaF_2 SIC2012	20x20x250
PWO SIC	28.5^2x220x30^2
LYSO SIC L2	25x25x200
BGO SIC2011	25x25x200
LYSO SG L2	25x25x200
BGO NIIC	25x25x200

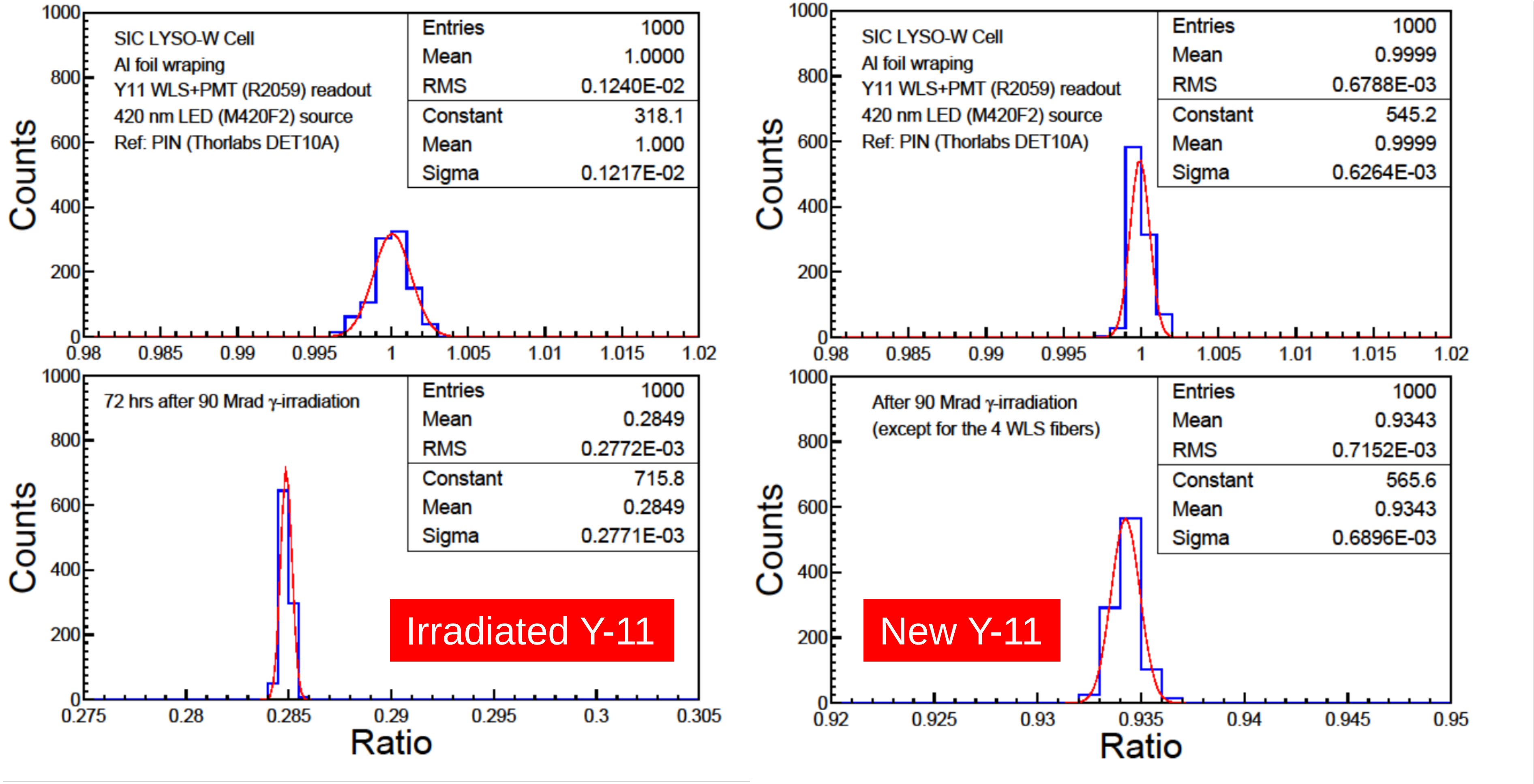
Monitoring LYSO/W/Al/Y-11Cell

Data taken ~72 h after 90 Mrad @ 1 Mrad/h
Systematic uncertainty: 1%, and 3% with fibers replaced



SIC LYSO/W/Al/Y-11

72/7% loss after 90 Mrad @ 1 Mrad/h with irradiated/replaced Y-11

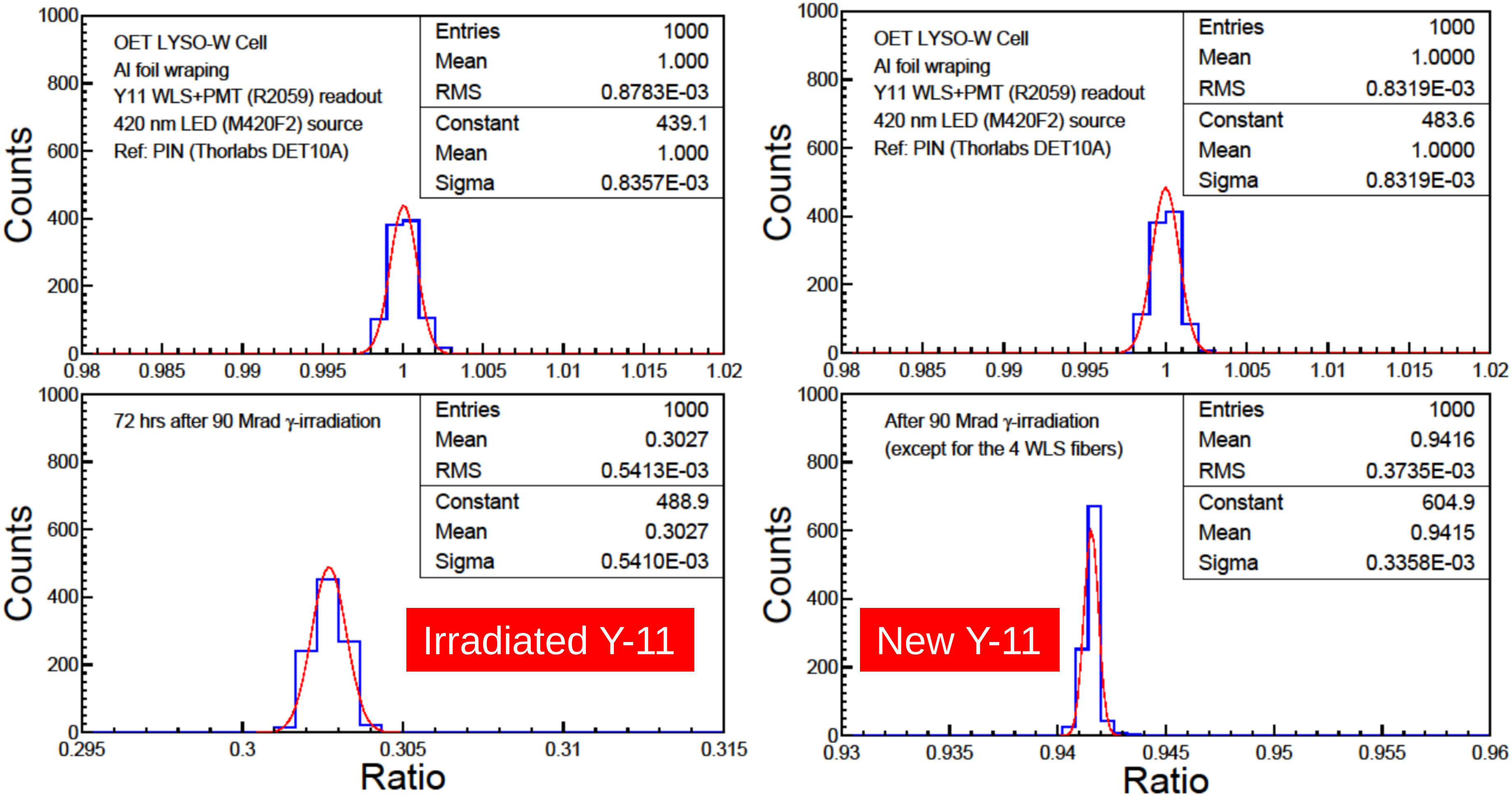


Irradiated Y-11

New Y-11

OET LYSO/W/Al/Y-11

70/6% loss after 90 Mrad @ 1 Mrad/h with irradiated/replaced Y-11



Irradiated Y-11

New Y-11

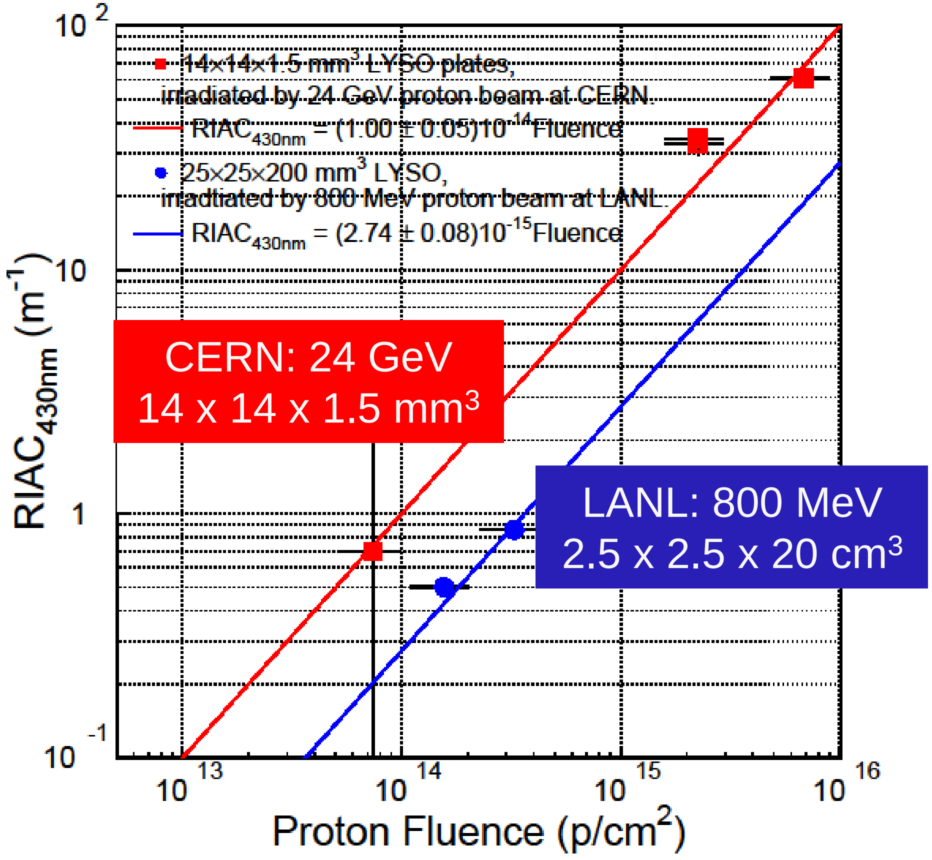
Summary of LYSO/W/Al/Y-11

LYSO/W/Al Cell	WLS Fibers	LED Response (%)
SIC-C1, 90 Mrad	Y-11 Irradiated	29 ± 1
SIC-C1, 90 Mrad	Y-11 Replaced	93 ± 3
OET-C1, 90 Mrad	Y-11 Irradiated	30 ± 1
OET-C1, 90 Mrad	Y-11 Replaced	94 ± 3

- Consistent degradation was found in LYSO/W/Al Shashlik cells constructed by using LYSO plates from SIC and OET.
- After replacing damaged Y-11 fibers with non-irradiated ones the net damage in LYSO/W/Al cells after 90 Mrad @ 1 Mrad/h is measured to be 7%, indicating less than 1%/year caused by ionization dose.
- Combined with the excellent radiation hardness of quartz capillaries, damage at this level is easy to be followed by a light monitoring system *in situ*. Plan to look charged and neutral hadrons at Los Alamos.

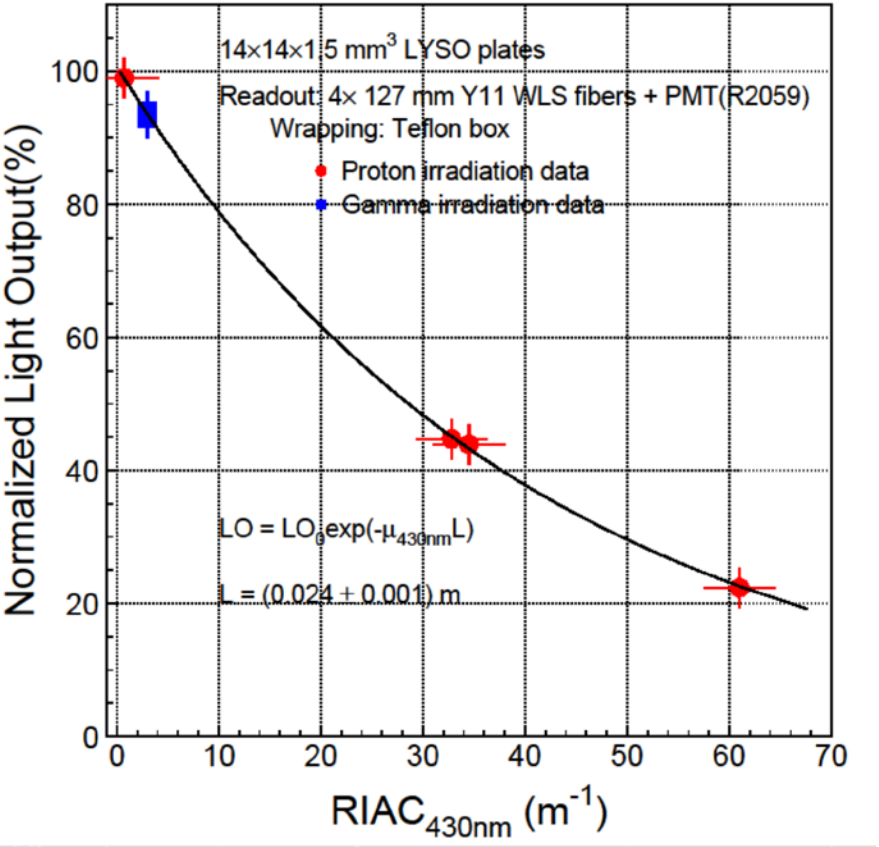
Summary of Proton Damage

A 20 cm long and four 14×14×1.5 mm^3 LYSO crystals were irradiated by 800 MeV and 24 GeV protons respectively at LANL and CERN. The result shows that the expected RIAC at the HL-LHC is a few m^{-1}, indicating loss of 4 and 6% respectively for direct and WLS readout.



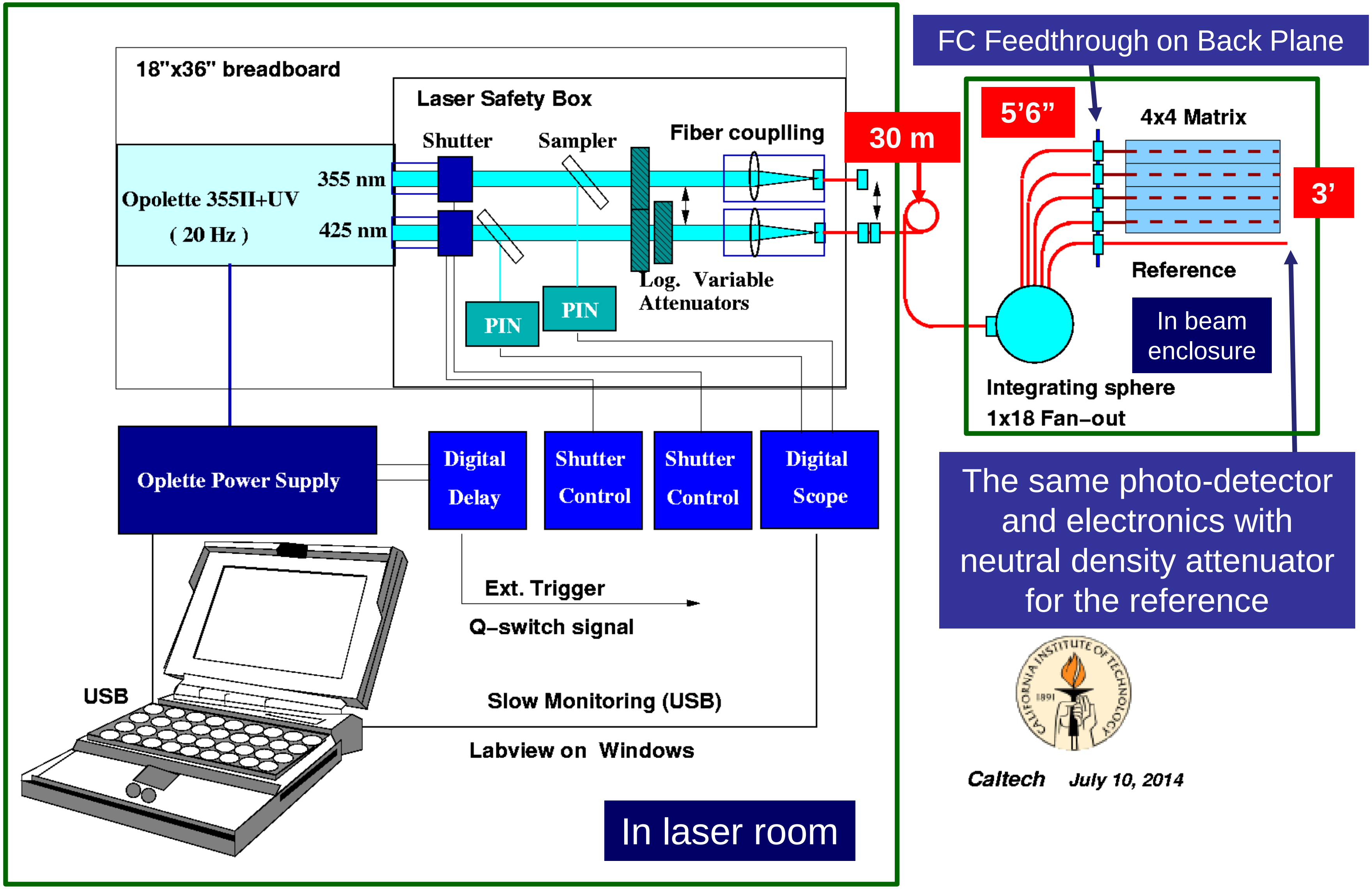
CERN: 24 GeV
14 x 14 x 1.5 mm^3

LANL: 800 MeV
2.5 x 2.5 x 20 cm^3



An Opolette Laser Based Monitoring System

Used in LYSO/W Shashlik beam test at Fermilab



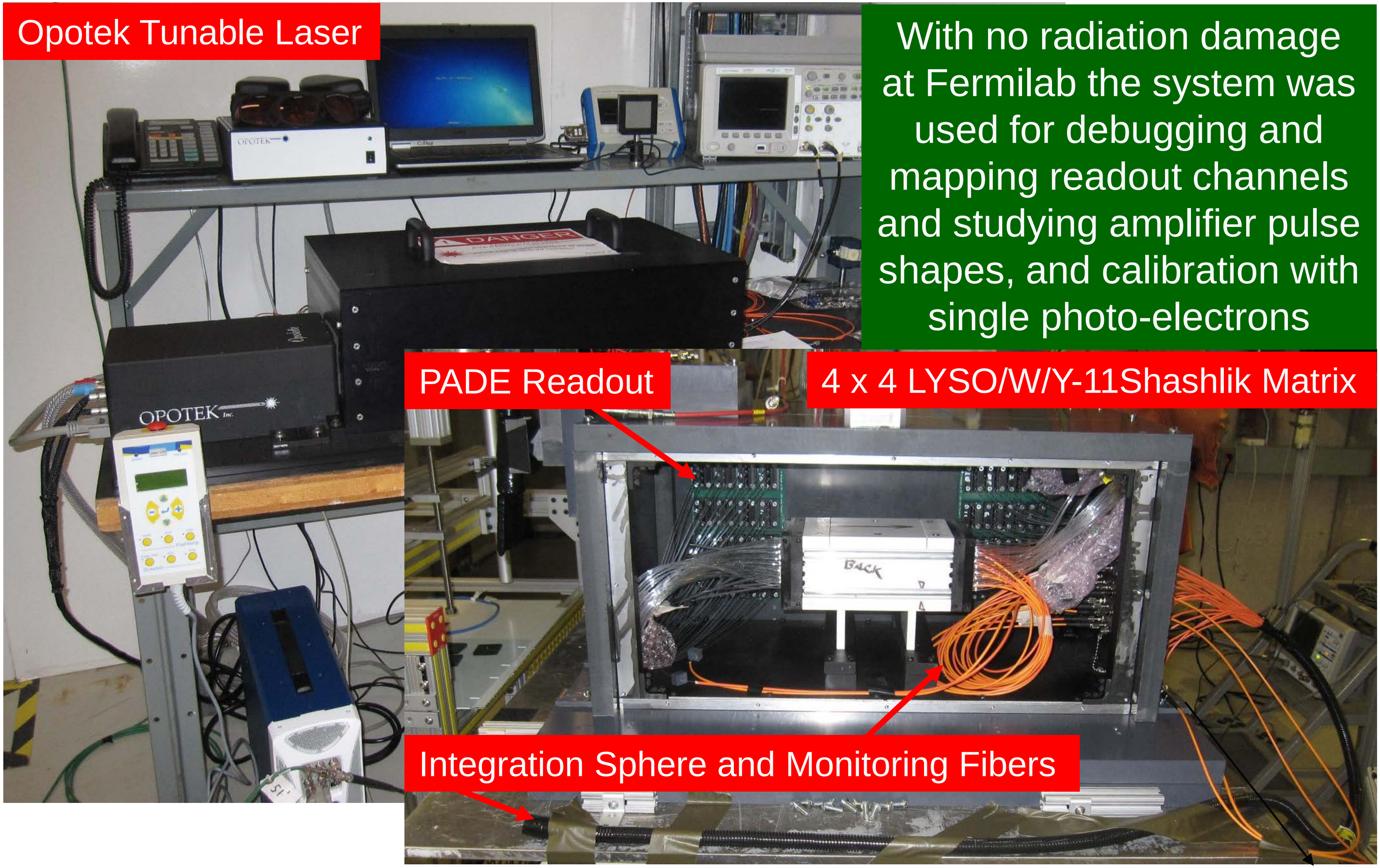
FC Feedthrough on Back Plane

In beam enclosure

The same photo-detector and electronics with neutral density attenuator for the reference

In laser room

Monitoring System at Fermilab



Opotek Tunable Laser

With no radiation damage at Fermilab the system was used for debugging and mapping readout channels and studying amplifier pulse shapes, and calibration with single photo-electrons

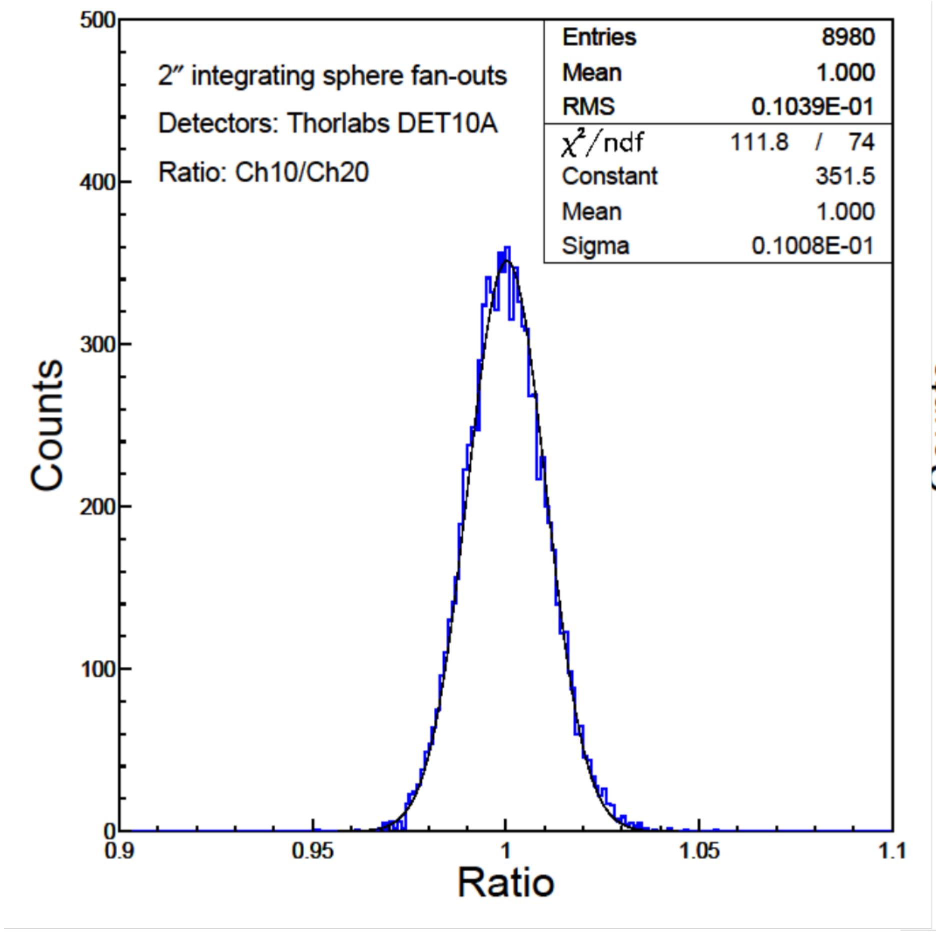
PADE Readout

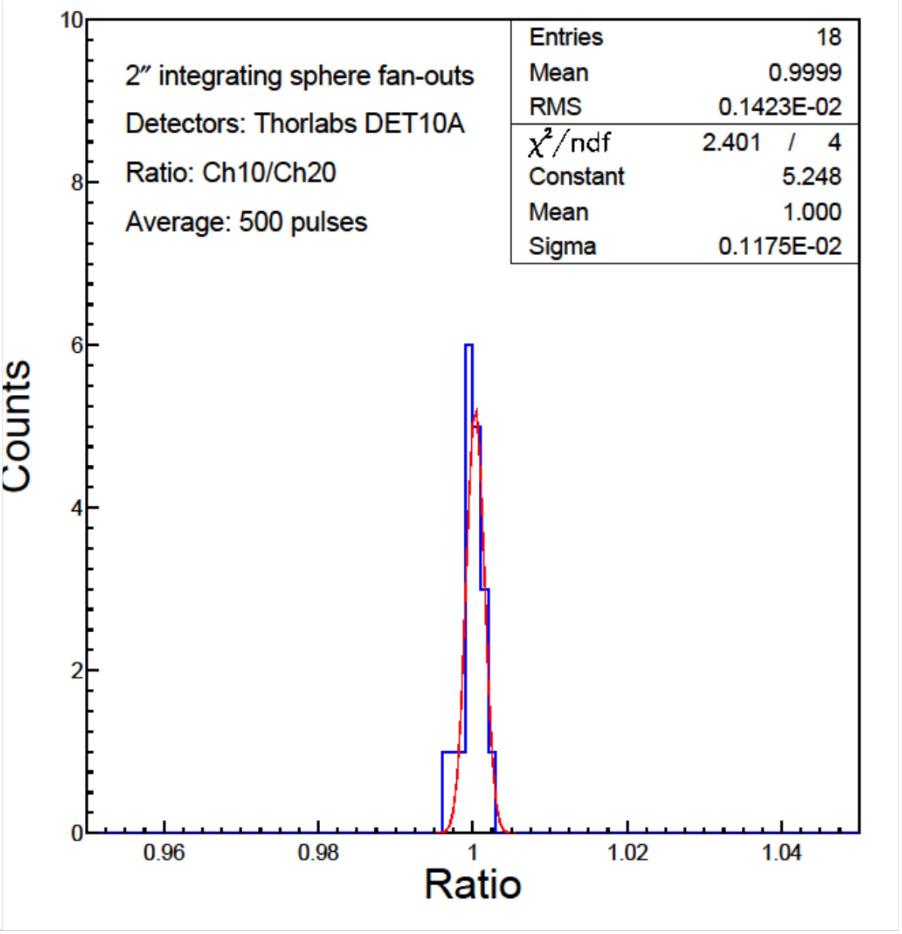
4 x 4 LYSO/W/Y-11Shashlik Matrix

Integration Sphere and Monitoring Fibers

Monitoring Precision

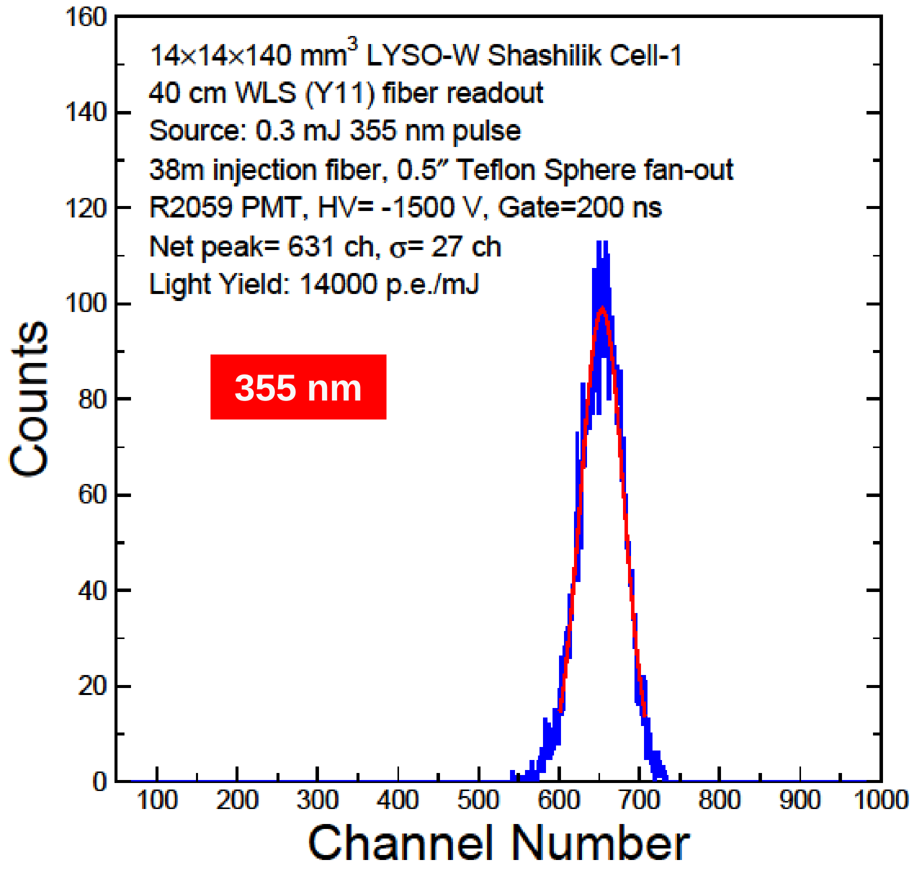
Pulse to pulse monitoring precision: 1%
0.1% reached with average of 500 pulses

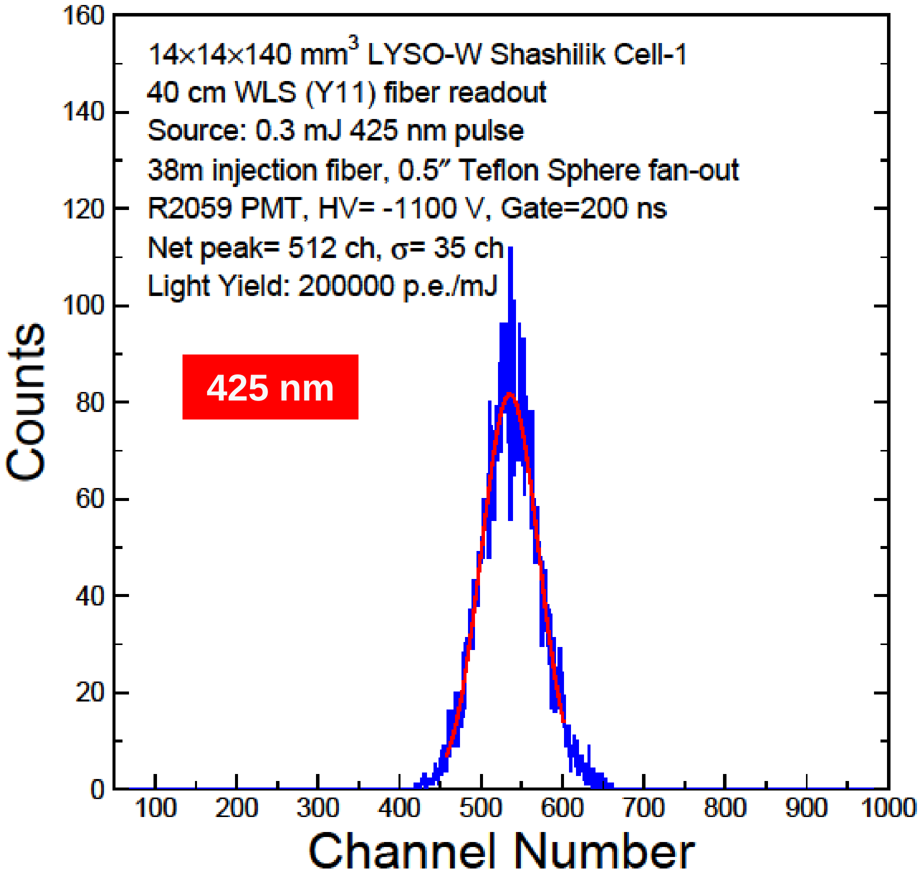




Dynamic Range with Quartz Fiber Leakage

355 nm: 14,000 p.e./mJ, corresponding to 2.5 GeV/mJ
425 nm: 200,000 p.e./mJ, corresponding to 36.5 GeV/mJ

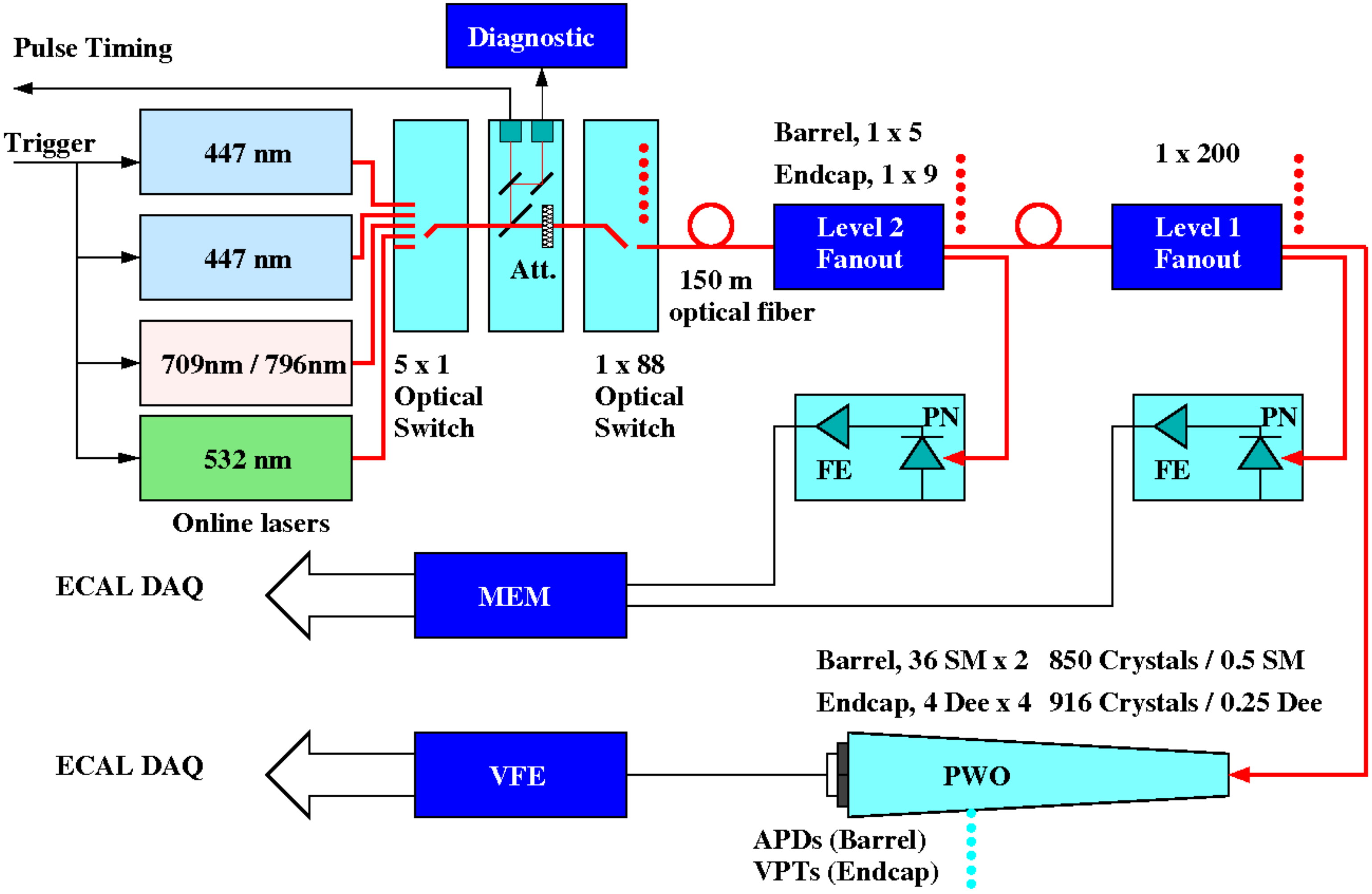




A factor of **15** lower dynamic range for 355 nm caused by excitation and attenuation
Commercial DPSS lasers @ 355 nm have pulse energy of **15** times of the blue

Existing PWO Monitoring System

Total loss from laser source to crystal is 72 dB



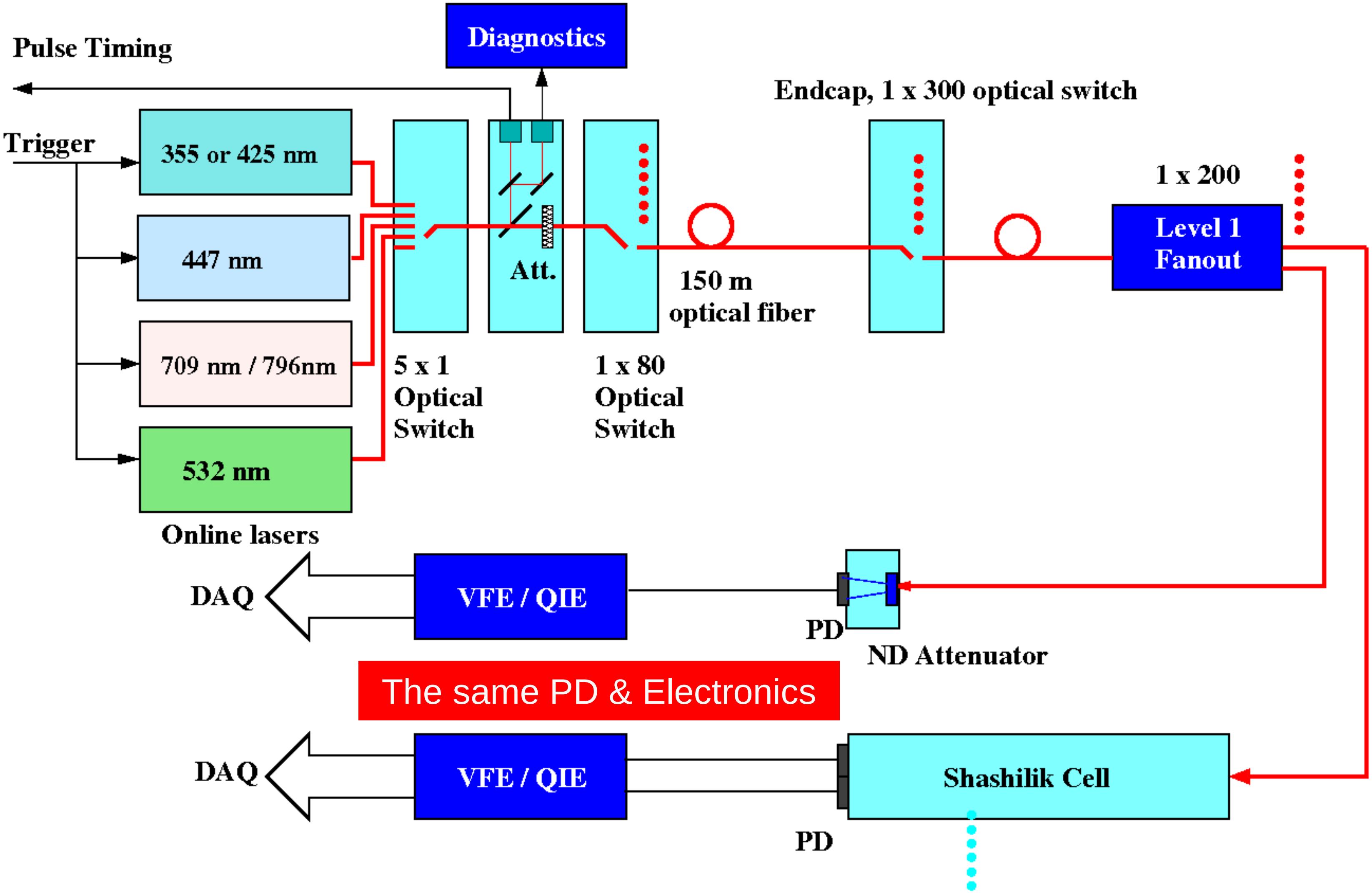
Light Distribution Efficiency

After removing the module conversion efficiency (UV-VIS) the PHENIX system has a total attenuation of 74.5 dB, similar to the 72 dB of the CMS ECAL monitoring system

CMS ECAL Monitoring at 440/447 nm (dB)				PHENIX ECAL (Lead Scintillator) Monitoring at 355 nm (dB)			
	Fanout	Extra	Total		Fanout	Extra	Total
LSDS	0	13	13	LSDS	7.8	0.1	7.9
Optical Fiber (150M)	0	3	3	Optical Fiber (50M)	0	3	3
Level 2 (1:7)	8.5	8.5	17	Level 1 (1:21)	13.3	12.2	25.5
Level 1 (1:240)	24	15	39	Level 2 (1:38)	15.8	10.8	26.6
				Module Conv. Eff. (UV-VIS)	0	31.2	31.2
				Connections and extra	0	11.5	11.5
Total	32.5	39.5	72		36.9	68.8	105.7

A Preliminary Design

1 x 300 switch used to increase the dynamic range



The same PD & Electronics

Dynamic Range

The design on page 28 provides a dynamic range of 140 GeV for an LYSO crystal based total absorption calorimeter by laser pulses of 1 mJ at 425 nm. The corresponding dynamic range for the proposed LYSO/W Shashlik calorimeter is 110 GeV, requiring 15% efficiency of the leaky fiber (or loss <8 dB).

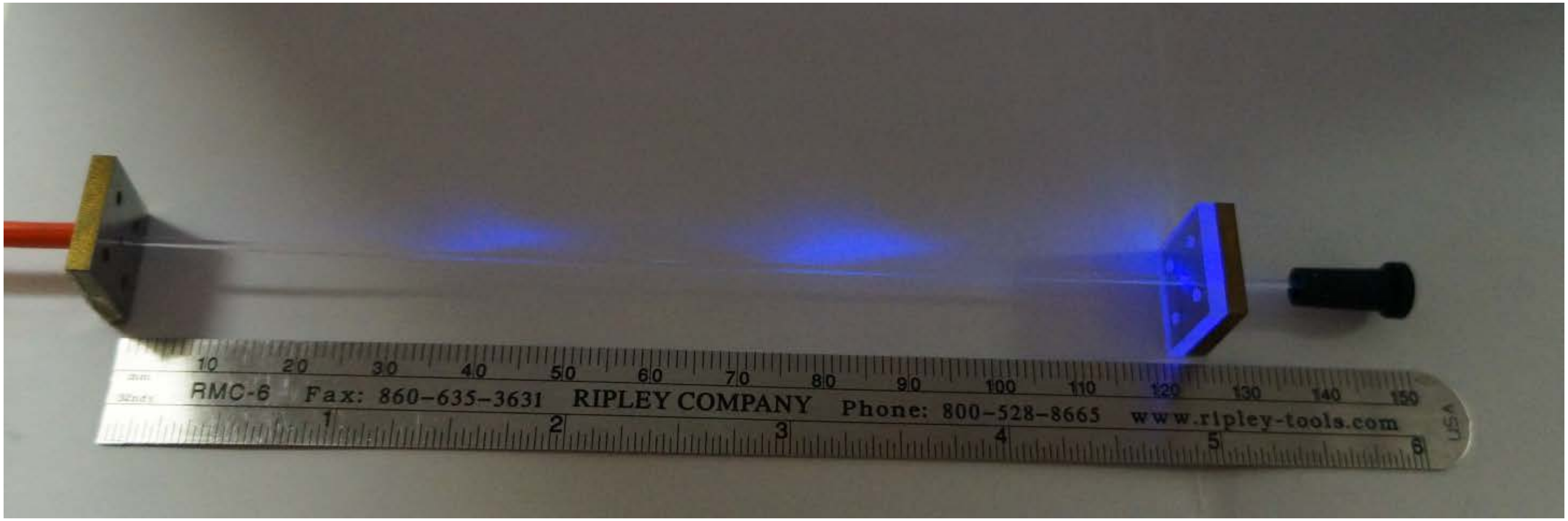
Light Distribution	**Crystal Calorimeter Loss (dB)**	**Shashlik Calorimeter Loss (dB)**
LSDS	13	13
Optical Fiber (150m)	3	3
Optical Switch	2	2
L-1 Fan-out	39	39
Coupling/Leaky Eff.	0	8
Total Loss	57	65
Dynamic Range (GeV) 1mJ@425 nm	140*	110**

*E = 2.1×10^{15} ph. $\times 2.0 \times 10^{-6}$/(30000 ph/MeV) = 140 GeV

** A sampling fraction of 0.2, or a factor of 5, is included in Shashlik dynamic range calculation.

Leaky Quarts Fiber or Rod

Because of its excellent radiation hardness leaky quartz fiber/rod is under investigation for LYSO/W Shashlik calorimeter monitoring. Techniques under study are mechanical scribing, chemical and laser etching etc.



Summary

- LSO/LYSO crystals suffer from transparency loss, leading to light output loss. A light monitoring system is important for keeping precision of the proposed LYSO crystal based calorimeters.
- Because of the small damage level and no recovery the required monitoring frequency for the proposed LYSO/W Shashlik calorimeter is much lower than the ½ hour required for the CMS PWO ECAL.
- The monitoring wavelength for LYSO is 425 nm for transparency and 355 nm for both excitation and transparency.
- By using an optical switch a dynamic range of 100 GeV can be achieved by using commercial lasers with 1 or 15 mJ/pulse for the emission or excitation approach respectively.
- R&D Issues for the monitoring system:
  - An effective light leak system;
  - An efficient level 1 split; and
  - Radiation hardness of monitoring components.