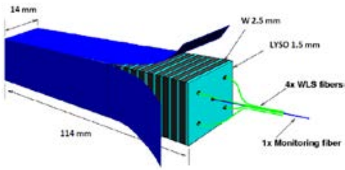

Radiation Damage in LYSO Crystals Induced by Neutrons and Protons

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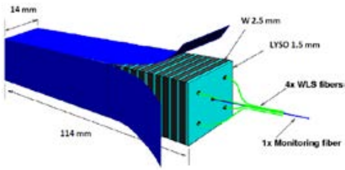
April 9, 2015

Introduction



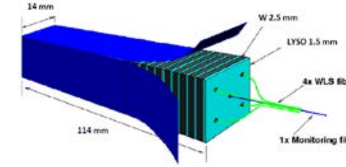
- Three LYSO plates of 14 x 14 x 1.5 mm were irradiated at Caltech by fast neutrons from a pair of Cf-252 source up to 4 x 10^{13} n/cm^2.
- Nine LYSO plates of 14 x 14 x 1.5 mm were irradiated by protons at CERN (24 GeV) and UC Davis up to 6.9 x 10^{15} and 9.5 x 10^{13} p/cm^2 respectively.
- Six LYSO/LSO/LFS crystals of 20 cm long from different vendors were irradiated by ɣ-rays at JPL up to 180 Mrad [1].
- Two LYSO/W/Al Shashlik cells with thirty LYSO plates of 14 x 14 x 1.5 mm were irradiated by ɣ-rays at JPL to 90 Mrad [2].
- One LYSO crystal of 20 cm long and four sealed capillaries of 5.5 cm long were irradiated by protons at Los Alamos (800 MeV) to 3.3 x 10^{14} and 2.7 x 10^{14} p/cm^2 respectively [3].

[1] https://indico.cern.ch/event/379443/contribution/1/material/slides/0.pdf

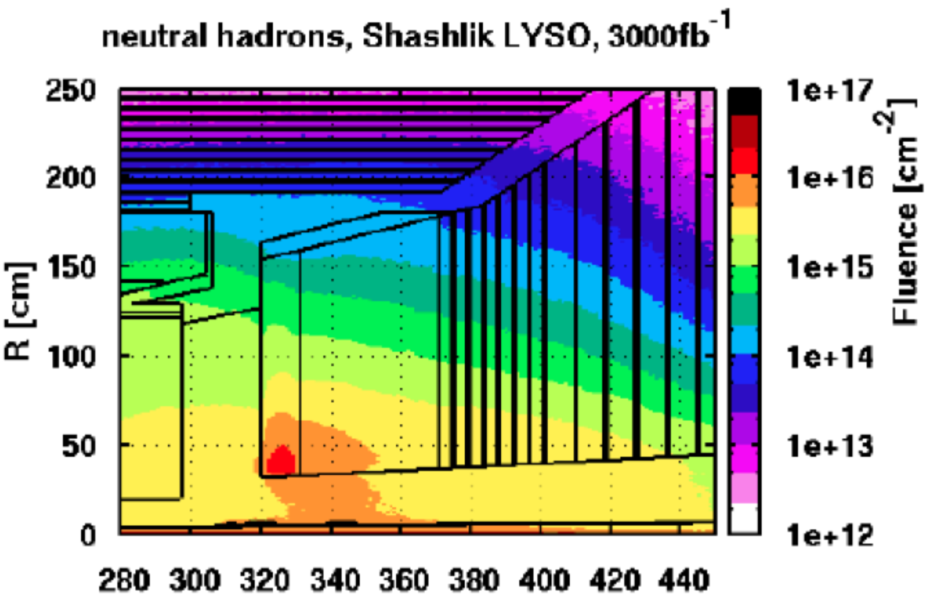
[2] https://indico.cern.ch/event/354810/contribution/5/material/slides/0.pdf

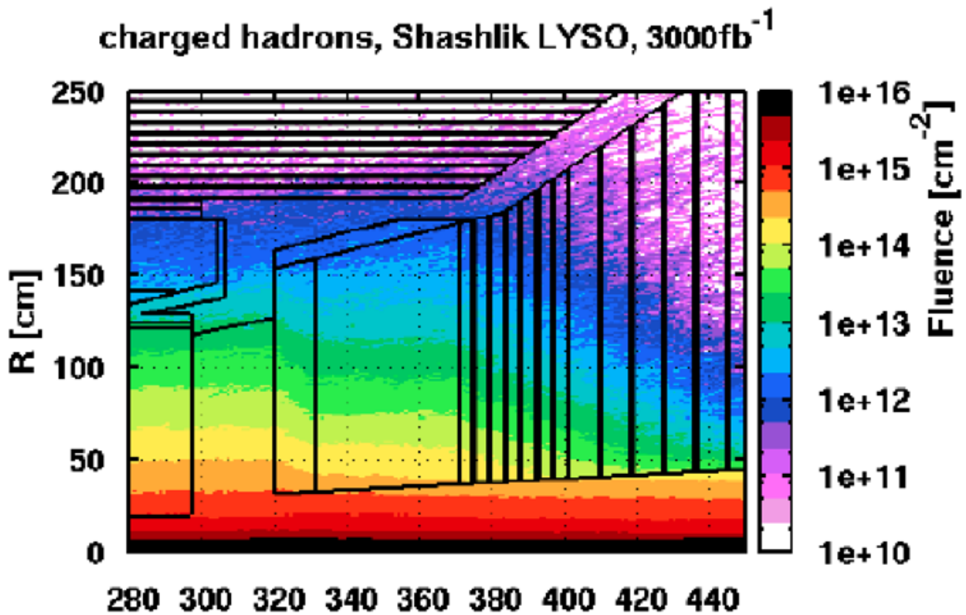
[3] https://indico.cern.ch/event/368990/contribution/2/material/slides/0.pdf

Hadron Fluence @ 3,000 fb^{-1}



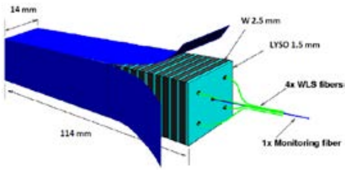
Expected neutral and charged hadron fluence is $5 \times 10^{15}/cm^2$ and $3 \times 10^{14}/cm^2$ respectively for the proposed Shashlik endcap at $|\eta| = 3$





No experimental data show that hadrons (charged or neutral) of > 20 MeV would damage scintillators equally, so they are treated separately

Expected Fluence from FLUKA

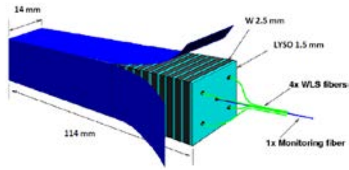


CMS Radiation	LHC (10^{34} $cm^{-2}s^{-1}$, 500 fb^{-1})		HL-LHC (5×10^{34} $cm^{-2}s^{-1}$, 3000 fb^{-1})	
	Barrel (max)	Endcap (max)	Barrel (max)	Endcap (max)
Absorbed dose (rad)	**3.50E+05**	**2.10E+07**	2.10E+06	1.26E+08
Dose rate (rad/h)	25	1512	126	7560
Fast neutrons fluence (E>100KeV, cm^{-2})	**3.00E+13**	**8.00E+14**	1.80E+14	4.80E+15
Fast neutrons flux (E>100KeV, $cm^{-2}s^{-1}$)	6.00E+05	1.60E+07	3.00E+06	8.00E+07
Charged hadrons fluence (cm^{-2})	**4.00E+11**	**5.00E+13**	2.40E+12	3.00E+14
Charged hadrons flux ($cm^{-2}s^{-1}$)	8.00E+03	1.00E+06	4.00E+04	5.00E+06

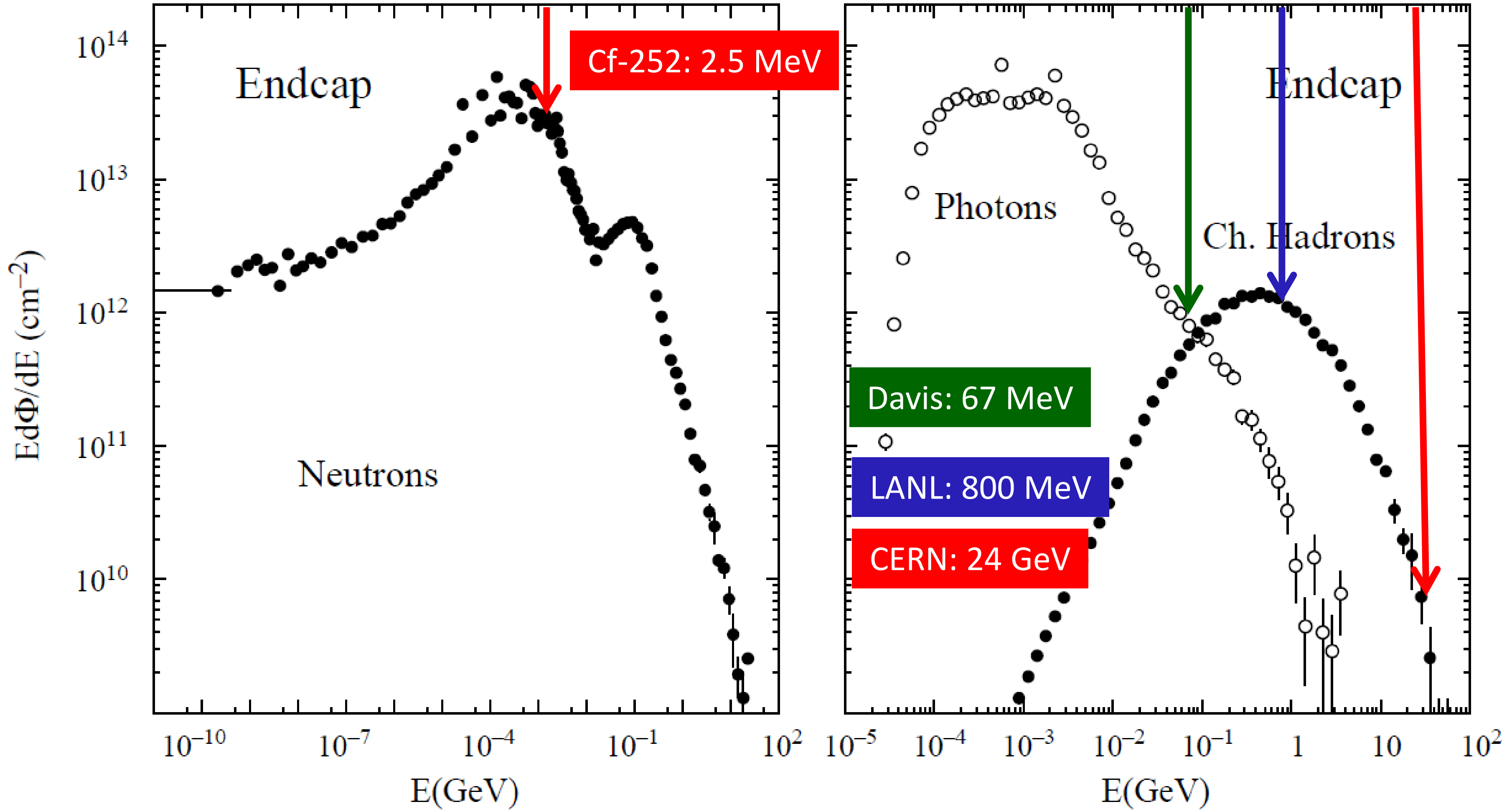
ɣ-rays: Up to 130 Mrad at 7.6 krad/h, See [1] and [2]
Fast Neutrons: Up to 5 x 10^{15} n/cm^2 at 8 x 10^7 n/cm^2/s
Charged hadrons: Up to 3 x 10^{14} p/cm^2 at 5 x 10^6 p/cm^2/s

Data on slides 4 and 5 are from ECAL TDR for PWO
Minor adjustment will be made for the Shashlik TDR

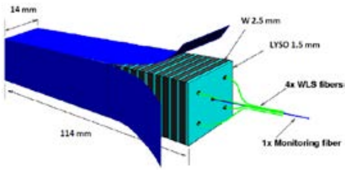
Energy Spectra Expected at HL-LHC



The peak energy of charged hadron at CMS endcap is hundreds MeV
Proton energy in irradiations: 67 MeV/800 MeV/24GeV @ Davis/LANL/CERN
Neutron energy used in irradiation: 2.5 MeV from a pair of Cf-252 source



No Neutron Damage in PWO

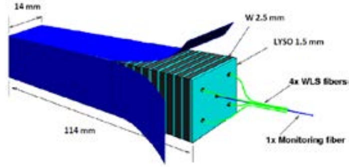


5.2 Radiation damage effects under neutron irradiation

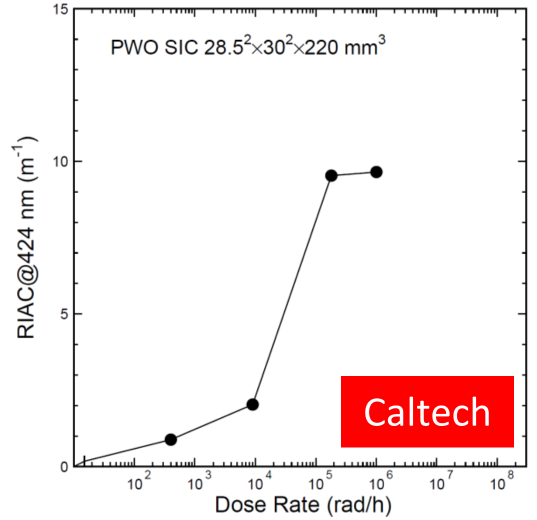
In view of the intense neutron flux expected in CMS (see section 2) the effects on lead tungstate of neutron exposure were studied in nuclear reactors [47, 48]. The neutron fluxes and energies in these exposures were comparable to those expected in CMS. However, in reactors there is a strong associated gamma dose. The effect arising from neutrons was estimated by comparing the reactor results with results obtained from pure gamma irradiations. This indicated that there was no specific effect due to neutrons on the optical and scintillating properties of lead tungstate, at least up to fluences of 10^{14} cm^{-2}. This was confirmed by later independent studies [49]. It is also to be mentioned that recent tests performed at a very high fluence, of the order of 10^{19} to 10^{20} n·cm^{-2} and 330 MGy (i.e. well above the level that will be ever achieved in any physics experiment) revealed the robustness of lead tungstate crystals which were not destroyed nor locally vitrified, and remained scintillating after such heavy irradiation [50].

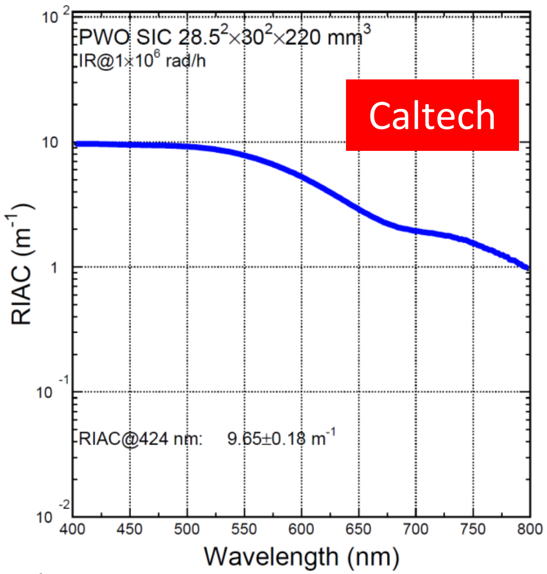
The CMS Electromagnetic Calorimeter Group, ***Radiation hardness qualification of $PbWO_4$ scintillation crystals for the CMS Electromagnetic Calorimeter,*** 2010 JINST 5 P03010

A Saclay Paper on Neutron Damage to E19



Gamma Irradiation at JPL





7.8E18/1.2E19/4.0E19 n/cm² for fast/epithermal/thermal n
The dose received is estimated to 330E8 rad (3E8 rad/h)

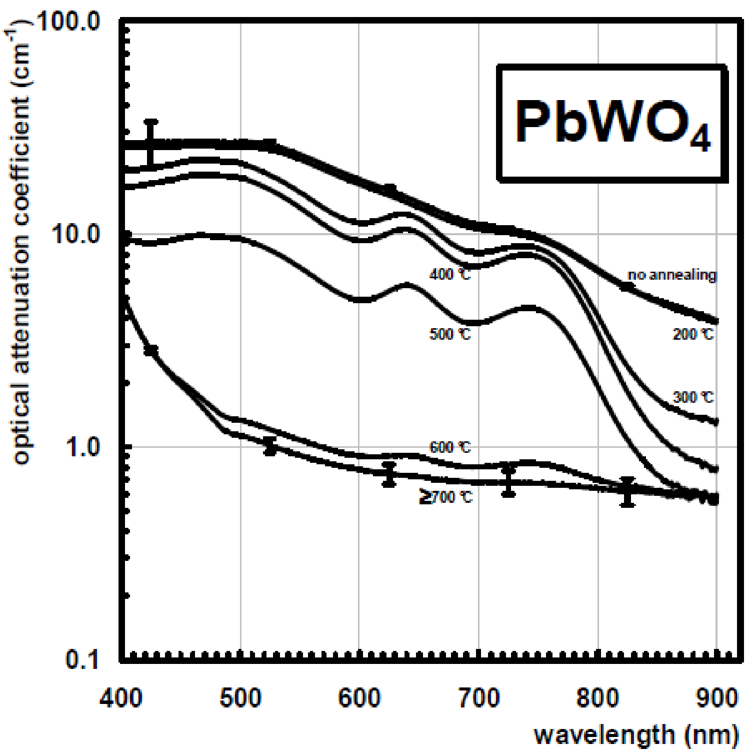
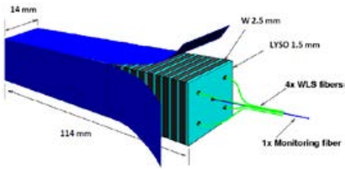
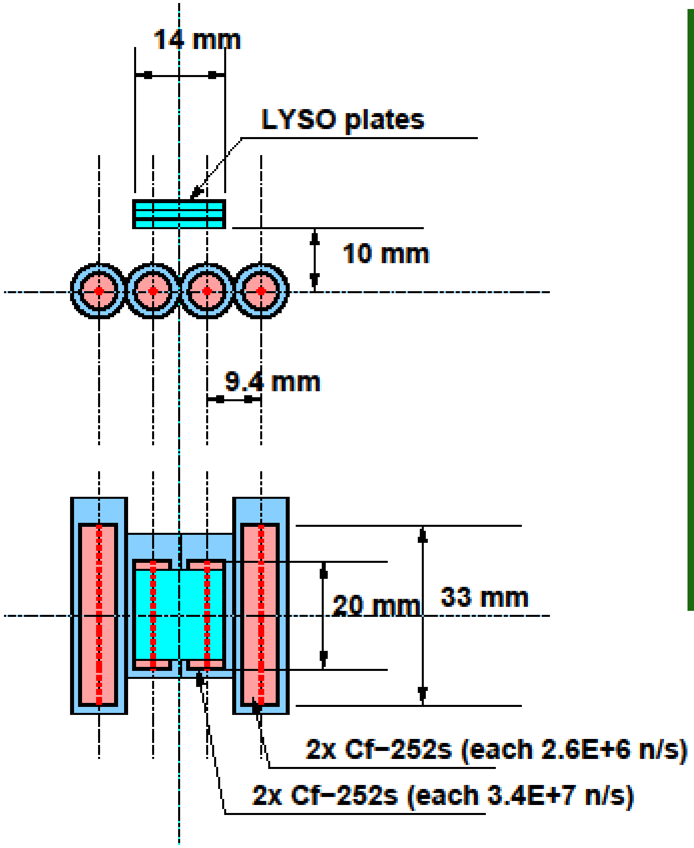


Fig. 2. Optical attenuation coefficient of the irradiated sample before annealing and after successive annealing temperatures.

[50] R. Chipaux et al., ***Behaviour of PWO scintillators after high fluence neutron irradiation,*** in Proc. 8th Int. Conference on Inorganic Scintillators,SCINT2005, A. Getkin and B. Grinyov eds, Alushta, Crimea, Ukraine, September 19–23 (2005), pp. 369–371

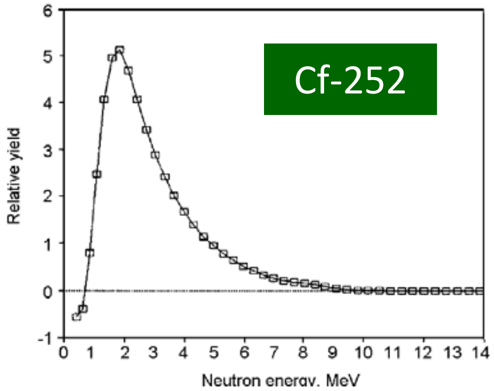
Cf-252 Setup for LYSO Plates

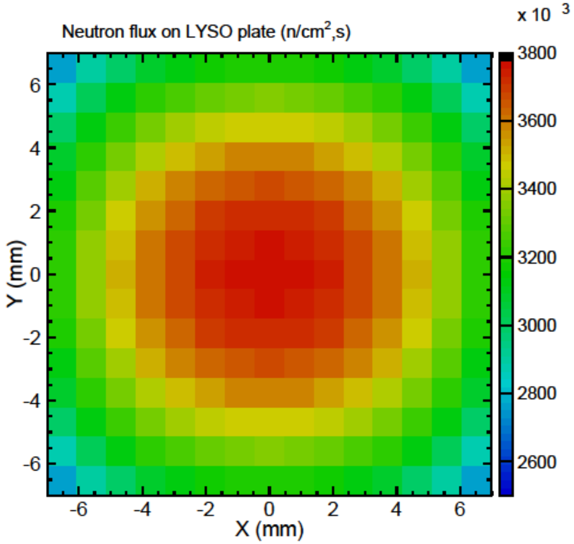


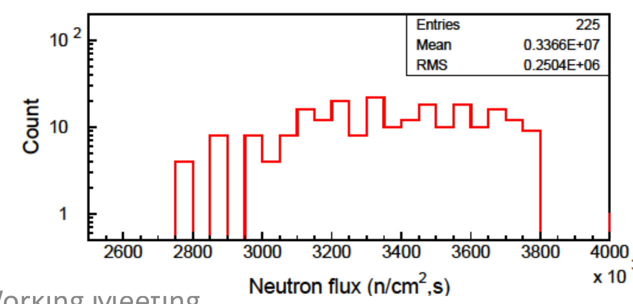


A pair of Cf-252 sources of 14.6 µg each was procured last Fall for crystal irradiation

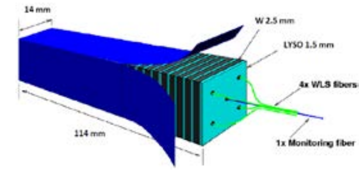
Together with an old pair they provide a neutron flux of 3.4E6 n/cm²/s last Fall

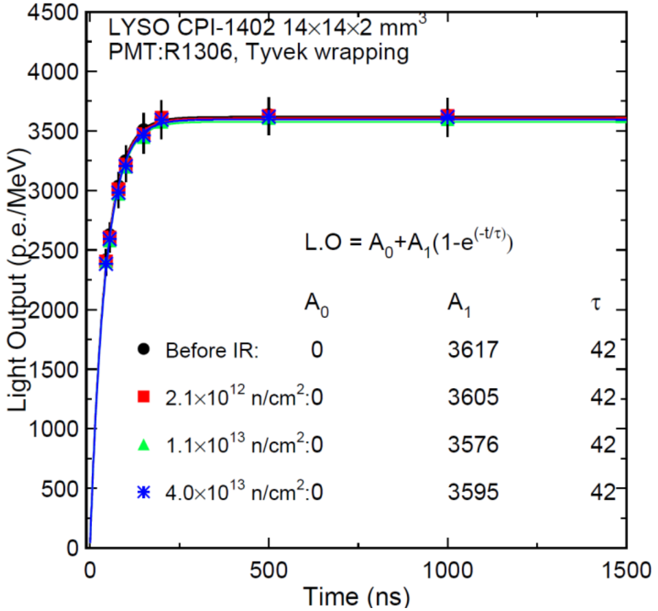


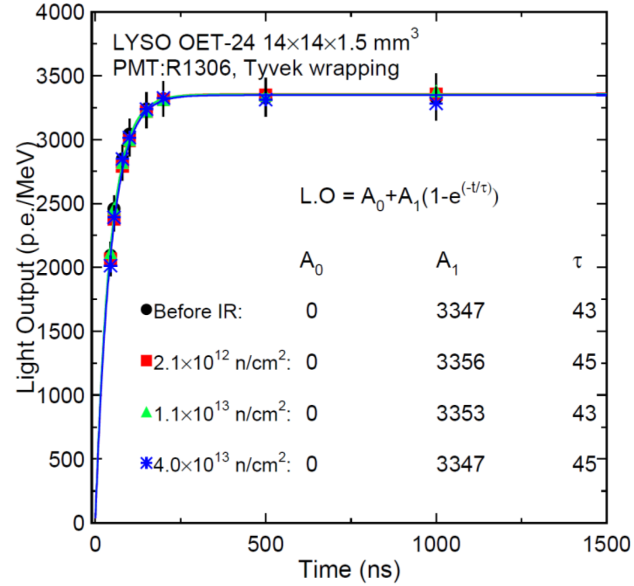


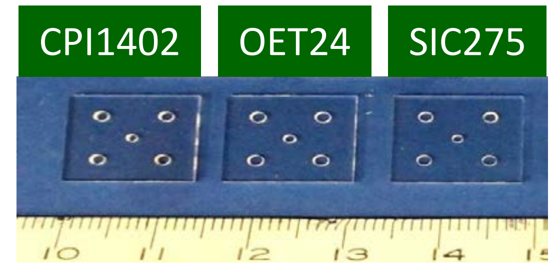


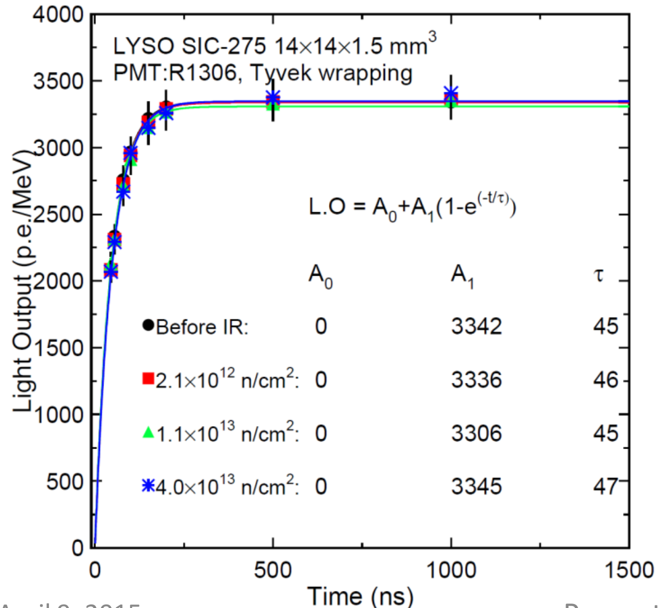
Result of Fast Neutron Irradiation

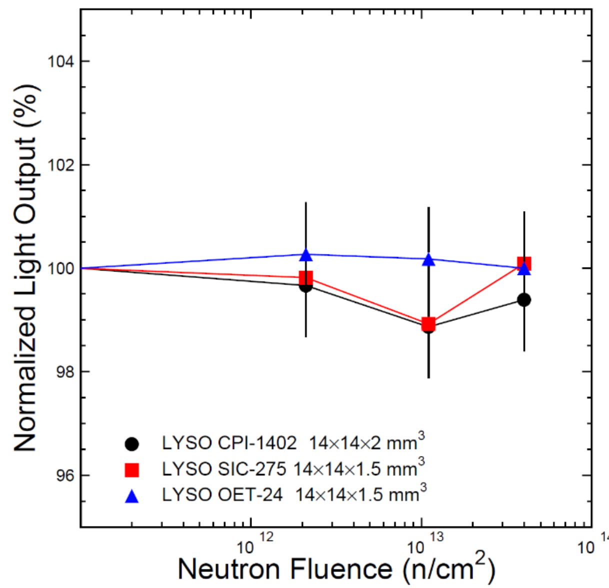






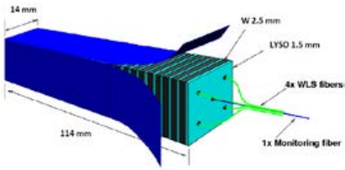


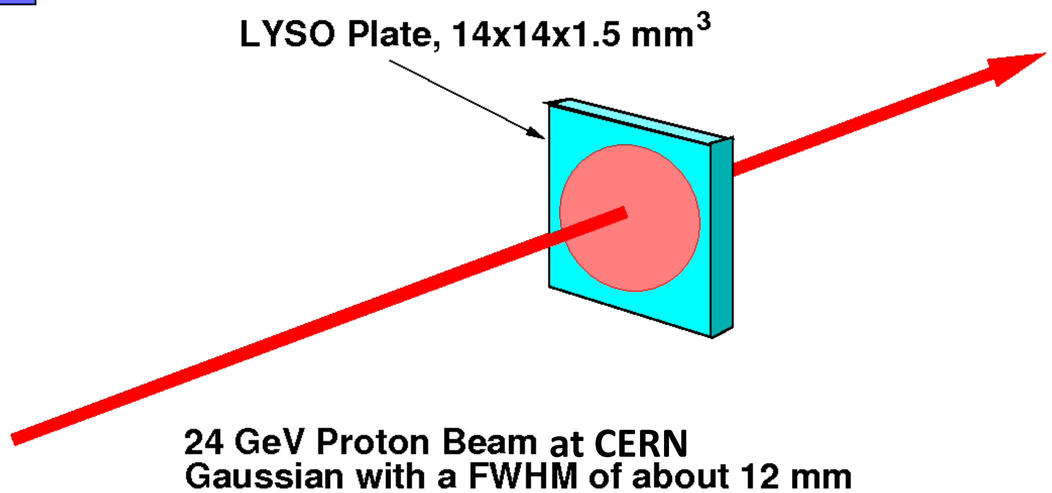




No damage in LO observed up to 4E13 n/cm². Irradiation will continue. To make absolutely sure irradiation at Maryland or ORNL or Sandia up to 5E15 is in plan.

Proton Irradiation for LYSO Plates



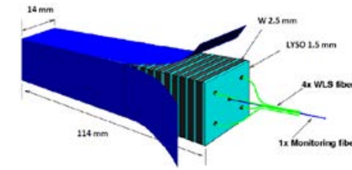


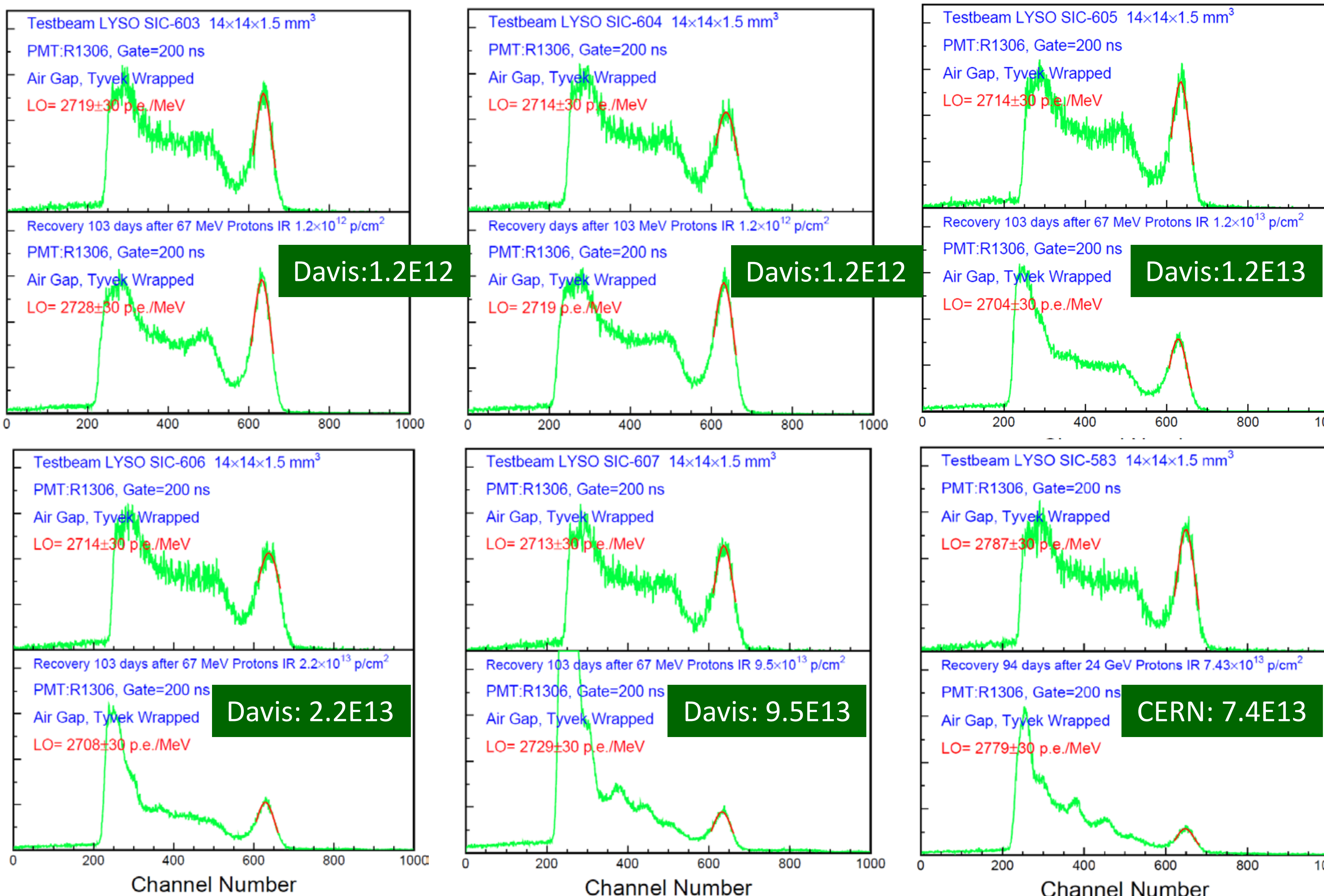
CERN 24 GeV:
Four LYSO plates to 7.4E13, 2 x 2.4E15 and 6.9E15 p/cm2
Thanks to
David Bailleux and Federico Ravotti

SET Number	USER	Description	BOX	StorageTempReq	IRRAD	Flu. Step	Al 1	Al 2	Al 3	Al 4	Al 5	Al 6	Fluence	Unit	Error (+/- %)	Surface
Set-1986-End-2014		Y11 WLS Fiber	113	Shipping RT	7	1.00E+14	2963	-	-	-	-	-	9.28E+13	p/cm^2	8.2	5x5
Set-1985-End-2014		LYSO Plate 001	113	Shipping RT	7	1.00E+16	2966	2972	2975	2979	-	-	6.86E+15	p/cm^2	6.3	10x10
Set-1984-End-2014	David BAILLEUX	LYSO Plate 609	113	Shipping RT	7	1.00E+15	2989	-	-	-	-	-	2.26E+15	p/cm^2	6.5	10x10
Set-1983-End-2014		LYSO Plate 594	113	Shipping RT	7	3.00E+14	2989	-	-	-	-	-	2.26E+15	p/cm^2	6.5	10x10
Set-1982-End-2014		LYSO Plate 583	113	Shipping RT	7	1.00E+14	2964	-	-	-	-	-	7.43E+13	p/cm^2	7.6	10x10

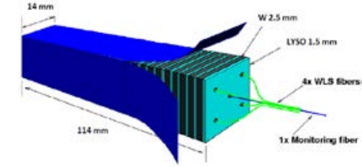
Davis 67 MeV proton beam on a large area:
Five LYSO plates: 2 x 1.2E12, 1.2E13, 2.2E13 and 9.5E13 p/cm^2
Thanks to Bob Hirosky and Mike Mulhearn

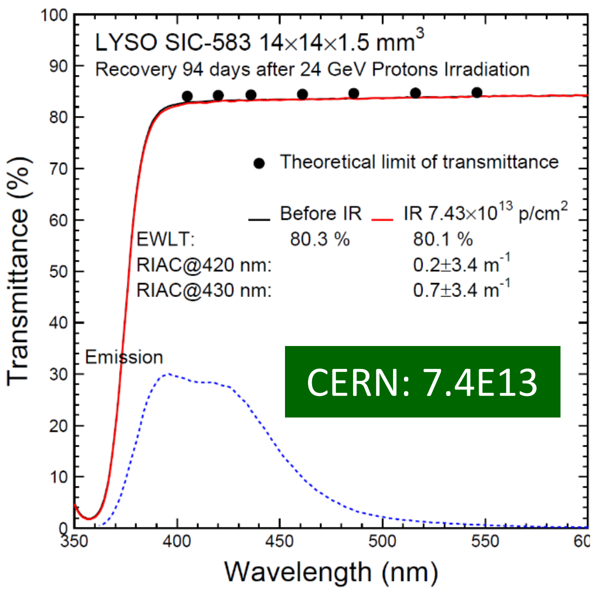
No LO Loss up to 10^{14} p/cm^2

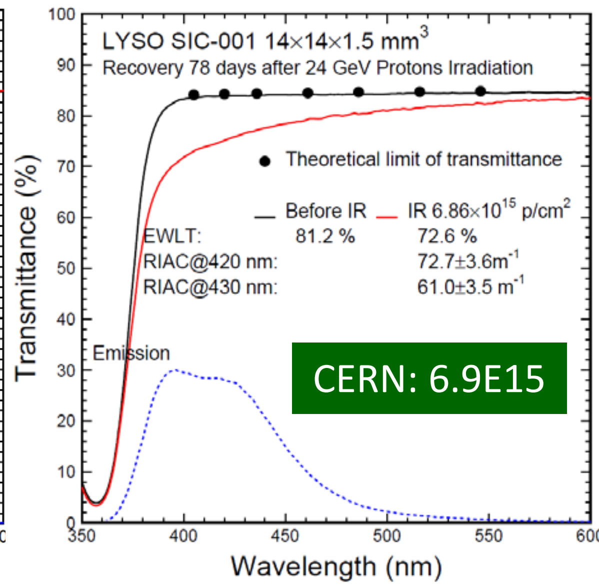


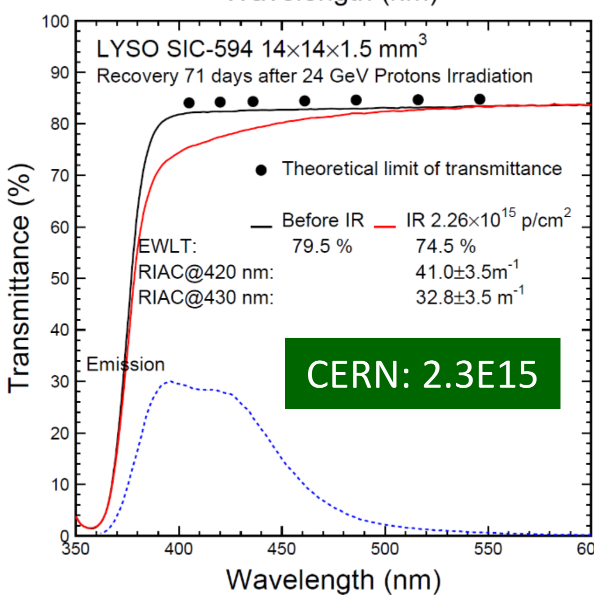


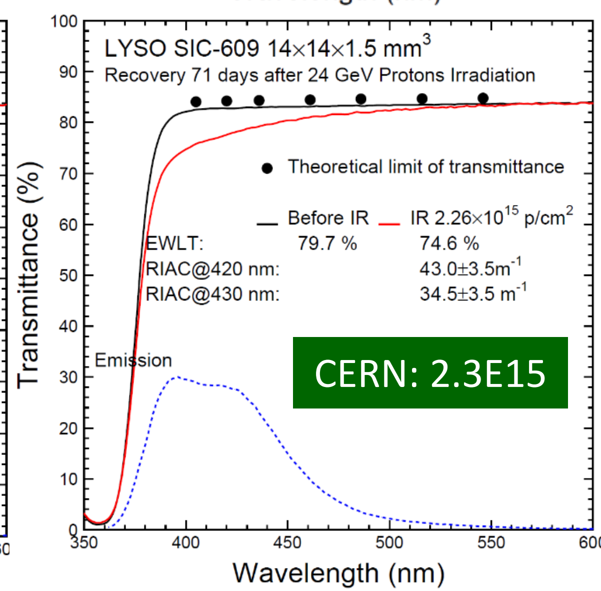
Transmission Loss by 24 GeV Protons







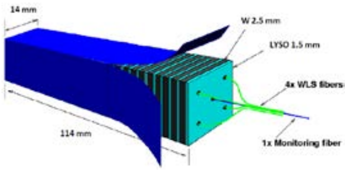


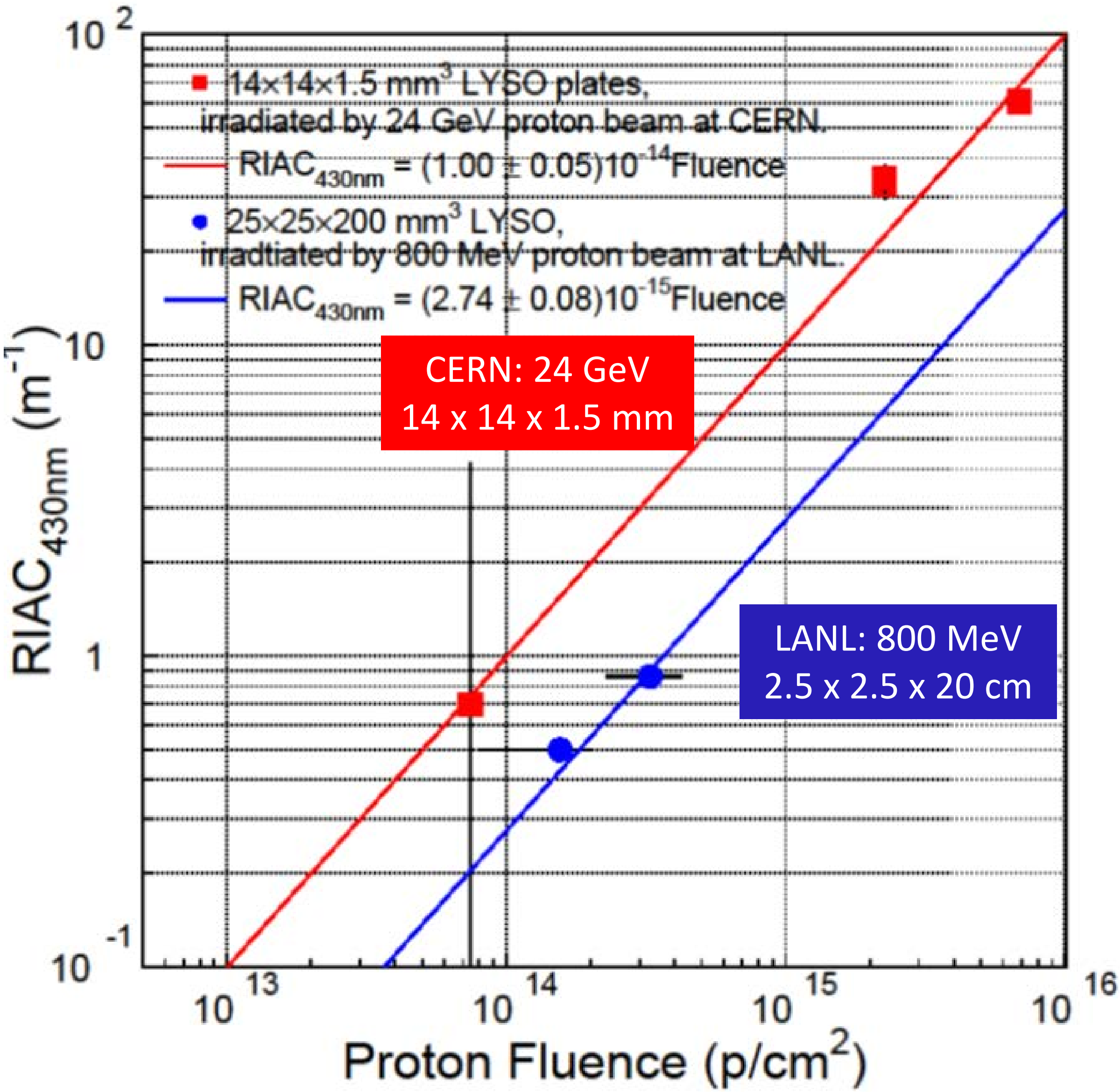


Transmittance measured by a PerkinElmer Lambda 950 spectrophotometer with 0.15% precision, corresponding to 3.5/m for RIAC

Consistent damage within 5% observed for two plates irradiated to 2.3E15. EWLT degrades to 80.1%, 74.5% and 72.6% after 7.4E13, 2.3E15 and 6.9E15 of 24 GeV protons with corresponding RIAC at 430 nm of 0.7, 34 and 61 m^{-1} respectively

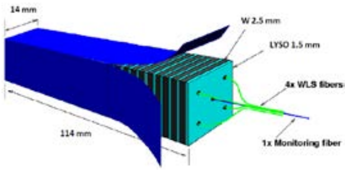
Proton Induced Absorption

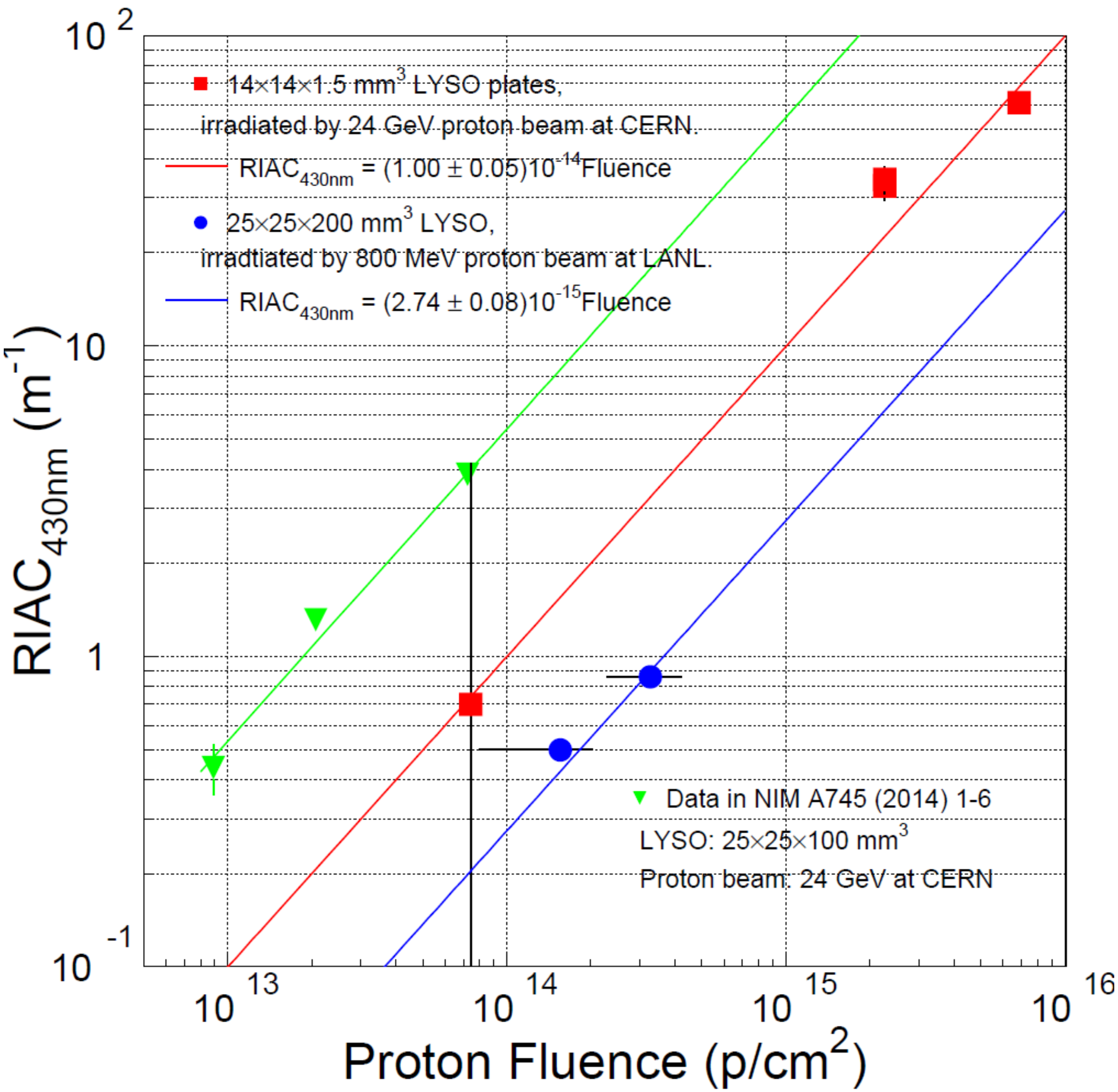




Linear fits show RIAC @430 nm as a function of fluence of 24 GeV and 800 MeV protons for 14 x 14 x 1.5 mm plates and 20 cm long crystal respectively, indicating a RIAC value of 3 m^{-1} after 3E14 p/cm^2 and 6% LO loss with WLS readout

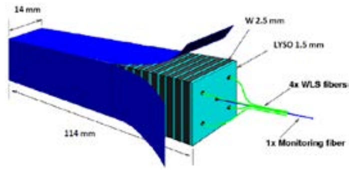
Comparison with ETH Data



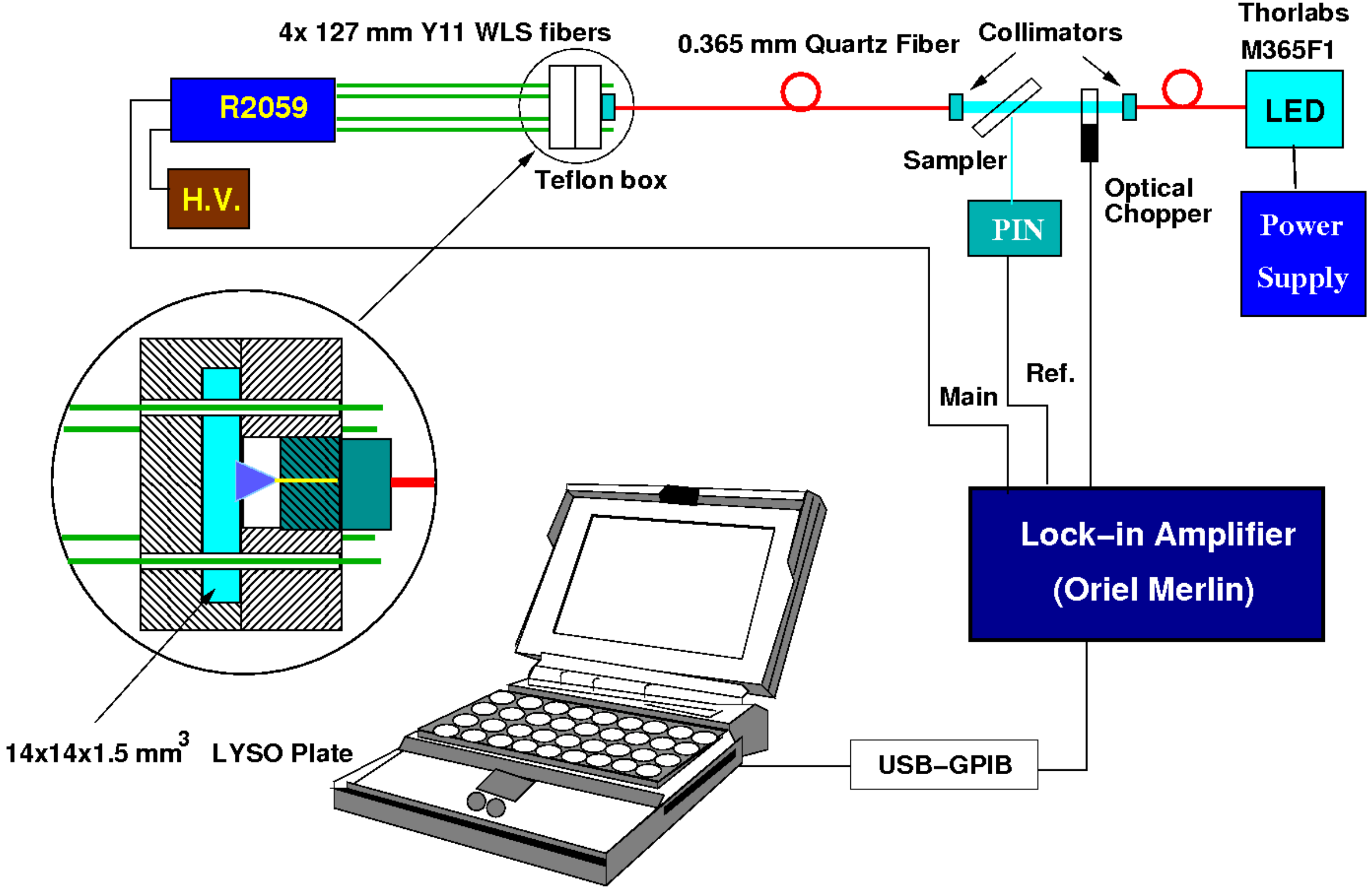


A factor of five difference observed between the LYSO plates and the 10 cm long LYSO crystals irradiated by 24 GeV protons seems caused by the EM component in hadronic shower which is counted already in the ionization dose

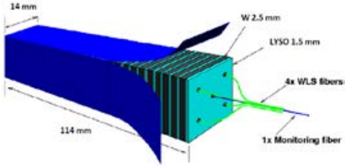
LO Measurement with WLS



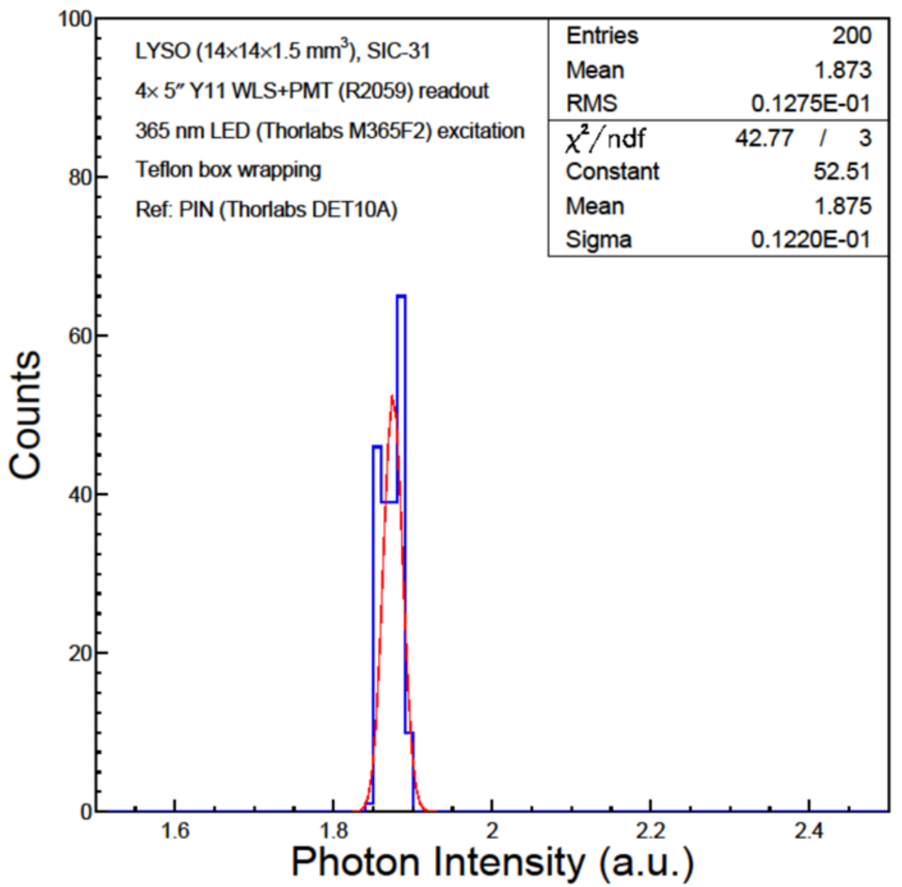
Lock-in amplifier used to mitigate phosphorescence

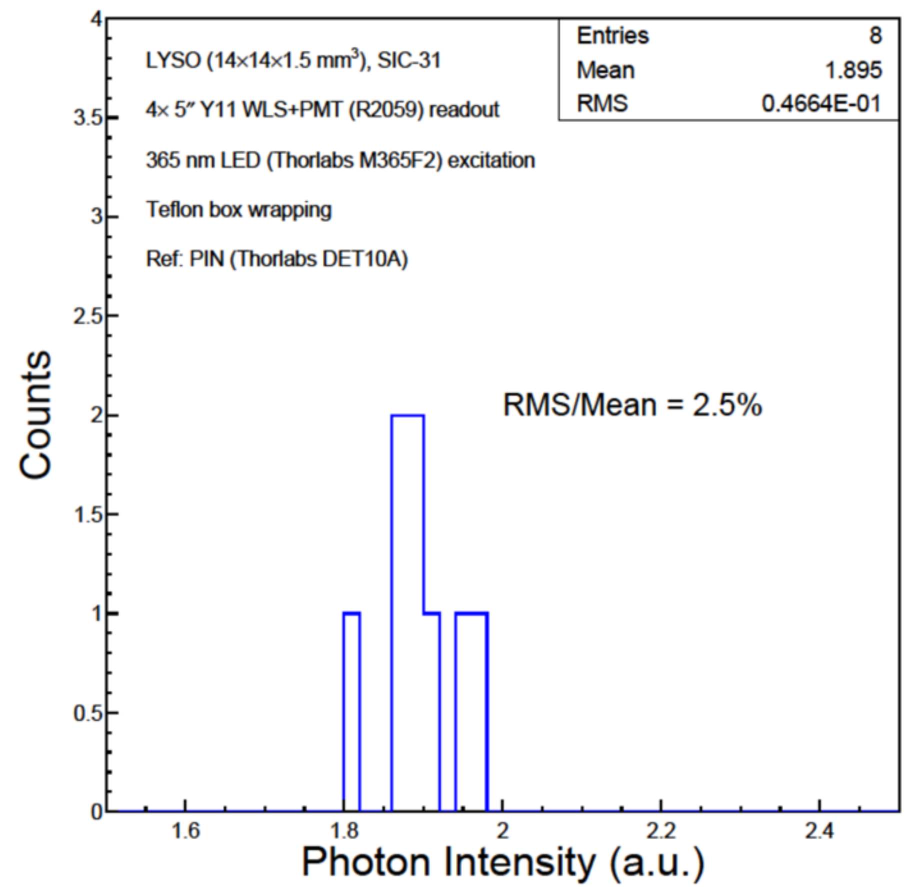


Systematic Uncertainties

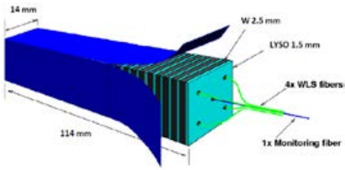


< 1% for repeated measurements for a LYSO plate on the fixture, and 2.5% with mounting/dismounting

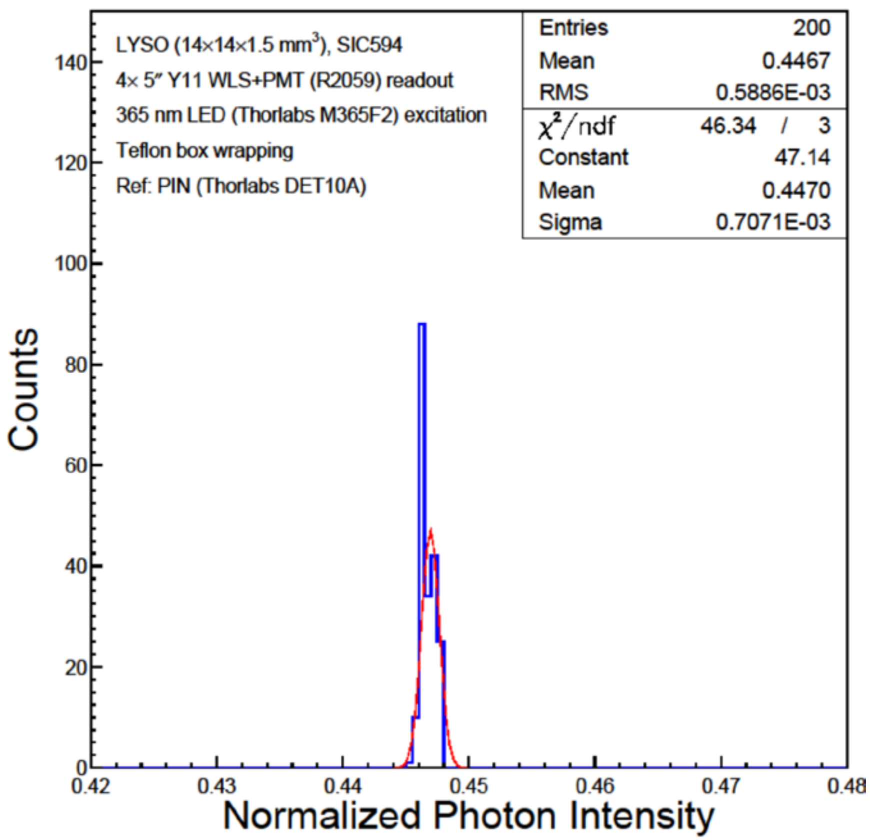


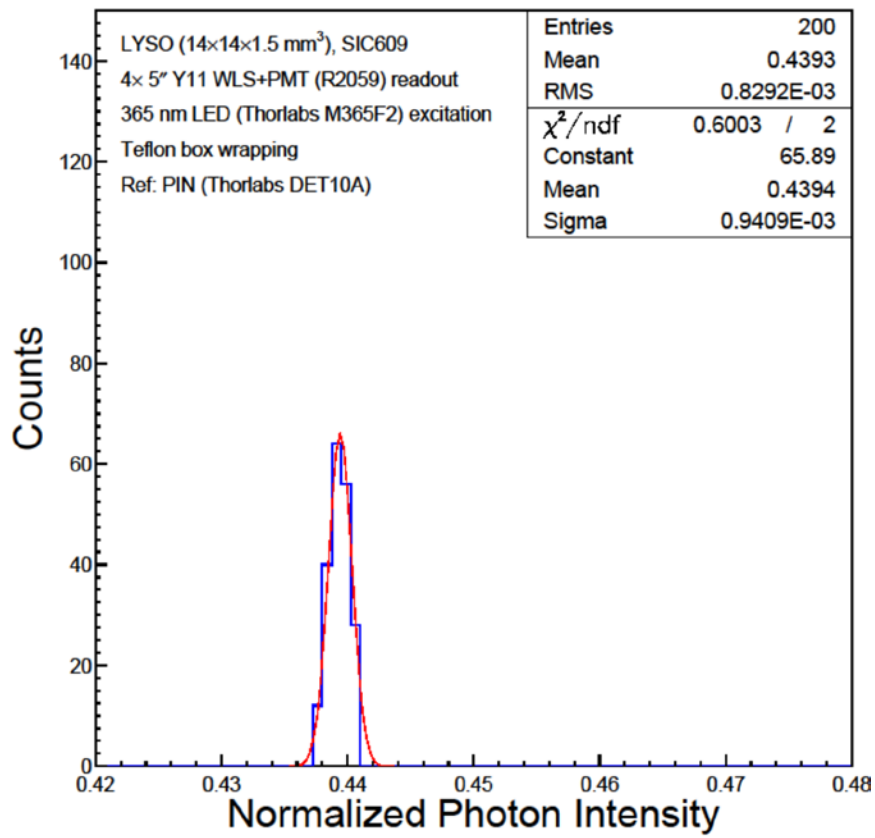


LO Loss after 2E15 24 GeV Protons

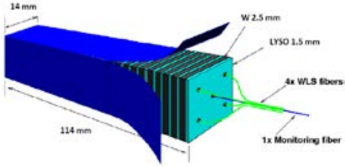


Consistent LO loss at a level of 56% observed for two LYSO plates with WLS readout after 2.3E15 p/cm^2

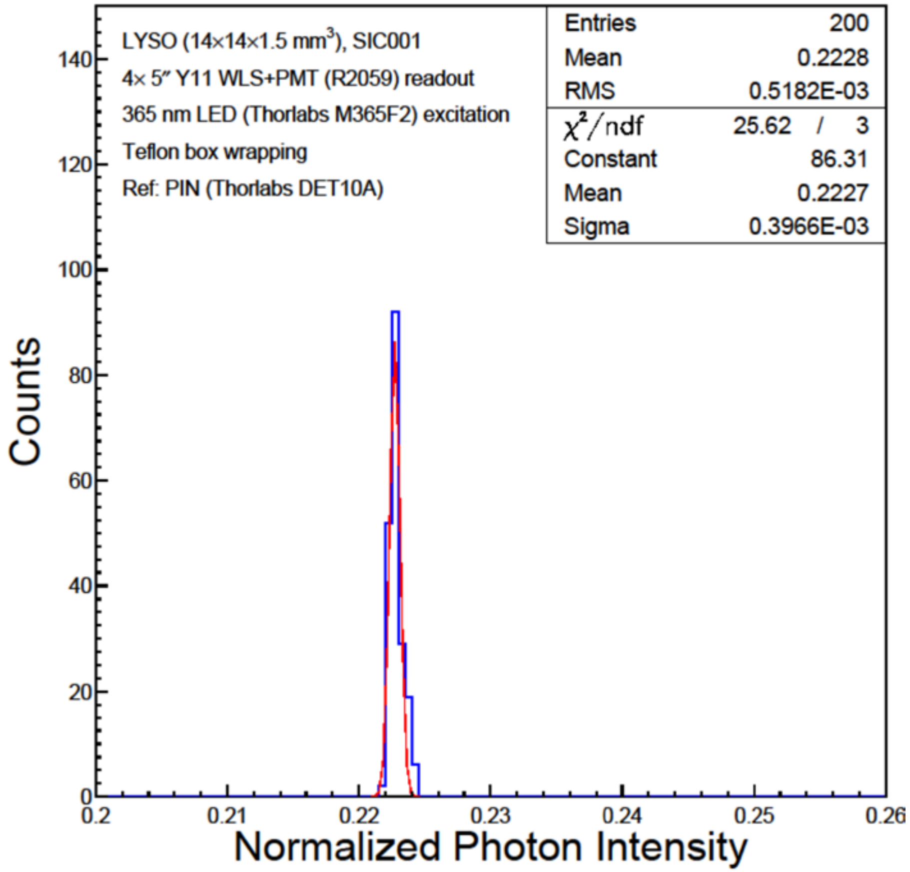


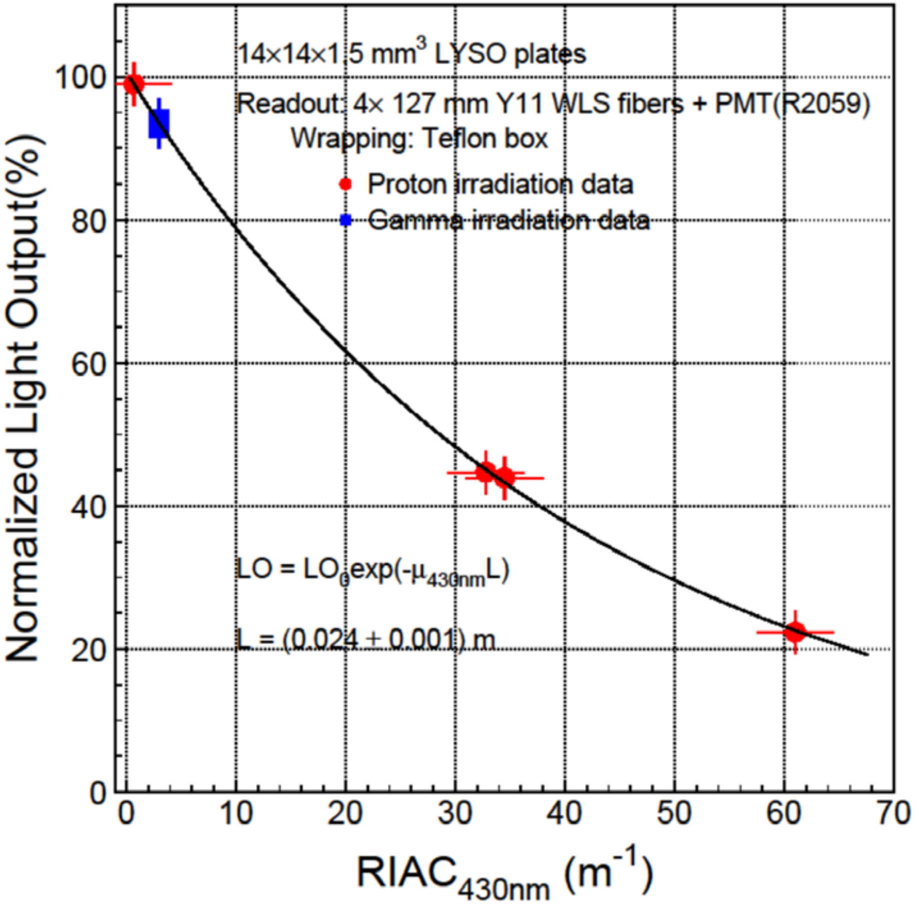


LO Loss after 7E15 24 GeV Protons

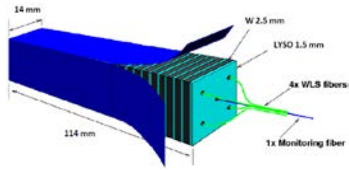


A LO loss of 78% was observed for a LYSO plate irradiated to 7E15
A fit between LO and induced μ@430 nm shows 2.4 cm path length
Damage caused by protons and ɣ-rays are consistent: 6% for 3/m



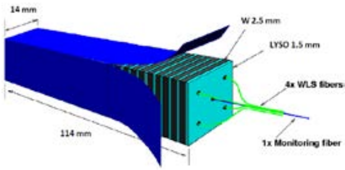


Summary of Proton Damage



ID	Dimension (mm^3)	Initial EWLT (%)	Initial LO (p.e./MeV)	Coupling	Proton Energy (MeV)	Fluence (p/cm^2)	Beam Size (mm)	EWLT after IR (%)	Direct Coupling LO after IR (p.e./MeV)	RIAC @ 420 nm (m^{-1})	RIAC@ 430 nm (m^{-1})	WLS Readout Signal Loss (%)
SIC603	14×14×1.5	80.0	2719 ±30	Air Gap	64	1.2E12			2728±30			
SIC604	14×14×1.5	80.7	2714 ±30	Air Gap	64	1.2E12			2719±30			
SIC605	14×14×1.5	80.2	2714±30	Air Gap	64	1.2E13			2704±30			
SIC606	14×14×1.5	80.7	2714±30	Air Gap	64	2.2E13			2708±30			
SIC607	14×14×1.5	80.0	2713±30	Air Gap	64	9.5E13			2729±30			
SIC583	14×14×1.5	80.3	2787±30	Air Gap	2.4E4	7.43E13	10×10	80.1	2779±30	0.2 ±3.5	0.7 ±3.5	
SIC594	14×14×1.5	79.5	2761±30	Air Gap	2.4E4	2.26E15	10×10	74.5	-	41.0 ±3.5	32.8 ±3.5	56±3
SIC609	14×14×1.5	79.7	2709±30	Air Gap	2.4E4	2.26E15	10×10	74.6	-	43.0 ±3.5	34.5 ±3.5	56±3
SIC001	14×14×1.5	81.2	3616±30	Air Gap	2.4E4	6.86E15	10×10	72.6	-	72.7 ±3.5	61.0 ±3.5	78±3
SG3	25×25×200	58.9	2737±30	Grease	800	1.56E14 3.27E14	Φ25	51.14 7.3	-	0.68 1.14	0.50 0. 86	-

Expected LO Loss for Shashlik



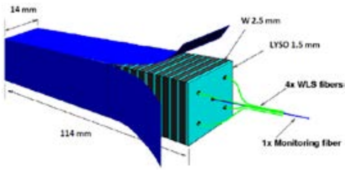
HL-LHC Radiation	Max. at Endcap (5×10^{34} cm^{-2}s^{-1}, 3000 fb^{-1})	14×14×0.5 mm LYSO plate with WLS readout	
		LO Loss (%)	(1-Loss)(%)
Ionization Dose (rad)	1.26E+08	6.0	94.0
Charged Hadrons Fluence (cm^{-2})	3.00E+14	6.0	94.0
Fast Neutrons Fluence (E>100KeV, cm^{-2})	4.80E+15	?	
Total Light Output = $(1-L_\gamma)(1-L_p)(1-L_n)$ (%)			88.4

The loss by ionization dose was measured for LYSO/W Shashlik cells irradiated by Co-60 source at JPL with WLS readout

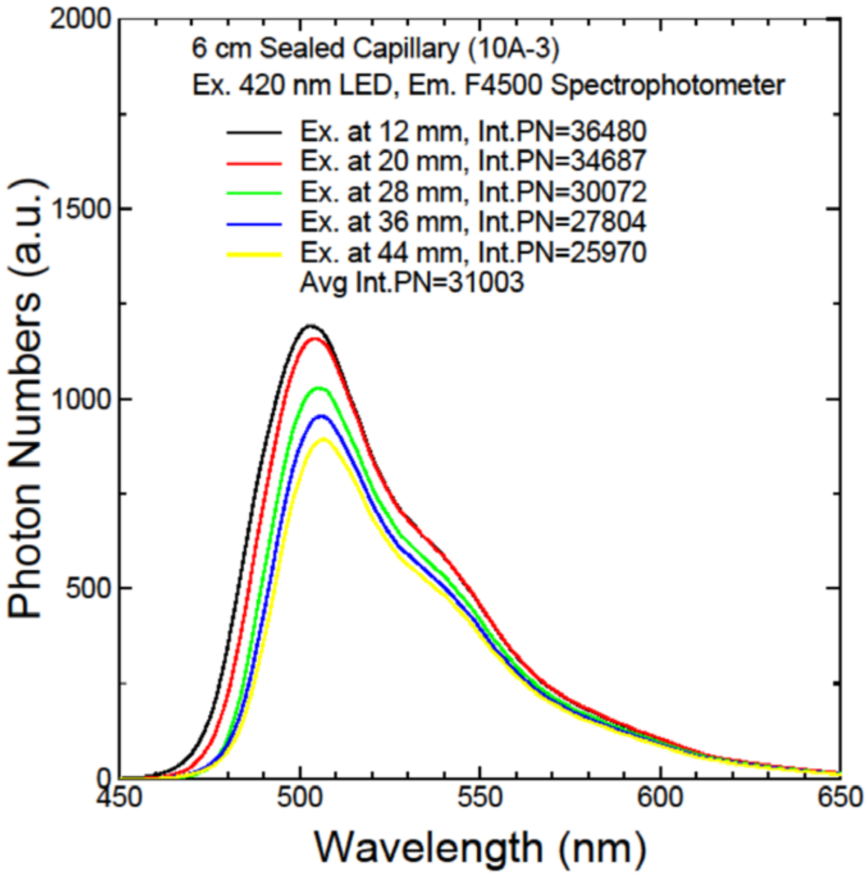
The loss by charged hadrons was measured for LYSO plates irradiated by 24 GeV protons at CERN to 3E14 with WLS readout

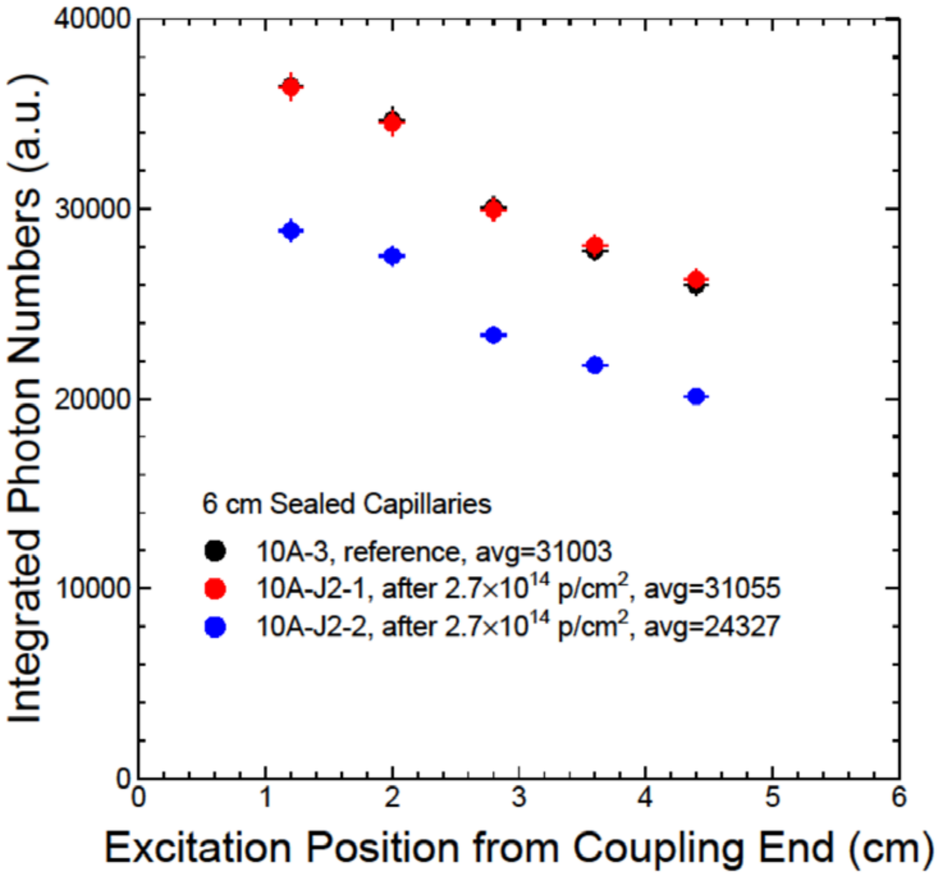
The loss by neutrons is expected to be very small or none based upon Saclay data on PWO, but will be measured in future

Comparison with Un-irradiated J2

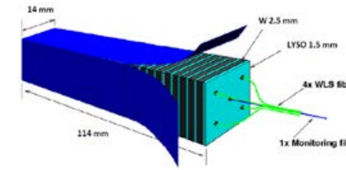


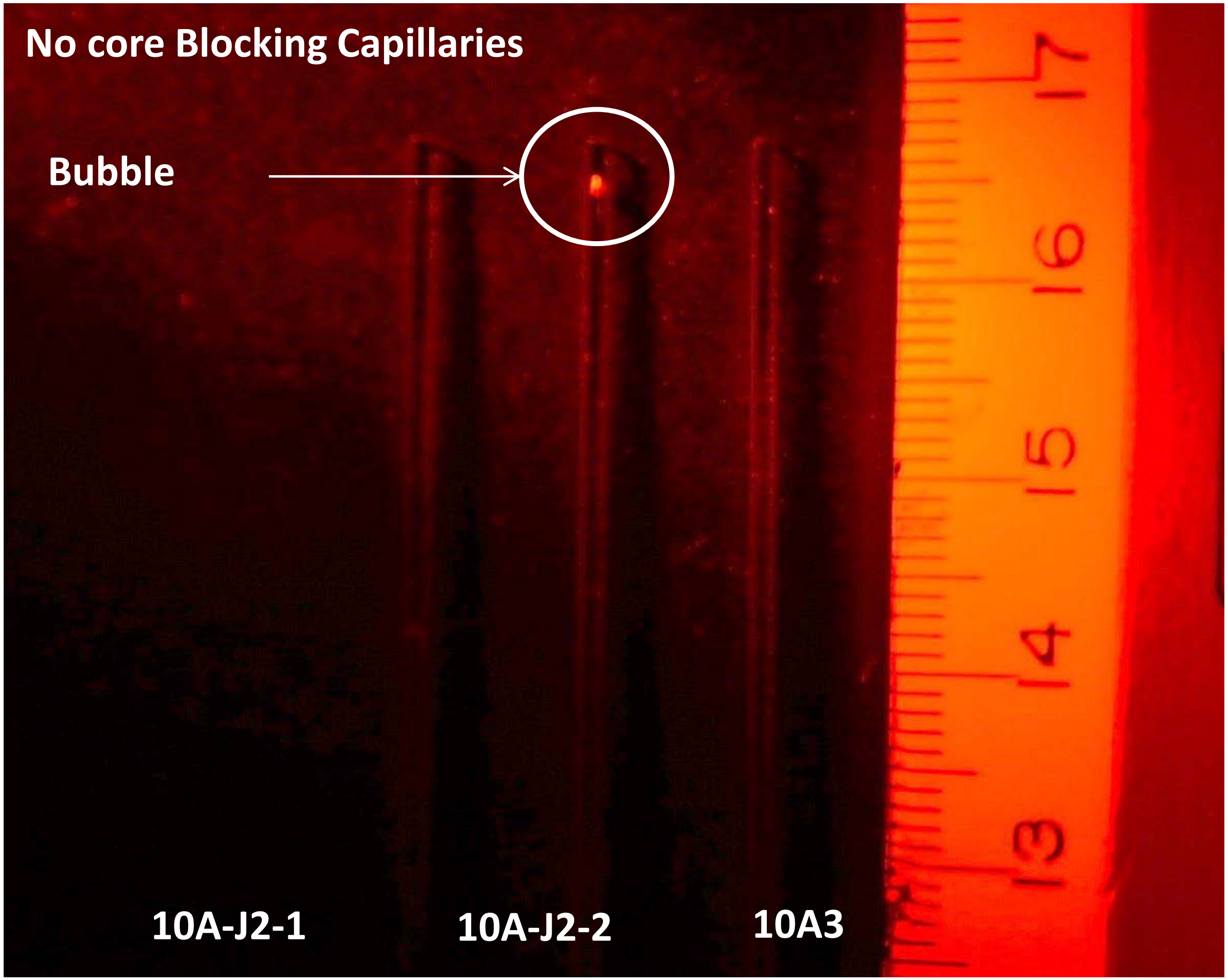
All three 10A-J2 capillaries show consistent emission spectrum
Consistent photon intensity between 10A-J2-1 and 10A-3 is observed
10A-J2-2 is 22% lower than the other two because of a bubble in it.



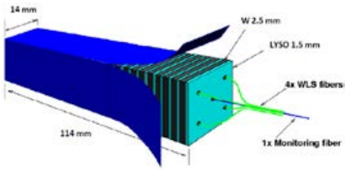


A Bubble Observed in 10-J2-2



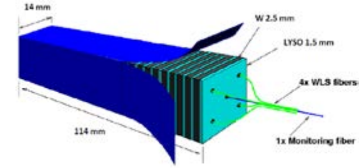


Summary

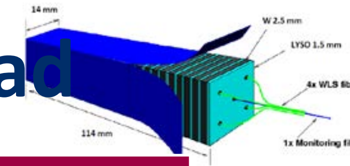


- LYSO plates of 14 x 14 x 1.5 mm with five holes were irradiated by γ-rays up to 90 Mrad. LO loss with WLS readout is 6%. The rms of LO distribution in 30 LYSO plates is 2.3%.
- No damage is observed in LYSO plates irradiated by 2.5 MeV neutrons up to 4E13 n/cm^2. Damage by neutrons at HL-LHC is expected very small or none based on Saclay data on PWO.
- No damage in LO is observed in LYSO plates irradiated by protons of either 67 MeV or 24 GeV up to E14 p/cm^2.
- The RIAC at 430 nm induced by protons of 24 GeV and 800 MeV is measured to be 1 and 0.27 E-14 x Fluence m^{-1} respectively for 14 x 14 x 1.5 mm LYSO plates and a 2.5 x 2.5 x 20 cm crystal. This difference is understood due to shower leakage in 1 lambda.
- LO losses of LYSO plates with WLS readout is expected to be 6% each by EM dose and charged hadrons. Neutron induced damage is expected very small or none, but will be measured.

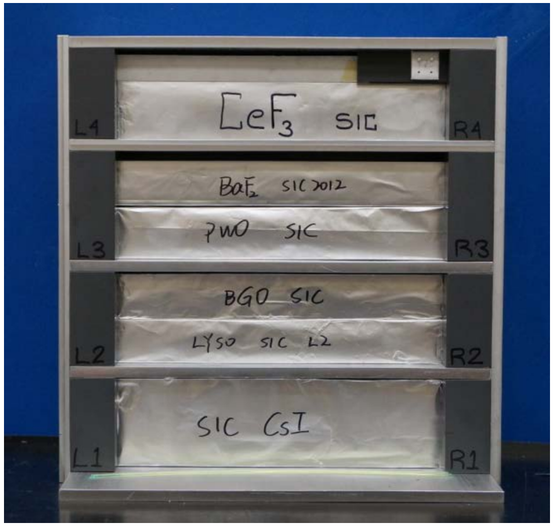
Long Crystals from Six Vendors



Samples Irradiated in the 1st 100 Mrad



10 Mrad @ 180 krad/h

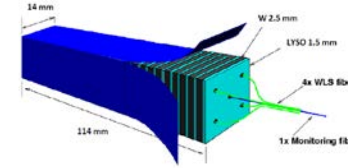


90 Mrad @ 1 Mrad/h

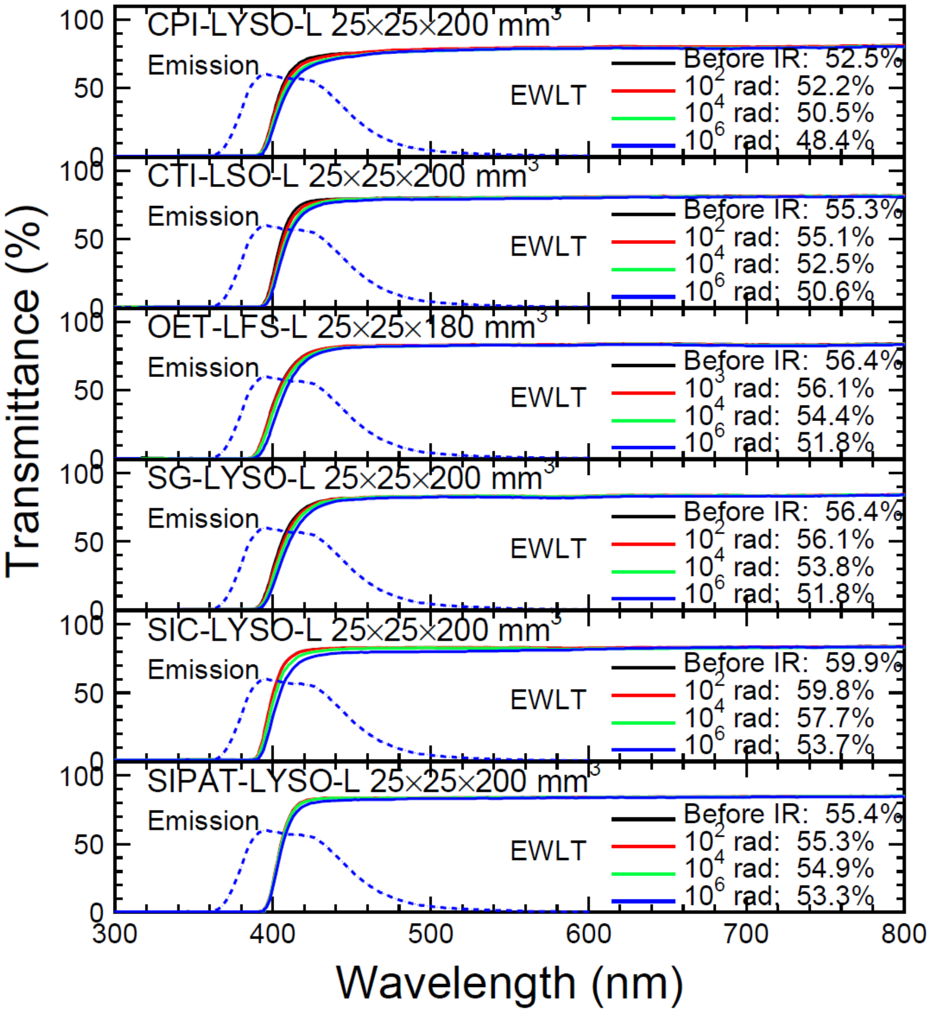
ID	Dimension (mm)
Shashlik (LYSO/W)	14x14x150
LYSO SIC Plate	14x14x1.5
CeF_3 SIC	33x32x191
BaF_2 SIC2012	20x20x250
PWO SIC	28.5^2x220x30^2
BGO SIC2011	25x25x200
LYSO SIC L2	25x25x200
CsI SIC2013	50x50x200

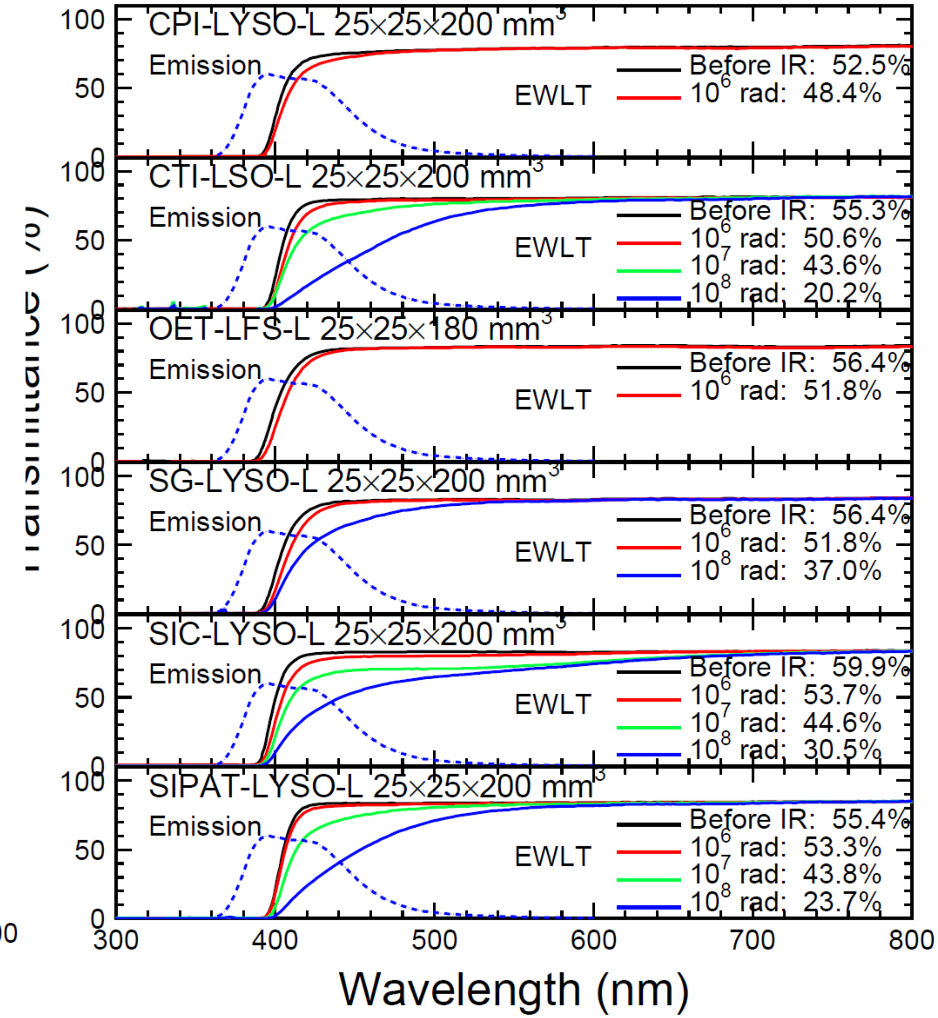
ID	Dimension (mm)
Shashlik (LYSO/W)	14x14x150
LYSO SIC Plate	14x14x1.5
LYSO SIC Plate	14x14x2
LYSO CPI Plate	14x14x2
CeF_3 SIC	33x32x191
BaF_2 SIC2012	20x20x250
PWO SIC	28.5^2x220x30^2
LYSO SIC L2	25x25x200
BGO SIC2011	25x25x200
LYSO SG L2	25x25x200
BGO NIIC	25x25x200

Radiation Damage in Long LYSO



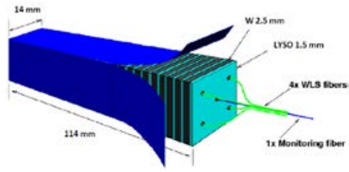
Consistent damage in LT up to 10 Mrad for LYSO crystals from six vendors





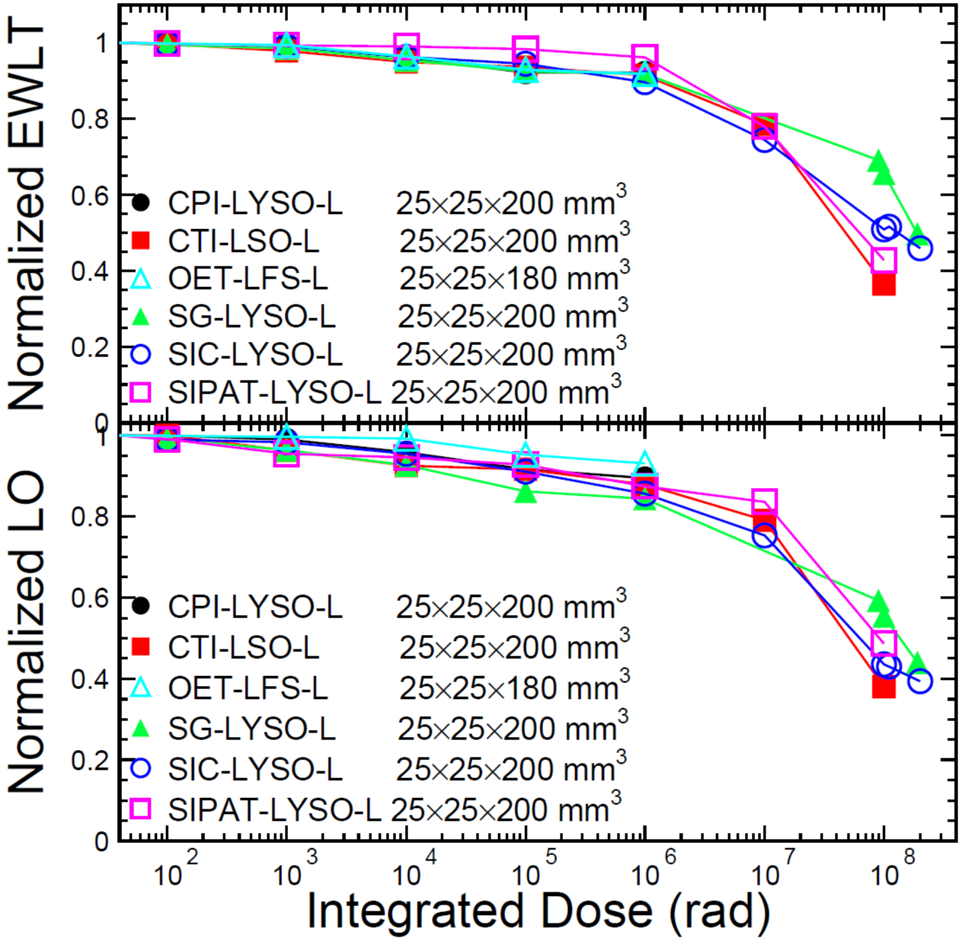
Difference between vendors appears at 100 Mrad, pointing to further R&D

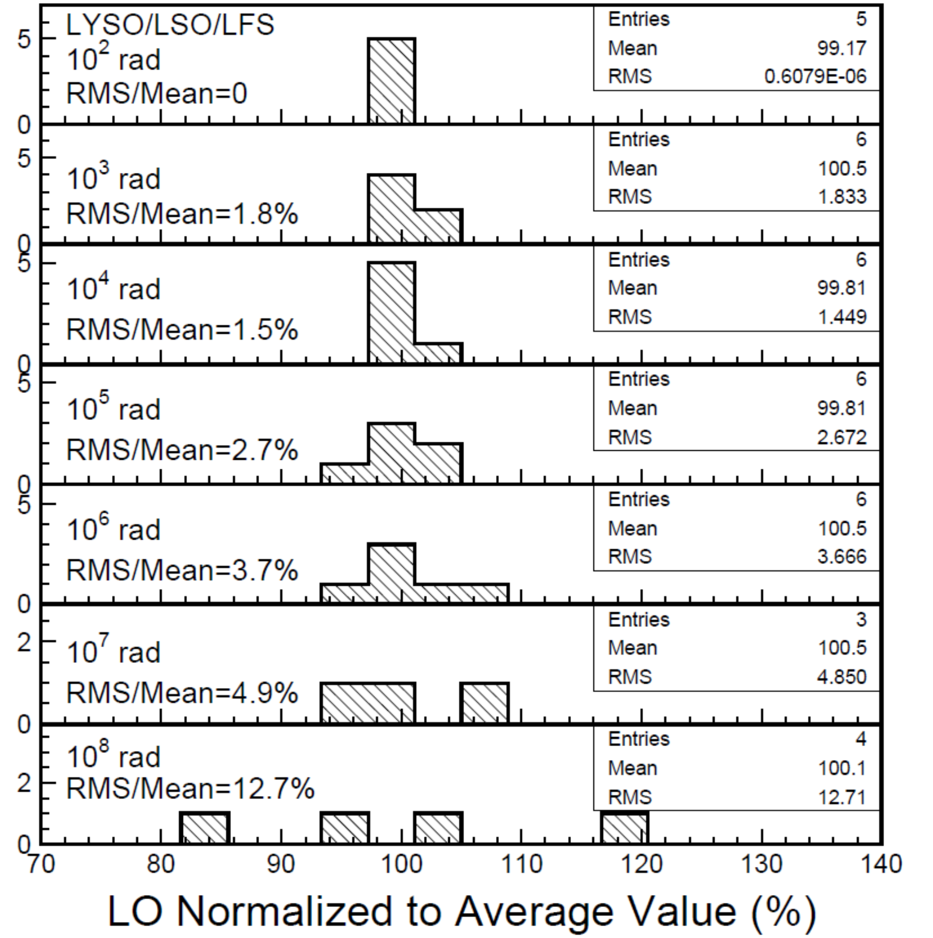
Consistent Radiation Damage in Long LYSO crystals from Six Vendors



Normalized EWLT and Light Output

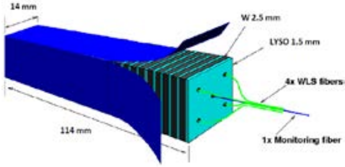
Light Output



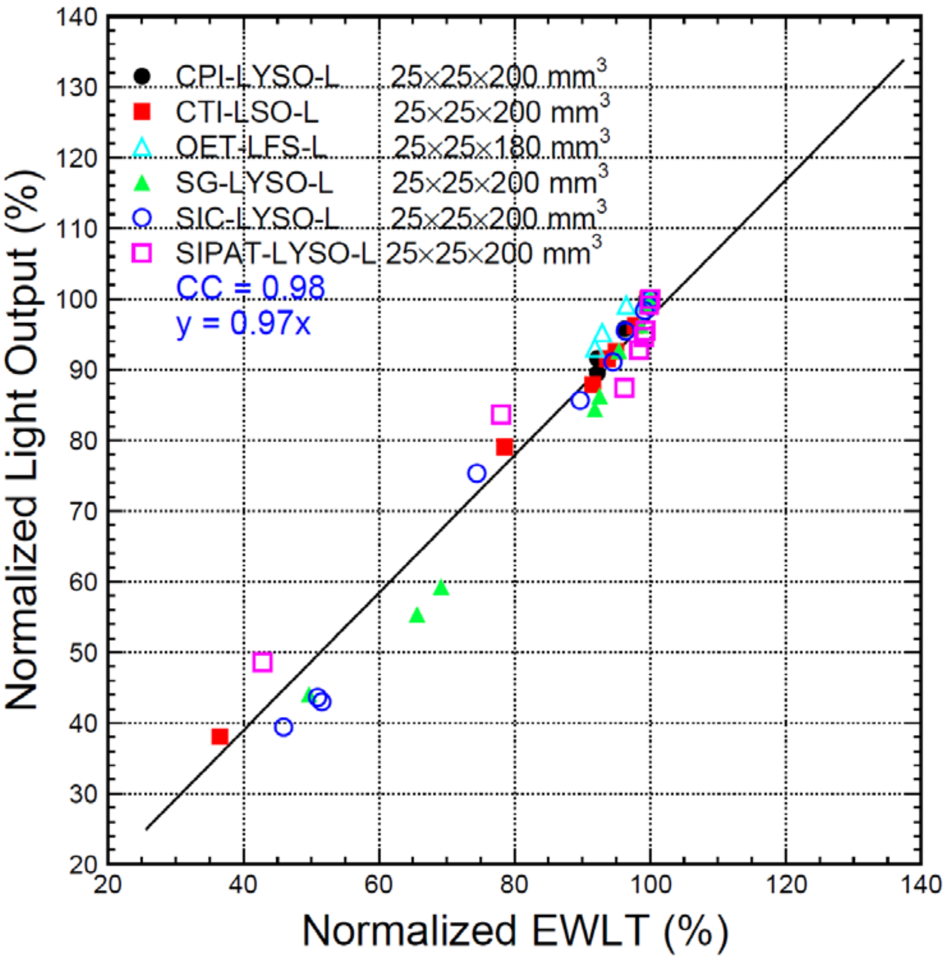


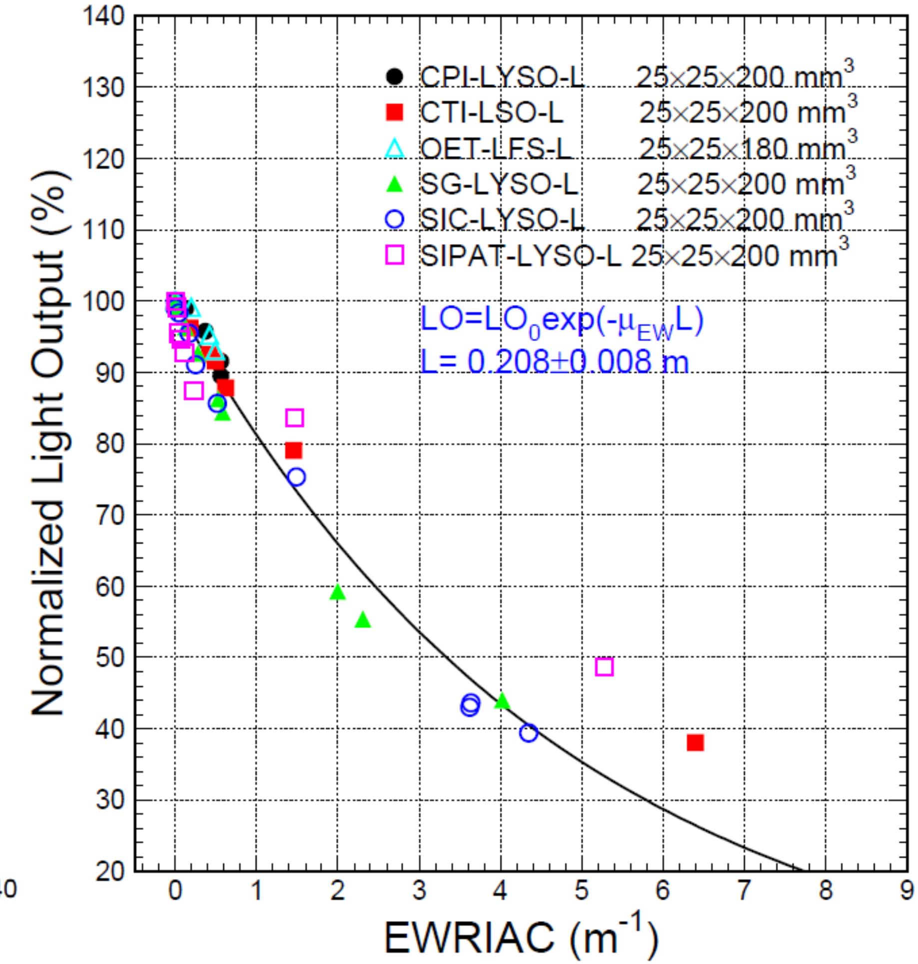
Less than 5% up to 10 Mrad, and 13% divergence after 100 Mrad

Relation between Normalized LO, EWLT and RIAC for Long LYSO

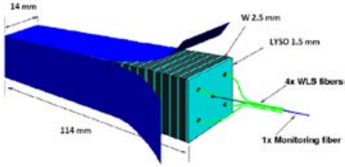


Good correlation between LO and LT and Consistent LO loss versus RIAC





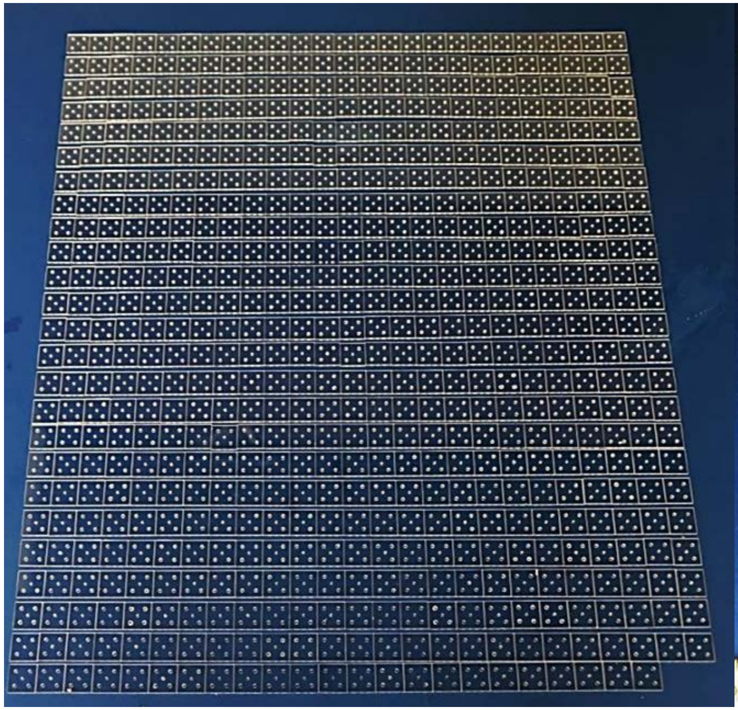
14 x 14 x 1.5 mm Plates



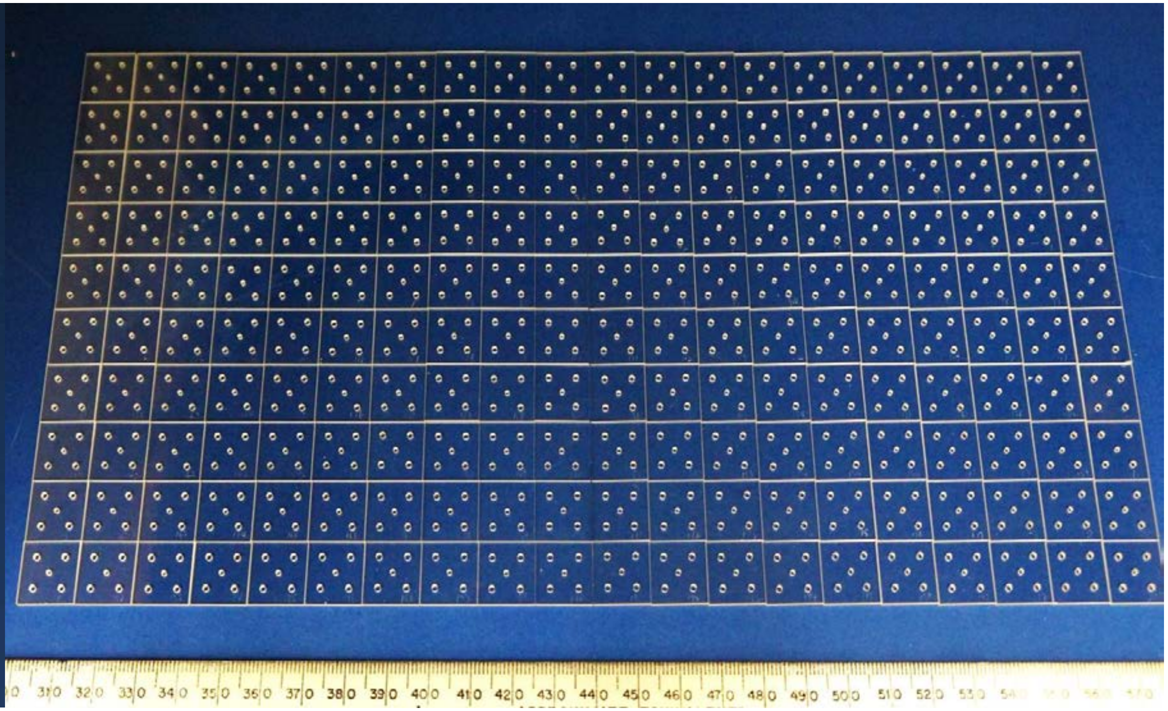
BOET-LFS-L

SIC/BOET plates with five holes were measured

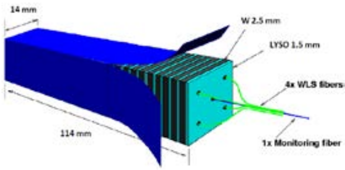
623 SIC LYSO Plates



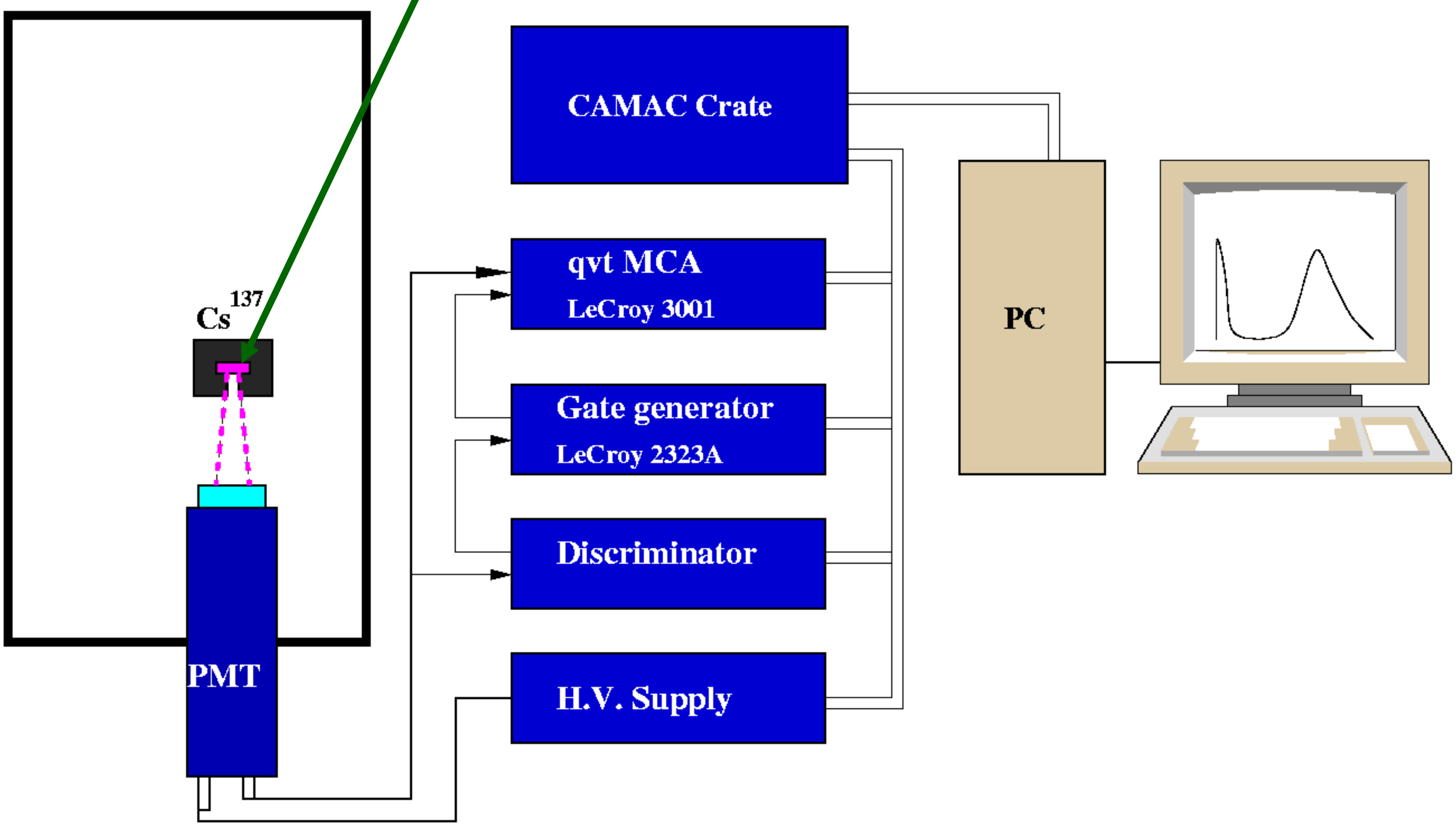
200 BOET LFS Plates



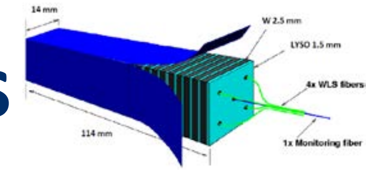
LO Measurement for LYSO Plates



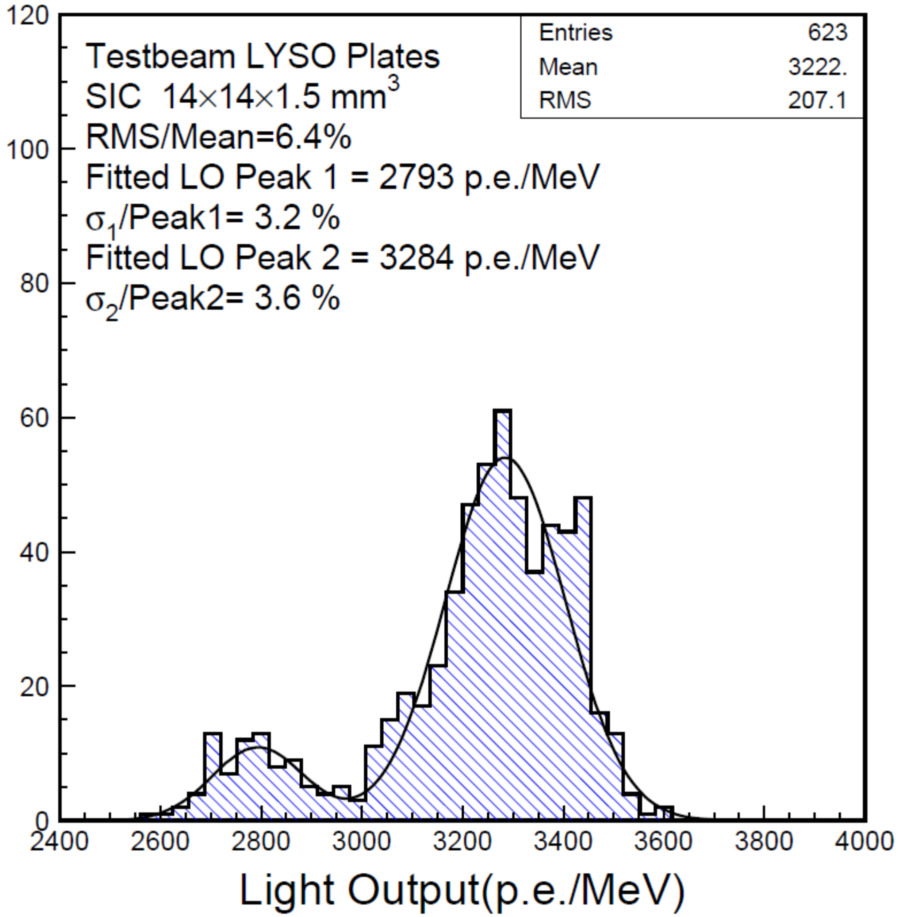
14 x 14 mm LYSO plates with Tyvek wrapping are directly coupled to a R1306 PMT with an air gap



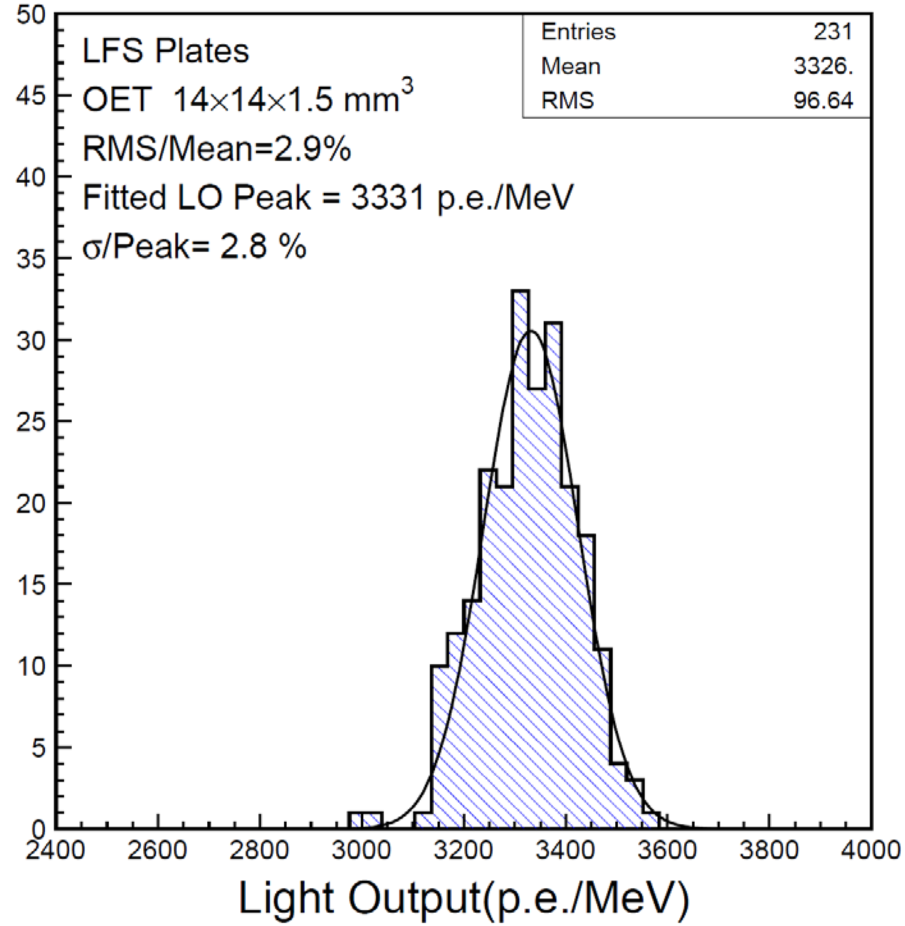
LO Distribution of LYSO/LFS Plates



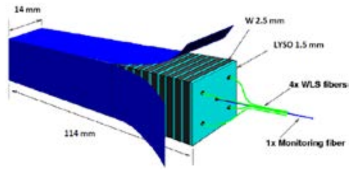
623 SIC LYSO: 6.4%



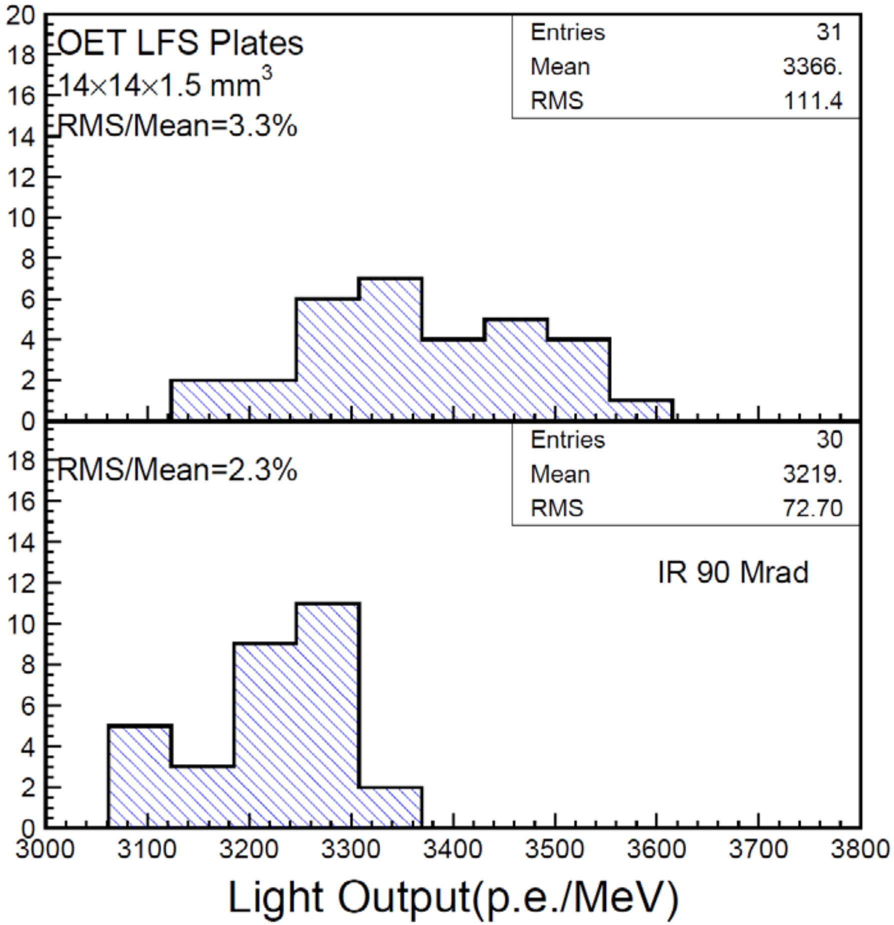
231 BOET LFS: 2.9%

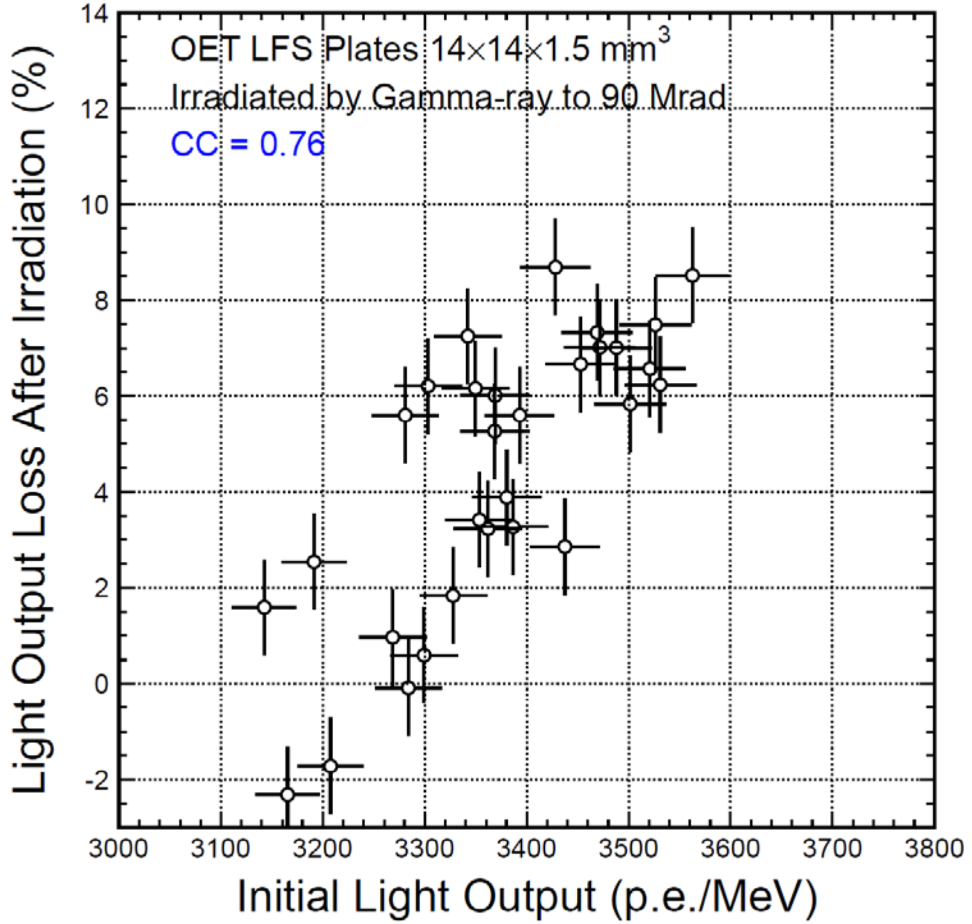


30 BOET LFS Plates after 90 Mrad

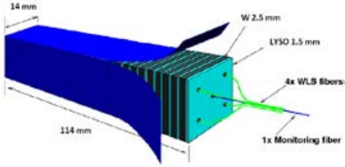


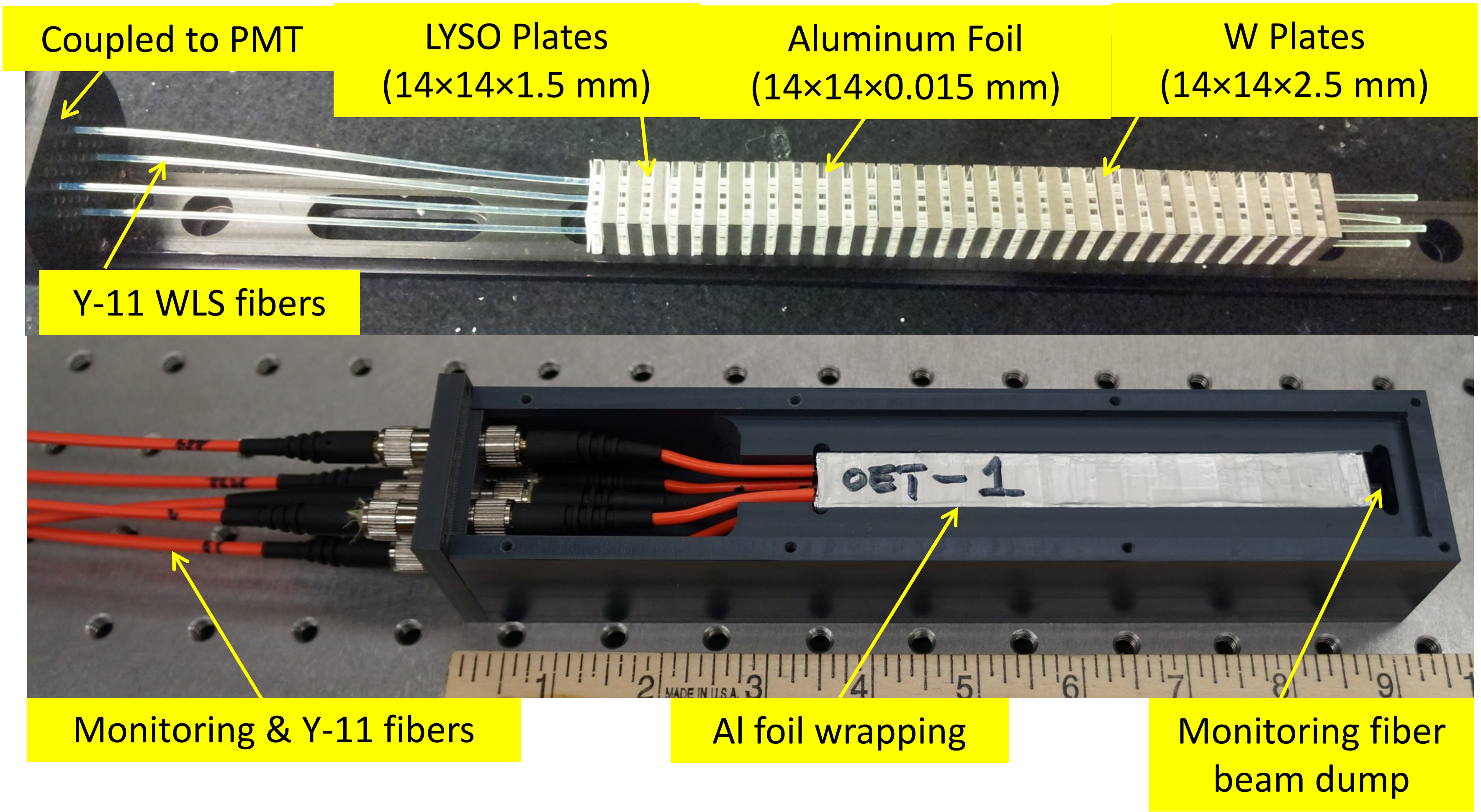
Consistency of light output is 3.3%/2.3% before/after 90 Mrad irradiation
Better consistency after irradiation shows consistent RIAC





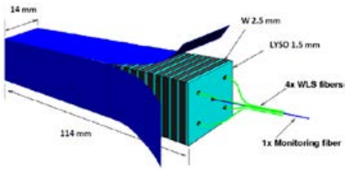
A LYSO/W/Al Shashlik Cell



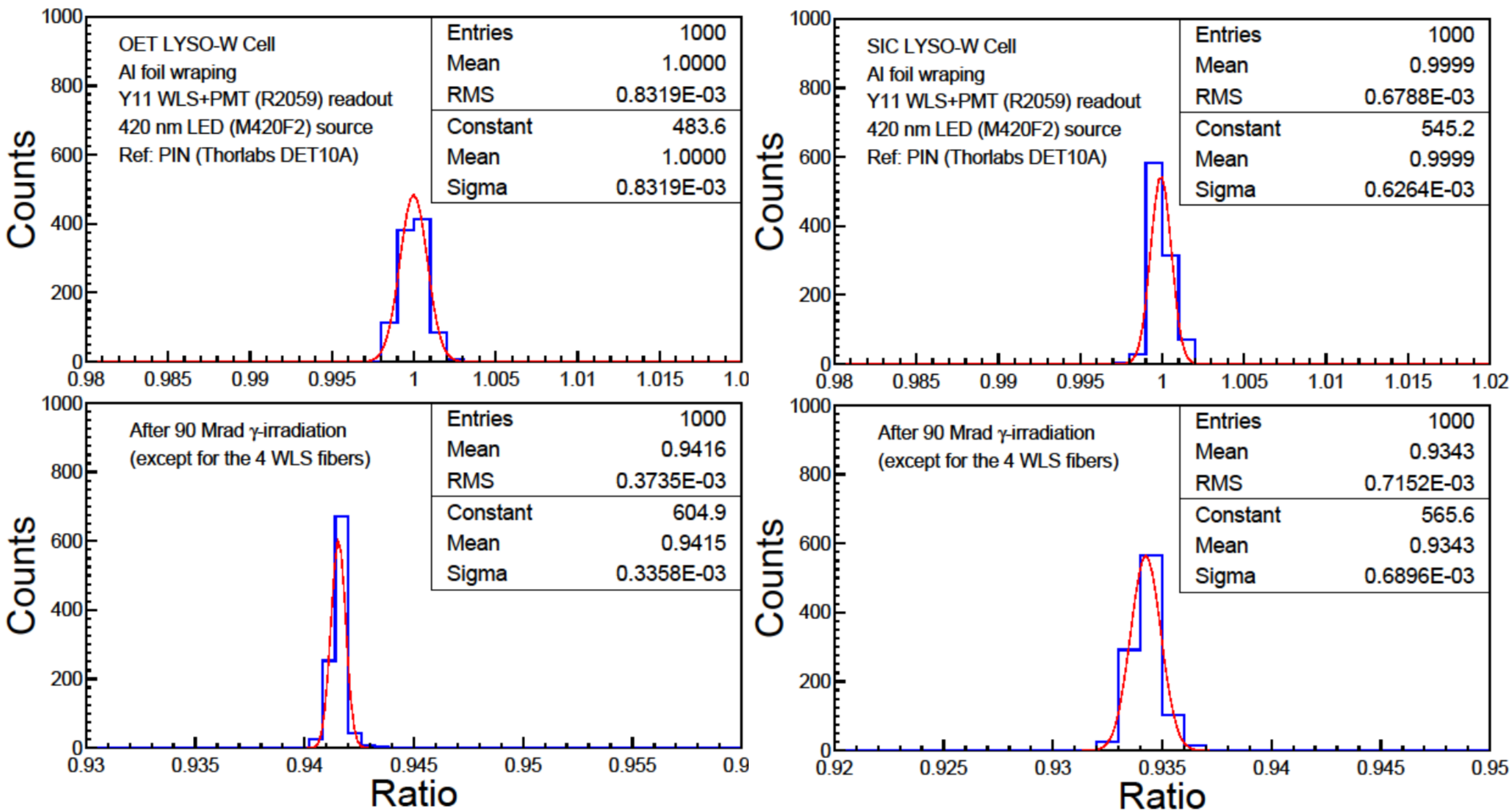


Two LYSO/W/Al Shashlik cells were irradiated at JPL to 90 Mrad
Its light output was measured before and after irradiation by WLS

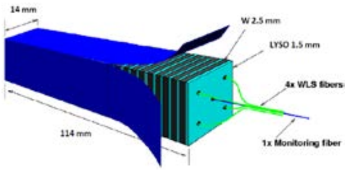
LO Loss of Shashlik Cells



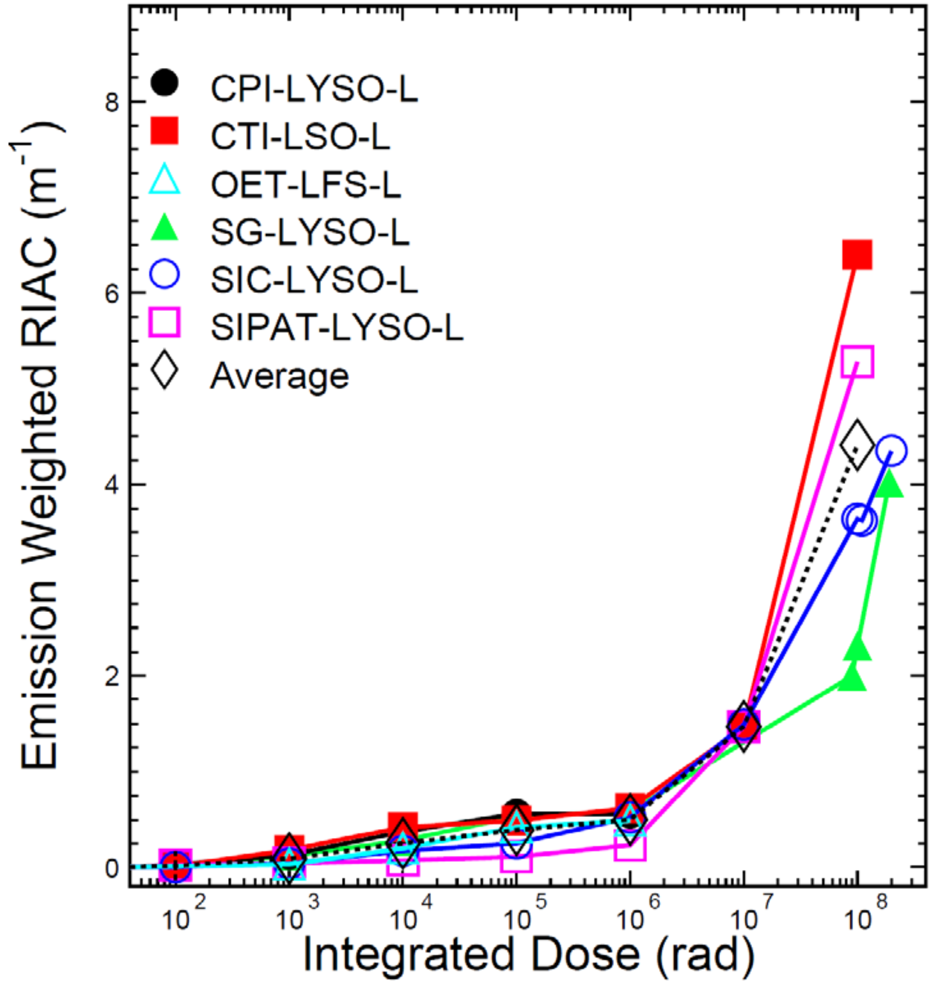
Consistent LO loss of 5.8% and 6.6% observed in two Shashlik cells

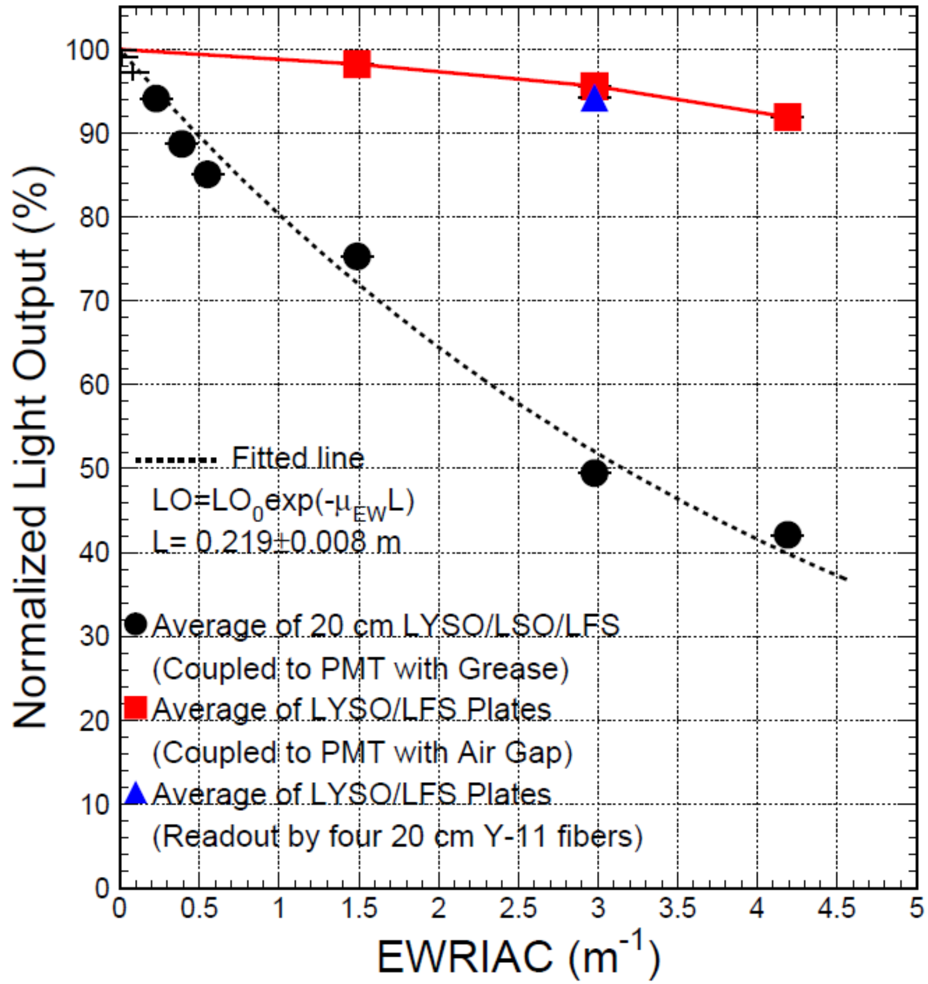


Summary of γ-ray Damage

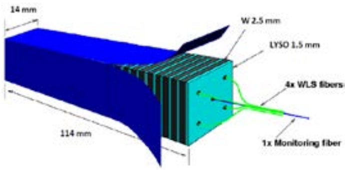


EWRIAC = 1.5, 3 and 4 m^{-1} after 10, 100 and 180 Mrad
LO loss after 100 Mrad is 4 and 6% respectively for direct and WLS readout





Proton Irradiation at Los Alamos



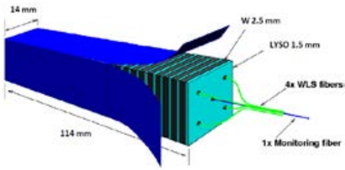
Beam FWHM: 1 inch

Sample	ID	Dimension (cm^3)
LYSO/W/Y-11 Shashlik Cell	Y-11	1.4×1.4×15
Four Sealed Capillaries and Three Y-11 Fibers	Capillaries	1.4×1.4×15
LYSO	SG	2.5×2.5×20
LFS	OET	2.5×2.5×18
BGO	SIC BGO	2.5×2.5×20
CeF_3	SIC CeF_3	$2.2^2 \times 2.6^2 \times 15$

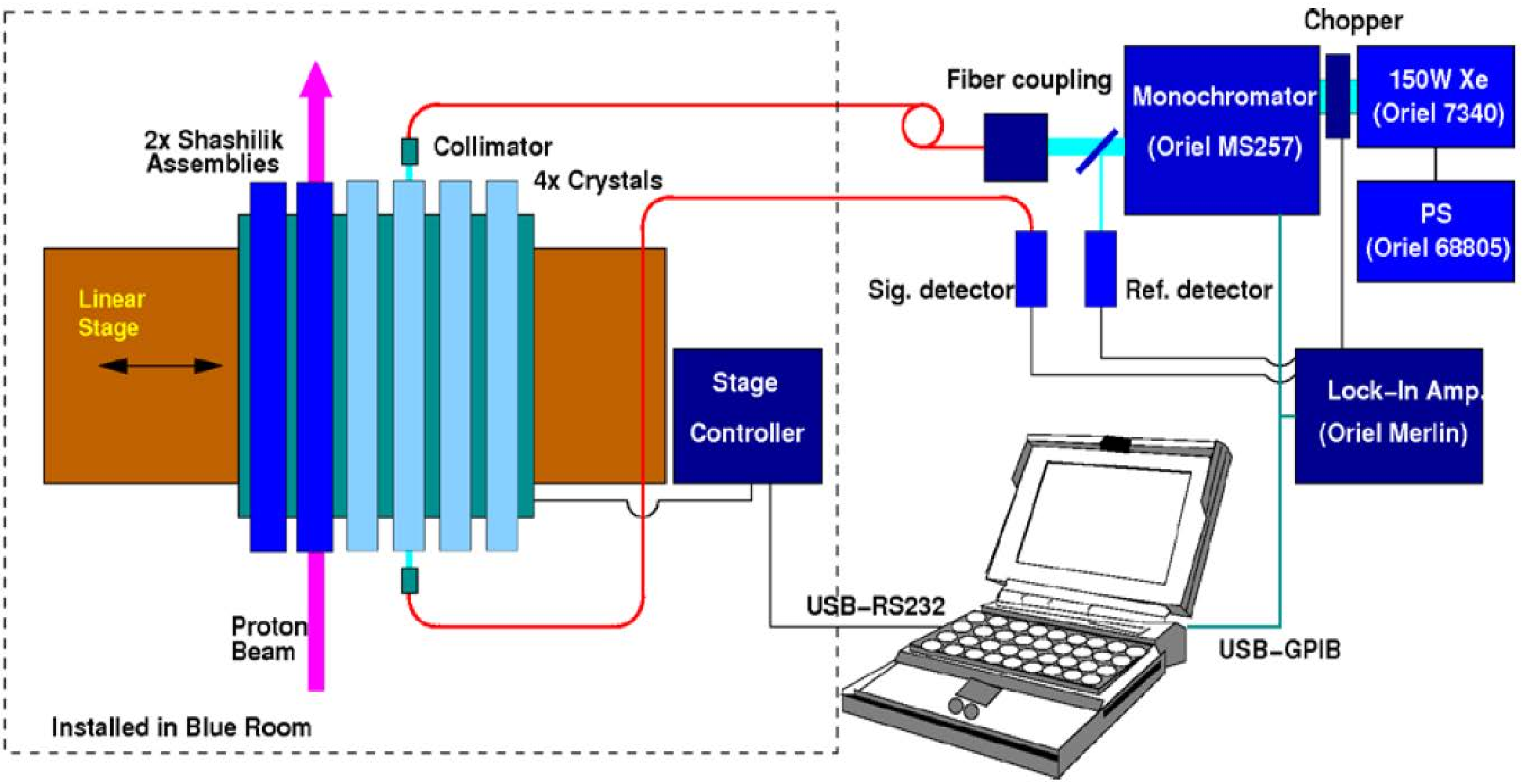
Because of a power black out only three samples were irradiated

Four 6 cm long sealed capillaries and three 20 cm long Y-11: 2.7E14
One 2.5 x 2.5 x 20 cm LYSO crystal: 3.3E14
One 2.2 x 15 x 2.6 cm CeF3 crystal: 1.4E14

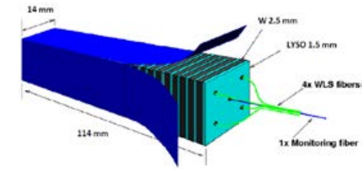
Los Alamos Experiment Setup



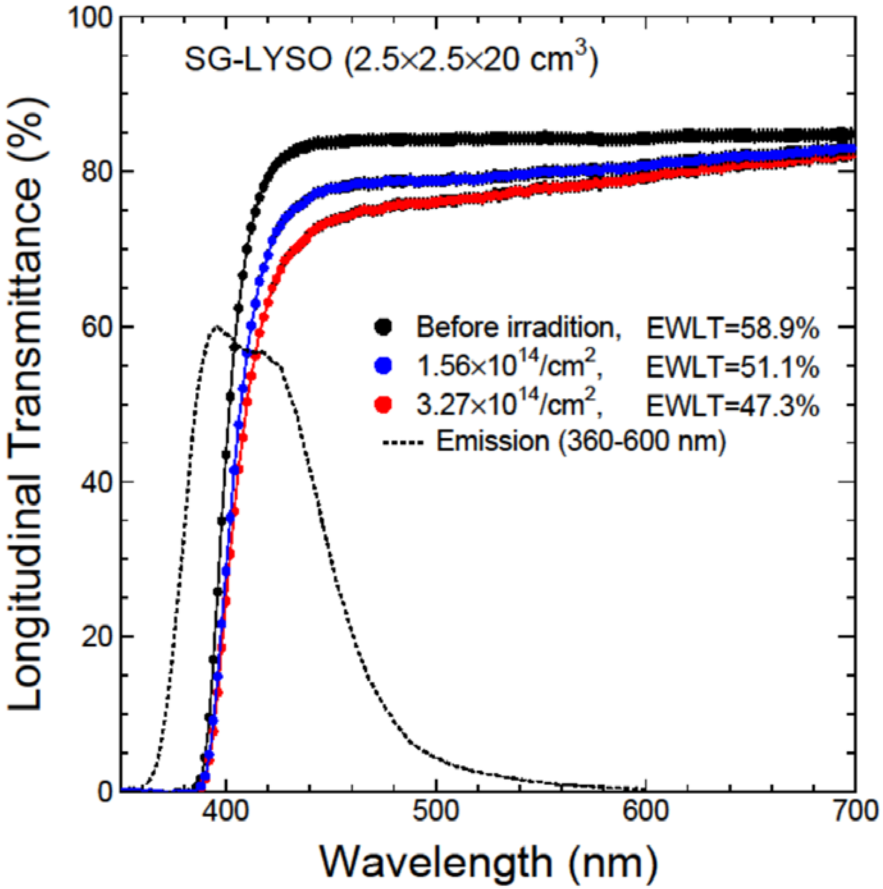
Up to six crystals are hosted on a linear stage. Each crystal can be irradiated by 800 MeV protons in steps with its longitudinal transmittance measured *in situ.*

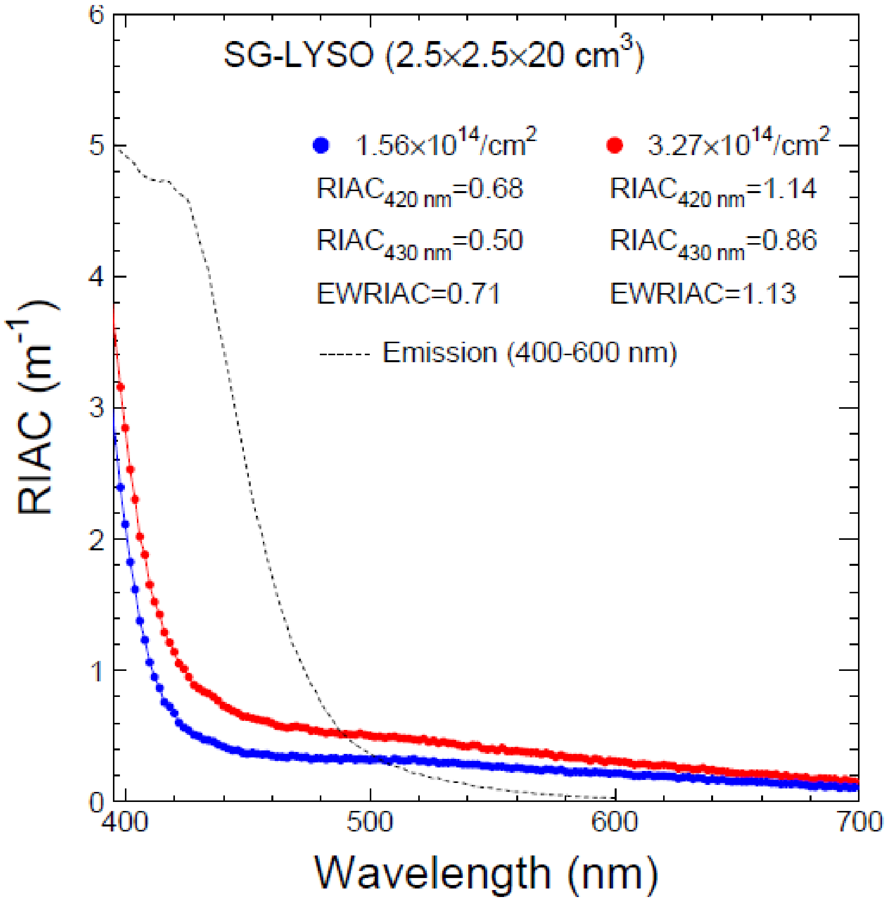


LANL Result: LT and RIAC



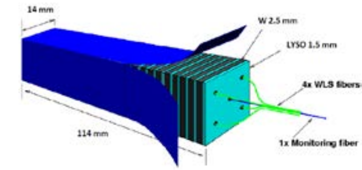
Emission weighted longitudinal transmittance (EWLT)
Emission weighted radiation induced absorption coefficient (EWRIAC)



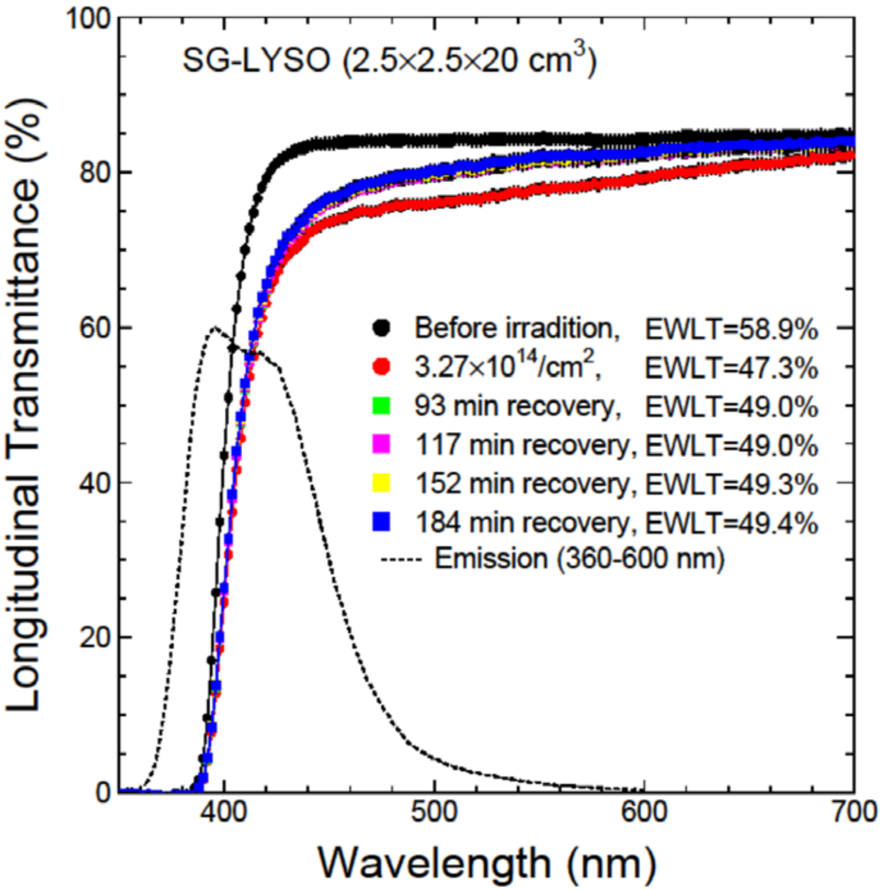


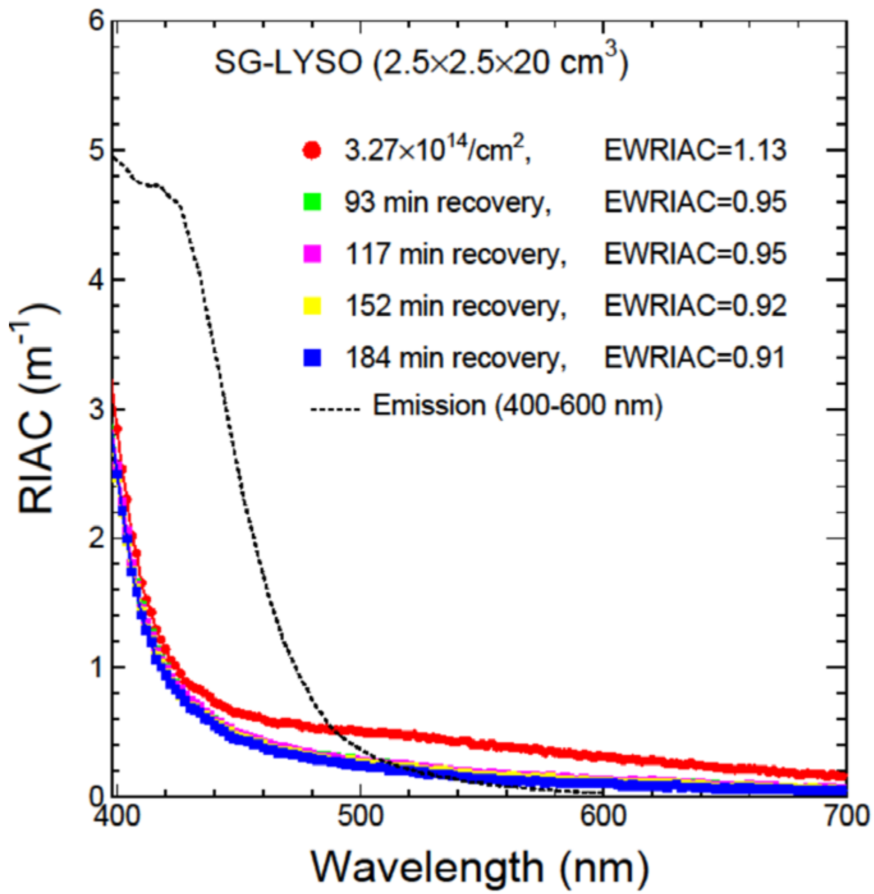
About 1 m^{-1} was observed for a 20 cm long LYSO after 3.3E14

LANL Result: Recovery of LT & RIAC

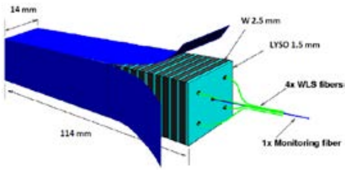


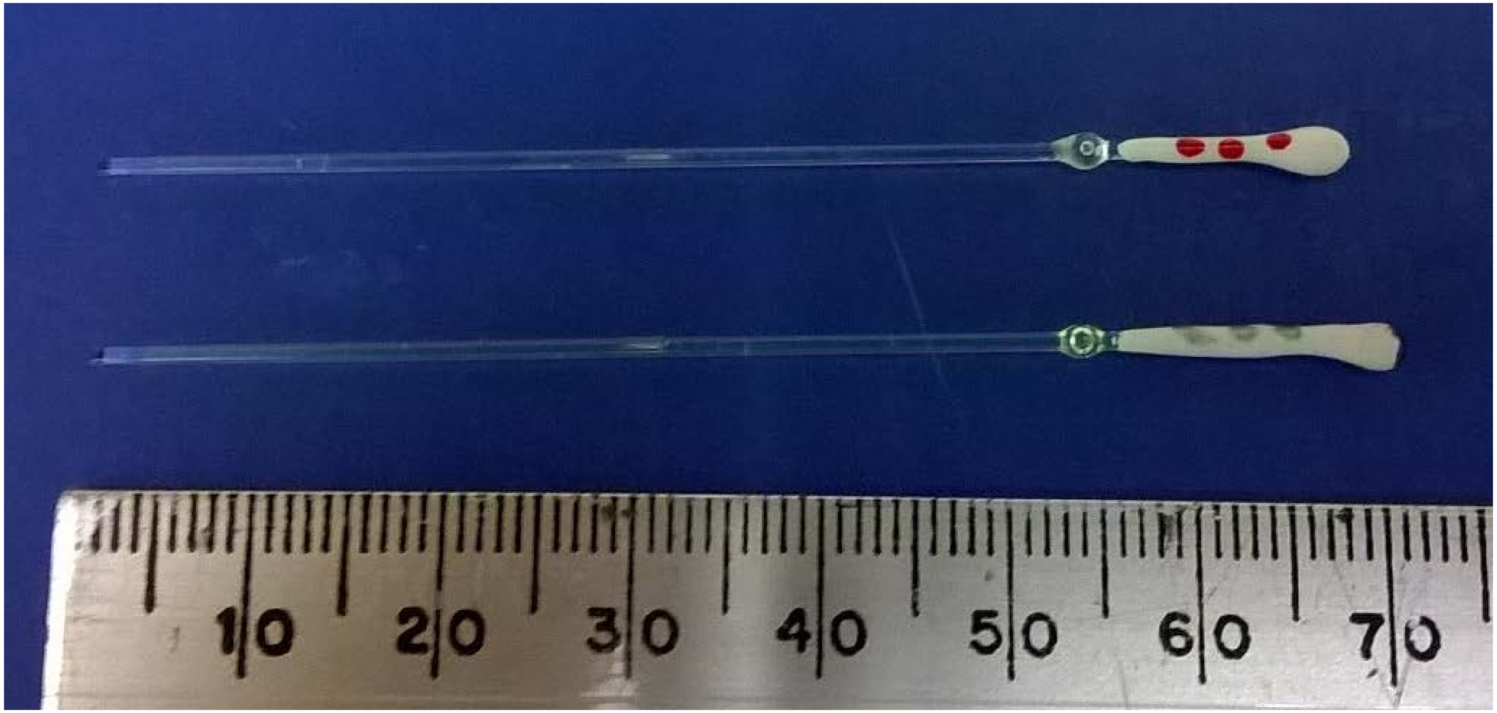
Recovery in long wavelength observed *in situ* which is caused by thermal relaxation





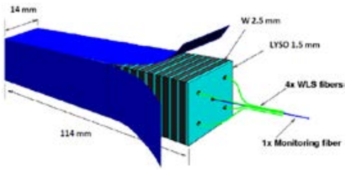
Two Type Sealed Capillaries

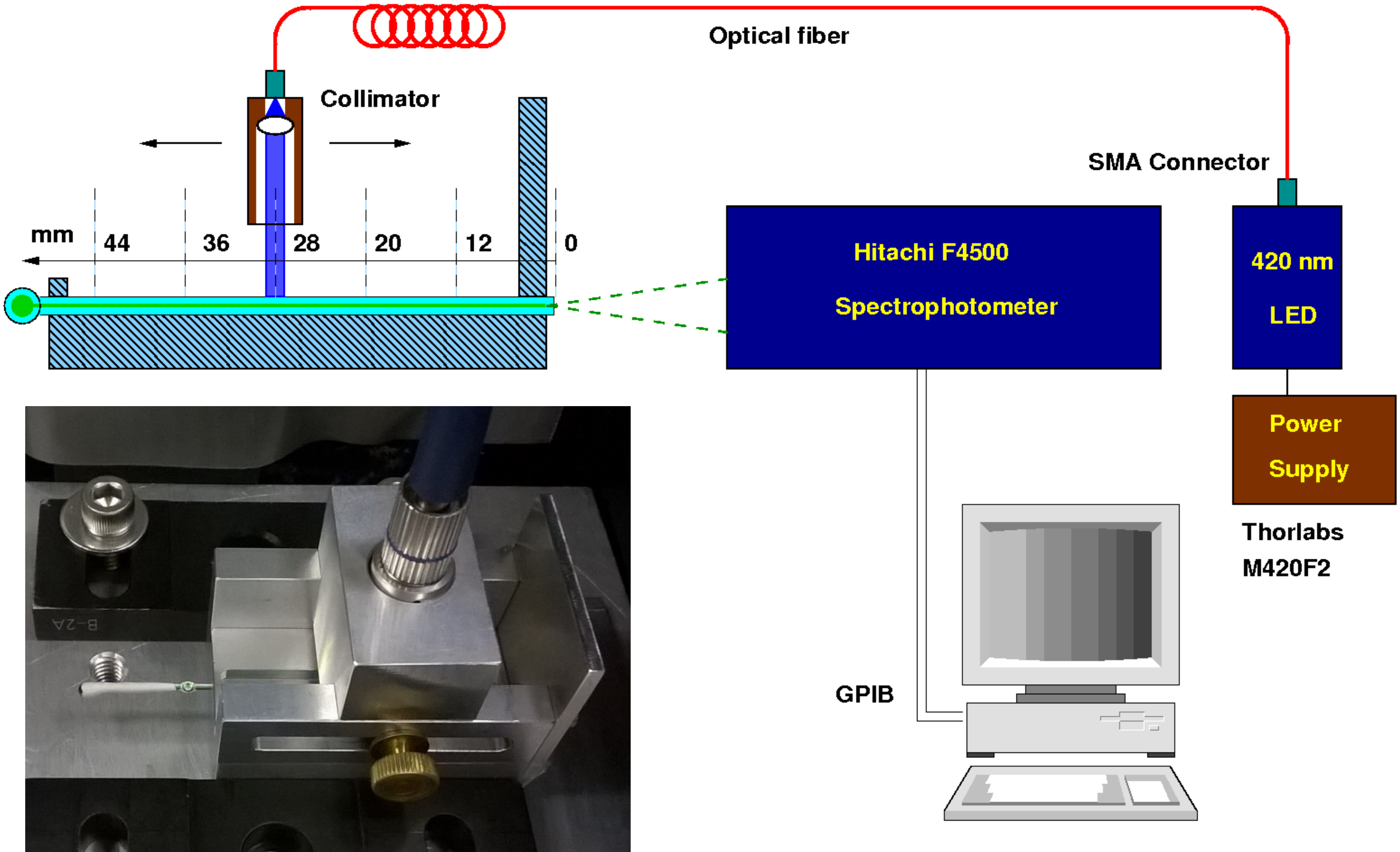




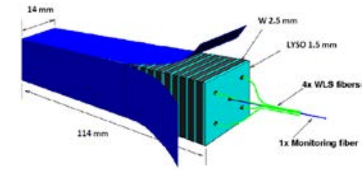
- 10A J2-1 and 2, and 11A DSB1-1 and 2 were irradiated by protons at Los Alamos.
- 10A 3 and 11A 3 are used as references.

Capillary Measurement Setup

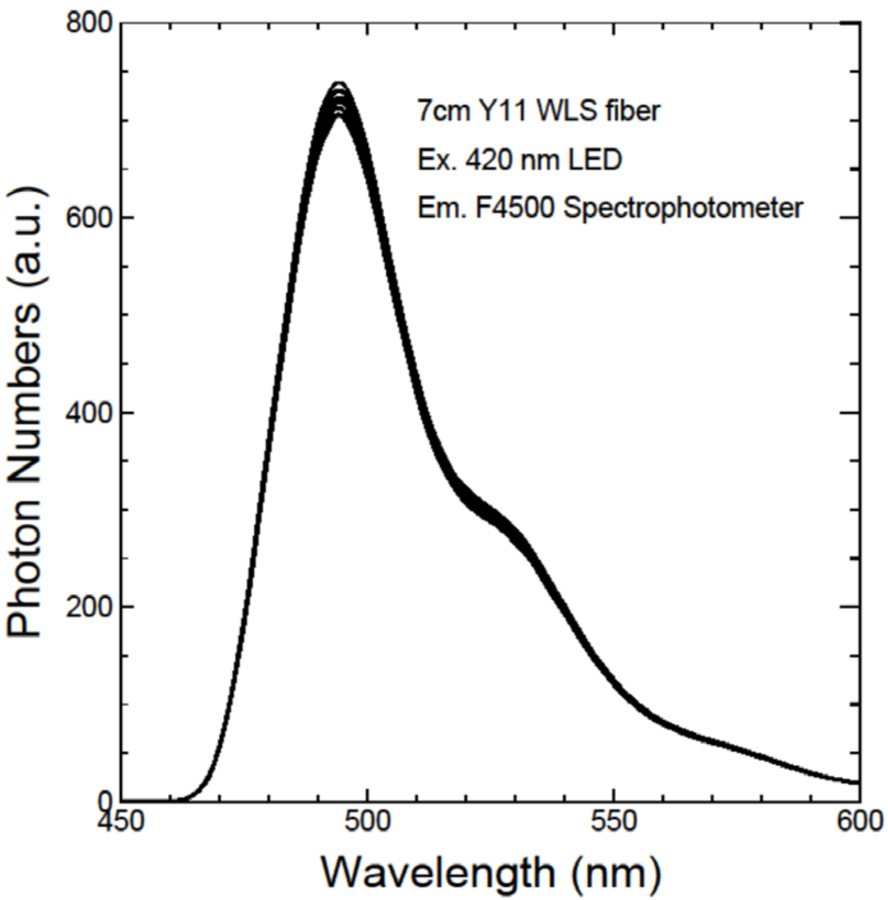


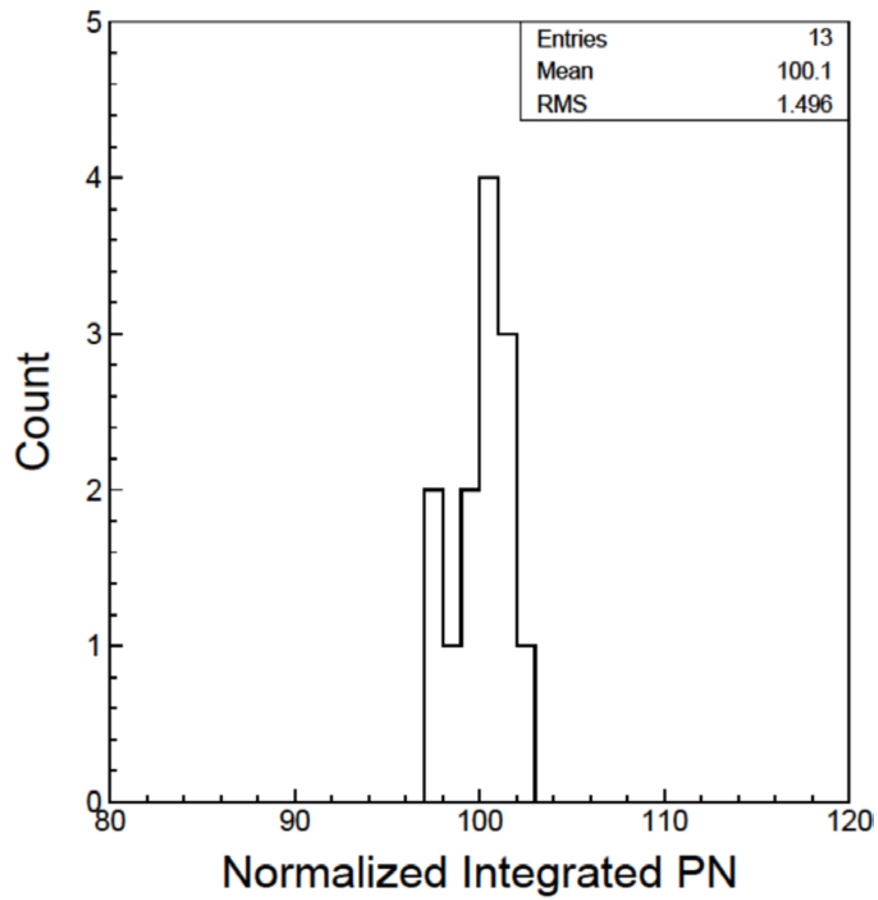


Systematic Uncertainties

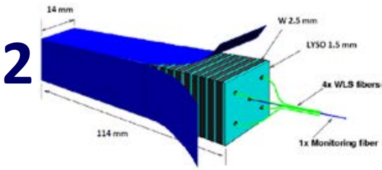


Checked with a Y-11 WLS fiber of 6 cm, the systematic uncertainty is 1.5%

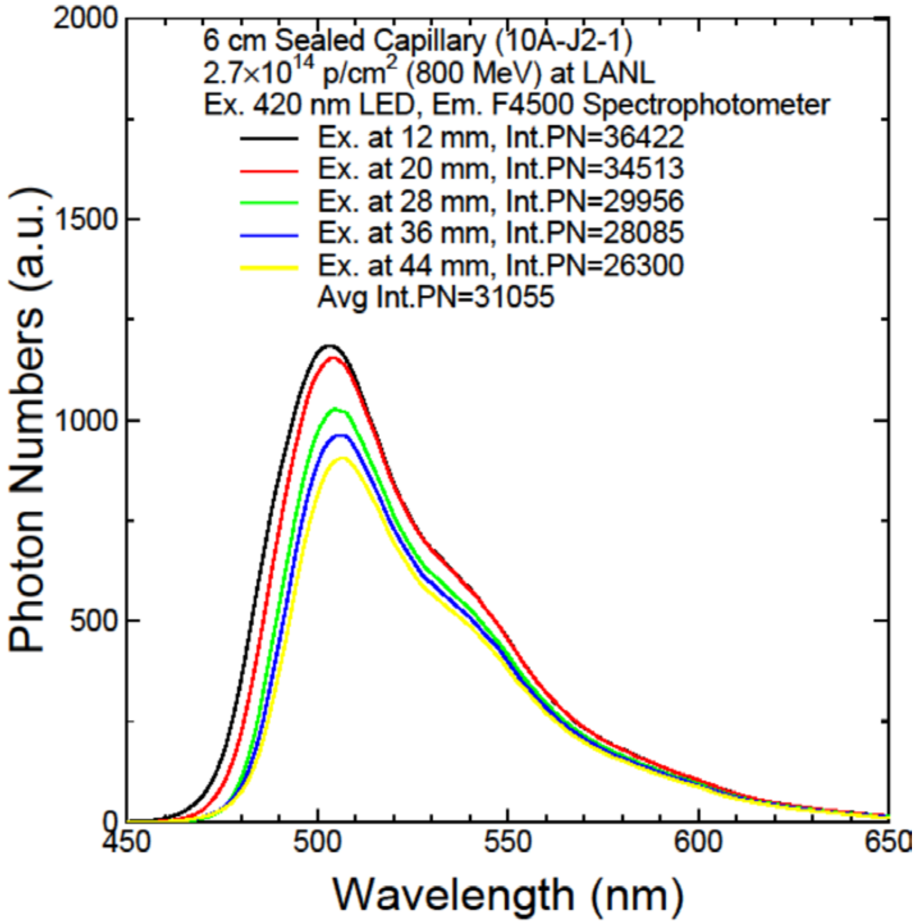


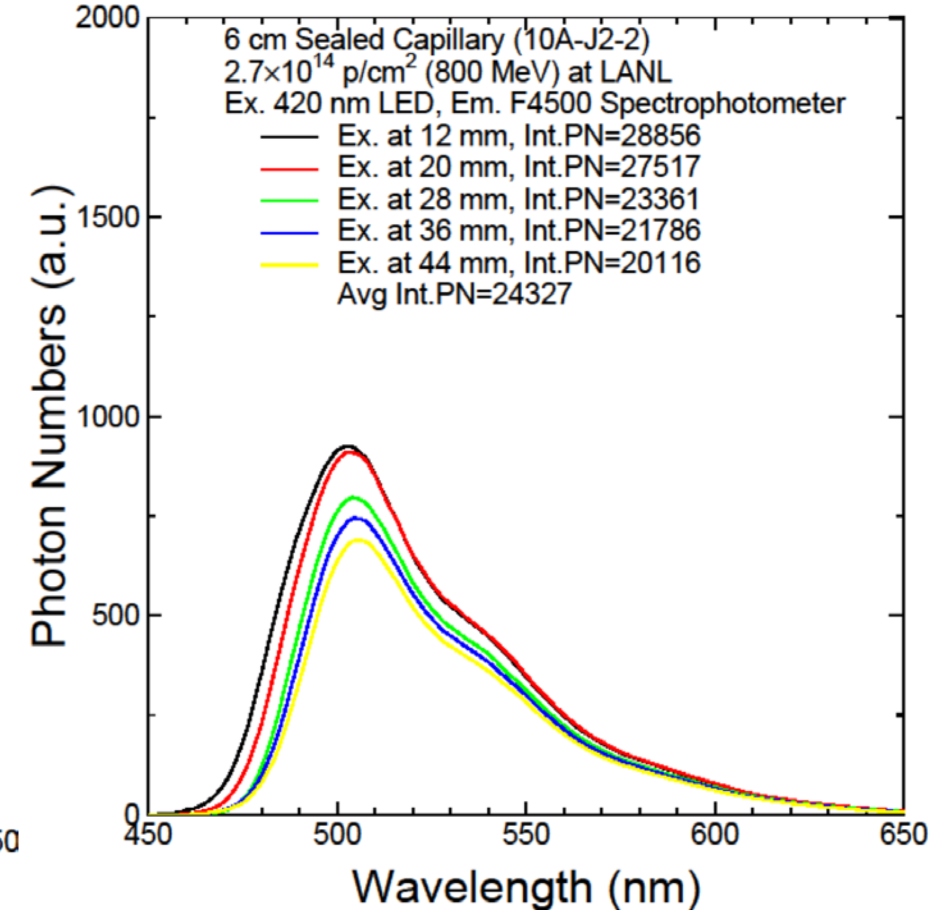


J2 Capillaries after 2.7 x 10^{14} p/cm^2

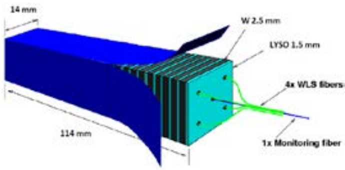


Emission intensity as function of the distance to the coupling end

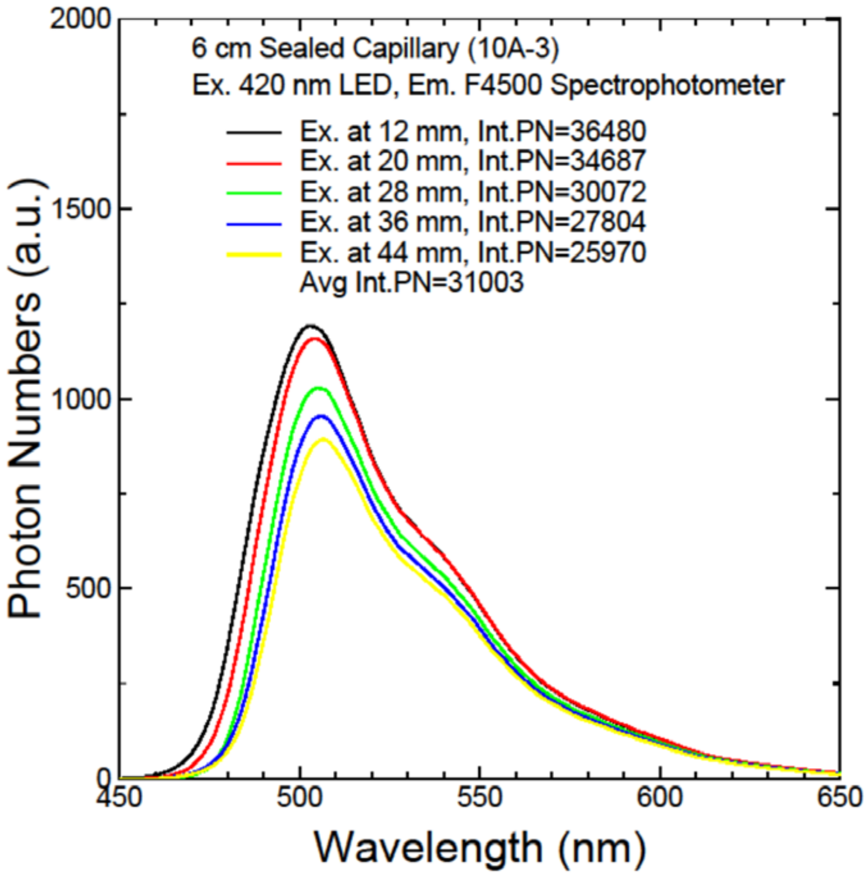


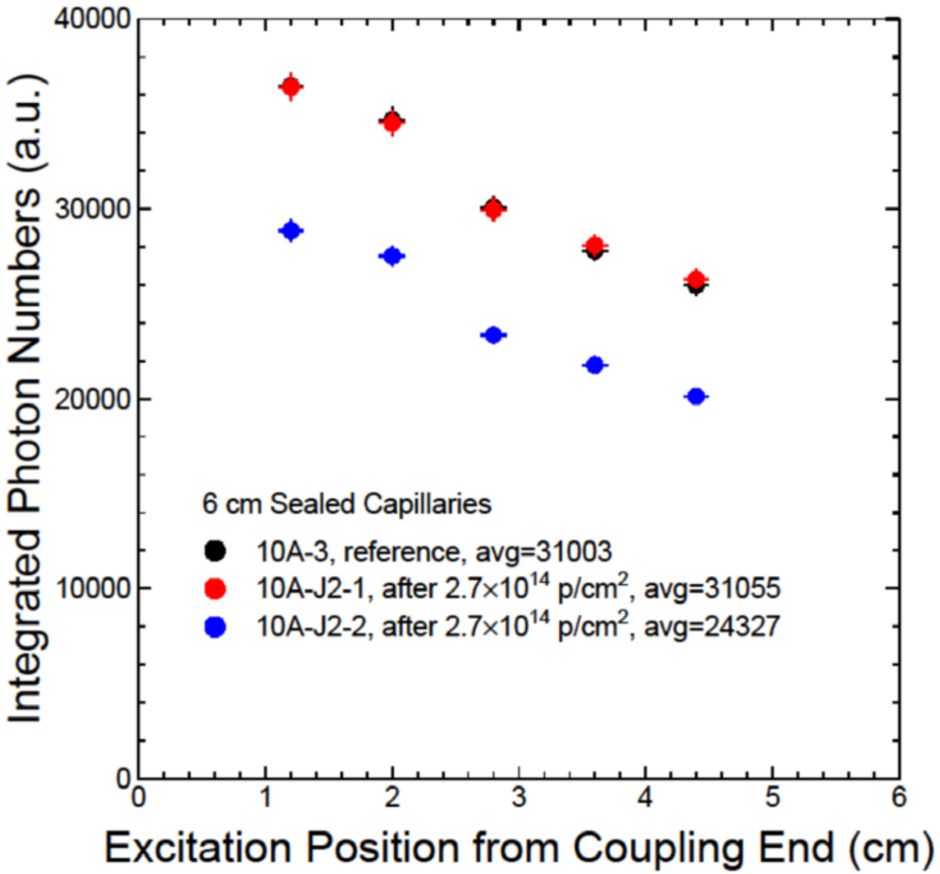


Comparison with Un-irradiated J2

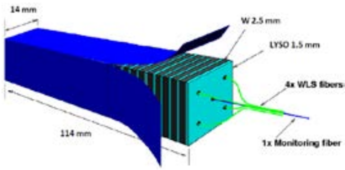


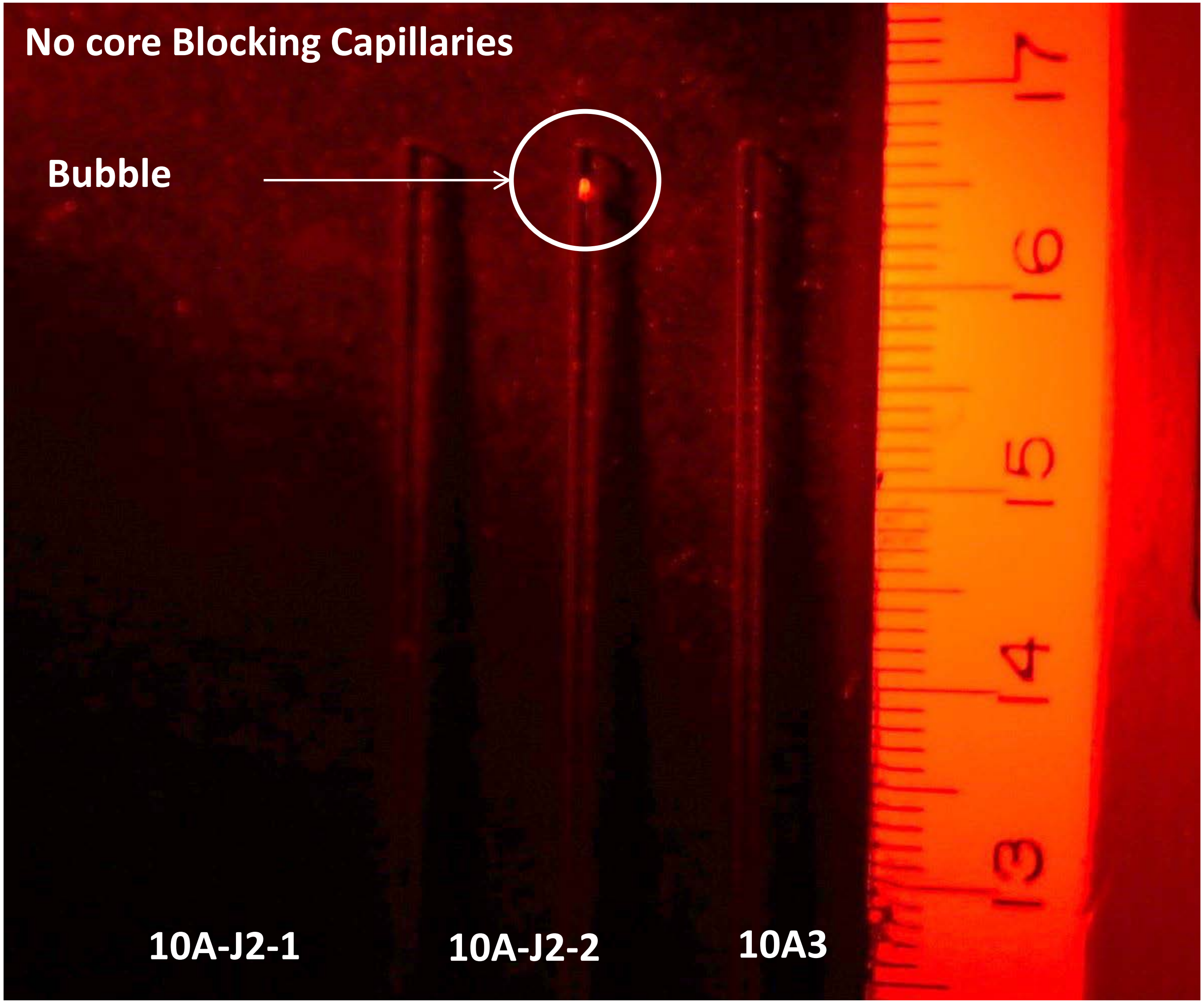
All three 10A-J2 capillaries show consistent emission spectrum
Consistent photon intensity between 10A-J2-1 and 10A-3 is observed
10A-J2-2 is 22% lower than the other two because of a bubble in it.



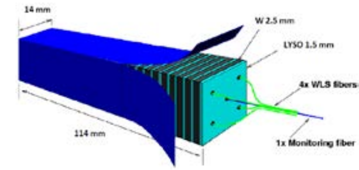


A Bubble Observed in 10-J2-2

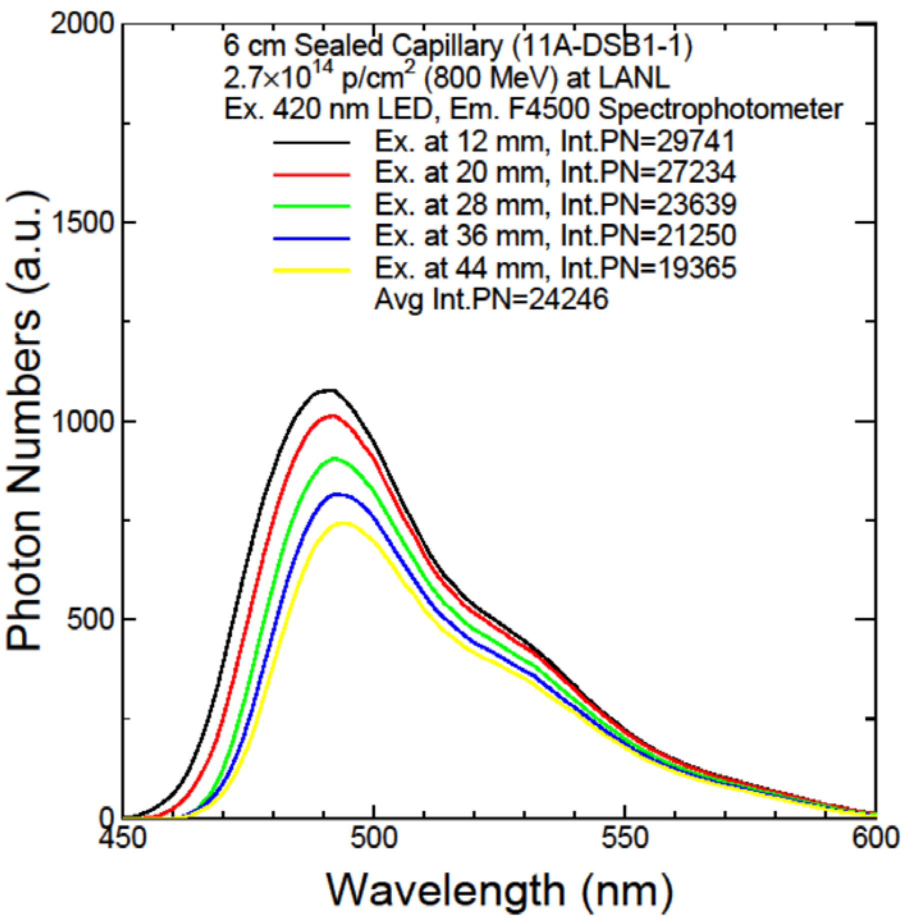


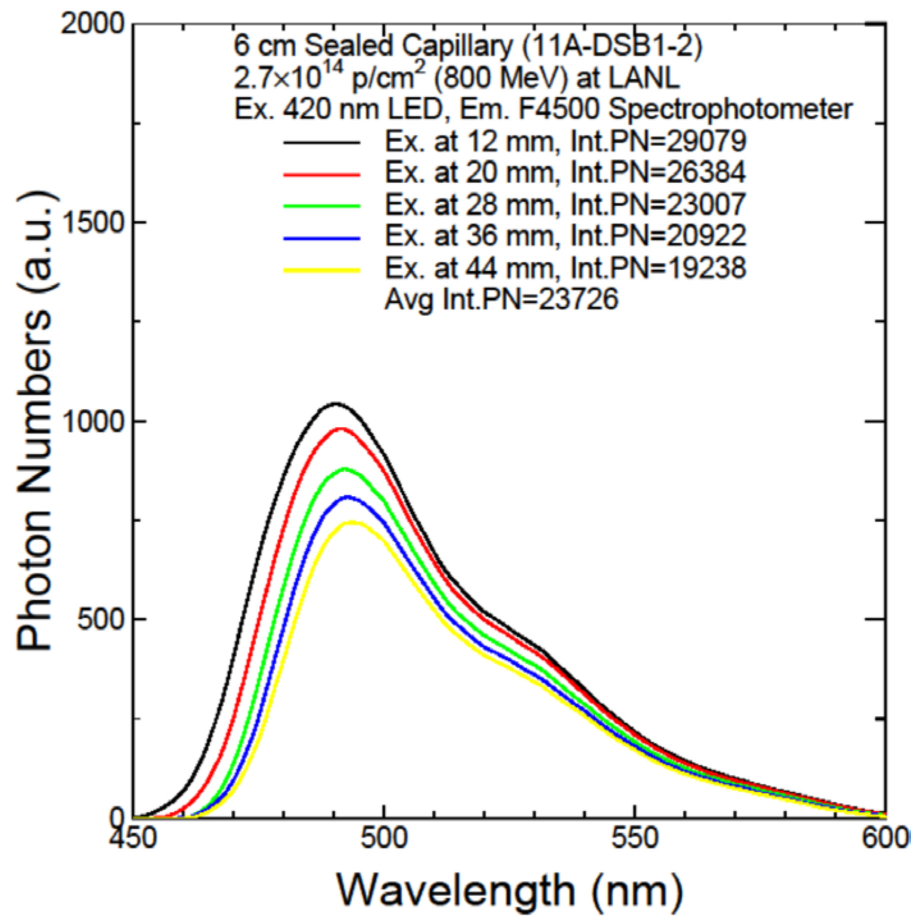


DSB Capillaries after 2.7 x 10^{14} p/cm^2

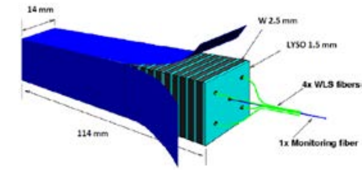


Emission intensity as function of the distance to the coupling end





Comparison with Un-irradiated DSB



All three DSB capillaries show consistent emission spectrum
11A-DSB-1 and 11A-DSB-2 show 5% and 3% higher photon intensity as compared to the un-irradiated 11A-3