Hadron Induced Radiation Damage in Fast Crystal Scintillators

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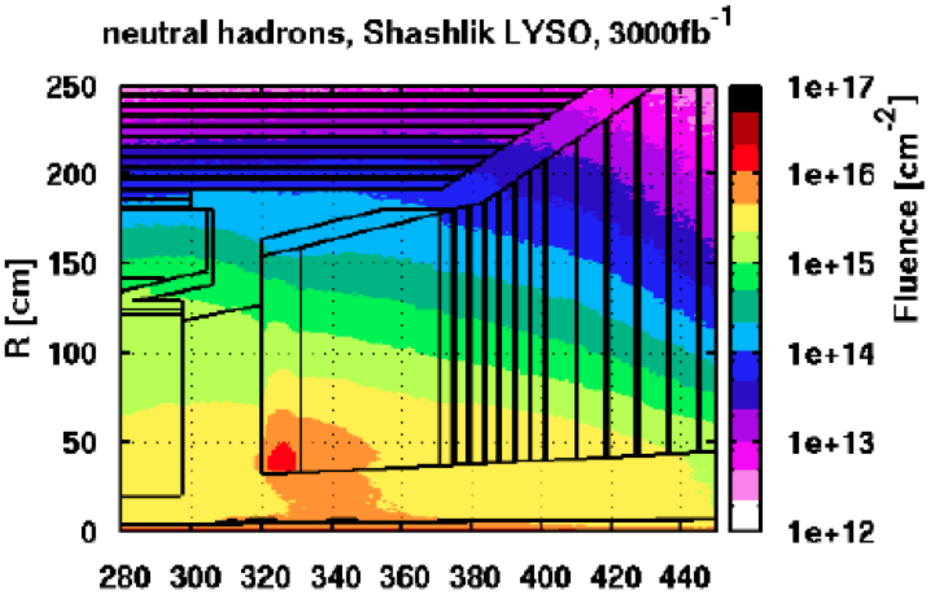
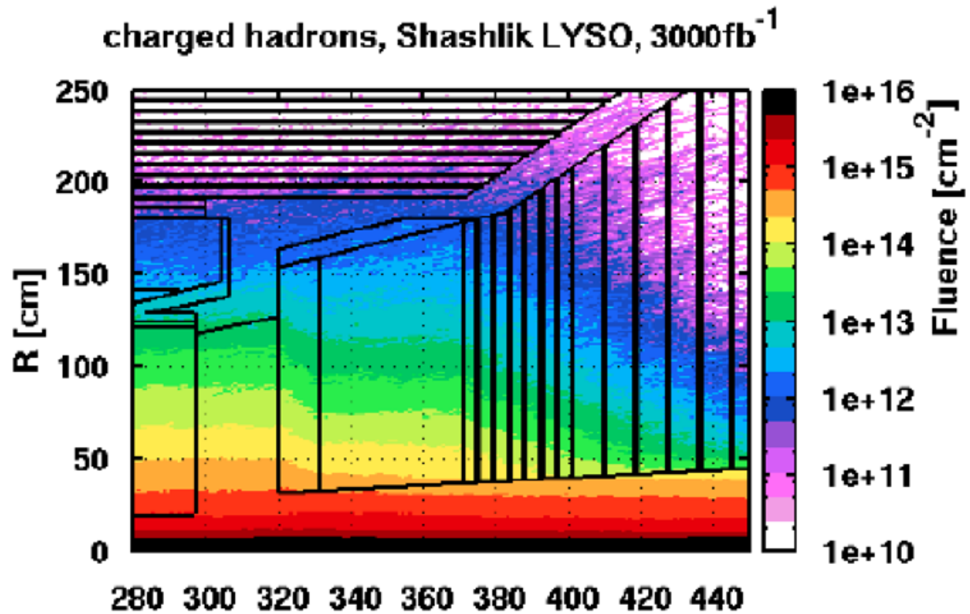
Introduction

- Because of the severe radiation environment expected in future HEP experiments at the energy frontier, e.g. the proposed HL-LHC, radiation damage caused by charged hadrons and neutrons in addition to ionization dose is a crucial issue for crystal scintillators.
- The 800 MeV proton beam at the Weapons Neutron Research facility of Los Alamos National Lab Neutron Research Center (WNR of LANSCE) is ideal for the investigation on charged hadron induced radiation damage in crystal scintillators. LYSO/CeF_3 crystals of 2.5 x 2.5 x 20/2.2 x 15 x 2.6 cm^3 were irradiated to 3.3/1.4 x 10^{14} p/cm^2 at Los Alamos in December, 2014.
- To avoid multiple Coulomb scattering and hadronic shower leakage in long crystals, LYSO plates of 14 x 14 x 1.5 mm^3 were irradiated by 24 GeV/67 MeV protons at CERN/UC Davis up to 6.9 x 10^{15}/9.5 x 10^{13} p/cm^2.
- LYSO plates of 14 x 14 x 1.5 mm^3 were also irradiated by 2.5 MeV fast neutrons from Cf-252 sources to 4 x 10^{13} n/cm^2 at Caltech.

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

FLUKA simulations: the neutron and charged hadron fluence expected by the CMS FCAL at |η| = 3 is 5 x 10^{15}/cm^2 and 3 x 10^{14}/cm^2 respectively at the HL-LHC

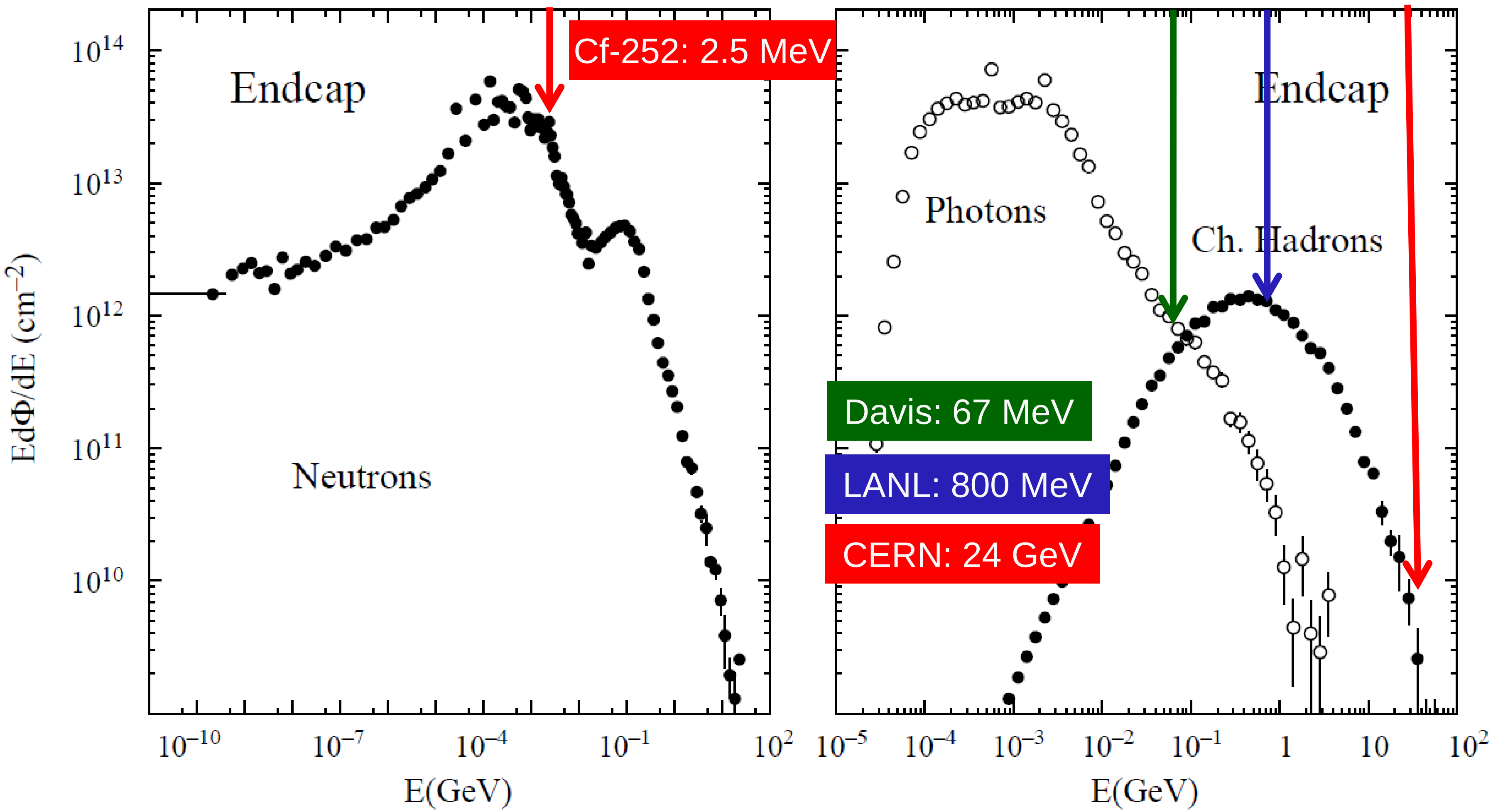




No experimental data show that neutrons and charged hadrons would damage crystal scintillators equally, so they are treated separately

Energy Spectra Expected at HL-LHC

FLUKA simulations: neutrons and charged hadrons are peaked at MeV and several hundreds MeV respectively. Neutron energy of 2.5 MeV from Cf-252 source and proton energy of 800 MeV at LANL are ideal for such investigation

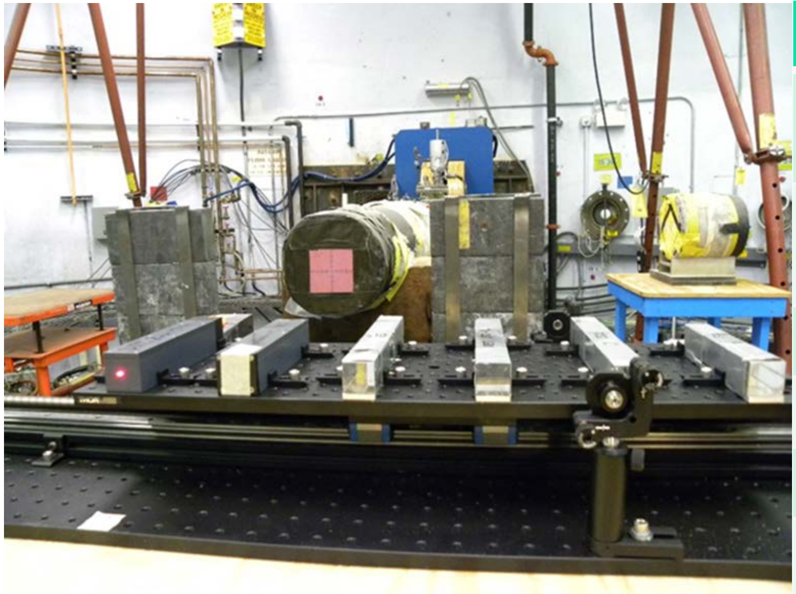


800 MeV Proton Beam at LANL

Environment/Source	Proton Flux ($p\ s^{-1}\ cm^{-2}$)	Fluence on Crystal ($p\ cm^{-2}$)
CMS FCAL (η=1.4) at HL-LHC	4.0×10^{4}	2.4×10^{12} / 3000 fb^{-1}
CMS FCAL (η=3.0) at HL-LHC	5.0×10^{6}	3.0×10^{14} / 3000 fb^{-1}
WNR facility of LANSCE	**Up to 2×10^{10}**	**Up to 3×10^{14}**

One end of a long crystal is bombarded by 800 MeV protons of a Gaussian shape with FWHM of one inch

Samples for Proton Irradiation at LANL



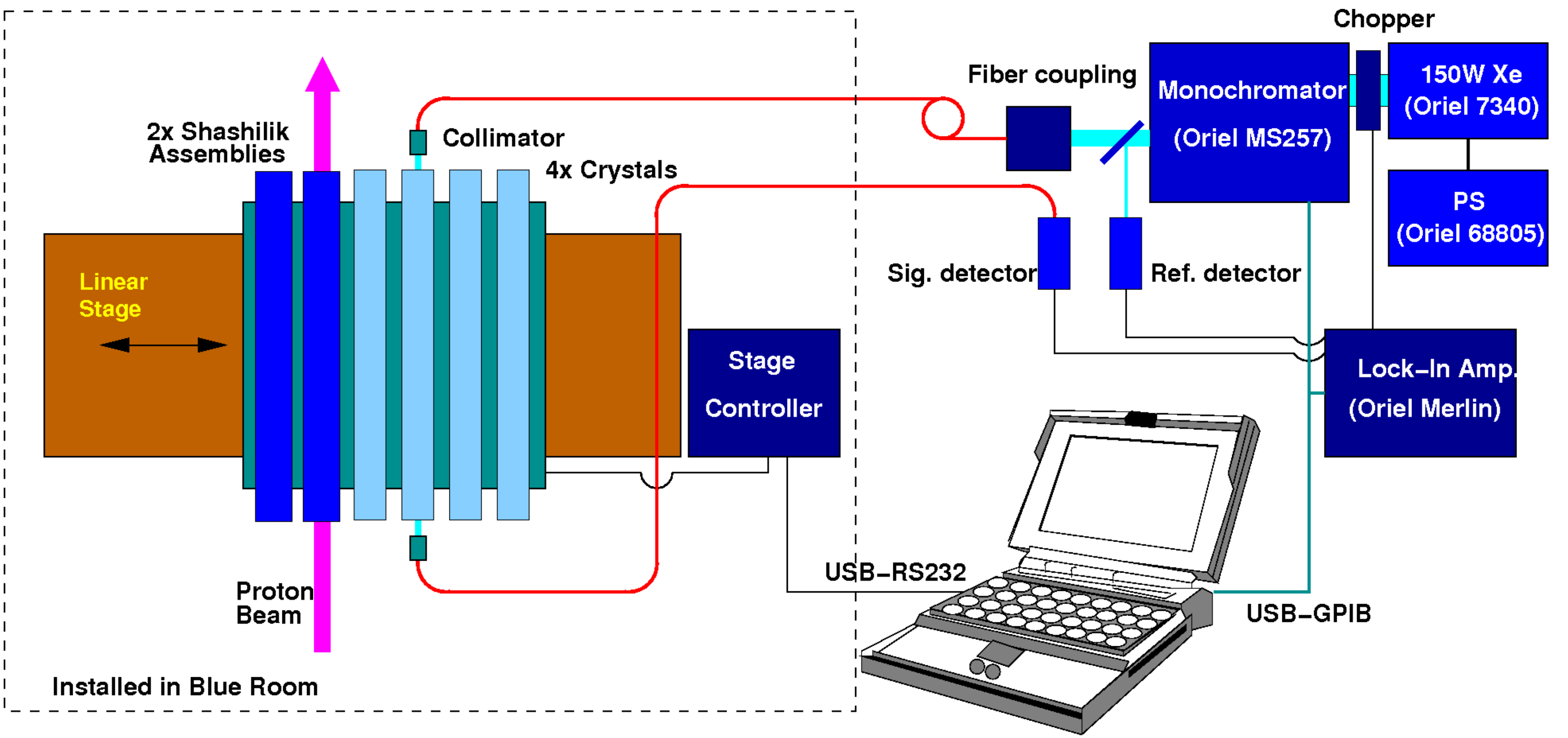
Sample	ID	Dimension (cm^3)
LYSO/W Shashlik Cell	Y-11	1.4×1.4×15
Four Sealed Capillaries and Three Y-11 Fibers	Capillaries	1.4×1.4×15
LYSO	SG LYSO	2.5×2.5×20
LFS	OET LFS	2.5×2.5×18
BGO	SIC BGO	2.5×2.5×20
CeF_3	SIC CeF_3	$2.2^2 \times 2.6^2 \times 15$

Because of a power black out only 3 samples were irradiated in 4.5h

- Four 6 cm long sealed capillaries and three 20 cm long Y-11 WLS fibers: 2.7 x 10^{14} p/cm^2;
- One 2.5 x 2.5 x 20 cm LYSO crystal: 3.3 x 10^{14} p/cm^2; and
- One 2.2 x 15 x 2.6 cm CeF_3 crystal: 1.4 x 10^{14} p/cm^2.

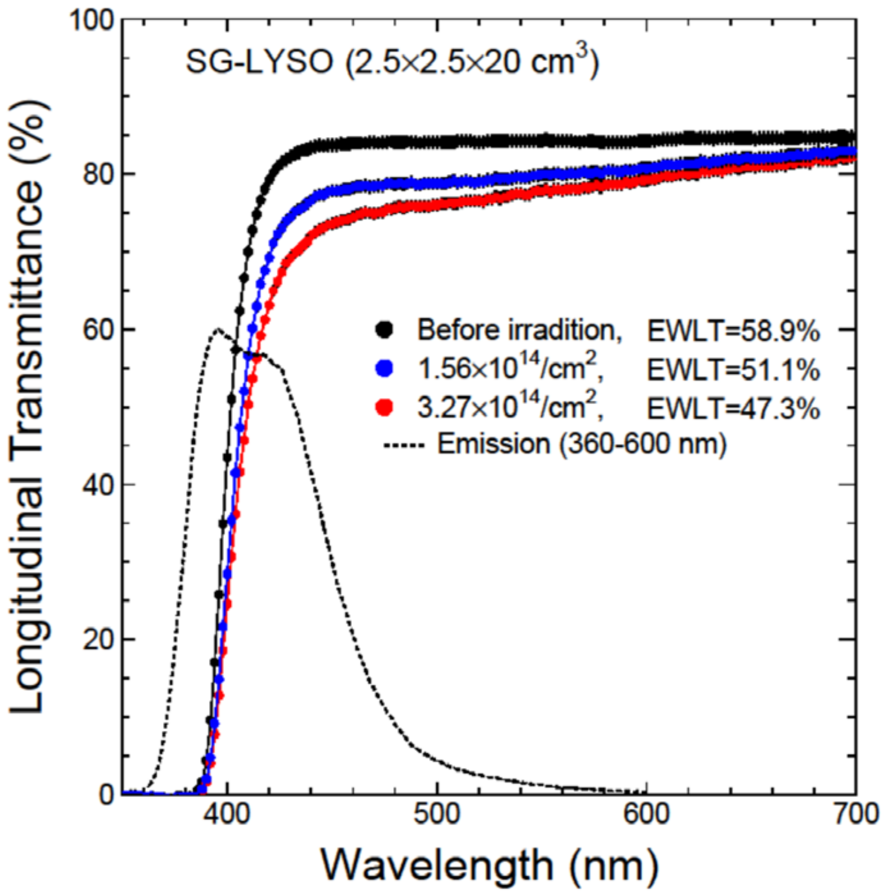
The Experimental Setup

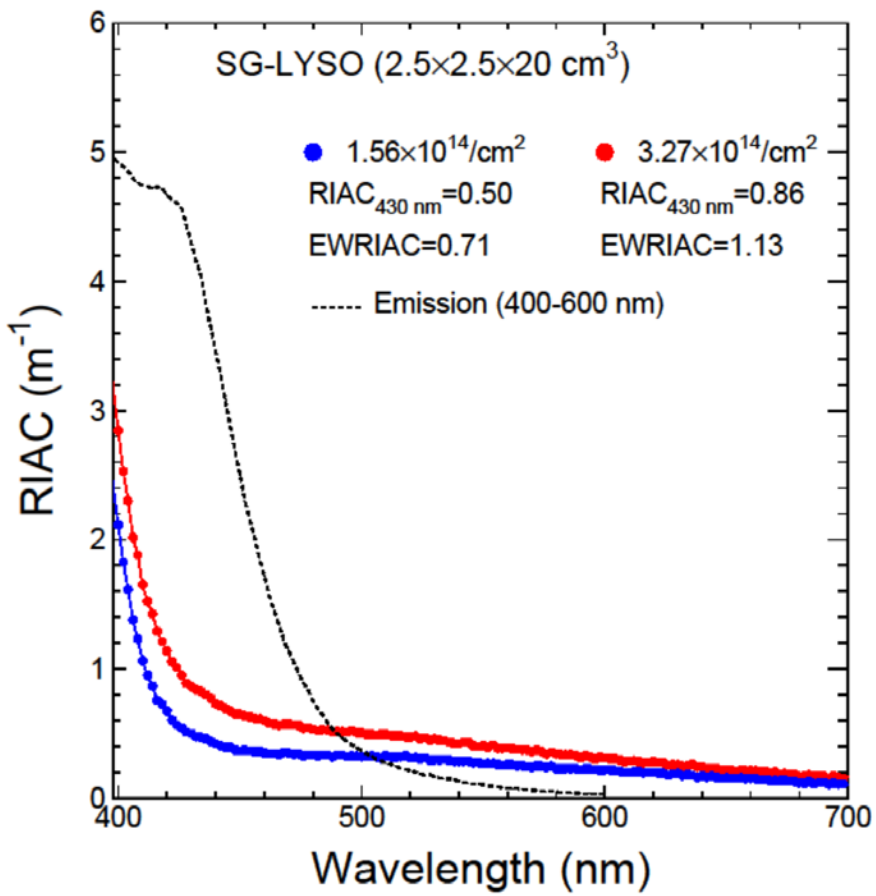
Up to six crystals are hosted on a linear stage. Each crystal may be irradiated by 800 MeV protons in steps with its longitudinal transmittance measured *in situ*



LYSO: LT Damage and RIAC

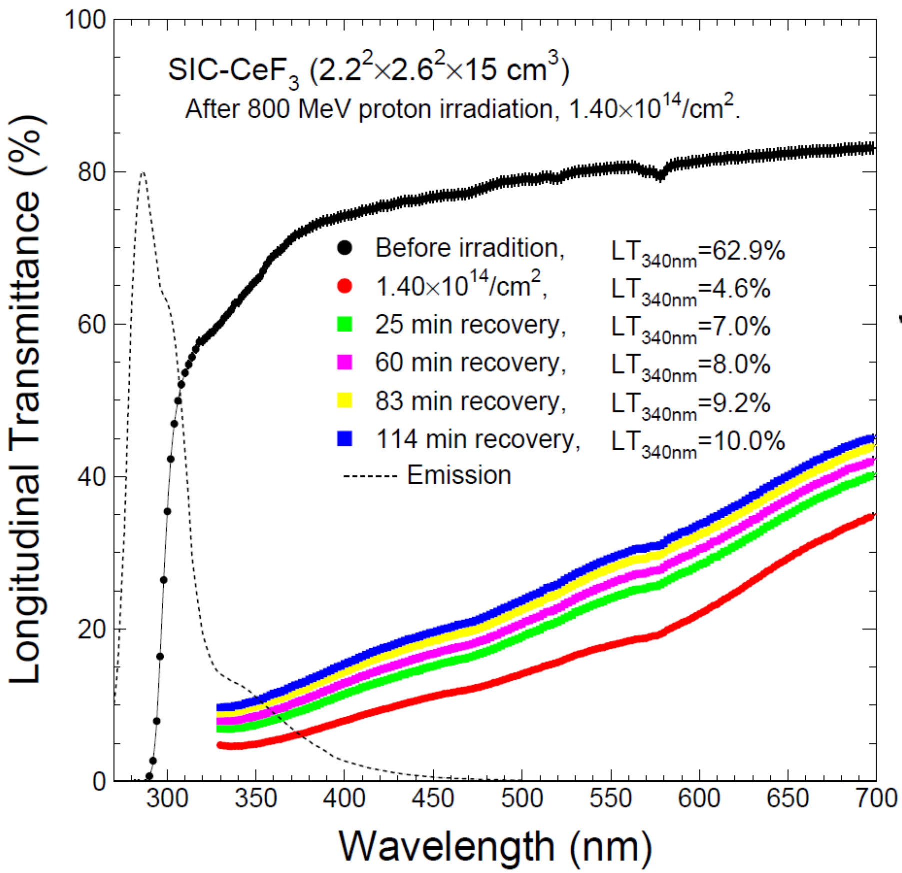
An LYSO of 2.5×2.5×20 cm^3 was irradiated to 3.3×10^{14} p/cm^2 with EWRIAC of 1 m^{-1}, indicating excellent radiation hardness of LYSO against protons

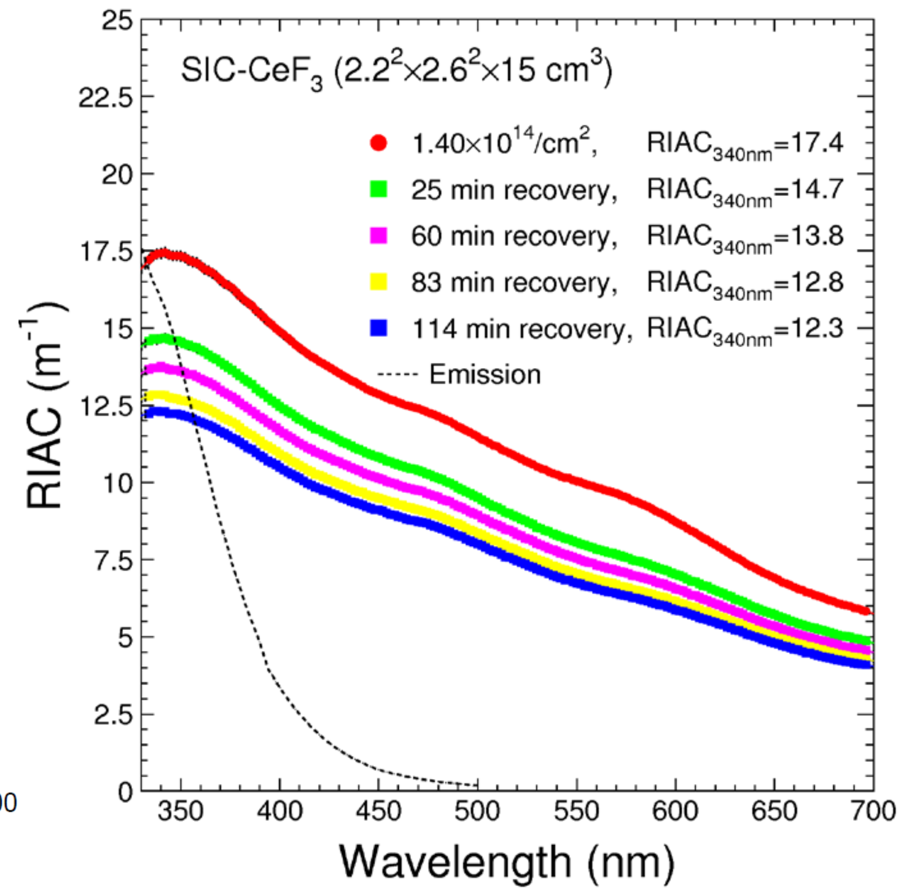




CeF_3: Recovery of LT & RIAC

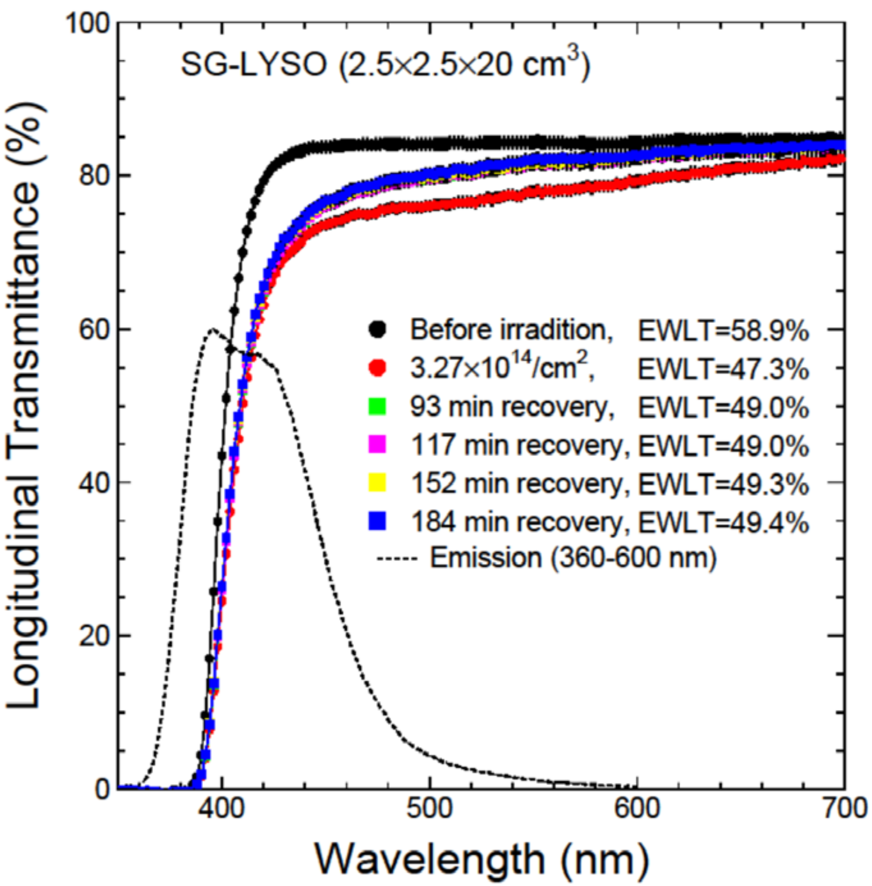
An order of magnitude larger absorption in a CeF_3 of $2.2^2 \times 15 \times 2.6^2$ cm^3 after 1.4×10^{14} p/cm^2 irradiation, indicating optimized samples are needed.

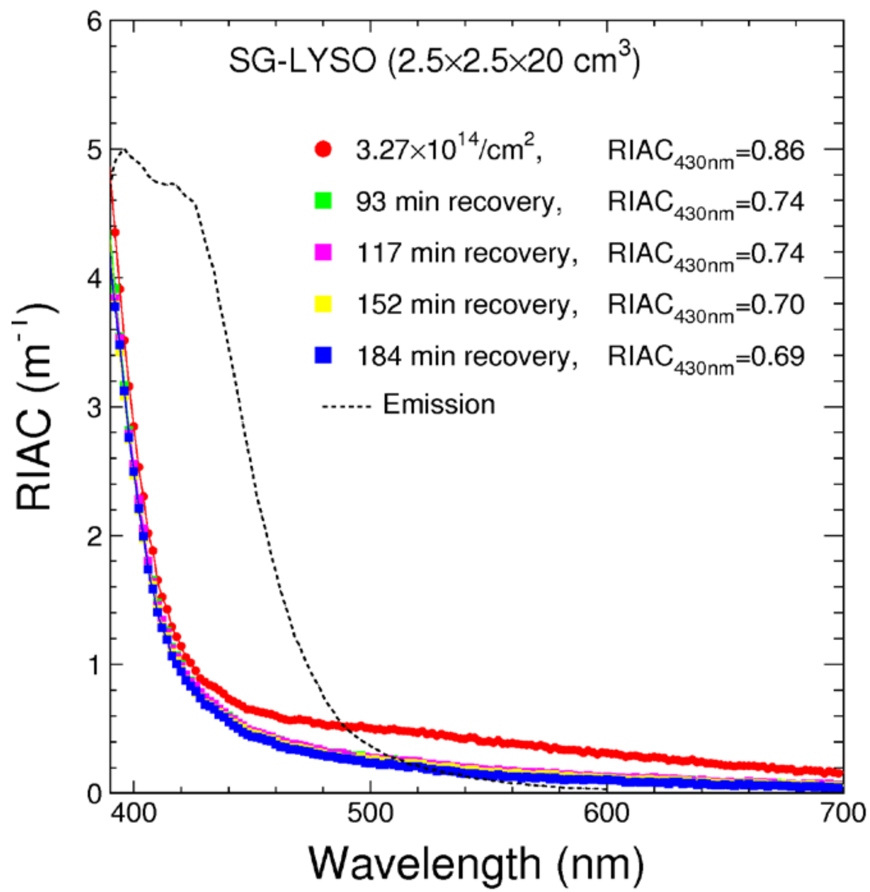




LYSO: Recovery of LT & RIAC

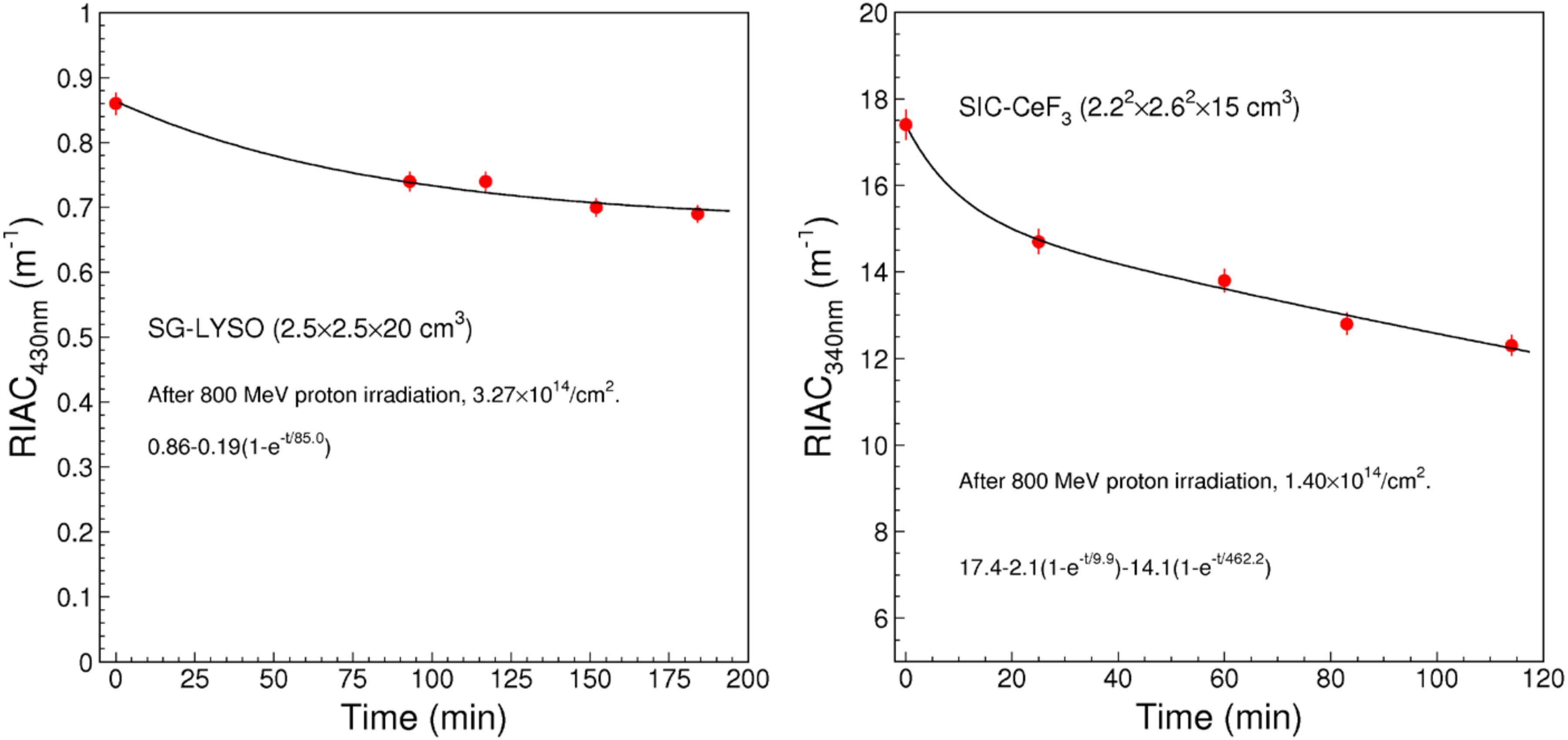
Small recovery attributed to thermal relaxation





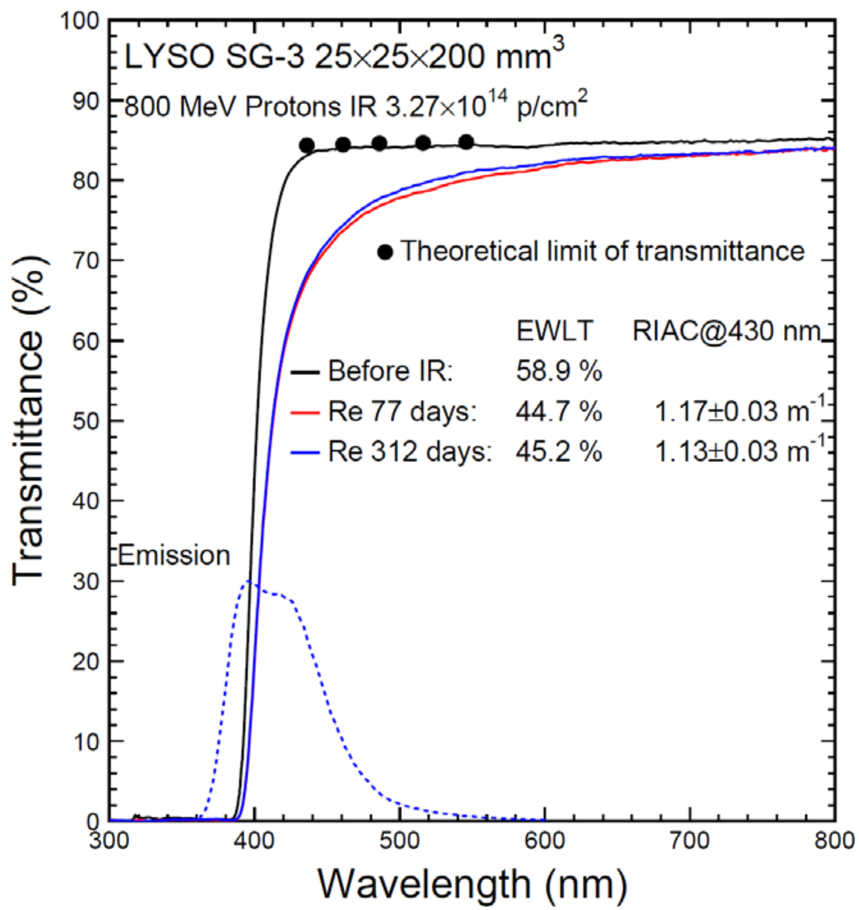
Recovery: LYSO and CeF_3

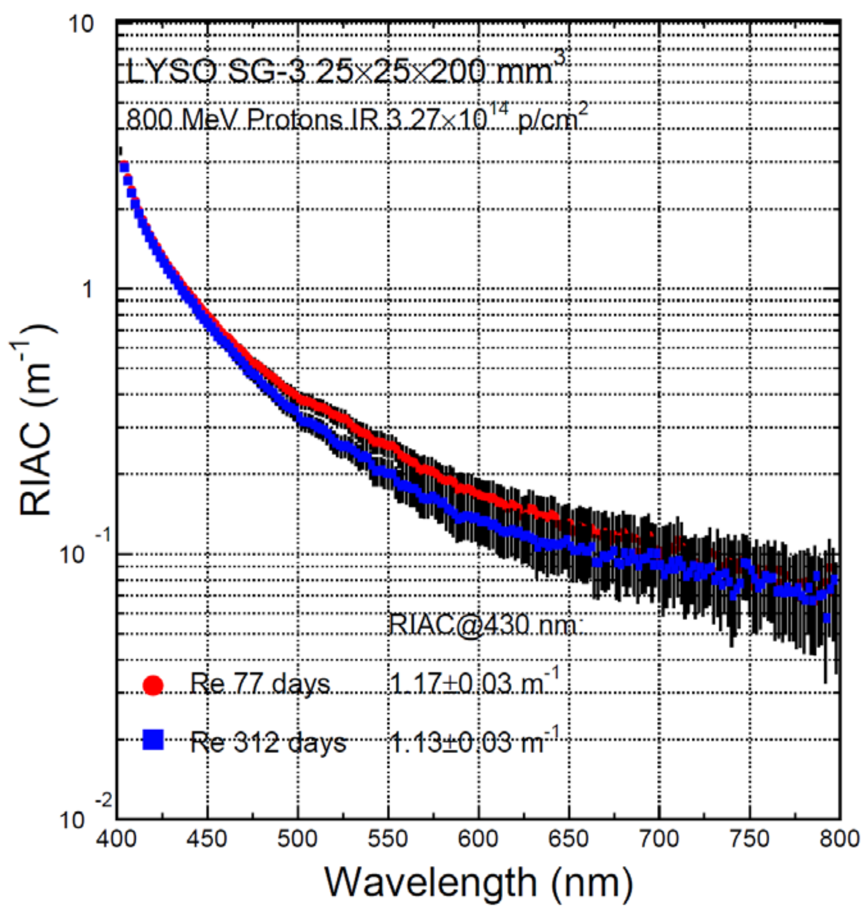
Recovery observed in CeF_3 during 2 hours with a main τ~462 mins



LYSO Measurements at Caltech

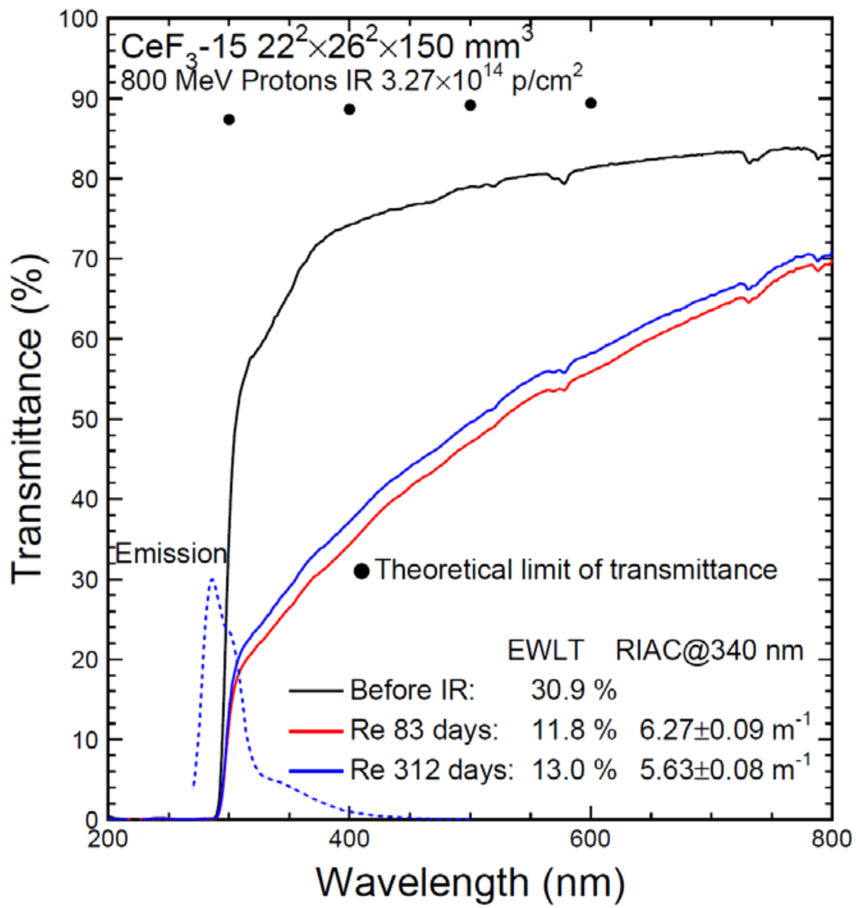
Measurement after crystal back to Caltech is consistent with that *in situ*
No recovery between 77 and 312 days beyond measurement uncertainties

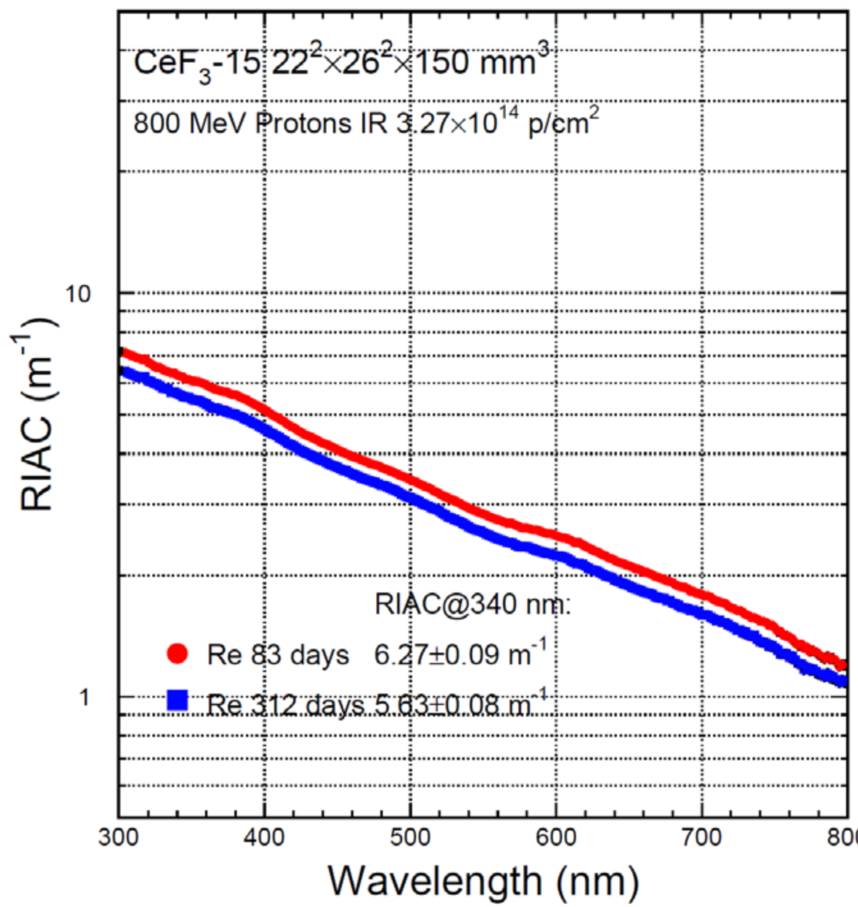




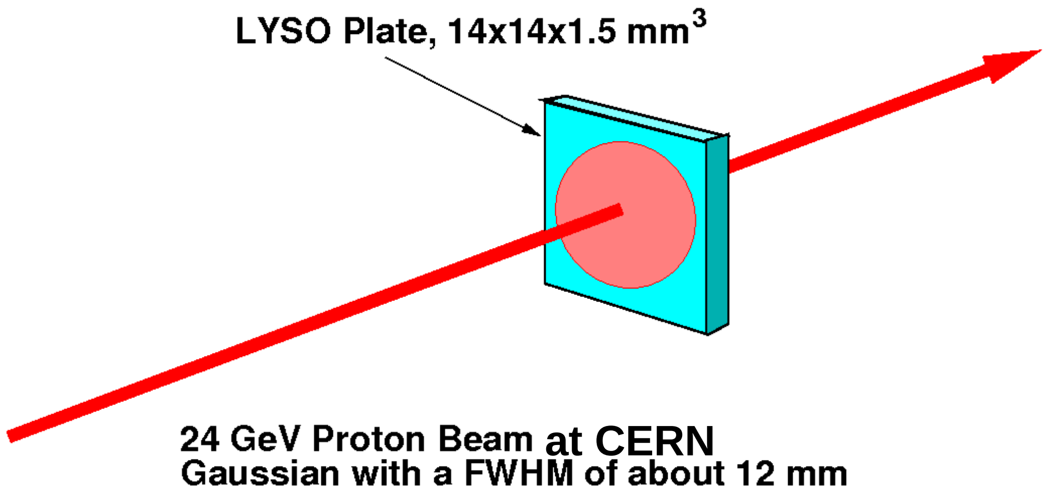
CeF_3 Measurements at Caltech

Measurement after crystal back to Caltech is consistent with that *in situ*
Recovery was observed between 83 and 312 days after irradiation





Proton Irradiation for LYSO Plates

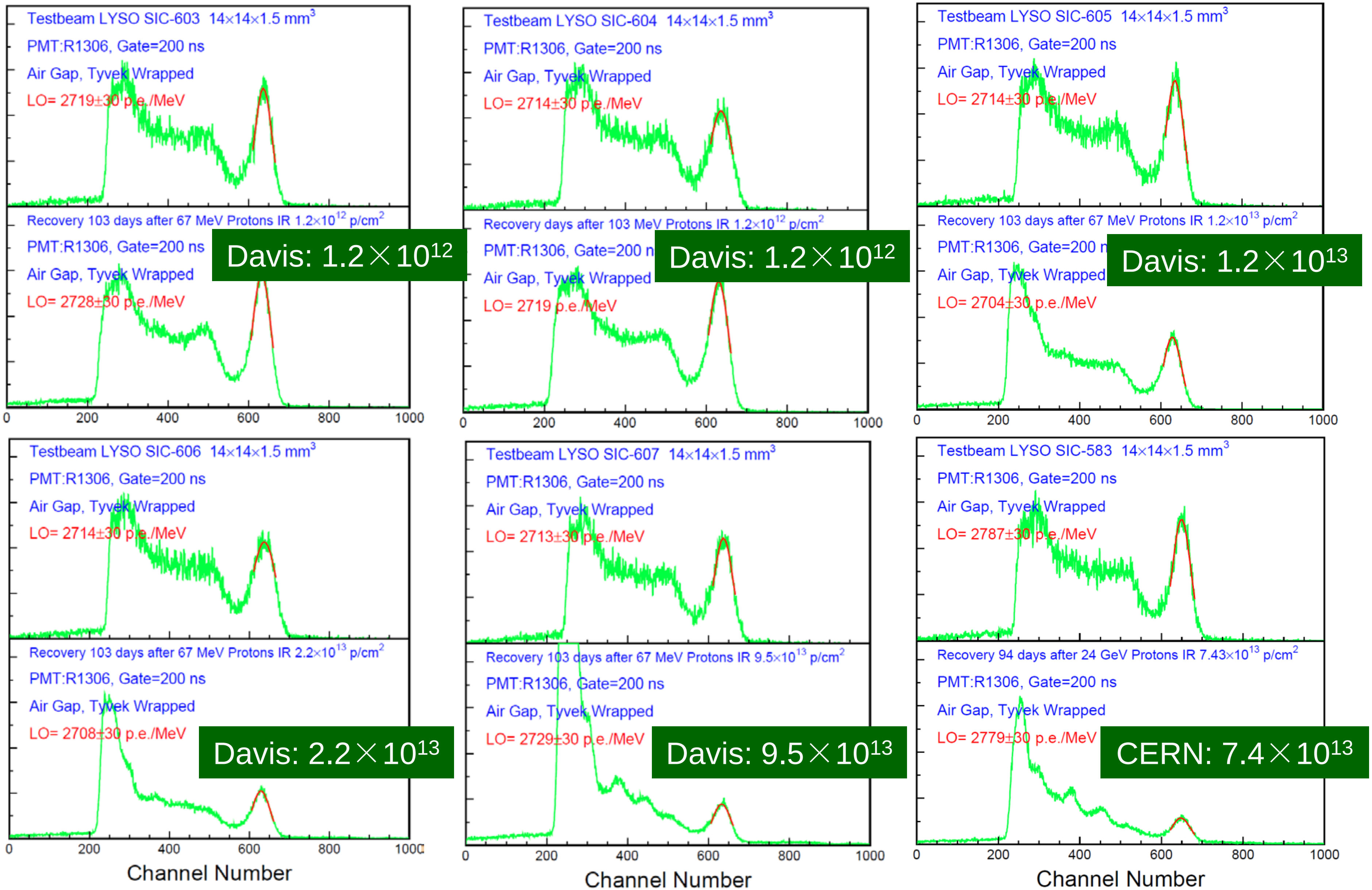


CERN 24 GeV
Four LYSO plates:
7.4×10^{13},
2x 2.4×10^{15} and
6.9×10^{15} p/cm^2.
Thanks to David Bailleux and Federico Ravotti

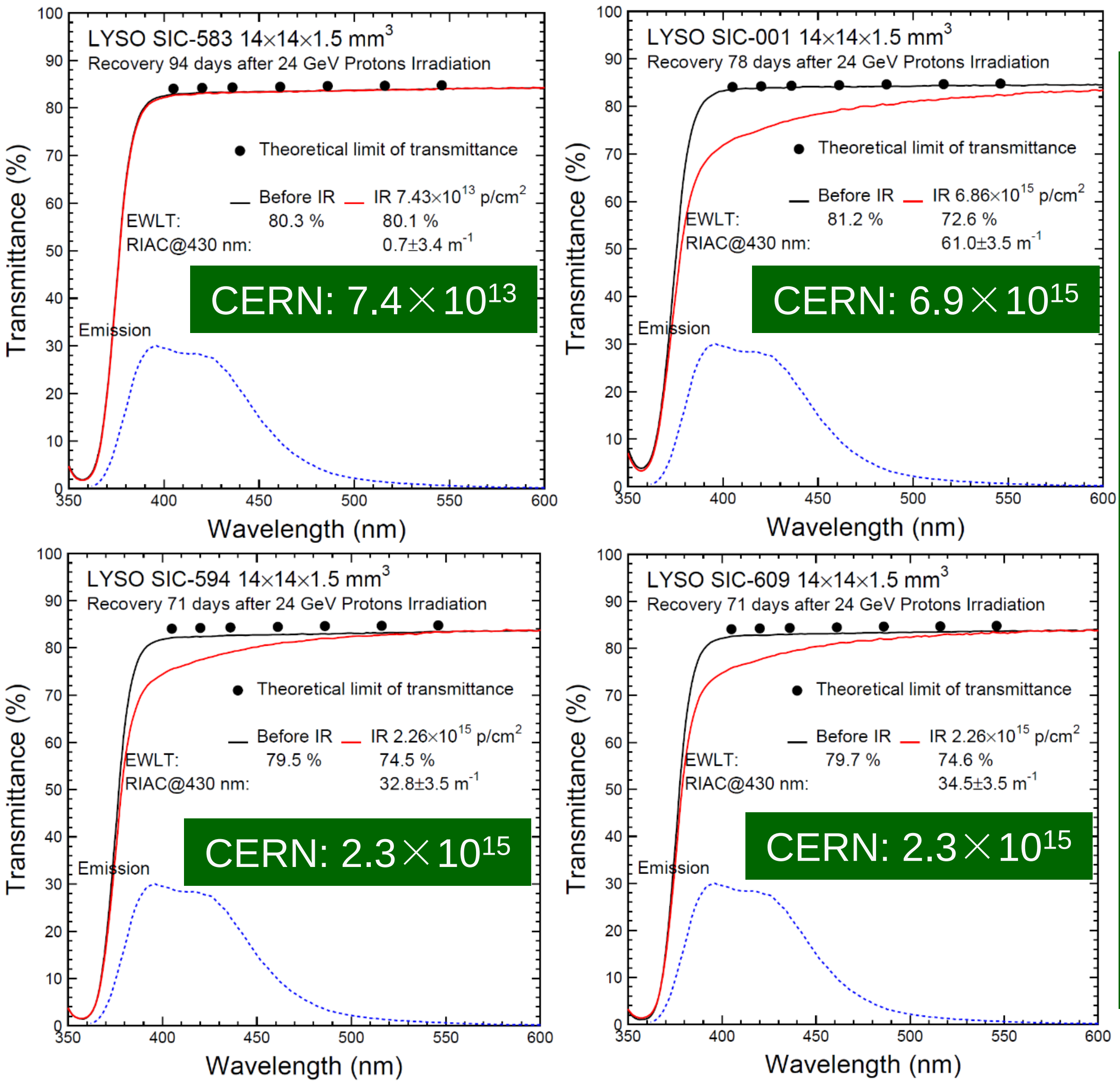
SET Number	USER	Description	BOX	StorageTempReq	IRRAD	Flu. Step	Al 1	Al 2	Al 3	Al 4	Al 5	Al 6	Fluence	Unit	Error (+/- %)	Surface
Set-1986-End-2014	David BAILLEUX	Y11 WLS Fiber	113	Shipping RT	7	1.00E+14	2963	-	-	-	-	-	9.28E+13	p/cm^2	8.2	5x5
Set-1985-End-2014		LYSO Plate 001	113	Shipping RT	7	1.00E+16	2966	2972	2975	2979	-	-	6.86E+15	p/cm^2	6.3	10x10
Set-1984-End-2014		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 with a FWHM of 25 mm
Five LYSO plates: 2x 1.2×10^{12}, 1.2×10^{13}, 2.2×10^{13} and 9.5×10^{13} p/cm^2
Thanks to Bob Hirosky and Mike Mulhearn

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



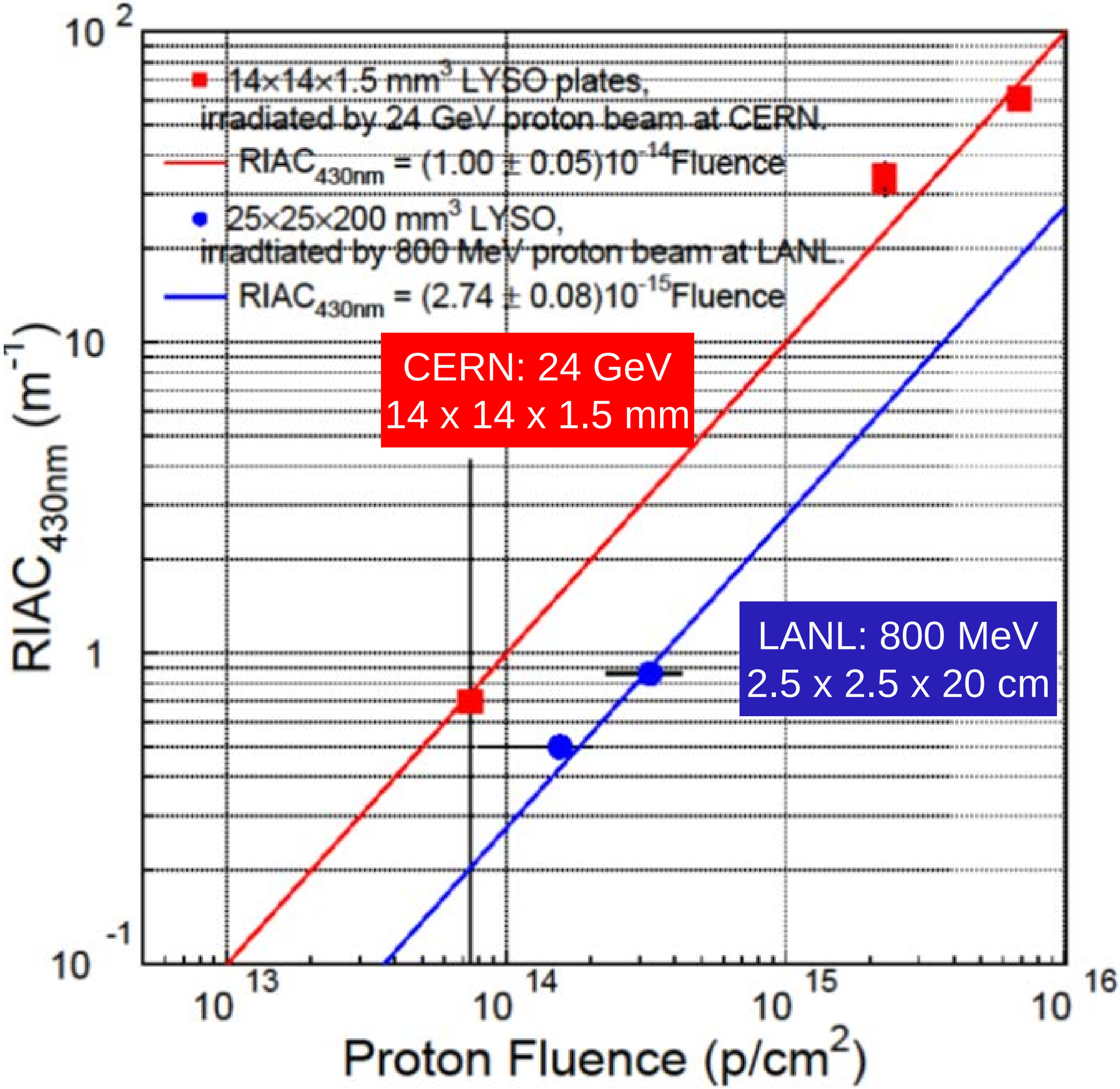
Transmission Loss by 24 GeV Protons



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

Consistent damage observed for two plates irradiated to 2.4×10^{15}. EWLT degrades to : 80.1%, 74.5% & 72.6% for 7.4×10^{13}, 2.3 & 6.9×10^{15} of 24 GeV protons with corresponding RIAC at 430 nm of 0.7, 33 and 61 m^{-1} respectively.

Proton Induced Absorption in LYSO

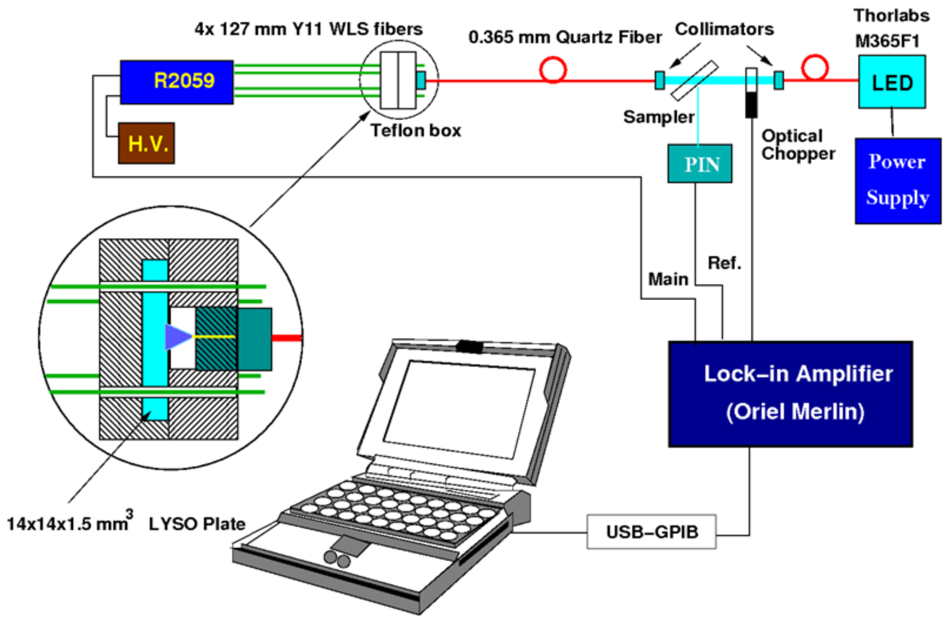


Linear fits show RIAC values @430 nm as a function of fluence of 24 GeV and 800 MeV protons respectively for 14 x 14 x 1.5 mm plates and 20 cm long crystals with difference caused by shower leakage

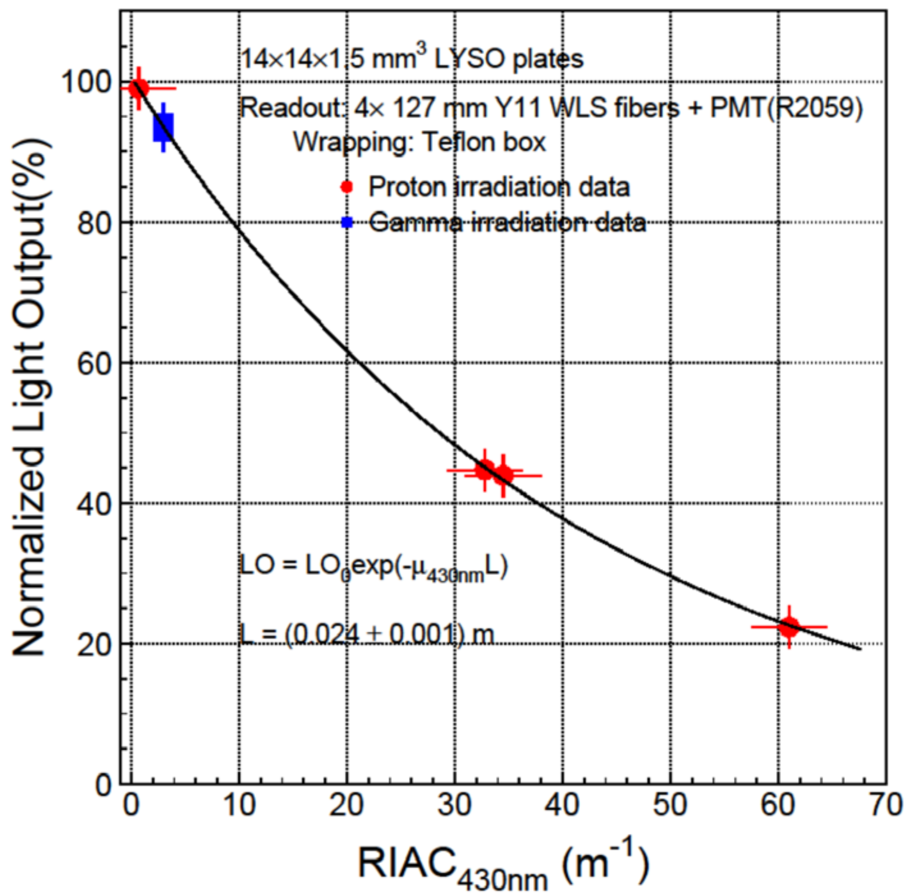
An RIAC value of 3 m^{-1} after 3×10^{14} p/cm^2 indicates a LO loss of 6% for 14 x 14 x 1.5 mm plates with WLS readout

LO Loss by Protons up to $7x10^{15}$ p/cm^2

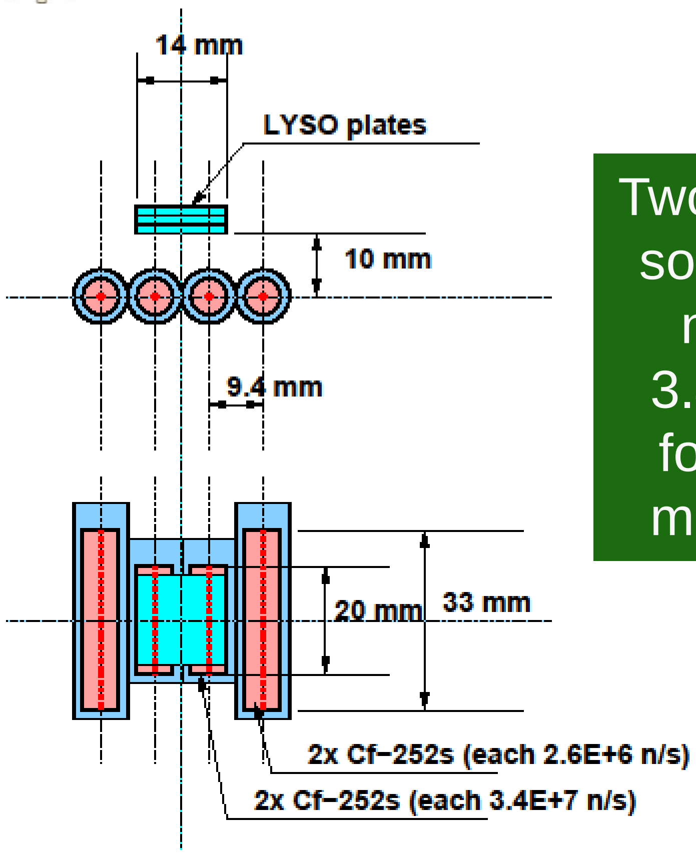
A fit for LO vs induced μ@430 nm shows 2.4 cm path length
Damage caused by protons and ɣ-rays are consistent: 6% for 3m^{-1}



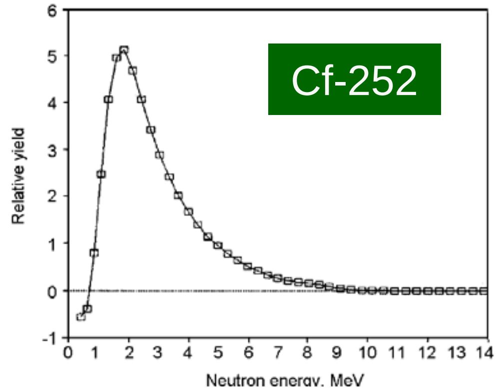
LO measurement setup for 14 x 14 x 1.5 mm LYSO plates with WLS readout

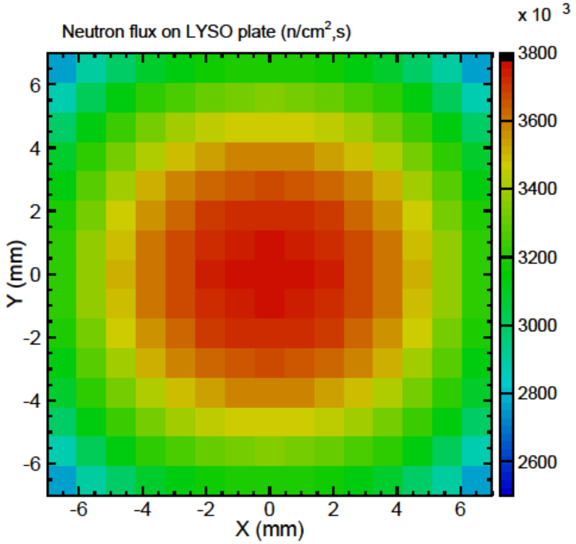


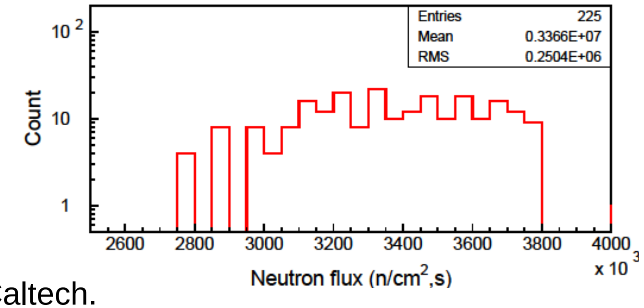
Cf-252 Setup for LYSO Plates



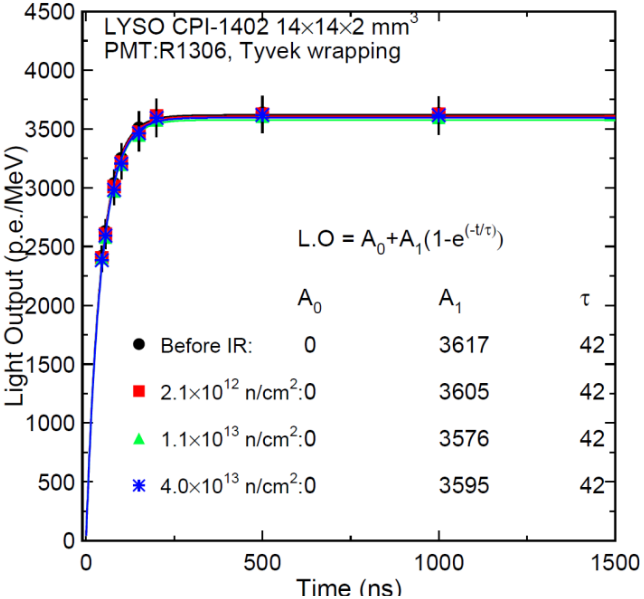
Two pairs of Cf-252 sources provide a neutron flux of 3.4×10^6 n/cm²/s for 14 x 14 x 1.5 mm LYSO plates

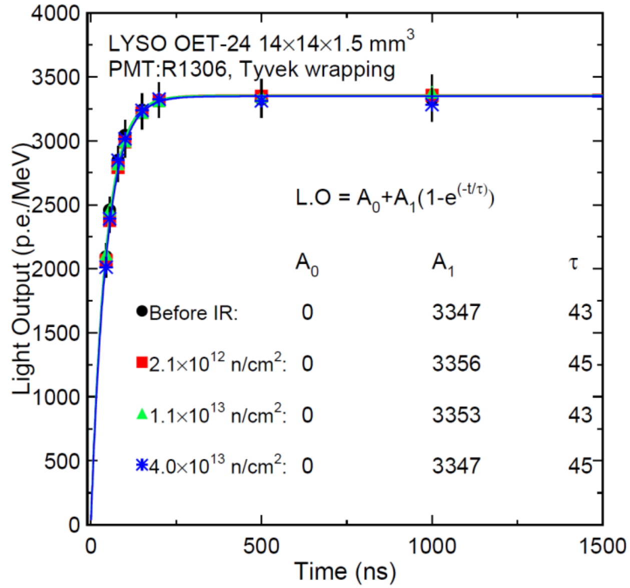


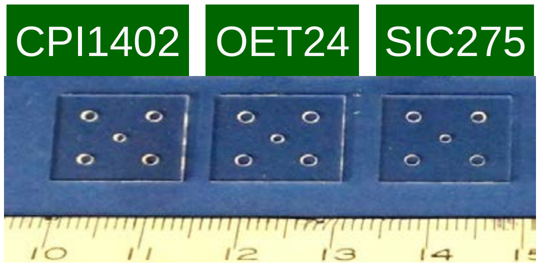


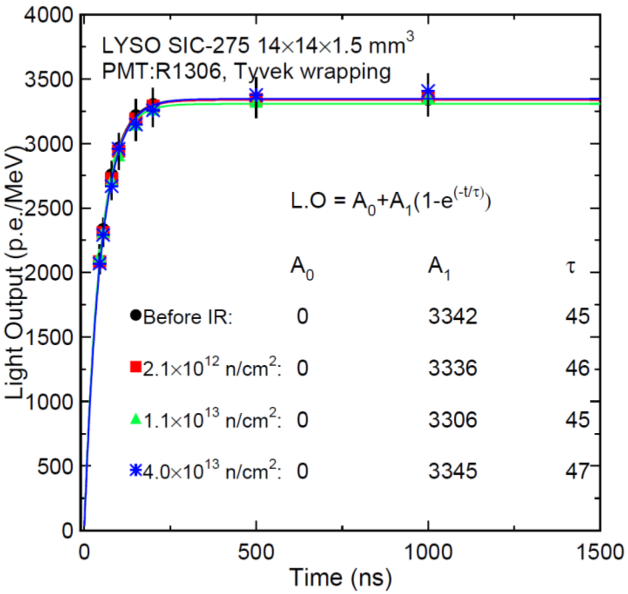


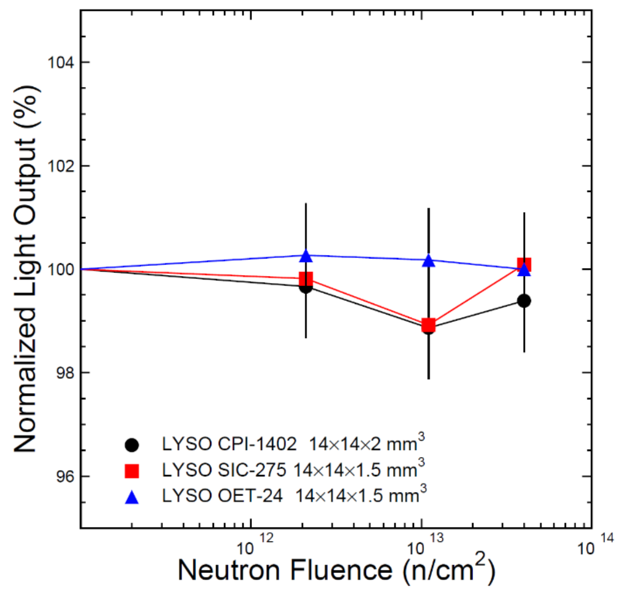
Result of Fast Neutron Irradiation







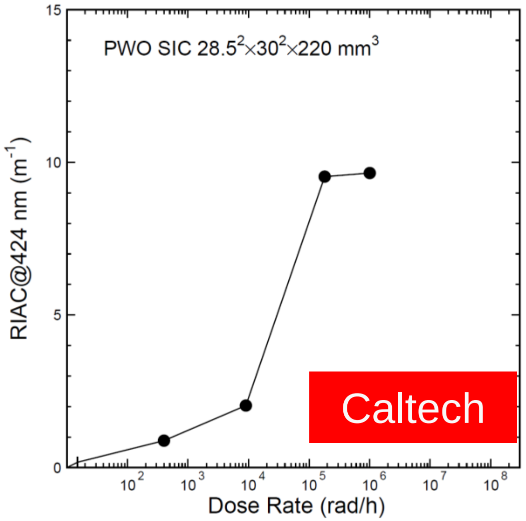


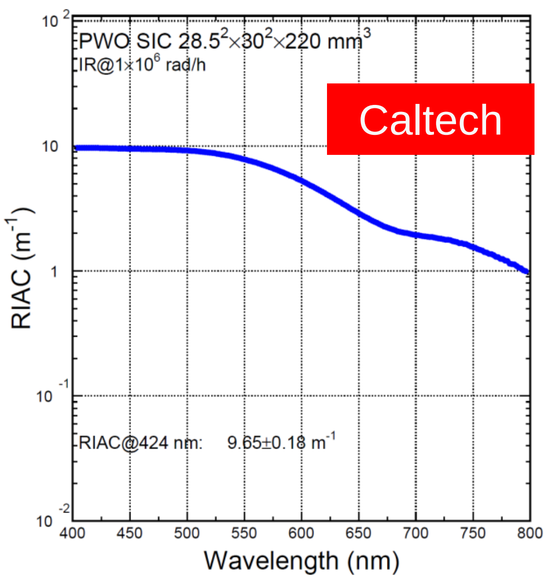


No degradation in LO was observed after 4×10^{13} n/cm^2 for 14 x 14 x 1.5 mm LYSO plates

A Comparison of damages in PWO caused by ɣ-rays and Neutrons up to 10^{19} n/cm^2

Gamma Irradiation at JPL





$7.8\times10^{18}/1.2\times10^{19}/4.0\times10^{19}$ n/cm^2 for fast/epithermal/thermal
Corresponding dose received: 33 Grad @ 300 Mrad/h

Saclay neutron test:
30 cm^{-1}@ 420 nm
under 300 Mrad/h

Caltech gamma test:
0.1 cm^{-1}@ 420 nm
Under 1 Mrad/h

Neutron induced damage seems negligible

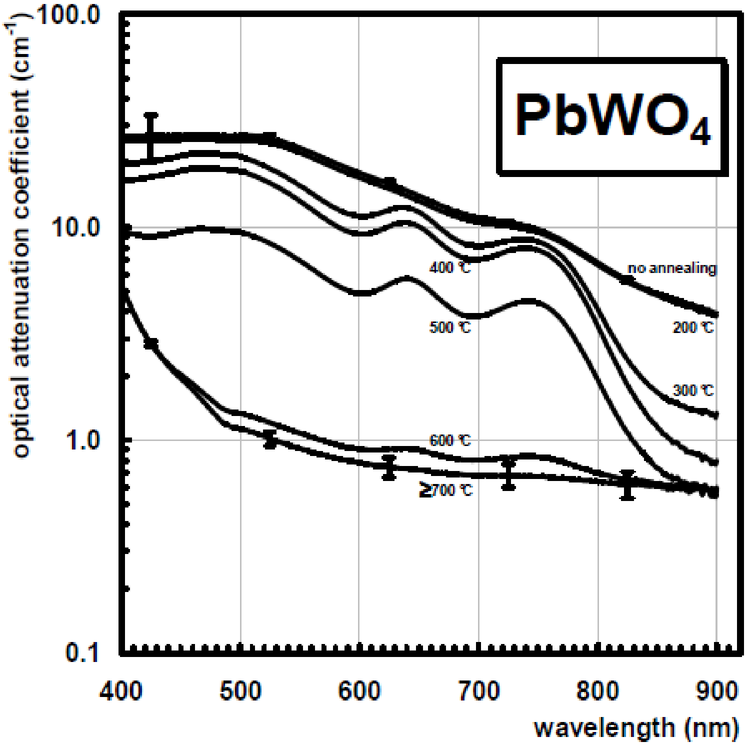


Fig. 2. Optical attenuation coefficient of the irradiated sample before annealing and after successive annealing temperatures.

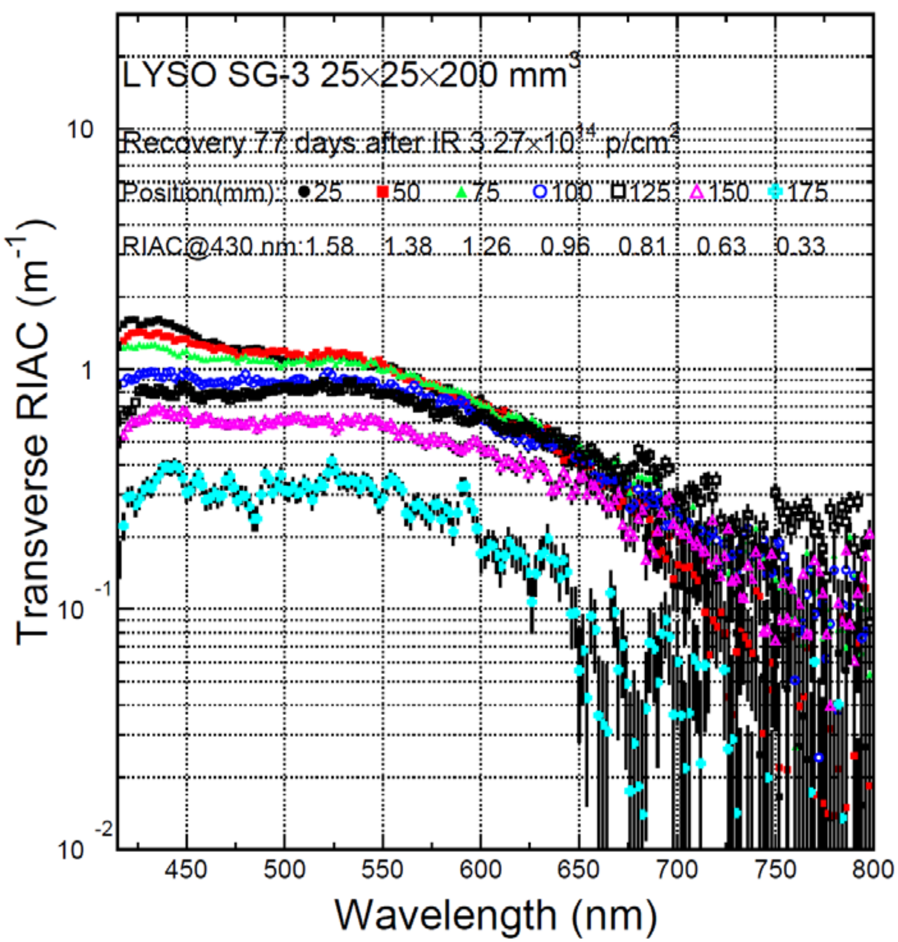
[50] R. Chipaux et al., ***Behaviour of PWO scintillators after high fluence neutron irradiation,*** in Proc. 8th Int. Conference on Inorganic Scintillators,SCINT2005, A. Getkin and B. Grinyov eds, Alushta, Crimea, Ukraine, September 19–23 (2005), pp. 369–371

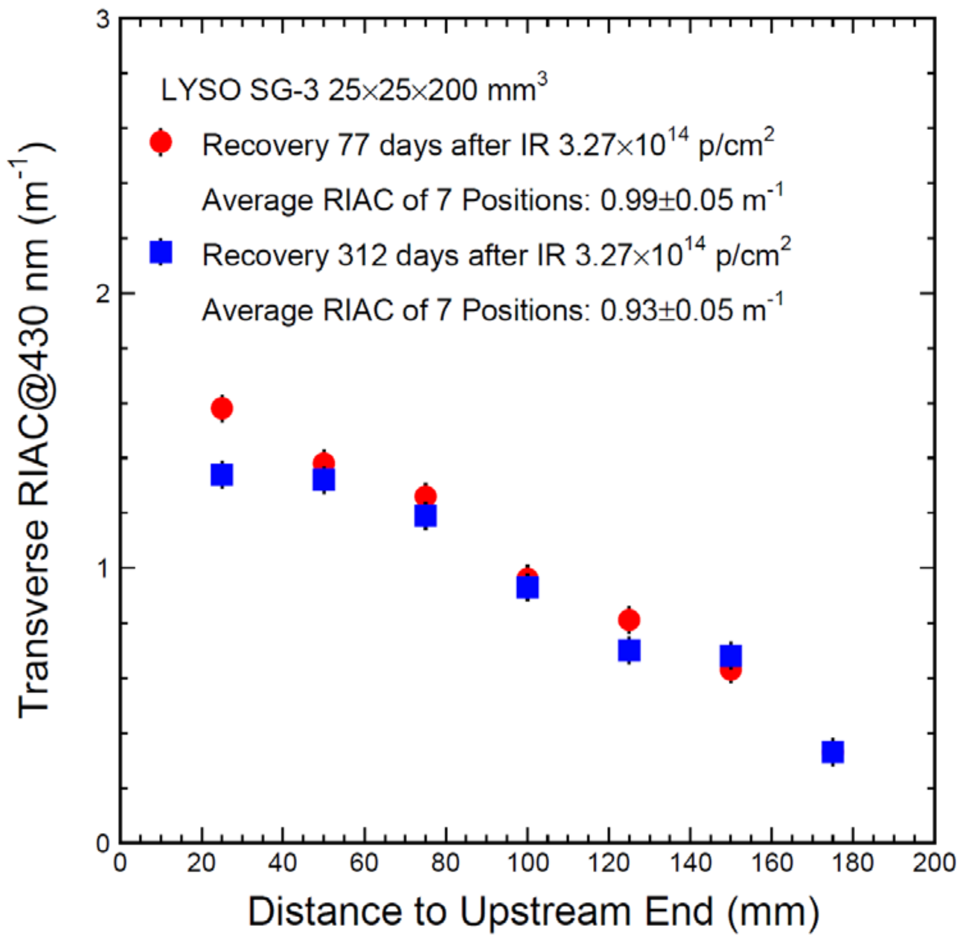
Summary

- No damage observed in 14 x 14 x 1.5 mm LYSO plates up to 10^{14} p/cm^2 by protons of either 67 MeV or 24 GeV.
- The EWRIAC value is 1 m^{-1} in a 20 cm long LYSO crystal after 800 MeV protons of 3.3 x 10^{14} p/cm^2. Taking into account multiple Coulomb scattering and hadronic shower leakage this result is consistent with 3 m^{-1} measured for 14 x 14 x 1.5 mm LYSO plates irradiated by 24 GeV protons. Radiation hardness of LYSO crystals against charged hadrons is excellent as compared to CeF_3 crystals.
- Proton induced radiation damage in LYSO does not recover under room temperature, while that in CeF_3 recovers.
- LO losses caused by 24 GeV protons and ɣ-rays are consistent: about 6% for 14 x 14 x 1.5 mm LYSO plates of 3 m^{-1} with WLS readout, which can be corrected for by a monitoring system.
- Existing data show that neutron induced radiation damage in crystal scintillators is negligible.
- Additional investigation is needed to fully understand hadron induced radiation damage in crystal scintillators, where special attention should be paid to damage induced by accompanying ionization dose.

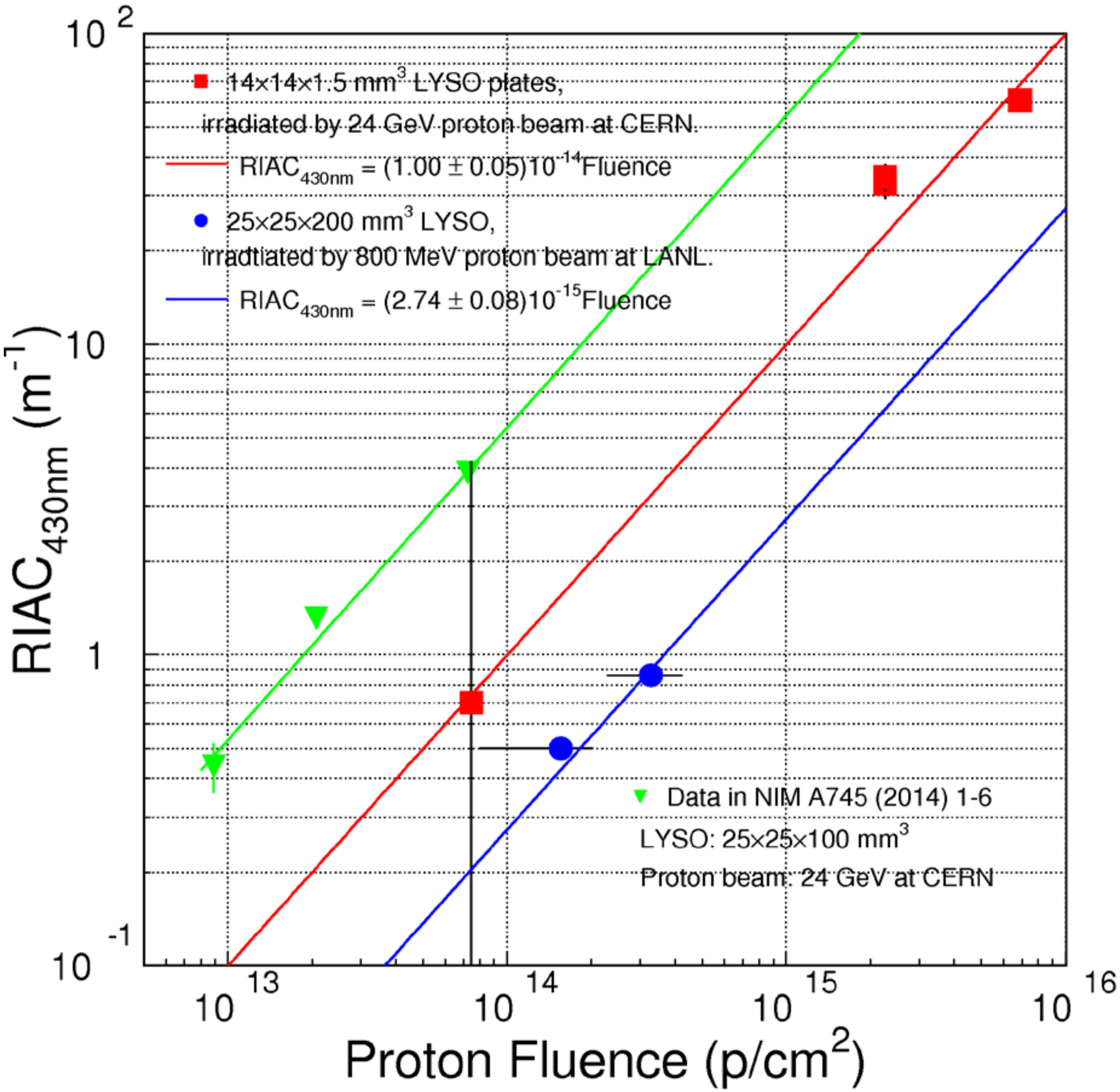
LYSO Transverse Transmittance

Transverse transmittance was measured after crystal back to Caltech
RIAC depends on position with average consistent to that from LT





Comparison with the ETH Data



A factor of five difference is observed between the LYSO plates and the 10 cm long LYSO crystals irradiated by 24 GeV protons

This seems caused by the EM component in hadronic shower which is counted already in the ionization dose