Proton Induced Radiation Damage in Fast Crystal Scintillators

Fan Yang, Liyuan Zhang, Ren-Yuan Zhu

California Institute of Technology

Jon Kapustinsky, Ron Nelson and Zhehui Wang

Los Alamos National Laboratory

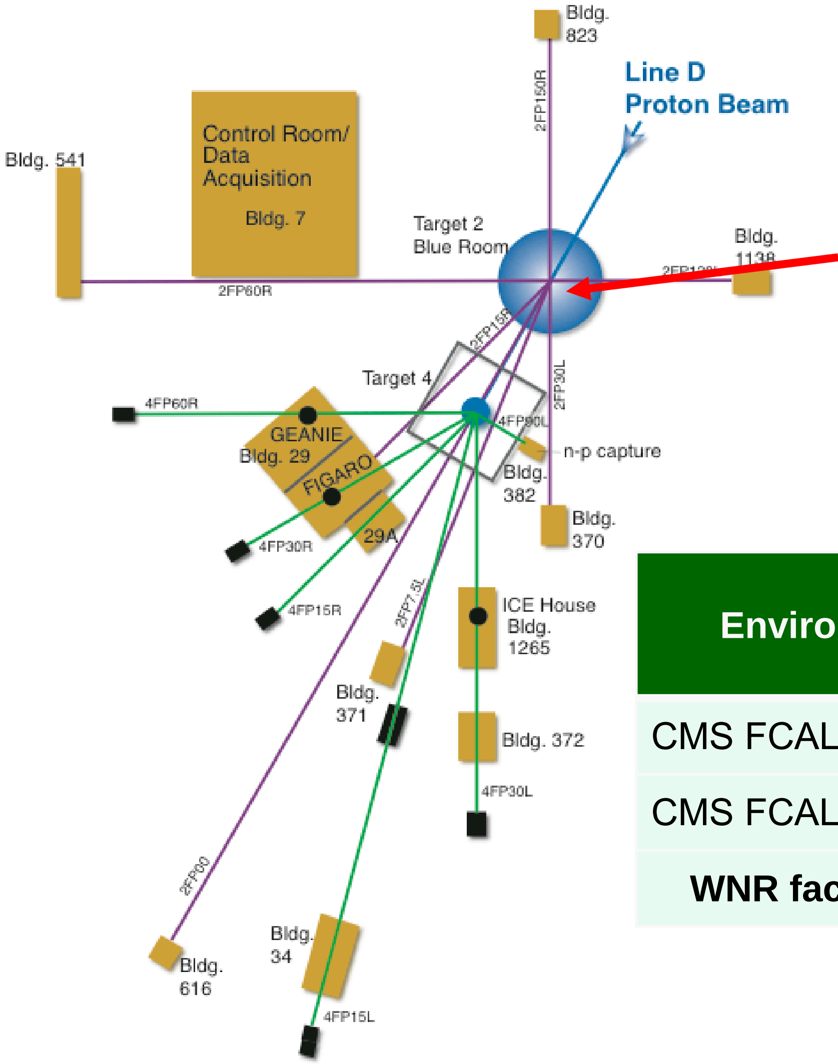
Paper N41-4 presented in NSS-MIC-2016 at Strasbourg on Nov. 2, 2016

Introduction

- Future HEP experiments at the energy frontier (HL-LHC) faces a challenge of radiation damage by charged hadrons and neutrons in addition to ionization dose.
- 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.
- Following the experiment 6501 in 2014, long crystals of 20 cm, BGO, LYSO and PWO, were irradiated up to 3 x 10^{15} p/cm^2 at Los Alamos in 2015 (6990), with degradation of their longitudinal transmittance measured *in situ*..
- LYSO plates of 14 x 14 x 1.5 mm^3 were also irradiated by 24 GeV protons at CERN up to 8 x 10^{15}/cm^2.

800 MeV Proton Irradiation at LANL

Los Alamos Neutron Science Center (LANSCE)



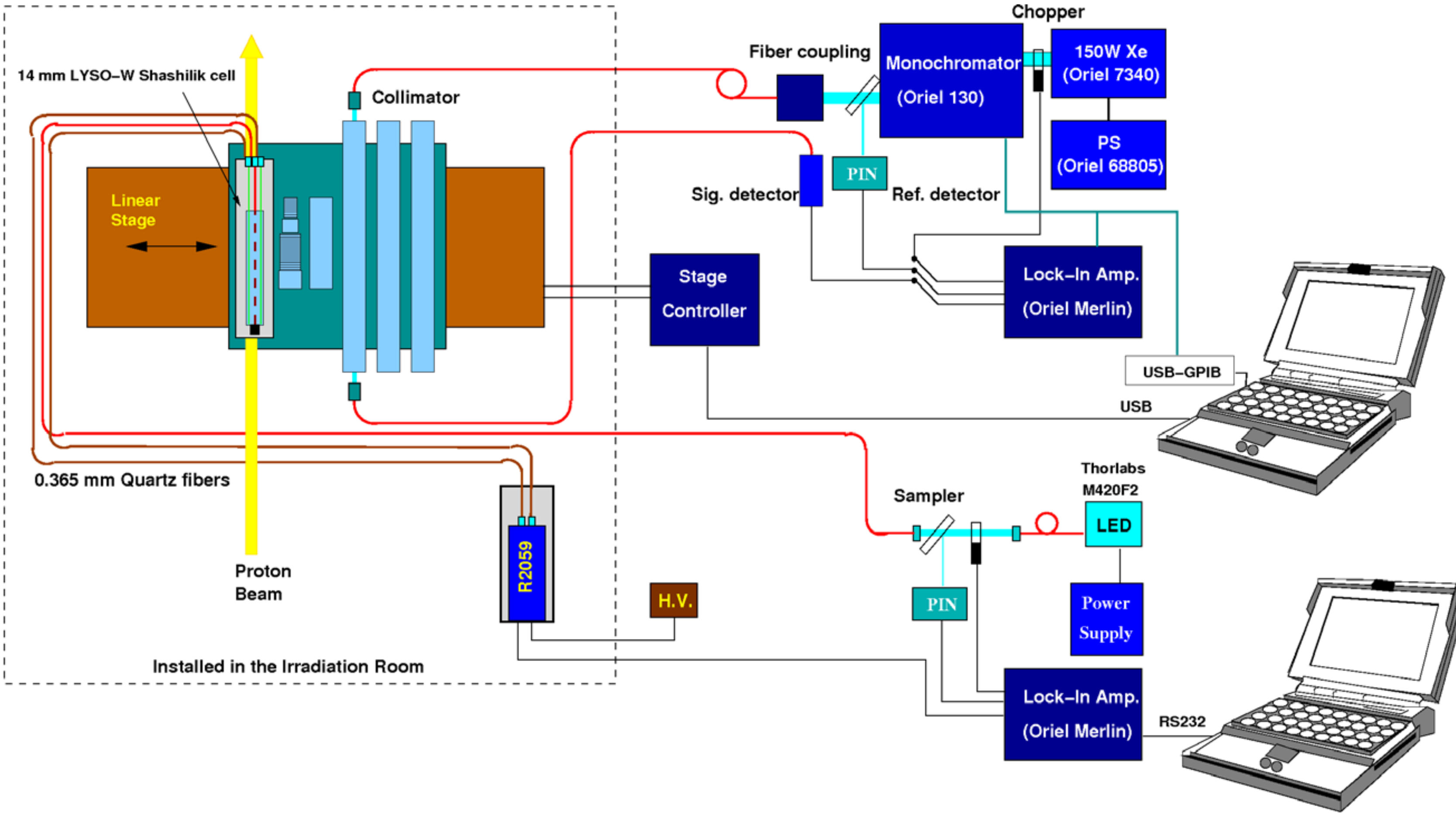
800 MeV proton beam (FWHM= 2.5 cm)

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^{15}**

Experiment 6990 at LANL

Experimental 6990 Setup

- LT (300-800 nm) of long crystals was measured before and after each irradiation step by a Xenon lamp and fiber based spectrophotometer.
- A LYSO-W-Capillary Shashlik cell was monitored before and after each irradiation step by a 420 LED based monitoring system.

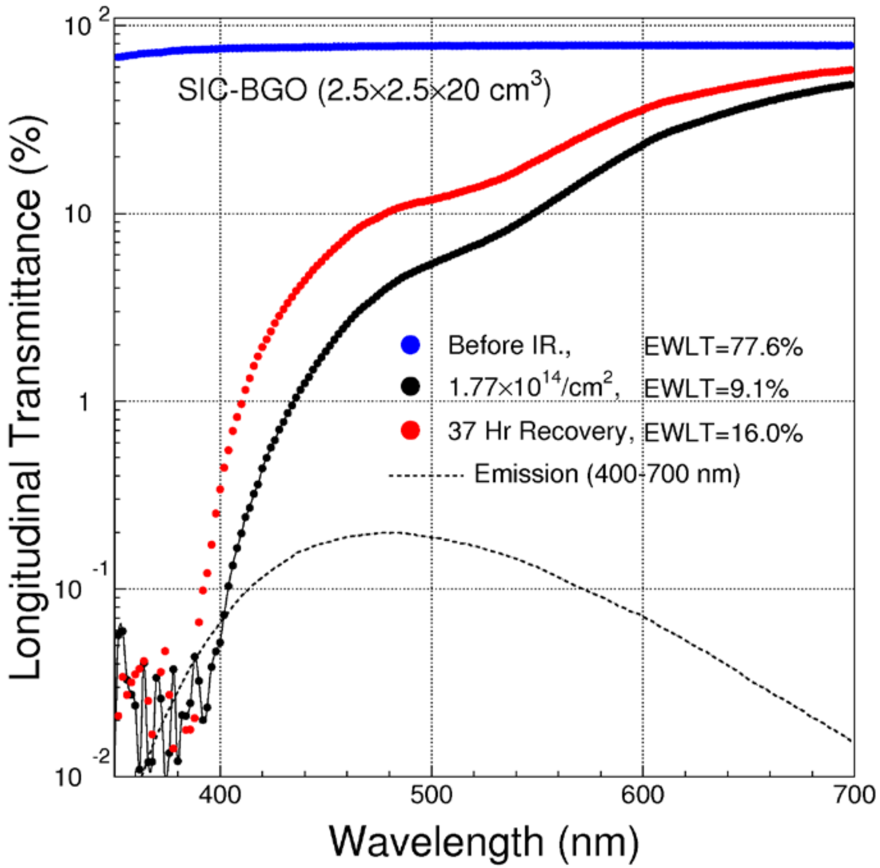


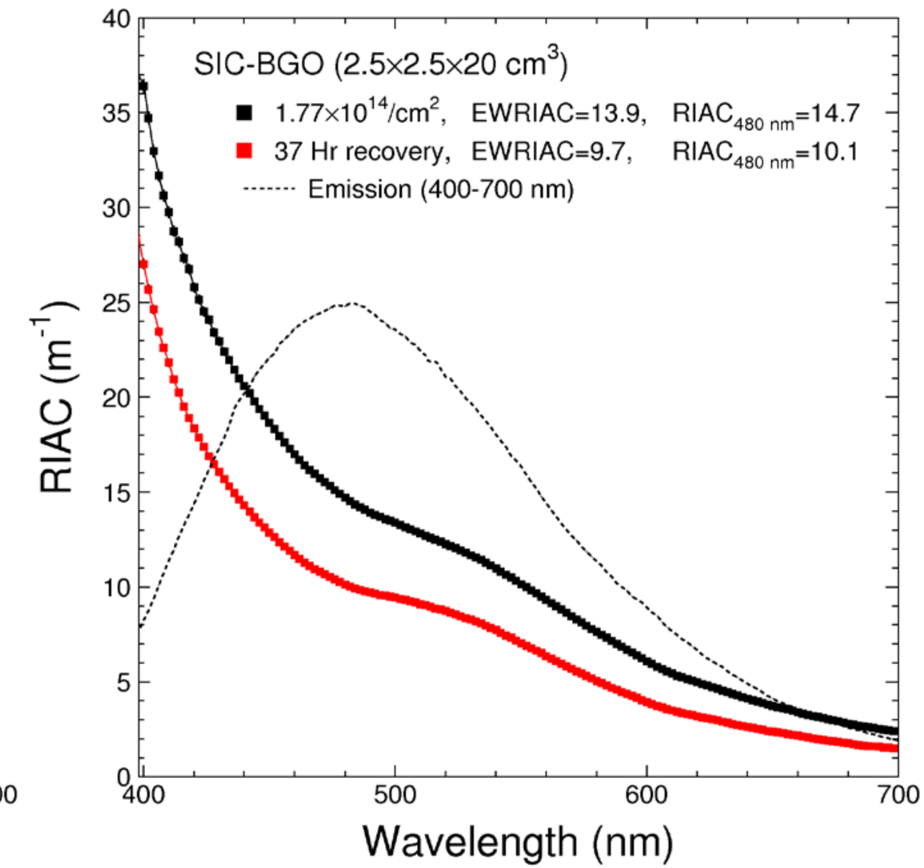
Samples in Experiment 6990

Samples	Dimensions (mm^3)	In-situ Measurement	Fluence (p/cm^2)
Shashlik Cell	34×34×215	420 LED Monitoring / Al	1.24×10^{15}
BaF_2	30×30×20	Al foil activation	2.94×10^{14}
LuAG Ceramic	25×25×0.4		
10 PWOs	25×25×10		
BGO	17×17×17		
20 LFS Plates	14×14×1.5		
2 Capillaries + 2 Y11s	Φ1×200	Al foil activation	3.05×10^{15}
PWO	$28.5^2\times30^2\times220$	LT (350-700 nm)	1.80×10^{14}
LFS	25×25×180	LT (350-700 nm)	2.87×10^{15}
BGO	25×25×200	LT (350-700 nm)	1.77×10^{14}

BGO: LT Damage and RIAC

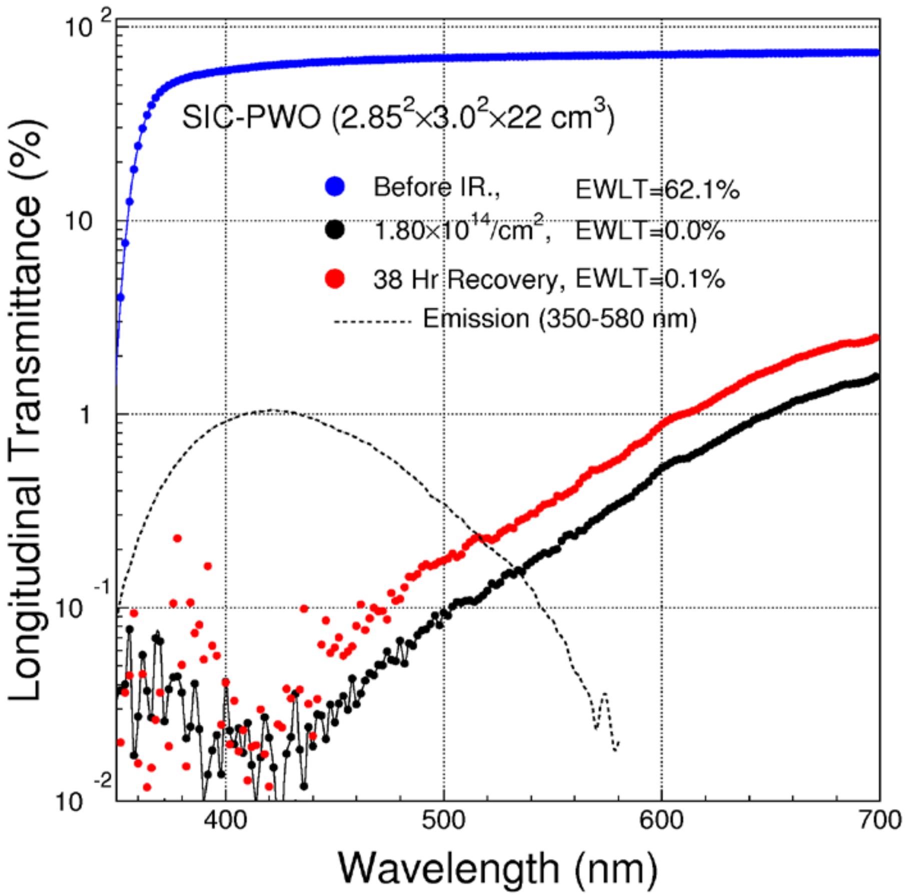
The 20 cm BGO sample irradiated to 1.8×10^{14} p/cm^2 with a flux of about 3.1×10^{14} p/cm^2/hr is completely black below 400 nm with recovery recorded from 15 to 10 m^{-1} at its emission peak after 37 hr

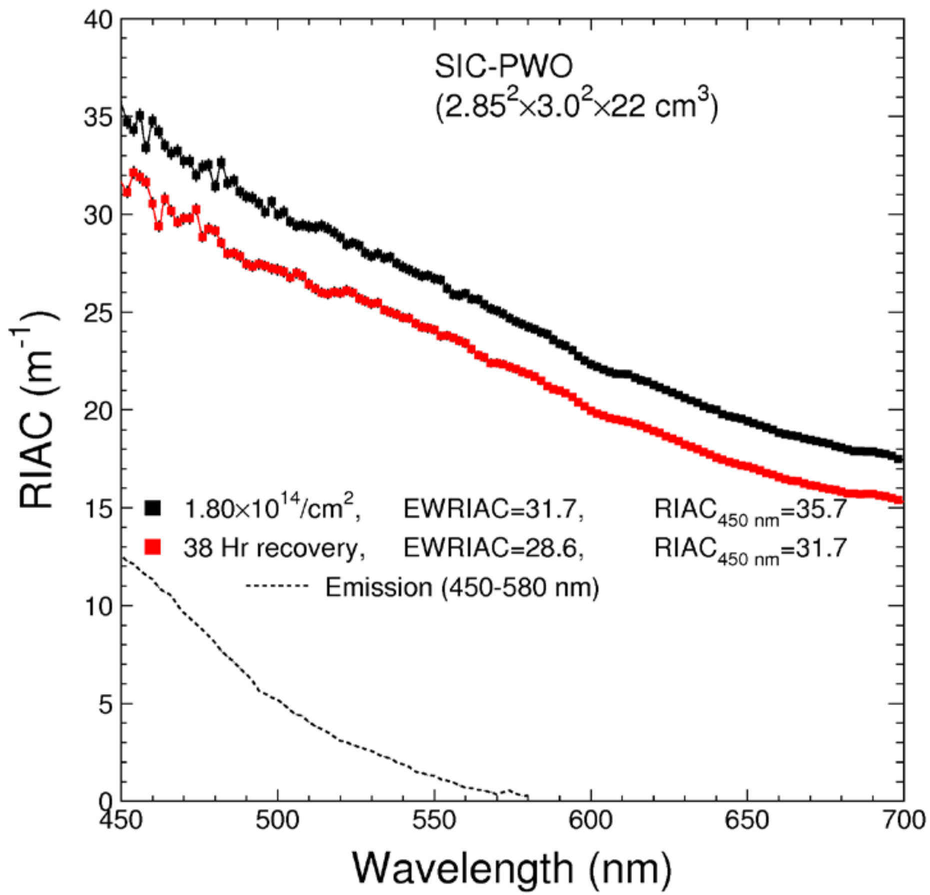




PWO: LT Damage and RIAC

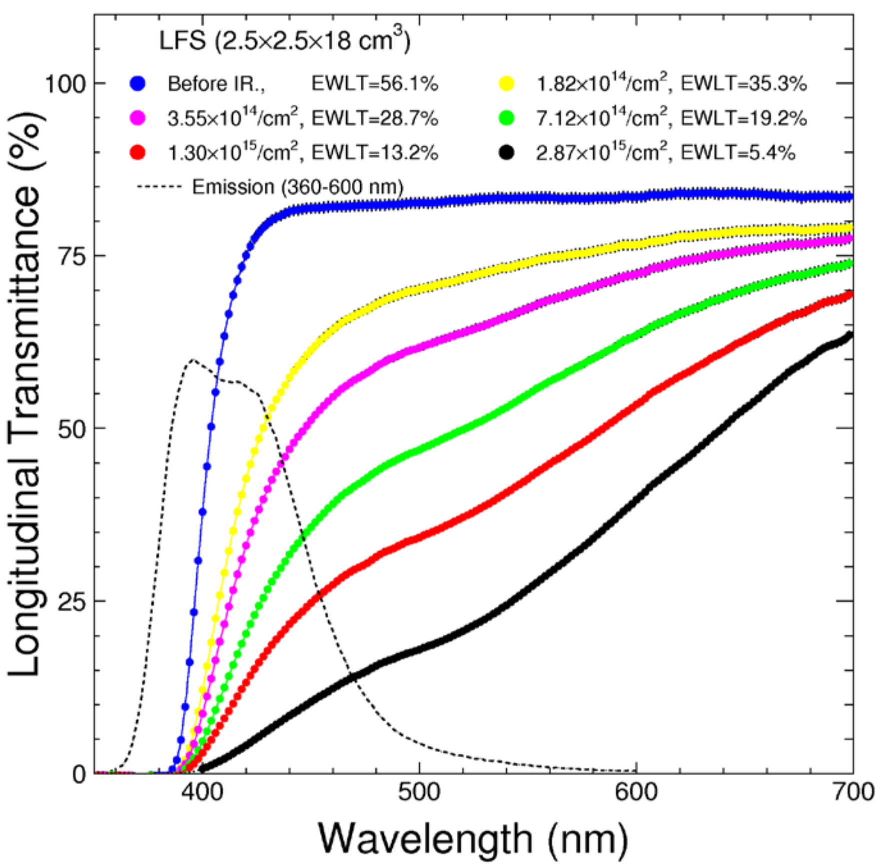
The 22 cm PWO sample irradiated to 1.8×10^{14} p/cm^2 with a flux of 3.1×10^{14} p/cm^2/hr is completely black below 440 nm with recovery observed after 38 hr

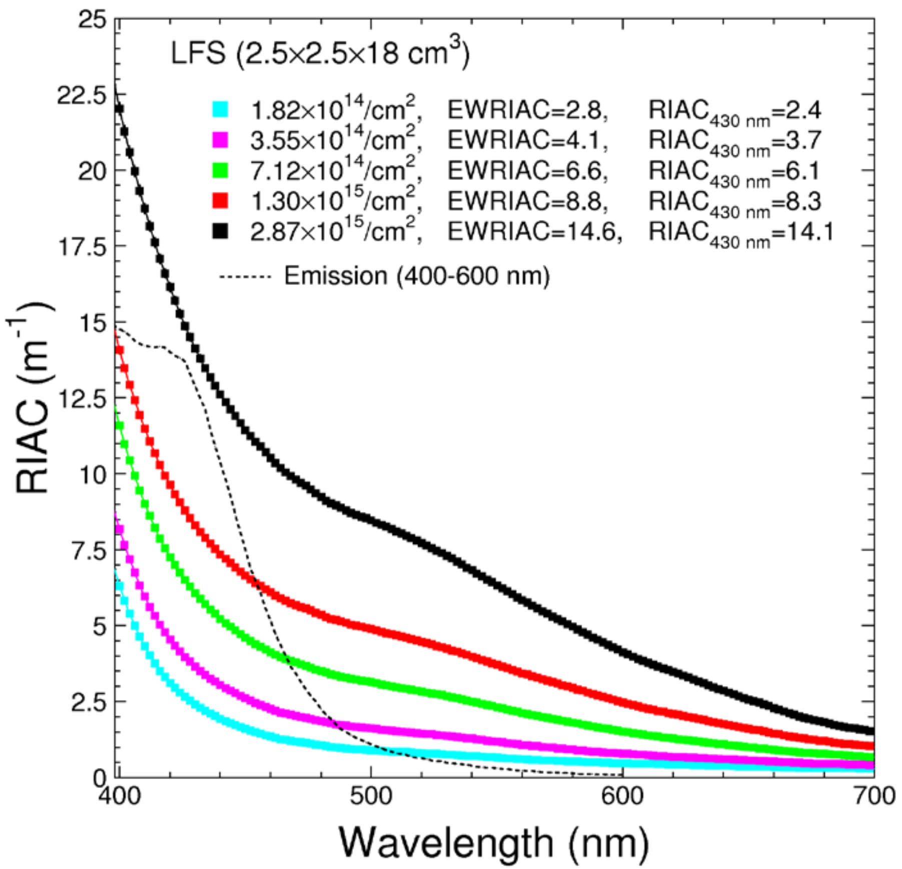




LFS: LT Damage and RIAC

The 18 cm LFS crystal irradiated to 2.9×10^{15} p/cm^2 in five steps with the RIAC at 430 nm of 3.7 / 14.1 m^{-1} after 3.6×10^{14} / 2.9×10^{15} p/cm^2 respectively





RIAC at Emission Peak

Measured Values are used to extract the values expected @3E14 p/cm^2.

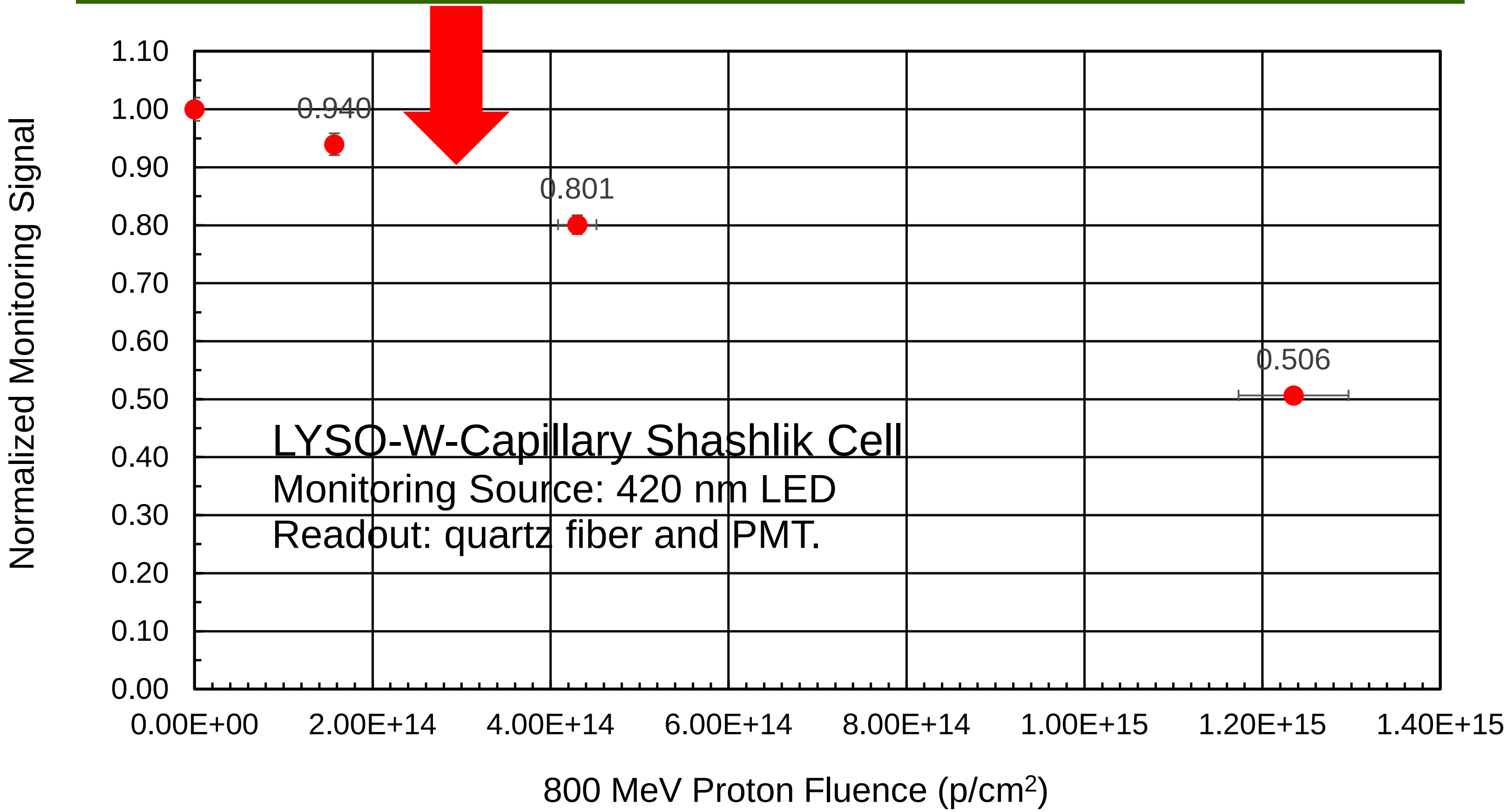
Crystal	Dimensions (mm^3)	ID	Emission Peak (nm)	Fluence (p/cm^2)	RIAC at EP (m-1)	RIAC @3E14 (m^{-1})
BGO	25×25×200	SIC-BGO	480	1.77E+14	14.7	24.9
CeF_3*	22^2×26^2×150	SIC-CeF	340	1.40E+14	17.4	37.3
LYSO*	25×25×200	SG-LYSO	430	3.27E+14	0.86	0.8
LFS	25×25×180	OET-LFS	430	3.55E+14	3.7	3.1
PWO**	28.5^2×30^2×220	SIC-PWO	450	1.80E+14	32	53

* Measured in 2014, **RIAC at 450 nm of PWO is listed.

LYSO is the most radiation hard among all tested at LANL

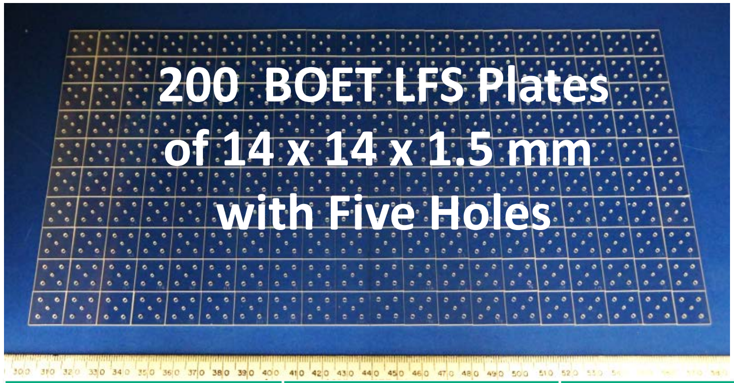
LFS/W/Capillary Shashlik Cell

The Shashlik cell irradiated to 1.2×10^{15} p/cm^2 in 3 steps with degradation of 20%/50% after 4.3×10^{14} / 1.24×10^{15} p/cm^2



The LYSO/capillary based Shashlik is radiation hard against charged hadrons

P Irradiated LYSO Plates, 2015

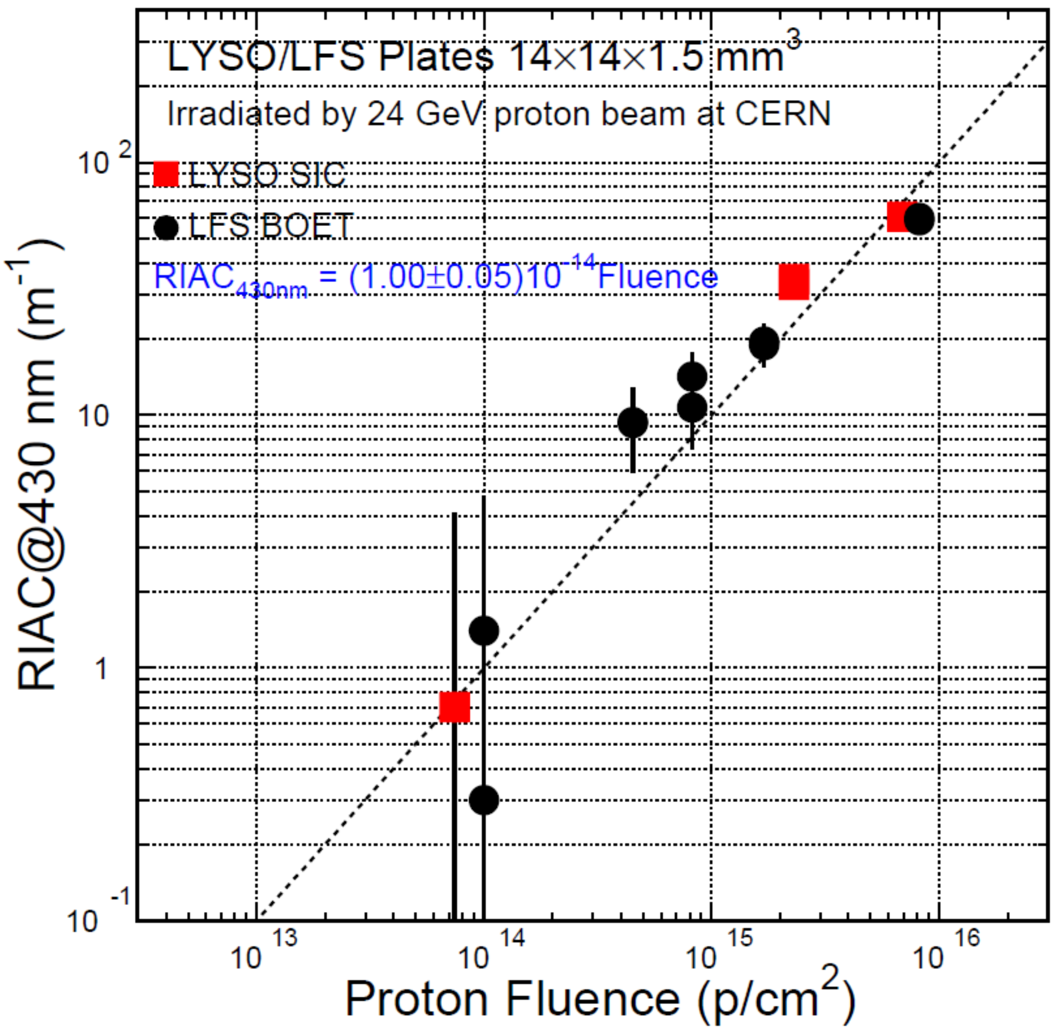


CERN 24 GeV Protons

- Ten LFS plates were irradiated as five pairs from 9.97×10^{13} up to 8.19×10^{15} p/cm^2.
- Samples were returned to Caltech in 2016 after cooled down.
- Transmittance and light output were measured and compared to that of 2014.

ID	Dimension (mm^3)	Facility	Protons (GeV)	Irradiation Set	Fluence (p/cm^2)	Error (+/- %)
LFS BOET-6	**14×14×1.5**	CERN	24	2045	9.97×10^{13}	7.0
LFS BOET-7	**14×14×1.5**	CERN	24	2045	9.97×10^{13}	7.0
LFS BOET-8	**14×14×1.5**	CERN	24	2046	4.48×10^{14}	8.4
LFS BOET-9	**14×14×1.5**	CERN	24	2046	4.48×10^{14}	8.4
LFS BOET-10	**14×14×1.5**	CERN	24	2047	8.21×10^{14}	7.6
LFS BOET-11	**14×14×1.5**	CERN	24	2047	8.21×10^{14}	7.6
LFS BOET-12	**14×14×1.5**	CERN	24	2048	1.65×10^{15}	7.5
LFS BOET-13	**14×14×1.5**	CERN	24	2048	1.65×10^{15}	7.5
LFS BOET-14	**14×14×1.5**	CERN	24	2049	8.19×10^{15}	7.3
LFS BOET-15	**14×14×1.5**	CERN	24	2049	8.19×10^{15}	7.3

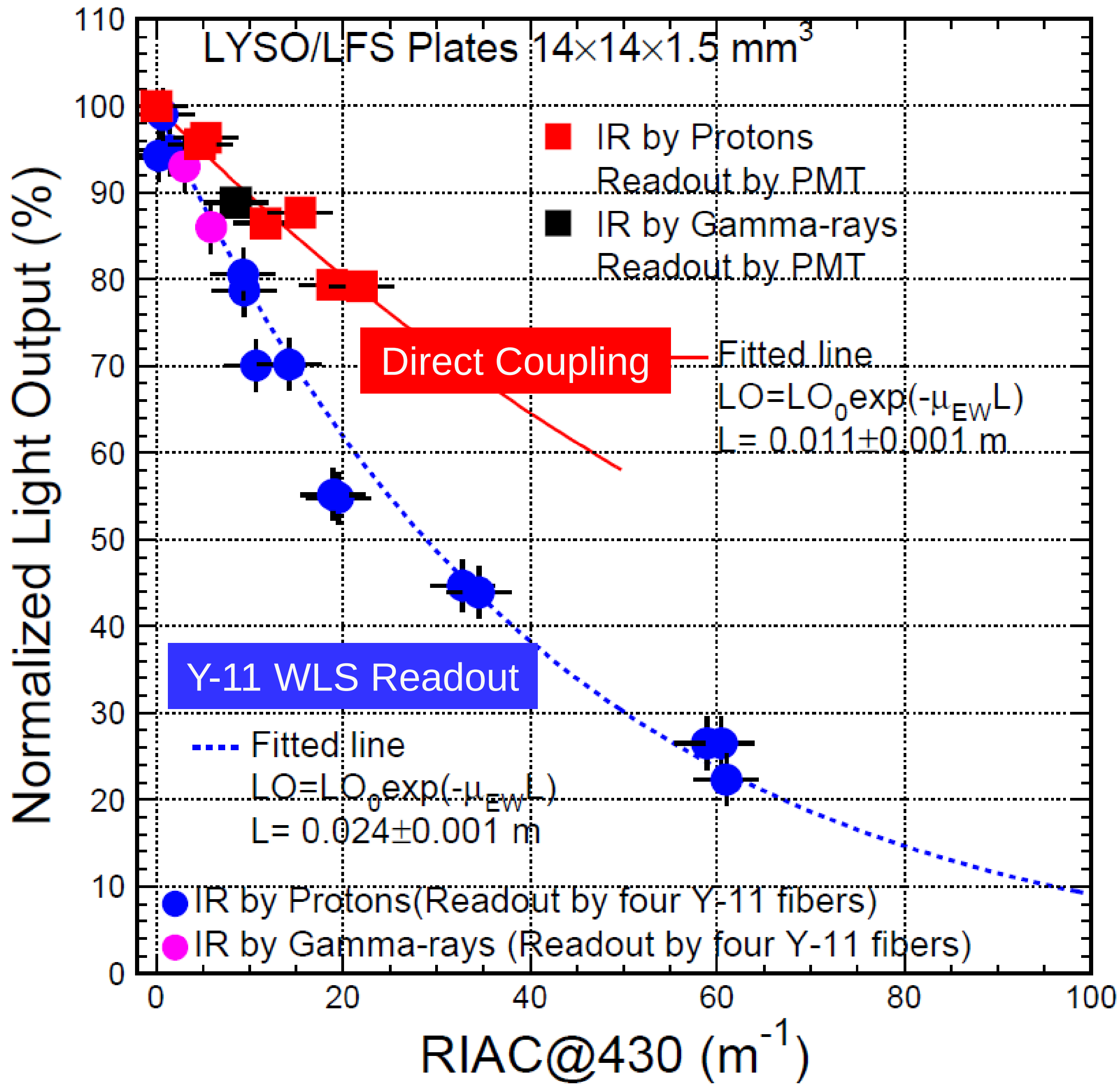
RIAC at 430 nm in LYSO



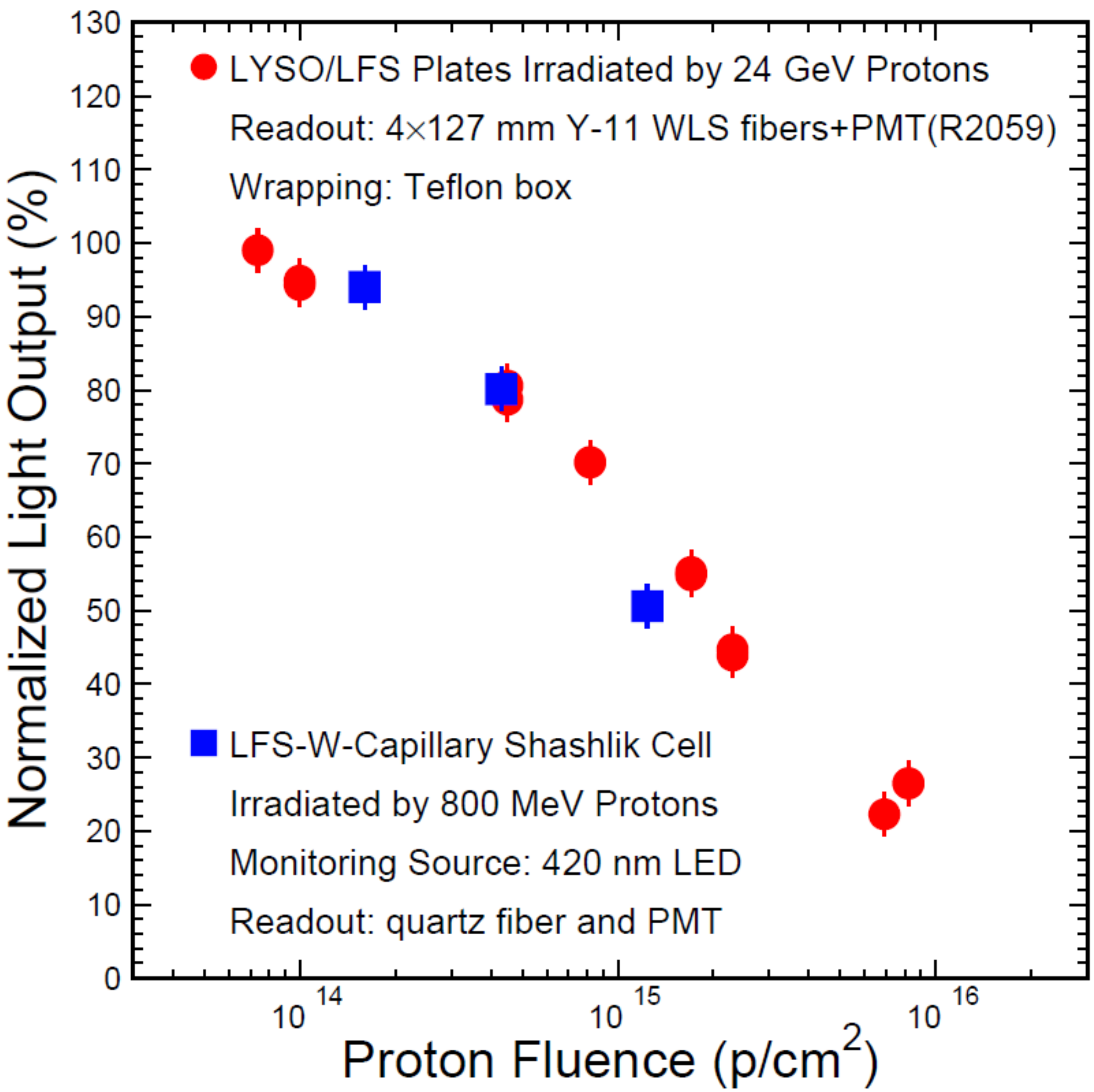
Consistent RIAC at 430 nm is observed in LYSO and LFS plates irradiated by 24 GeV protons up to 8.19 x 10^{15}p/cm^2 at CERN in 2014 and 2015.

LO of LYSO/LFS Plates

Data consistent with average light path length of 1.1 and 2.4 cm at 430 nm for direct and Y-11 readout respectively.



LO of Plates & Shashlik Cell



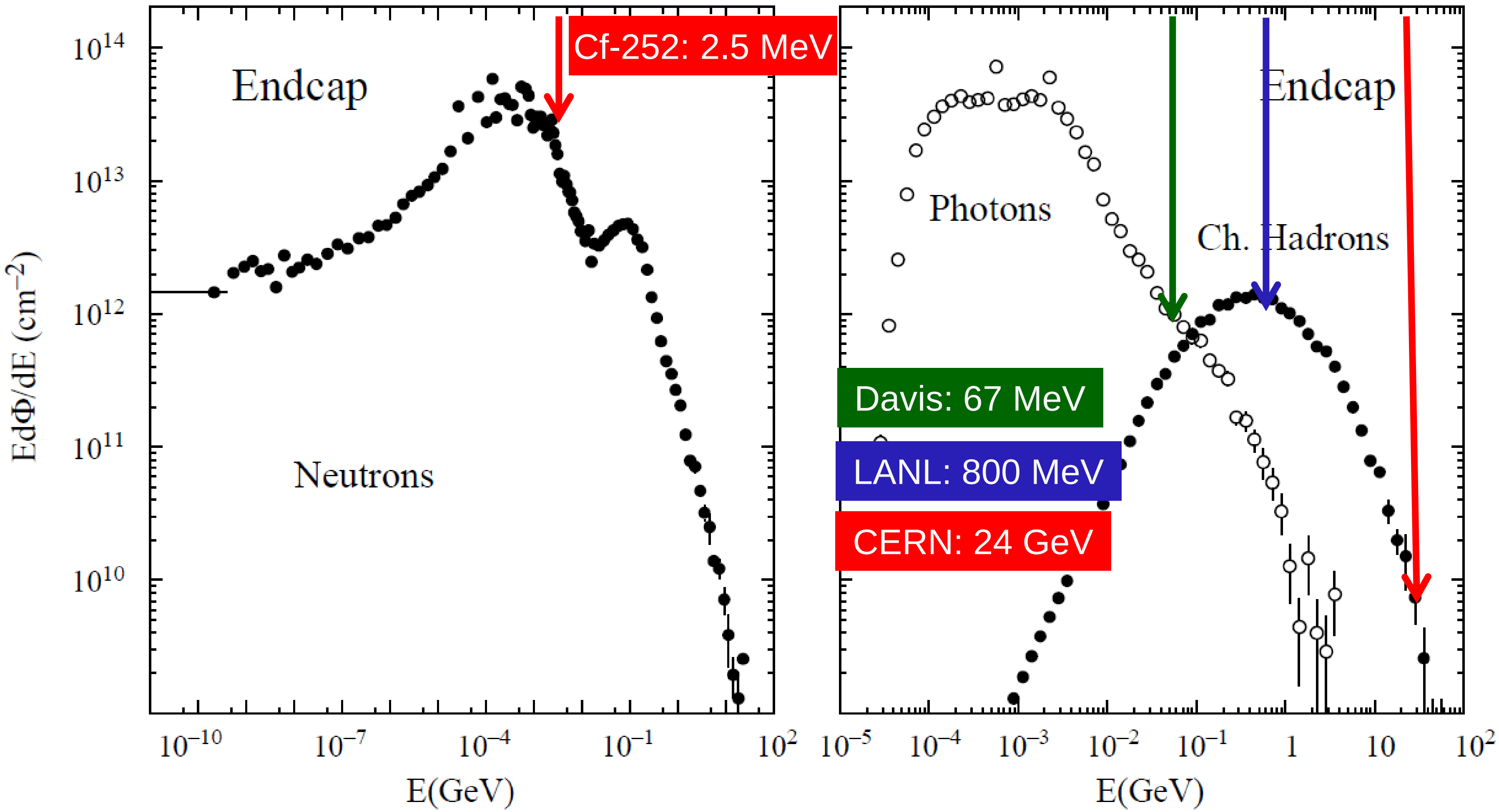
Consistent damage for plates and a Shashlik cell indicates small degradation in quartz capillaries & no difference between protons of 800 MeV and 24 GeV.

Summary

- After 2 x 10^{14} p/cm^2 BGO and PWO are black at wavelength below 400 nm. The RIAC values at emission peaks after 3 ×10^{14} p/cm^2 are 25, 37 and 53 m^{-1} respectively for BGO, CeF_3 and PWO.
- LYSO and LFS crystals show consistent RIAC values of about 3 m^{-1} after 3 ×10^{14} p/cm^2 of 800 MeV or 24 GeV, which is consistent with the 10% light output loss observed in a LYSO/quartz capillary shashlik cell after 3×10^{14} p/cm^2 by 800 MeV protons at Los Alamos.
- Investigations will continue to compare damage in various inorganic crystal scintillators induced by ionization dose, protons and neutrons.

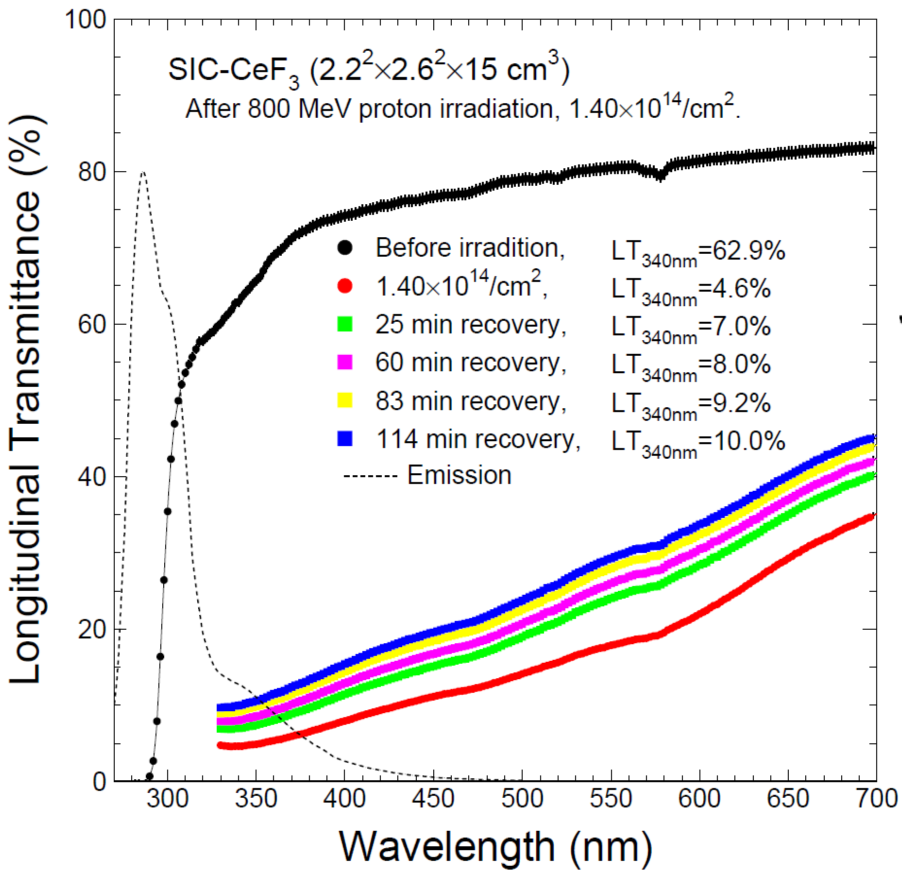
Energy Spectra Expected at HL-LHC

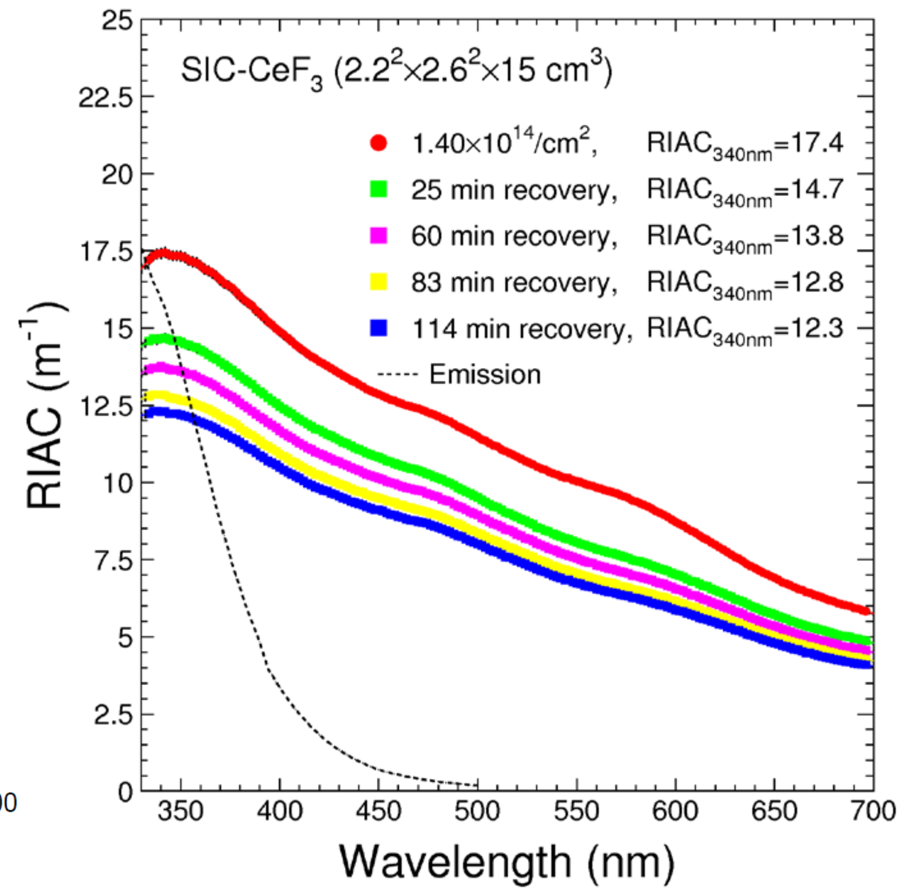
FLUKA simulations: neutrons and charged hadrons are peaked at MeV and hundreds MeV respectively. Neutron energy of 2.5 MeV from Cf-252 source and proton energy of 800 MeV at LANL are ideal for such investigation



CeF_3: LT Damage and RIAC

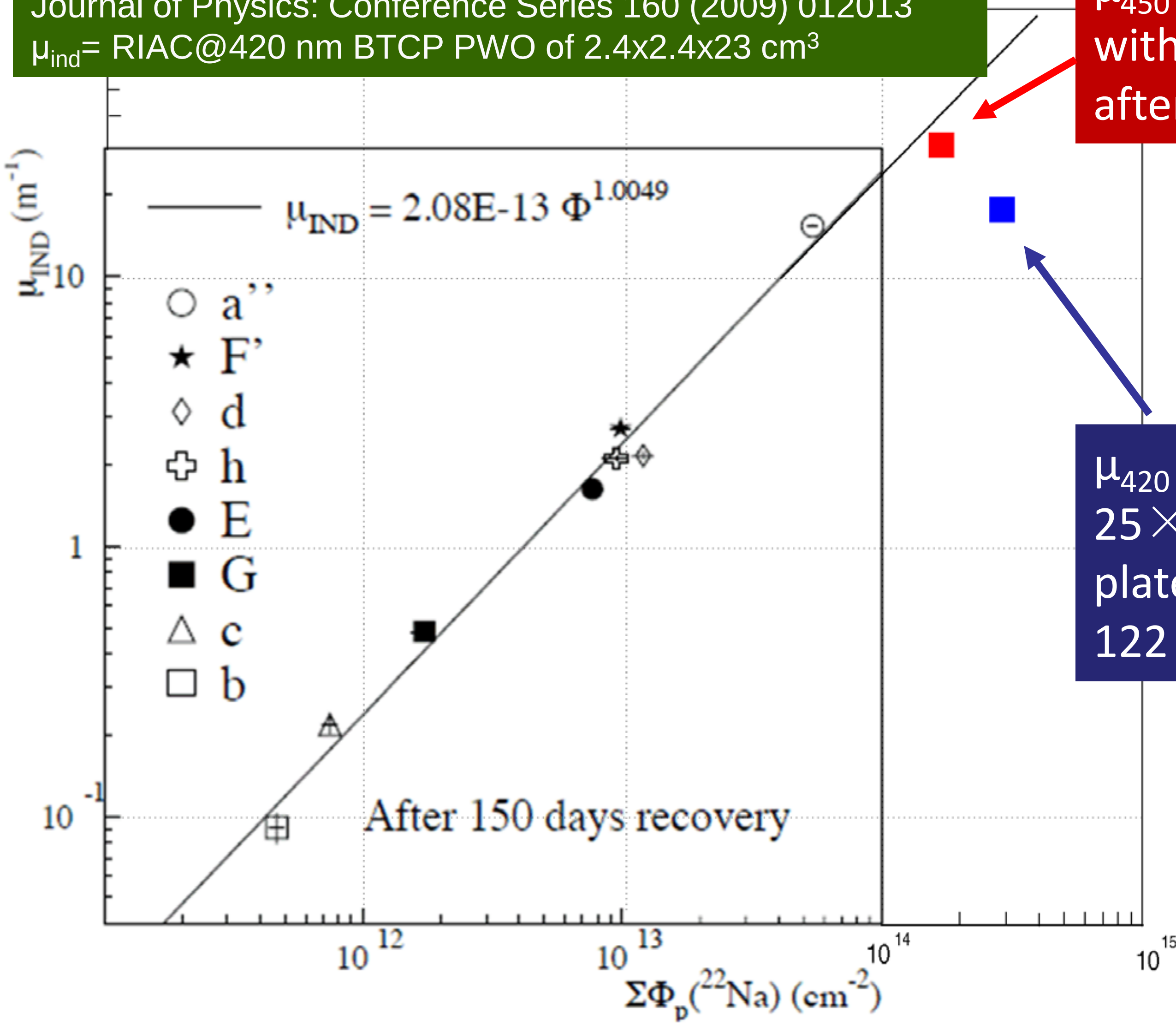
A CeF_3 of $2.2^2 \times 15 \times 2.6^2$ cm^3 was irradiated to 1.4×10^{14} p/cm^2 with RIAC @ 340 nm of 17 m^{-1}





Comparison with ETH data

Journal of Physics: Conference Series 160 (2009) 012013
μ_{ind}= RIAC@420 nm BTCP PWO of 2.4x2.4x23 cm^3



$\mu_{450\ nm}$ *in-situ* measurement with 22 cm long PWO at 38 hr after the irradiation at LANL.

$\mu_{420\ nm}$ average of 10 25×25× 10 mm^3 PWO plates measured at Caltech, 122 days after the irradiation.

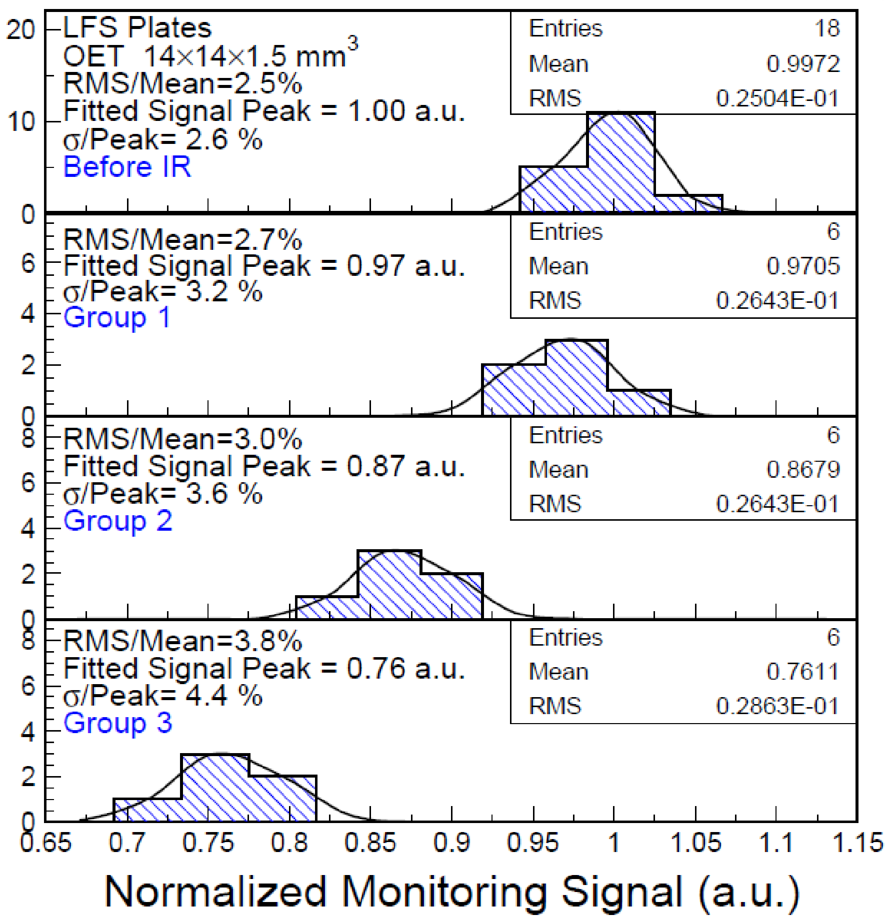
Neutron Irradiation at LANL

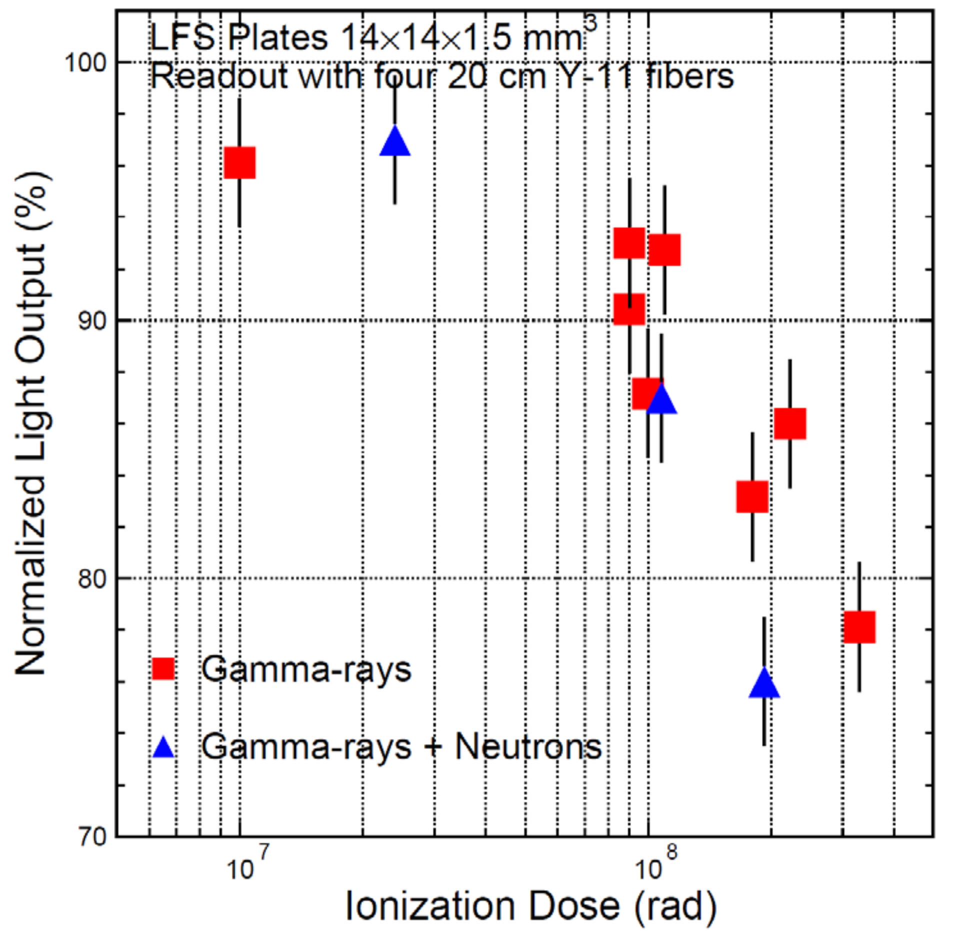
18 LFS plates of 14×14×1.5 mm^3 in 3 groups were removed after 13.4, 54.5 and 118 days respectively. Light output and transmittance were measured at Caltech after cooled down.

Particles / Dose	Group-1 (BOET 107-112) Fluence (cm^{-2})	Group-2 (BOET 101-106) Fluence (cm^{-2})	Group-3 (BOET 95-100) Fluence (cm^{-2})
Thermal and Epithermal, Neutrons (0<En < 1 eV)	7.01E+14	3.16E+15	5.64E+15
Slow and Intermediate Neutrons (1 eV <En < 1 MeV)	2.56E+15	1.15E+16	2.05E+16
Fast Neutrons (En > 1 MeV)	2.24E+14	1.01E+15	1.80E+15
Protons (Ep>1 MeV)	5.31E+11	2.39E+12	4.27E+12
Protons Ionization Dose (rad)	1.39E+04	6.25E+04	1.12E+05
Photons (Eg>150 KeV)	6.71E+14	3.02E+15	5.39E+15
Photons Ionization Dose (rad)	2.40E+07	1.08E+08	1.93E+08

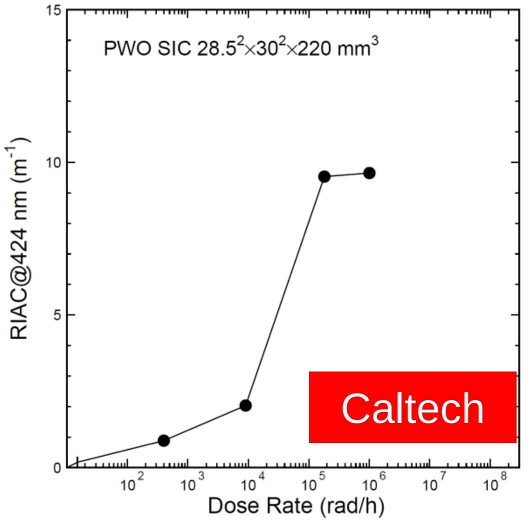
LO Loss after Neutron Irradiation

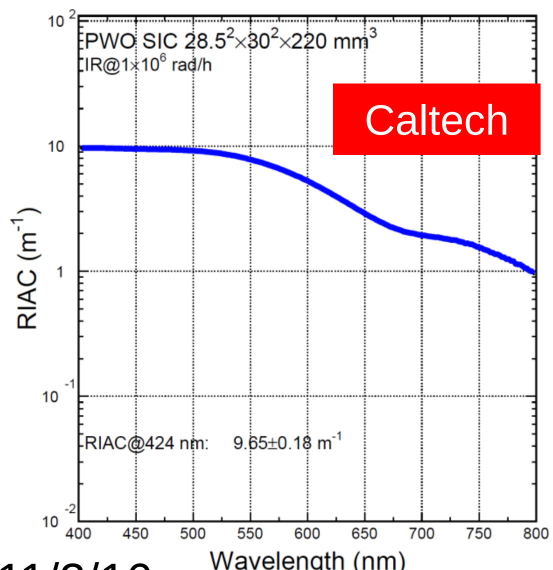
Light output measured by UV LED excitation and Y-11 WLS fibers with degradations of 3%,13% and 24% for Group-1, 2 and 3 respectively, which may be explained by ionization dose only. Pb shielding is implemented in 2016





Gamma Irradiation at JPL





$7.8\times10^{18}/1.2\times10^{19}/4.0\times10^{19}$ n/cm² 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

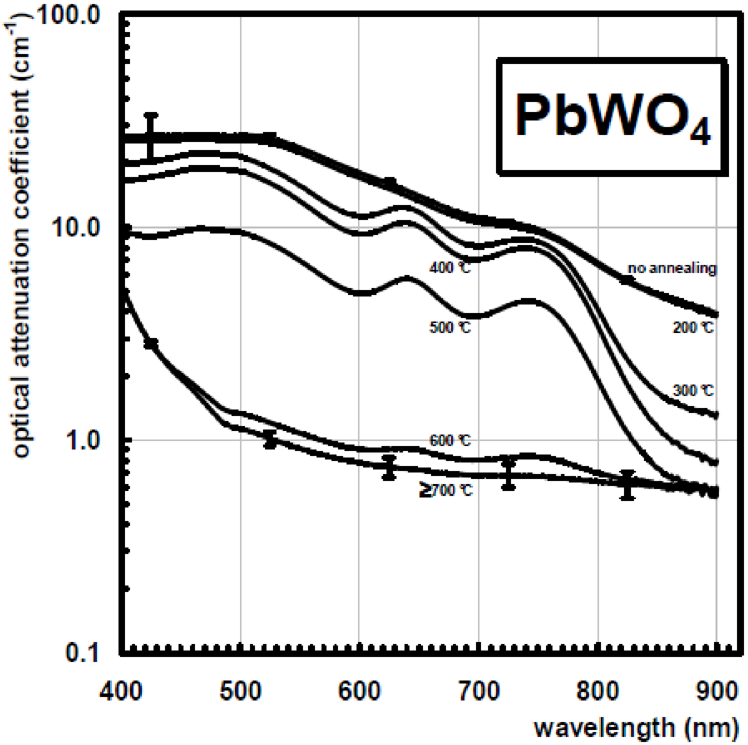


Fig. 2. Optical attenuation coefficient of the irradiated sample before annealing and after successive annealing temperatures.

[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