A Comparison of Monitoring Data with Radiation Damage in PWO Crystals by Ionization Dose and Charged Hadrons

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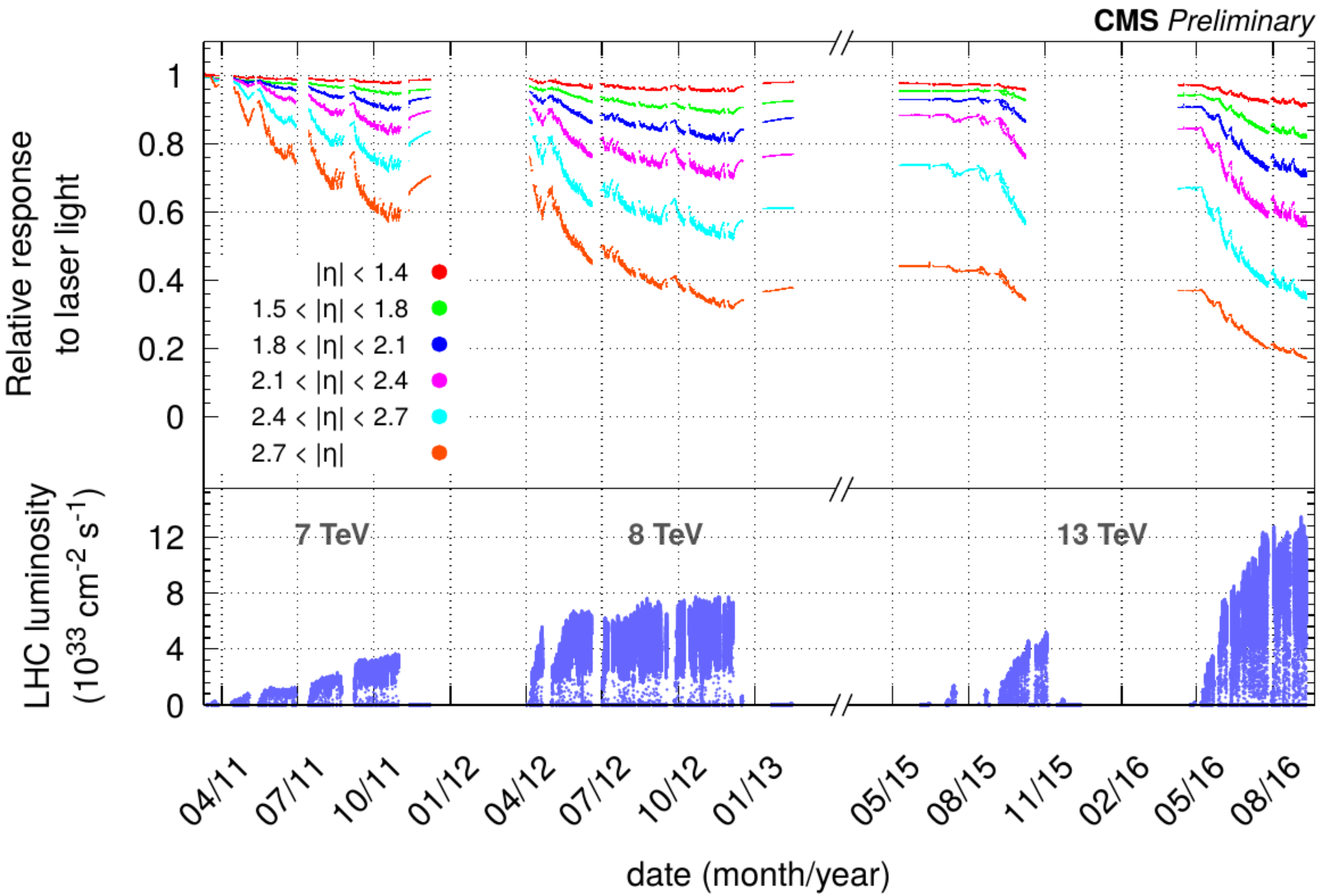
Introduction

- Both ionization dose and charged hadrons cause radiation damage in PWO crystals.
- Ionization dose induced damage in PWO recovers, so is dose rate dependent. Damage caused by deep centers recovers slowly.
- Degradations shown in ECAL monitoring data include effects of both PWO crystals and photodetectors.
- Degradations in PWO crystals can be estimated by using ionization dose and charged hadrons induced absorption in the radiation environment calculated by BRIL.

ECAL Laser Monitoring Data

How much the degradation is due to crystals?



Dose Rate Dependent Damage

IEEE Trans. Nucl. Sci., Vol. 44 (1997) 458-476

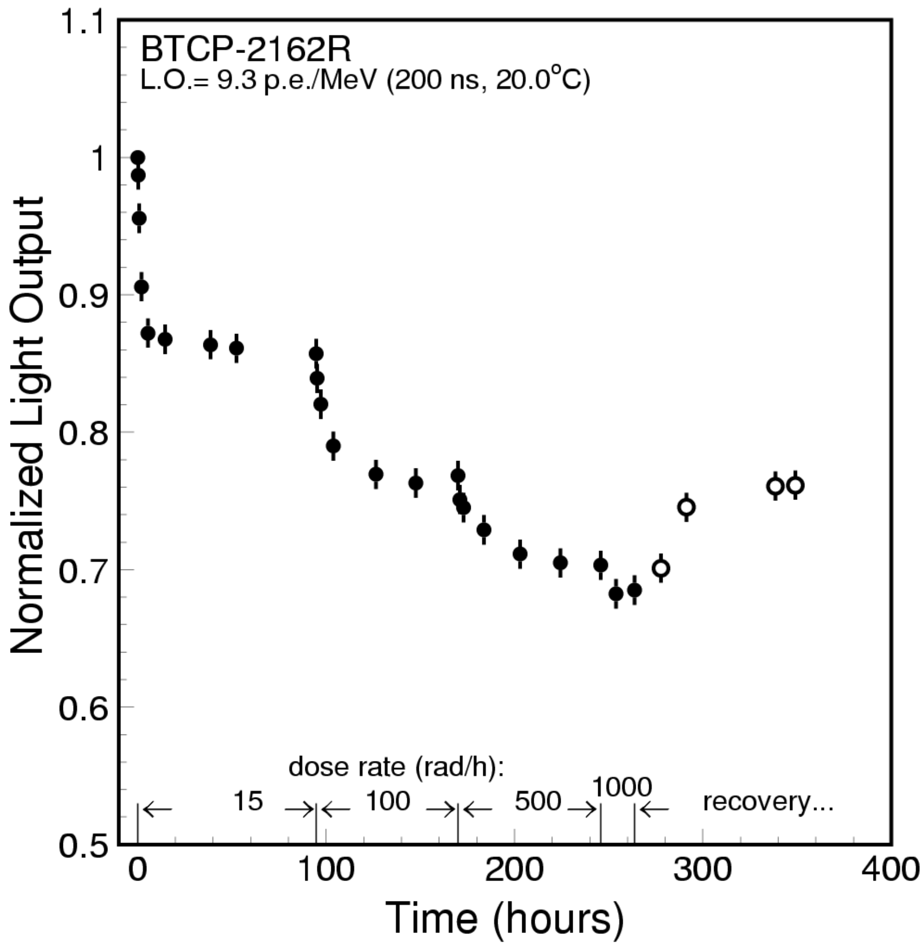
Light output reaches an equilibrium during irradiation under a defined dose rate, showing dose rate dependent damage

$$dD = \sum_{i=1}^{n} \{-a_i D_i dt + (D_i^{all} - D_i)\, b_i R dt\}$$

$$D = \sum_{i=1}^{n} \{\frac{b_i R D_i^{all}}{a_i + b_i R}\,[1 - e^{-(a_i+b_iR)t}] + D_i^0 e^{-(a_i+b_iR)t}\}$$

- D_i: color center density in units of m^{-1};
- D_i^0: initial color center density;
- D_i^{all} is the total density of trap related to the color center in the crystal;
- a_i: recovery costant in units of hr^{-1};
- b_i: damage contant in units of kRad^{-1};
- R: the radiation dose rate in units of kRad/hr.

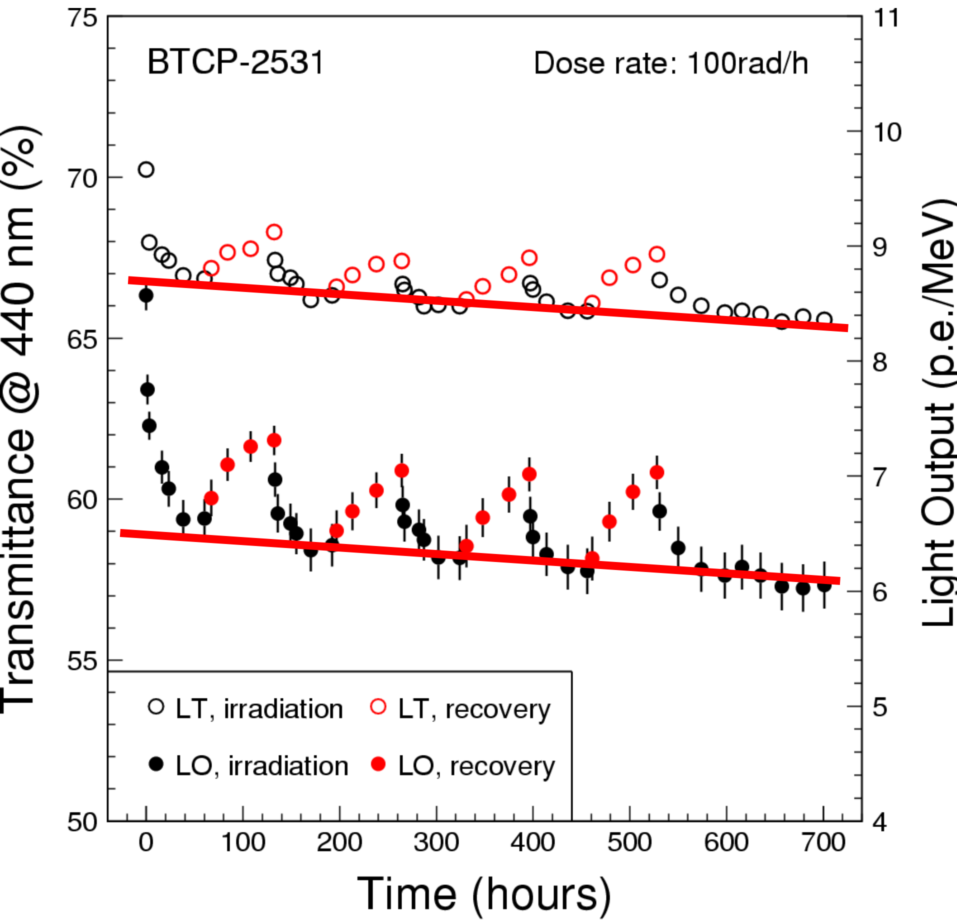
$$D_{eq} = \sum_{i=1}^{n} \frac{b_i R D_i^{all}}{a_i + b_i R}$$

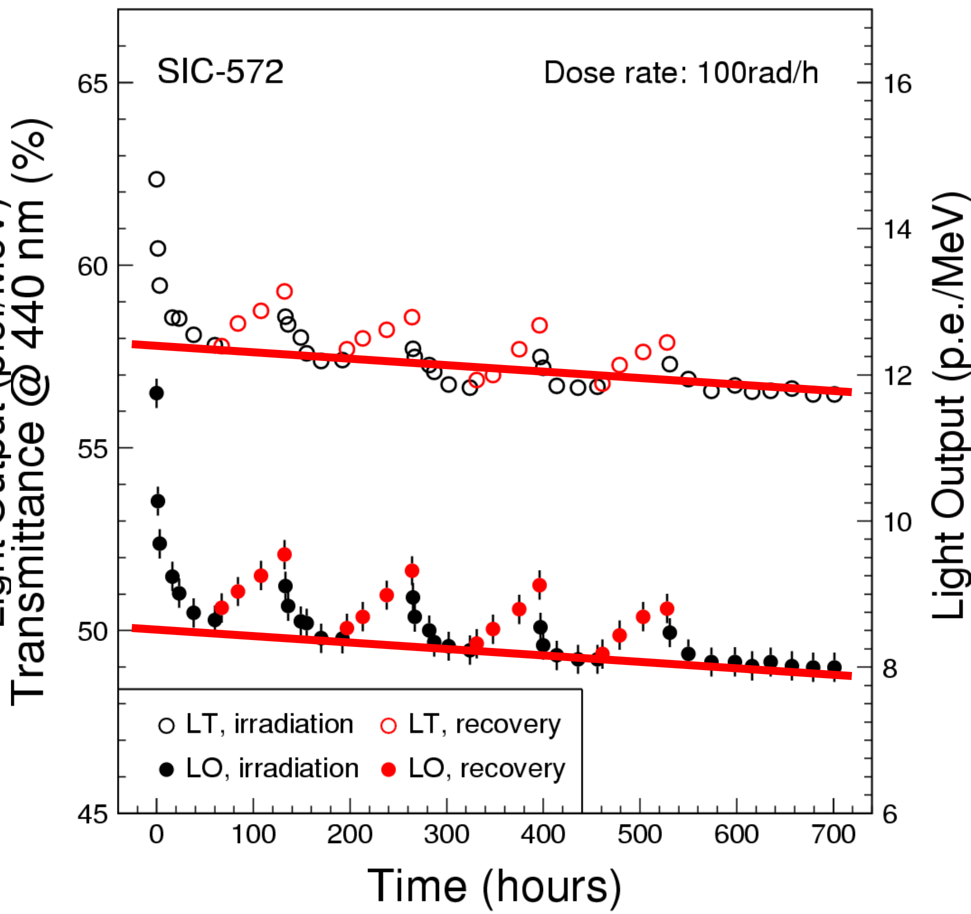


Light and Transmittance Loss

BTCP & SIC PWO @ 100 and 400 rad/h & recovery

AIP Conference Proceedings 867 (2006) 252

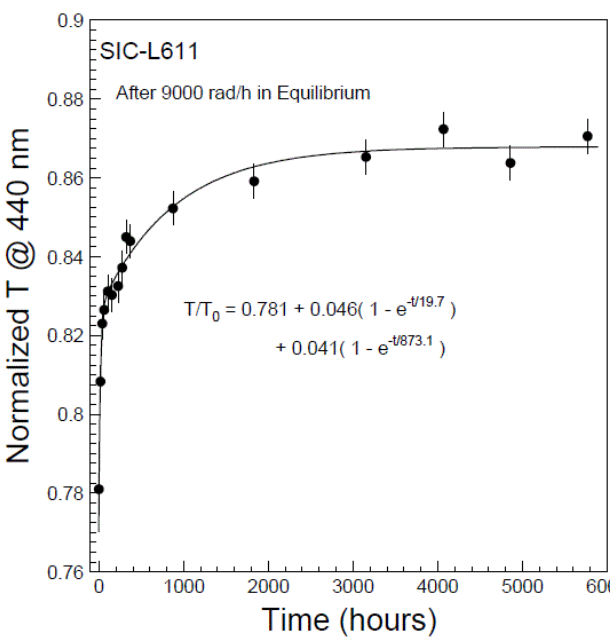


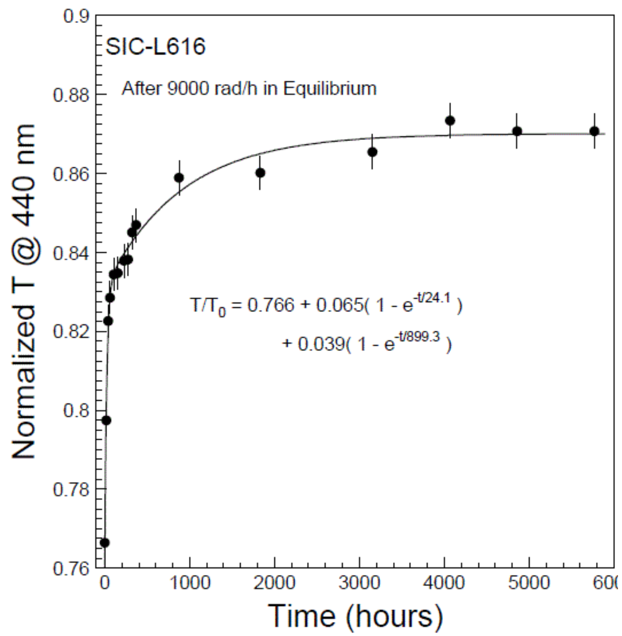


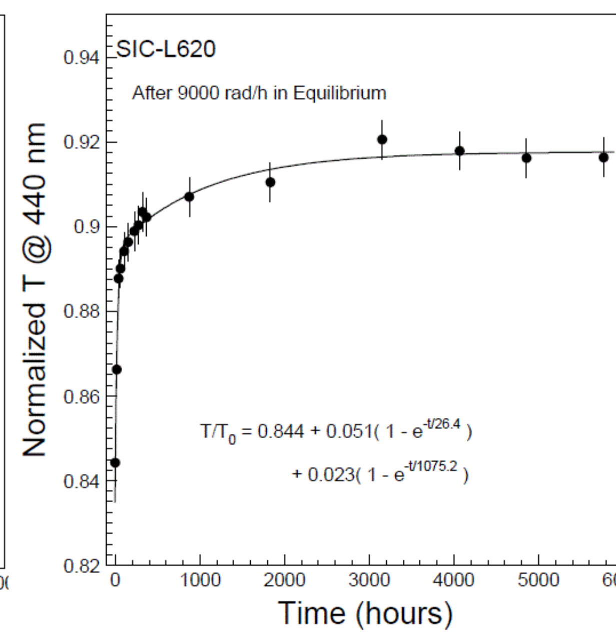
Recovery after γ Irradiation

Deep color centers recover slowly, which would cause cumulative radiation damage

Sample	T/T_0 @ 9 krad/hr	T/T_0 after recovery	μ @9 krad/hr (cm^{-1})	μ after recovery (cm^{-1})	Not recovery ratio (%)
SIC-L611	0.781	0.868	1.124	0.643	57.3
SIC-L616	0.766	0.870	1.212	0.633	52.2
SIC-L620	0.844	0.918	0.771	0.389	50.4

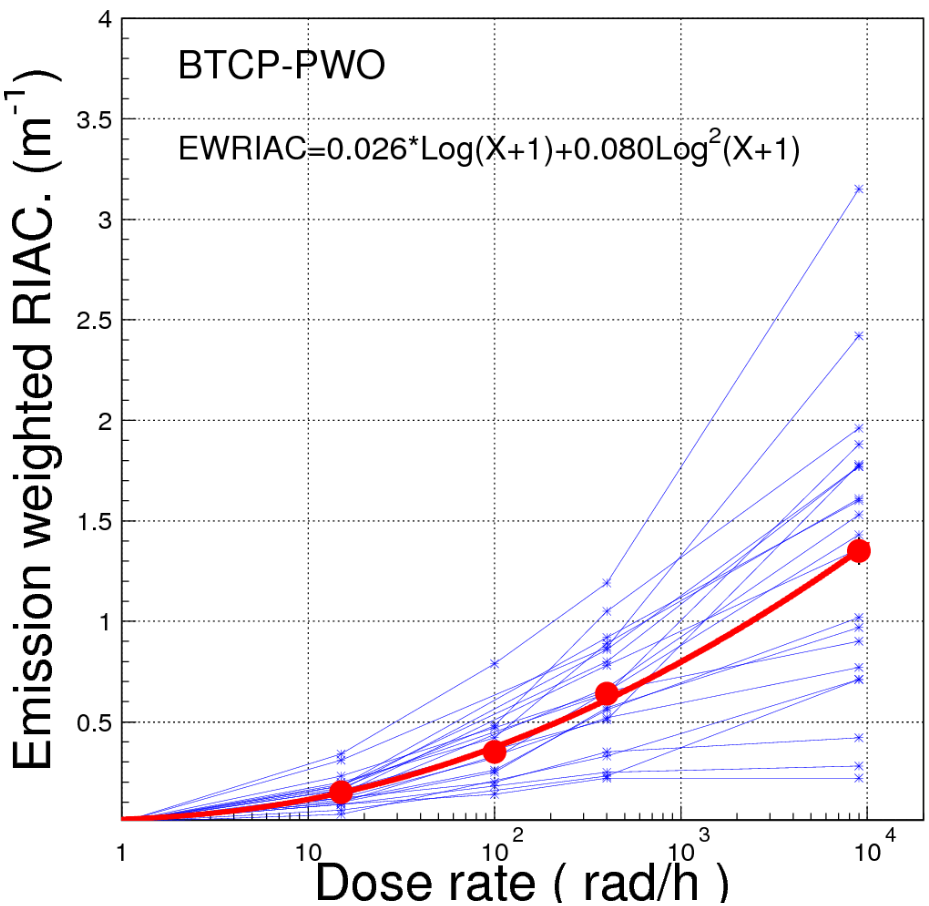


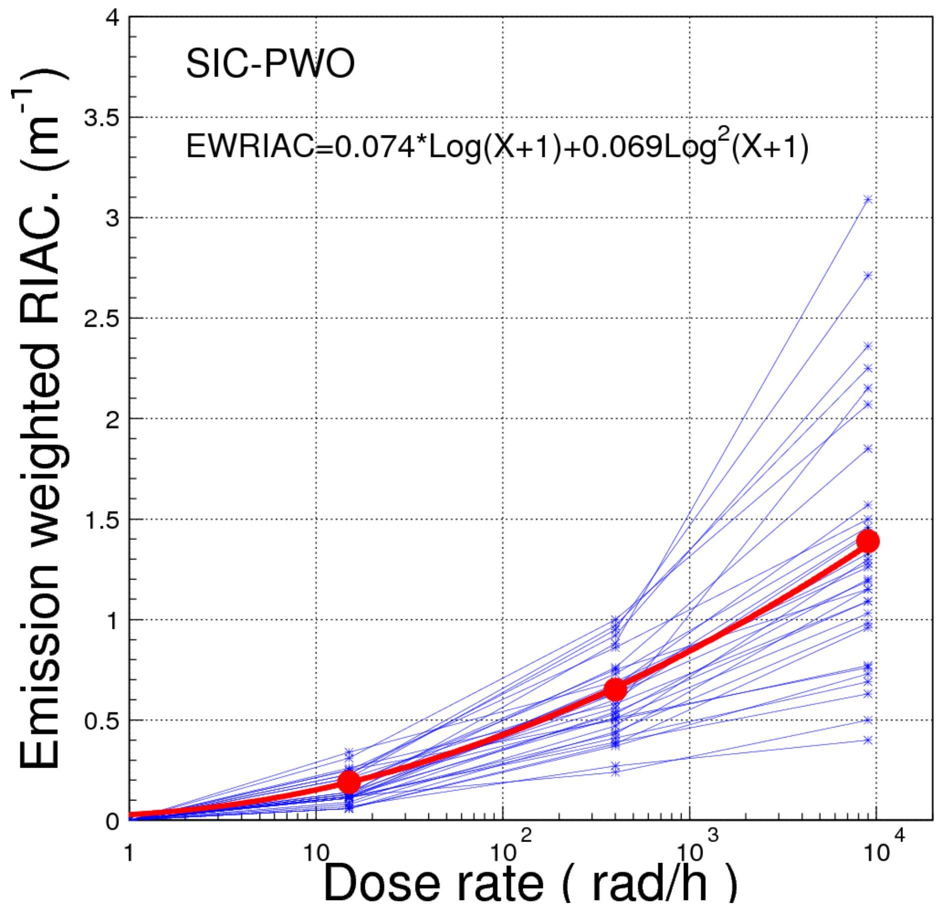




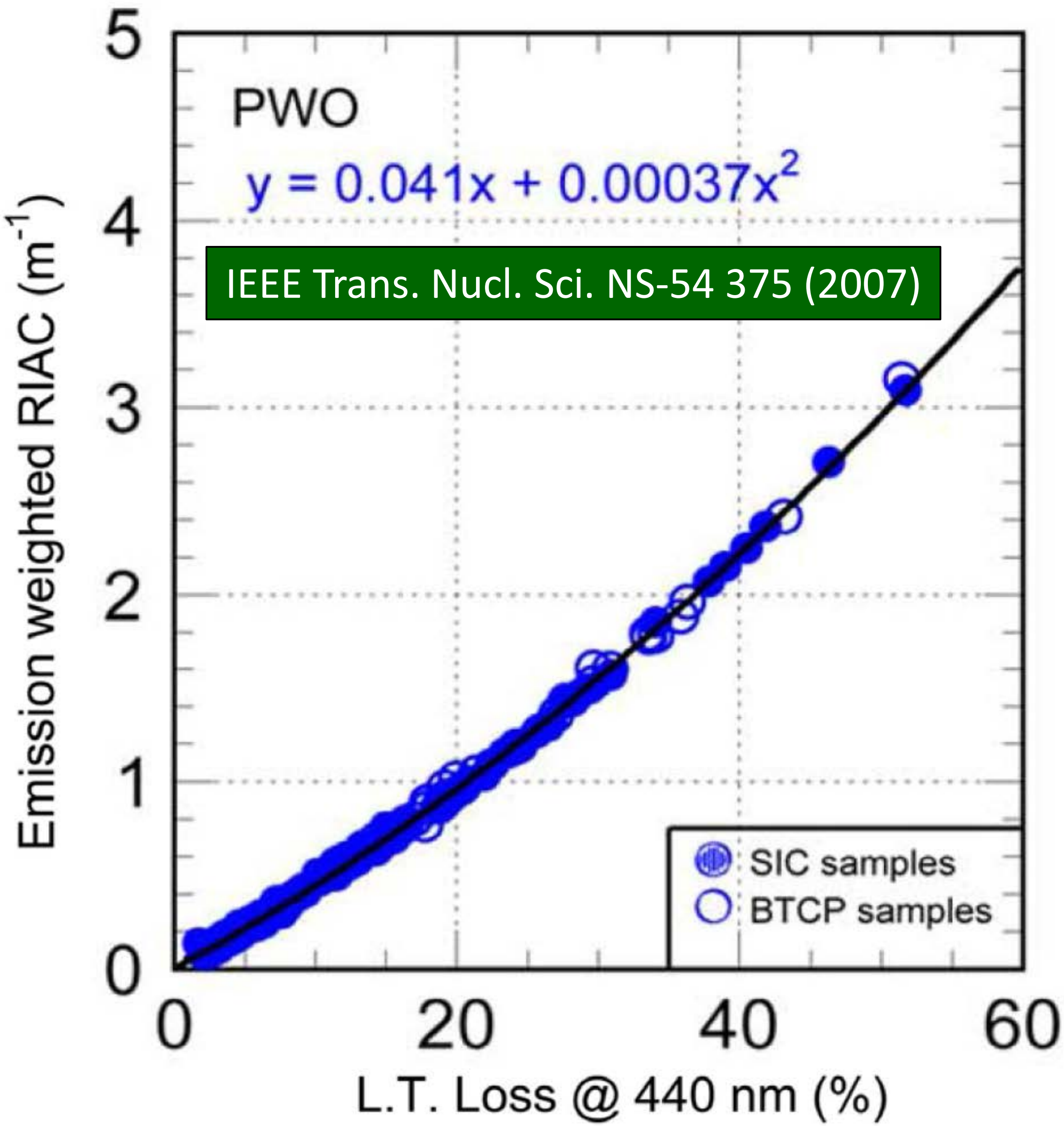
EWRIAC versus Dose Rate

Average EWRIAC: 2^{nd} order polynomials of dose rate
Large spread at high dose rate; consistent BTCP and SIC
IEEE Trans. Nucl. Sci. NS-51 1777 (2004)



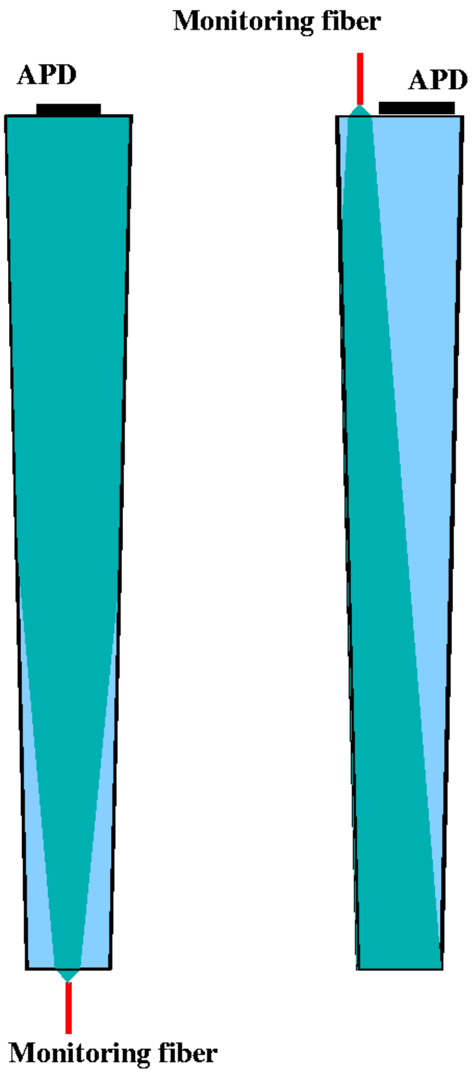


EWRIAC and μ_{440} in PWO



Excellent correlation between EWRIAC and $\mu_{440\ nm}$ measured for all BTCP and SIC PWO crystals

Monitoring Light Path Length



Average optical path lengths in EB/EE crystals are estimated by a ray-tracing simulation to be 1.3 and 2.3 PWO length for the barrel and endcaps respectively

EB PWO: $22^2 \times 230 \times 26^2$ mm^3
Readout: 2x 5×5 mm^2 APDs with n=1.5
One lateral face semi-polished Ra=0.25 µm
All other faces optically polished
Reflectivity of wrapping: R=0.98.

EE PWO: $28.5^2 \times 220 \times 30^2$ mm^3
Readout: Φ26.6 mm VPT with n=1.5.
All faces optically polished
Reflectivity of wrapping: R=0.98

Ionization Damage in PWO

Dose rate for pp obtained from BRIL

(https://cms-project-fluka-flux-map.web.cern.ch/cms-project-fluka-flux-map/

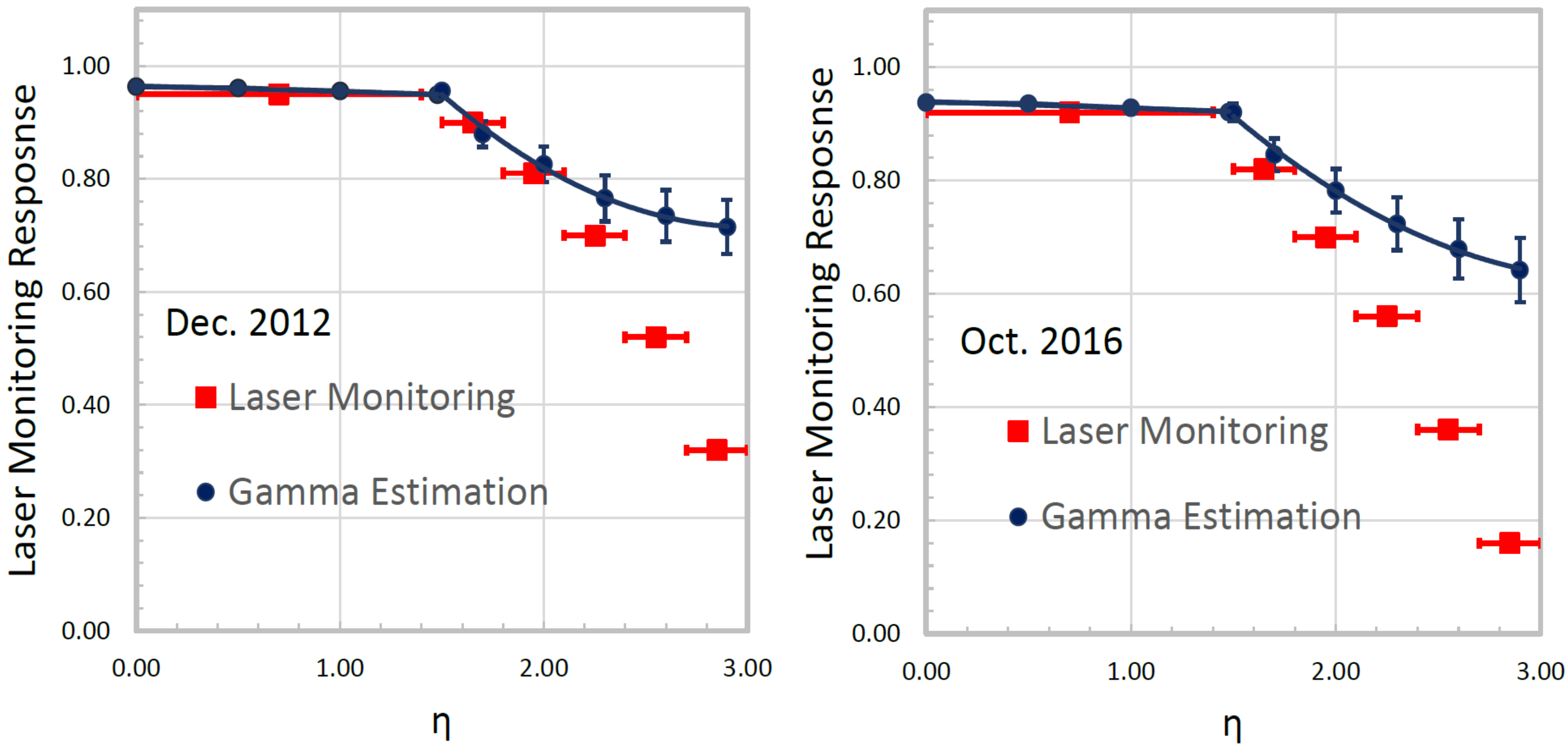
Run I: CMS_pp_4.0TeV_2012_FLUKA

Run II: CMS_pp_7TeV_v3.0.0.0_FLUKA

CMS ECAL	η=0	η=0.5	η=1.0	η=1.478	η=1.5	η=1.7	η=2.0	η=2.3	η=2.6	η=2.9
Run I Dose rate (rad/hr)	10	11	14	17	6	35	86	211	329	433
Run I μ_{440nm} (m^{-1})	0.125	0.133	0.152	0.175	0.089	0.254	0.378	0.527	0.610	0.664
Run II Dose rate (rad/hr)	25	27	34	42	16	63	167	385	706	1170
Run II μ_{440nm} (m^{-1})	0.216	0.223	0.250	0.276	0.165	0.332	0.486	0.640	0.765	0.877

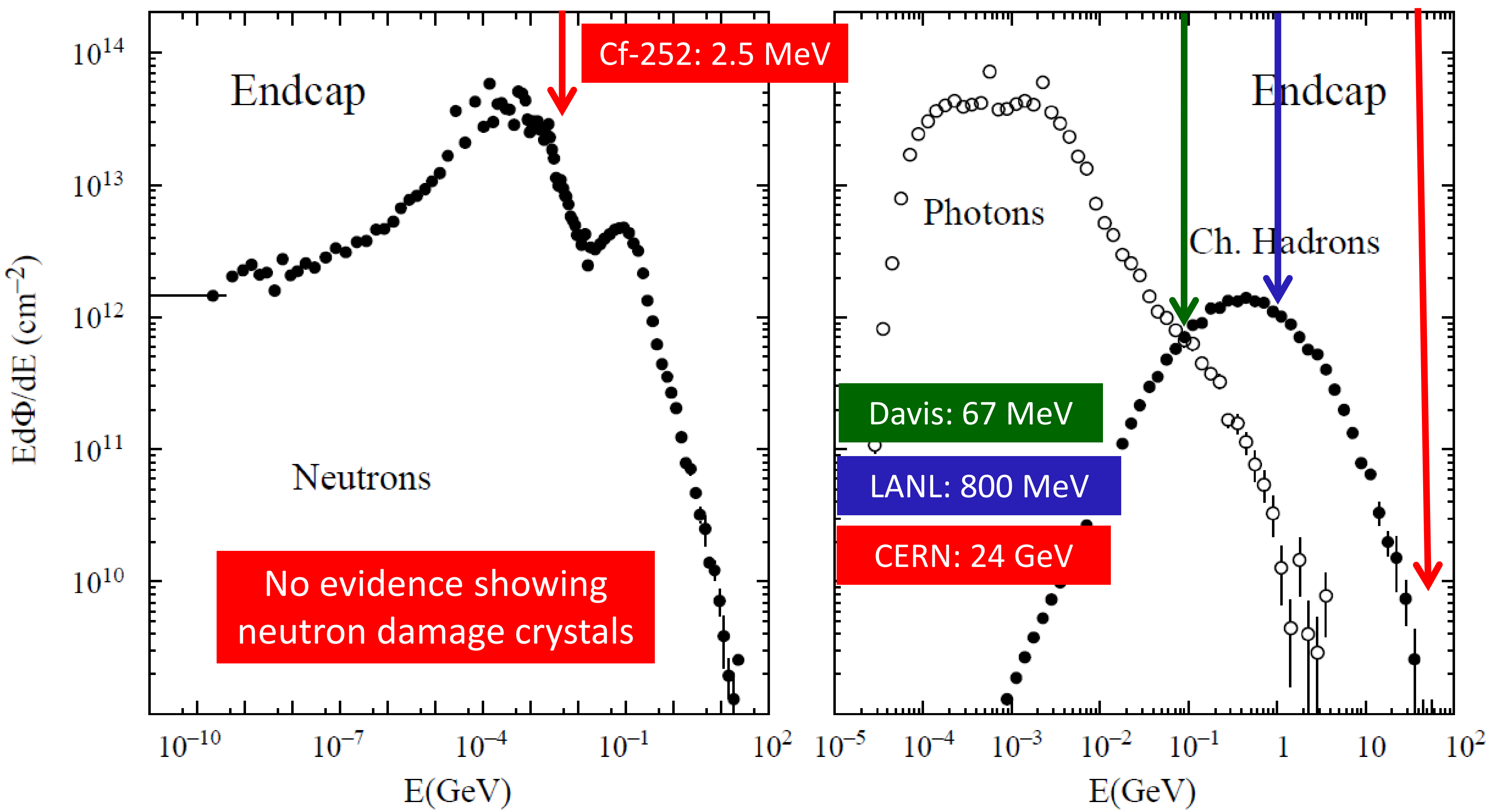
Dose Rate Dependent Monitoring Loss

ɣ-ray induced absorption can not explain monitoring loss @ high rapidity: look damage caused by charged hadron

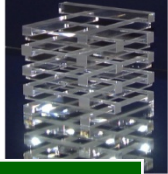


Particle Energy Spectra at HL-LHC

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

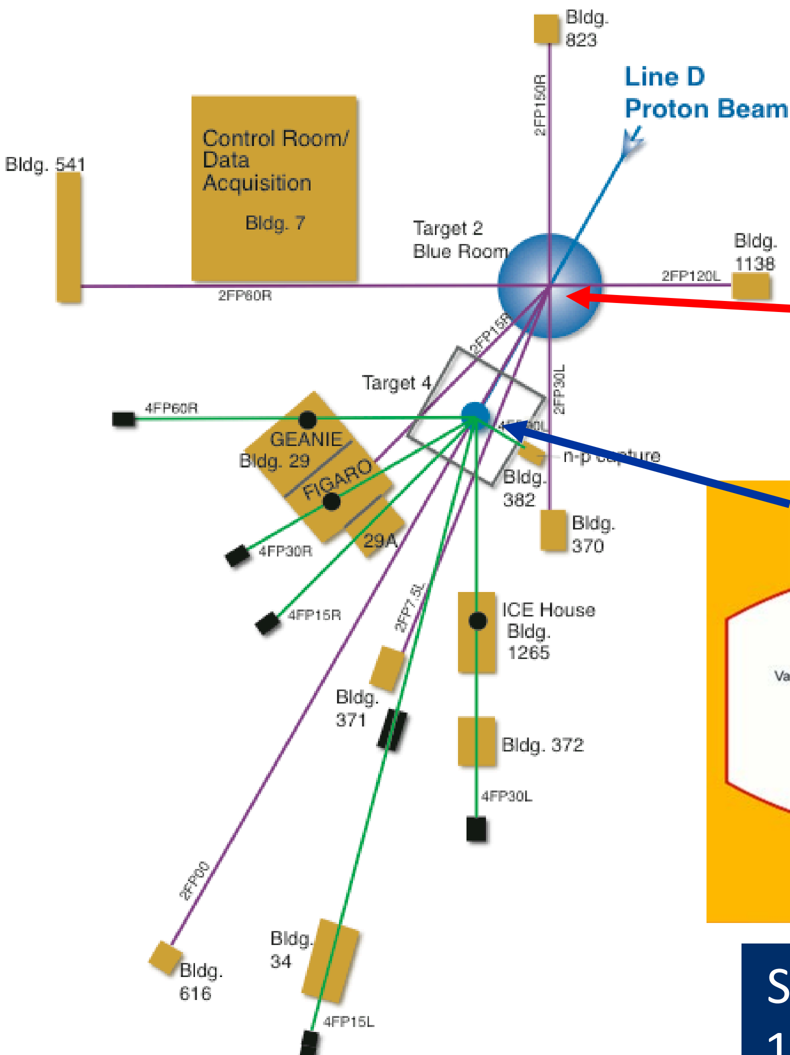


Proton/Neutron Irradiation at LANL

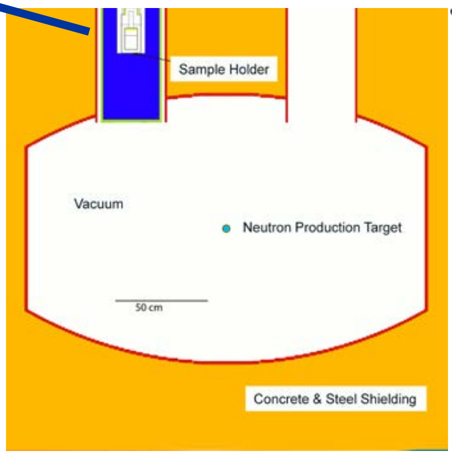


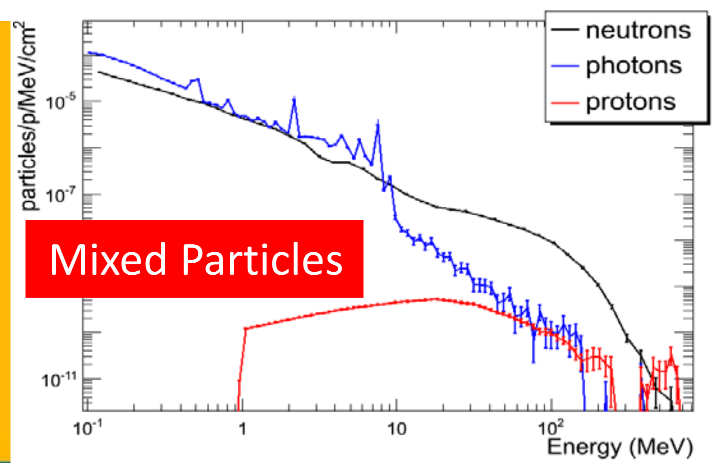
Environment/Source	Proton Flux ($p\ s^{-1}\ cm^{-2}$)	Fluence on Crystal ($p\ cm^{-2}$)
CMS FCAL (η=1.4) at HL-LHC	4.0×10^4	2.4×10^{12} / 3000 fb^{-1}
CMS FCAL (η=3.0) at HL-LHC	5.0×10^6	3.0×10^{14} / 3000 fb^{-1}
WNR facility of LANSCE	**Up to 2×10^{10}**	**Up to 3×10^{15}**

Los Alamos Neutron Science Center (LANSCE)



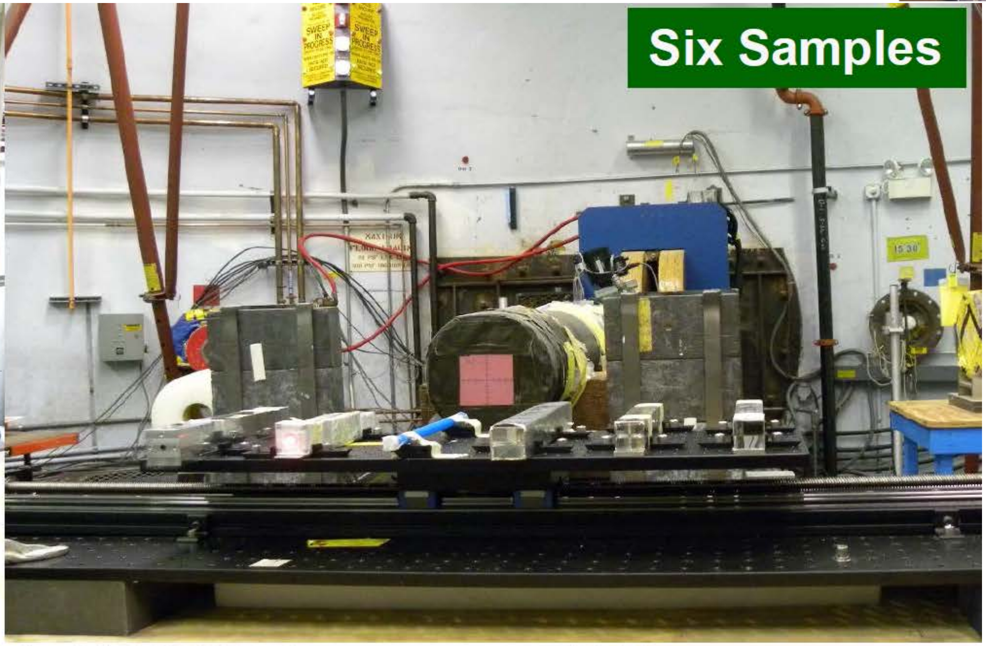
800 MeV proton beam in blue room (FWHM:1")

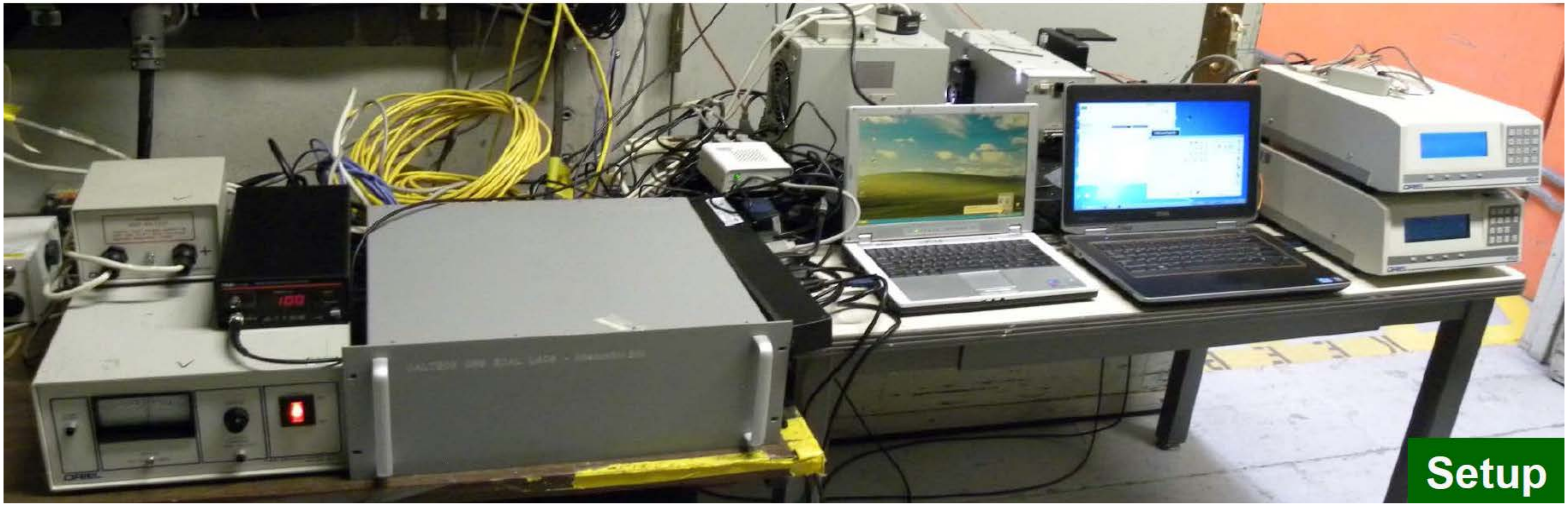




Samples are placed at Target-4 East Port, about 1.2 m away from the neutron production target

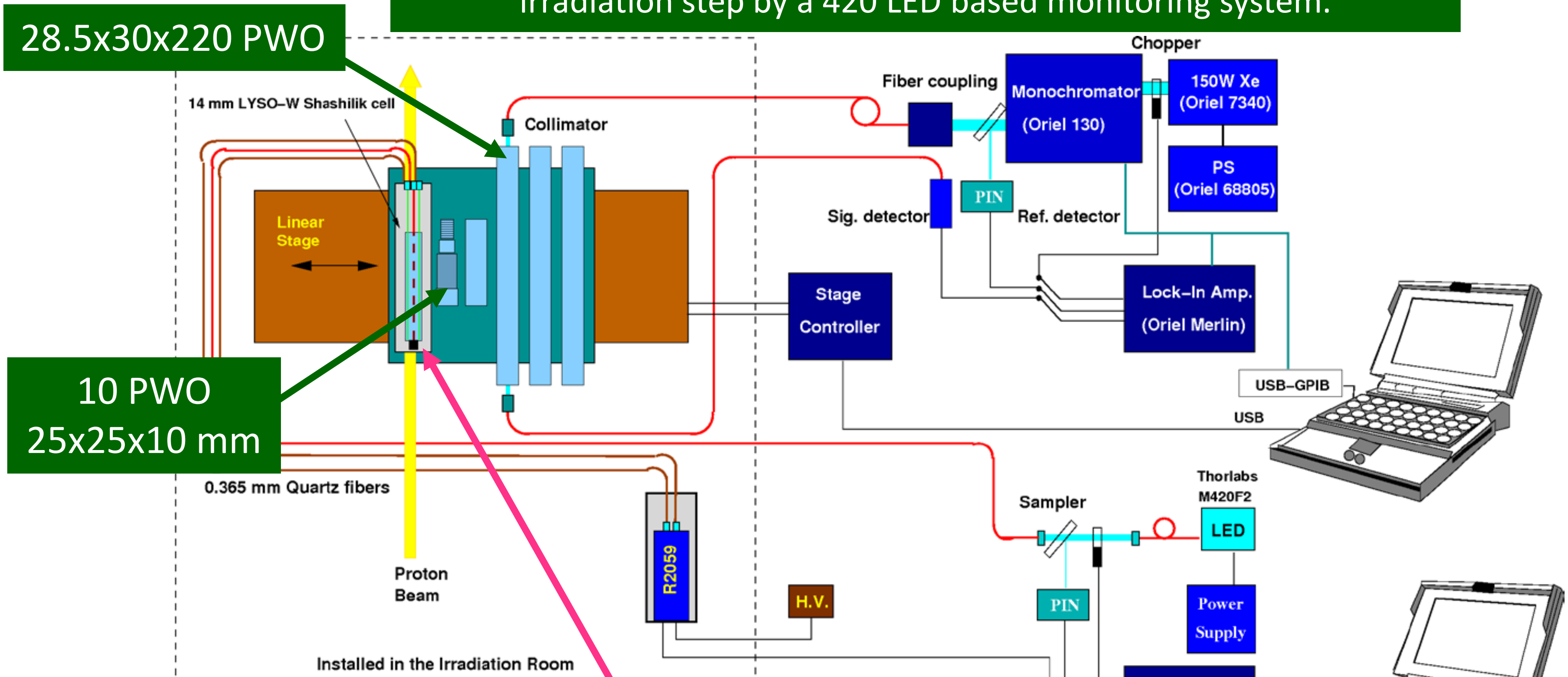
800 MeV p-Irradiation at LANL

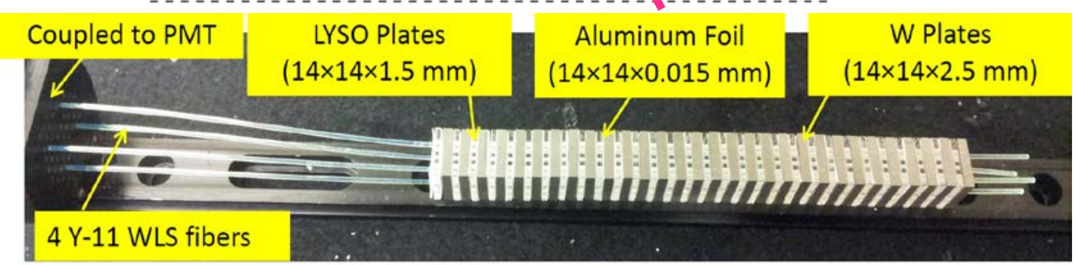




The Proton-Irradiation Setup

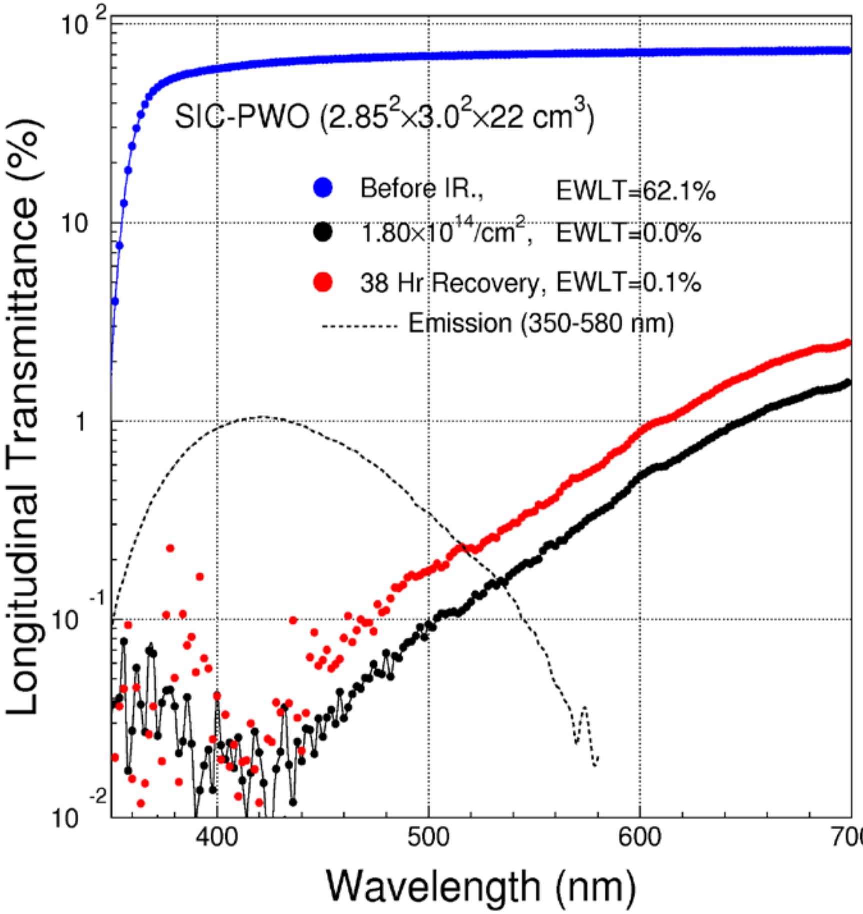
LT (300-800 nm) of long crystals was measured before and after each irradiation step by a Xenon lamp and fiber based spectrophotometer. A LYSO-W-Capillary Shashlik cell was monitored before and after each irradiation step by a 420 LED based monitoring system.

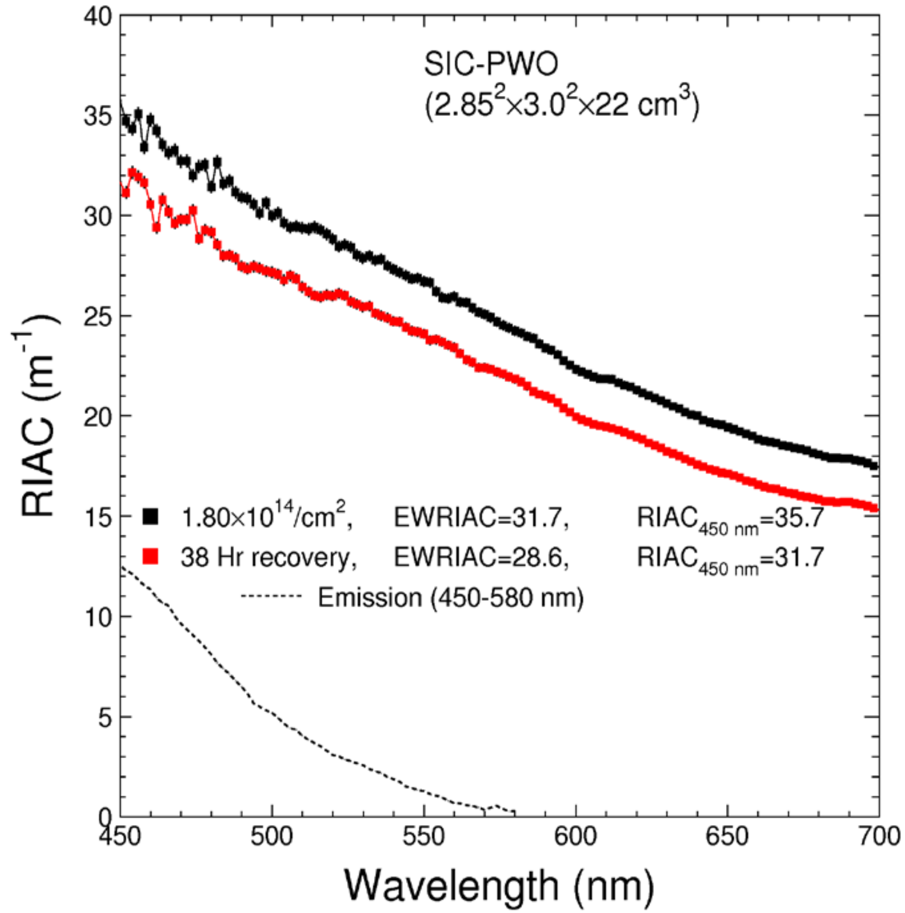




Proton Irradiation at LANL 2015

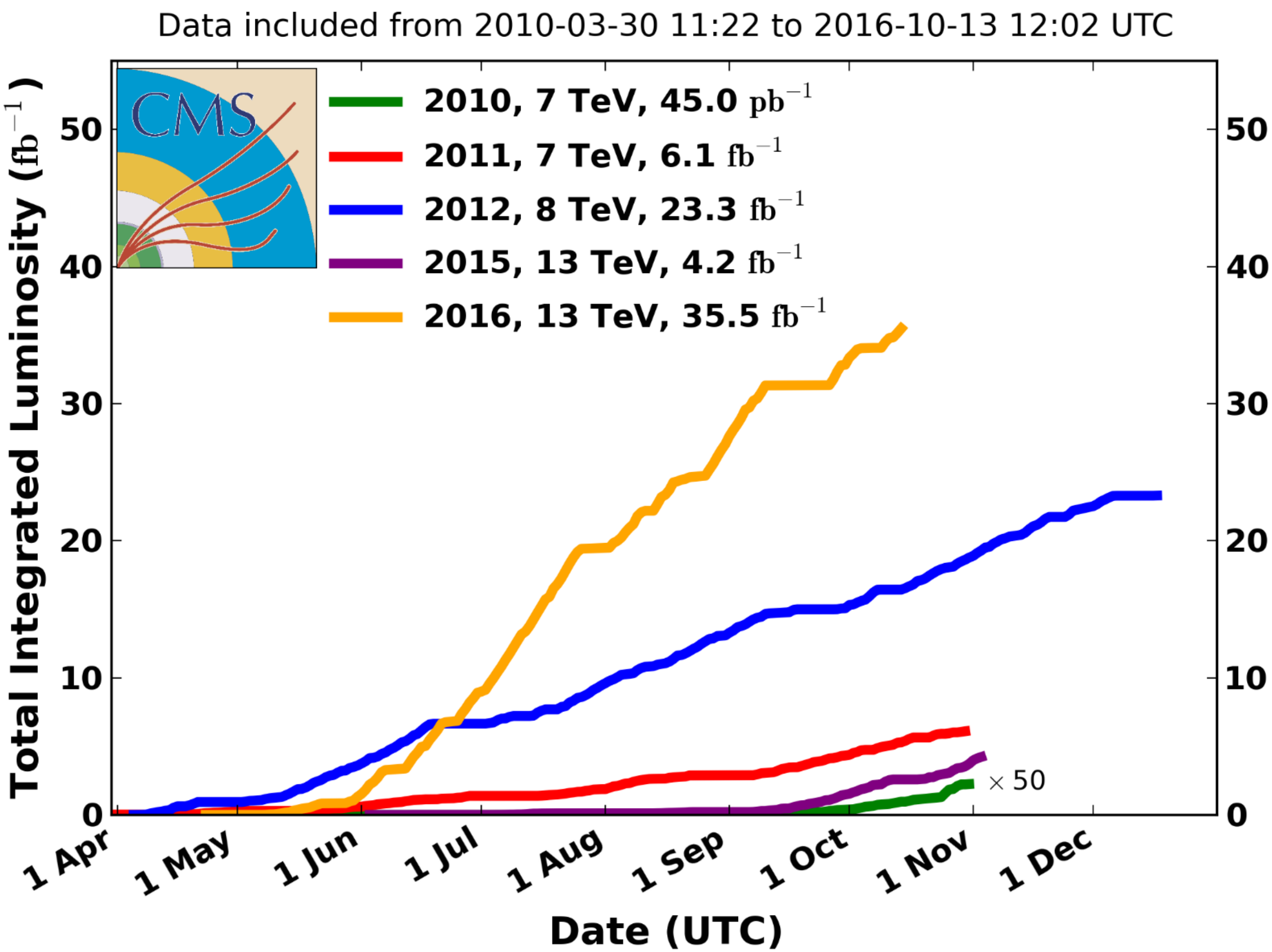
A 22 cm PWO sample shows 32 m^{-1} at 450 nm 38 hours after 1.8×10^{14} p/cm^2 of 800 MeV protons



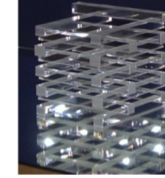


CMS Integrated Luminosity

Run I (2010-2012) : 7-8 TeV, 30 fb^{-1}. Run II (2015-2016 Oct.): 13 TeV, 40 fb^{-1}



Charged Hadron Fluence



https://cms-project-fluka-flux-map.web.cern.ch/cms-project-fluka-flux-map/

Run I: CMS_pp_4.0TeV_2012_FLUKA

Run II: CMS_pp_7TeV_v3.0.0.0_FLUKA

CMS ECAL	η=0	η=0.5	η=1.0	η=1.48	η=1.5	η=1.7	η=2.0	η=2.3	η=2.6	η=2.9
Run I (cm^{-2})	3.63E+10	3.26E+10	3.66E+10	4.38E+10	2.46E+10	1.10E+11	3.51E+11	9.19E+11	1.95E+12	3.59E+12
Run II (cm^{-2})	4.09E+10	4.17E+10	4.49E+10	5.04E+10	4.93E+10	1.56E+11	5.31E+11	1.28E+12	2.92E+12	5.91E+12
Total (cm^{-2})	7.72E+10	7.43E+10	8.15E+10	9.42E+10	7.39E+10	2.66E+11	8.82E+11	2.20E+12	4.87E+12	9.50E+12

Estimated RIAC @ 440 nm

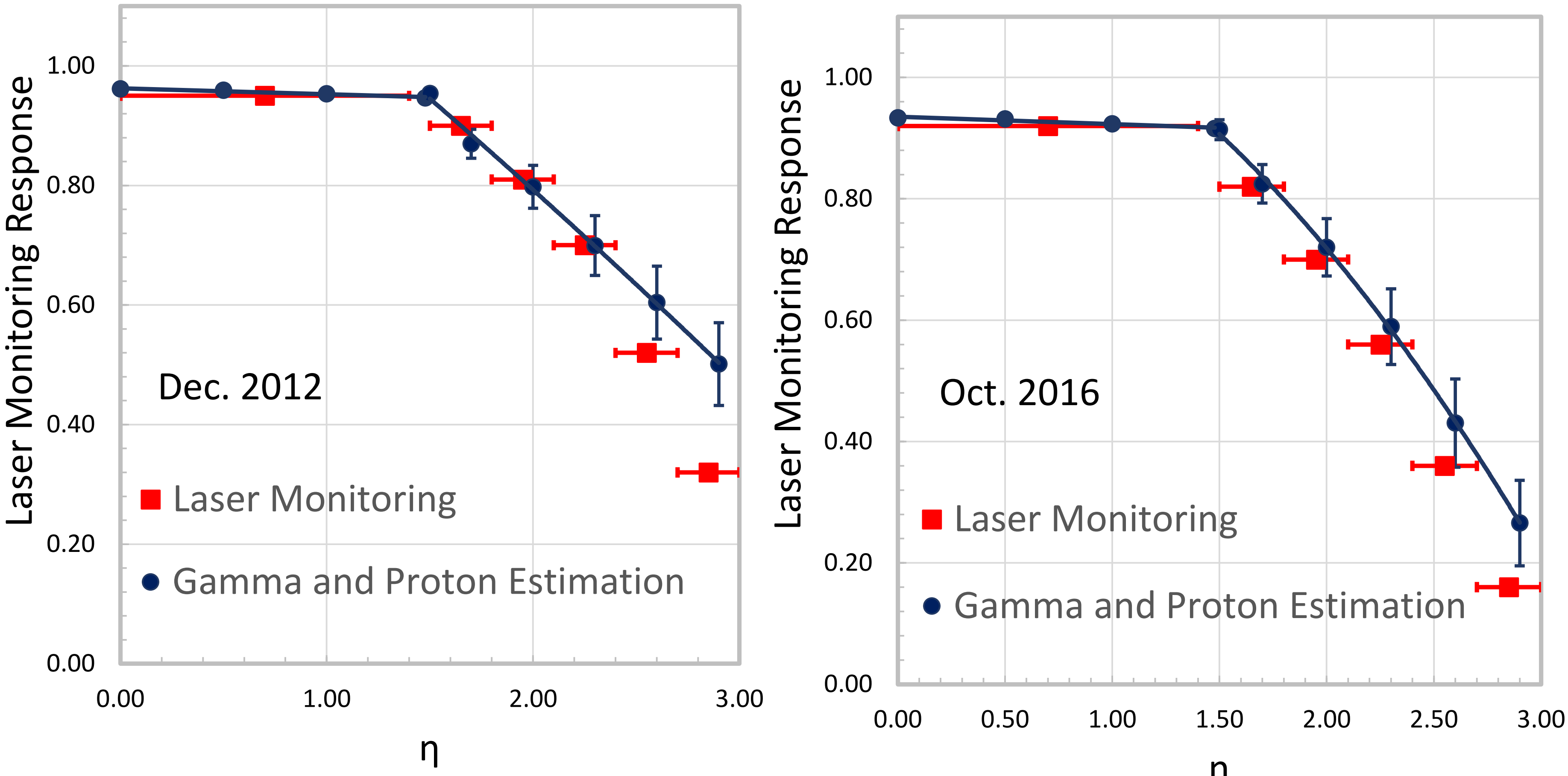
RIAC values at 440 nm calculated using ɣ-ray and proton irradiation data
Damage in EB is dominated by ionization dose
Charged hadron starts to play role at large η

Run-I RIAC (m^{-1})	η=0	η=0.5	η=1.0	η=1.478	η=1.5	η=1.7	η=2.0	η=2.3	η=2.6	η=2.9
CH. Run I	0.007	0.007	0.008	0.008	0.004	0.022	0.068	0.179	0.386	0.701
Ionization Run I	0.125	0.133	0.152	0.175	0.089	0.254	0.378	0.527	0.610	0.664
Total	0.132	0.140	0.160	0.184	0.094	0.275	0.447	0.706	0.996	1.365

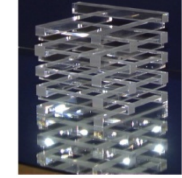
Run-II RIAC (m^{-1})	η=0	η=0.5	η=1.0	η=1.478	η=1.5	η=1.7	η=2.0	η=2.3	η=2.6	η=2.9
CH. Run I	0.007	0.007	0.008	0.008	0.004	0.022	0.068	0.179	0.386	0.701
CH. Run II	0.007	0.007	0.008	0.009	0.009	0.028	0.094	0.225	0.515	1.041
Ionization Run II	0.216	0.223	0.250	0.276	0.165	0.332	0.486	0.640	0.765	0.877
Total	0.230	0.237	0.265	0.294	0.178	0.381	0.648	1.044	1.666	2.619

Comparison with Monitoring Data

Agreement observed in ECAL of η<2.5 after adding contribution from charged hadrons. Additional contribution needed for η>2.5



Other Contributions (VPT)?



An extra degradation factor at η>2.0 up to 0.6 observed.

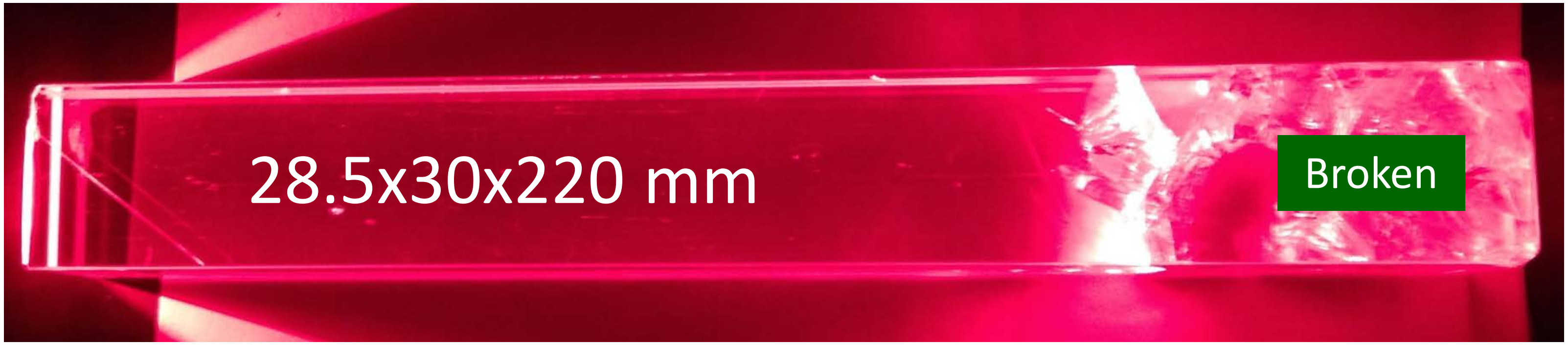
Run I (Dec. 2012)	η=0	η=0.5	η=1.0	η=1.478	η=1.5	η=1.7	η=2.0	η=2.3	η=2.6	η=2.9
CH. Run I RIAC (m^{-1})	0.007	0.007	0.008	0.008	0.004	0.022	0.068	0.179	0.386	0.701
Ionization Run I (m^{-1})	0.125	0.133	0.152	0.175	0.089	0.254	0.378	0.527	0.610	0.664
Total RIAC (m^{-1})	0.132	0.140	0.160	0.184	0.094	0.275	0.447	0.706	0.996	1.365
Estimated Monitoring	0.961	0.959	0.953	0.947	0.954	0.870	0.798	0.699	0.604	0.501
Monitoring Data	**0.95**	**0.95**	**0.95**	**0.95**	**0.95**	**0.9**	**0.81**	**0.7**	**0.52**	**0.32**
Additional Factor Needed	**0.99**	**0.99**	**1.00**	**1.00**	**1.00**	**1.03**	**1.02**	**1.00**	**0.86**	**0.64**

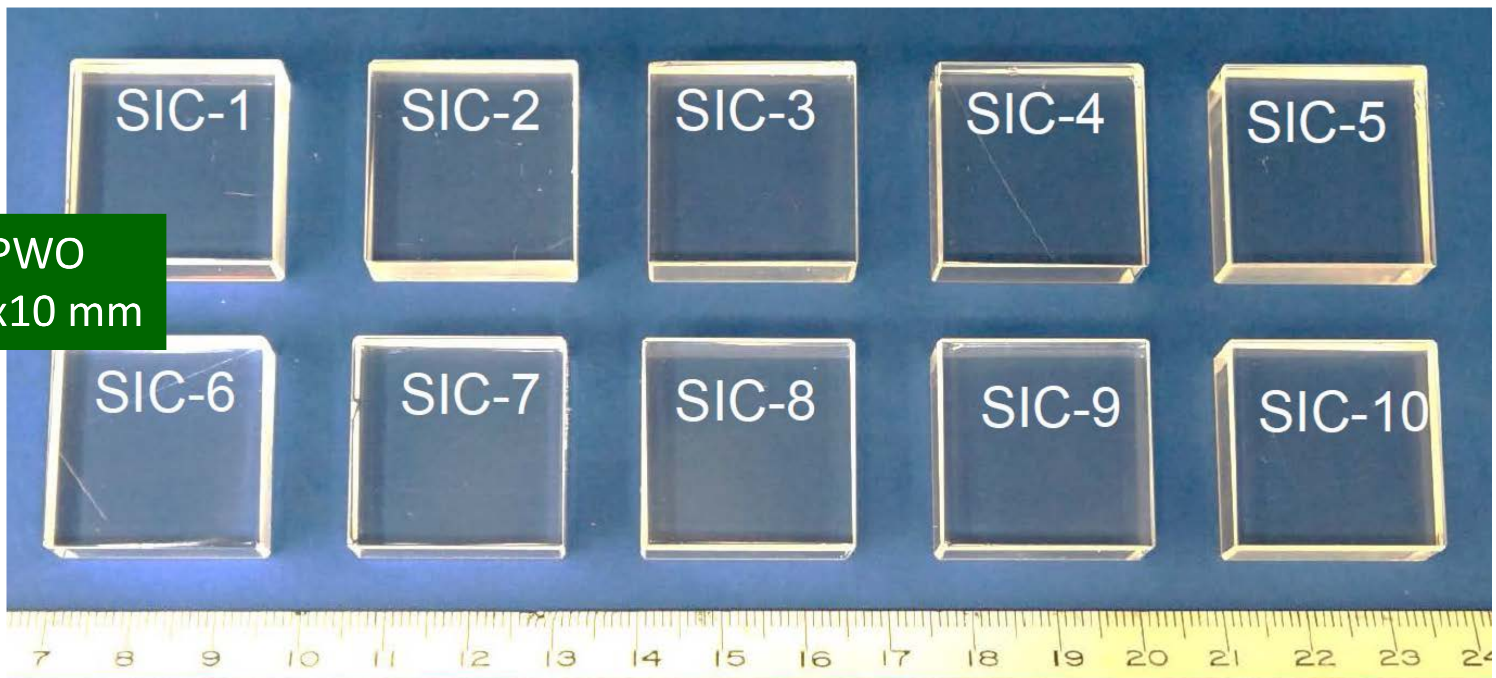
Run II (Oct. 2016)	η=0	η=0.5	η=1.0	η=1.478	η=1.5	η=1.7	η=2.0	η=2.3	η=2.6	η=2.9
CH. Run I RIAC (m^{-1})	0.007	0.007	0.008	0.008	0.004	0.022	0.068	0.179	0.386	0.701
CH. Run II RIAC (m^{-1})	0.007	0.007	0.008	0.009	0.009	0.028	0.094	0.225	0.515	1.041
Ionization Run II (m^{-1})	0.216	0.223	0.250	0.276	0.165	0.332	0.486	0.640	0.765	0.877
Total RIAC (m^{-1})	0.230	0.237	0.265	0.294	0.178	0.381	0.648	1.044	1.666	2.619
Estimated Monitoring	0.934	0.932	0.924	0.916	0.914	0.825	0.720	0.589	0.430	0.266
Monitoring Data	**0.92**	**0.92**	**0.92**	**0.92**	**0.92**	**0.82**	**0.7**	**0.56**	**0.36**	**0.16**
Additional Factor Needed	**0.99**	**0.99**	**1.00**	**1.00**	**1.01**	**0.99**	**0.97**	**0.95**	**0.84**	**0.60**

Summary

- Lead tungstate crystals suffer from radiation damges caused by ionization dose and charged hadrons.
- Absorption in PWO crystals induced by ionization dose and charged hadrons can explain monitoring data up to η=2.5. An additional VPT degradation factors at 60% level shown in Sasha's talk explains data at η>2.5.
- Taking into account deep color centers, the ionization dose induced damage may be underestimated. There are still large uncertainties in hadron induced damage.
  - Charged hadron induced damage in PWO; and
  - Neutron induced damage if any.
- Next two years are crucial to see more degradation in PWO. Additional data on hadron induced damage in PWO will make the whole picture more clear.

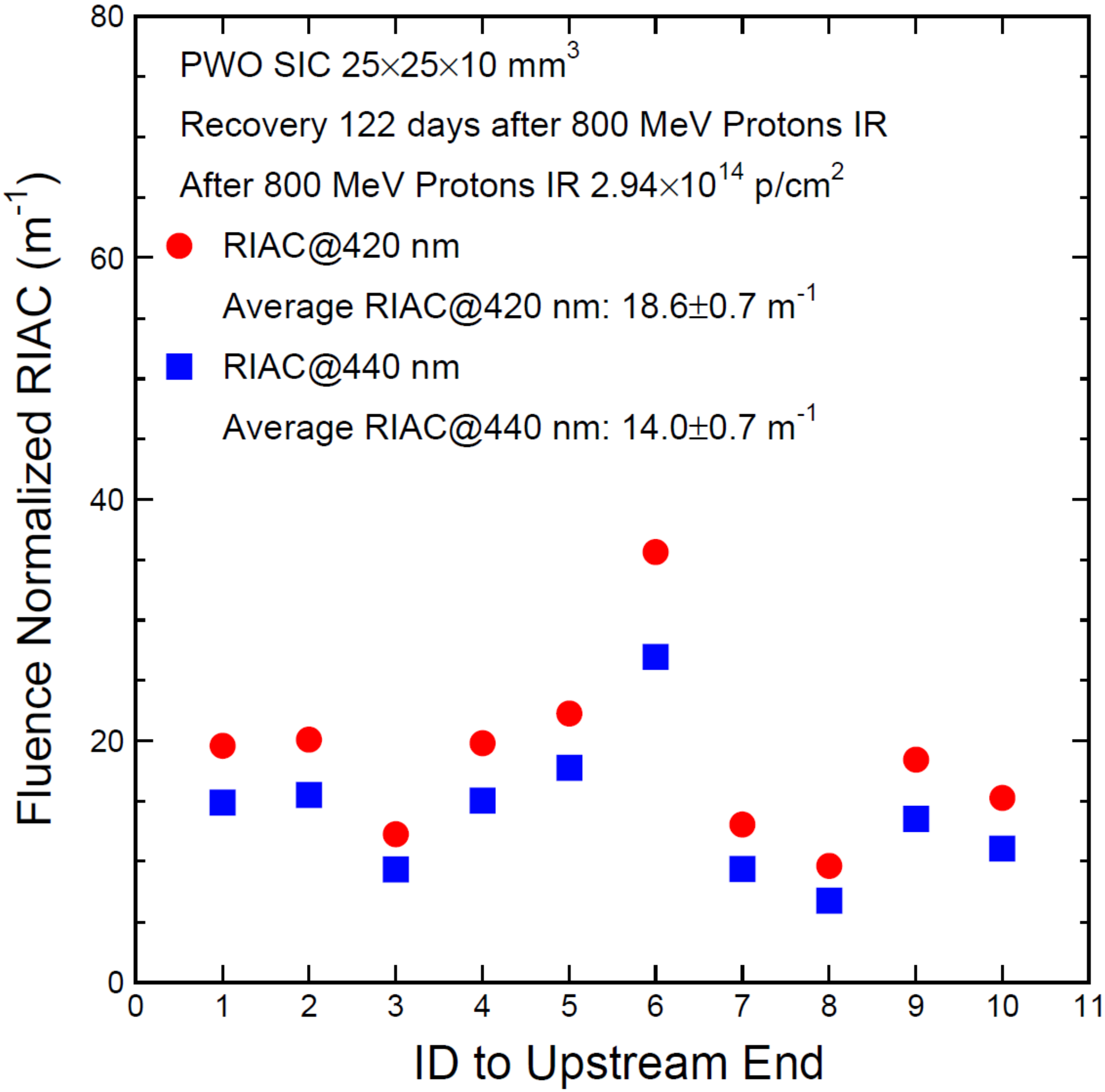
132 Days after Irradiation





10 PWO
25x25x10 mm

Result of 10 PWO after 122 Days



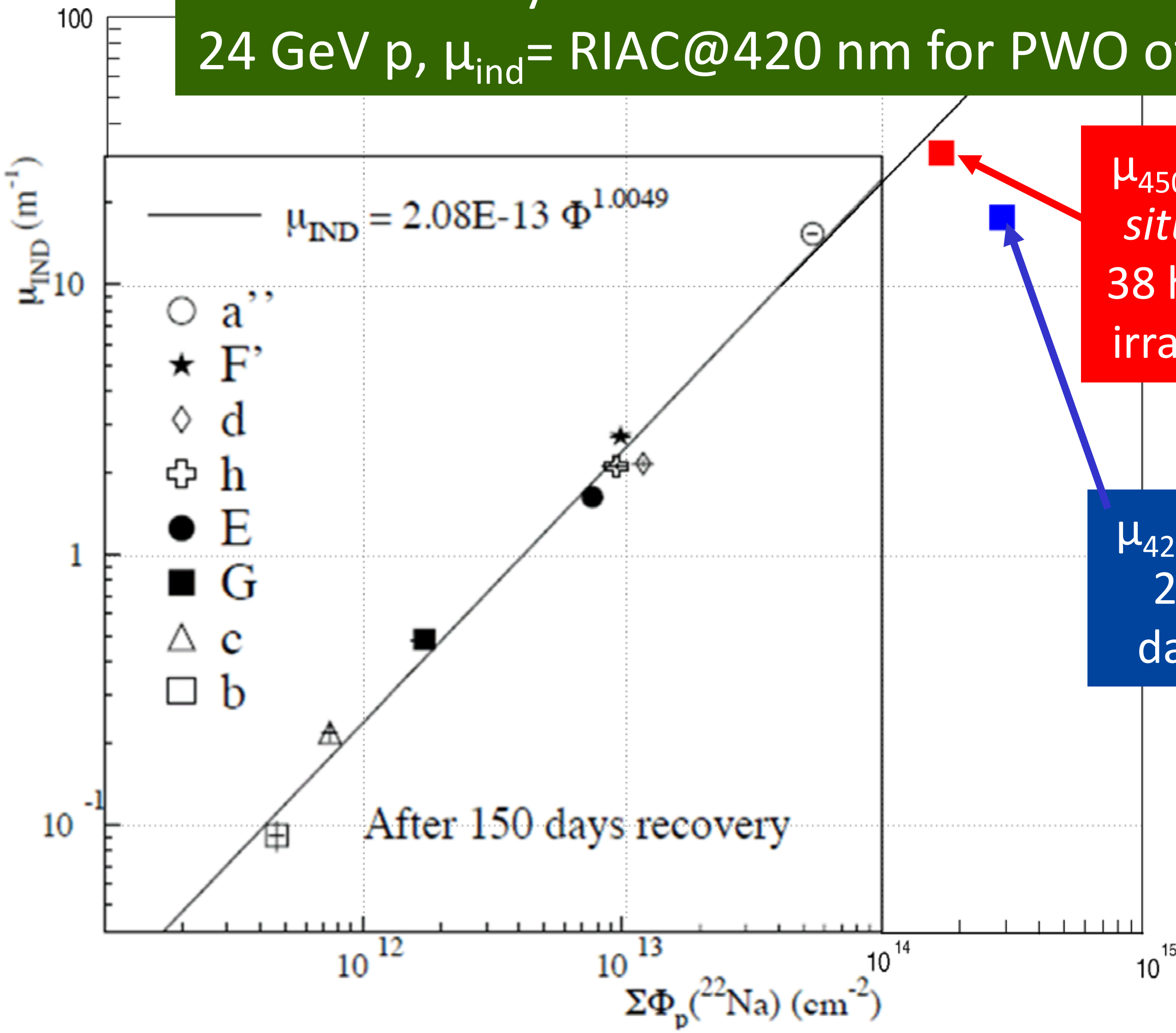
Average RIAC value of 14 m^{-1} at 440 nm 122 days after 2.94×10^{14} p/cm^2 of 800 MeV protons.

A factor of 3.7 lower than that measured 38 h after, showing damage recovery In PWO

Comparison with ETH data

Journal of Physics: Conference Series 160 (2009) 012013

24 GeV p, μ_{ind}= RIAC@420 nm for PWO of 2.4x2.4x23 cm^3

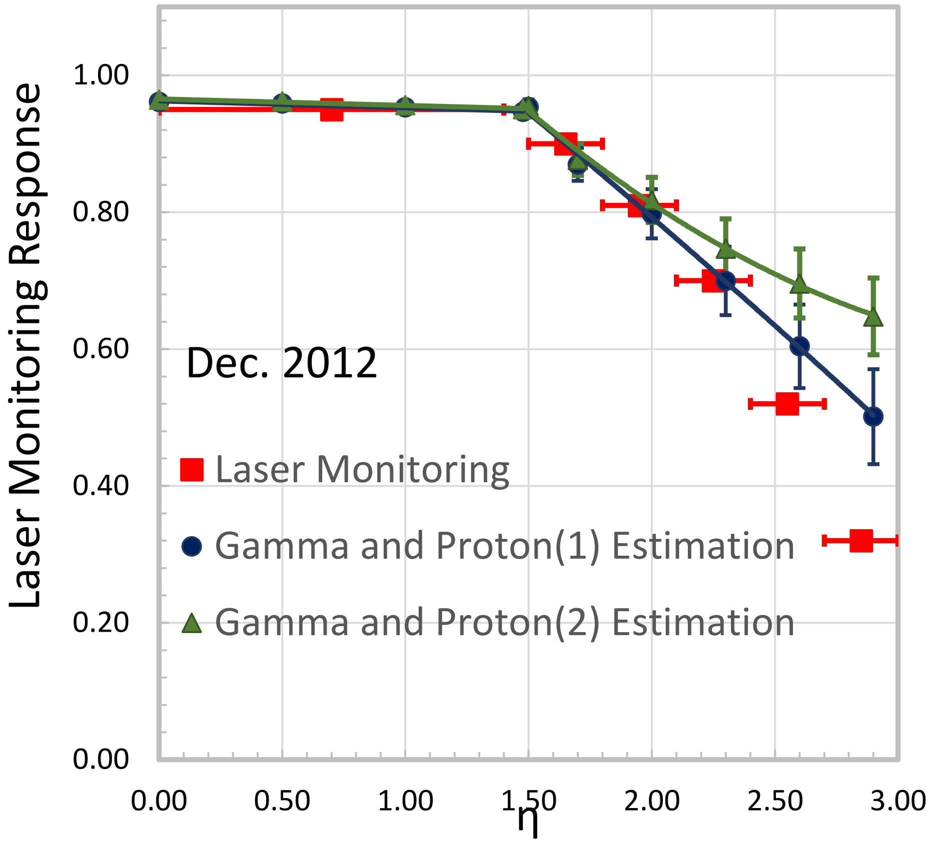


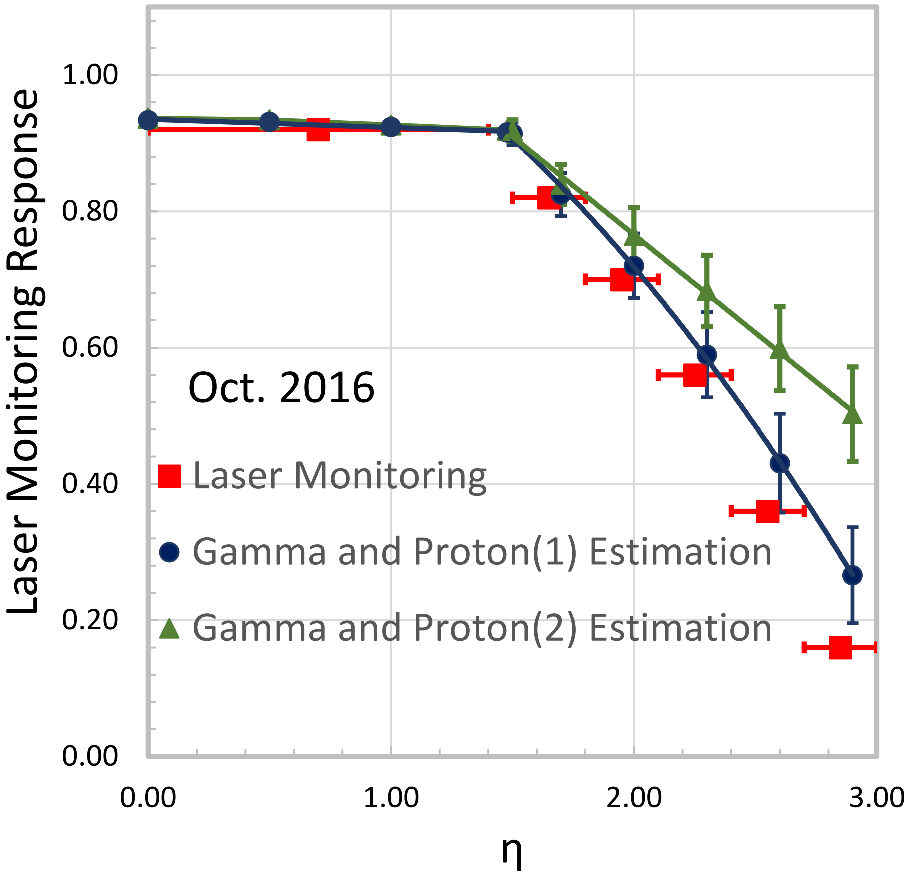
$\mu_{450\ nm}$ = 32 m^{-1} measured *in-situ* with a 22 cm long PWO 38 hr after a 800 MeV proton irradiation of 1.8×10^{14} p/cm^2

$\mu_{420\ nm}$ = 14 m^{-1} average of 10 $25\times25\times10$ mm^3 PWO 122 days after 2.94×10^{14} p/cm^2

Use RIAC after 122 Days

A larger additional factor needed at large rapidity, indicating more works are needed to pin down effect from charged hadrons





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 n-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 irradiation to reach a conclusion.