LANSCE-2022-9168:
A Proton Irradiation Experiment

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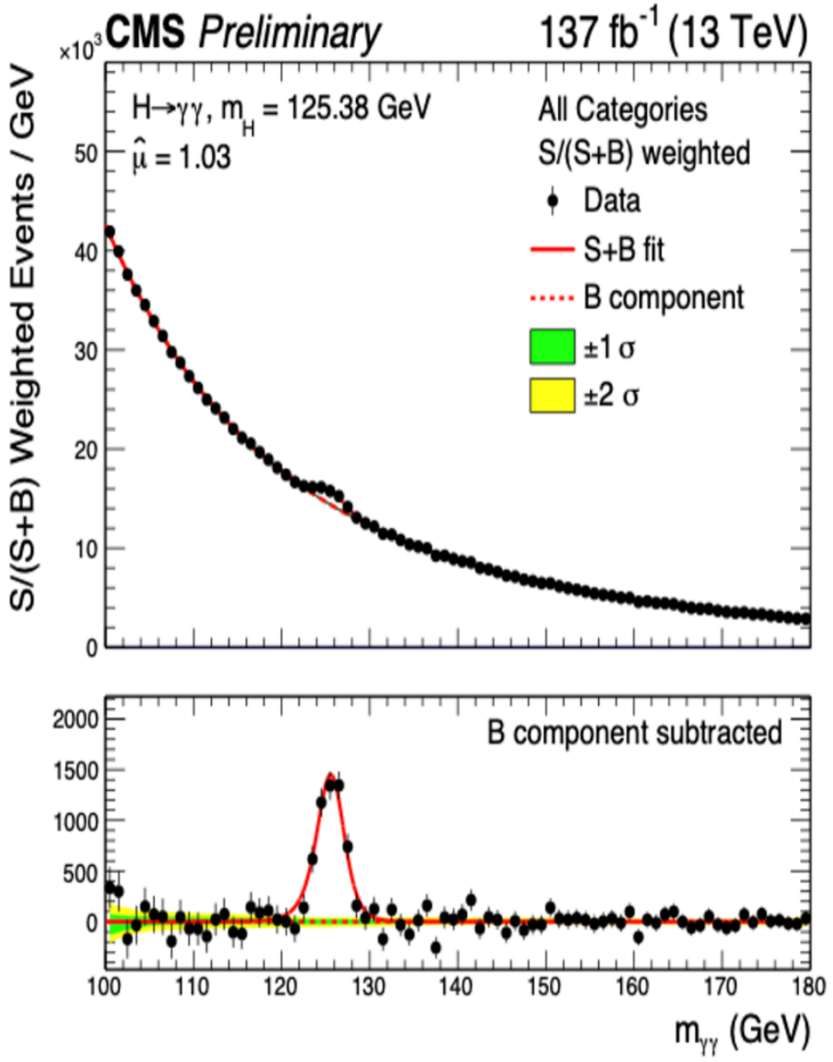
2019 DOE BRN Study
Priority Research Directions for Calorimetry

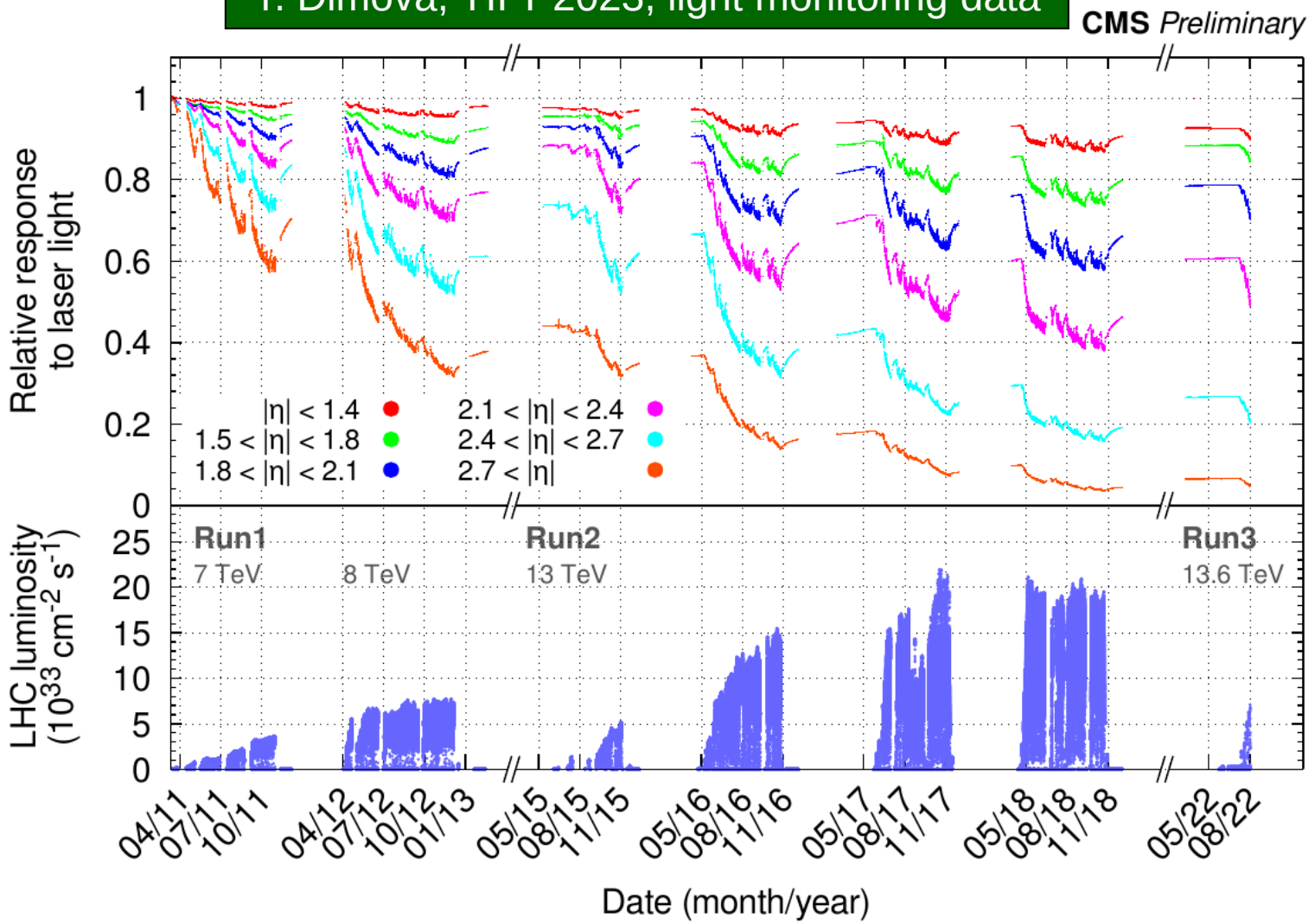
- Enhance calorimetry energy resolution for precision electroweak mass and missing-energy measurements;
- Advance calorimetry with spatial and timing resolution and radiation hardness to master high-rate environments;
- Develop ultrafast media to improve background rejection in calorimeters and particle identication detectors.

DOE 2019: https://www.osti.gov/servlets/purl/1659761
ECFA 2021: https://cds.cern.ch/record/2784893
Snowmass 2021: https://arxiv.org/abs/2209.14111
Fast/ultrafast, radiation hard and cost-effective inorganic scintillators

CMS H -> γγ and PWO Damage

T. Dimova, TIPP2023, light monitoring data

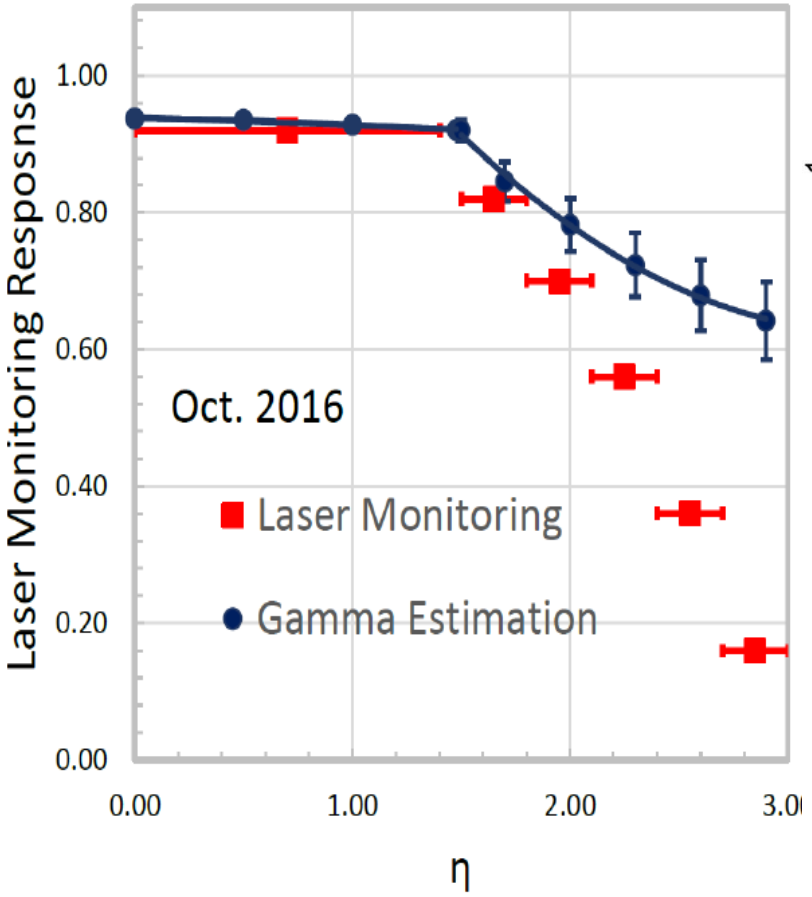


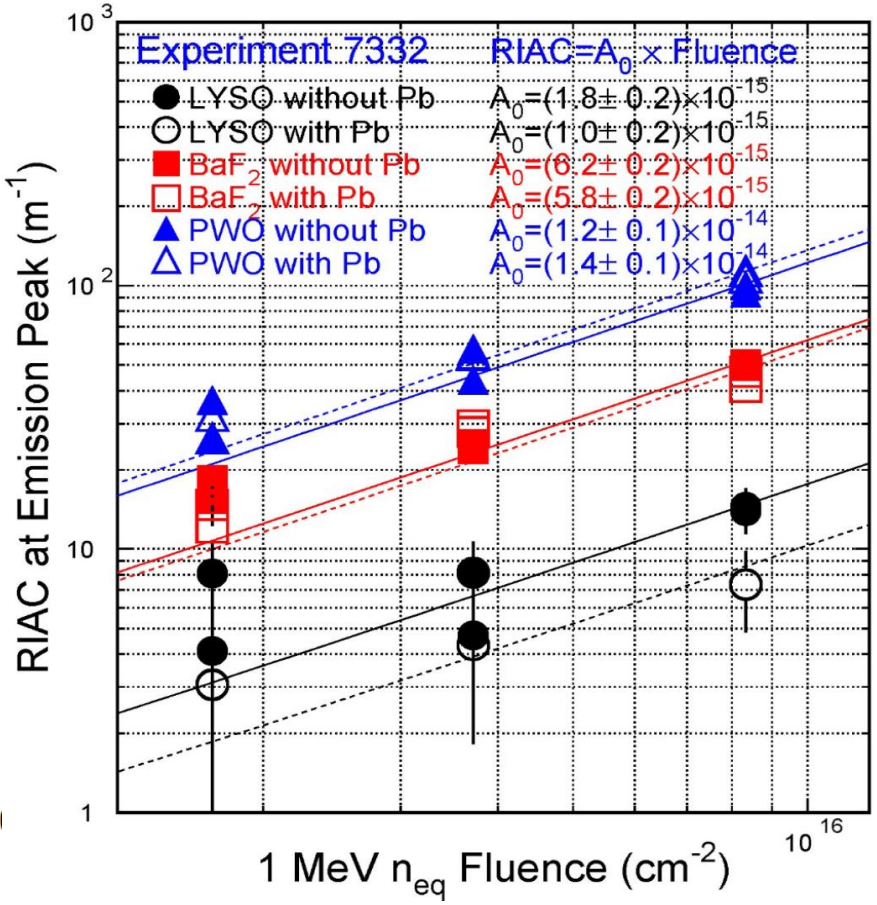


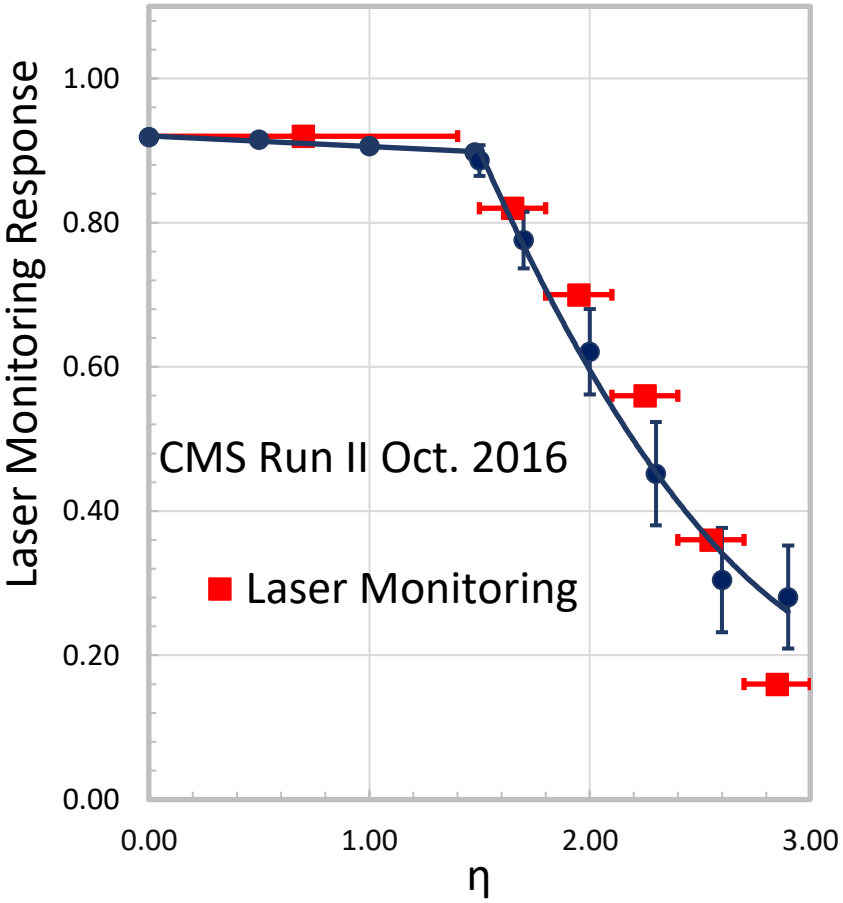
PWO damage due to ionization dose and hadrons

PWO Damage by Ionization & Neutrons

RIAC in PWO = $1.4 \times 10^{-14} \times$ 1 MeV n_{eq} Fluence







γ-ray and hadron induced absorption explains CMS PWO monitoring data

http://www.its.caltech.edu/~rzhu/talks/ryz_161028_PWO_mon.pdf & Trans. NS. 67 (2020) 1086-1092

LANCE Experiments for Investigation on Hadron-Induced Damage in Inorganic Scintillators

Proton and Neutron irradiation carried out at the Blue Room and East Port of LANSCE respectively, starting 2014 and 2015

Year	2014	2015	2016	2017	2018	2022
800 MeV Protons at the Blue Room	6501	6990	7324	-	8051	9168
Broad Band Neutrons at the East Port	-	6991	7332	7638	-	-

Thanks LANSCE for providing beam time

Cancelled: Proton: 7640 (2017), 8362 (2019), 8588 (2020), 8842 (2021) and Neutron: 8057 (2018), 8351 (2019), 8597 (2020)

Published Papers

Chen Hu, Fan Yang, Liyuan Zhang, Ren-Yuan Zhu, Jon Kapustinsky, Xuan Li, Michael Mocko, Ron Nelson, Steve Wender and Zhehui Wang, “Hadron-Induced Radiation Damage in Fast Heavy Inorganic Scintillators”, Instruments 2022, 6, 57 (2022), doi:10.33390/instruments6040057. All

Chen Hu, Liyuan Zhang, Ren-Yuan Zhu, Jin Li, Benxue Jiang, Jon Kapustinsky, Michael Mocko, Ron Nelson, Xuan Li, and Zhehui Wang, *Hadron-Induced Radiation Damage in LuAG:Ce Scintillating Ceramics*, IEEE TNS Nucl. Sci. **69** (2022) 181—186, doi:10.1109/TNS.2021.3139050. 7638, 8051

Chen Hu, Fan Yang, Liyuan Zhang, Ren-Yuan Zhu, Jon Kapustinsky, Michael Mocko, Ron Nelson, and Zhehui Wang, *Neutron-Induced Radiation Damage in LYSO, BaF_2, and PWO Crystals*, IEEE TNS Nucl. Sci. **67** (2020) 1086-1092, doi:10.1109/TNS.2018.2808841. 6991, 7332, 7638

Chen Hu, Fan Yang, Liyuan Zhang, Ren-Yuan Zhu, Jon Kapustinsky, Ron Nelson, and Zhehui Wang, Proton-Induced Radiation Damage in BaF_2, LYSO, and PWO Crystal Scintillators, IEEE TNS Nucl. Sci. **65** (2018) 1018-1024, doi:10.1109/TNS.2018.2808841. 6501, 6990, 7324

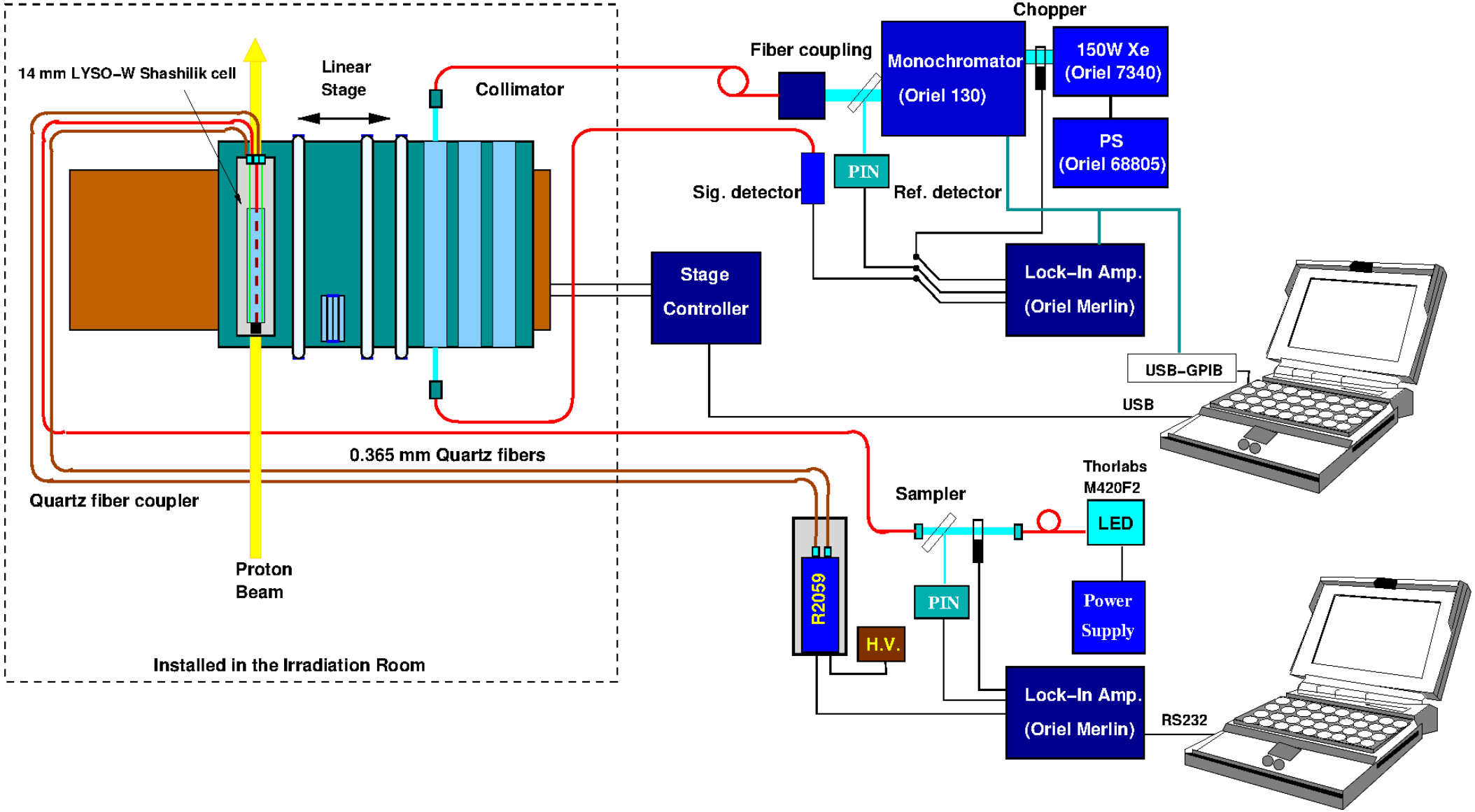
C. Hu, F. Yang, L. Zhang, R.-Y. Zhu, J. Kapustinsky, R. Nelson and Z. Wang, "Neutron-Induced Radiation Damage in BaF2, LYSO and PWO Crystals“, paper N22-6 presented in of the 2016 IEEE Nuclear Science Symposium, Medical Imaging Conference and Room-Temperature Semiconductor Detector Workshop (NSS/MIC/RTSD); IEEE, October 2016; pp. 1–4. 6991

F. Yang, L. Zhang, R.-Y. Zhu, J. Kapustinsky, R. Nelson and Z. Wang, “Proton-Induced Radiation Damage in Fast Crystal Scintillators”, SCINT 2017, IEEE Trans. Nucl. Sci, vol. **64**, (2017) 665-672. doi:10.1109/TNS.2016.2633427. 6501, 6990

F. Yang, L. Zhang, R.-Y. Zhu, J. Kapustinsky, R. Nelson and Z. Wang, “Proton-Induced Radiation Damage in BGO, LFS, PWO and a LFS/W/Quartz Capillary Shashlik Cell”, in p\Proceedings of the 2016 IEEE Nuclear Science Symposium, Medical Imaging Conference and Room-Temperature Semiconductor Detector Workshop (NSS/MIC/RTSD); IEEE, October 2016; pp. 1–4. 6501

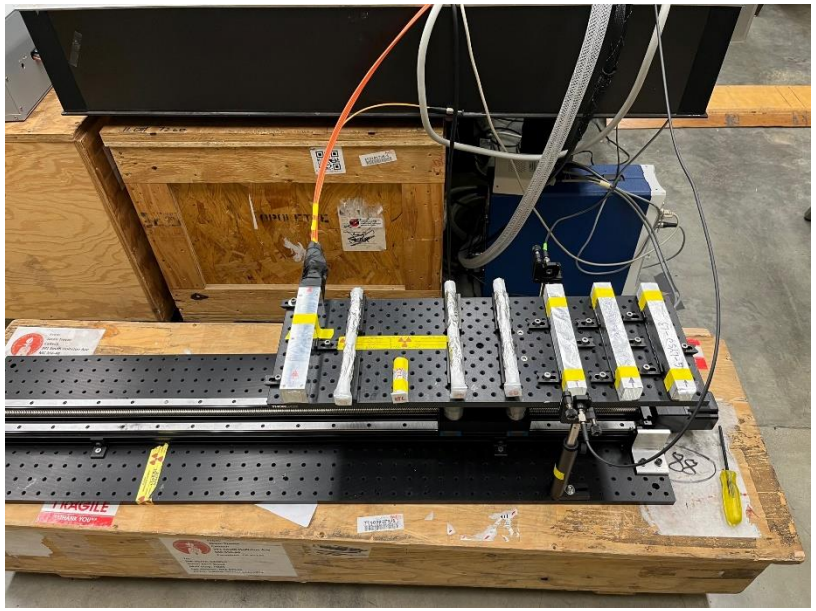
F. Yang, L. Zhang, R.-Y. Zhu, J. Kapustinsky, R. Nelson and Z. Wang, "Proton induced radiation damage in fast crystal scintillators," NIM A, vol. **824**, (2016) 726-728, doi:10.1016/j.nima.2015.11.100. 6501

LANSCE-9168 Setup (10/18-22/2022)



Samples & Instruments at Caltech

Wrapped samples mounted on a linear stage
Transmittance measured *in-situ* by a fiber-based spectrometer
RADiCAL WLS response monitored by a 425 nm LED



Three Crates Shipped on 10/6/22

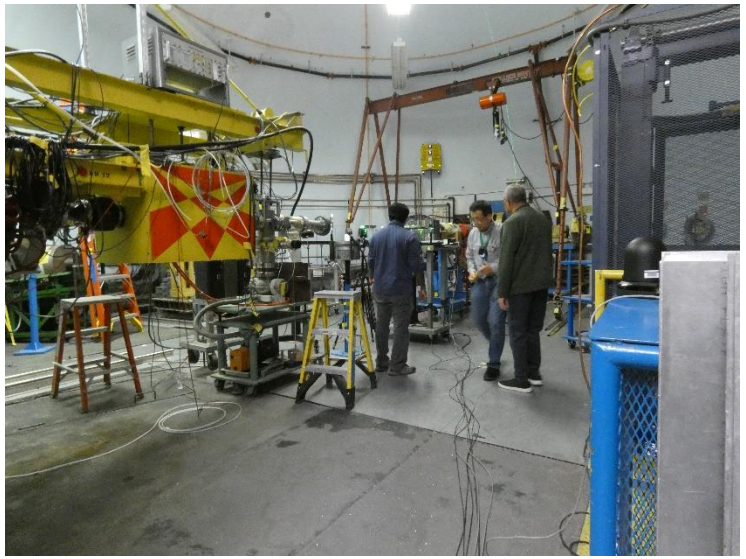
Fifty Samples for LANSCE-9168

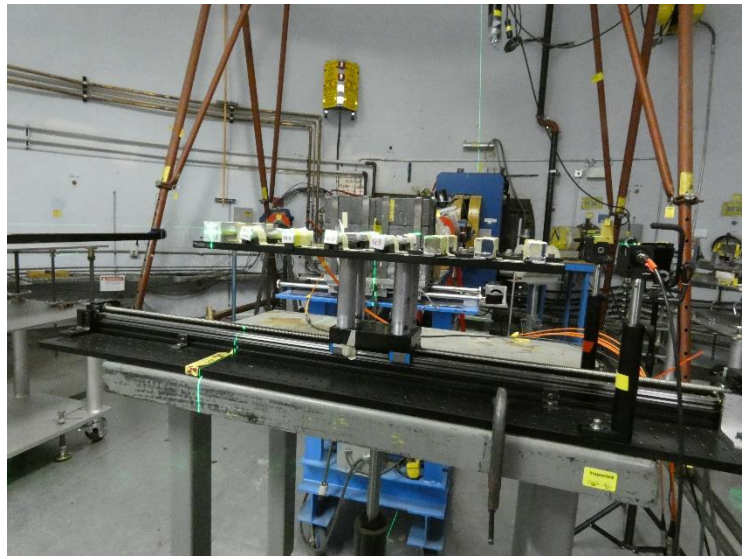
No.	Sample	ID	Dimension (mm^3)	Qty	Lowell irradiation (n_{eq}/cm^2)	Caltech γ irradiation (Mrad)	Data before Irradiation	Al ID (Front/Back)	Proton Fluence (p/cm^2)	Irradiation Time (min)	Comments
1	LYSO-W Shashlik Cell	Ch1: LuAG fiber	Φ1×185	1				E/	3.00E+15	500	44 mm Qz+40 mm LuAG:Ce+101 mm Qz
		Ch2: LuAG fiber	Φ1×160	1							120 mm LuAG:Ce+40mm Qz
		Ch3: Y11	Φ1×185	1							
		Ch4: Timing cap. T041	Φ1×185	1							56 mm Qz+15 mm DSB1+114 mm Qz
2	LYSO bar	CPI -10	3.1×3.1×57	1	1.00E+13	5.0	Yes	A/F	1.00E+13	1.7	
	LYSO bar	SIC -9	3.1×3.1×57	1	1.00E+13	5.0	Yes				
	LYSO bar	Tianle -9	3.1×3.1×57	1	1.00E+13	5.0	Yes				
	LYSO bar	Tianle -18	3.1×3.1×57	1	1.00E+13	5.0	Yes				
	LuAG:Ce	RMD R36	Φ9×1.5	1	1.00E+13		Yes				
	LuAG:Ce, Ca	SIC S91	Φ14.3×1	1	1.00E+13		Yes				
	LuAG:Ce, Ca	SIOM S10-3	Φ17×1	1	1.00E+13		Yes				
	Timing cap.	T042	Φ1×185	1			Yes				
	LuAG:Ce fiber	SIC LuAG-40-1.0-6	Φ1.0×40	1			Yes				included one 15 mm DSB1 in the same tube
3	BTL LYSO bars	BTL-LYSO-ID	3.1×3.0×56.3	16	3.20E+14	5.0	Yes	B/G	2.50E+13	4.2	IDs: 2,4,6,8,10,12,14,16,18 w and w/o ESR
4	LYSO bar	CPI -2	3.1×3.1×57	1	3.20E+14	5.0	Yes	C/H	3.00E+14	50	
	LYSO bar	SIC -7	3.1×3.1×57	1	3.20E+14	5.0	Yes				
	LYSO bar	Tianle -7	3.1×3.1×57	1	3.20E+14	5.0	Yes				
	LYSO bar	Tianle -14	3.1×3.1×57	1	3.20E+14	5.0	Yes				
	LuAG:Ce	RMD R28	Φ9×2	1	3.20E+14		Yes				
	LuAG:Ce, Ca	SIC S80	Φ14.3×1	1	3.20E+14		Yes				
	LuAG:Ce, Ca	SIOM 88-1	Φ17×1	1	3.20E+14		Yes				
	Timing cap.	T043	Φ1×185	1			Yes				
	LuAG:Ce fiber	SIC LuAG-40-1.0-9	Φ1.0×40	1			Yes				included one 15 mm DSB1 in the same tube
5	LYSO bar	CPI -7	3.1×3.1×57	1	1.10E+15	5.0	Yes	D/I	1.00E+15	167	
	LYSO bar	SIC -8	3.1×3.1×57	1	1.10E+15	5.0	Yes				
	LYSO bar	Tianle -8	3.1×3.1×57	1	1.10E+15	5.0	Yes				
	LYSO bar	Tianle -19	3.1×3.1×57	1	1.10E+15	5.0	Yes				
	LuAG:Ce	RMD R29	Φ9×2	1	1.10E+15		Yes				
	LuAG:Ce, Ca	SIC S82	Φ14.3×1	1	1.10E+15		Yes				
	LuAG:Ce, Ca	SIOM S10-1	Φ17×1	1	1.10E+15		Yes				
	Timing cap.	T044	Φ1×185	1			Yes				
	LuAG:Ce fiber	SIC LuAG-40-1.0-10	Φ1.0×40	1			Yes				included one 15 mm DSB1 in the same tube
6	BaF_2:Y	SIC-2020	25×25×200	1		1.0			1.00E+15	167	Online measurement 350-700 nm
7	BaF_2:Y	BGRI-2020	25×25×200	1		1.0			1.00E+15	167	
8	LYSO:Ce	S-G	25×25×200	1					3.00E+15	500	

Original Plan for LANSCE 9168

Date	No.	Activity	Comment
Oct. 18		Safety training and setting up experiment at Blue room.	
Oct. 19	1.1	Starting with initial and 1st irradiation/measurement for BaF:Y & LYSO, and recovery.	
	1.2	Finish Shashlik (>3E15). LYSO/LuAG damage small and no recovery.	Watch recovery
Oct. 20	2.1	Measuring Shashlik after 3E15.	
	2.2	The 2nd irradiation/measurement for BaF:Y and LYSO, and recovery.	
	2.3	Finish 4 groups for 1.0E13, 2.5E13, 3.0E14 and 1.0E15, respectively.	
	2.4	Finish LYSO (>3E+15).	
Oct. 21	3.1	Measuring LYSO after >3E15.	
	3.2	The 3rd irradiation/measurement for BaF:Y and LYSO, and recovery.	
	3.3	Try more fluence and measurement for BaF:Y, LYSO and Shashlik.	Depending on the online data
Oct. 22		Disassembling and packing instruments.	

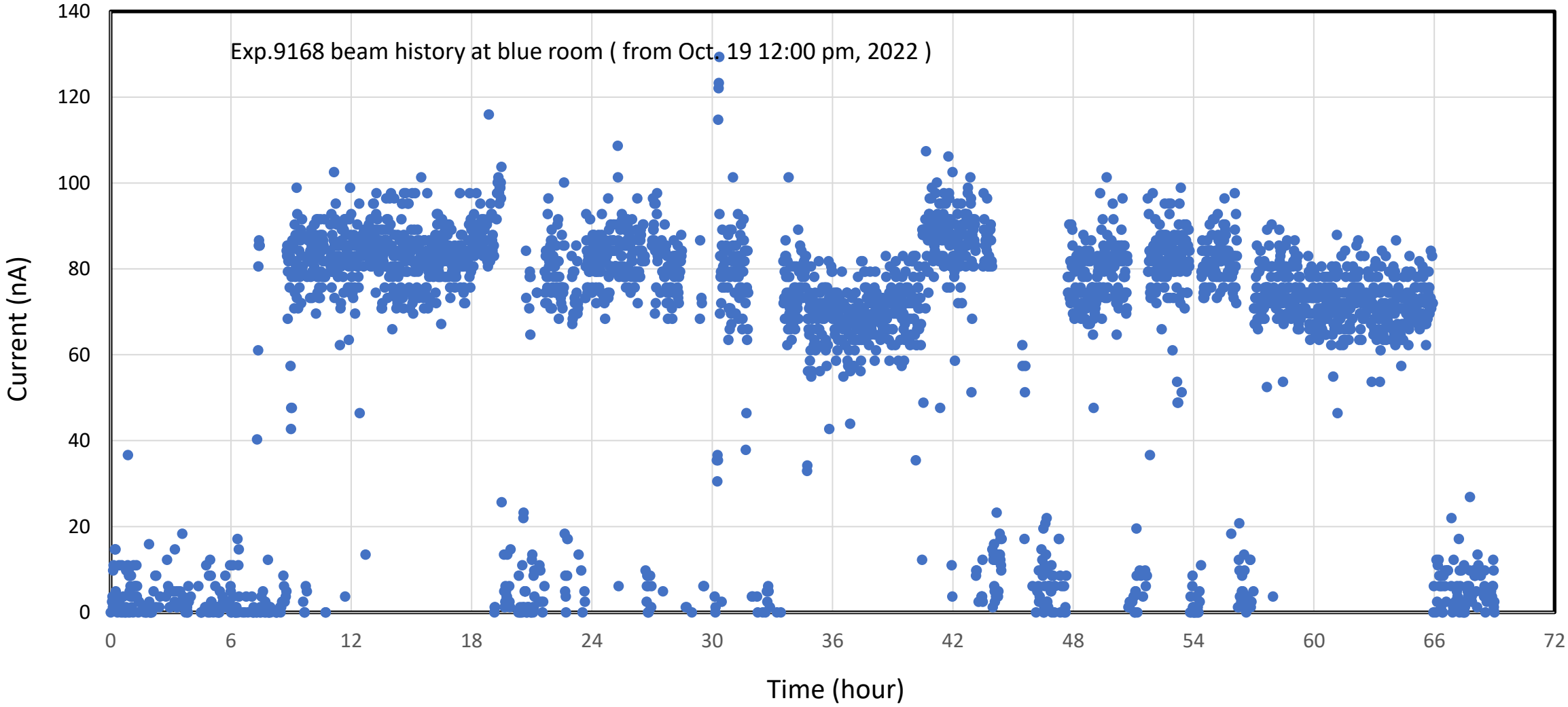
Experiment Completed as Planed





Blue Room Beam Current History

Fluence calculated by integrating beam current, assuming nominal beam size (FWHM) of 2.5 cm

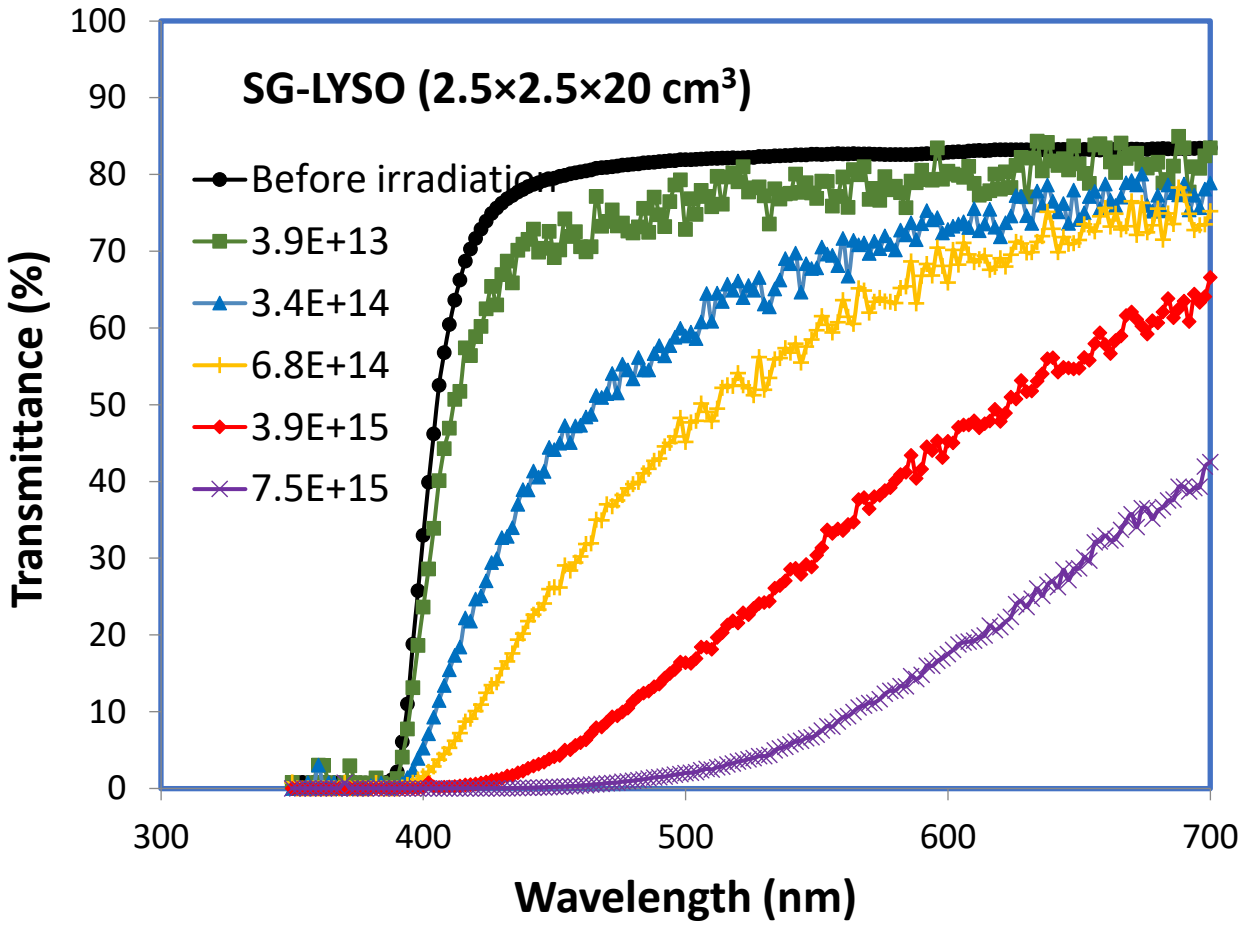


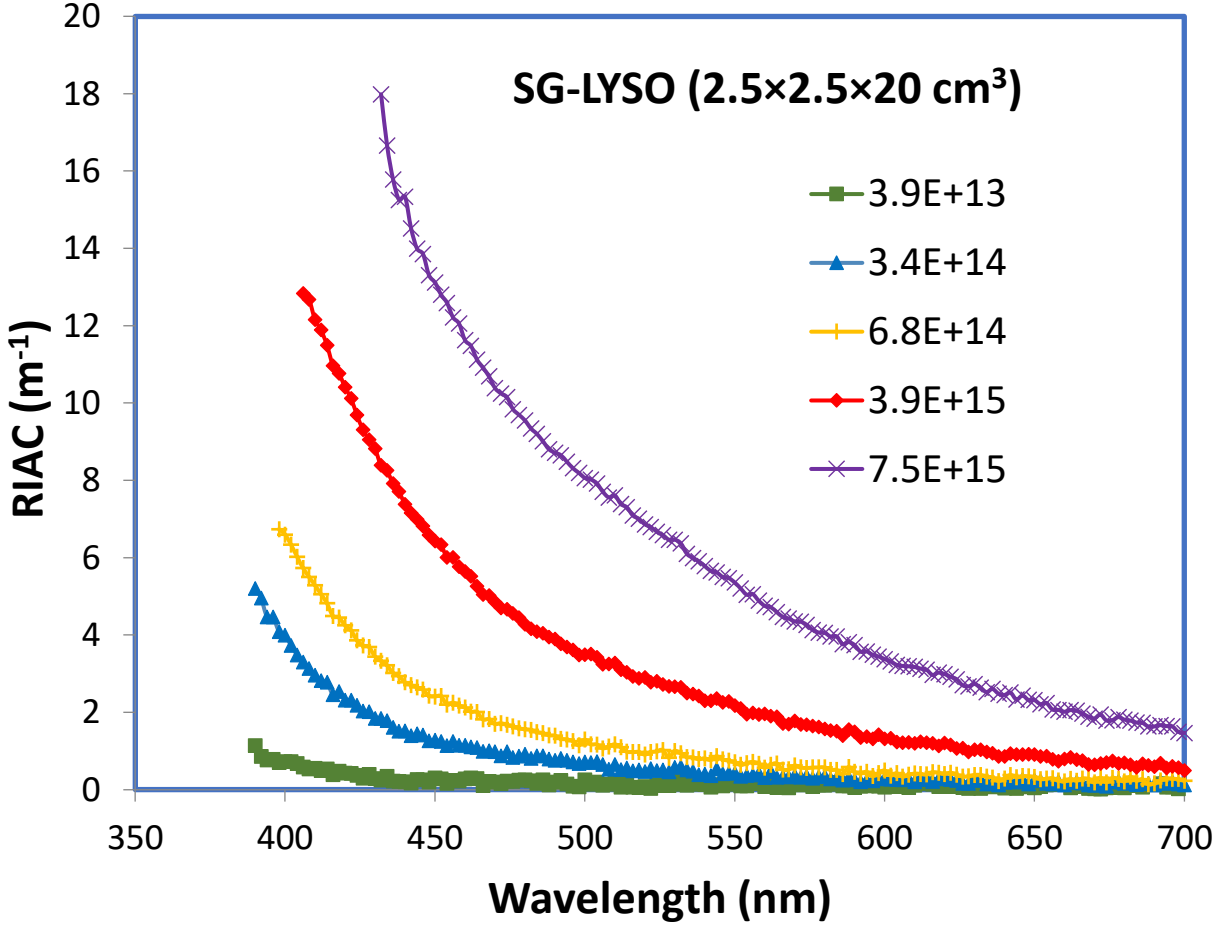
Irradiation & Estimated Fluence

No.	Sample	ID	Dimension (mm^3)	Al ID (Front/Back)	Irradiation Time (min)	Proton Fluence (p/cm^2)
1	LYSO-W Shashlik Cell	Shashlik	30×30×200	E/	2	1.1E+13
					22	1.3E+14
					112	6.9E+14
					202	1.2E+15
					802	4.7E+15
					922	5.4E+15
2	LYSO bars, LuAG:Ce fiber and ceramics, Timing capillary, DSB1 fiber	G1	Φ15×200	A/G	2	1.2E+13
3	BTL LYSO bars	BTL	Φ20×60	B/F	5	2.8E+13
4	LYSO bars, LuAG:Ce fiber and ceramics, Timing capillary, DSB1 fiber	G2	Φ15×200	C/H	60	3.7E+14
5	LYSO bars, LuAG:Ce fiber and ceramics, Timing capillary, DSB1 fiber	G3	Φ15×200	D/I	180	1.1E+15
					360	2.2E+15
6	BaF_2:Y	SIC-2020	25×25×200		2	1.2E+13
					4	2.1E+13
7	BaF_2:Y	BGRI-2020	25×25×200		2	1.1E+13
					4	2.0E+13
8	LYSO:Ce	S-G	25×25×200		2	3.9E+13
					52	3.4E+14
					102	6.8E+14
					612	3.9E+15
					1302	7.5E+15

Longitudinal Transmittance: SG-LYSO

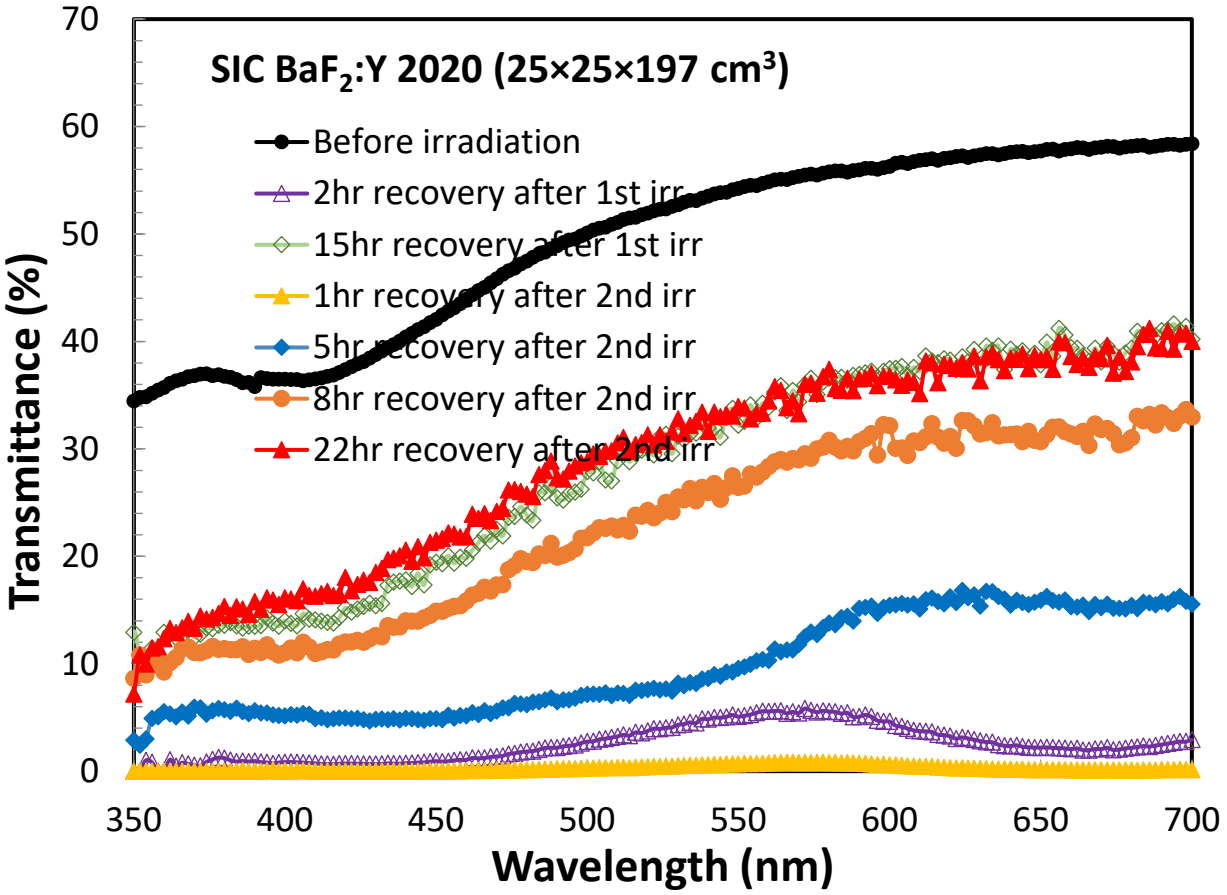
SG-LYSO irradiated up to 7.5E+15 p/cm^2 in five steps
No significant recovery observed after each step

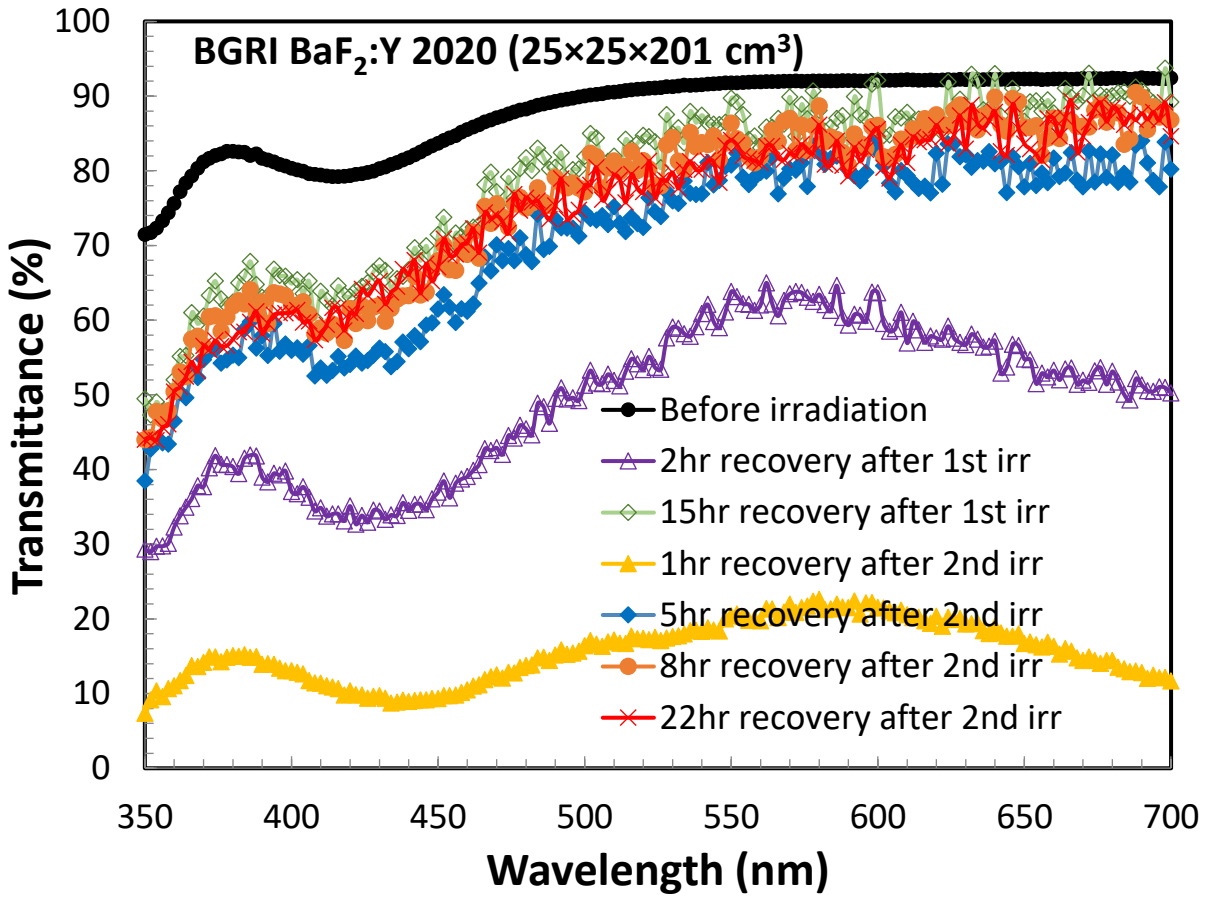




Longitudinal Transmittance: BaF_2:Y

SIC and BGRI BaF_2:Y crystals irradiated twice with 1.0E13 each
Both crystals became opaque in 350-700 nm after irradiation
Recovery observed between 1 to 22 hours after irradiation





Post-Experiment Analysis

After cooling down all samples were shipped back to Caltech on Aug. 4, 2023. The linear stage, cables and optical fibers etc. will be shipped back from LANSCE after further cooling-down.

Christina measured Na-22 peaks for activated Al foils at Caltech, providing calibration for proton fluence and corrections to that from current integration.

Christina measured transmittance of BaF_2:Y and LYSO:Ce crystals with spectrophotometer, and calculated radiation induced absorption coefficient and color centers.

On-going work is to measure other proton irradiated samples, including BTL LYSO bars from different vendors, LuAG:Ce ceramic samples and LuAG:Ce ceramic fibers and RADiCAL capillaries etc.

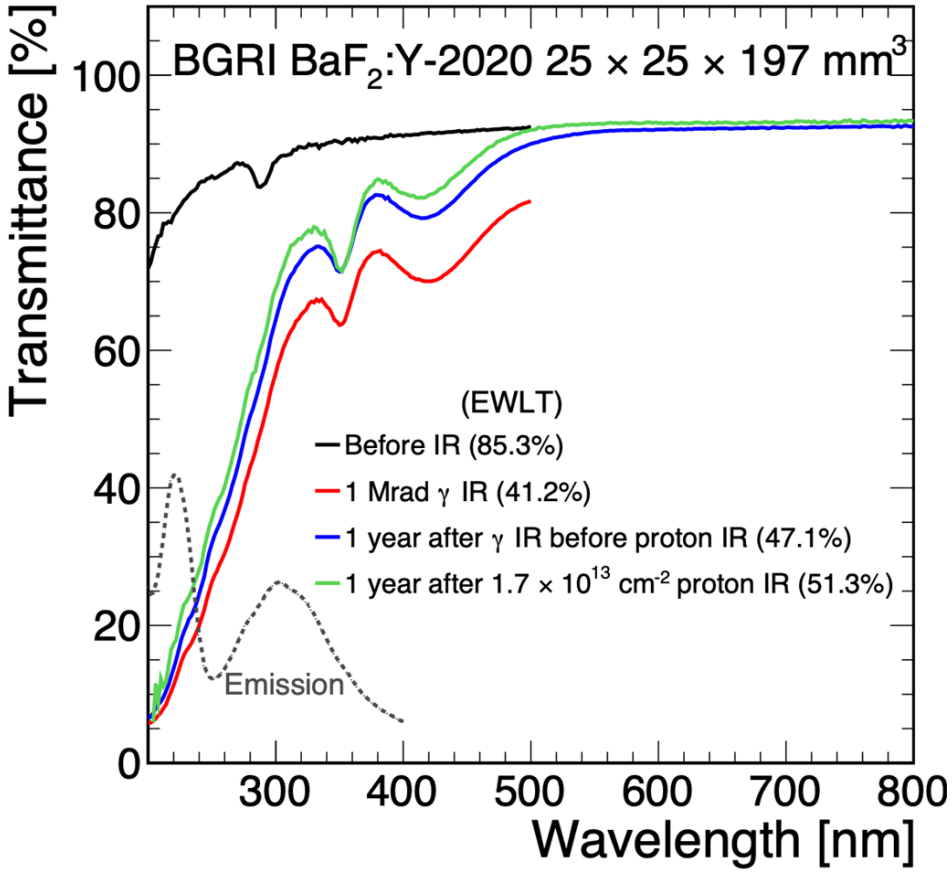
Final Fluence After Al foil Calibration

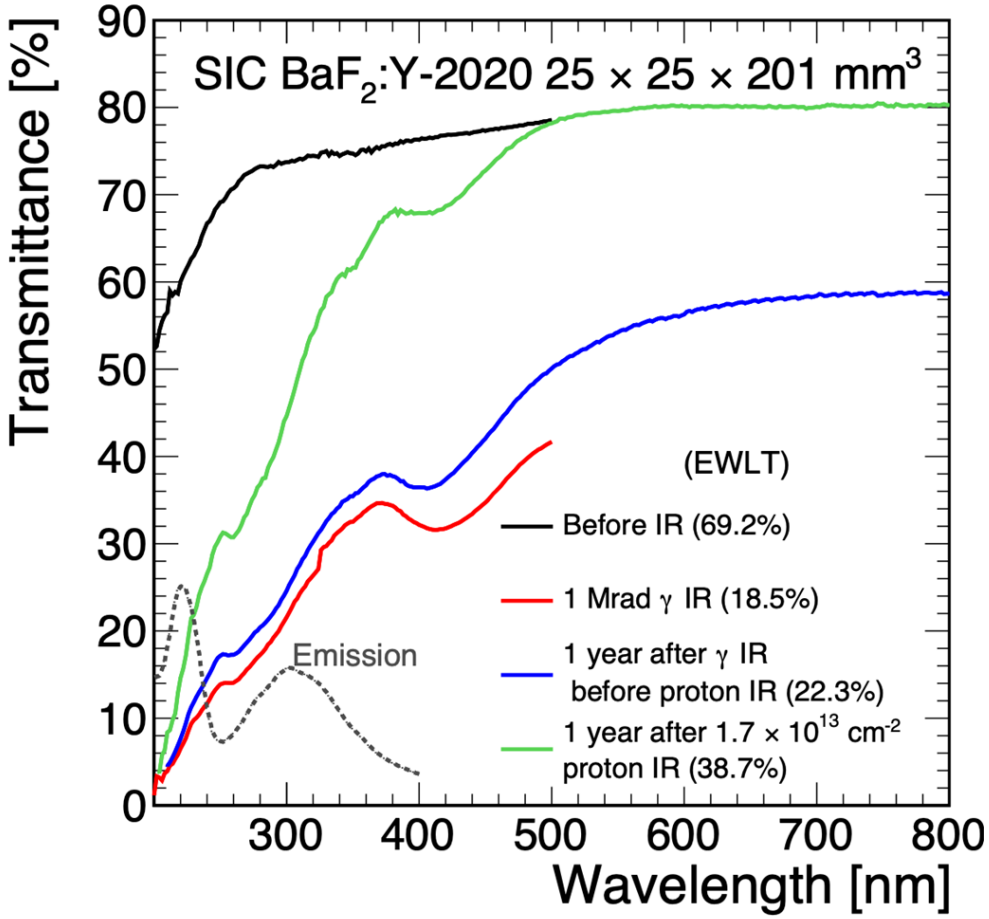
No.	Sample	ID	Dimension (mm^3)	Qty	Lowell irradiation (n_{eq}/cm^2)	Caltech γ irradiation (Mrad)	Data before Irradiation	Al ID (Front/Back)	Proton Fluence (p/cm^2)	Irradiation Time (min)	Comments
1	LYSO-W Shashlik Cell	Ch1: LuAG fiber	Φ1×185	1				E/	**4.6E+15**	922	44 mm Qz+40 mm LuAG:Ce+101 mm Qz
		Ch2: LuAG fiber	Φ1×160	1							120 mm LuAG:Ce+40mm Qz
		Ch3: Y11	Φ1×185	1							
		Ch4: Timing cap. T041	Φ1×185	1							56 mm Qz+15 mm DSB1+114 mm Qz
2	LYSO bar	CPI -10	3.1×3.1×57	1	1.00E+13	5.0	Yes	A/G	**1.0E+13**	2	
	LYSO bar	SIC -9	3.1×3.1×57	1	1.00E+13	5.0	Yes				
	LYSO bar	Tianle -9	3.1×3.1×57	1	1.00E+13	5.0	Yes				
	LYSO bar	Tianle -18	3.1×3.1×57	1	1.00E+13	5.0	Yes				
	LuAG:Ce	RMD R36	Φ9×1.5	1	1.00E+13		Yes				
	LuAG:Ce, Ca	SIC S91	Φ14.3×1	1	1.00E+13		Yes				
	LuAG:Ce, Ca	SIOM S10-3	Φ17×1	1	1.00E+13		Yes				
	Timing cap.	T042	Φ1×185	1			Yes				
	LuAG:Ce fiber	SIC LuAG-40-1.0-6	Φ1.0×40	1			Yes				included one 15 mm DSB1 in the same tube
3	BTL LYSO bars	BTL-LYSO-ID	3.1×3.0×56.3	16	3.20E+14	5.0	Yes	B/F	**2.4E+13**	5	ID: 2,4,6,8,10,12,14,16,18 w and w/o ESR
4	LYSO bar	CPI -2	3.1×3.1×57	1	3.20E+14	5.0	Yes	C/H	**3.2E+14**	60	
	LYSO bar	SIC -7	3.1×3.1×57	1	3.20E+14	5.0	Yes				
	LYSO bar	Tianle -7	3.1×3.1×57	1	3.20E+14	5.0	Yes				
	LYSO bar	Tianle -14	3.1×3.1×57	1	3.20E+14	5.0	Yes				
	LuAG:Ce	RMD R28	Φ9×2	1	3.20E+14		Yes				
	LuAG:Ce, Ca	SIC S80	Φ14.3×1	1	3.20E+14		Yes				
	LuAG:Ce, Ca	SIOM 88-1	Φ17×1	1	3.20E+14		Yes				
	Timing cap.	T043	Φ1×185	1			Yes				
	LuAG:Ce fiber	SIC LuAG-40-1.0-9	Φ1.0×40	1			Yes				included one 15 mm DSB1 in the same tube
5	LYSO bar	CPI -7	3.1×3.1×57	1	1.10E+15	5.0	Yes	D/I	**1.9E+15**	360	
	LYSO bar	SIC -8	3.1×3.1×57	1	1.10E+15	5.0	Yes				
	LYSO bar	Tianle -8	3.1×3.1×57	1	1.10E+15	5.0	Yes				
	LYSO bar	Tianle -19	3.1×3.1×57	1	1.10E+15	5.0	Yes				
	LuAG:Ce	RMD R29	Φ9×2	1	1.10E+15		Yes				
	LuAG:Ce, Ca	SIC S82	Φ14.3×1	1	1.10E+15		Yes				
	LuAG:Ce, Ca	SIOM S10-1	Φ17×1	1	1.10E+15		Yes				
	Timing cap.	T044	Φ1×185	1			Yes				
	LuAG:Ce fiber	SIC LuAG-40-1.0-10	Φ1.0×40	1			Yes				included one 15 mm DSB1 in the same tube
6	BaF_2:Y	SIC-2020	25×25×200	1		1.0			**1.8E+13**	4	Online measurement 350-700 nm
7	BaF_2:Y	BGRI-2020	25×25×200	1		1.0			**1.7E+13**	4	
8	LYSO:Ce	S-G	25×25×200	1					**6.5E+15**	1302	

BaF_2:Y LT after γ and Proton Irradiation

Presented by Christina in 2023 IEEE NSS/MIC/RTSD conference

Longitudinal transmittance (LT) history of two 20 cm-long BaF_2:Y crystals (BGRI and SIC)
Both crystals were irradiated by 1 Mrad gamma ray in 2021 and by 1.7e13 p/cm^2 in 2022
Long term recovery observed a year after 1 Mrad ionization and 1.7E13 p/cm^2

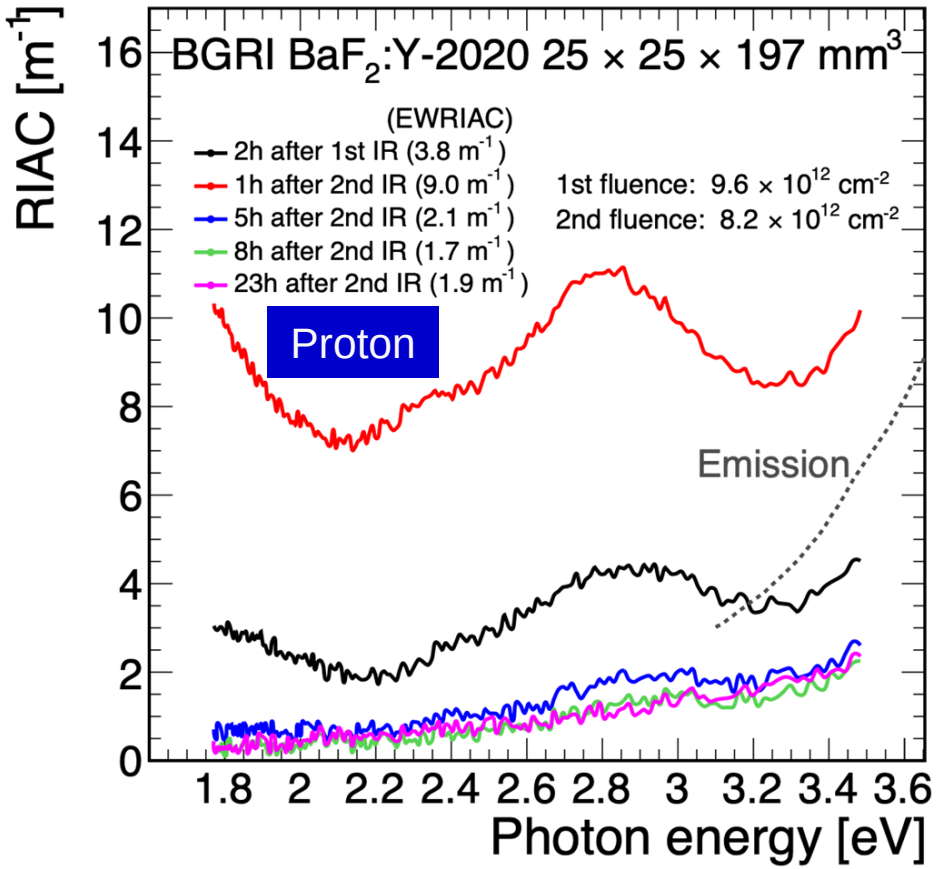


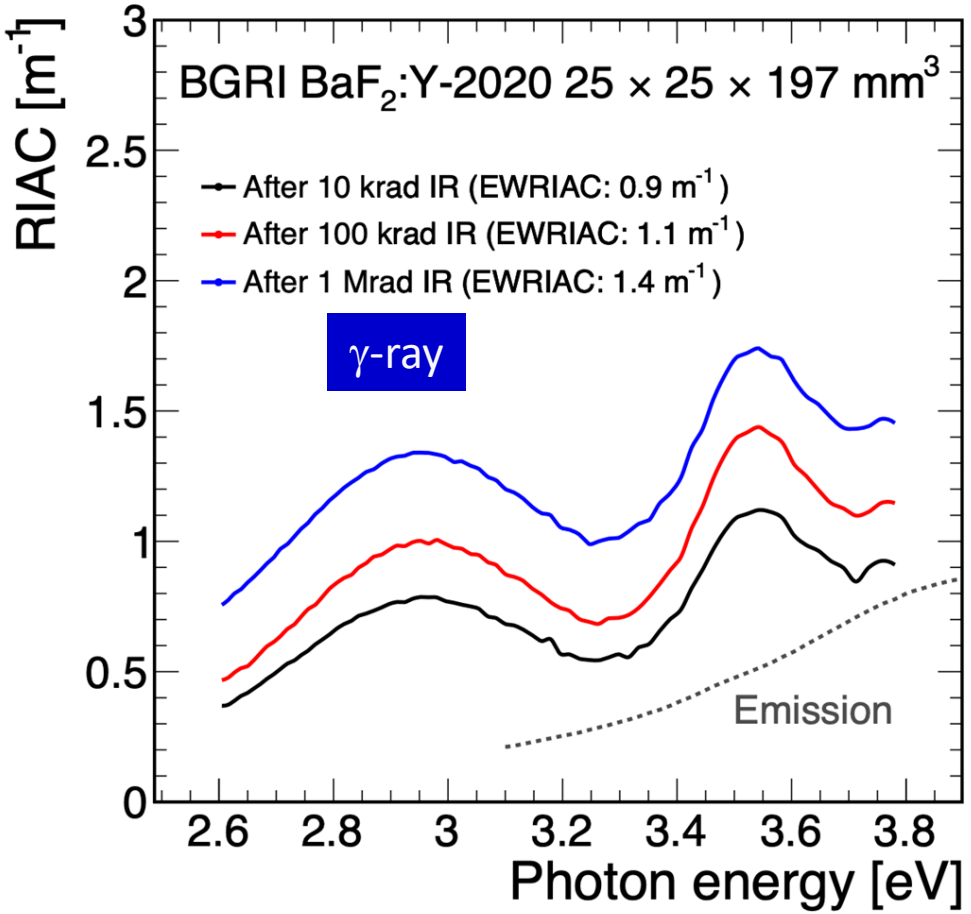


BaF_2:Y Radiation-Induced Absorption Coefficient

Presented by Christina in 2023 IEEE NSS/MIC/RTSD conference

RIAC calculated for LT > 5% to reduce systematic uncertainties
A fast recovery may be attributed to thermal relaxation

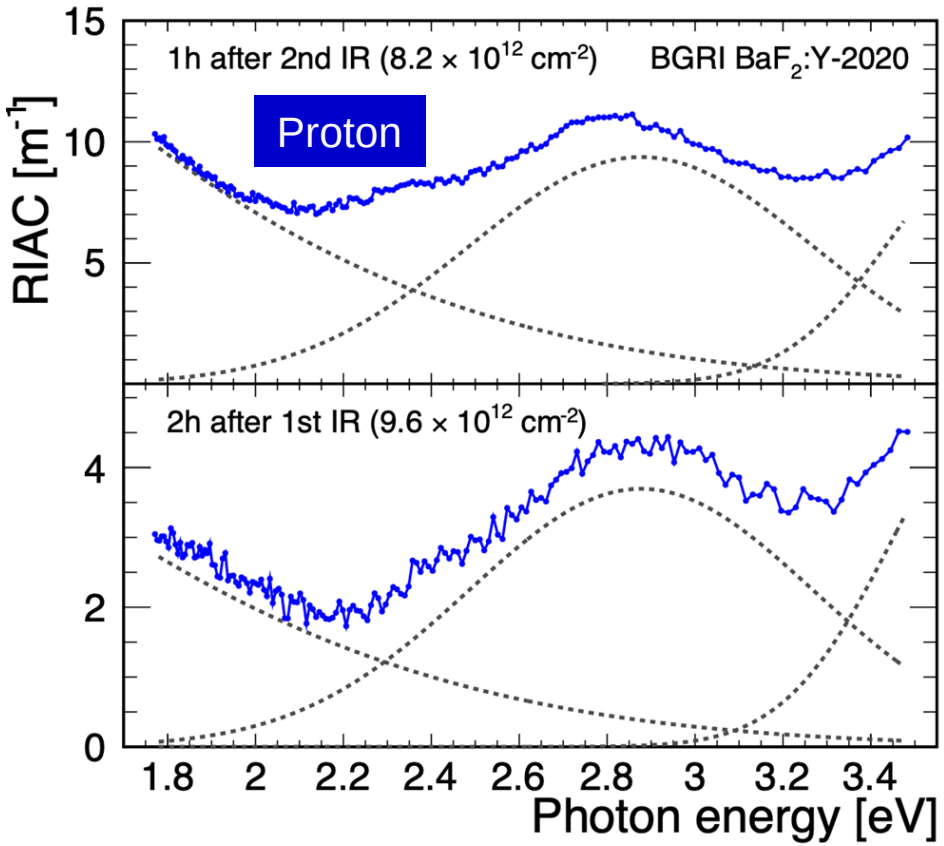


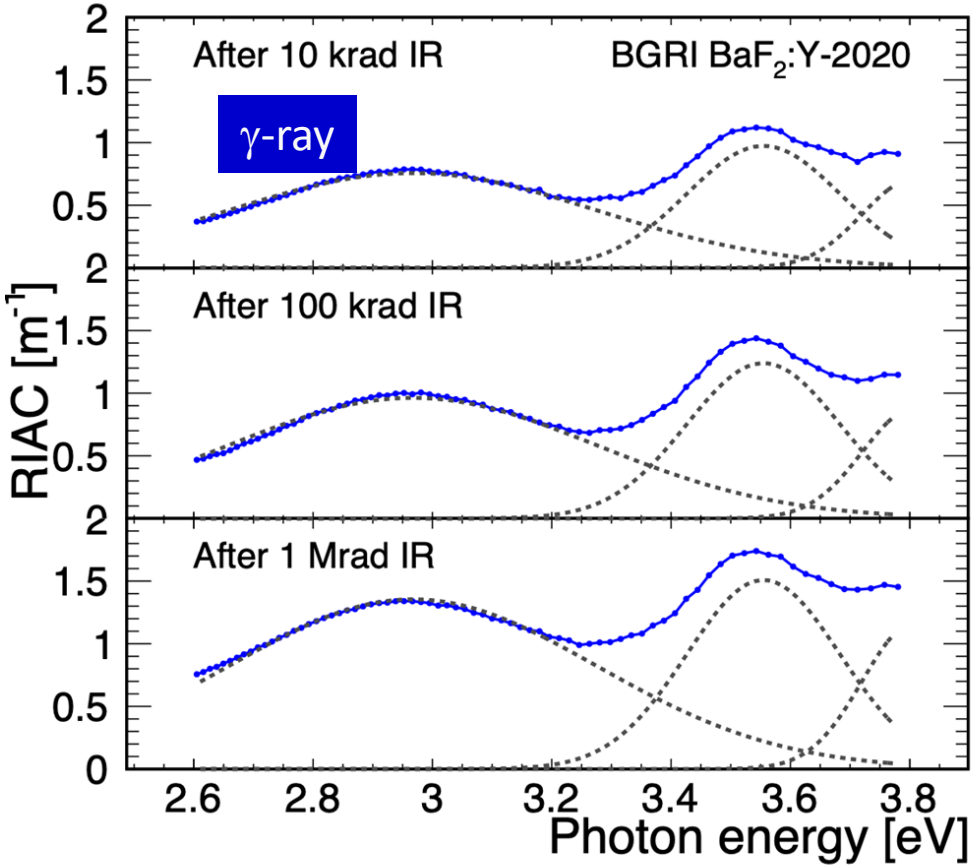


BaF_2:Y Radiation-Induced Color Centers

Presented by Christina in 2023 IEEE NSS/MIC/RTSD conference

Proton and gamma-induced RIACs can be described by three color centers of Gaussian shape
Proton-induced color centers at 3, 3.6, and 3.8 eV, gamma-induced color centers at 1.2, 2.8, and 3.7 eV



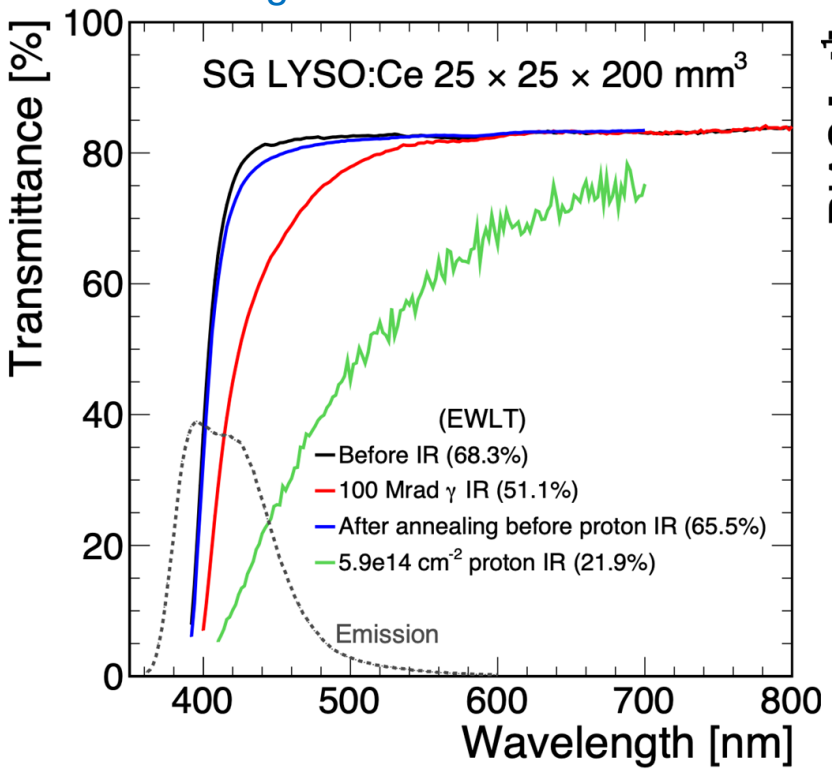


LYSO:Ce LT and RIAC

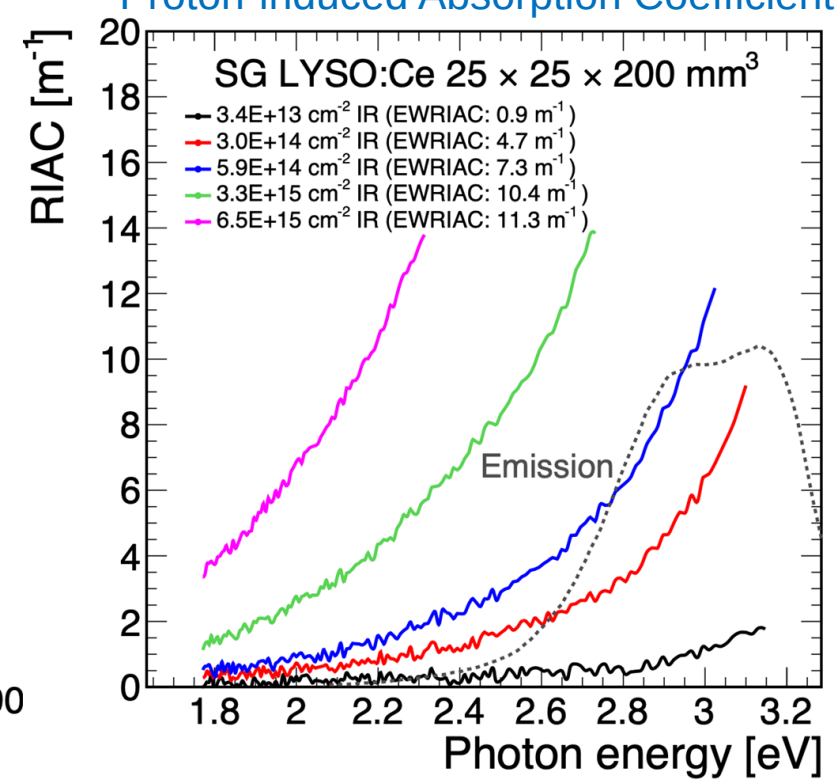
Presented by Christina in 2023 IEEE NSS/MIC/RTSD conference

LYSO:Ce shows EWRIAC of 2.5 m^{-1} after 100 Mrad and 0.9 m^{-1} after 3.4E13 p/cm^2
Meeting the CMS BTL specification: < 3 m^{-1} after 2.5 Mrad and 1.7E13 p/cm^2 protons
No color centers identified in LYSO:Ce.

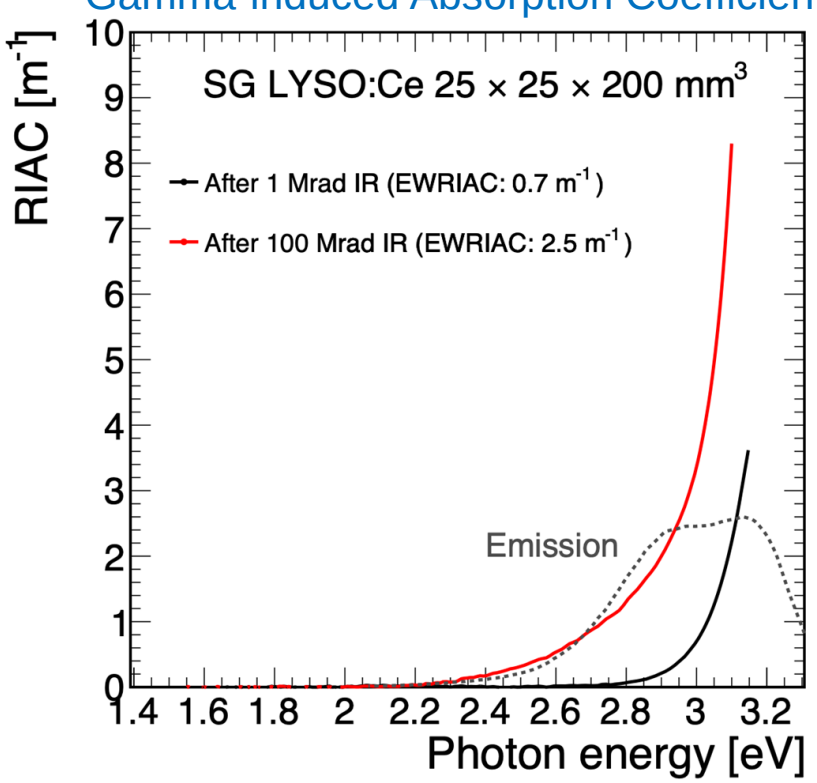
Longitudinal Transmittance



Proton-induced Absorption Coefficient



Gamma-induced Absorption Coefficient



Summary

Presented by Christina in IEEE NSS/MIC/RTSD 2023 with CR paper published in IEEE Explore*
* https://nssmic.ieee.org/2023/information/

Proton and gamma-ray induced damage in 20 cm-long LYSO:Ce and BaF_2:Y crystals were reported by Christina at IEEE NSS 2023.

BaF_2:Y samples were irradiated by gamma rays up to 1 Mrad, and by protons up to 1.7×10^{13} p/cm^2. Fast recovery was observed in several hours after the proton irradiation.

Radiation-induced color centers for BaF_2:Y were analyzed with distinct color centers for proton and gamma irradiation with photon energy between 1 and 4 eV.

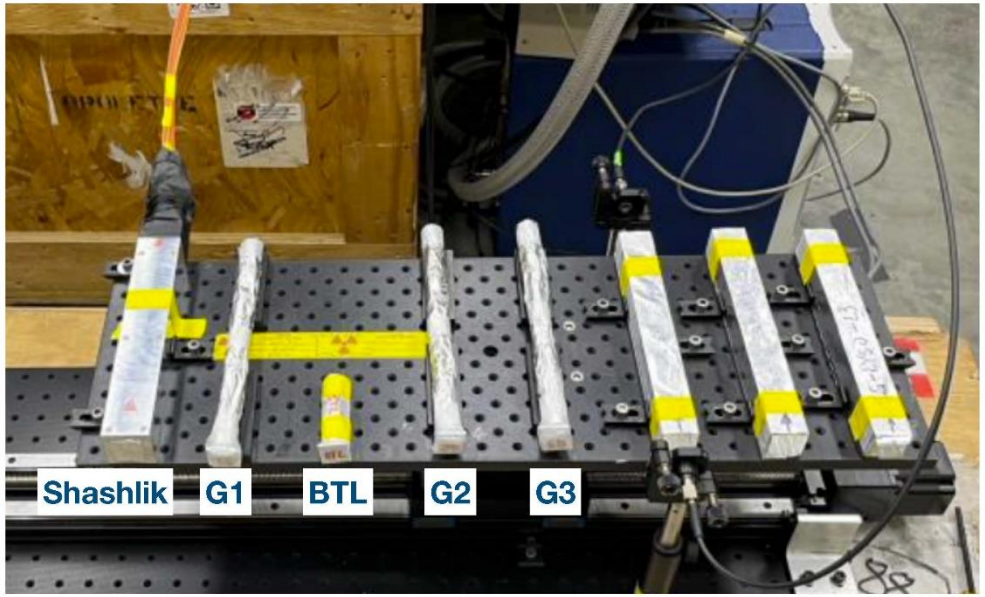
The SG LYSO:Ce sample shows excellent radiation hardness against gamma-rays and protons, consistent with previous publications.

Acknowledgements: DOE HEP Award DE-SC0011925 and DE-AC52-06NA25396

Christina's Report on Al Foil (I)

Introduction

- Aluminum foils are taped to the two ends of 4 groups of crystals: G1, G2, G3, and BTL and the front of shashlik cell to measure the proton fluence
- Na22 radioactivity measured at Caltech with HPGe detector a year after irradiation
- The proton fluence calculated from Al foils are compared against time integration of LANSCE beam current data and used to calculate correction factor



Christina's Report on Al Foil (II)

Front Foils

Al foil	Crystals	Fluence from beam current	Fluence from Al foil [cm^{-2}]	uncertainty from Al foil [cm^{-2}]	% relative uncertainty	Ratio between two measurements
A	G1	**1.2E+13**	**1.9E+13**	2.3E+12	13%	1.56
B	G2	**3.7E+14**	**3.0E+14**	1.7E+13	6%	0.80
C	G3	**2.2E+15**	**1.8E+15**	8.5E+13	5%	0.81
D	BTL	**2.8E+13**	**2.7E+13**	2.5E+12	10%	0.95
E	Shashlik	**5.4E+15**	**4.9E+15**	2.3E+14	5%	0.92

- Proton fluence measured from Al foil 60% larger for A, due to the scattering/shower from the adjucent Shashlik cell irradiated up to 5E15 /cm^2 in the same experiment
- Correction factor of 0.86 +- 0.15 is applied to all proton fluence measurement from beam current data
  - The correction factor is determined by using the highest fluence foils C and E to reduce scattering background from neighboring crystals

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Christina's Report on Al Foil (III)

Back Foils

Al foil	Crystals	From beam current	Al foil measurement	Uncertainty	% Relative uncertainty	Ratio between two measurements
G	G1	1.2E+13	4.0E+13	3.9E+12	10%	3.35
H	G2	3.7E+14	1.7E+14	1.2E+13	7%	0.47
I	G3	2.2E+15	8.5E+14	4.5E+13	5%	0.39
F	BTL	2.8E+13	2.3E+13	2.4E+12	10%	0.83

- Proton fluence measured from Al foil 3 times larger for G, due to the scattering/shower from the adjucent Shashlik cell irradiated up to 5E15 /cm^2 in the same experiment
- Proton fluence measured from Al foil are smaller compared to that from beam current for the others, which is consistent with the multiple scattering effect of 800 MeV protons (more details in next 2 slides)

Christina's Report on Al Foil (IV)

Summary

- The proton fluence measured from the front Al foils is consistent with beam current data
- The correction factor of 0.86 +- 0.15 was determined by using the highest fluence foils C and E, and was applied to all proton fluence values obtained from beam current integration
- The observed B/F ratio of 48% is consistent with the expectation from proton multiple-scattering in LYSO sample