Fast Neutron Induced Radiation Damage in Fast Inorganic Scintillators

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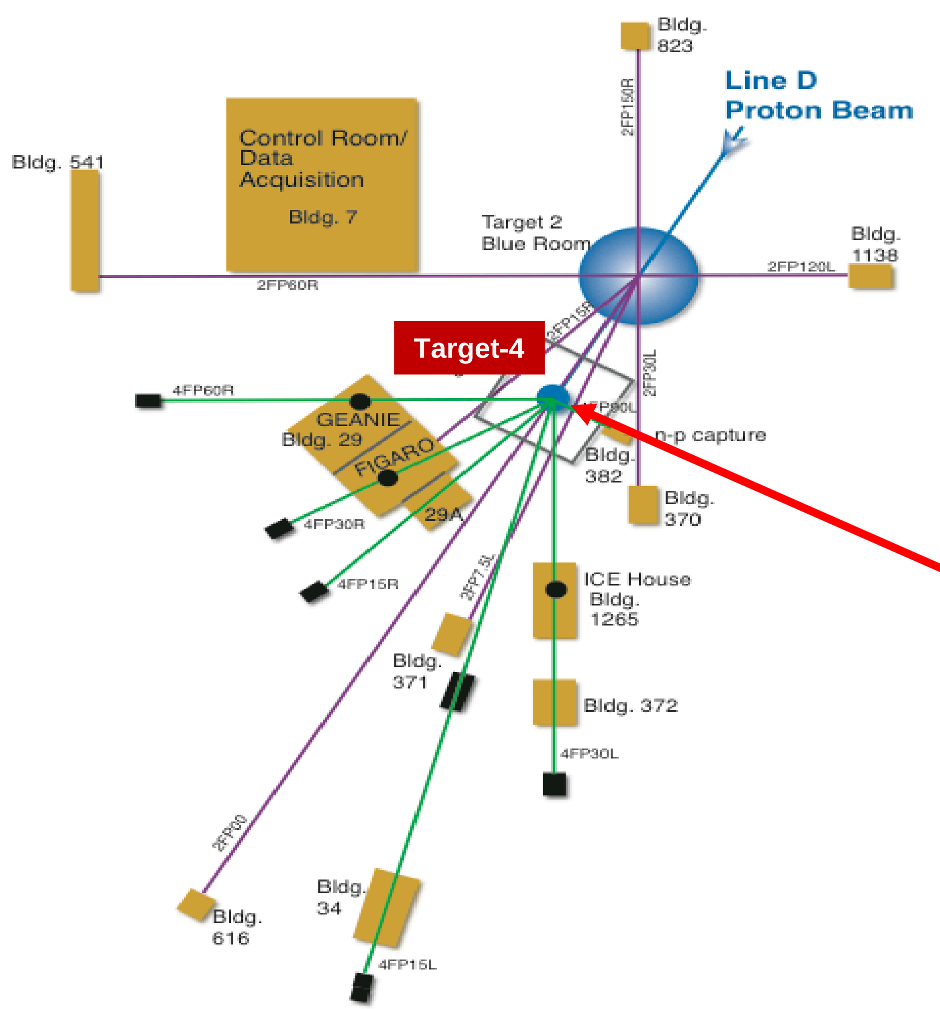
Introduction

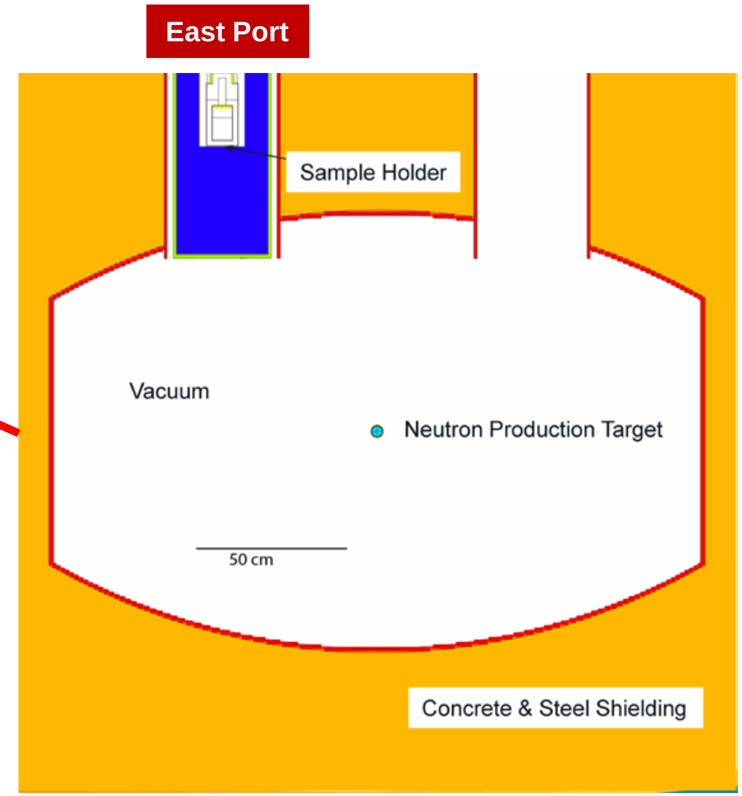
- A crucial issue for applications of scintillation crystals in future HEP calorimeters is radiation damage in severe radiation environment, such as at the HL-LHC, where up to 130 Mrad ionization dose, 3×10^{14} charged hadrons/cm^2 and 5×10^{15} n/cm^2 are expected.
- In this paper, we report an investigation on radiation damage induced by mixed particles of up to 2 x 10^{15}/cm^2 fast neutrons plus 4 Mrad ionization dose and 5 x 10^{12}/cm^2 protons in BaF_2, LYSO and PWO crystals irradiated at the Weapons Neutron Research facility of Los Alamos Neutron Science Center (WNR facility of LANSCE).
- In 2015 (Exp. 6991), 18 LFS plates of $14\times14\times1.5$ mm^3 were irradiated. In 2016 (Exp. 7332) 36 samples of 5 mm thick LYSO, BaF_2, and PWO were irradiated.

Irradiation at East Port of LANSCE

Los Alamos Neutron Science Center (LANSCE)

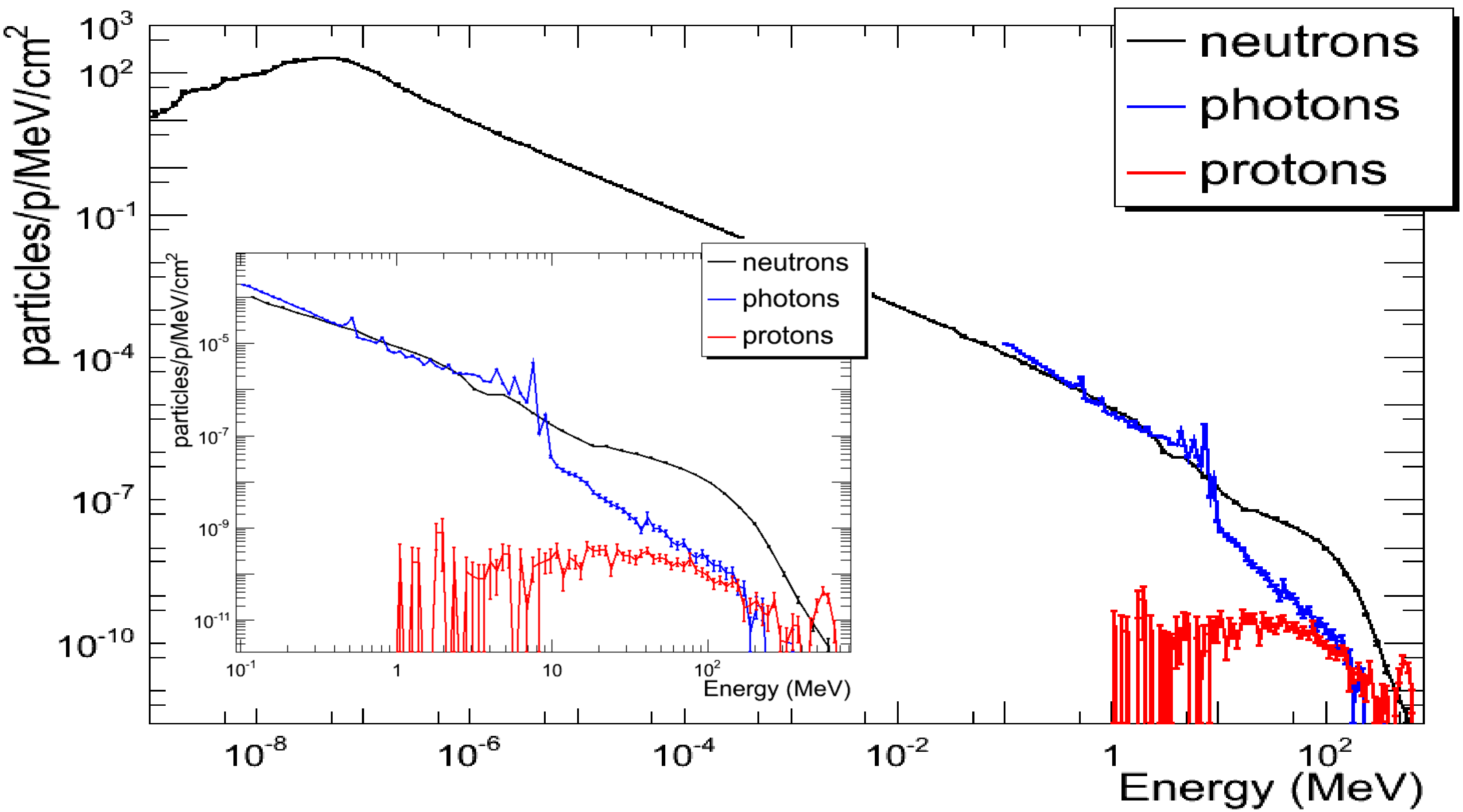


Samples are located at East Port in the Target-4, about 1.2 m away from the neutron production target



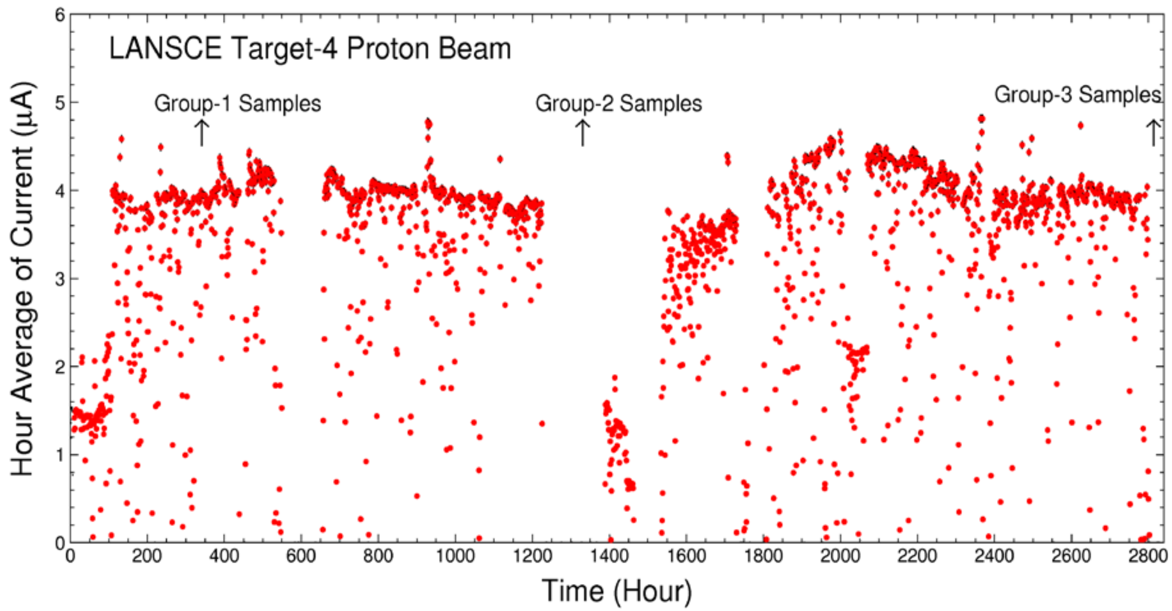
n/γ/p Spectra and Production Rate

Neutrons/Photons/Protons fluxes are calculated by using MCNPX (Monte Carlo N-Particle eXtended) package. Plotted spectra are tallied in the largest sample volume (averaging)



Samples & Beam for Exp. 6991 (2015)

- In 2015 run, 18 LFS plates of 14×14×1.5 mm3 were divided into three groups of six each, and were irradiated for 13.4, 54.5 and 118 days respectively.
- The fluence of each kind of particle was calculated by integration of 800 MeV proton beam current and MC production rate.



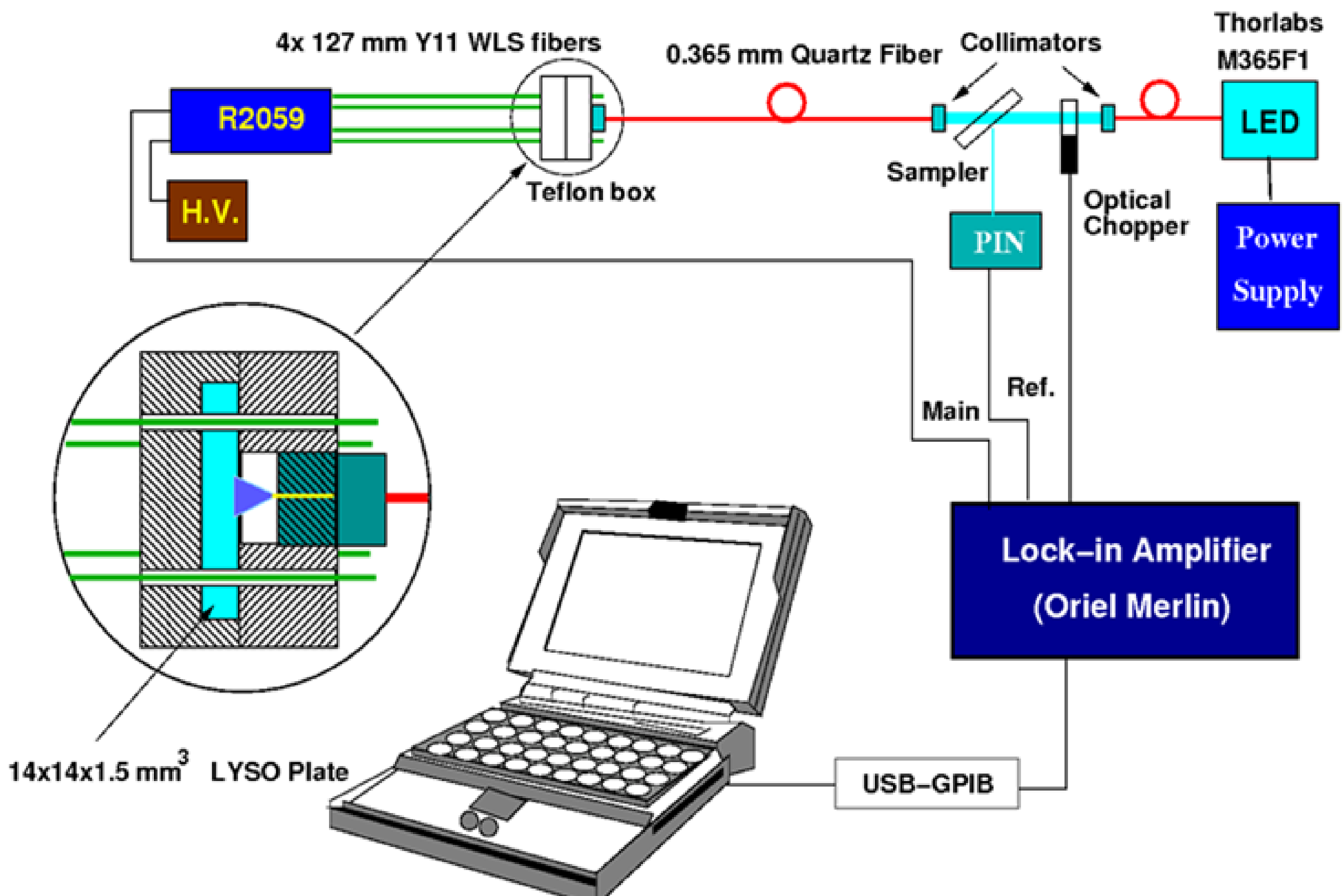
Fluence and Dose in Exp. 6991 (2015)

- According our proton irradiation test result, the effect of the proton fluence and dose is negligible.
- The photon ionization dose of up to 4.3 Mrad may induce significant radiation damage.

Particles	Group 1 Fluence (cm^{-2})	Group 2 Fluence (cm^{-2})	Group 3 Fluence (cm^{-2})
Thermal and Epithermal (0<En < 1 eV)	7.01E+14	3.16E+15	6.72E+15
Slow and Intermediate Neutrons (1 eV <En < 1 MeV)	2.56E+15	1.15E+16	2.45E+16
Fast neutrons 1 (En > 1 MeV)	**2.24E+14**	**1.01E+15**	**2.14E+15**
Fast neutrons 2 (En > 20 MeV)	**4.34E+13**	**1.96E+14**	**4.16E+14**
Protons (Ep>1 MeV)	5.31E+11	2.39E+12	5.08E+12
Protons Dose (rad)	1.39E+04	6.25E+04	1.33E+05
Photons (Eg>150 KeV)	6.71E+14	3.02E+15	6.43E+15
Photons Dose (rad) in Air	**4.53E+05**	**2.04E+06**	**4.34E+06**

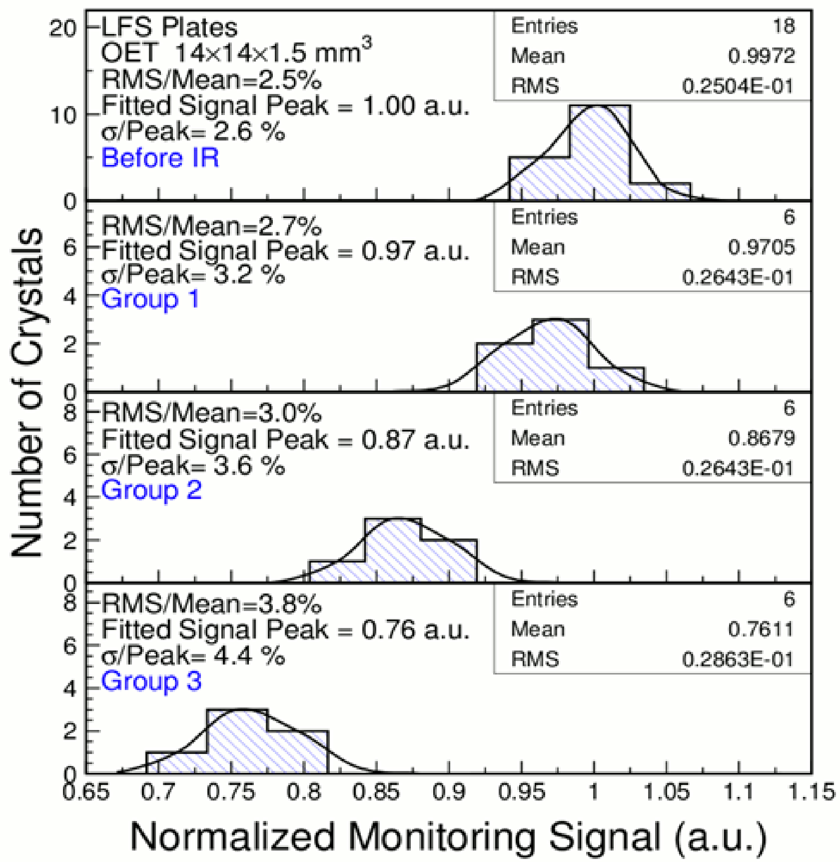
Light Output of LFS Plates

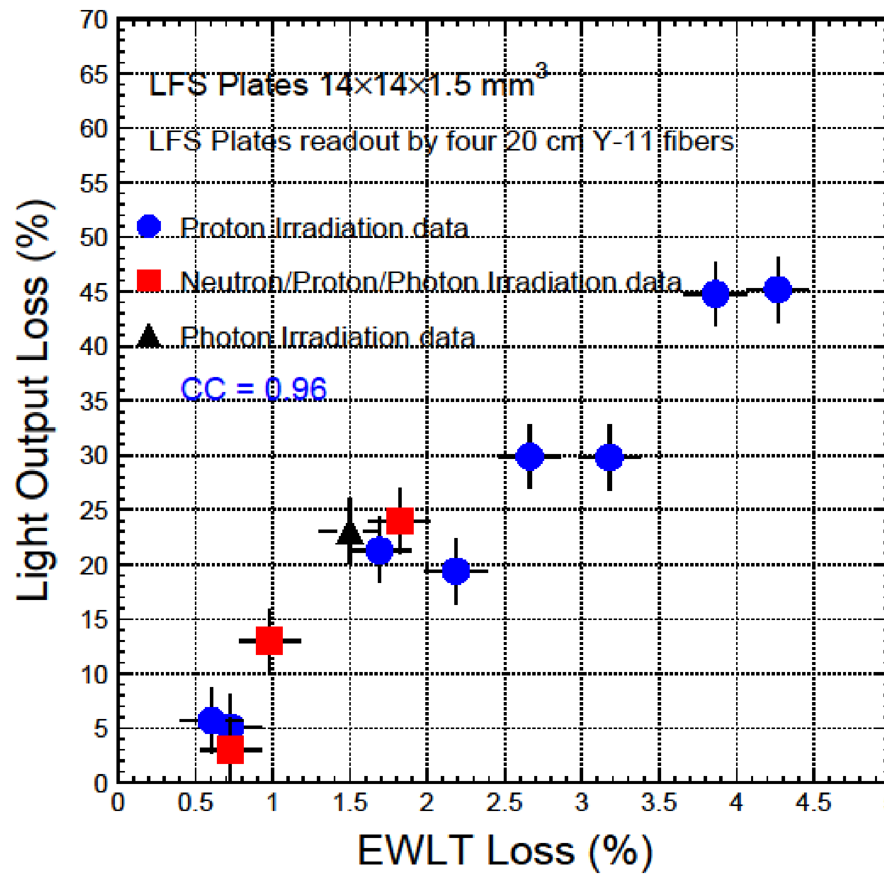
- Light output of LFS samples was measured before and about 90 days after the neutron irradiation by monitoring photo-excited luminescence intensity via 4 x Y11 WLS fibers.
- Two non-irradiated LFS plates used as reference, the systematic uncertainty ~2.5%.
- A lock-in amplifier was used to mitigate the residual phosphorescence in the samples after irradiation.



Light Output Loss of LFS Plates

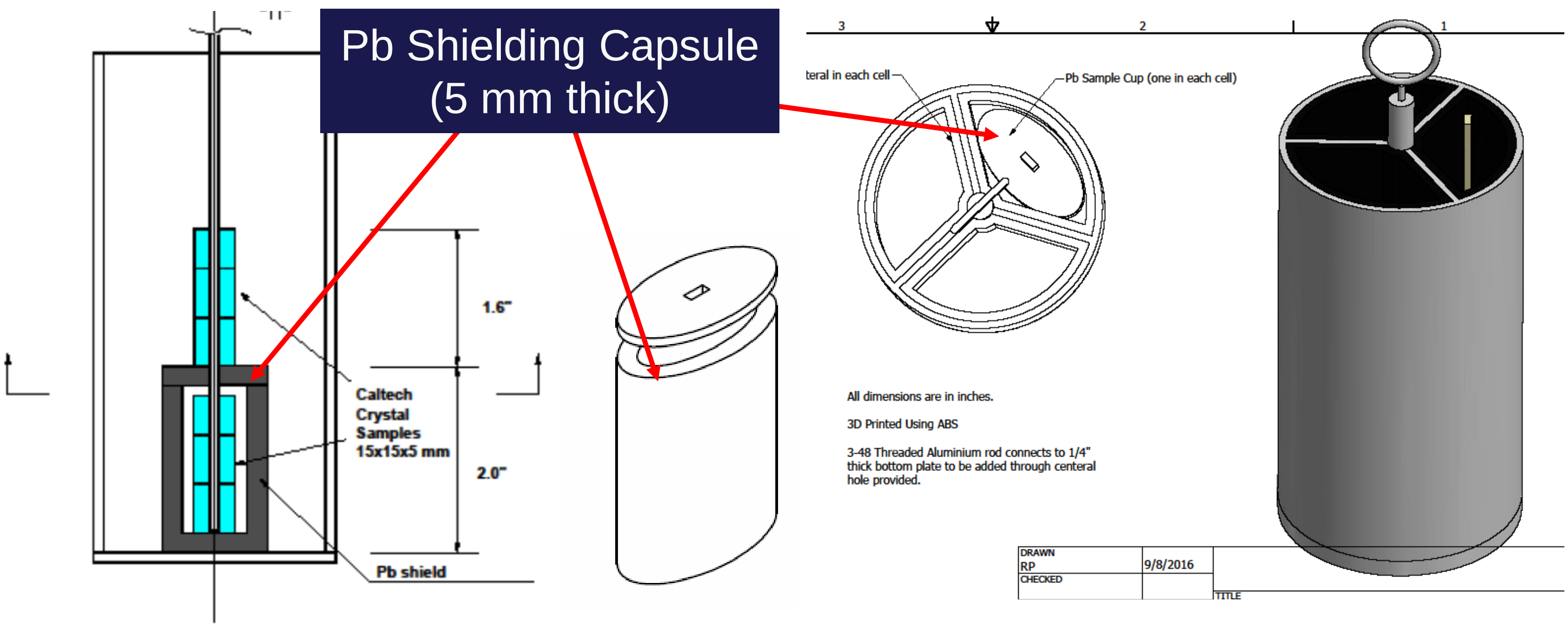
- A degradation of 3%,13% and 24% is observed for Group-1, 2 and 3.
- The light output loss is highly correlated to the EWLT loss (96% CC), indicating it can be corrected by a light monitoring.
- Pb shielding is need to understand effect of ionization dose.





5 mm Pb Shielding Introduced in Exp. 7332 (2016)

Pb shielding introduced for half samples in each group for a comparison, which attenuated the ionization dose by ~30%, but not fast neutrons

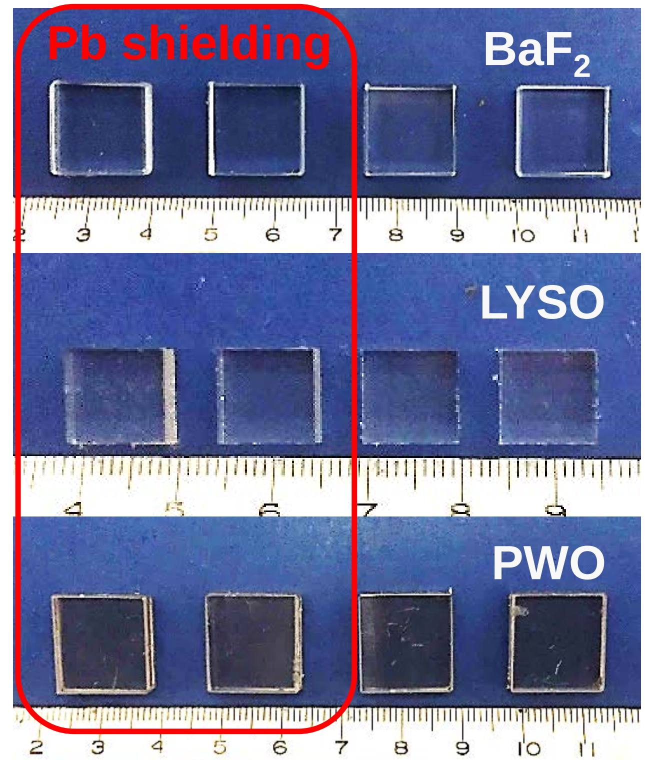


Samples for Exp. 7332 (2016)

Four BaF_2, LYSO and PWO samples in each group

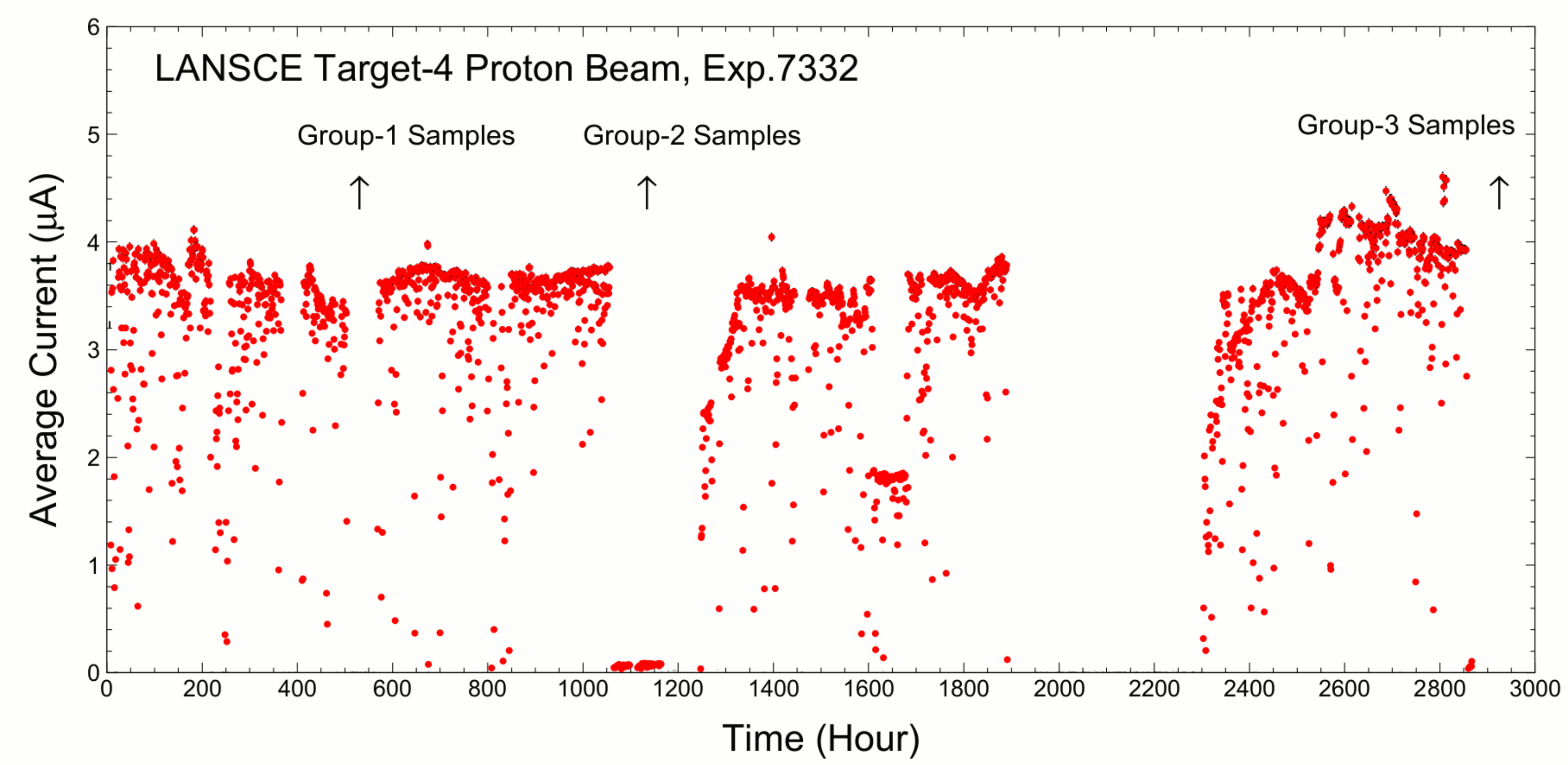
Group	Samples	Dimensions (mm³)	SN	Shielding
1	BaF_2	15×15×5	B1, B2	Pb
			B3, B4	
	LYSO	10×10×5	LS1, LS2	Pb
			LS3, LS7	
	PWO	15×15×5	P2, P3	Pb
			P1, P4	
2	BaF_2	15×15×5	B7, B8	Pb
			B5, B6	
	LYSO	10×10×5	LS4, LS6	Pb
			LS9, LS10	
	PWO	15×15×5	P5, P7	Pb
			P6, P10	
3	BaF_2	15×15×5	B10, B11	Pb
			B9, B12	
	LYSO	10×10×5	LS5, LS8	Pb
			LC1, LC4	
	PWO	15×15×5	P8, P9	Pb
			P11, P12	

Group-3 Samples
90 days after Irradiation



Beam Current for Exp. 7332 (2016)

The 3 groups were irradiated for 21.2, 46.3 and 120 days respectively, and measured at Caltech about 90 days after the irradiation.



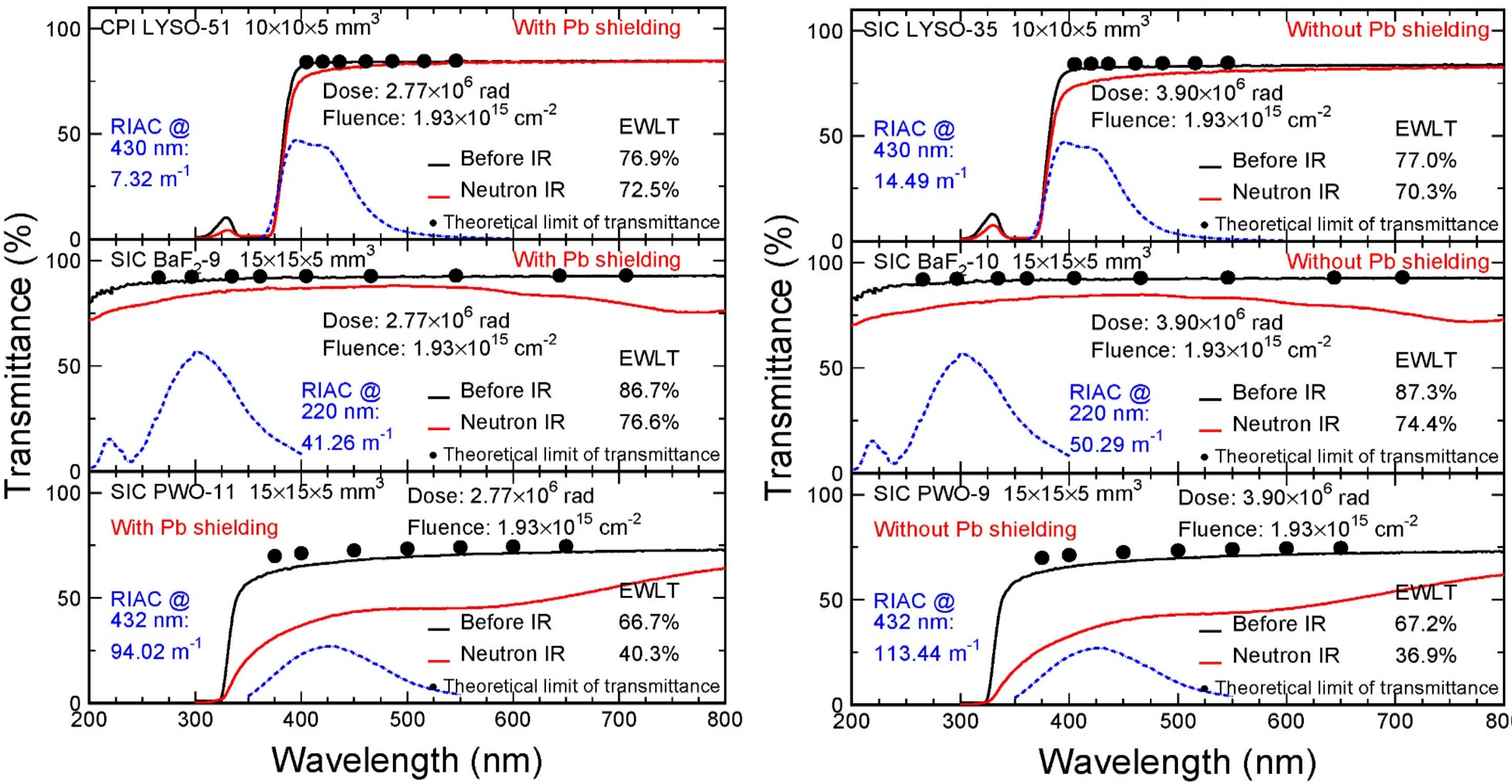
Fluence/Dose in Exp. 7332 (2016)

Similar fluences and dose as the Exp. 6991 (2015)

Particles	Group-1 Fluence (cm^{-2})	Group-2 Fluence (cm^{-2})	Group-3 Fluence (cm^{-2})
Thermal and Epithermal Neutrons (0<En < 1 eV)	1.23E+15	2.69E+15	6.04E+15
Slow and Intermediate Neutrons (1 eV <En < 1 MeV)	4.50E+15	9.80E+15	2.20E+16
Fast neutrons Fluence 1: (En > 1 MeV)	**3.94E+14**	**8.58E+14**	**1.93E+15**
Fast neutrons Fluence 2: (En>20 MeV)	**7.64E+13**	**1.66E+14**	**3.74E+14**
Protons (Ep>1 MeV)	9.34E+11	2.03E+12	4.57E+12
Protons Dose (rad)	2.44E+04	5.32E+04	1.20E+05
Photons (Eg>150 KeV)	1.18E+15	2.57E+15	5.78E+15
Photons Dose (rad)	**7.97E+05**	**1.74E+06**	**3.90E+06**
Photons Dose (rad) with 5 mm Pb shielding	**5.66E+05**	**1.23E+06**	**2.77E+06**

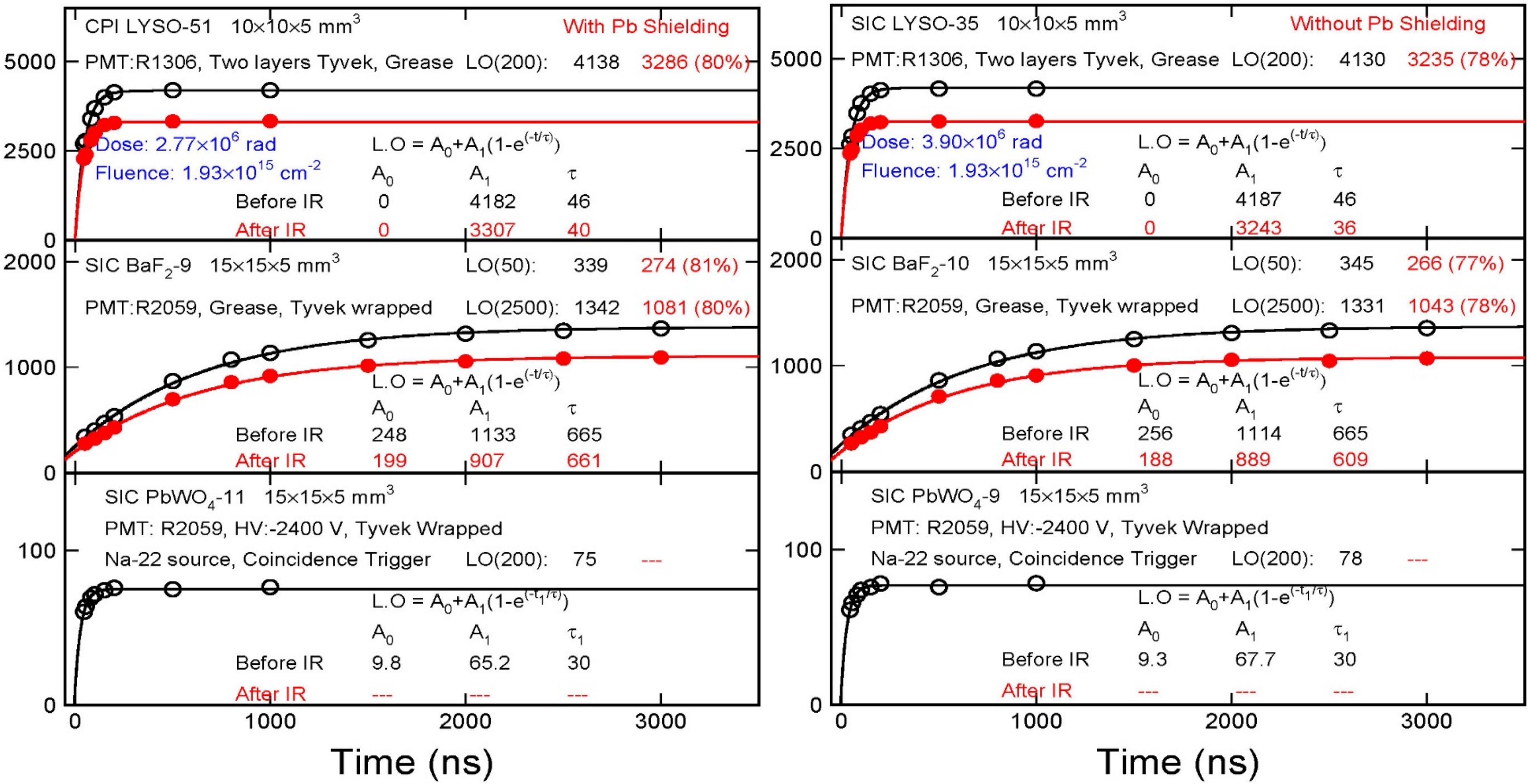
Transmittance of LYSO, BaF_2 and PWO

- LYSO and BaF_2 show less absorption than PWO.
- Pb shielding reduce RIAC for all 3 kinds of crystals.



Light Output of LYSO, BaF_2 and PWO

- LYSO and BaF_2 show less light output loss than PWO.
- Pb shielding reduce light output loss of LYSO and BaF_2 crystals.



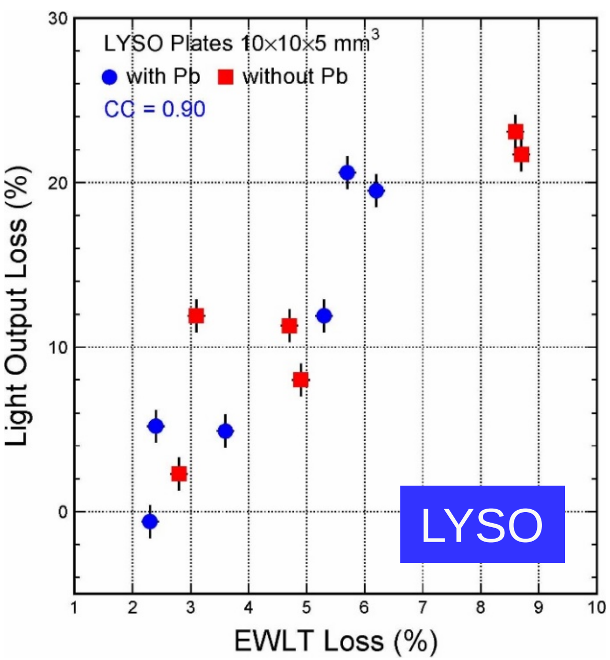
Summary: LYSO, BaF_2 and PWO

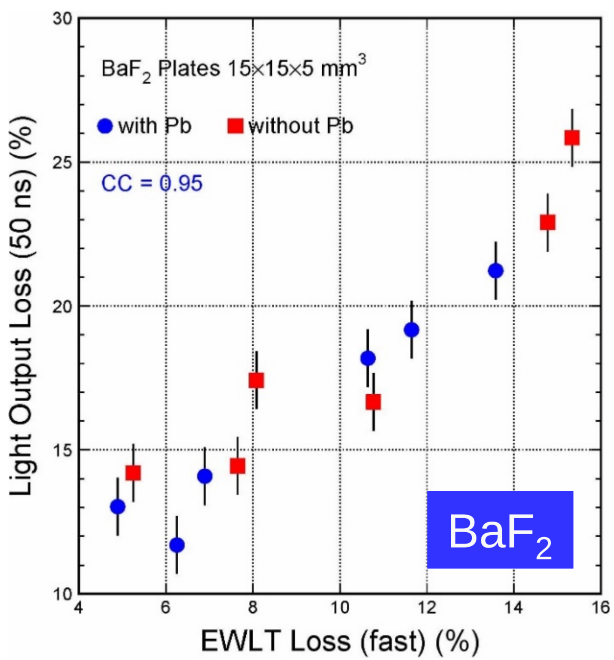
LO loss <25% of BaF_2 and LYSO after $2\times10^{15}/cm^2$ fast neutrons (>1MeV) plus 4 Mrad ionization dose indicates an excellent radiation hardness.

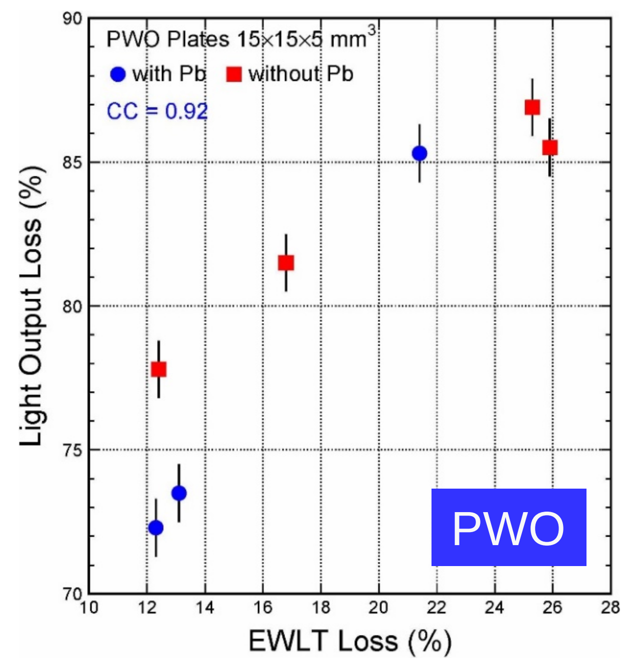
Group No.	Crystal	With Pb Shielding		Without Pb Shielding	
		EWLT Loss (%)	L.O. Loss (%)	EWLT Loss (%)	L.O. Loss (%)
Group-1 Fluence (cm^{-2}) Fast n (>1 MeV): 3.94×10^{14} Fast n (>20 MeV): 7.64×10^{13}	Dose (rad)	5.66×10^5		7.97×10^5	
	LYSO	2.4	2.3	3.8	6.8
	BaF_2	5.9	13.6	6.4	15.3
	PWO	12.7	72.9	14.6	79.7
Group-2 Fluence (cm^{-2}) Fast n (>1 MeV): 8.58×10^{14} Fast n (>20 MeV): 1.66×10^{14}	Dose (rad)	1.23×10^6		1.74×10^6	
	LYSO	4.5	8.4	4.0	10.0
	BaF_2	8.4	14.9	9.4	17.0
	PWO	24.2	86.2	25.6	100
Group-3 Fluence (cm^{-2}) Fast n (>1 MeV): 1.93×10^{15} Fast n (>20 MeV): 3.74×10^{14}	Dose (rad)	2.77×10^6		3.90×10^6	
	LYSO	6.0	20.1	8.7	22.4
	BaF_2	12.6	20.2	15.1	24.4
	PWO	40.5	100	44.3	100

LO Loss vs EWLT Loss

Good correlations between LO losses & EWLT losses are observed in all samples, indicating that they can be corrected by a light monitoring system

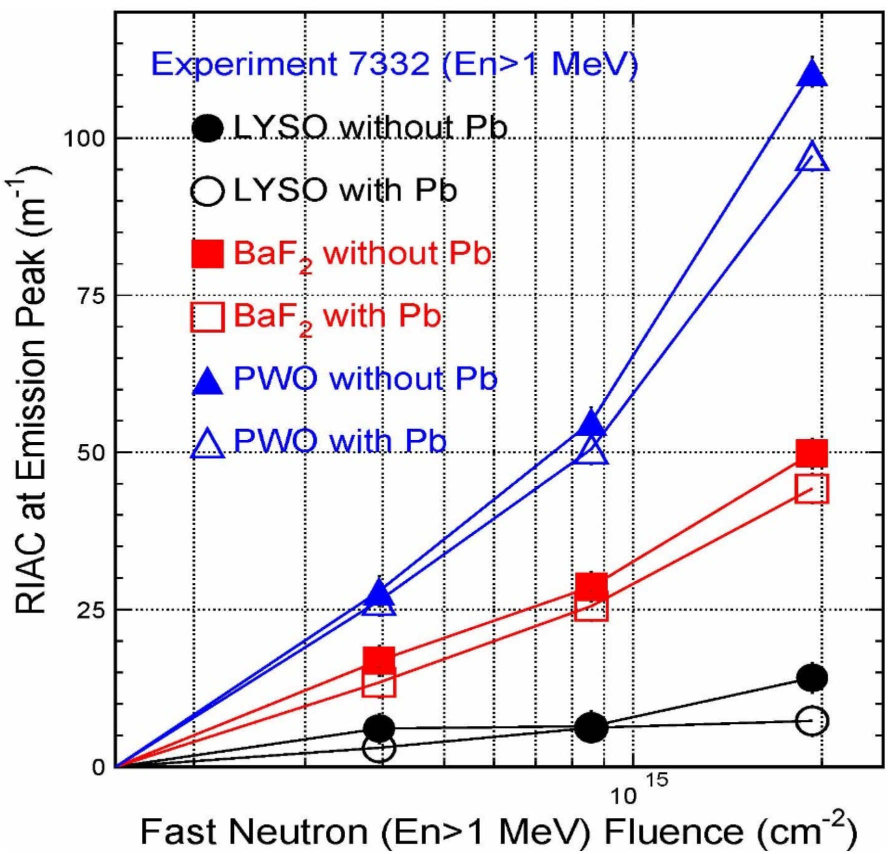


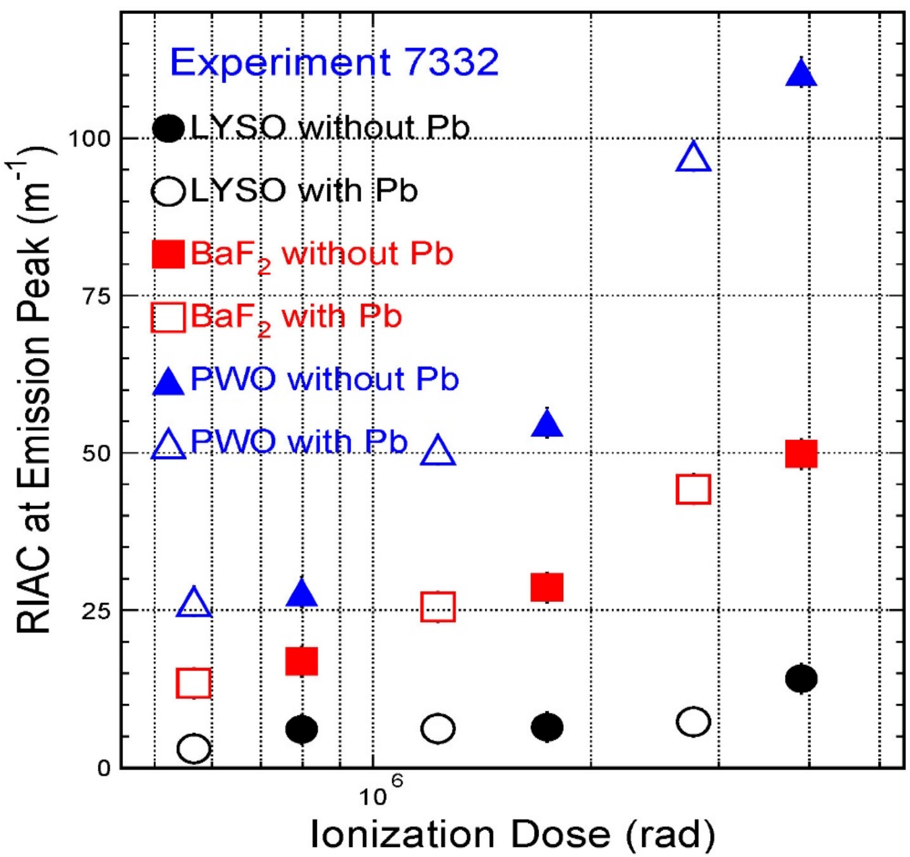




RIAC of LYSO, BaF_2 and PWO

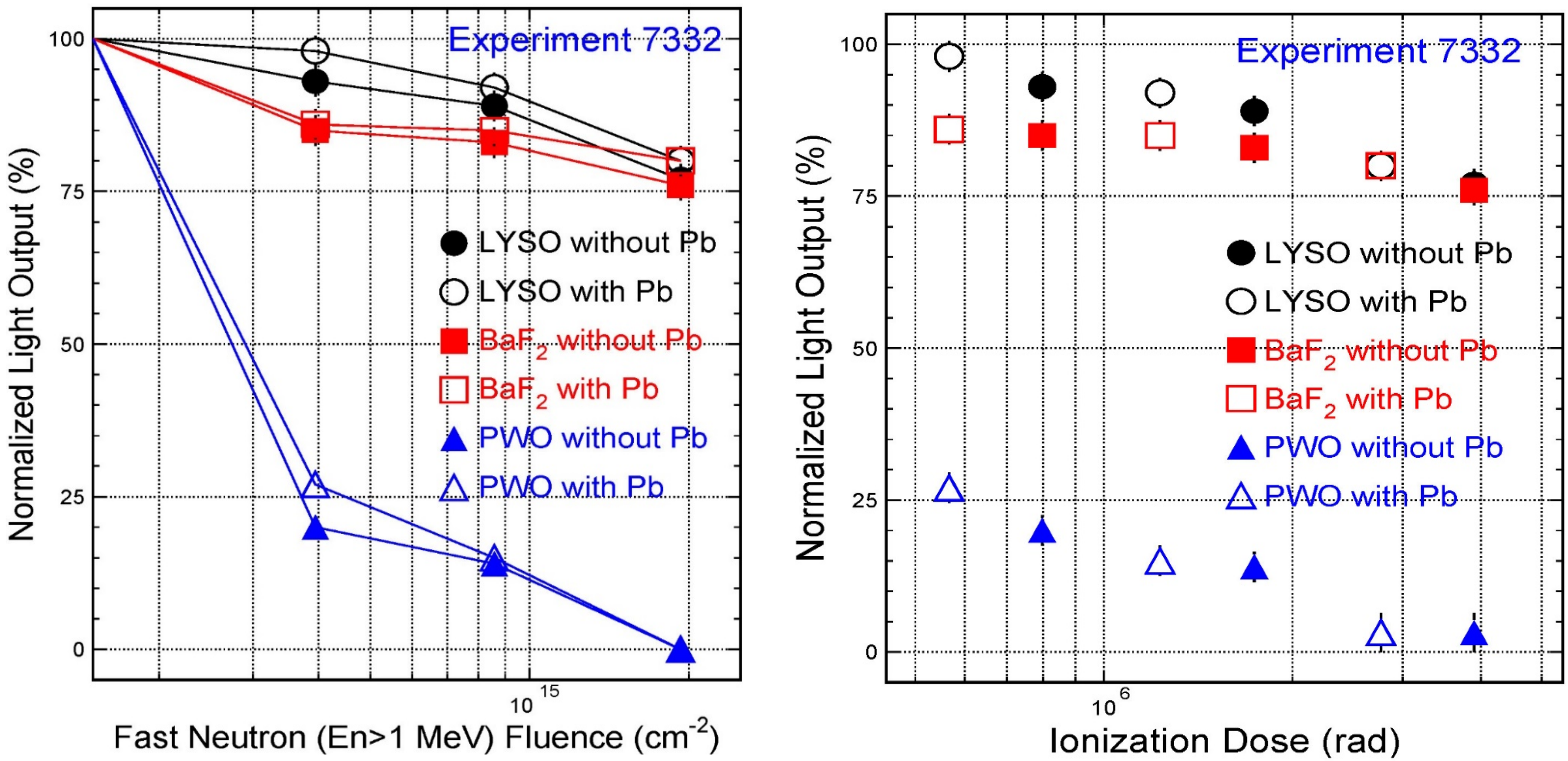
RIAC consistent with the ionization dose, indicating its dominance in the damage
LYSO and BaF_2 show much lower RIAC than PWO





LO of LYSO, BaF_2 and PWO

25% LO loss of LYSO and BaF_2 after irradiation, indicating radiation hardness

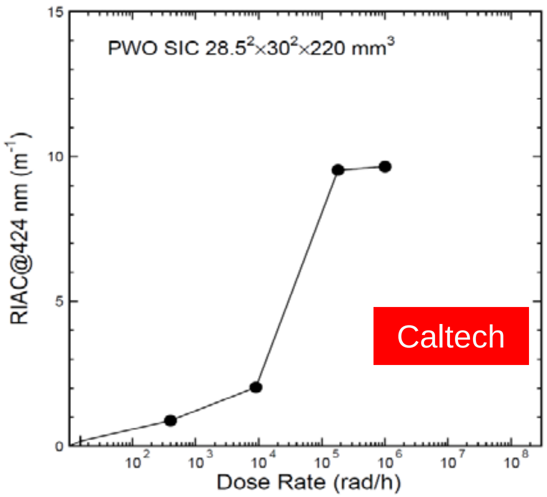


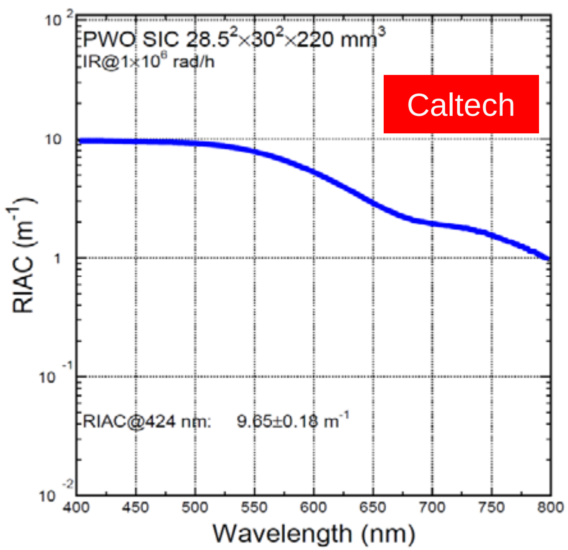
Summary

- BaF_2, LYSO and PWO crystals were irradiated by a combination of up to 2 x $10^{15}/cm^2$ fast neutrons plus 4 Mrad ionization dose and 5 x $10^{12}/cm^2$ protons at LANSCE in 2015 and 2016.
- Less than 25% light output loss is observed in 5 mm thick BaF_2 and LYSO crystal plates, indicating they survive the severe radiation environment expected at the HL-LHC.
- Radiation damage observed in transmittance and light output is correlated with the ionization dose, indicating that damage is dominated by the ionization dose in these experiments.
- Neutron induced damage is small in these experiments, which is consistent with early publications. Additional experiments are under way for quantitative comparison.

Neutron Damage in PWO up to 10^{19} n/cm²

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

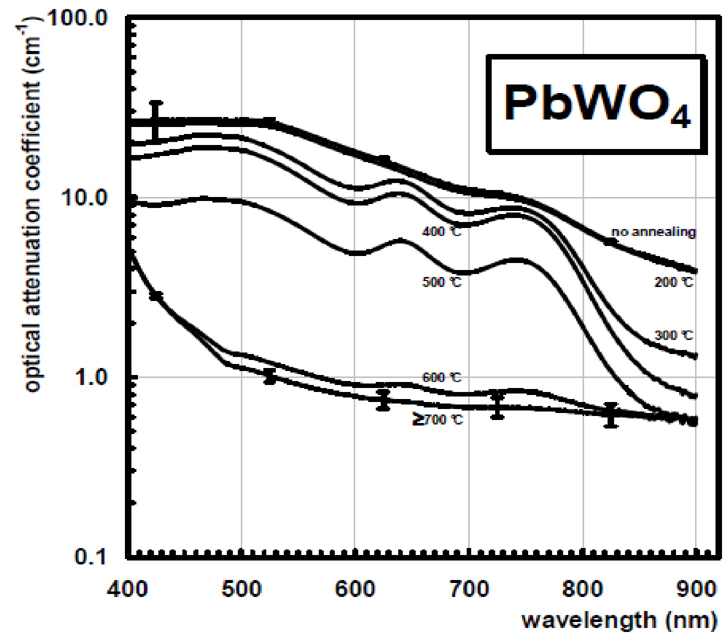


Fig. 2. Optical attenuation coefficient of the irradiated sample before annealing and after successive annealing temperatures.

[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

Energy Spectra Expected at HL-LHC

FLUKA simulations: Neutrons and charged hadrons are peaked at MeV and hundreds MeV respectively.