Neutron Induced Radiation Damage in BaF_2, LYSO and PWO Scintillation Crystals

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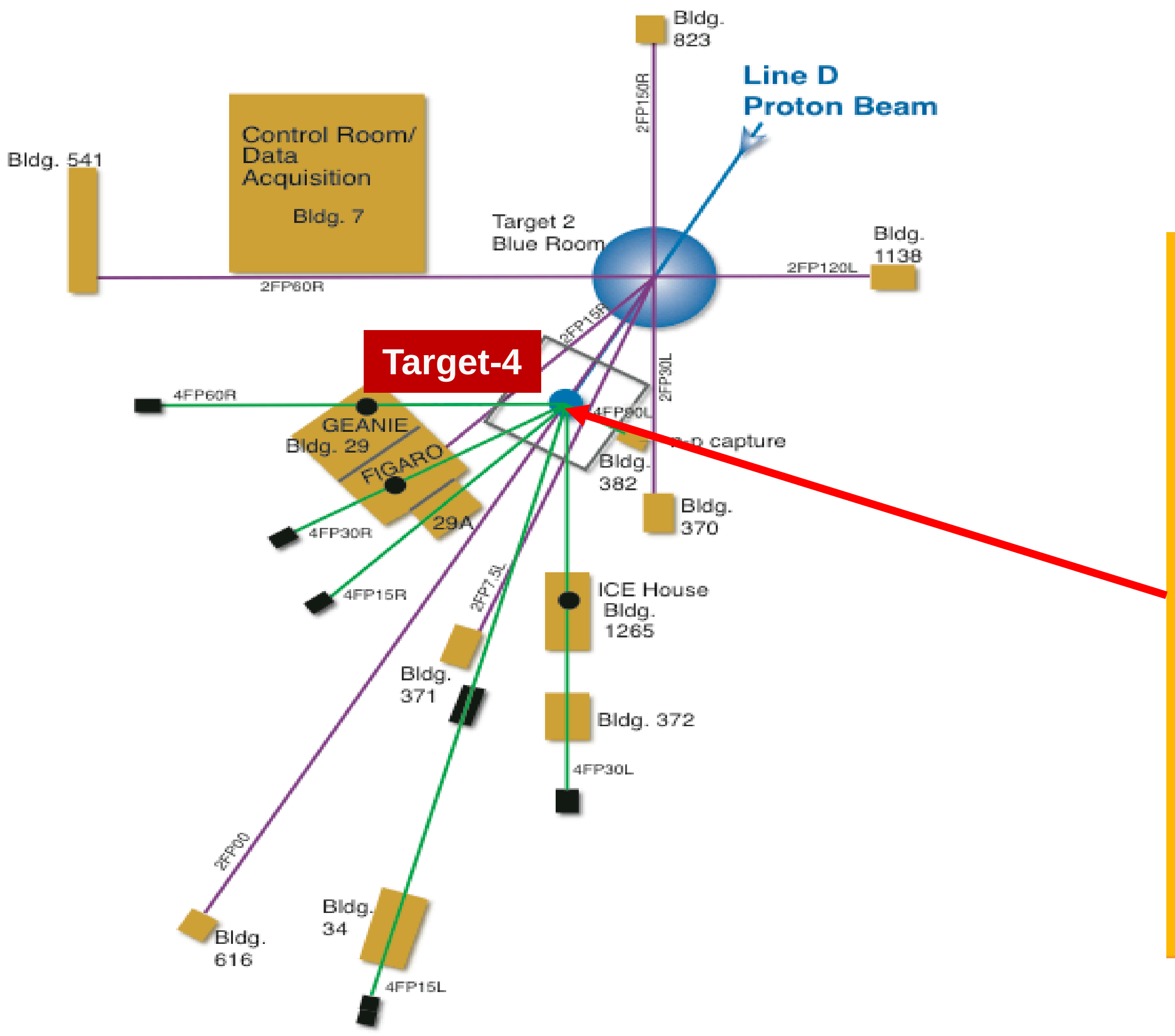
Introduction

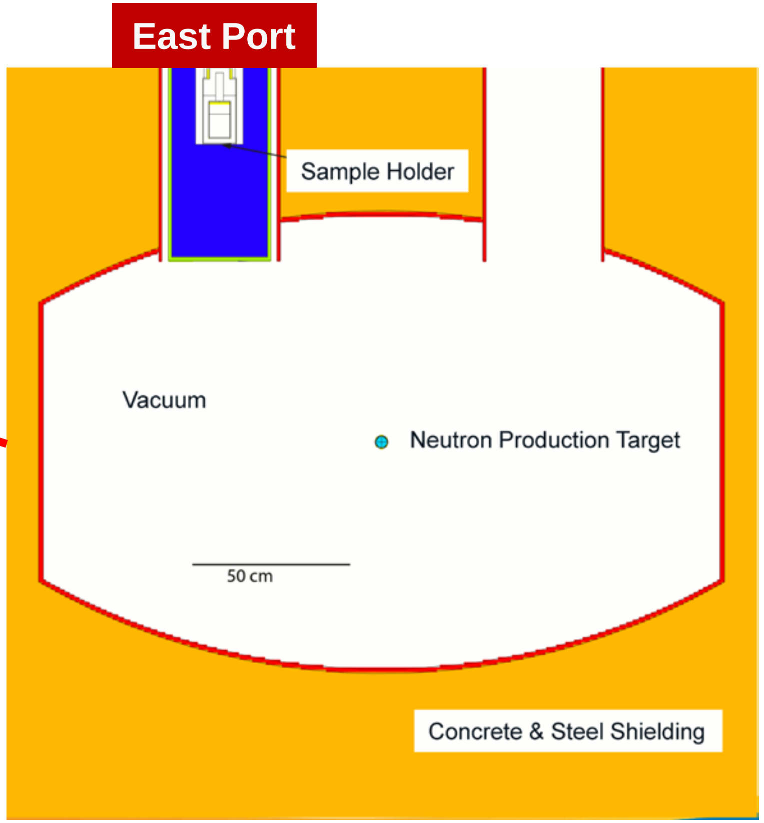
- One crucial issue for applications of scintillation crystals in HEP calorimeters is radiation damage in severe radiation environment, such as at the HL-LHC, with 5×10^{34} $cm^{-2}s^{-1}$ luminosity and 3,000 fb^{-1} integrated luminosity, up to 130 Mrad ionization dose, 3×10^{14} charged hadrons/cm^2 and 5×10^{15} n/cm^2 will be expected.
- In this paper, we report an investigation on neutron induced radiation damage in BaF_2, LYSO and PWO crystals by using the neutrons at the Weapons Neutron Research facility of Los Alamos Neutron Science Center (WNR facility of LANSCE).
- In 2015 (Exp. 6991), 18 LFS plates of $14 \times 14 \times 1.5$ mm3 were irradiated. In 2016 (Exp. 7332) 36 samples of 5 mm thick LYSO, BaF_2, and PWO were irradiated.

Neutron Irradiation at LANSCE

Los Alamos Neutron Science Center (LANSCE)

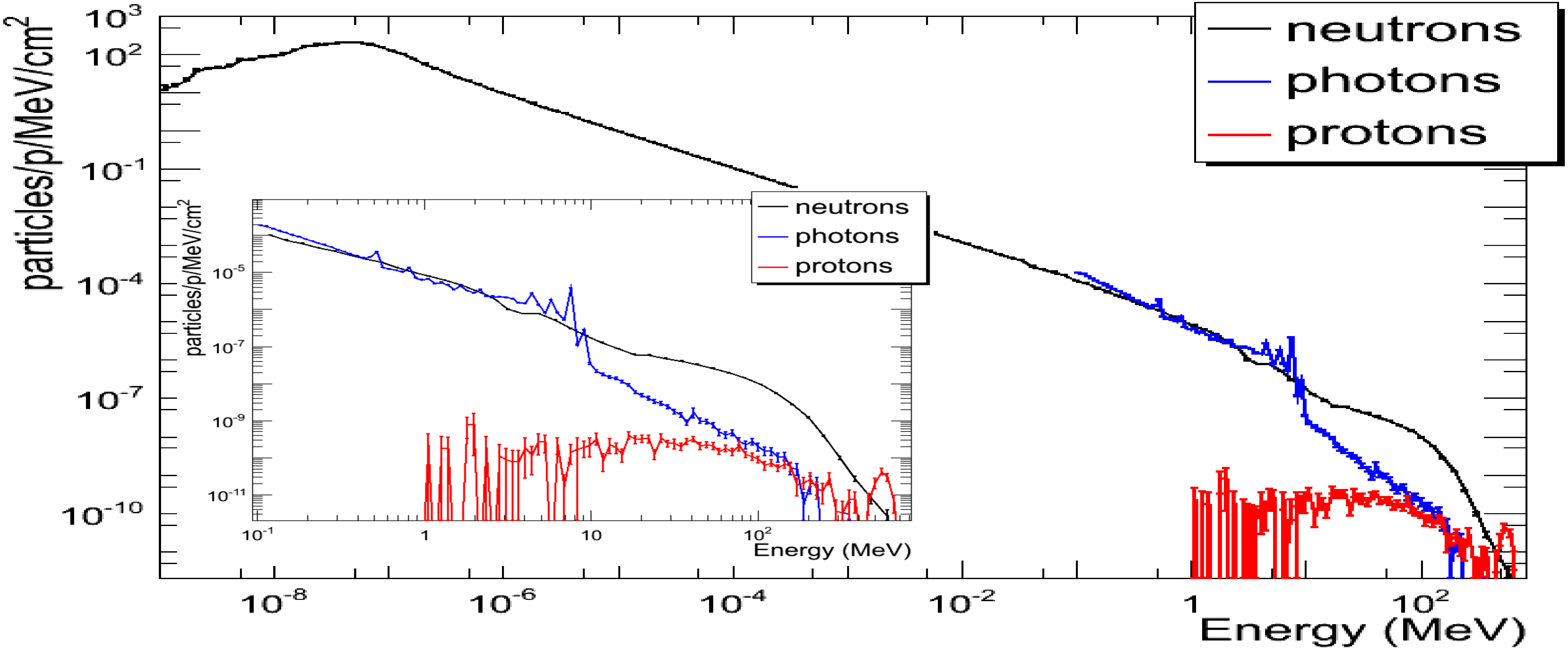


Samples are placed at Target-4 East Port, about 1.2 m away from the neutron production target.



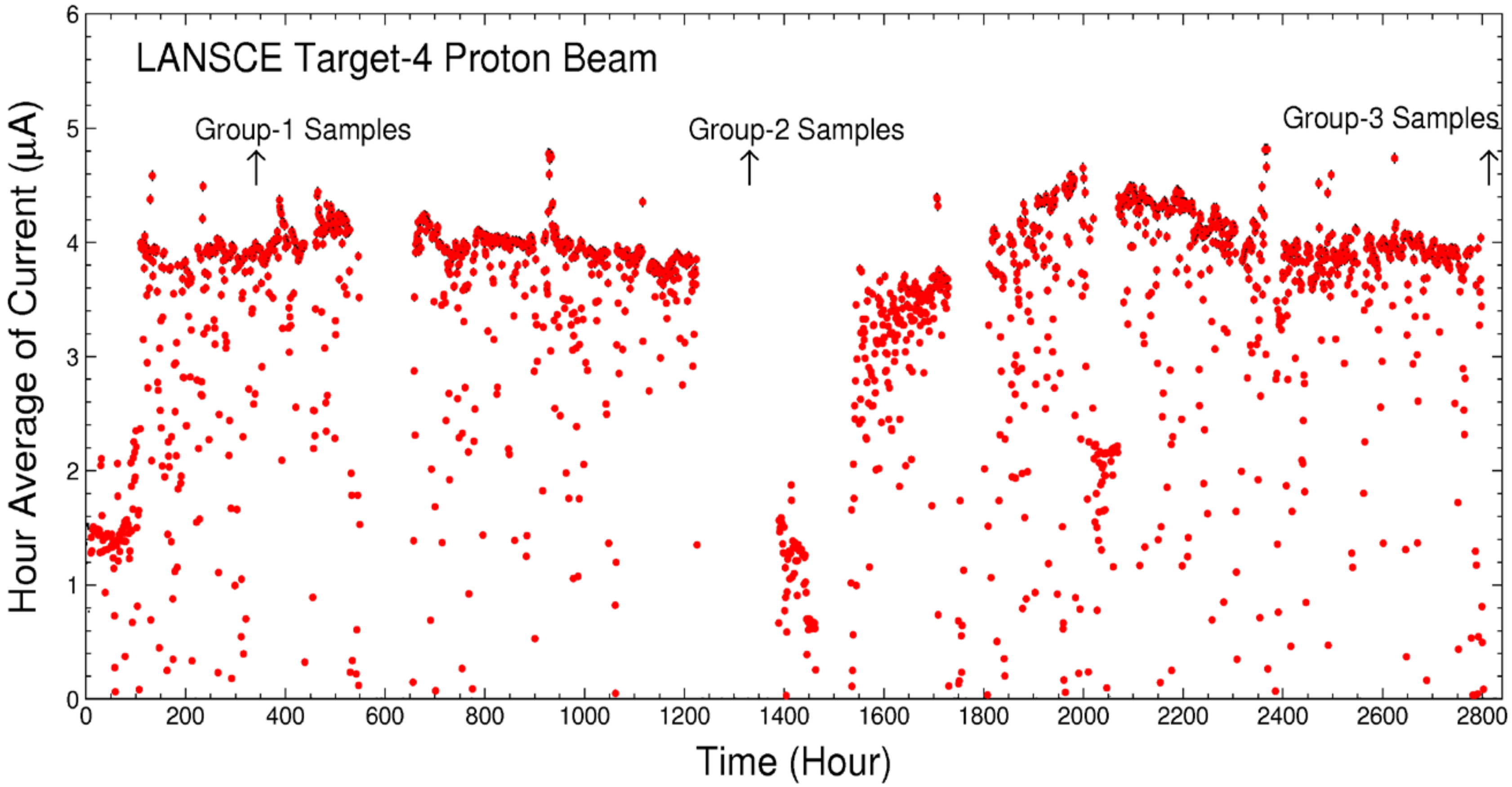
n/γ/p Spectra and Production Rate

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)



Radiation Dose and Fluence Calculation

- 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.



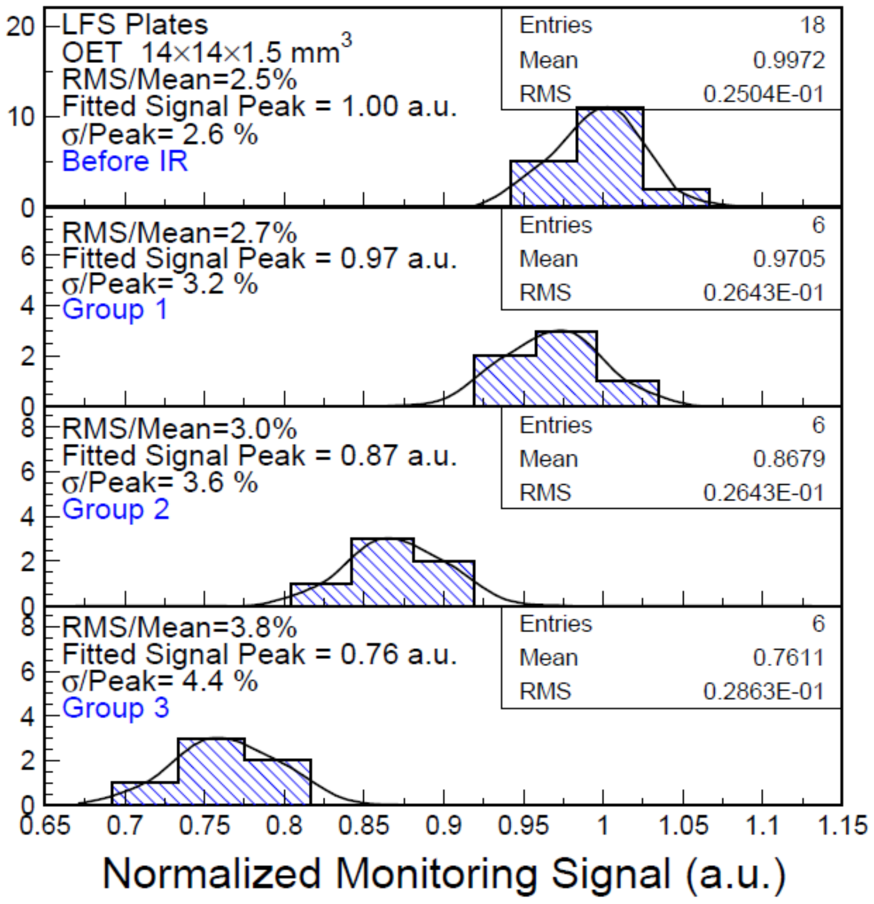
Fluence and Dose in Exp. 6991 (2015)

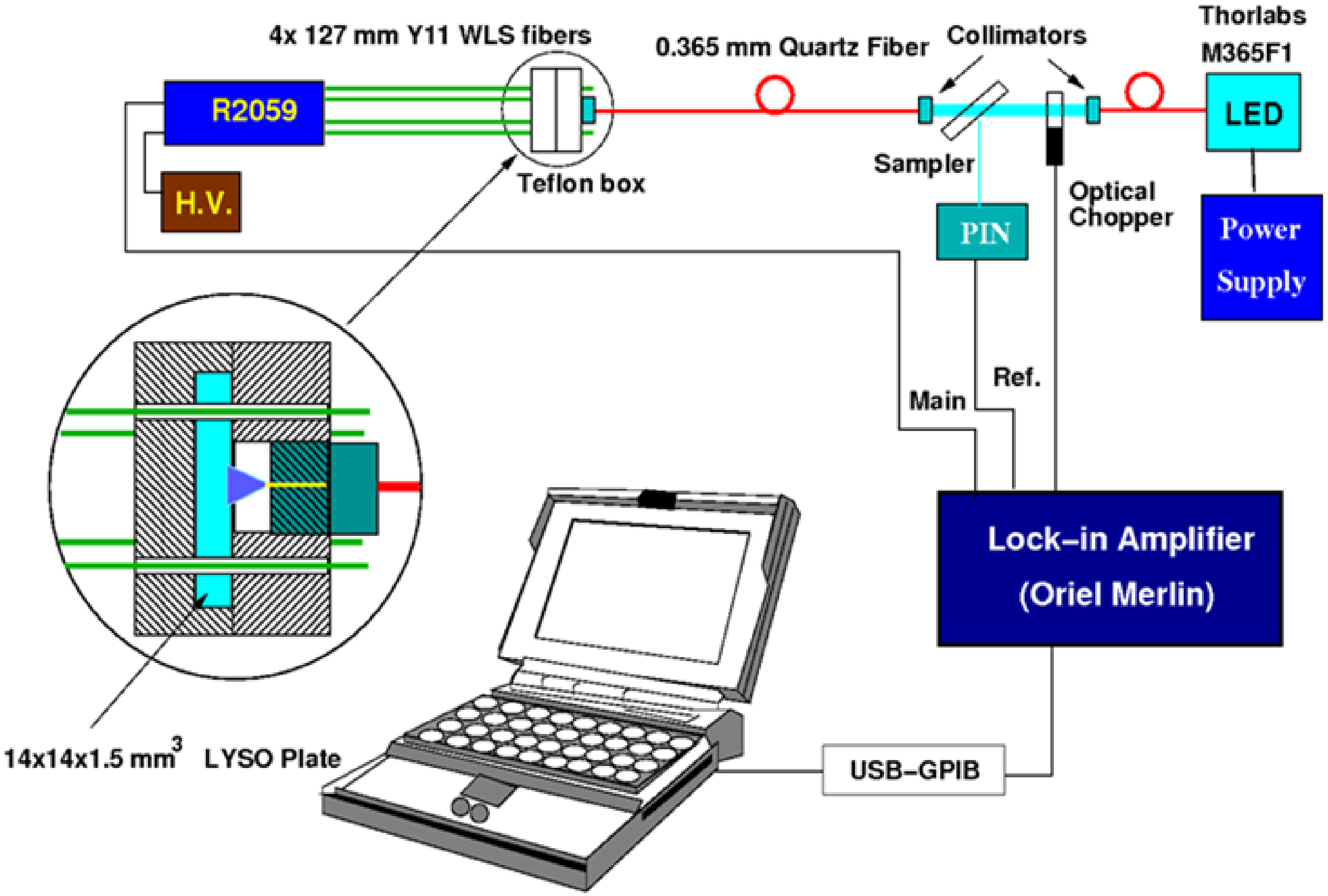
- According our proton irradiation test result, the effect of the proton fluence and dose is negligible.
- The photon ionization dose of up to 230 Mrad is significant, comparing to neutron fluence.

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	**2.40E+07**	**1.08E+08**	**2.30E+08**

Light Output Loss of LFS Plates

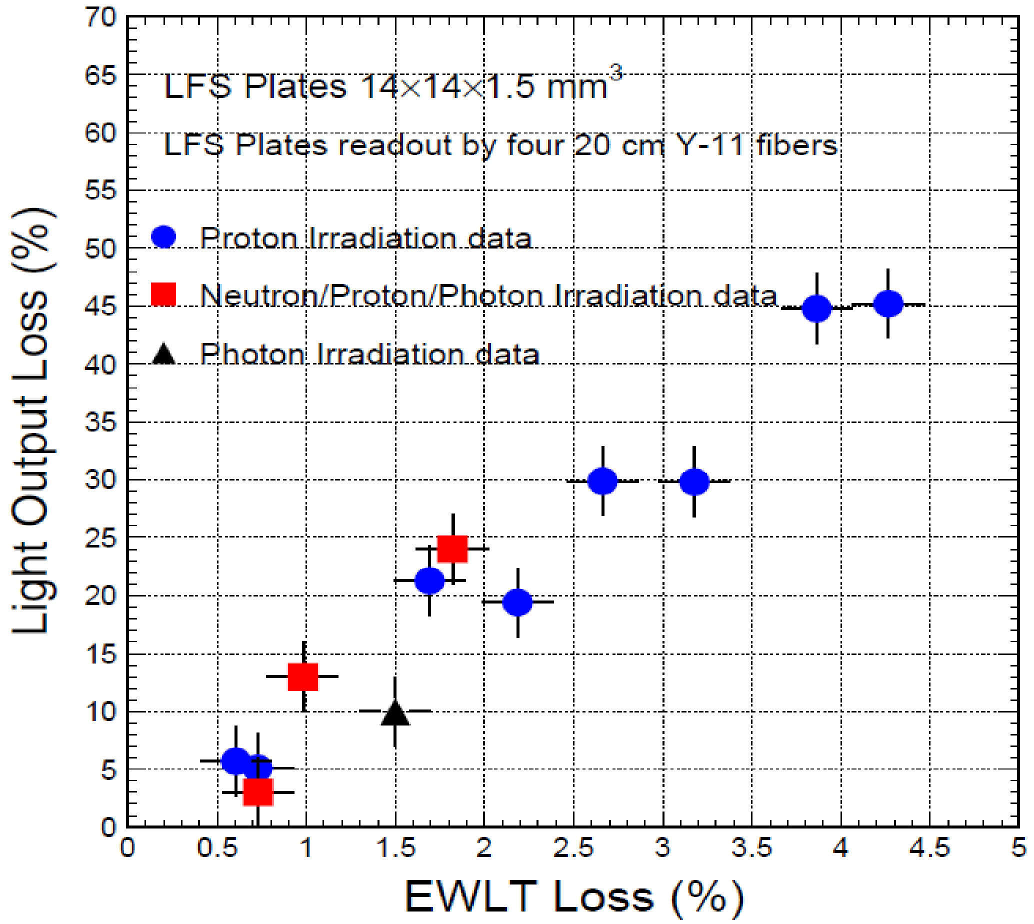
- ➢ The light response of LFS samples, group-1, 2 and 3, was measured before and after the neutron irradiation.
- ➢ A degradation of 3%,13% and 24% is observed for Group-1, 2 and 3.

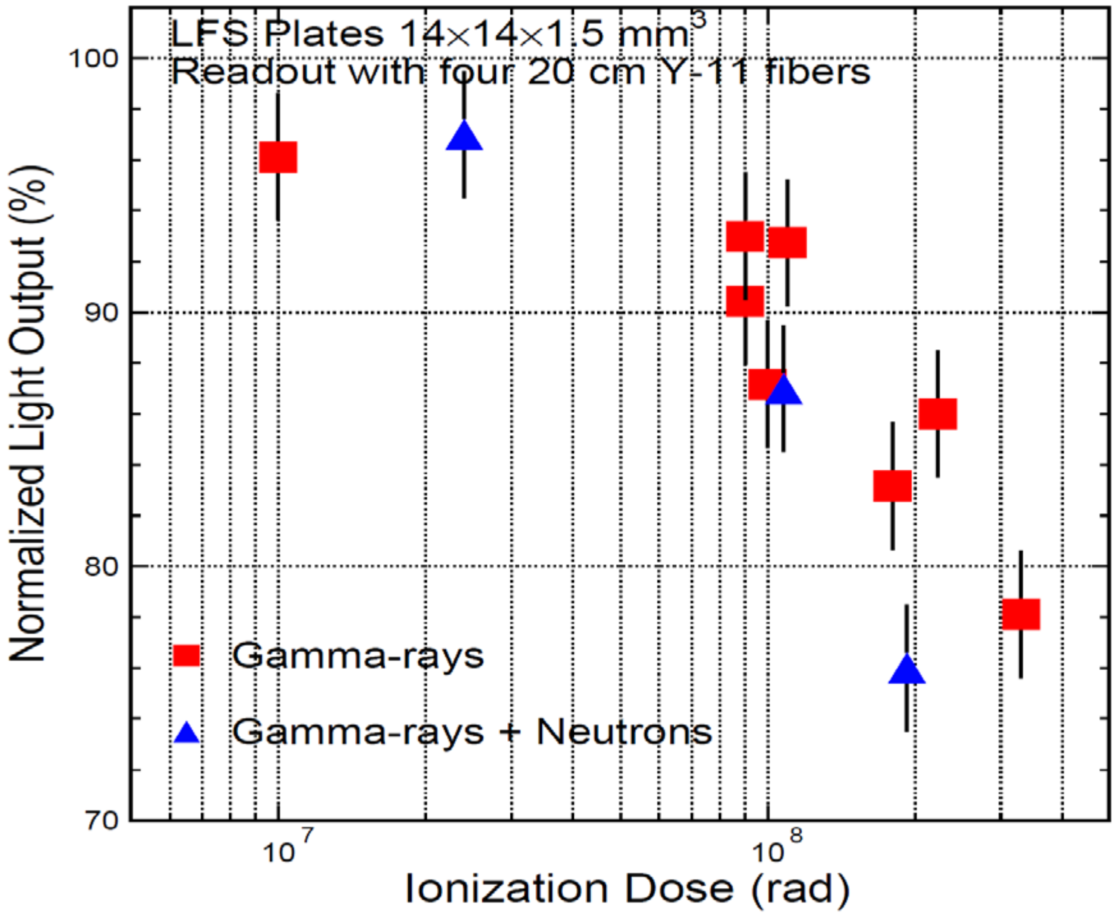




Comparison with γ/p irradiated Samples

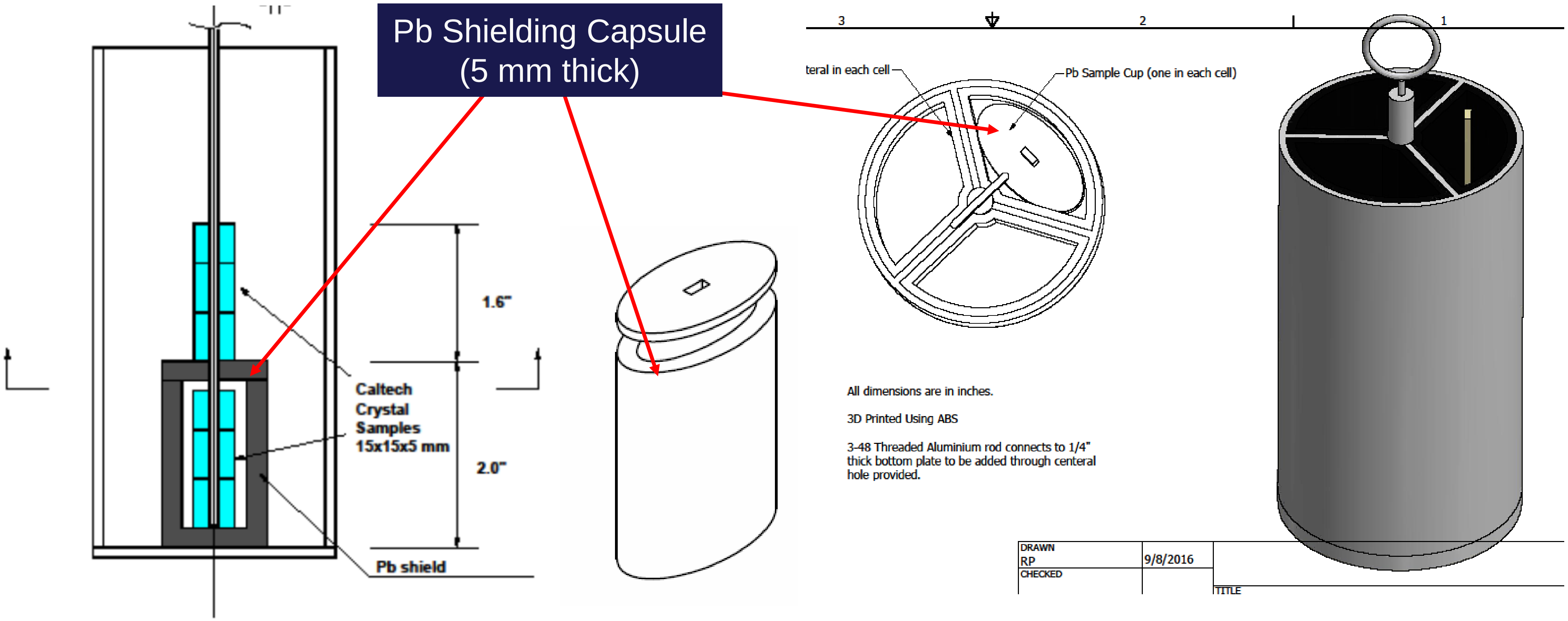
- Neutron irradiated LFS show consistent light output loss vs. EWLT loss, indicating LO loss can be corrected by a light monitoring.
- Consistent LO loss as a function of ionization dose indicates a negligible neutron induced damage.





Pb Shielding Introduced in Exp. 7332 (2016)

5 mm thick Pb shielding was introduced for half of the samples in each group, which attenuated the ionization dose, but not fast neutrons

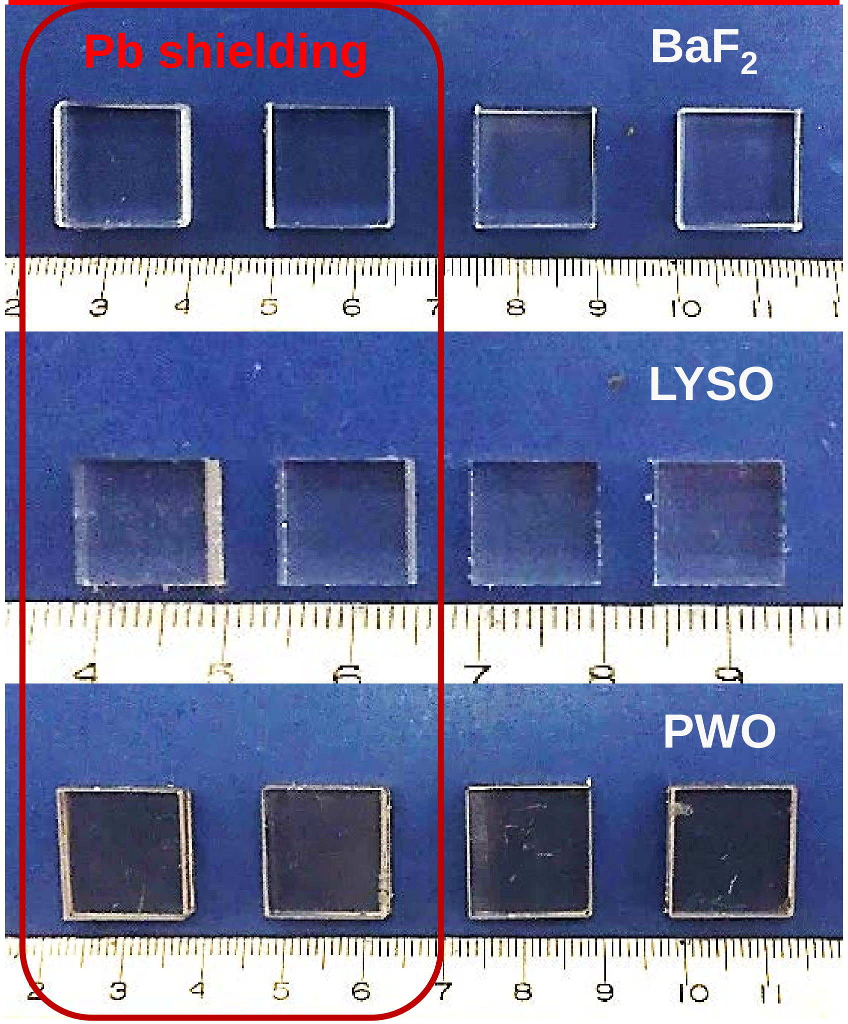


Samples of Exp. 7332 (2016)

Three Groups of four BaF_2, LYSO and PWO samples each were irradiated

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 after Irradiation



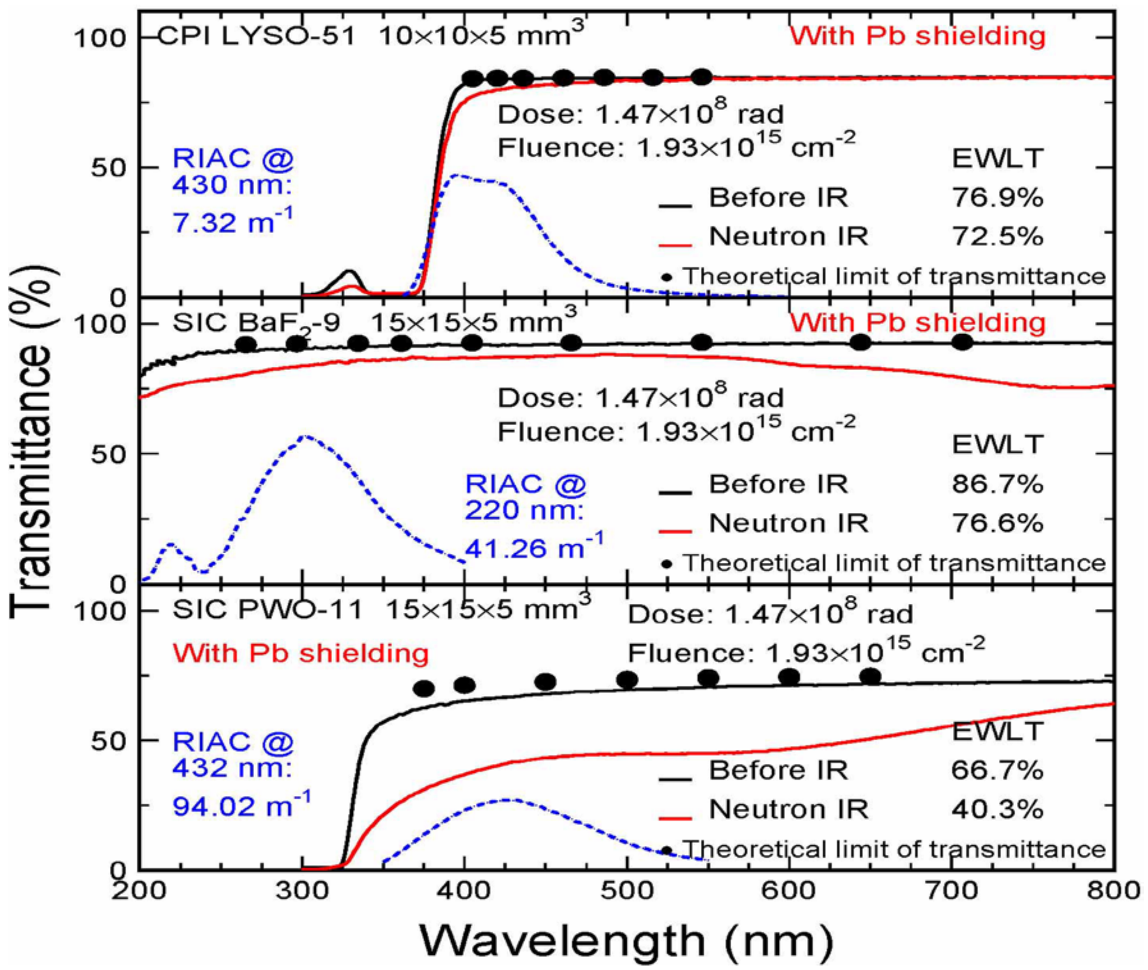
Fluence/Dose in Exp. 7332 (2016)

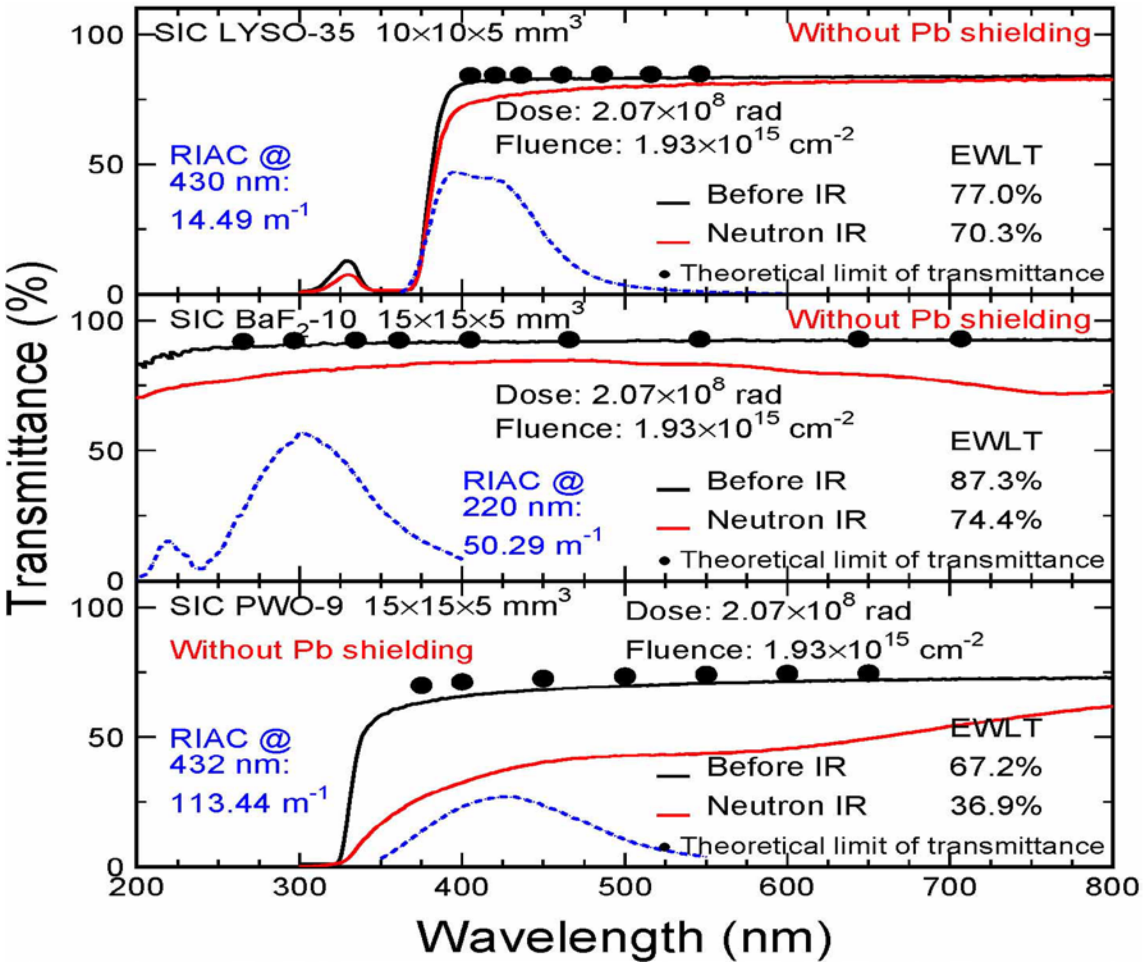
The 3 groups were irradiated for 21.2, 46.3 and 120 days respectively

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)	**4.22E+07**	**9.21E+07**	**2.07E+08**
Photons Dose (rad) with 5 mm Pb shielding	**3.00E+07**	**6.54E+07**	**1.47E+08**

Transmittance of LYSO, BaF_2 and PWO

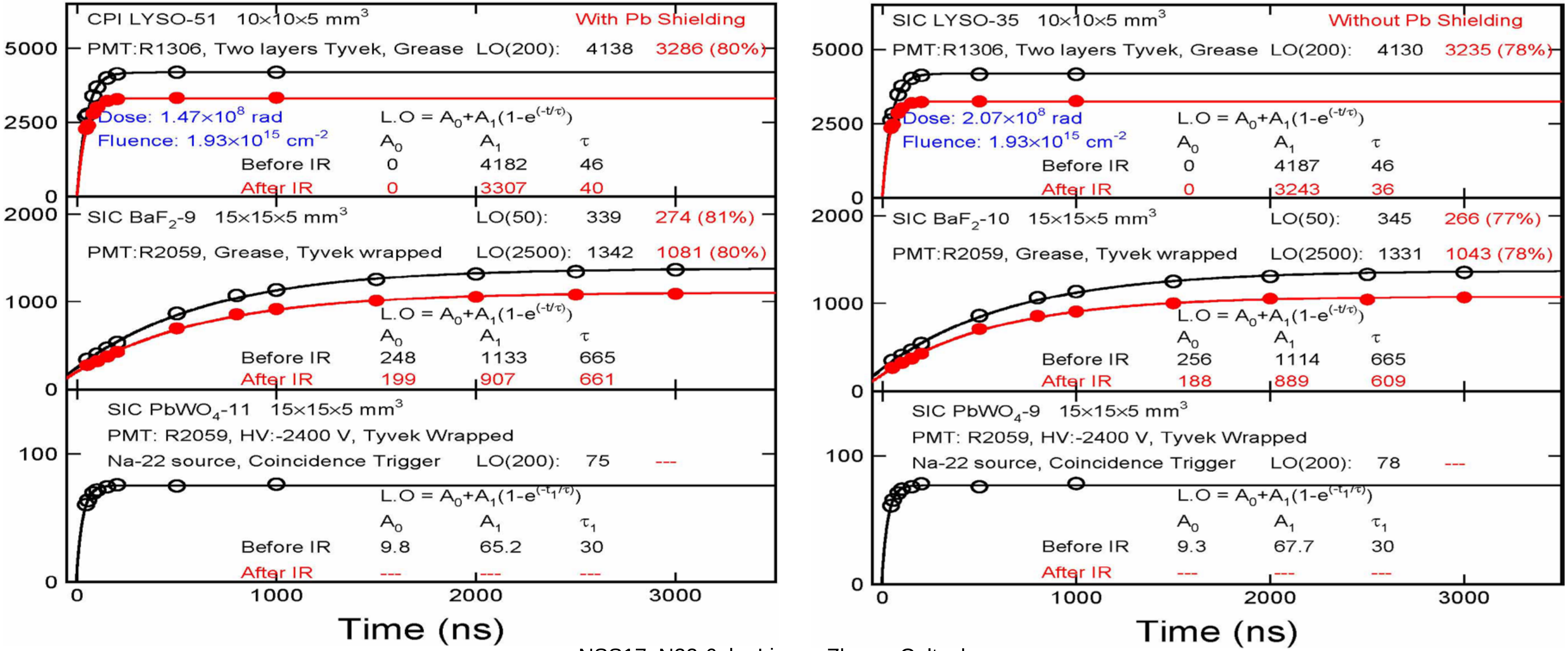
- LYSO and BaF_2 show less neutron induced absorption than PWO.
- Pb shielding reduce RIAC for all 3 kinds of crystals.





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.



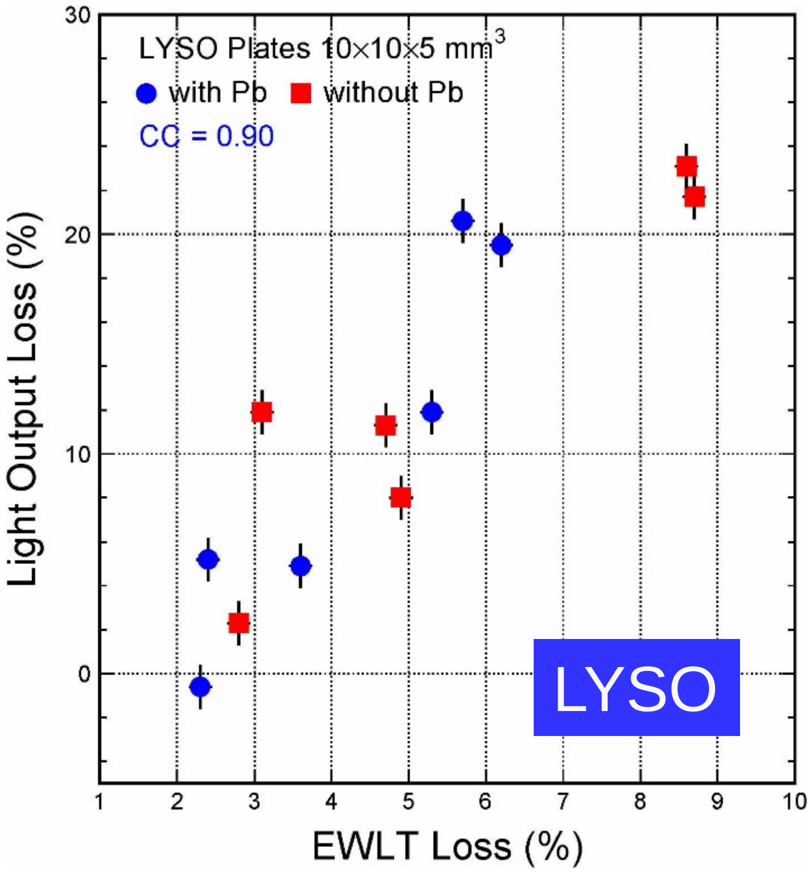
Summary: LYSO, BaF_2 and PWO

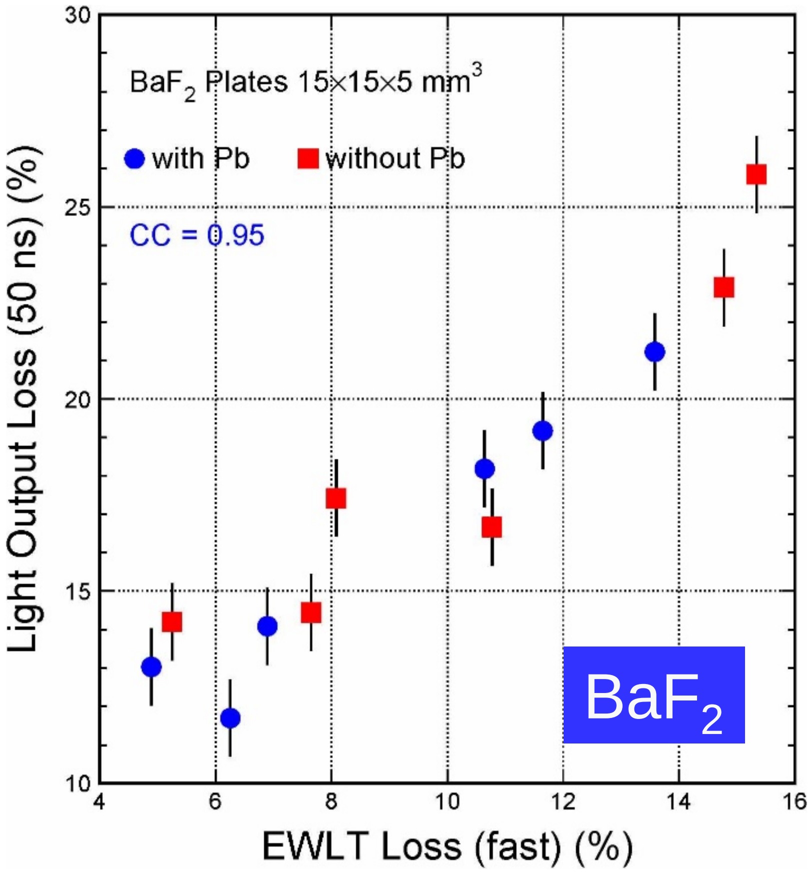
LO loss <25% of BaF_2 and LYSO after 200 Mrad plus $2\times10^{15}/cm^2$ fast neutrons (>1MeV) indicates an excellent radiation hardness

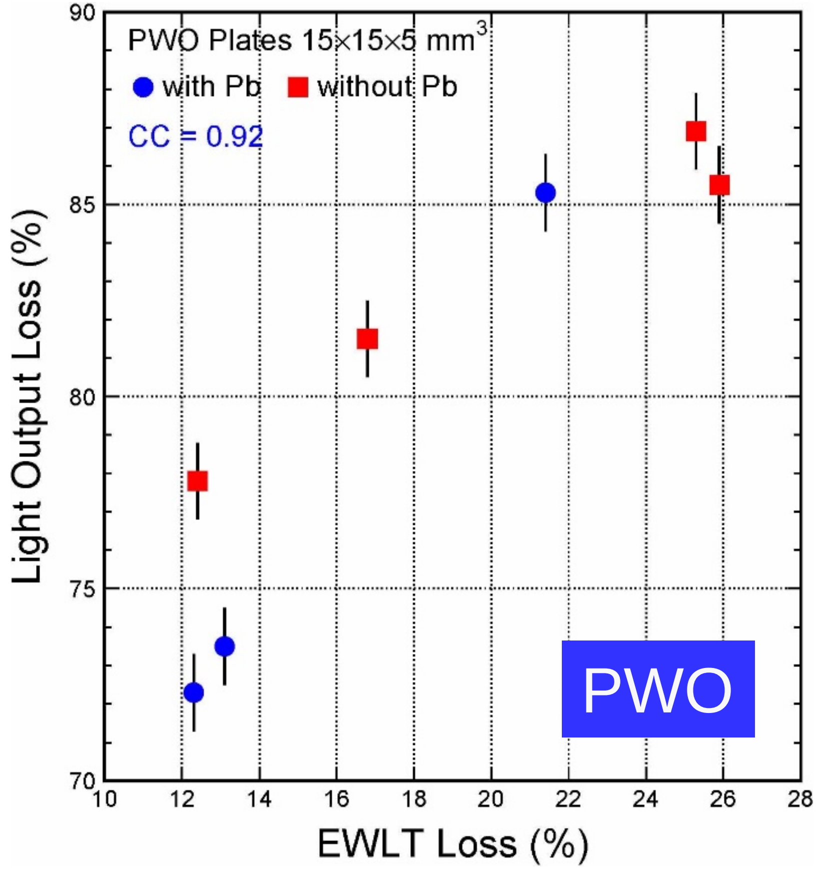
Group No.	Crystal	With Pb Shielding		Without Pb Shielding	
		EWLT Loss (%)	L.O. Loss (%)	EWLT Loss (%)	L.O. Loss (%)
Group-1 Fluence (cm^{-2}) Fast n (>1 MeV): 3.94×10^{14} Fast n (>20 MeV): 7.64×10^{13}	Dose	3.0×10^7		4.22×10^7	
	LYSO	2.4	2.3	3.8	6.8
	BaF_2	5.9	13.6	6.4	15.3
	PWO	12.7	72.9	14.6	79.7
Group-2 Fluence (cm^{-2}) Fast n (>1 MeV): 8.58×10^{14} Fast n (>20 MeV): 1.66×10^{14}	Dose	6.54×10^7		9.21×10^7	
	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	1.47×10^8		2.07×10^8	
	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 correlation between LO loss & EWLT loss is observed in all samples, indicating that crystal's LO can be corrected by a light monitoring system

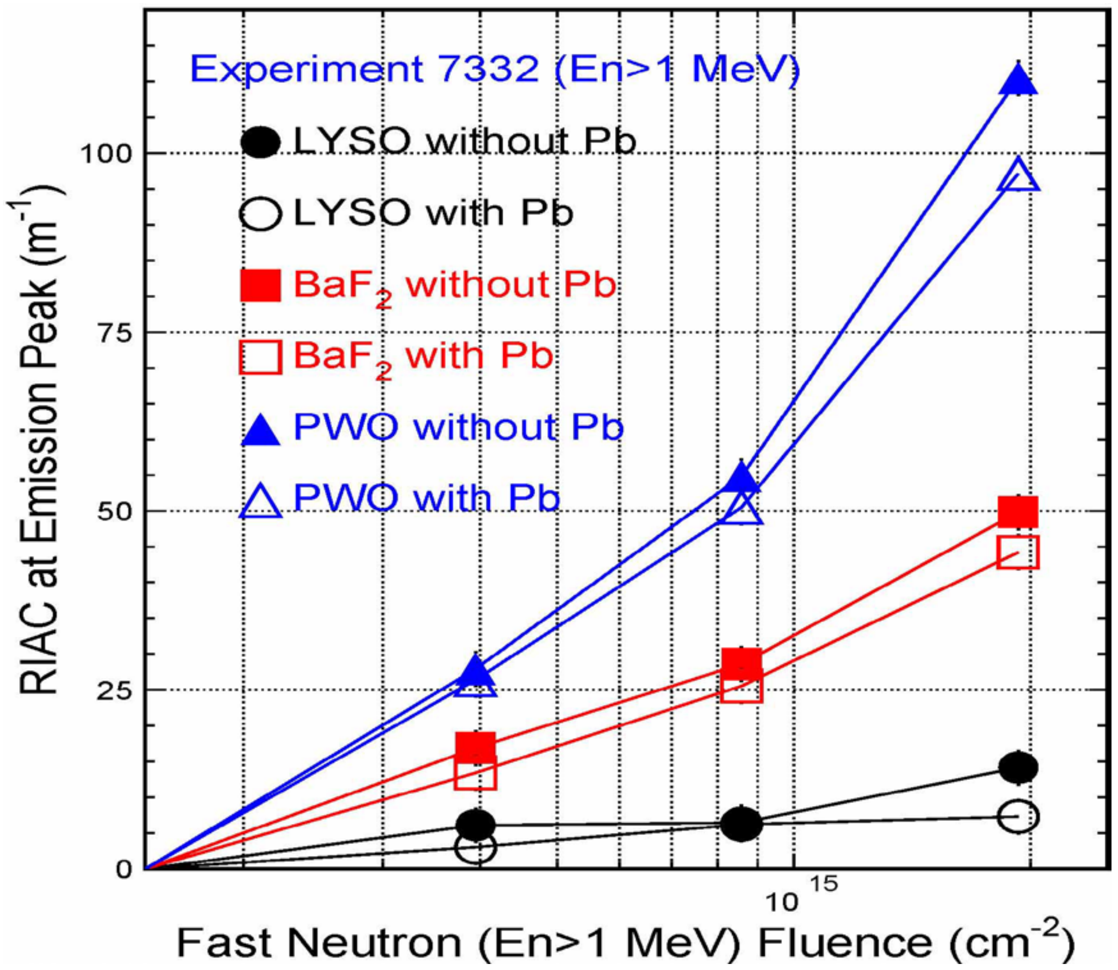


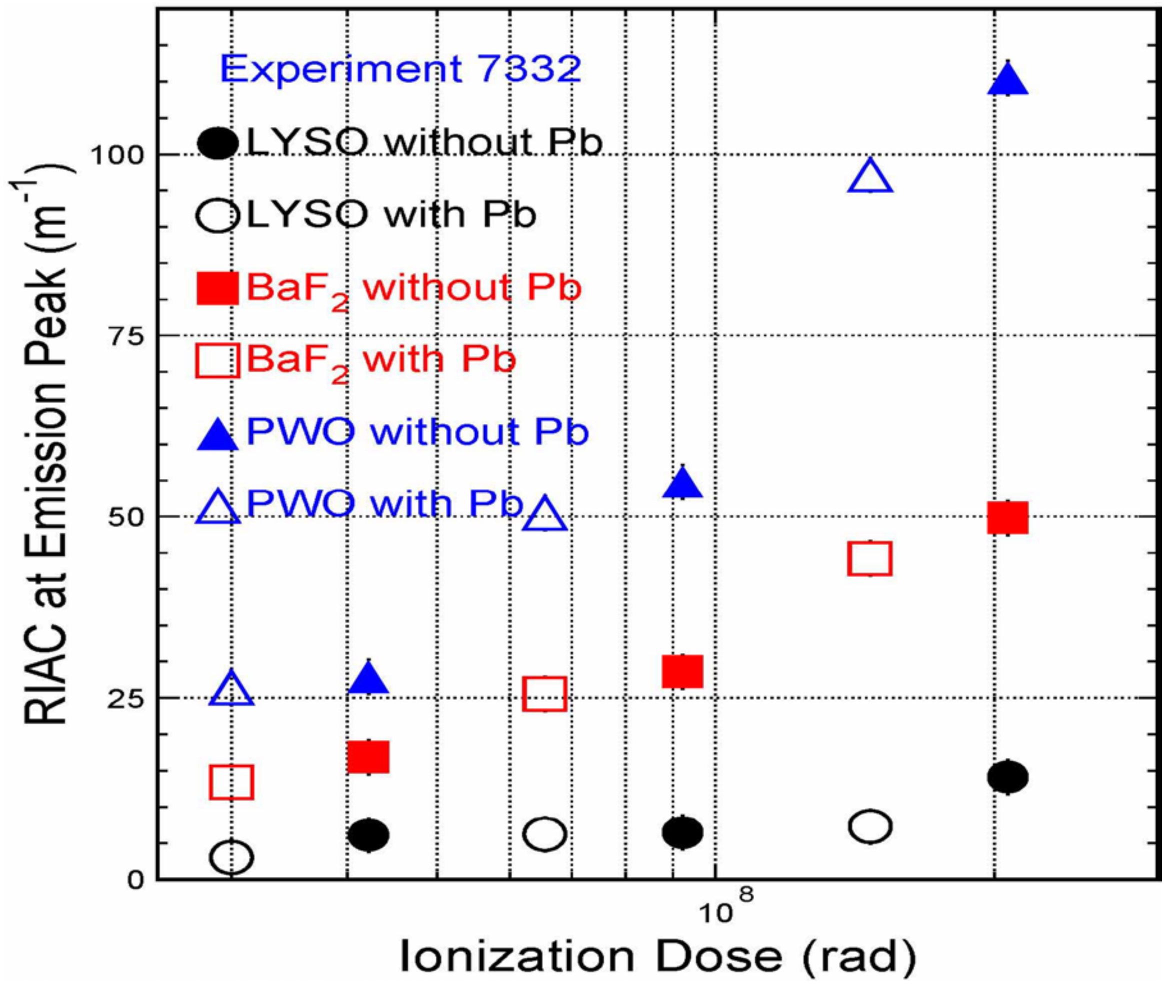




RIAC of LYSO, BaF_2 and PWO

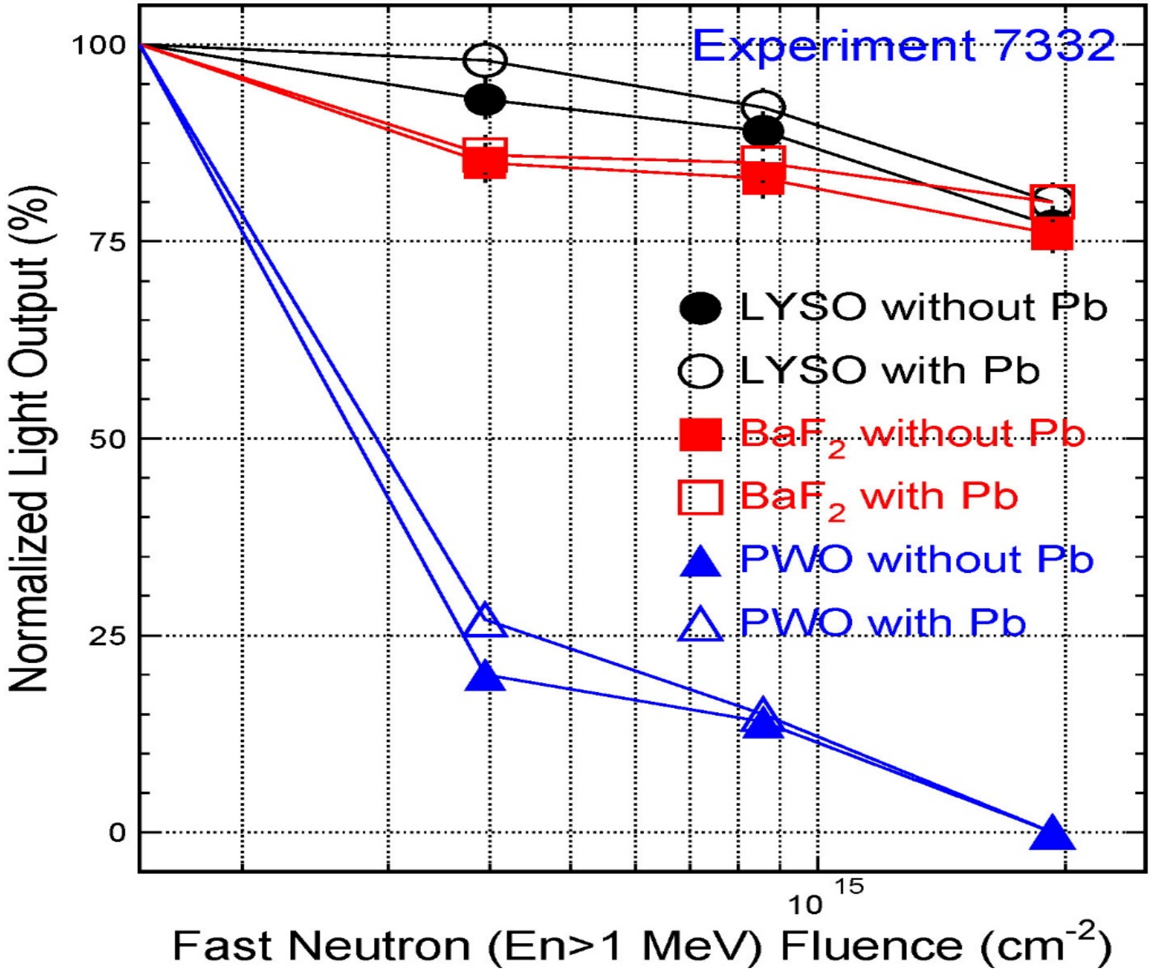
- RIAC consistent with the ionization dose, indicating neutron induced damage is negligible
- LYSO and BaF_2 show RIAC of 15 and 50 m^{-1} after 200 Mrad, much less than that of PWO

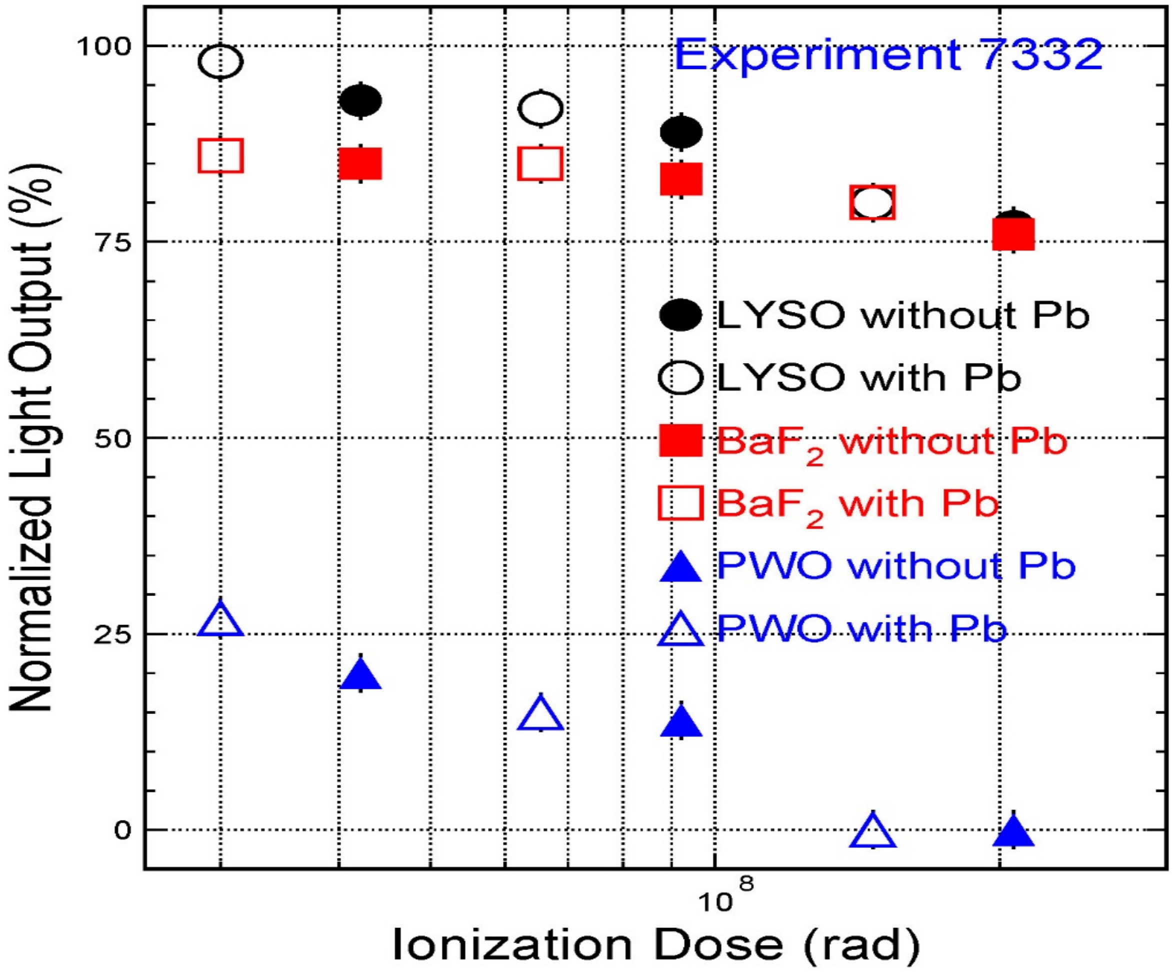




LO of LYSO, BaF_2 and PWO

- LO consistent correlation with the ionization dose, indicating neutron induce damage is negligible
- 25% LO loss of LYSO and BaF_2 after 207 Mrad plus 2×10^{15} n/cm^{-2}, indicating their excellent radiation hardness against ionization dose and fast neutrons.





Summary

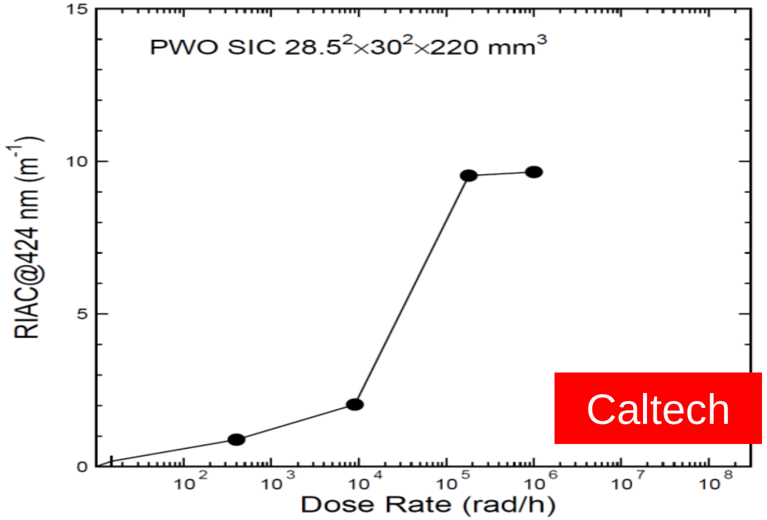
- BaF_2, LYSO and PWO crystals were irradiated by a combination of ɣ-rays, neutrons and protons at LANSCE in 2015 and 2016.

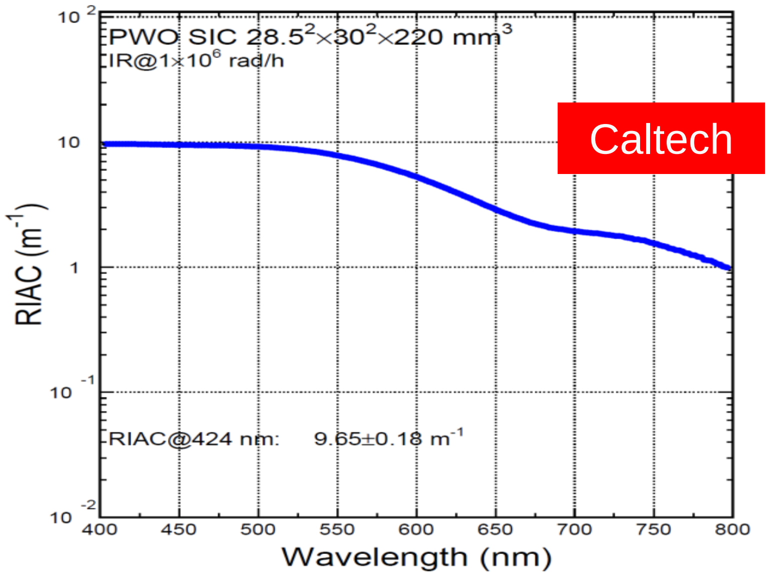
- Less than 25% light output loss is observed in BaF_2 and LYSO crystals after 200 Mrad and 2×10^{15} n/cm^2, indicating they survive the severe radiation environment expected as the HL-LHC.

- Radiation damage observed in transmittance and light output is consistent with the ionization dose, indicating neutron induced damage is negligible. This result is consistent with an early observation for PWO crystals irradiated by neutrons up to 10^{19} n/cm^2 at the Saclay reactor.

Neutron Damage in PWO 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

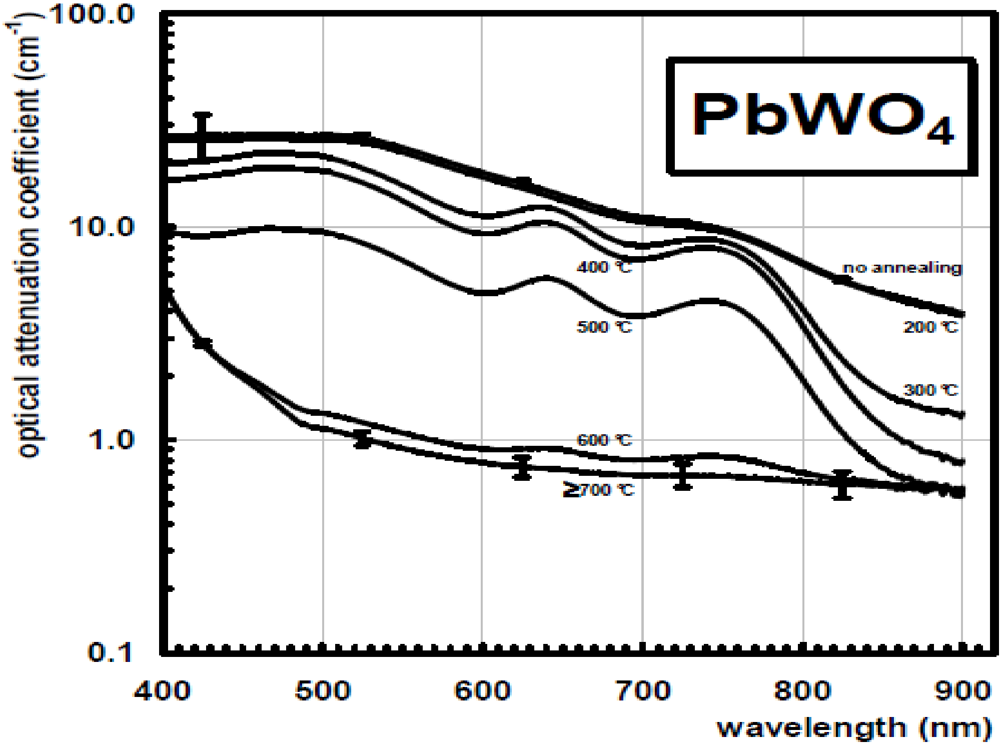


Fig. 2. Optical attenuation coefficient of the irradiated sample before annealing and after successive annealing temperatures.

[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

Energy Spectra Expected at HL-LHC

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