Irradiation Studies on Inorganic Scintillators (LYSO & BaF_2)

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Fast & Radiation Hard Scintillators

- Supported by the DOE HEP advanced detector R&D program we are developing fast and radiation hard inorganic scintillators to face the challenge for future HEP experiments at the energy and intensity frontiers.
- Our investigation shows that LYSO:Ce, BaF_2 and LuAG:Ce will survive the radiation environment expected at the HL-LHC with 3,000 fb^{-1}. LYSO is proposed for a precision MIP Timing Detector for the CMS Phase-II upgrade for the HL-LHC:
  - Ionizations dose: up to 100 Mrad,
  - Charged hadron fluence: up to 6×10^{14} p/cm^2,
  - Fast neutron fluence: up to 3×10^{15} n/cm^2.
- Ultra-fast scintillators with excellent radiation hardness is also needed to face the challenge of unprecedented event rate expected by future HEP experiments at the intensity frontier, such as Mu2e-II, and the GHz hard X-ray imaging for the proposed Marie project at Los Alamos National Laboratory.
- Yttrium doped BaF_2 with a sub-ns FWHM pulse width and a suppressed slow scintillation component is a leading candidate for both applications.

Fast Inorganic Scintillators for HEP

	LSO:Ce	LYSO:Ce,Ca [1]	LuAG:Ce[2]	LuAG:Pr[3]	GGAG:Ce[4,5]	CsI	BaF_2[6]	BaF_2:Y	$CeBr_3$	$LaBr_3$:Ce[7]
Density (g/cm^3)	7.4	7.4	6.76	6.76	6.5	4.51	4.89	4.89	5.23	5.29
Melting points (°C)	2050	2050	2060	2060	1850[d]	621	1280	1280	722	783
X_0 (cm)	1.14	1.14	1.45	1.45	1.63	1.86	2.03	2.03	1.96	1.88
R_M (cm)	2.07	2.07	2.15	2.15	2.20	3.57	3.1	3.1	2.97	2.85
λ_I (cm)	20.9	20.9	20.6	20.6	21.5	39.3	30.7	30.7	31.5	30.4
Z_{eff}	64.8	64.8	60.3	60.3	51.8	54.0	51.6	51.6	45.6	45.6
dE/dX (MeV/cm)	9.55	9.55	9.22	9.22	8.96	5.56	6.52	6.52	6.65	6.90
λ_{peak} [a] (nm)	420	420	520	310	540	310	300 220	300 220	371	360
PL Emission Peak (nm)	402	402	500	308	540	310	300 220	300 220	350	360
PL Excitation Peak (nm)	358	358	450	275	445	256	<200	<200	330	295
Absorption Edge (nm)	170	170	160	160	190	200	140	140	n.r.	220
Refractive Index[b]	1.82	1.82	1.84	1.84	1.92	1.95	1.50	1.50	1.9	1.9
Normalized Light Yield[a,c]	100	116[e]	35[f] 48[f]	44 41	40 75	4.2 1.3	42 5.0	1.7 5.0	99	153
Total Light yield (ph/MeV)	30,000	34,800[e]	25,000[f]	25,800	34,700	1,700	13,000	2,100	30,000	46,000
Decay time[a] (ns)	40	31[e]	981[f] 64[f]	1208 26	319 101	30 6	600 0.6	600 0.6	17	20
Light Yield in 1st ns (photons/MeV)	740	950	240	520	260	100	1200	1200	1,700	2,200
Issues					neutron x-section	Slightly hygroscopic	Slow component	DUV PD	hygroscopic	

Fast Inorganic Scintillators (II)

a. Top line: slow component, bottom line: fast component;

b. At the wavelength of the emission maximum;

c. Excited by Gamma rays;

d. For $Gd_3Ga_3Al_2O_{12}$:Ce

e. For 0.4 at% Ca co-doping

f. Ceramic with 0.3 Mg at% co-doping

g. Defined as LY(2 to 4 ns)/LY(0 to 2 ns)

[1] Spurrier, et al., *IEEE T. Nucl. Sci.* 2008,55 (3): 1178-1182

[2] Liu, et al., *Adv. Opt. Mater.* 2016, 4(5): 731–739

[3] Hu, et al., *Phys. Rev. Applied* 2016, 6: 064026

[4] Lucchini, et al., *NIM A* 2016, 816: 176-183

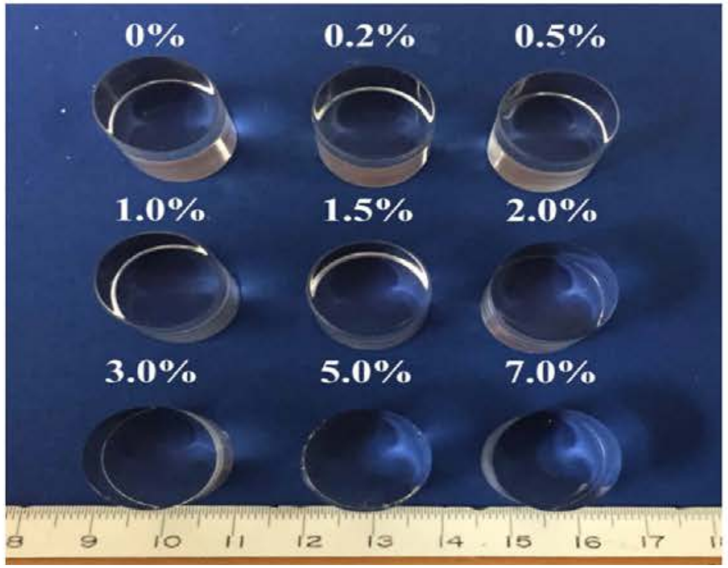
[5] Meng, et al., *Mat. Sci. Eng. B-Solid* 2015, 193: 20-26

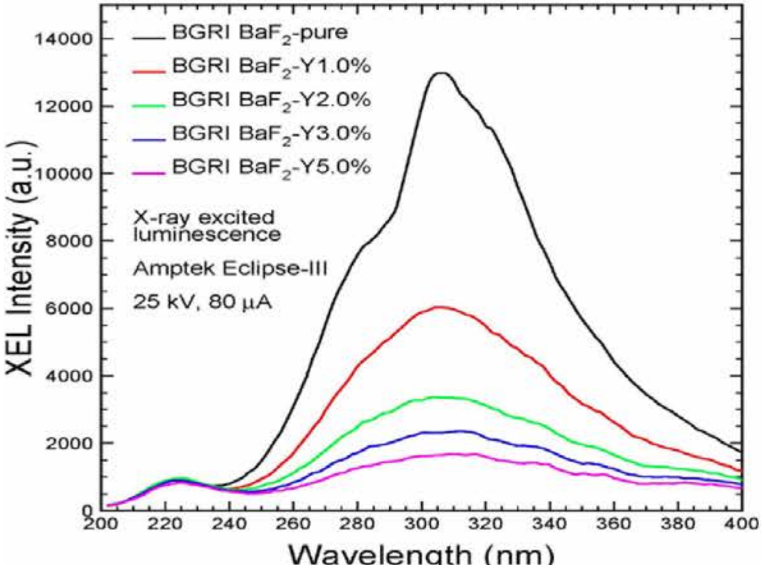
[6] Diehl, et al., *J. Phys. Conf. Ser* 2015, 587: 012044

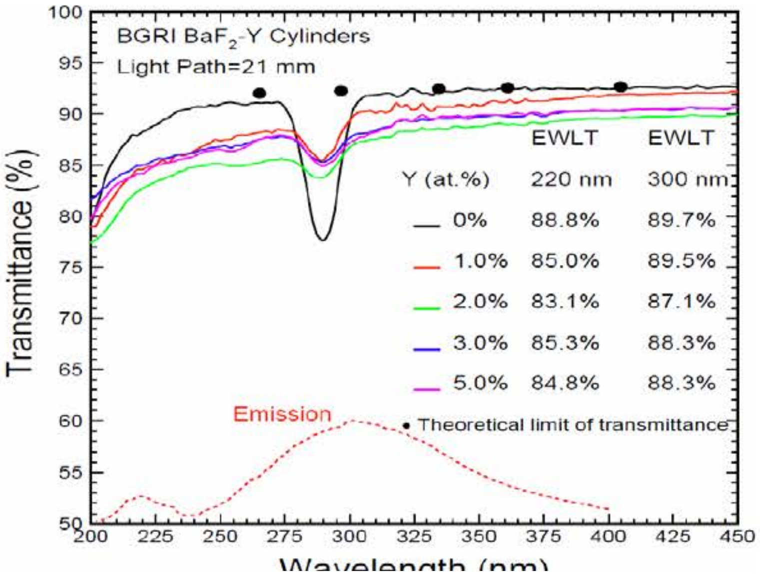
[7] Pustovarov, et al., Tech. Phys. Lett. 2012, 784-788

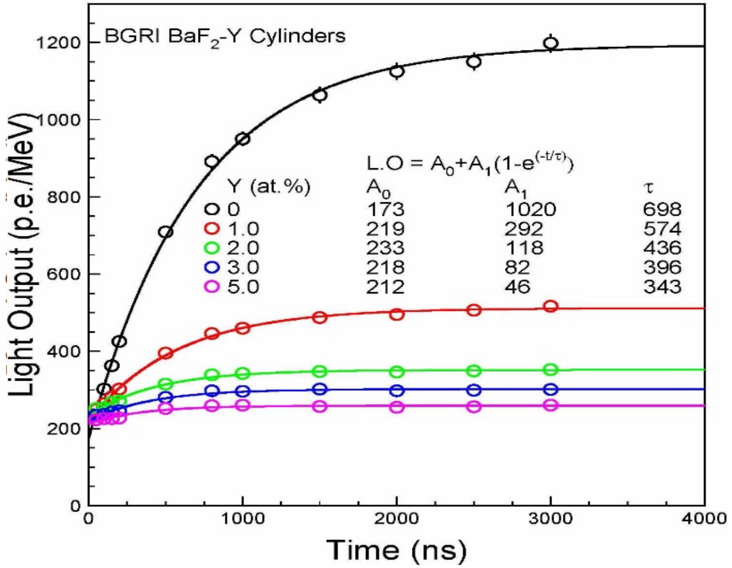
Optimization of Yttrium Doping in BaF_2

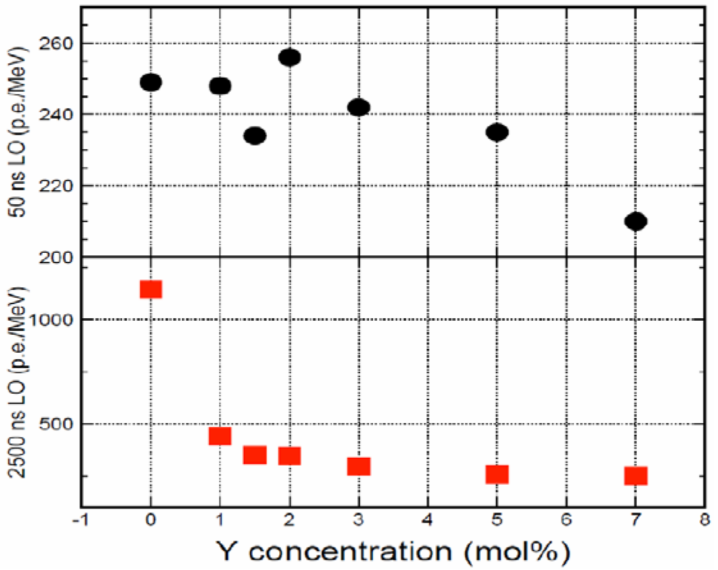
F/S ratio from 1/5 to 5/1 , presented in TIPP 2017, Beijing

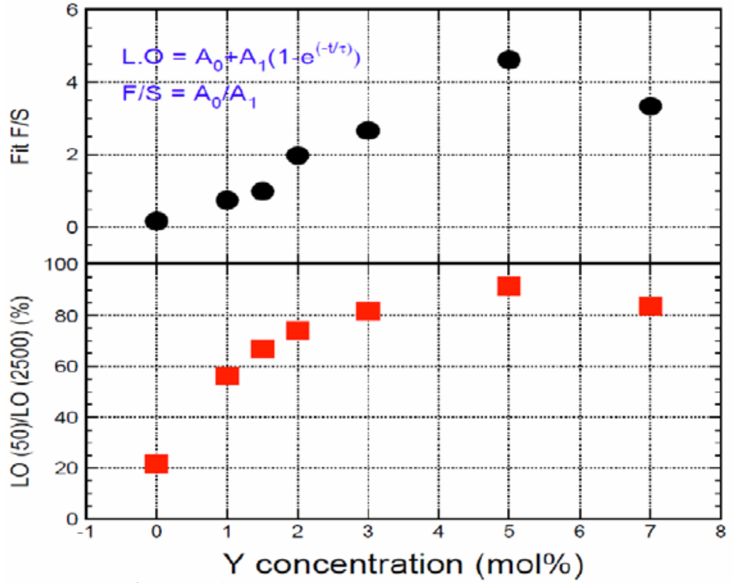






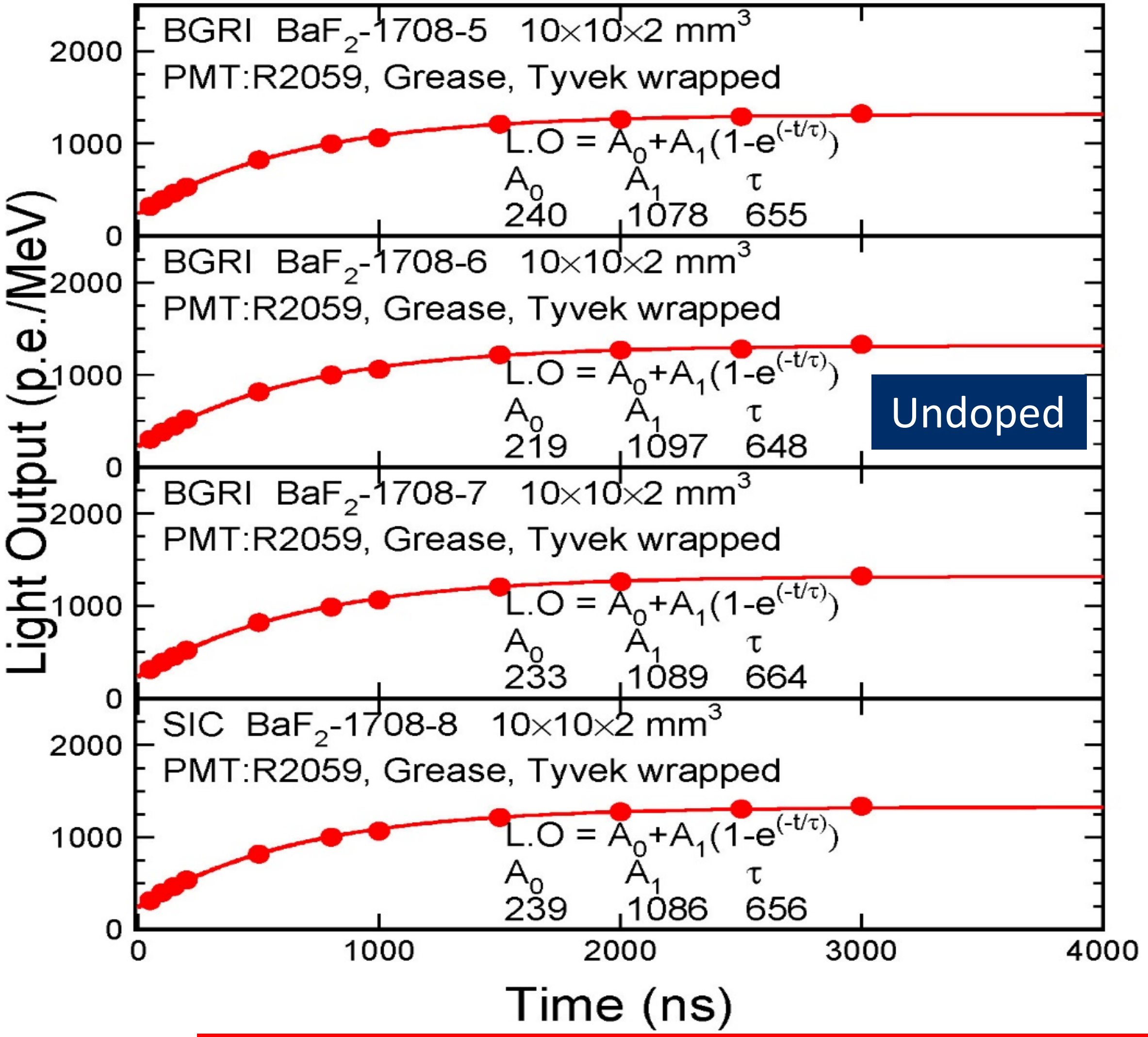


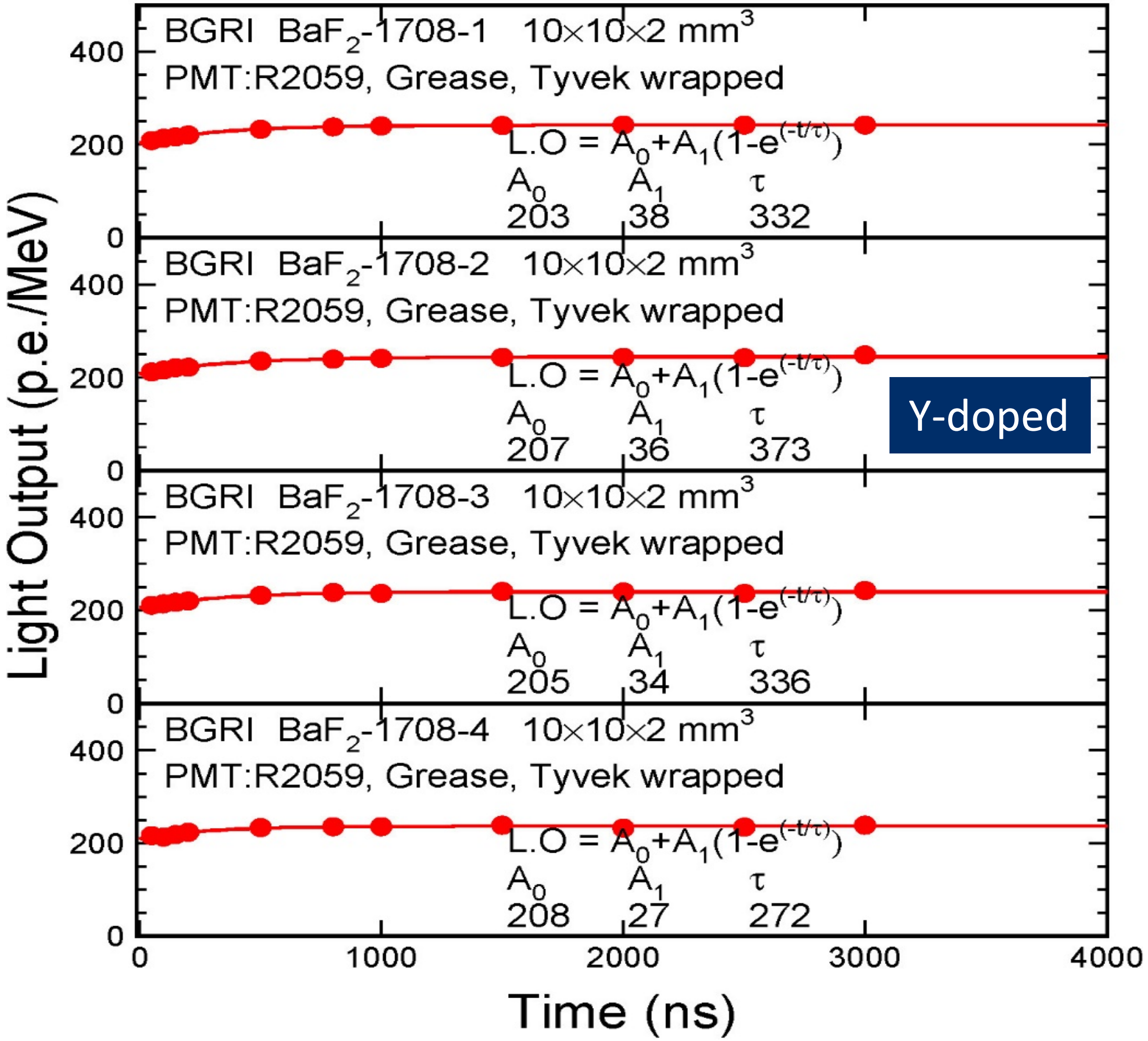




Optimized Y Doping in BaF_2

F/S ratio increased from 0.21 to 6 .2, presented in CPAD 2017, Albuquerque

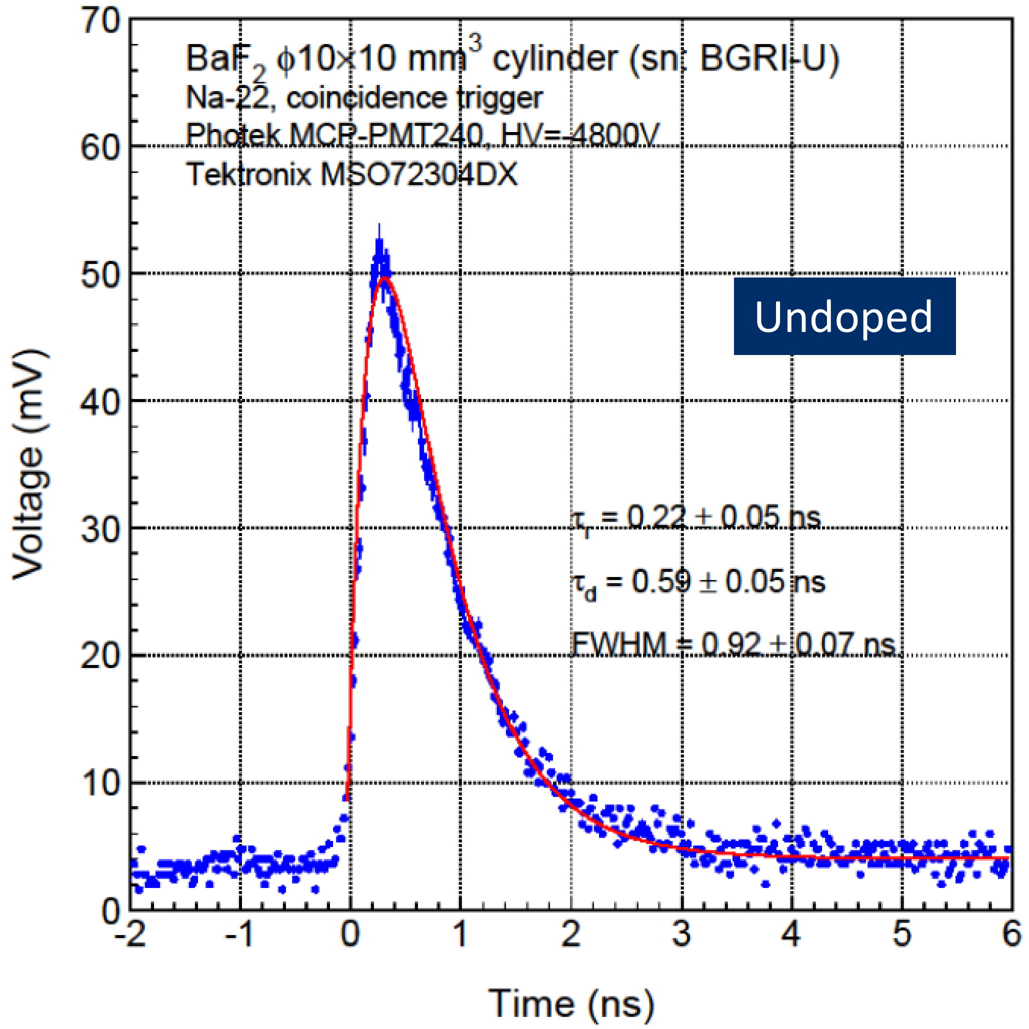


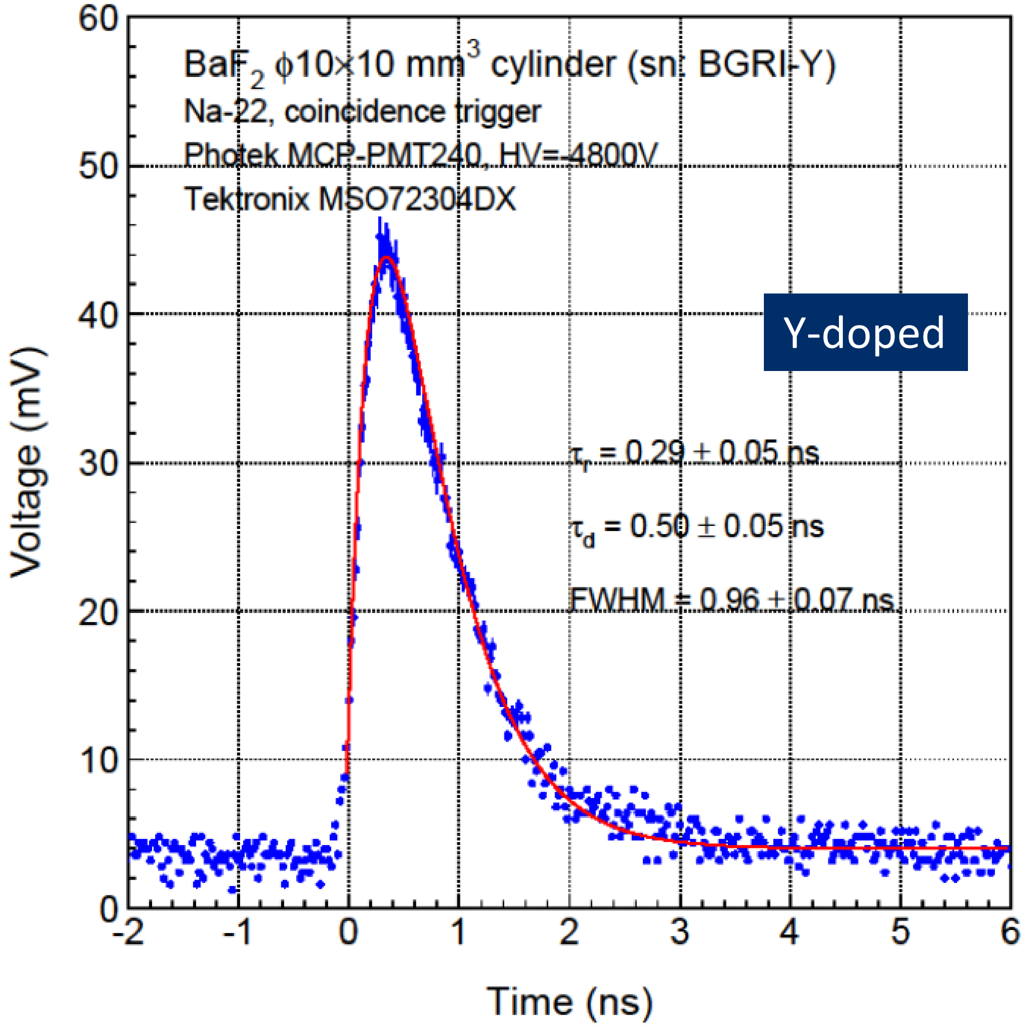


Samples are being irradiation up to 200 Mrad and $2x10^{15}$ n/cm^2 in East Port of LANSCE

Pulse Shape: BaF_2 Cylinders

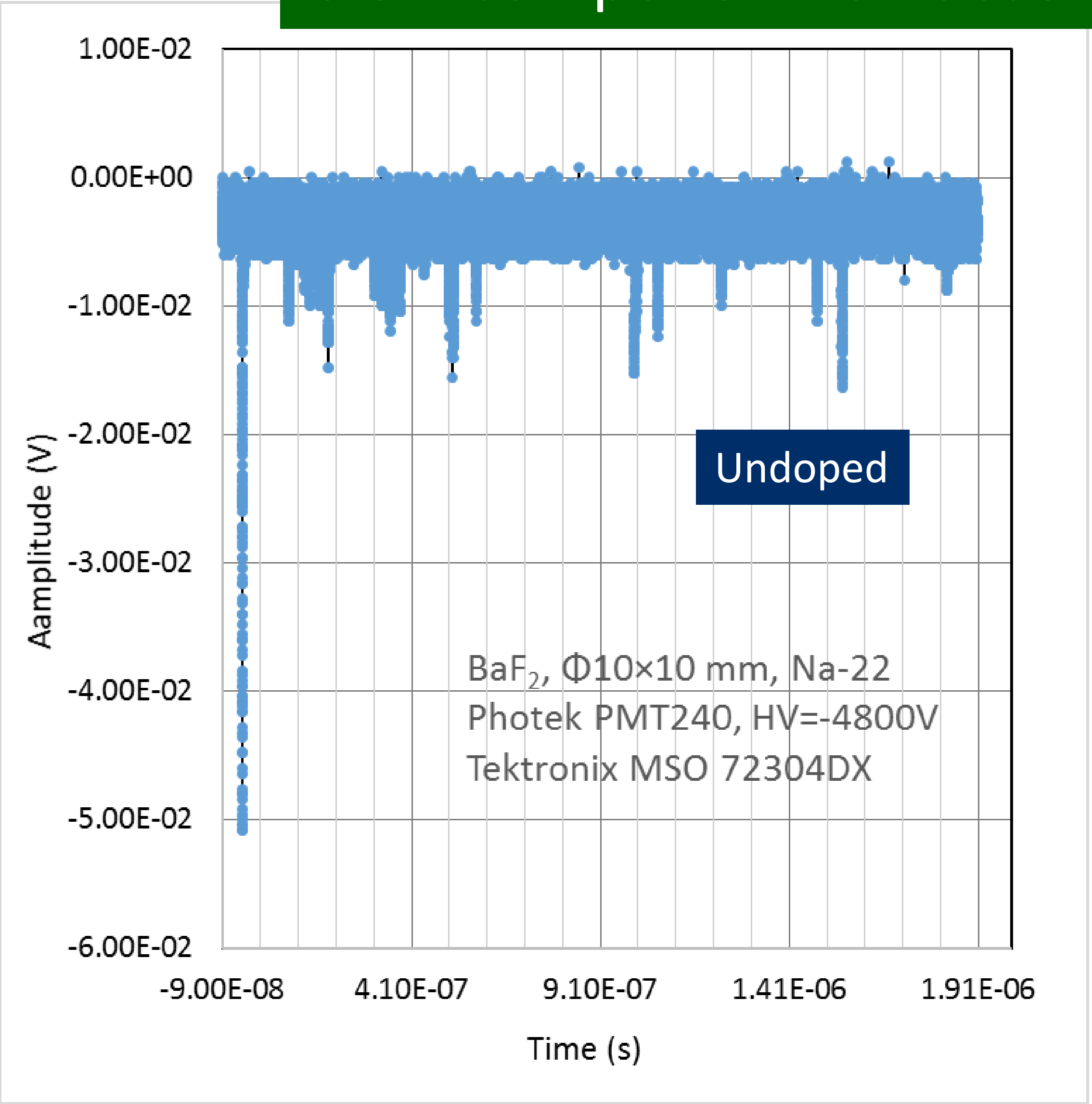
BGRI BaF_2 cylinders of Φ10×10 mm^3 shows ɣ-ray response: 0.26/0.55/0.94 ns of rising/decay/FWHM width

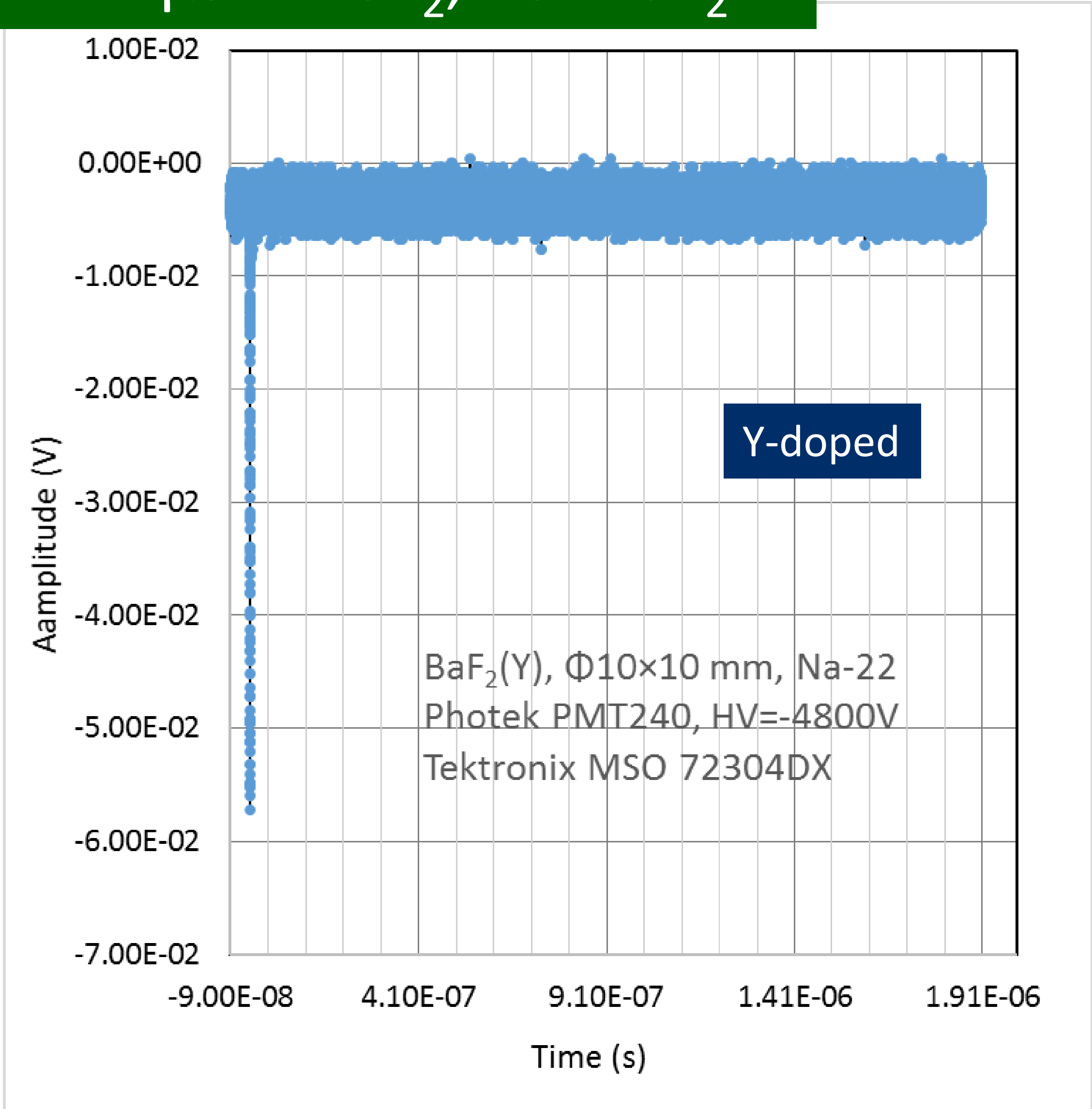




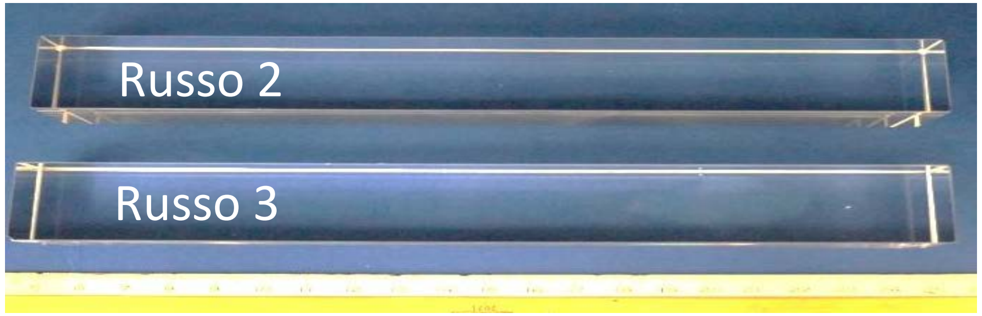
Scintillation Pulse Tail Reduced in BaF_2:Y

Slow component tail observed in 2 μs in BaF_2, not BaF_2:Y





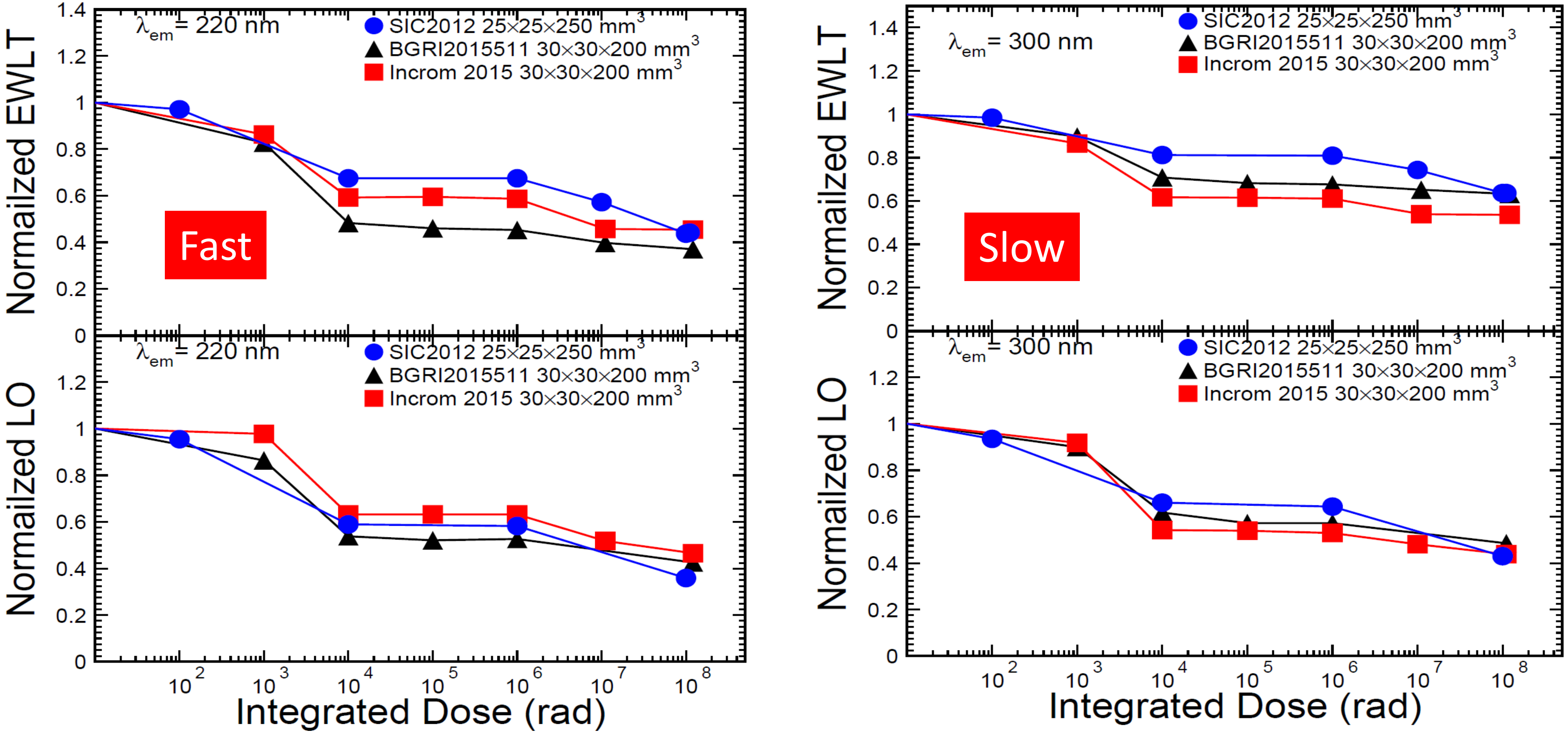
BGRI/Incrom/SIC BaF_2 Crystals



ID	Vendor	Dimension (mm^3)	Polishing
SIC 1-20	SICCAS	30x30x250	Six faces
BGRI-2015 D, E, 511	BGRI	30x30x200	Six faces
Russo 2, 3	Incrom	30x30x200	Six faces

γ-ray Induced Damage in BaF_2

Consistent damage in crystals from three vendors

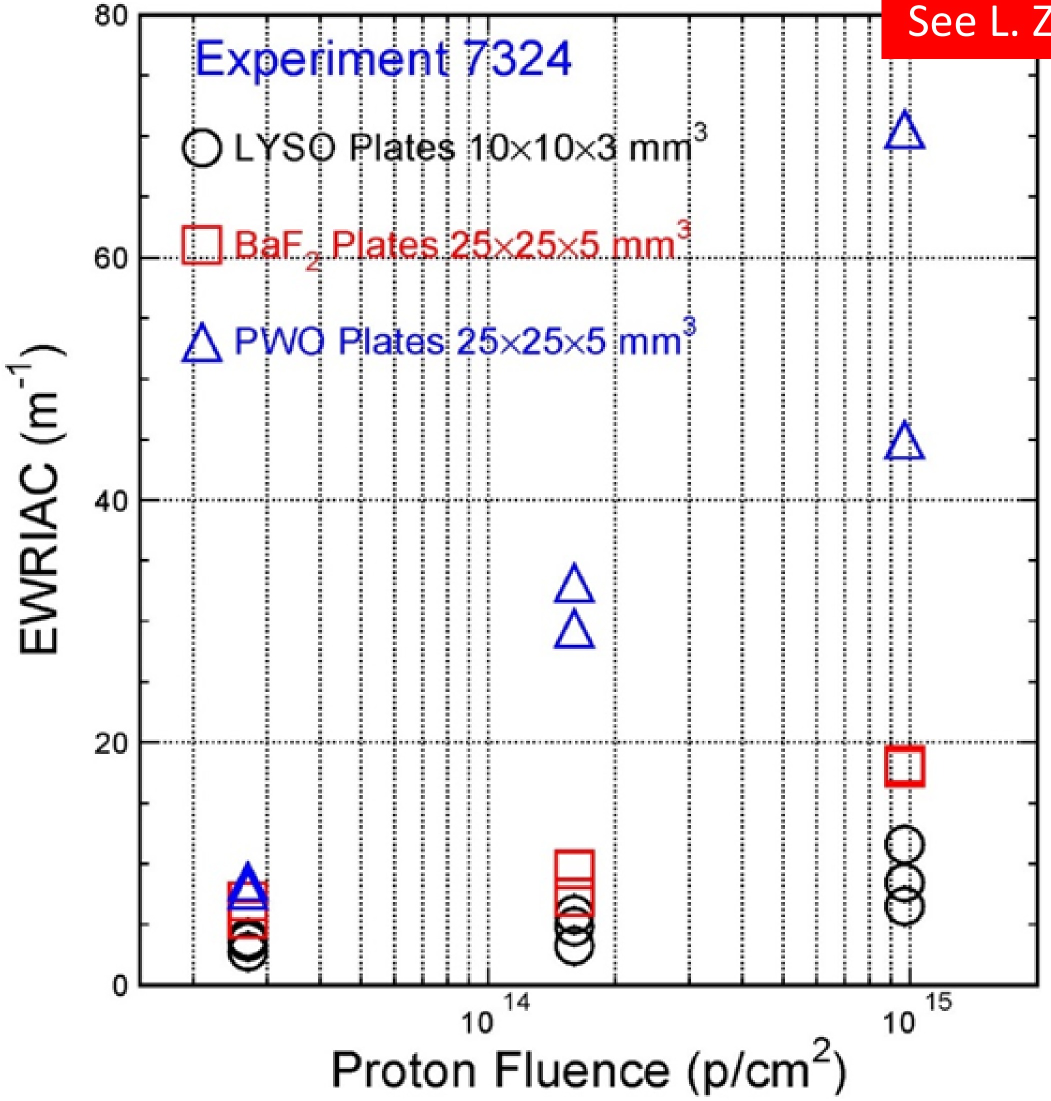


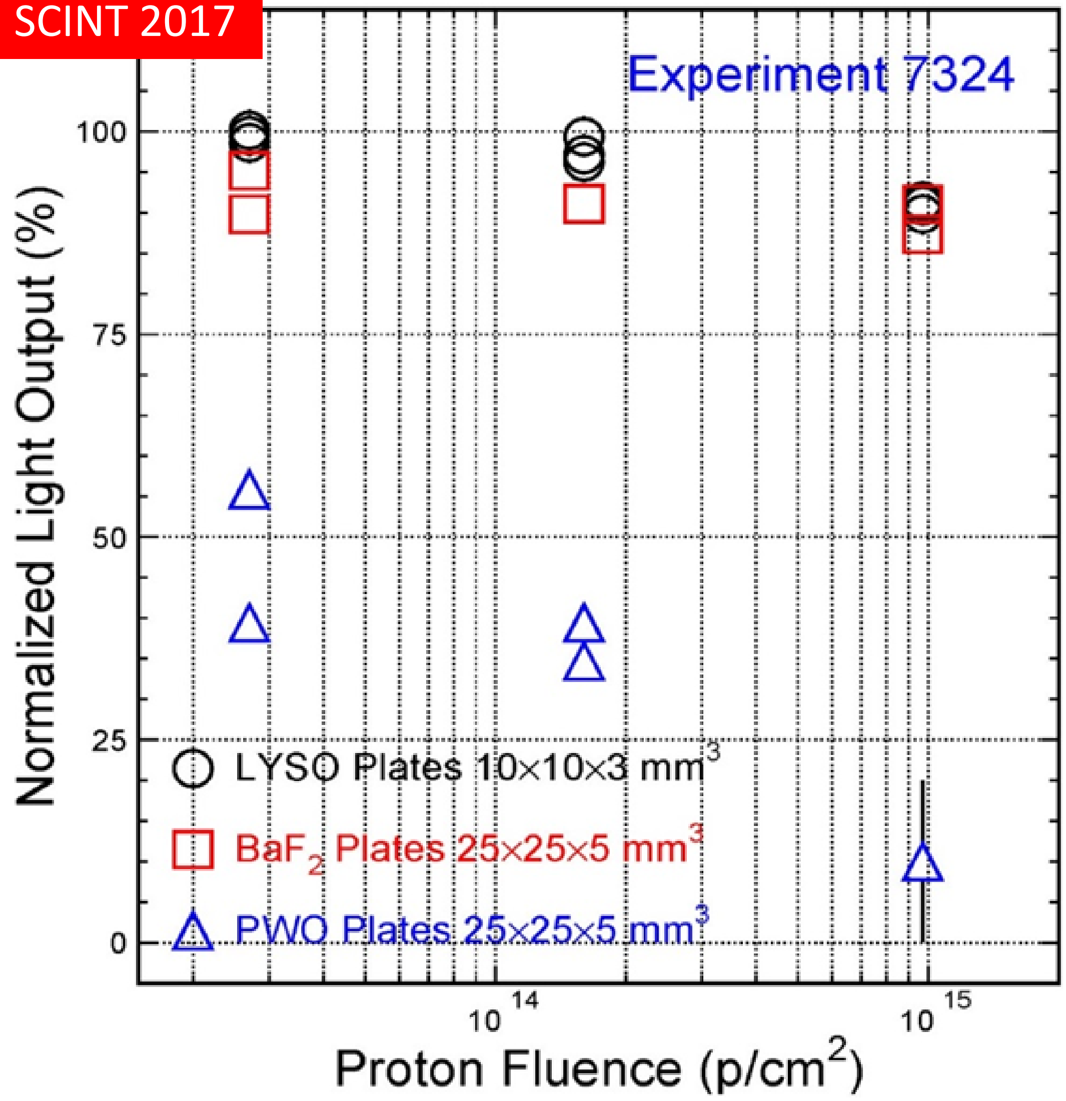
Remaining light output after 120 Mrad: 40%/45% for the fast/slow component

Proton Damage in LYSO/BaF_2/PWO

Excellent radiation hardness of LYSO and BaF_2 up to 10^{15} p/cm^2

See L. Zhang in SCINT 2017

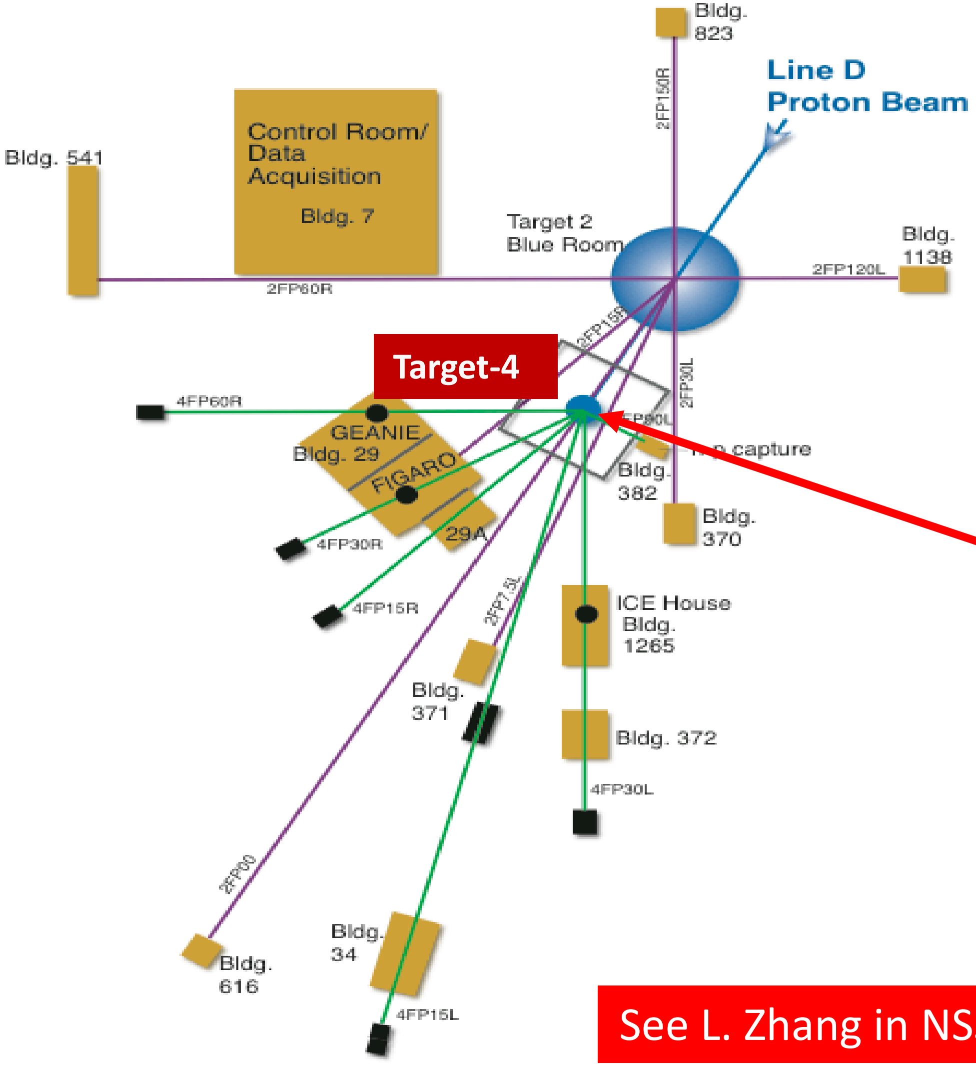


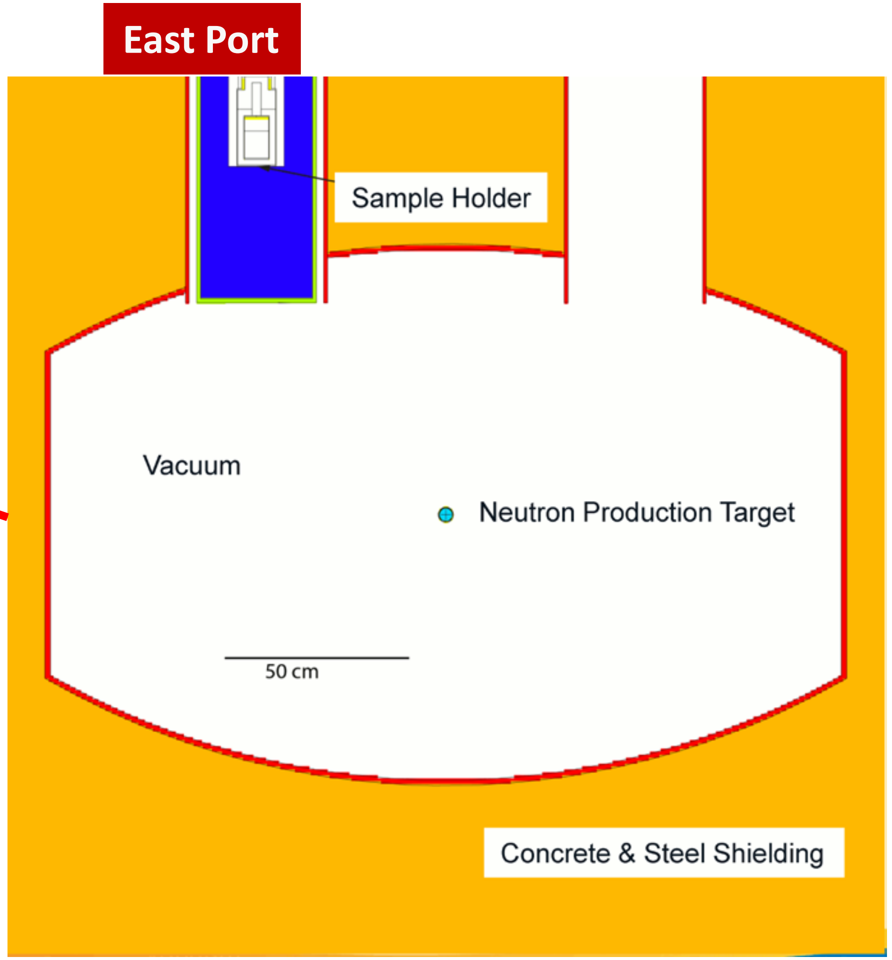


Neutron Irradiation at LANSCE

Los Alamos Neutron Science Center (LANSCE)

Samples placed at Target-4 East Port about 1.2 m away from the target

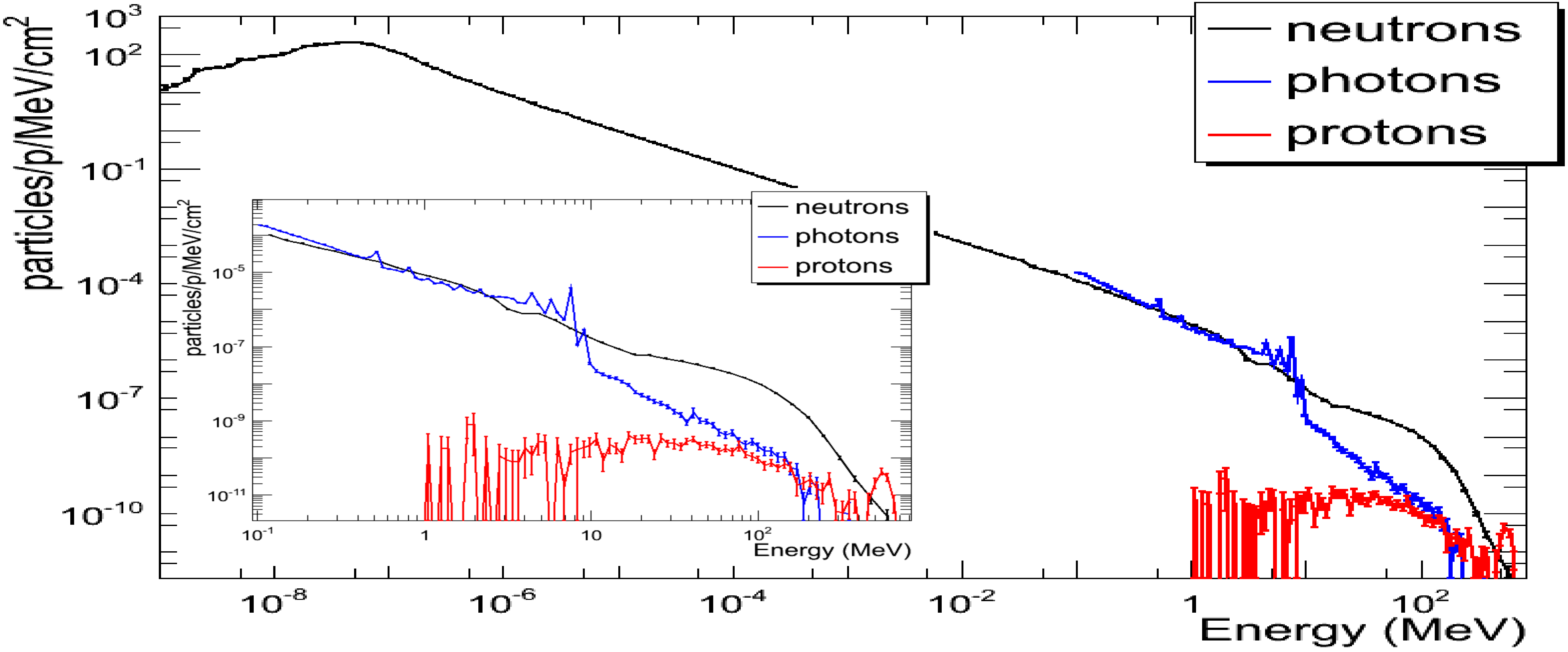




See L. Zhang in NSS 2017

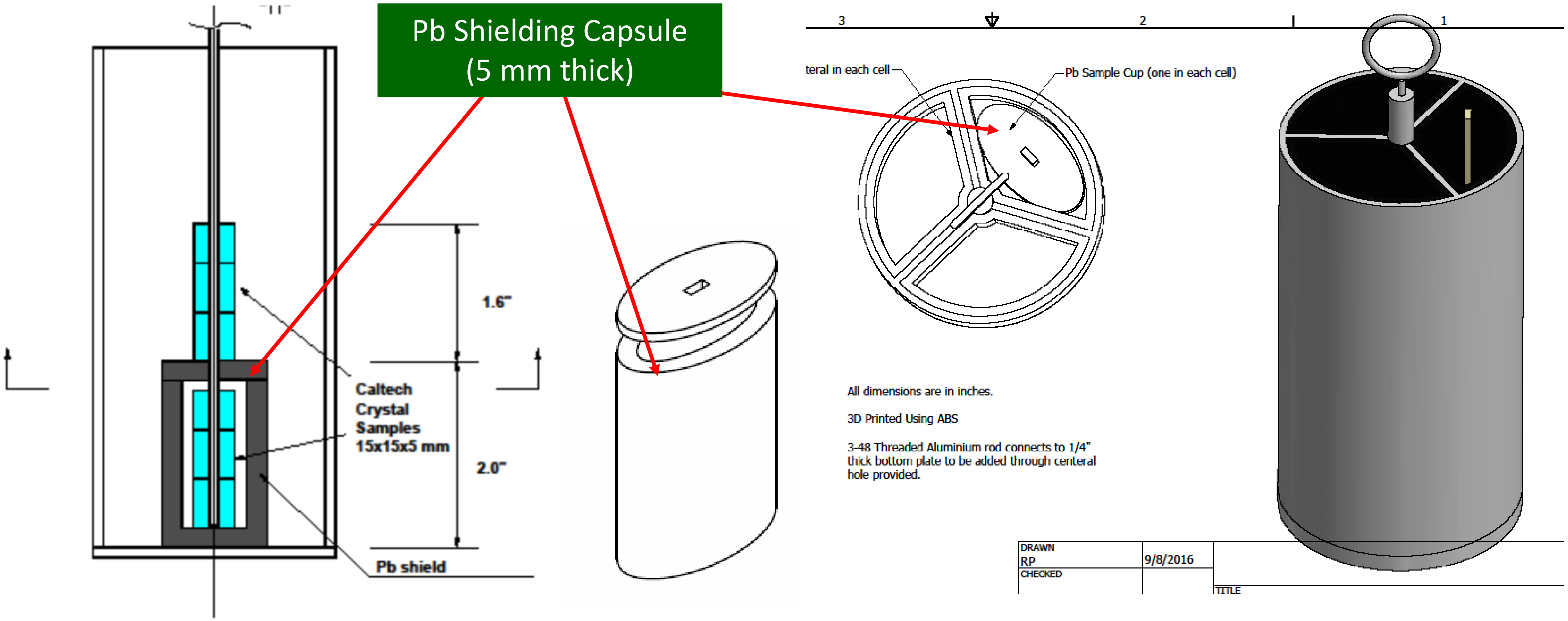
n/γ/p Spectra and Production Rate

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)



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

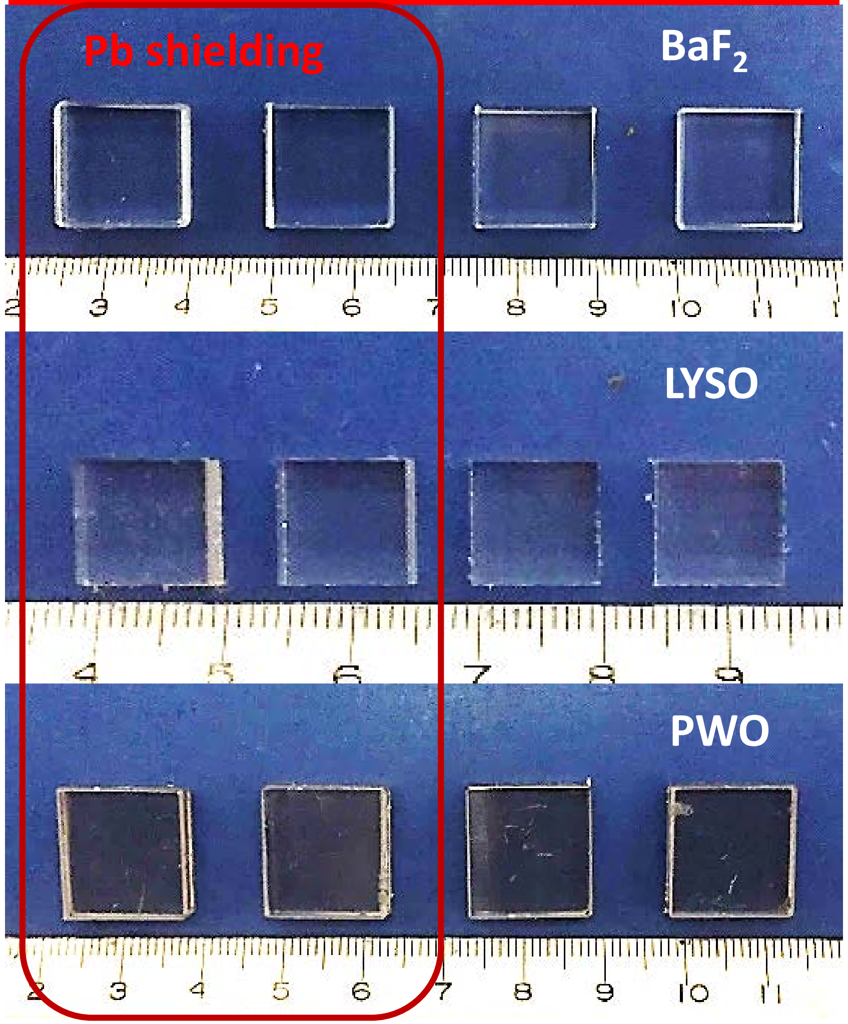


Samples of Exp. 7332 (2016)

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	

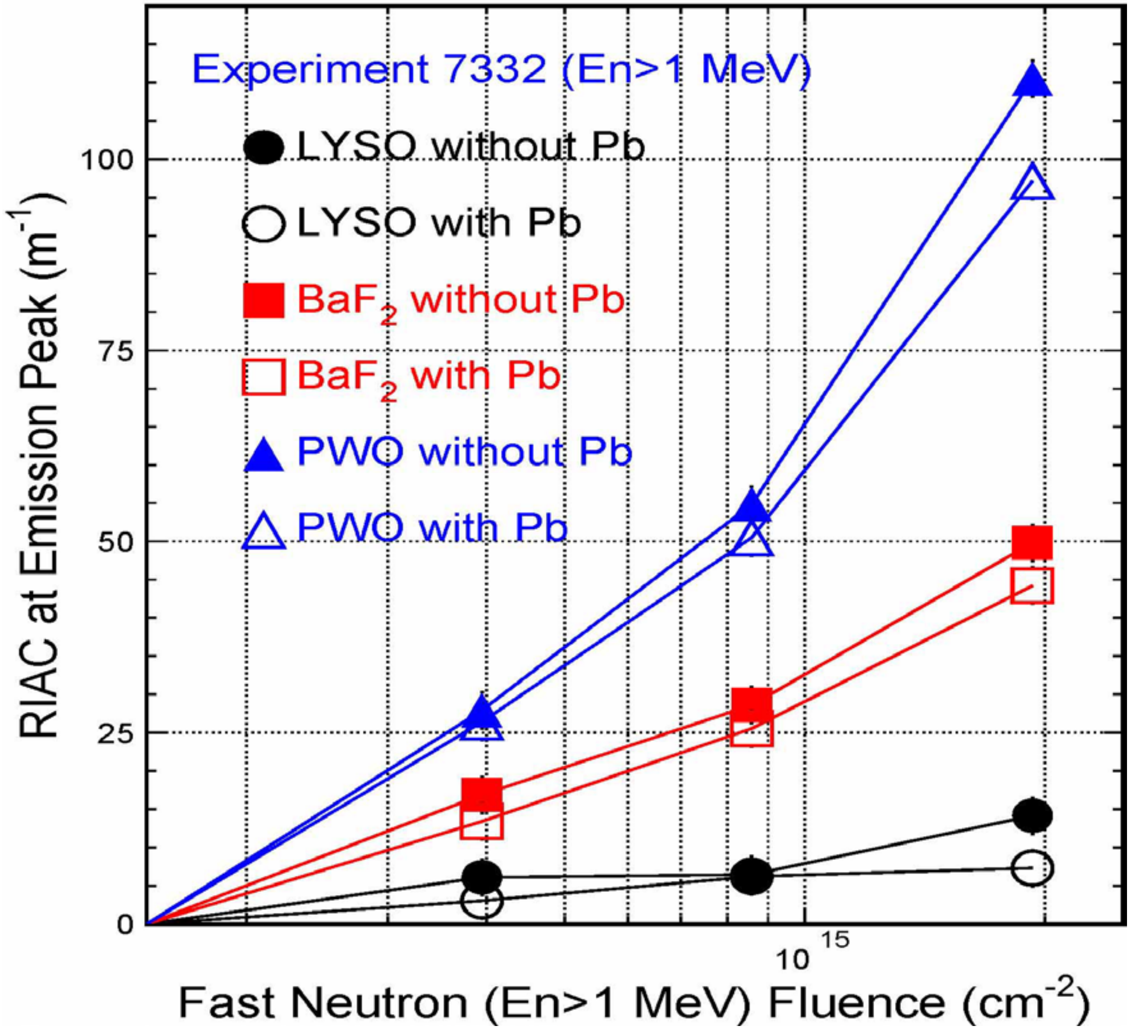
Group-3 Samples after Irradiation

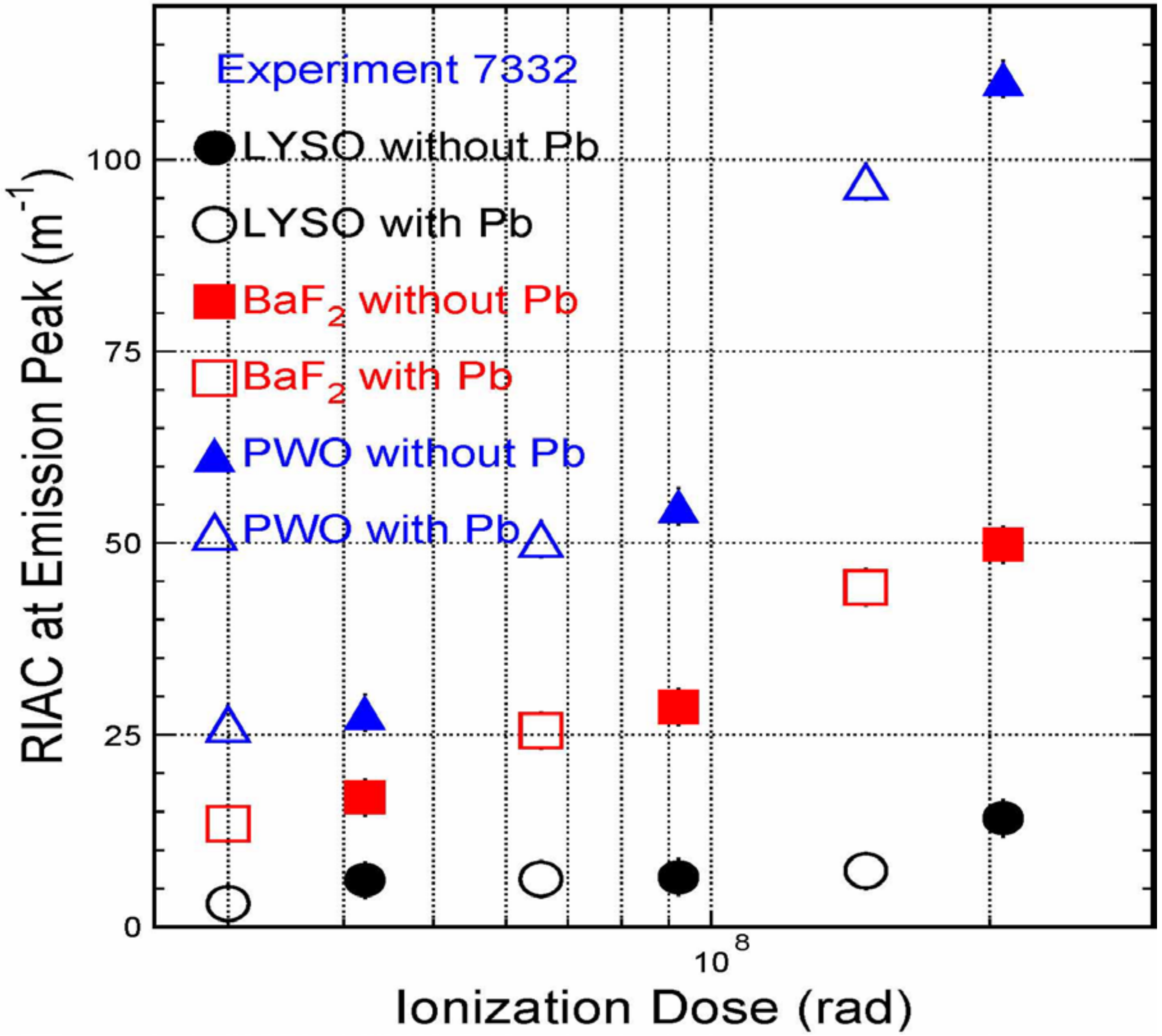


RIAC of LYSO, BaF_2 and PWO

RIAC consistent with the ionization dose, indicating neutron induced damage is negligible

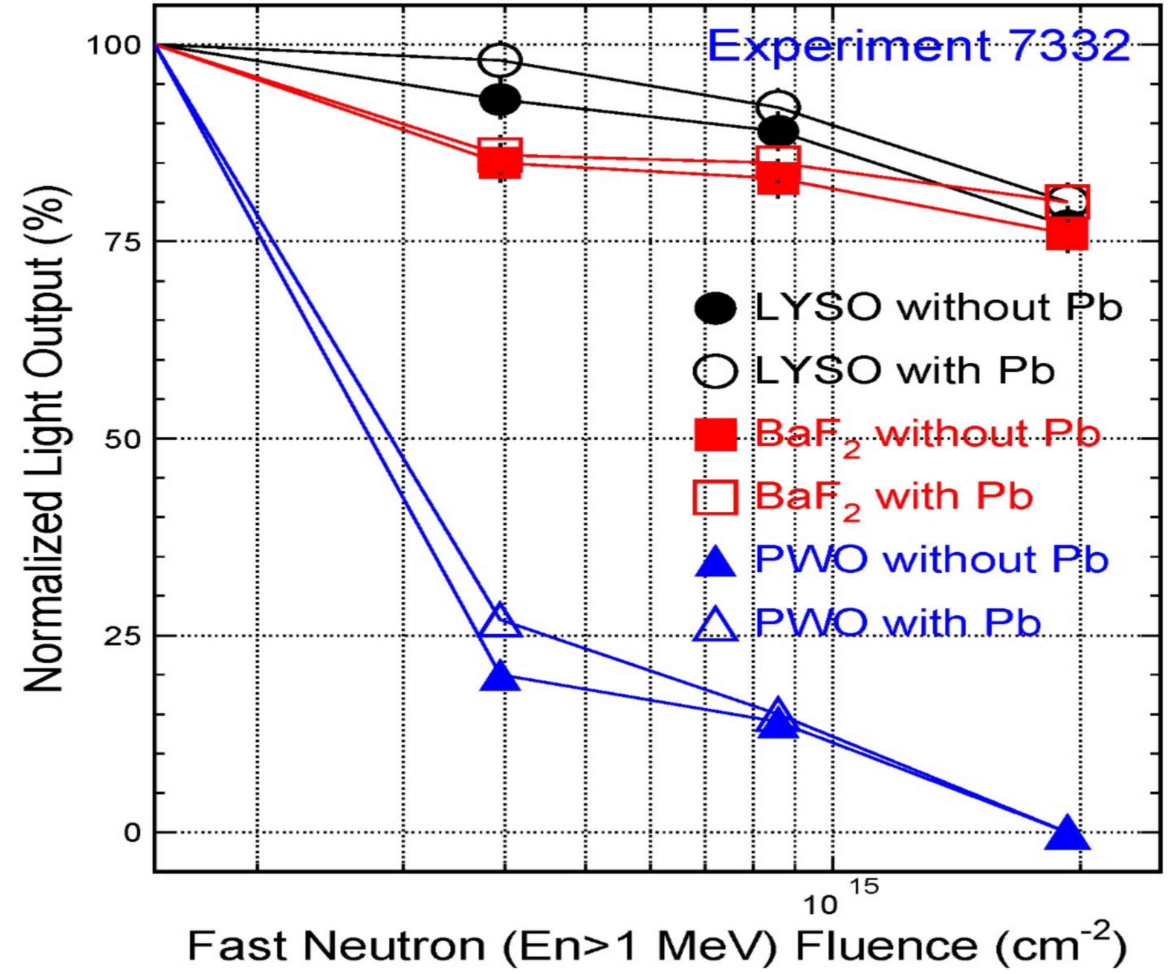
LYSO and BaF_2 show RIAC of 15 and 50 m^{-1} after 200 Mrad, much less than that of PWO

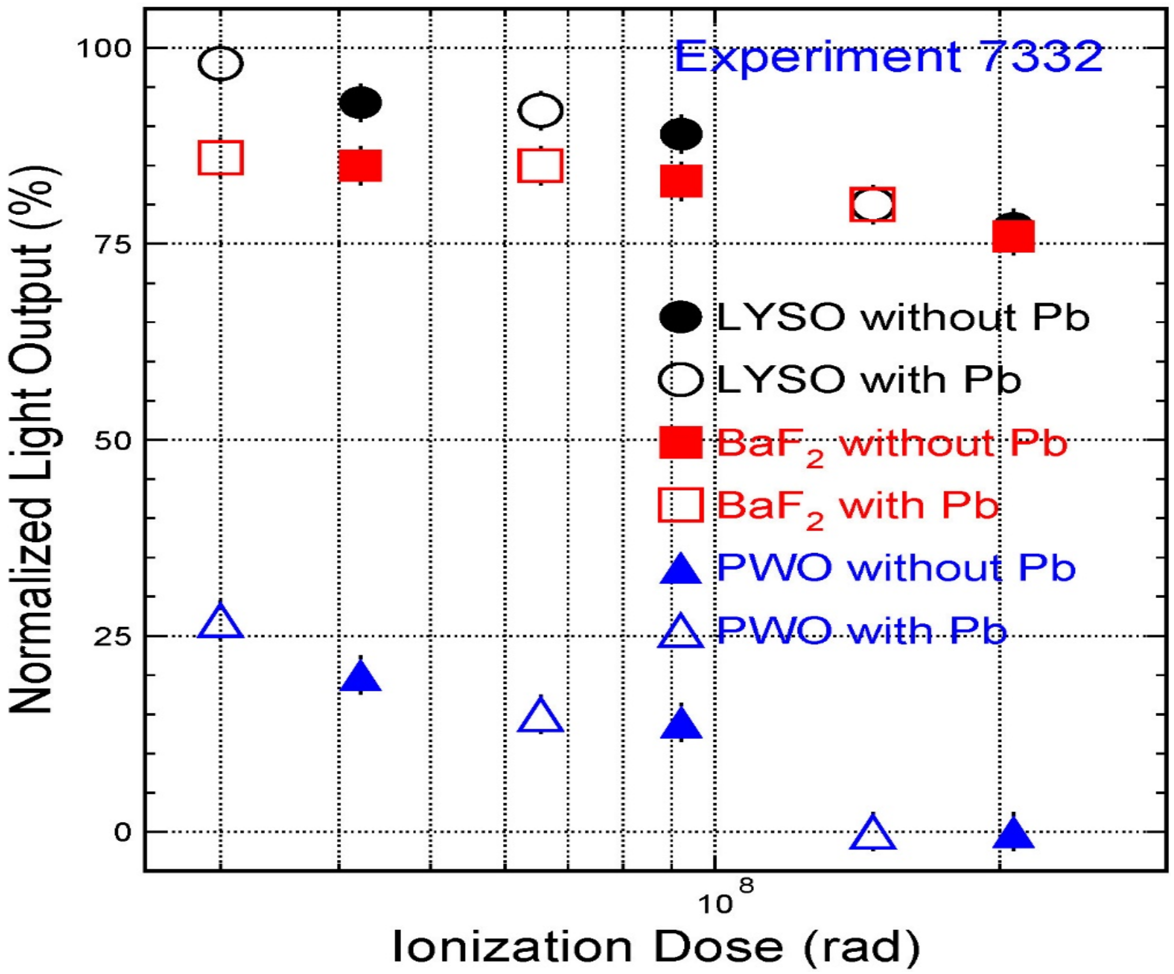




LO of LYSO, BaF_2 and PWO

LO consistent 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

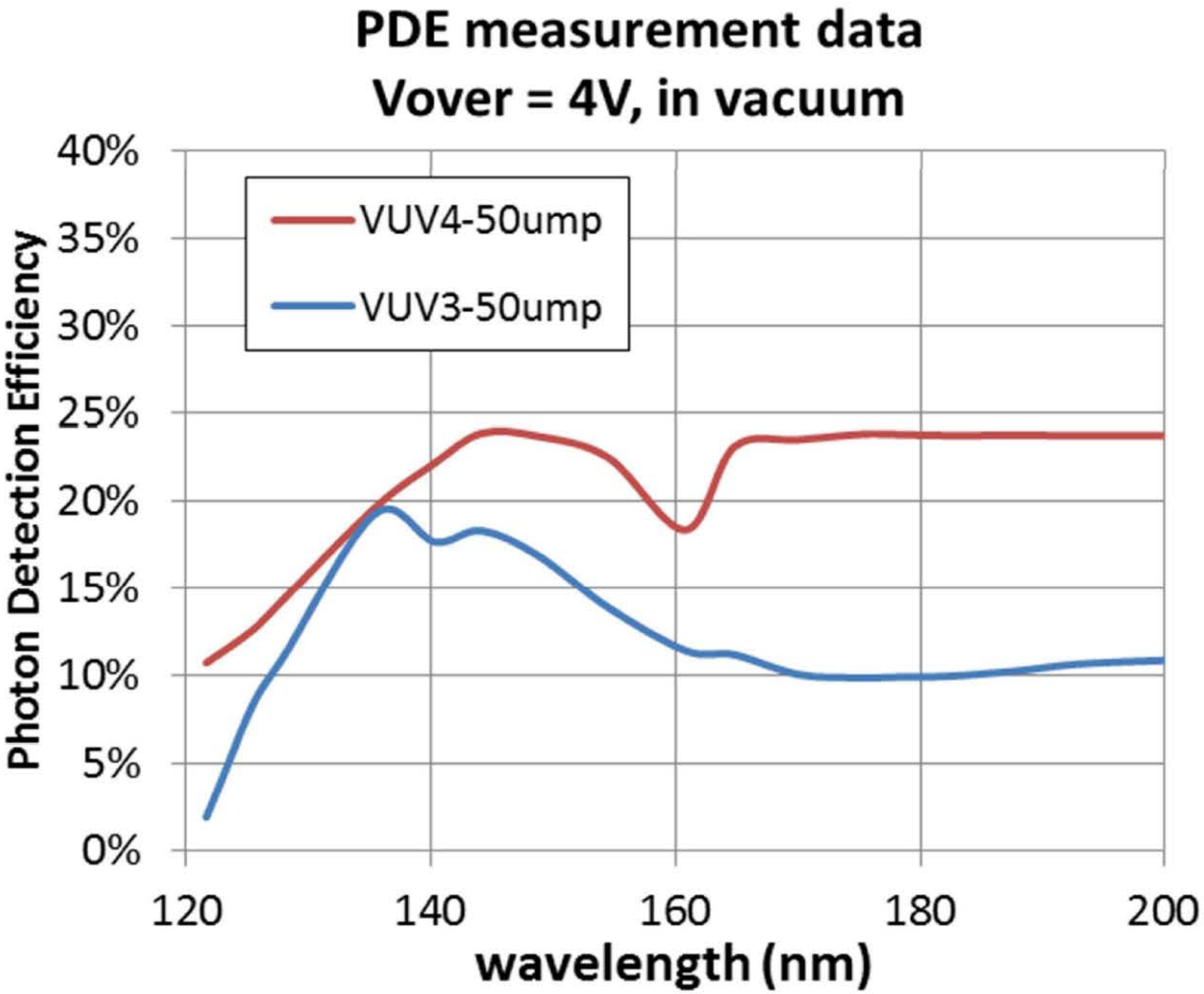
LYSO and BaF_2 crystals show excellent radiation hardness beyond 100 Mrad, 1 x 10^{15} p/cm^2 and 2 x 10^{15} n/cm^2. They will survive a severe radiation environment, such as the HL-LHC.

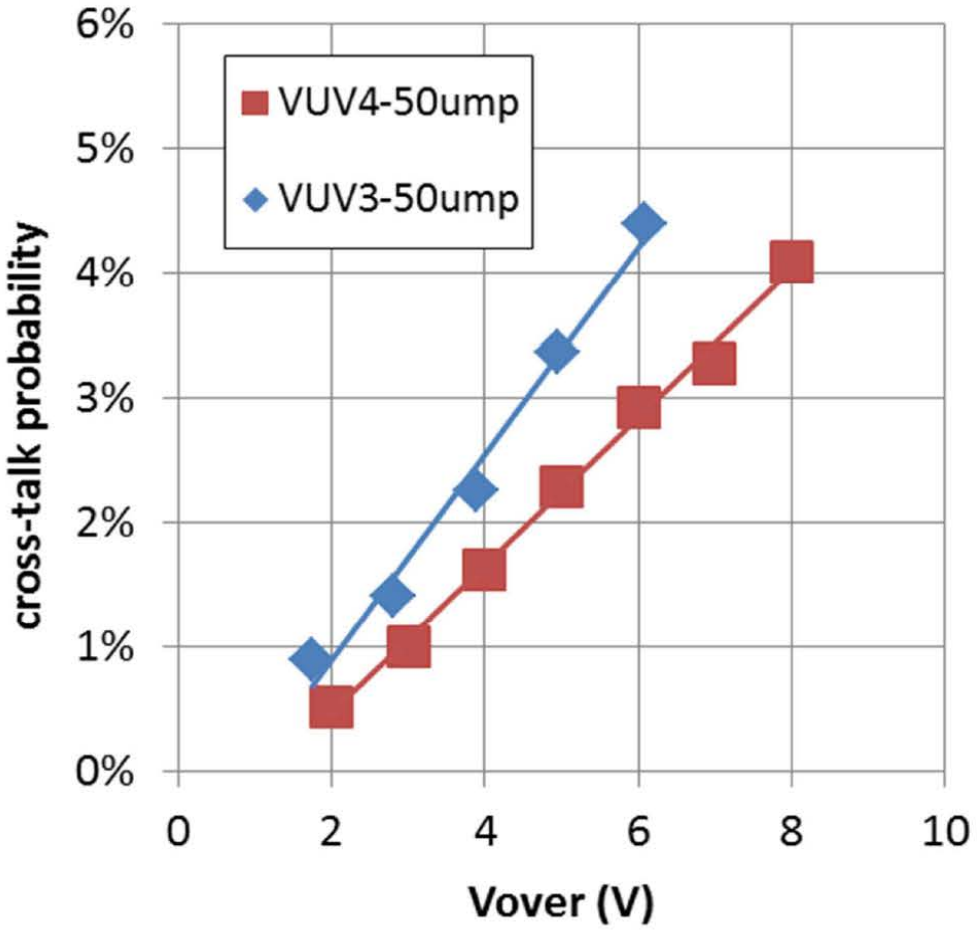
Undoped BaF_2 crystals provide fast light with sub-ns FWHM pulse width. Recently, yttrium doping increases its F/S ratio from 1/5 to 6/1 while maintaining its fast component intensity. At this level, its fast component and Fast/slow is similar to and less than undoped CsI. This material is proposed to Mu2e-II and Marie. It may also be considered for the CMS MTD barrel sensor.

We plan to optimize Y:BaF_2 further and test its radiation hardness. Will also pay an attention to DUV photodetectors: LAPPD, Si (Hamamatsu S13370 with 25% PDE at 200 nm) or diamond based solid state detector.

Hamamatsu S13370 VUV SiPM

VUV-4 has a much better performance than VUV3





Diamond Photodetector

E. Monroy, F. Omnes and F. Calle,"Wide-bandgap semiconductor ultraviolet photodetectors, IOPscience 2003 Semicond. Sci. Technol. 18 R33

E. Pace and A. De Sio, "Innovative diamond photo-detectors for UV astrophysics", Mem. S.A.It. Suppl. Vol. 14, 84 (2010)

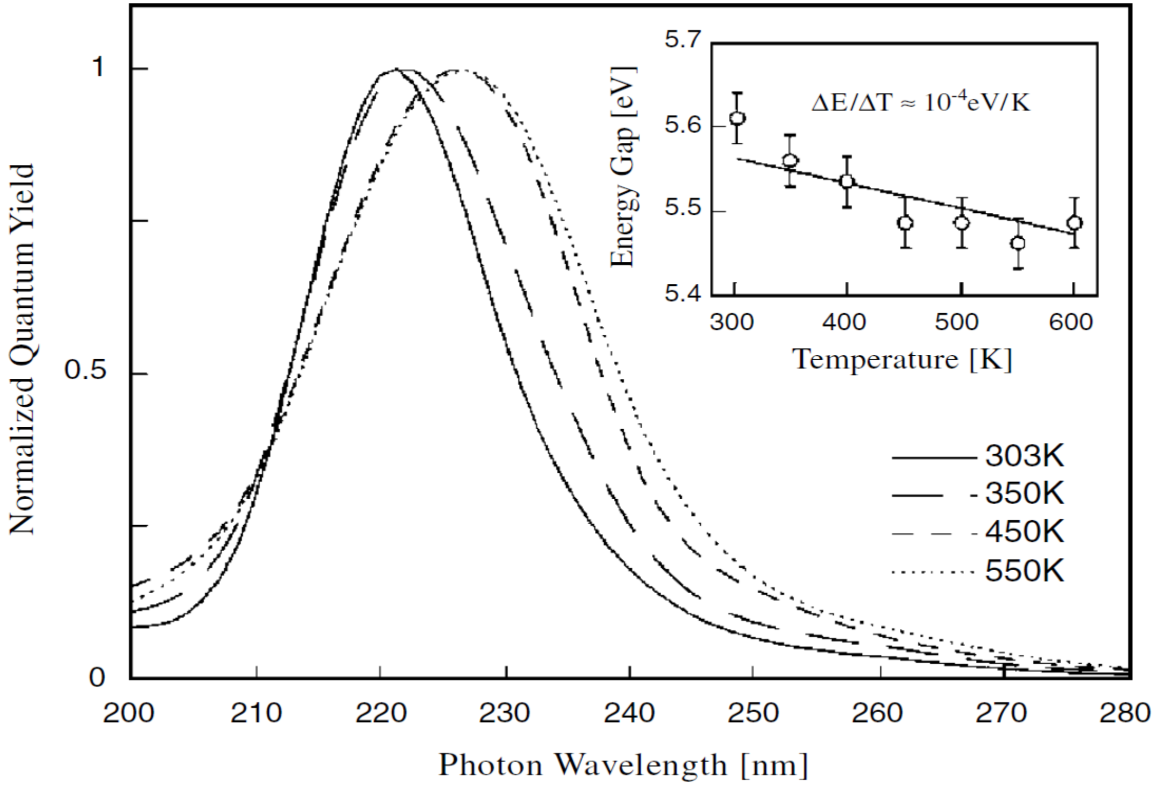


Figure 6. Quantum efficiency of diamond photoconductors at different temperatures and Arrhenius plot of the peak value (inset). (From [Sal00].)

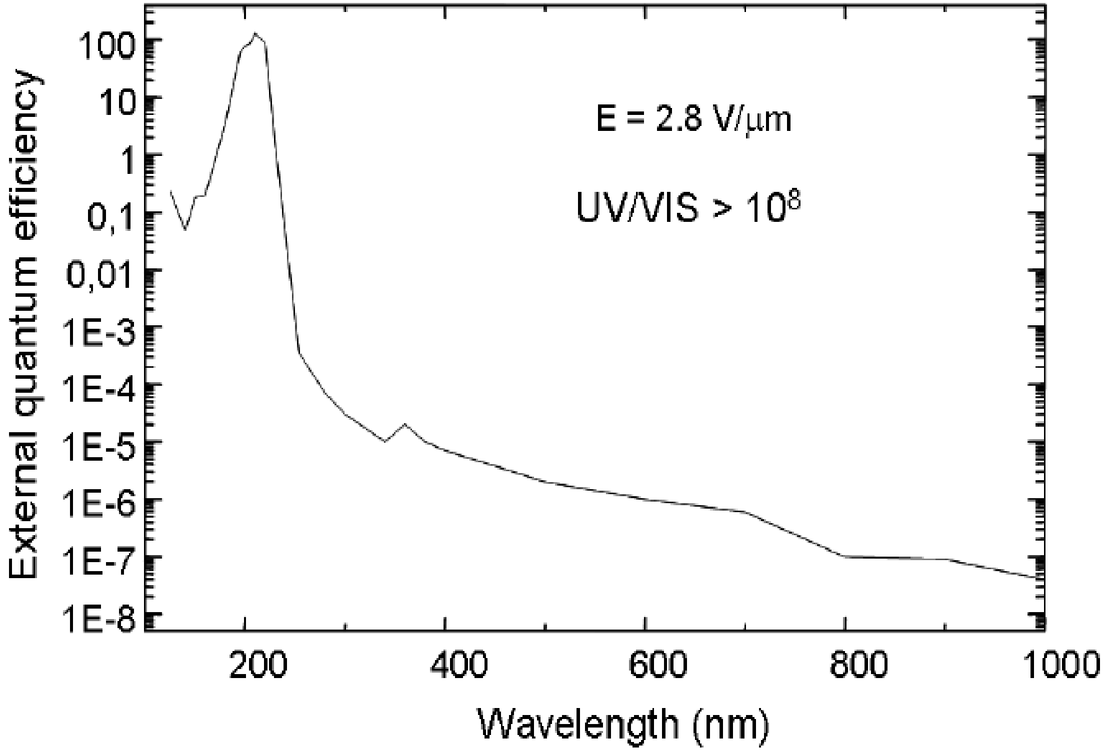


Fig. 4. External quantum efficiency extended to visible and near infrared wavelength regions. The