Rare Earth Doped BaF_2 Crystals

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Introduction

- Undoped CsI crystal used for the Mu2e calorimeter has a fast scintillation at 310 nm with 30 ns decay time and survives an ionization dose up to 100 krad.
- BaF_2 crystal has a ultrafast scintillation at 220 nm with 0.5 ns decay time and a similar intensity as CsI, and may survive 100 Mrad. Its slow scintillation at 300 nm with 650 ns decay time, however, causes pileup in a high rate environment.
- Two approaches have been used to suppress the slow scintillation in BaF_2: (1) rare earth doping and/or (2) dedicated photodetector. Yttrium doping in BaF_2 crystals is found effective, promising a ultrafast calorimeter.
- Mass production capability of BaF_2 exists in industry:
  - BGRI (China), Incrom (Russia) and SICCAS (China);
  - Hellma (Germany).
- Reported today is the progress in rare earth doped BaF_2 crystals.

Some Fast Inorganic Scintillators

	LSO/LYSO	GSO	YSO	CsI	BaF_2	CeF_3	$CeBr_3$	$LaCl_3$	$LaBr_3$	Plastic scintillator (BC 404) ①
Density (g/cm^3)	7.4	6.71	4.44	4.51	4.89	6.16	5.23	3.86	5.29	1.03
Melting point (°C)	2050	1950	1980	621	1280	1460	722	858	783	70[#]
Radiation Length (cm)	1.14	1.38	3.11	1.86	2.03	1.7	1.96	2.81	1.88	42.54
Molière Radius (cm)	2.07	2.23	2.93	3.57	3.1	2.41	2.97	3.71	2.85	9.59
Interaction Length (cm)	20.9	22.2	27.9	39.3	30.7	23.2	31.5	37.6	30.4	78.8
Z value	64.8	57.9	33.3	54	51.6	50.8	45.6	47.3	45.6	5.82
dE/dX (MeV/cm)	9.55	8.88	6.56	5.56	6.52	8.42	6.65	5.27	6.9	2.02
Emission Peak[a] (nm)	420	430	420	310	300 220	340 300	371	335	356	408
Refractive Index[b]	1.82	1.85	1.8	1.95	1.5	1.62	1.9	1.9	1.9	1.58
Relative Light Yield[a,c]	100	45	76	3.6 1.1	42 4.1	8.6	99	15 49	153	35
Decay Time[a] (ns)	40	73	60	30 6	650 0.5	30	17	570 24	20	1.8
d(LY)/dT[d] (%/°C)	-0.2	-0.4	-0.1	-1.4	-1.9 0.1	~0	-0.1	0.1	0.2	~0

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

b. At the wavelength of the emission maximum.

c. Relative light yield normalized to the light yield of LSO

d. At room temperature (20°C)

#. Softening point

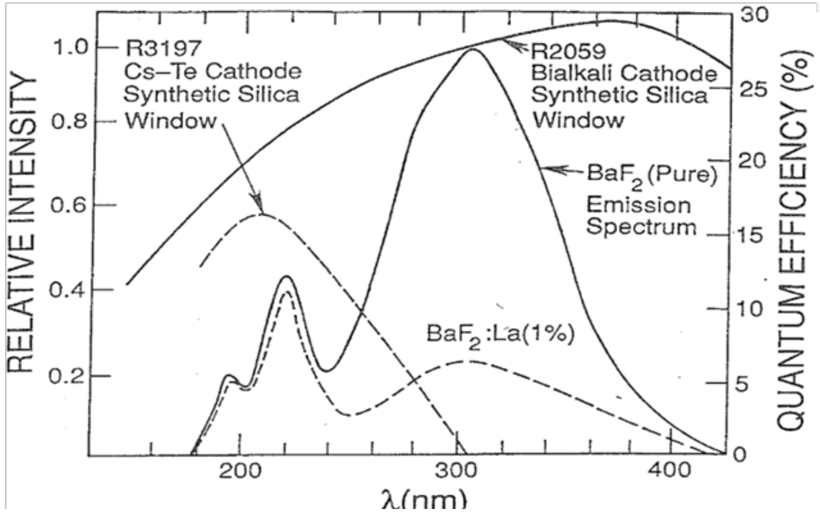
1. http://www.detectors.saint-gobain.com/Plastic-Scintillator.aspx
   http://pdg.lbl.gov/2008/AtomicNuclearProperties/HTML_PAGES/216.html

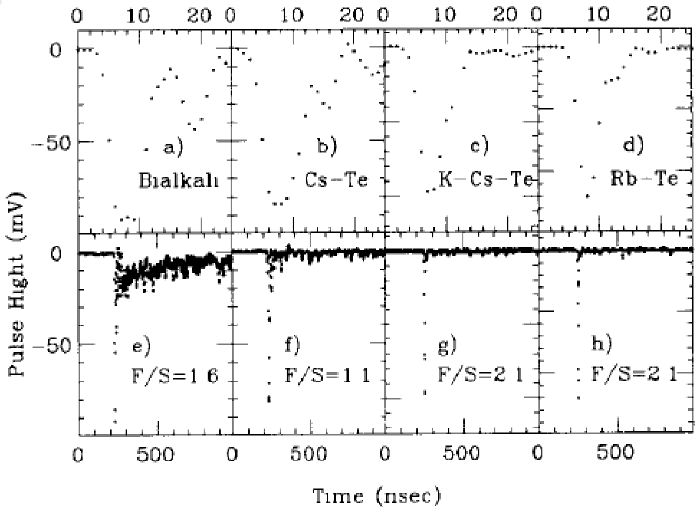
The 0.5 ns scintillation in BaF_2 promises a ultrafast crystal calorimeter to face the challenge of high event rate expected by Mu2e-II

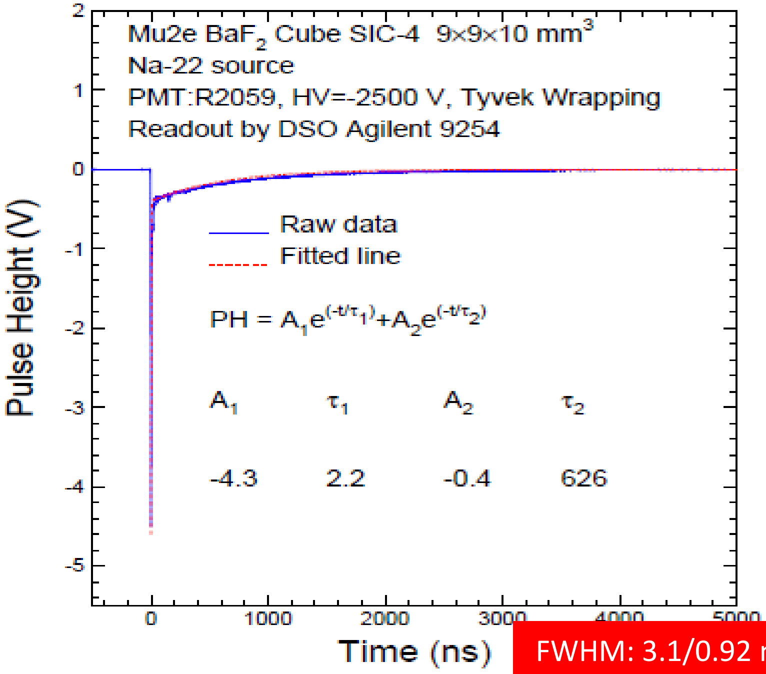
Ultrafast and Slow Light from BaF_2

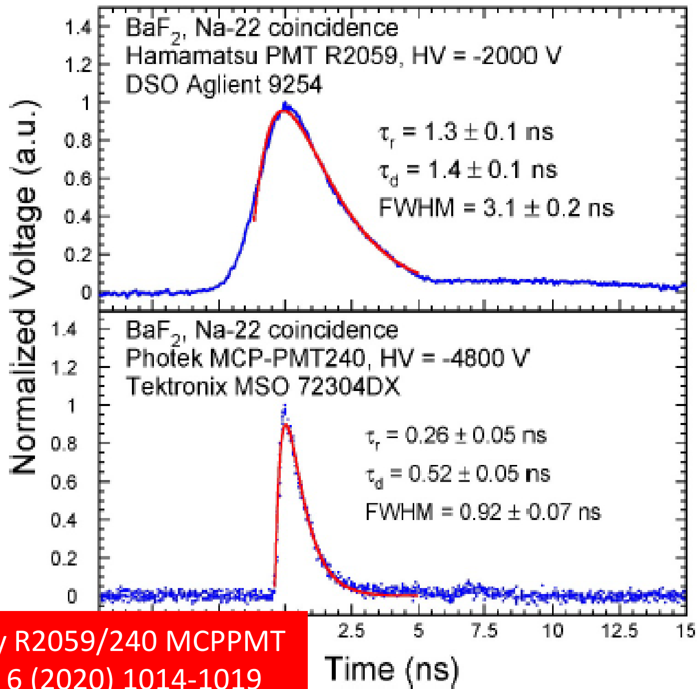
BaF_2 has a ultrafast scintillation component @ 220 nm with 0.5 ns decay time and an intensity similar to undoped CsI. It has also a factor of 5 larger slow component @ 300 nm with 300 ns decay time.

Slow suppression may be achieved by rare earth (Y, La and Ce) doping, and/or solar-blind photo-detectors, e.g. Cs-Te, K-Cs-Te and Rb-Te cathode
NIMA 340 (1994) 442-457



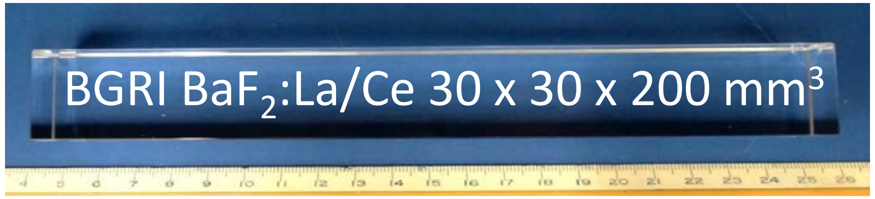


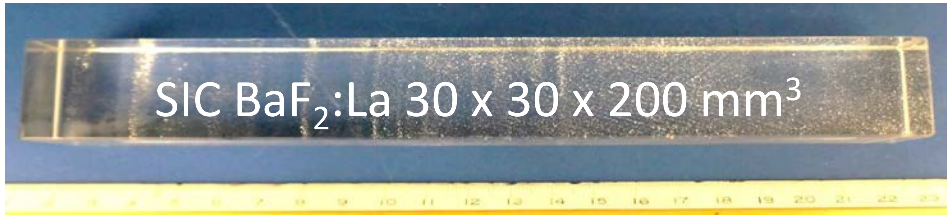


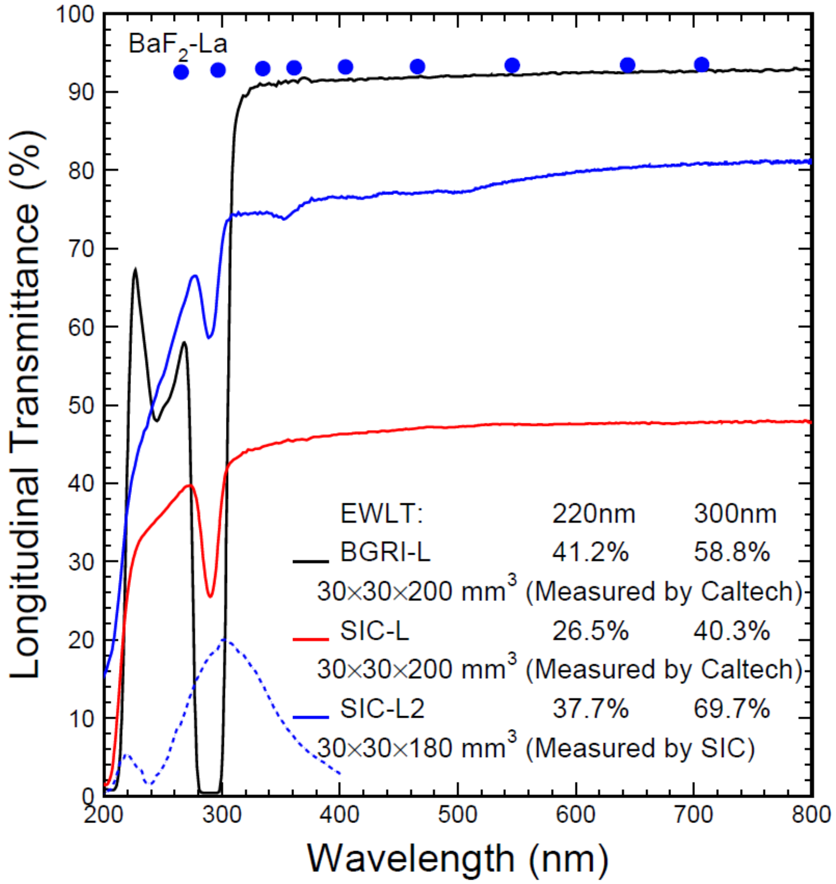


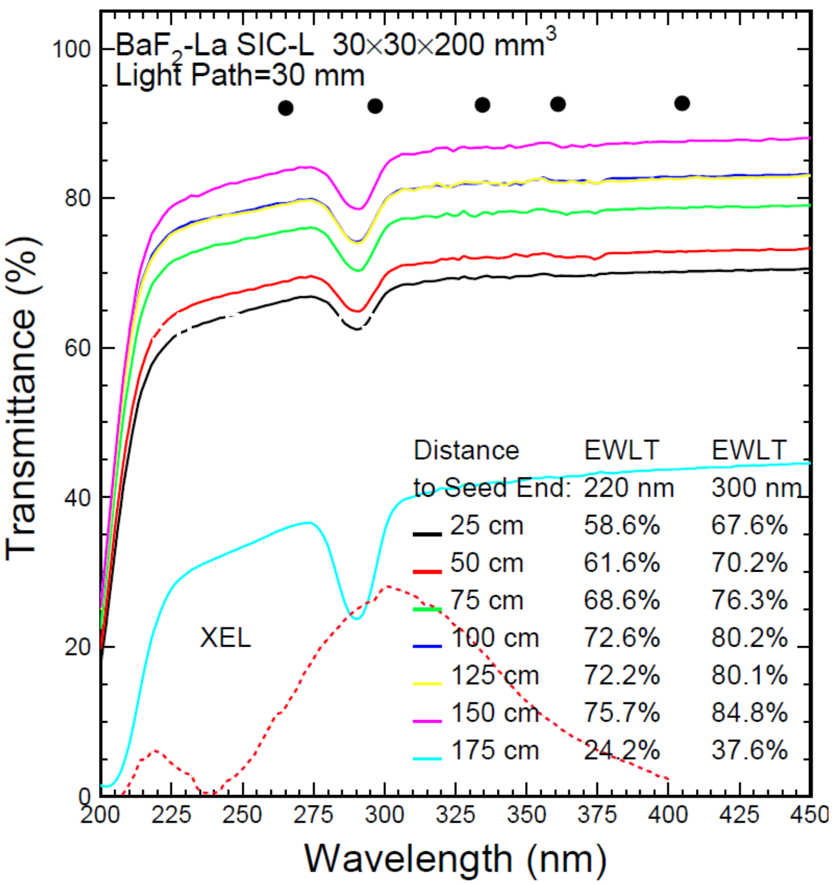
FWHM: 3.1/0.92 ns by R2059/240 MCPPMT
IEEE TNS NS 67, NO. 6 (2020) 1014-1019

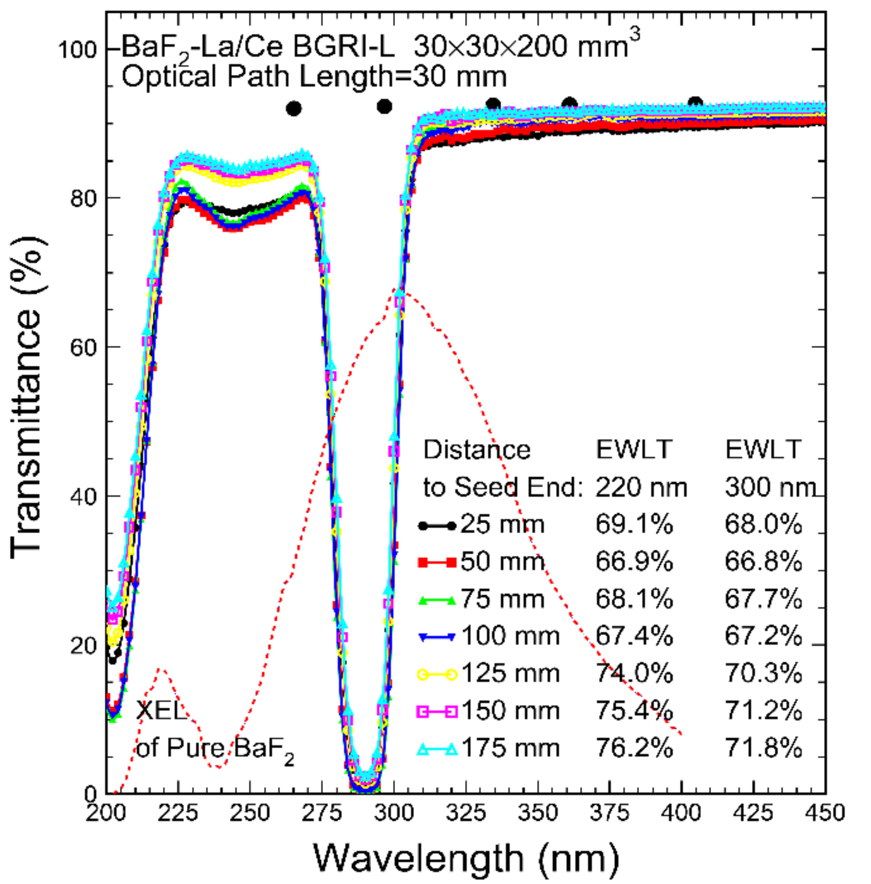
Transmittance of BaF_2:La and BaF_2:La/Ce







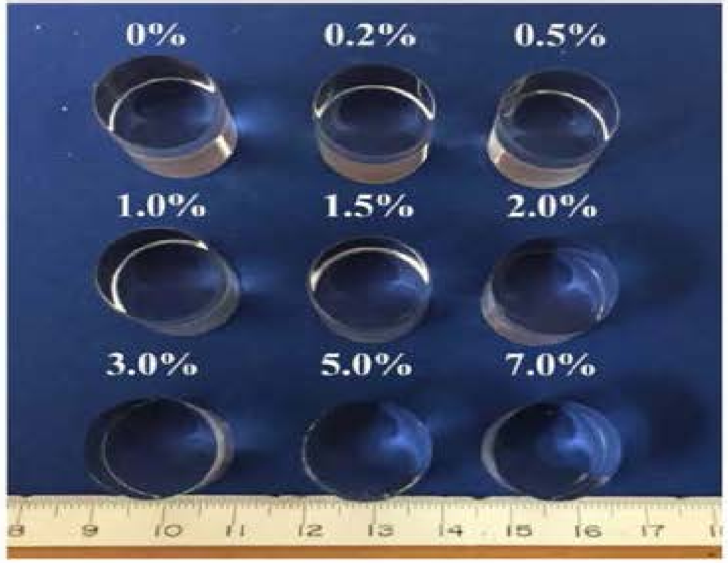


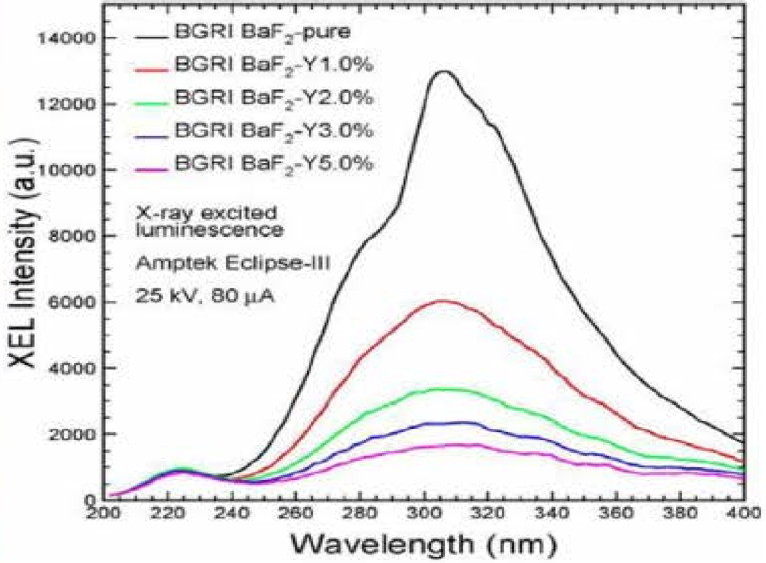


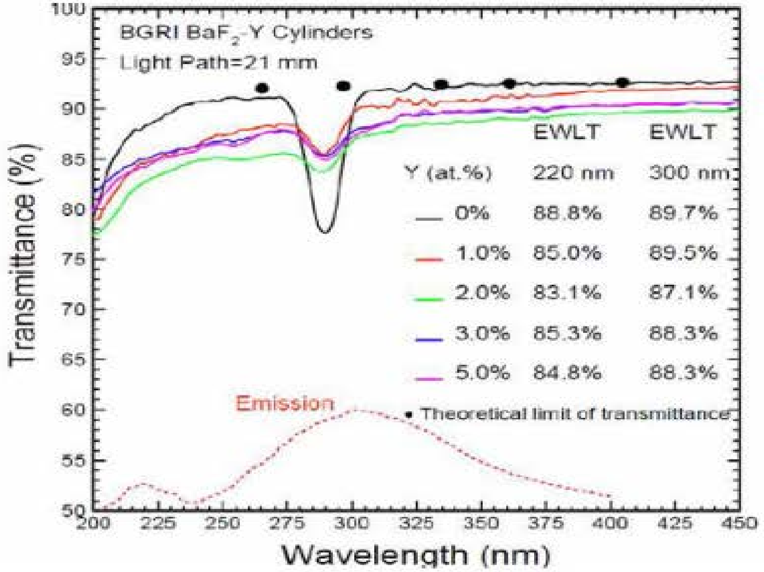
Absorptions observed in La and La/Ce doped BaF_2 IEEE TNS 66 (2019) 506-518

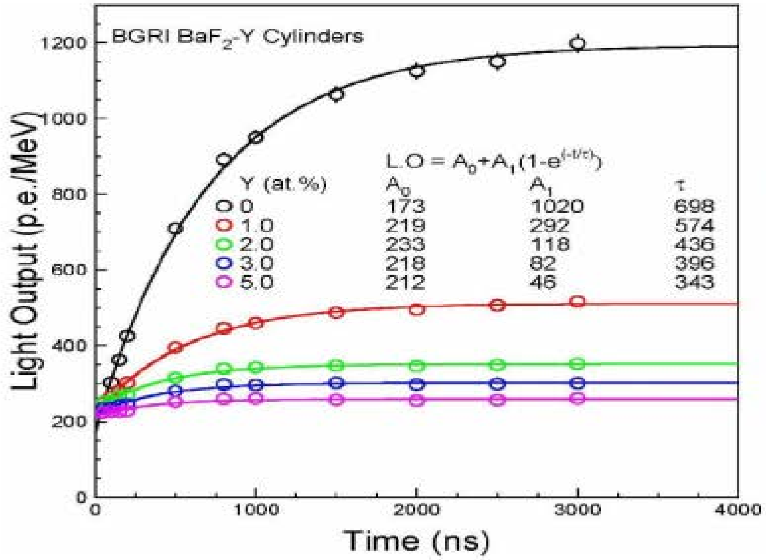
Yttrium Doped Small BaF_2 Samples

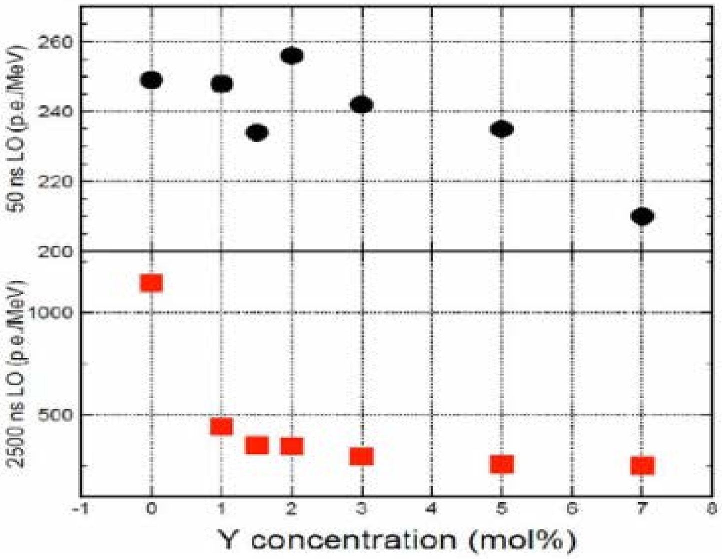
Increased F/S ratio observed in BGRI BaF_2:Y crystals, Proc. SPIE 10392 (2017)

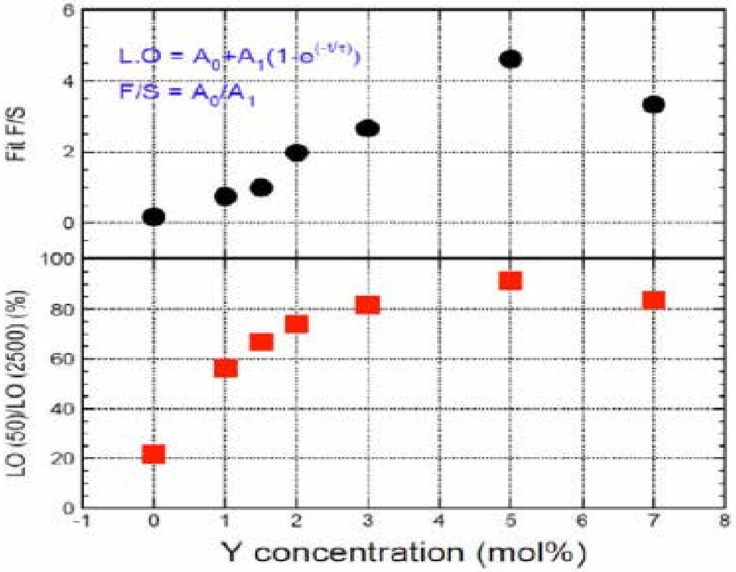






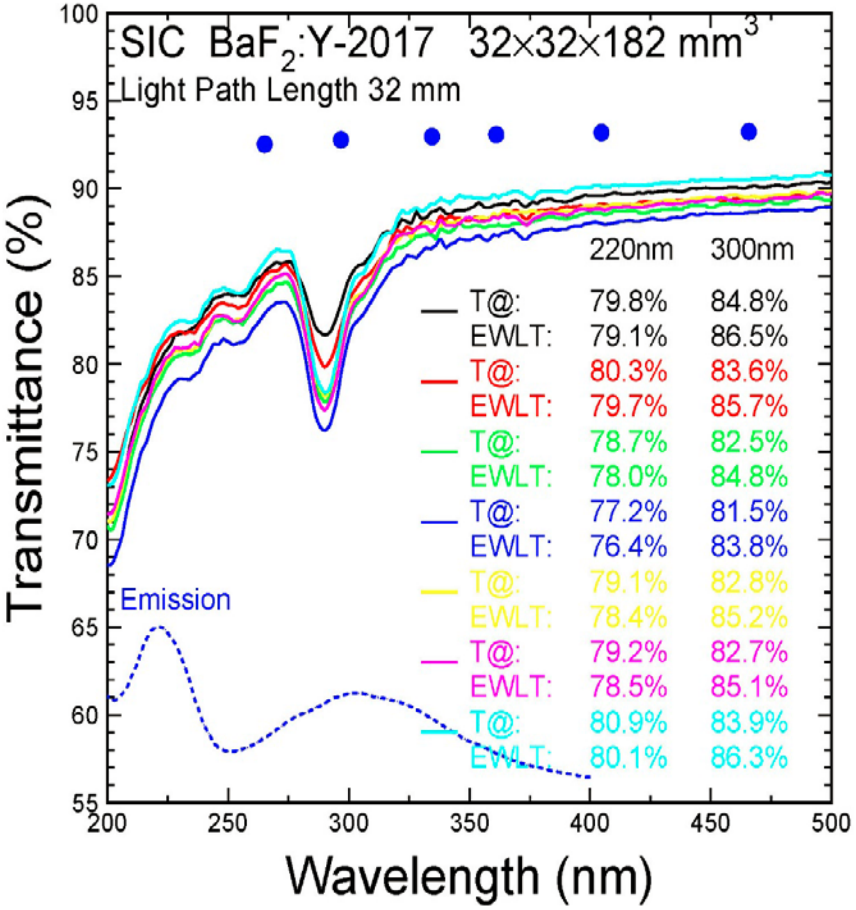


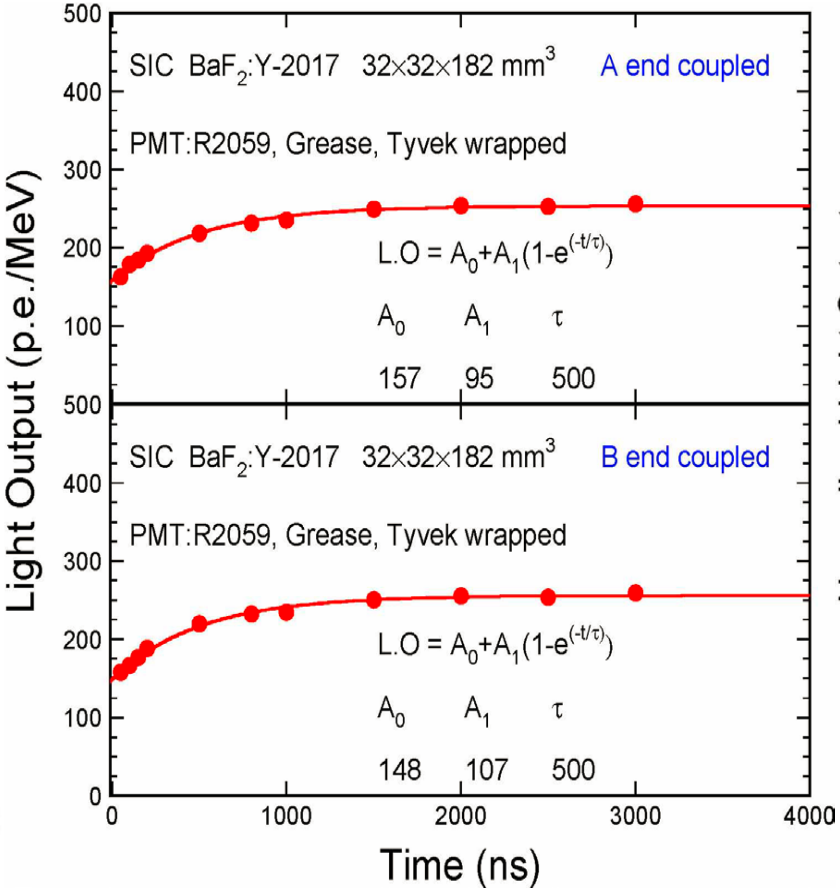


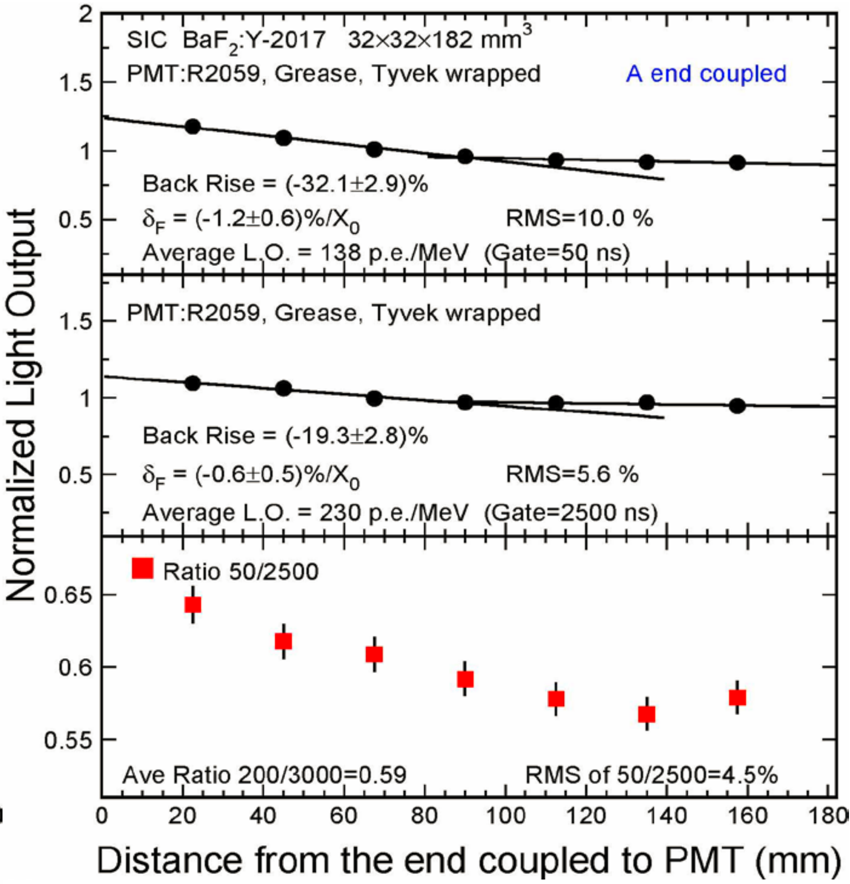


SIC BaF_2:Y-2017

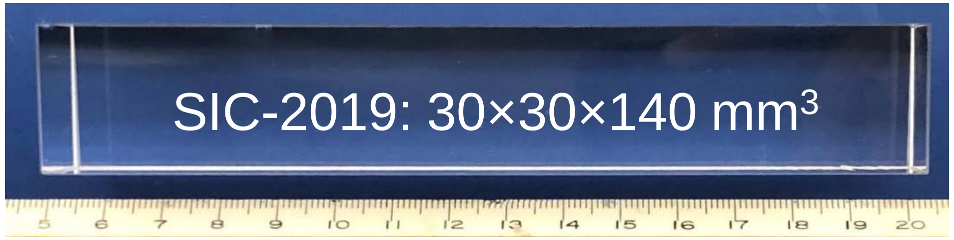
F: 150 p.e./MeV, F/S: 1.5
F/T LRU: 10%/6%, δ_F:-1.2%/X_0





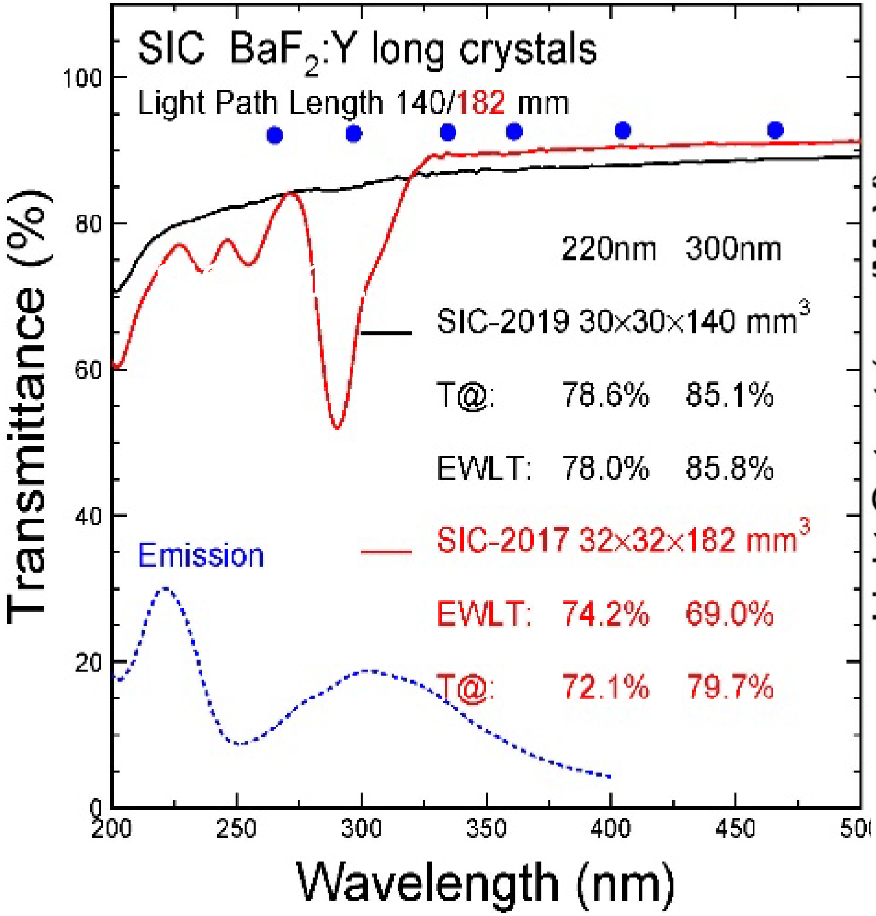


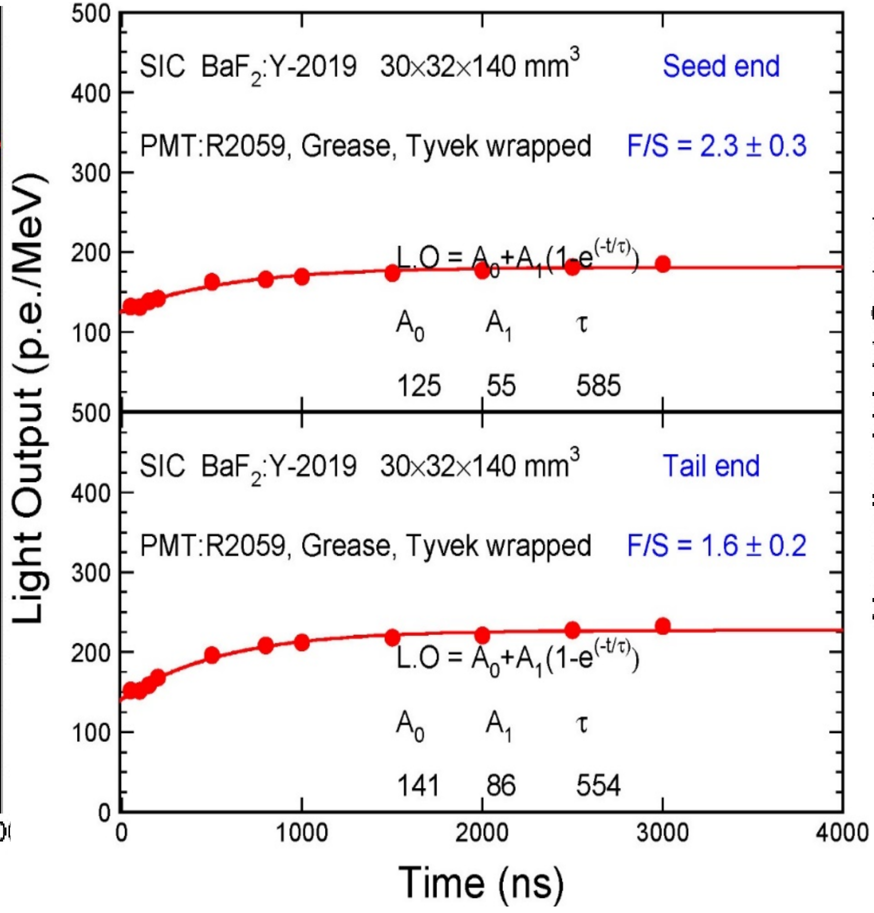
SIC BaF_2:Y-2019

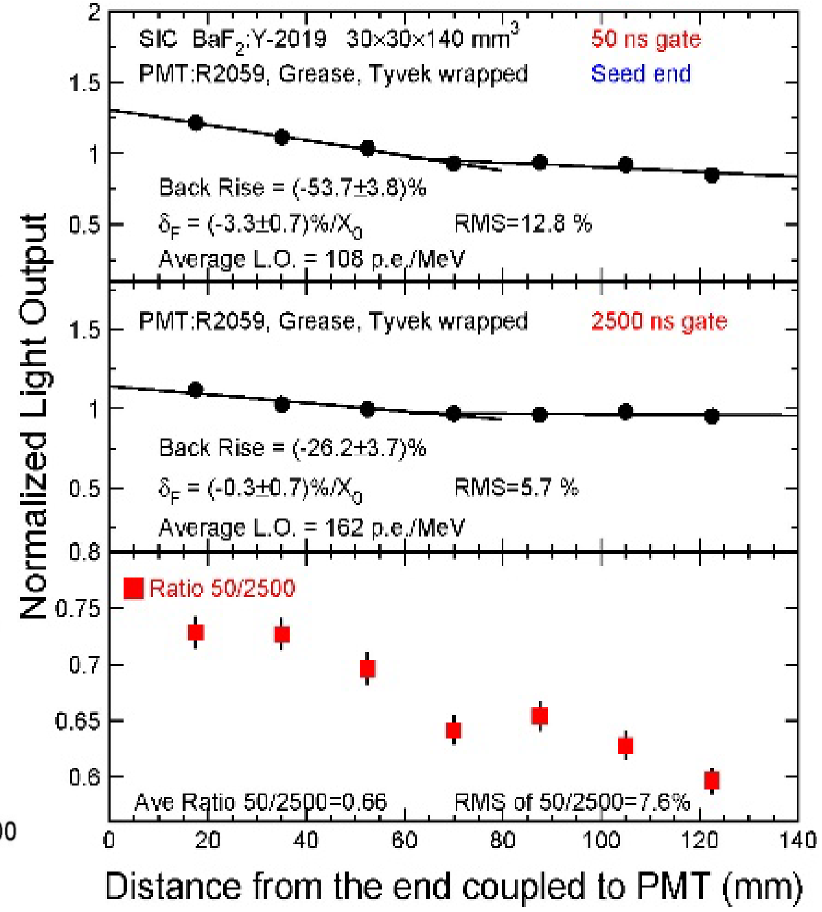


F: 130 p.e./MeV, F/S: 2

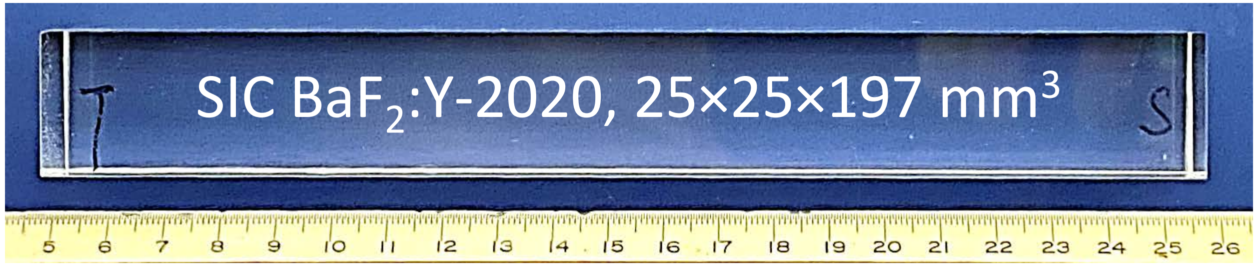
F/T LRU: 13%/6% %, δ_F:-3.3%/X_0



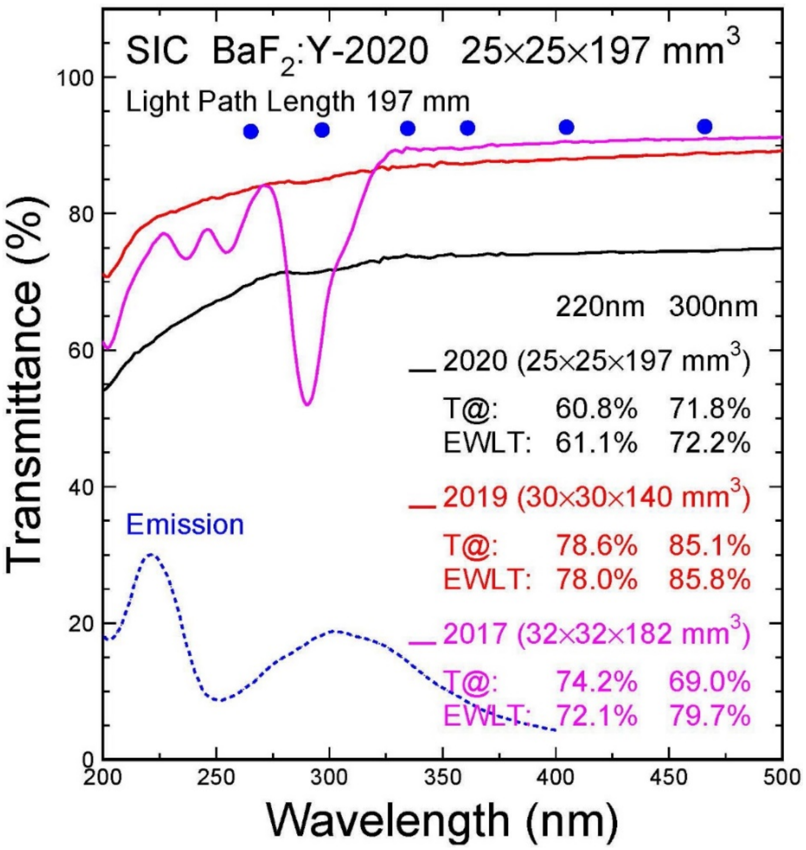


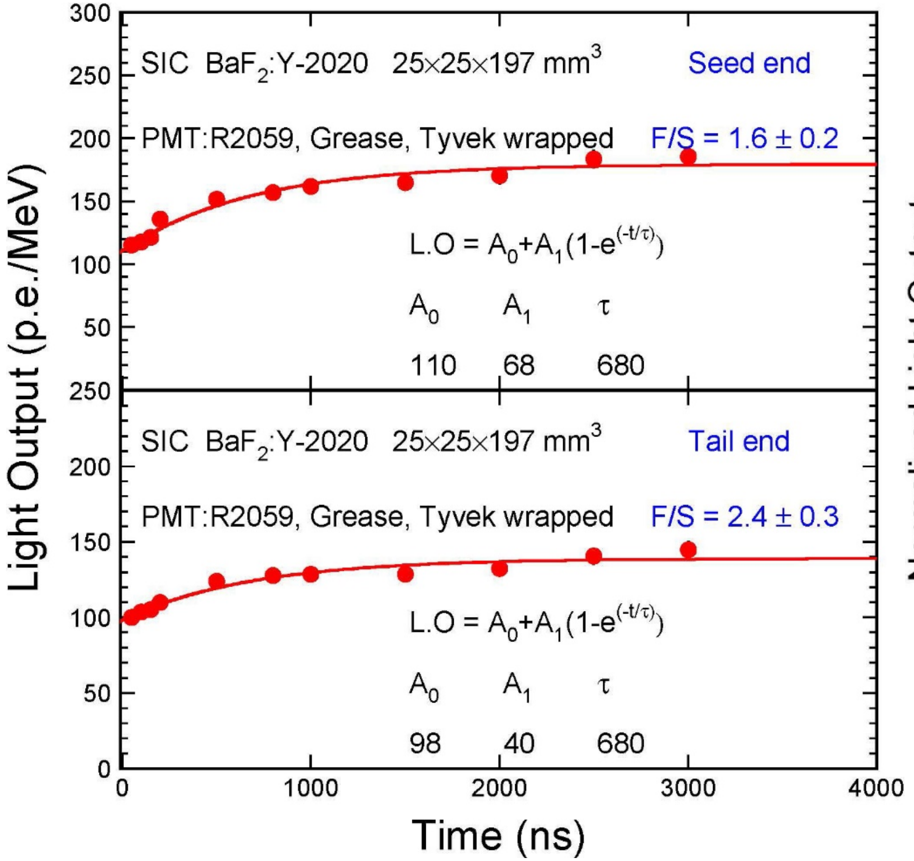


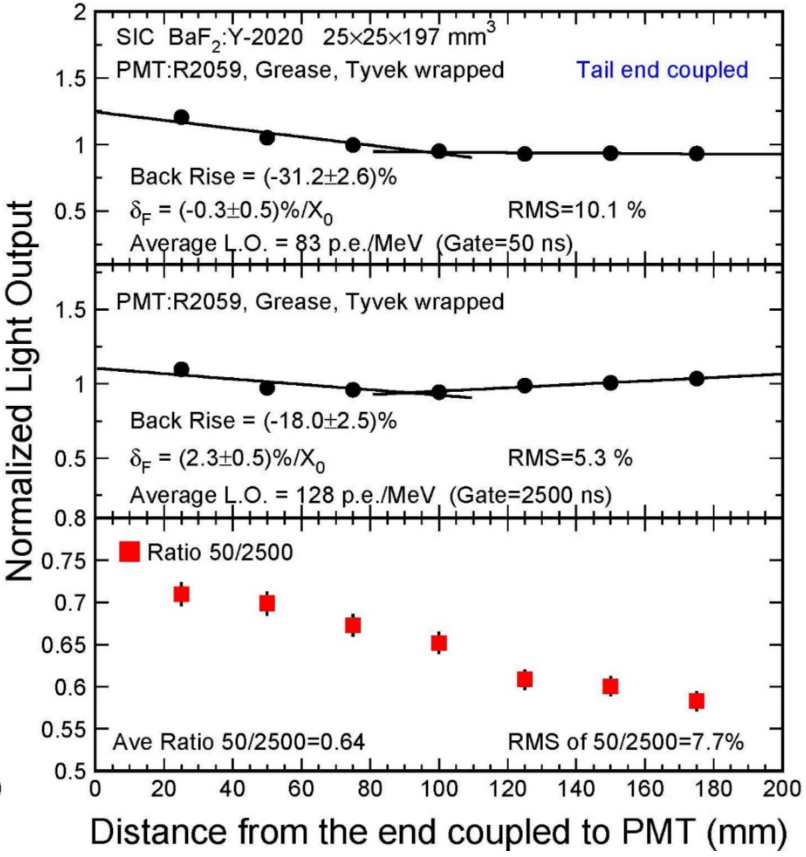
SIC BaF_2:Y-2020



F: 100 p.e./MeV, F/S: 2
F/T LRU: 10%/5% %, δ_F:-0.3%/X_0

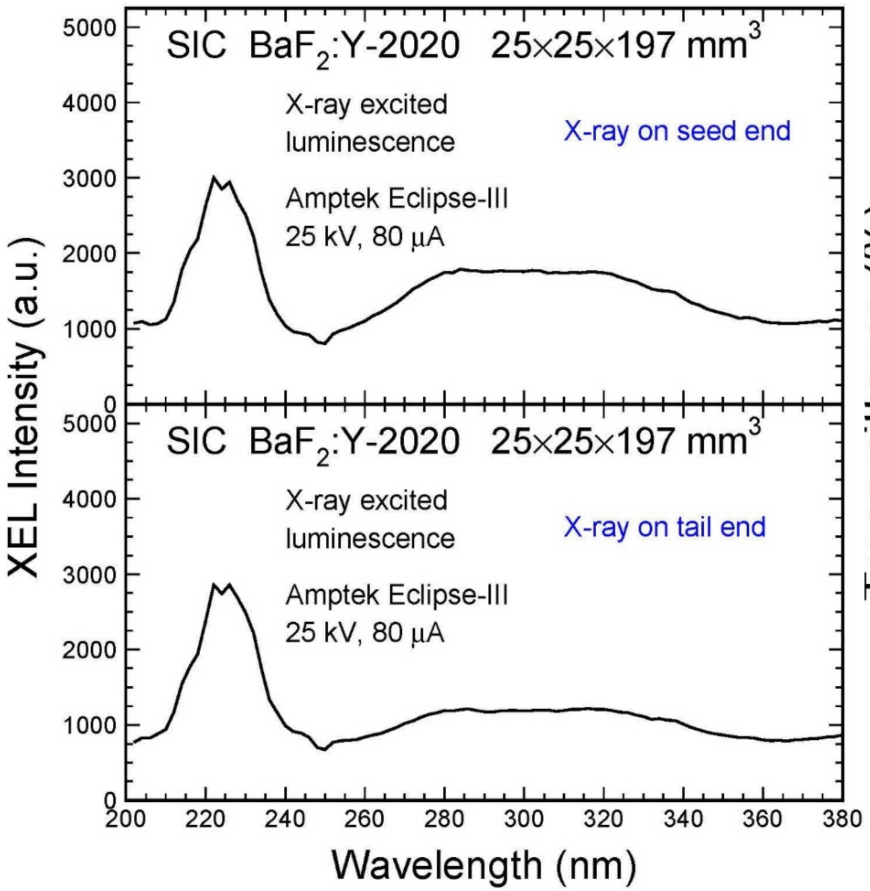


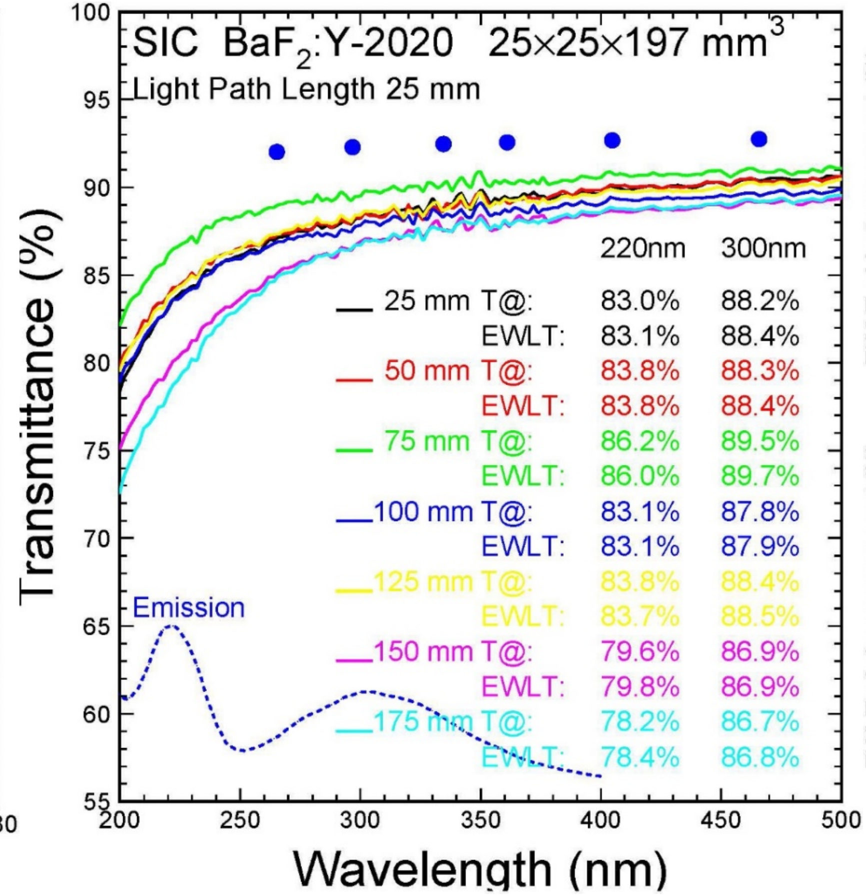


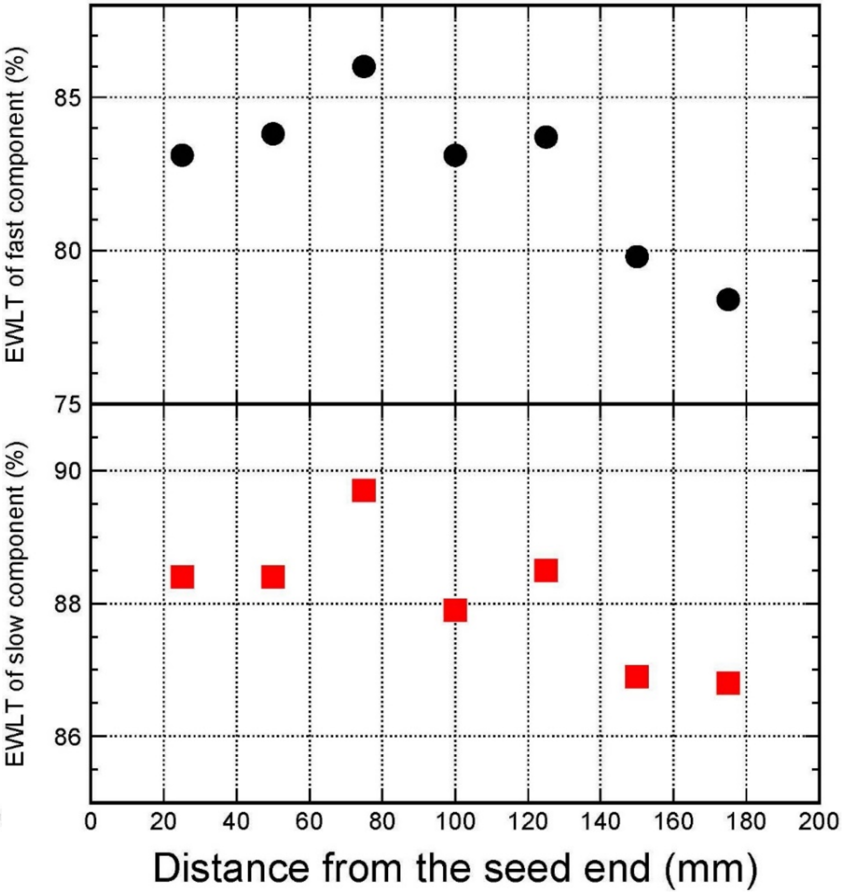


SIC BaF_2:Y-2020: Transverse T

A variation of slow emission intensity and more scattering centers starting from 15 cm from the seed





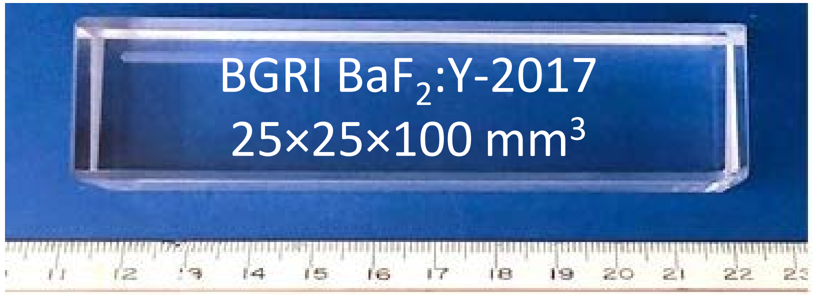


Summary: SIC BaF_2:Y Long Crystals

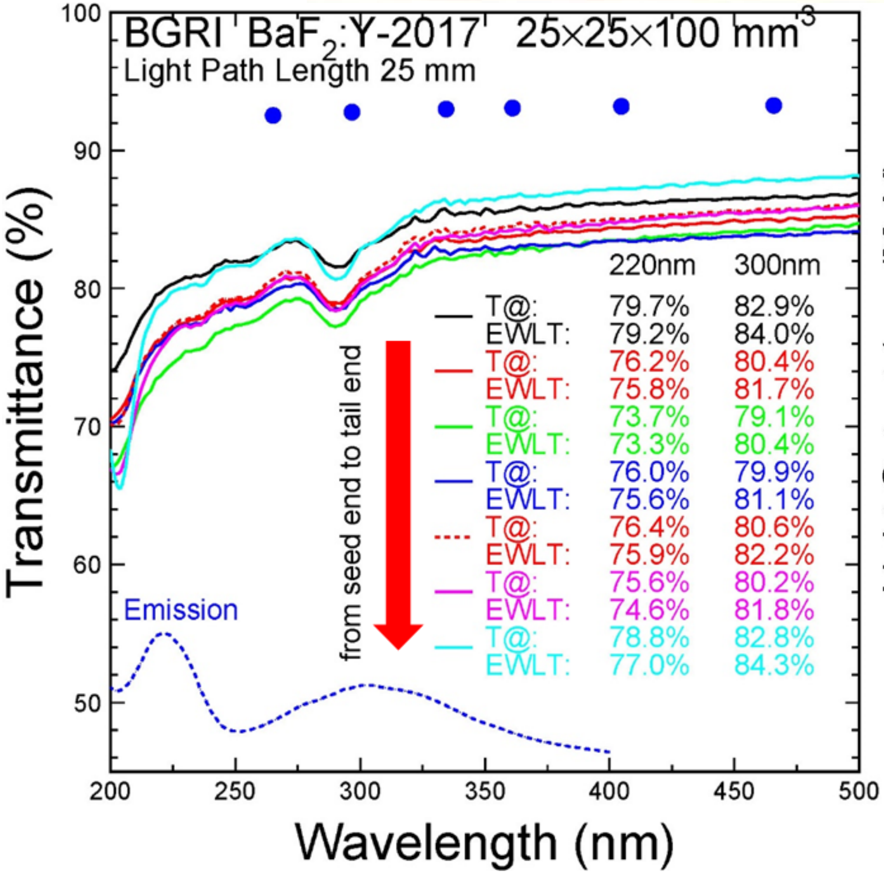
Achievable: LO_F>100 p.e./MeV, F/S>2, 10% LRU and $|\delta_F|<3\%/X_0$

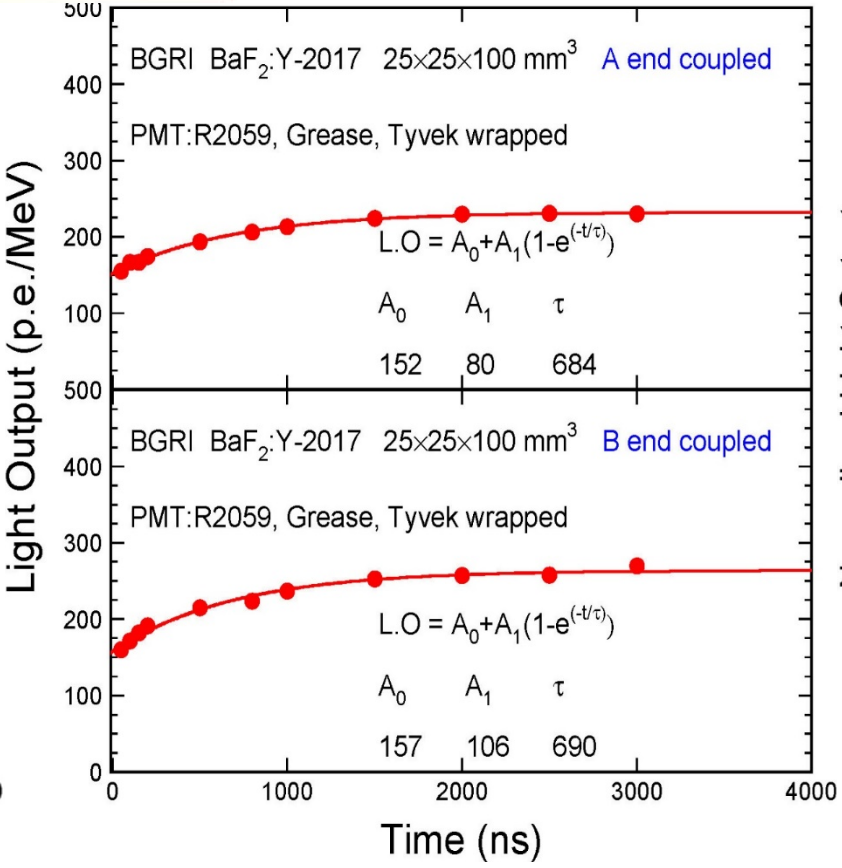
ID	Dimension (mm^3)	EWLT Fast (%)	EWLT Slow (%)	Coupling end	Basic Scintillation Performance ^{22}Na source @ 1/8 length from the coupling end					Light Response Uniformity		
					50 ns LO (p.e./MeV)	2500 ns LO (p.e./MeV)	LO(50) /LO(2500)	F	F/S	50 ns LO	2500 ns LO	LO(50)/ LO(2500)
SIC BaF_2:Y-2017	32×32×182	72.1	79.7	A	162	253	0.64	157	1.7	138 (10.0%)	230 (5.6%)	0.59 (4.5%)
				B	158	254	0.62	148	1.4	116 (19.1%)	200 (16.4%)	0.57 (3.7%)
SIC BaF_2:Y-2019	30×30×140	78.0	85.8	A	132	181	0.73	125	2.3	108 (12.8%)	162 (5.7%)	0.66 (7.6%)
				B	152	227	0.67	141	1.6	117 (15.6%)	177 (14.9%)	0.66 (1.5%)
SIC BaF_2:Y-2020	25×25×197	61.1	72.2	Seed	115	183	0.63	110	1.6	88 (17.7%)	136 (20.5%)	0.64 (2.8%)
				Tail	100	141	0.71	98	2.4	83 (10.1%)	128 (5.3%)	0.64 (7.7%)

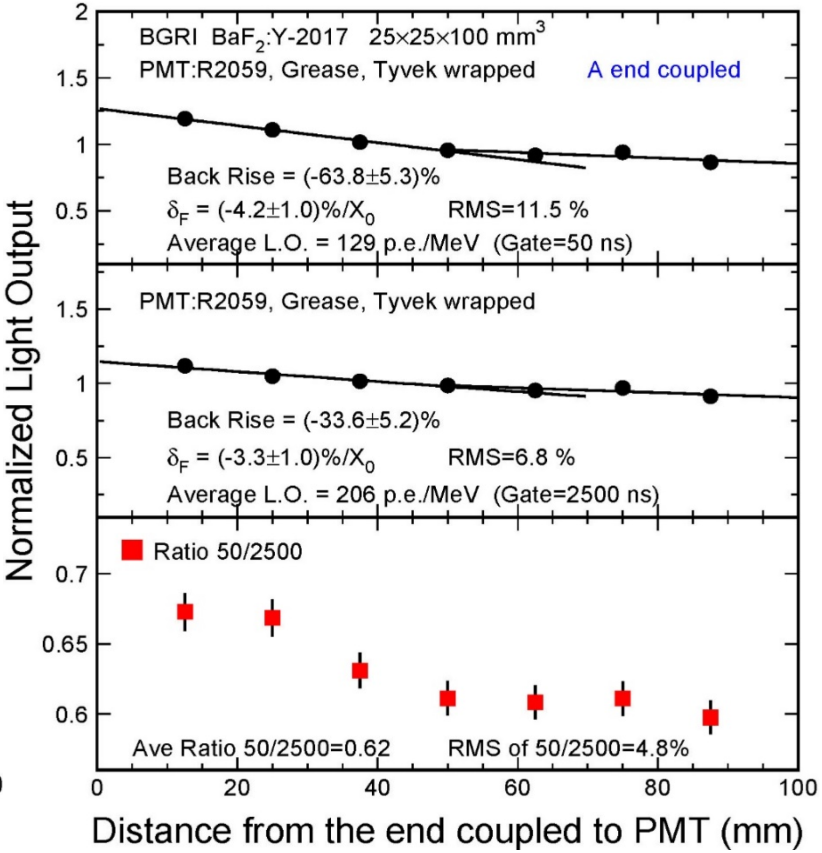
BGRI BaF_2:Y-2017



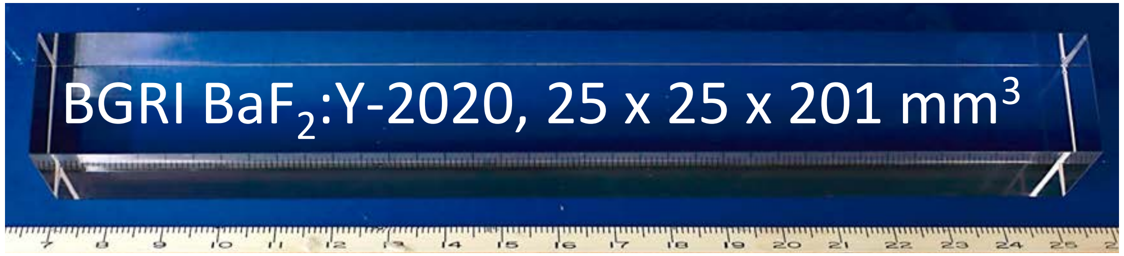
F: 150 p.e./MeV, F/S: 1.5
F/T LRU: 12%/7% %, δ_F:-4.2%/X_0





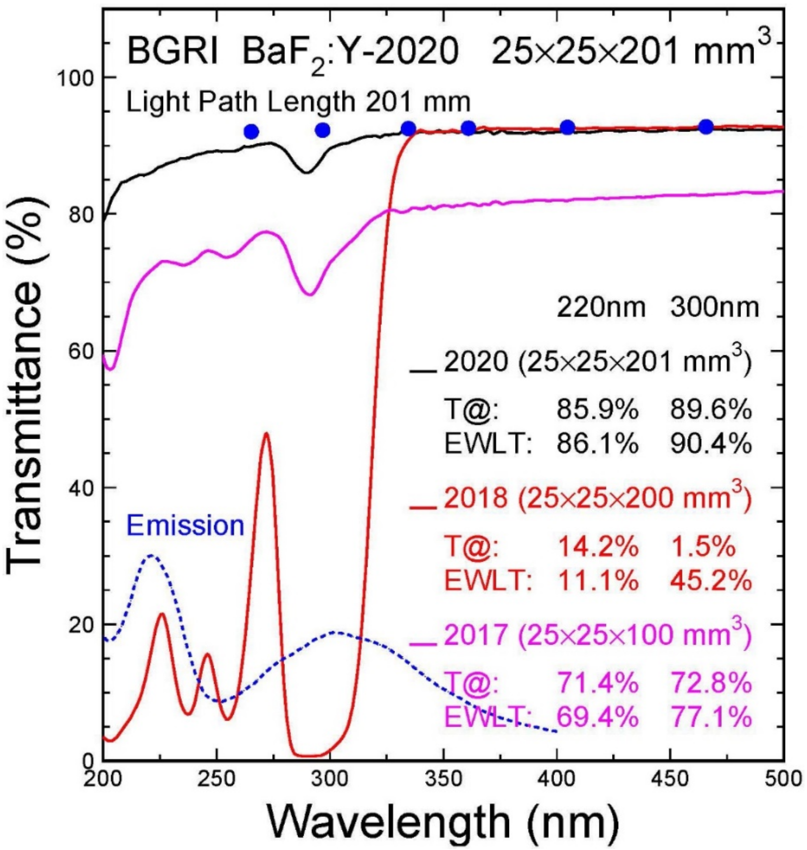


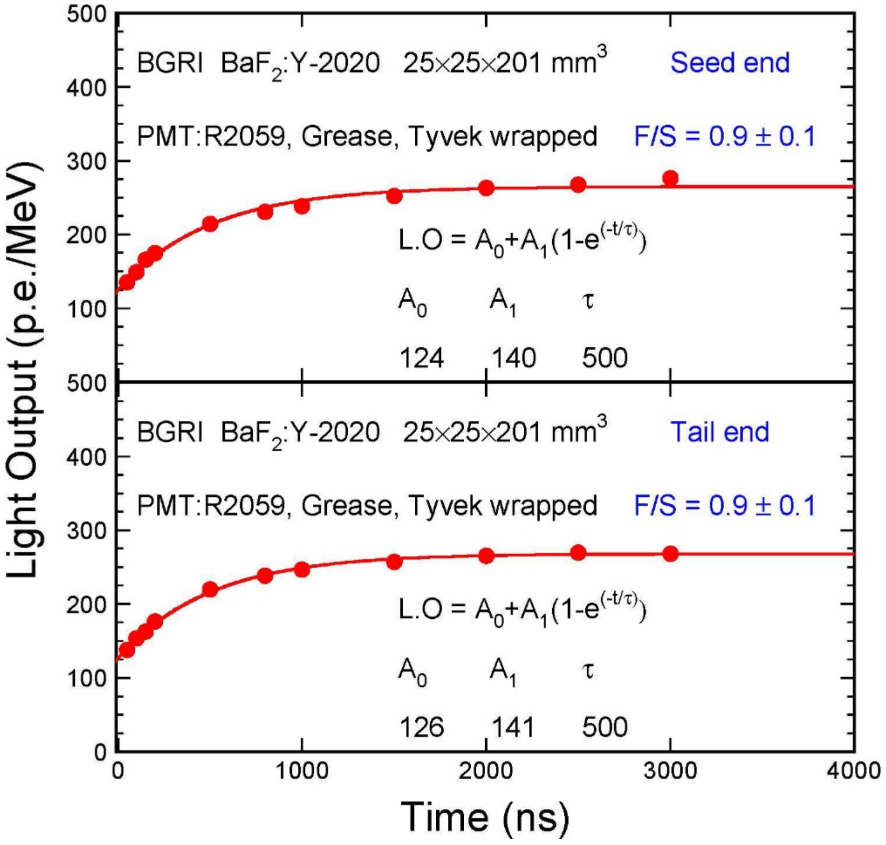
BGRI BaF_2:Y-2020

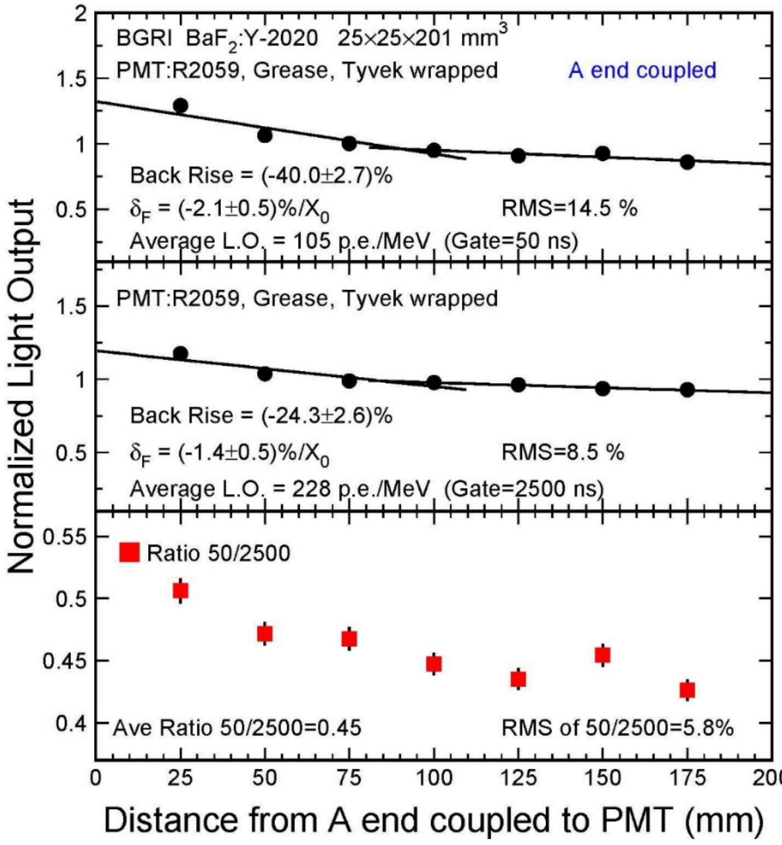


F: 125 p.e./MeV, F/S: 0.9

F/T LRU: 15%/9% %, δ_F:-2.1%/X_0

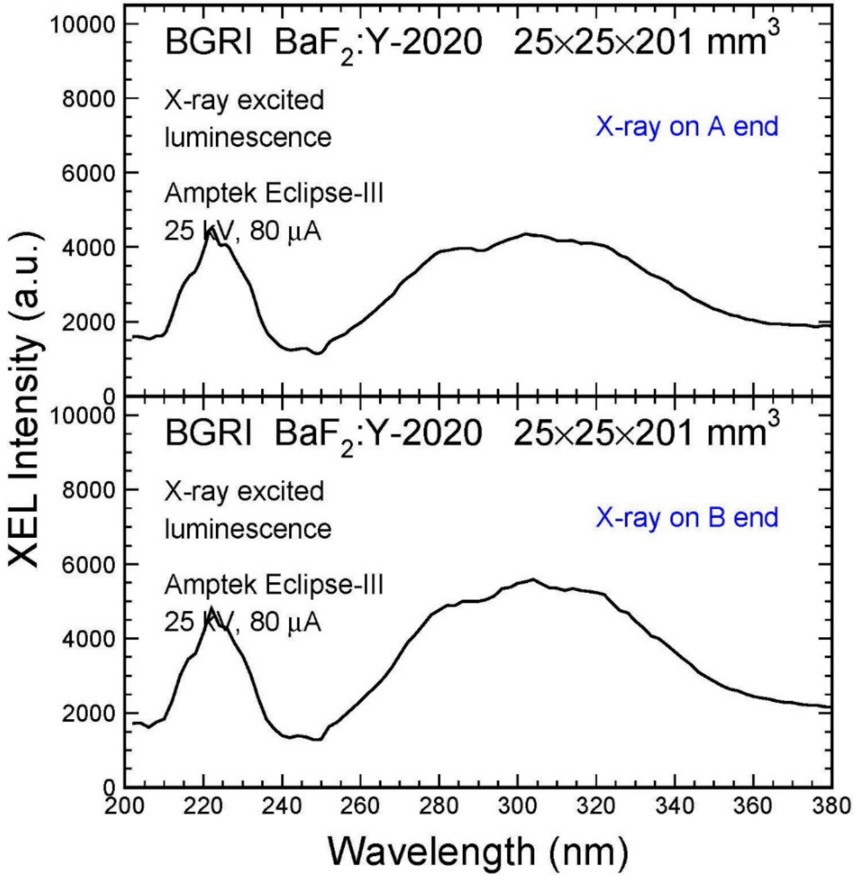


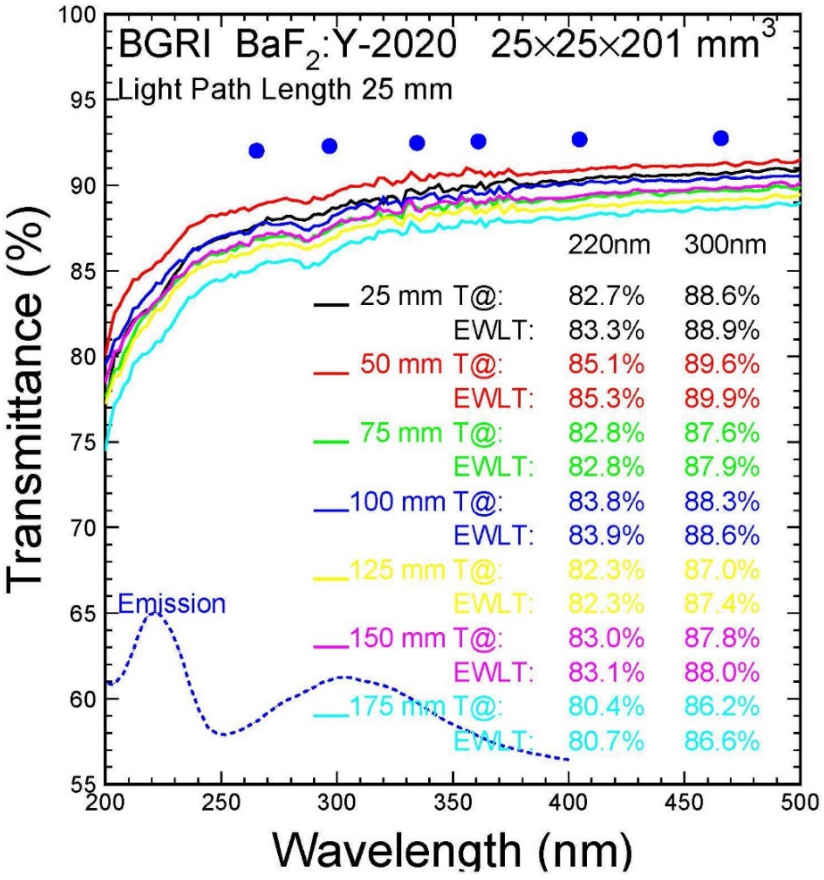


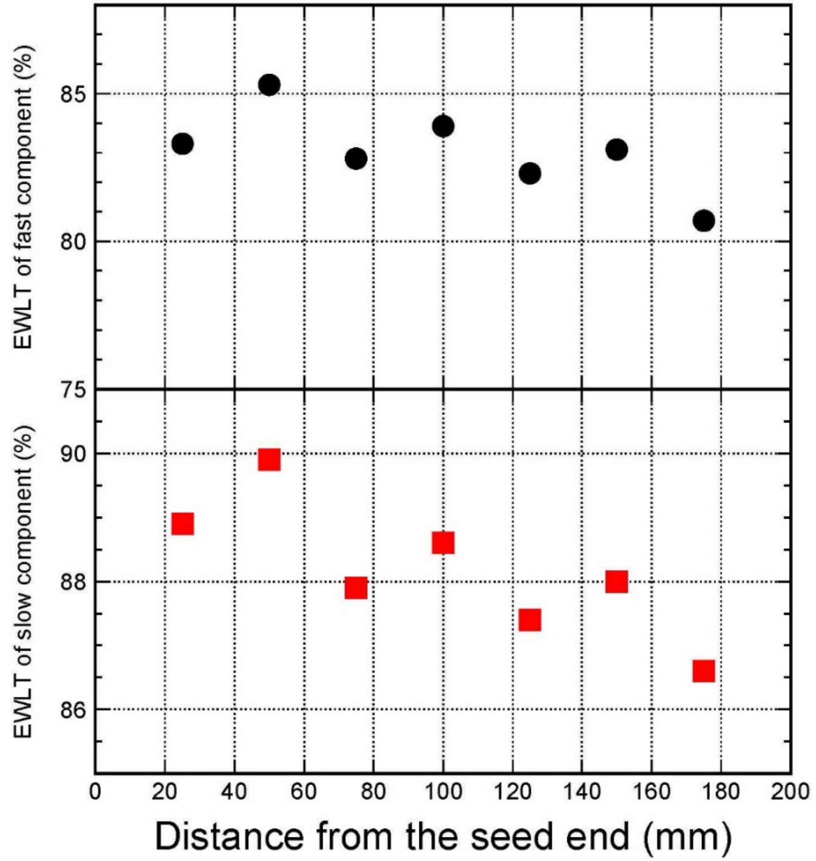


BGRI BaF_2:Y-2020: Transverse T

A variation of slow emission intensity and good optical quality along the crystal length







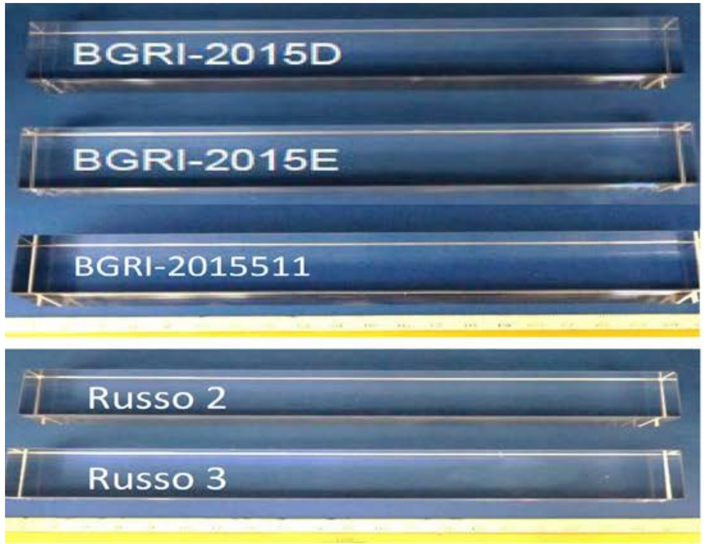
Summary: BGRI BaF_2:Y Long Crystals

Achievable: LO_F>100 p.e./MeV, F/S>2, 10% LRU and $|\delta_F|<3\%/X_0$

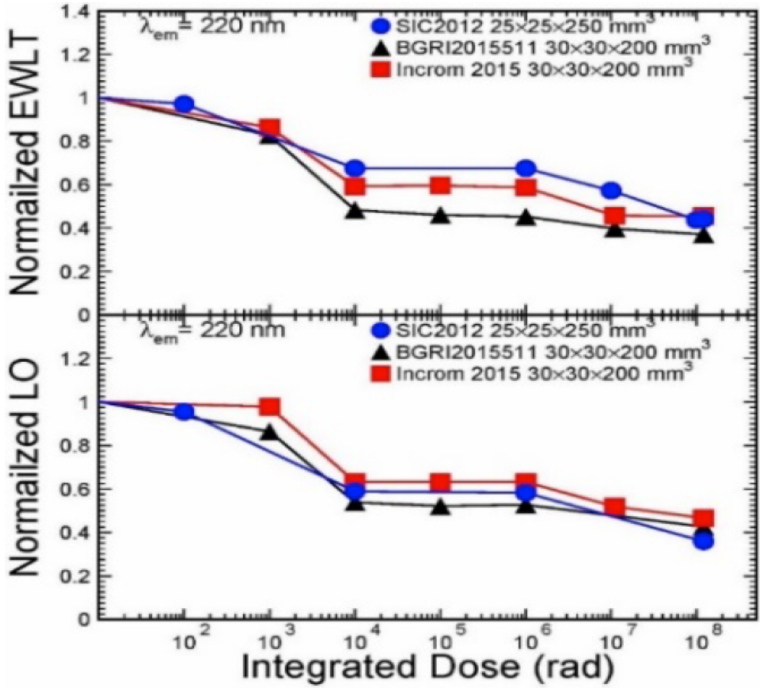
ID	Dimension (mm^3)	EWLT Fast (%)	EWLT Slow (%)	Coupling end	Basic Scintillation Performance ^{22}Na Source @ 1/8 length from the coupling end: 50 ns LO (p.e./MeV)	2500 ns LO (p.e./MeV)	LO(50) /LO(2500)	F	F/S	Light Response Uniformity: 50 ns LO	2500 ns LO	LO(50)/ LO(2500)
BGRI BaF_2:Y-2017	25×25×100	69.4	77.1	A	155	231	0.67	152	1.9	129 (11.5%)	206 (6.8%)	0.62 (4.8%)
				B	160	258	0.62	157	1.5	129 (15.4%)	214 (13.7%)	0.60 (2.1%)
BGRI BaF_2:Y-2018*	25×25×200	11.1	45.2	A	133	317	0.42	203	NA	83 (30.6%)	229 (20.4%)	0.35 (9.4%)
				B	133	265	0.52	159	NA	89 (26.4%)	228 (8.7%)	0.38 (17.2%)
BGRI BaF_2:Y-2020	25×25×201	61.1	72.2	A	135	268	0.50	124	0.9	105 (14.5%)	228 (8.5%)	0.45 (5.8%)
				B	138	270	0.51	126	0.9	106 (17.1%)	221 (14.7%)	0.47 (3.1%)

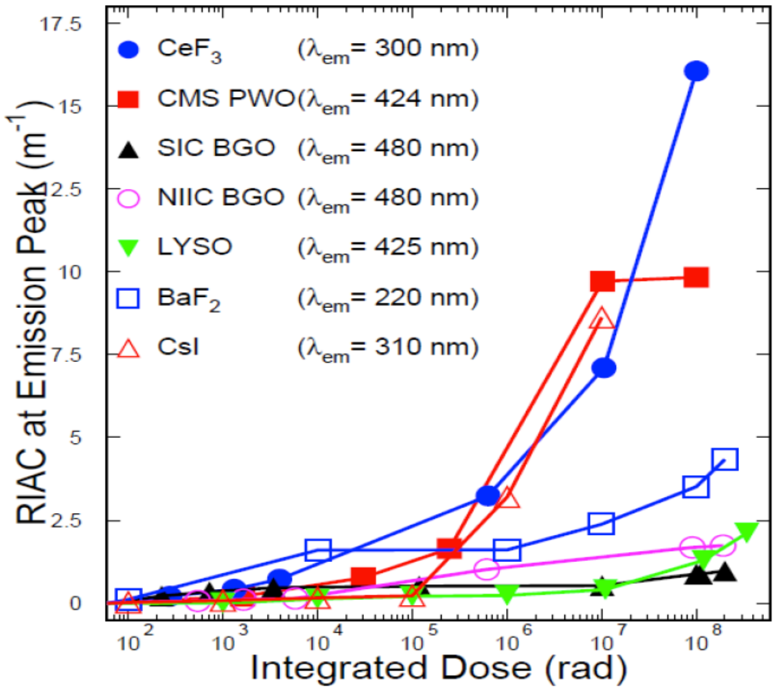
*CeF_3: Only one component with 30~50 ns decay time is observed, but no ultrafast component

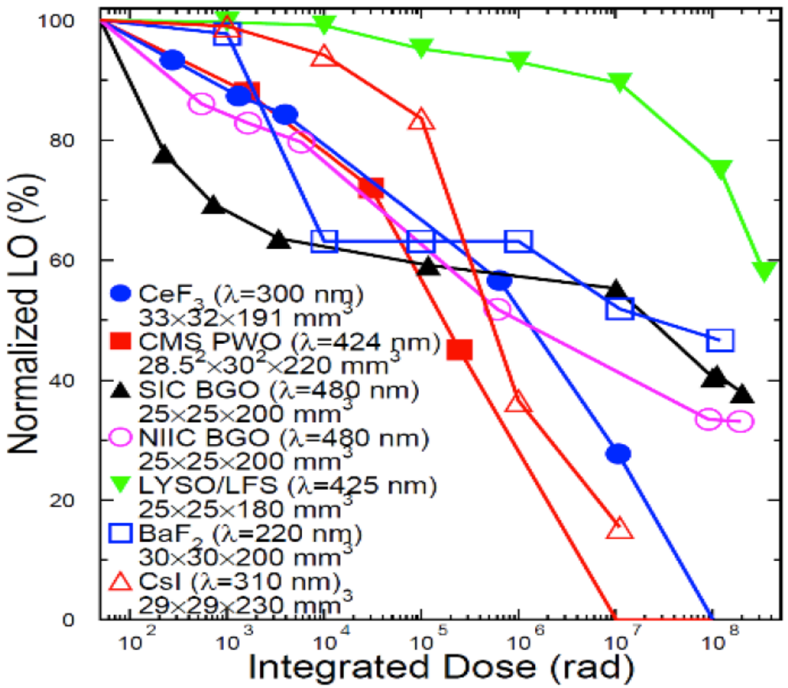
γ-Ray Induced Damage in Large BaF_2



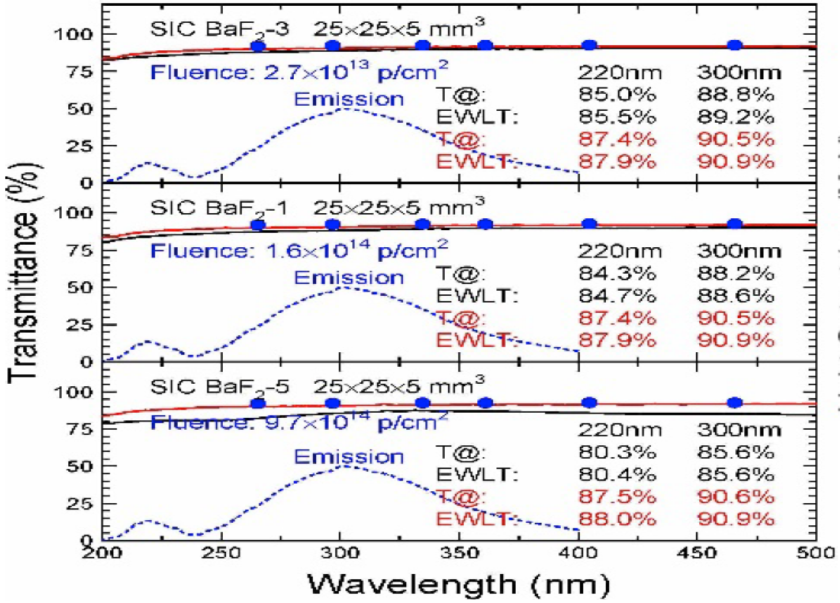
20 cm long BaF_2 shows ~50% light output loss after 120 Mrad, indicating good radiation resistance against ionization dose.
IEEE TNS 63 (2016) 612-619

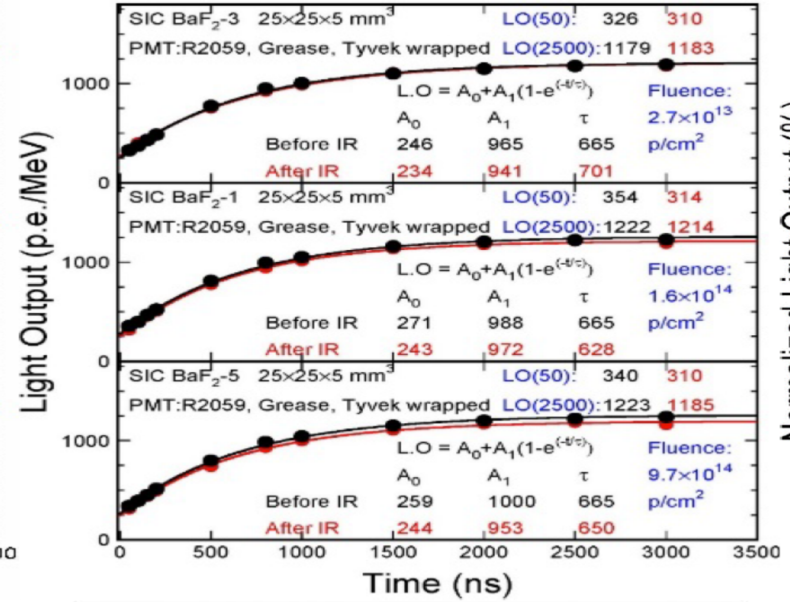


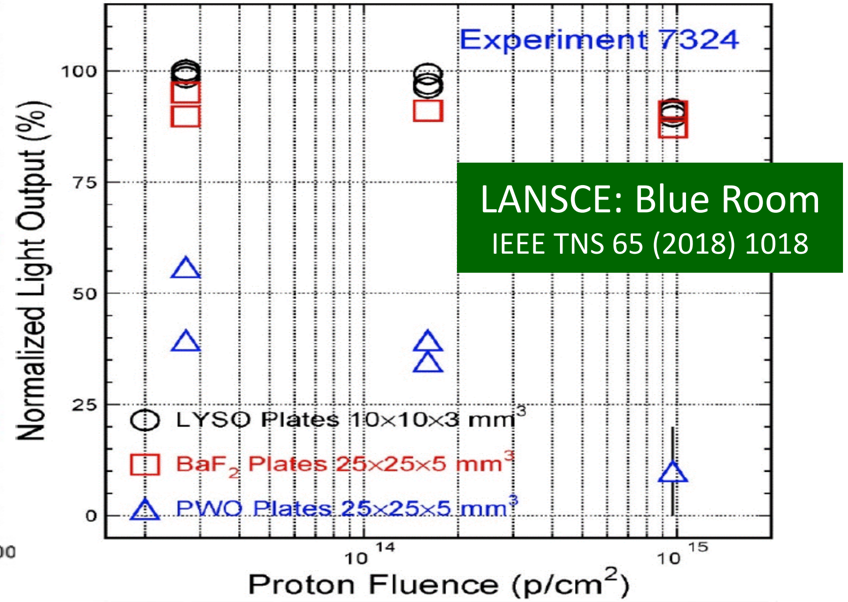


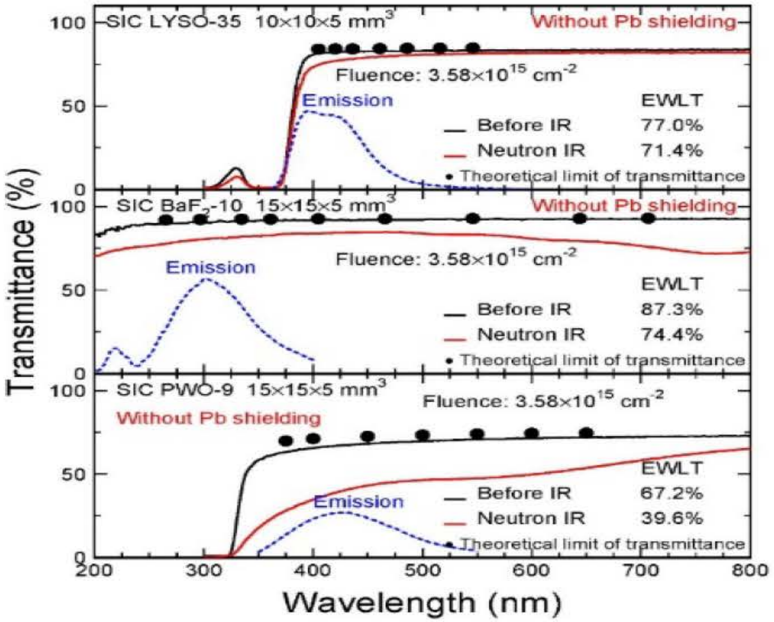


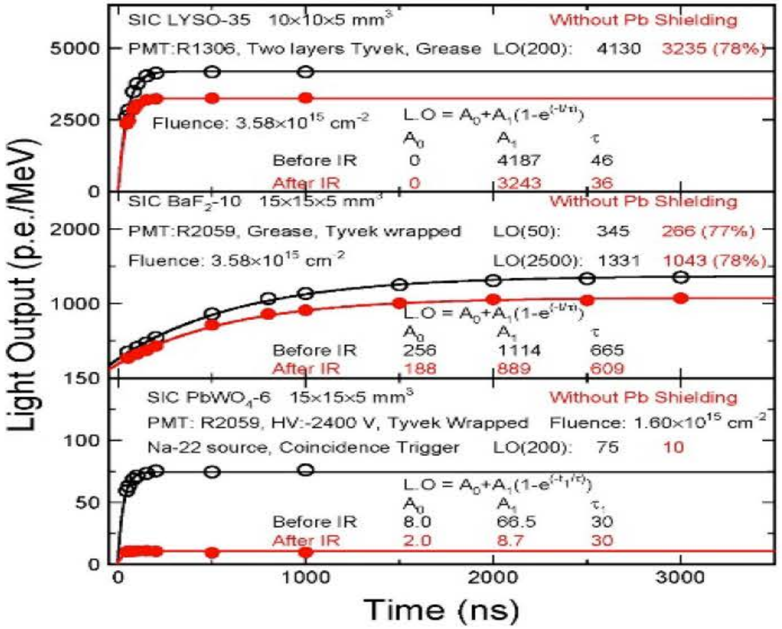
Proton and Neutron Induced Damage in BaF_2

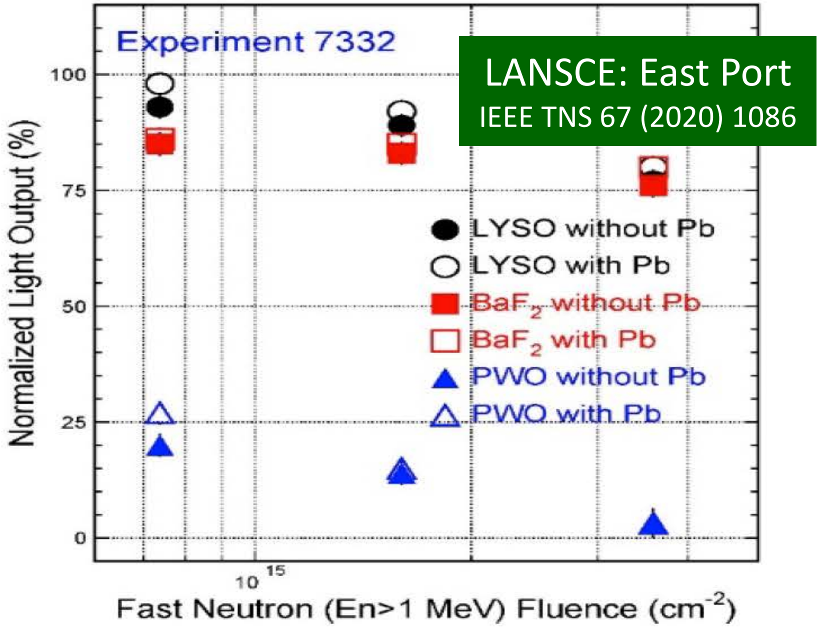












Summary

- BaF$_2$ crystals provide ultrafast light with 0.5 ns decay time. Yttrium doping increases the F/S ratio while maintaining the ultrafast light intensity. With sub-ns pulse width BaF$_2$:Y promises a ultrafast calorimeter.
- 20 cm long BaF$_2$ crystals show ~50% LO loss after 120 Mrad. 5 mm thick BaF$_2$ plates show less than 20% LO after 1 x 10^{15} p/cm^2 or 3.6 x 10^{15} n_{eq}/cm^2, indicating that BaF$_2$ of short light path may be used in a severe radiation environment.
- Achievable performance of 20 cm long BaF$_2$:Y crystals: LO_F>100 p.e./MeV, F/S>2, <10% LRU and $|\delta_F|$<3%/X_0. R&D will continue to optimize yttrium doping in large size BaF$_2$:Y crystals for Mu2e-II.
  - SIC plans to reduce scattering centers by refining growth parameters.
  - BGRI plans to eliminate residual cerium contamination by purifying raw material.
  - Caltech plans to investigate radiation hardness of BaF$_2$:Y crystals.
- Effort is also needed to develop VUV photodetector, such as solar-blind SiPM, LAPPD or diamond-based photodetectors.

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