Development of Large Size Yttrium Doped BaF_2 Crystals for Future HEP Experiments

Chen Hu[1], Chao Xu[2], Liyuan Zhang[1]
Qinhui Zhang[2] and Ren-Yuan Zhu[1]

[1]California Institute of Technology

[2]Beijing Glass Research Institute

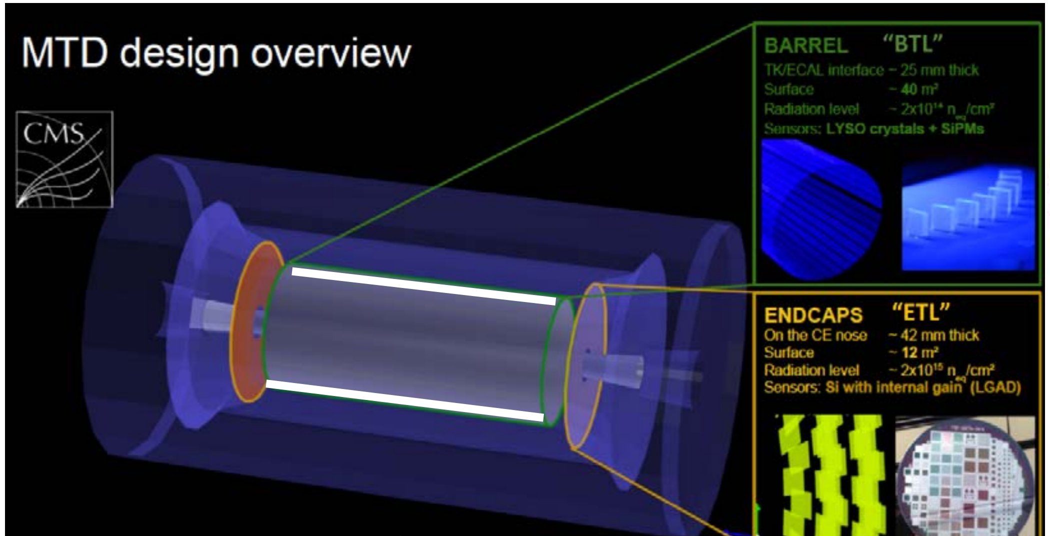
November 14, 2018

Paper N21-04 presented in the IEEE NSS/MIC 2018 Conference at Sydney, Australia

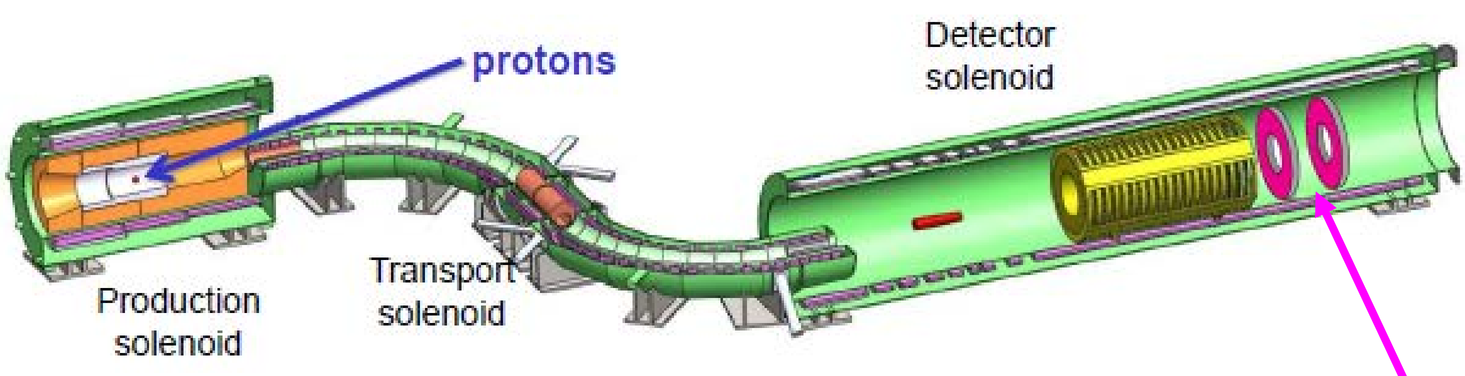
Introduction

- Mu2e-I at Fermilab is building a pure CsI calorimeter, which has 30 ns fast scintillation and survives ionization dose up to 100 krad. A radiation level beyond 100 krad is expected by Mu2e-II, where CsI will be blackened and can not be cured.
- With sub-ns fast scintillation and excellent radiation hardness BaF_2 crystals promise a very fast and robust calorimeter for Mu2e-II.
- There are two effective approaches to handle the 600 ns slow scintillation in BaF_2: solar blind photodetector and/or selective doping. Recent progress in yttrium doped BaF_2 promises an ultrafast calorimeter for future HEP applications.
- Mass production capability of BaF_2 exists in industry:
  - BGRI (China), Incrom (Russia) and SICCAS (China): tested;
  - Hellma (Germany): in contact
- Status of large size BaF_2 crystals for the Mu2e-II experiments is reported.

Application of Fast Inorganic Scintillators

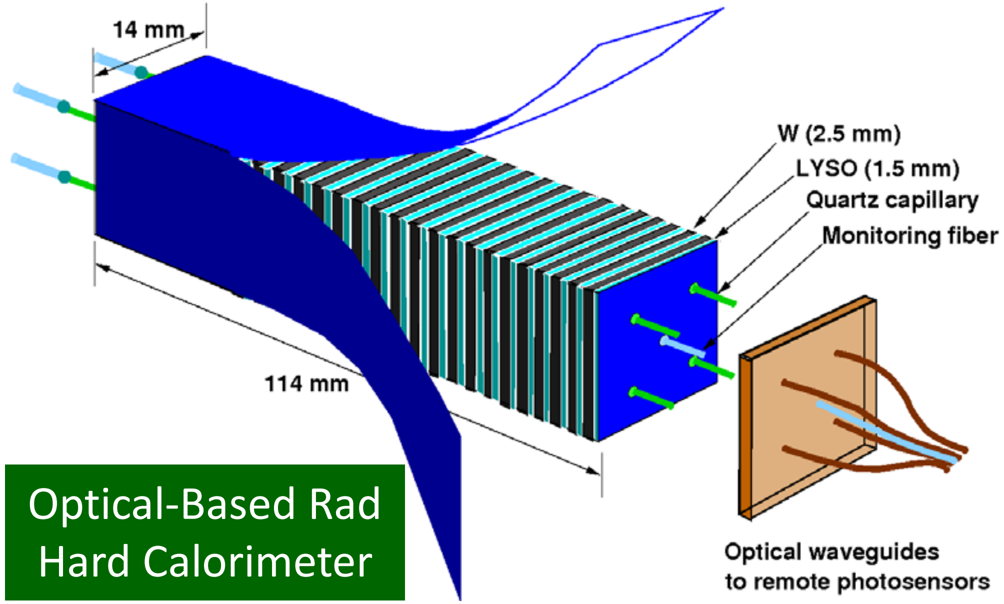


CMS BTL: An LYSO + SiPM Layer



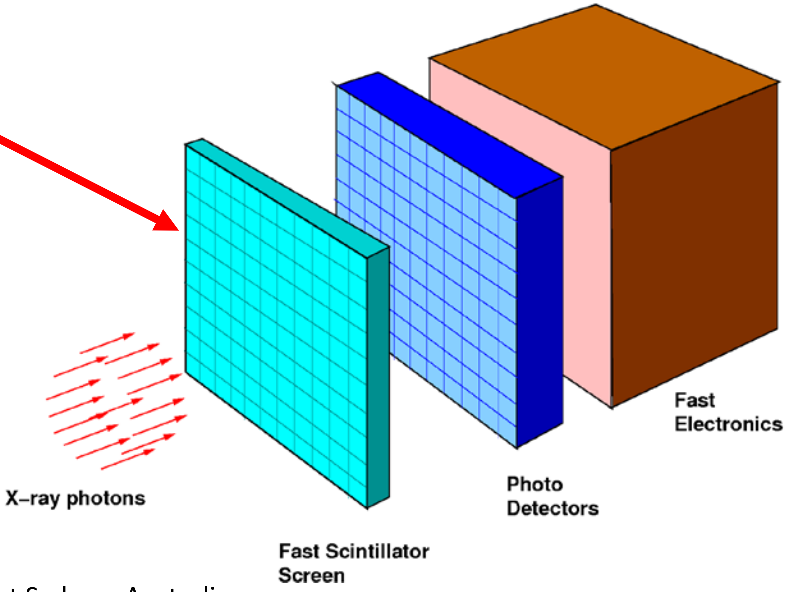
Mu2e-II: arXiv:1802.02599
See papers N37-4, N40-3

Mu2e-I: 1,348 CsI of 34 x 34 x 200 mm
Mu2e-II: 1,940 BaF_2:Y of 30 x 30 x 218 mm



Optical-Based Rad Hard Calorimeter

A BaF_2 crystal based ultrafast front imager proposed for GHz hard X-ray imaging for the proposed MaRIE project in the 2016 workshop at Santa Fe



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 (℃)	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	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	4.2 1.3	42 4.8	8.6	99	15 49	153	35
Decay Time[a] (ns)	40	73	60	30 6	650 0.6	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

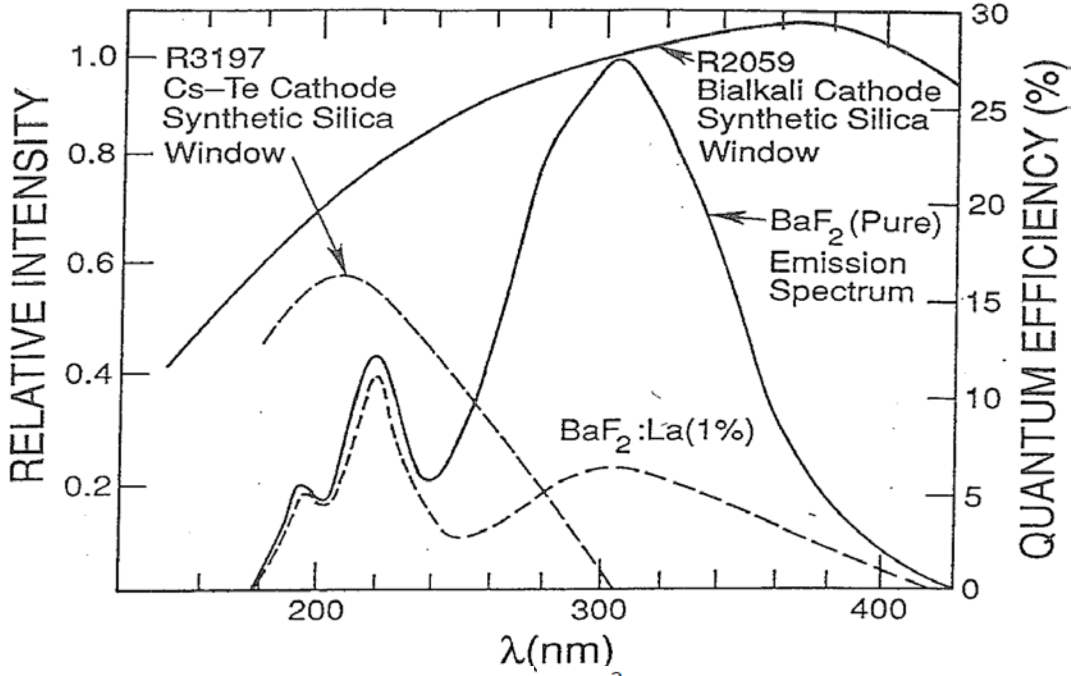
The sub-ns fast scintillation in BaF_2 promises a very fast crystal calorimeter to face the challenge of high event rate expected by future HEP experiments at the intensity frontier

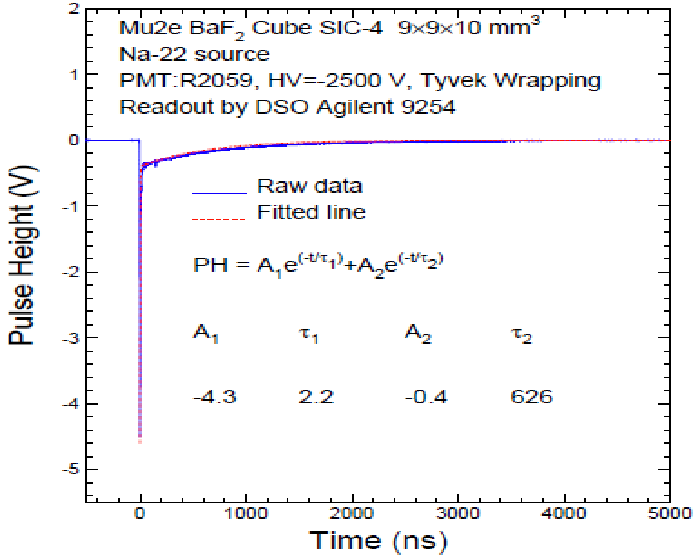
Ultrafast and Slow Light from BaF_2

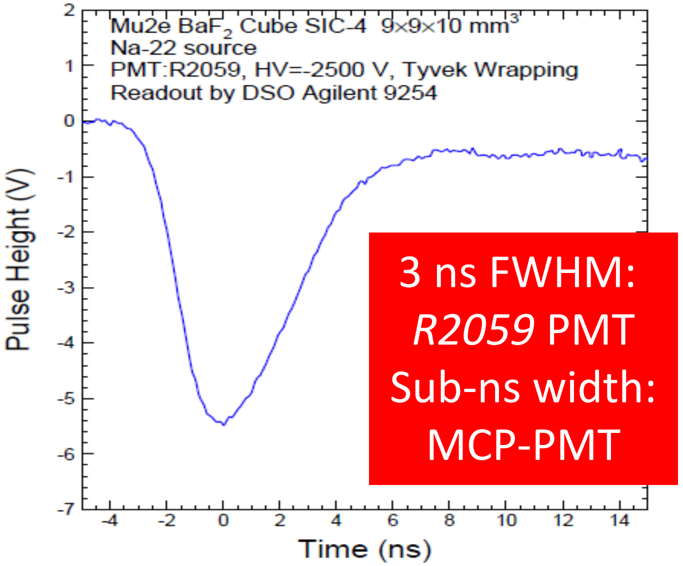
BaF_2 has a fast scintillation component with sub-ns decay time, and a 600 ns slow component.

The amount of the fast light is similar to undoped CsI, and is 1/5 of the slow component.

Spectroscopic readout of the fast component may be realized by (1) selective doping with rare earths or (2) a solar blind photodetector.



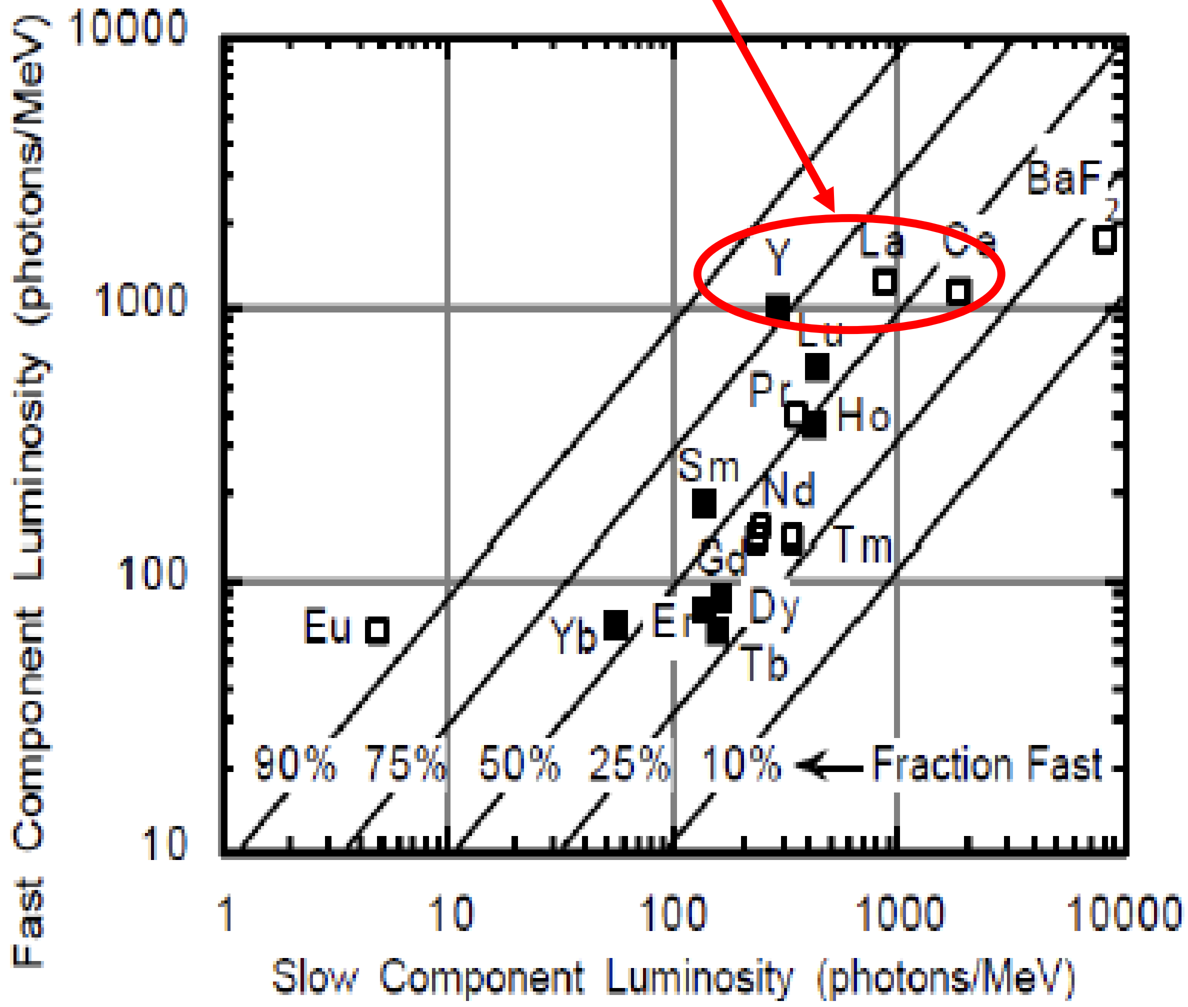


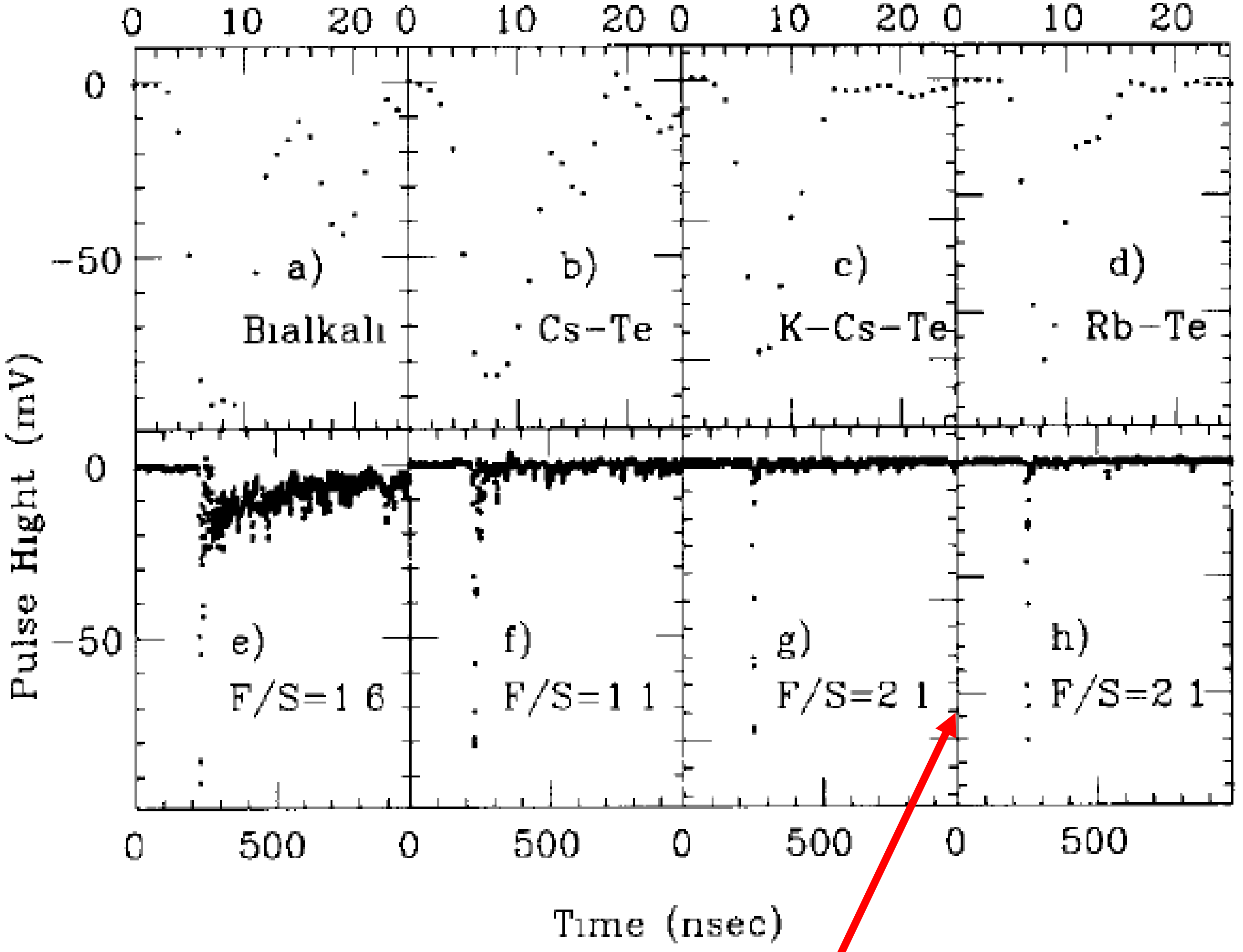


3 ns FWHM: *R2059* PMT
Sub-ns width: MCP-PMT

Slow Suppression: RE Doping & SB Readout

MRS Proceedings (1994) 277: Slow suppression by RE doping

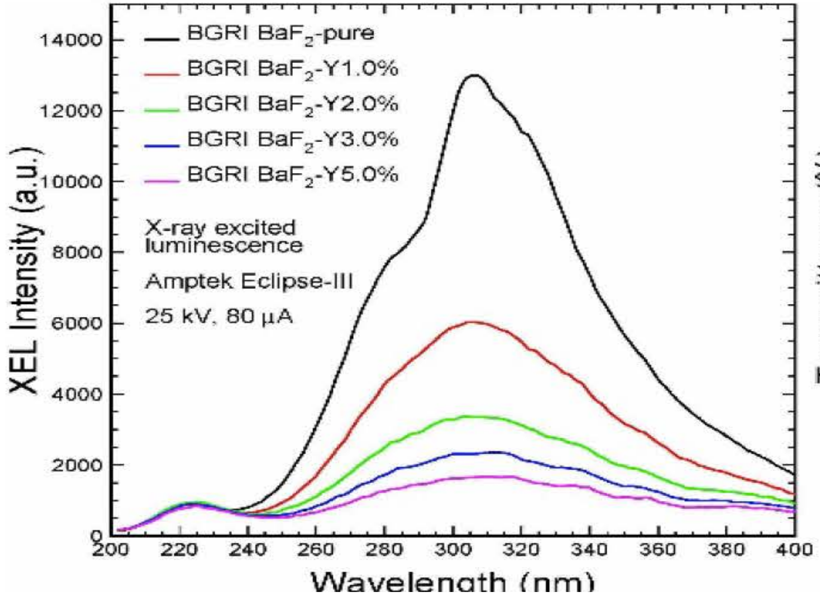


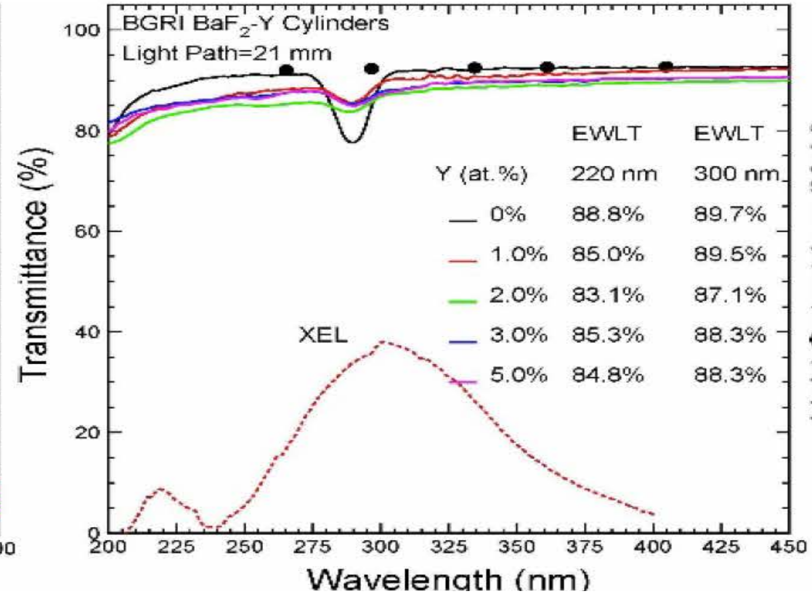


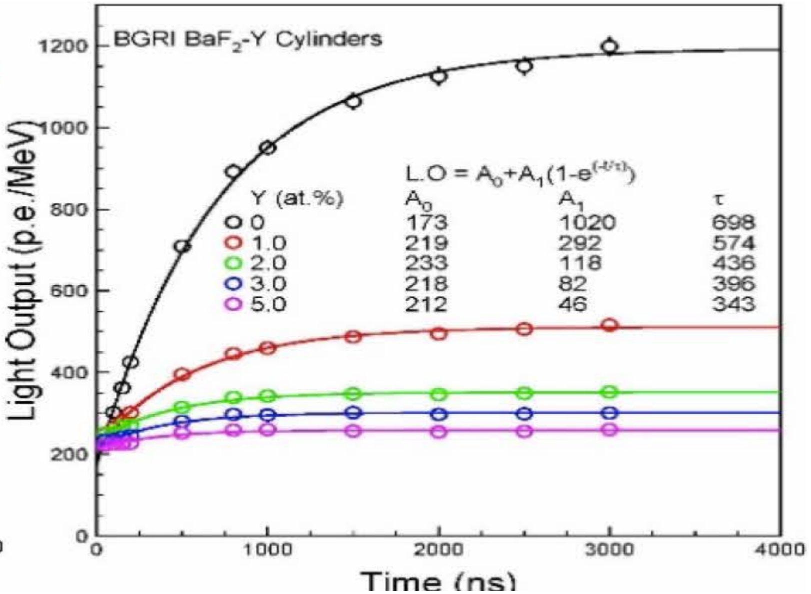
NIM 240 (1994) 442: Cs-Te, K-Cs-Te and Rb-Te cathode achieved F/S = 2/1

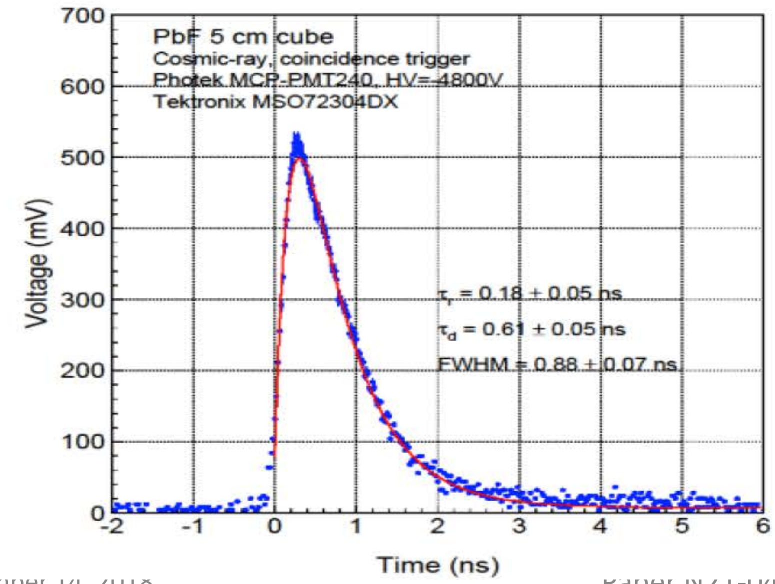
Yttrium Doped Barium Fluoride: BaF_2:Y

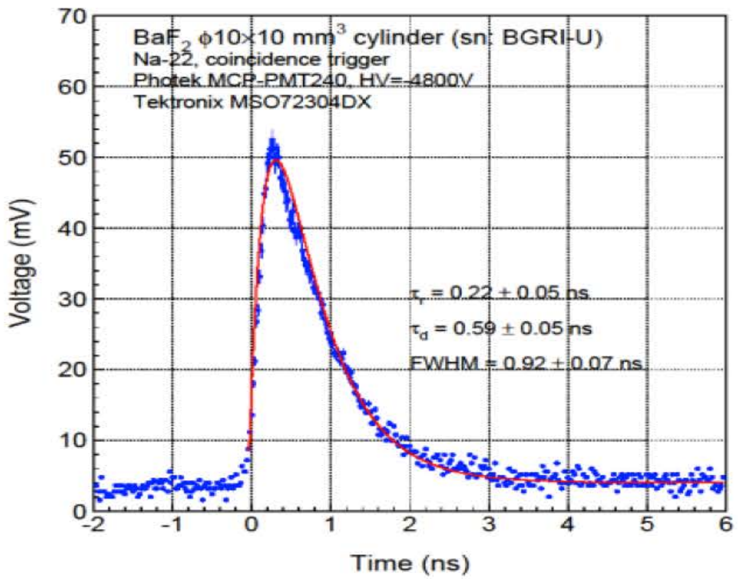
Significant increased F/S ratio in BaF_2:Y. Sub-ns FWHM by MCP-PMT. See also paper N40-3.

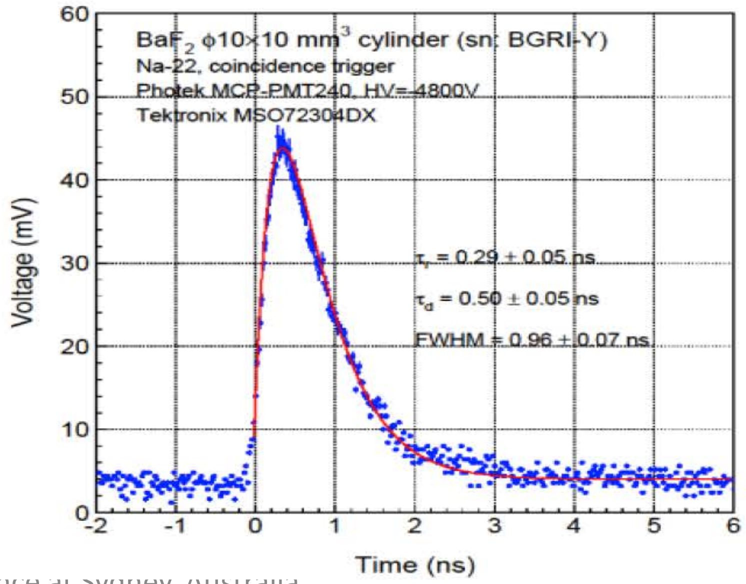




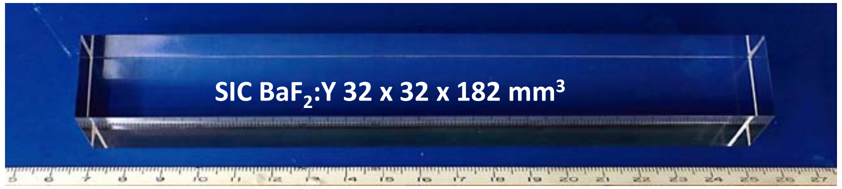


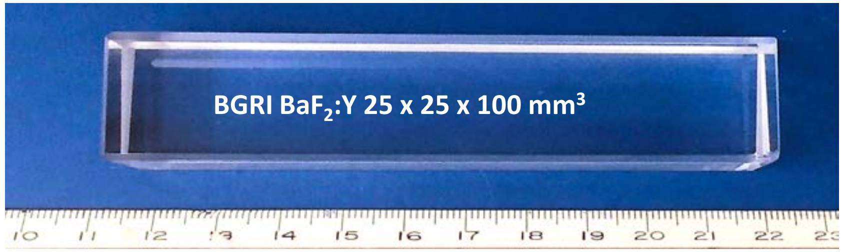


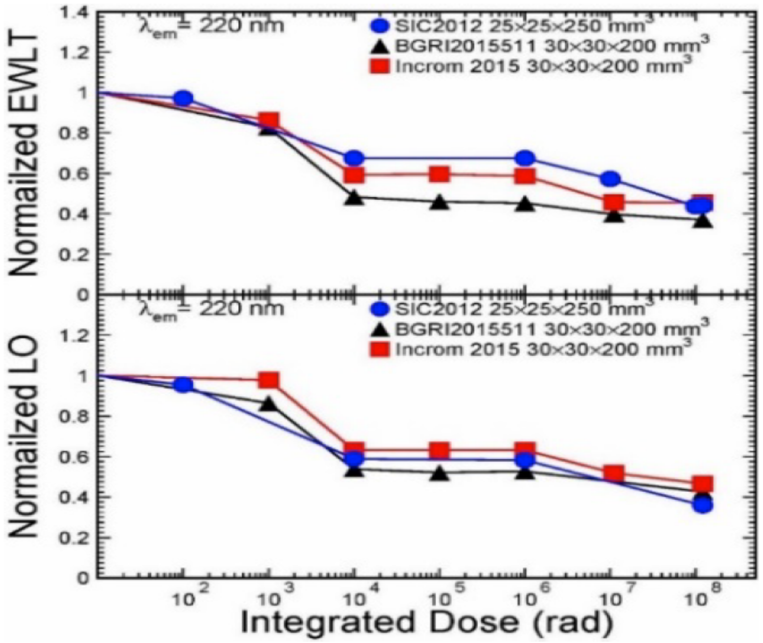


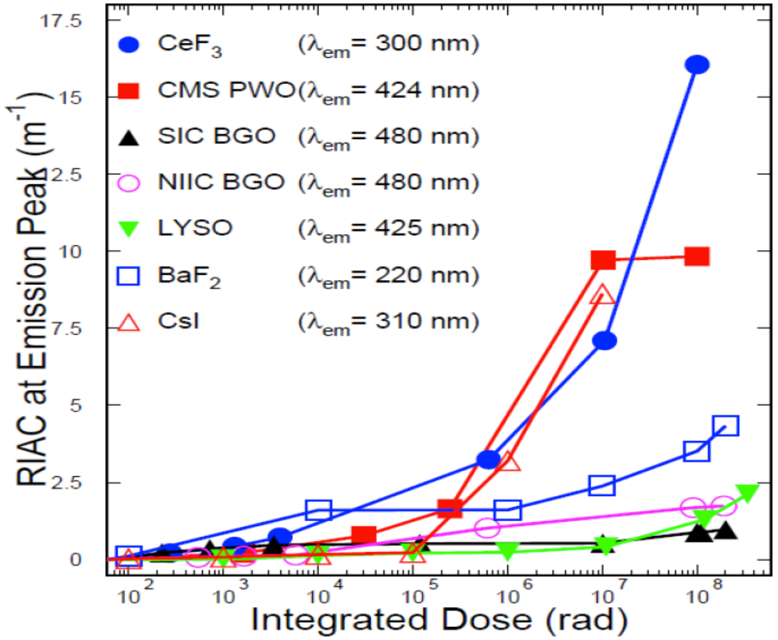


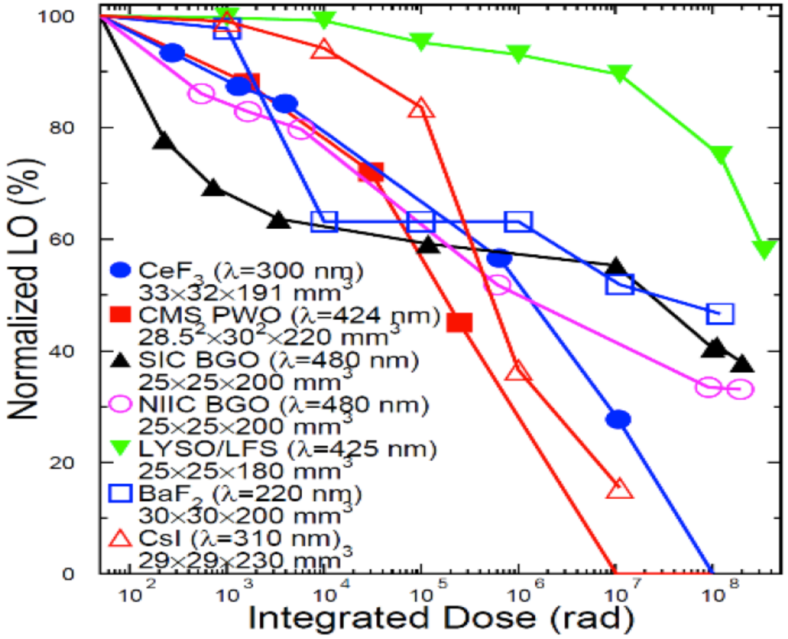
γ-Ray Induced Damage in Large Samples



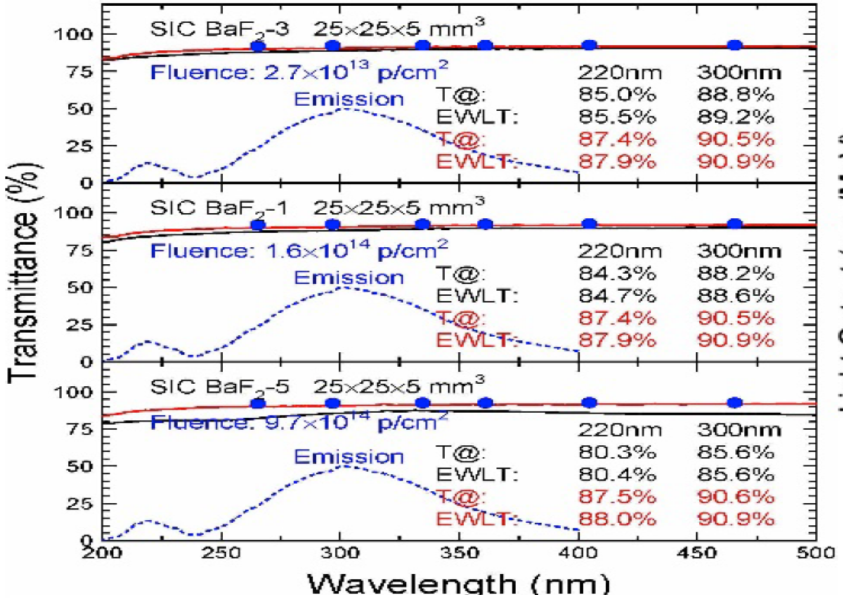


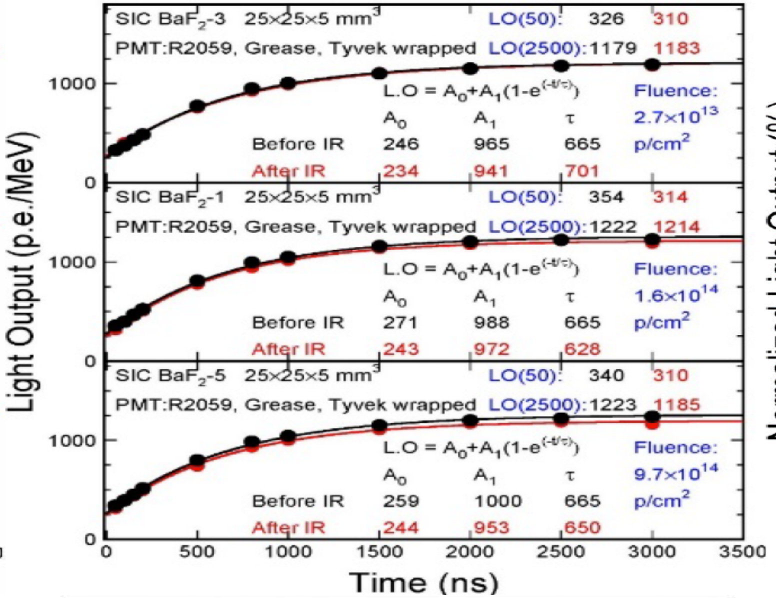


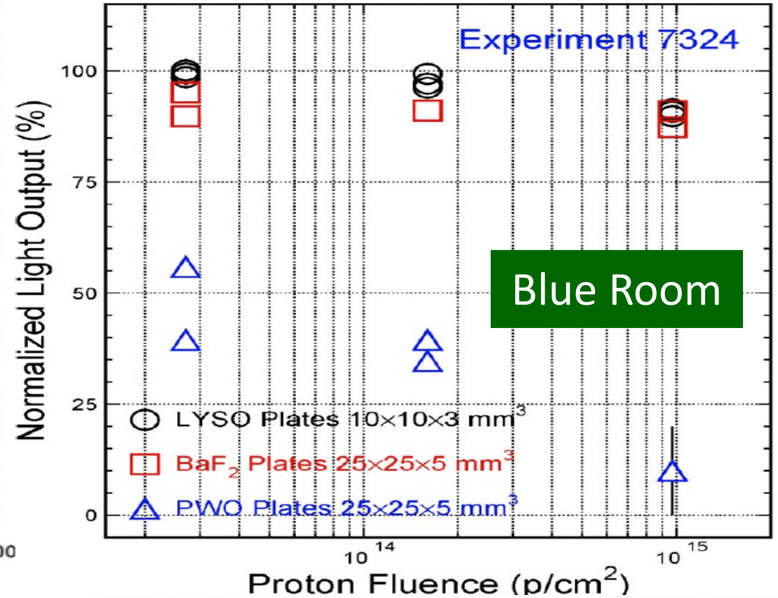


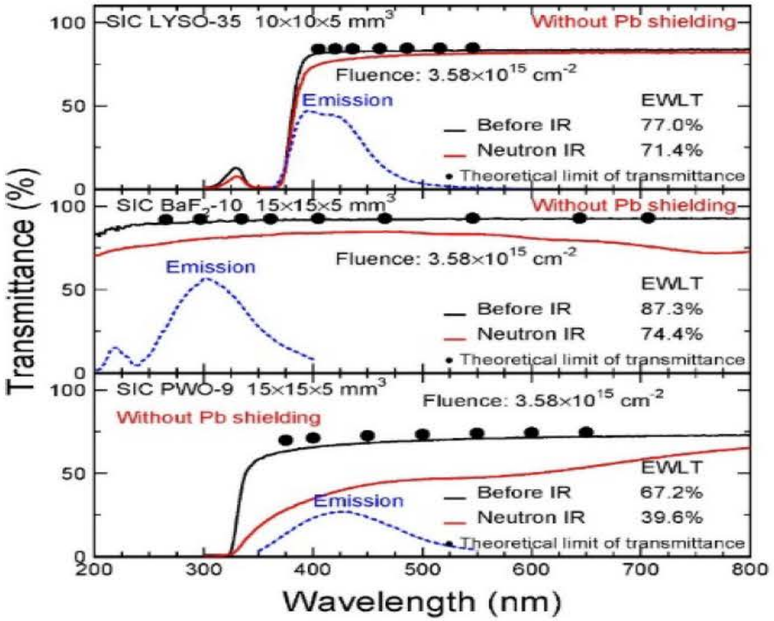


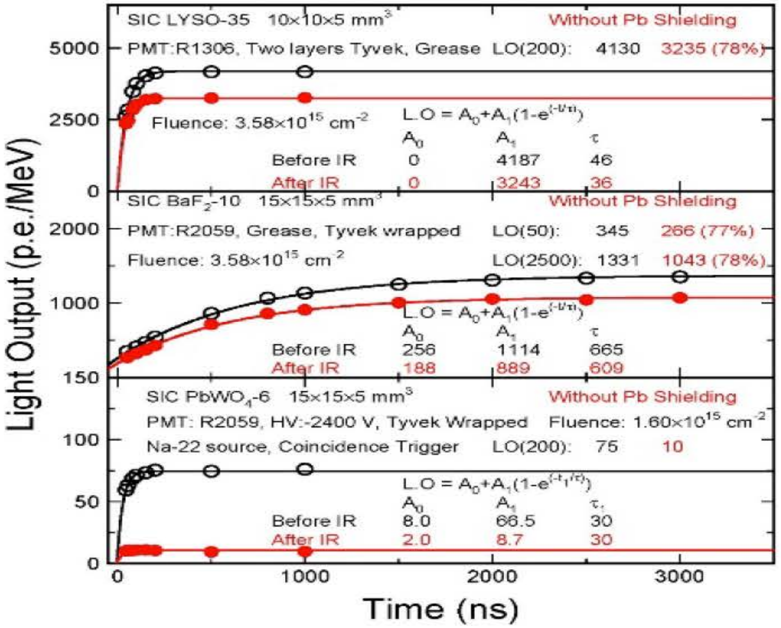
Proton and Neutron Induced Damage

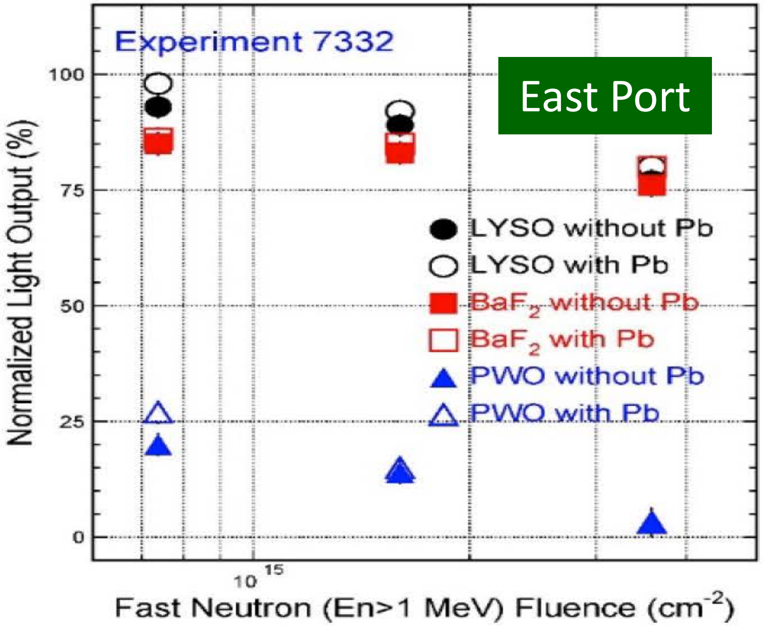




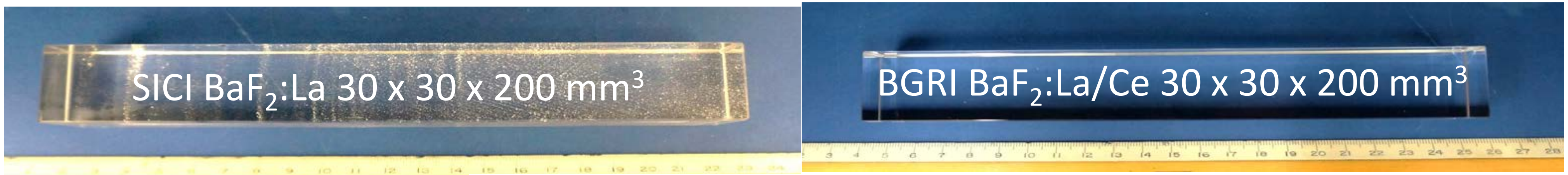


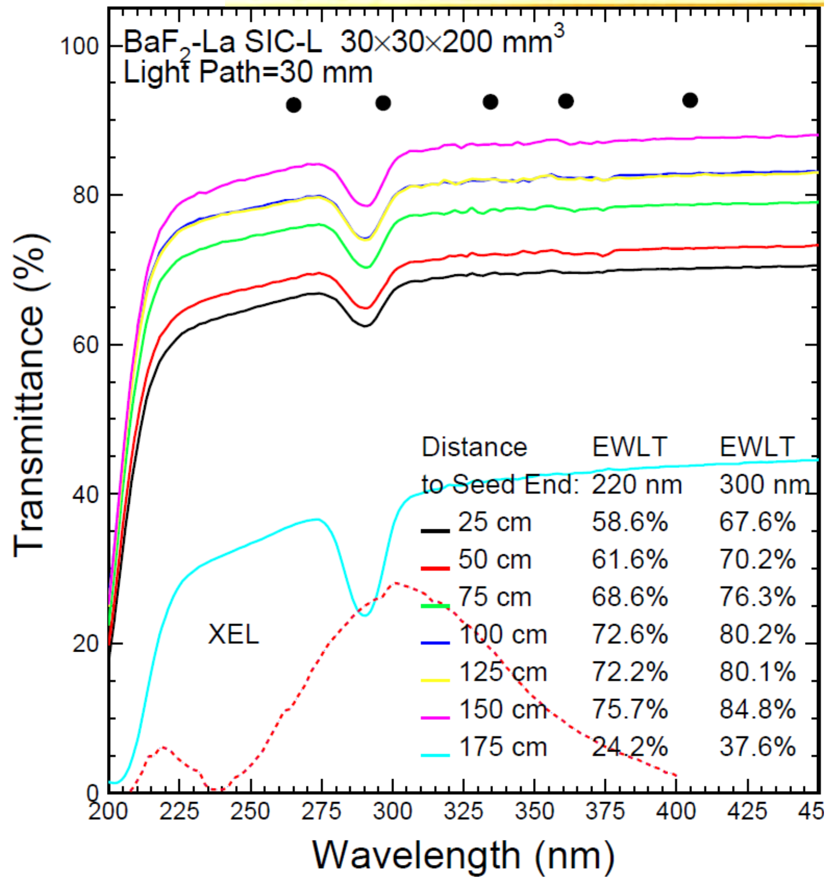


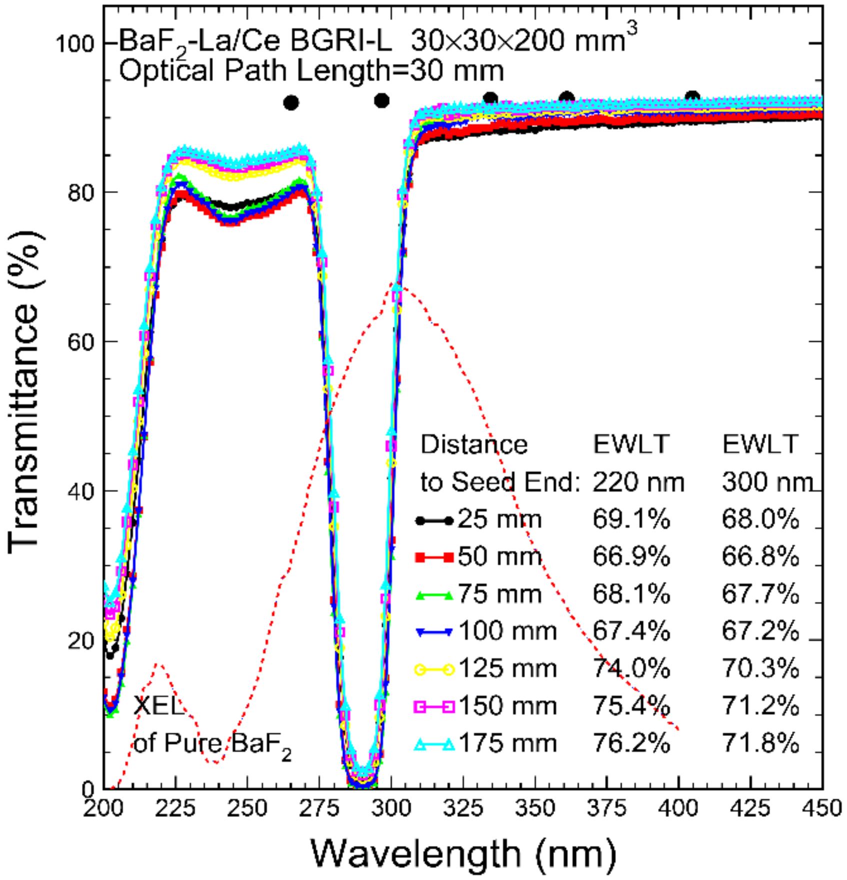


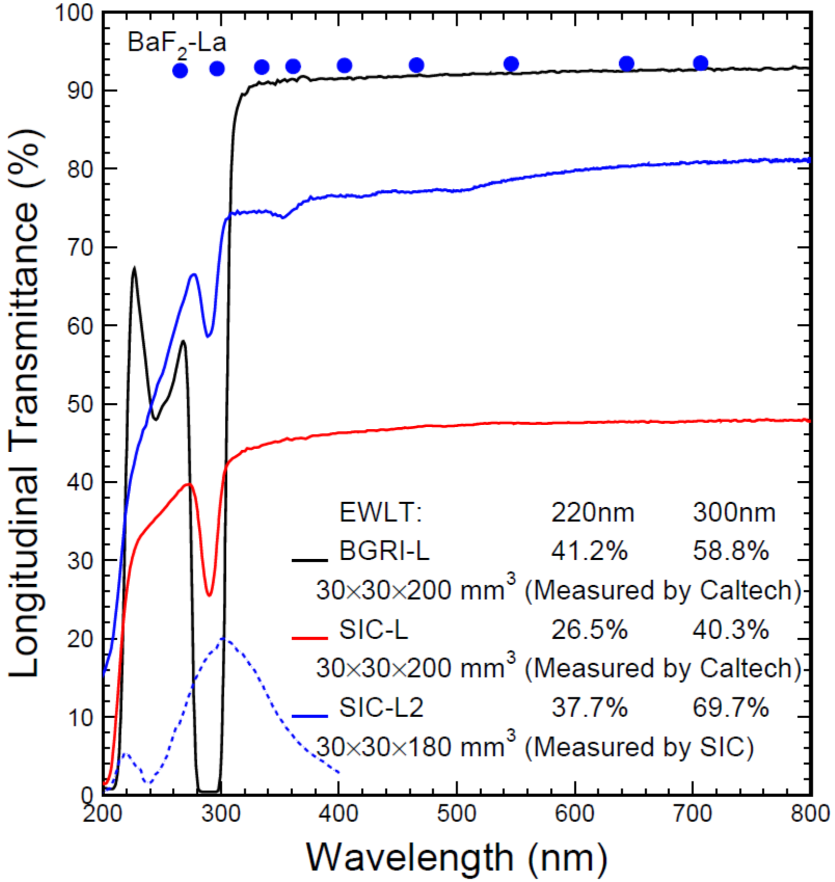


Transmittance of BaF_2:La and BaF_2:La/Ce





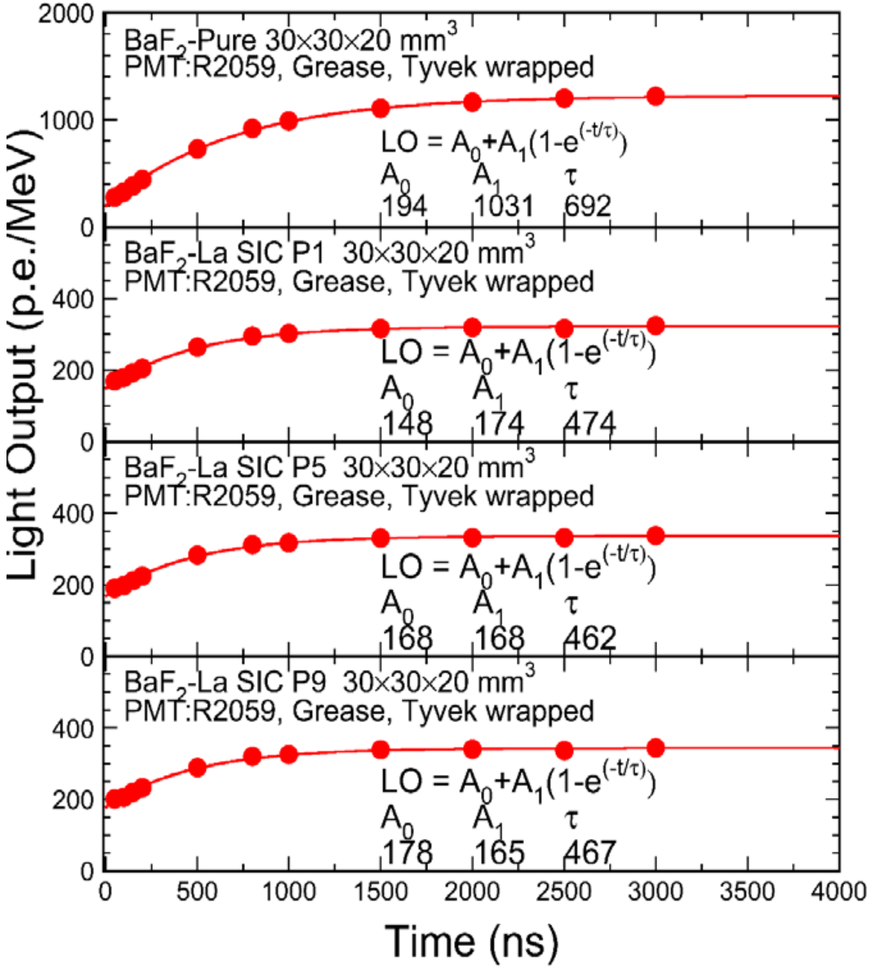


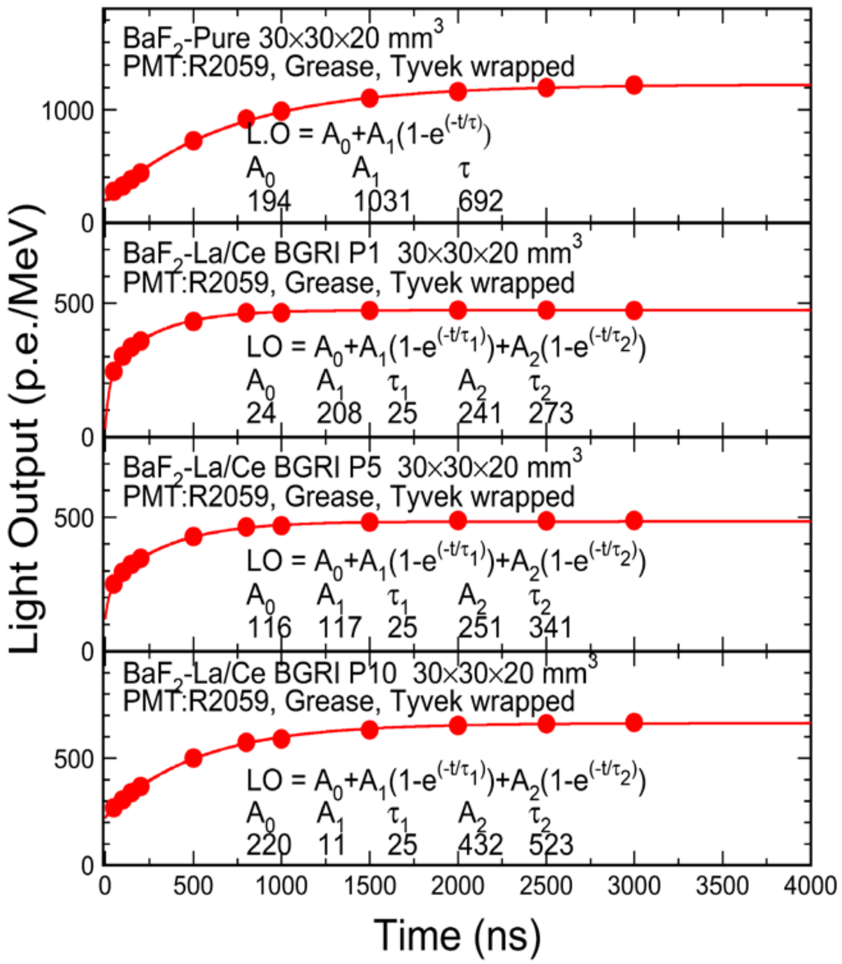


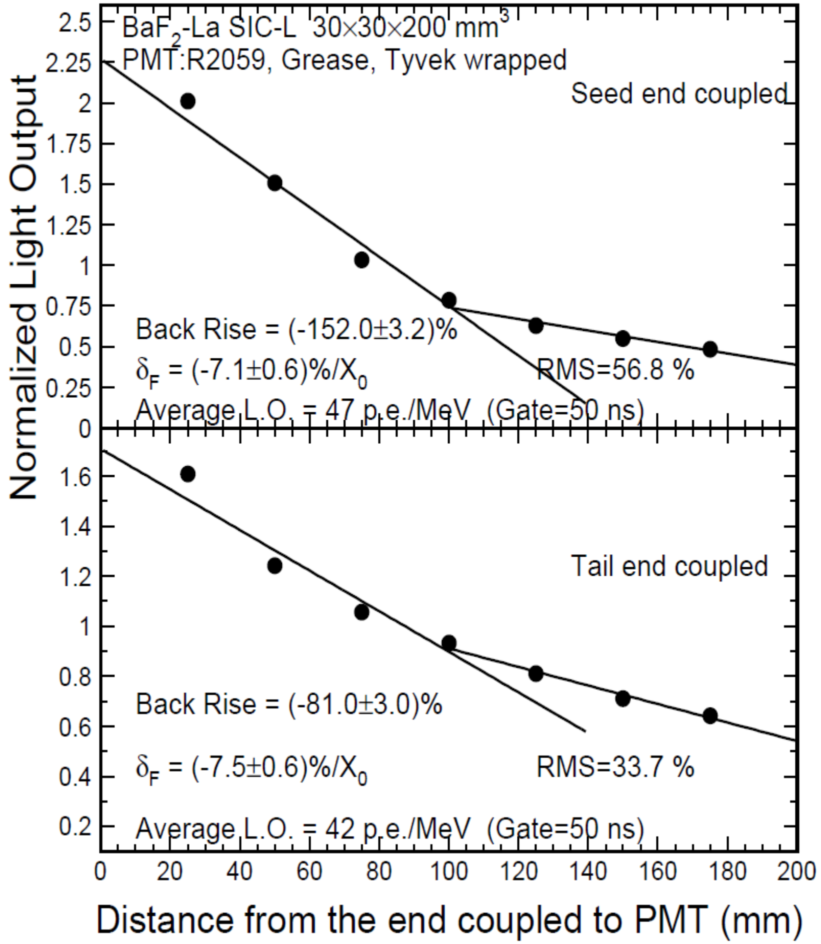
Significant absorptions observed in both La and La/Ce doped BaF_2

Light Output of BaF_2:La and BaF_2:La/Ce

F/S increased up to 1; LRU: Poor LRU for the fast component

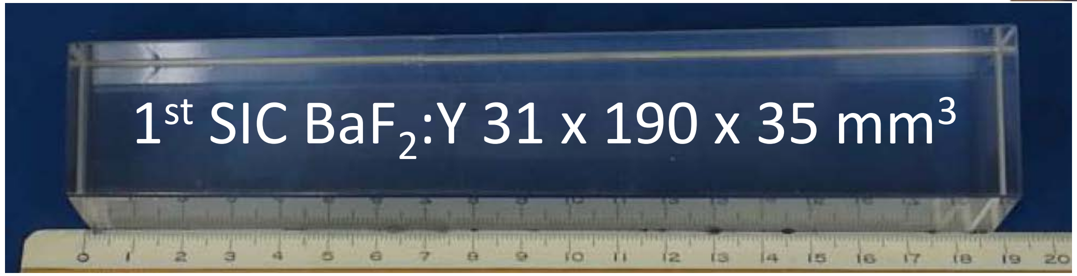


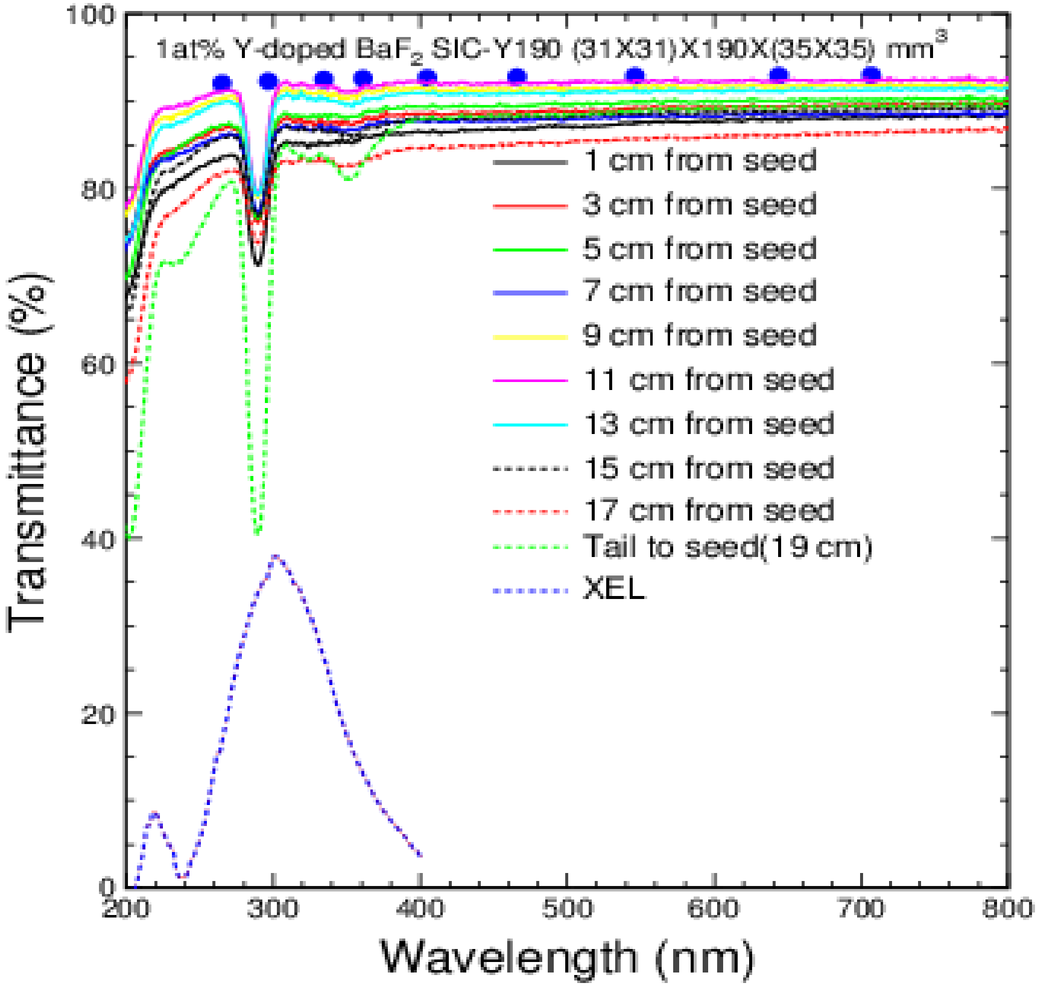


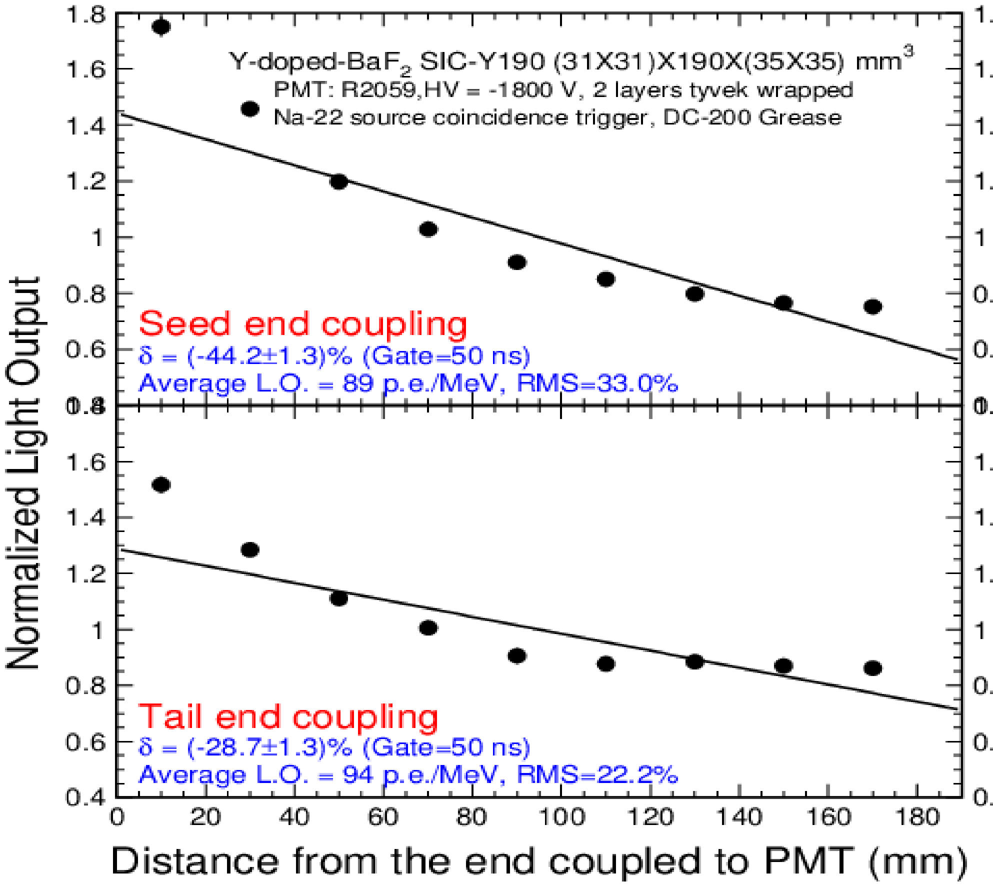


The 1st 19 cm BaF_2:Y from SIC

J. Chen *et al*, IEEE TNS 65 (2018) 2147-2151
F/S ratio: 1.3; LRU: 22% & 33%

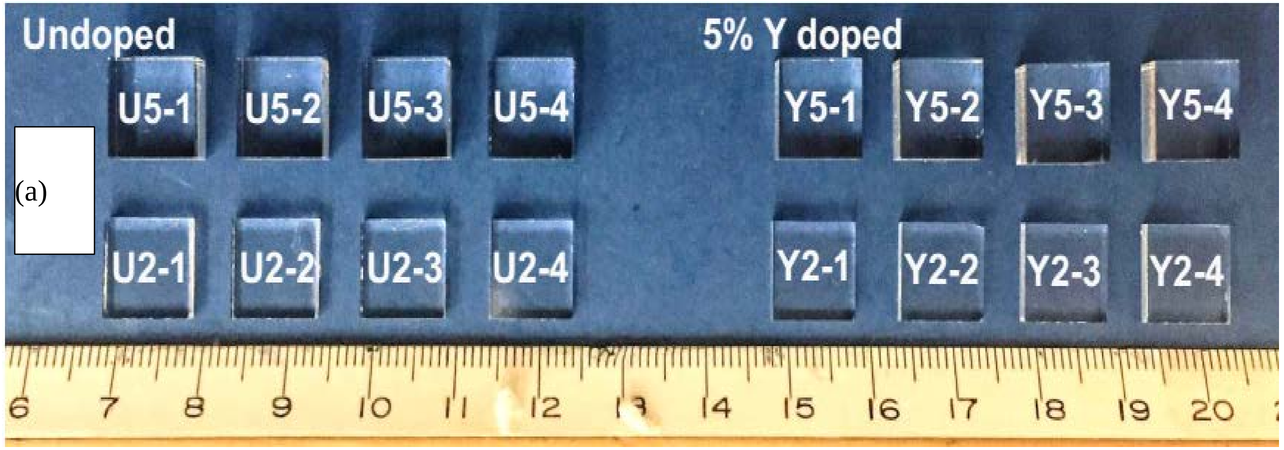




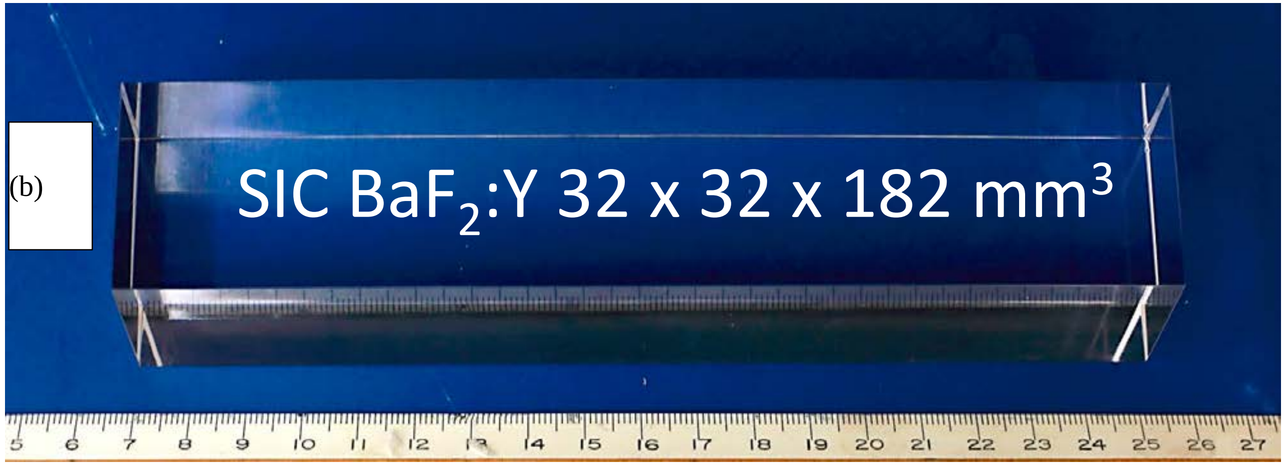


The 2nd SIC BaF_2:Y Sample of 18 cm

Low yttrium doping level needs to be optimized

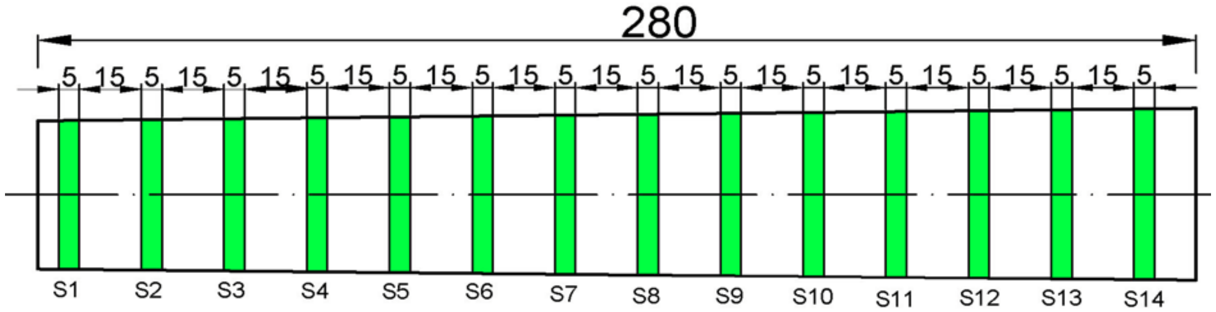


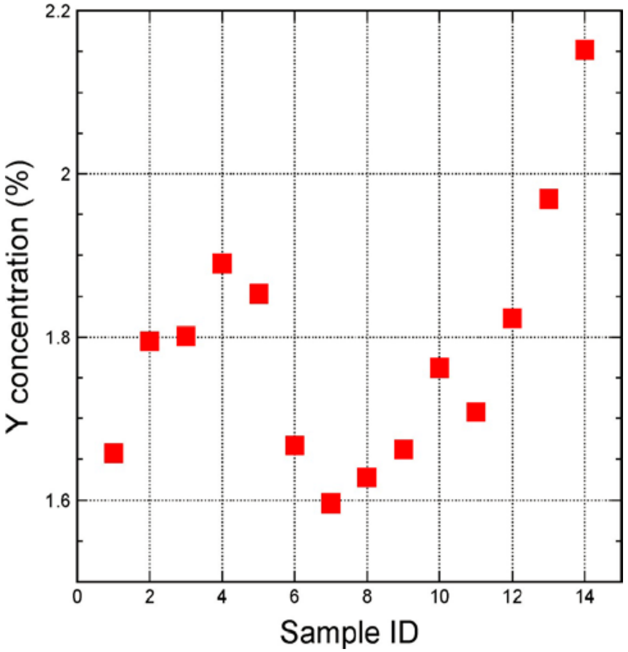
(a)



(b)

SIC BaF_2:Y 32 x 32 x 182 mm^3

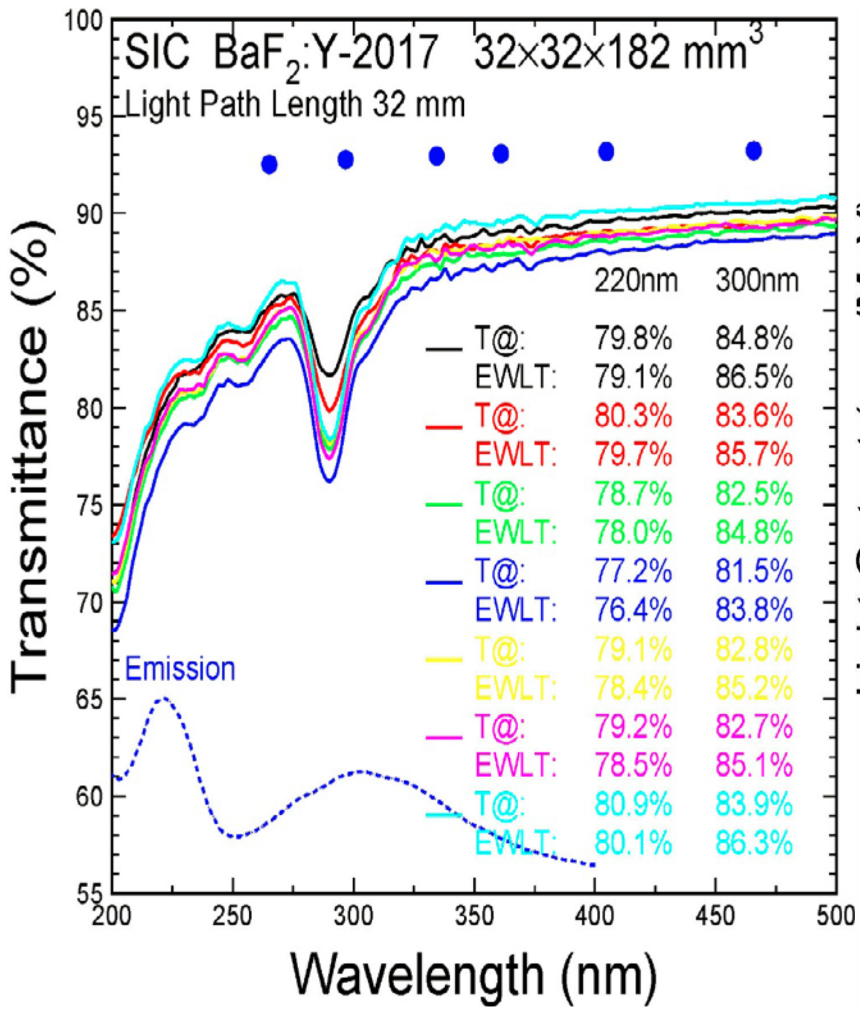


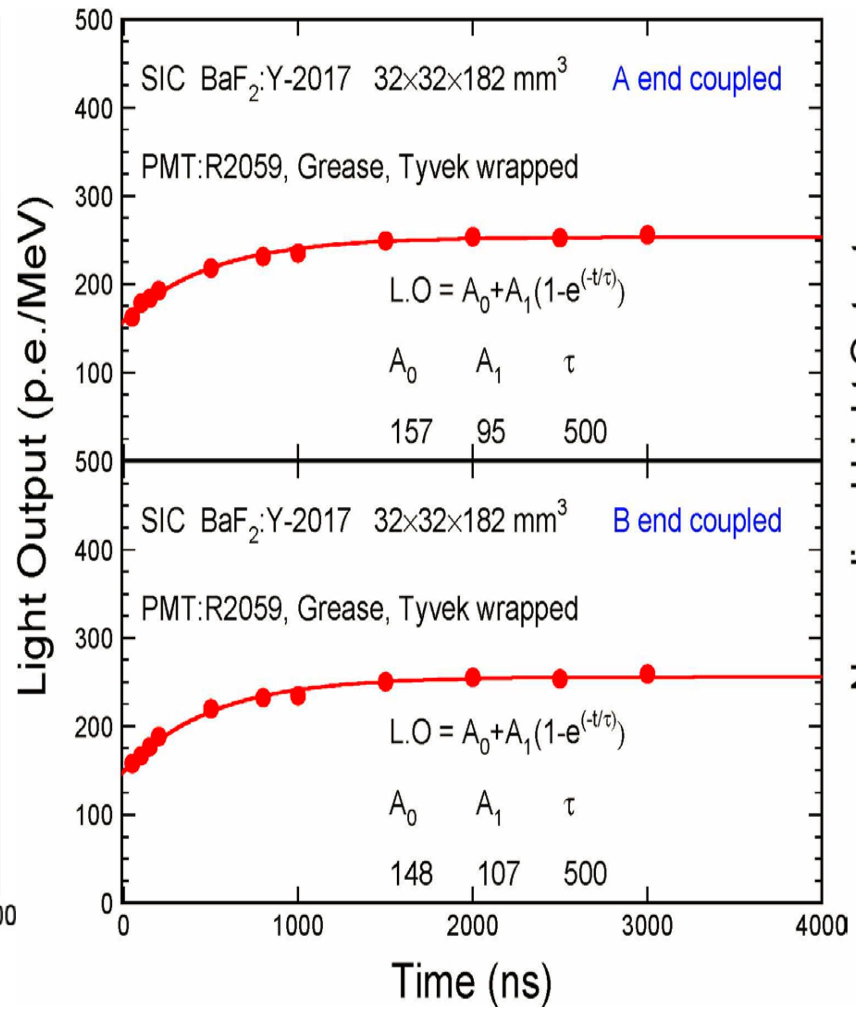


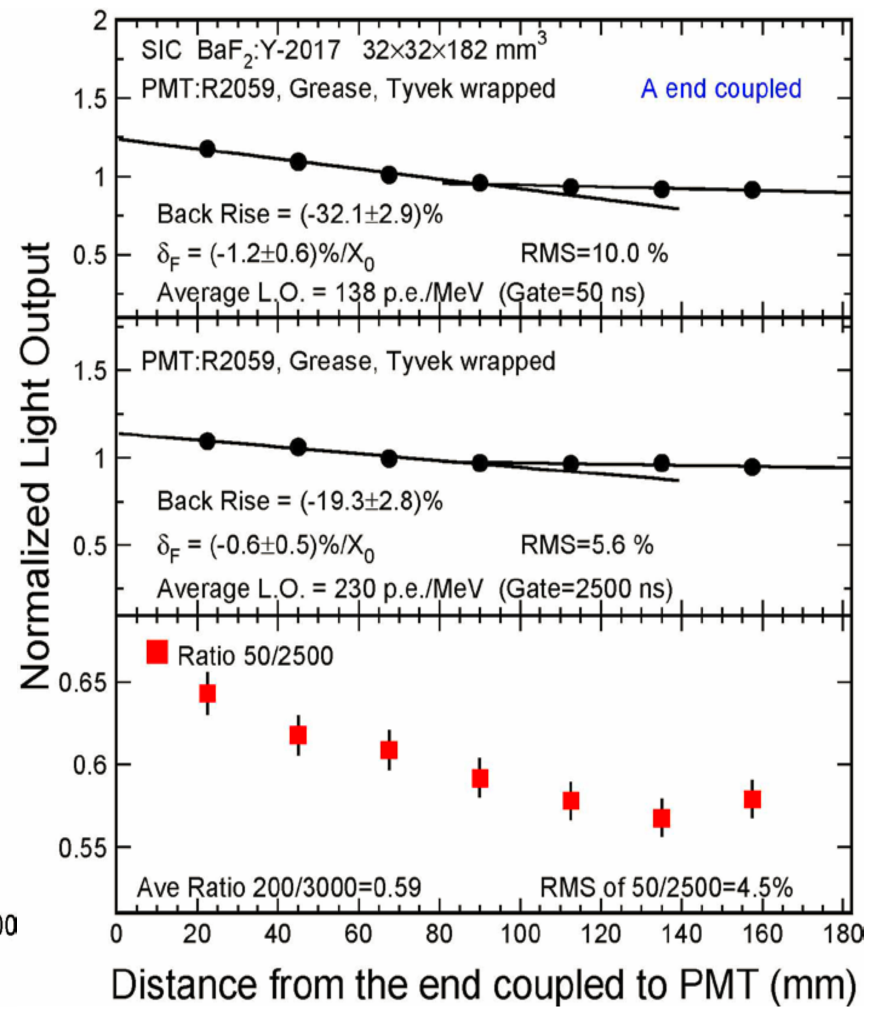
Sample ID	Concentration (%)		
	Ce	Pb	Y
S1	<0.0007	<0.002	1.658
S2	<0.0007	<0.002	1.795
S3	<0.0007	<0.002	1.801
S4	<0.0007	<0.002	1.890
S5	<0.0007	<0.002	1.853
S6	<0.0007	<0.002	1.667
S7	<0.0007	<0.002	1.596
S8	<0.0007	<0.002	1.628
S9	<0.0007	<0.002	1.662
S10	<0.0007	<0.002	1.762
S11	<0.0007	<0.002	1.708
S12	<0.0007	<0.002	1.823
S13	<0.0007	<0.002	1.969
S14	<0.0007	<0.002	2.152

Performance of the 2^{nd} SIC 18 cm BaF_2:Y

F/S of 1.6 and LRU of 10% for the fast. See also paper N37-4.

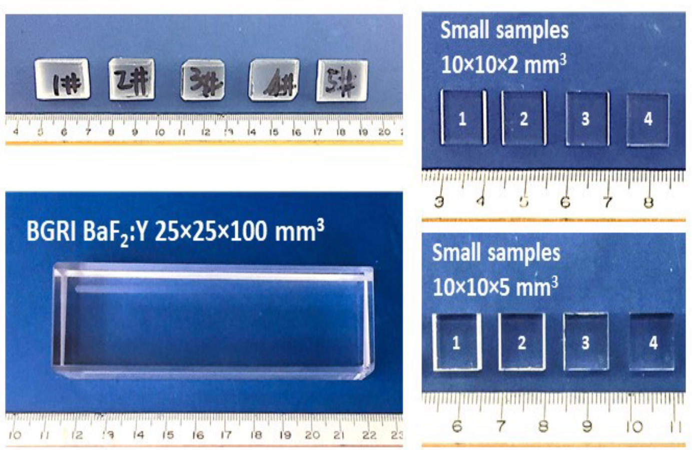


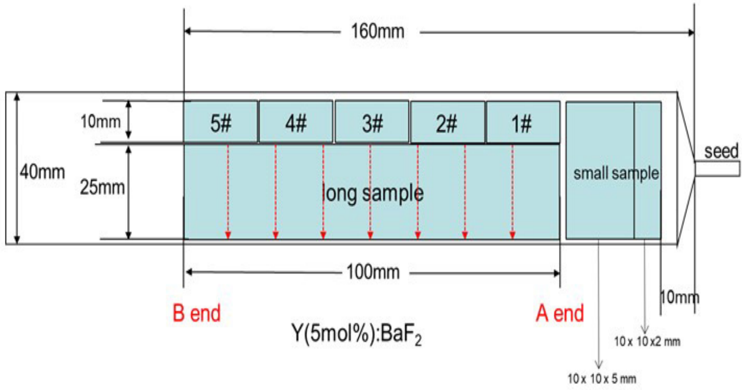


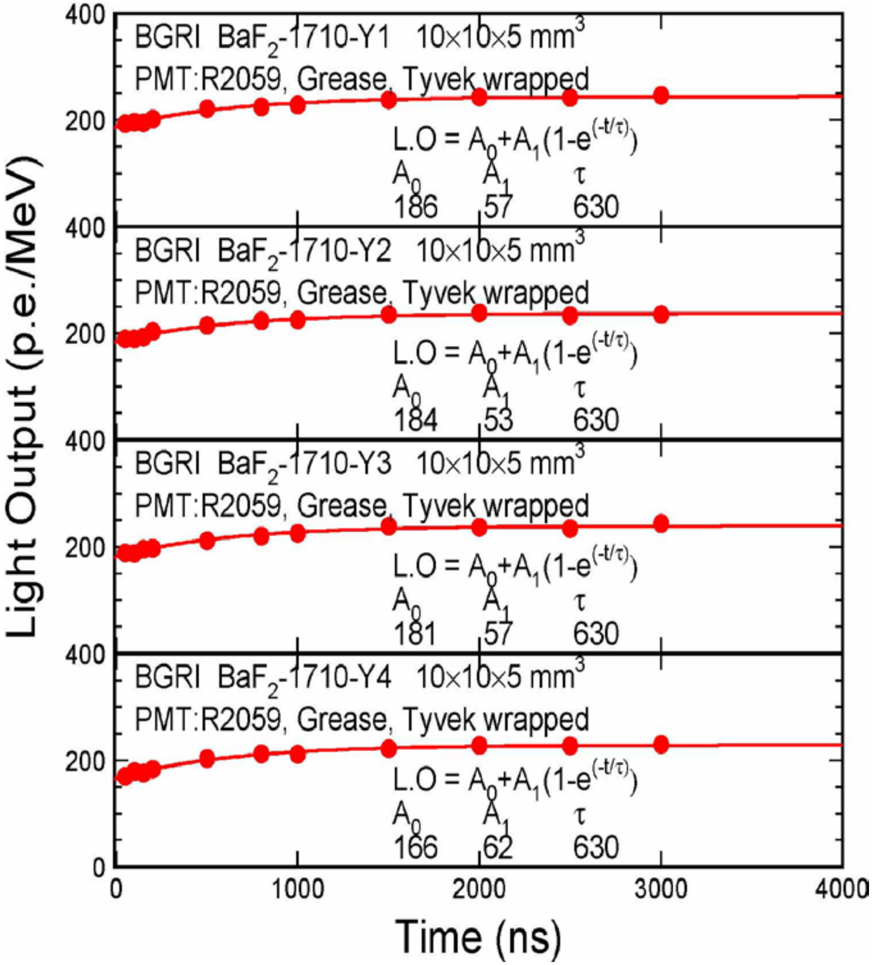


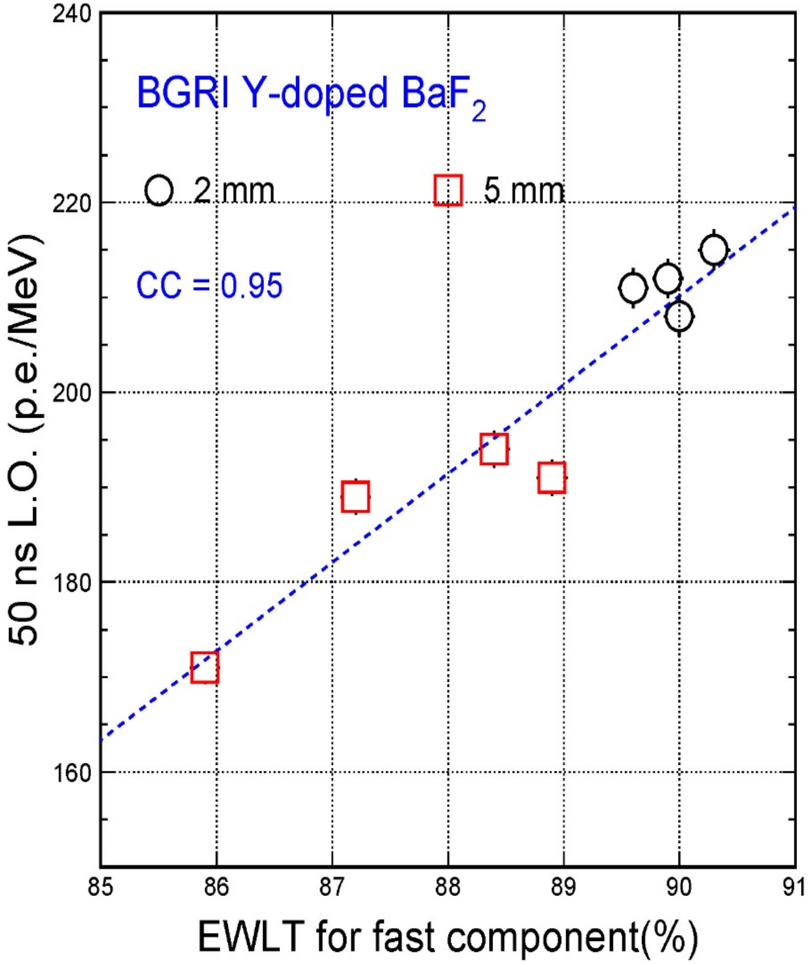
1^{st} BGRI 10 cm BaF_2:Y Sample

F/S of 3.5 is found, and good correlation between LO and EWLT



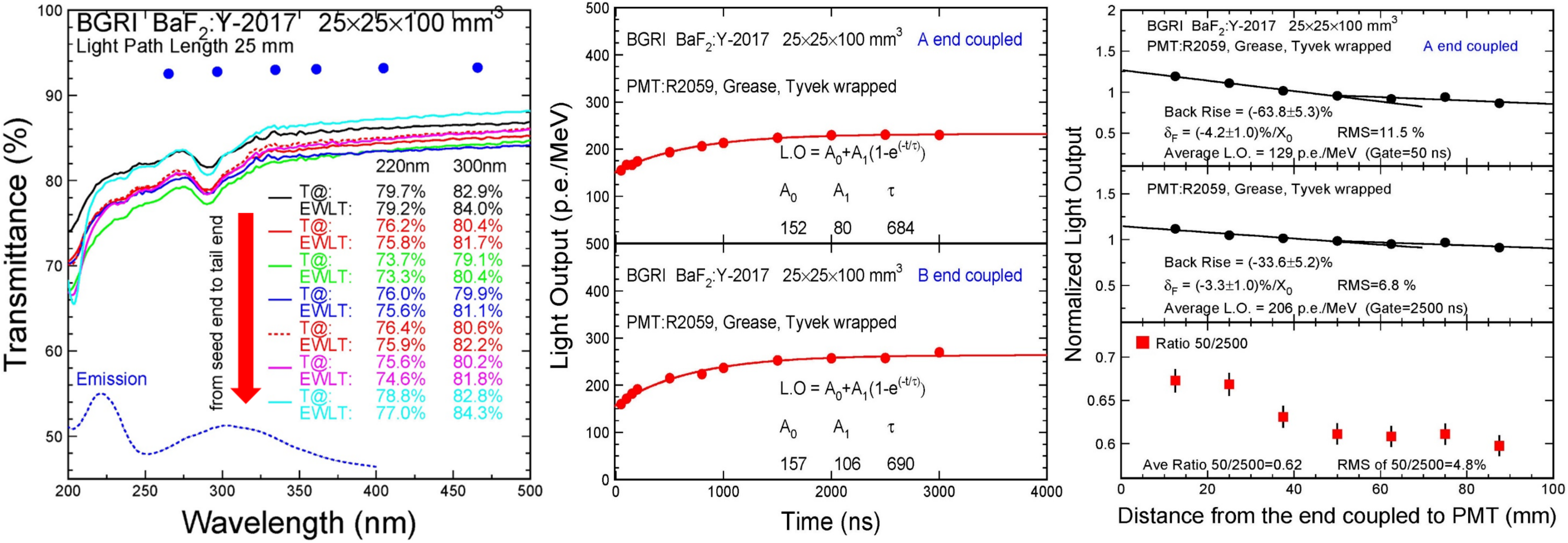






Performance of BGRI 10 cm BaF_2:Y

F/S increased up to 1.9; LRU: 12% and 6.8% for fast and total

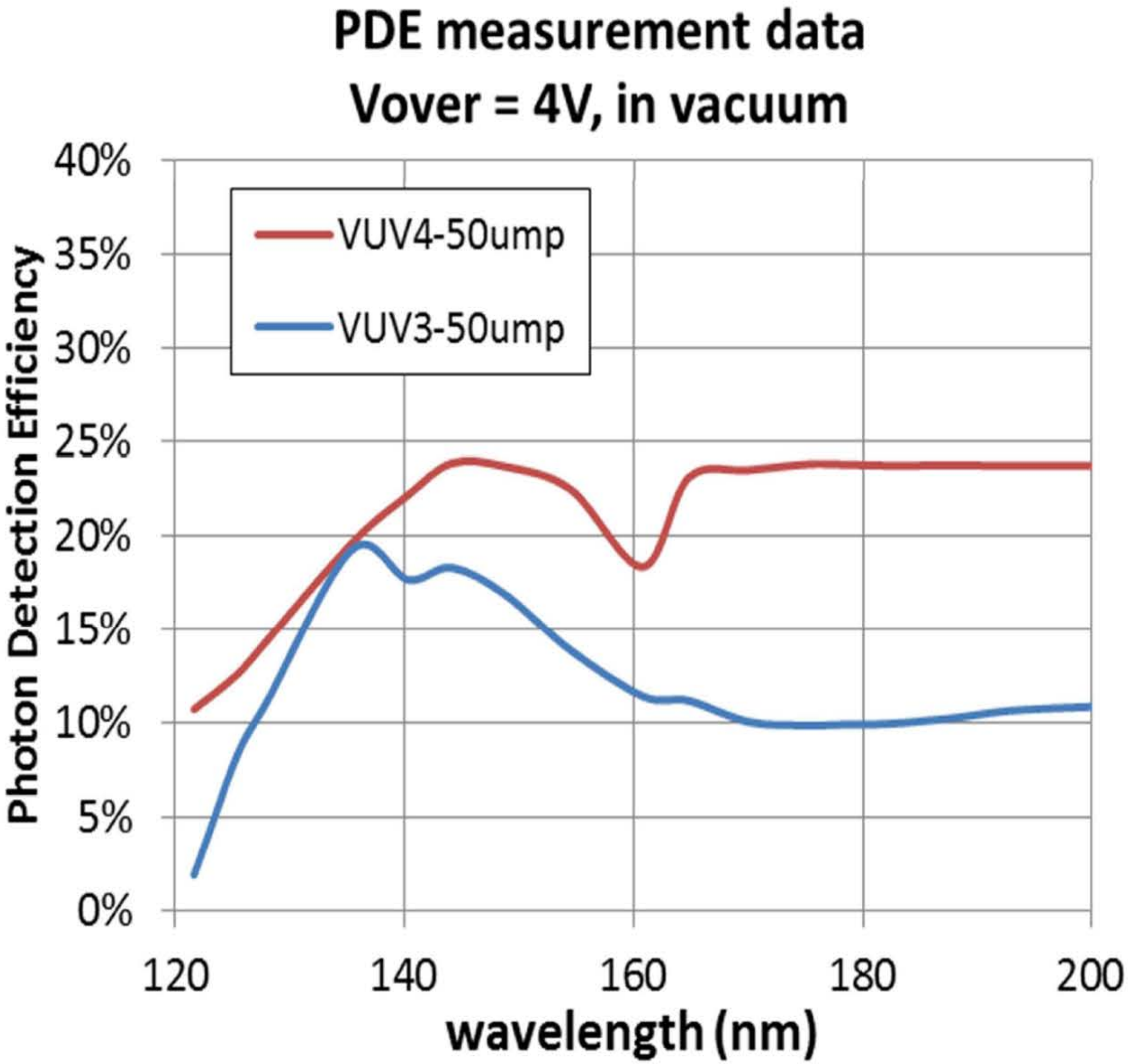


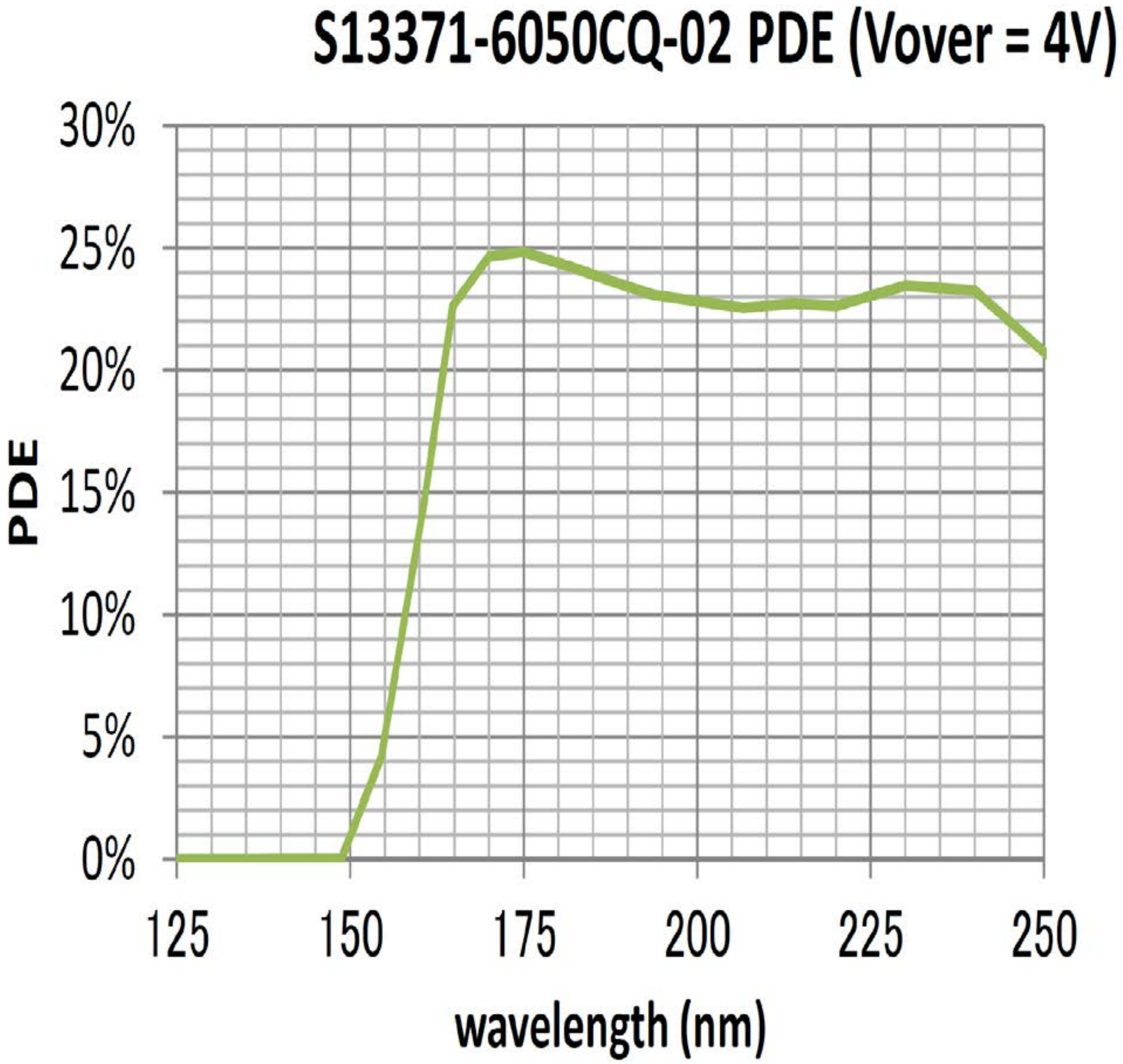
Summary

- Commercially available undoped BaF_2 crystals provide sufficient ultrafast light with sub-ns decay time. Yttrium doping in BaF_2 crystals increases its F/S ratio significantly while maintaining the intensity of the sub-ns fast component. With sub-ns pulse width BaF_2:Y promises an ultrafast calorimeter for Mu2e-II.
- 20 cm long BaF_2 crystals are rad hard up to 120 Mrad against ionization dose. Results of the LANL experiments show 800 MeV protons and fast neutrons up to 1 x 10^{15} p/cm^2 and 3.6 x 10^{15} n/cm^2 do not cause significant light output loss in 5 mm thick LYSO and BaF_2 plates, promising a fast and robust detector in a severe radiation environment, such as the HL-LHC.
- Progresses in both the F/S ratio and the LRU are observed in large size BaF_2:Y crystals. R&D will continue to develop large size yttrium doped BaF_2 crystals for Mu2e-II. Attention should also be paid to develop photodetector with VUV response: Solar blind LAPPD, VUV sensitive Si or diamond based photodetectors.

Acknowledgements: DOE HEP Award DE-SC0011925

Hamamatsu S13371 VUV SiPM





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)

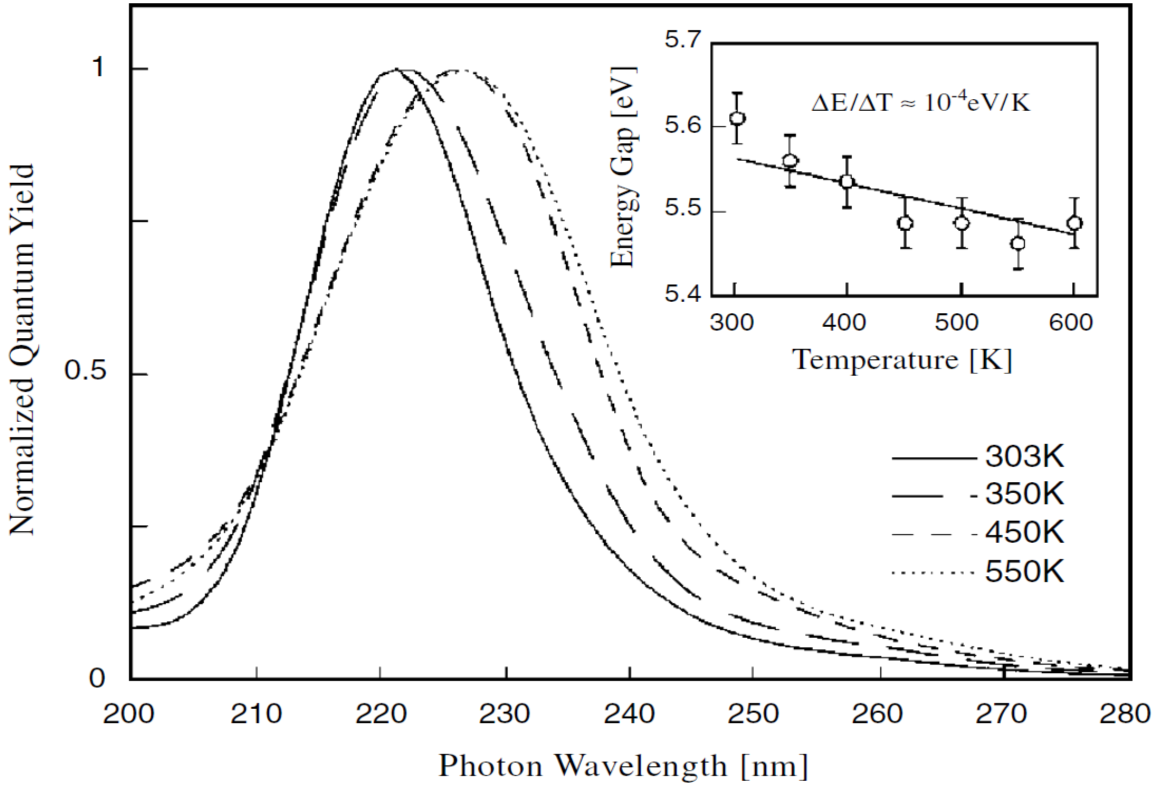


Figure 6. Quantum efficiency of diamond photoconductors at different temperatures and Arrhenius plot of the peak value (inset). (From [Sal00].)

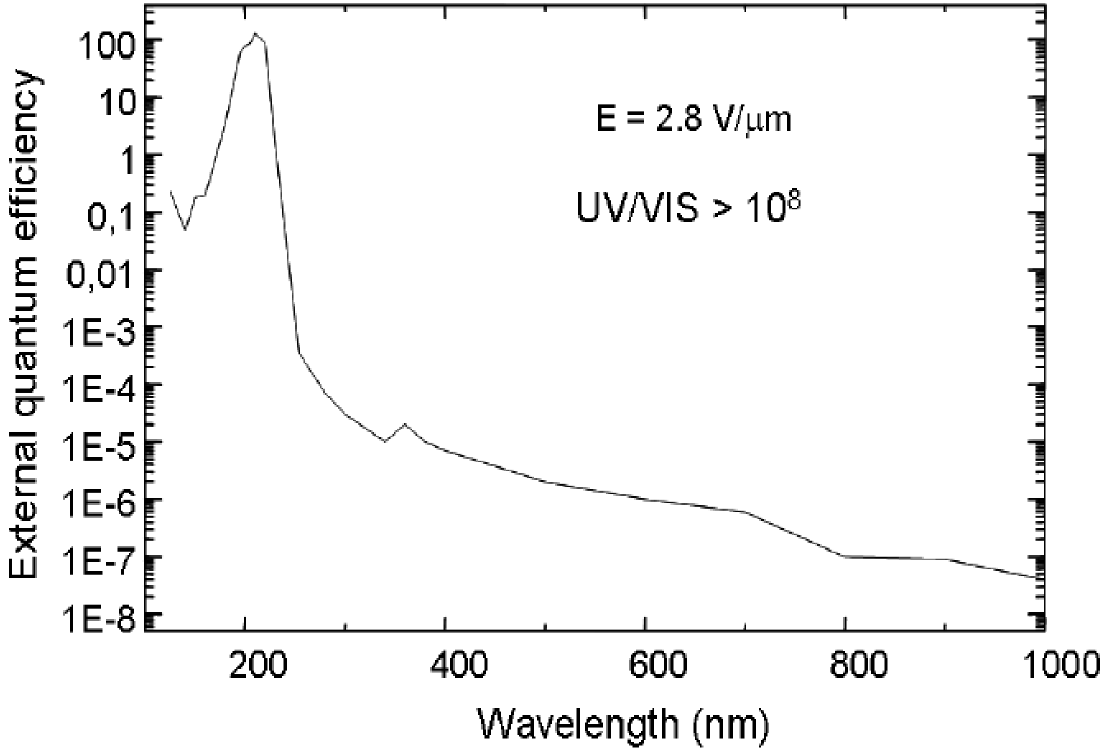


Fig. 4. External quantum efficiency extended to visible and near infrared wavelength regions. The