A Very Fast and Radiation Hard BaF_2 Calorimeter for Mu2e-II

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Introduction

- Mu2e-I 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 promise a ultrafast scintillator with sub-ns FWHM pulse width for HEP and GHz hard X-ray imaging.
- Mass production capability of BaF_2 exists in industry:
  - BGRI (China), Incrom (Russia) and SICCAS (China): tested;
  - Hellma (Germany): in contact

Fast Inorganic Crystal 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	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 0.9	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)

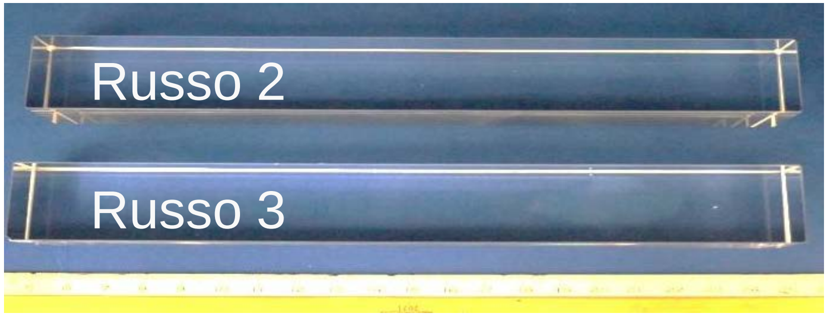
#. Softening point

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

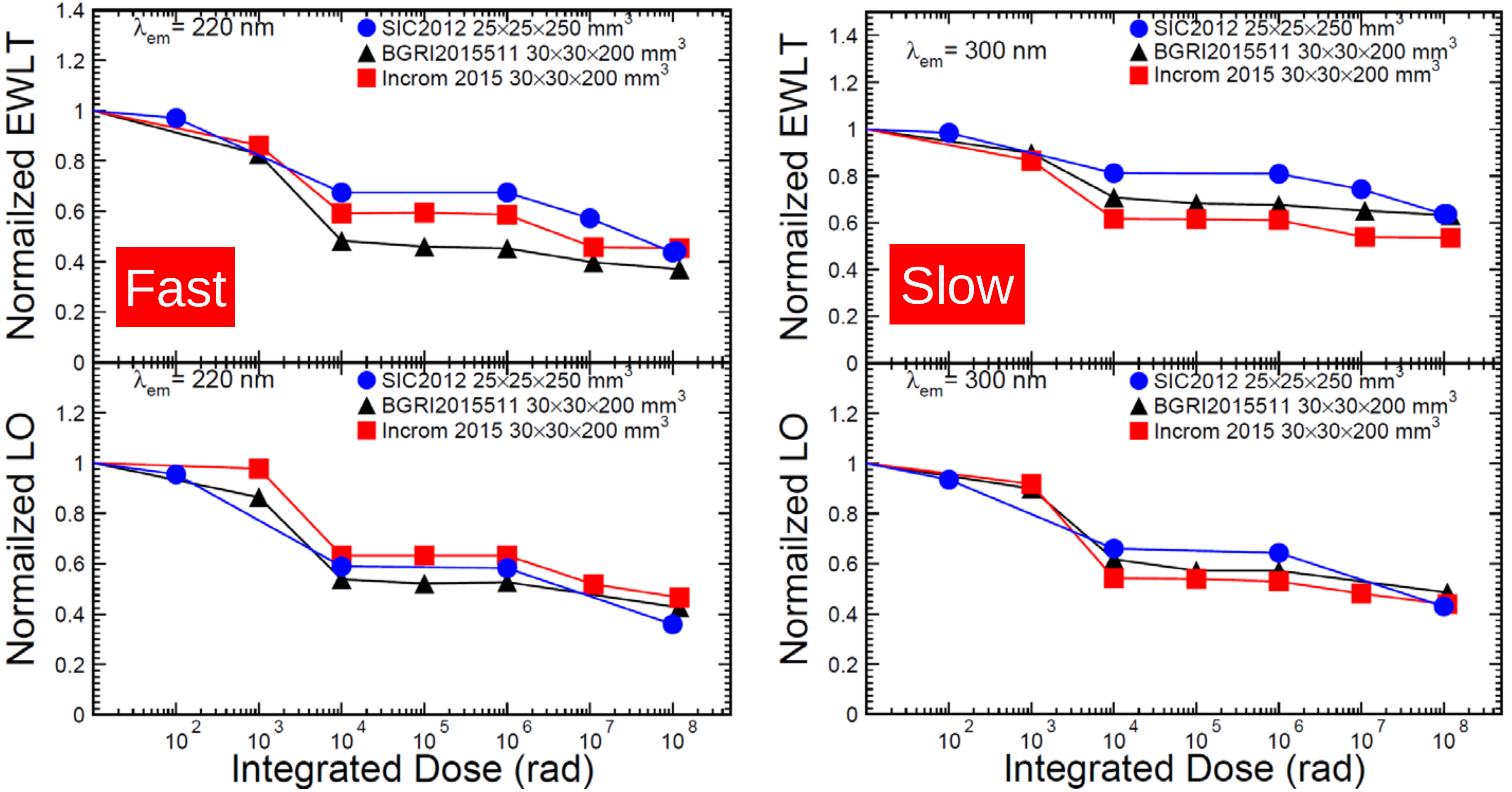
BGRI/Incrom/SIC BaF_2 Samples



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

BaF_2: Normalized EWLT and LO

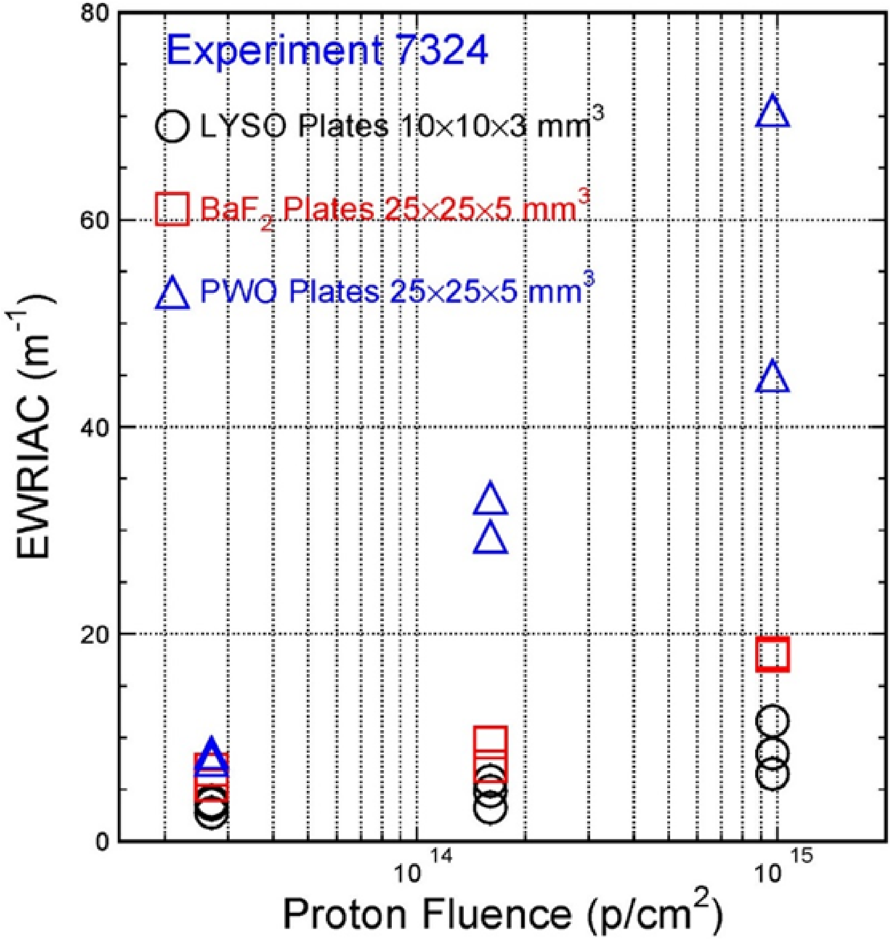
Consistent damage in crystals from three vendors

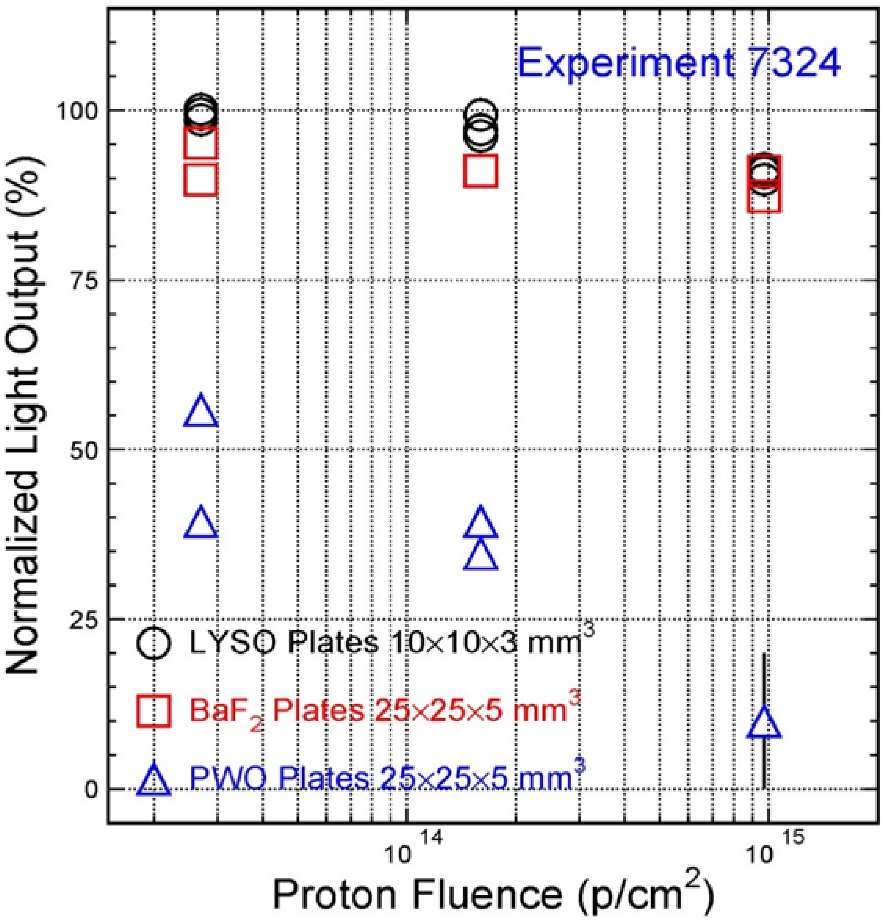


Remaining light output after 120 Mrad: 40%/45% for the fast/slow component

RIAC & LO Vs. Proton Fluence

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

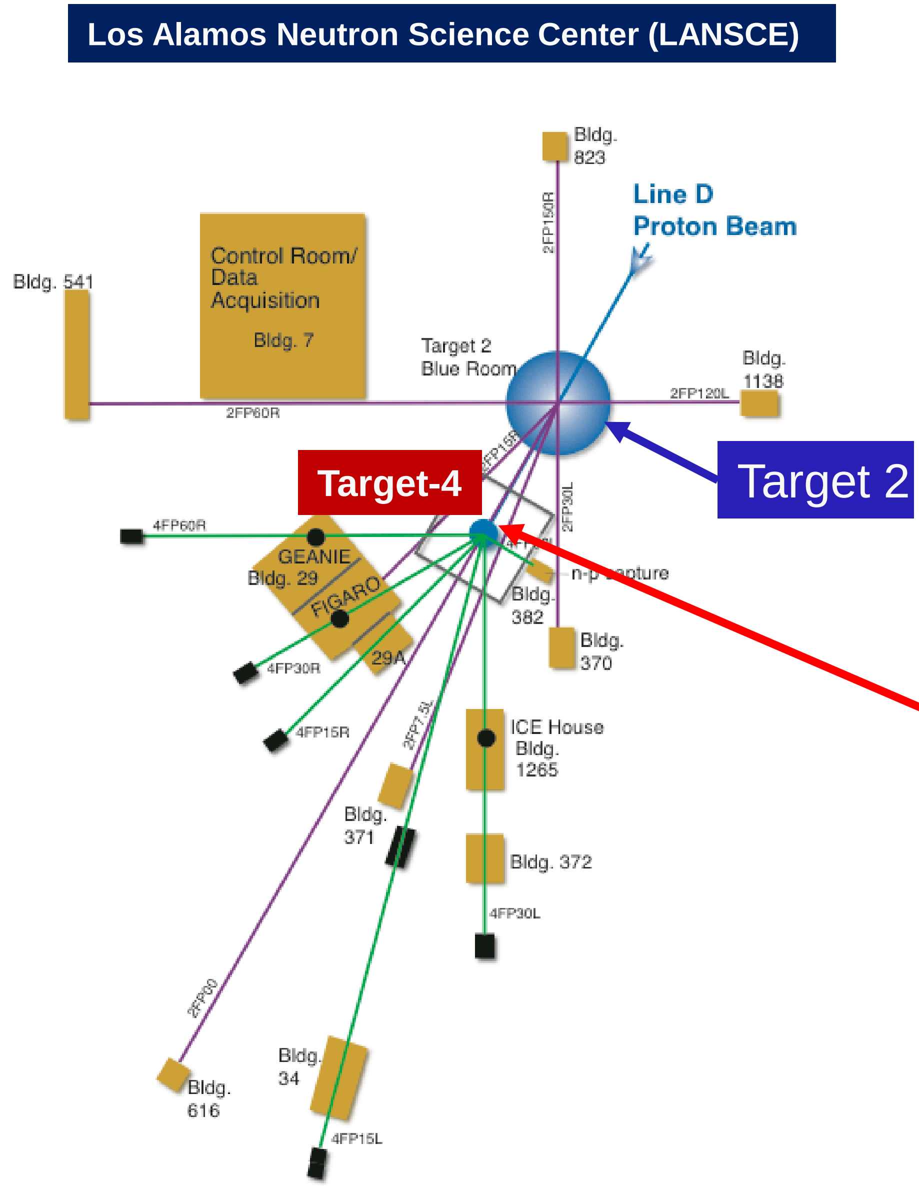


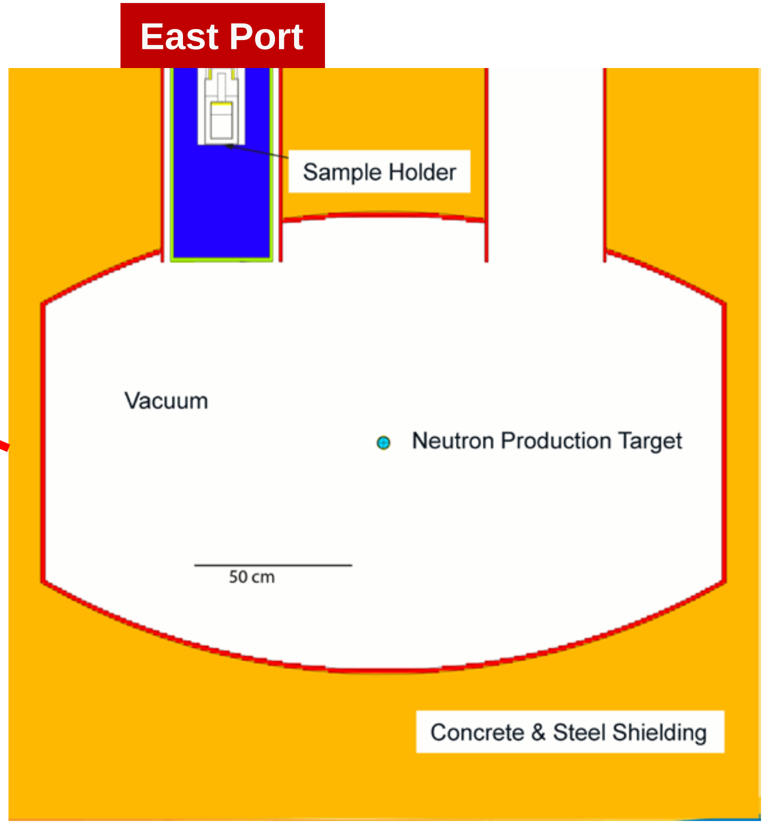


Presented in SCINT 2017, will be published in IEEE TNS NS

Neutron Irradiation Test at LANL

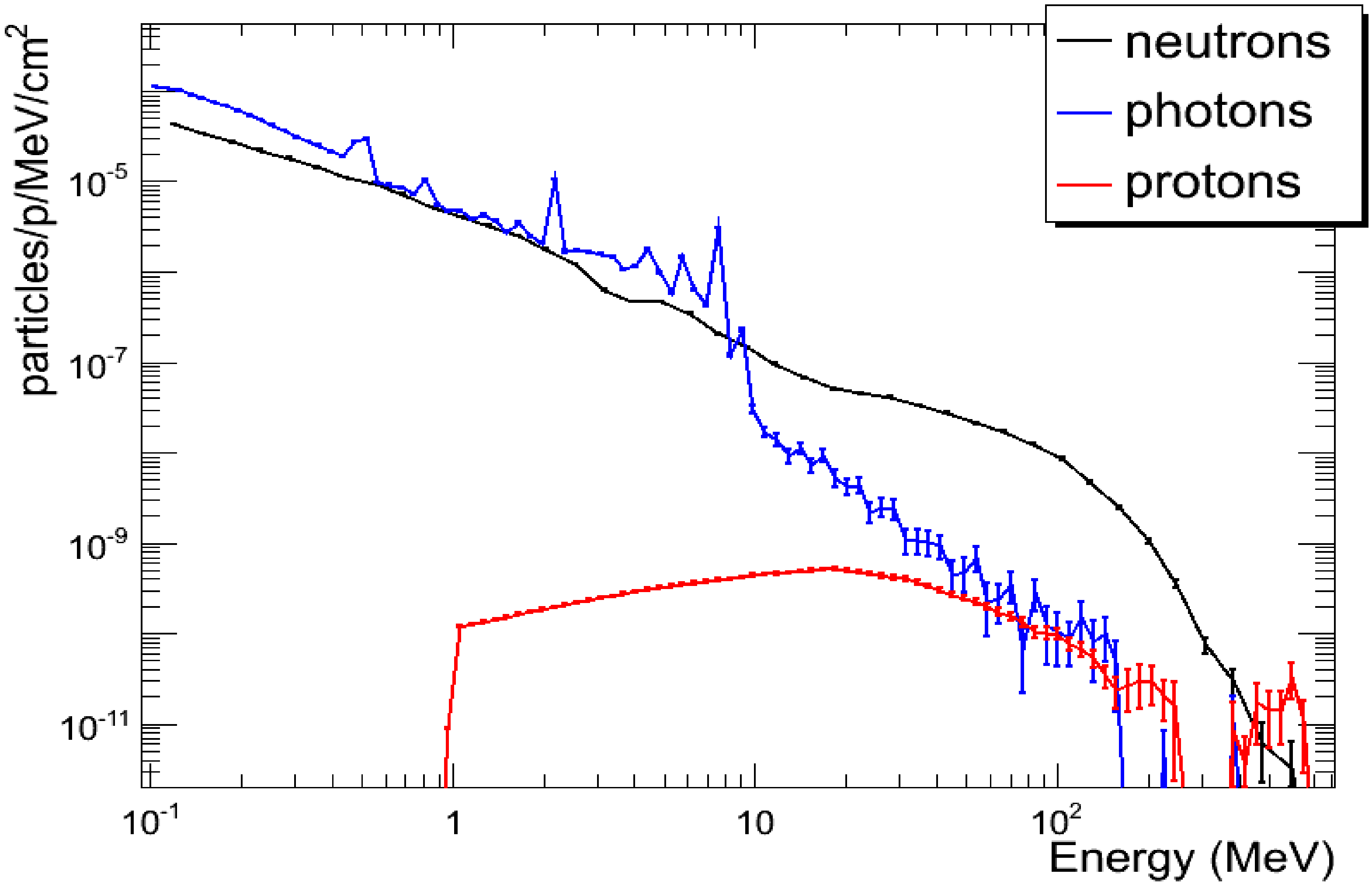
Samples are placed at the Target-4 East Port, about 1.2 m away from the neutron production target.





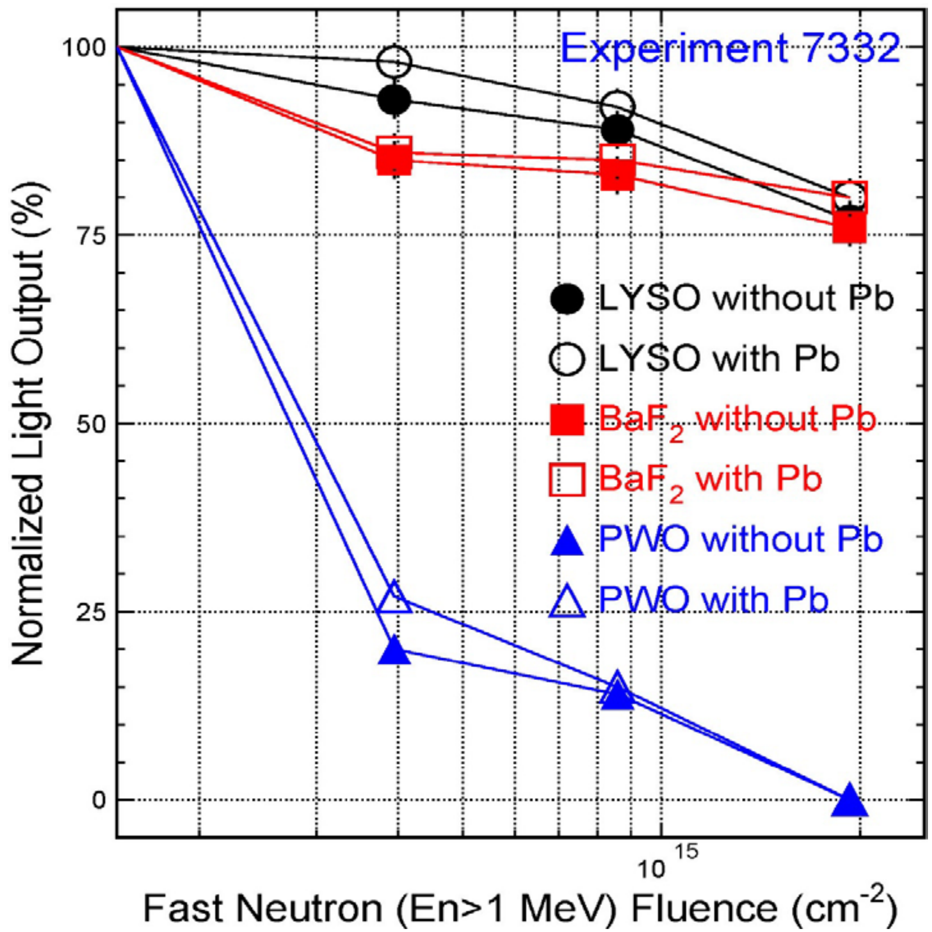
Neutrons/Photons/Protons Fluxes

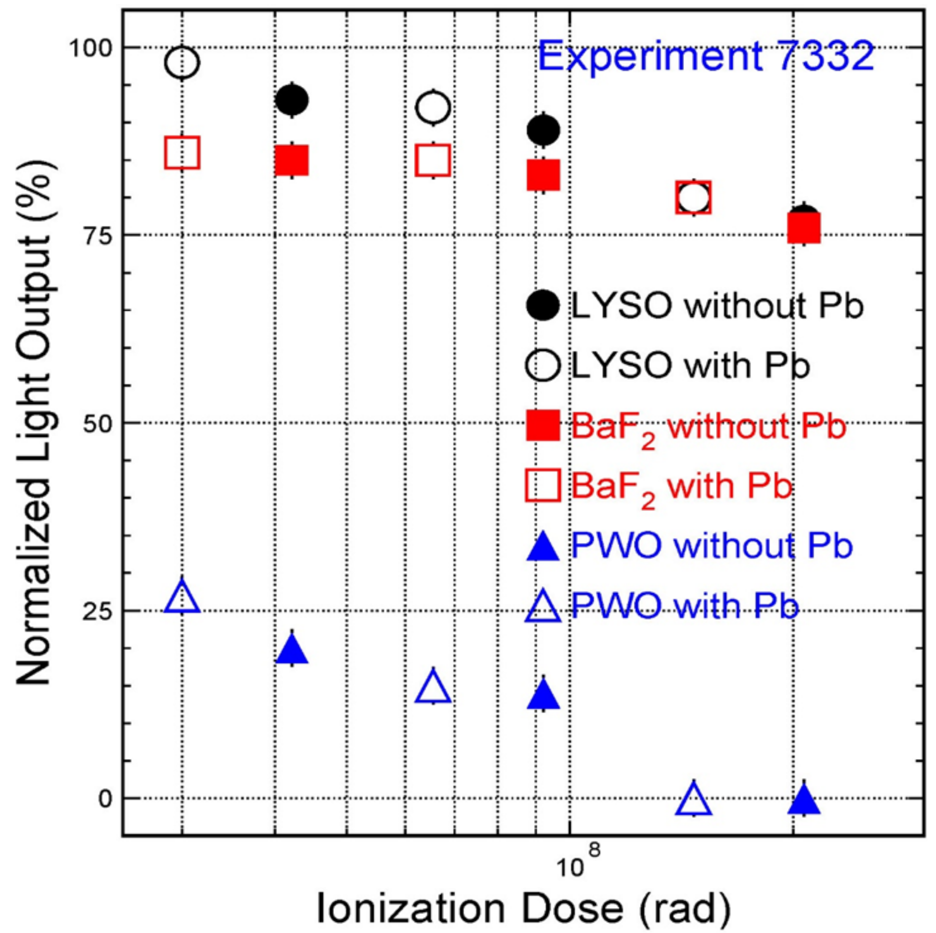
Neutrons/Photons/Protons fluxes are calculated by using MCNPX (Monte Carlo N-Particle eXtended). Plotted spectra are tallied in the largest sample volume (averaging)



LO Vs. Fast Neutron Fluence And Ionization Dose from γ-Rays

Robust LYSO and BaF_2: up to 200 Mrad and 2 x 10^{15} n/cm^2
No neutron specific damage in LYSO, BaF_2 & PWO





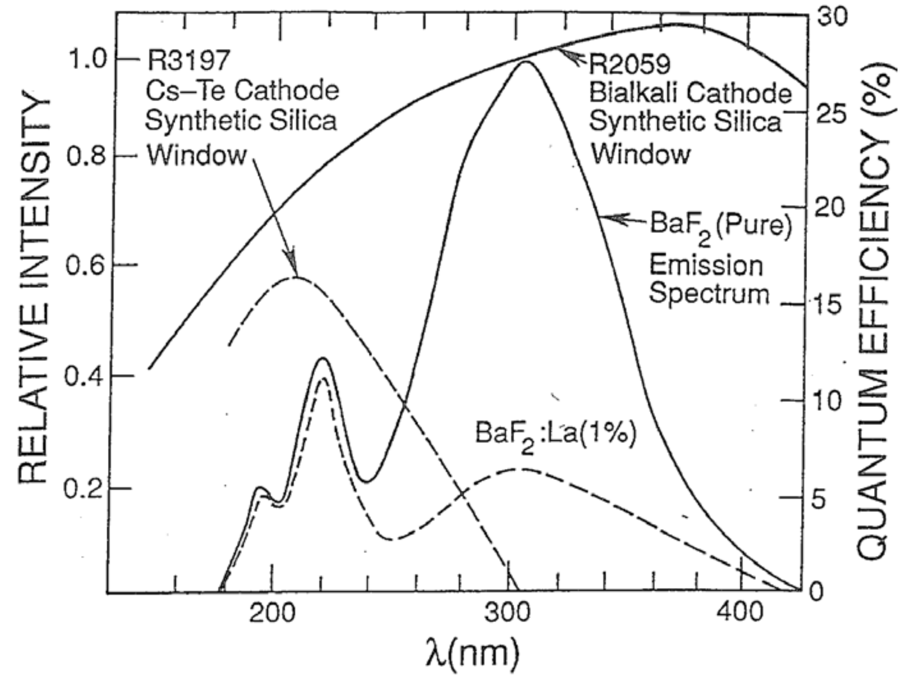
Presented in NSS2017, will be published in IEEE

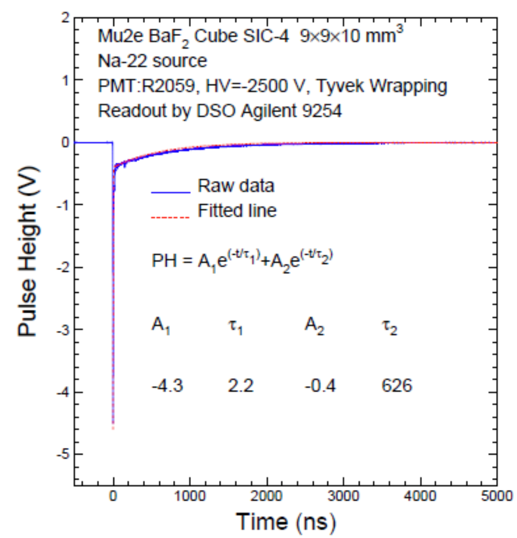
Fast and Slow Light from BaF_2

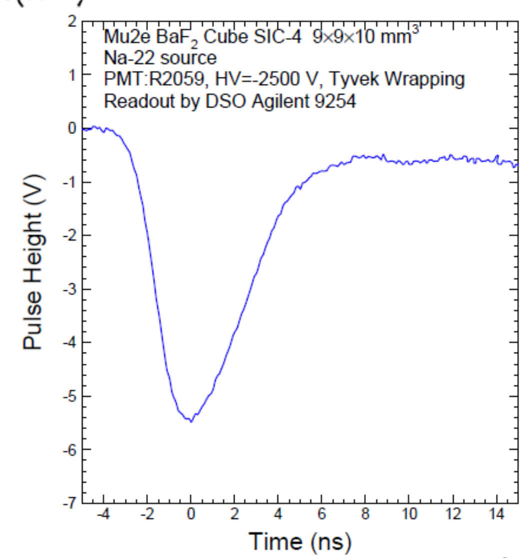
A radiation level exceeding 100 krad is expected at the proposed Mu2e-II, so BaF_2 is being considered.

The amount of light in the fast component of BaF_2 at 220 nm with sub-ns decay time is similar to CsI.

Spectroscopic selection of fast component may be realized by solar blind photocathode and/or selective doping.



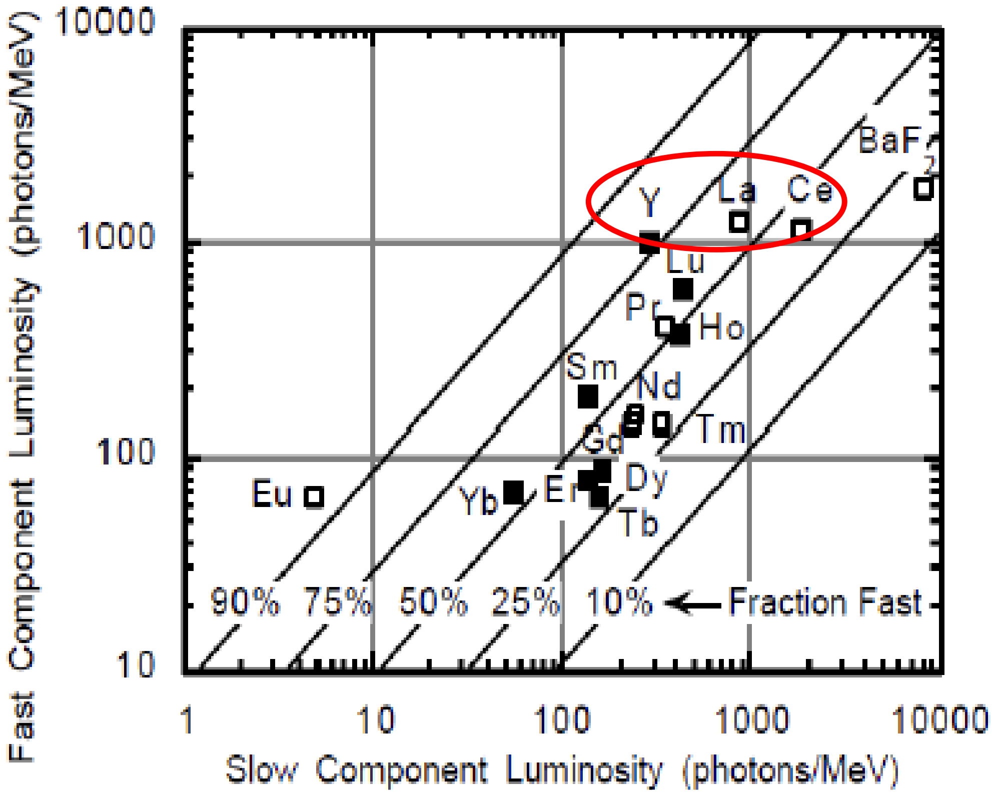


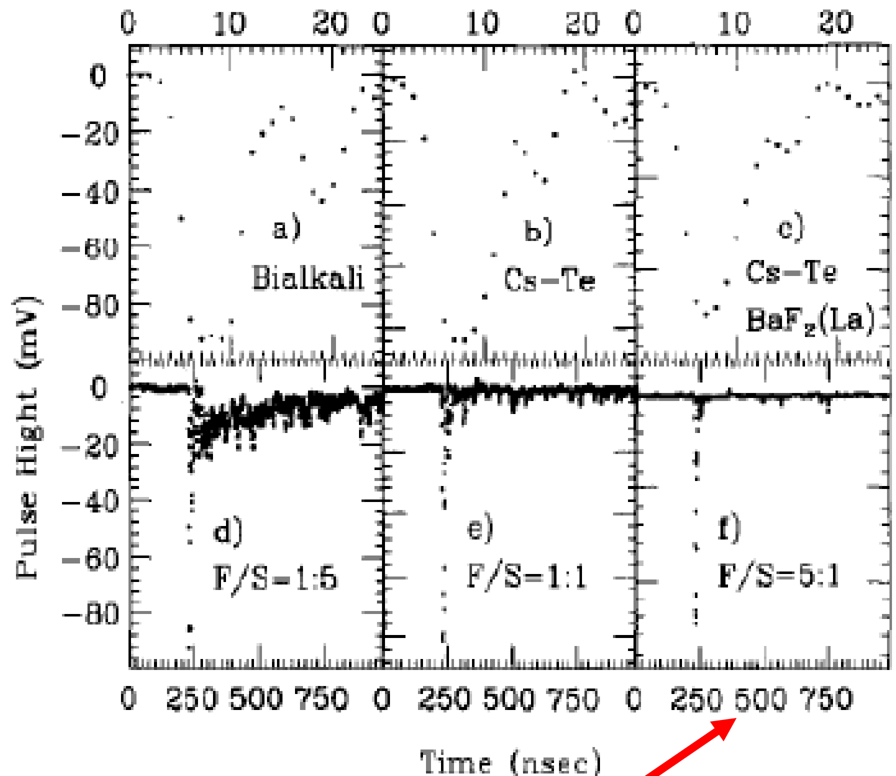


Slow Suppression: Doping & Readout

Slow component may be suppressed by RE doping: Y, La and Ce

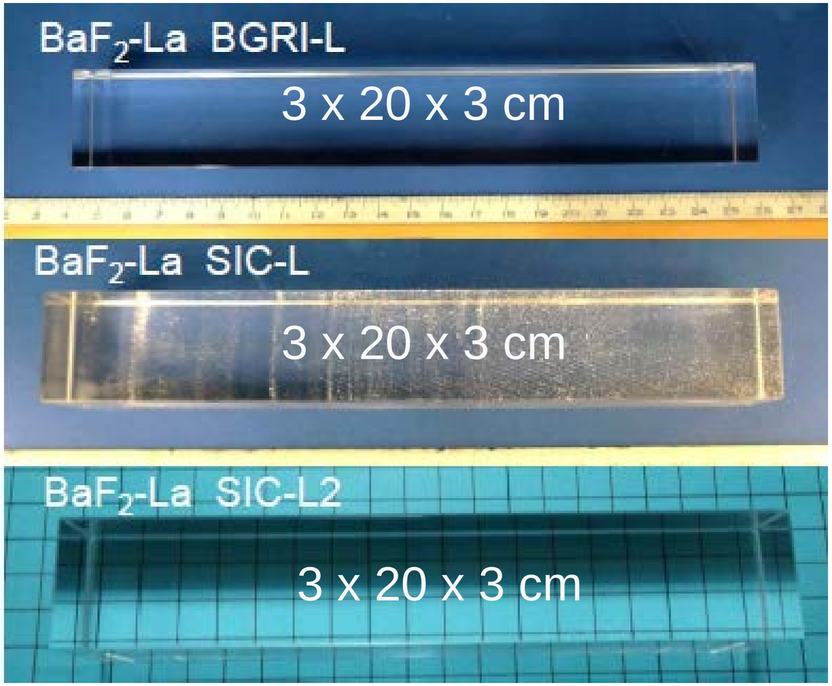
B.P. SOBOLEV et al., "SUPPRESSION OF BaF2 SLOW COMPONENT OF X-RAY LUMINESCENCE IN NON-STOICHIOMETRIC Ba0.9R0.1F2 CRYSTALS (R=RARE EARTH ELEMENT)," *Proceedings of The Material Research Society: Scintillator and Phosphor Materials*, pp. 277-283, 1994.



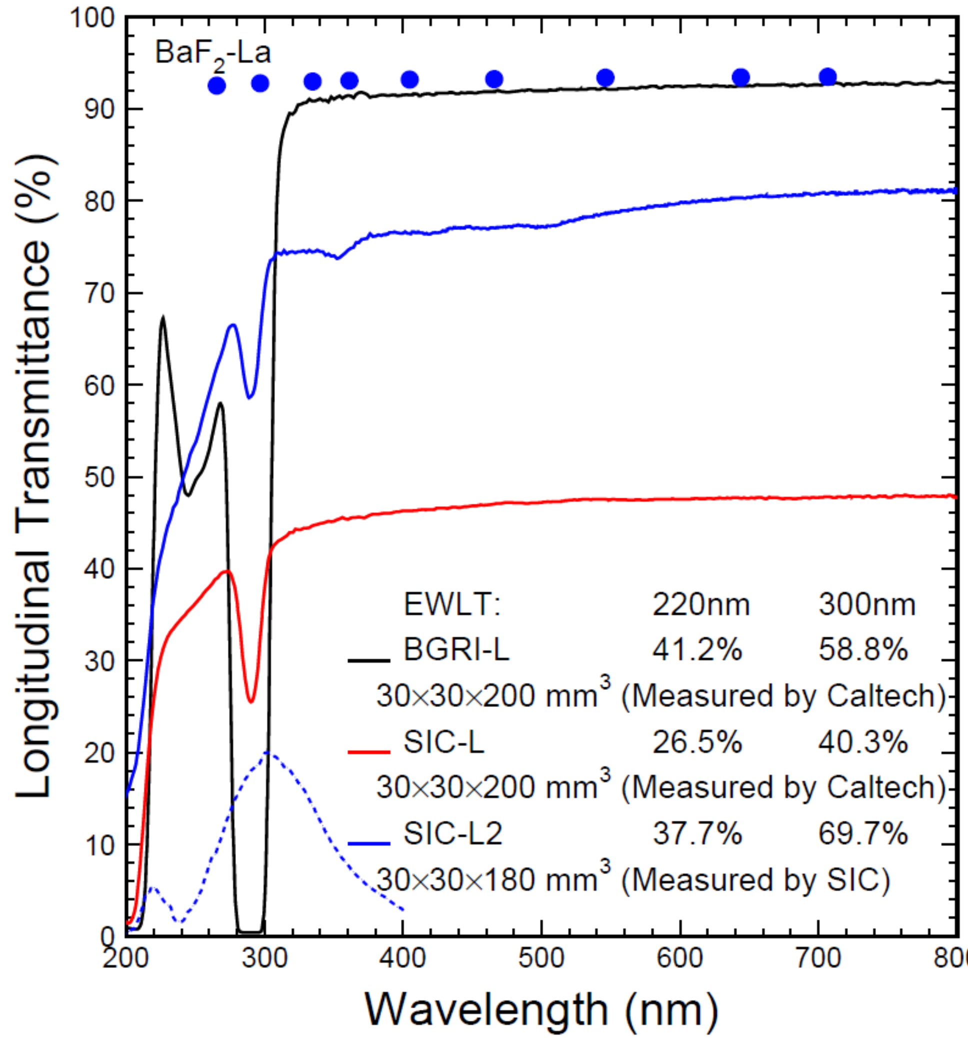


Solar-blind cathode (Cs-Te) + La doping achieved F/S = 5/1

20 cm La Doped BaF_2 for Mu2e



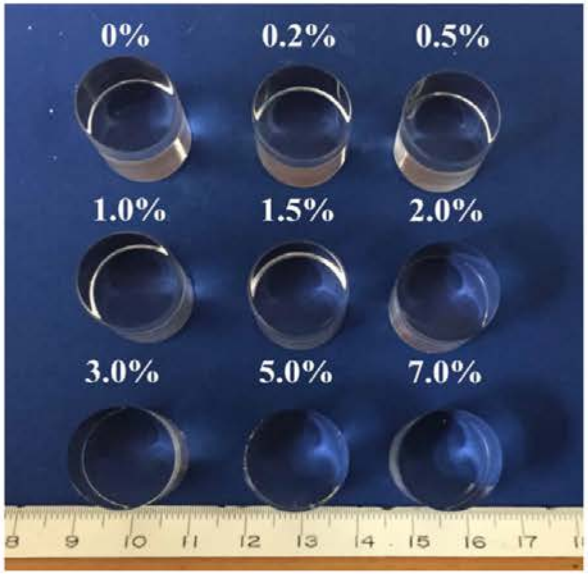
Reported in the 1st Mu2e-II workshop at Fermilab, 2/16/2016

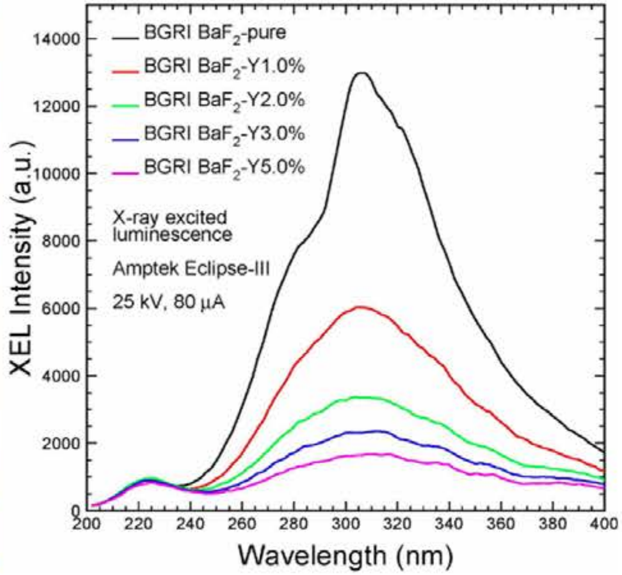


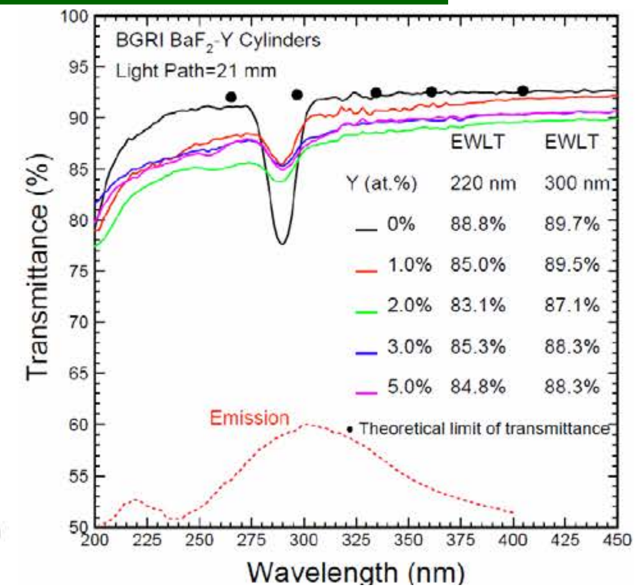
Absorptions observed in 20 cm long sample with 1% La doping are attributed to cerium contamination. The F/S ratio is increased from 1/5 to 1/2, not very effective.

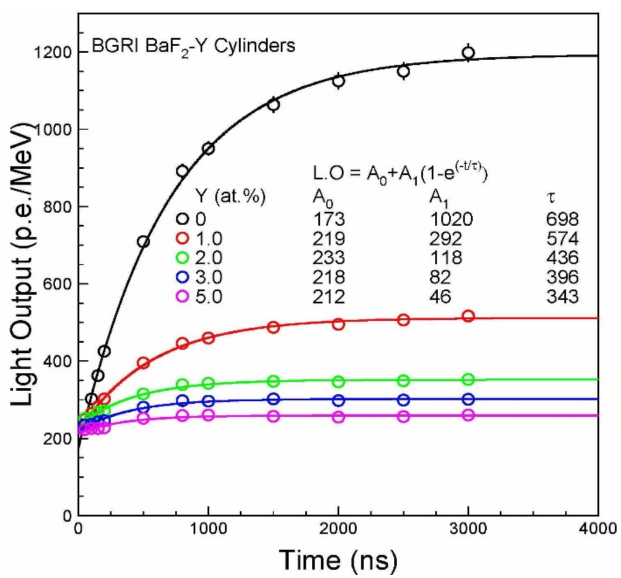
Yttrium Doped BaF_2 for Mu2e-II

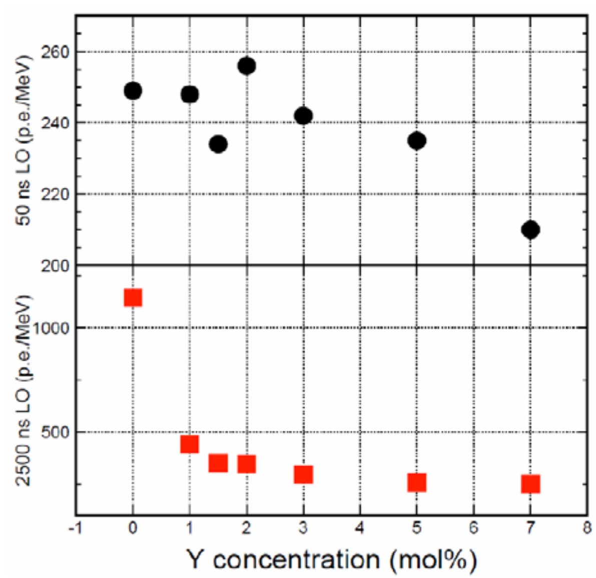
F/S ratio from 1/5 to 5/1 , presented in TIPP 2017 Beijing

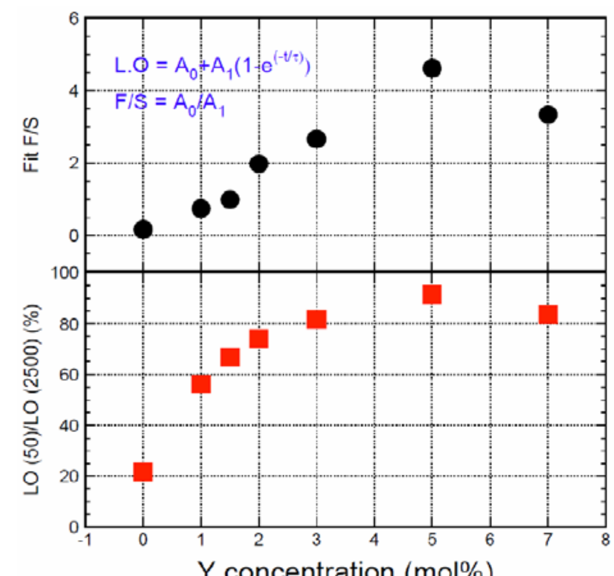




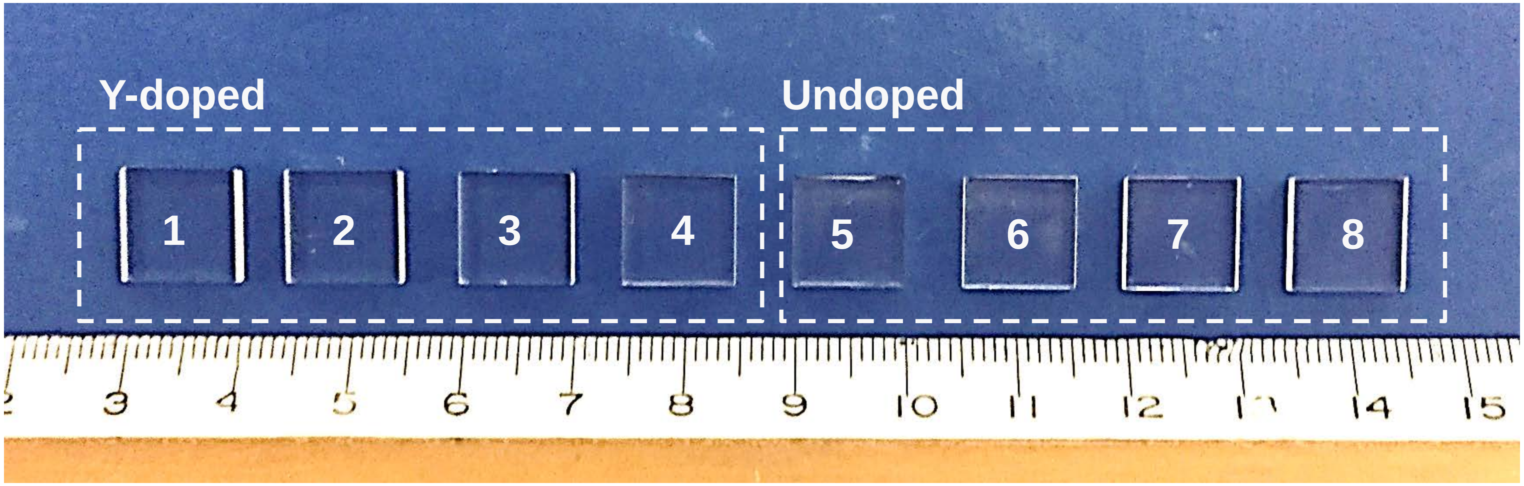








Eight BaF_2 Plates from BGRI



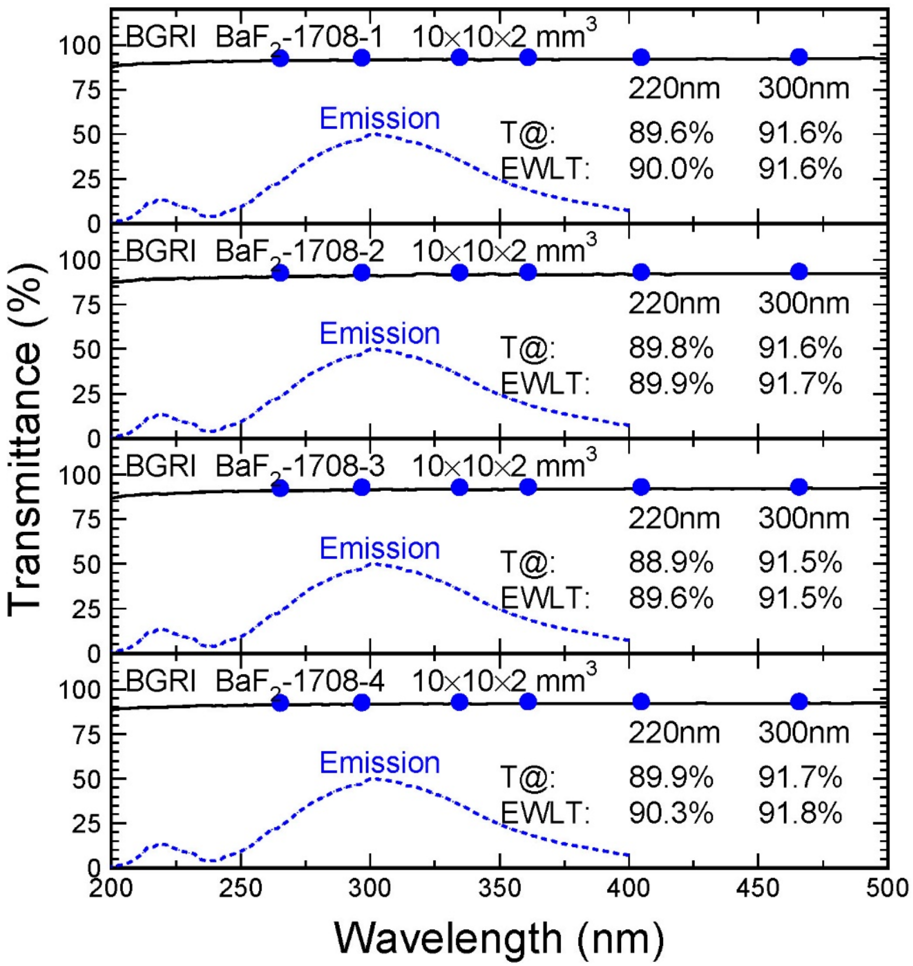
ID	Dimension (mm^3)	Polishing
BGRI Y-doped BaF_2-1708-1,4	10x10x2	Double faces
BGRI Undoped BaF_2-1708-5,8	10x10x2	Double faces
All samples received in August 31, 2017		

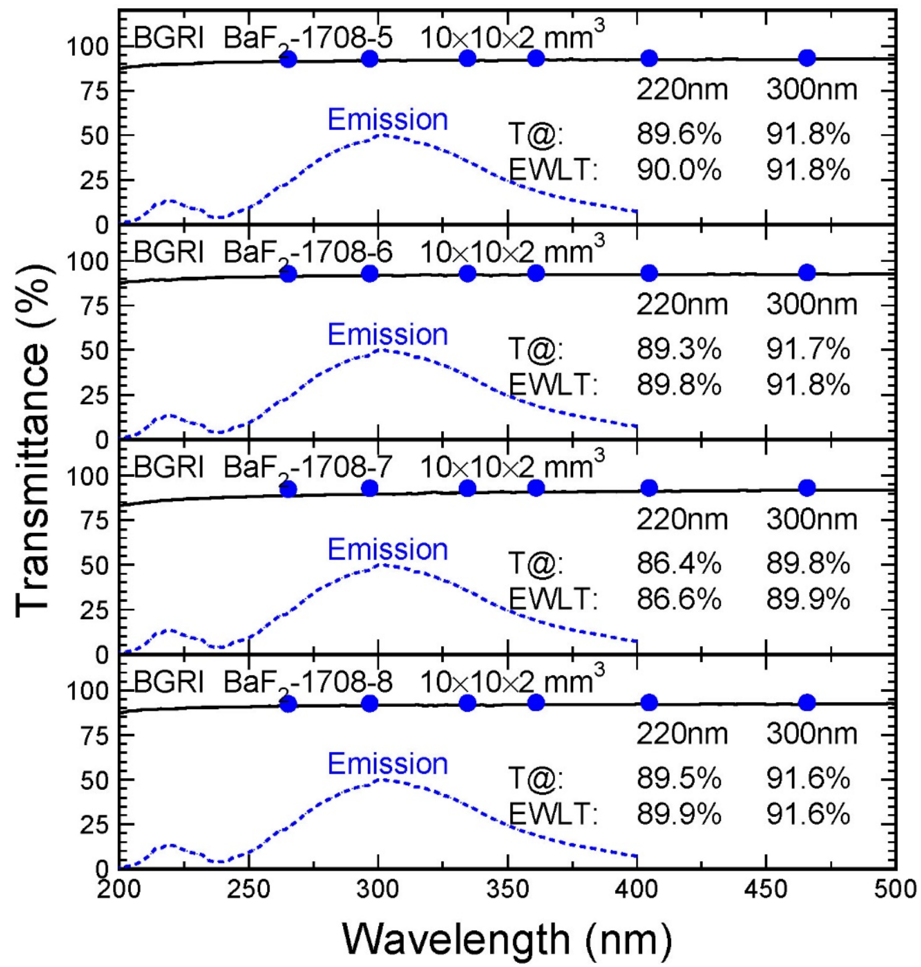
Experiments

- Properties measured at room temperature : PHS, LO & Decay kinetics

Transmittance: Y:BaF_2 and BaF_2

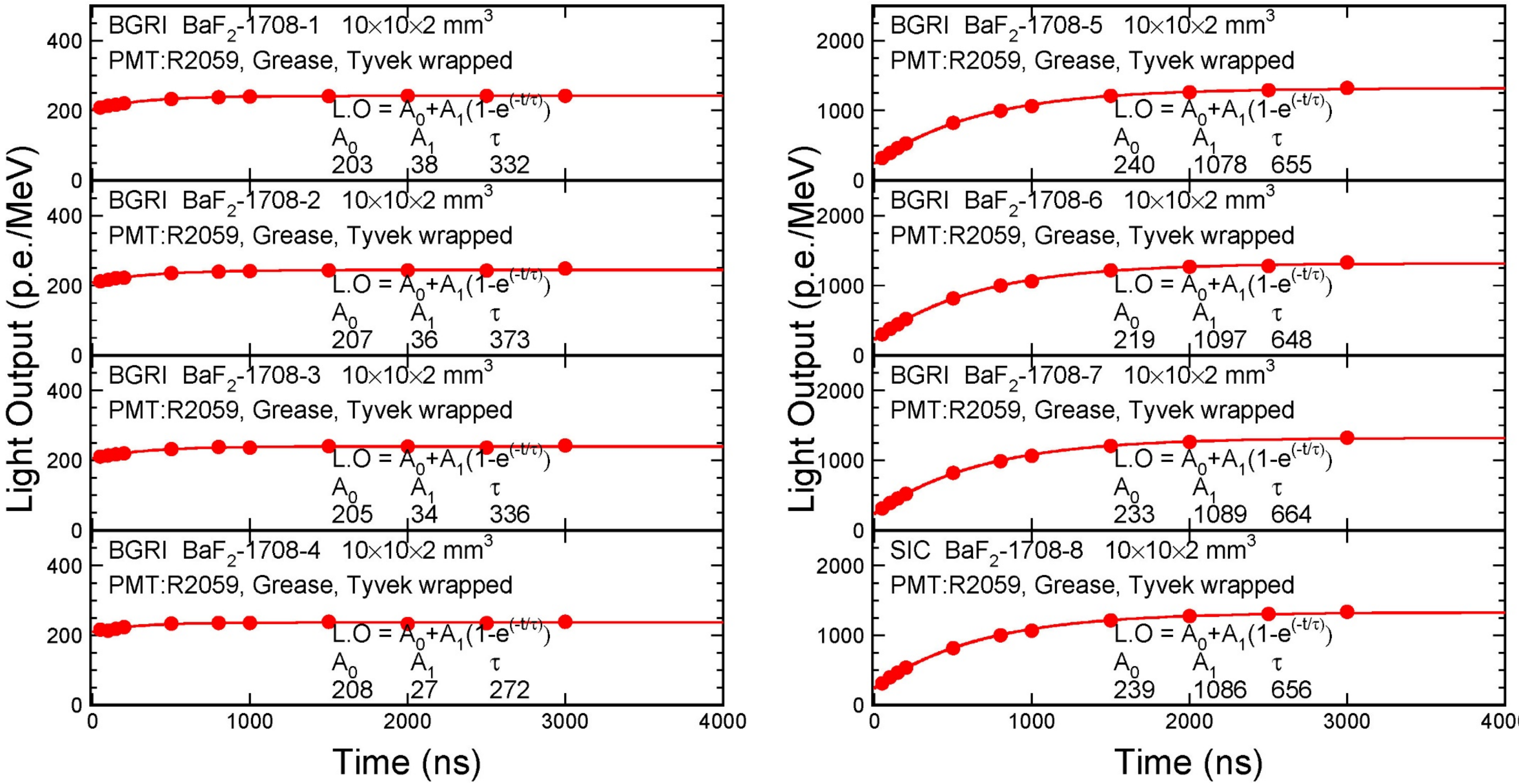
Good transparency for both fast and slow scintillation





Light Output Y:BaF_2 and BaF_2

F/S ratio increased from 0.21 to 6 .2, presented in NSS2017

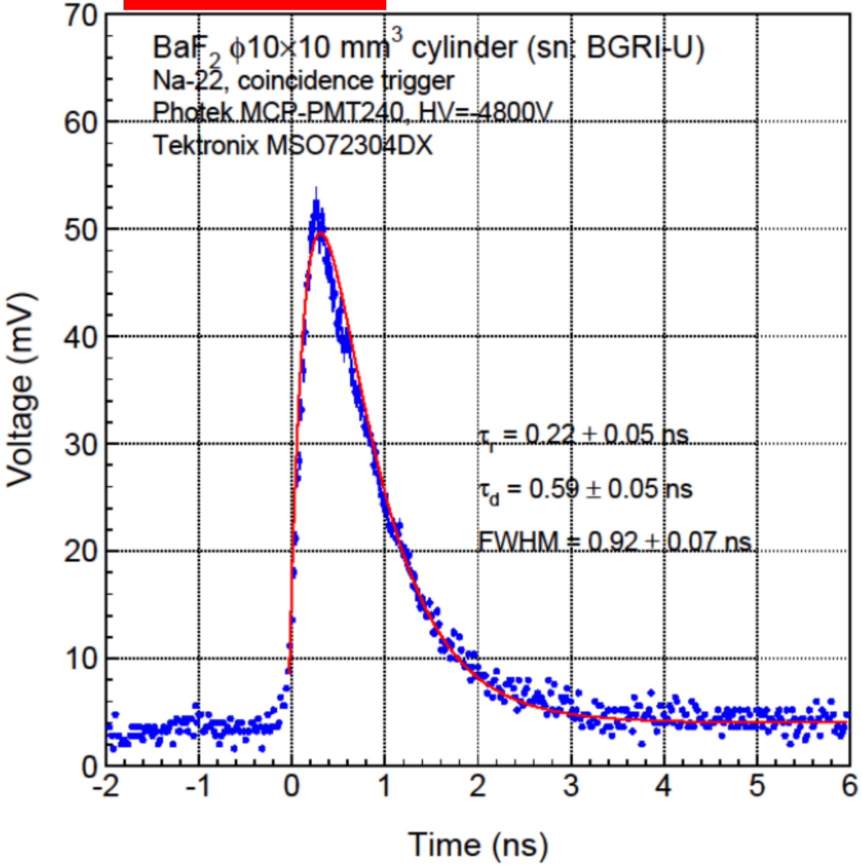


Being irradiation up to 200 Mrad and $2x10^{15}$ n/cm^2 at the East Port of LANSCE

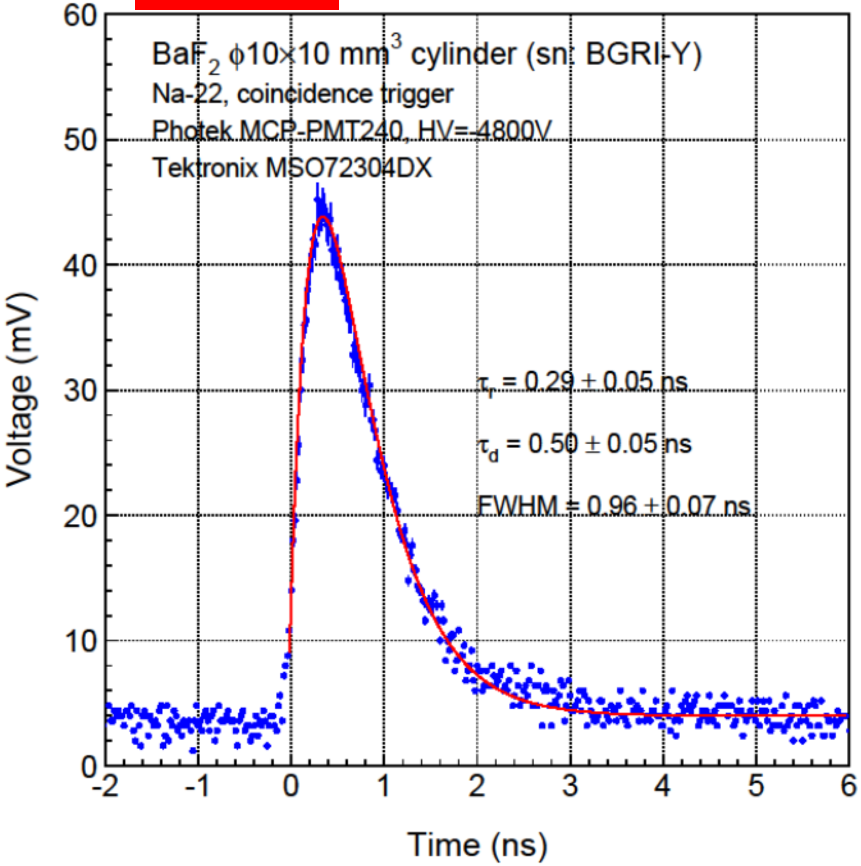
Pulse Shape: BaF_2 Cylinders

BGRI BaF_2 cylinders of Φ10×10 cm³ shows γ-ray response: 0.26/0.55/0.94 ns of rising/decay/FWHM width

Non-doped

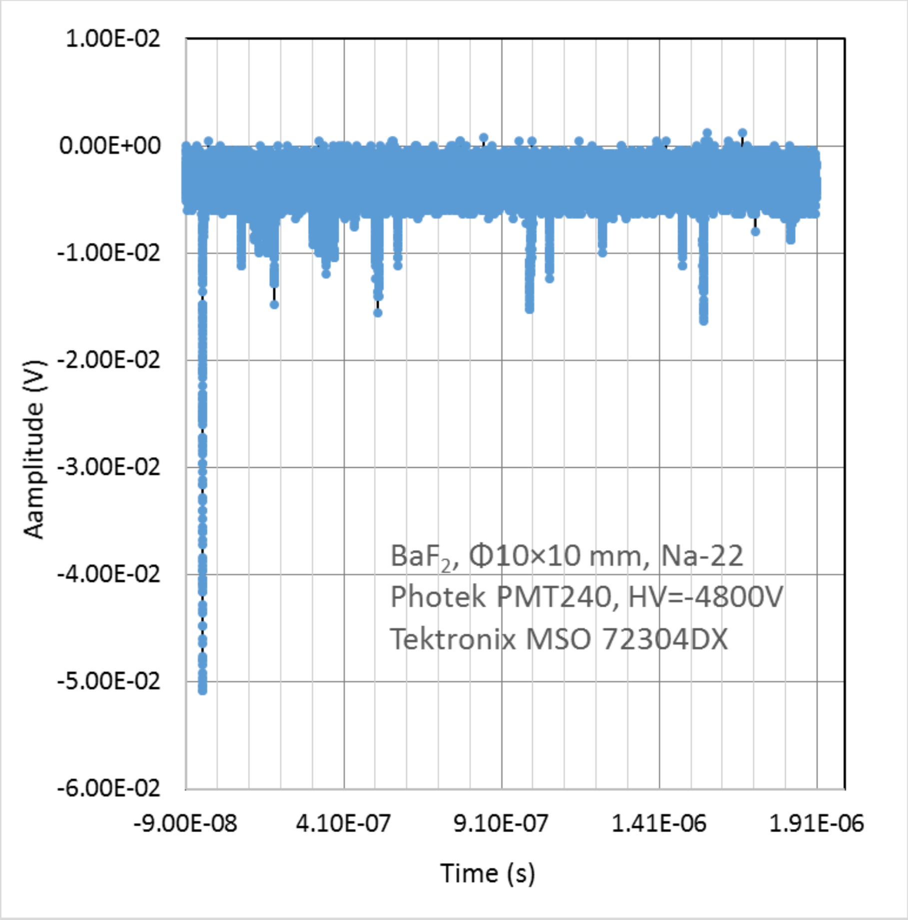


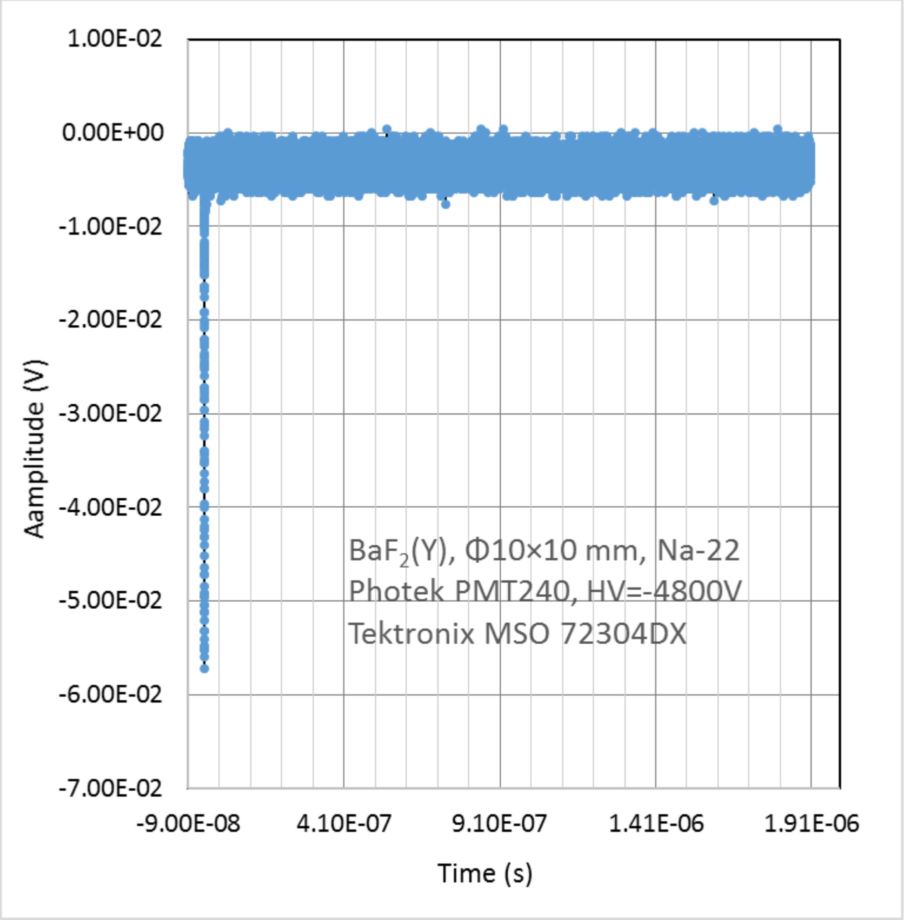
Y-doped



Tail Reduced in BGRI BaF_2:Y

Slow component tail observed in 2 μs in BaF2, not BaF2:Y





Summary of BaF_2 Cylinders

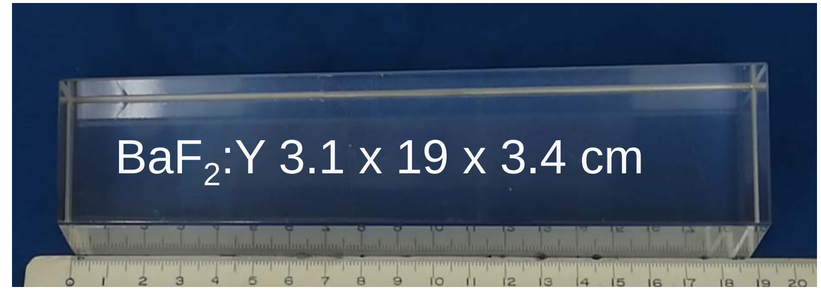
Consistent pulse shape observed between PbF_2 and BaF_2, indicating that the decay time of the fast component in BaF_2 less than 0.6 ns, faster than literature

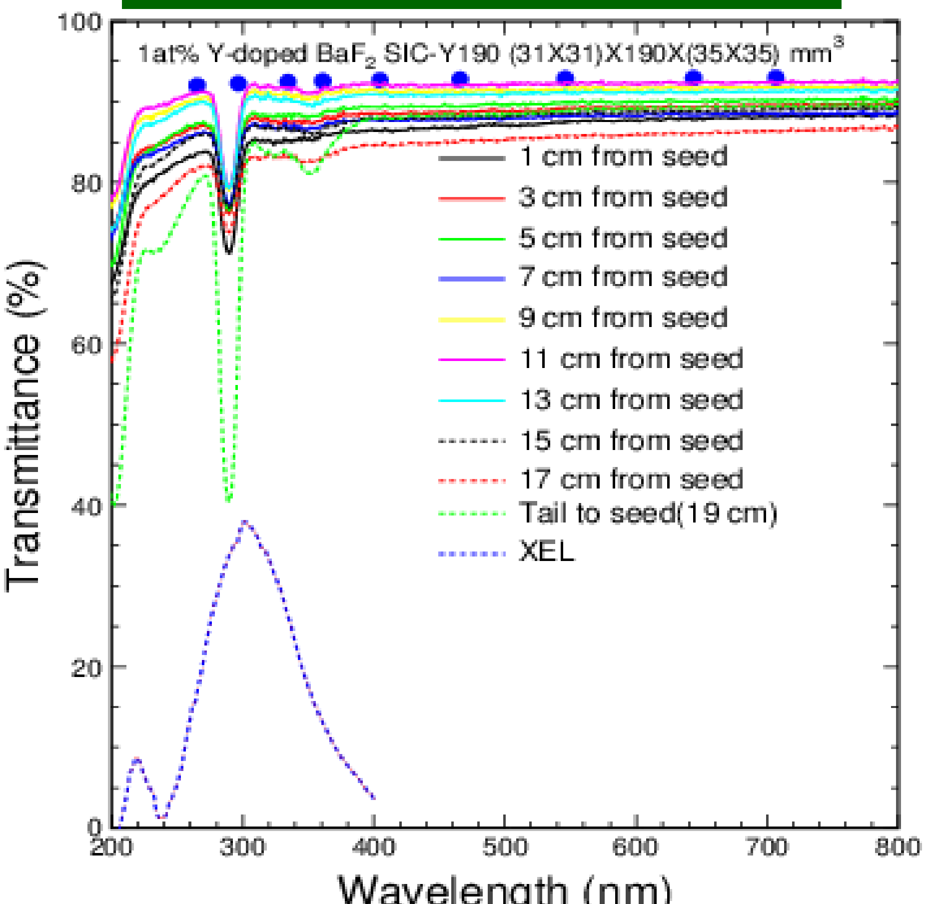
Samples	Dimensions	Excitation	Rise time (ns)	Decay time (ns)	FWHM (ns)
MCP-PMT240*	Φ40 mm	Laser pulse	0.185	N/A	1.36
PbF	50×50×50 mm^3	Cosmic-ray	0.18±0.05	0.61±0.05	0.88±0.07
SIC-U	Φ10×10 mm^3	Cosmic-ray	0.26±0.05	0.52±0.05	0.92±0.07
SIC-Y	Φ10×10 mm^3	Cosmic-ray	0.26±0.05	0.57±0.05	0.98±0.07
BGRI-U	Φ10×10 mm^3	Na-22 (511KeV)	0.22±0.05	0.59±0.05	0.92±0.07
BGRI-Y	Φ10×10 mm^3	Na-22 (511KeV)	0.29±0.05	0.50±0.05	0.96±0.07

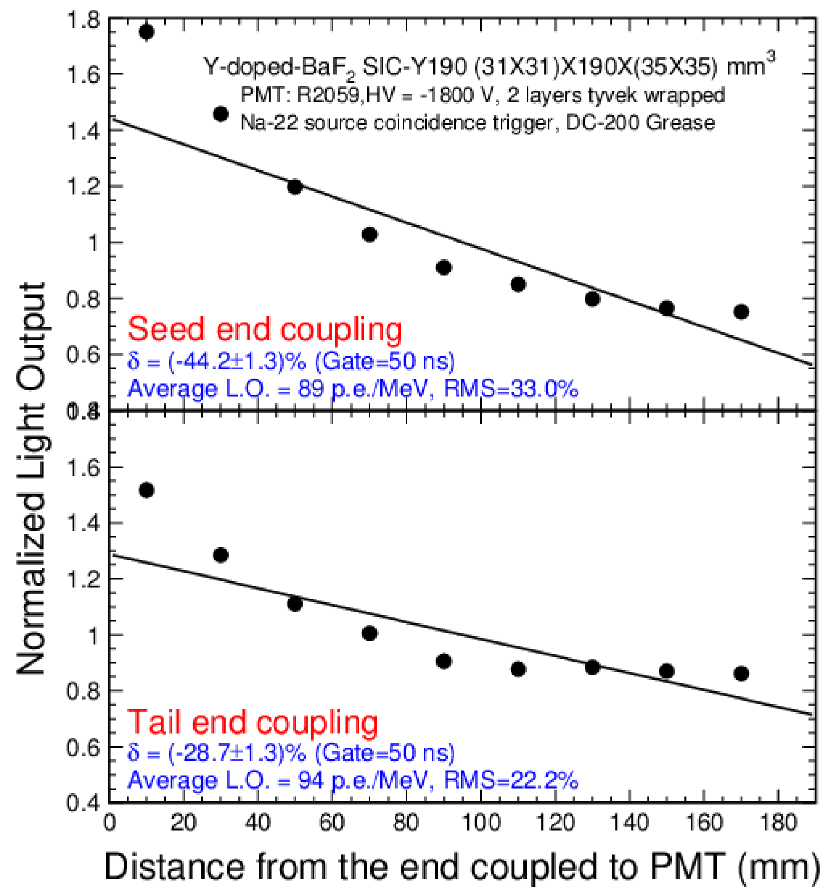
*From test report of the Photek PMT240 MCPT.

1st 19 cm Y Doped BaF_2

Absorption bands observed in 19 cm long sample with 1% yttrium doping. The F/S ratio is increased to 1.5. R&D is needed for Mu2e-II.





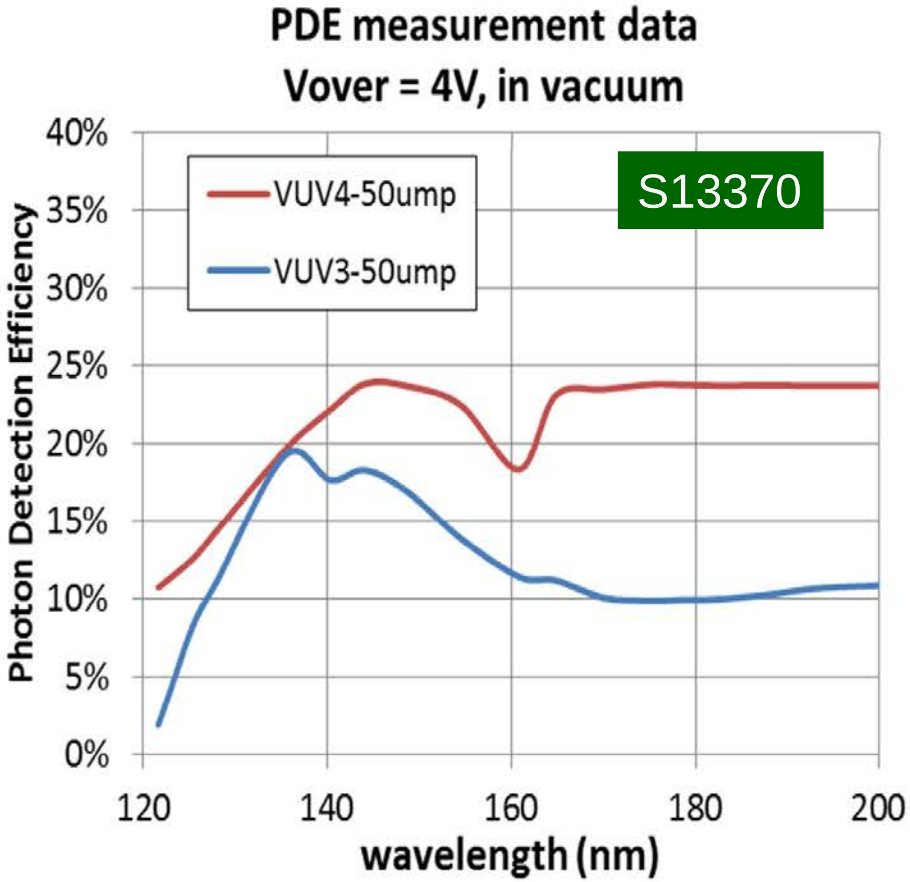


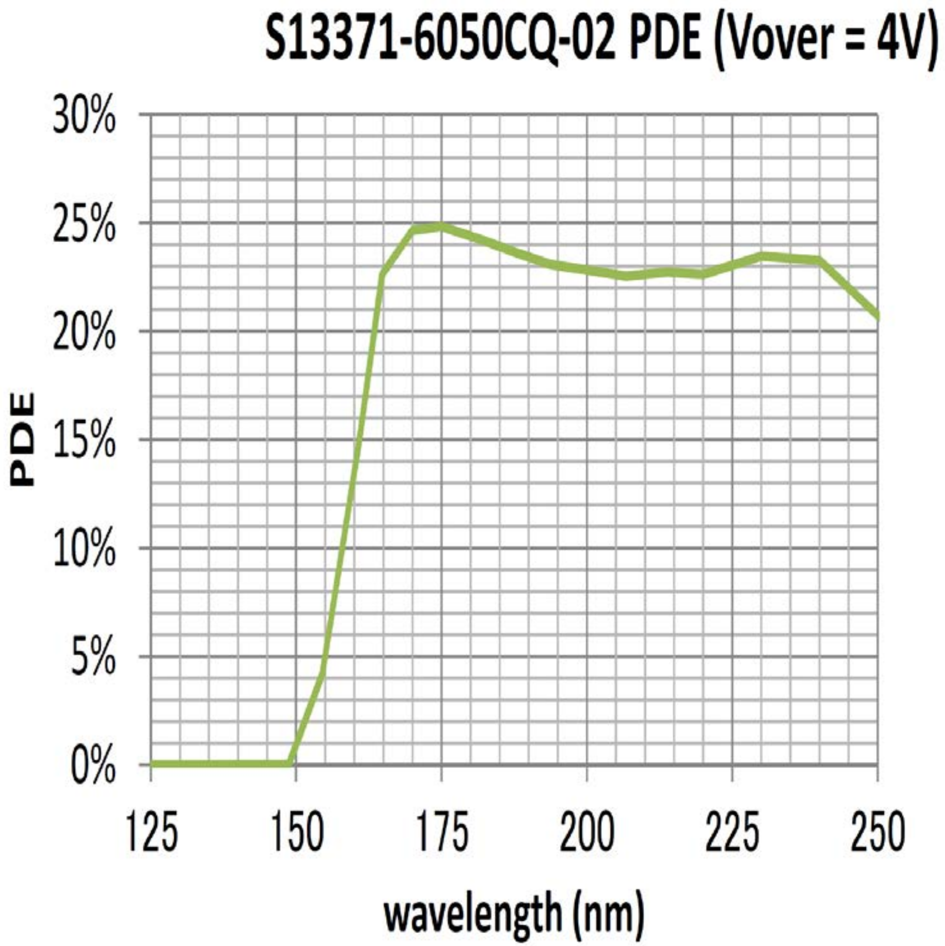
Summary

- 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 promise a very fast and robust calorimeter for Mu2e-II.
- Commercially available undoped BaF_2 crystals provide sufficient fast light with sub-ns FWHM pulse width. While lanthanum doping in BaF_2 crystals increases the F/S ratio from 1/5 to 1/1, yttrium doping increases the F/S ratio from 1/5 to 6/1 while maintaining the intensity of its sub-ns fast component unchanged. The slow contamination for BaF2:Y is already less than the commercially available undoped CsI, so is promising for the Mu2e-II.
- Additional R&D is crucial to develop yttrium doped BaF_2 crystals of large size for Mu2e-II. Will also pay an attention to photodetector with DUV response: LAPPD, Si or diamond based photodetectors

Hamamatsu S13371-6050CQ-02

SiPM with VUV response is available: QE = 22% at 220 nm





Diamond Photodetector

In addition to SiPM with VUV response

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

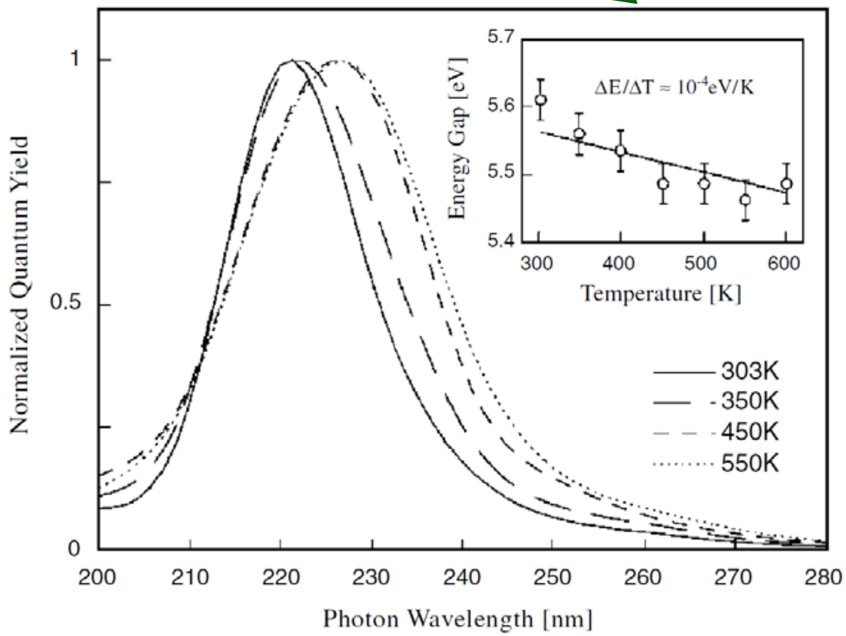


Figure 6. Quantum efficiency of diamond photoconductors at different temperatures and Arrhenius plot of the peak value (inset). (From [Sal00].)

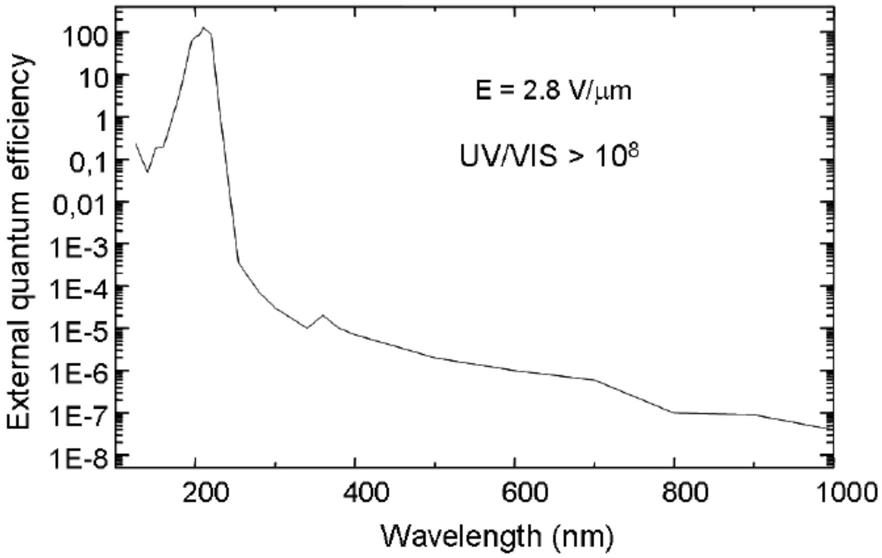


Fig. 4. External quantum efficiency extended to visible and near infrared wavelength regions. The

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