An Ultrafast and Robust BaF_2 Calorimeter for EIC

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Introduction

- Fermilab is building a undoped CsI calorimeter for the Mu2e-I experiment, which is featured with 30 ns scintillation and surviving ionization dose up to 100 krad and hadron fluence up to $10^{12}/cm^2$. A radiation level exceeding 100 krad is expected by the proposed Mu2e-II, so BaF_2 is being considered.
- With sub-ns fast scintillation and excellent radiation hardness beyond 100 Mrad and hadrons, BaF_2 promises a very fast and robust calorimeter.
- There are several approaches to handle 600 ns slow scintillation in BaF_2: solar blind photodetector and selective doping in crystal.
- Effective suppression of the slow component has been achieved in yttrium doped BaF_2 crystals.
- Mass production capability of BaF_2 exists in industry:
  - BGRI (China), Incrom (Russia) and SICCAS (China);
  - Hellma (Germany).

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	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

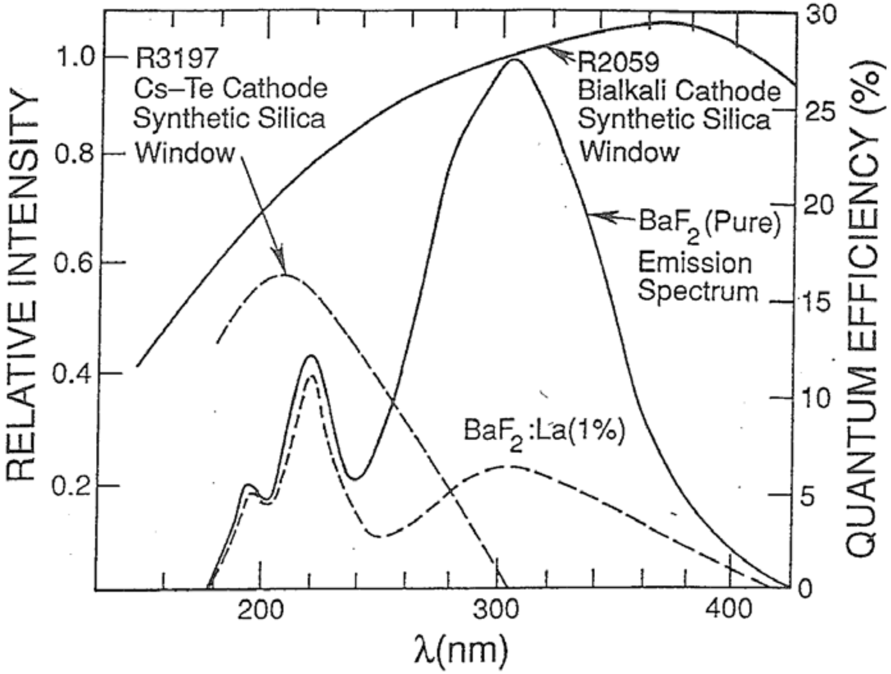
http://pdg.lbl.gov/2008/AtomicNuclearProperties/HTML_PAGES/216.html

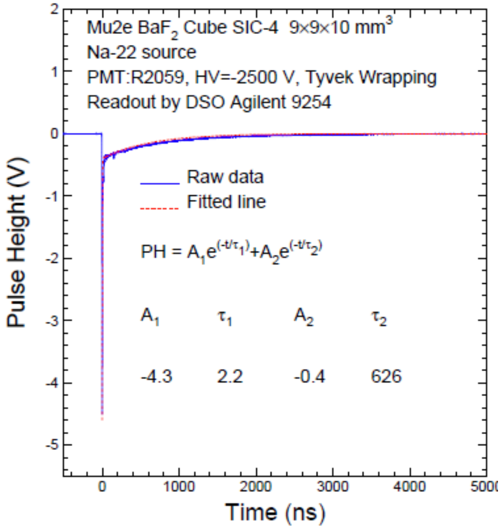
The 0.6 ns fast scintillation in BaF$_2$ promises a very fast crystal calorimeter to face the challenge of high event rate expected by future HEP experiments at the intensity frontier

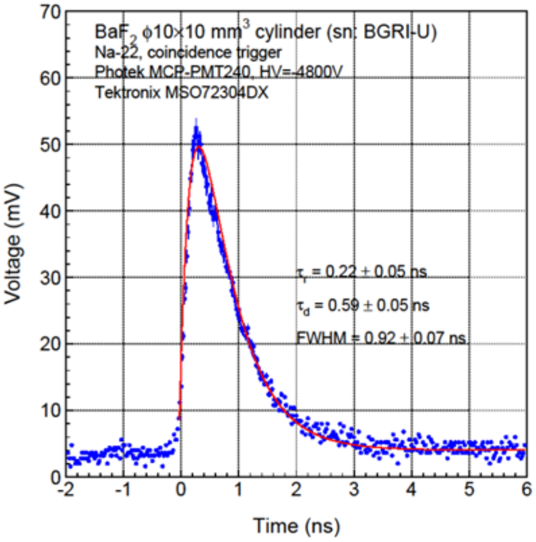
Fast and Slow Light from BaF_2

The fast component at 220 nm with 0.6 ns decay time has a similar LO as undoped CsI.

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



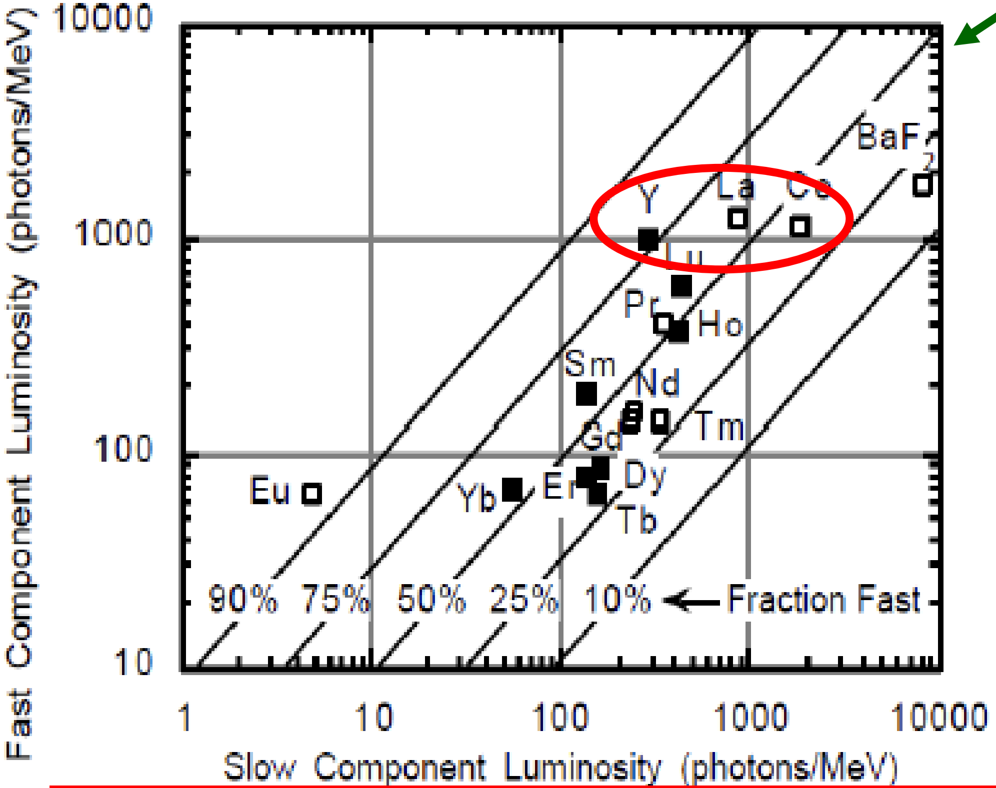


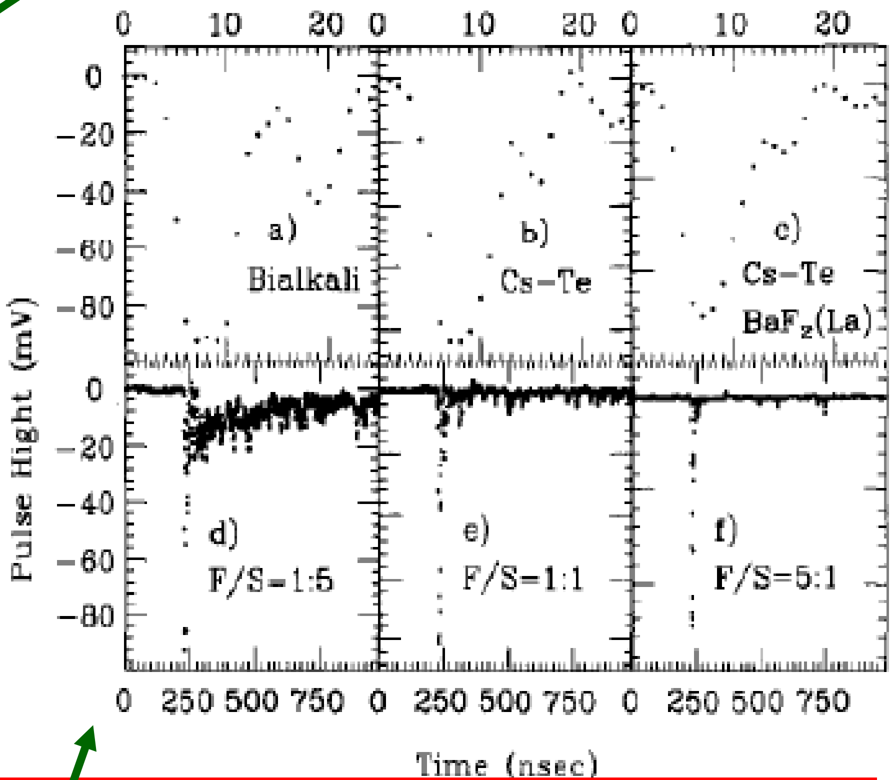


Slow Suppression: Doping & Readout

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.



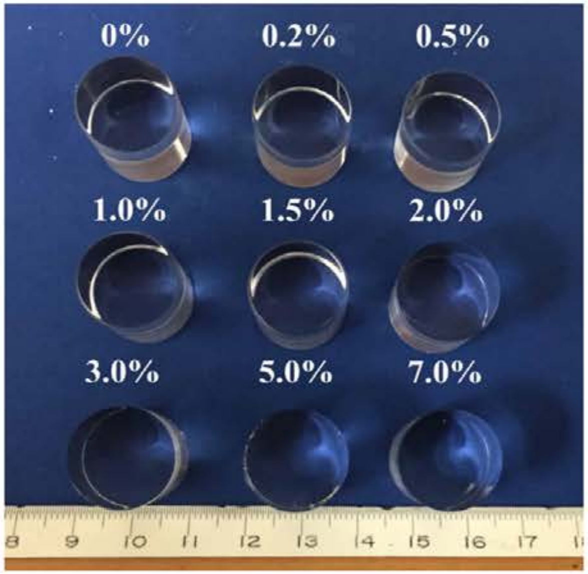


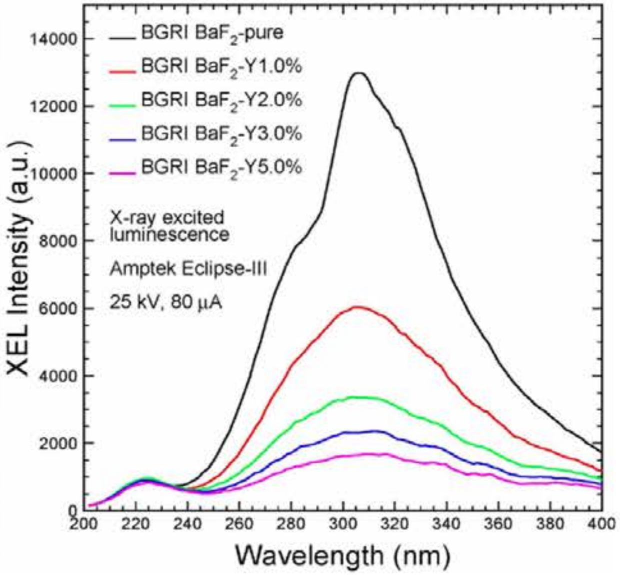
Solar-blind cathode (Cs-Te) + La doping achieved high F/S

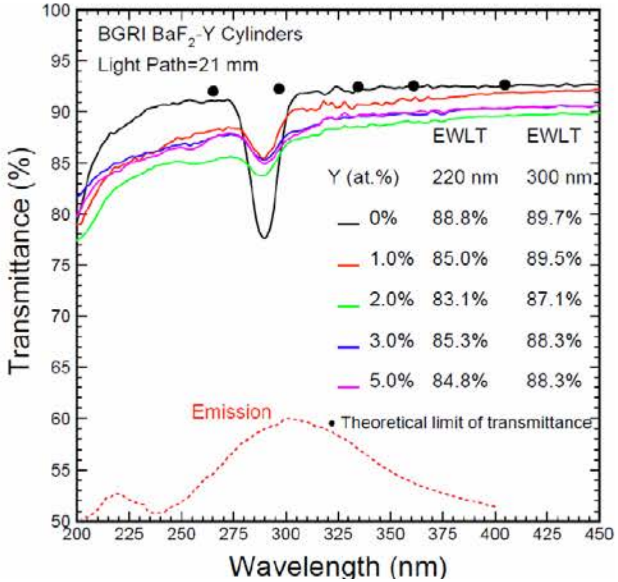
Z. Y. Wei, R. Y. Zhu, H. Newman, and Z. W. Yin, "Light Yield and Surface-Treatment of Barium Fluoride-Crystals," *Nucl Instrum Meth B*, vol. 61, pp. 61-66, Jul 1991.

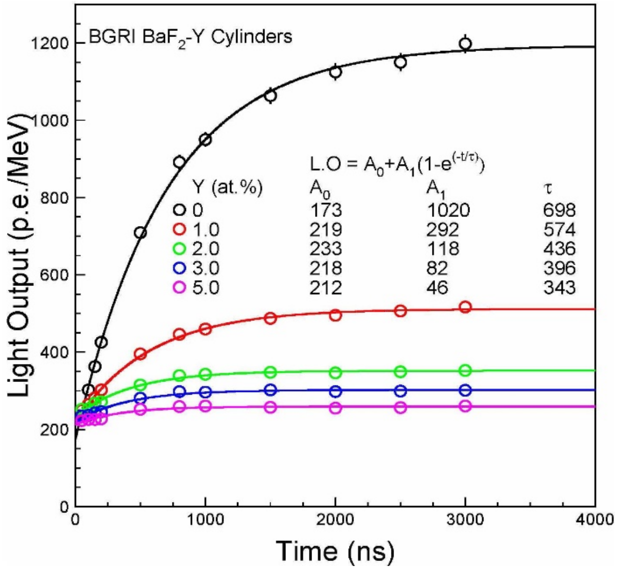
Yttrium Doping in BaF_2

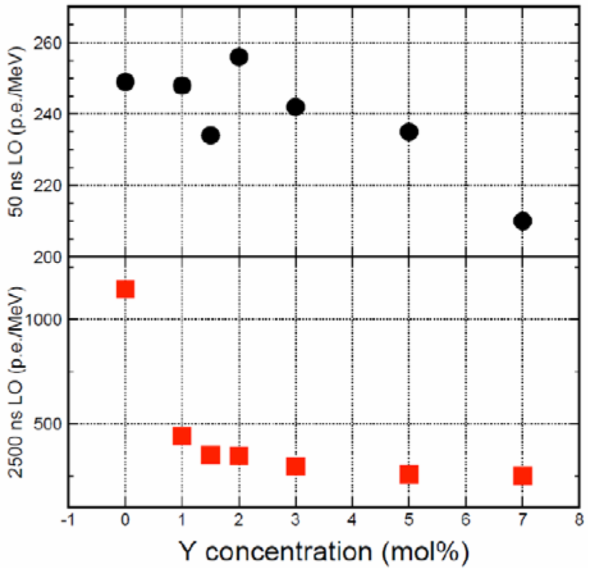
Significant increase in F/S ratio observed

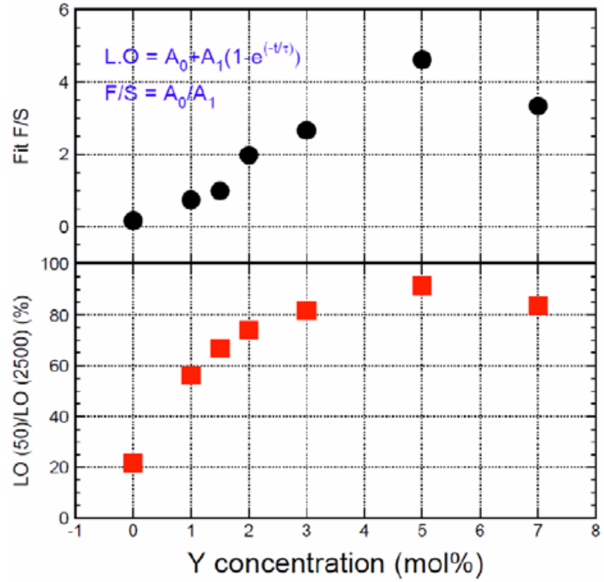












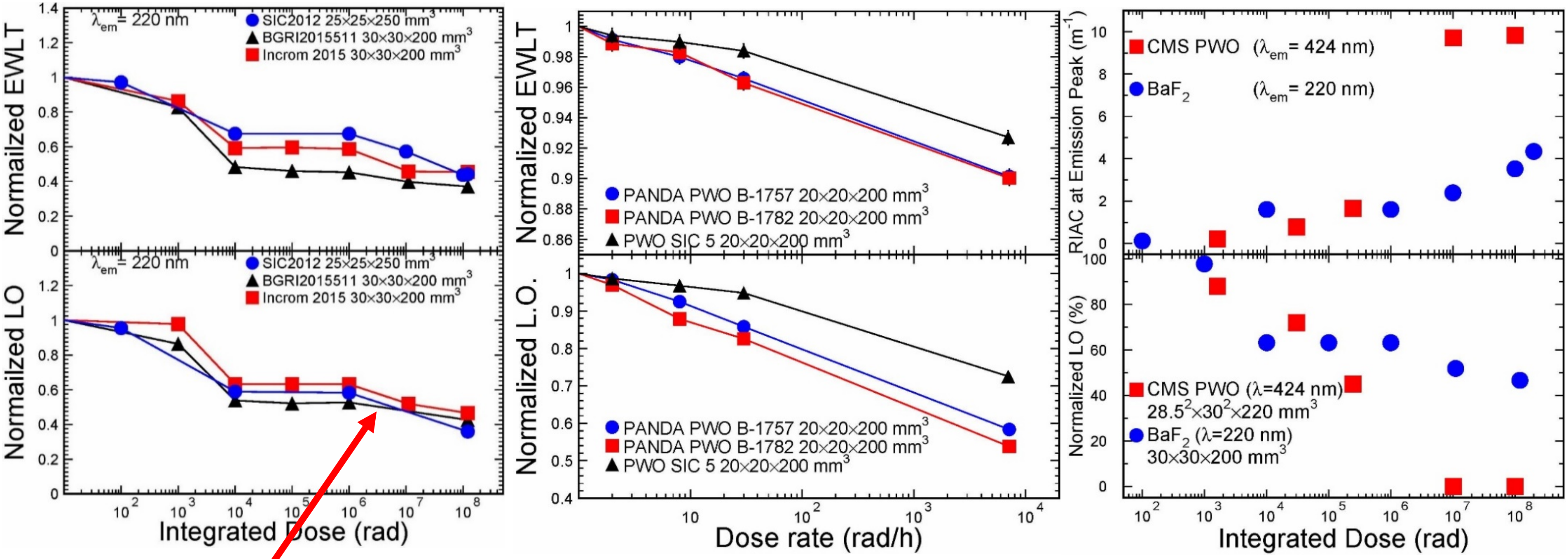
BGRI/Incrom/SIC BaF_2 Samples

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

Ionization Dose: BaF_2 and PWO

Dose rate dependent damage in PWO

Good radiation hardness in BaF_2 up to 100 Mrad

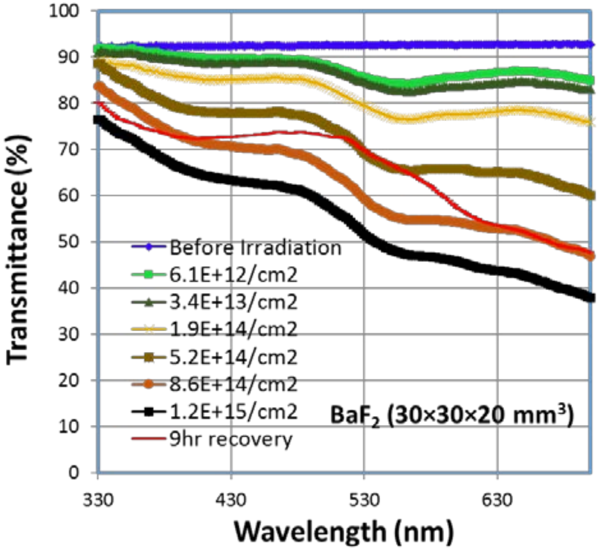


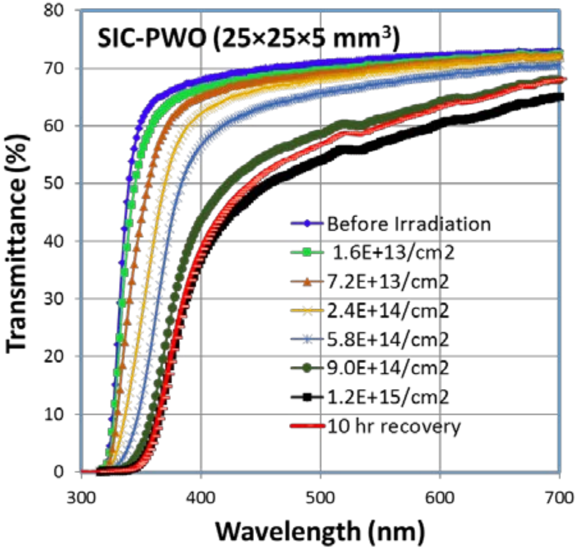
40% fast scintillation light remains after 120 Mrad ionization dose

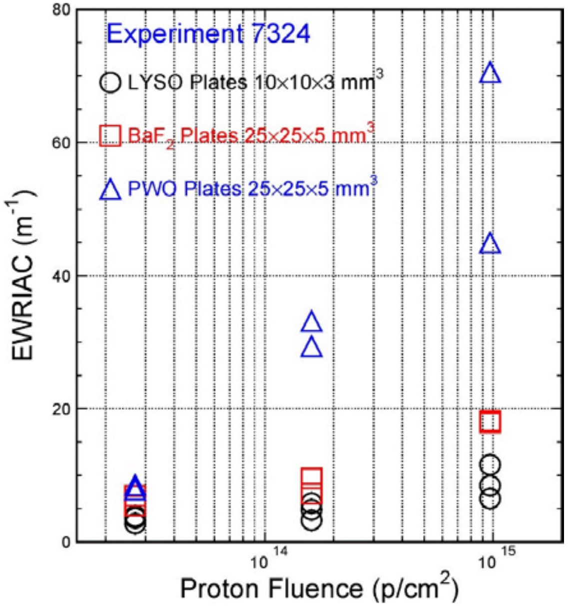
Fan Yang et al., IEEE TNS 64 (2017) 665-672

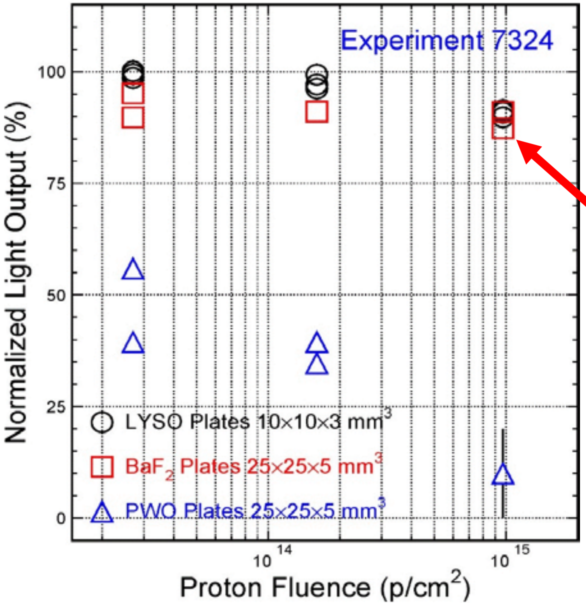
Protons: LYSO/BaF$_2$/PWO at LANSCE

A Hellma BaF$_2$ of 2 cm and a SIC PWO of 5 mm were irradiated up to 1.2×10^{15} p/cm^2 by 800 MeV protons at the blue room of LANSCE with transmittance measured *in-situ*.









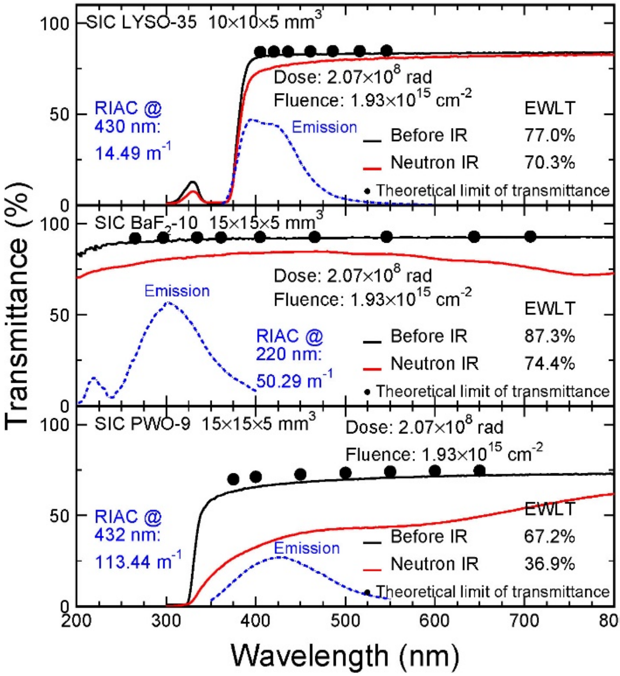
LYSO, BaF$_2$ and PWO plates of 3, 5 and 5 mm were also irradiated up to 1×10^{15} p/cm^2.

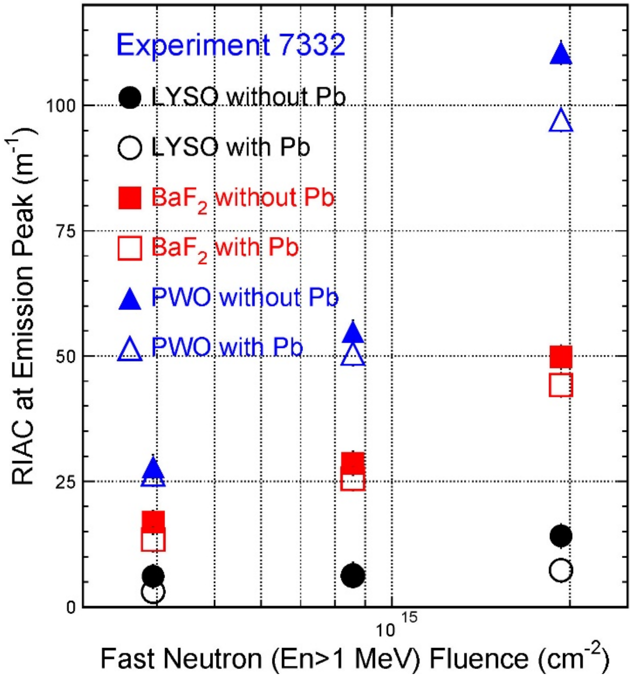
Excellent radiation hardness observed in LYSO and BaF$_2$, but not PWO.

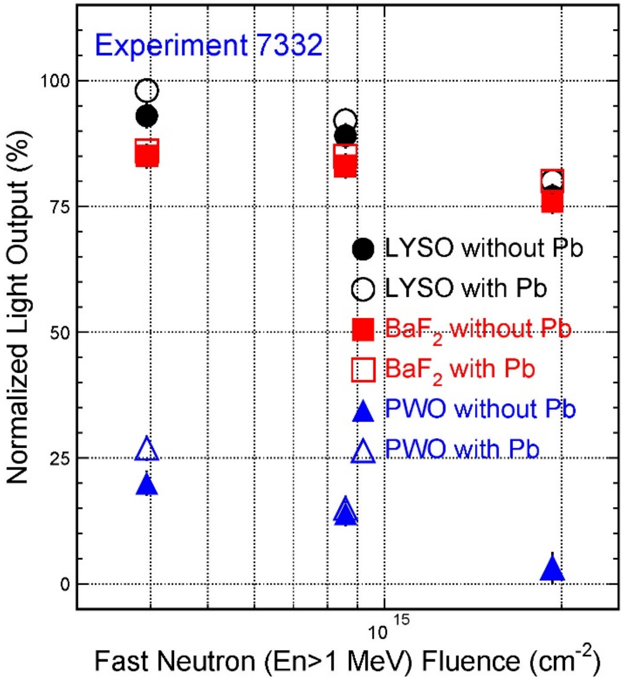
Proton-Induced Radiation Damage in BaF$_2$, LYSO and PWO Crystal Scintillators, IEEE TNS **65** (2018)
Digital Object Identifier 10.1109/TNS.2018.2808841

Neutrons: LYSO/BaF$_2$/PWO at LANSCE

LYSO, BaF$_2$ and PWO plates of 5 mm were irradiated up to 2×10^{15} n/cm^2 in three steps at the East Port of LANSCE





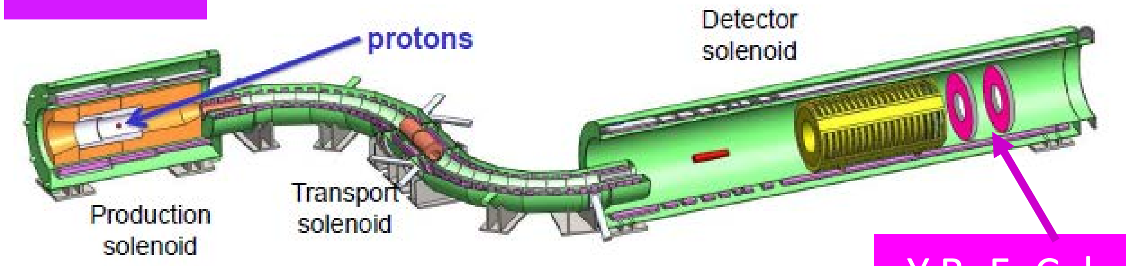


Excellent radiation hardness observed in LYSO and BaF$_2$, but not PWO

Ultrafast Barium Fluoride Applications

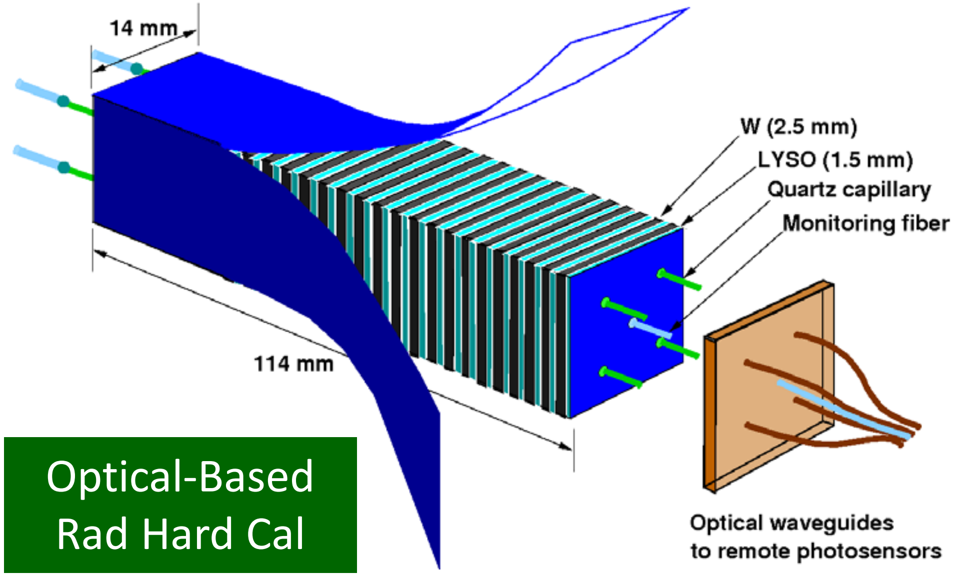
With sub-ns decay time/FWHM pulse width and excellent radiation hardness BaF_2 is an ultrafast inorganic scintillator for future HEP calorimeters at the energy and intensity frontiers

Mu2e-II



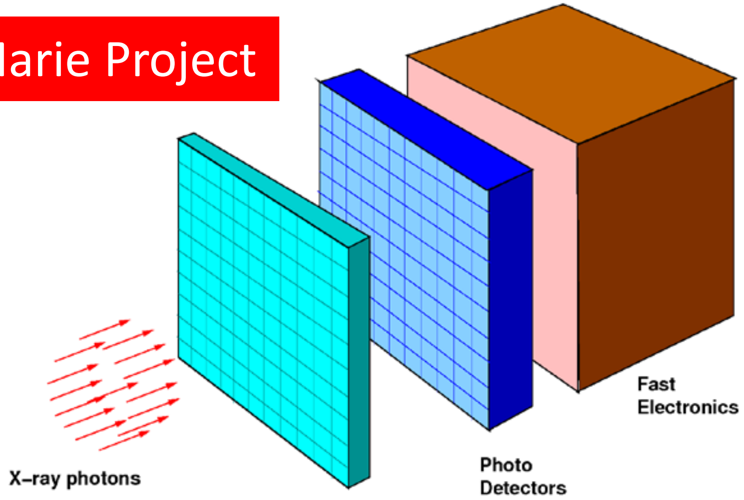
Y:BaF_2 Cal

Y:BaF_2 is also attractive for an ultrafast front imager for the FEL based GHz hard x-ray imaging



Optical-Based Rad Hard Cal

Marie Project



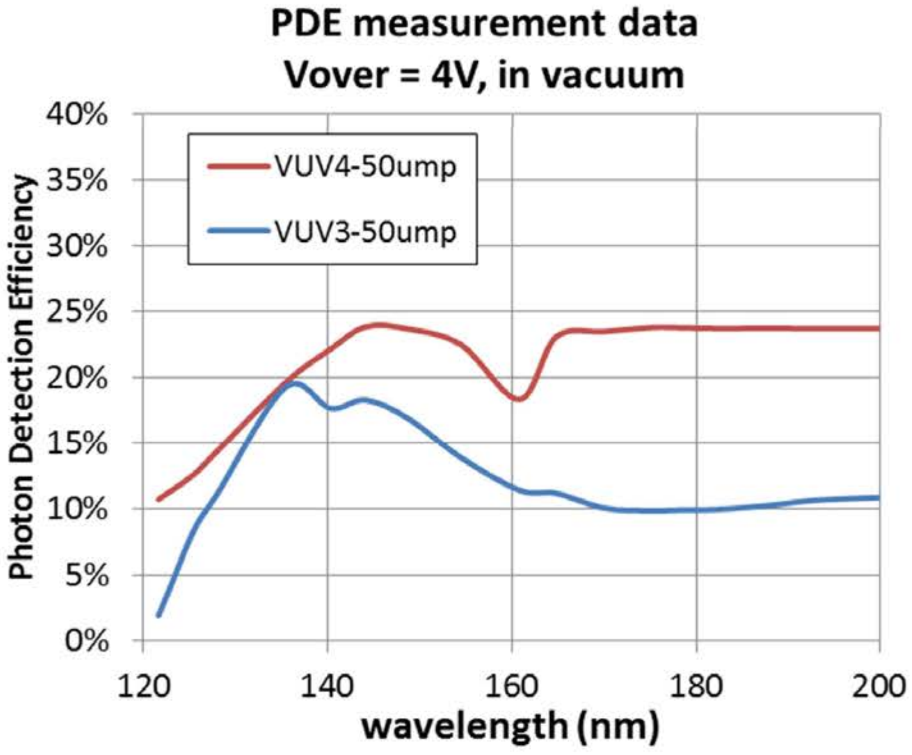
Y:BaF_2 Screen

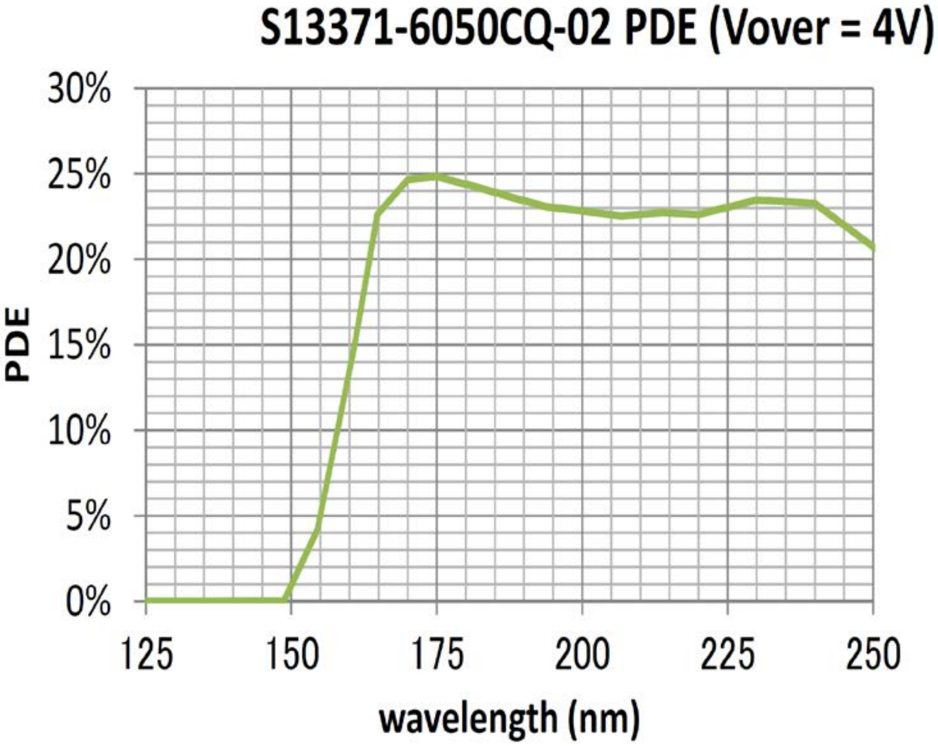
Summary

- Commercially available BaF_2 crystals provide sufficient fast light with 0.6 ns decay time and excellent radiation hardness against ionization dose and (100 Mrad) and hadrons (2 x 10^{15}/cm^2). They promise an ultrafast and robust calorimeter in a severe radiation environment.
- Yttrium doping in BaF_2 crystals significantly improves the F/S ratio without using selected readout. R&D is continued to develop BaF_2 crystals along this line.
- To be investigated is photodetectors with DUV response, e.g. Hamamatsu SiPM, diamond photodetector and solar-blind photodetector.
- It would be a joint effort with the HEP community if the EIC group chooses to pursue this novel crystal calorimeter.

Hamamatsu S13371-6050CQ-02

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





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)

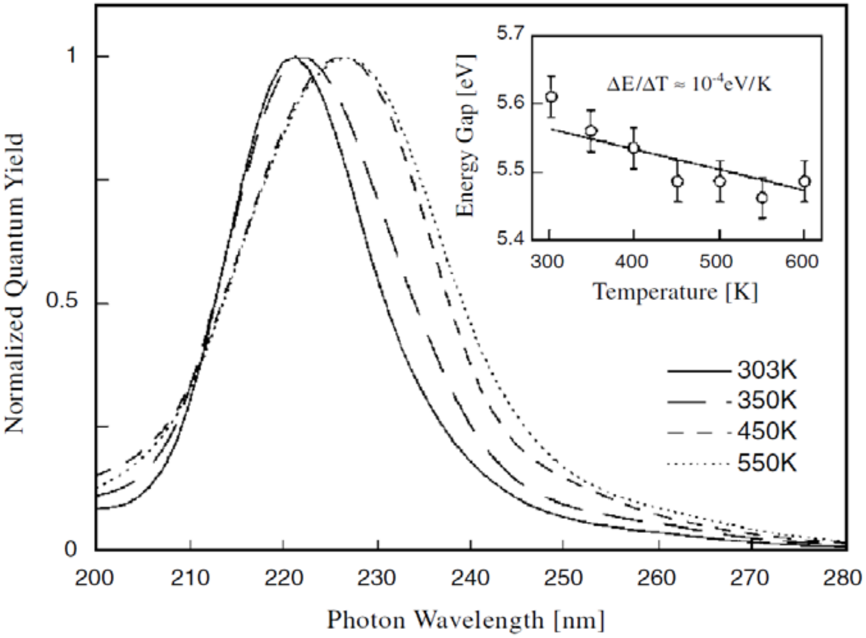


Figure 6. Quantum efficiency of diamond photoconductors at different temperatures and Arrhenius plot of the peak value (inset). (From [Sal00].)

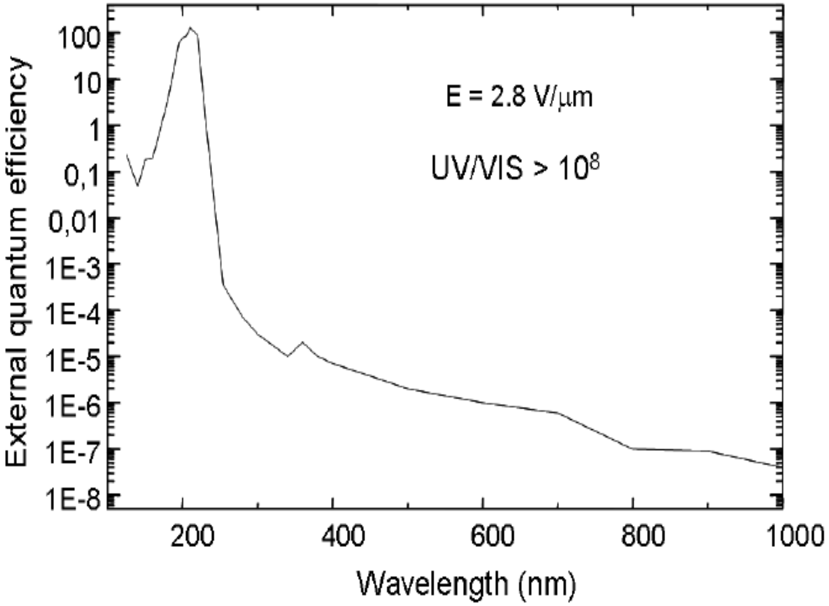


Fig. 4. External quantum efficiency extended to visible and near infrared wavelength regions. The