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 up to 120 Mrad BaF_2 promises a very fast and stable calorimeter for Mu2e-II.
- There are several approaches to handle 600 ns slow scintillation in BaF_2: solar blind photodetector, selective doping in crystal and/or electronics. A calorimeter with dual readout for both fast and slow component is interesting.
- 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)

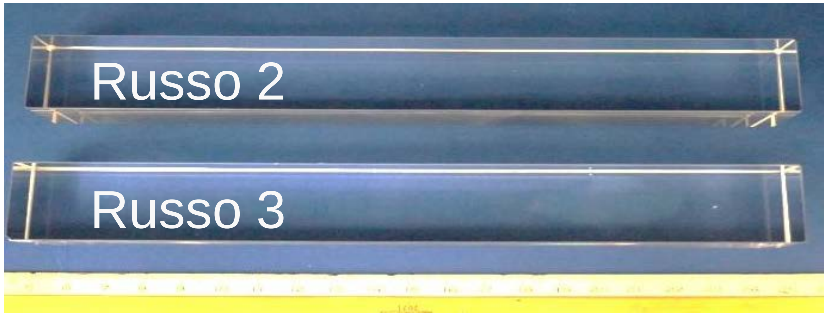
#. Softening point

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

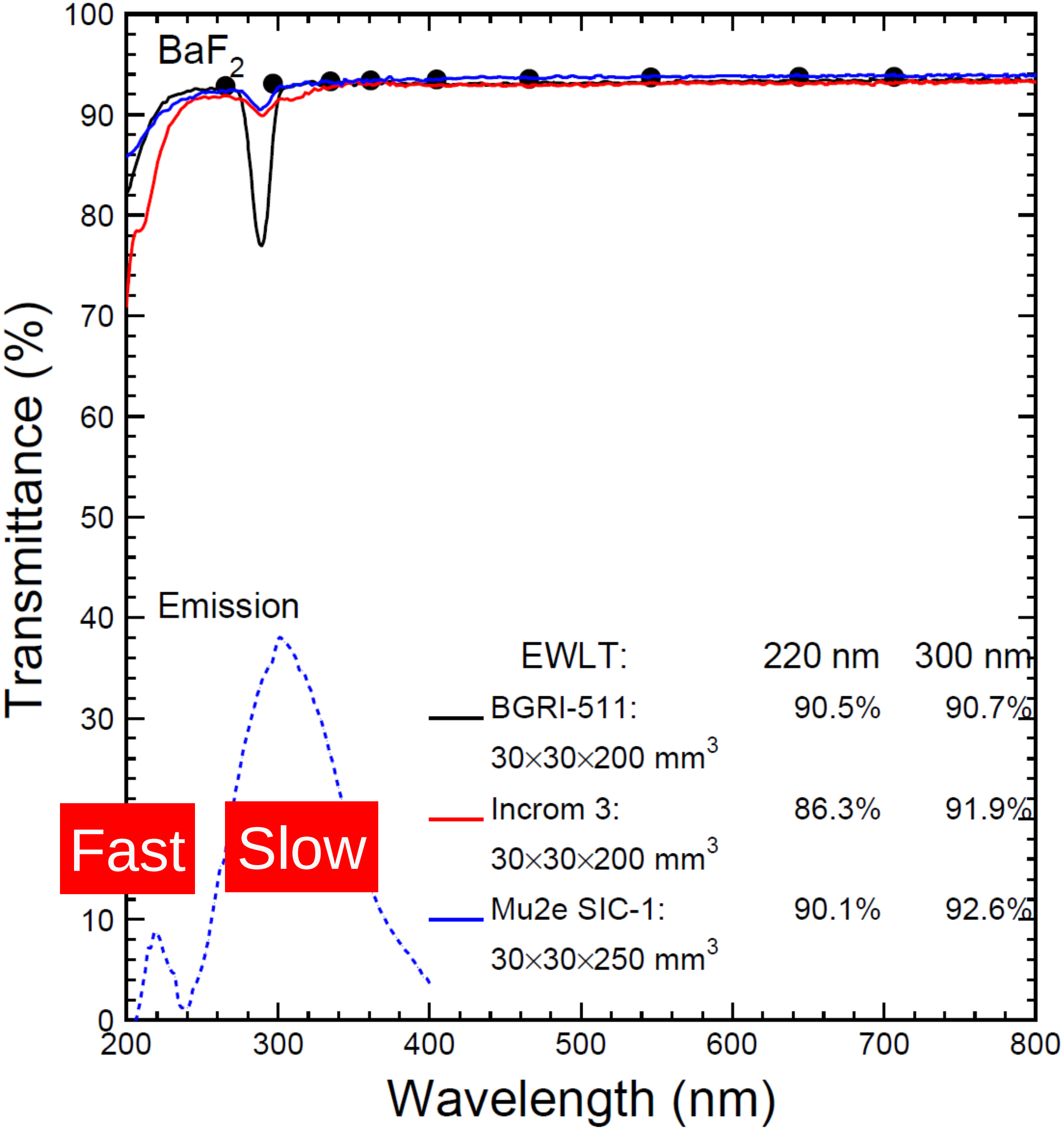
BGRI/Incrom/SIC BaF_2 Samples



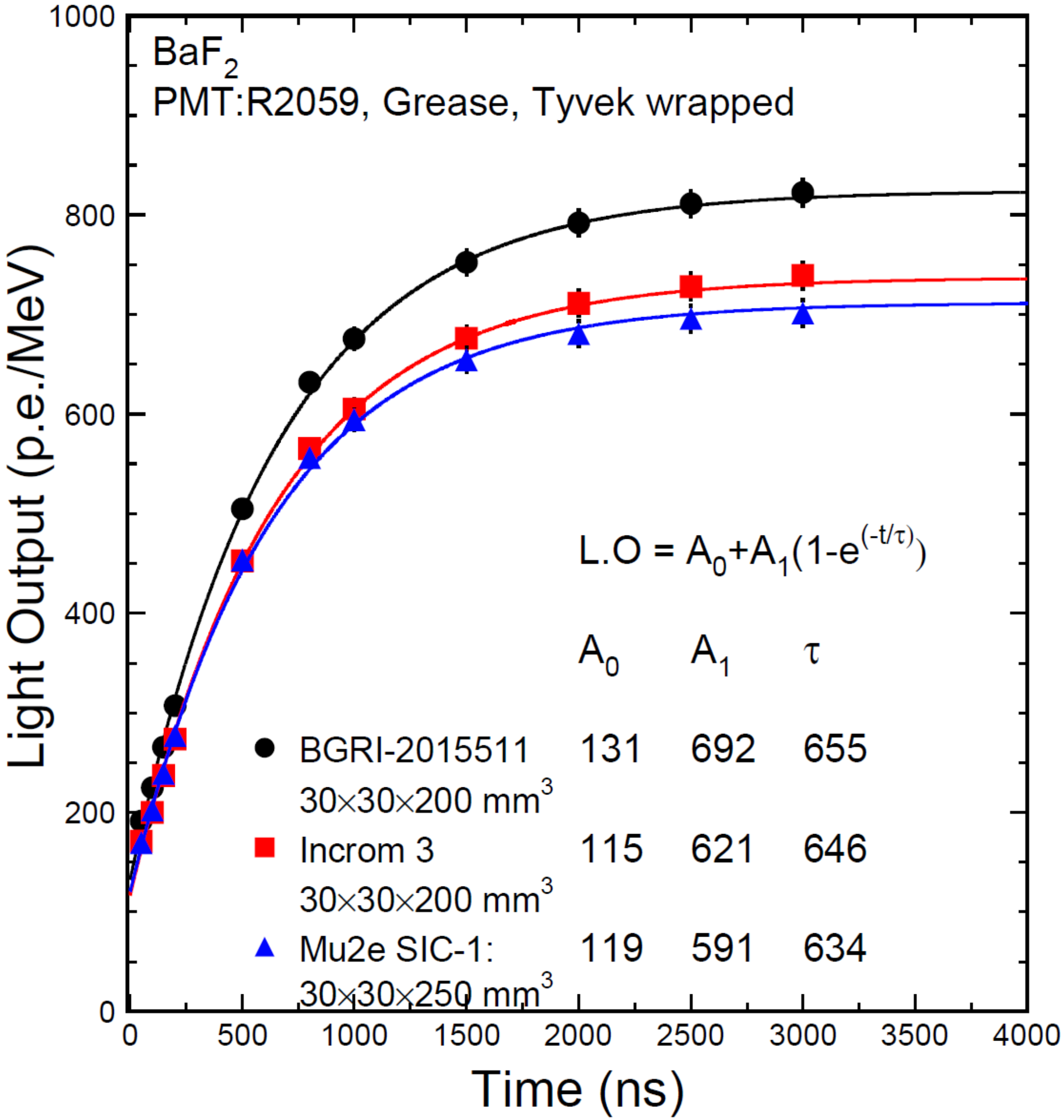
ID	Vendor	Dimension (mm^3)	Polishing
SIC 1-20	SICCAS	30x30x250	Six faces
BGRI-2015 D, E, 511	BGRI	30x30x200	Six faces
Russo 2, 3	Incrom	30x30x200	Six faces

BaF_2 Longitudinal Transmittance

Commercially available crystals have very good transmittance at both 220 and 300 nm



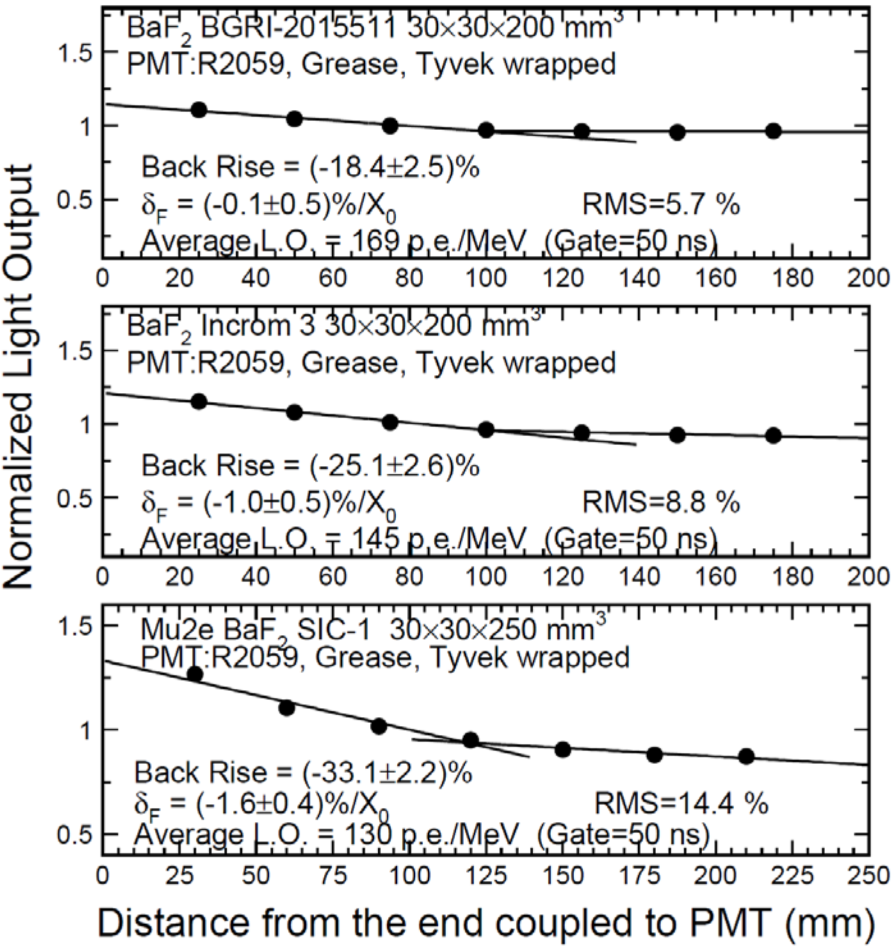
BaF_2 Scintillation Decay Kinetics

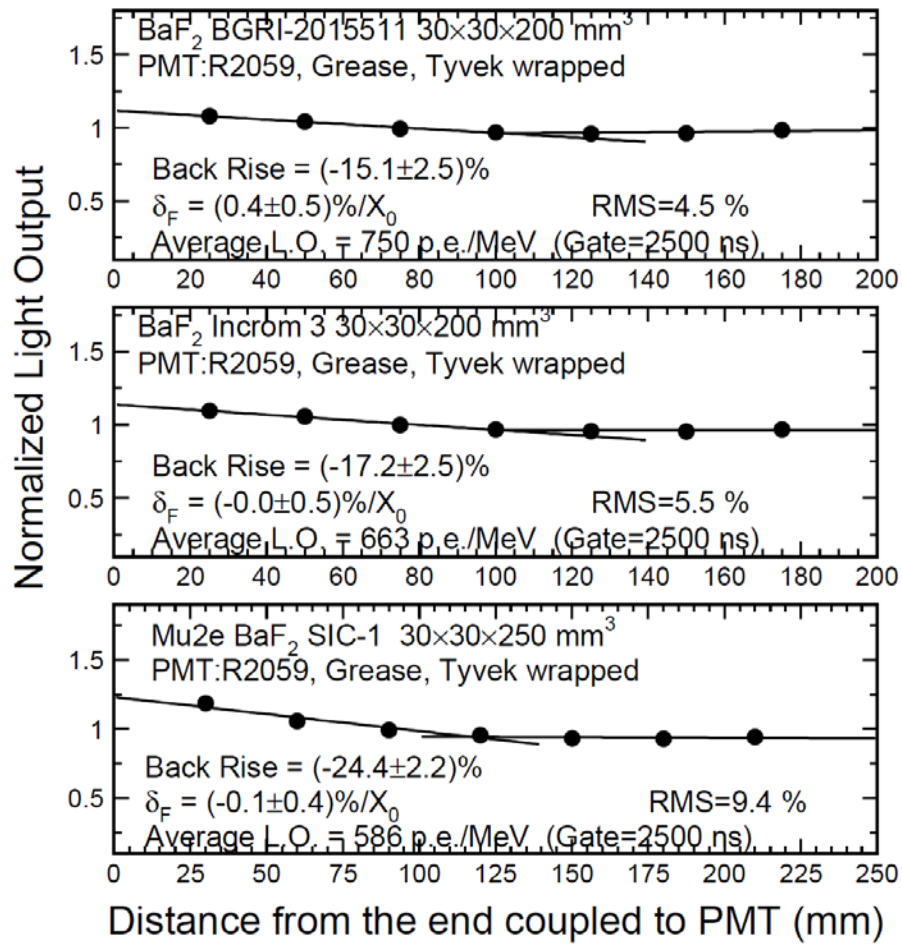


More than 100 p.e./MeV in the fast component, and about a factor of five in the slow component with 600 ns decay time

BaF_2 Light Response Uniformity

50 ns: >130 p.e./MeV	2.5 µs: >600 p.e./MeV



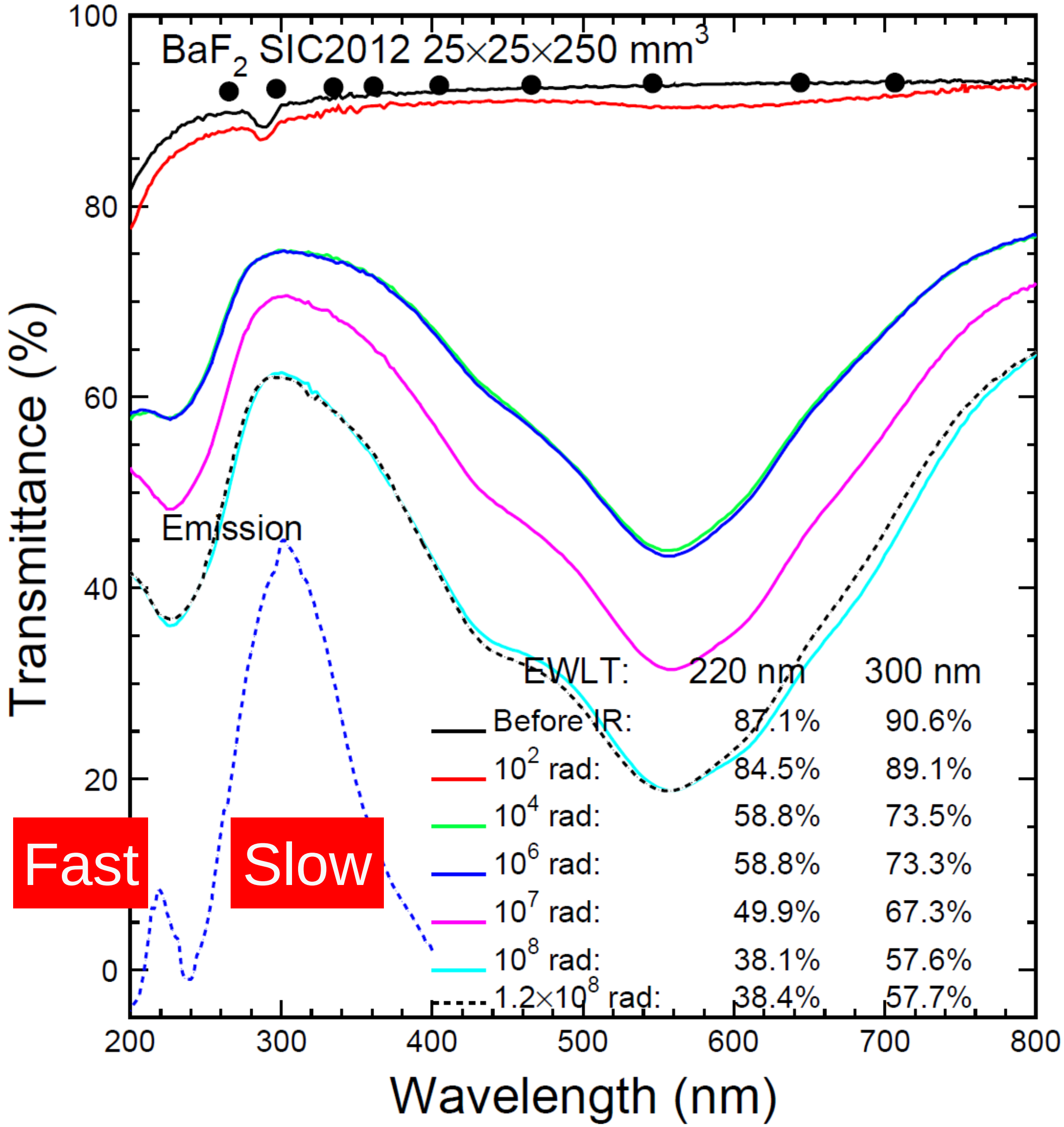


BaF_2 Summary: Initial Properties

Commercially available crystals are good for Mu2e calorimeter

ID	Ave of 20 SIC Crystals	Ave of BGRI	Ave of Russo
Dimension	30x30x250	30x30x200	30x30x200
T@220 nm (%)	85.5±0.2	87.7±0.2	85.0±0.2
T@300 nm (%)	91.3±0.2	92.3±0.2	92.2±0.2
EWLT of Fast Component (%)	86.1±0.2	88.8±0.2	86.8±0.2
EWLT of Slow Component (%)	91.1±0.2	91.8±0.2	92.4±0.2
LO 50 ns Gate (p.e./MeV)	119±1	139±1	139±1
Back Rise 50 ns Gate (%)	-38.4±2.5	-16.8±2.5	-25.4±2.5
δ_F 50 ns Gate (%/X_0)	-1.4±0.5	0.2±0.5	-1.2±0.5
RMS 50 ns Gate (%)	13.6	5.1	9.0
LO 2500 ns Gate (p.e./MeV)	562±6	730±7	646±7
Back Rise 2500 ns Gate (%)	-28.1±2.5	-14.1±2.5	-17.6±2.5
δ_F 2500 ns Gate (%/X_0)	-0.2±0.5	0.3±0.5	-0.4±0.5
RMS 2500 ns Gate (%)	9.3	4.1	5.9

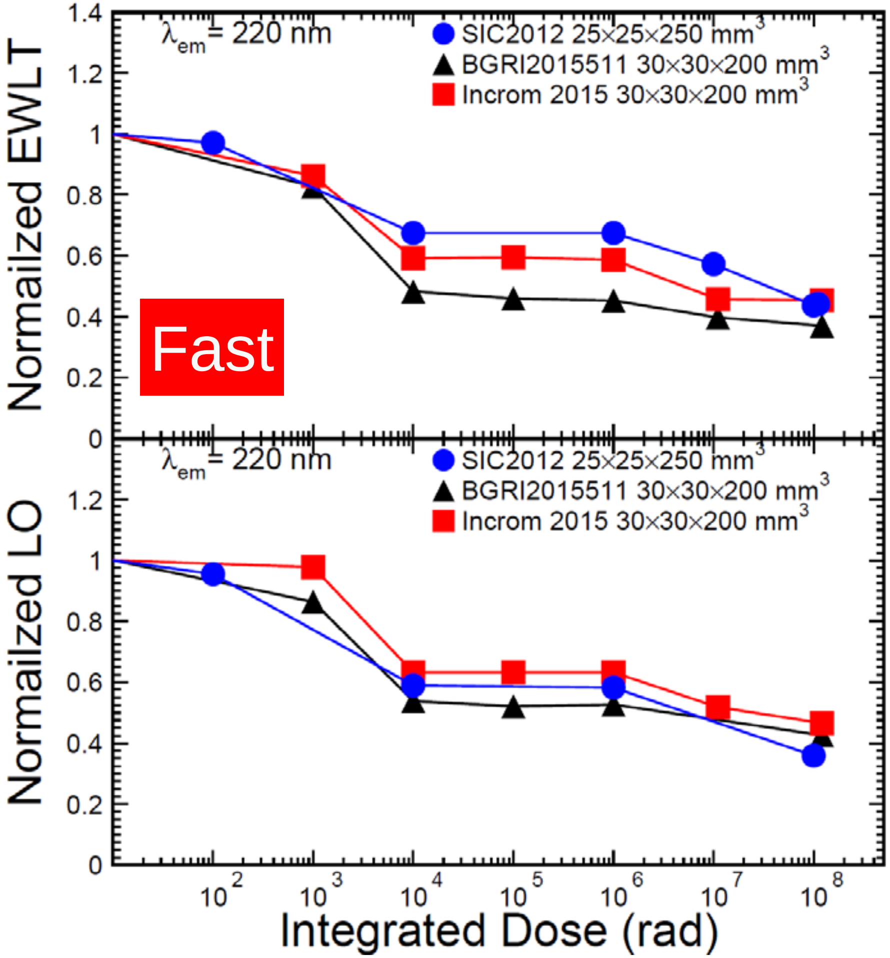
Damage in Longitudinal Transmittance

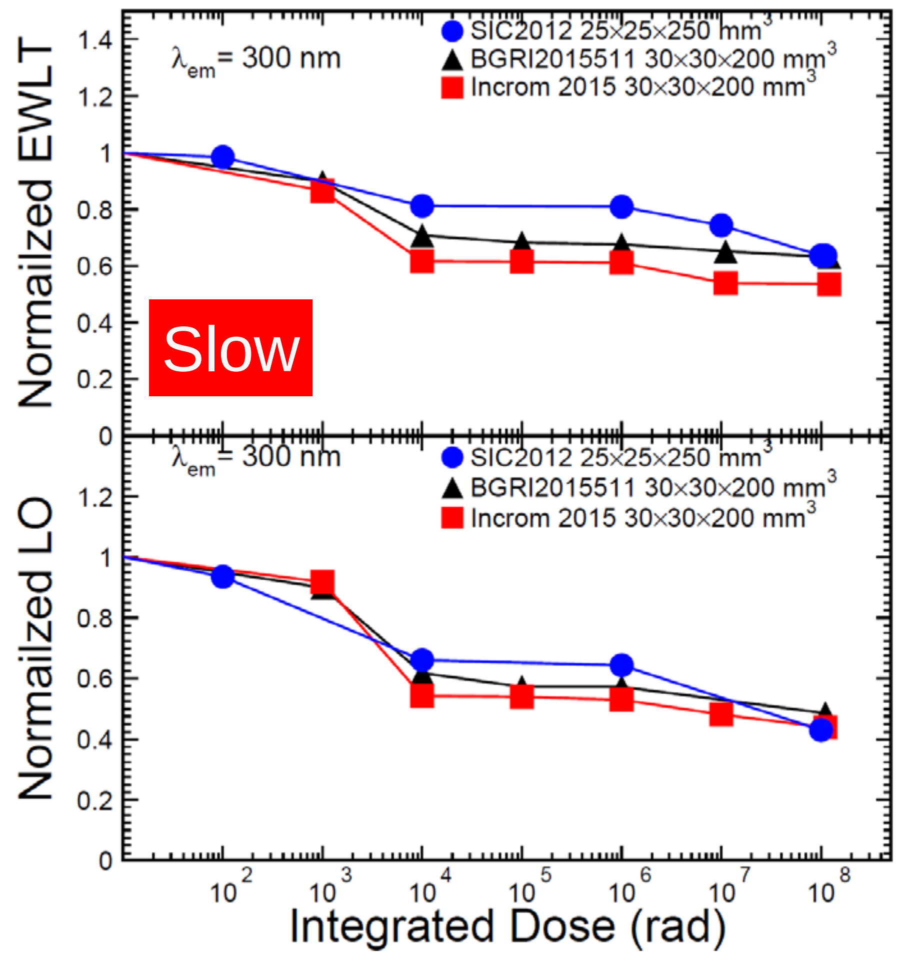


Remaining transmittance after 120 Mrad: 44% and 64 for the fast and slow scintillation component respectively

BaF_2: Normalized EWLT and LO

Consistent damage in crystals from three vendors





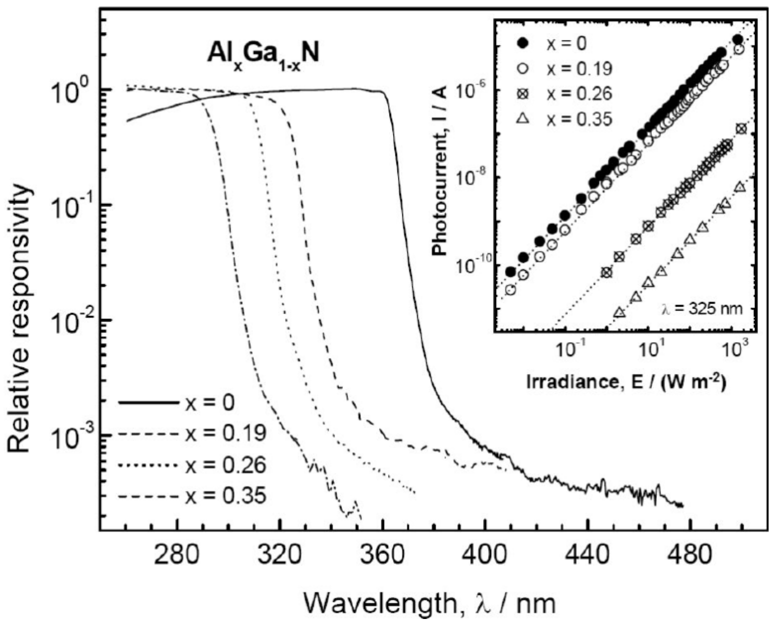
Remaining light output after 120 Mrad: 40%/45% for the fast/slow component

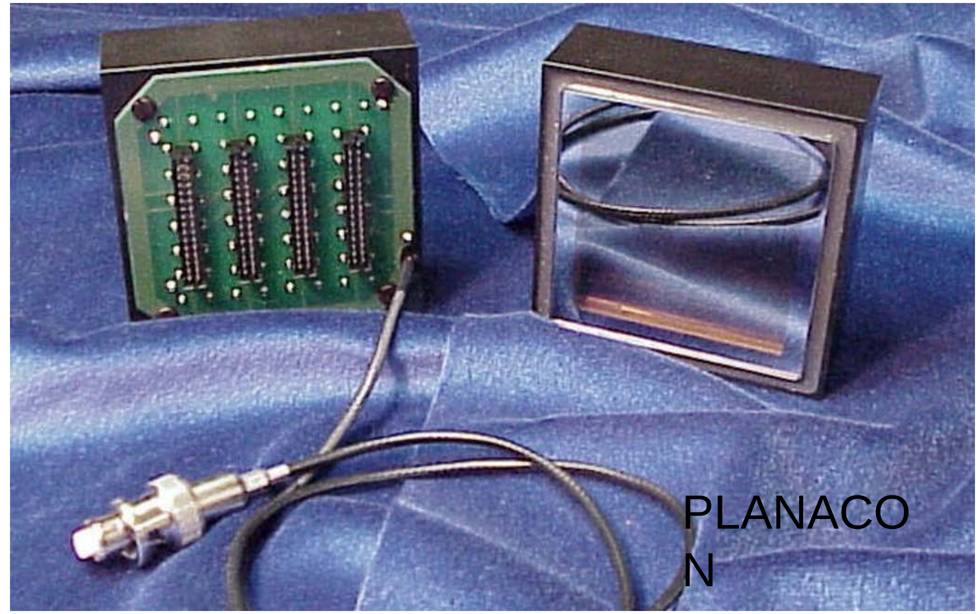
The Issue of Slow Component

- BaF_2 has a slow scintillation component at 300 nm with 600 ns decay time, which is a factor of five in intensity as compared to the fast component. It causes pile up noise.
- Approaches being pursued:
  - Solar blind photo-detector sensitive to 220 nm, not 300 nm. **See David's talk on APD/SiPM and approaches proposed by Pasha and Steve.**
  - Crystal development by selective doping: La doing has been successfully implemented at BGRI and SICCAS.
- Approach may be pursued:
  - Special electronics to eliminate the slow component.
  - Dual readout: Read both fast and slow component for timing and energy.
- The fast light in BaF_2 is of general interest. R&D along this line will serve a large community beyond the HEP.

Pasha's Approach: Solar-Blind Photocathode

U.Schühle, J.-F.Hochedez, "Solar-Blind UV detectors", in ISSI Scientific Report SR-009, ISBN: 978-92-9221-938-3





- Wide-band semiconductors make UV-sensitive, solar-blind photocathodes
- GaN (band gap ~3.5 eV) used in astrophysics and defense, radiation-hard
- $Al_xGa_{1-x}N$ – tune the efficiency cut-off wavelength by varying the Al fraction
- Compact packaging, can match the crystal size
- MCP-based photodetector with GaN photocathodes could be a natural choice for high-rate BaF2 calorimeters
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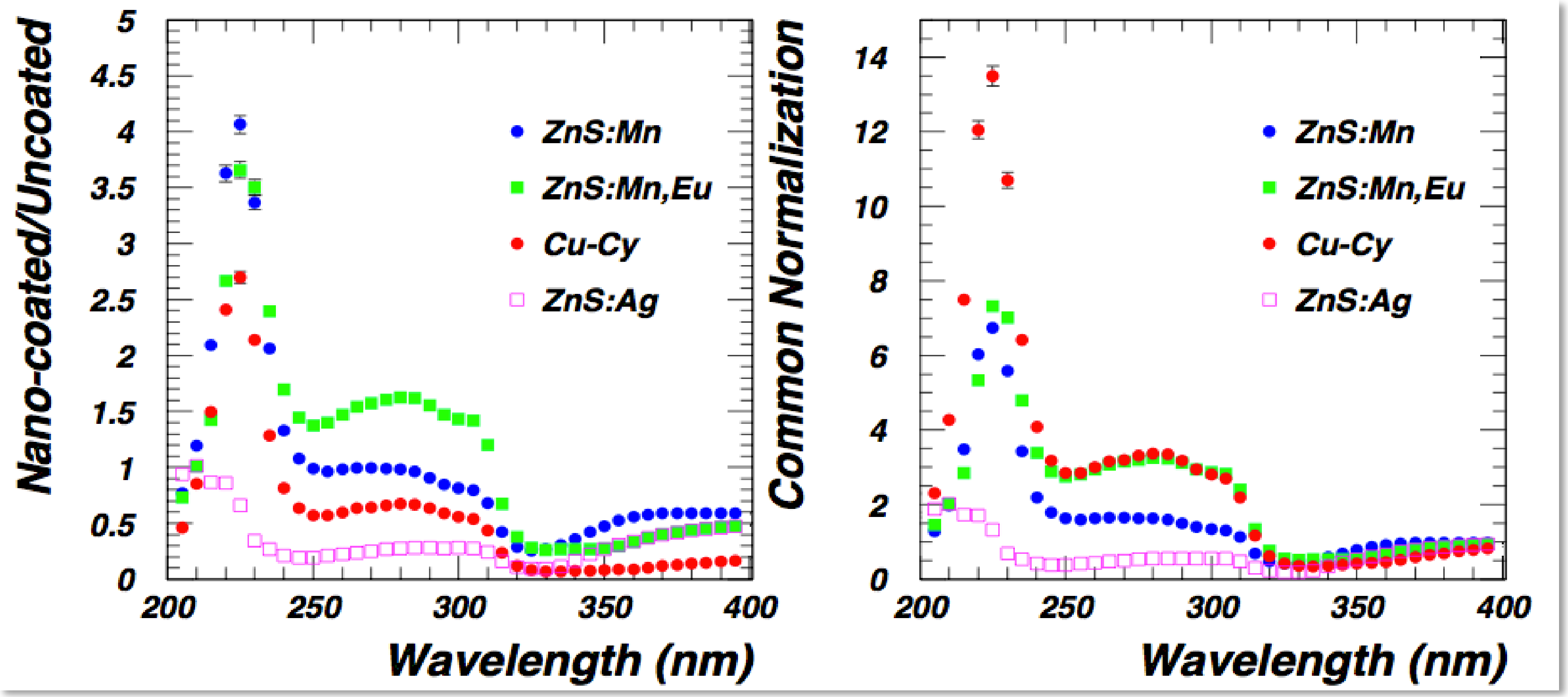
Steve's Approach: WLS Nano Particles



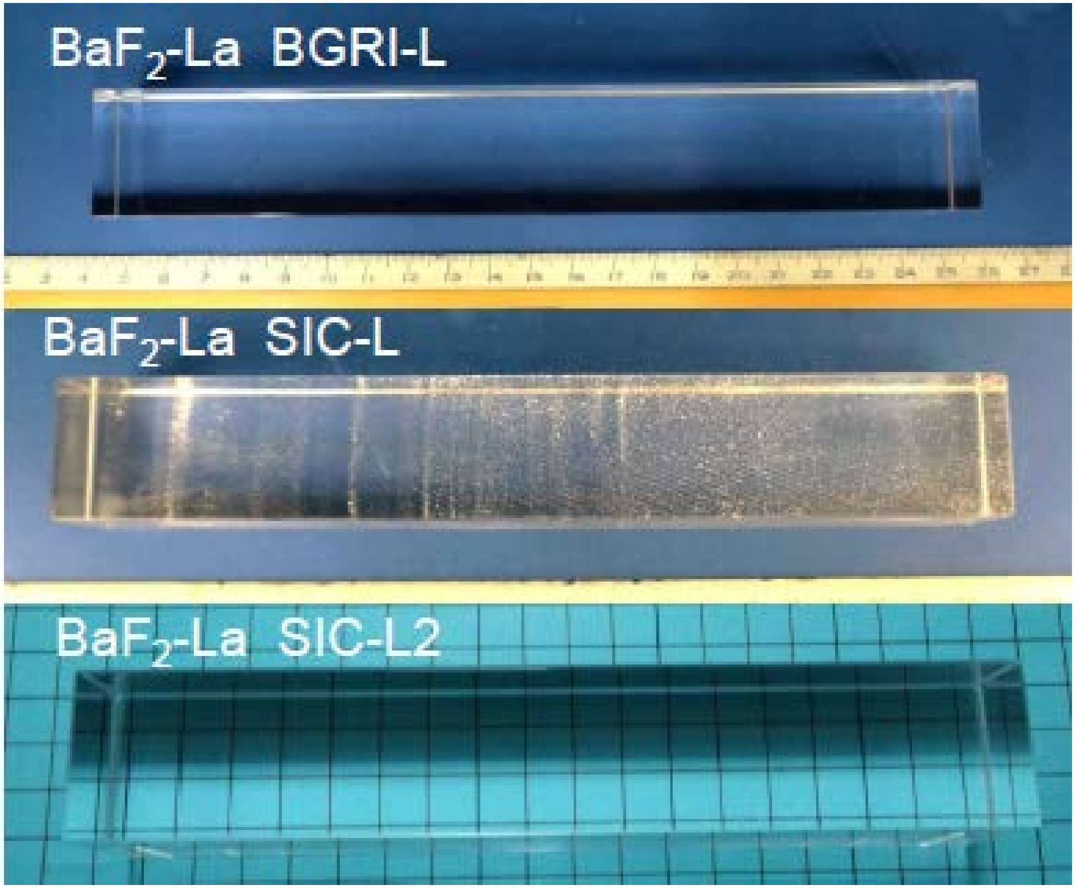
Test of UTA luminescent nanoparticles – 5 nm steps, 200 nm -> 400 nm

- Left – Coated/Uncoated (different thicknesses of samples)
- Right – Coated/Uncoated (common normalization at 400 nm)

Increase in 3 out of 4 samples for wavelengths < 320 nm

- *-> peaks at ~225 nm, visible blind?*

Large Size La Doped BaF_2 Samples



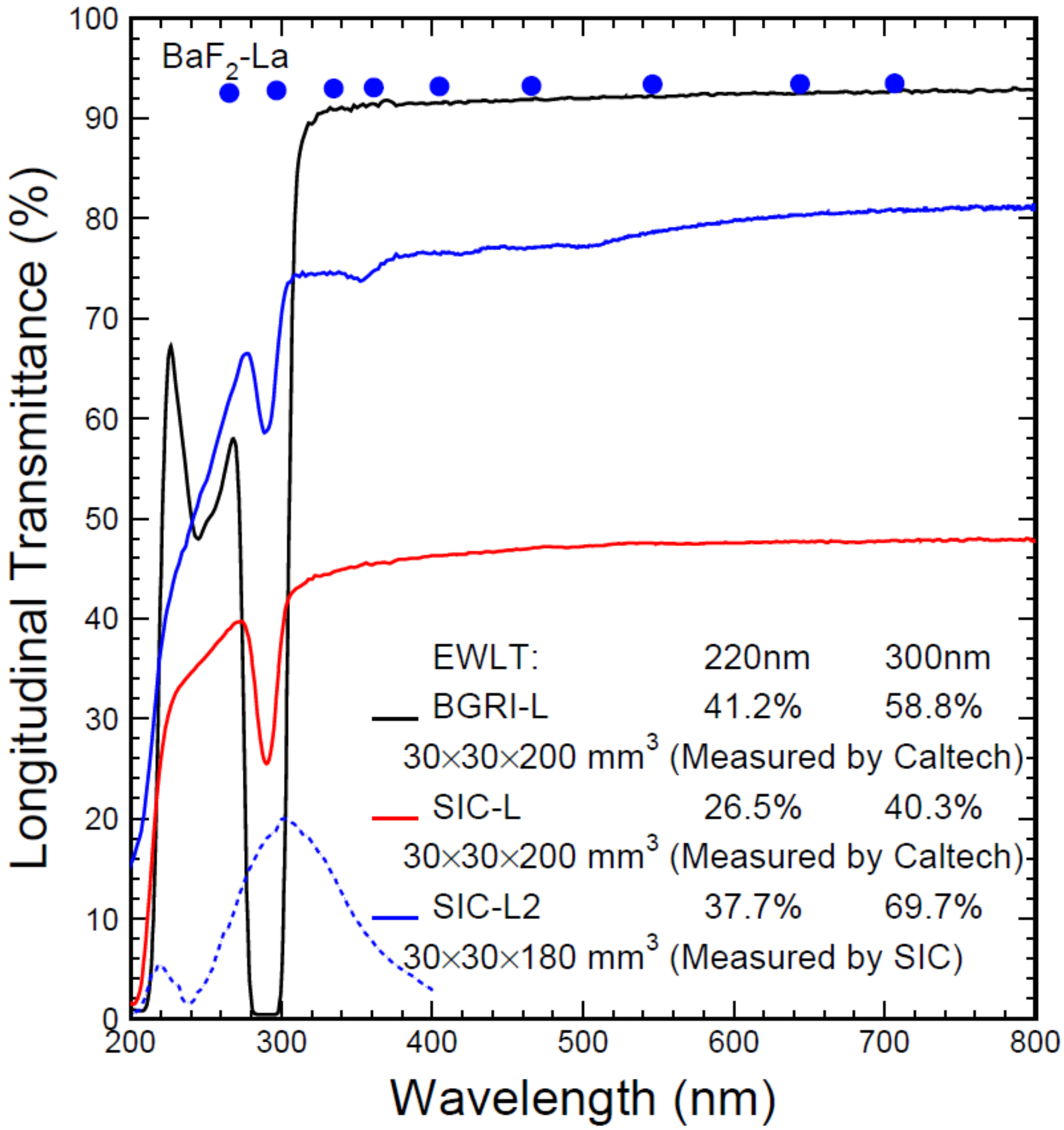
Two 20 cm long La doped BaF_2 samples were delivered in last Fall. One 18 cm long BaF_2 sample was delivered this week

ID	Dimension (mm³)	Polishing
BaF_2-La BGRI-L	30x30x200	All faces
BaF_2-La SIC-L	30x30x200	All faces
BaF_2-La SIC-L2	30x30x180	All faces

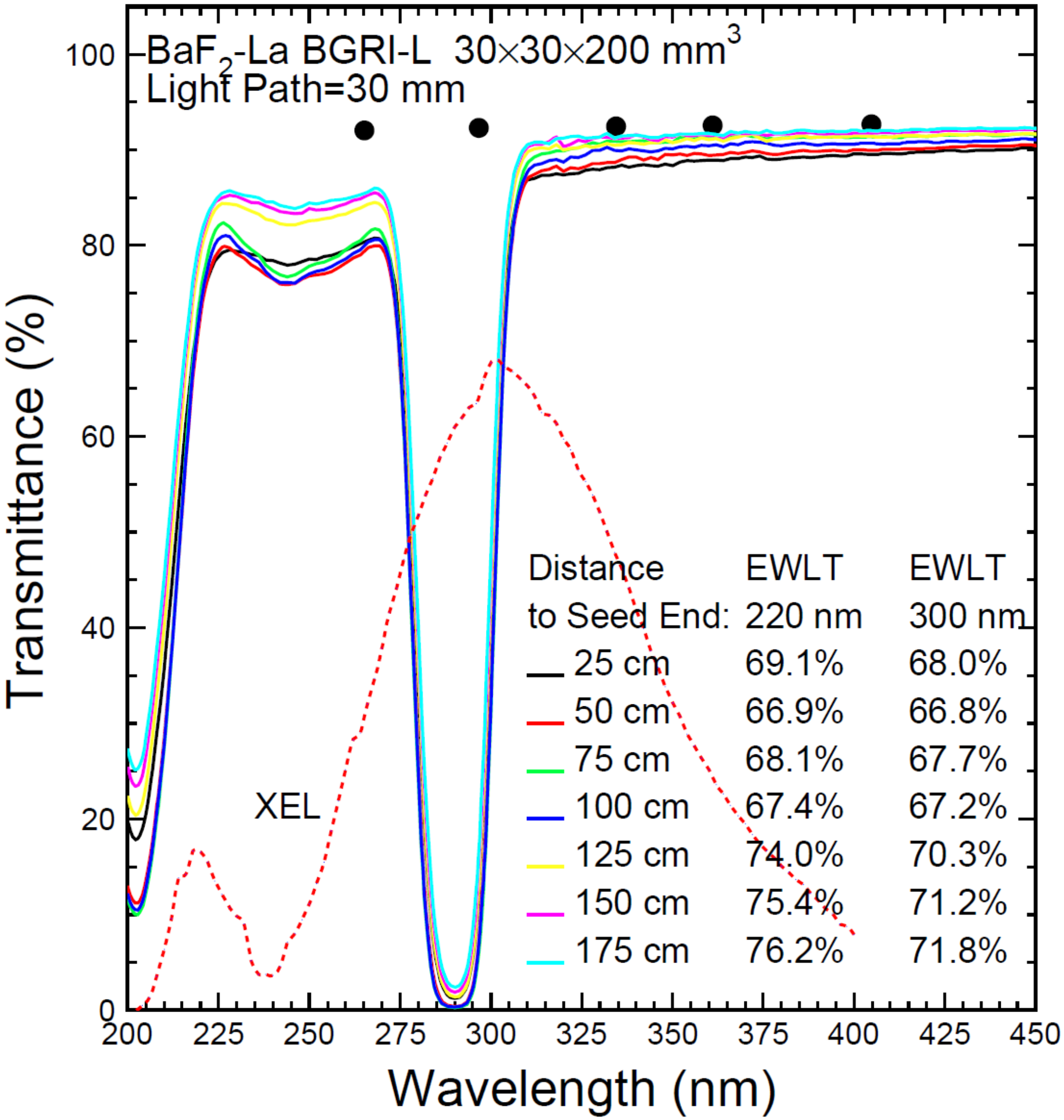
BaF_2:La: Longitudinal Transmittance

Two absorption bands observed at 203 and 290 nm. Poor transmittance of SIC samples is due to scattering centers.

The data of the 2nd SIC sample is provided by SIC, will be measured at Caltech.



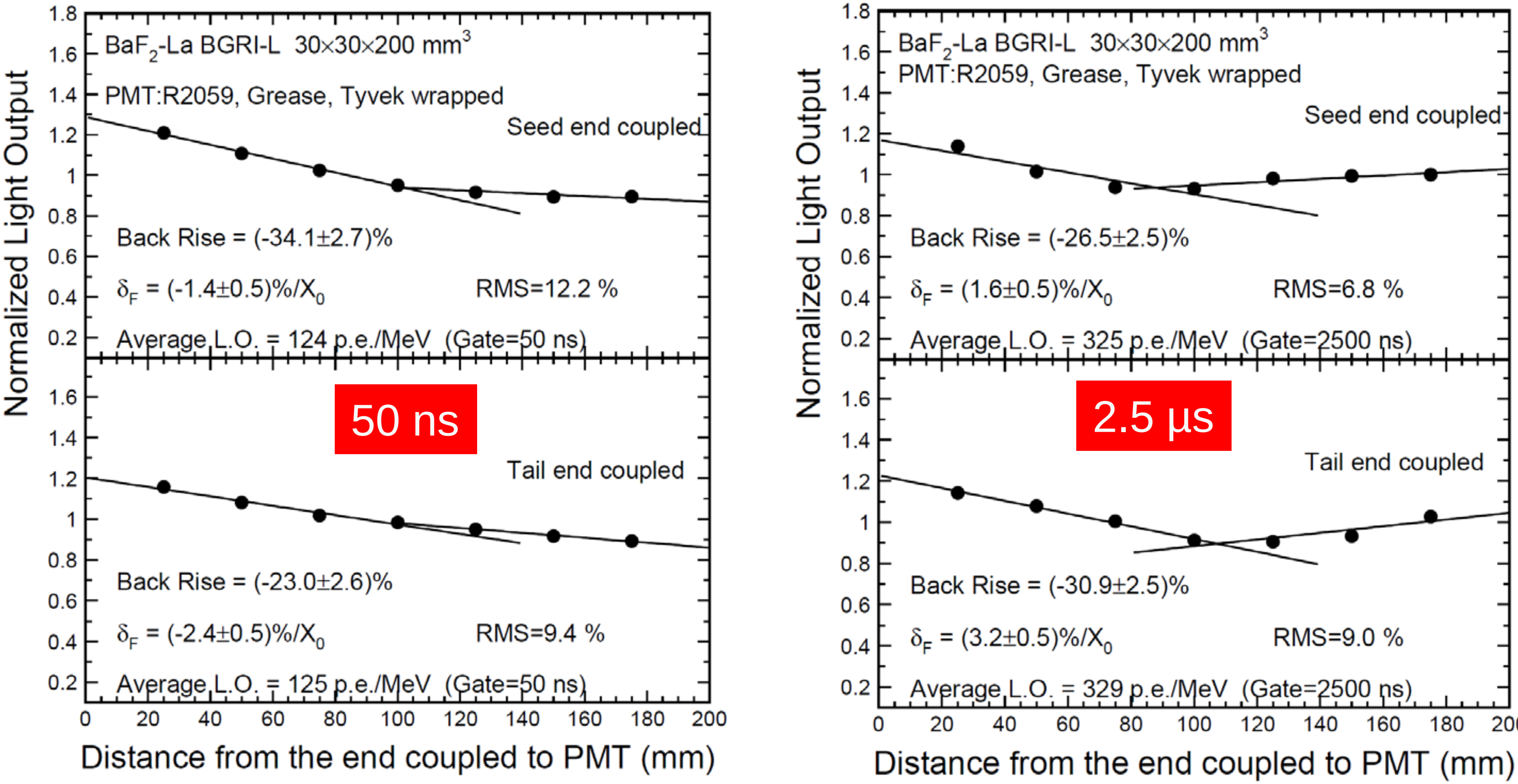
Transverse Transmittance: BGRI BaF_2:La



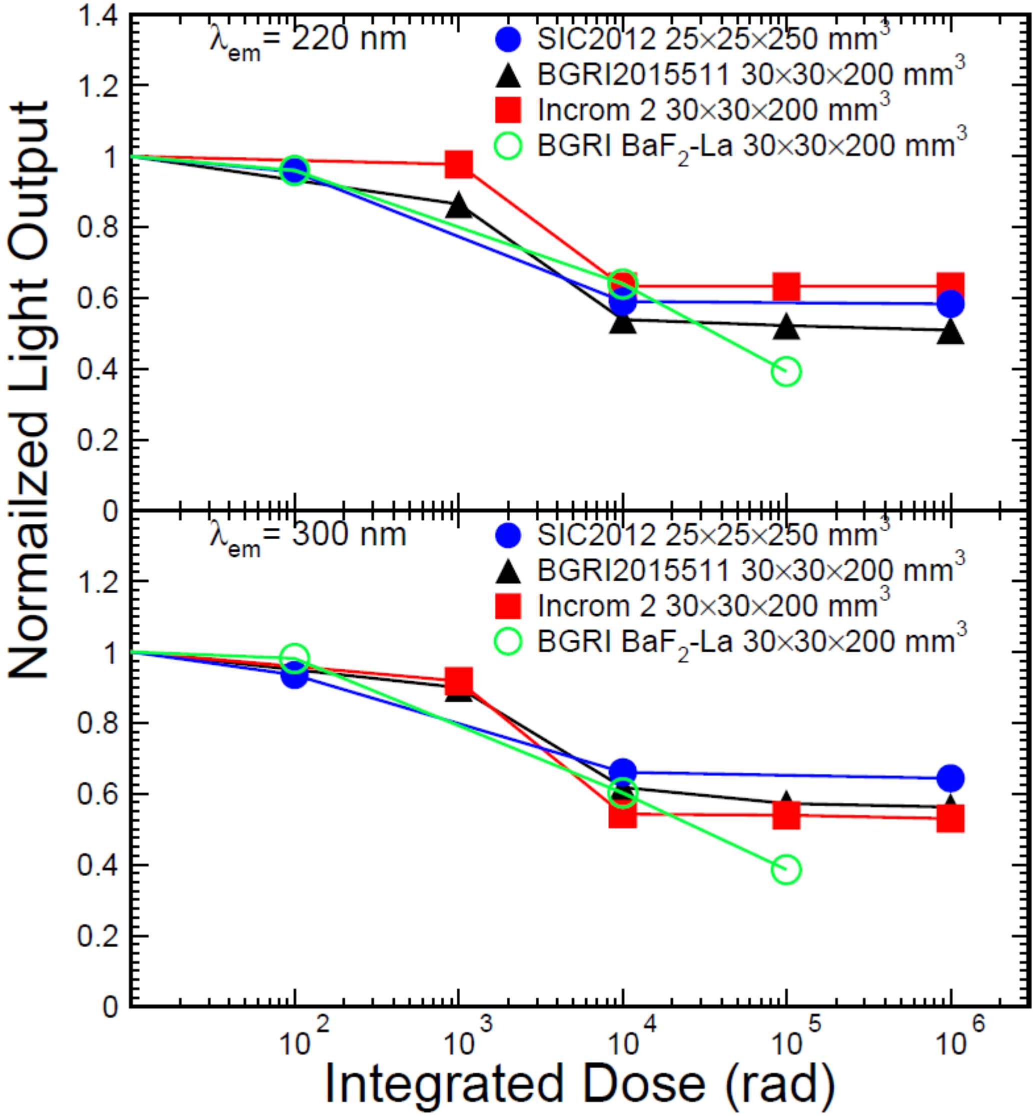
Consistent absorption bands observed along the crystal length

LRU: BGRI BaF_2:La

Good LRU for both fast and slow observed in the BGRI long sample



BaF_2:La: Radiation Damage



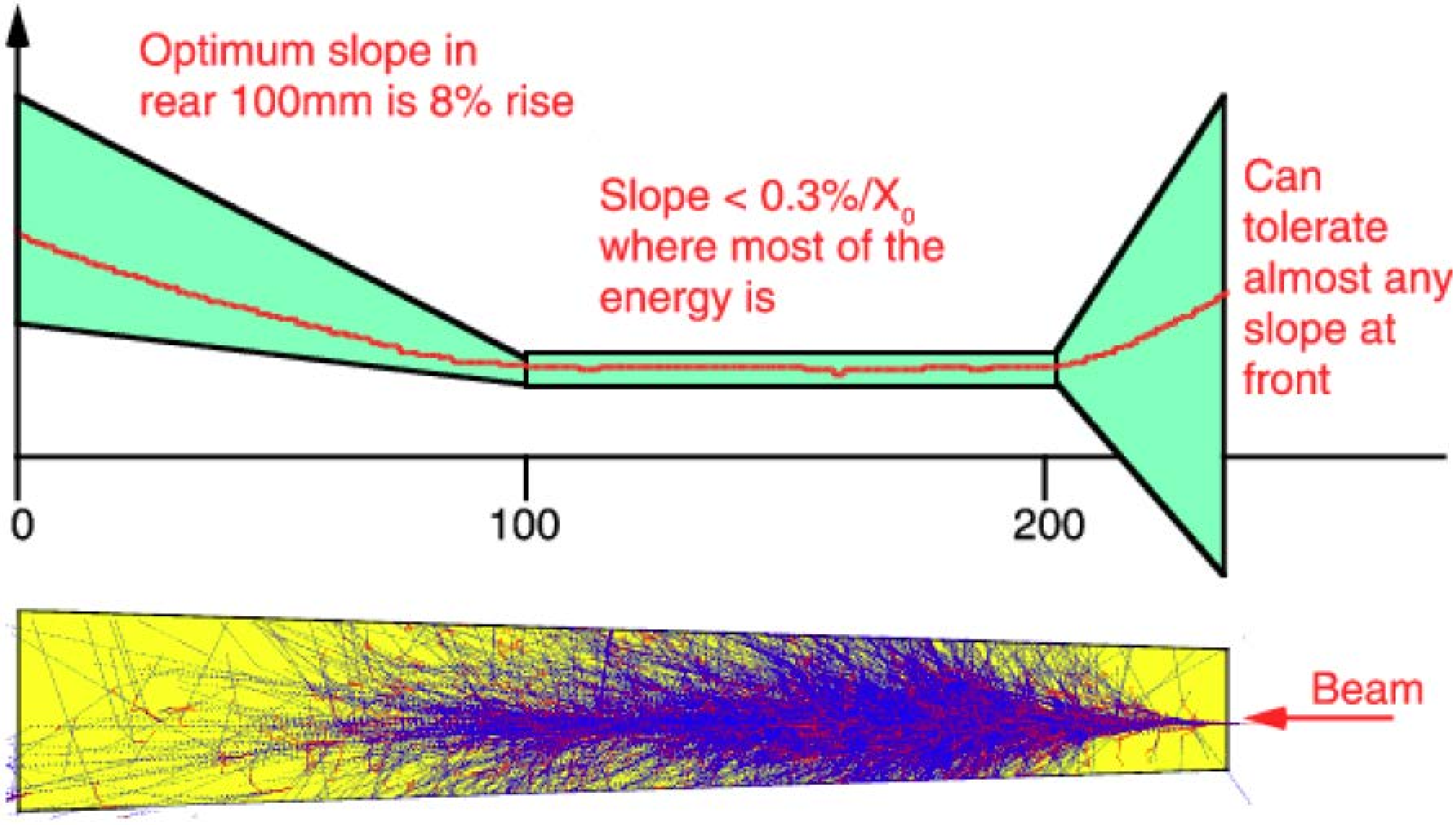
Compatible radiation hardness as un-doped samples up to 10 krad. Need optimization beyond 10 krad.

Summary

- Commercially available BaF_2 crystals provide sufficient fast light with sub-ns decay time and excellent radiation hardness up to 120 Mrad. They promise a very fast and stable calorimeter in a severe radiation environment.
- The issue of BaF_2 crystal's slow scintillation light with 600 ns decay time can be handled by several approaches: photo-detector, crystal and electronics. Dual readout is an interesting approach.
- Work on La doping in BaF_2 crystals started last Fall. The results show that the overall F/S ratio is increased from 1:5 to 1:2 in 20 cm long BaF_2:La samples with good light response uniformity. Their radiation hardness, however, need further investigation.
- It is important that research along this direction is supported by the Mu2e project.

CMS LRU Spec for Tapered Crystal

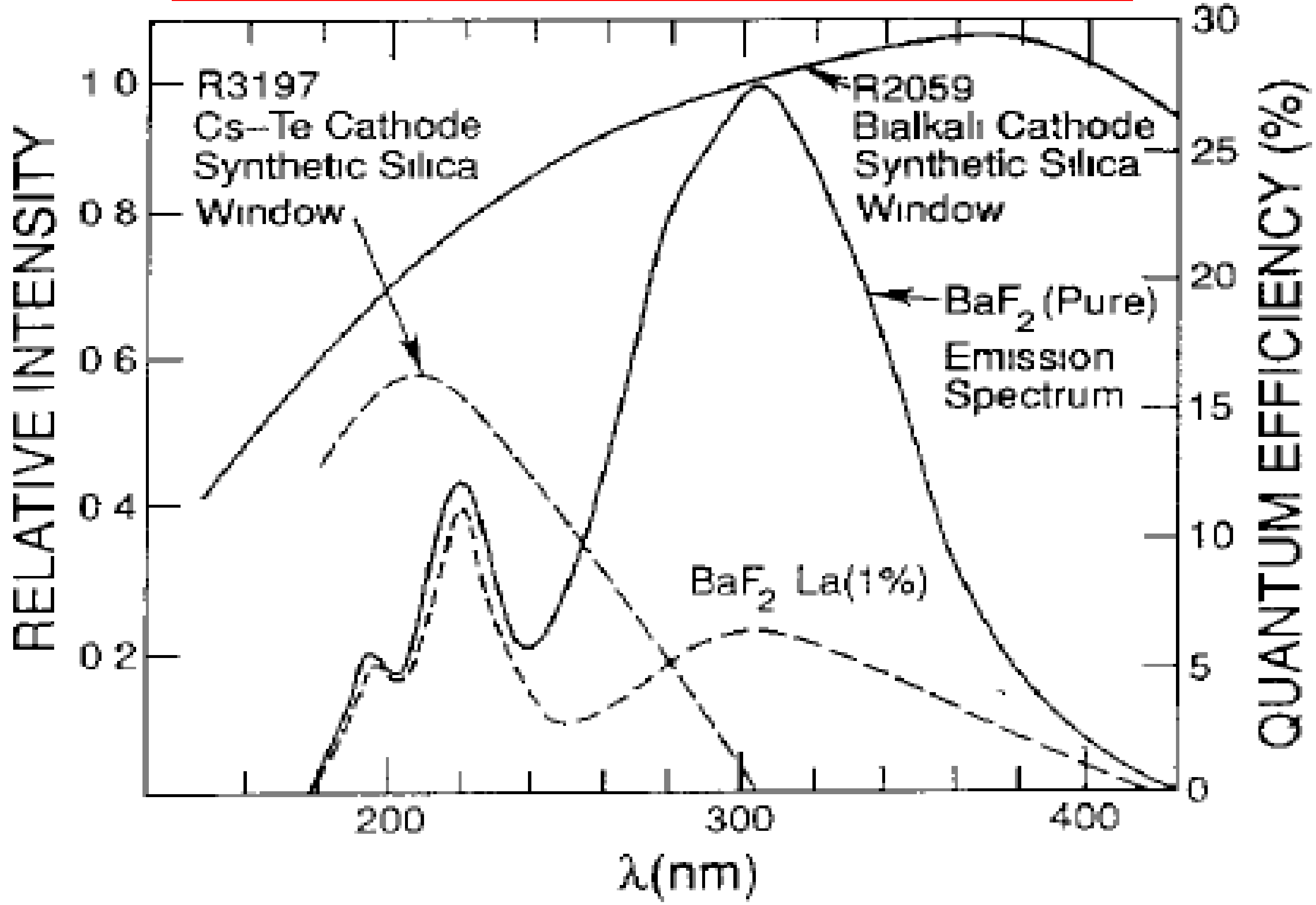
D. Graham & C. Seez, CMS Note 1996-002



BaF_2 Scintillation Light

Fast at 220 nm: 0.9 ns, Slow at 300 nm: 600 ns

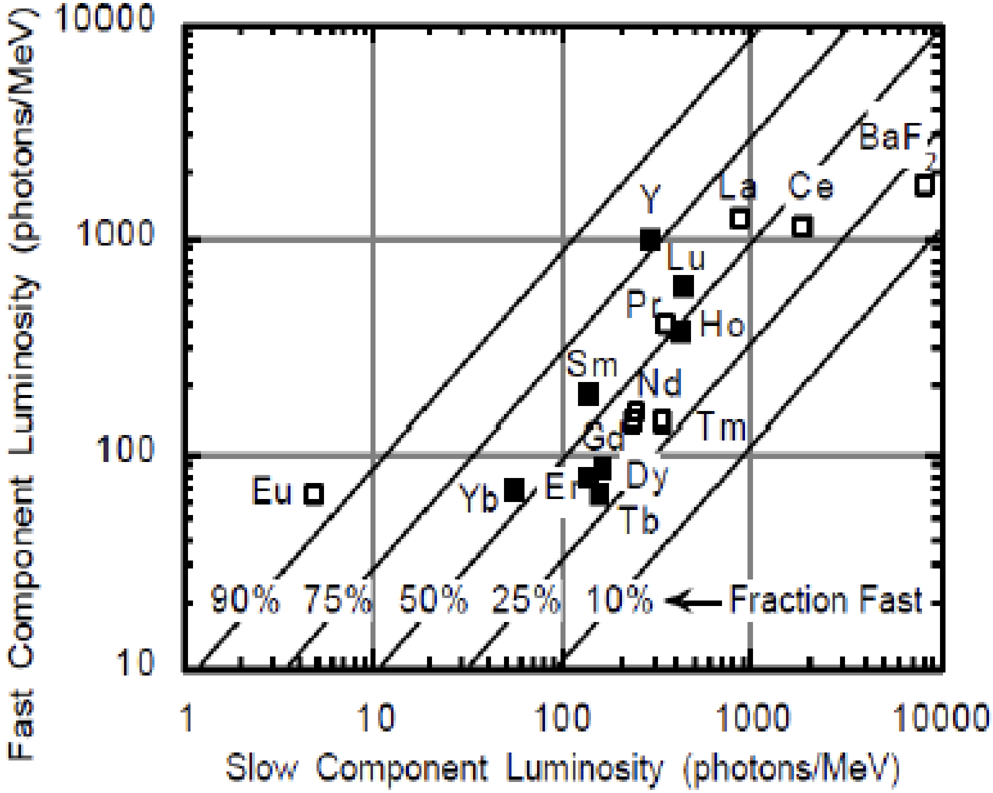
R. Y. Zhu, "On Quality Requirements to the Barium Fluoride-Crystals," *Nucl Instrum Meth A,* vol. 340, pp. 442-457, Mar 8 1994

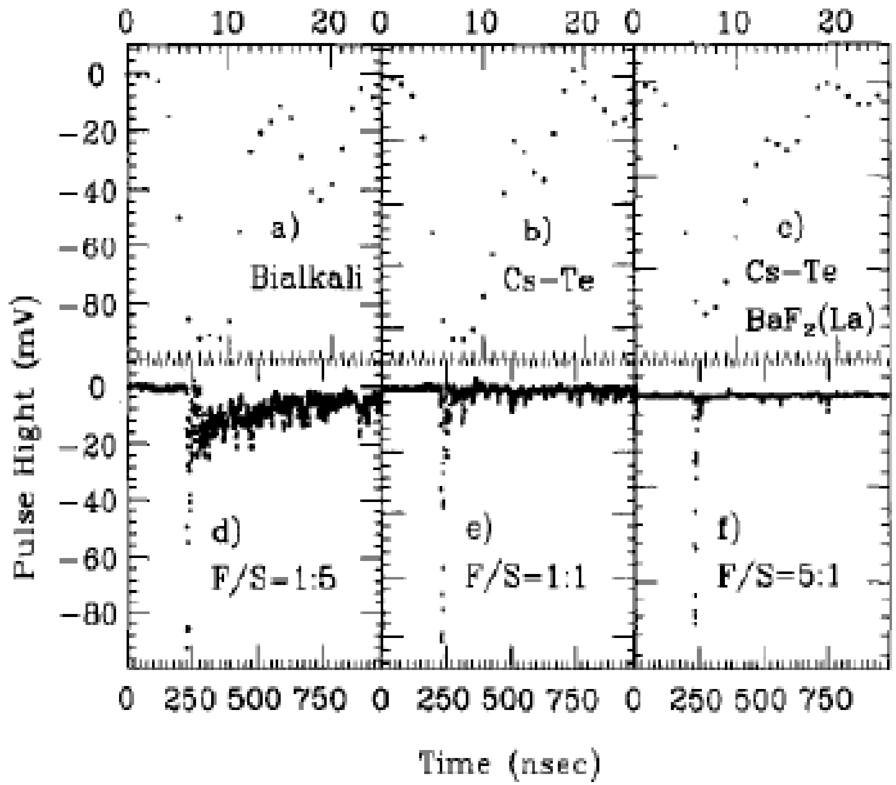


Slow Suppression by Doping and/or Readout

Y or La doping is effective in improving the F/S ratio for $Ba_{0.9}R_{0.1}F_2$ powders

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.





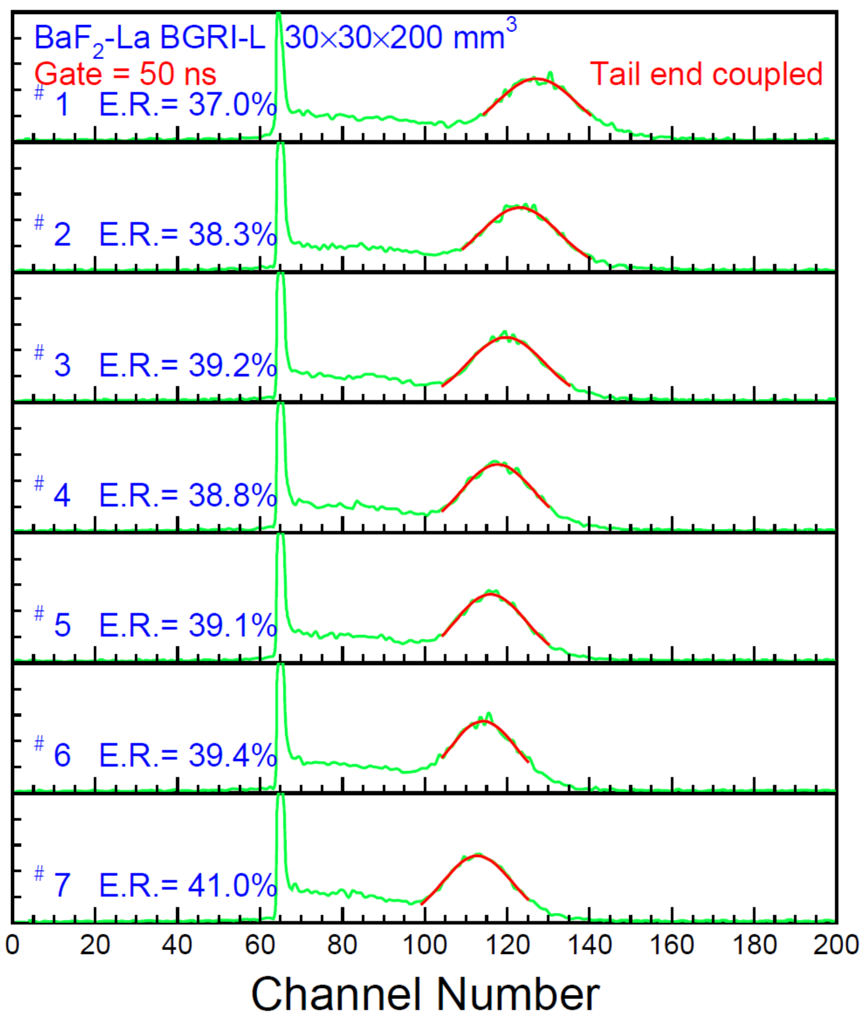
Solar blind cathode is also effective. R&D on doping will be carried out in 2015.

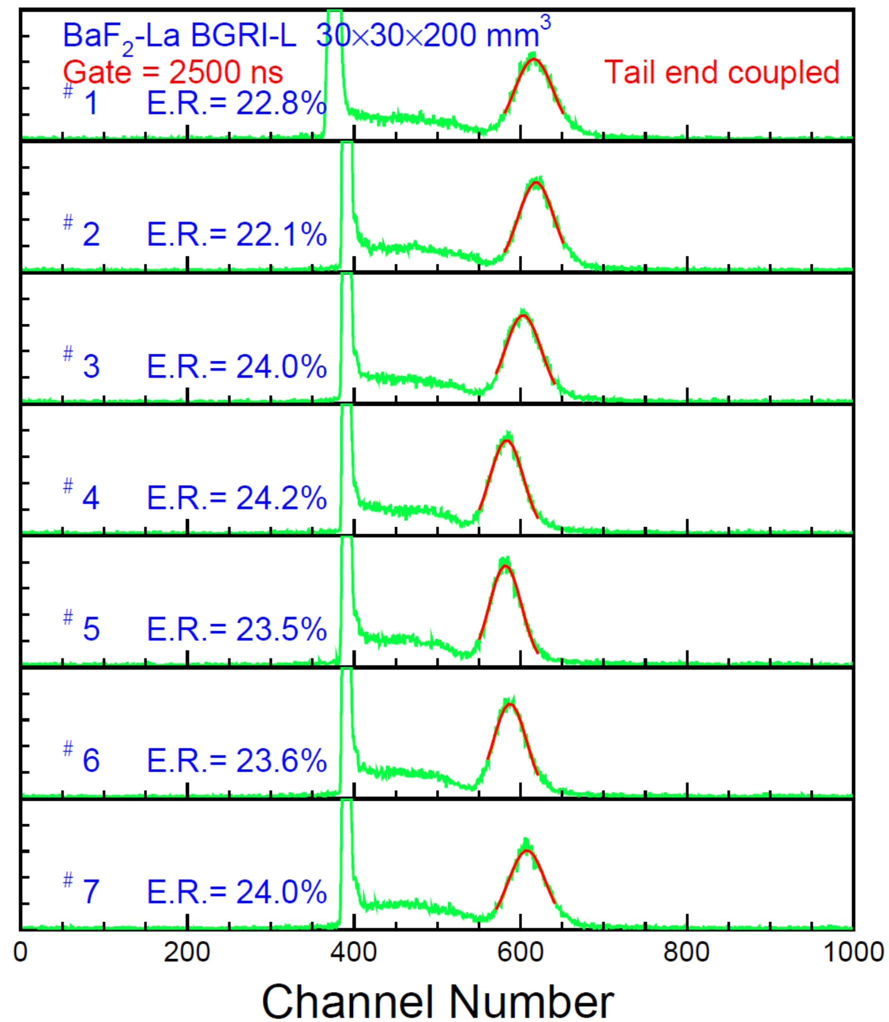
Z. Y. Wei, R. Y. Zhu, H. Newman, and Z. W. Yin, "Light Yield and Surface-Treatment of Barium Fluoride-Crystals," *Nucl Instrum Meth B*, vol. 61, pp. 61-66, Jul 1991.

PHS: BGRI BaF_2:La

50 ns

2.5 μs

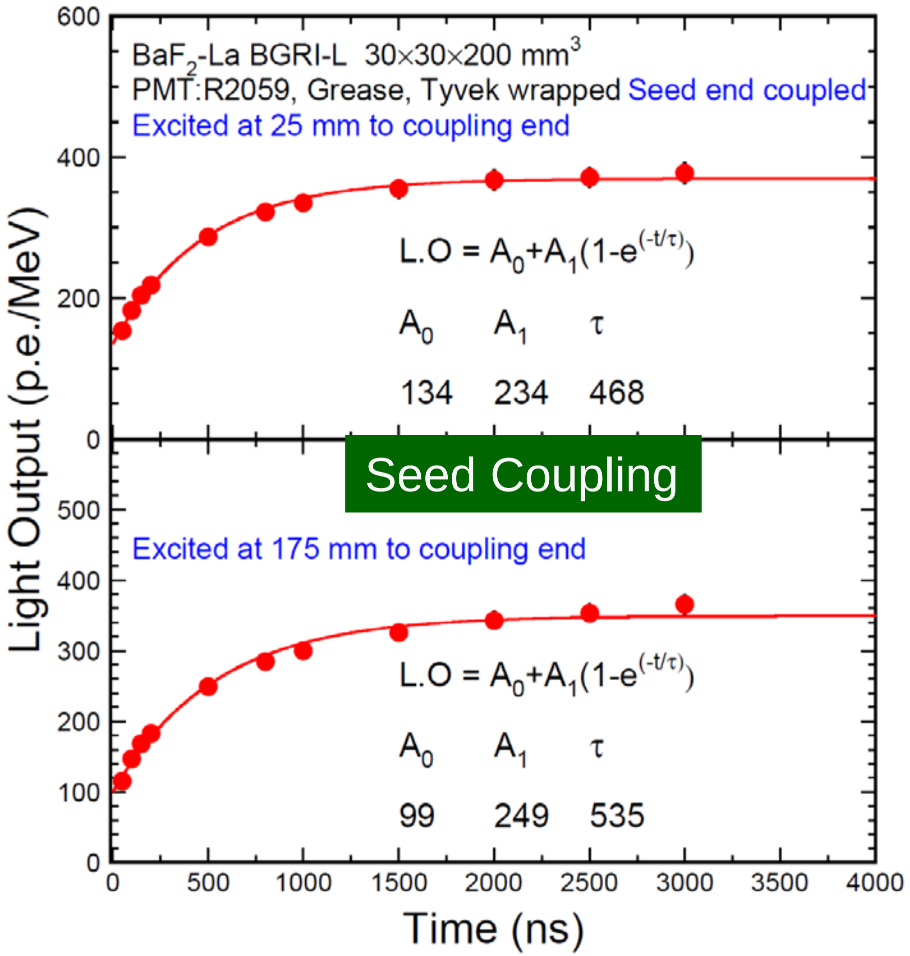


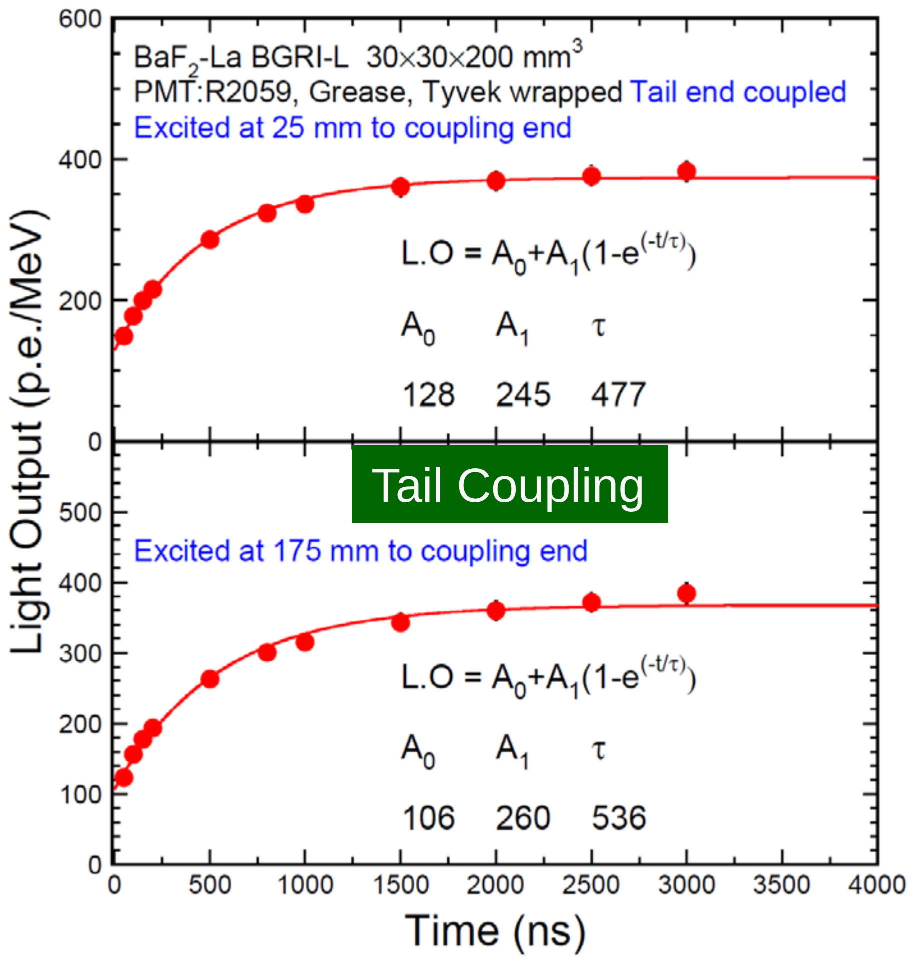


Decay Kinetics: BGRI BaF_2:La

F/S = 57.3-39.8%

F/S = 52.2-40.1%





Consist F/S ratio after switching the coupling end

Radiation Damage: BGRI BaF_2:La

This La doped BaF_2 crystal is radiation hard up to 10 krad