Mu2e CD-2 Review
475.07.02 Crystals

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Introduction

- Because of four times increase of the Lu_2O_3 price in the last four years, the price of LYSO crystals reaches $40/cc in the market, which is prohibitive for the Mu2e experiment.
- Using the sub-ns fast scintillation component, a very fast BaF_2 crystal calorimeter is base-lined to face the challenge of high event rate expected by the Mu2e experiment.
- Historically, a BaF_2 crystal calorimeter was built by the TAPS experiment at Germany, which provides an energy resolution of 0.79%/0.59% stochastic term and 1.8%/1.9% constant term for the fast/slow component with R2059 PMT readout.
  R. Novotny, Nucl. Phs. 61B (1998)137-142.
- The intrinsic slow component of 600 ns decay time, however, is to be suppressed.

Fast Inorganic Crystal Scintillators for HEP

	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

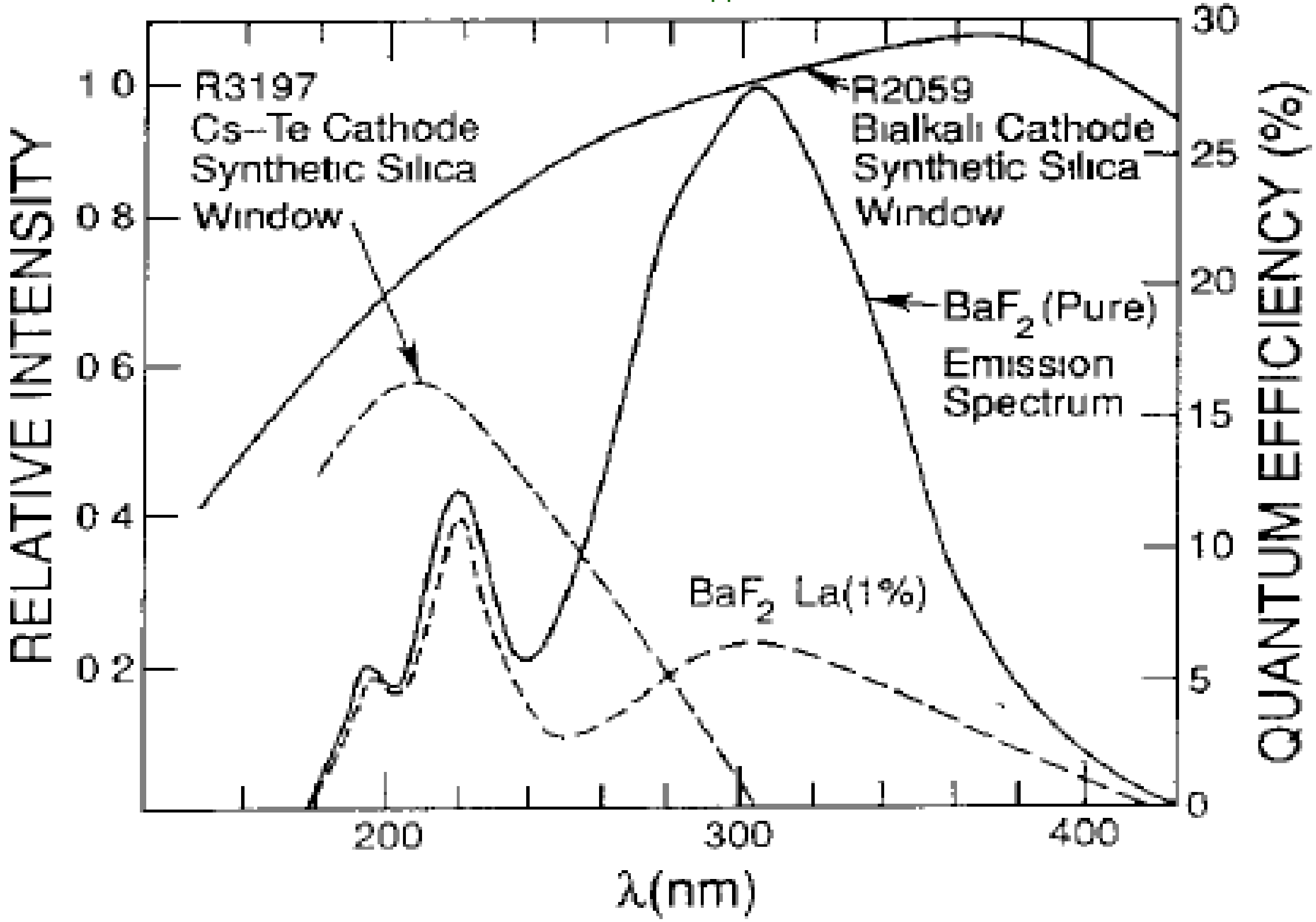
1. http://www.detectors.saint-gobain.com/Plastic-Scintillator.aspx

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

BaF_2 Scintillation Light

Fast at 220 nm: 0.6 ns, Slow at 300 nm: 600 ns

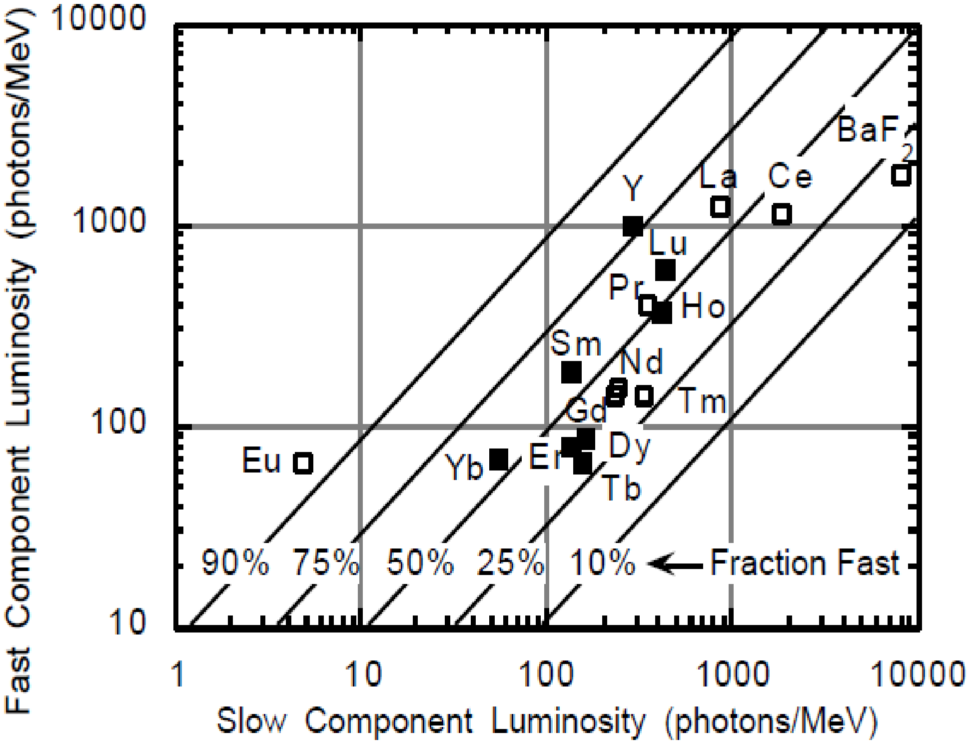
R. Y. Zhu, "On Quality Requirements to the Barium Fluoride-Crystals," *Nucl Instrum Meth A,* vol. 340, pp. 442-457, Mar 8 1994

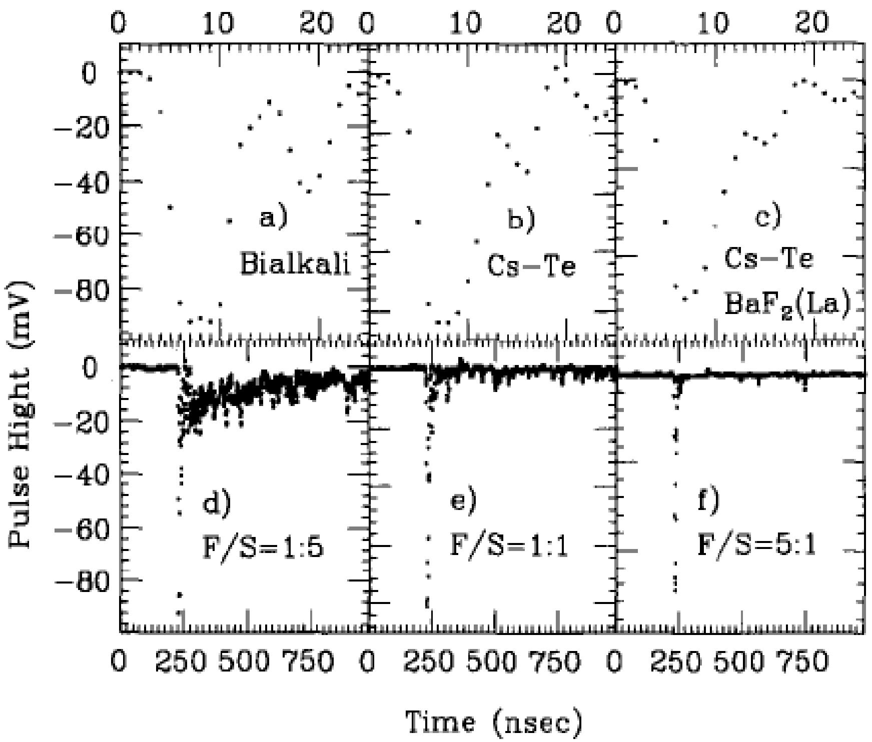


Slow Suppression by Doping and Readout

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.

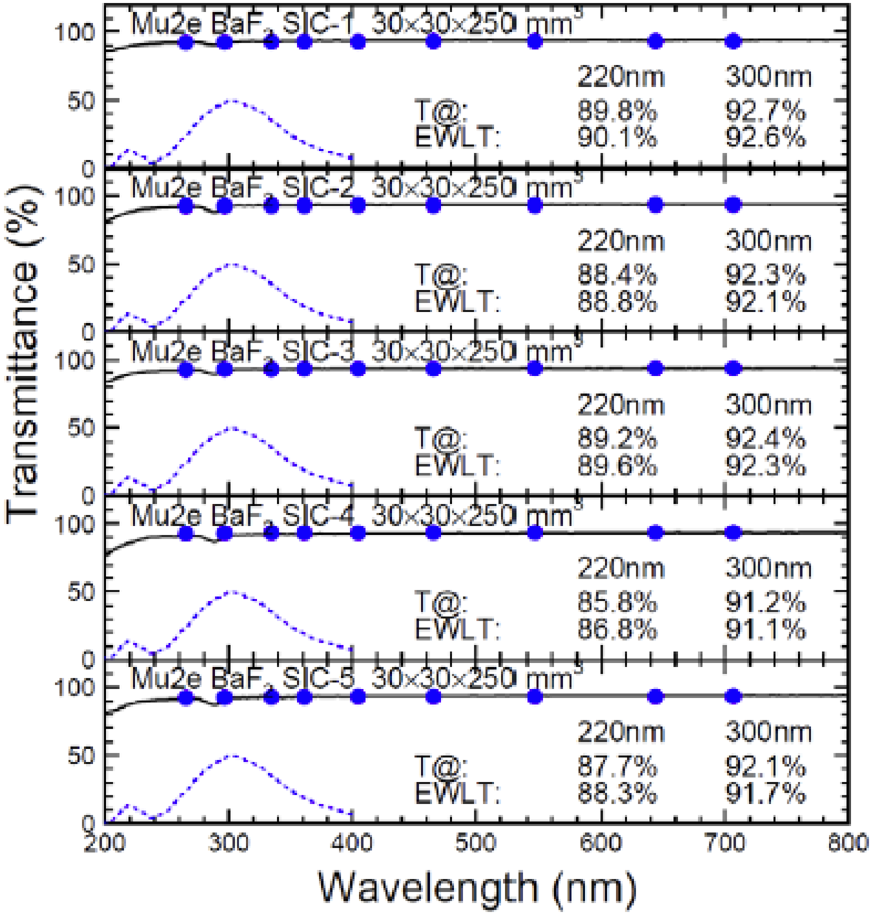
Twenty BaF_2 Crystals from SIC

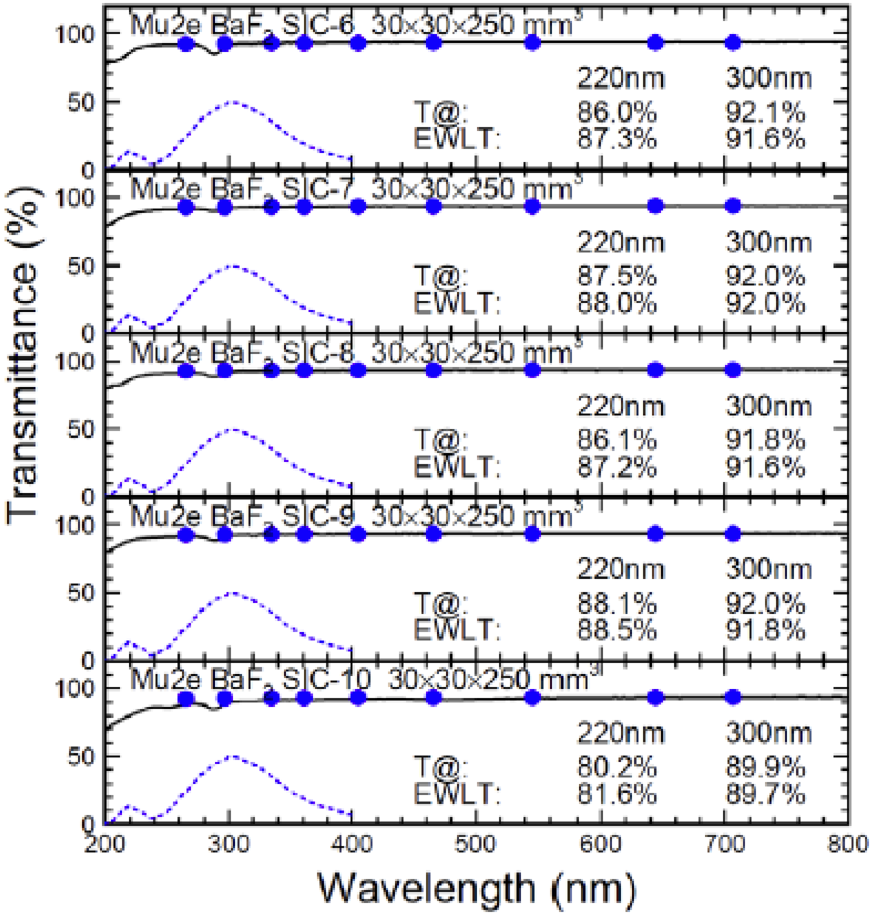
Sample ID	Received Date	Dimension (mm^3)	Total #	Polish
SIC-1,20	4/25/2014	30× 30 × 250	20	Six surfaces

Properties measured: longitudinal transmittance, FWHM resolution for 511 keV γ-rays, decay kinetics and light response uniformity.

Longitudinal Transmittance (LT)

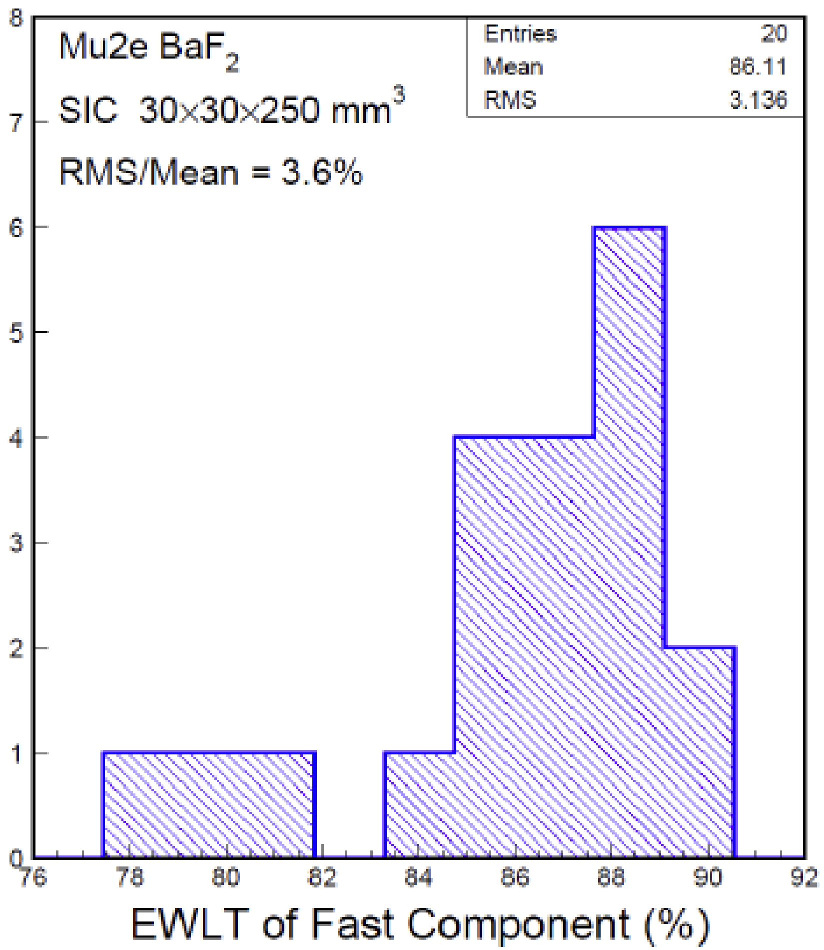
Good transmittance approaching theoretical limit

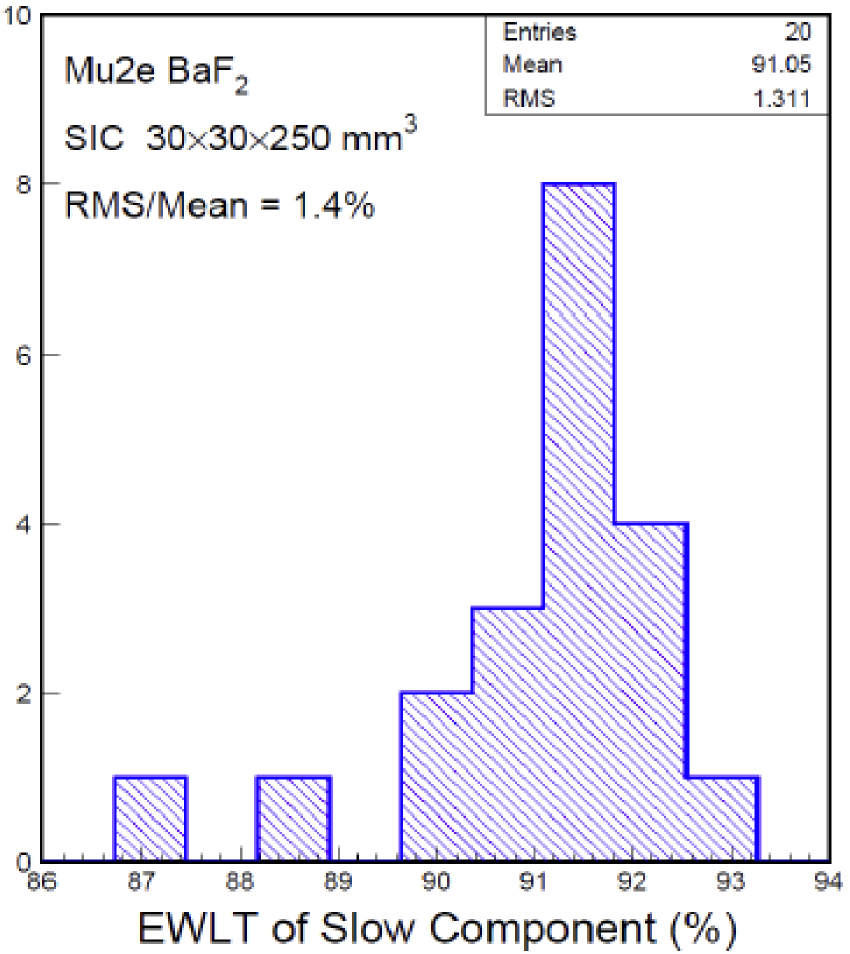




Summary: Emission Weighted LT

Consistency of 3.6% and 1.4% respectively for fast and slow component

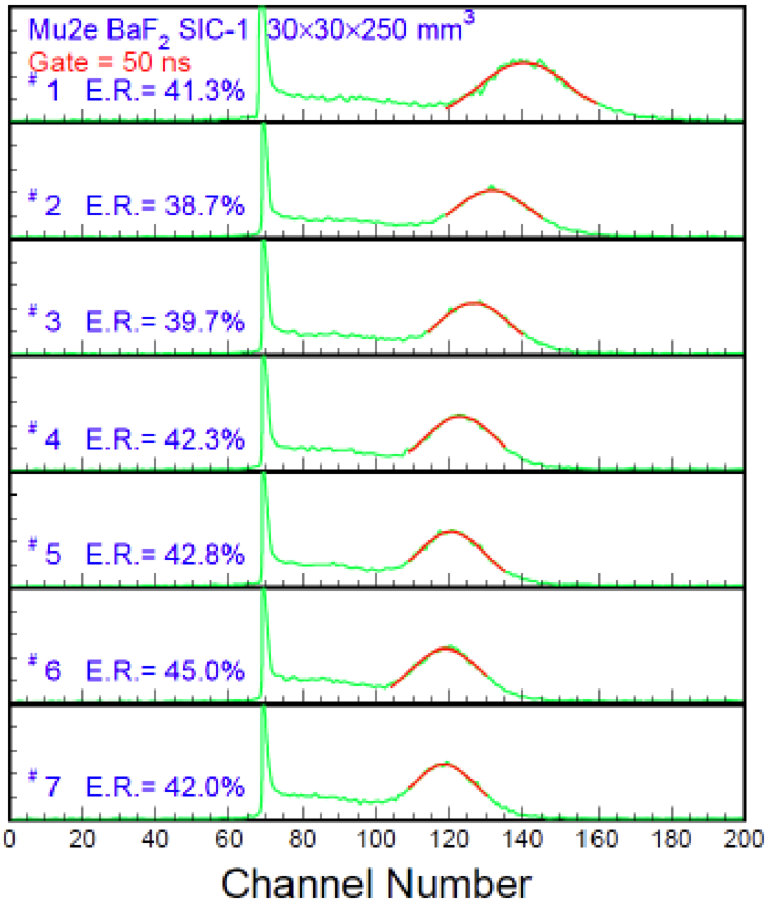




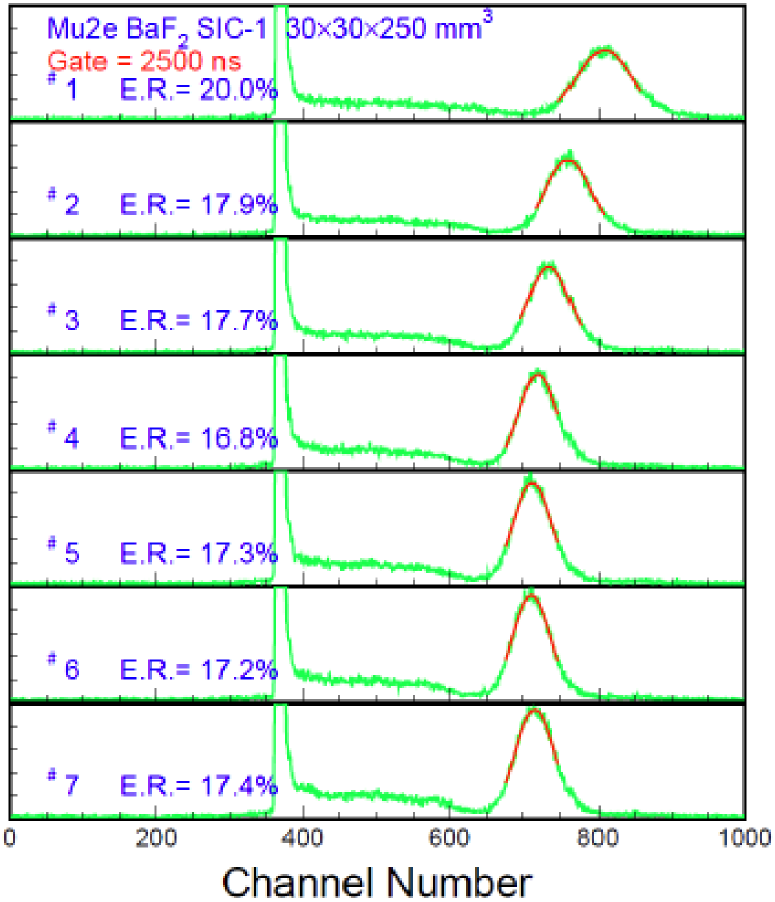
Pulse Height Spectra with ^{22}Na Source

2.5 μs gate sees 2.3 times better resolution than 50 ns gate

Average ER = 41.7% with 50 ns gate

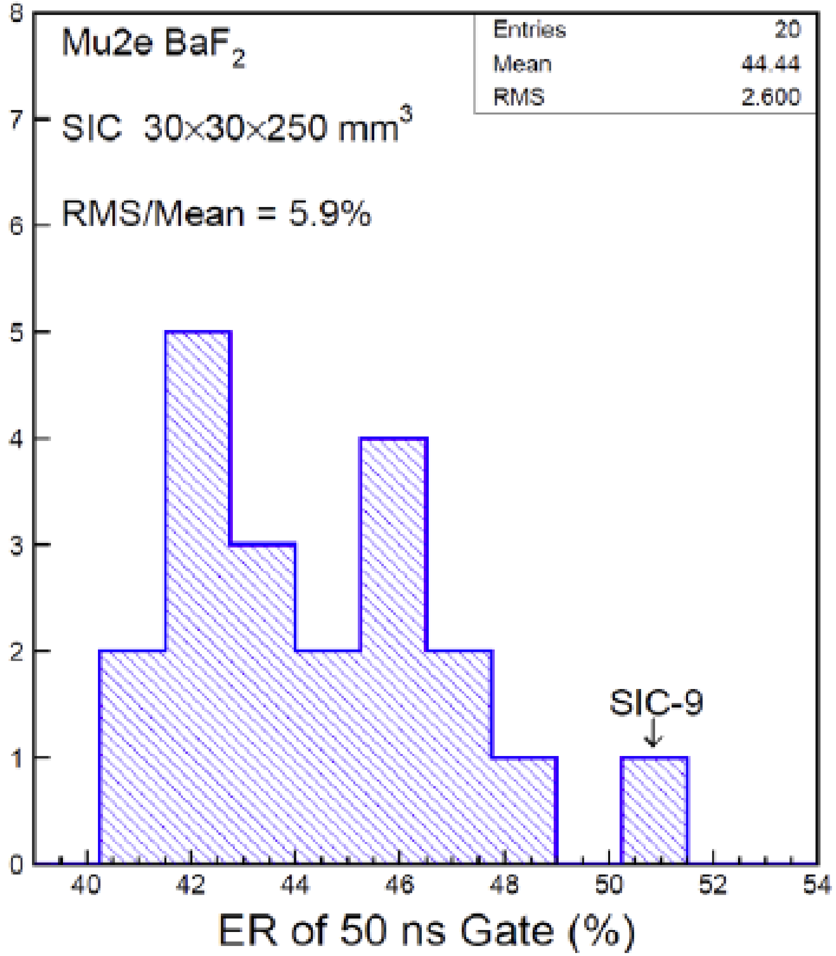


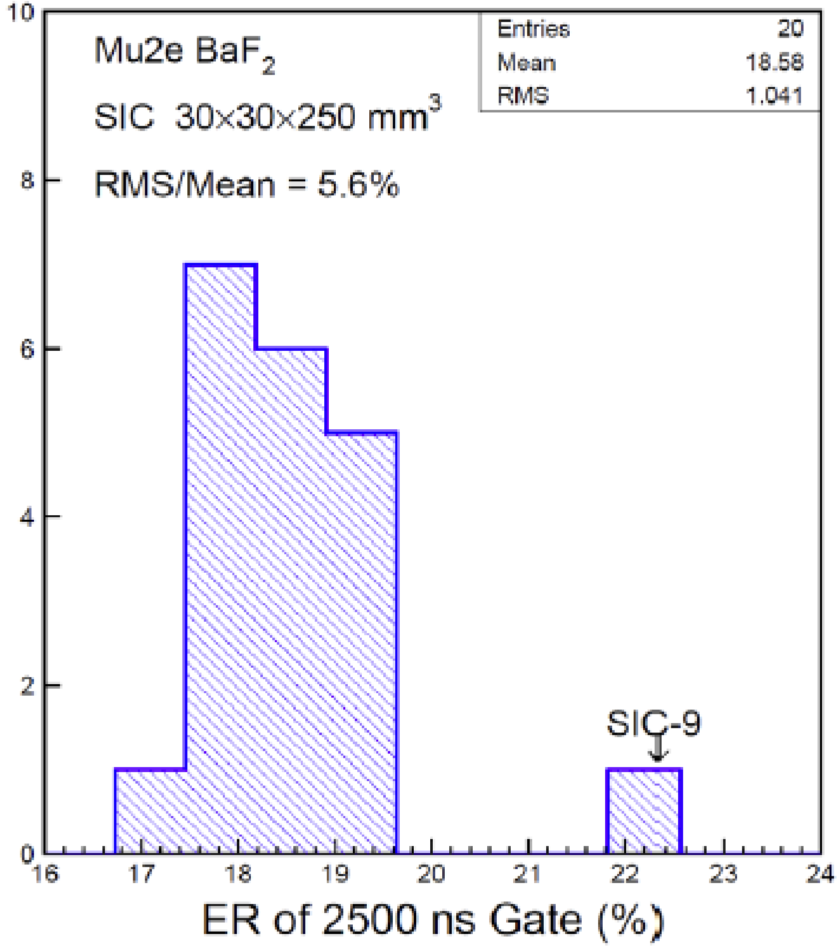
Average ER = 17.8% with 2.5 μs gate



Summary: FWHM Energy Resolution

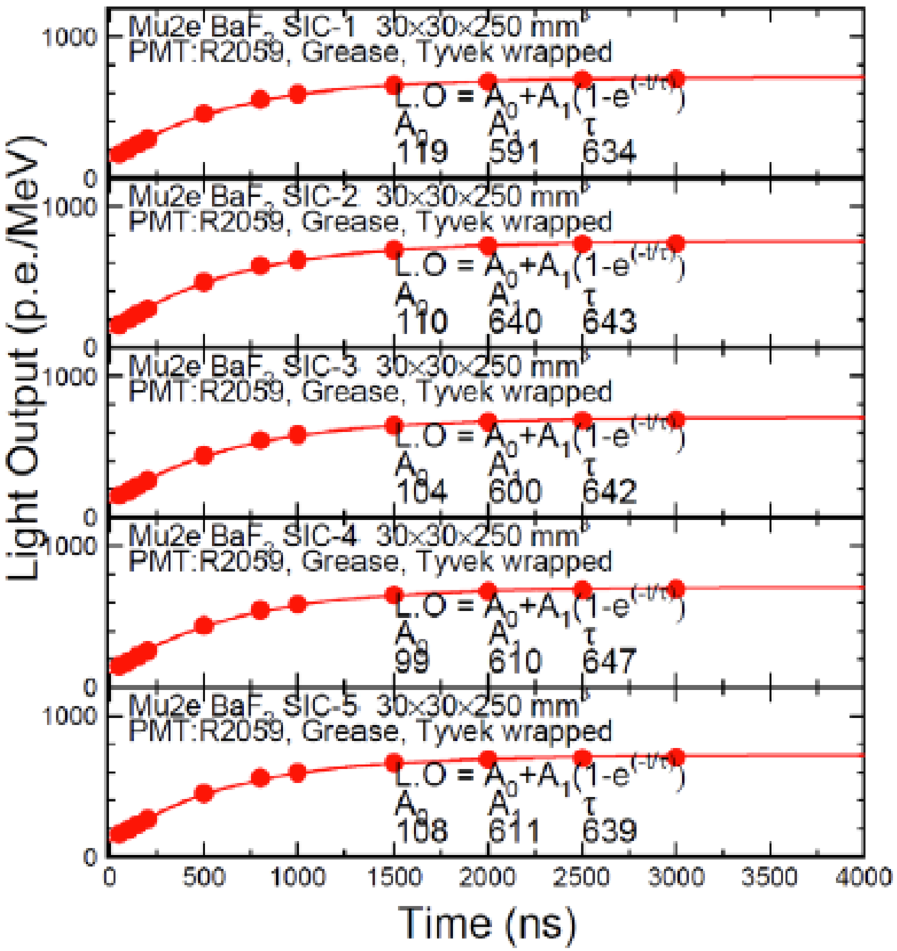
Consistency of 5.9% and 5.6% respectively for 50 ns and 2.5 μs gate

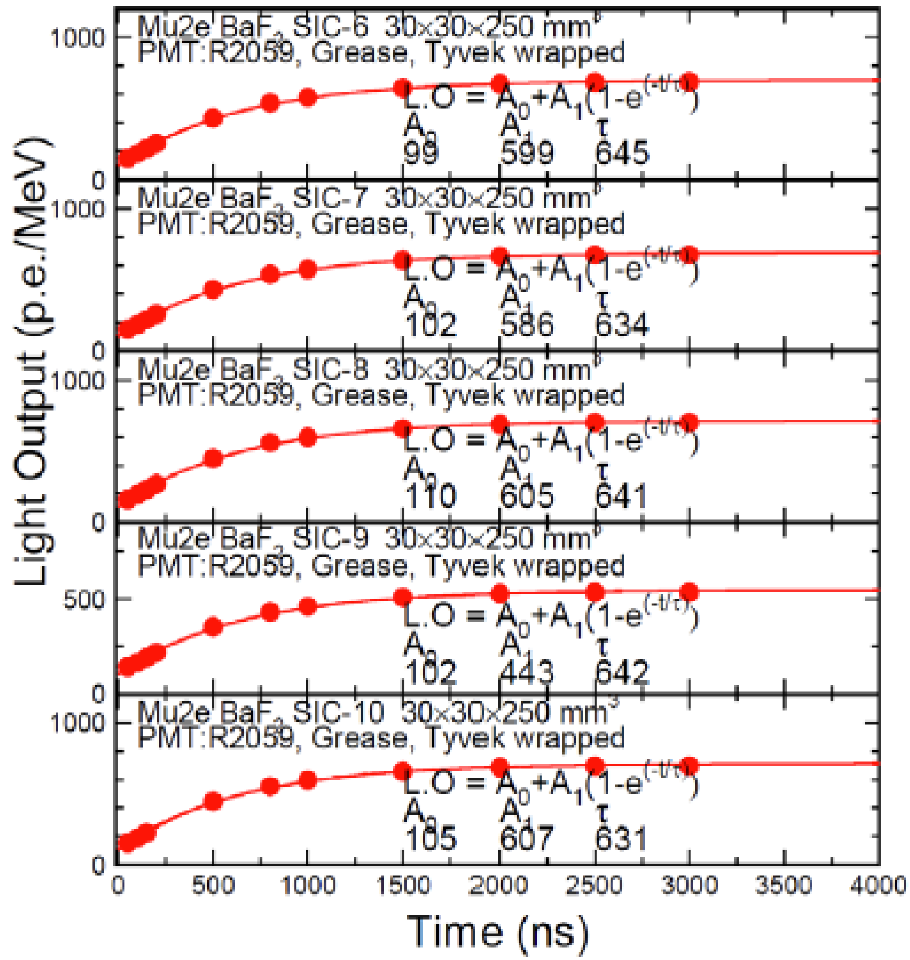




Decay Kinetics for BaF_2 Wrapped with Tyvek

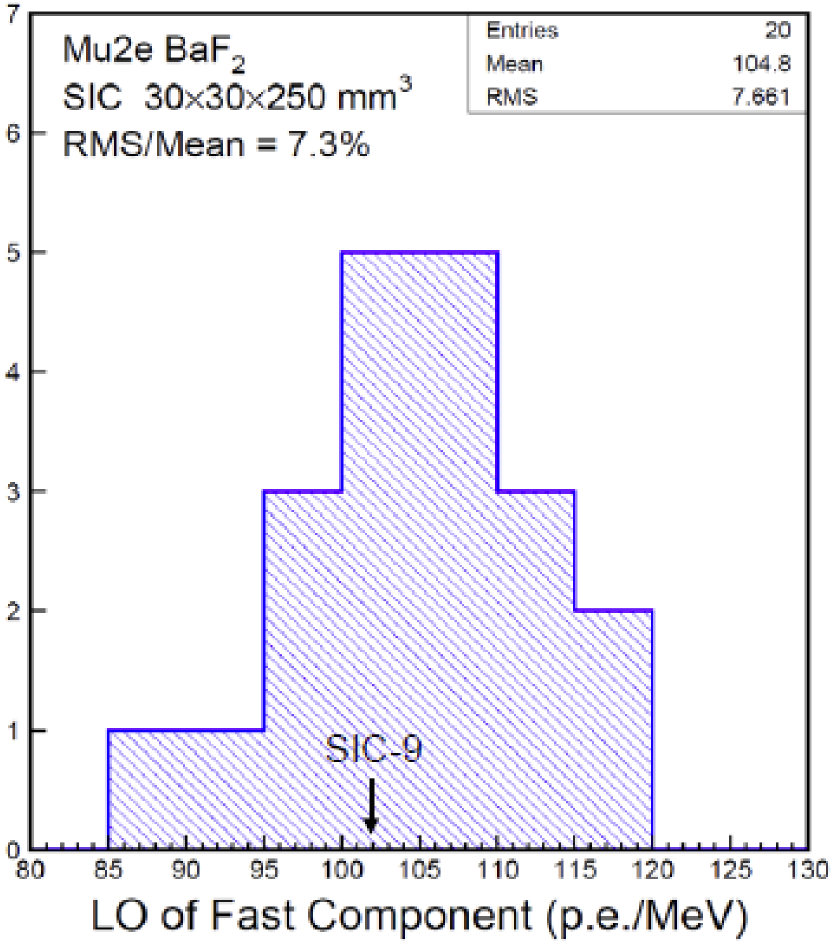
Consistent fast and slow scintillation component observed

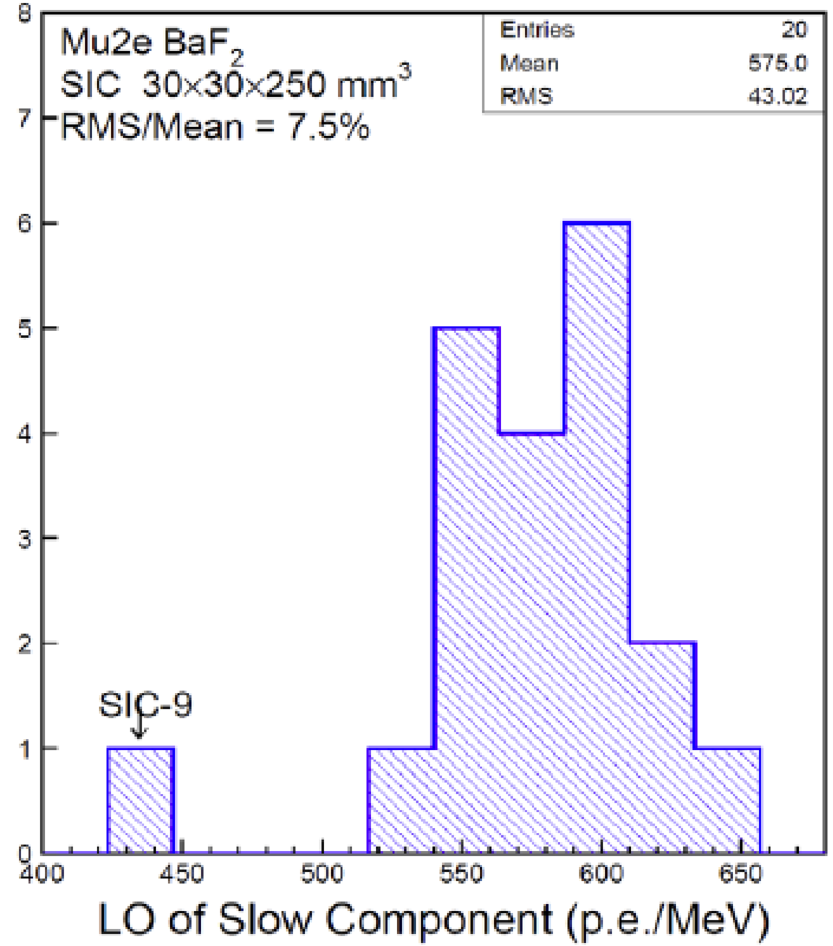




Summary of Fast and Total Light Output

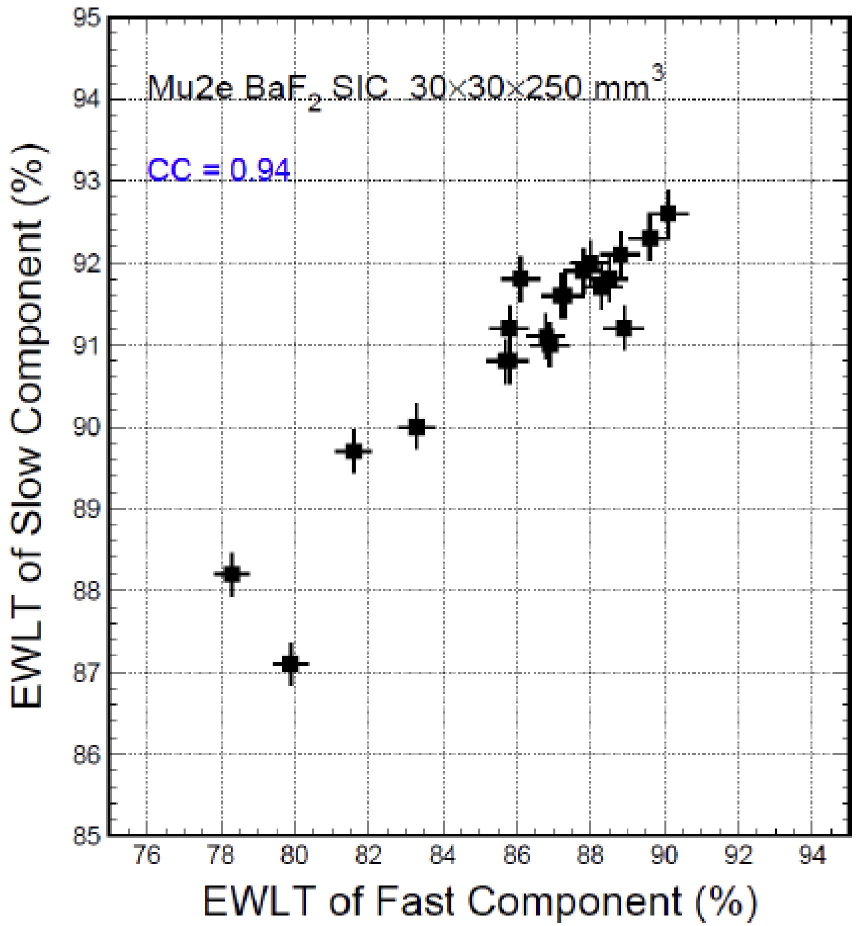
7.5% consistency observed

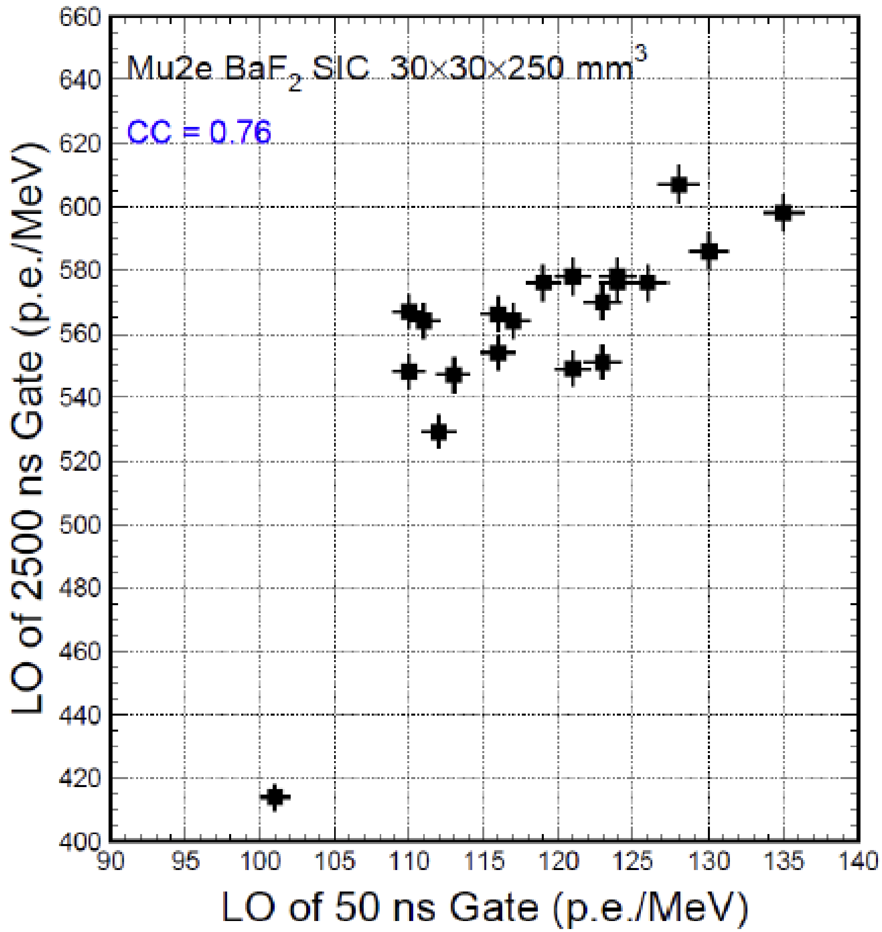




Correlations: Slow versus Fast Components

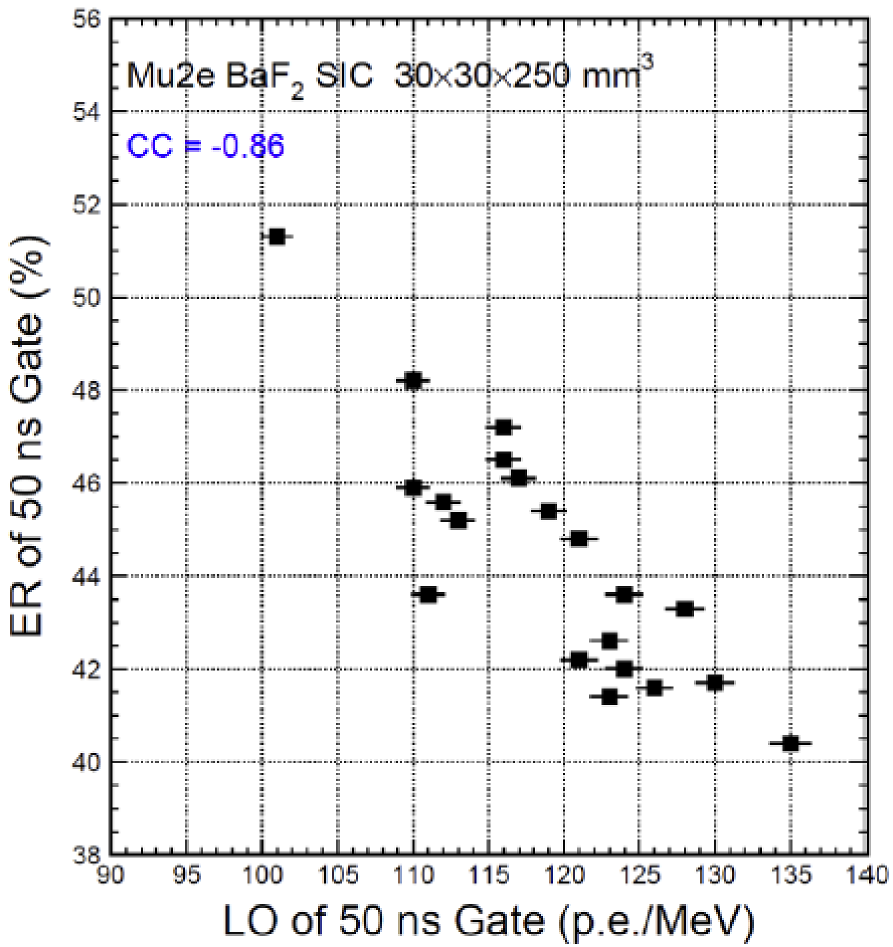
Positive correlations observed

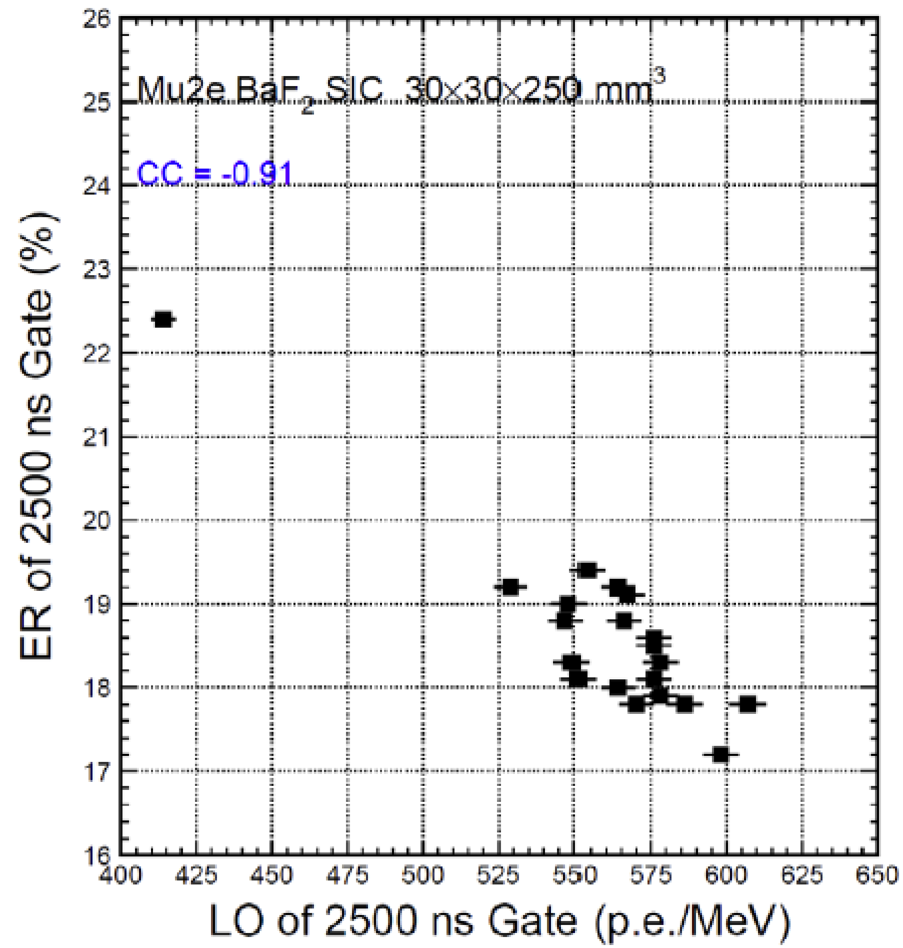




Correlations: Resolution versus LO

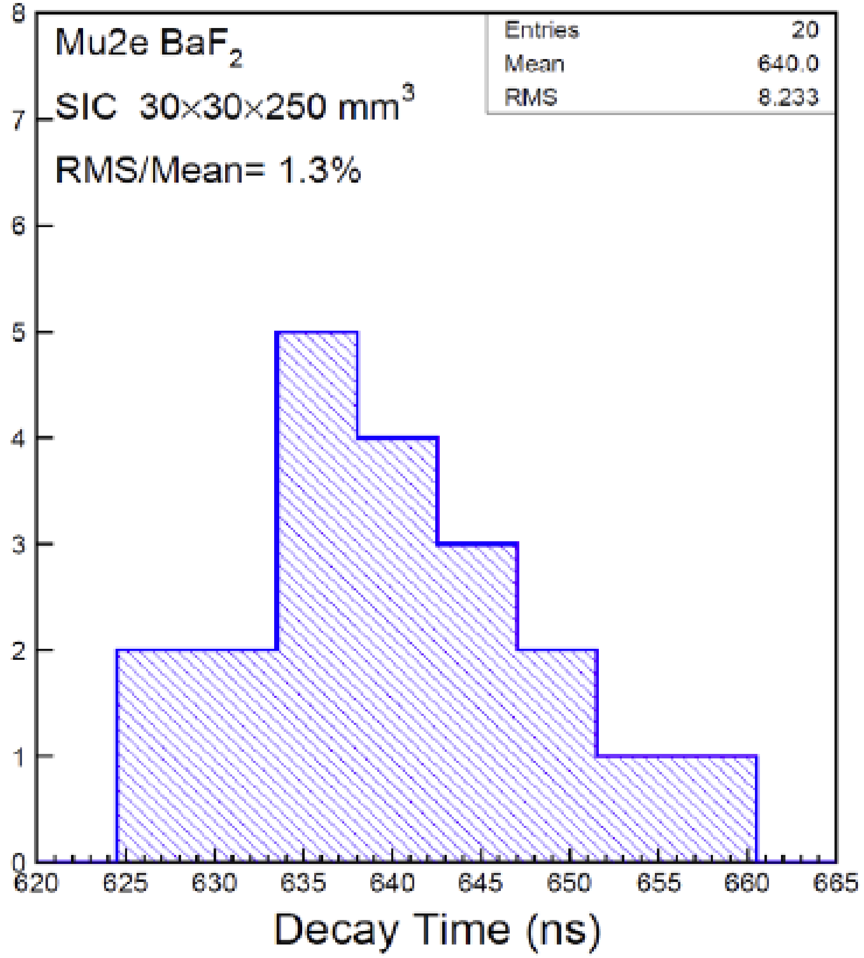
Negative correlations observed



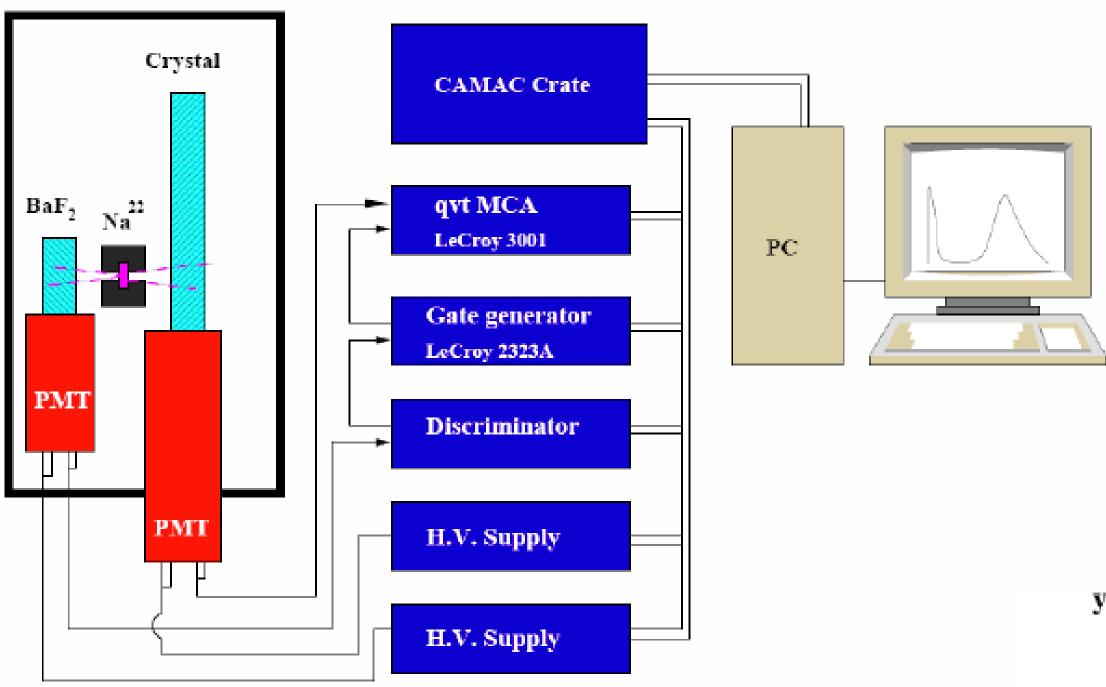


Summary: Decay Time of Slow Component

Consistency of 1.3% observed for decay time of the slow component



Light Response Uniformity Measurements

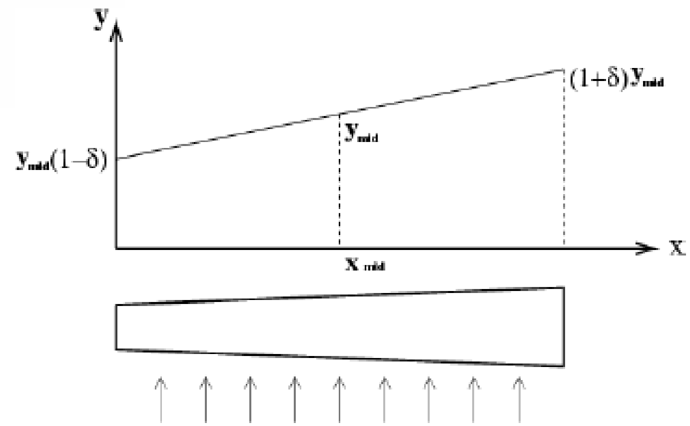


Crystals wrapped with two layers of Tyvek (2 x 150 μm)

One end coupled to

Hamamatsu R2059 PMT
With DC-200 grease coupling

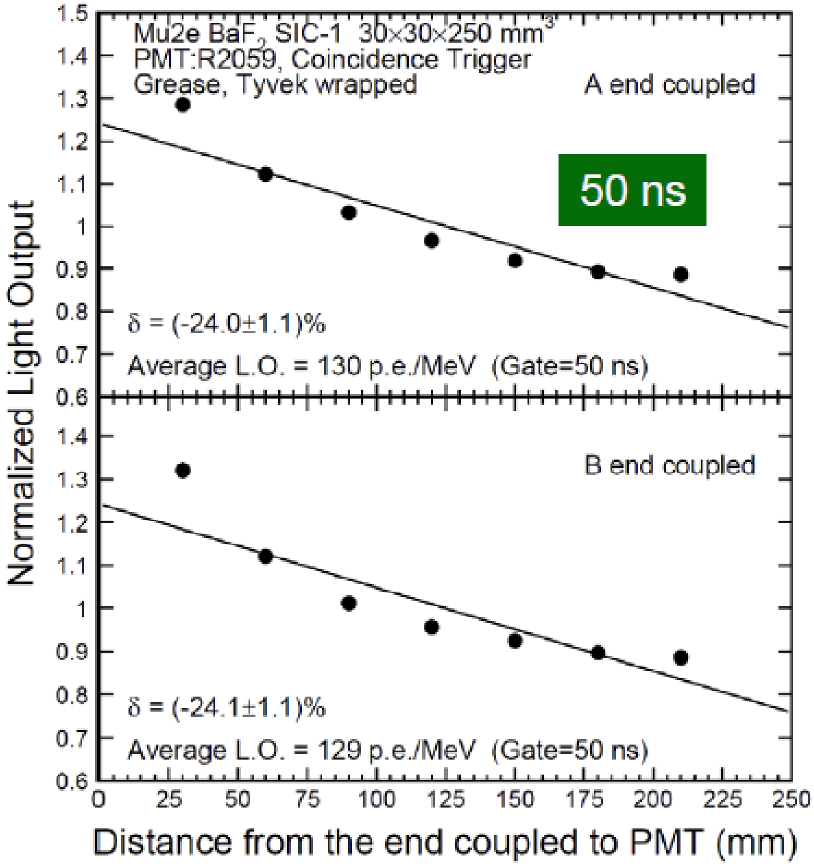
50 ns and 2.5 μs gate
Coincidence trigger from
a Na-22 source

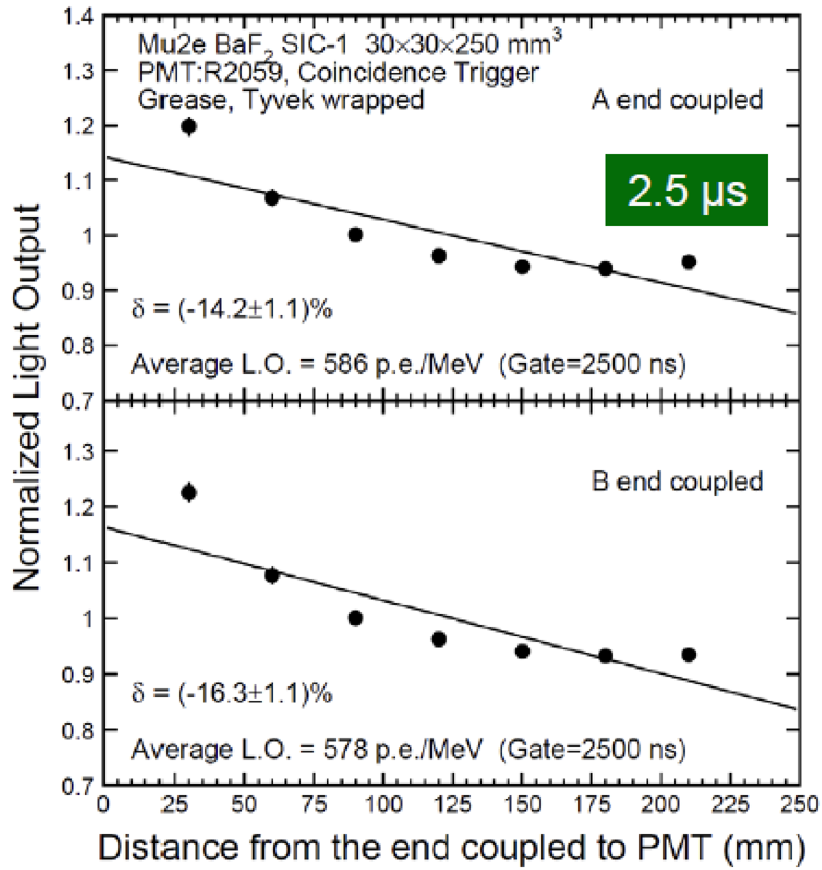


Light output and FWHM energy resolution (see report dated 6/25/14) are measured at seven points along the crystal

No Difference between Coupling Ends

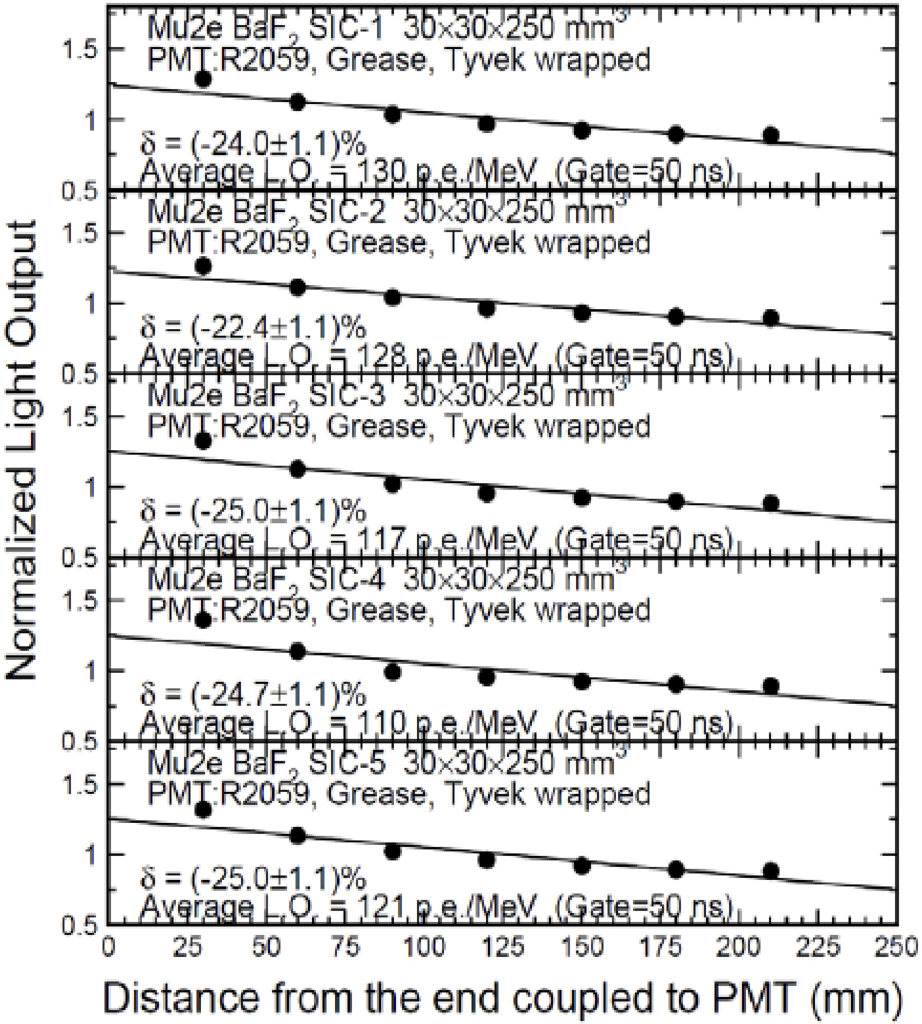
SIC1: No difference with alternative ends coupled to the PMT

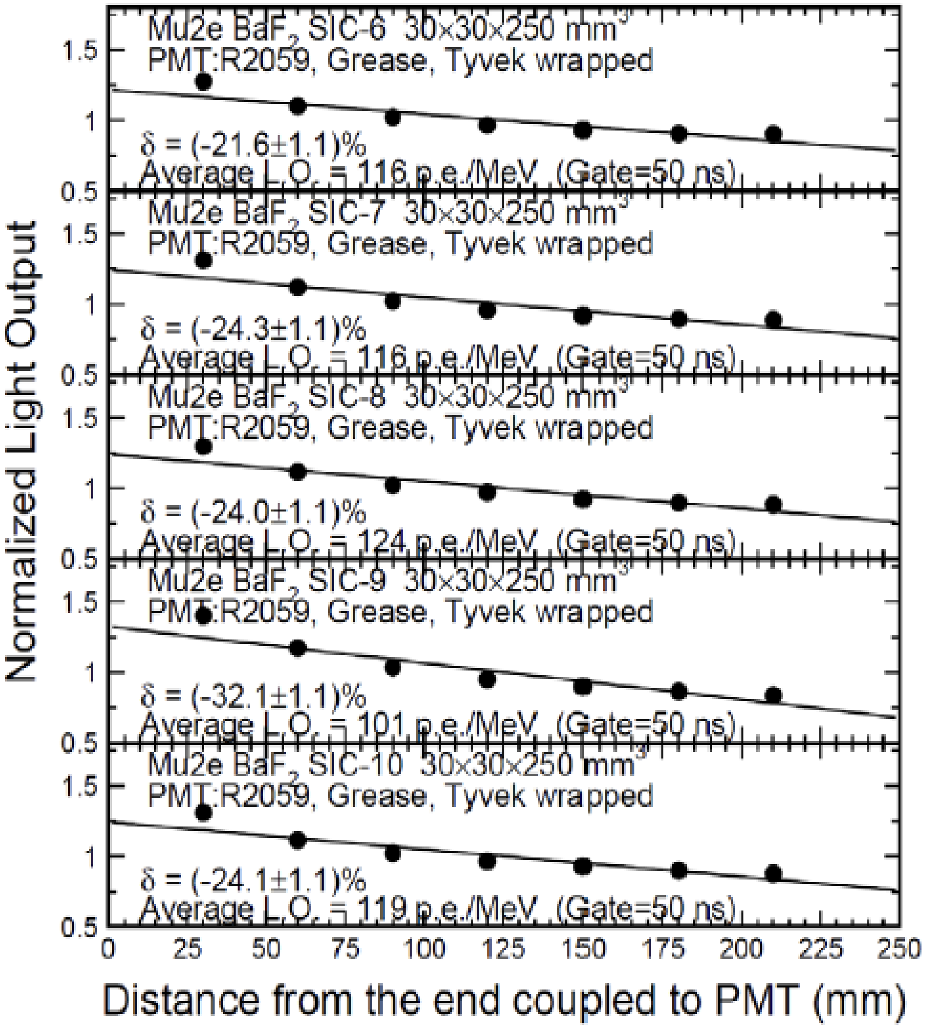




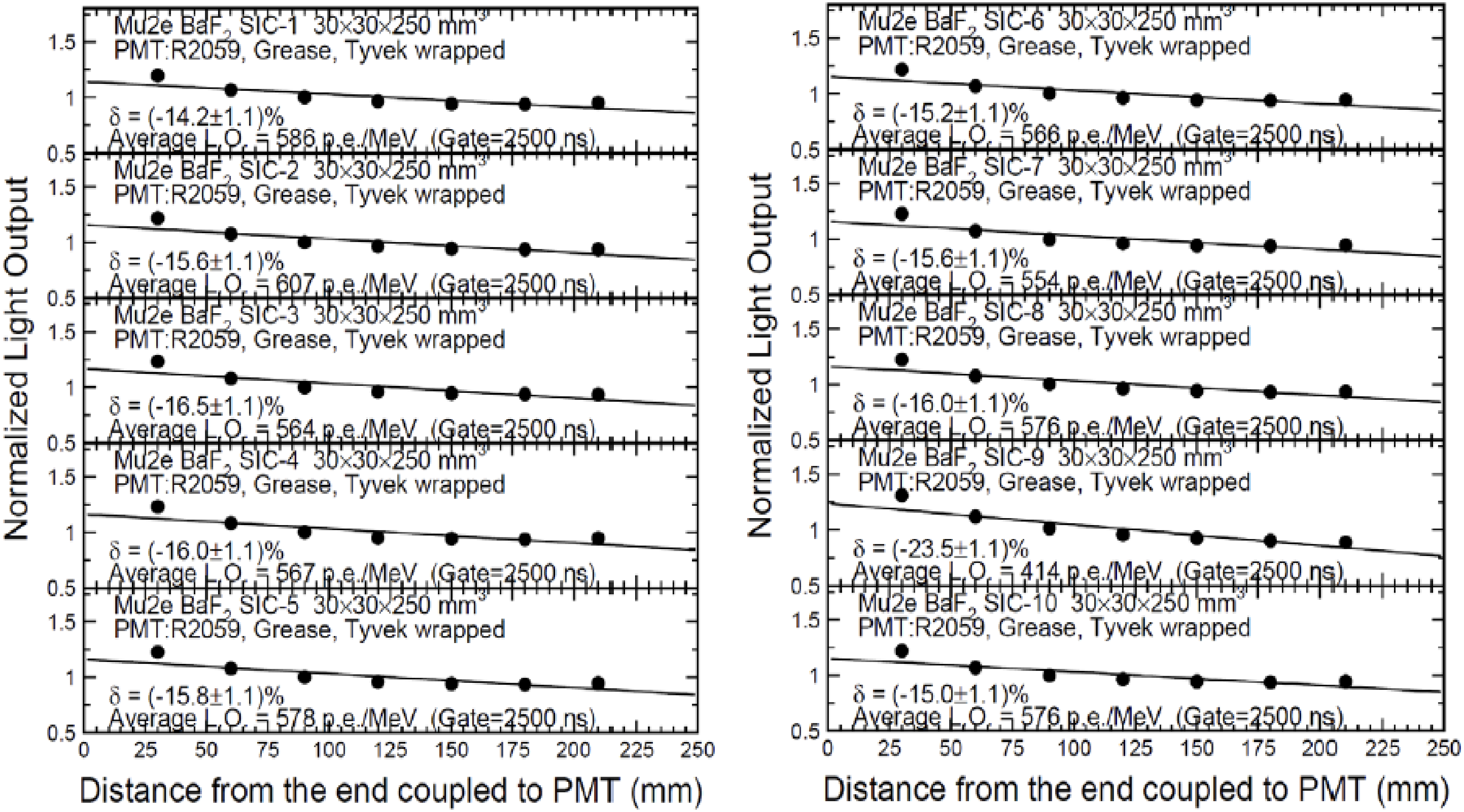
Intrinsic scintillation production is uniform

Light Response Uniformity (50 ns)



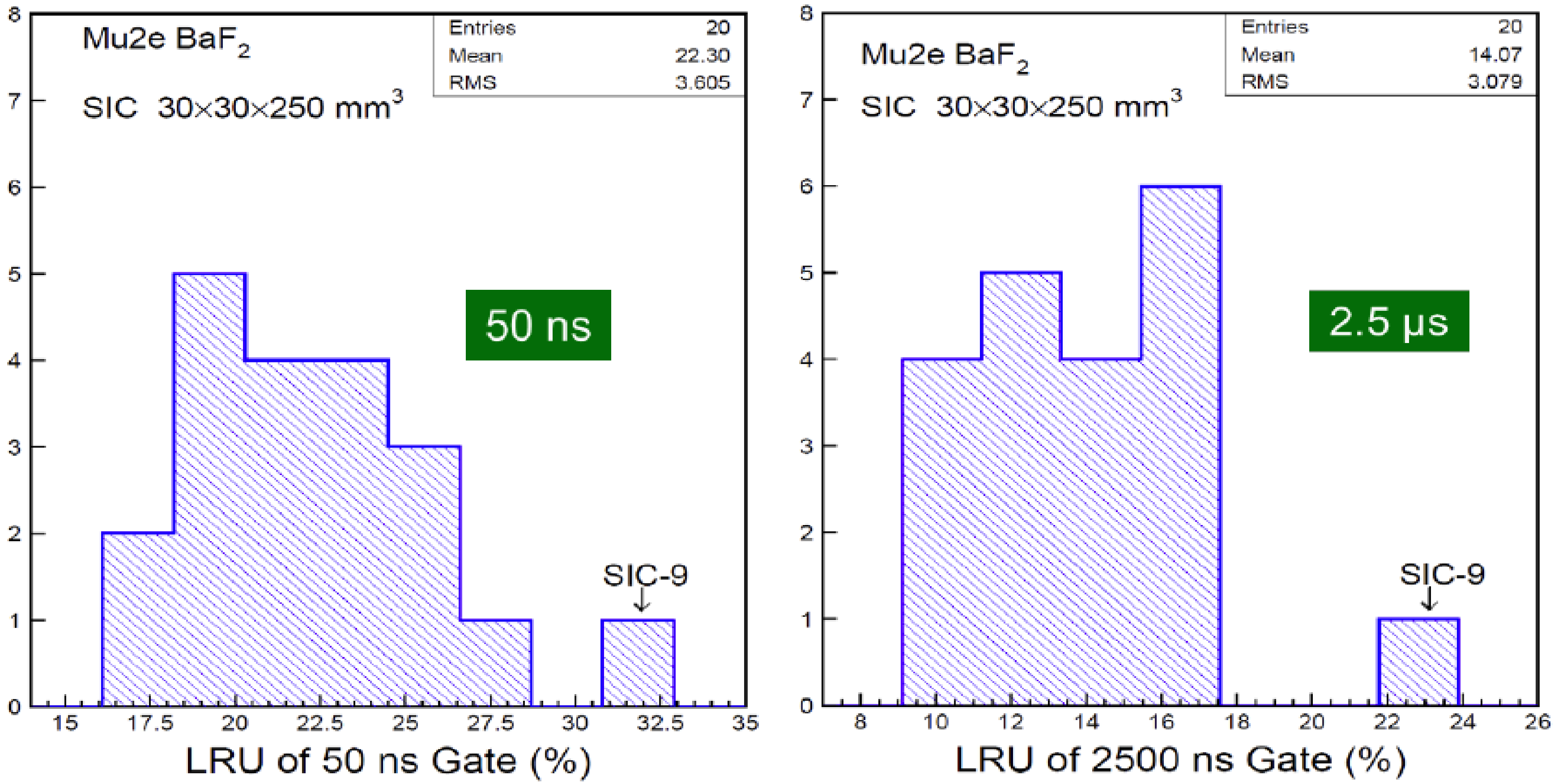


Light Response Uniformity (2.5 μs)



Summary: δ values of the Simple Linear Fit

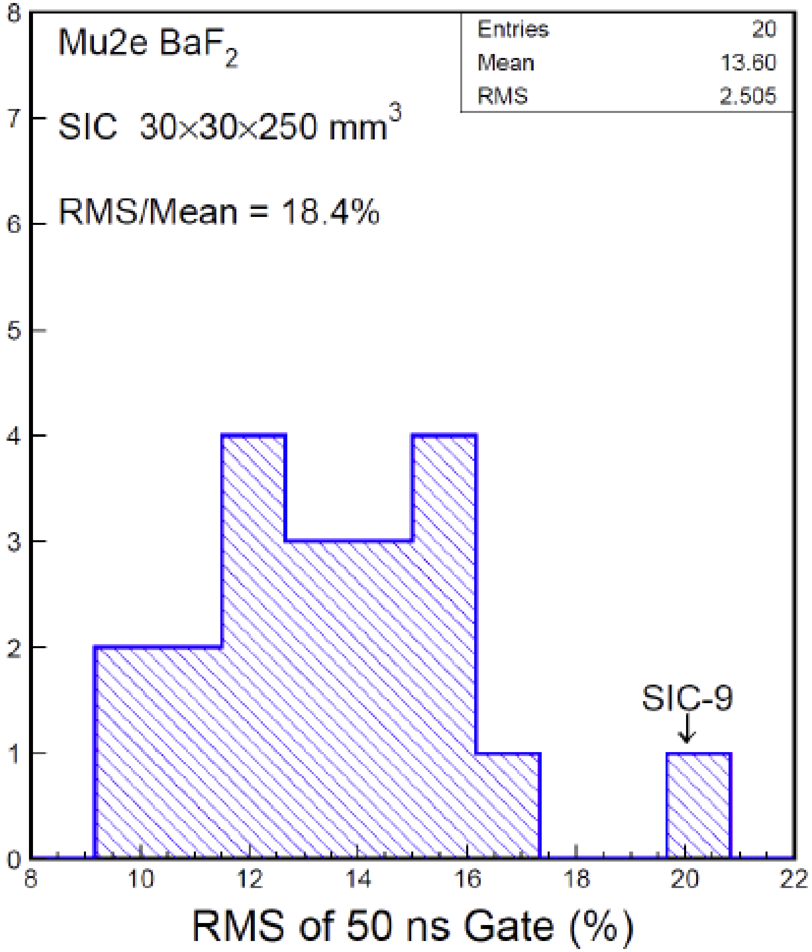
22/14% negative slope observed for 50 ns/2.5 μs gate

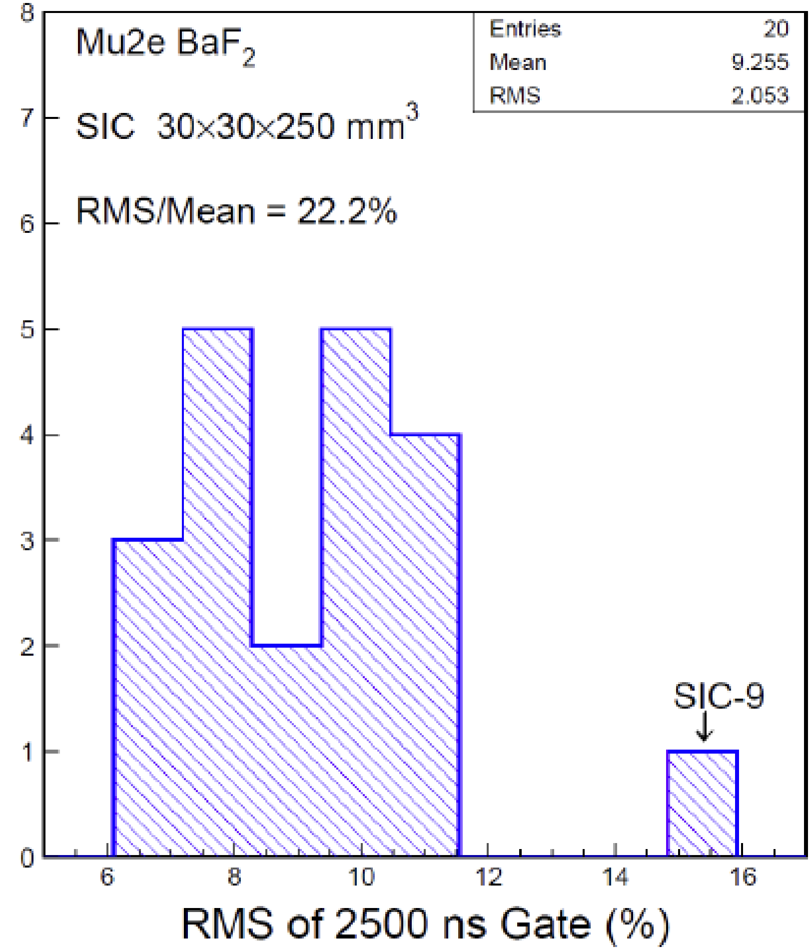


A consequence of UV absorption

Summary: rms of LO at 7 points

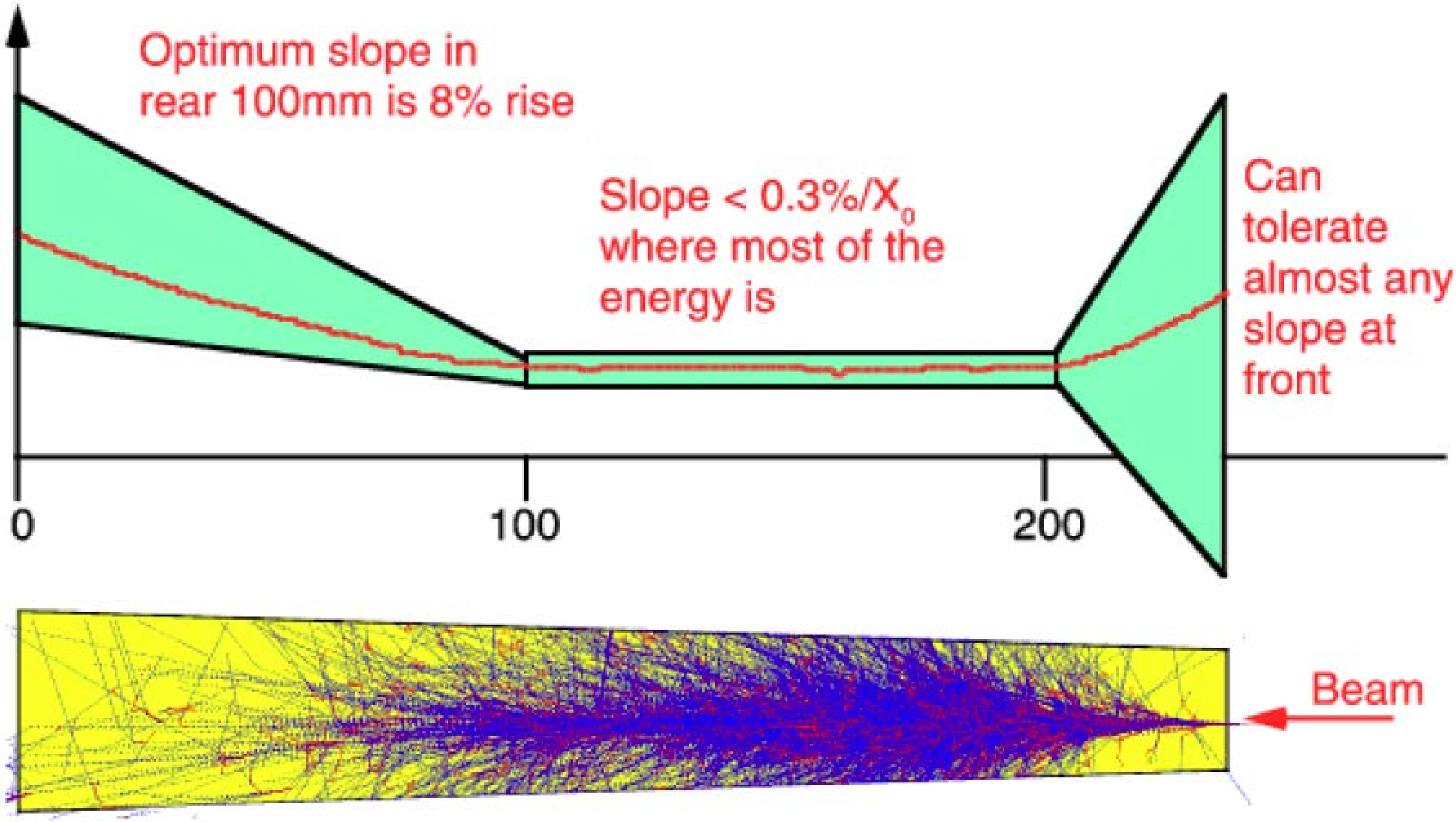
14/9% observed for 50 ns/2.5 μs gate



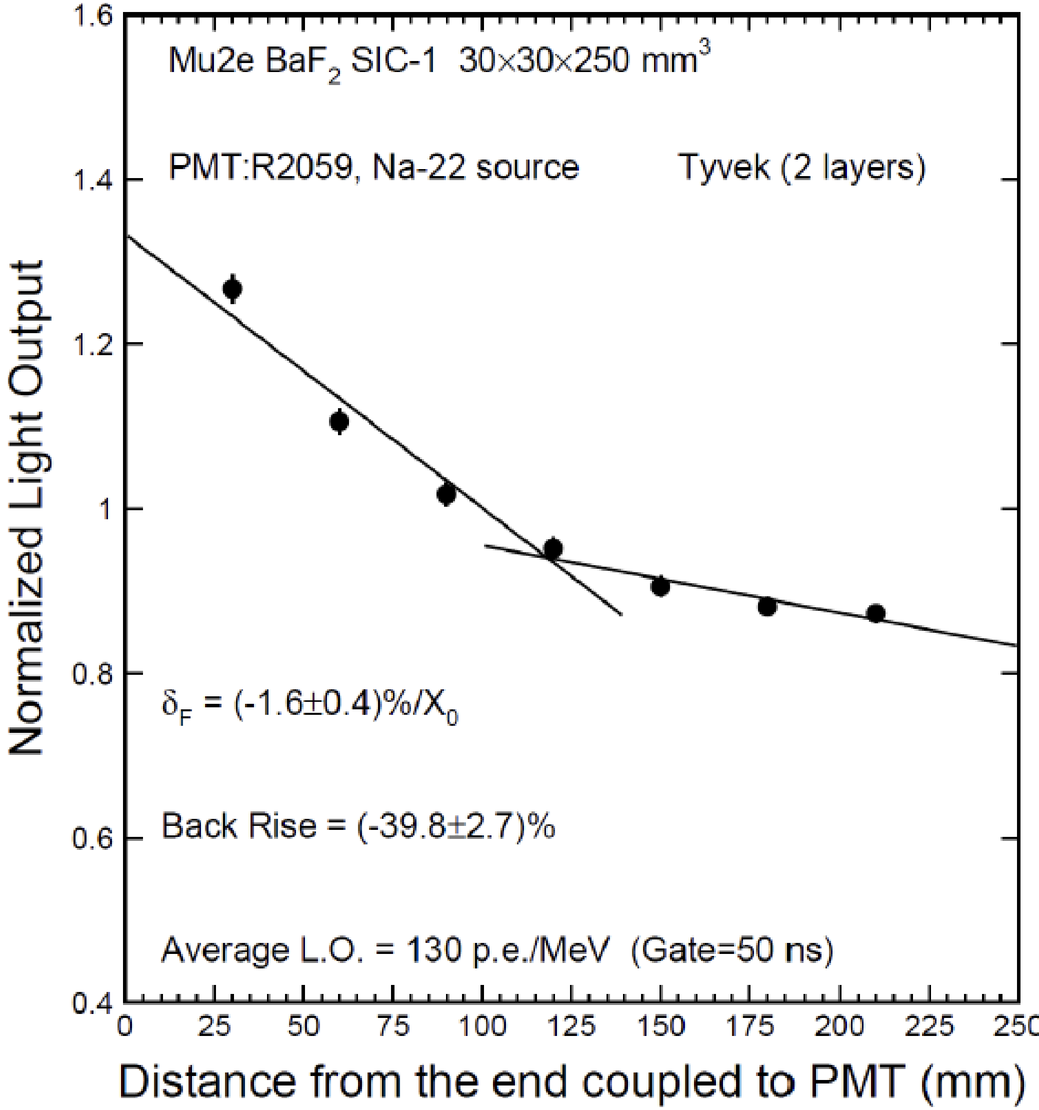


Light Response Uniformity Specification

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



Front Slope and Back Rise



First four points and last four points were fit to

Y = a + b × x and

Y = c + d × x

respectively.

Front Slope

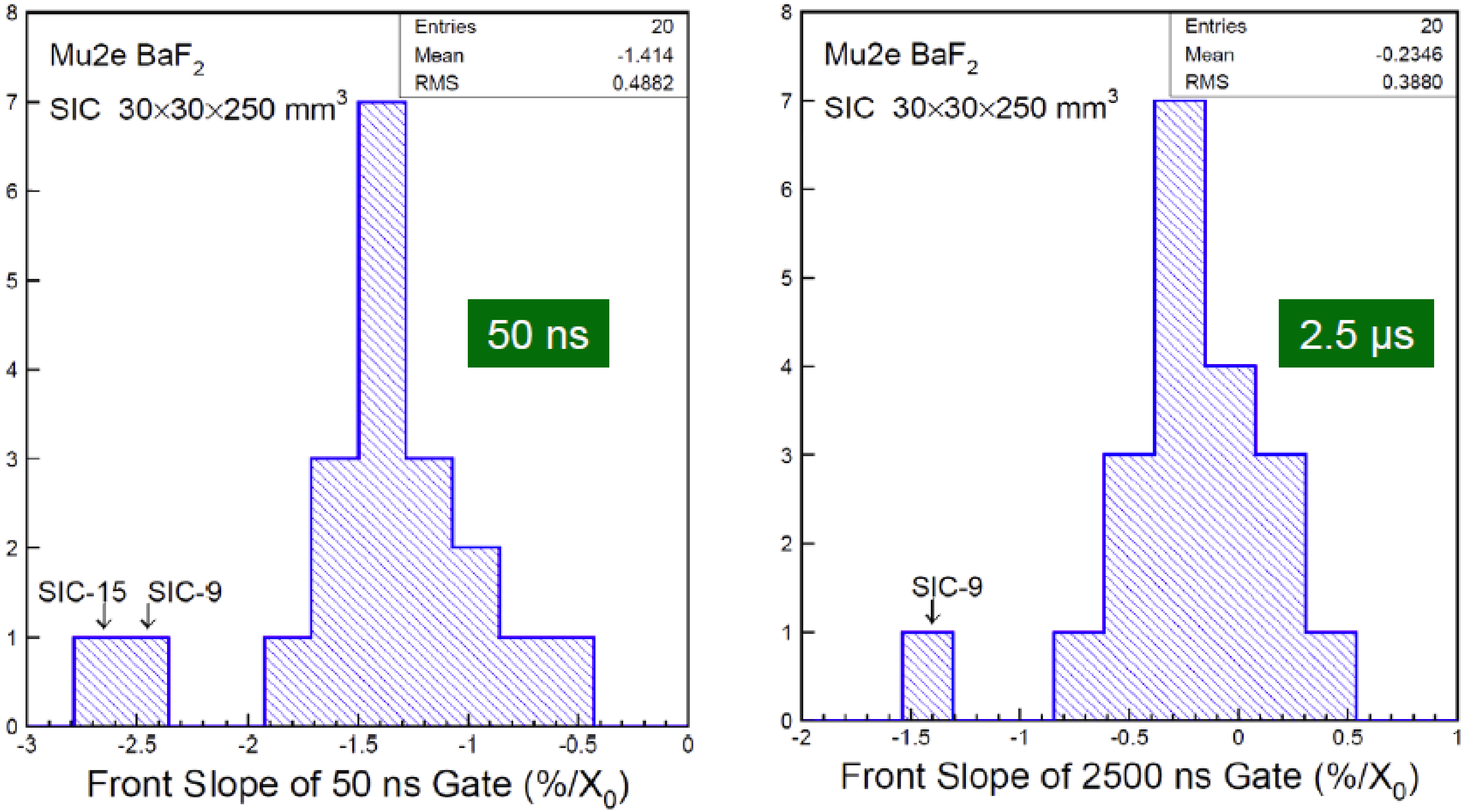
$$\delta_F = d \times 20.3\ mm$$

Back Rise

$$R_B = b \times 120\ mm$$

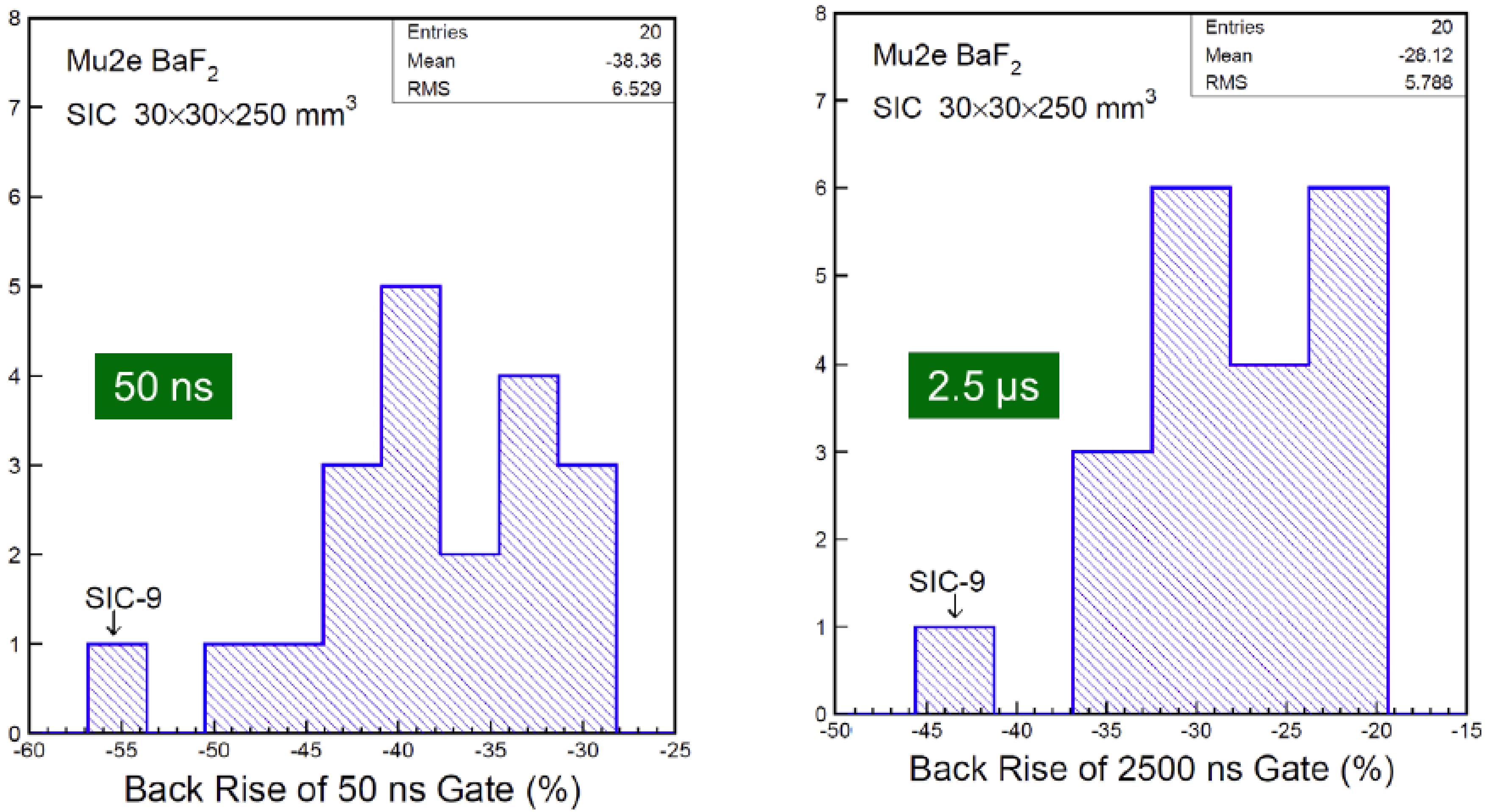
Front Slope: Too Large for Fast Component

1.4% & 0.2% per X_0 observed for fast & slow components



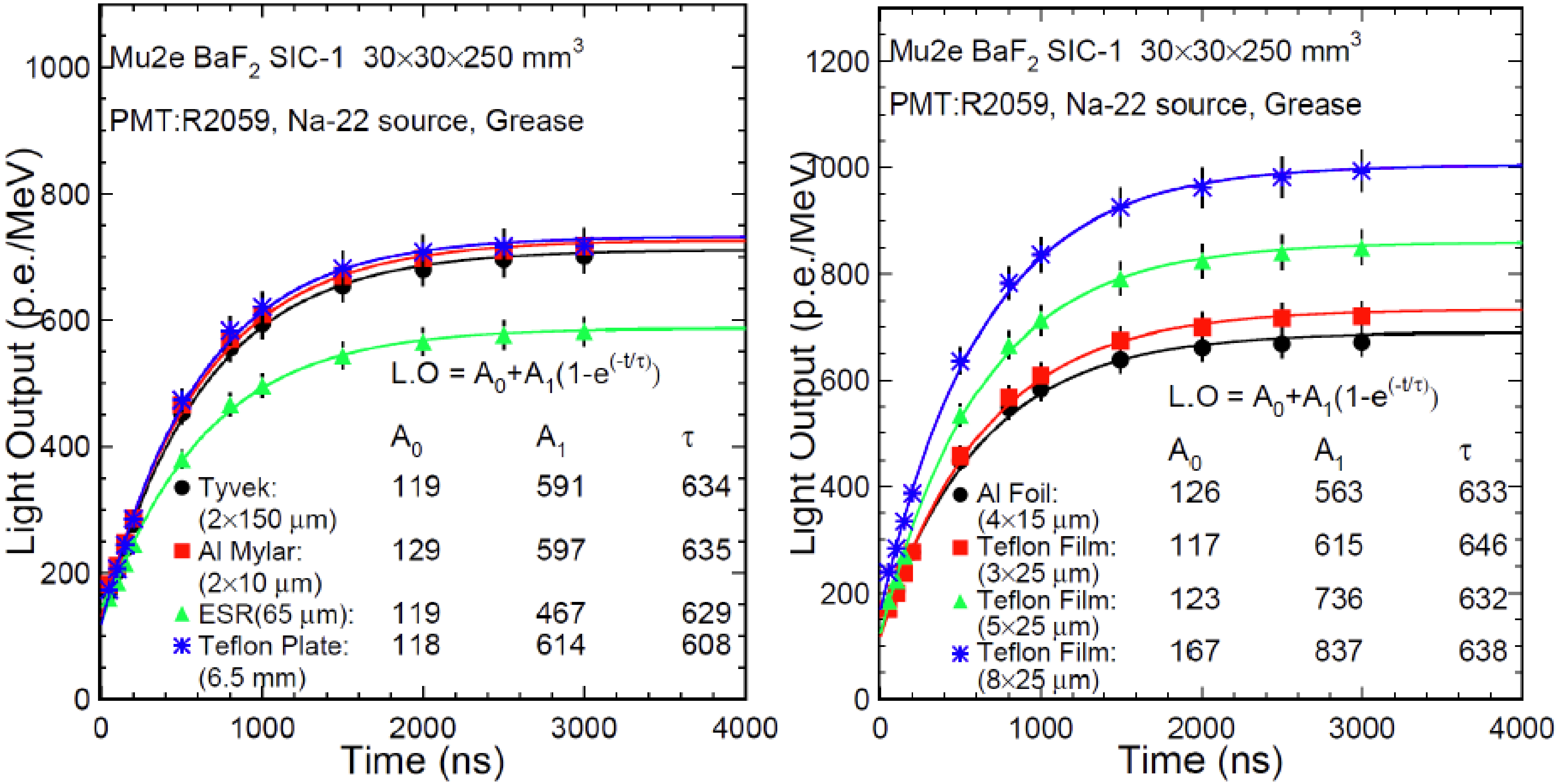
Back Rise: Too Large for both Fast and Slow

38% and 28% observed for fast and slow components



Effect of Crystal Wrapping

The highest LO is observed with 8 layer Teflon wrapping



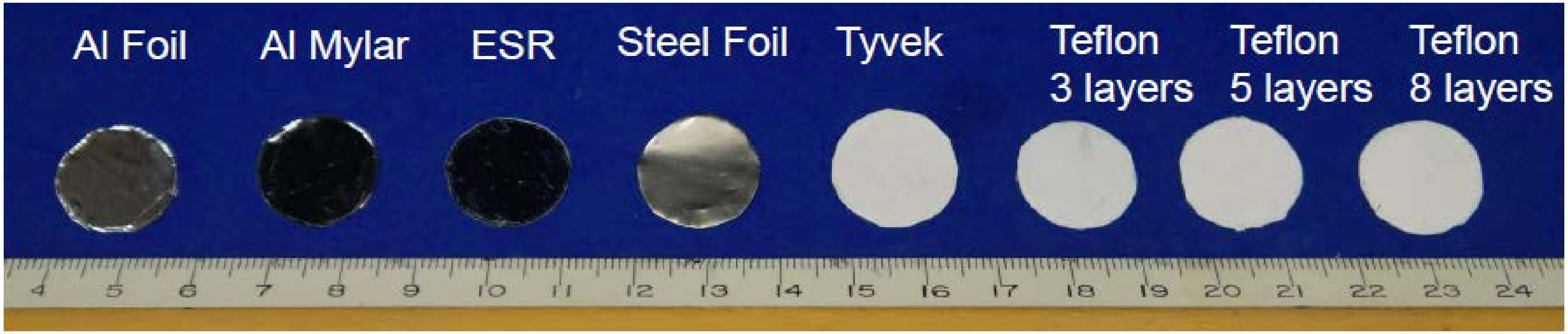
Summary of Crystal Wrapping

	Fast LO (p.e./MeV)	LO: 50 ns (p.e./MeV)	RMS 50 ns (%)	δ_F 50 ns (%/X_0)	R_B 50 ns (%)	Slow LO (p.e./MeV)	LO: 2.5 μs (p.e./MeV)	RMS 2.5 μs (%)	δ_F 2.5 μs (%/X_0)	R_B 2.5 μs (%)
Al Foil (4)	126	131	16.8	-2.0	-44.8	563	579	8.5	-0.3	-25.9
Al Mylar (2)	129	148	10.7	-0.9	-30.4	597	644	5.6	0	-17.3
ESR (2)	119	130	11.0	-1.4	-30.2	467	525	5.0	-0.4	-15.1
Teflon (3)	117	117	21.0	-0.5	-63.5	615	567	12.9	1.2	-43.6
Teflon (3) +Al Foil (2)	119	125	20.4	-0.8	-61.9	701	645	12.2	0.3	-39.0
Teflon (5)	123	135	18.3	-0.9	-53.5	736	706	9.7	0.3	-32.0
Teflon (5) +Al Foil (2)	123	135	17.9	-1.1	-52.8	775	741	13.0	-1.2	-37.6
Teflon (8)	167	172	20.7	-2.0	-58.2	837	788	13.0	-1.2	-37.9
Teflon (8) +Al Foil (2)	165	178	20.6	-2.2	-58.6	839	788	13.1	-1.3	-36.8
Teflon Plate	118	125	18.2	-1.1	-53.1	614	574	12.1	0.5	-39.4
Tyvek (2)	119	130	14.4	-1.6	-39.8	591	586	9.4	-0.1	-29.6

Summary: Light Response Uniformity

- Light response uniformity was measured for all twenty BaF_2 crystals wrapped with two layers of Tyvek paper.
  - No change of LRU when the crystal end coupled to PMT is altered.
  - An overall negative slope of 22% & 14% (rms of 14% & 9%) was observed for 50 ns & 2.5 μs gate, indicating absorption dominance.
  - An alternative fit with two segments shows 1.4%/X_0 & 0.2%/X_0 slope in the front 13 cm and 38% & 28% rise in the back 12 cm for 50 ns & 2.5 μs gate.
- R&D is needed to improve LRU of BaF_2 crystals after the choice of the UV-effective wrapping material is made.
  - Design longitudinal tunable reflection, such as painting black strips on the wrapping material.
  - Ray-tracing simulation will help the tuning: need to understand the reflectance of UV light.

Reflectance Measurements

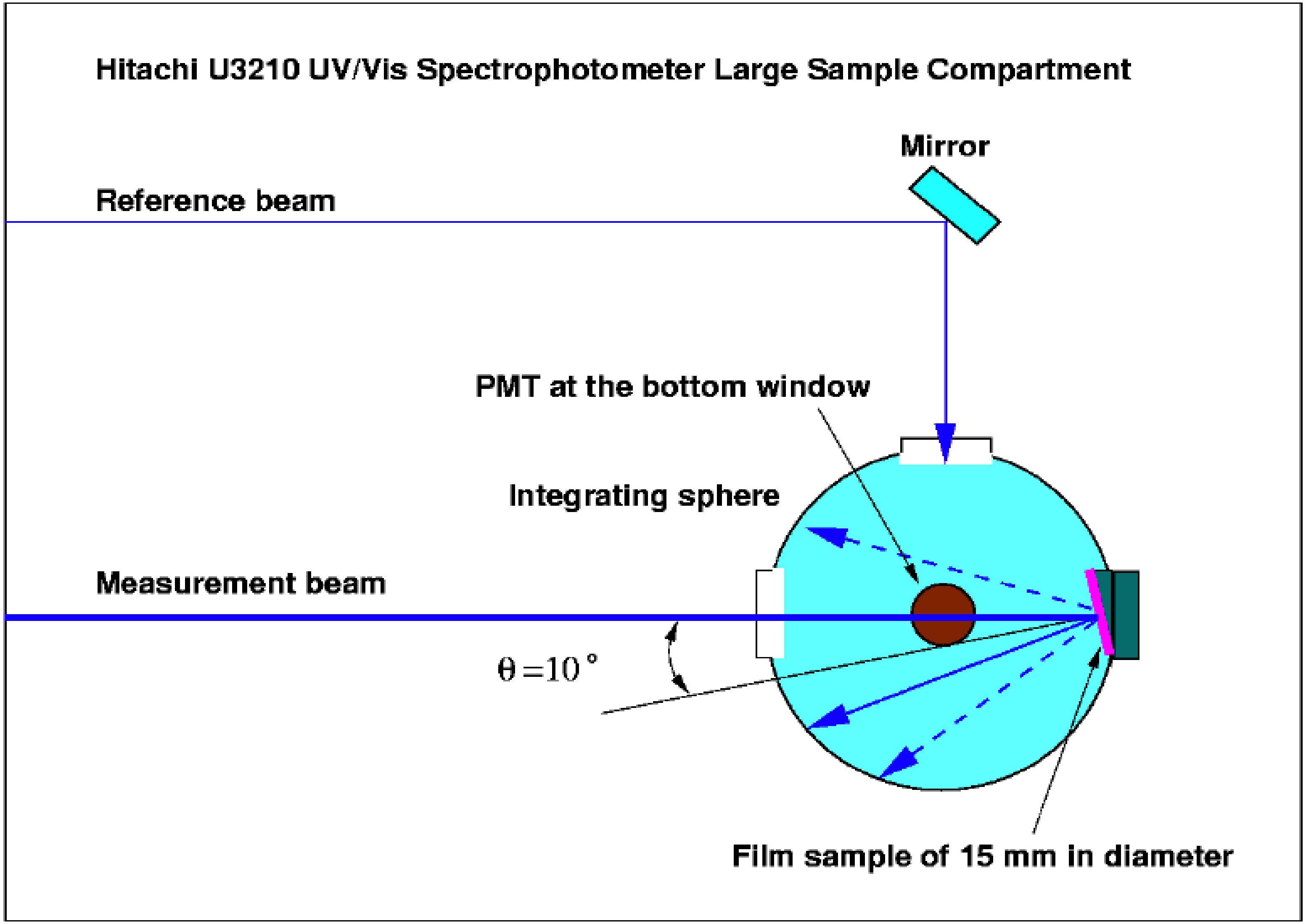


Sample ID	Thickness (μm)
Al Foil	15
Al Mylar	10
ESR	65
Steel Foil	50
Tyvek	150
Teflon ×3	25×3
Teflon ×5	25×5
Teflon ×8	25×8

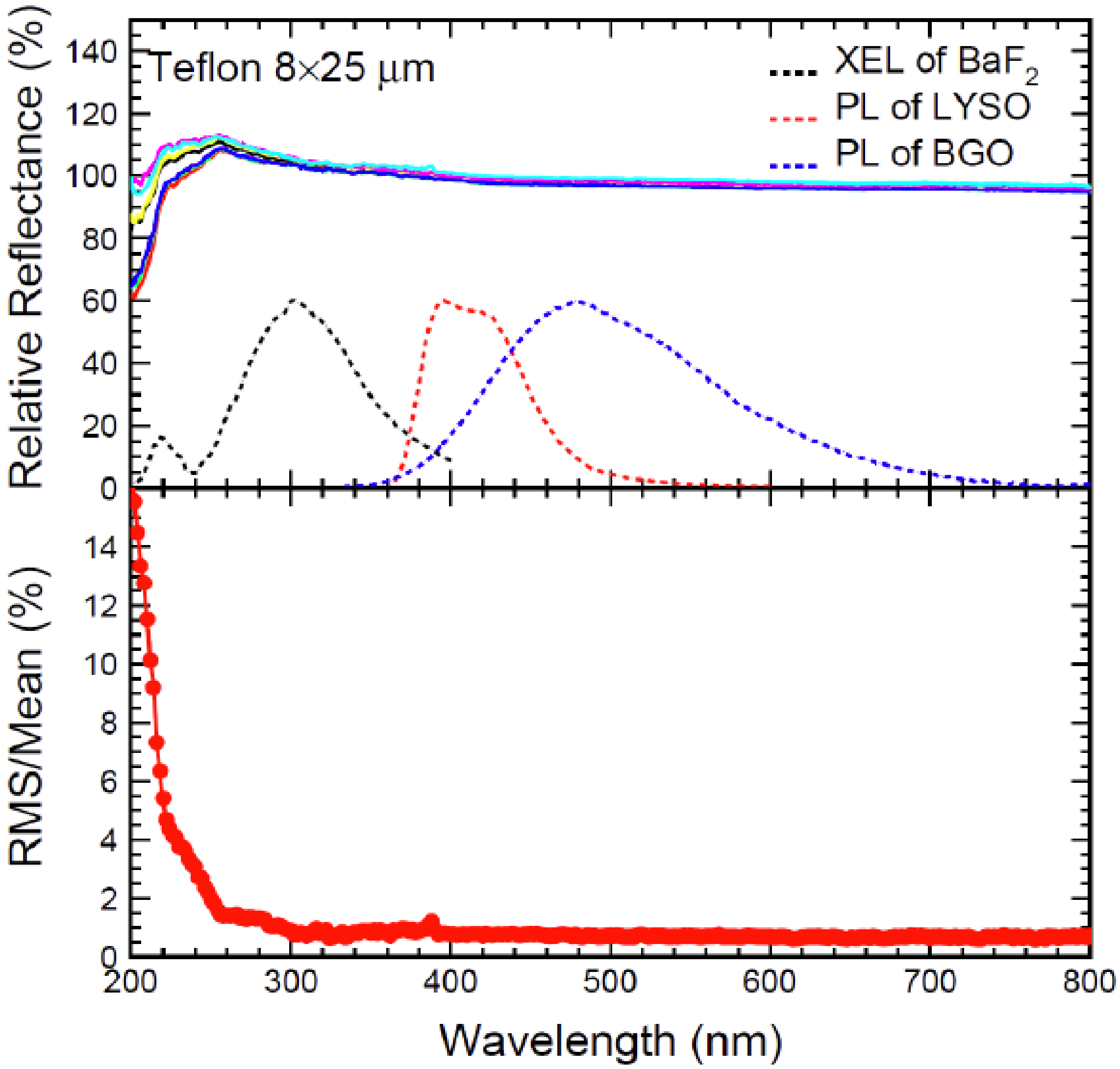
Properties measured at room temperature:

Reflectance as a function of wavelength

Set-up for Reflectance Measurements



Large Systematic Uncertainties for DUV



RMS values extracted from ten repeated measurements for 8 layers of Teflon films:

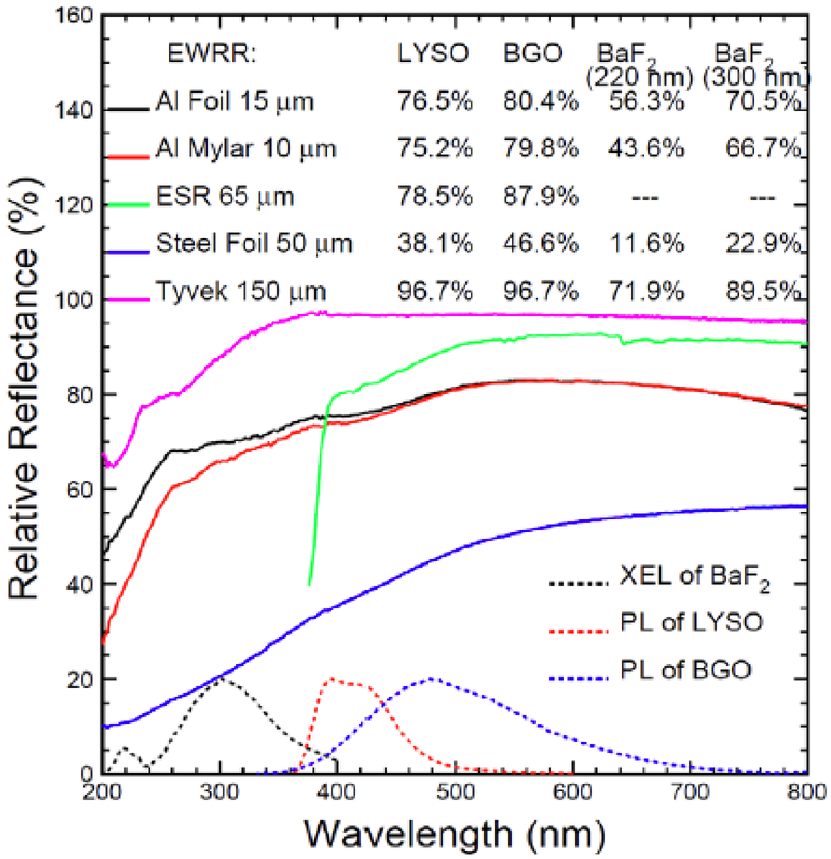
<1% with λ longer than 250 nm; and Up to 15% with λ shorter than 250 nm.

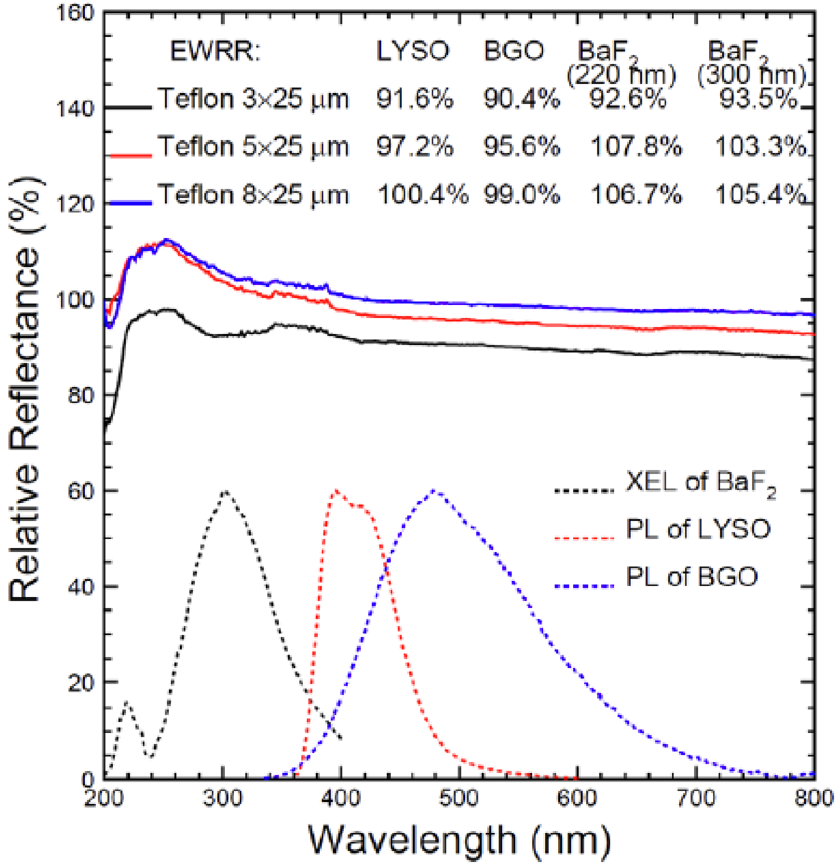
Normalized Reflectance relative to $BaSO_4$

$BaSO_4$ is the coating material used in the integrating sphere

EWRR : Emission weighted relative reflectance

$$EWRR = \int em(\lambda)\cdot reflectance(\lambda)d\lambda / \int em(\lambda)d\lambda$$

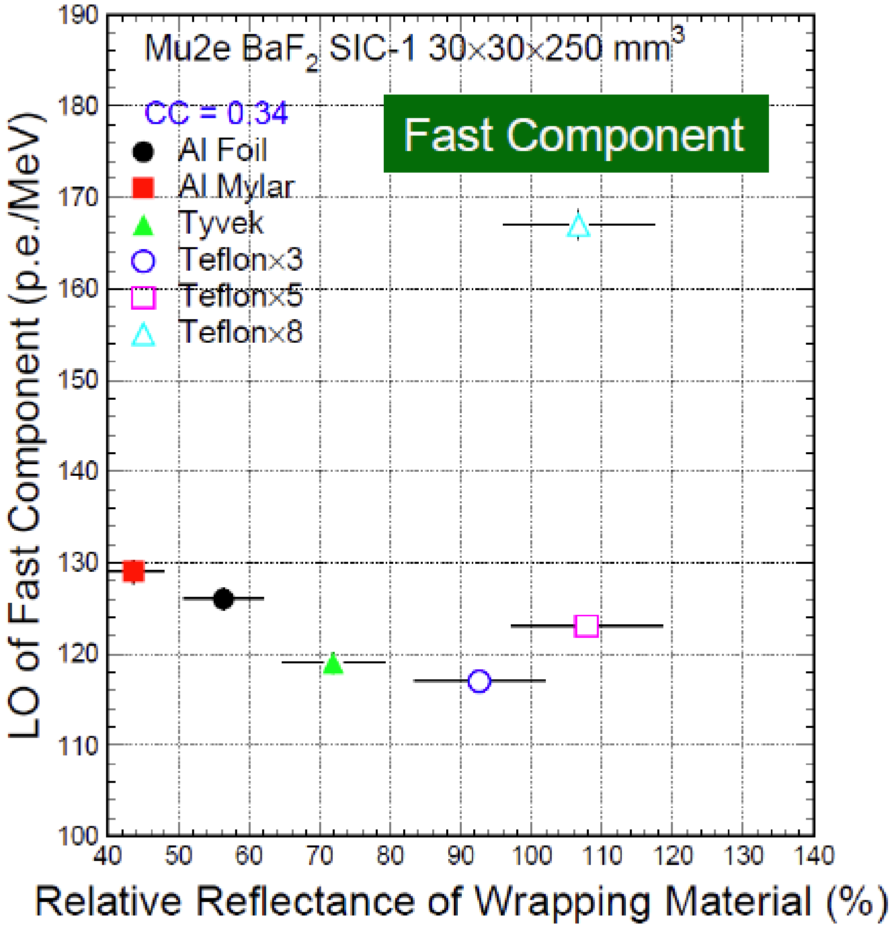


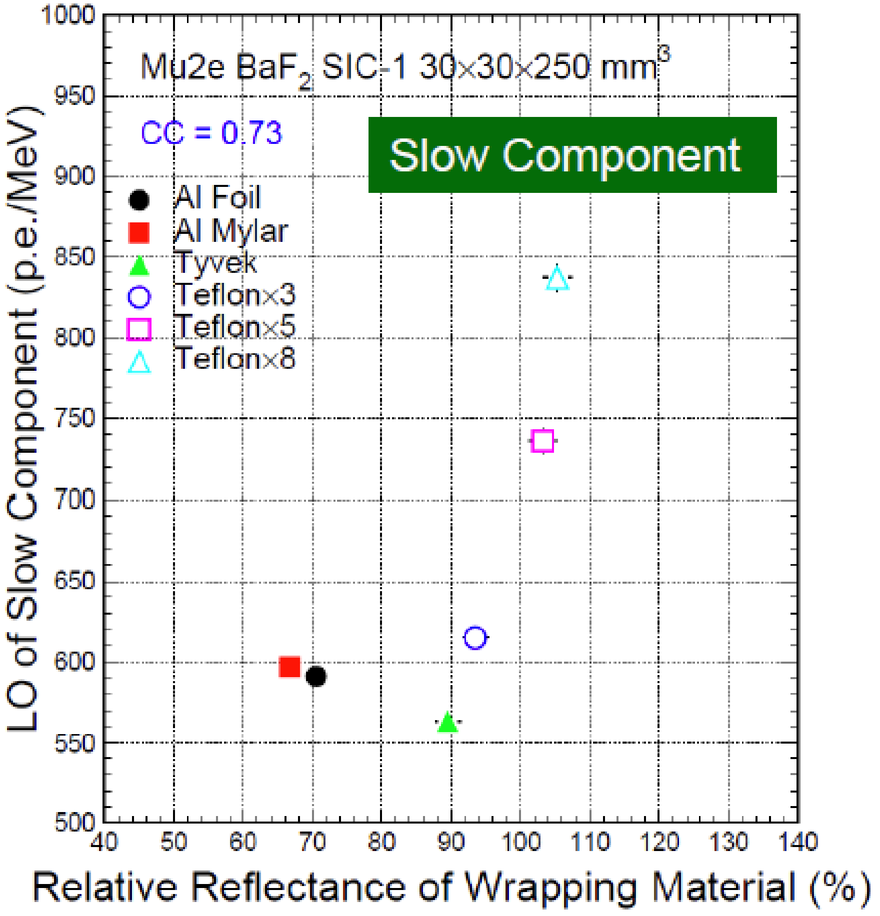


Mu2e

Light Output versus Reflectance

Positive correlations observed

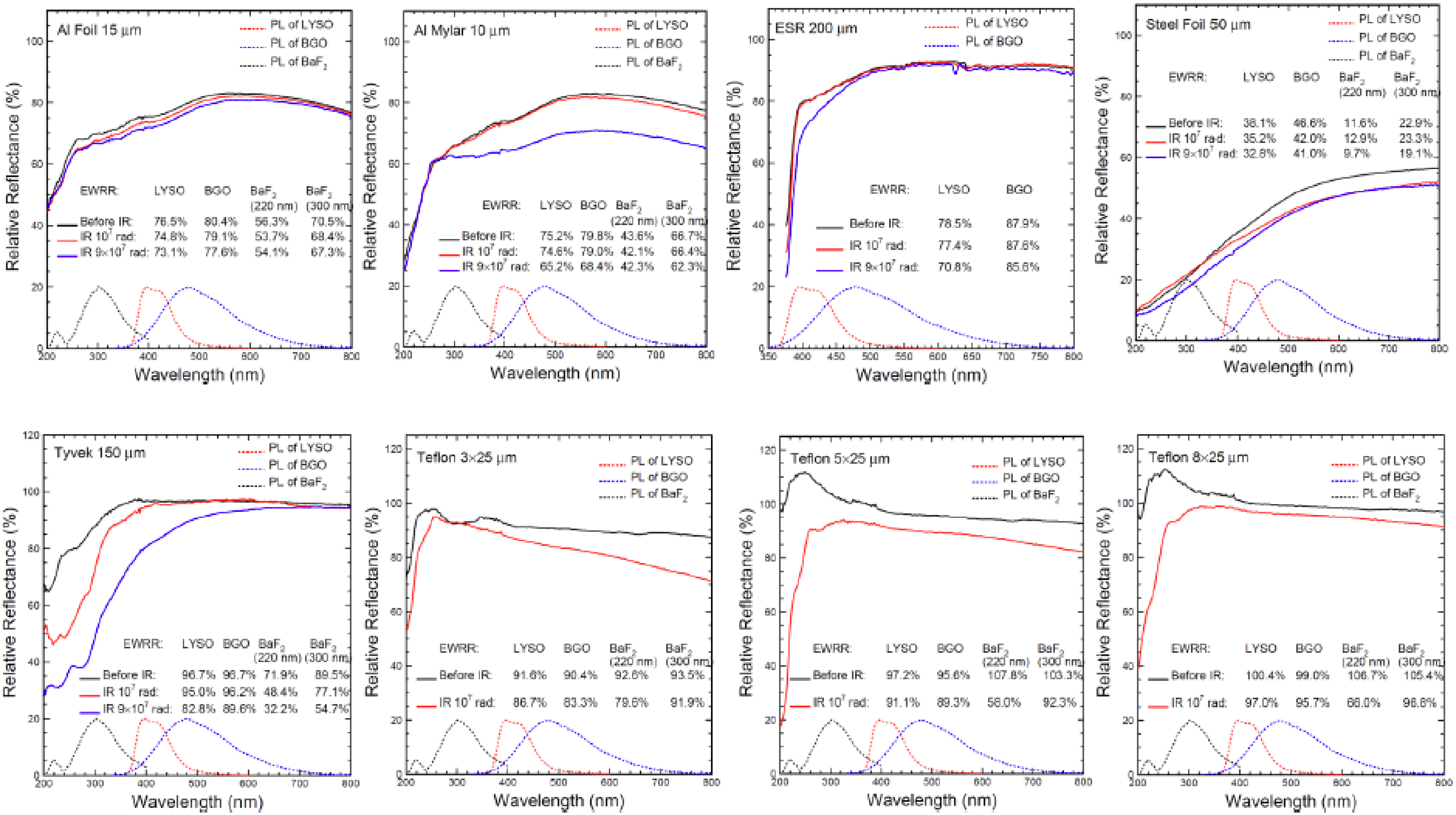




Mu2e

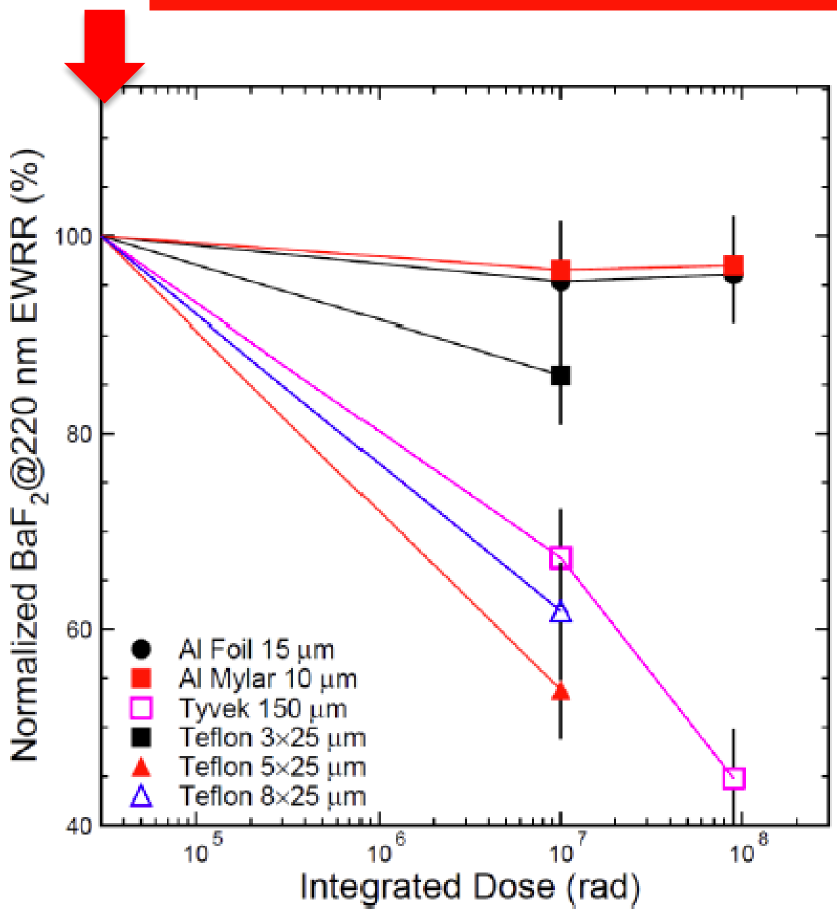
Radiation Damage in Wrapping Materials (I)

Aluminum foil is the best reflector up to 100 Mrad

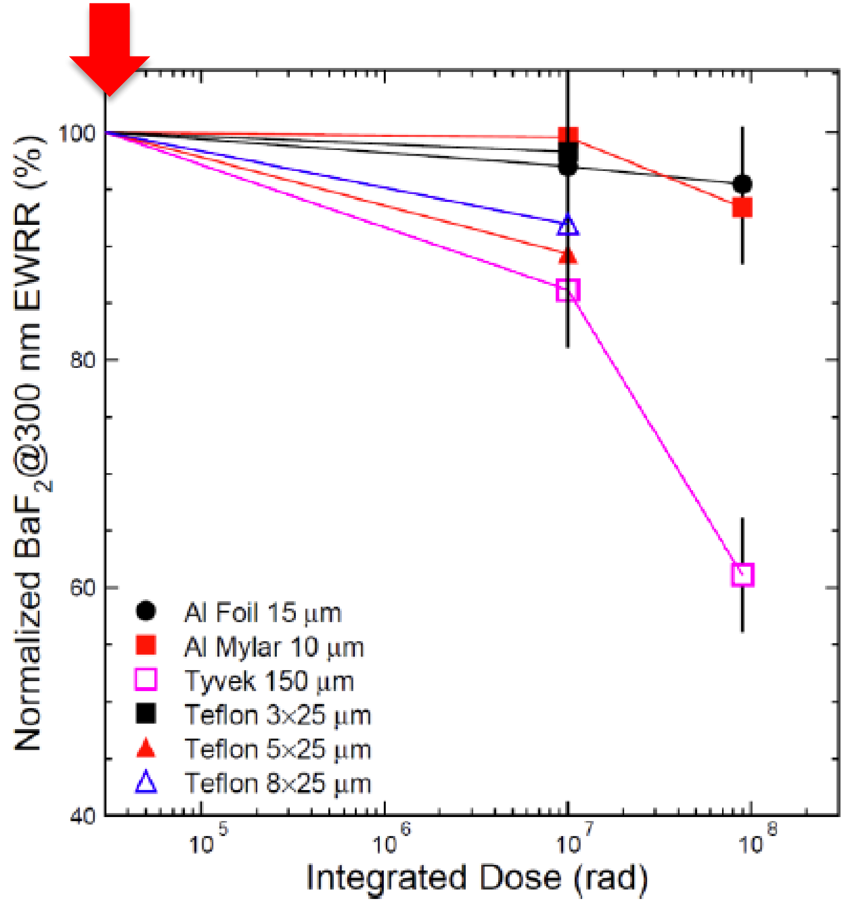


Radiation Damage in Wrapping Materials (II)

Al foil is radiation hard up to 100 Mrad for BaF_2



Fast Component



Slow Component

BaF_2: ɣ-ray Induced Radiation Damage (I)

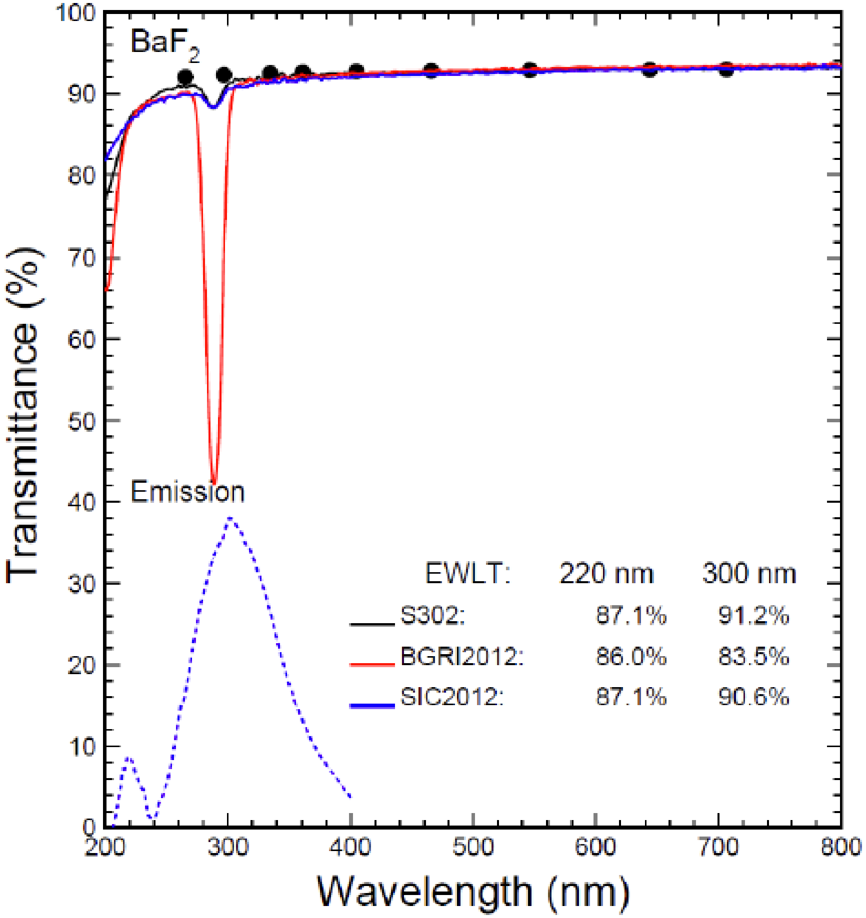
Sample ID	Received Date	Dimension (mm^3)	Polish
BaF_2-S302	1992	$30^2 \times 40^2 \times 250$	Six faces
BaF_2-BGRI2012	8/24/2012	$25 \times 25 \times 250$	Six faces
BaF_2-SIC2012	9/4/2012	$25 \times 25 \times 250$	Six faces

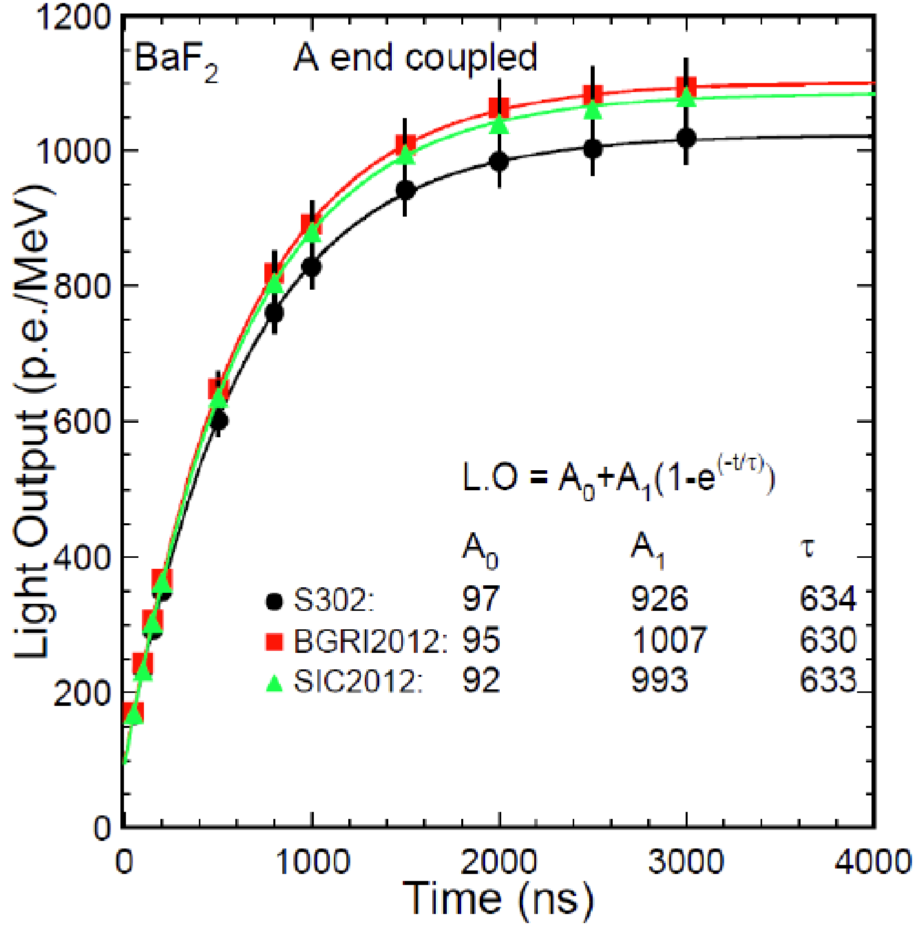
Experiments

- Three BaF_2 samples from two vendors were investigated
- Damage does not recover at room temperature
- All samples went through ɣ-ray irradiation @ 30 and 7k rad/h to reach 100, 1k,10k,100k and 1M rad
- Properties measured: LT, EWLT for fast/slow components, LO, decay time and LRU

BaF_2: ɣ-ray Induced Radiation Damage (II)

All crystals have good transmittance approaching theoretical limit
A strong absorption band peaked at 290 nm observed in BGRI2012



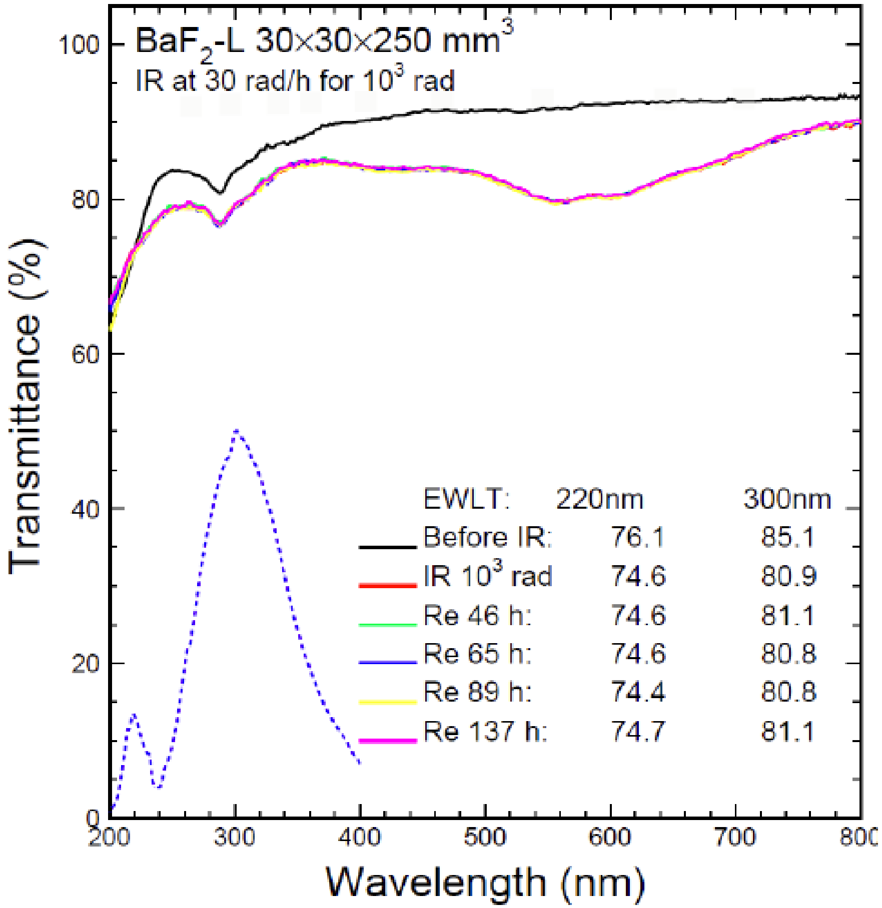


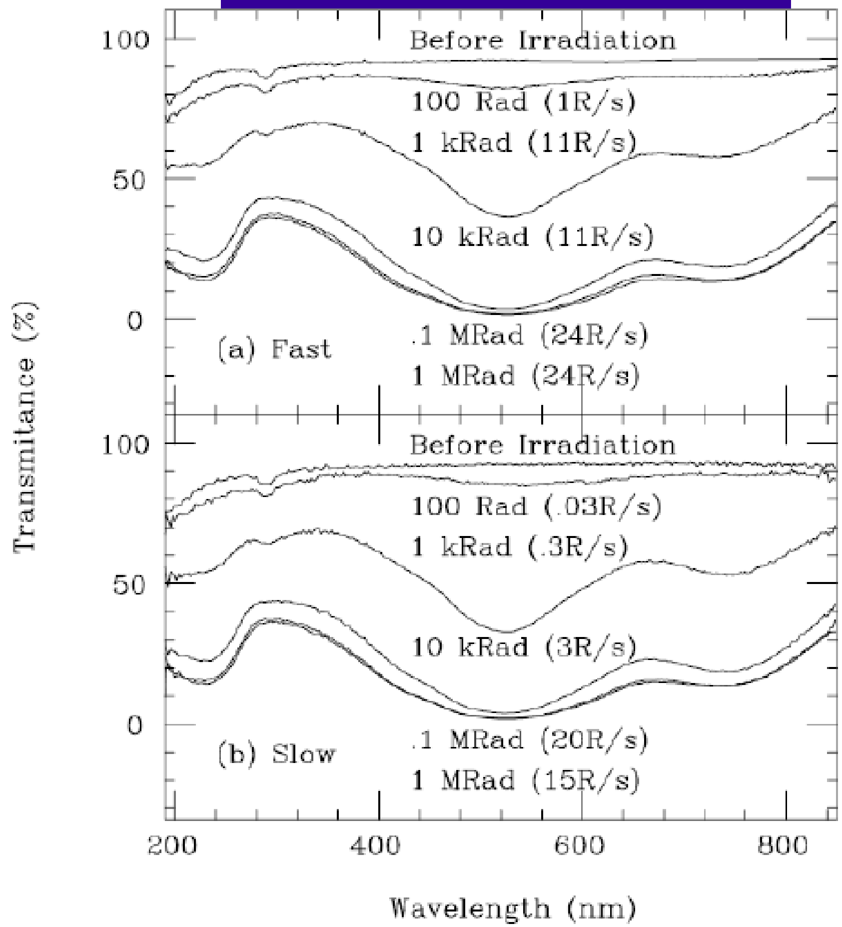
Mu2e

BaF_2: γ-ray Induced Radiation Damage (III)

Damage in BaF2 does not recover at RT, so is not dose rate dependent

Nucl. Ins. Meth. A 340 (1994) 442-457

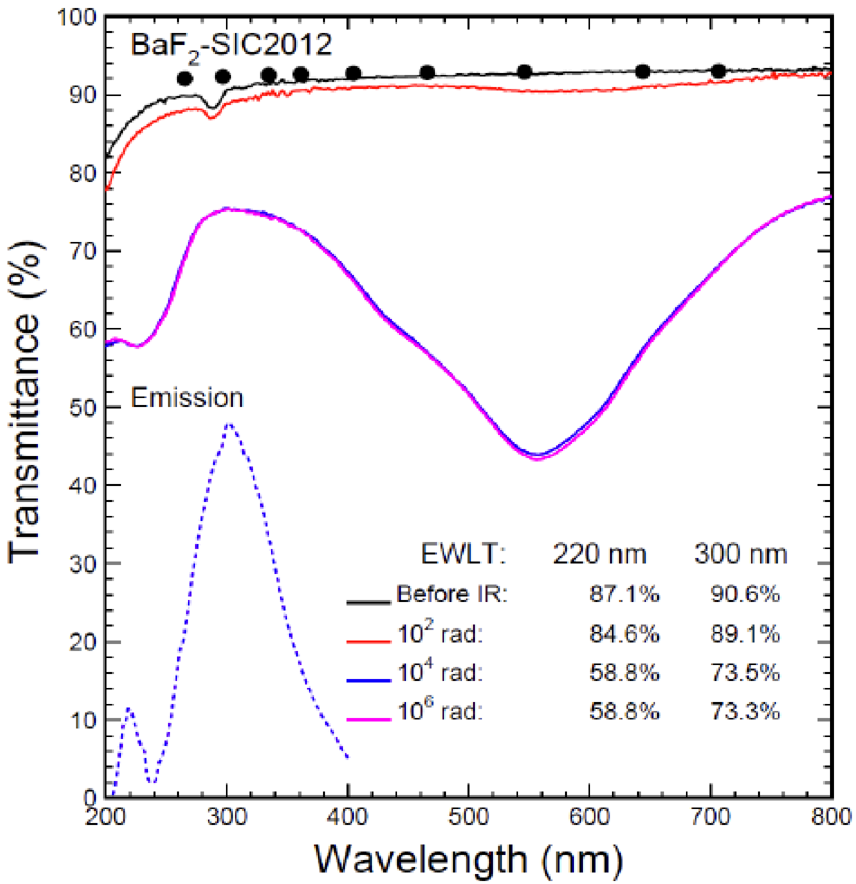


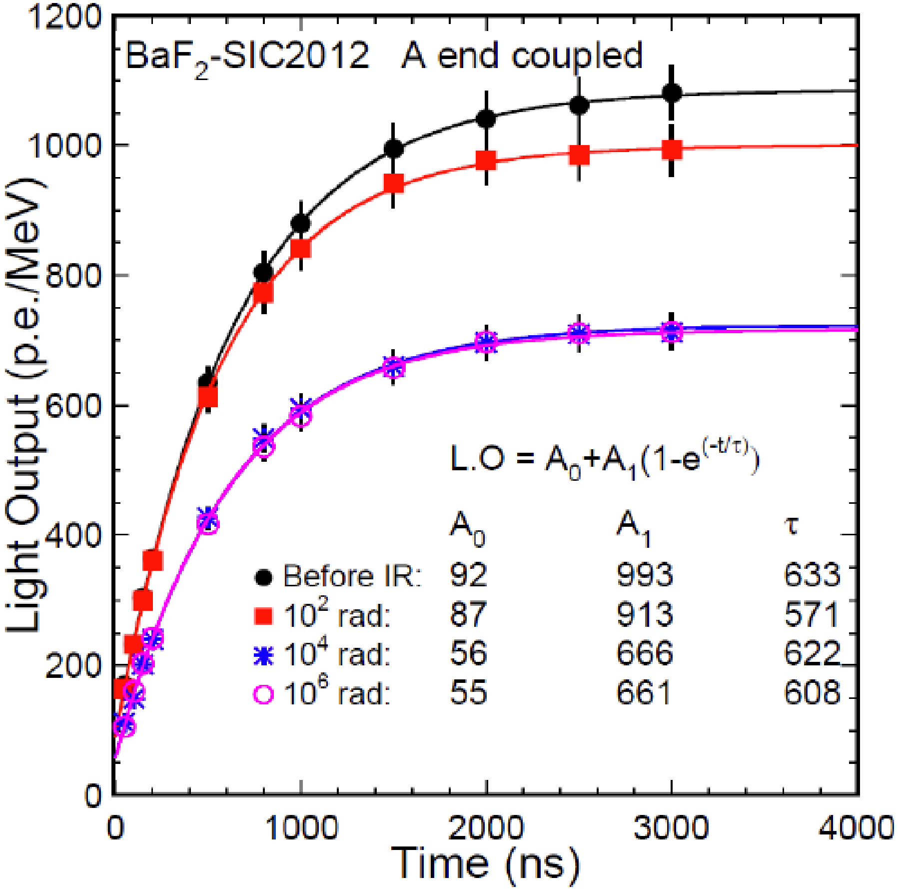


Mu2e

BaF_2: γ-ray Induced Radiation Damage (IV)

Damage in both LT and LO saturated after a few tens of krad, Indicating limited defect density in the crystal





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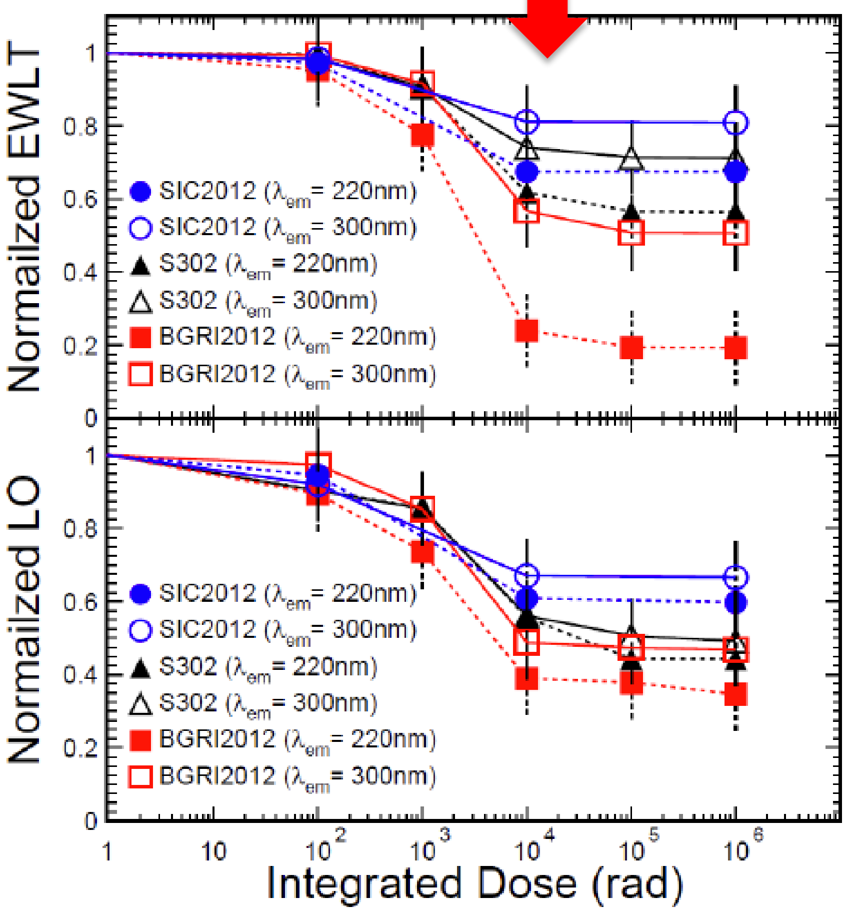
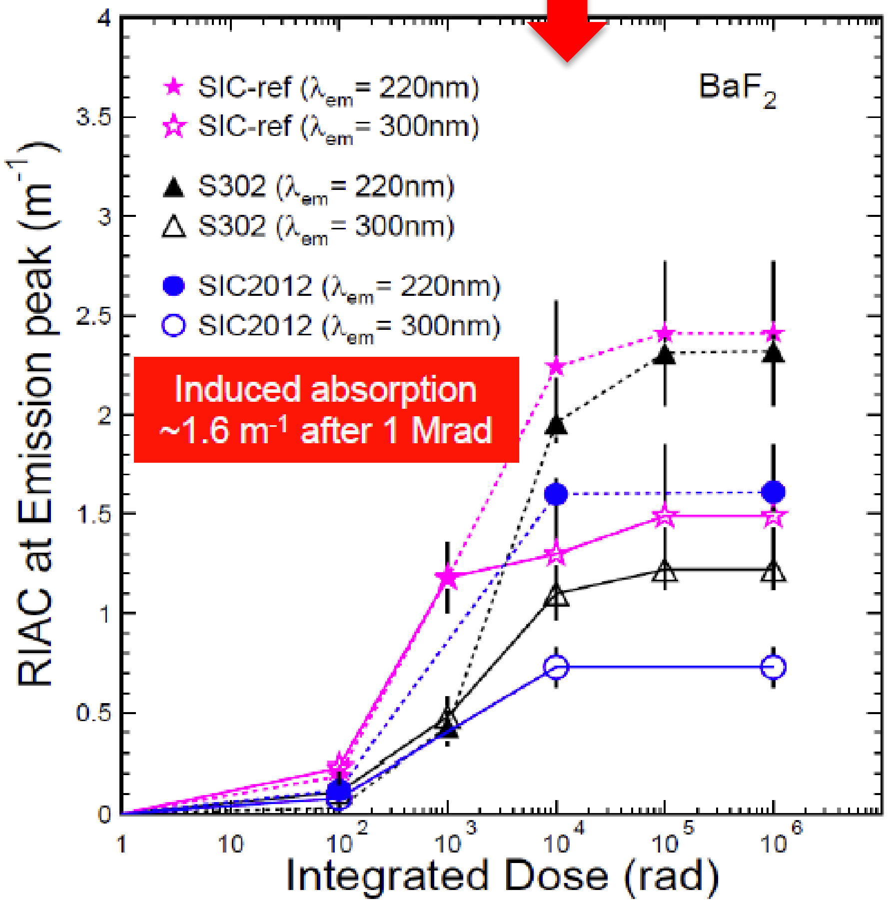
BaF_2: γ-ray Induced Radiation Damage (V)

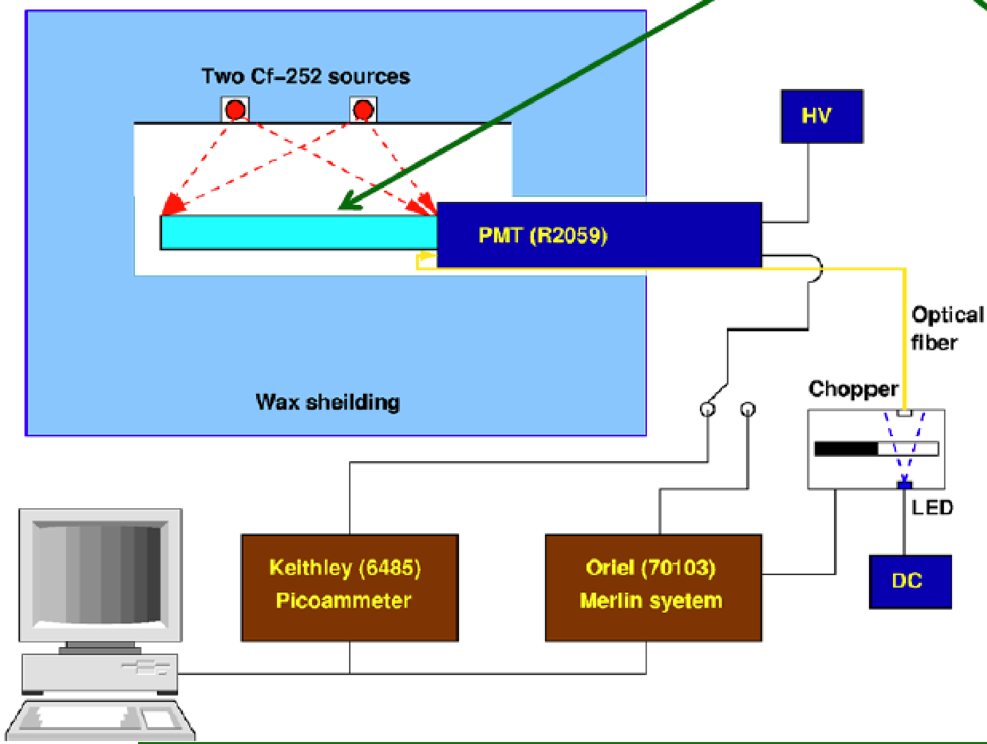
Damage in both EWLT and LO saturates after a few tens of krad at a level of less than 40% for the fast component.
Slow component is more radiation hard than the fast component

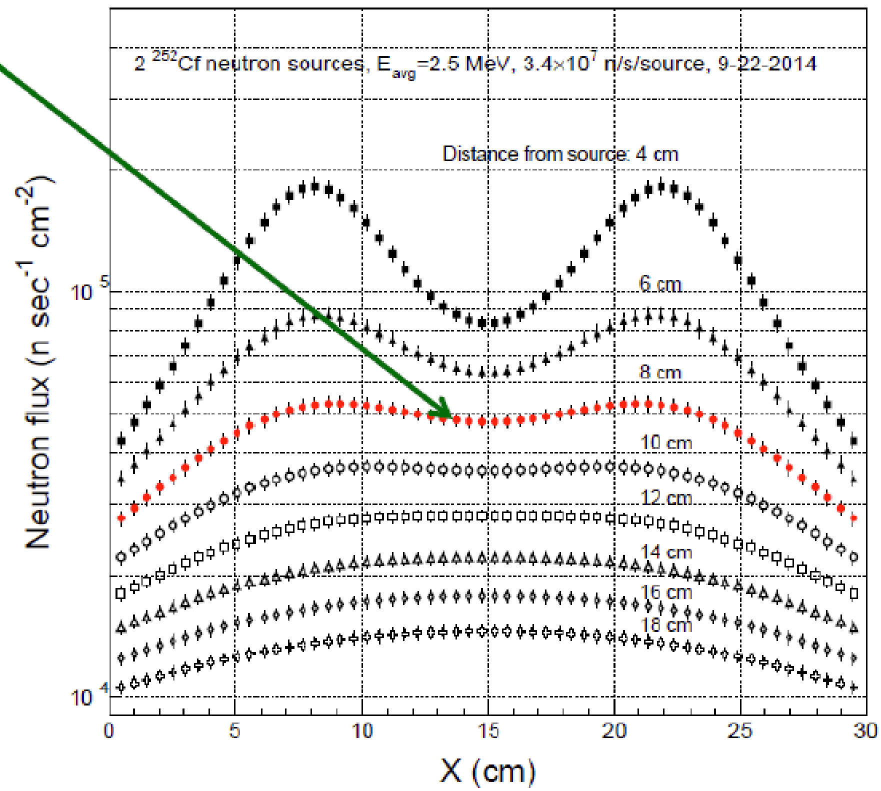




BaF_2: Fast Neutron Induced Damage

Samples were placed at 8 cm from two sources
Neutron flux at crystal surface is 5×10^4 cm^{-2} s^{-1}

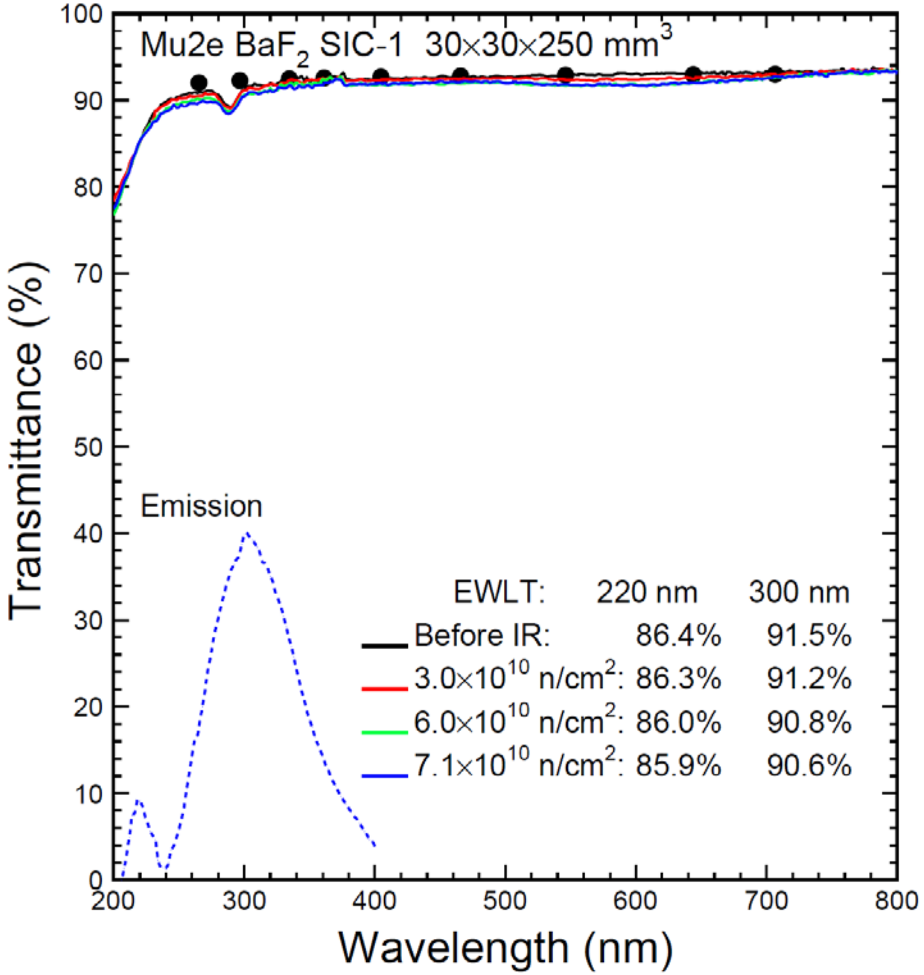


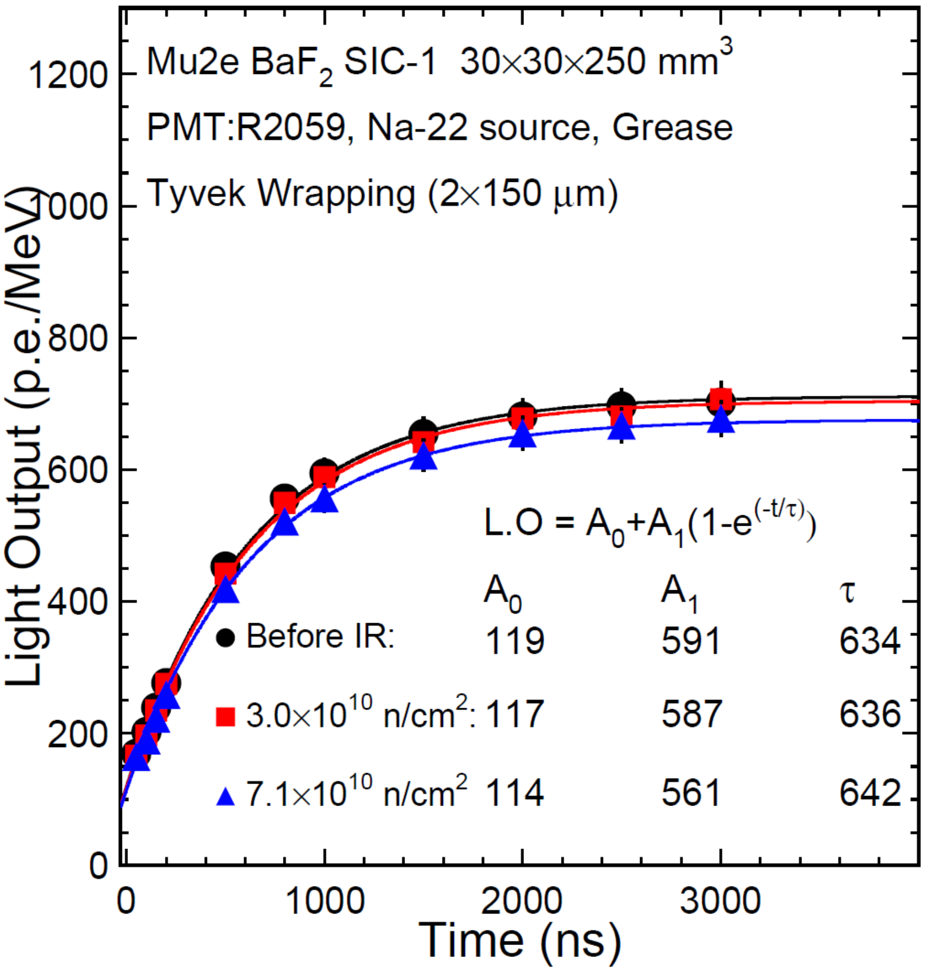


Two Cf-252 sources of 14.6 μg each was procured recently for crystal irradiation

Mu2e

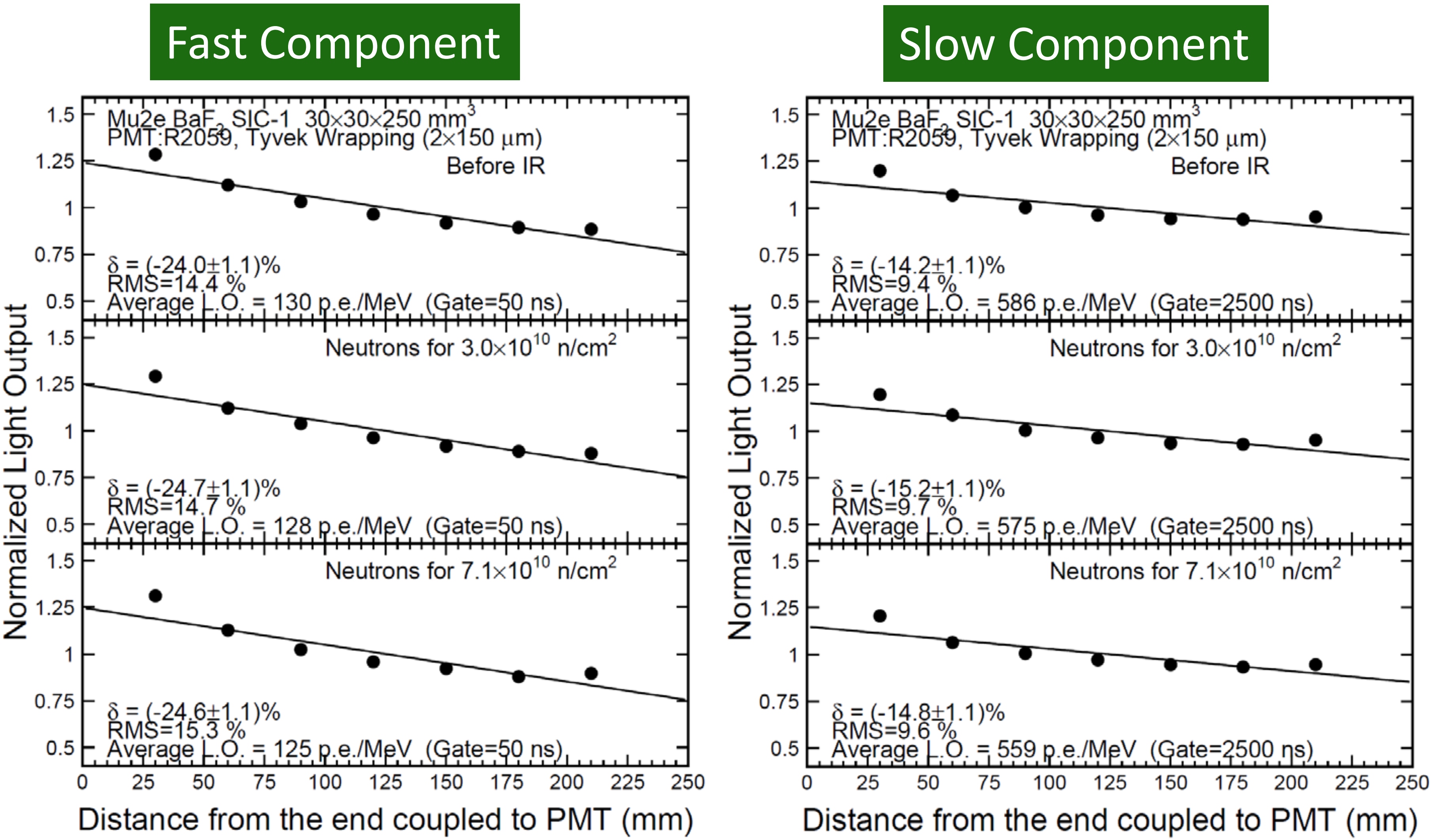
A Few Percent Loss in both LT and LO





Up to 7 x 10^{10} n/cm^2 of fast neutron of 2.5 MeV

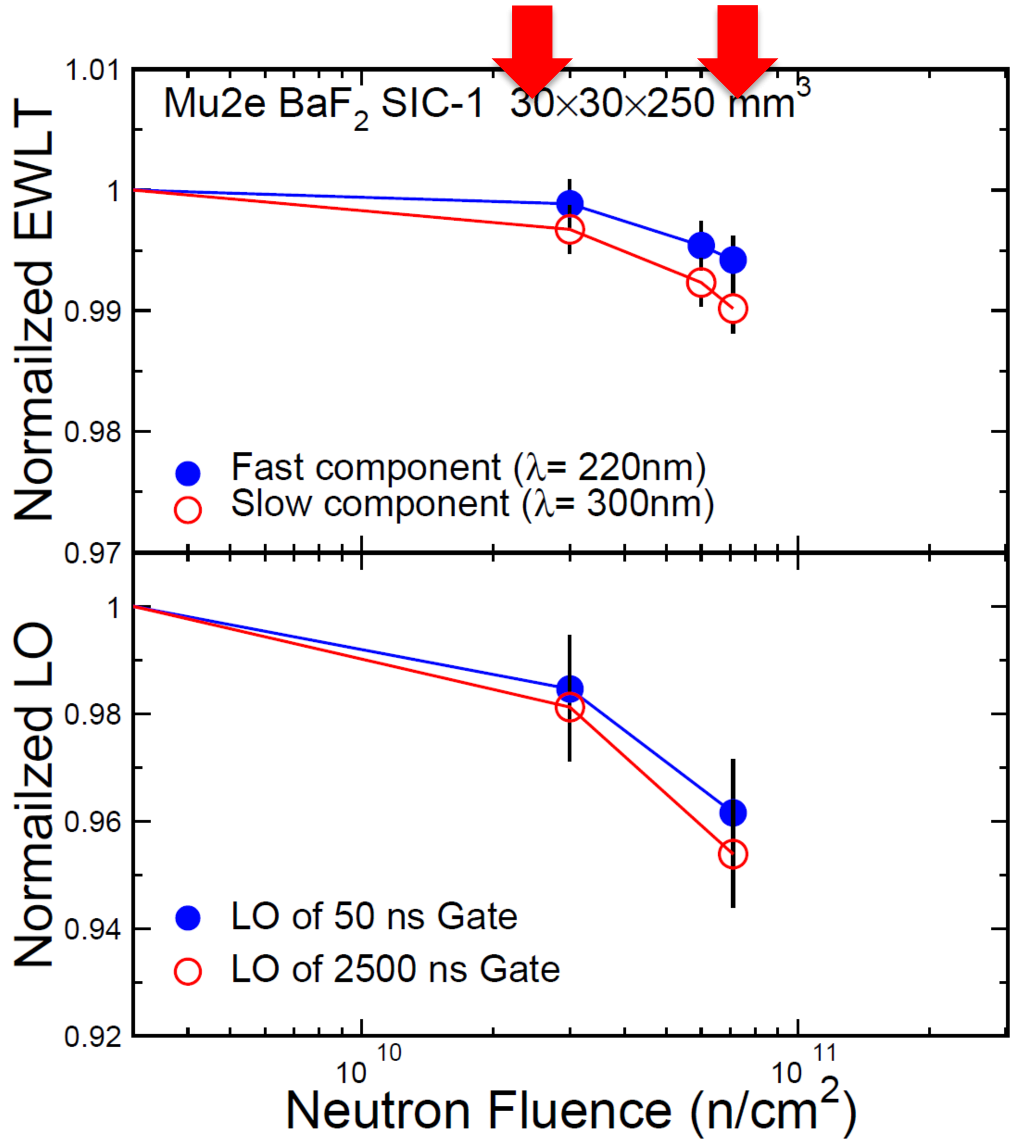
No Effect on LRU



Summary: Fast Neutron Induced Damage

The maximum yearly neutron fluence is 2.5 and 8 x 10^{10} n/cm^2 for disk 0 and 1.

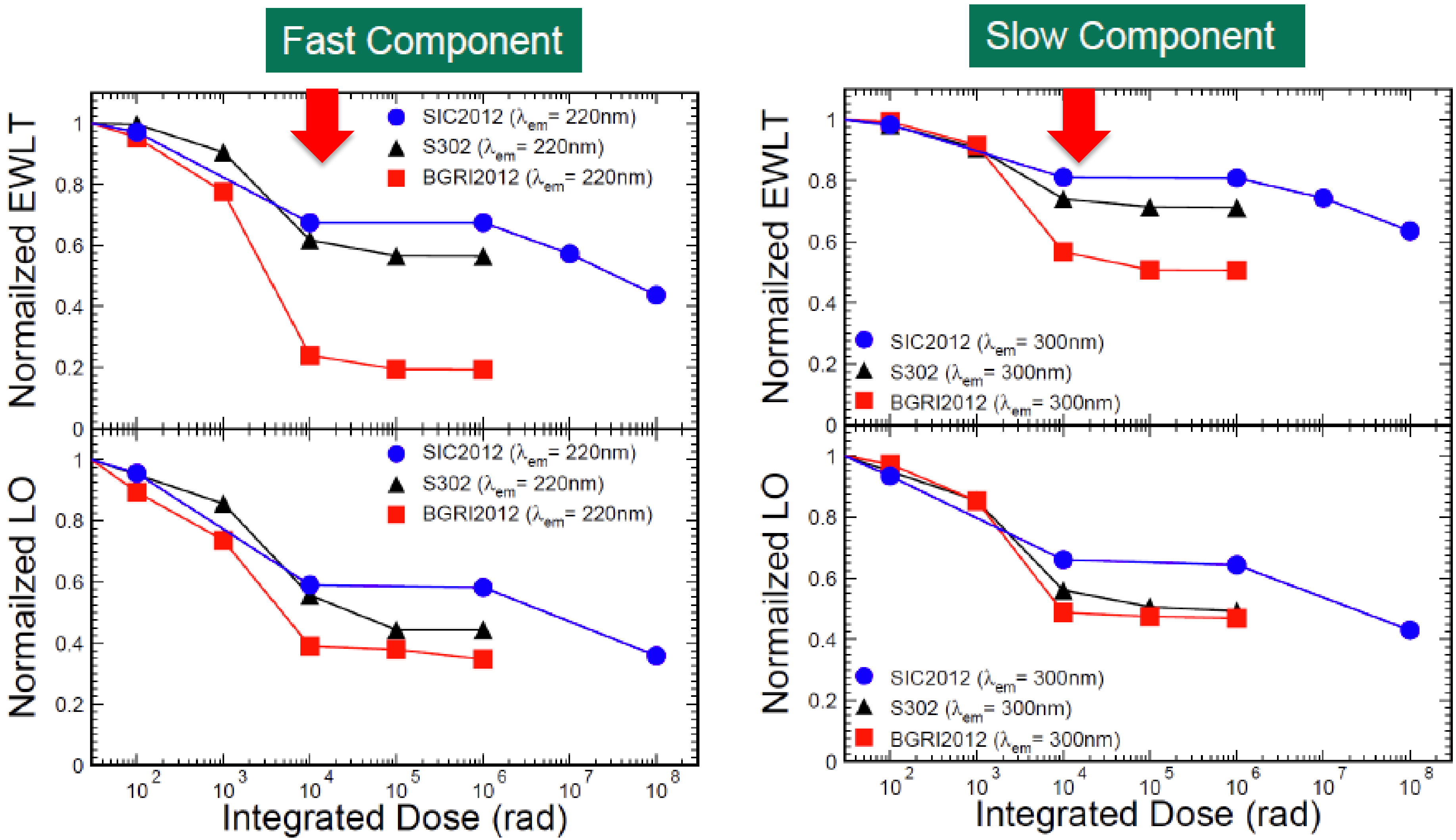
The radiation damage effect caused by fast neutron is smaller than γ-rays.



Summary

- With the fast component of sub-ns decay time BaF_2 crystals promise a very fast calorimeter for the Mu2e experiment.
- BaF_2 crystals from SICCAS show adequate optical quality and consistency.
- Radiation hardness of existing BaF_2 crystals against ɣ-rays and fast neutrons seems adequate for the Mu2e experiment.
- Two R&D issues are identified to further improve the quality of BaF_2 crystals.
  - LRU at 22% needs to be improved by controlled wrapping longitudinally.
  - The pile-up effect caused by the slow scintillation component needs to be mitigated by selective doping (in project), and/or selective readout. See David's Talk for solar-blind APD.

BaF_2: γ-ray Induced Radiation Damage



Mu2e