Fermilab

Calorimeter Technical Review:
Crystals: Quality & Radiation Hardness

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Introduction

- The Mu2e baseline choice is BaF_2 with pure CsI as backup.
- Requirements:
  - Light Output (LO): 100 p.e./MeV by bi-alkali PMT;
  - Light response uniformity (LRU): TBD, < 20%.
- Radiation environment:
  - Ionization dose: 10 krad/year → 100 krad;
  - Neutron fluence: 2 x 10^{11} n/cm^2/year → 10^{12} n/cm^2.
- Requirements after 100 krad and 10^{12} n/cm^2:
  - LO: > 50 p.e./MeV, no significant damage to LRU;
  - Radiation induced phosphorescence is under control.
- Since the CD-2 review investigations were concentrated on BaF_2 and pure CsI as backup from various vendors:
  - BaF_2: BGRI (Beijing), Incrom (St. Petersburg) and SICCAS;
  - Pure CsI: Kharkov, Opto Materials (Italy) and SICCAS.

Measurements

- Longitudinal transmittance (LT) was measured by using a Perkin-Elmer Lambda 950 spectrophotometer. (0.15%)
- Pulse height spectrum (PHS), FWHM energy resolution of 511 keV ɣ-rays (ER), LO, LRU and decay time were measured by a Hamamatsu R2059 PMT and coincidence triggers from a ^{22}Na source. All samples were wrapped with two layers of Tyvek paper. (<1%)
- PHS/ER/LO/LRU were measured with Dow-Corning 200 grease and air gap respectively for BaF_2 and pure CsI because of the soft and hygroscopic surface of CsI.
- Gamma-ray irradiation was carried out at Caltech with degradations in LT, LO, FWHM and LRU measured.
- Neutron irradiation was carried out at Caltech and INFN.

Basic Property of BaF_2 and pure CsI

	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	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)

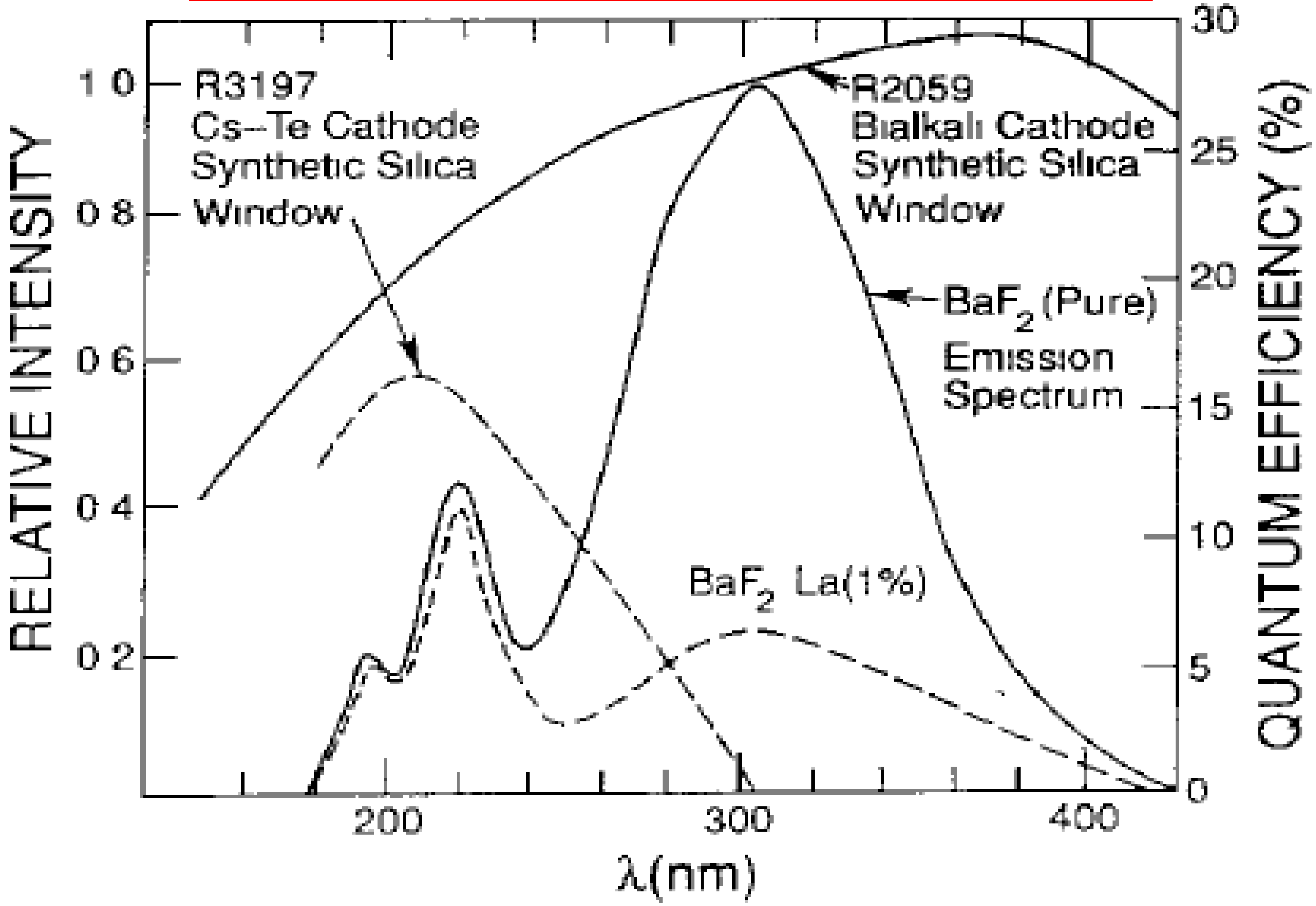
#. Softening point

Pure CsI and the fast component of BaF_2 provide similar LO
The slow component of BaF_2 provides much high LO

BaF_2 Scintillation Light

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

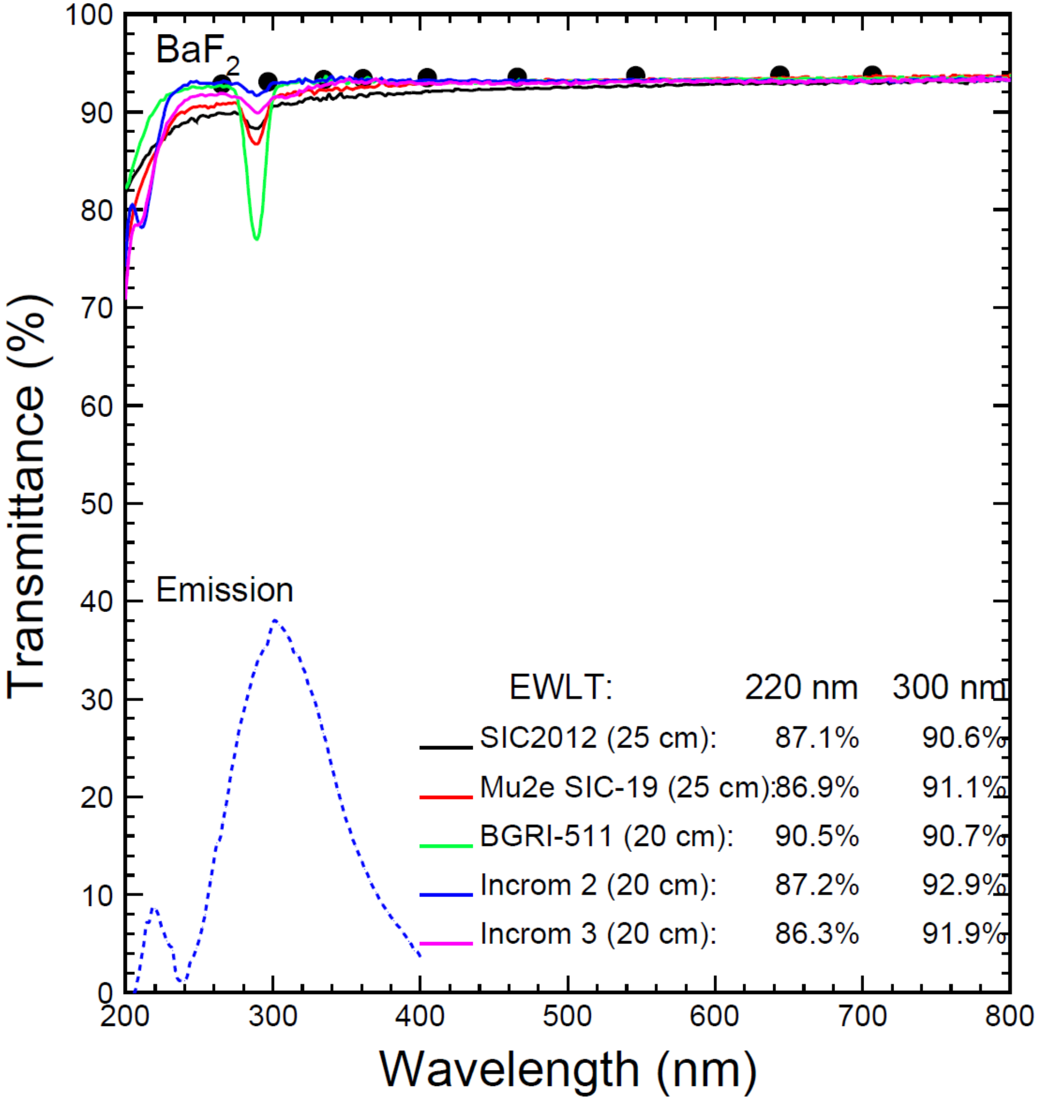
R. Y. Zhu, "On Quality Requirements to the Barium Fluoride-Crystals," *Nucl Instrum Meth A,* vol. 340, pp. 442-457, Mar 8 1994



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
Incrom 2, 3	Incrom	30x30x200	Six faces

Comparison of BaF_2 Optical Properties



EWLT, or emission weighted longitudinal transmittance, is defined as:

$$\mathrm{EWLT} = \frac{\int \mathrm{LT}(\lambda)\mathrm{Em}(\lambda)d\lambda}{\int \mathrm{Em}(\lambda)d\lambda}$$

RADIATION EFFECTS: RIAC, or radiation induced absorption coefficient, is defined as:

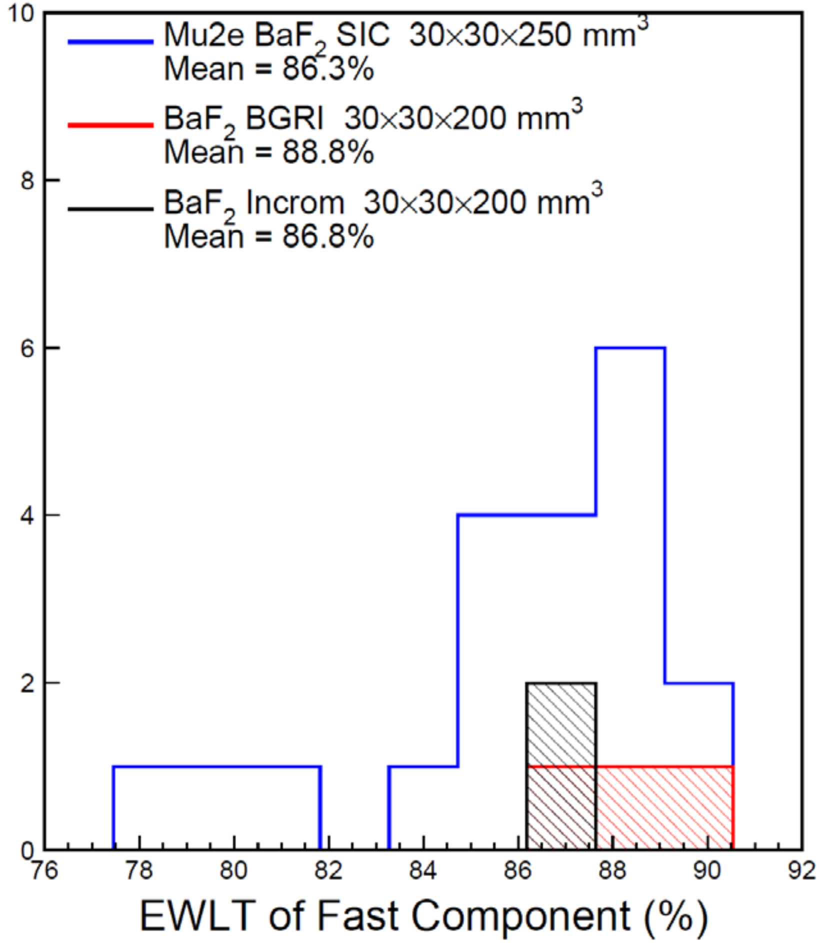
$$\mathrm{RIAC} = \frac{1}{l}\ln\frac{T_0(\lambda)}{\mathrm{T}(\lambda)}$$

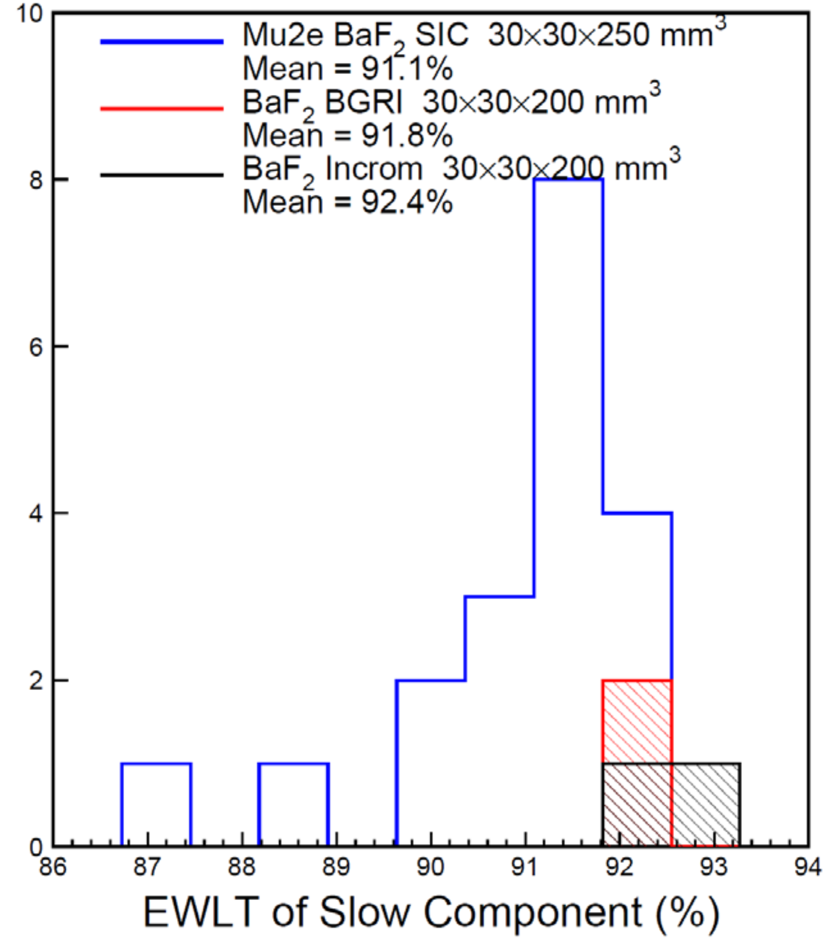
EWRIAC or emission weighted radiation induced absorption coefficient is defined as:

$$\mathrm{EW}RIAC = \frac{\int RIAC(\lambda)\mathrm{Em}(\lambda)d\lambda}{\int \mathrm{Em}(\lambda)d\lambda}$$

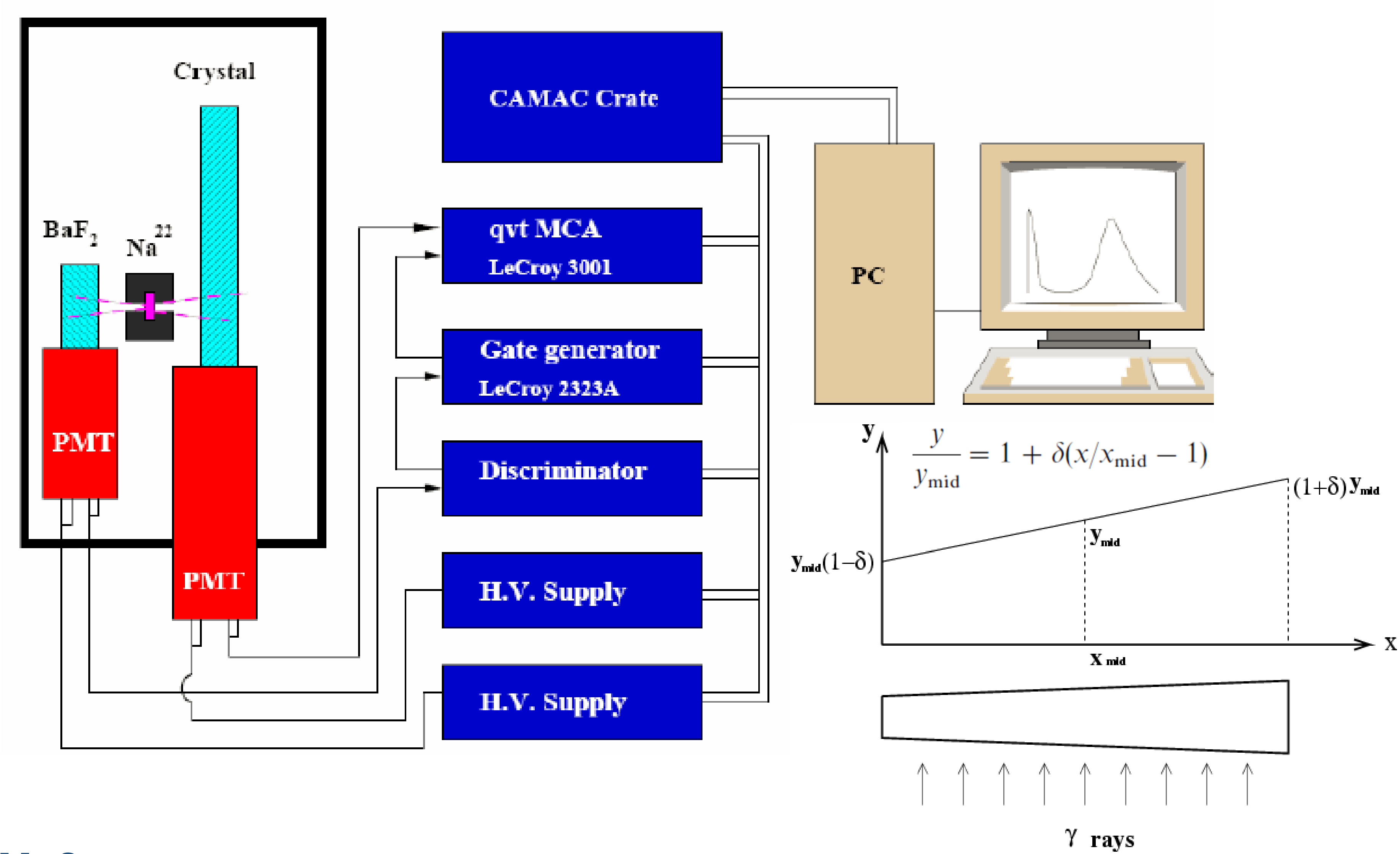
Comparison of BaF_2 EWLT

BGRI and Incrom consist; 20 cm samples is better than 25 cm samples





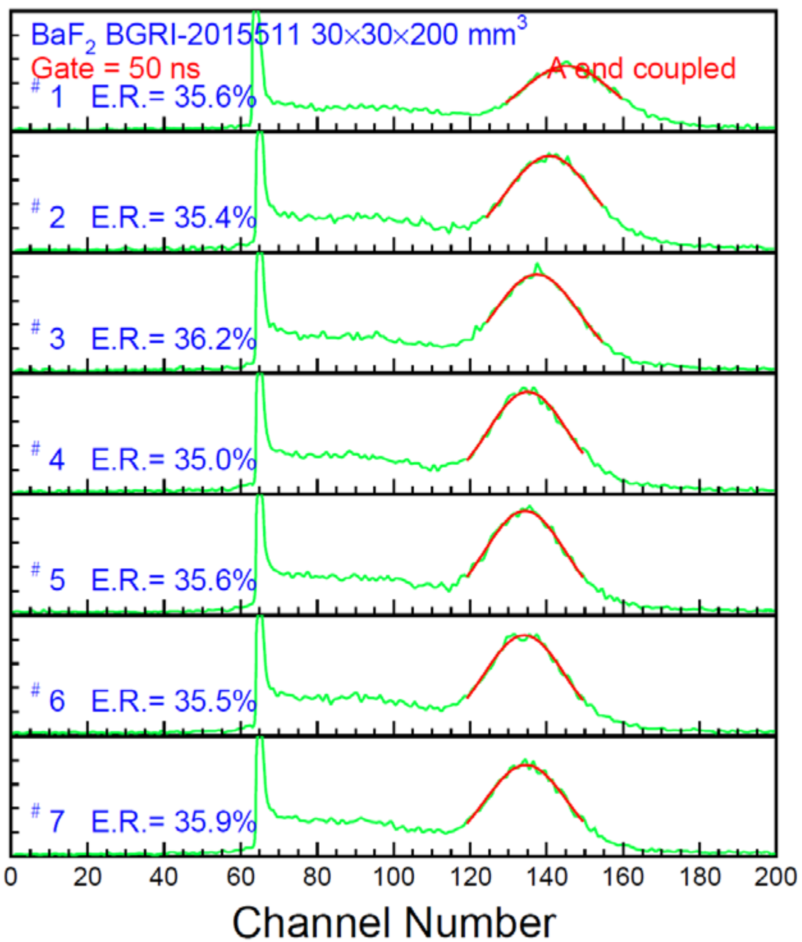
Setup for LO & LRU Measurements

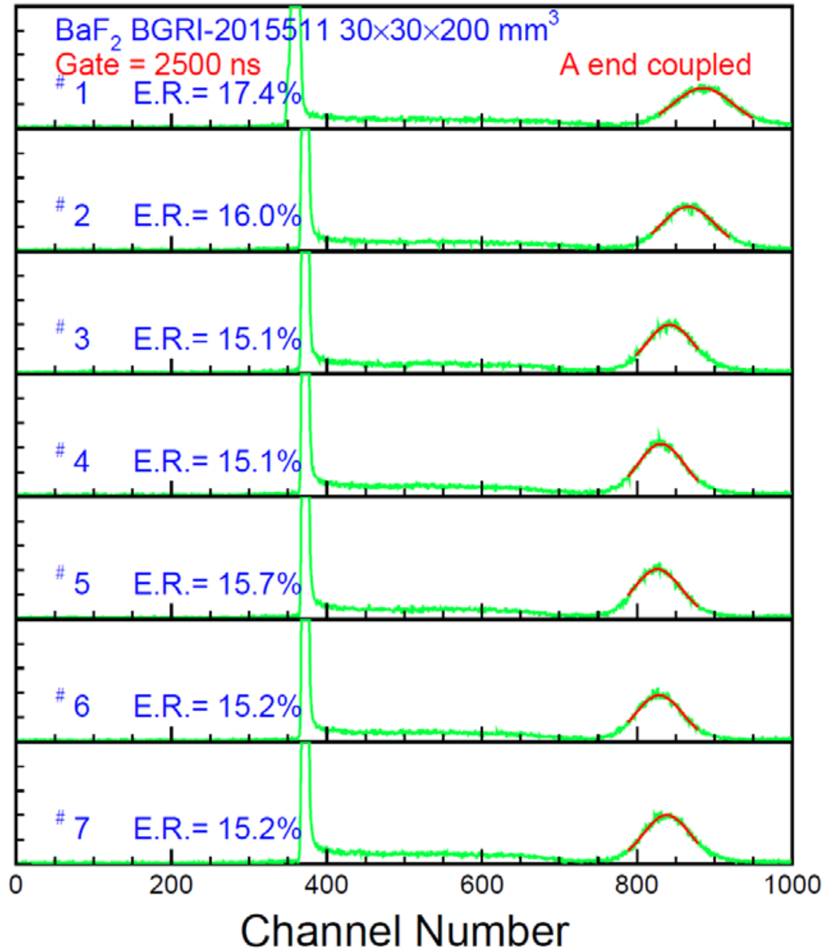


Pulse Height Spectra: BGRI 511

50 ns: ER = 35.6%

2.5 µs: ER = 15.7%

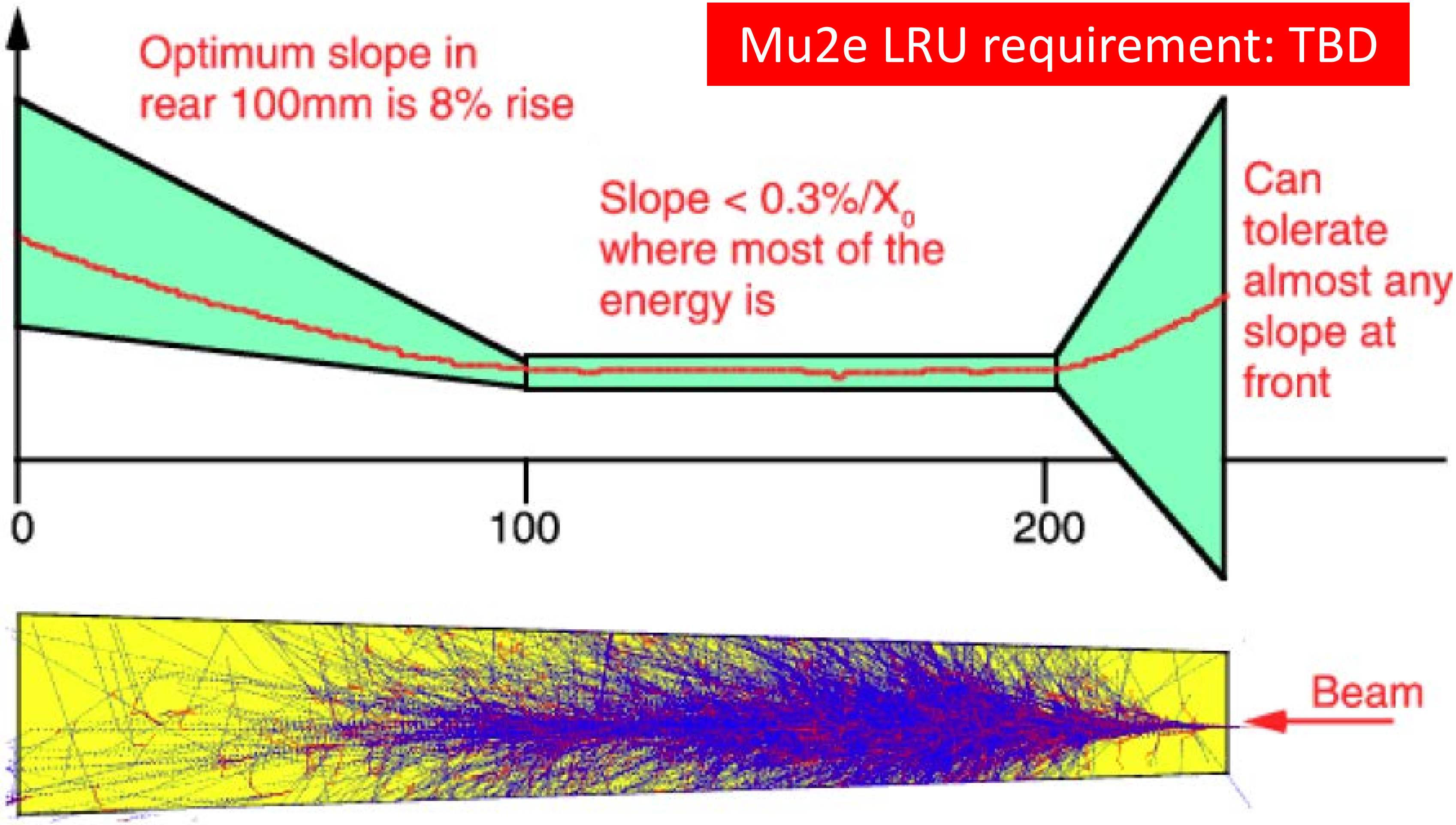




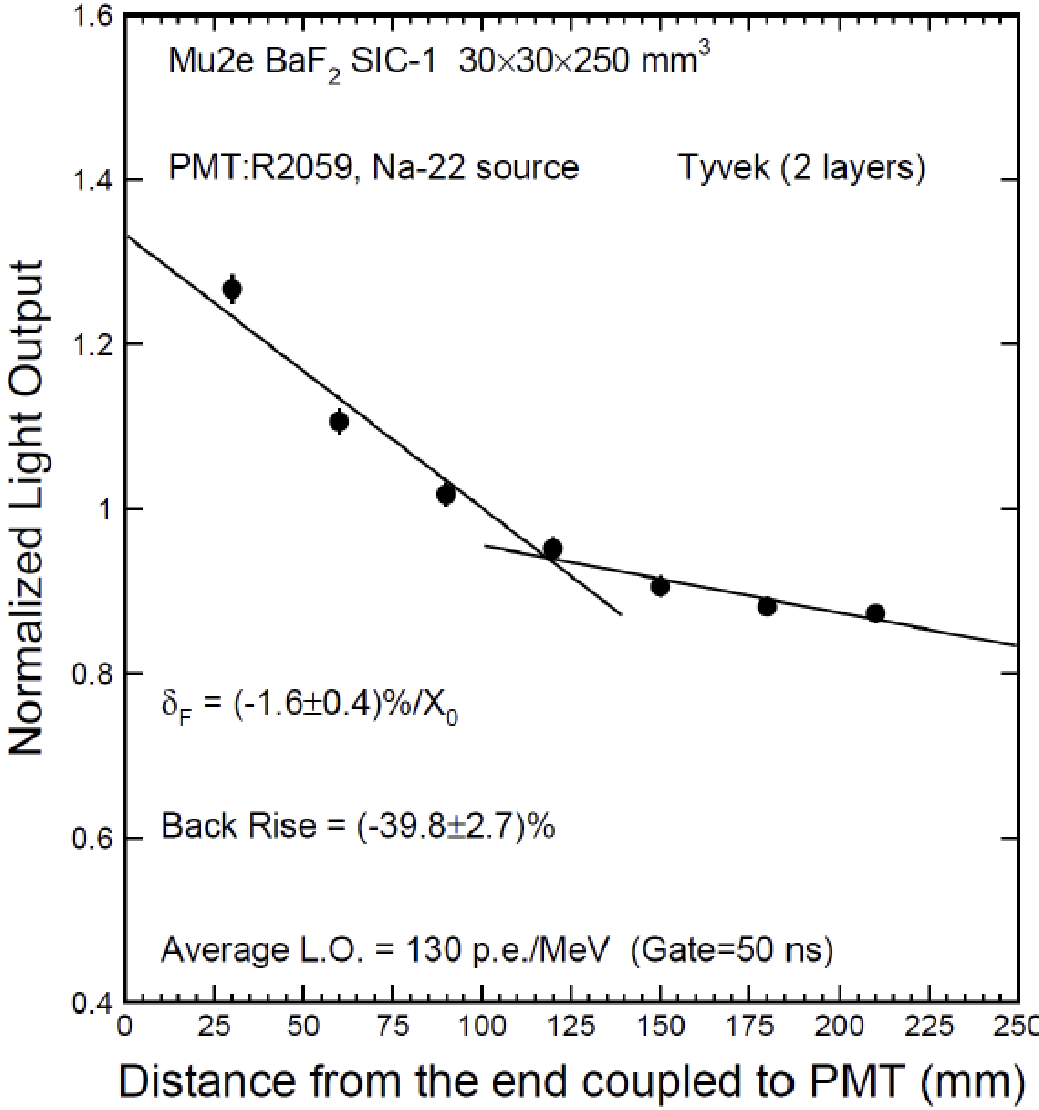
CMS LRU Spec for Tapered Crystal

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

Mu2e LRU requirement: TBD



Front Slope and Back Rise



First four points and last four points were fit to

$Y = a + b \times x$ and

$Y = c + d \times x$

respectively.

Front Slope

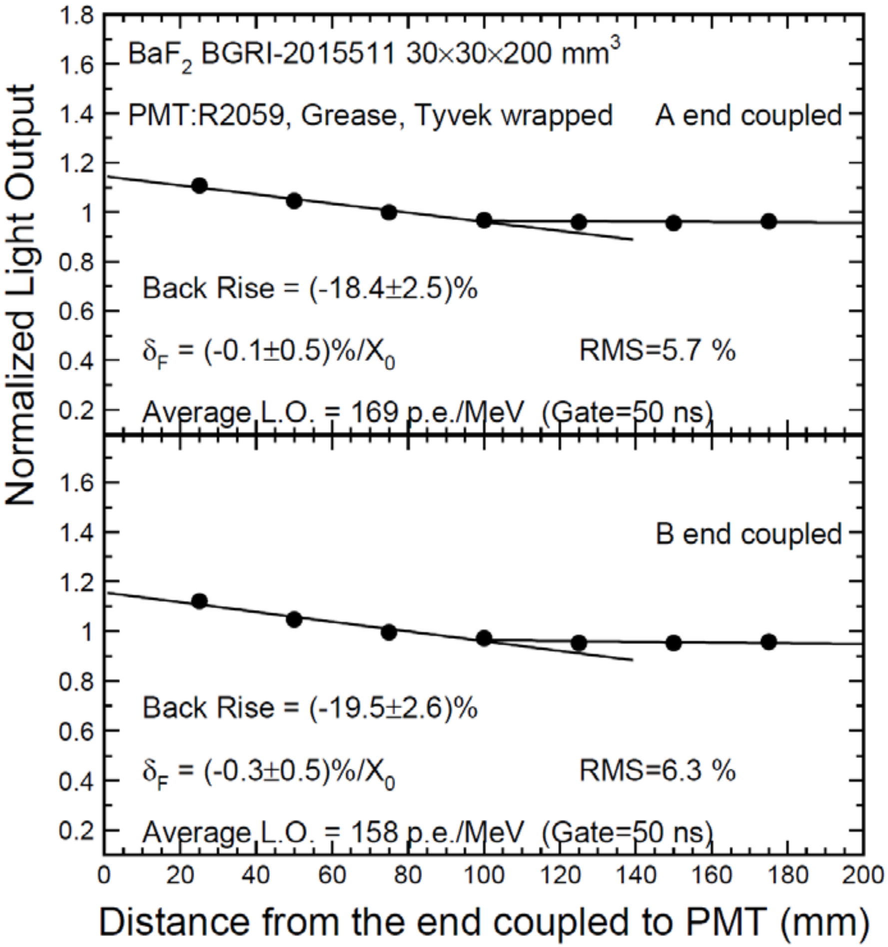
$$\delta_F = d \times 20.3\ mm$$

Back Rise

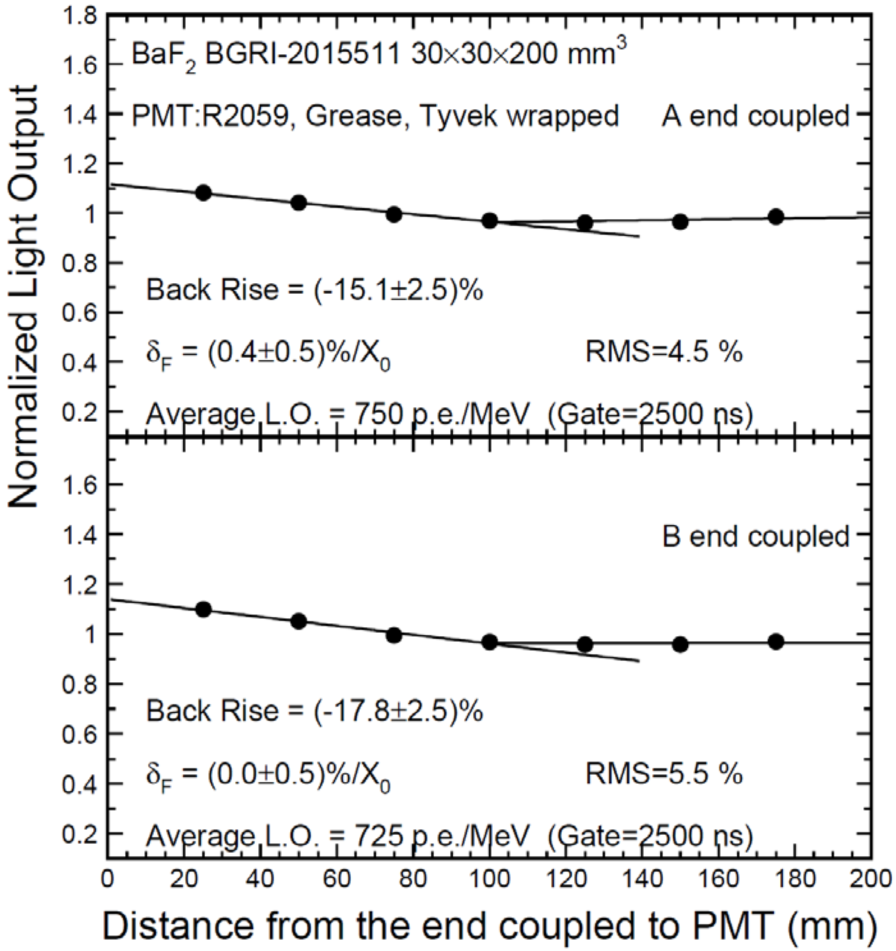
$$R_B = b \times 120\ mm$$

LO & LRU of BGRI 511 BaF_2 Sample

50 ns: 169 p.e./MeV



2.5 µs: 750 p.e./MeV

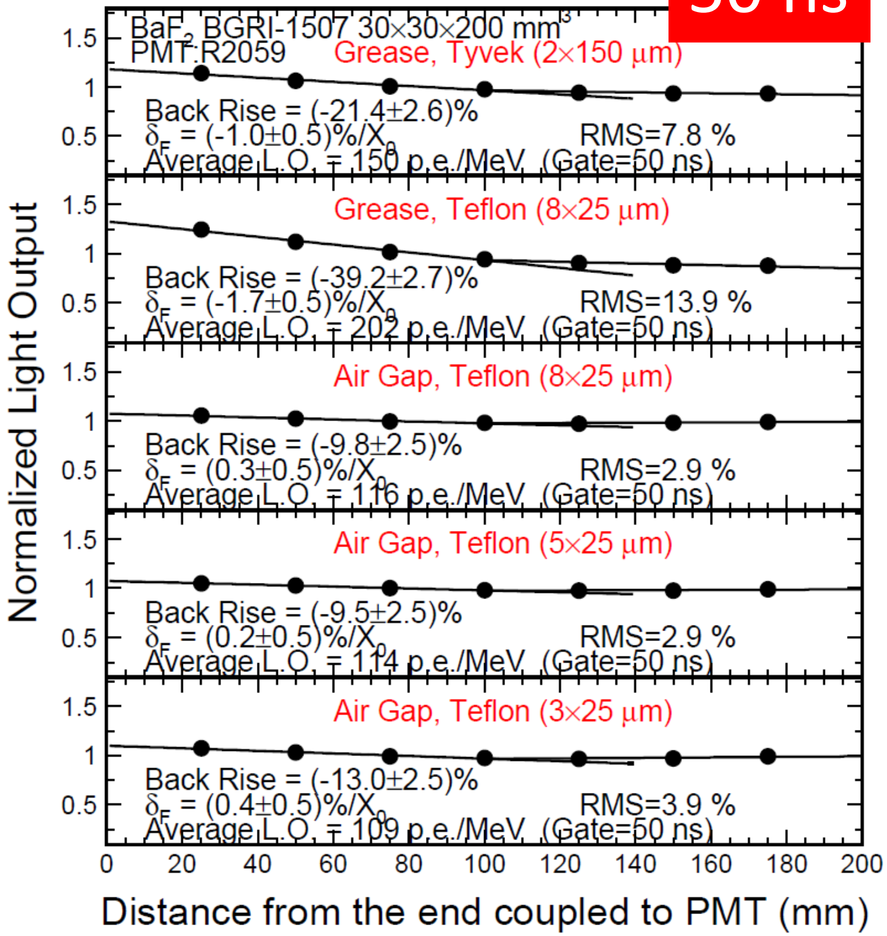


Summary: Initial BaF_2 Properties

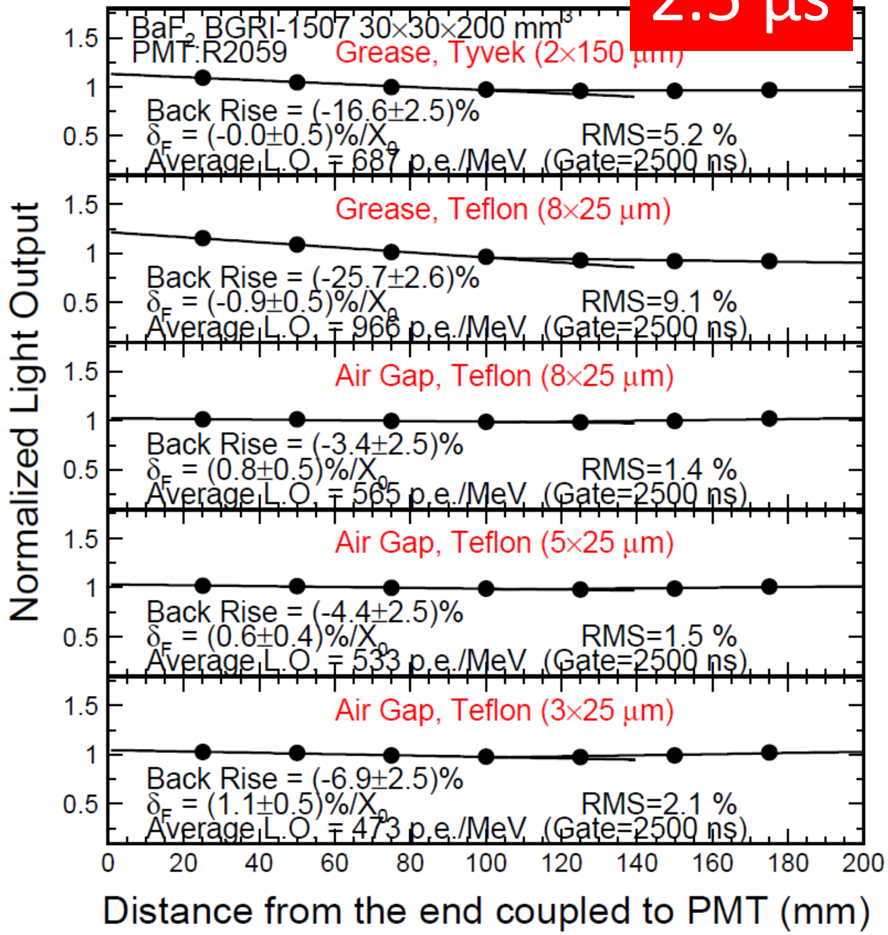
ID	Ave of 20 SIC Crystals	Ave of 3 BGRI	Ave of 2 Incrom
Dimension	30x30x250	30x30x200	30x30x200
T@220 nm (%)	85.5±0.2	87.7±0.2	85.0±0.2
T@300 nm (%)	91.3±0.2	92.3±0.2	92.2±0.2
EWLT of Fast Component (%)	86.1±0.2	88.8±0.2	86.8±0.2
EWLT of Slow Component (%)	91.1±0.2	91.8±0.2	92.4±0.2
LO 50 ns Gate (p.e./MeV)	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

BaF_2 LO & LRU: Different Wrapping

50 ns

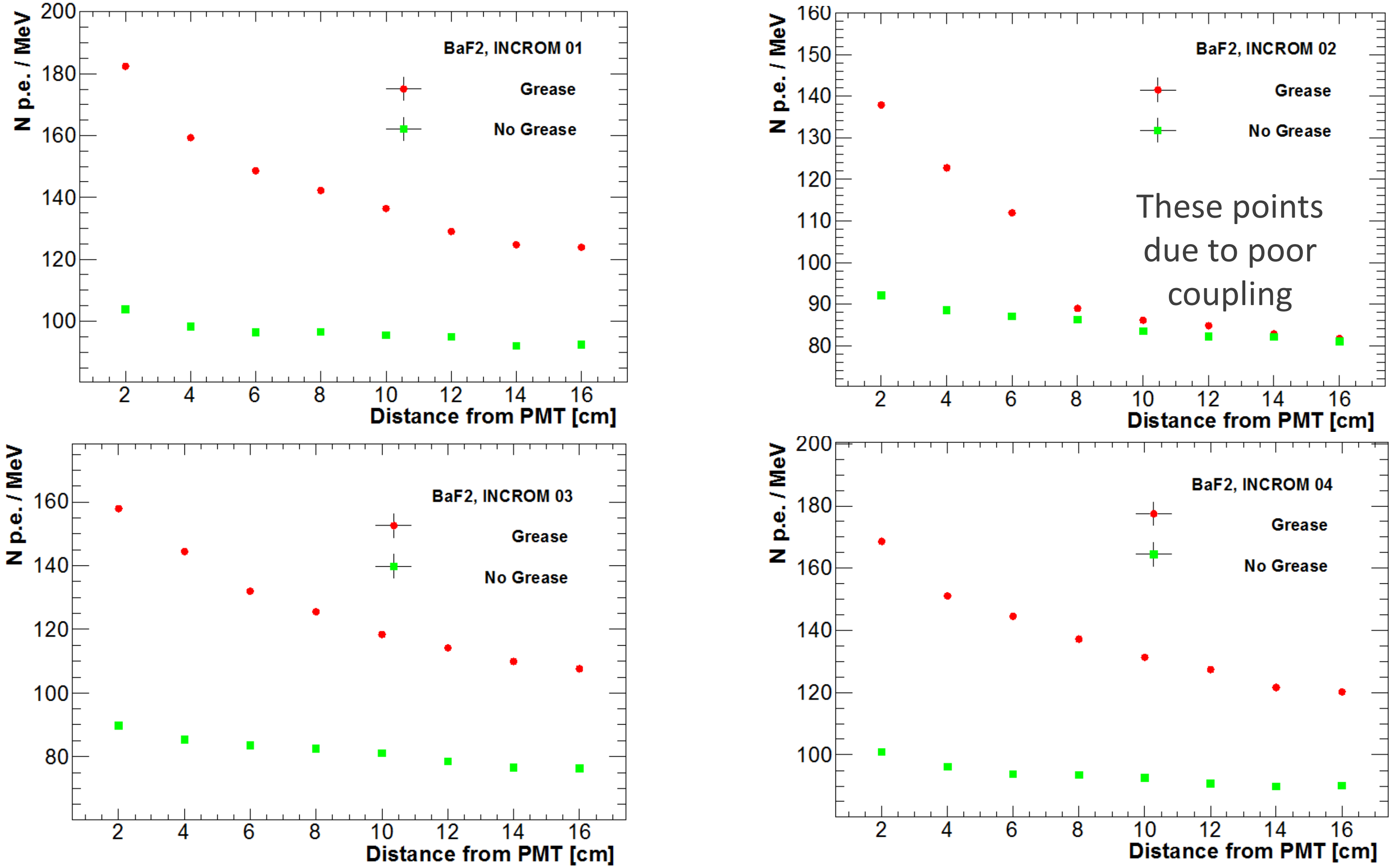


2.5 µs



Result measured at Caltech is consistent with INFN data

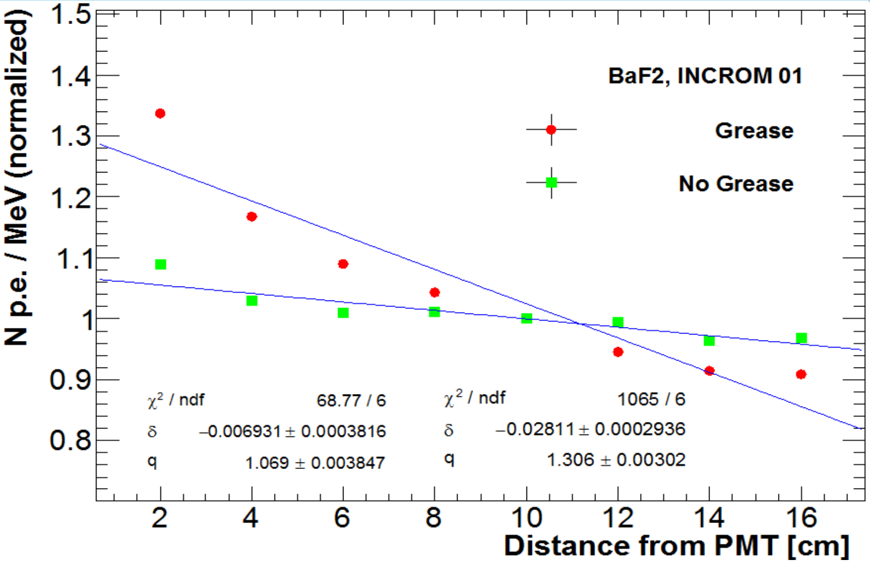
Incrom BaF_2 - Light Output (INFN)

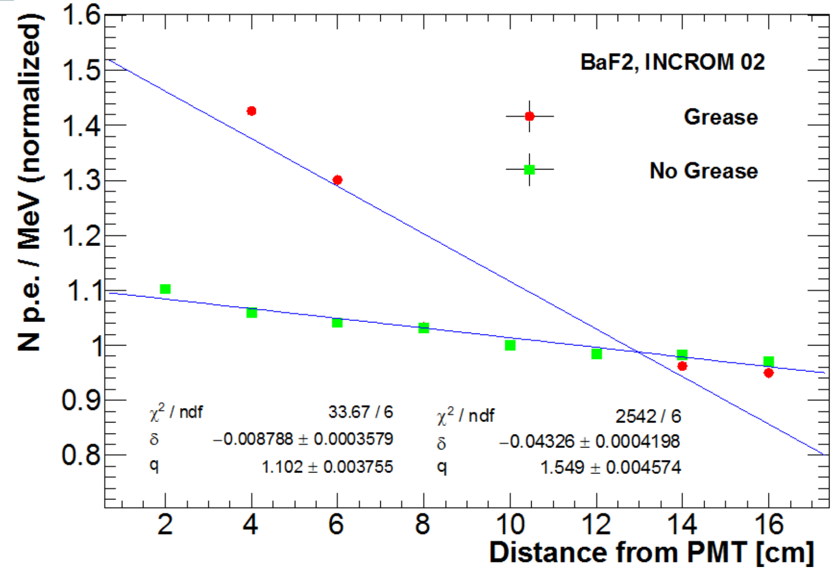


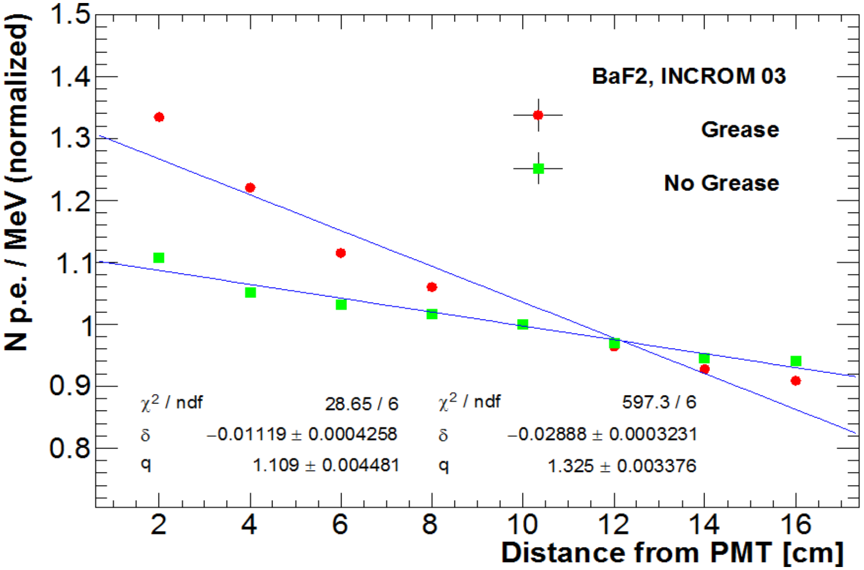
W grease -> LY ~ (80÷100)$N_{p.e}$/MeV, LRU ~±(7÷11)%

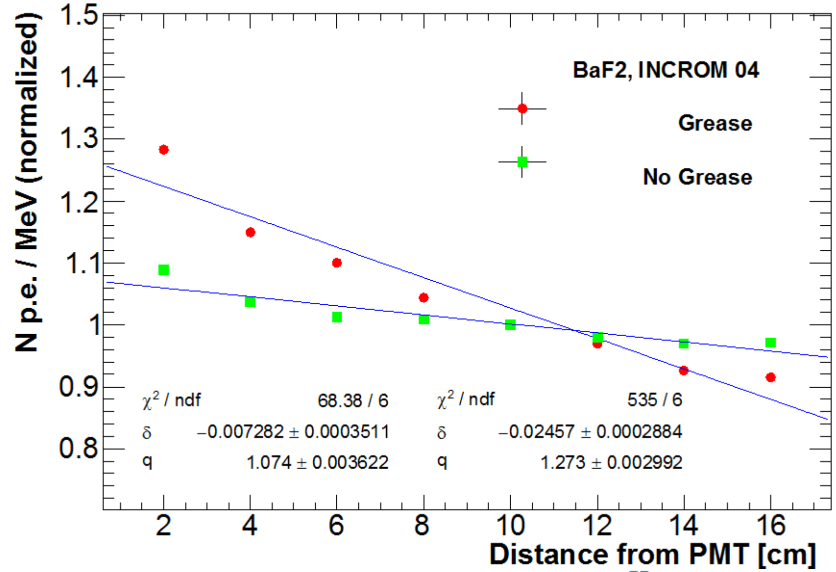
Wo grease -> LY ~ (120÷180)$N_{p.e}$/MeV, LRU ~±(25÷30)%

Incrom BaF_2 – Normalized LRU (INFN)



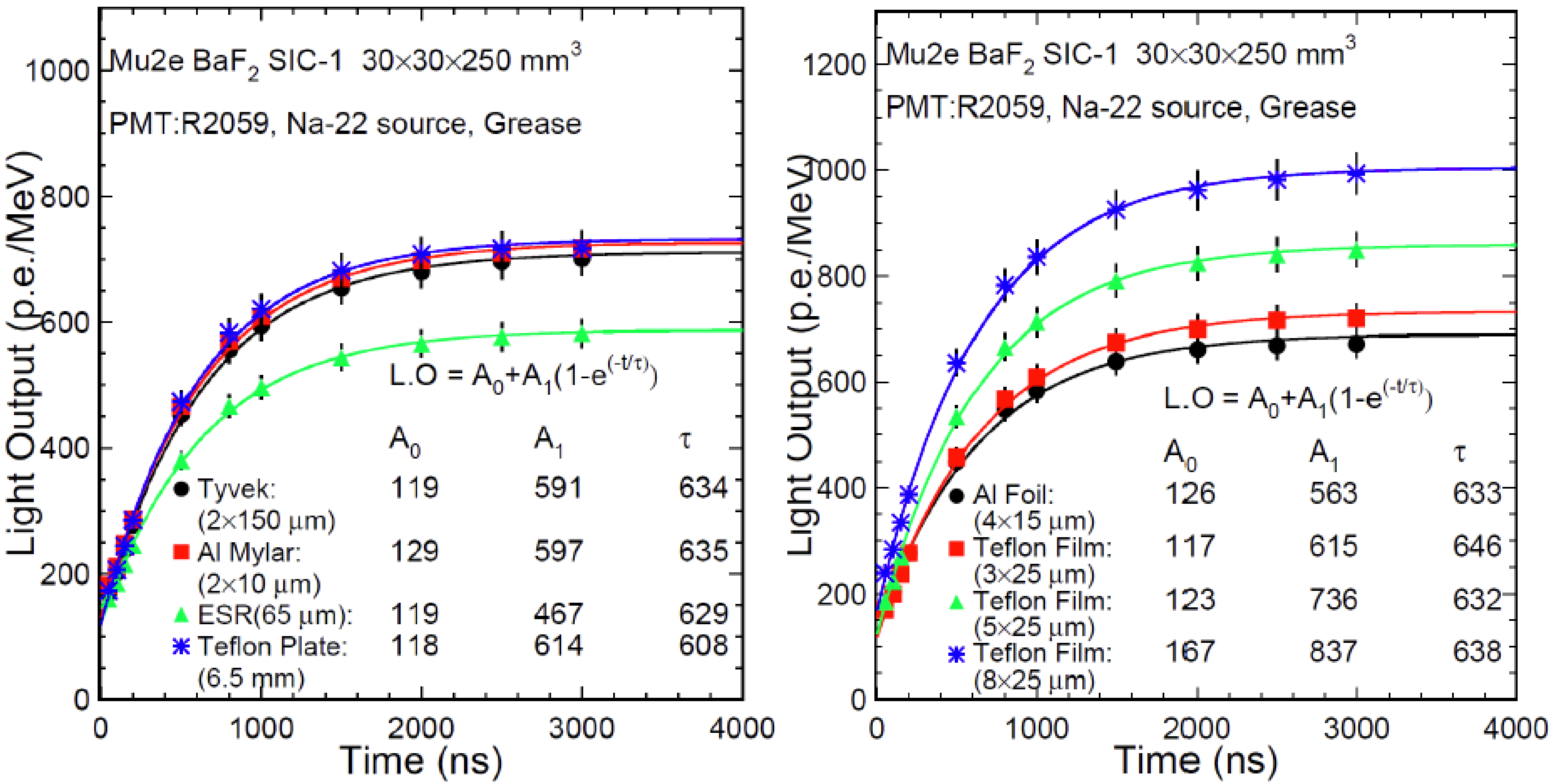




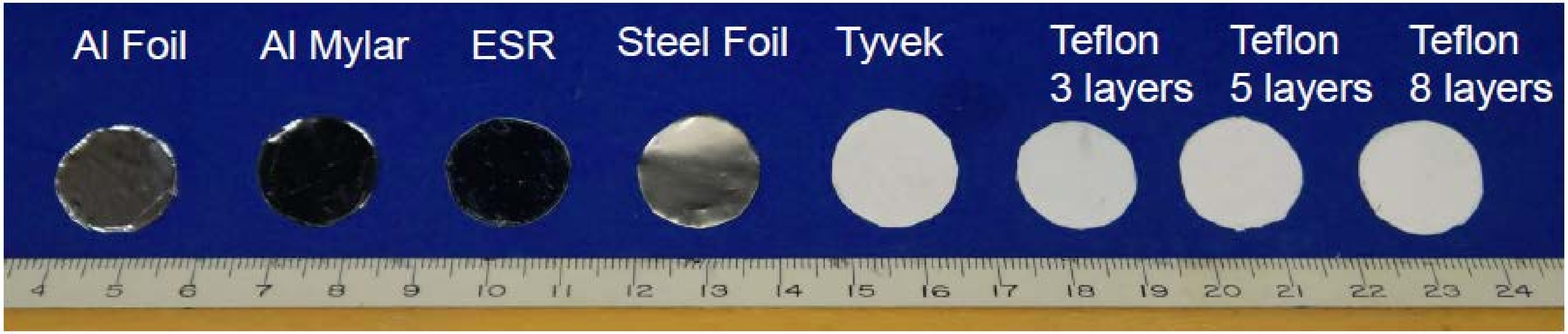


Effect of Crystal Wrapping for BaF_2

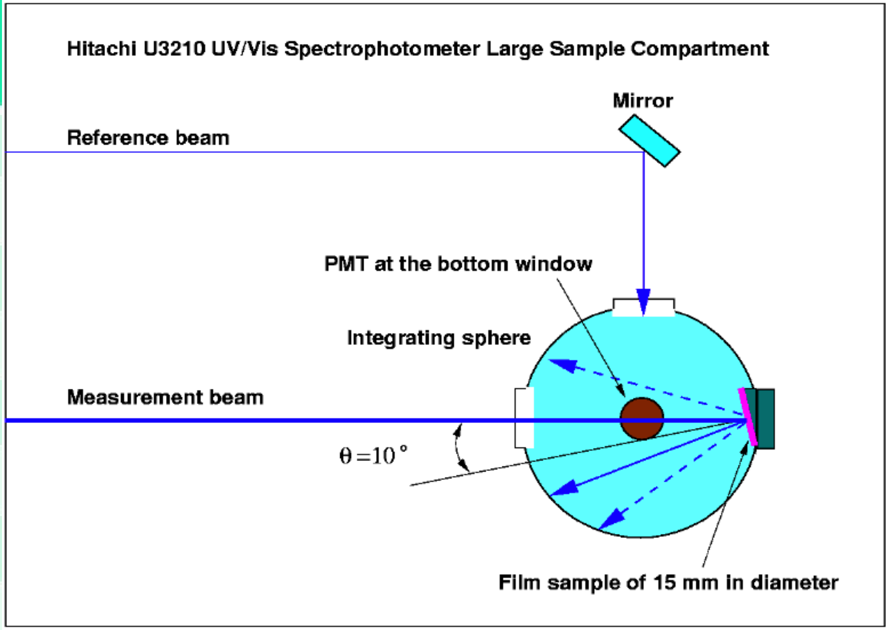
The highest LO is observed with 8 layer Teflon wrapping



Reflectance Measurements

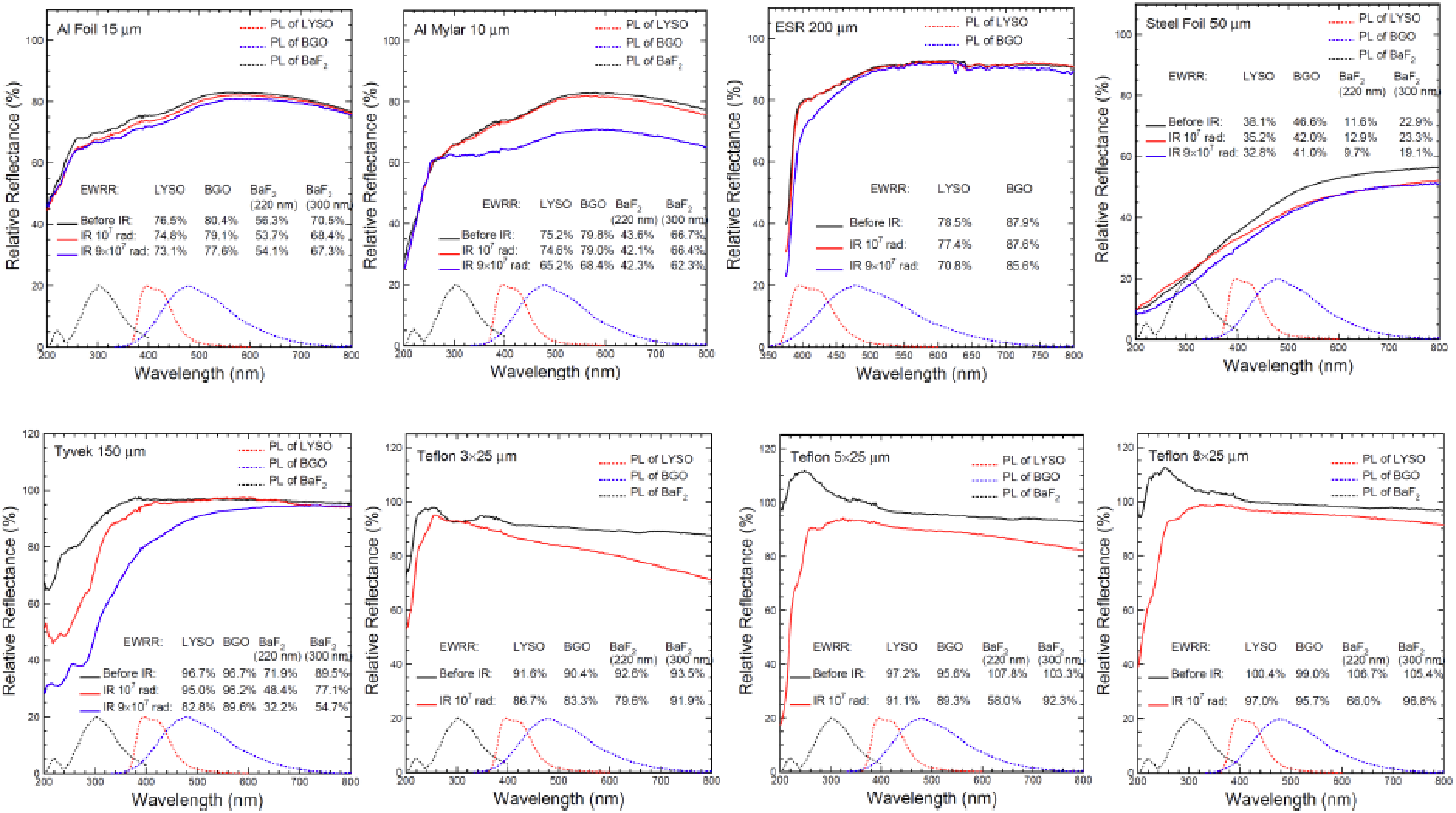


Sample ID	Thickness (μm)
Al Foil	15
Al Mylar	10
ESR	65
Steel Foil	50
Tyvek	150
Teflon ×3	25×3
Teflon ×5	25×5
Teflon ×8	25×8



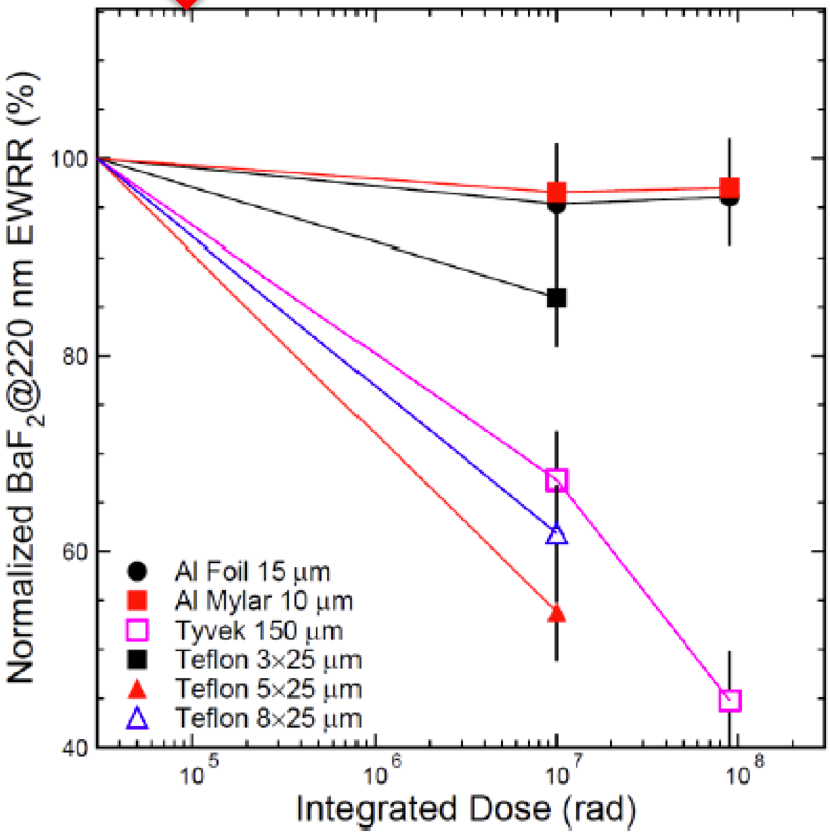
Radiation Damage in Wrapping Materials (I)

Both Al foil and Teflon film are good for Mu2e

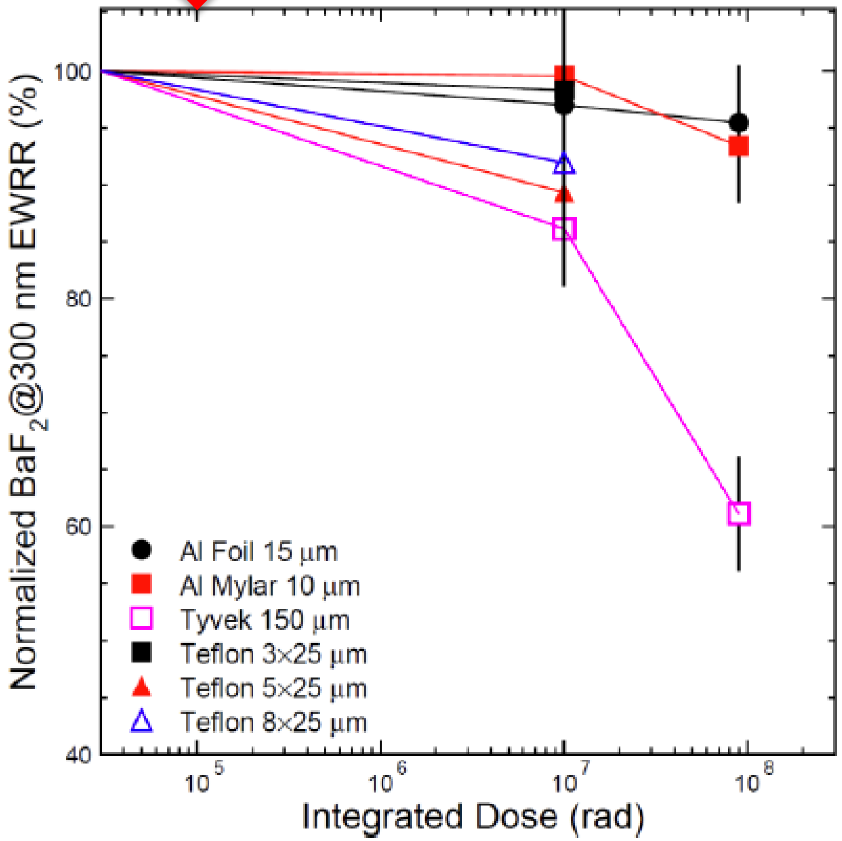


Radiation Damage in Wrapping Materials (II)

Both Al foil and Teflon film are good for Mu2e



Fast Component

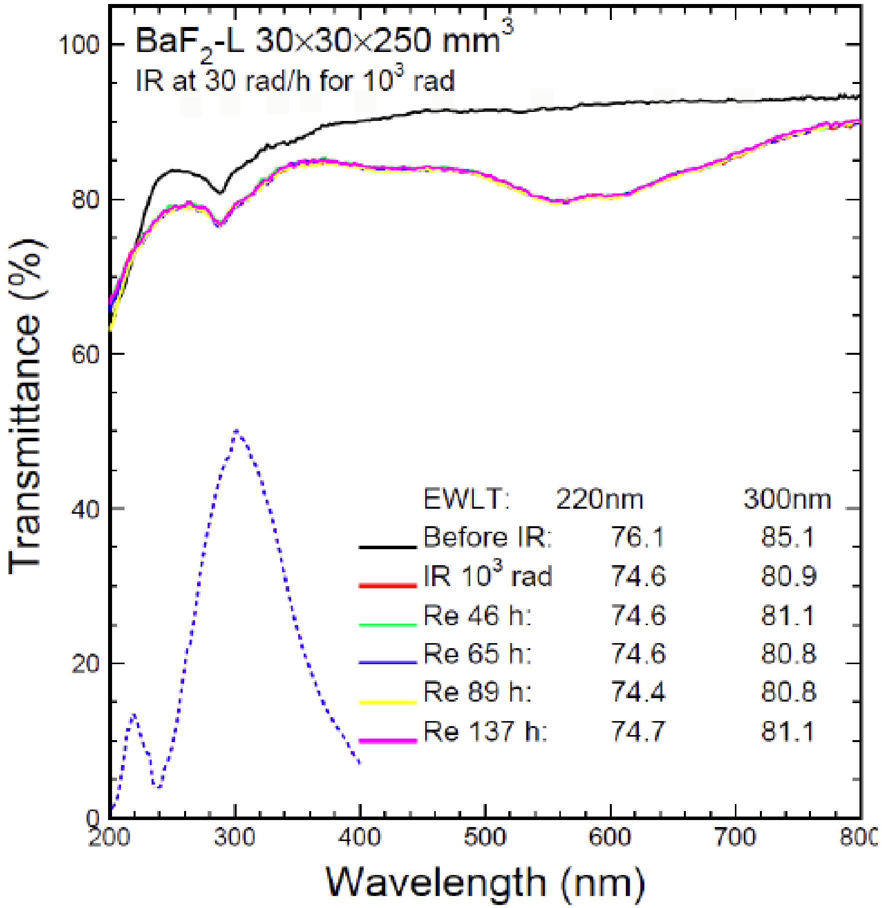


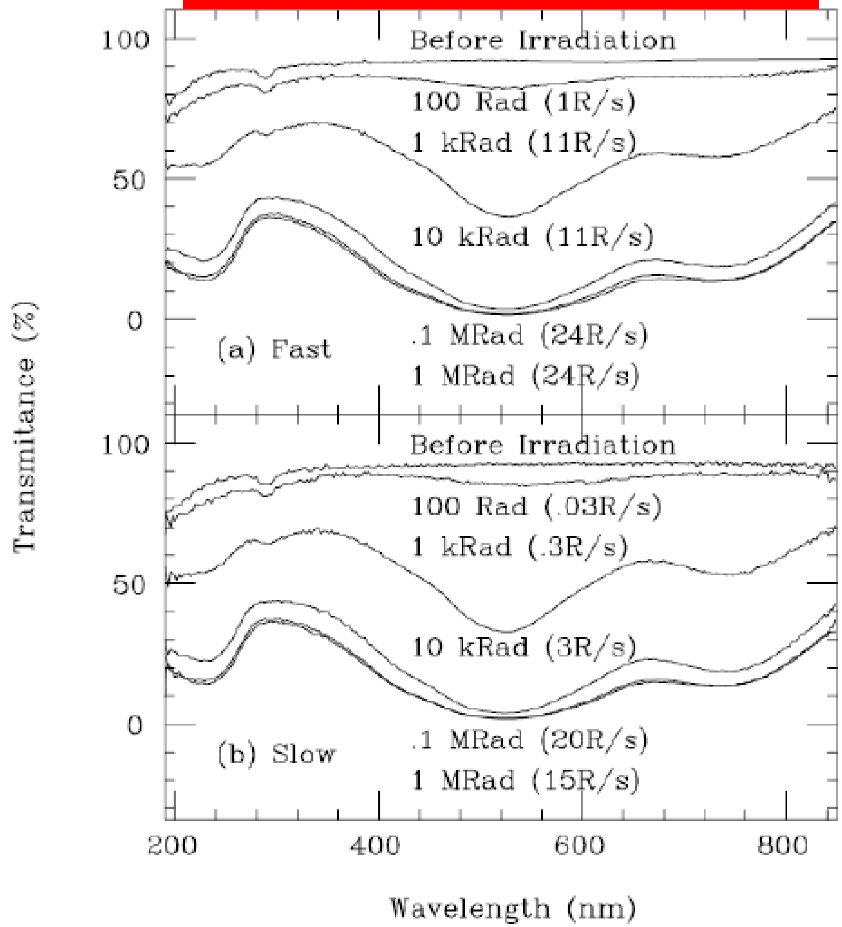
Slow Component

BaF_2: No Damage Recovery

Damage in BaF_2 does not recover, so is dose rate independent

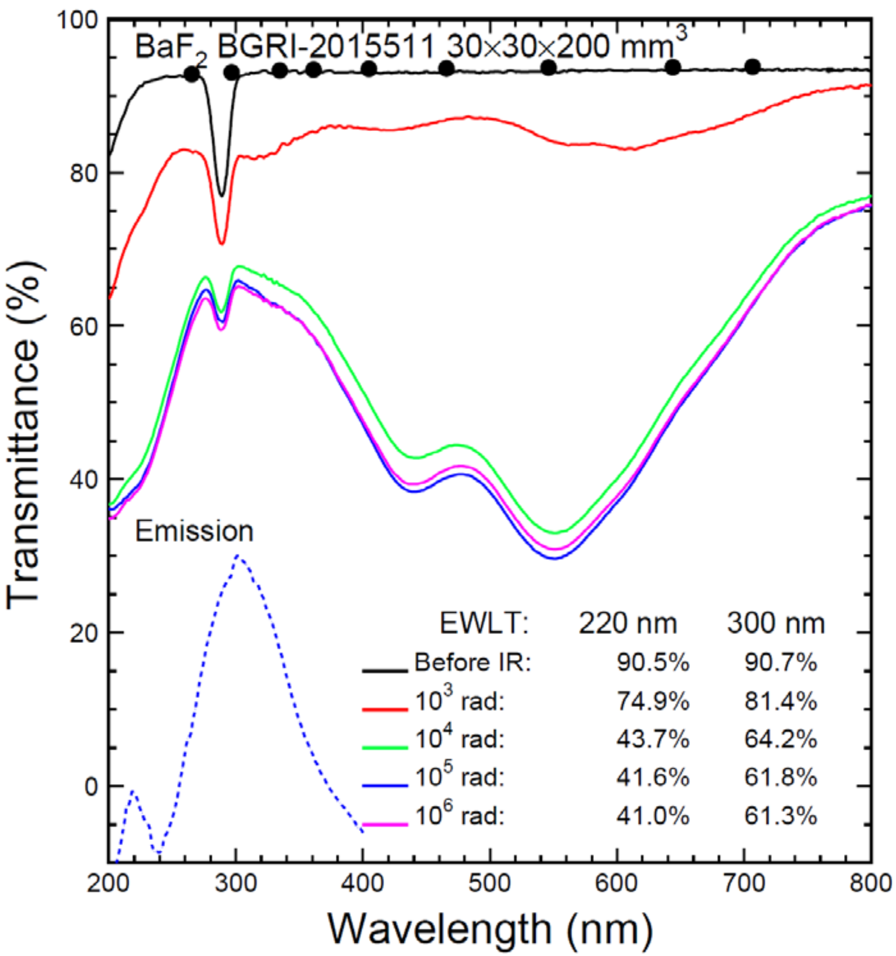
NIM A, vol. 340, pp. 442-457, Mar 8 1994

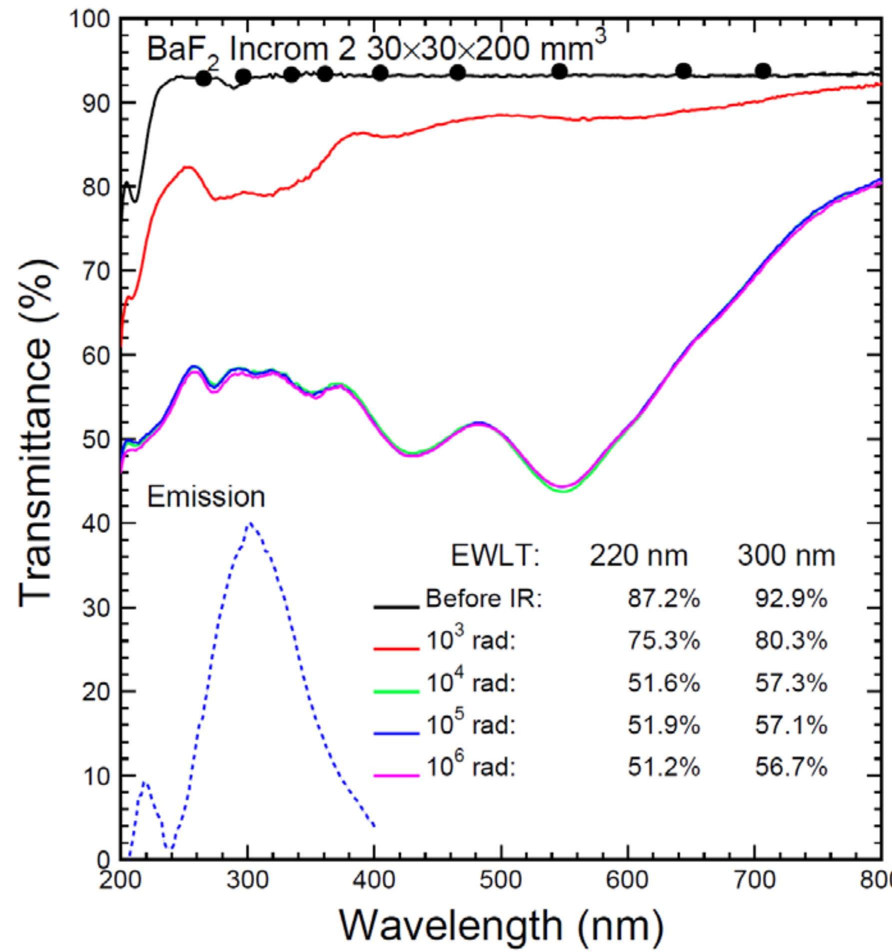




LT : BGRI 511 & Incrom 2 BaF_2 Samples

Radiation induced absorption is affected by raw materials and processing

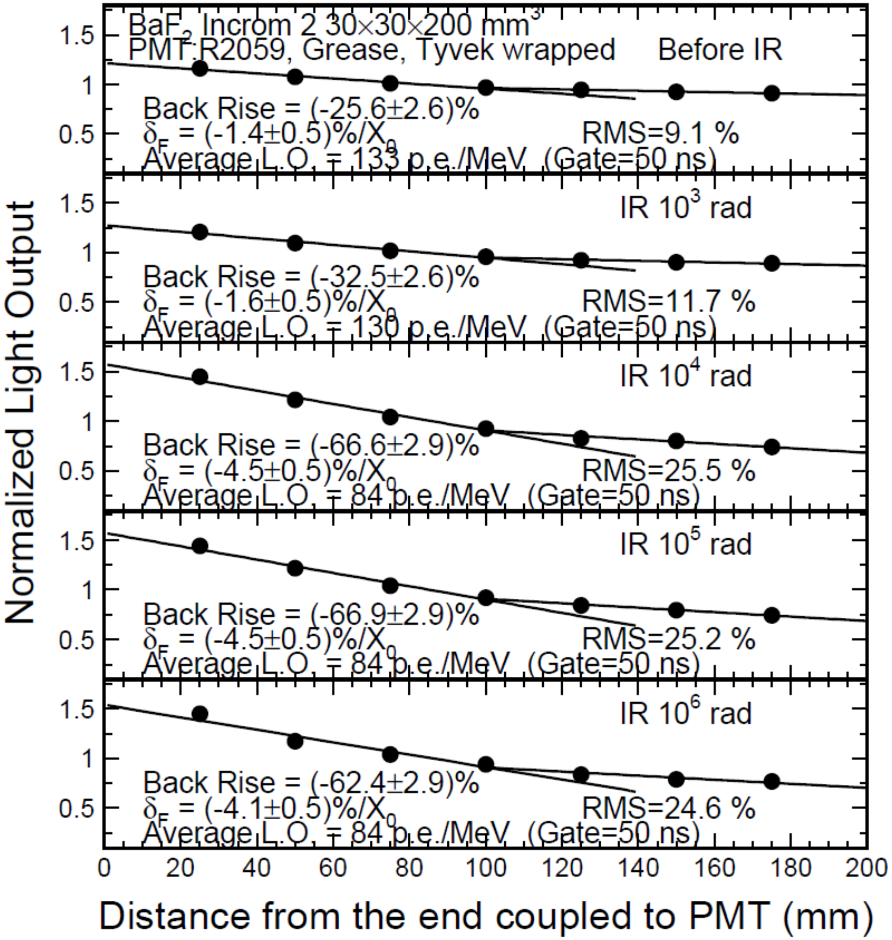


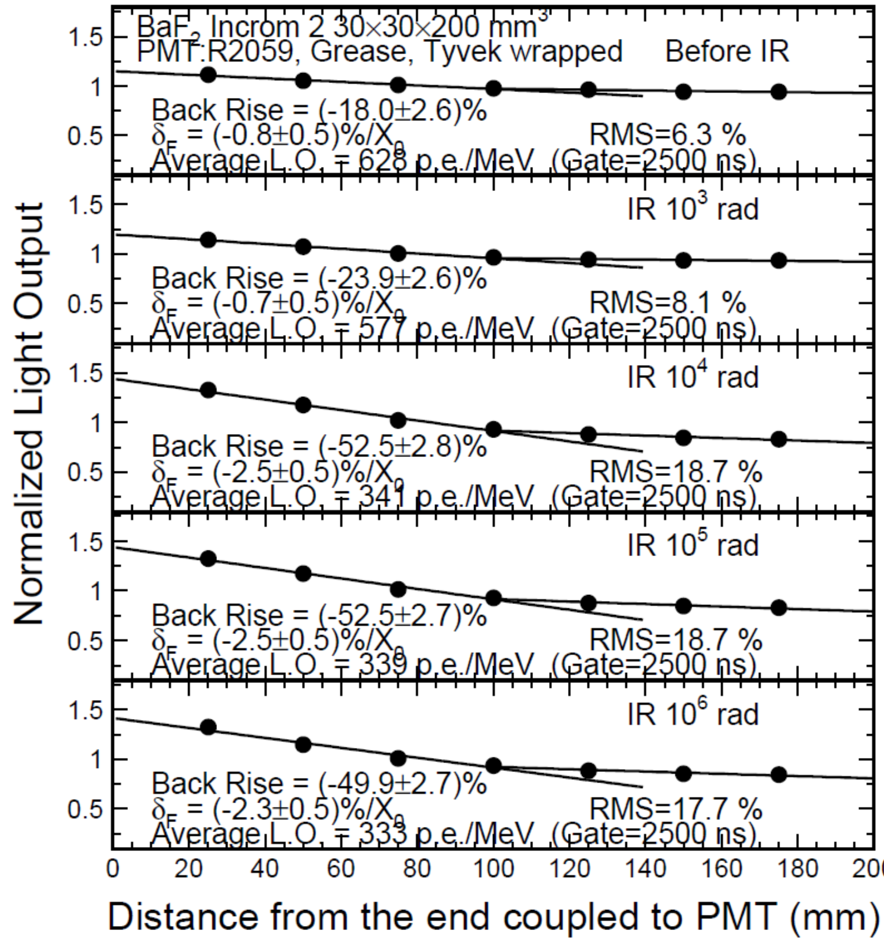


LO & LRU: Incrom 2 BaF_2 Sample

50 ns: 133 to 84 p.e./MeV

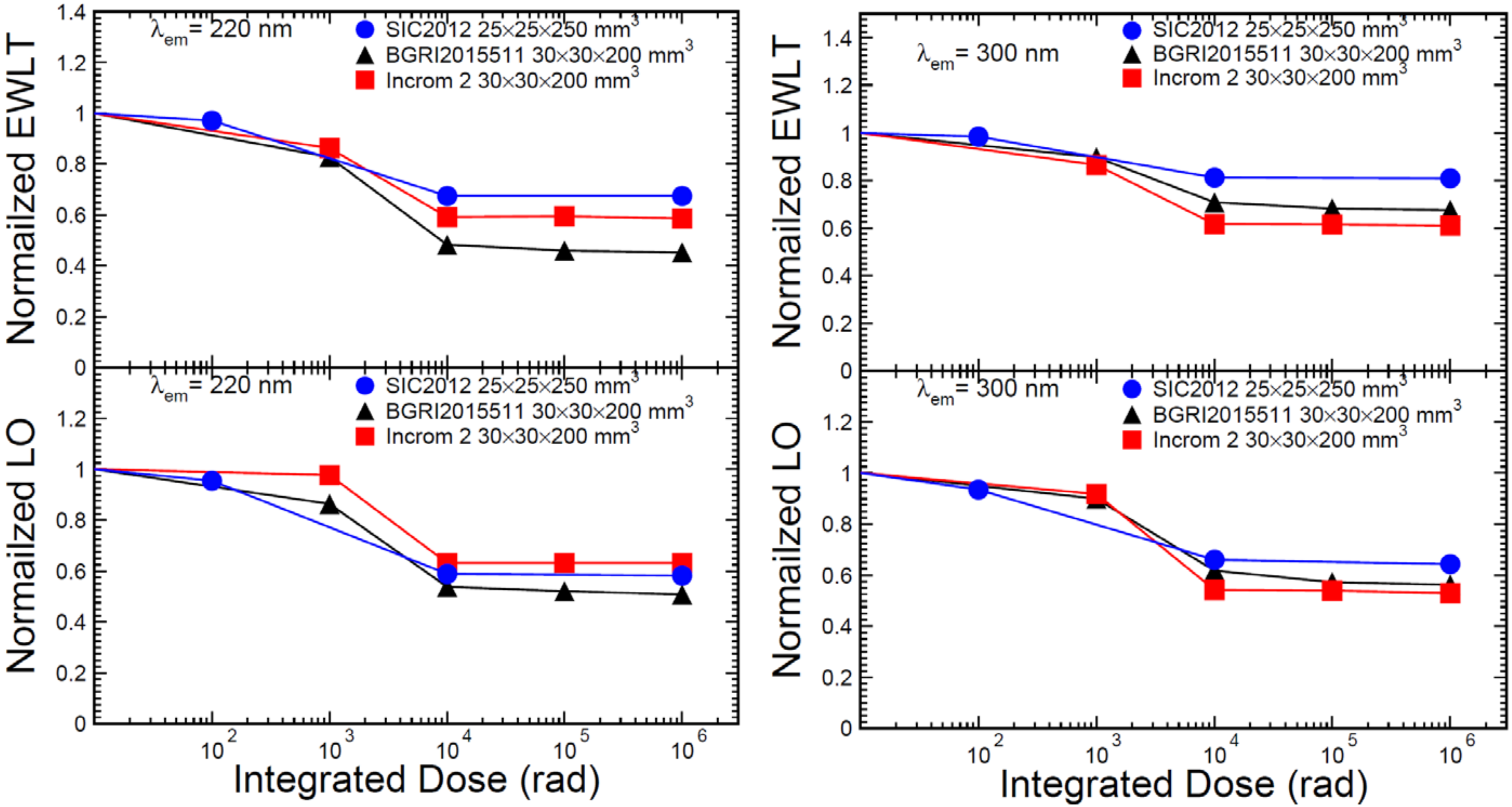
2.5 μs: 628 to 333 p.e./MeV



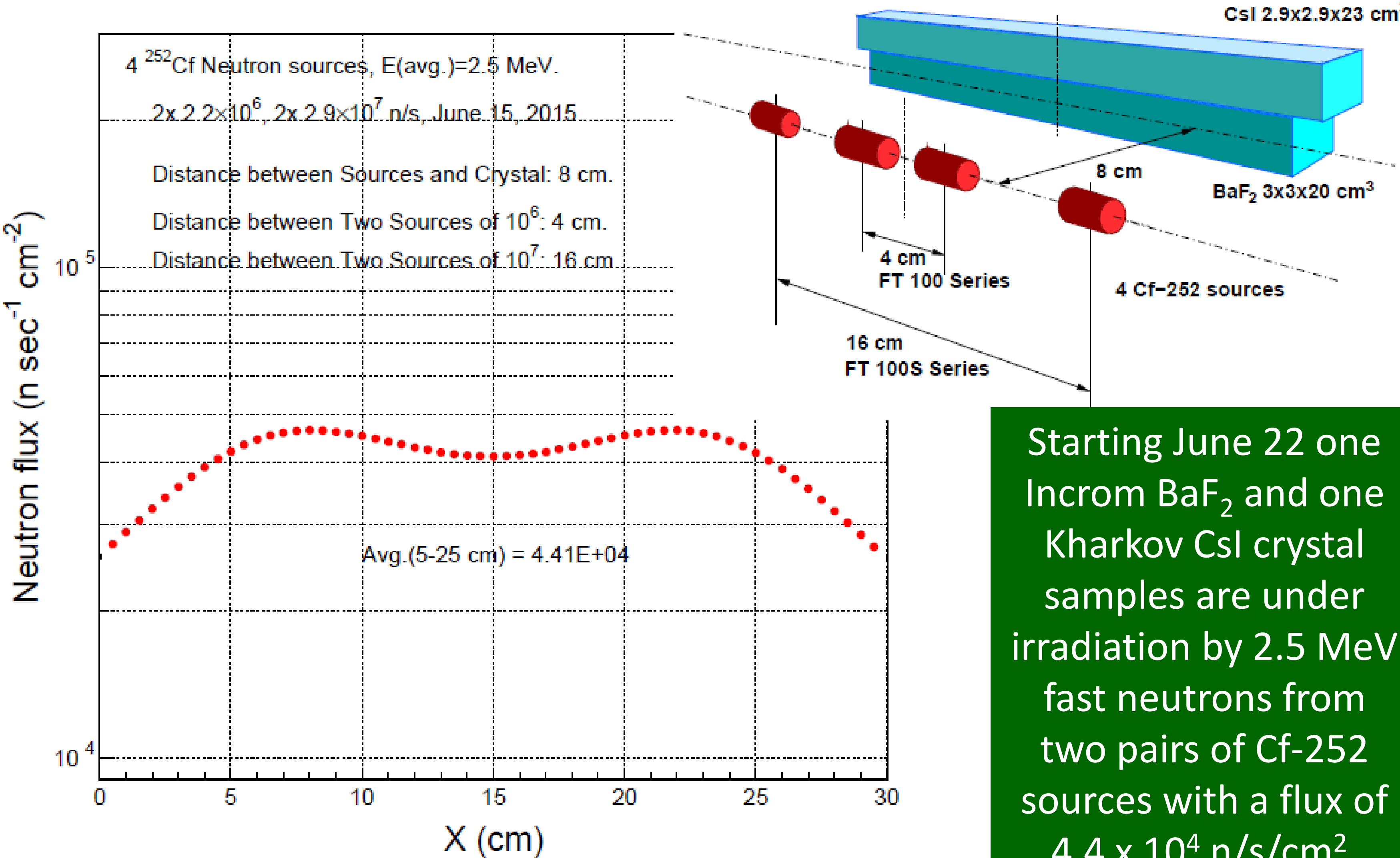


Normalized EWLT & LO: All BaF_2 Samples

Consistent performance observed in crystals from three vendors



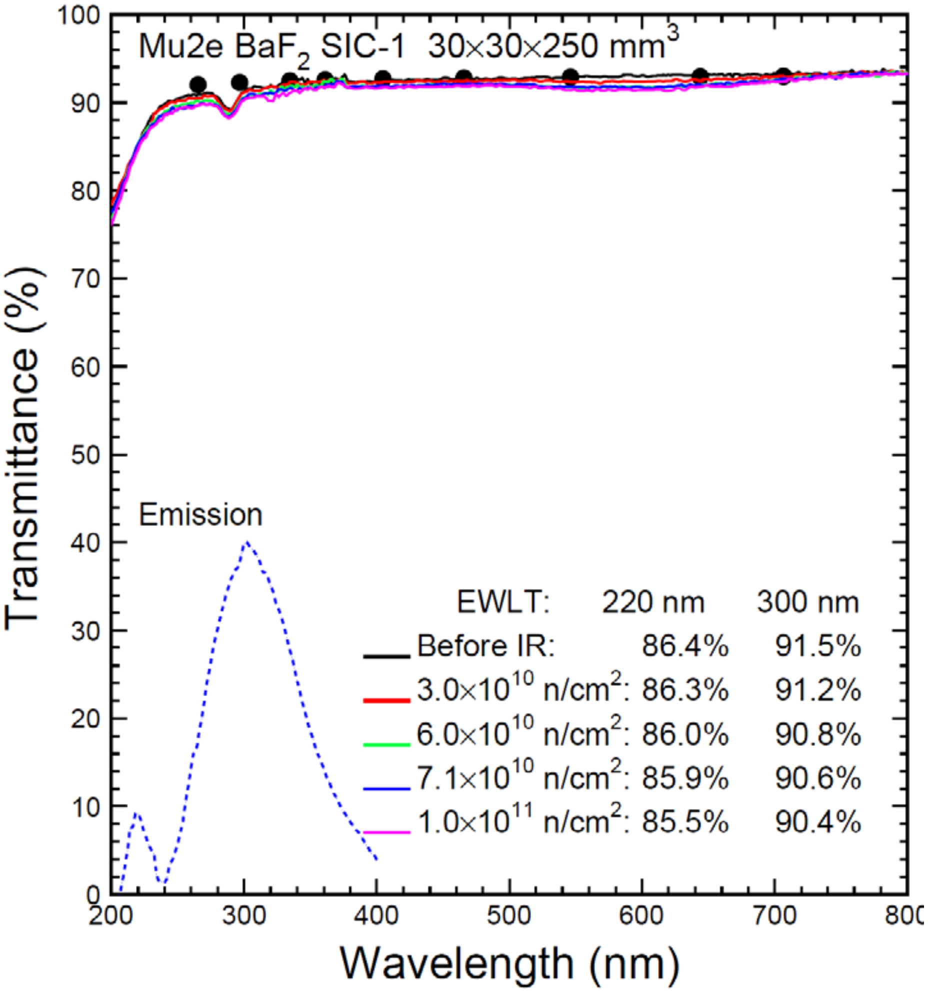
Two Cf-252 Neutron Source Pairs

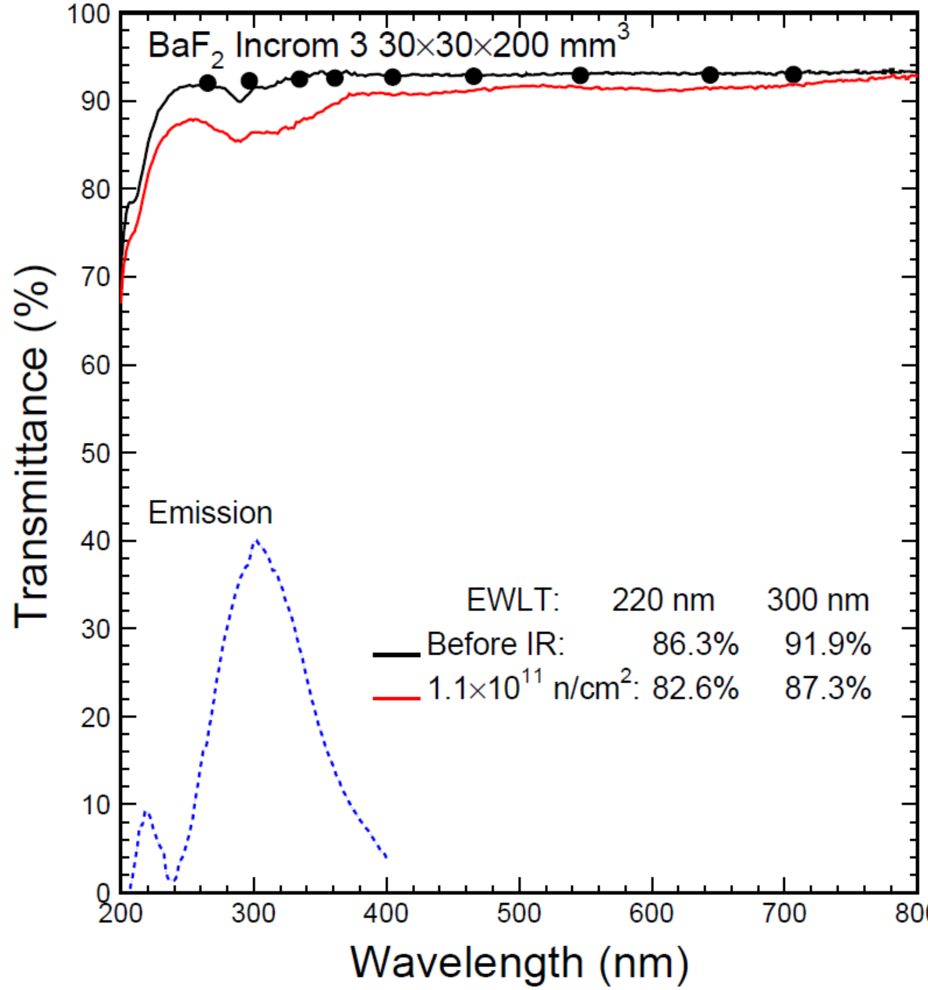


Starting June 22 one Incrom BaF_2 and one Kharkov CsI crystal samples are under irradiation by 2.5 MeV fast neutrons from two pairs of Cf-252 sources with a flux of 4.4 x 10^4 n/s/cm^2.

Small LT Loss in Both BaF_2 Samples

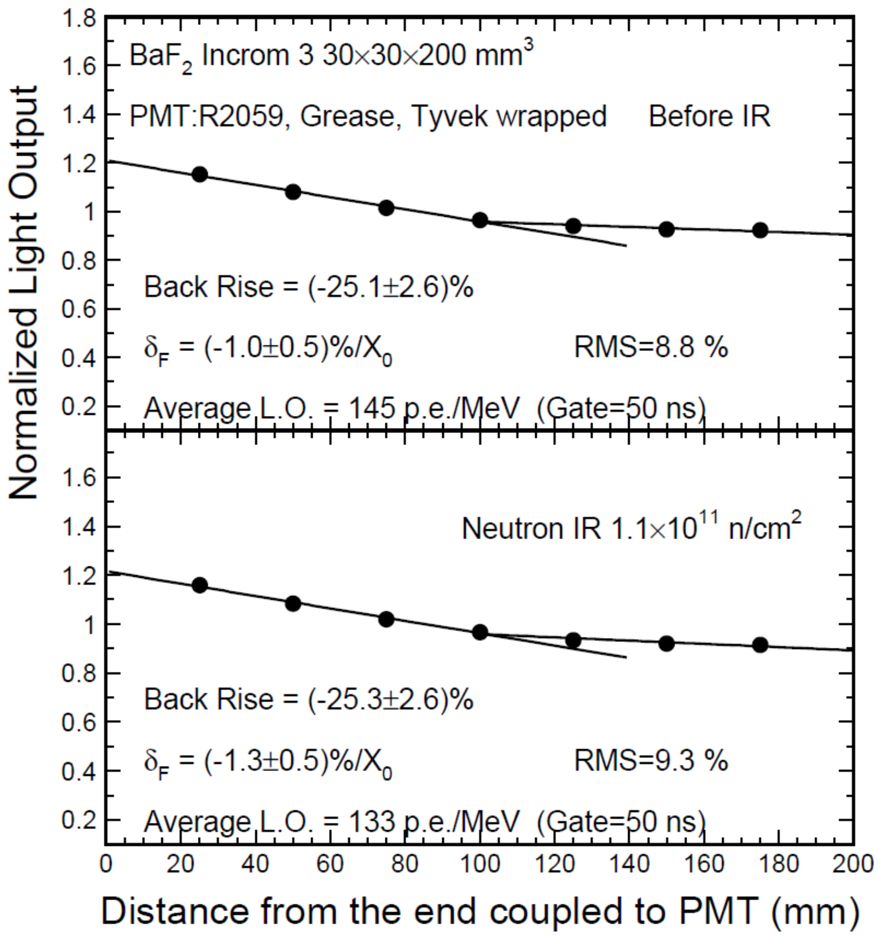
After 10^{11} n/cm^2: effect in optical quality is small



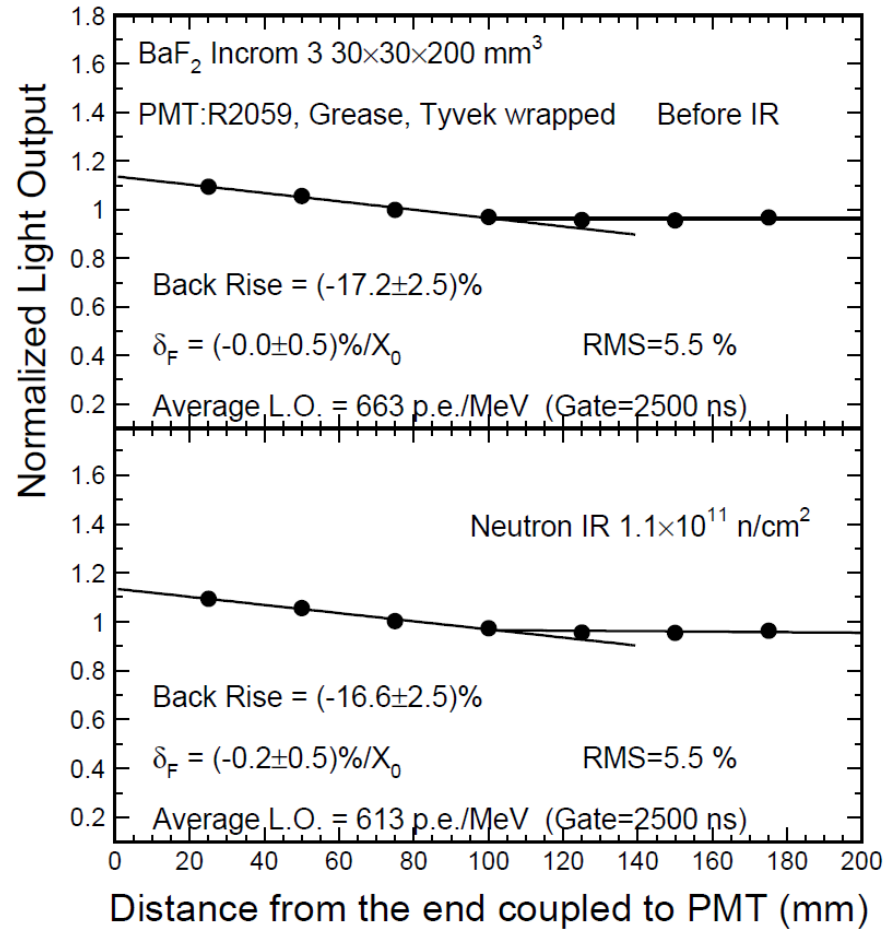


LO & LRU: Incrom 3 BaF_2 Sample

50 ns: 145 to 133 p.e./MeV

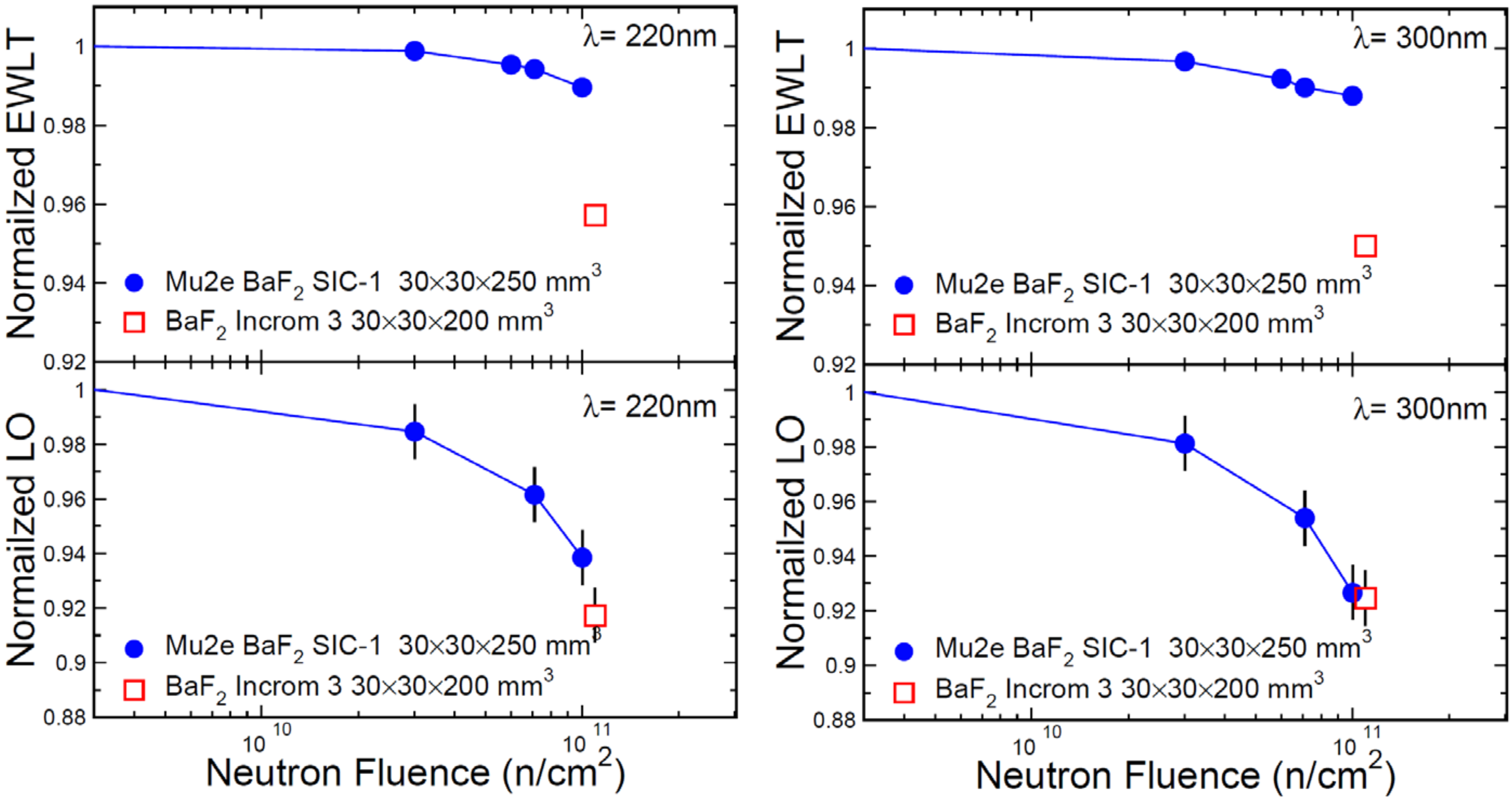


2.5 µs: 663 to 613 p.e./MeV



Normalized EWLT & LO: Both BaF_2 Samples

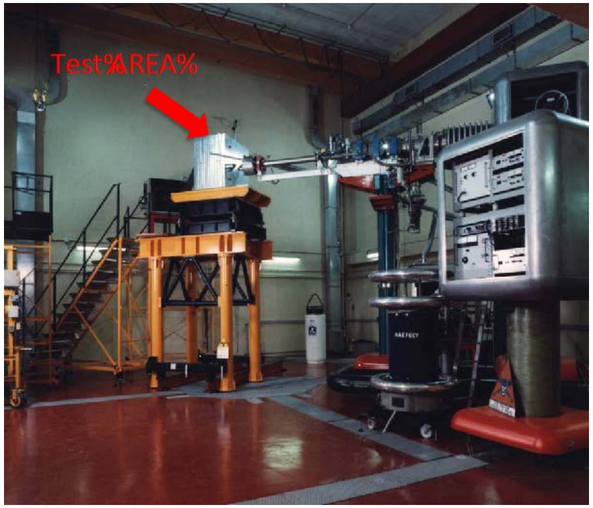
Taking out ɣ-ray background, neutron induced damage is negligible

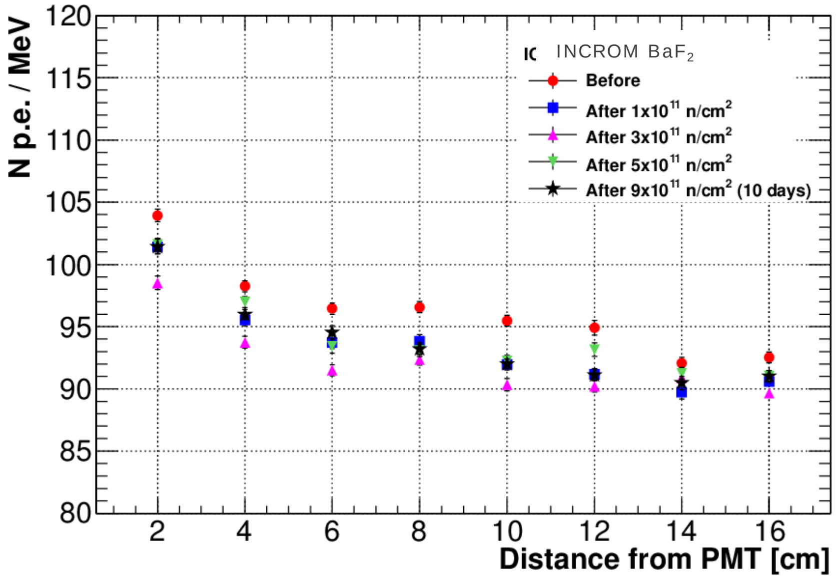


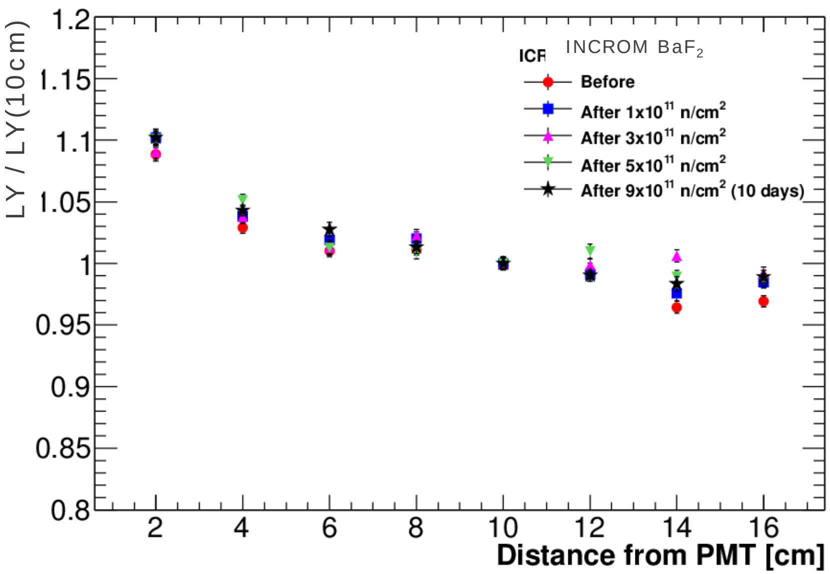
Caltech result is consistent with INFN result up to 9 x 10^{11} n/cm^2

BaF_2, Incrom 02 - Irradiation at FNG (INFN)

- 300 MeV deuteron beam on tritiated target
- Isotropic 14 MeV neutrons
- Max neutron flux = 0.5 x 10^{11} n/s close to target
- Radius dependence $\rightarrow$ $1/R^2$
- Neutron intensity selected moving the crystal position in the test area





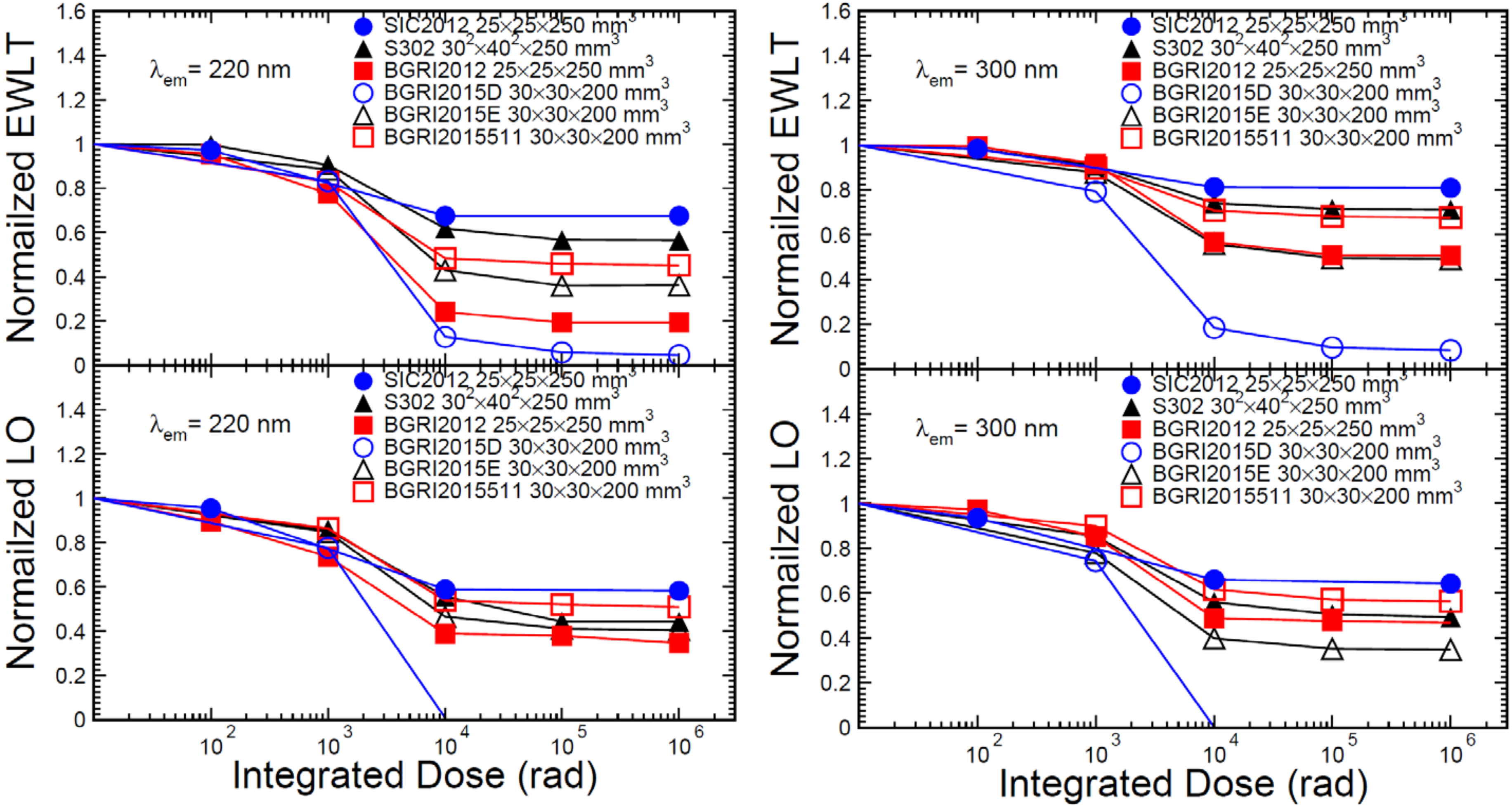


Summary: BaF_2

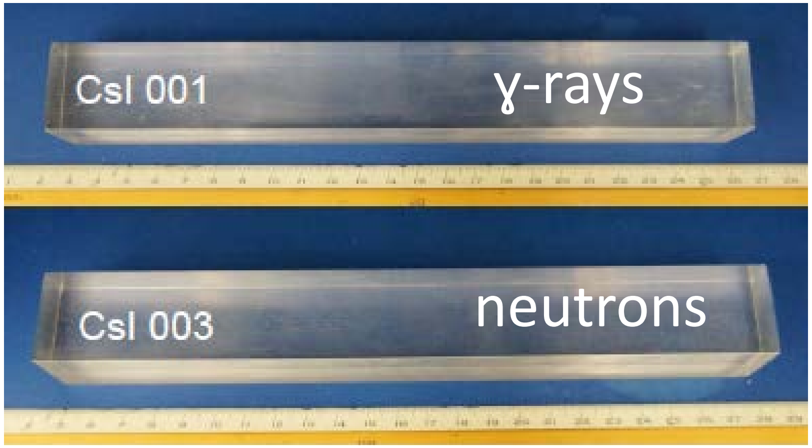
- 20 cm samples from BGRI and Incrom show better optical and scintillation properties than 25 cm SIC crystals.
- Both fast and slow scintillation components from all vendors show sufficient LO, and require photodetectors with selective or extended UV response respectively.
- Consistent ɣ-ray induced radiation damage is observed in recent BGRI and Incrom samples as compared to the SIC 2013 sample and samples grown 20 year ago.
- Improvement in BGRI samples is observed by controlling oxygen contamination: quality control required for production.
- Neutron induced radiation damage in BaF_2 is negligible as compared to the ionization dose.
- SICCAS decided to pursue non-vacuum growth. The first batch of two samples is to be evaluated.

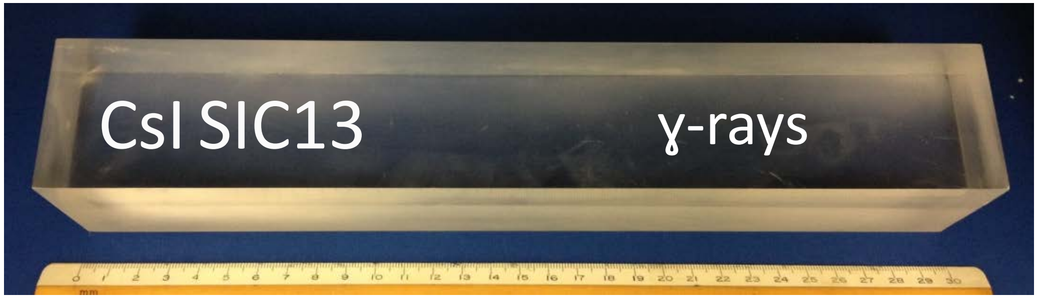
Normalized EWLT & LO: BGRI BaF_2

Progress observed in the BGRI samples



Kharkov/SIC CsI Samples

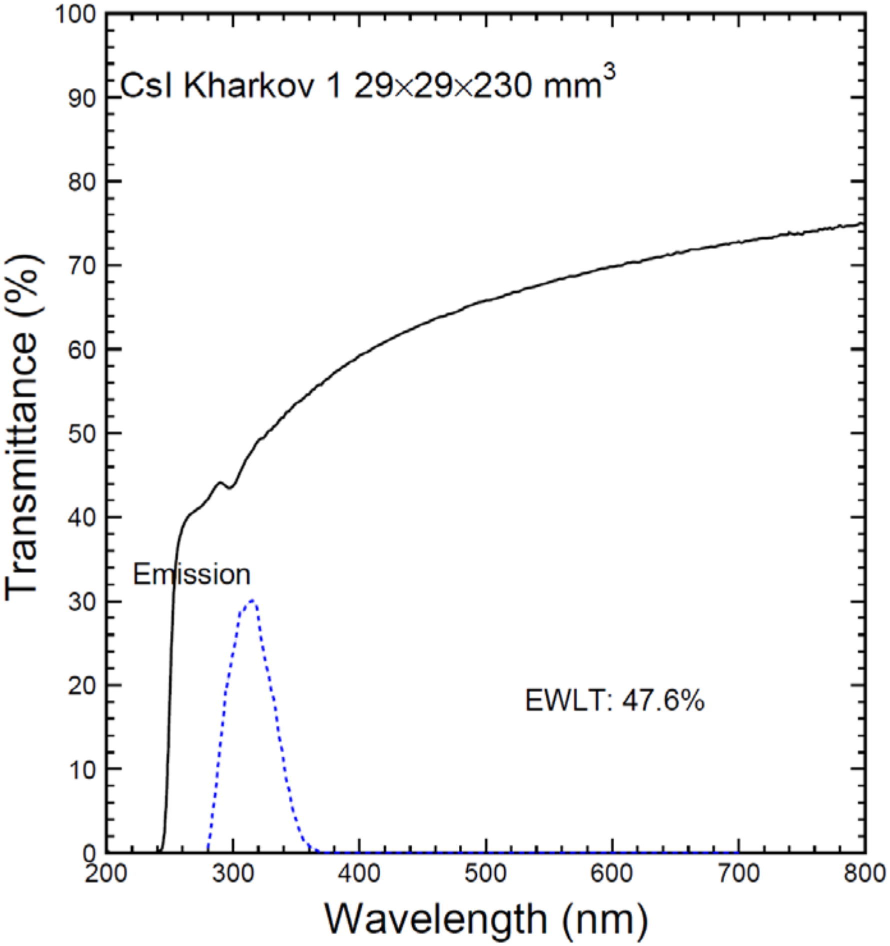


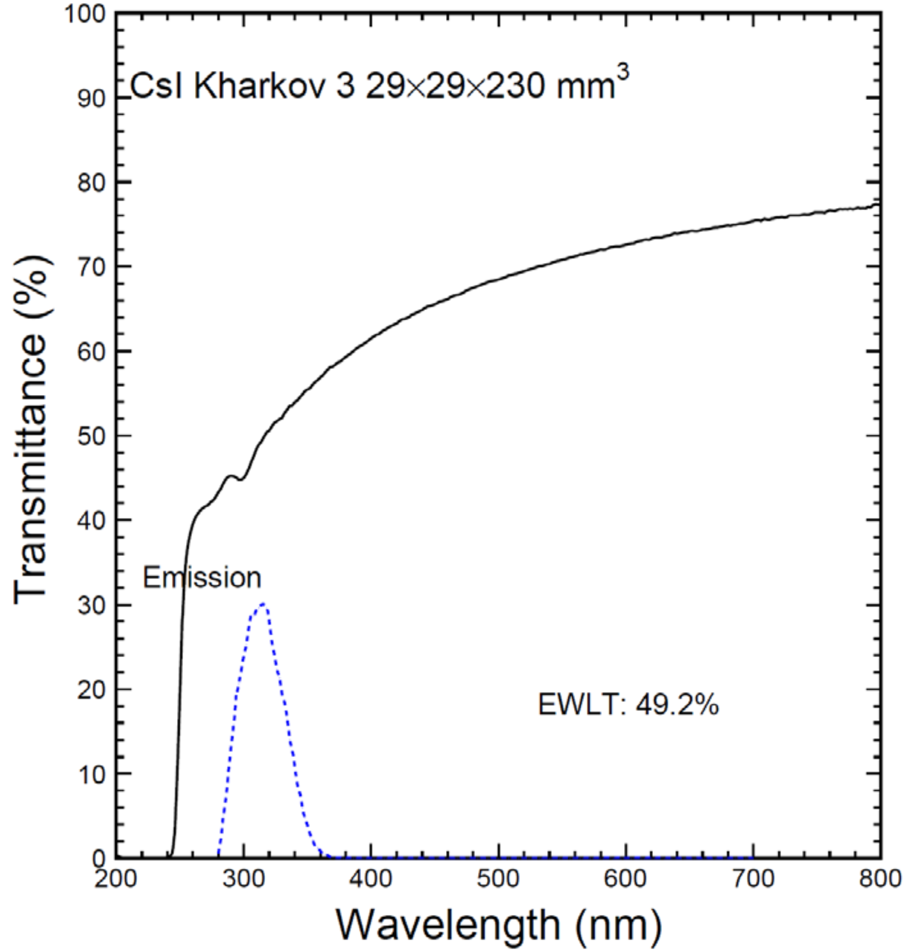


ID	Vendor	Dimension (mm³)	Polishing
SIC13	SICCAS	50x50x300	Six faces
Kharkov 1 and 3	BGRI	29x29x230	Six faces

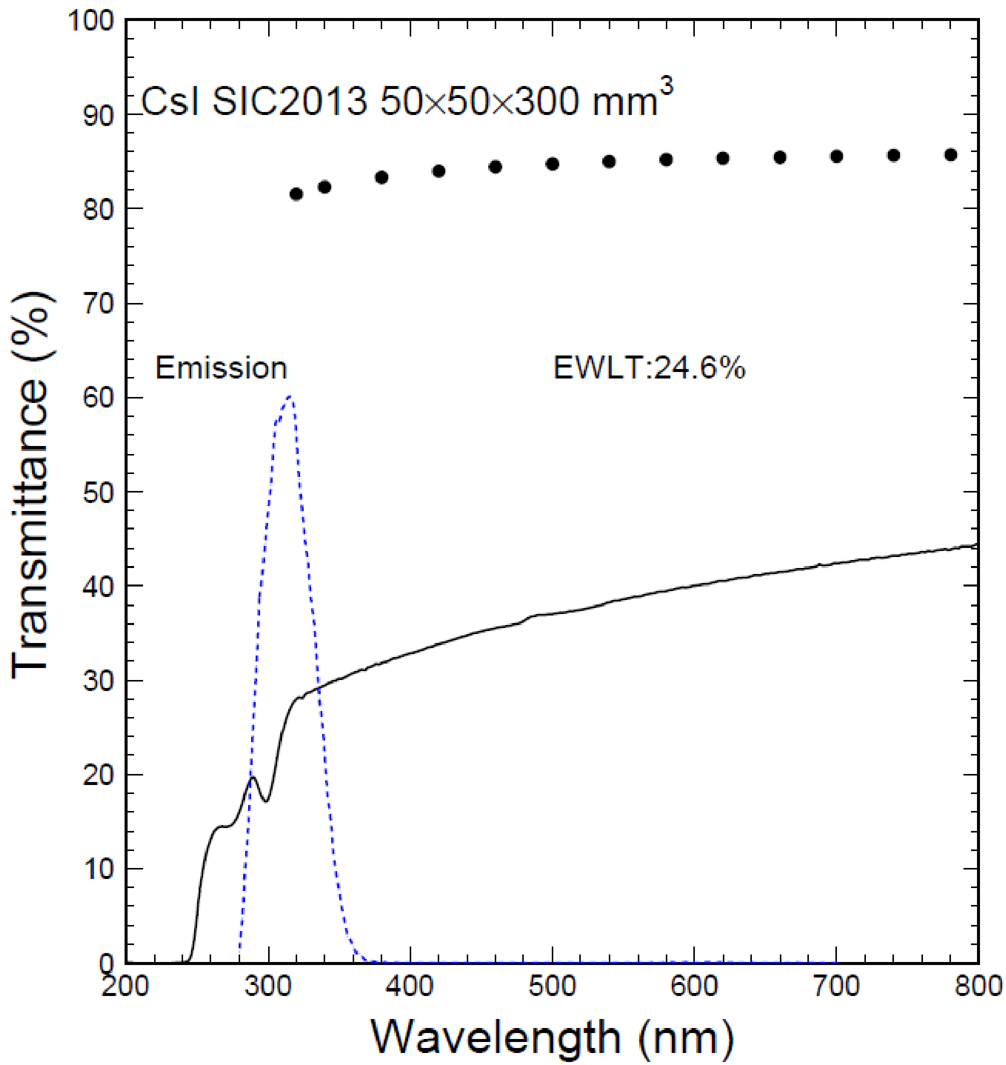
LT of 23 cm long Kharkov CsI

3% difference caused mainly by different surface quality





LT of 30 cm long SIC CsI

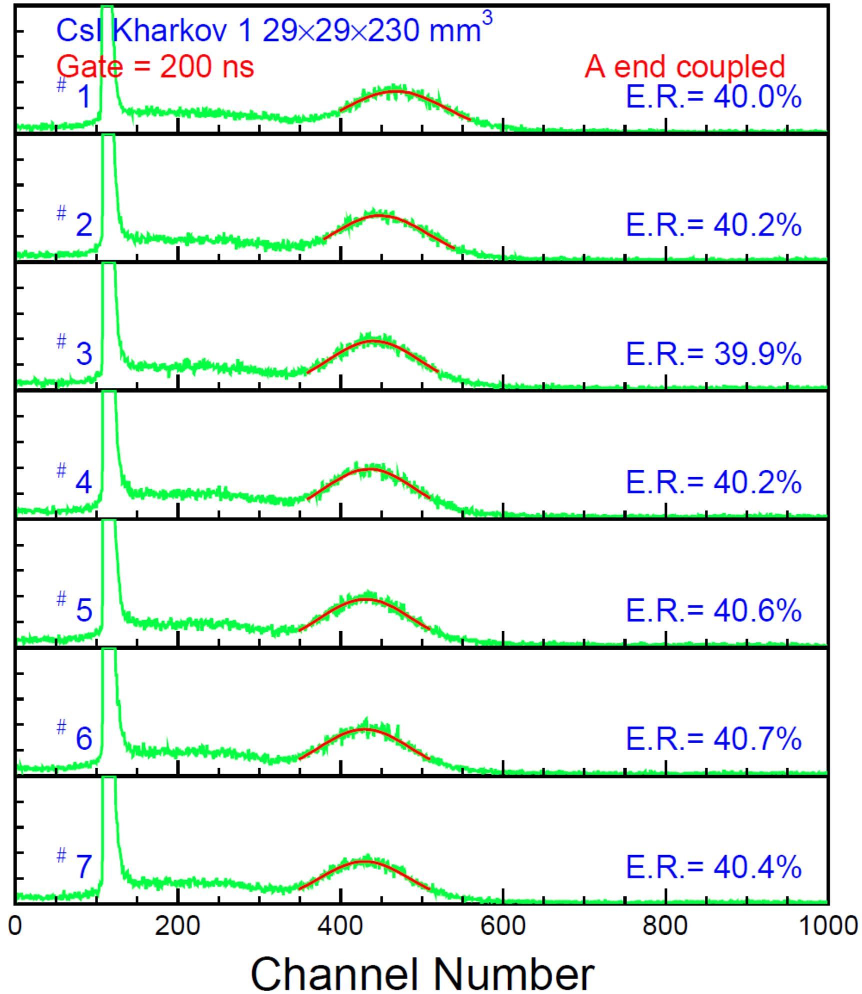


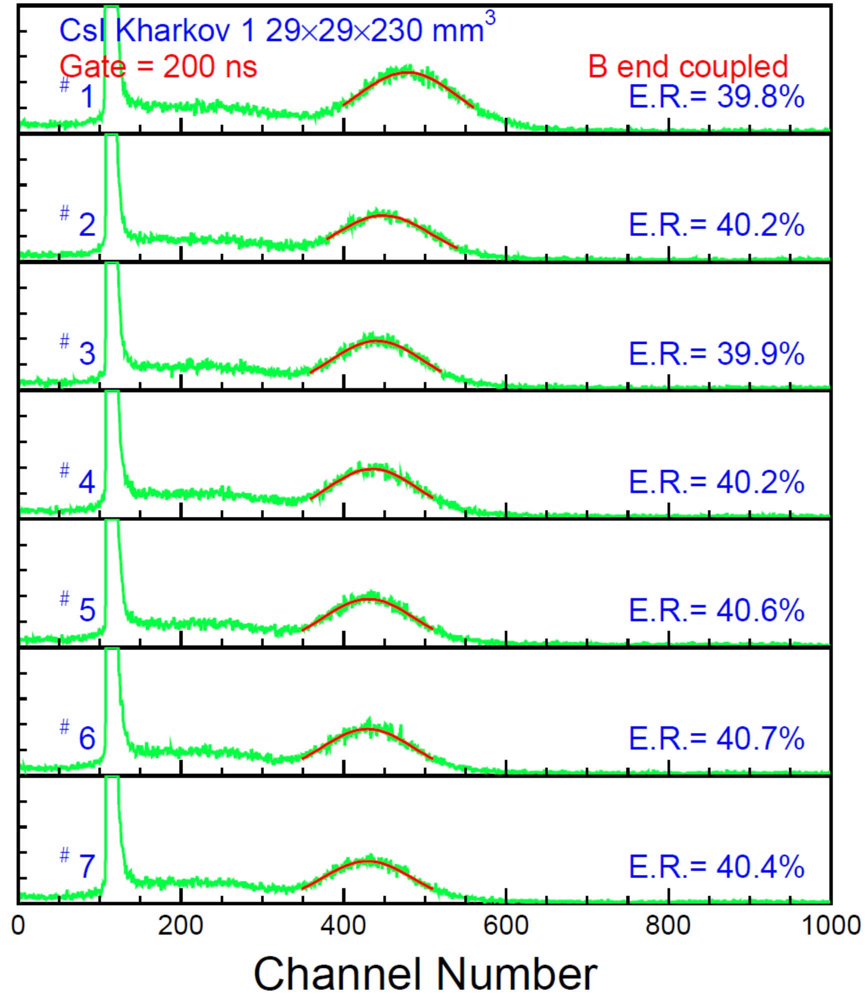
Low EWLT because of long path length and surface quality

Pulse Height Spectra: Kharkov 1 CsI

Ave ER= 40.3%

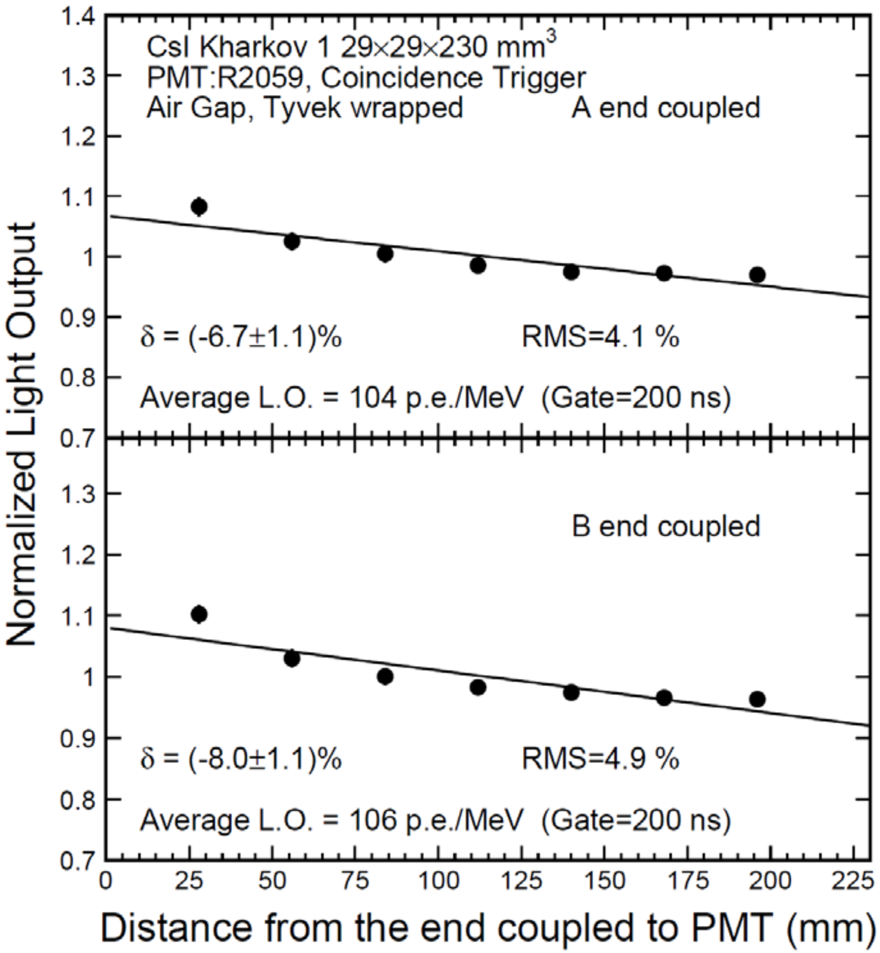
Ave ER= 40.3%

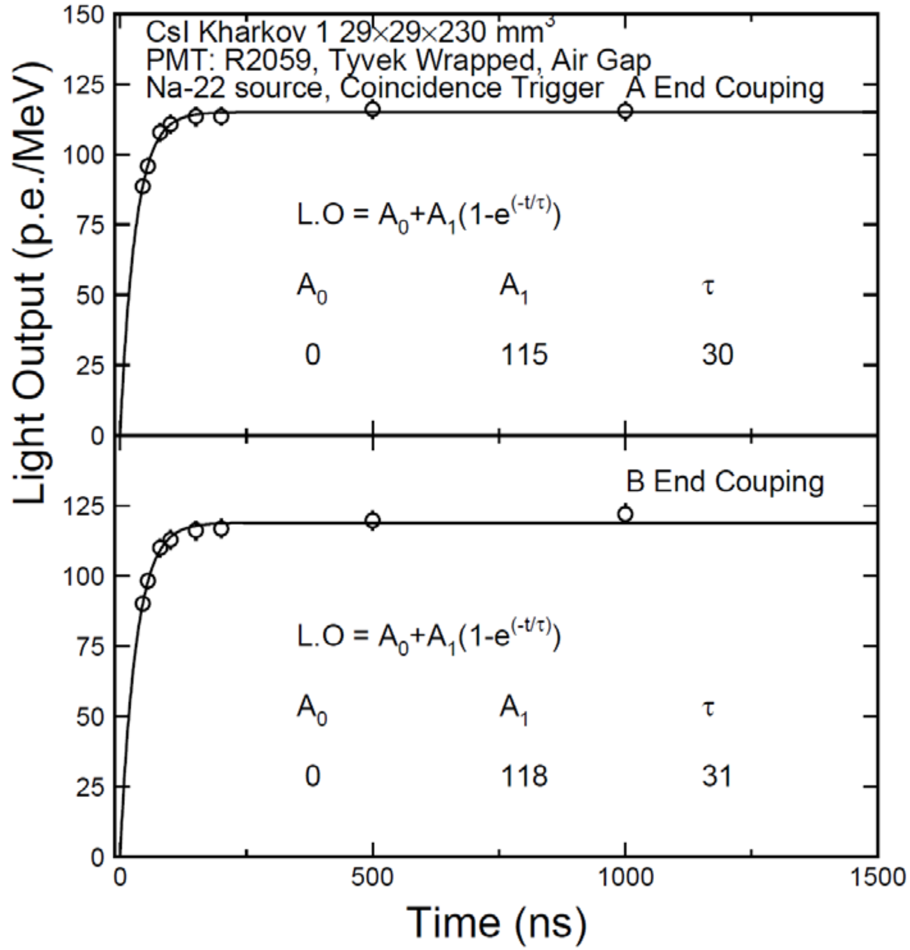




LO, LRU and Decay of Kharkov 1 CsI

Consistent uniformity & 30 ns decay time observed





Summary: Initial CsI Properties

No correlations between LO and LT because of variations of surface quality

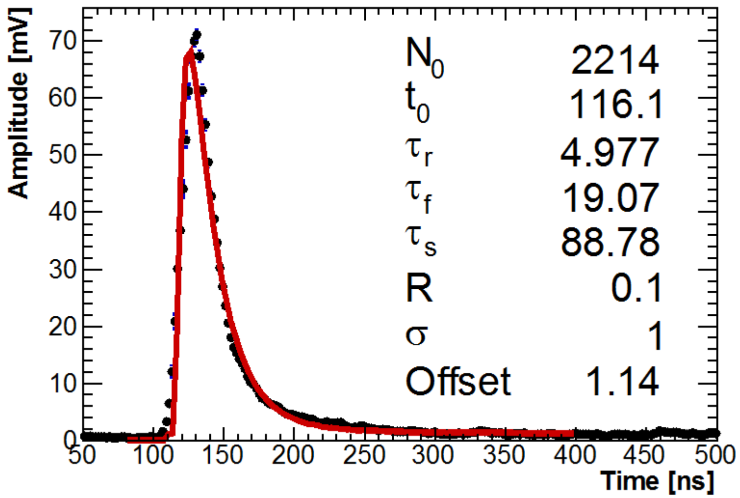
ID	Kharkov 1	Kharkov 3	SIC 13
Dimension (mm^3)	29x29x230	29x29x230	50x50x300
EWLT (%)	47.6	49.2	24.6
Ave ER (%)	40.3	42.0	44.3
LO@200 ns Gate (p.e./MeV)	104	98	83
LRU (%)	-6.7±1.1	-2.9±1.1	3.1±1.0
RMS (%)	4.1	2.7	1.7
Decay Time (ns)	30	29	27

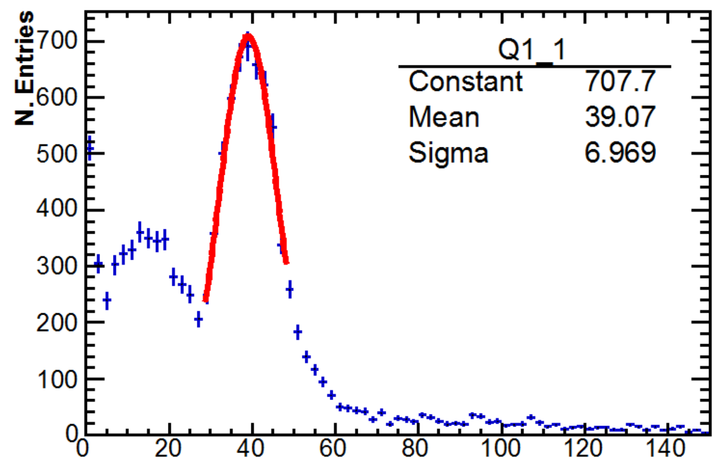
Result measured at Caltech is consistent with what measured at INFN

CsI Crystal Characterization @ INFN (1)

- CsI crystals characterized for LY and LRU also at INFN with similar Na^{22} test with WFD readout
- SICCAS, Kharkov and Opto Material (Italy) crystals characterized

Signal Shape With WFD



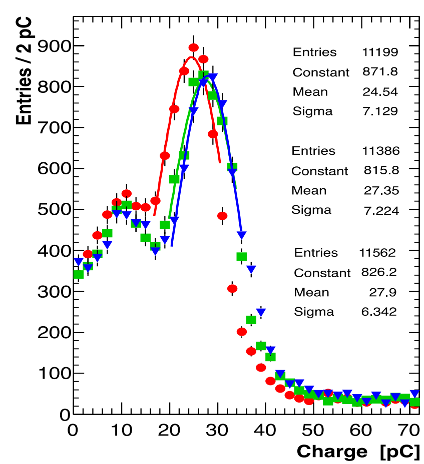


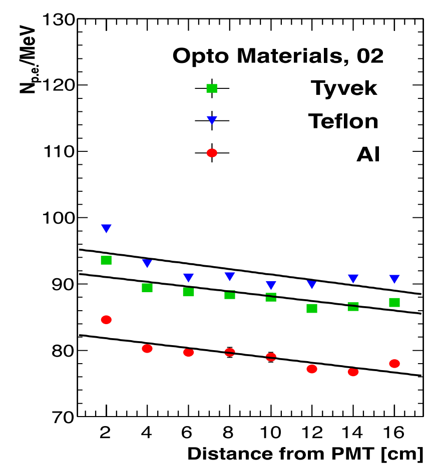
Na^{22} peak

✓ Teflon wrapping provides the best LY.

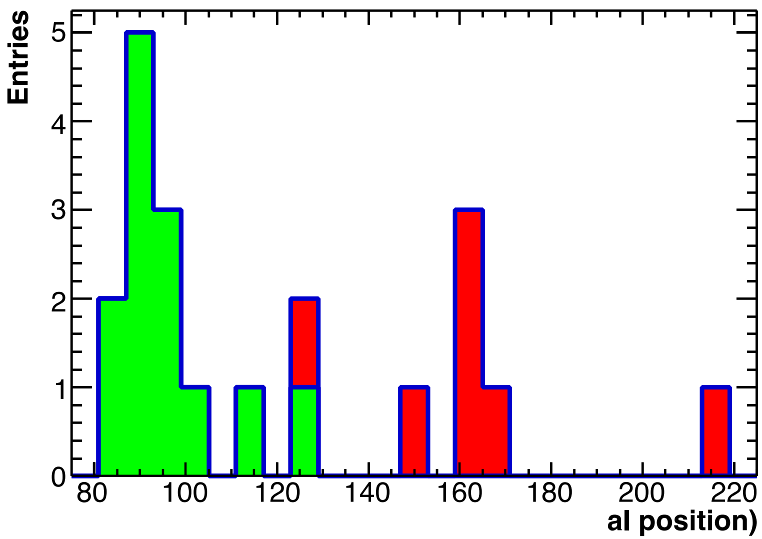
✓ Tyvek allows very close results and a much simpler handling.

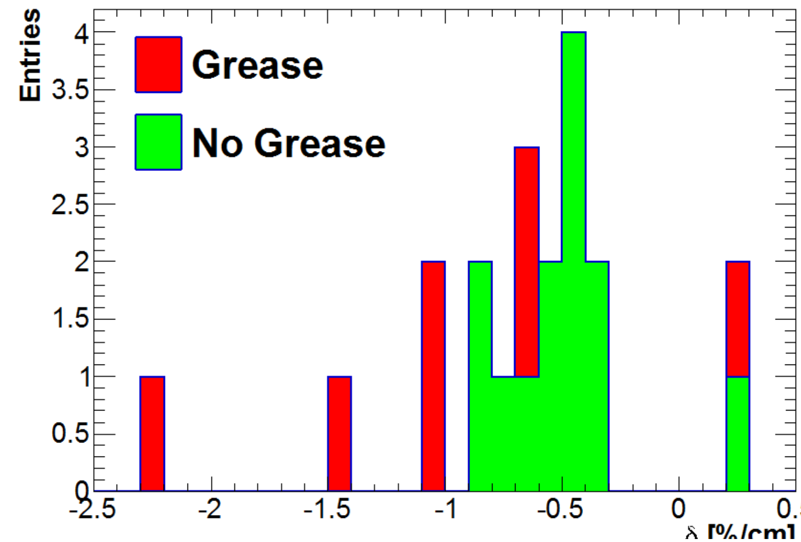
✓ Good uniformity of response observed along the axis

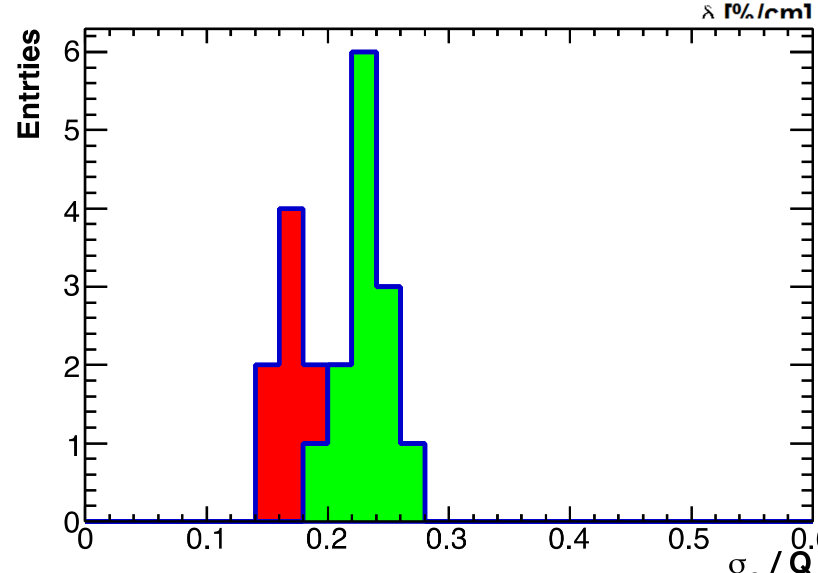




CsI Crystal Characterization @ INFN (2)



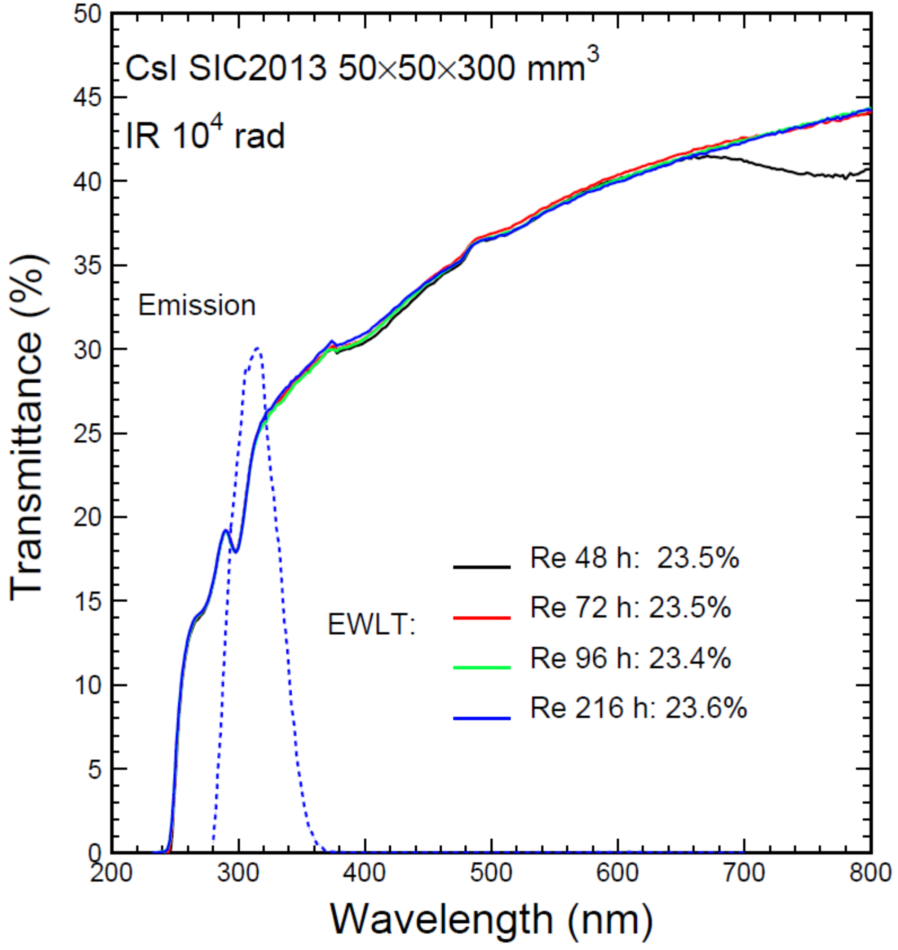


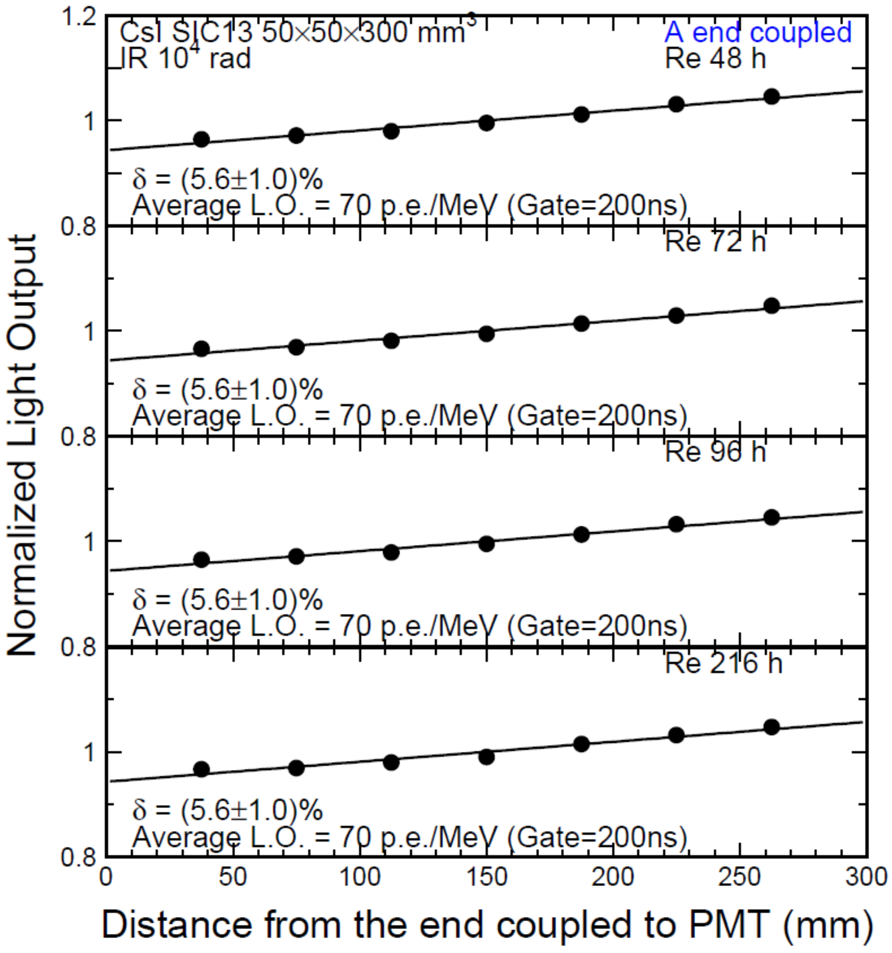


- Measurements done with Kharkov and SICCAS crystals agree
- τ of 30 ns measured looking at integrated charge with a moveable gate w.r.t. +6+20 ns in our fit
- No long/slow component observed (or practically negligible)

No Recovery at Emission: SIC2013 CsI

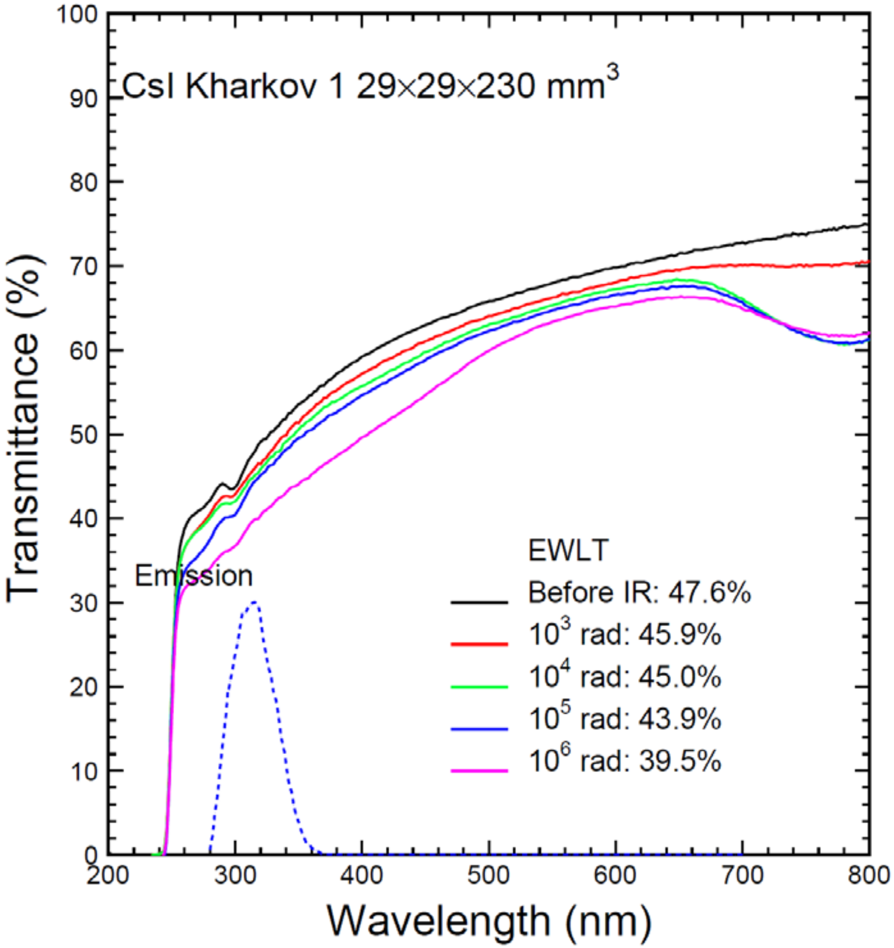
Damage does not recover, so is dose rate independent

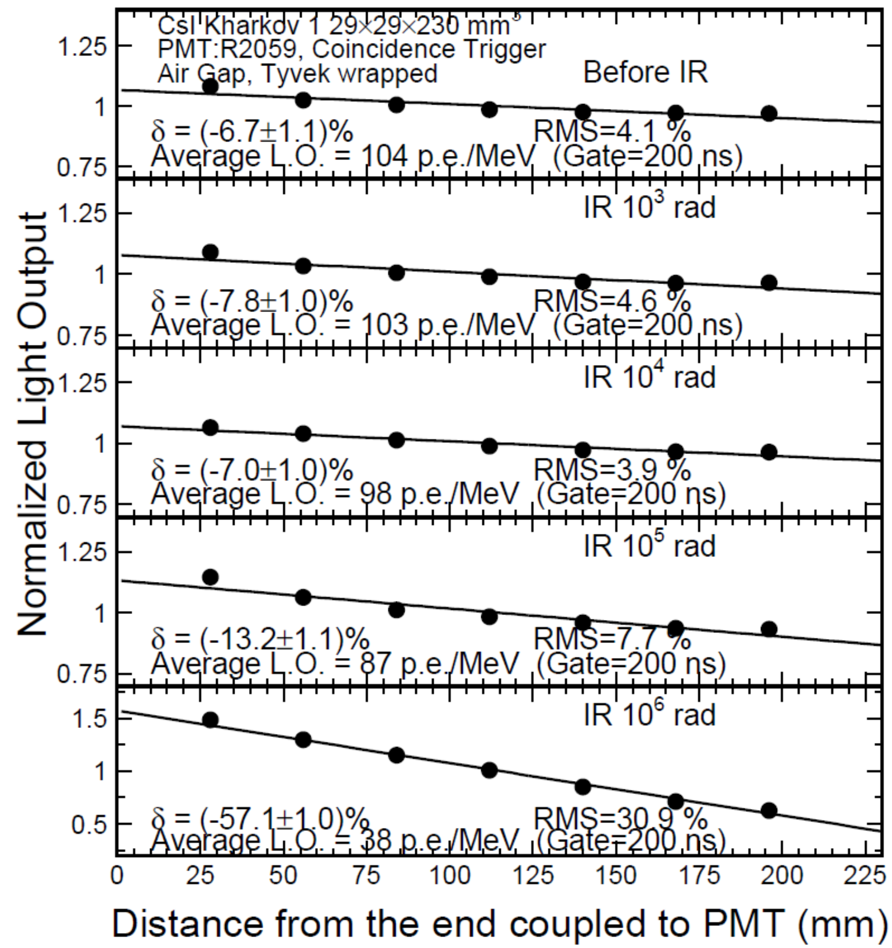




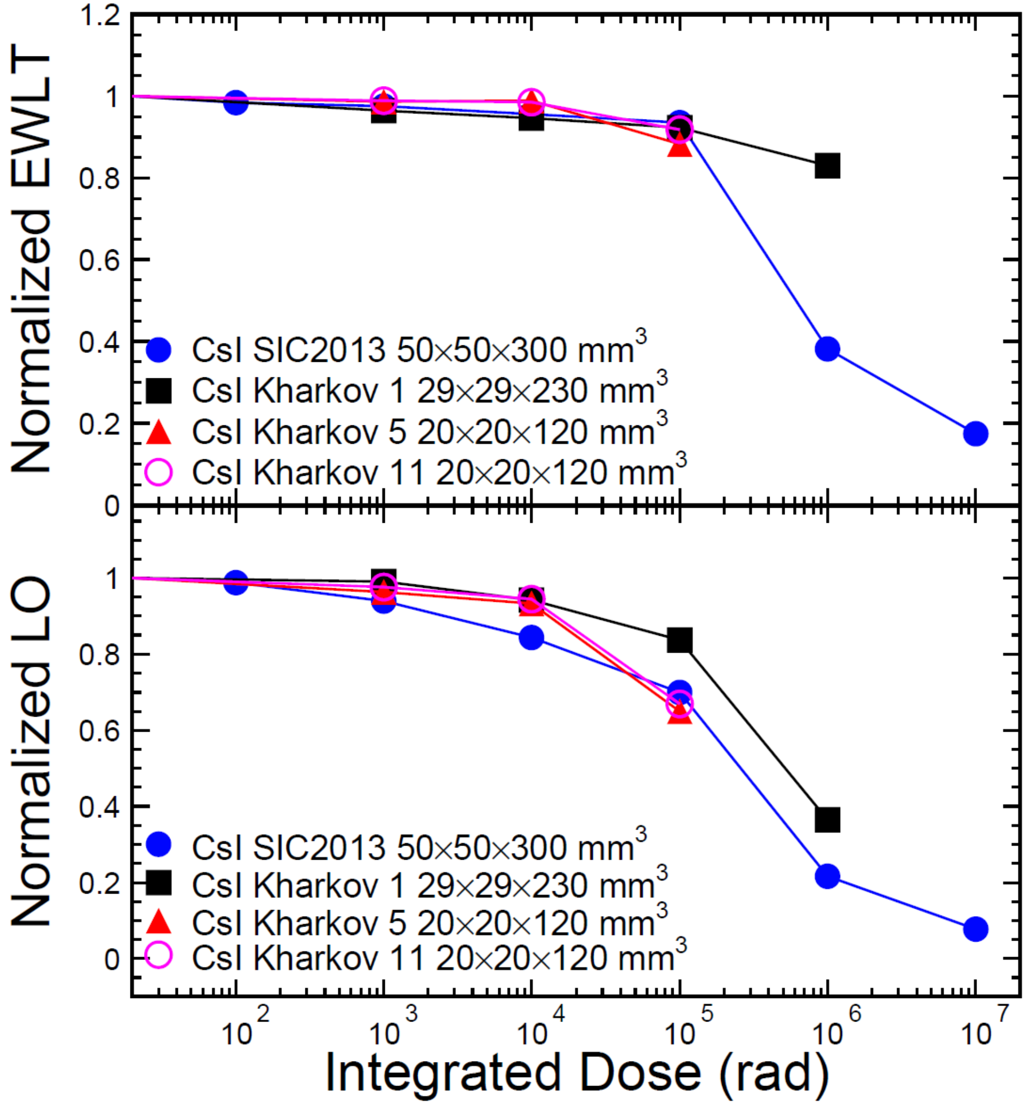
Radiation Damage: Kharkov 1 CsI

No significant degradation in LO and LRU up to 10 krad





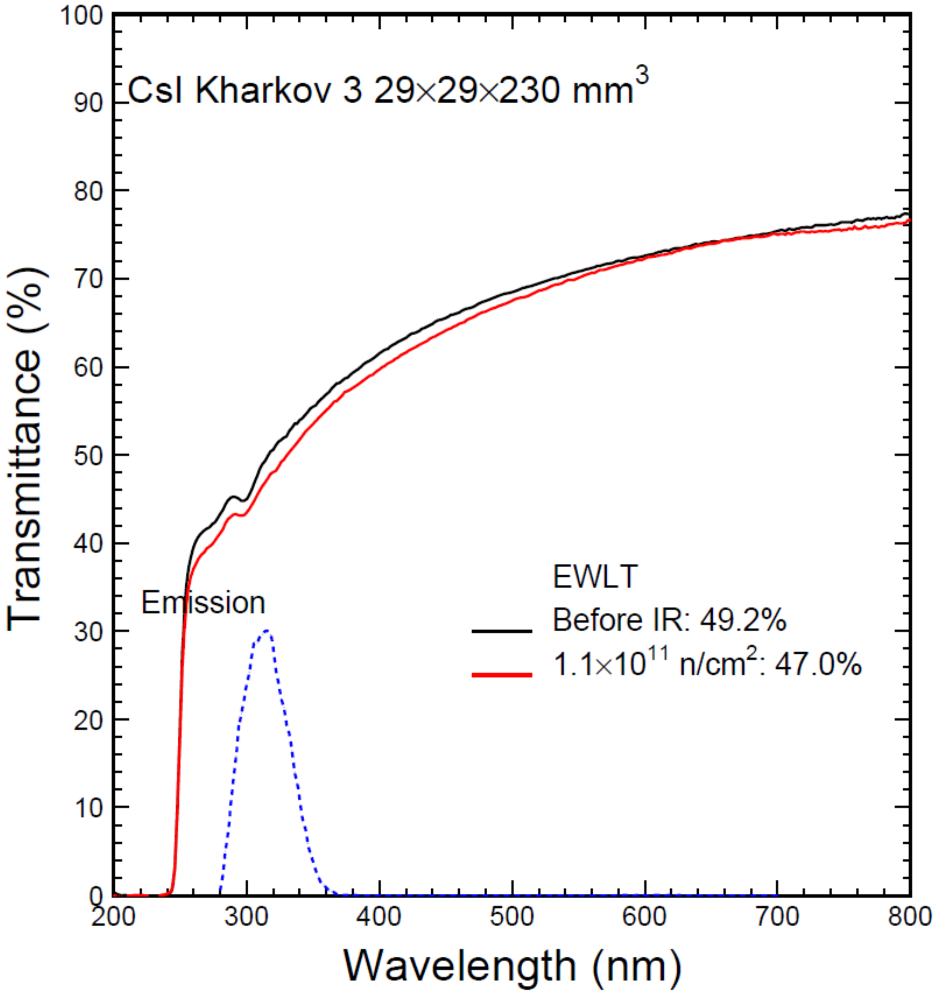
Normalized EWLT & LO: All CsI Samples

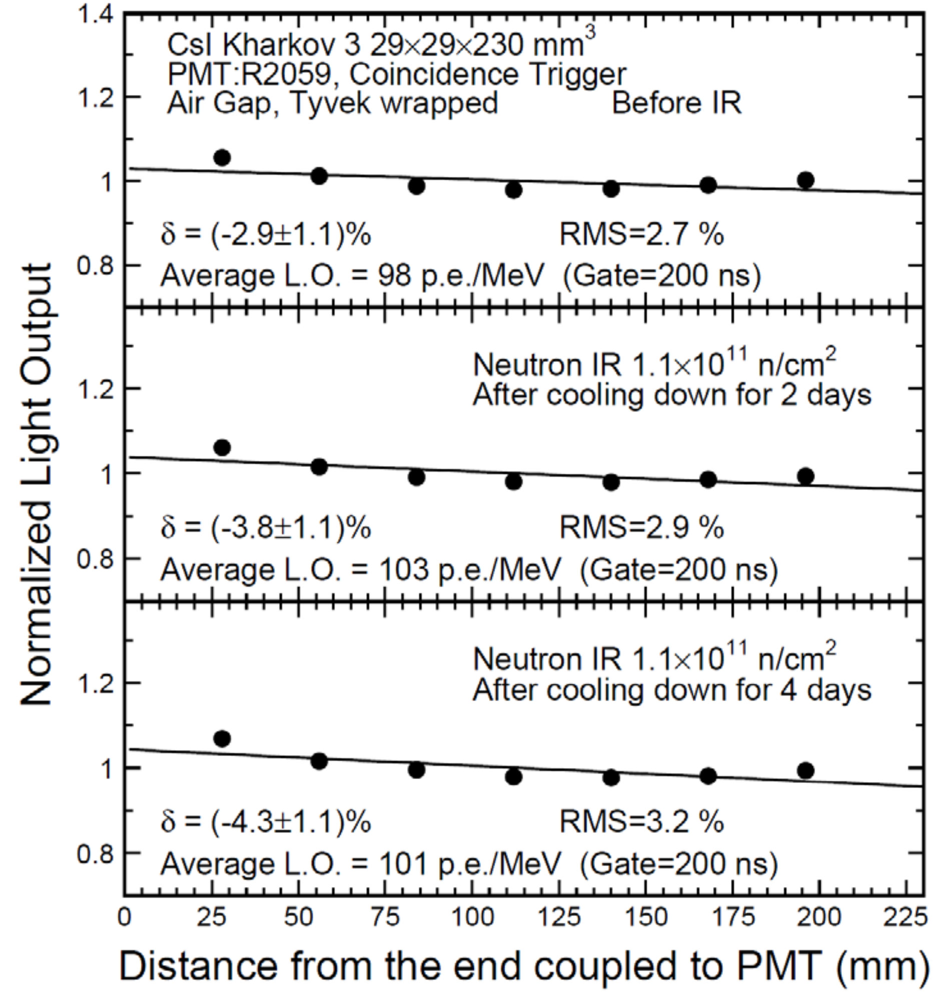


Consistent radiation hardness: no significant degradation in LO and LRU up to 100 krad.

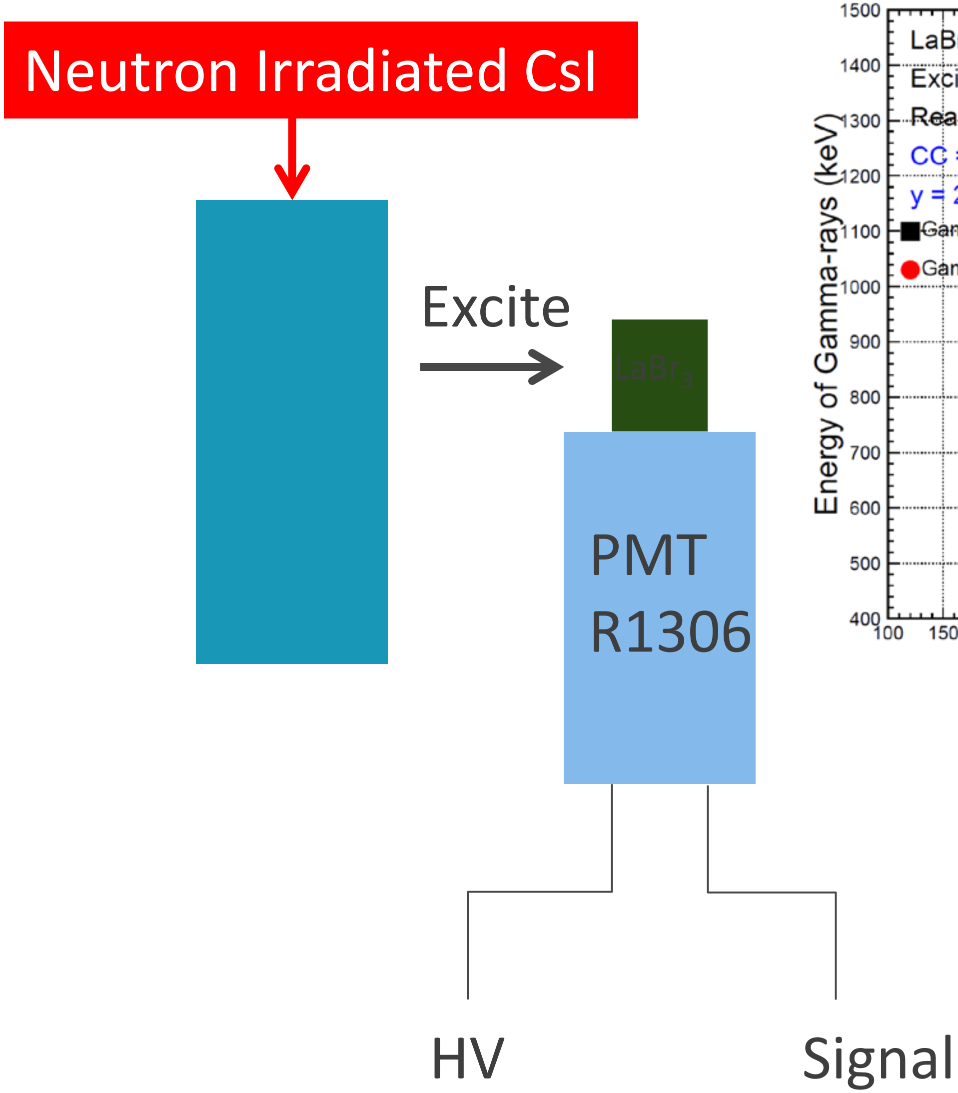
CsI: LT, LO & LRU Loss by Neutrons

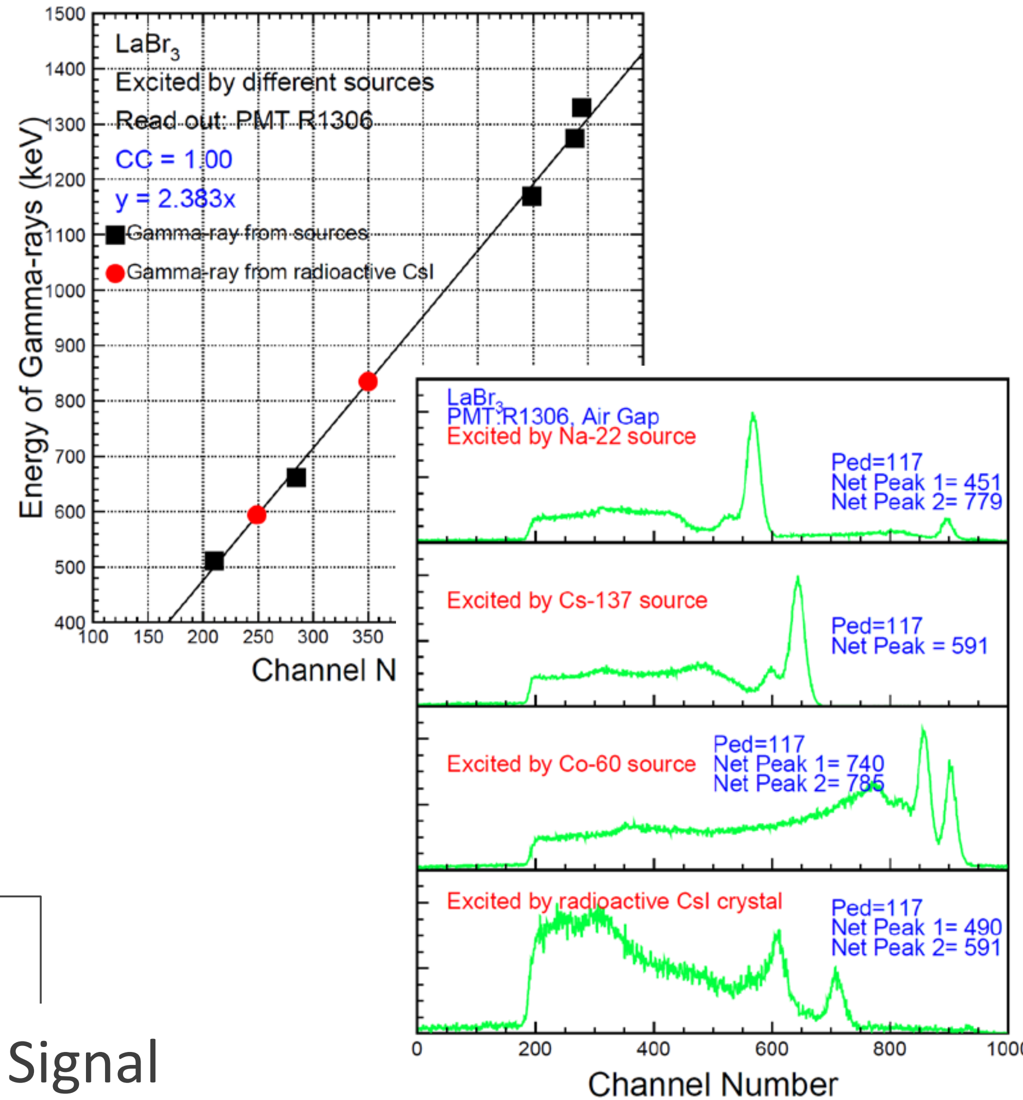
No significant damage in LT/LRU, LO increase by phosphorescence





Phosphorescence: 0.6 & 0.8 MeV





Phosphorescence from Cs-134

γ-rays from neutron irradiated CsI have energies of 0.6 and 0.8 MeV.

No long lifetime (> hour) radioactive isotopes generated via neutron capture by F-19, I-127 and Ba-138.

Cs-133 has large neutron capture x-section: 30b. Cs-134 emits in average 2.23 γ-rays with mean energy of 0.7 MeV and a half-life of 2.1 year.

An early observation is published in Phys. Stat. Sol. Vol.167, p. 253, 1998.

Gamma Emissions from Caesium-134

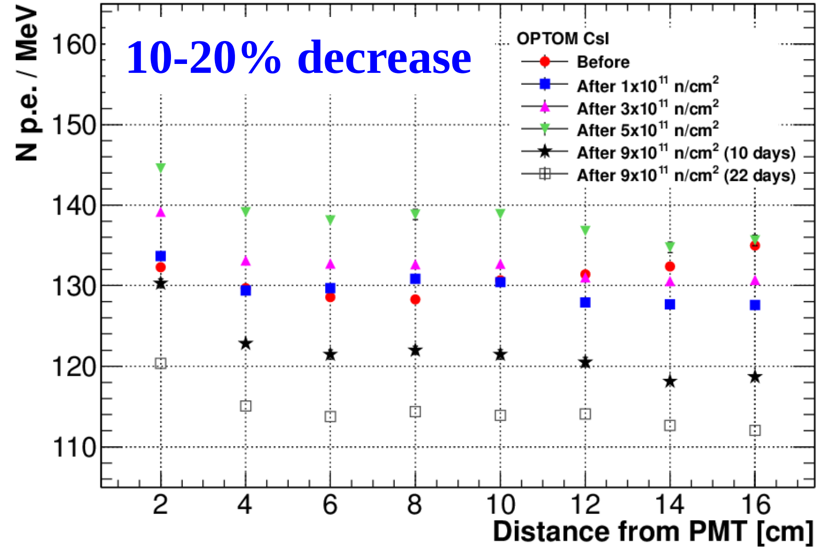
Energy (MeV)	Yield per Transformation
0.475	0.015
0.563	0.084
0.569	0.154
0.605	0.976
0.796	0.854
0.802	0.087
1.039	0.010

Result measured at Caltech is consistent with INFN data

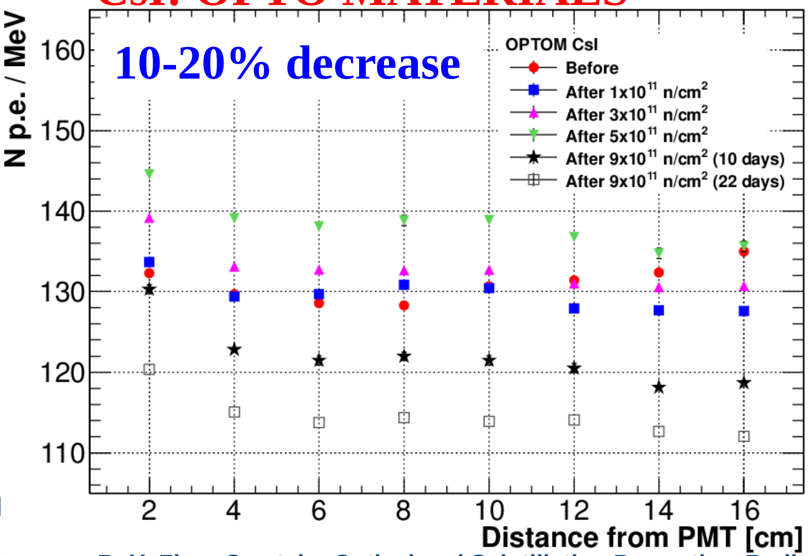
CsI (Opto Materials & Kharkov) at FNG

- Neutrons at FNG, ENEA
- Up to 9 x 10^{11} n/cm^2
- No large variation in LY
- SICCAS deterioration in LRU

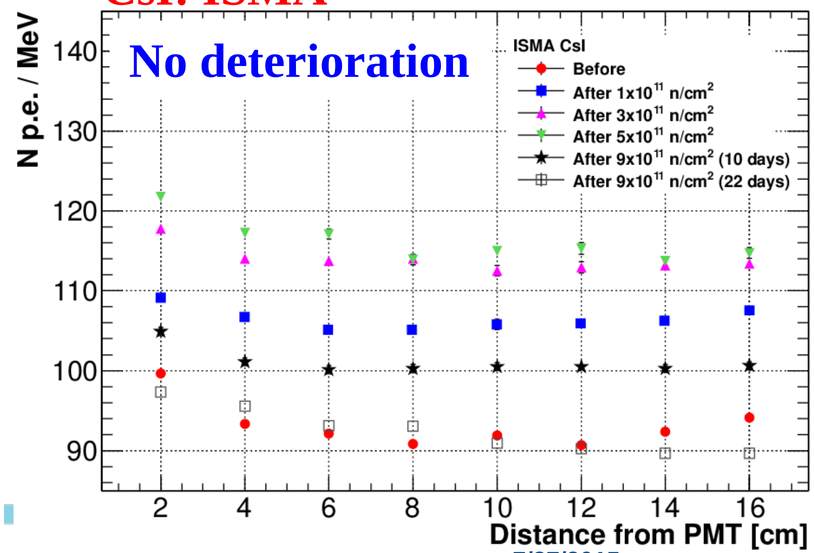
CsI: OPTO MATERIALS



CsI: OPTO MATERIALS



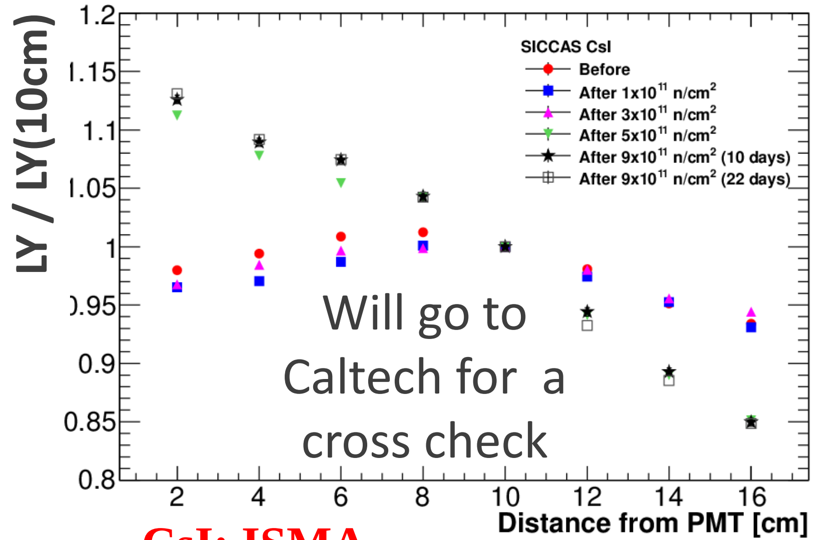
CsI: ISMA



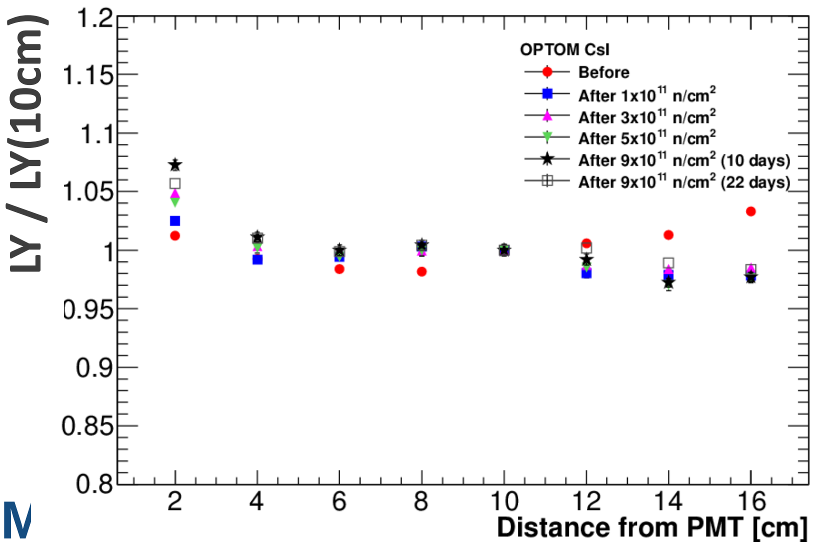
CsI, Neutron Irradiation at FNG

- Neutrons at FNG, ENEA
- Up to 9 x 10^{11} n/cm^2
- No large variation in LY
- SICCAS deterioration in LRU

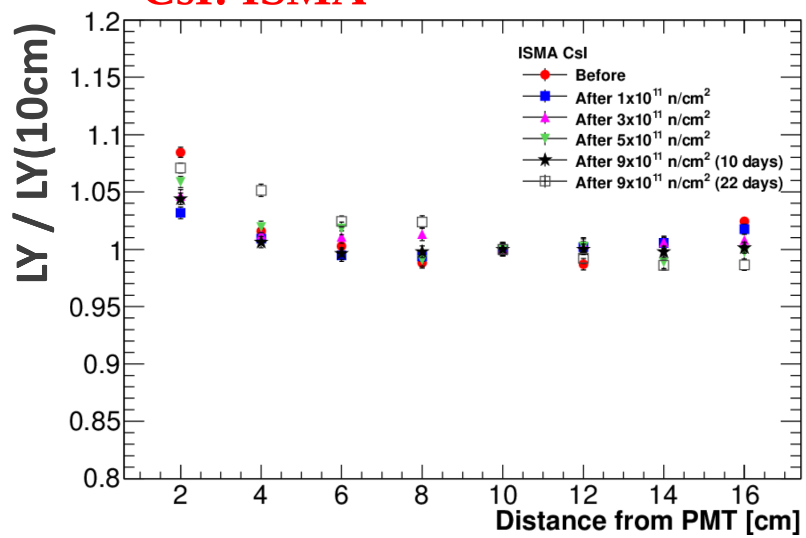
CsI: SICCAS



CsI: OPTO MATERIALS



CsI: ISMA



Summary: Pure CsI

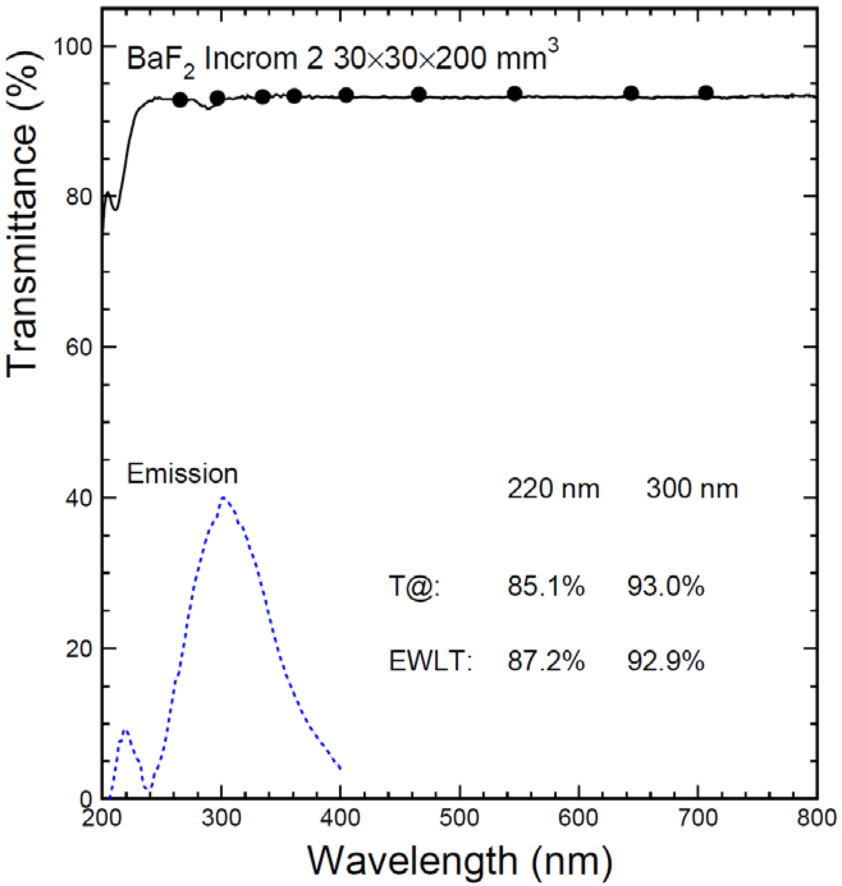
- LT Measurements for CsI crystals suffer from uncertainties caused by crystal's soft and hygroscopic surface.
- Pure CsI from both Kharkov and SICCAS show sufficient light output with emission peaked at 310 nm requiring UV extended photodetectors.
- Consistent radiation hardness against ionization dose is observed for crystals from Kharkov and SICCAS.
- Neutron induced phosphorescence requires further investigation to understand its consequence to the readout noise. http://www.hep.caltech.edu/~zhu/talks/liyuan_091028_N32-4.pdf.
- Quality control is required to control slow scintillation caused by contamination and radiation hardness.

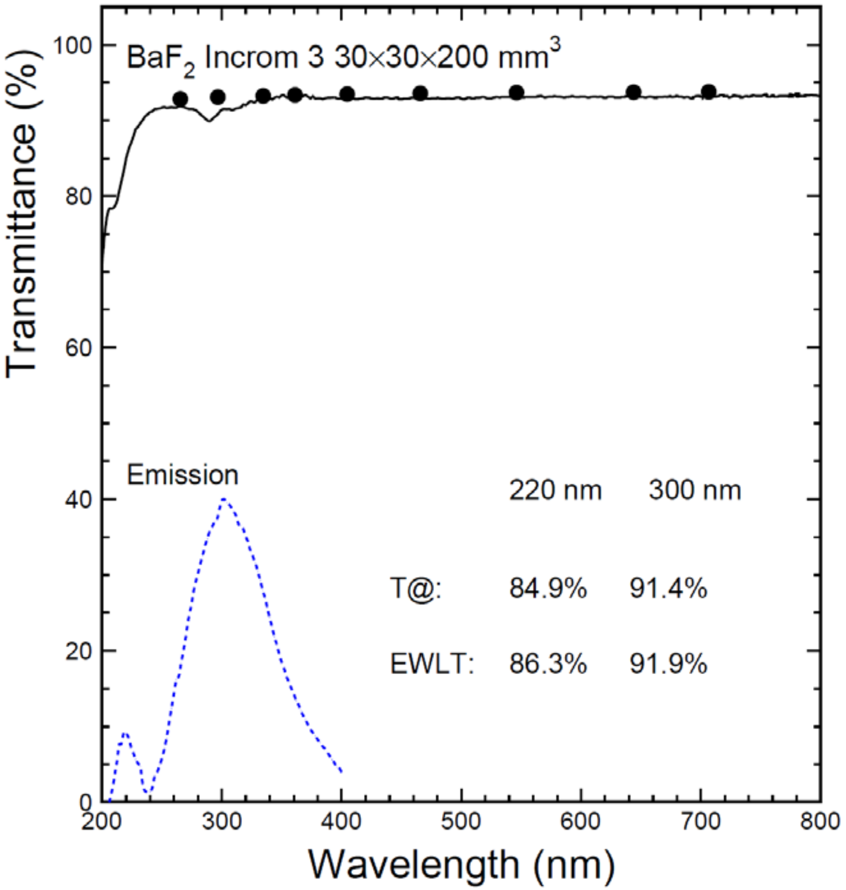
Conclusion

- A calorimeter utilizing the fast scintillation component of barium fluoride meets the Mu2e baseline requirements.
- Both the fast component of BaF_2 and pure CsI provide sufficient light, and can survive the total radiation dose of 100 krad and 10^{12} n/cm^2 expected by the Mu2e experiment.
- Commercial vendors are available for both crystals with adequate cost. CsI is somewhat less expensive.
- The sub-ns fast scintillation component in BaF_2 promises a very fast calorimeter to face the challenge of high event rate expected in future HEP experiments at the intensity frontier.
- BaF_2 also offers a slow scintillation component with 600 ns decay time, which may be used to pursue a novel calorimeter of dual readout: with fast and slow components readout by two individual photodetectors for fast timing/trigger and precision energy.
- In a brief summary, BaF2 provides more potential but is also more challenging.

LT of Incrom BaF_2

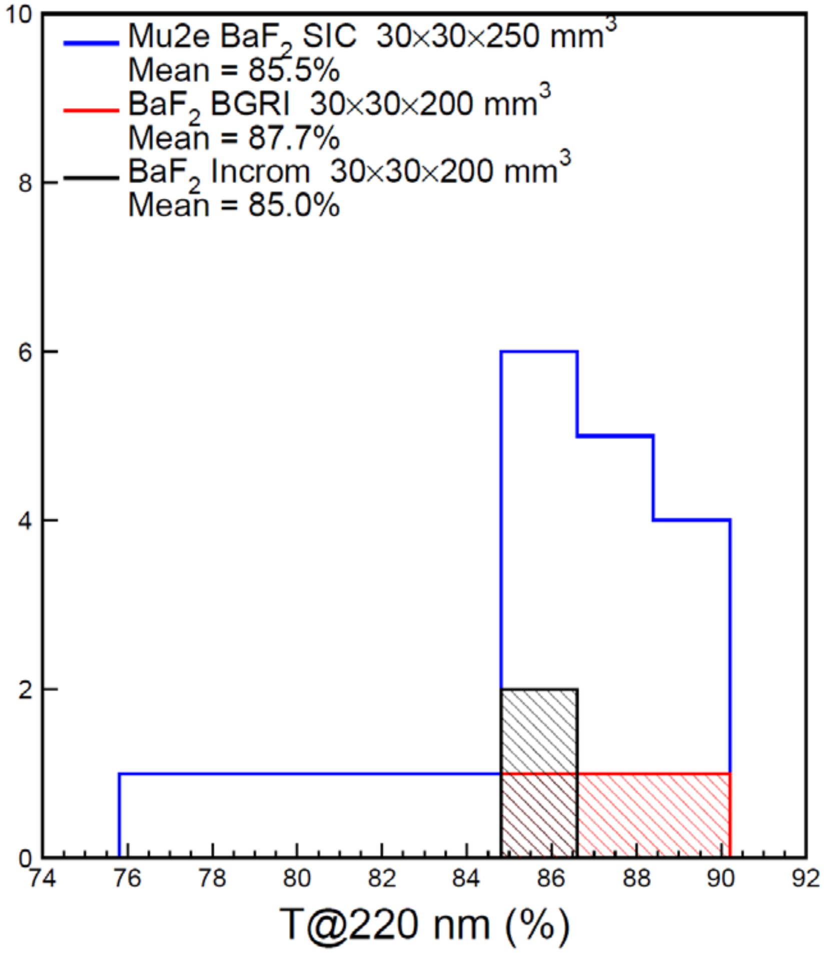
Approaching theoretical limit at long wavelengths
Intrinsic absorption below 230 nm observed

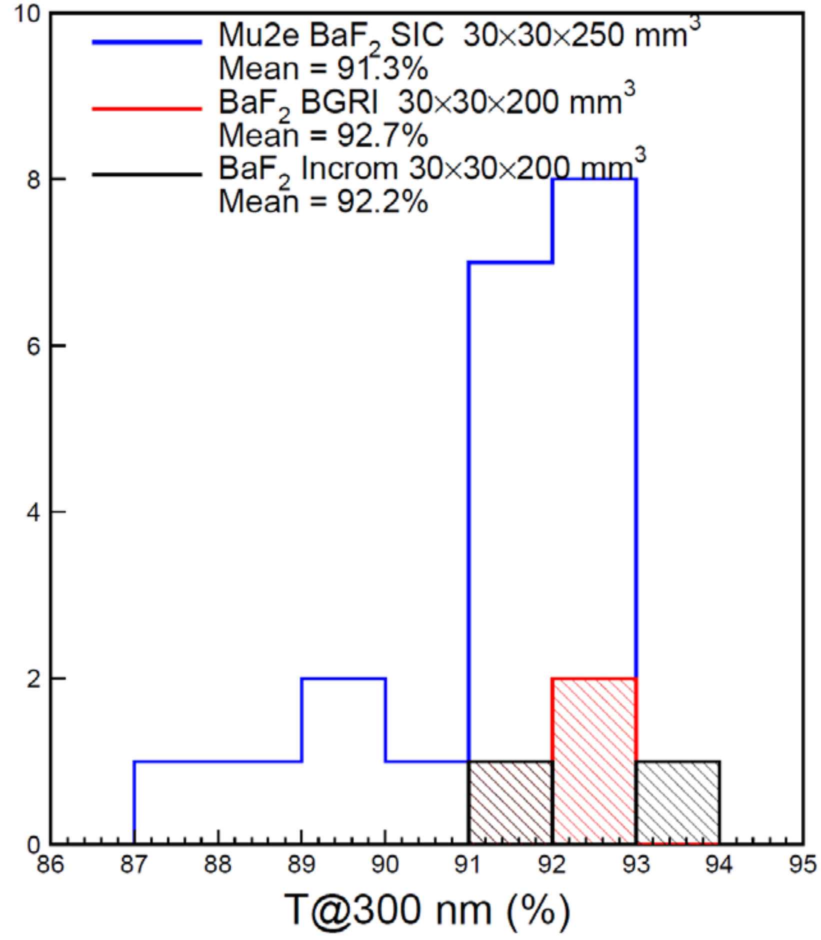




Comparison of Transmittance

20 cm long crystals have better transmittance than 25 cm samples

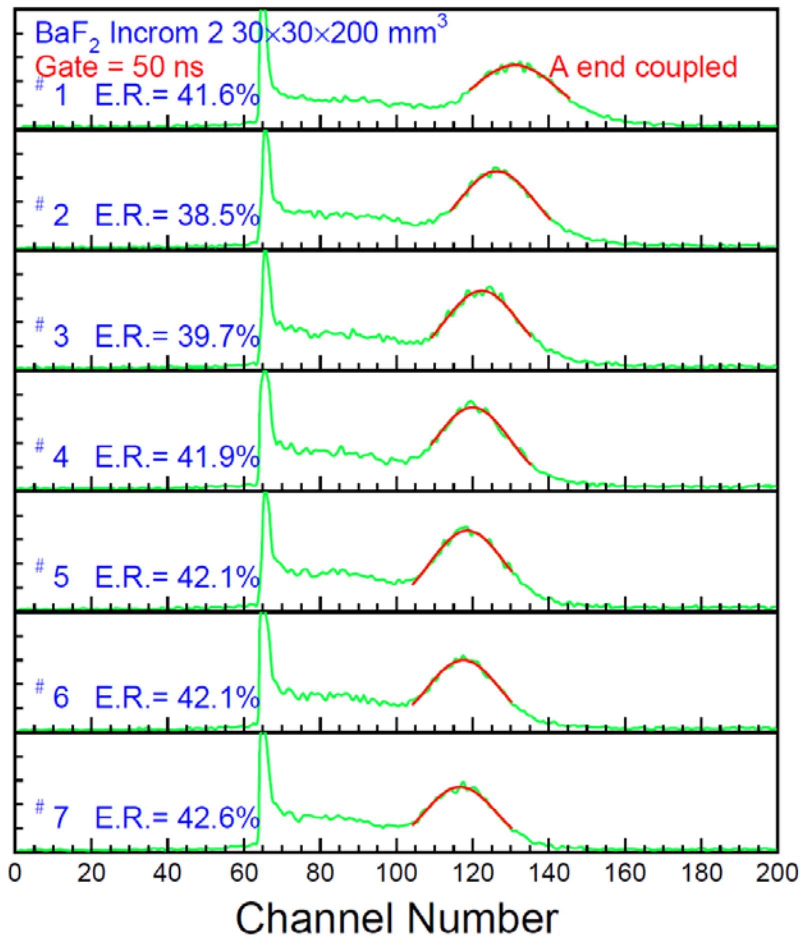


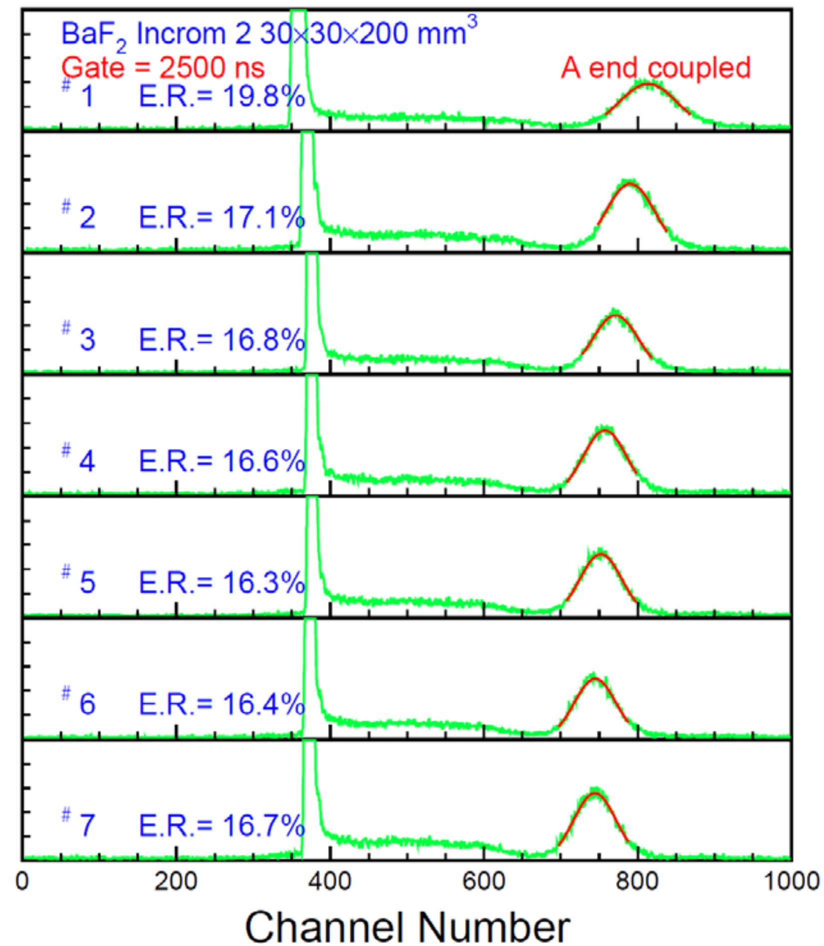


Pulse Height Spectra: Incrom 2

50 ns: ER = 41.2%

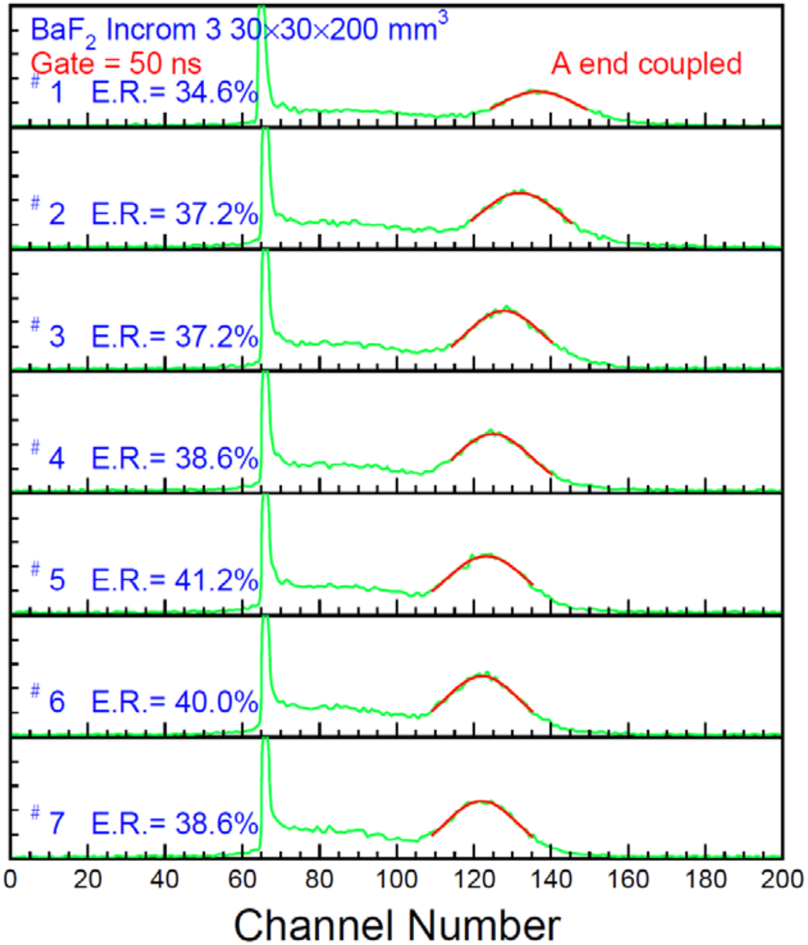
2.5 μs: ER = 17.1%



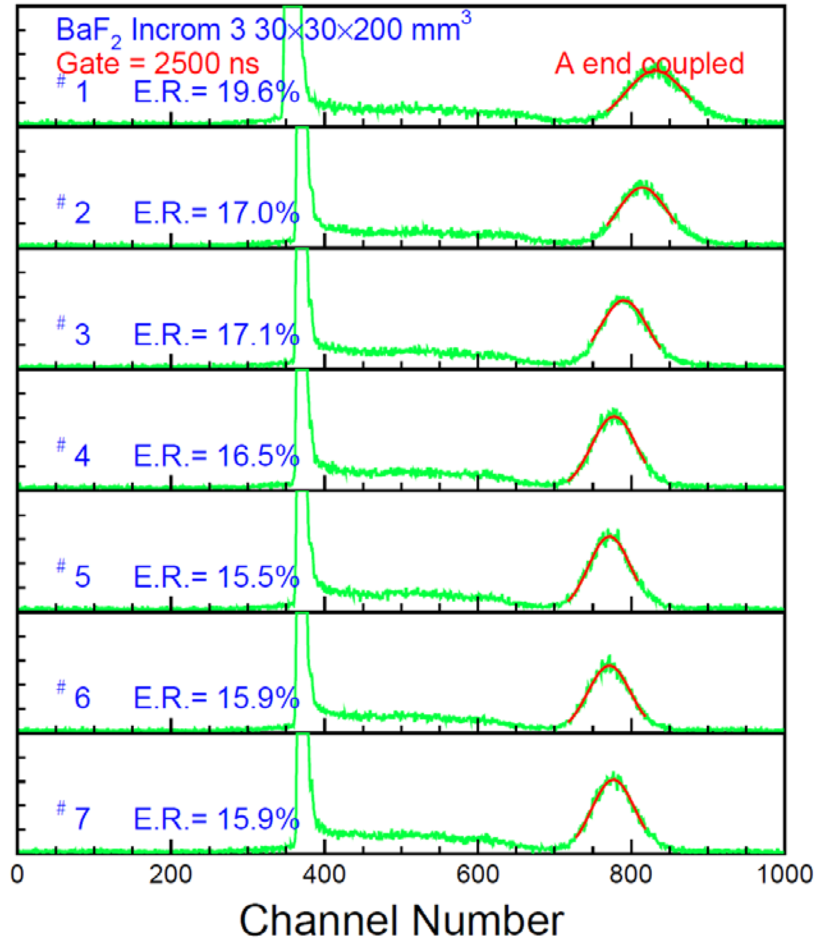


Pulse Height Spectra: Incrom 3

50 ns: ER= 38.2%

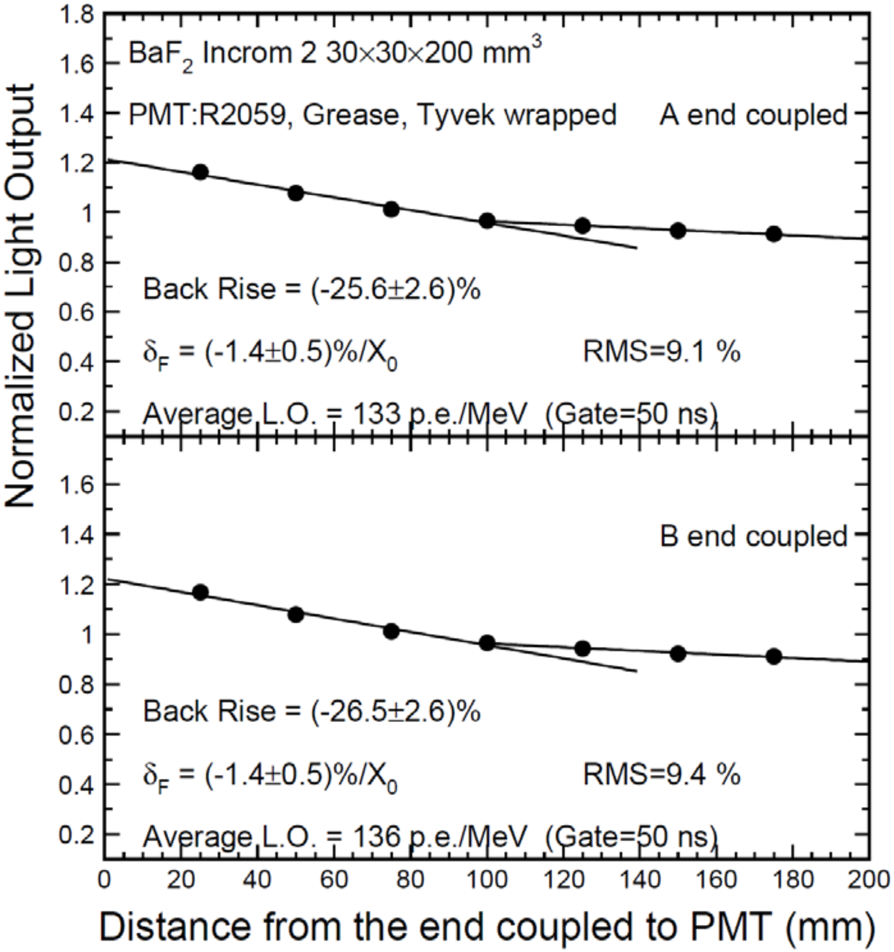


2.5 μs ER= 16.8%

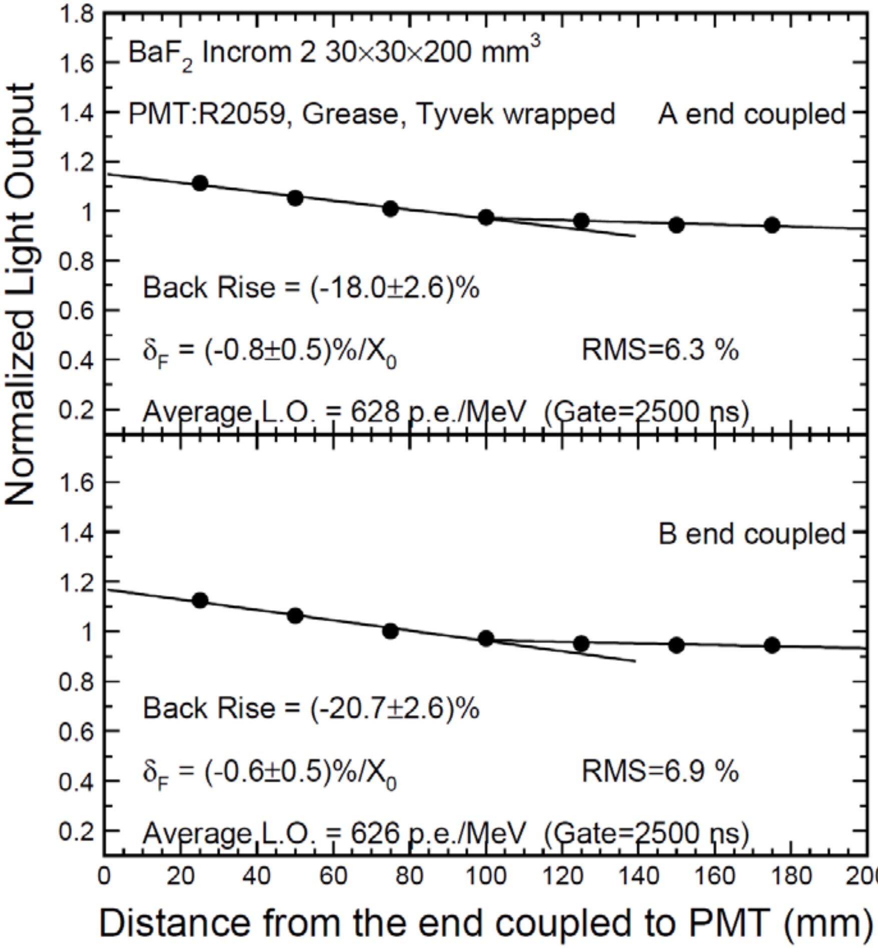


LO & LRU of Incrom 2

Gate: 50 ns

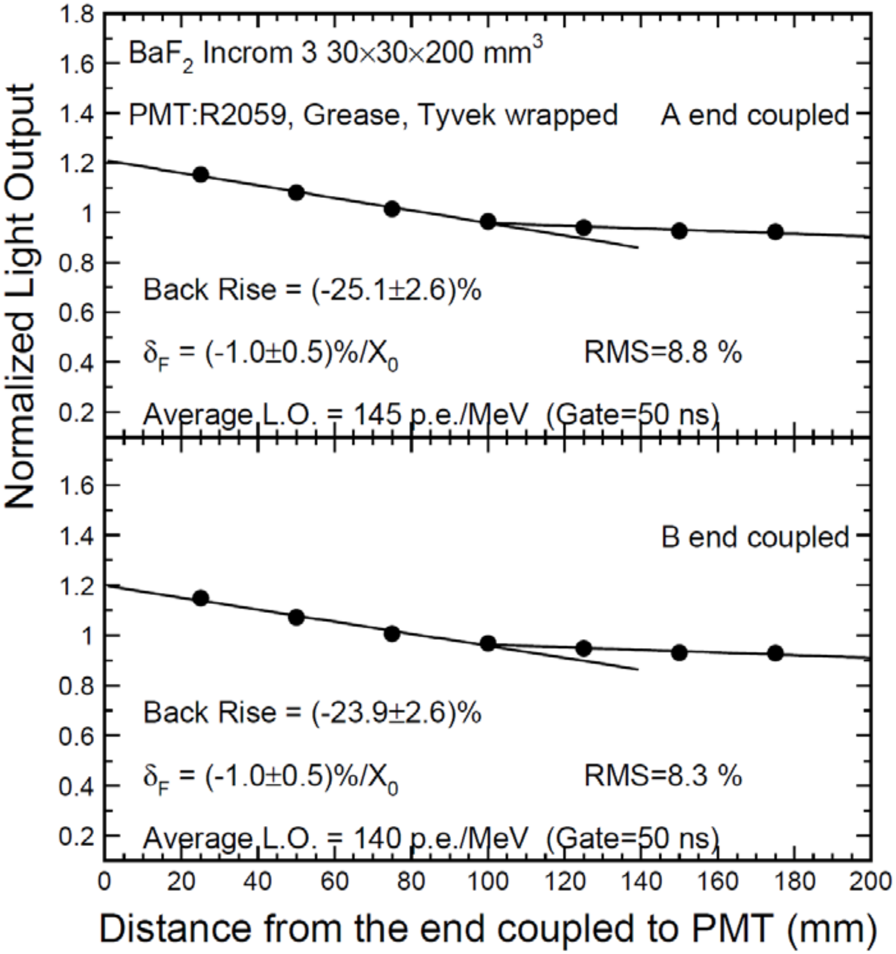


Gate: 2500 ns

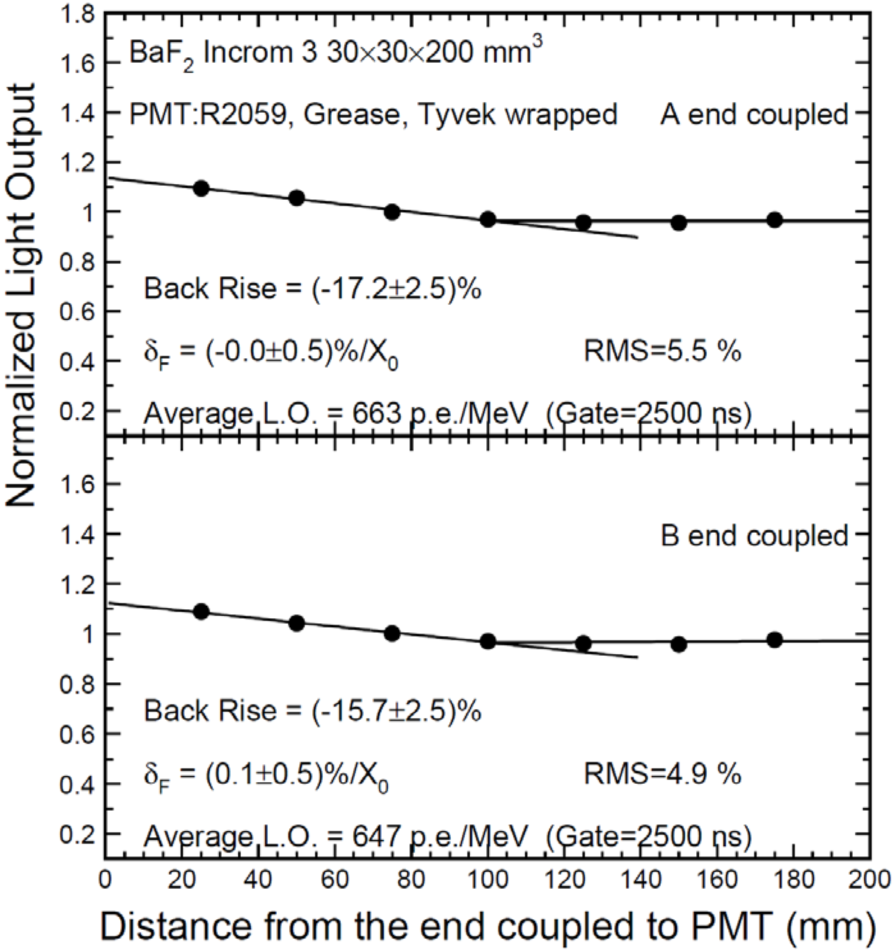


LO & LRU of Incrom 3

Gate: 50 ns

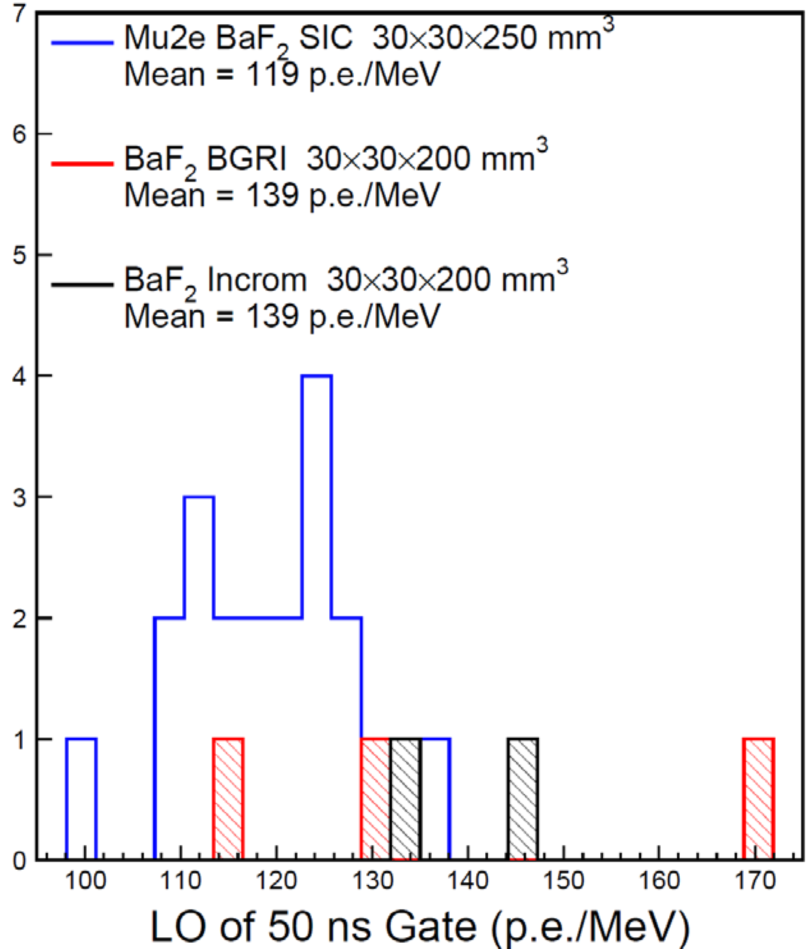


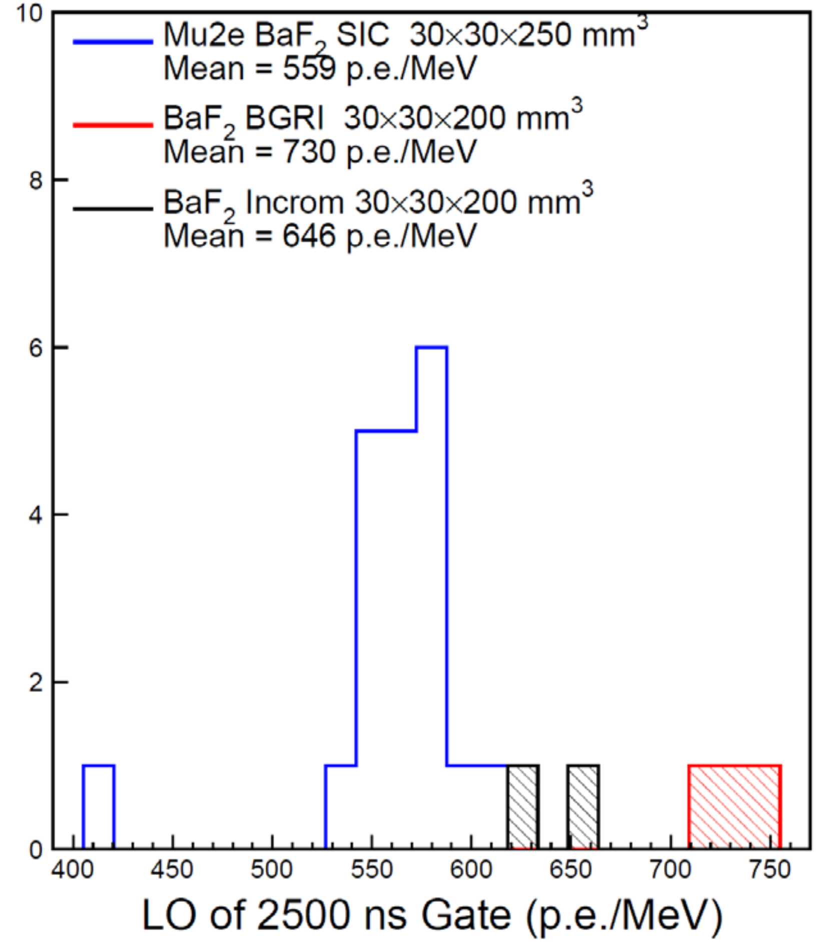
Gate: 2500 ns



Comparison of Light Output

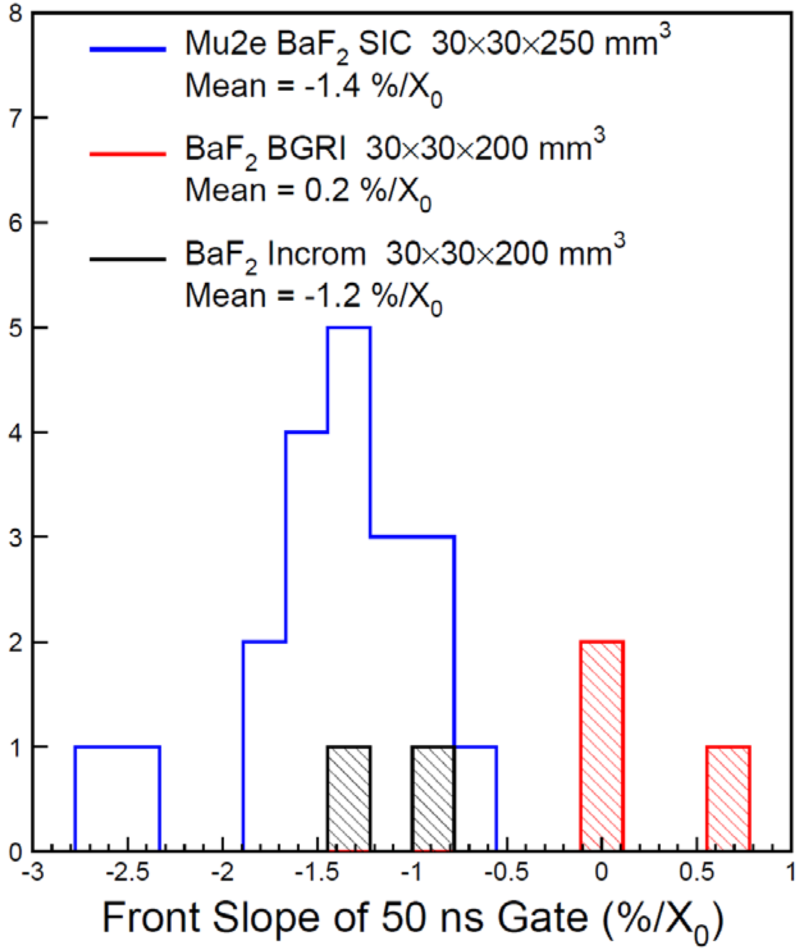
20 cm long crystals have better light output than 25 cm samples

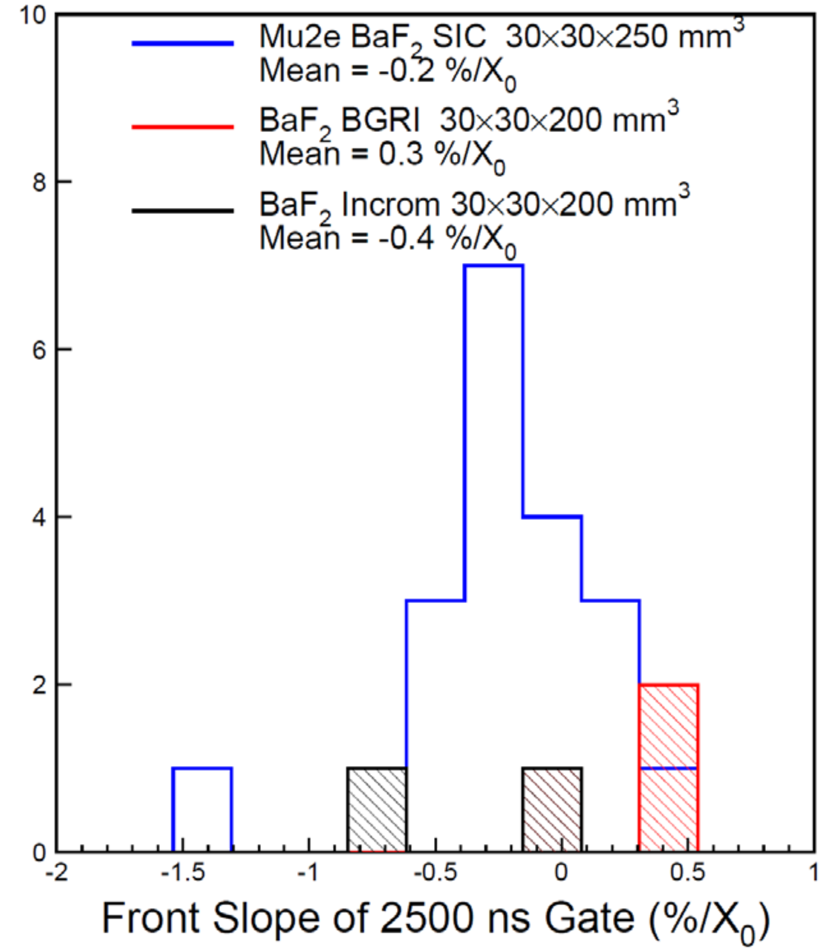




Comparison of Front Slope

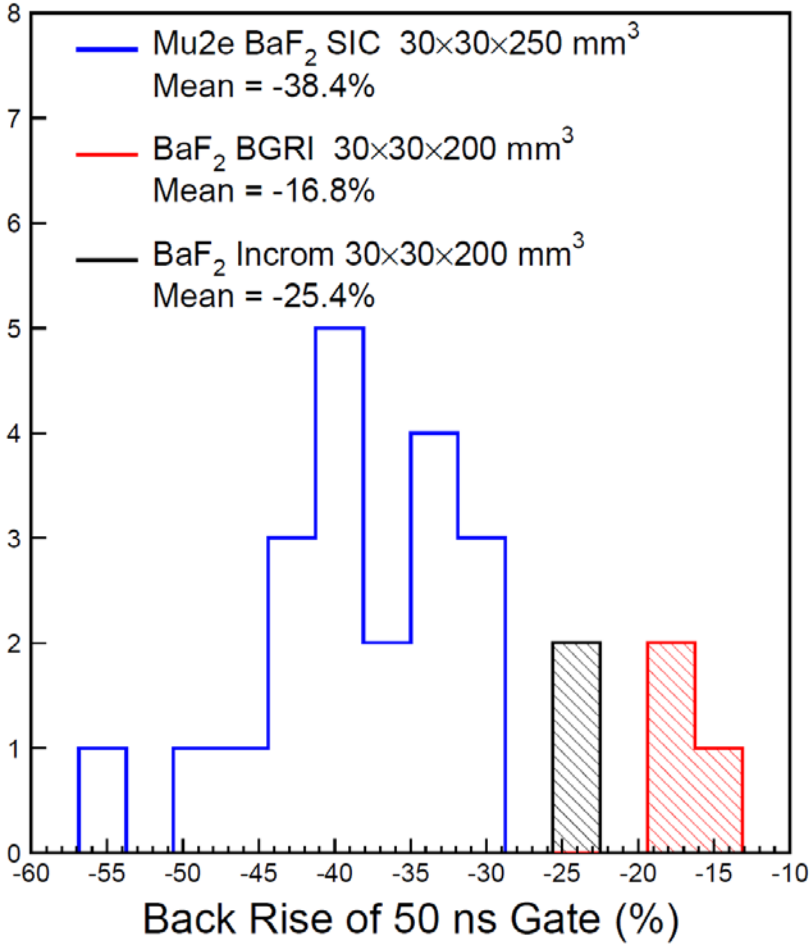
20 cm long crystals have smaller front slope than 25 cm samples

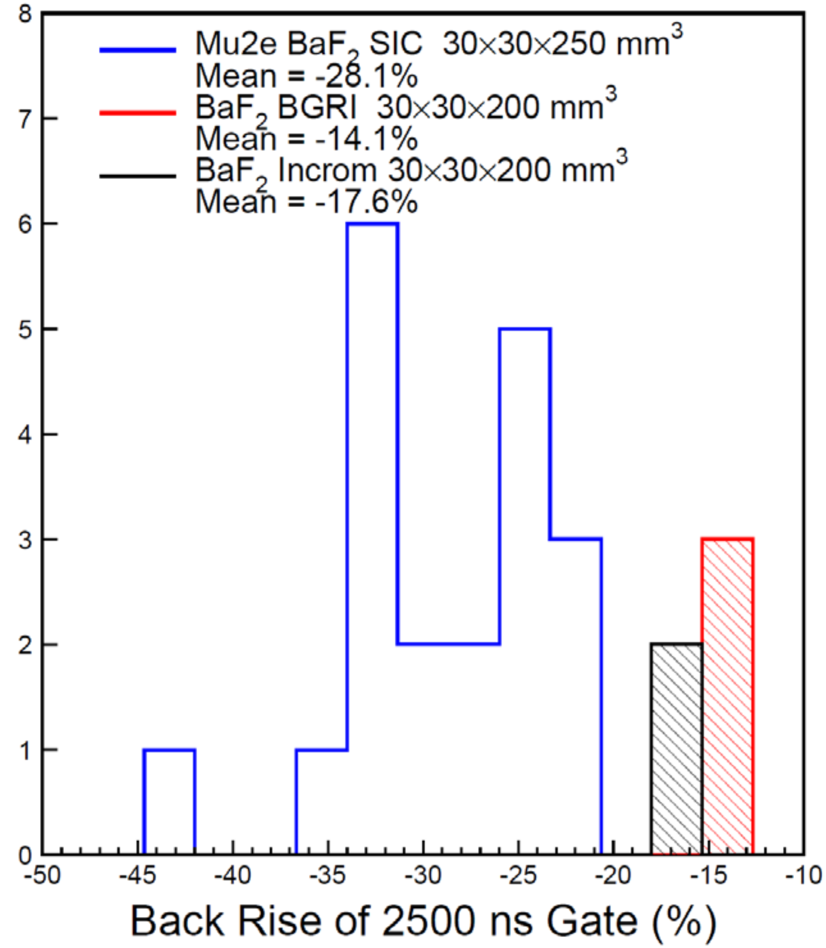




Comparison of Back Rise

20 cm long crystals have smaller back rise than 25 cm samples





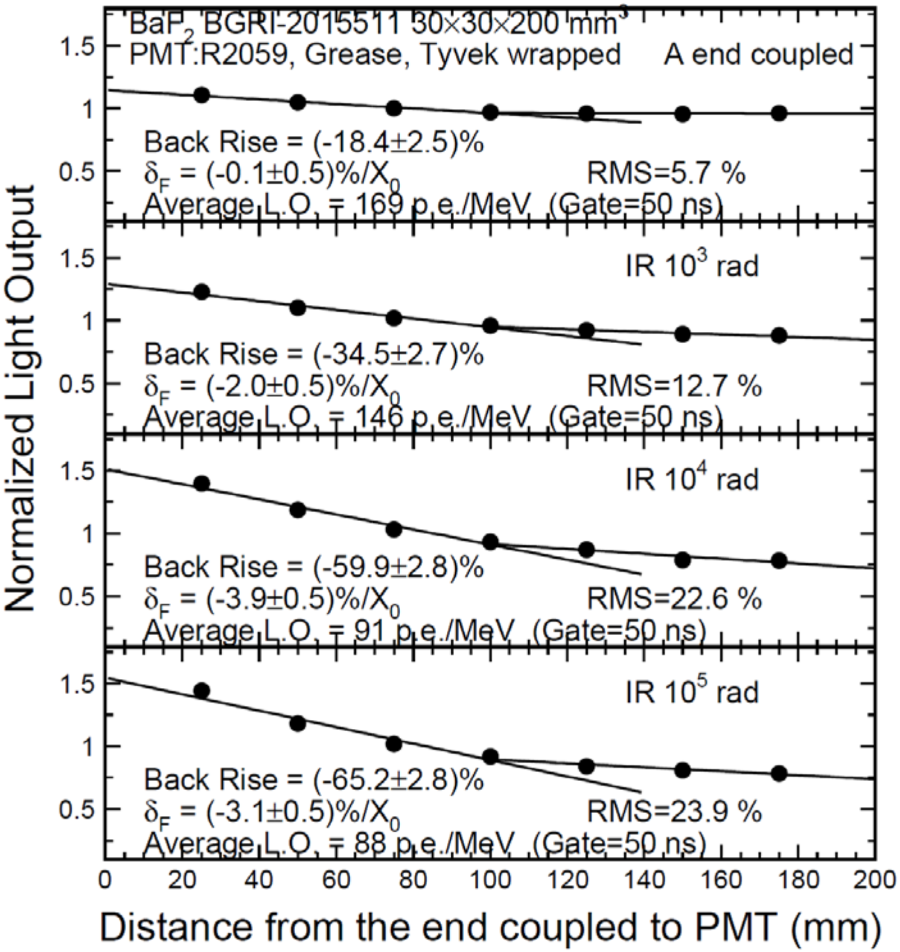
Summary of BaF_2 Wrapping

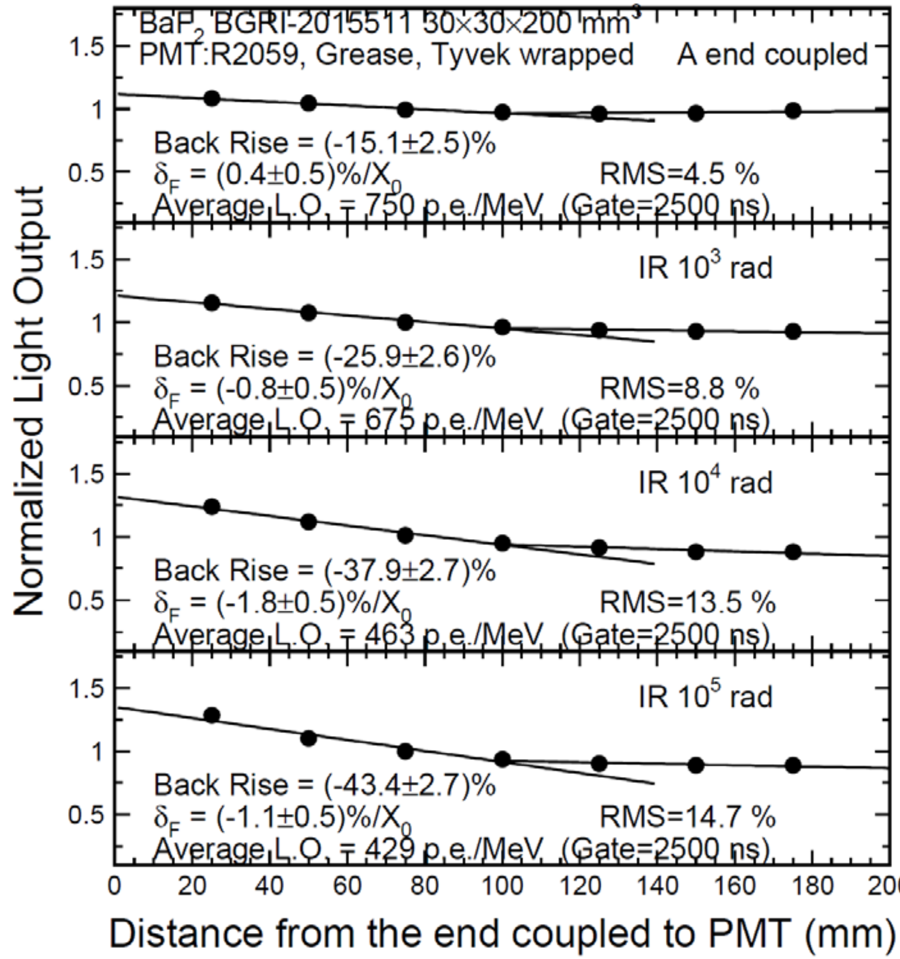
	Fast LO (p.e./MeV)	LO: 50 ns (p.e./MeV)	RMS 50 ns (%)	δ_F 50 ns (%/X_0)	R_B 50 ns (%)	Slow LO (p.e./MeV)	LO: 2.5 μs (p.e./MeV)	RMS 2.5 μs (%)	δ_F 2.5 μs (%/X_0)	R_B 2.5 μs (%)
Al Foil (4)	126	131	16.8	-2.0	-44.8	563	579	8.5	-0.3	-25.9
Al Mylar (2)	129	148	10.7	-0.9	-30.4	597	644	5.6	0	-17.3
ESR (2)	119	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

LO & LRU: BGRI 511

Gate: 50 ns

Gate: 2500 ns



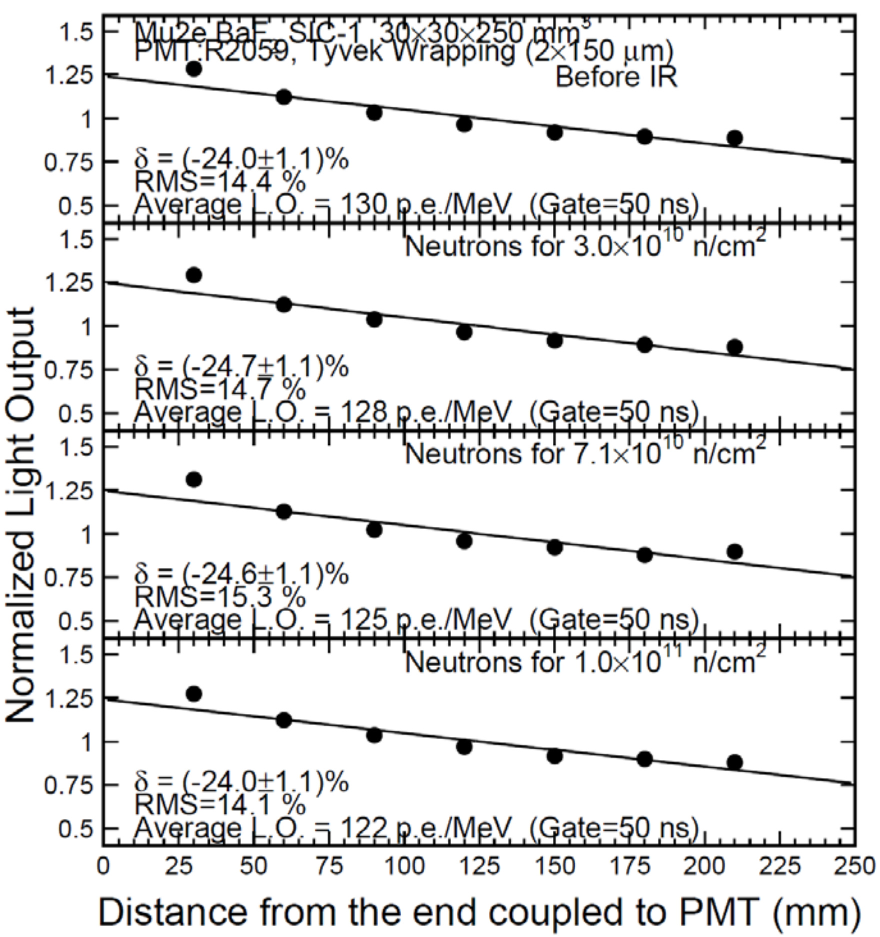


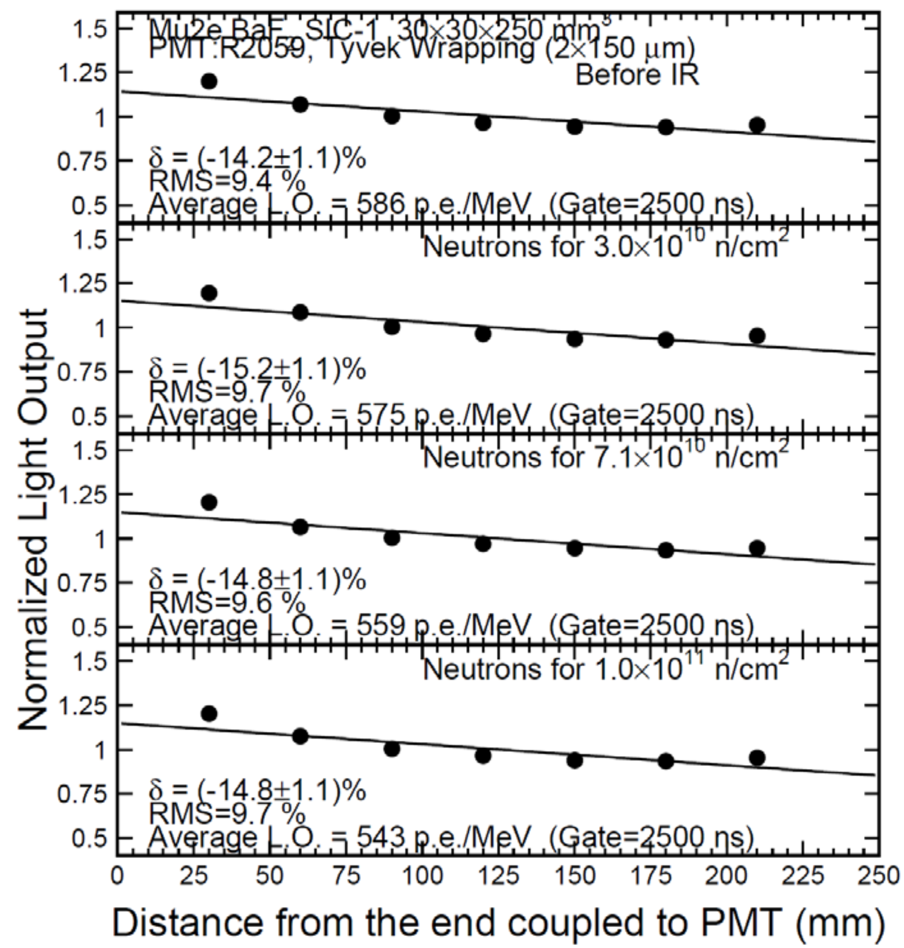
LO & LRU: SIC-1

50 ns

Neutron effect is small up to 10^{11} n/cm^2

2500 ns

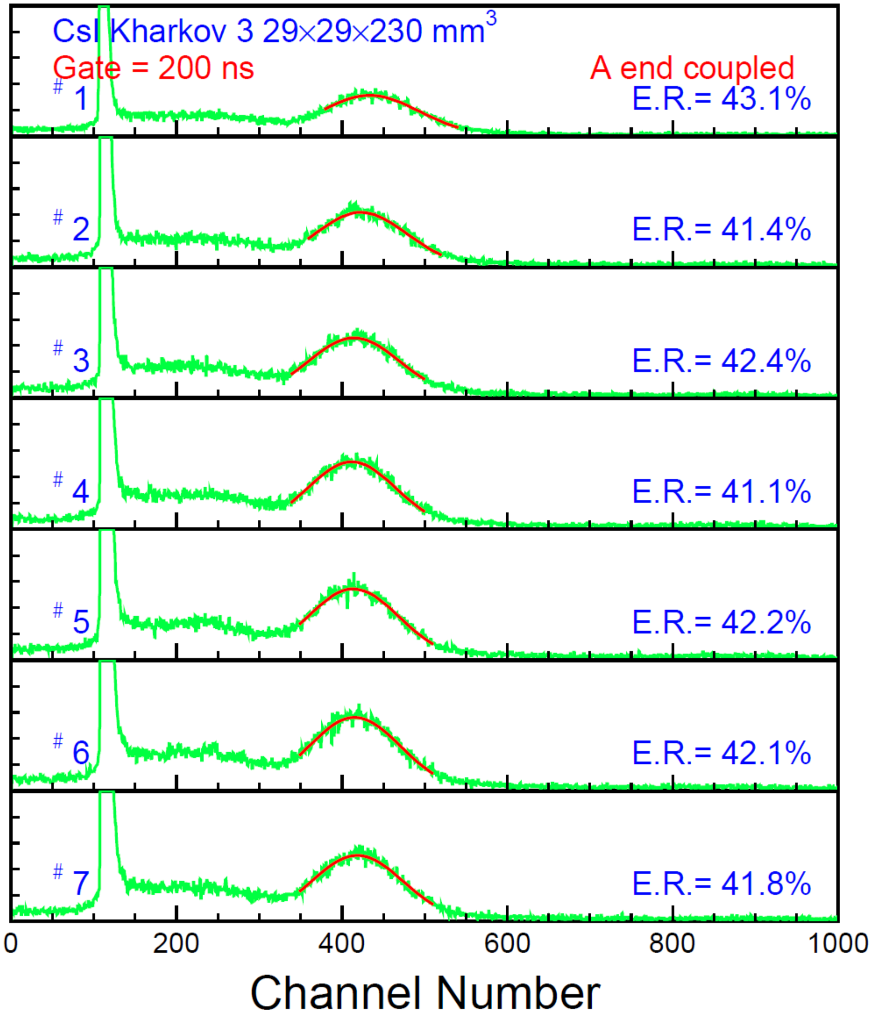


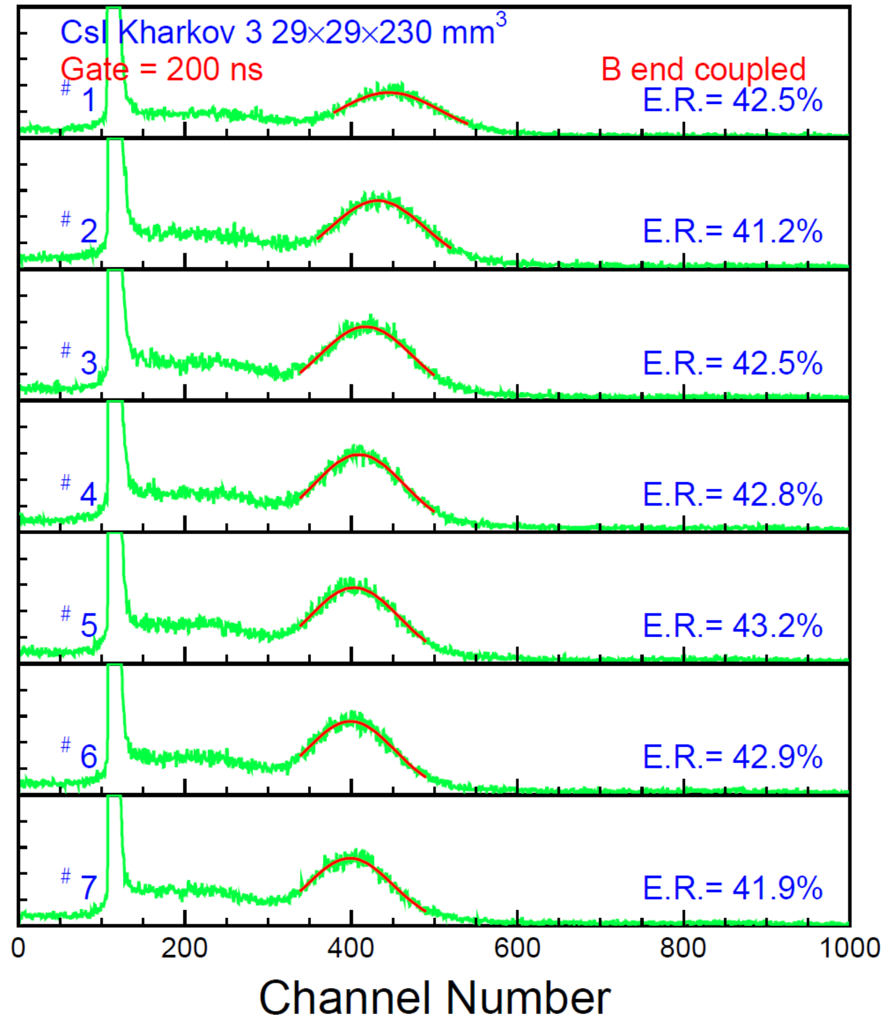


Pulse Height Spectra: Kharkov 3

Ave ER= 42.0%

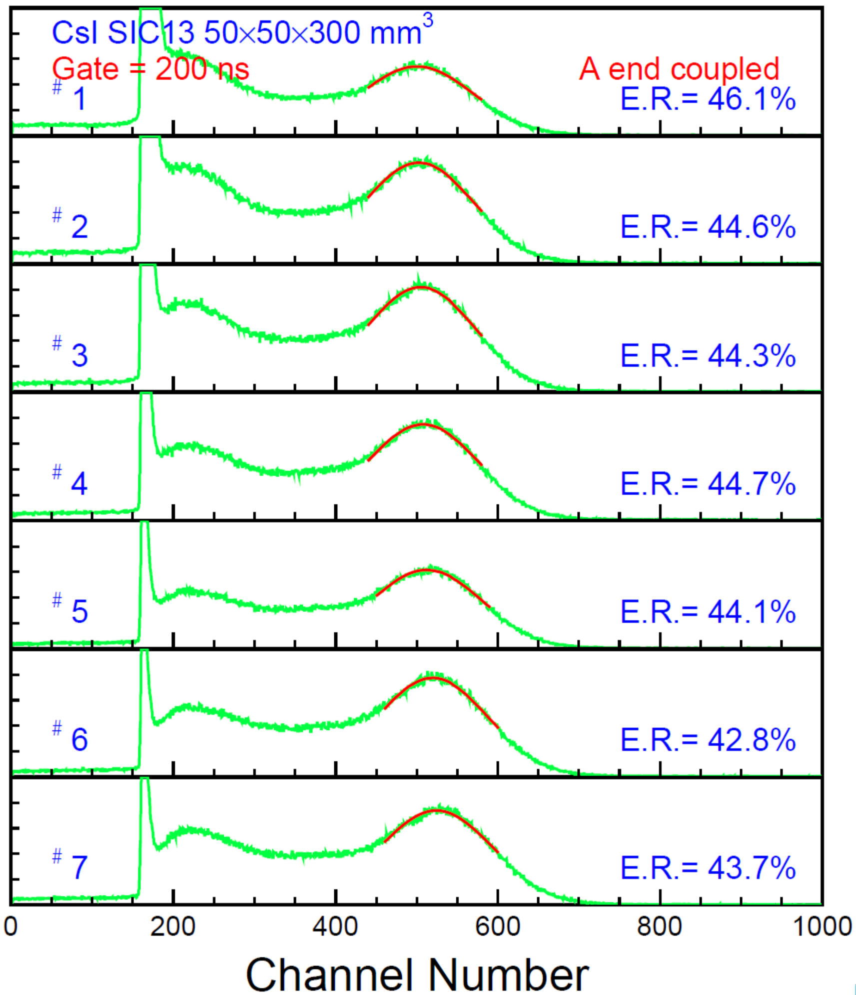
Ave ER= 42.4%



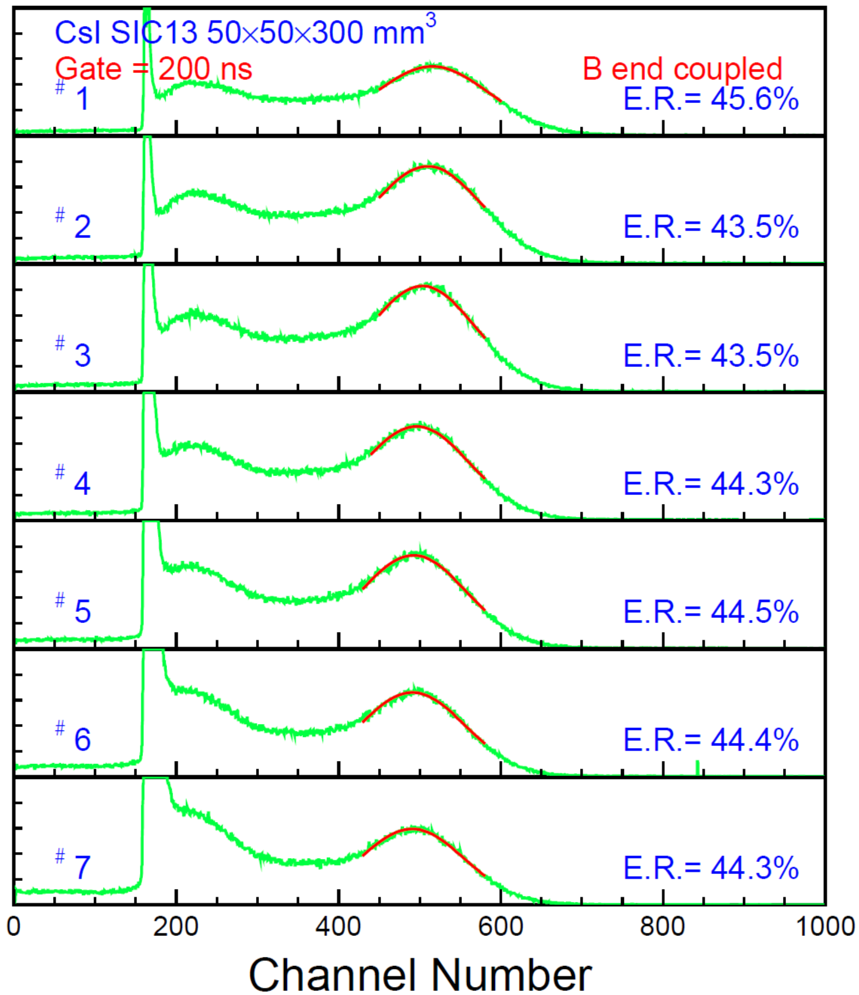


Pulse Height Spectra: SIC 13

Ave ER=44.3%

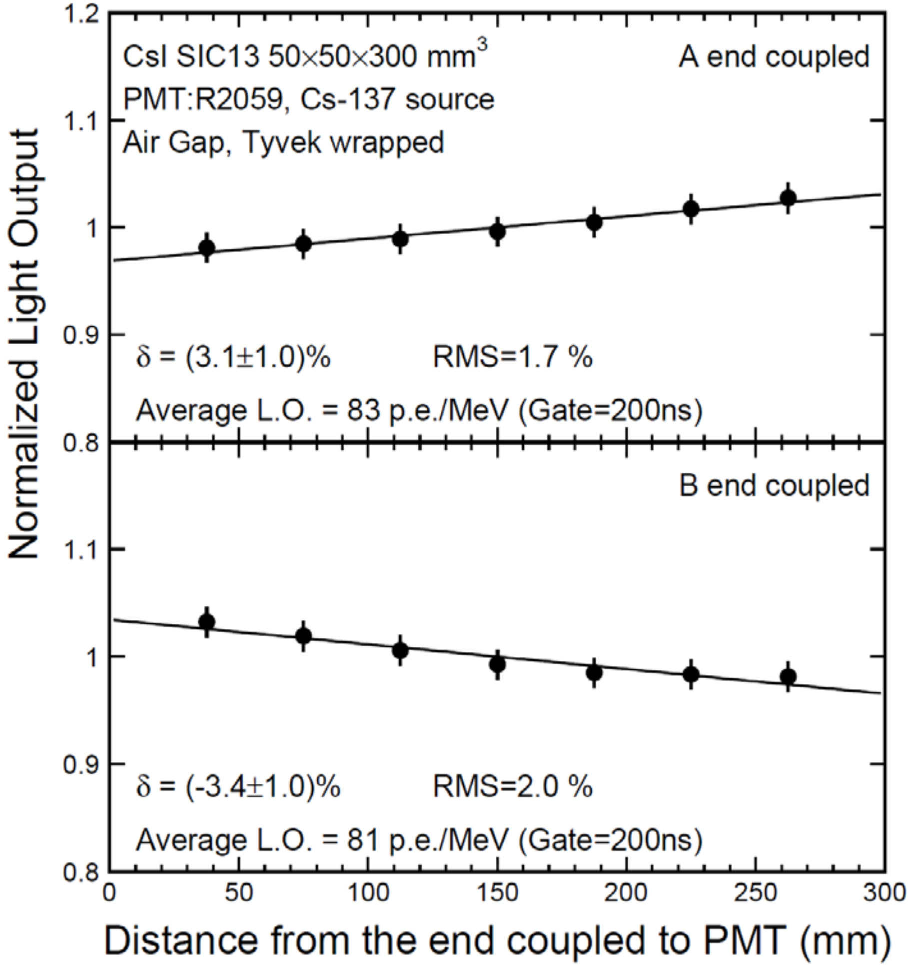


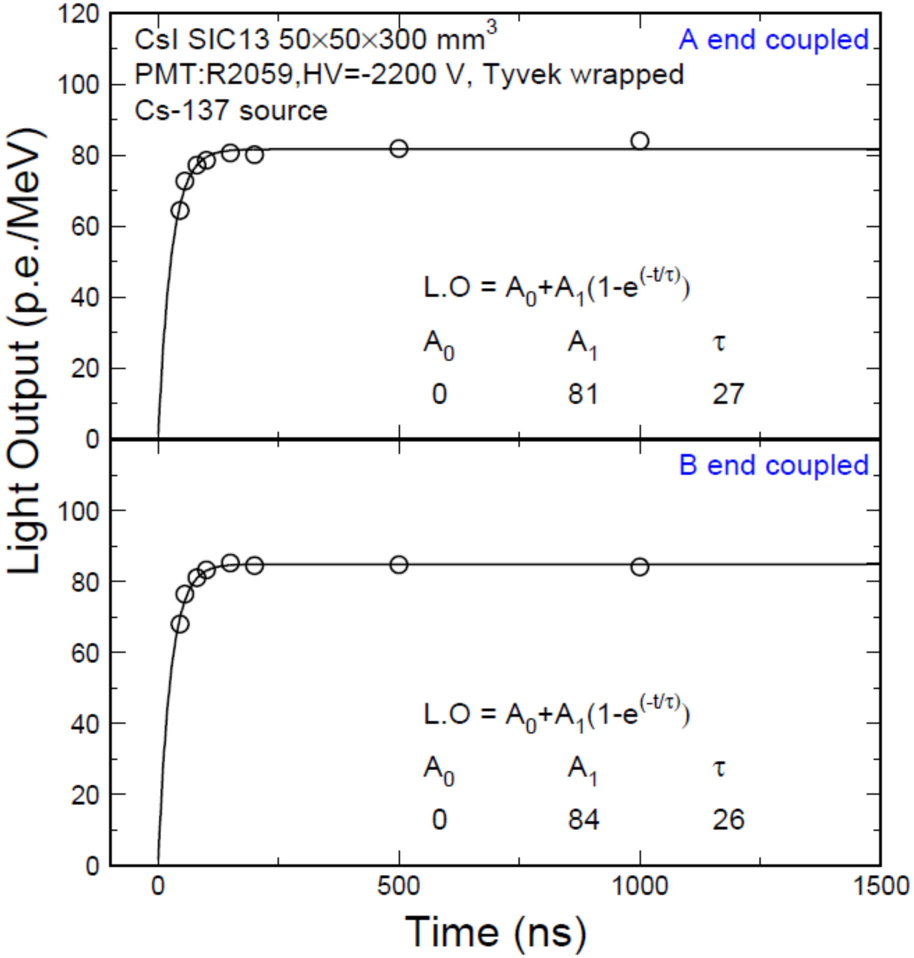
Ave ER=44.3%



LO, LRU and Decay of SIC13

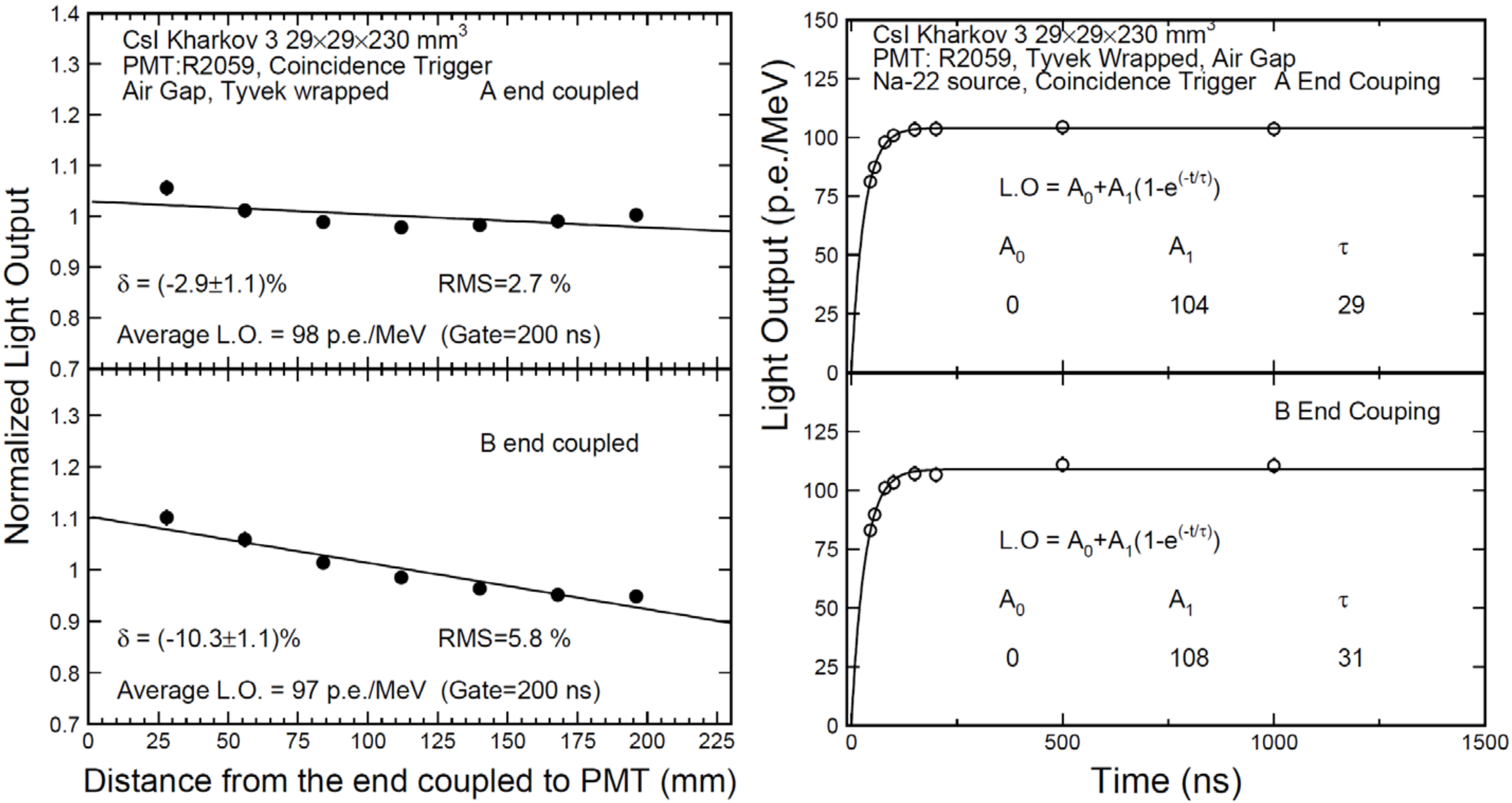
Non-uniformity and 27 ns decay time observed





LO, LRU and Decay of Kharkov 3

Non-uniformity and 30 ns decay time observed



Radiation Damage: SIC2013

No significant degradation in LO and LRU up to 10 krad