Fermilab

Calorimeter Technical Review:
Crystals: Quality & Radiation Hardness

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Introduction

- The Mu2e baseline choice is pure CsI.
- Requirements:
  - Light Output (LO): 100 p.e./MeV by bi-alkali PMT;
  - Light response uniformity (LRU): TBD, < 20%.
- Radiation environment (in hot region, x 3 safety):
  - 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.
- Investigations on pure CsI from various vendors:
  - Kharkov (Ukraine), Opto Materials (Italy) and SICCAS (China): tested
  - In contact: Hilger (UK) and Saint-Gobain (France).

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), light output (LO), light response uniformity(LRU) and decay kinetics were measured by a Hamamatsu R2059 PMT with coincidence triggers from a ^{22}Na source. All samples were wrapped with two layers of Tyvek paper with precision and reproducibility of <1%.
- PHS/ER/LO/LRU were measured with air gap for pure CsI because of the soft and hygroscopic surface.
- Both Caltech and INFN groups contributed to the work presented in this report.

Basic Property of 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

1. http://www.detectors.saint-gobain.com/Plastic-Scintillator.aspx
   http://pdg.lbl.gov/2008/AtomicNuclearProperties/HTML_PAGES/216.html

Mu2e Pure CsI Samples

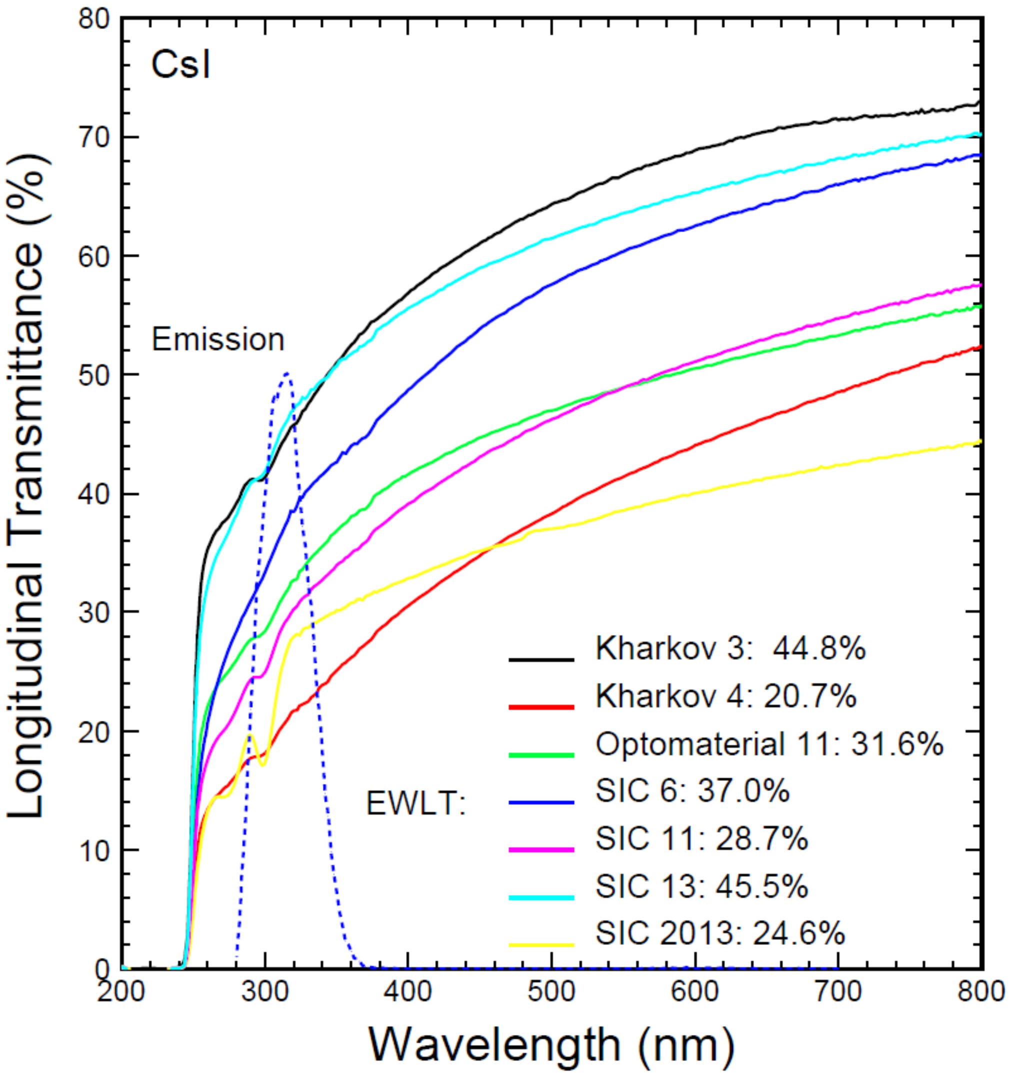
From INFN Sample to Compare Test stations

ID	Dimension (mm^3)	Polishing
Kharkov 1	29x29x230	All faces
Kharkov 3	29x29x230	All faces
Kharkov 4	29x29x230	All faces
Kharkov 5	20x20x120	All faces
Kharkov 11	20x20x120	All faces
Optomaterial 11	30x30x200	All faces
SIC 6	30x30x200	All faces
SIC 11	30x30x200	All faces
SIC 13	30x30x200	All faces
SIC 2013	50x50x300	All faces

Experiments

Properties measured at room temperature: LT, Decay Kinetics, LO and LRU

Mu2e CsI: Longitudinal Transmittance

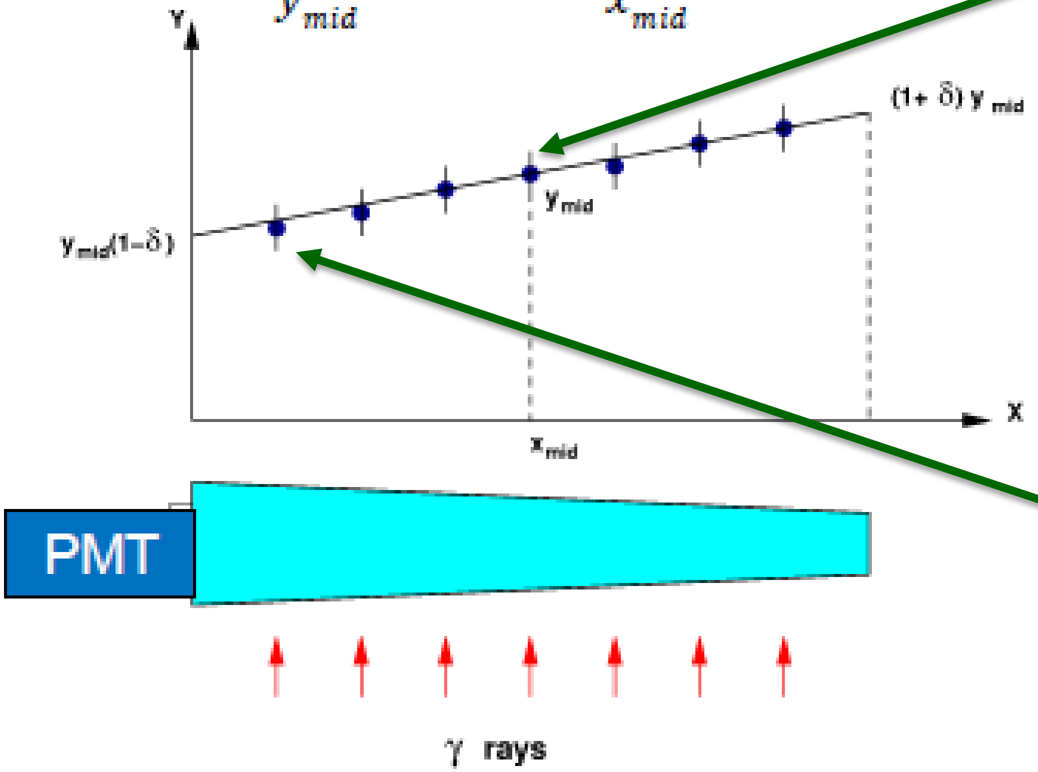


Longitudinal transmittance of pure CsI depends on crystal surface quality, so can not be used in specification, but may be used in radiation damage investigation if crystal surface is kept stable.

Mu2e CsI: LO, LRU and Decay Kinetics

LRU, *Light Response Uniformity*, is defined as follow:

$$\frac{y}{y_{mid}} = 1 + \delta(\frac{x}{x_{mid}} - 1)$$

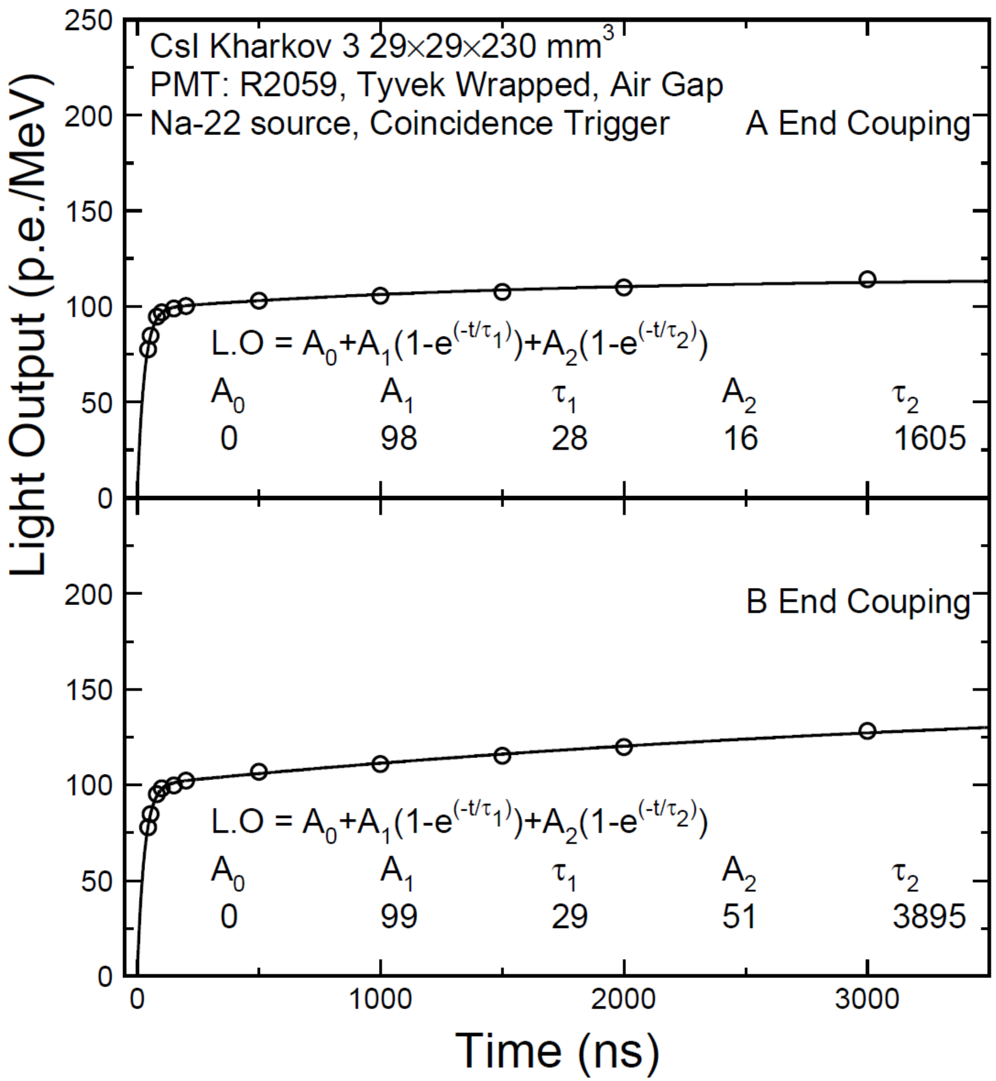


LO is defined as the average of LO values measured at seven points

Decay kinetics was measured at the point closest to the PMT

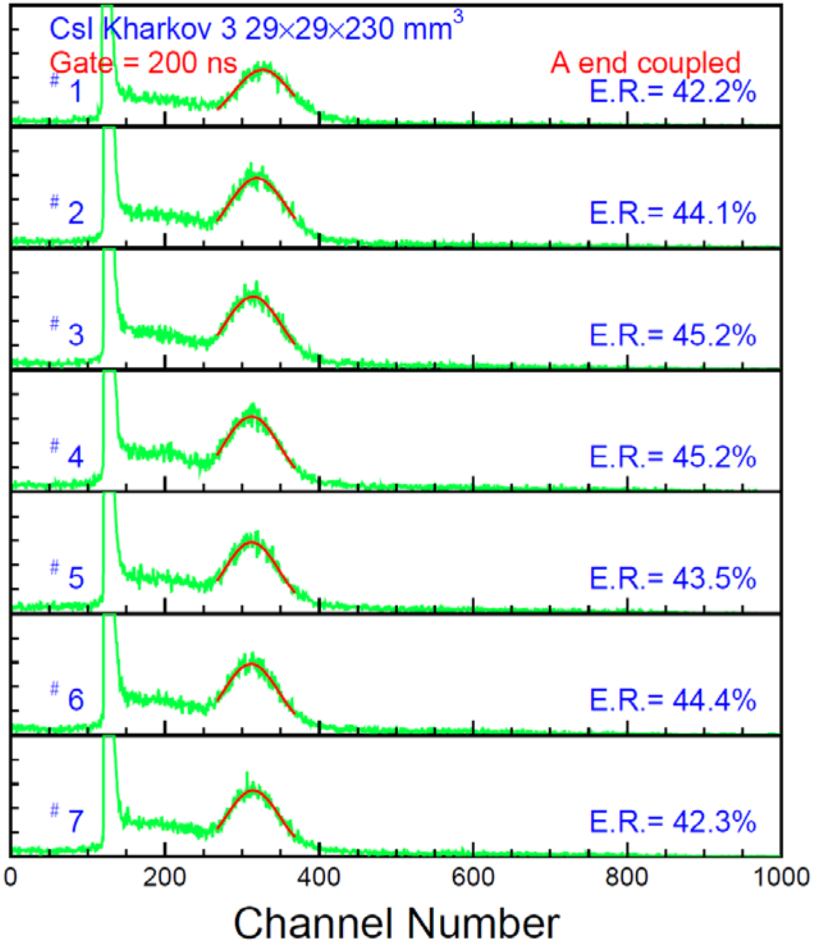
Decay Kinetics: Kharkov 3

A slow component with different intensity and decay time of 1.6 and 4 us was observed

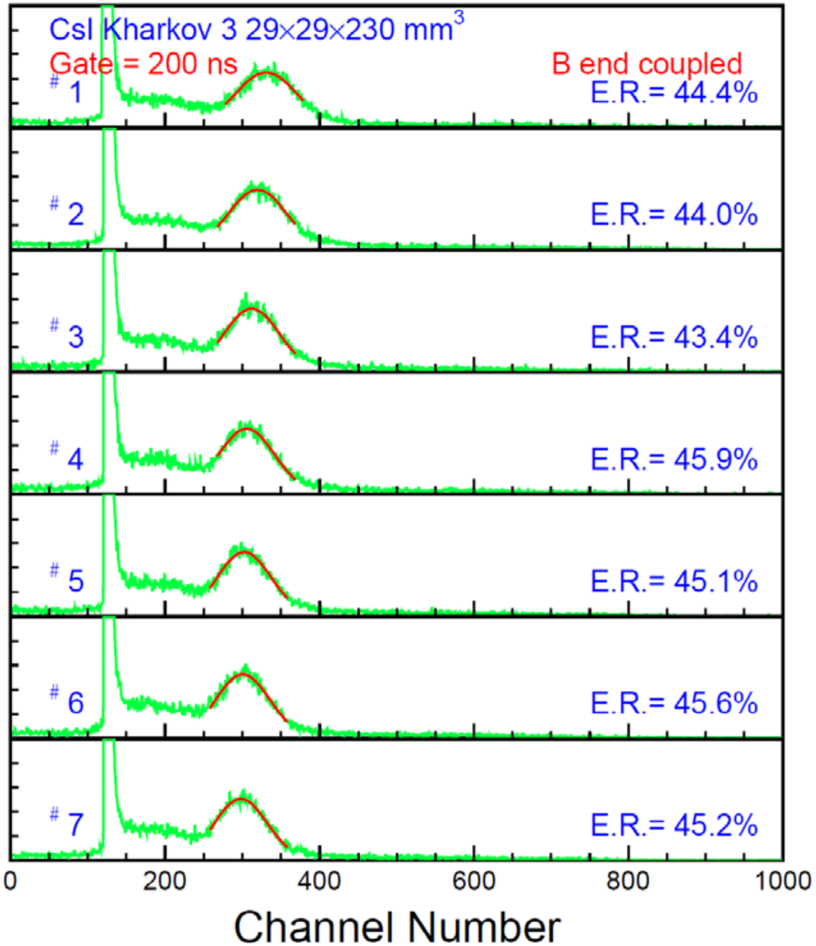


PHS (200 ns): Kharkov 3

Ave ER= 43.8%

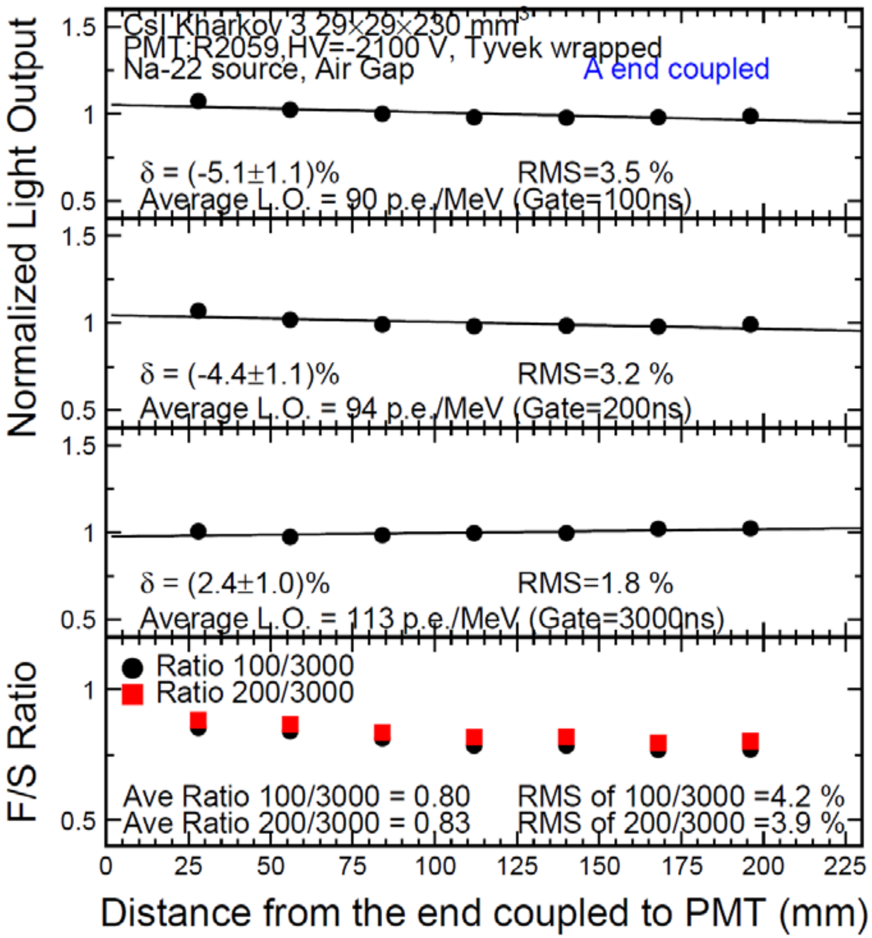


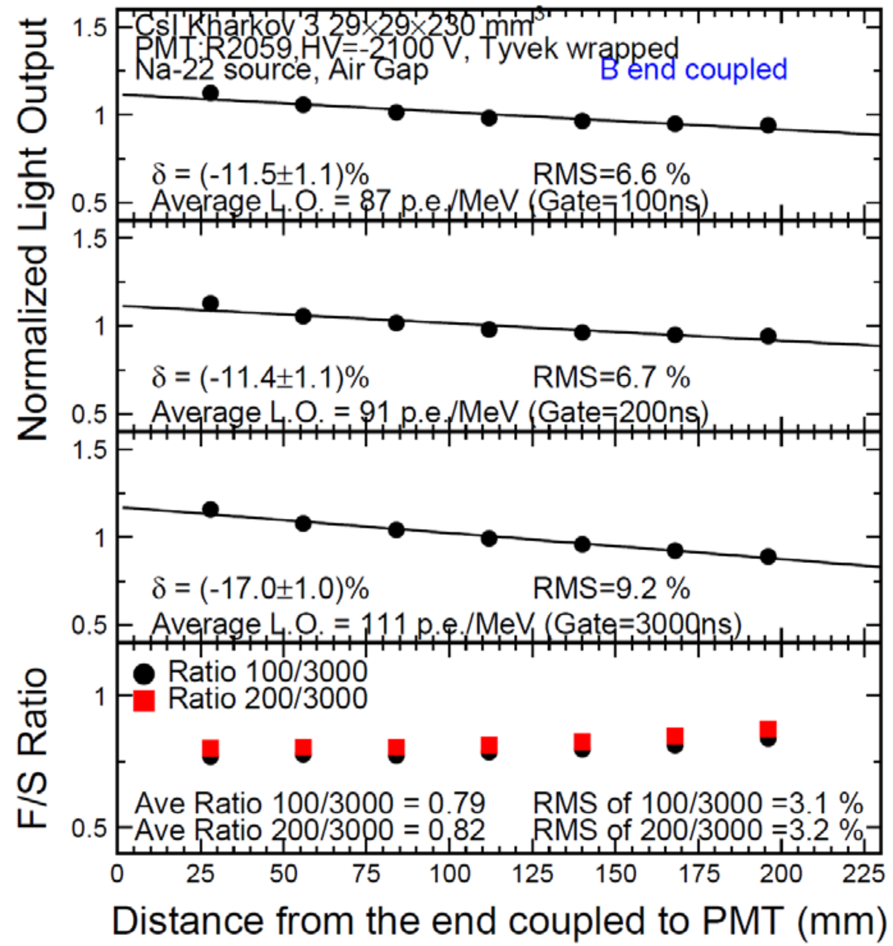
Ave ER= 44.8%



LO & LRU (Different Gate): Kharkov 3

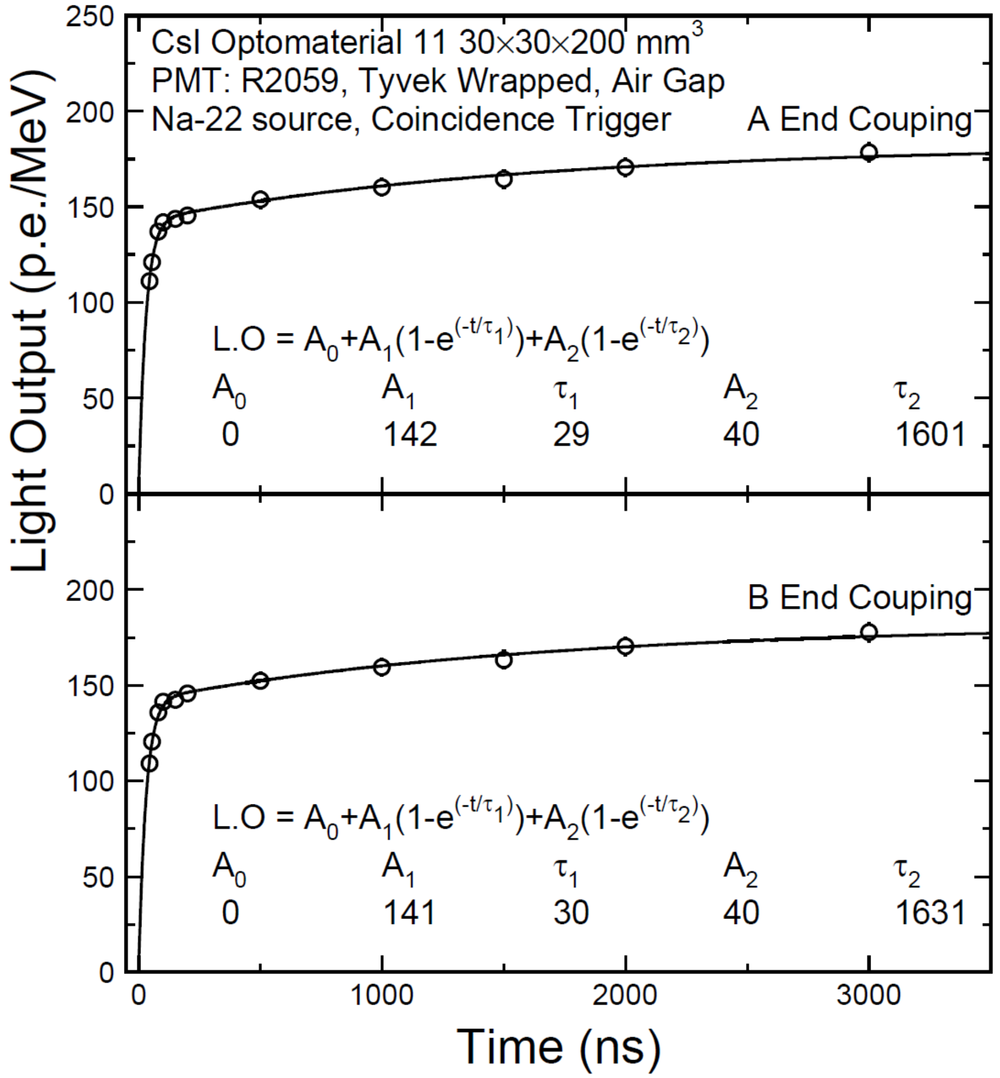
F/T ratio changes from one end to other





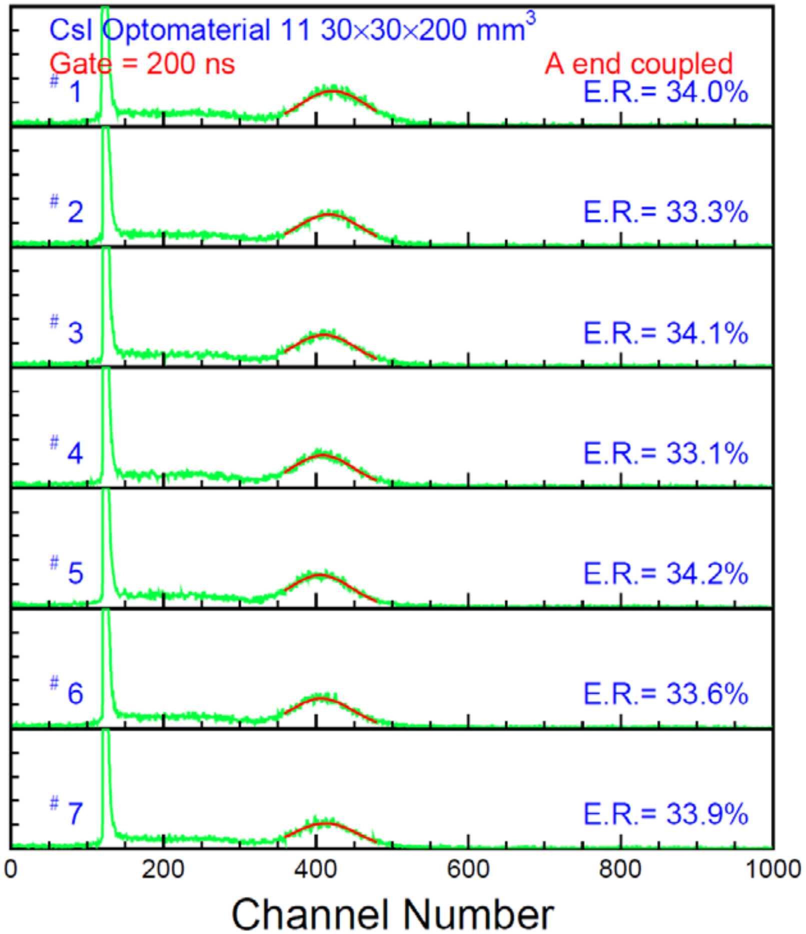
Decay Kinetics: Optomaterial 11

A slow component with a decay time of 1.6 us and no position dependence was observed, which is at a level of 30% of the fast component with 30 ns decay time

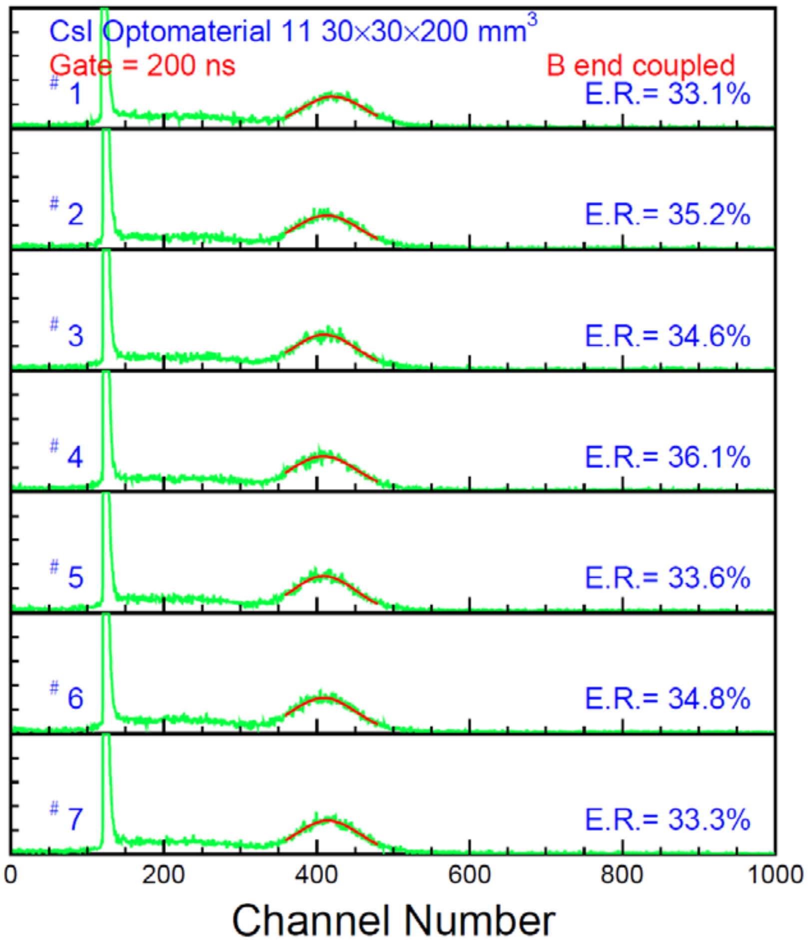


PHS (200 ns): Optomaterial 11

Ave ER= 33.7%

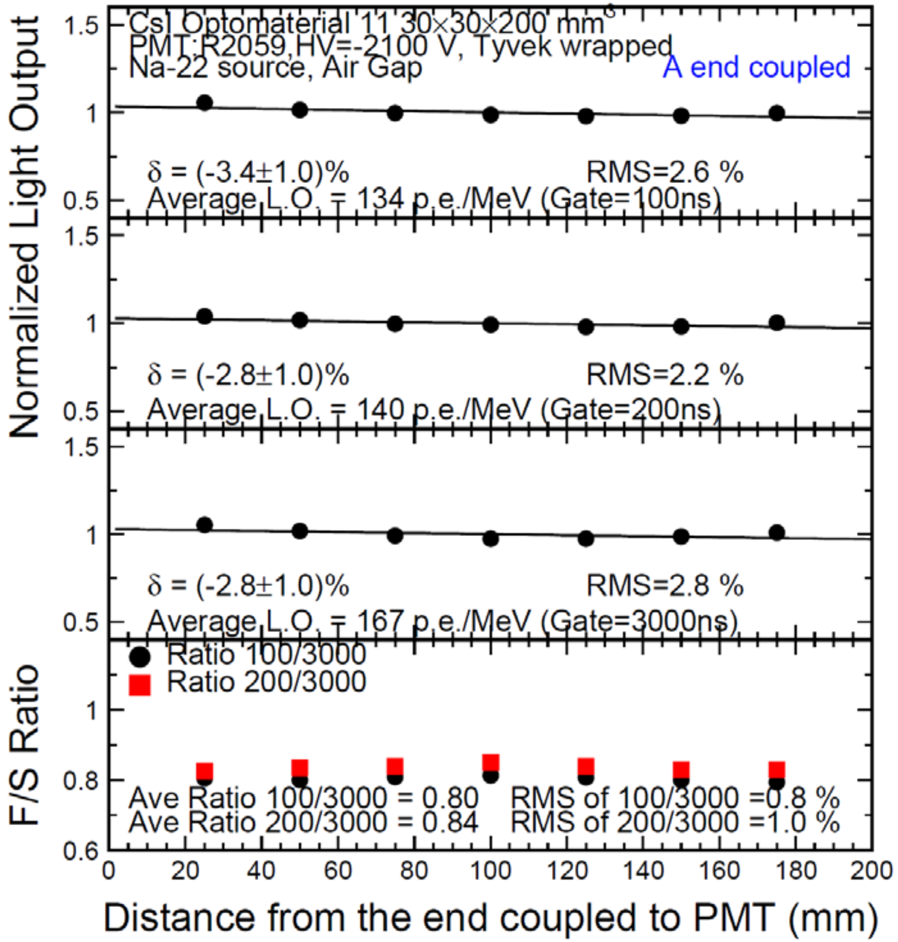


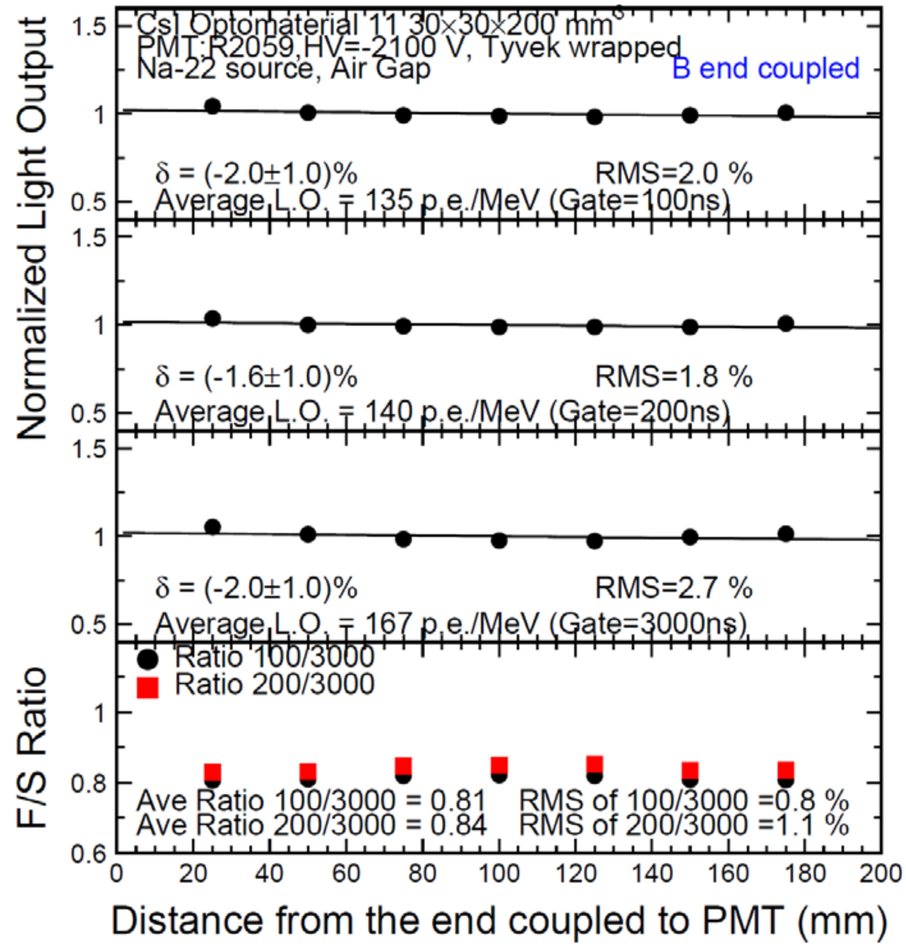
Ave ER= 34.4%



LO & LRU (Different Gate): Optomaterial 11

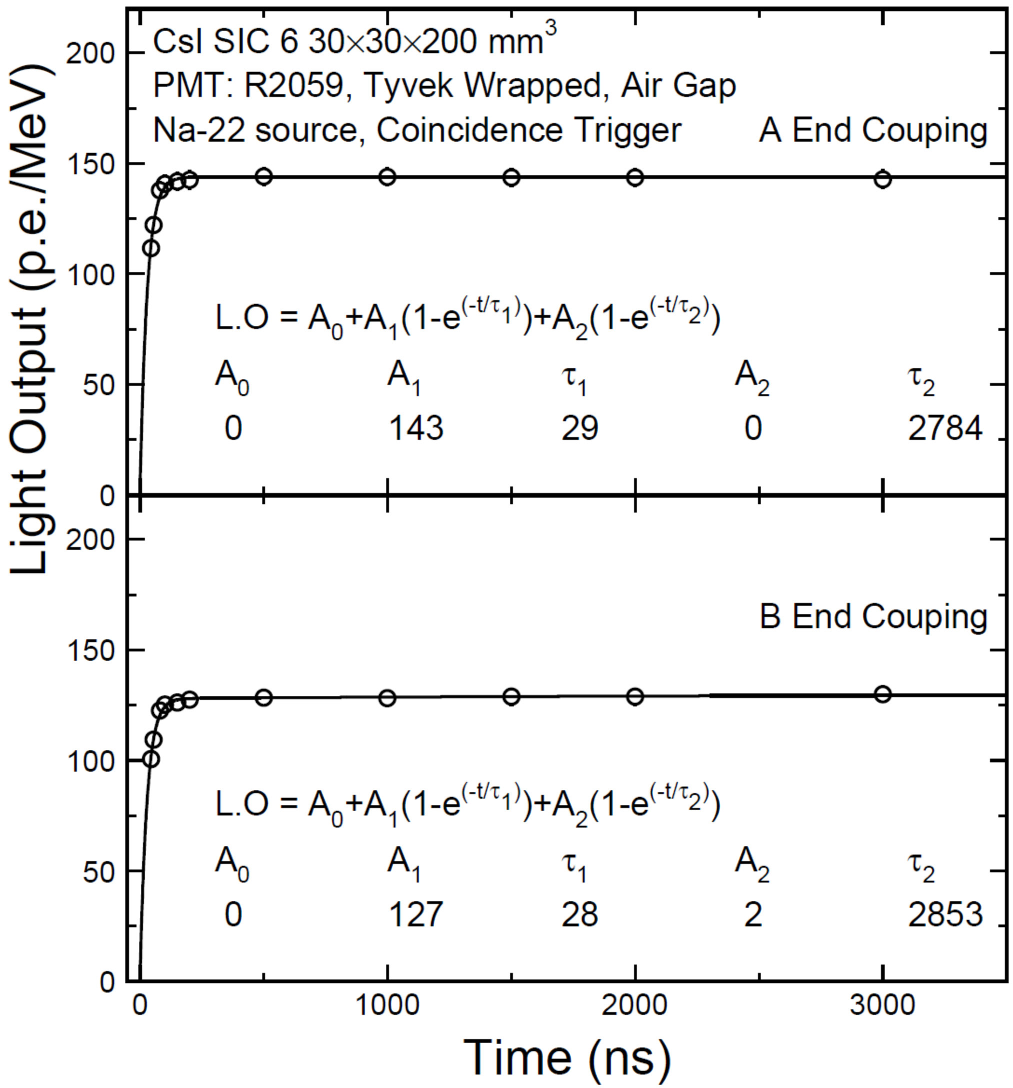
F/T ratio is constant along the crystal





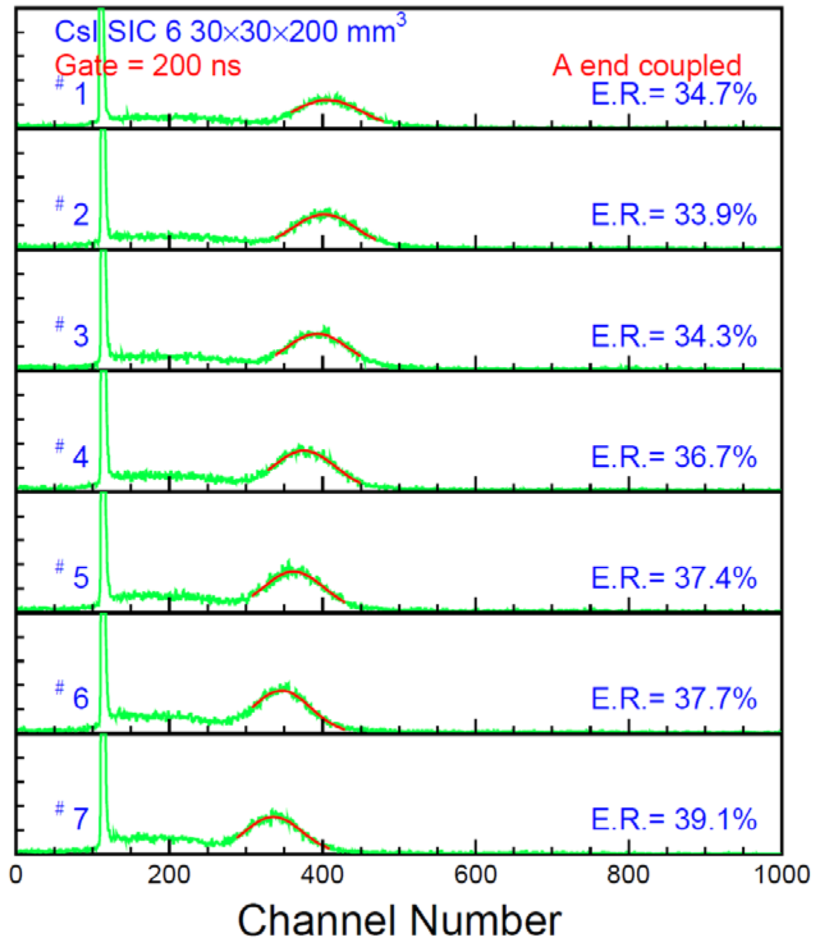
Decay Kinetics: SIC 6

No slow component was observed

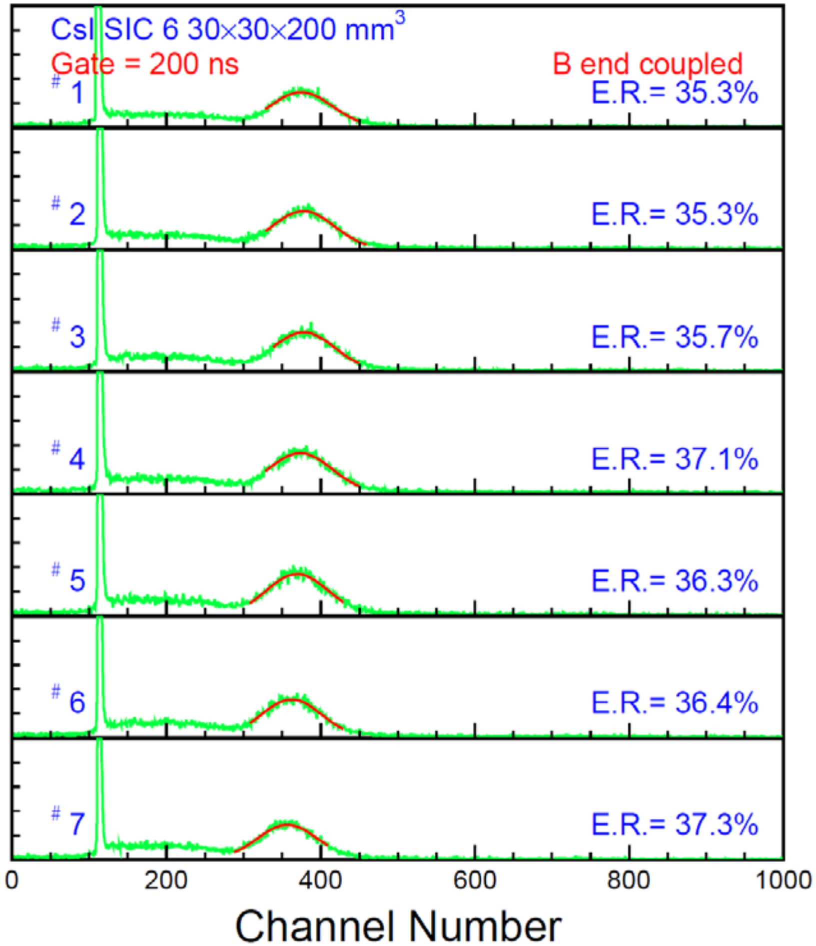


PHS (200 ns): SIC 6

Ave ER= 36.3%

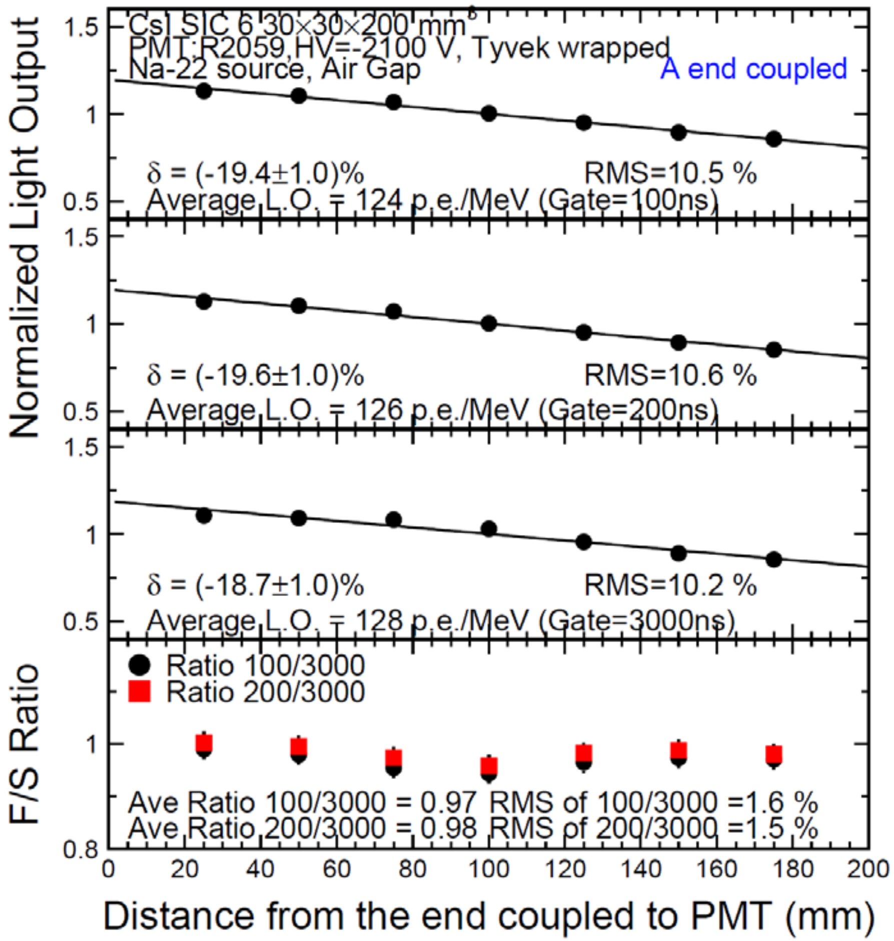


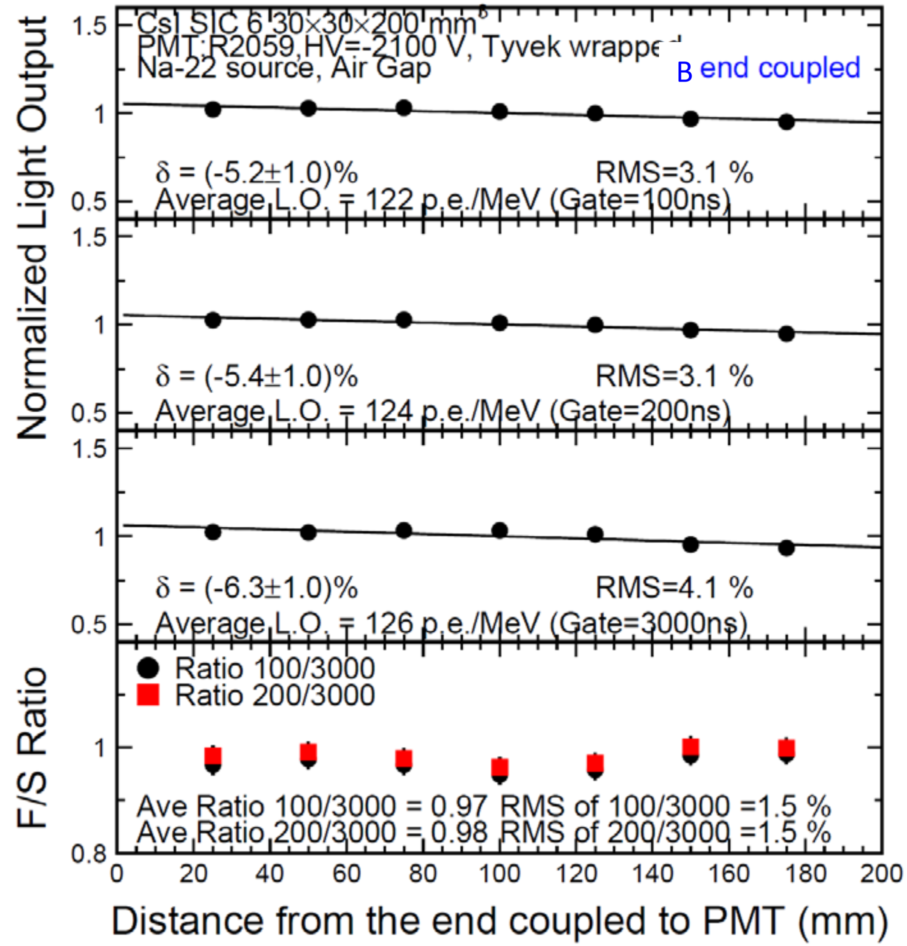
Ave ER= 36.2%



LO & LRU (Different Gate): SIC 6

F/T ratio is constant along the crystal



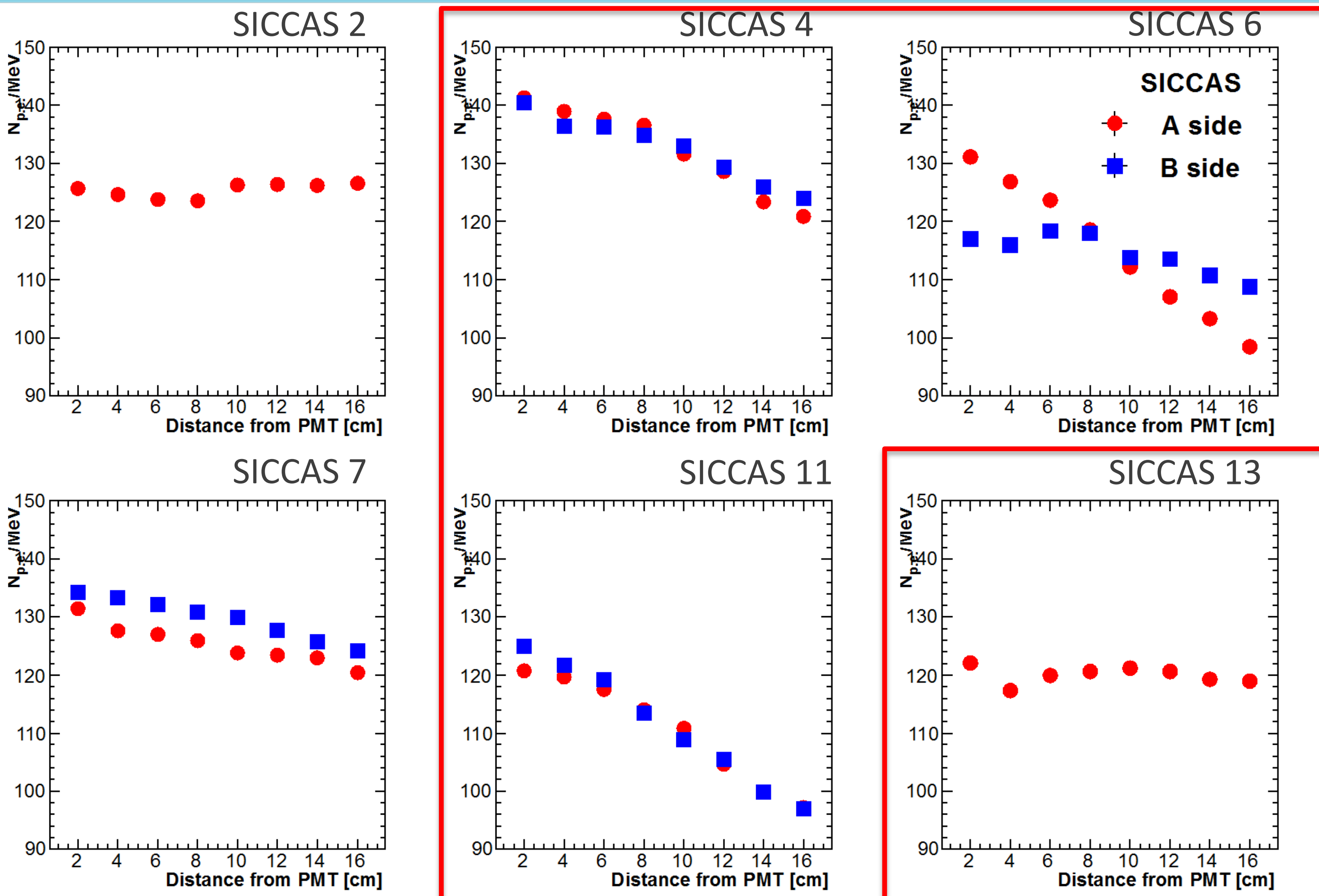


Mu2e CsI: Basic Property

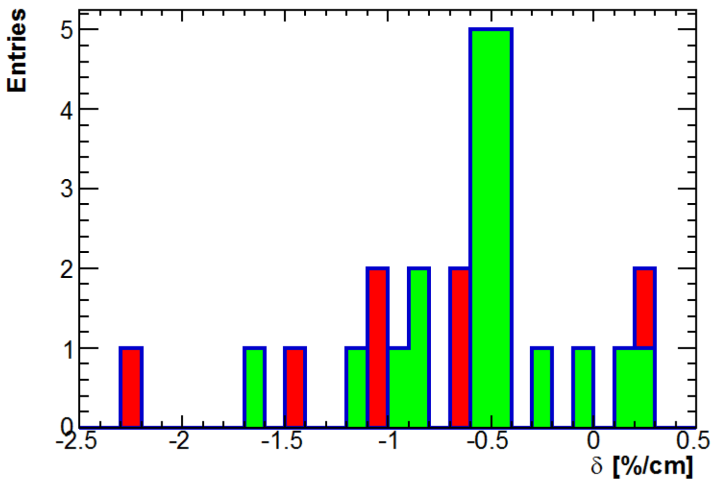
ID	Dimension (mm³)	EWLT (%)	Ave ER (%)	Ave LO in 100 ns Gate (pe/MeV)	Ave LO in 200 ns Gate (pe/MeV)	Ave LO in 3000 ns Gate (pe/MeV)	100 ns/ 3μs	200 ns/ 3μs	Fast component (pe/MeV)	Slow component (pe/MeV)
Kharkov 3	29x29x230	44.8	44.3	89	93	112	0.80	0.83	99	34
Kharkov 4	29x29x230	20.7	41.3	93	96	128	0.73	0.75	102	45
Opto-material 11	30x30x200	31.6	34.1	135	140	167	0.81	0.84	142	40
SIC 6	30x30x200	37.0	36.3	123	125	127	0.97	0.98	135	1
SIC 11	30x30x200	28.7	36.3	124	128	137	0.91	0.93	145	12
SIC 13	30x30x200	45.5	35.4	127	130	144	0.88	0.90	135	18

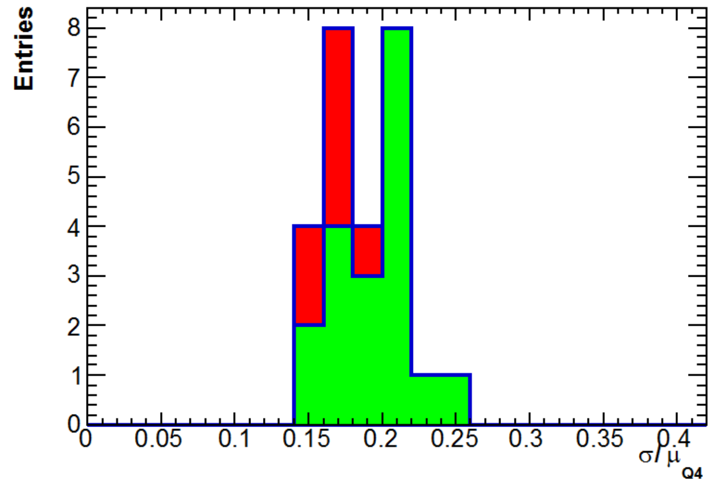
Specifications on LO and F/T will be made according to data

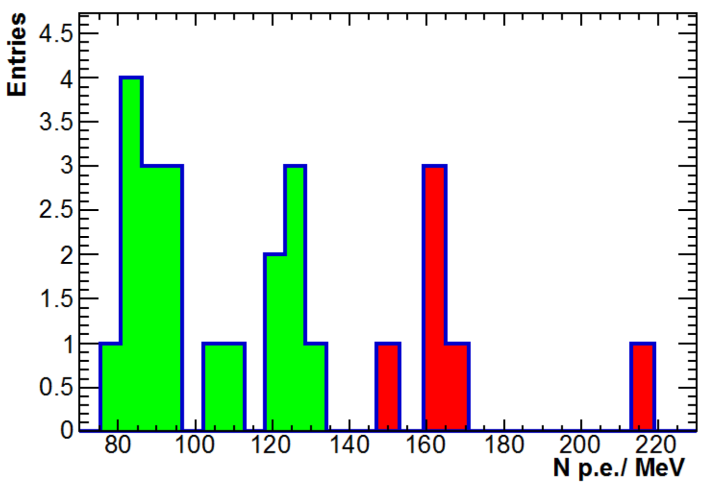
Mu2e CsI: Comparison at LNF Stations, LY, LRU

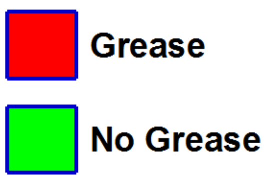


Mu2e CsI: Comparison at LNF Stations, LY,LRU



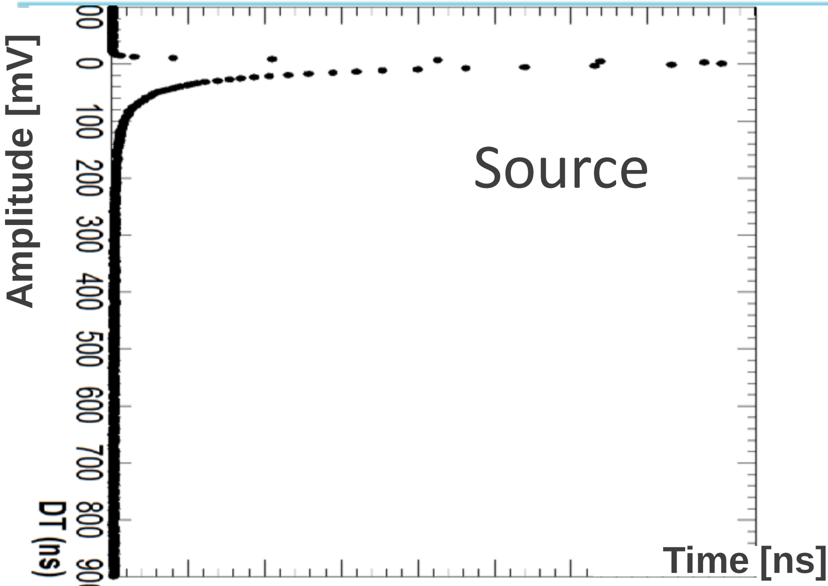


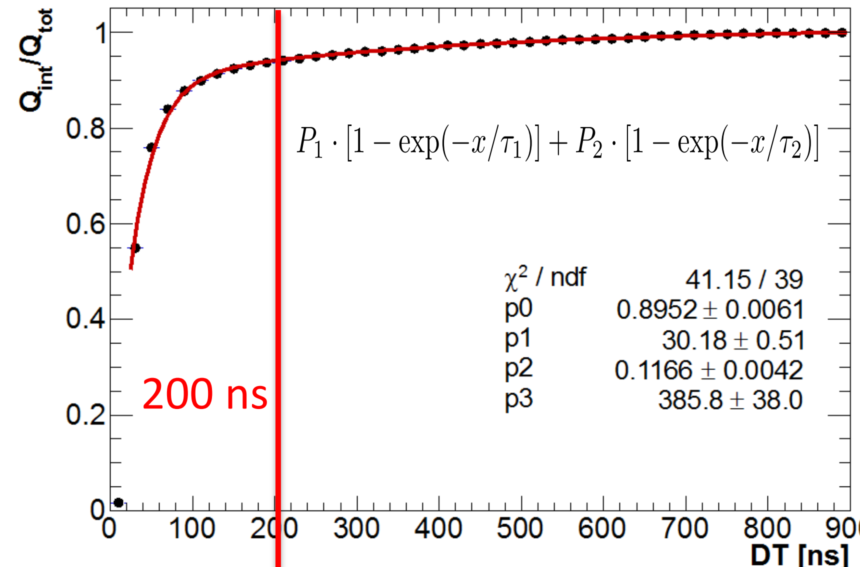


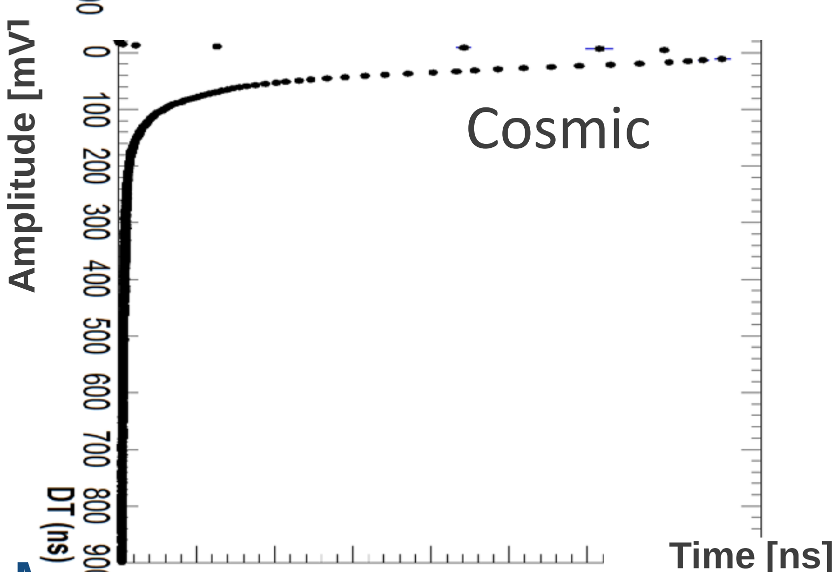


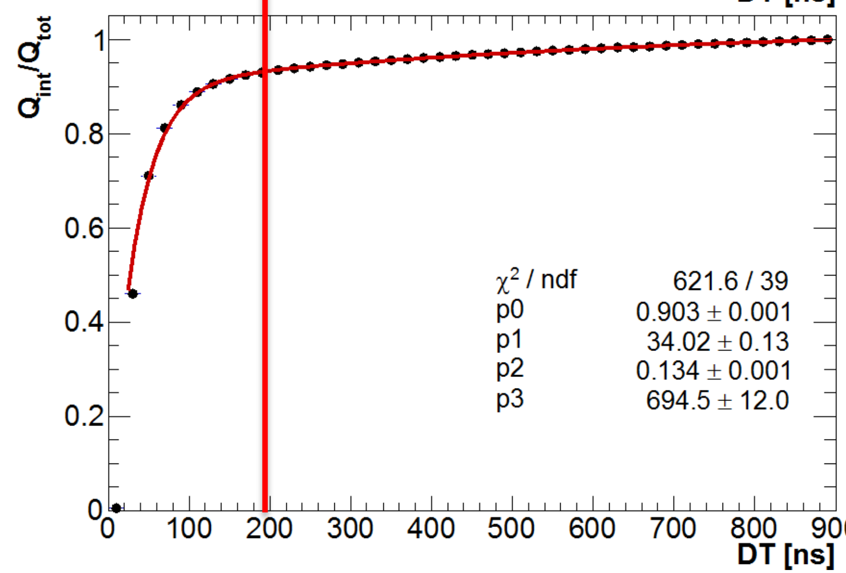
- Good agreement with Caltech measurement (shift of -8%) on LY, good LRU with air-gap.
- Spread in quality between test samples from different producers.

Mu2e CsI: Slow Component @ LNF with WFD









Mu2e CsI: Slow Component @ LNF with WFD

Crystal	Run Type	τ_1 (ns)	τ_2 (ns)	$f(200)$
SICCAS 2	Source	34.6 ± 0.1	$6.6 \cdot 10^8 \pm 1.3 \cdot 10^6$	92.3%
SICCAS 4	Source	36.0 ± 0.2	1853 ± 258	94.3%
SICCAS 6	Source	33.6 ± 0.2	913 ± 117	97.0%
SICCAS 7	Source	34.5 ± 0.1	3576 ± 981	96.5%
SICCAS 11	Source	35.2 ± 0.2	717 ± 35	93.9%
SICCAS 13	Source	34.9 ± 0.2	1033 ± 132	95.1%
ISMA 3	Source	31.4 ± 0.5	470 ± 44	93.1%
ISMA 5	Source	31.0 ± 0.4	519 ± 28	89.5%
ISMA 6	Source	32.0 ± 0.4	706 ± 50	90.1%
ISMA 7	Source	32.6 ± 0.3	542 ± 32	93.0%
ISMA 8	Source	31.3 ± 0.4	344 ± 24	95.4%
ISMA 9	Source	32.0 ± 0.3	394 ± 35	96.2%
ISMA 10	Source	32.6 ± 0.3	948 ± 106	92.2%
ISMA 11	Source	31.3 ± 0.4	477 ± 31	92.1%
OPTOM 1	Source	33.8 ± 0.2	537 ± 31	94.3%
OPTOM 2	Source	30.2 ± 0.5	385 ± 38	93.9%
ISMA	Cosmics	34.0 ± 0.1	695 ± 12	93.4%

Table 1: Summary of decay times and $f(200)$ values obtained for all tested crystals.

Mu2e Radiation Induced Readout Noise

Assuming 230 days' run (2×10^{7} sec) of each year we get this average irradiation in the hottest places:

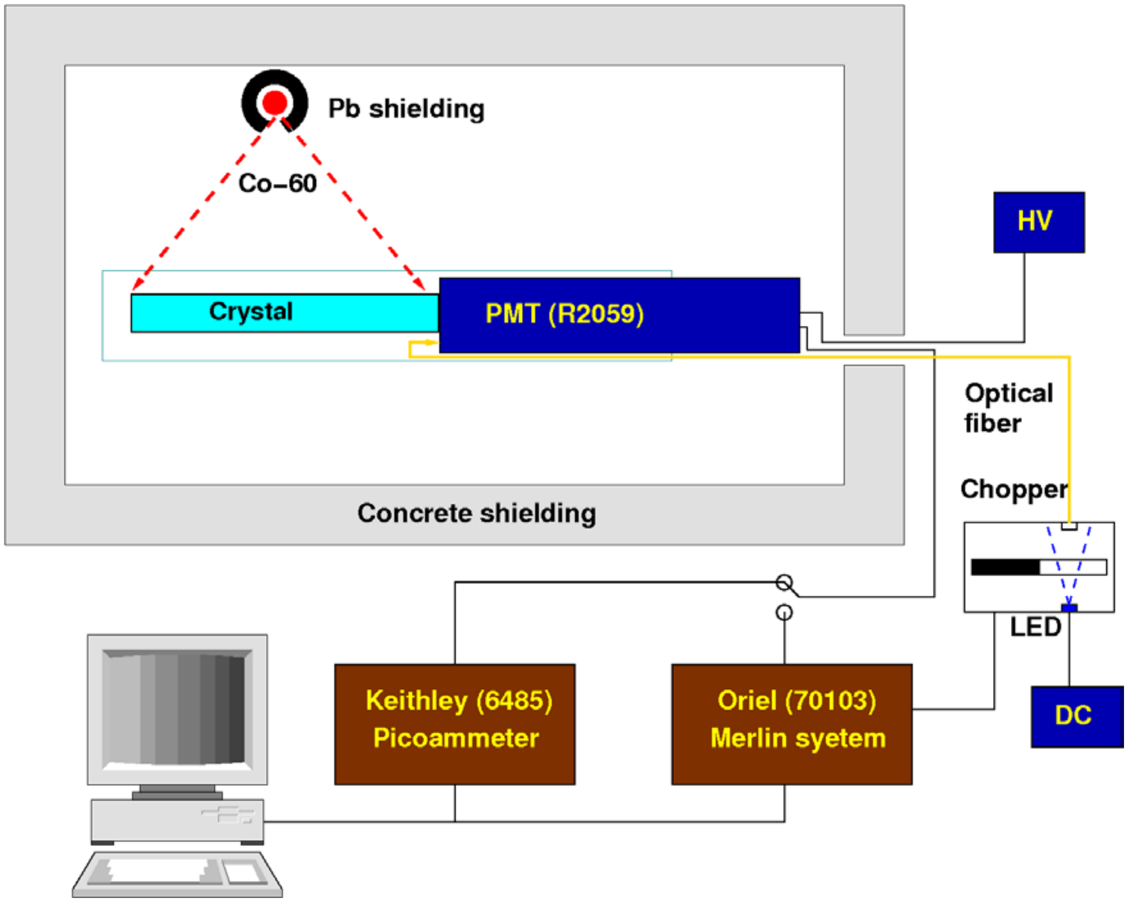
- Ionization dose: 10 krad/year ➡ 1.8 rad/h
- Neutron fluence: 2×10^{11} n/cm^2/year ➡ 1.0×10^{4} n/cm^2/s.

The energy equivalent noise (σ) is derived as the standard deviation of photoelectron number (Q) in the readout gate:

$$\sigma = \frac{\sqrt{Q}}{LO} \quad \text{(MeV)}$$

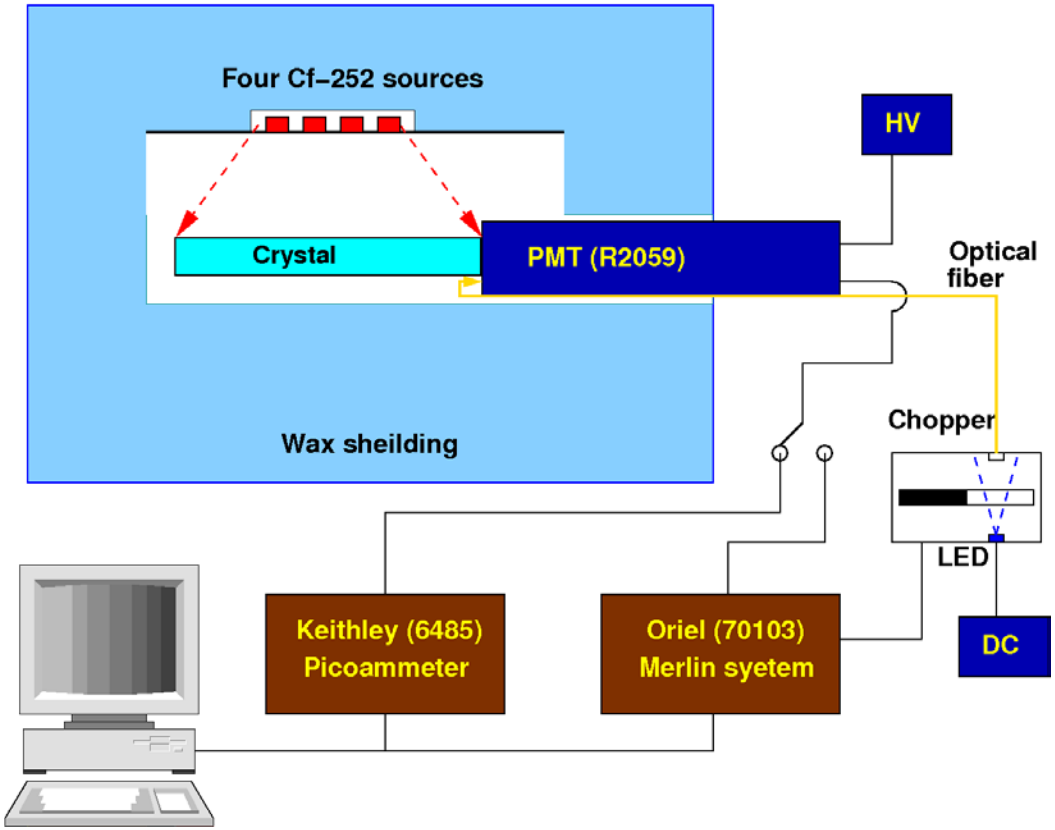
Gamma Induced Photo-Current

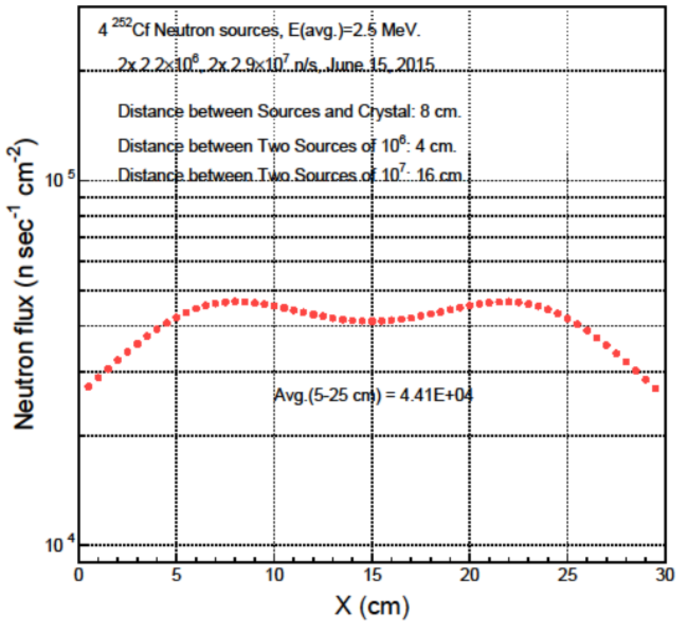
Dose rate from a Co-60 source is 2 rad/hr at the sample



Neutron Induced Photo-current

Neutron flux from four Cf-252 sources is about 4E4/cm2/s at the sample





Cf-252 has γ-ray background, so result is a upper limit

Radiation Induced Photoelectron Coefficient

F is defined as radiation induced photoelectron numbers per second, determined by using the measured anode current in the PMT.

$$F = \frac{\dfrac{Photocurrent}{Charge_{electron} \times Gain_{PMT}}}{Dose\ rate_{\gamma-ray}\ or\ Flux_{neutron}}$$

Phosphorescence of BaF_2 and Pure CsI

ID	Dimension (mm^3)	Polishing
BaF_2 Incrom 3	30x30x200	All faces
CsI Kharkov 3	29x29x230	All faces
CsI SIC 14	25x25x200	All faces

Experiments

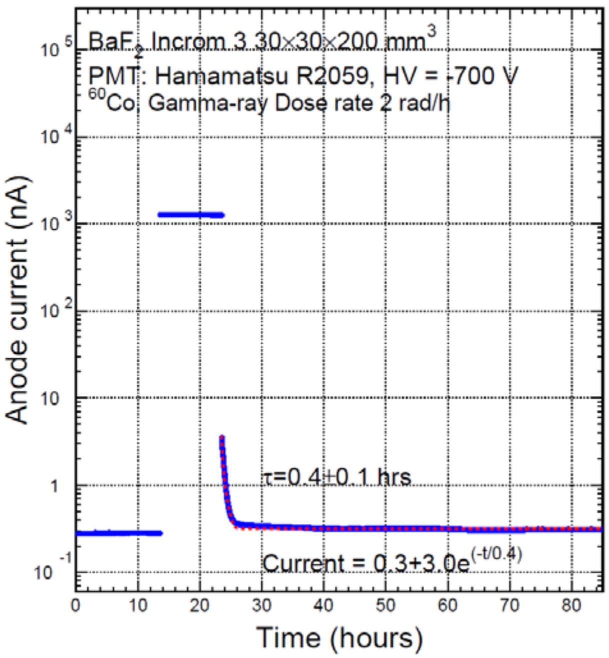
- Measured at room temperature : Anode current of PMT R2059

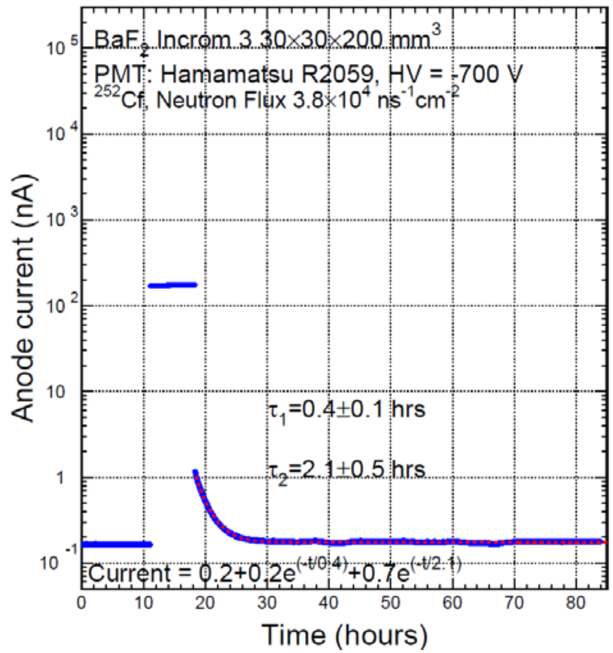
Incrom BaF_2 under ɣ-Rays and Neutrons

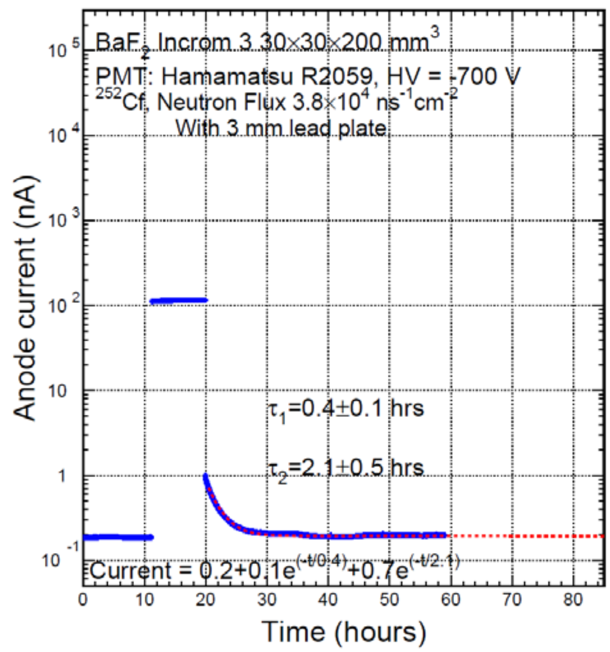
2 rad/h on sample

3.8E4 n/cm²/s on sample

3.8E4 n/cm²/s on sample with 3 mm Pb plate



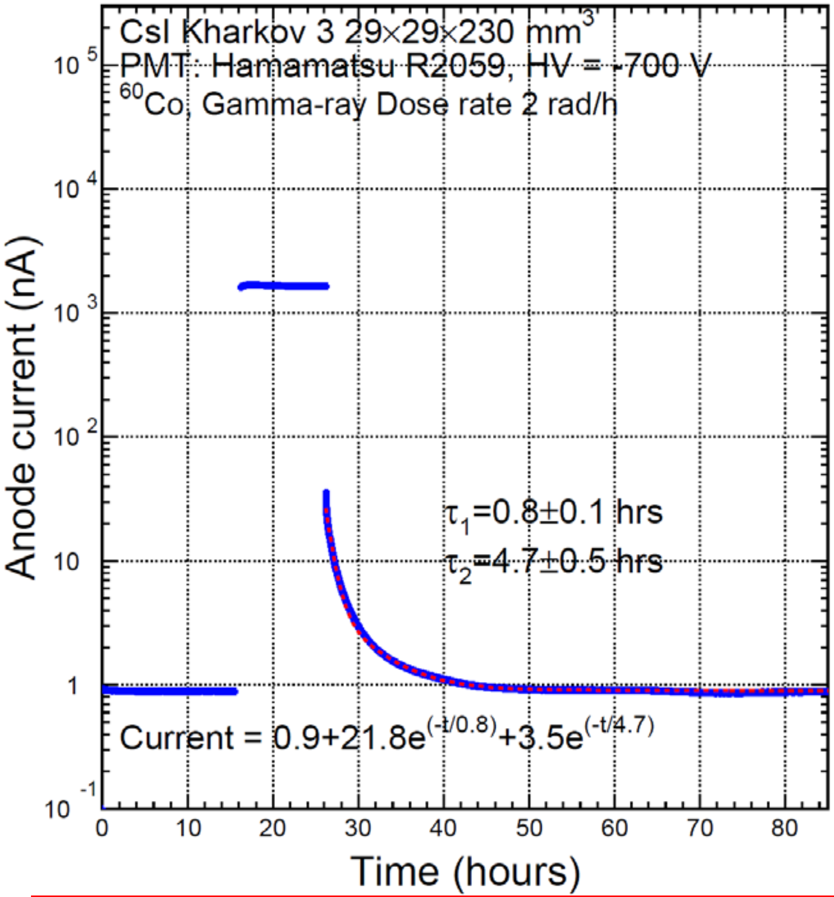




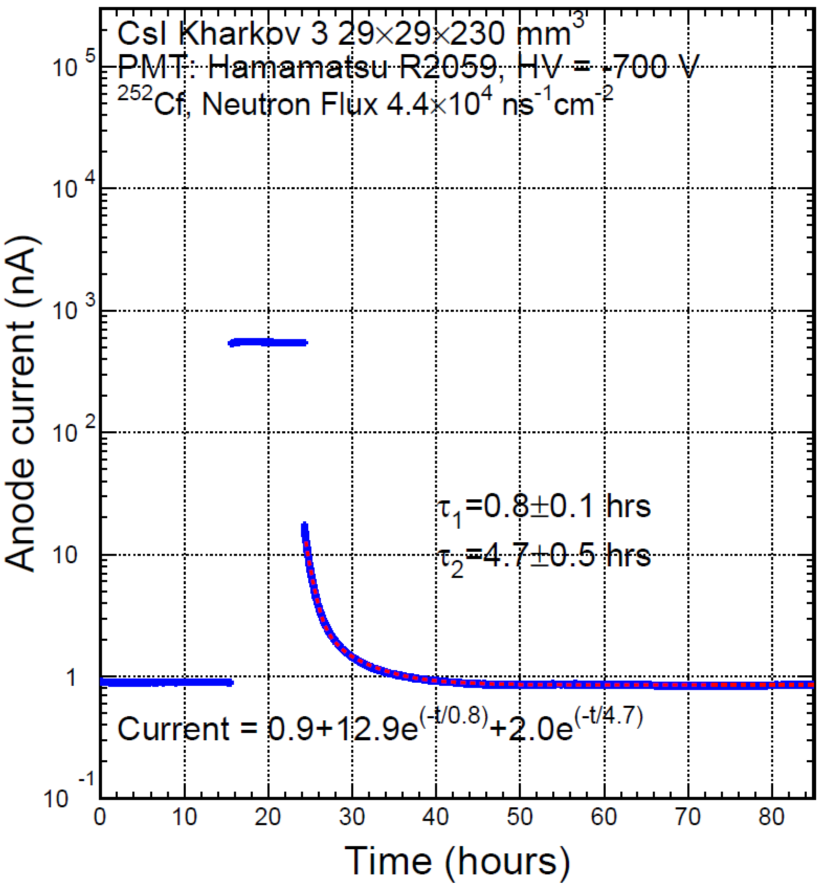
Afterglow decay time constant caused by ɣ/neutron is 0.4/2.1hrs

Kharkov CsI under γ-Rays and Neutrons

2 rad/h on sample



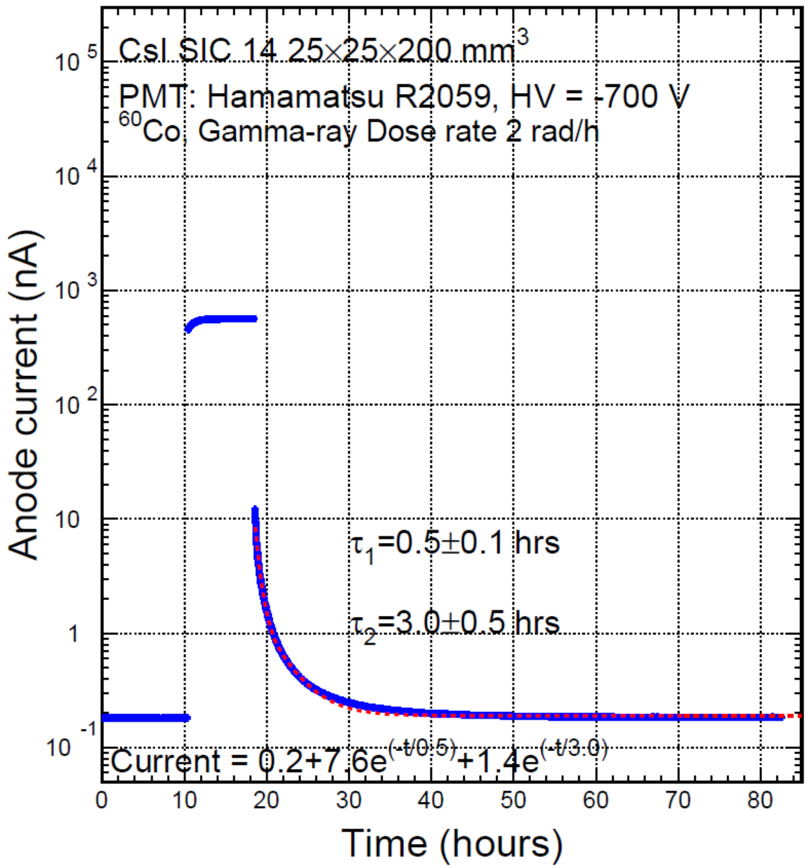
4.4E4 n/cm²/s on sample



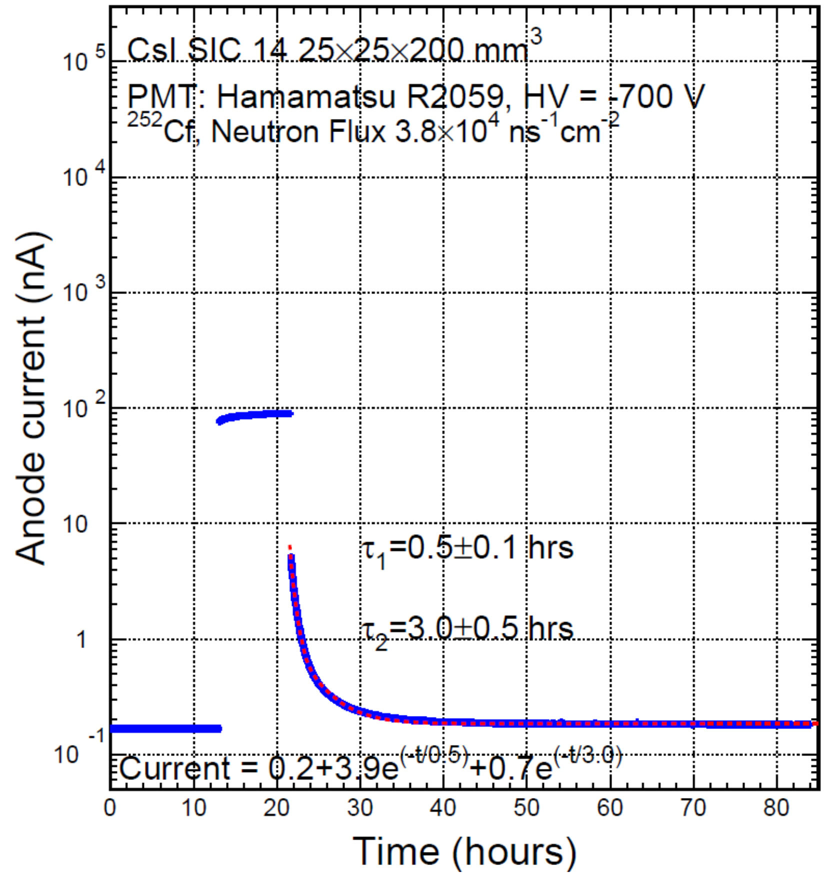
Afterglow decay time constants are the same for γ-rays and neutrons

SIC CsI under γ-Rays and Neutrons

2 rad/h on sample



3.8E4 n/cm^2/s on sample



Afterglow decay time constants are the same for γ-rays and neutrons

Gamma-Ray Induced Noise

Assuming a readout gate of 50 ns/2,500 ns and 200 ns for the BaF_2 fast/slow component and CsI respectively, the readout noise is < 1 MeV for both BaF_2 and CsI.

Sample	Dimensions (cm^3)	Readout gate (ns)	LO (p.e./MeV)	Gamma (rad/hr)	Photo current (μA)	F (p.e./s/rad/hr)	Mu2e ECAL (rad/hr)	σ (MeV)
BaF_2 Incrom-3	3 × 3 × 20	50	78	2	1.27	1.25E+10	1.8	4.3E-1
BaF_2 Incrom-3	3 × 3 × 20	2500	367	2	1.27	1.25E+10	1.8	6.5E-1
CsI Kharkov-3	2.9 × 2.9 × 23	200	97	2	1.66	1.63E+10	1.8	7.9E-1
CsI SIC-14*	2.5× 2.5 × 20	200	140	2	0.88	8.66E+9	1.8	4.0E-1

* Photo current, F and σ are corrected to the volume 2.9 × 2.9 × 23 cm^3.

Neutron Induced Noise

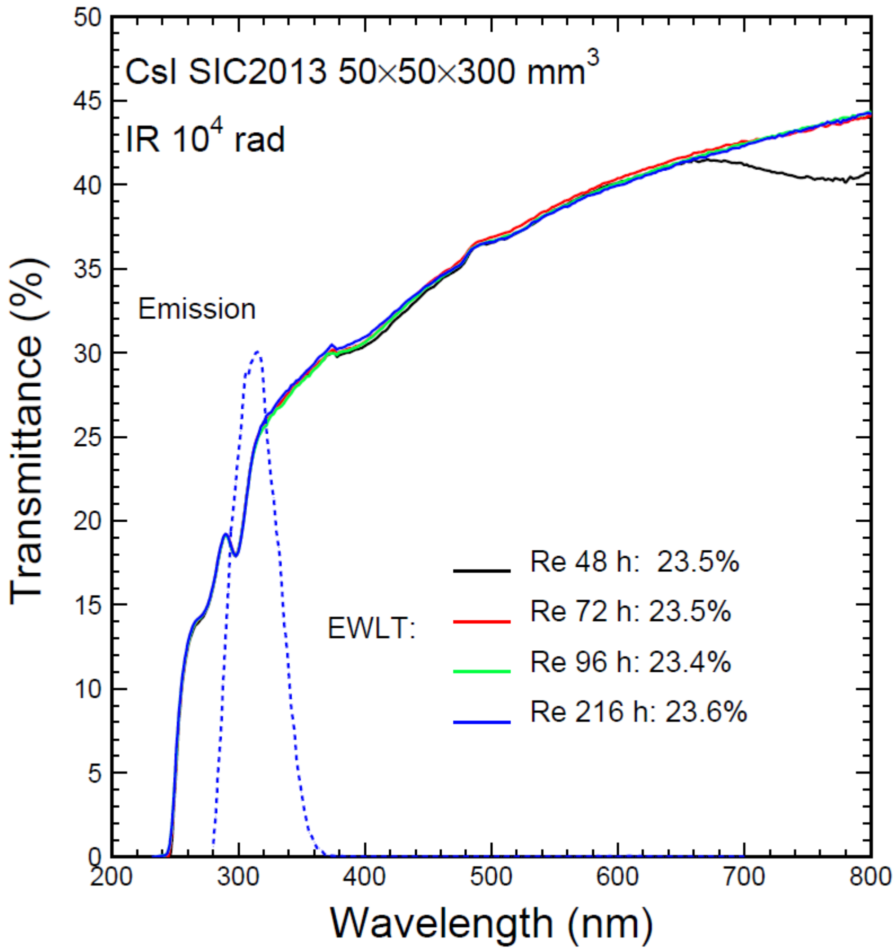
Assuming a readout gate of 50 ns/2,500 ns and 200 ns for the BaF_2 fast/slow component and CsI respectively, the neutron induced readout noise is negligible for BaF_2 and CsI

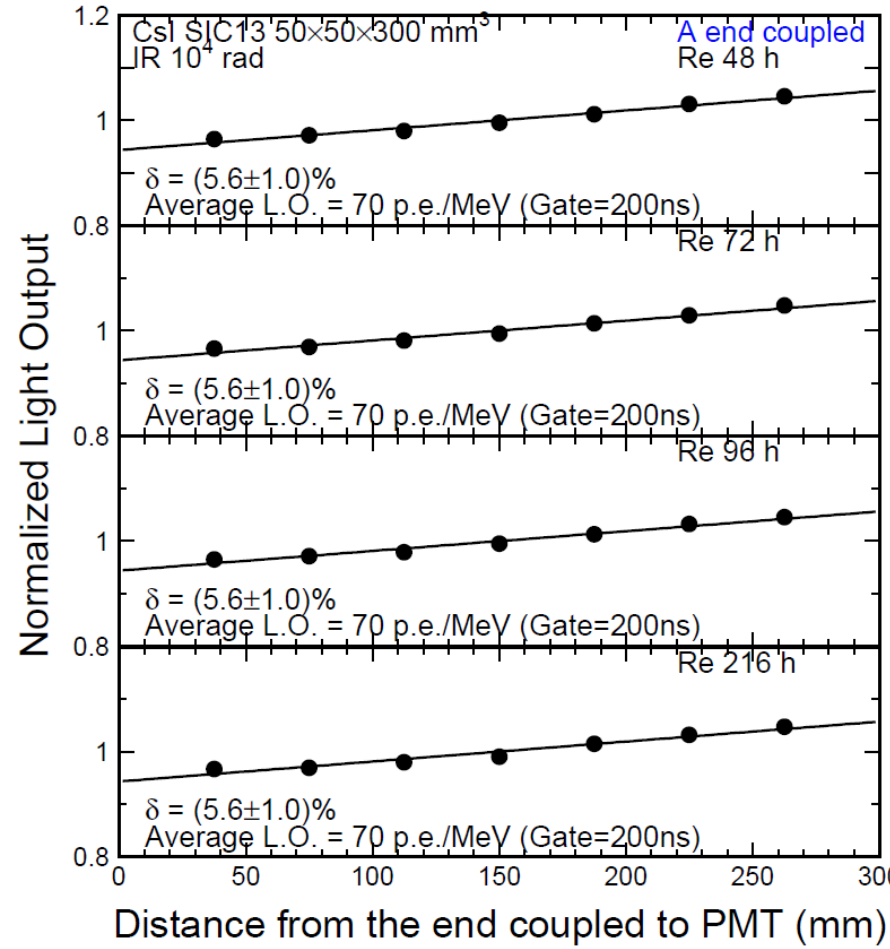
Sample	Dimensions (cm^3)	Readout gate (ns)	LO (p.e./MeV)	N-flux ($n/cm^2/s$)	Photo current (μA)	F ($p.e./n/cm^2$)	Mu2e ECAL ($n/cm^2/s$)	σ (MeV)
BaF_2 Incrom-3	3 × 3 × 20	50	78	3.80E+04	0.24	1.07E+05	1.0E+4	9.4E-02
BaF_2 Incrom-3	3 × 3 × 20	2500	367	3.80E+04	0.24	1.07E+05	1.0E+4	1.4E-01
CsI Kharkov-3	2.9 × 2.9 × 23	200	97	4.40E+04	0.54	2.42E+05	1.0E+4	2.3E-01
CsI SIC-14*	2.5 × 2.5 × 20	200	140	3.80E+04	0.14	7.25E+04	1.0E+4	8.6E-02

* Photo current, F and σ are corrected to the volume 2.9 × 2.9 × 23 cm^3.

No Recovery at Emission: SIC2013 CsI

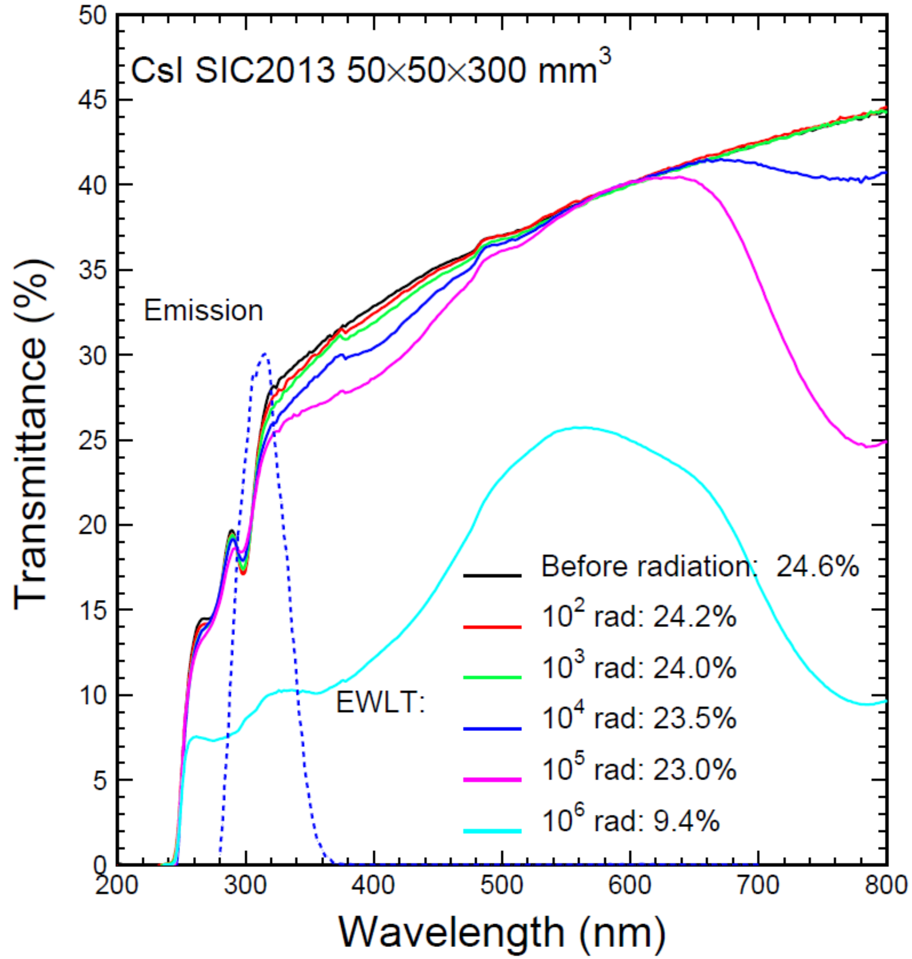
Damage does not recover, so is dose rate independent

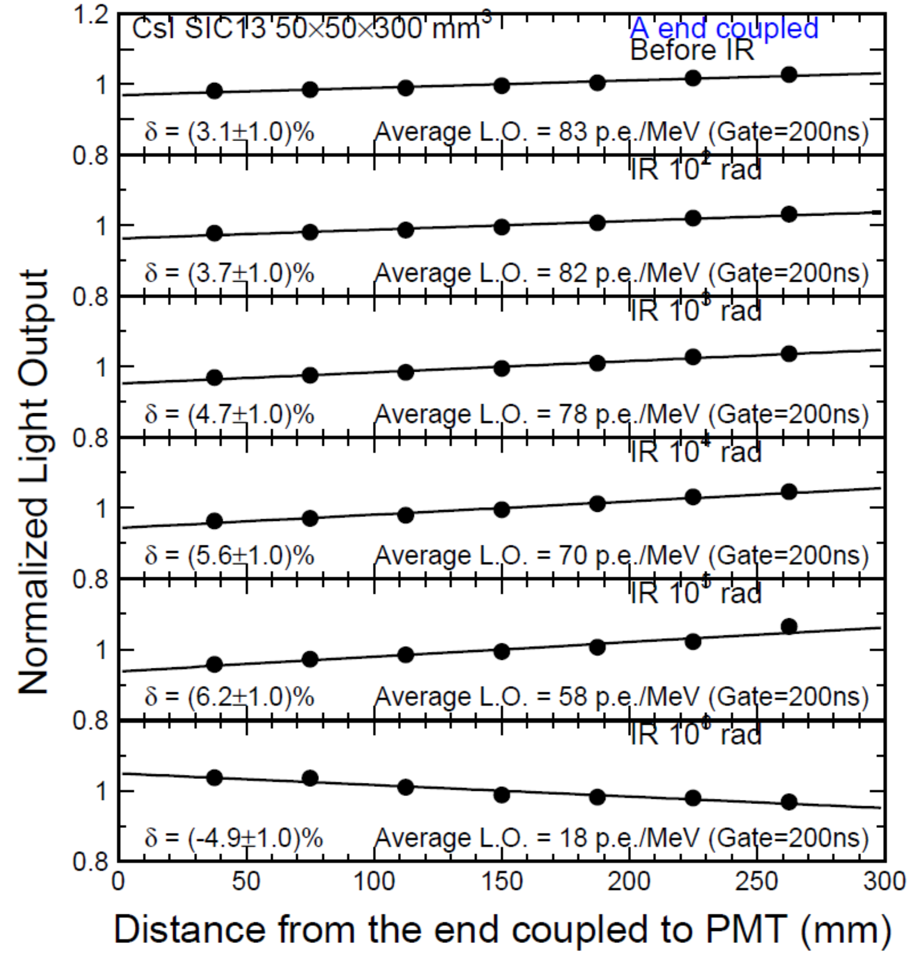




Radiation Damage: SIC2013

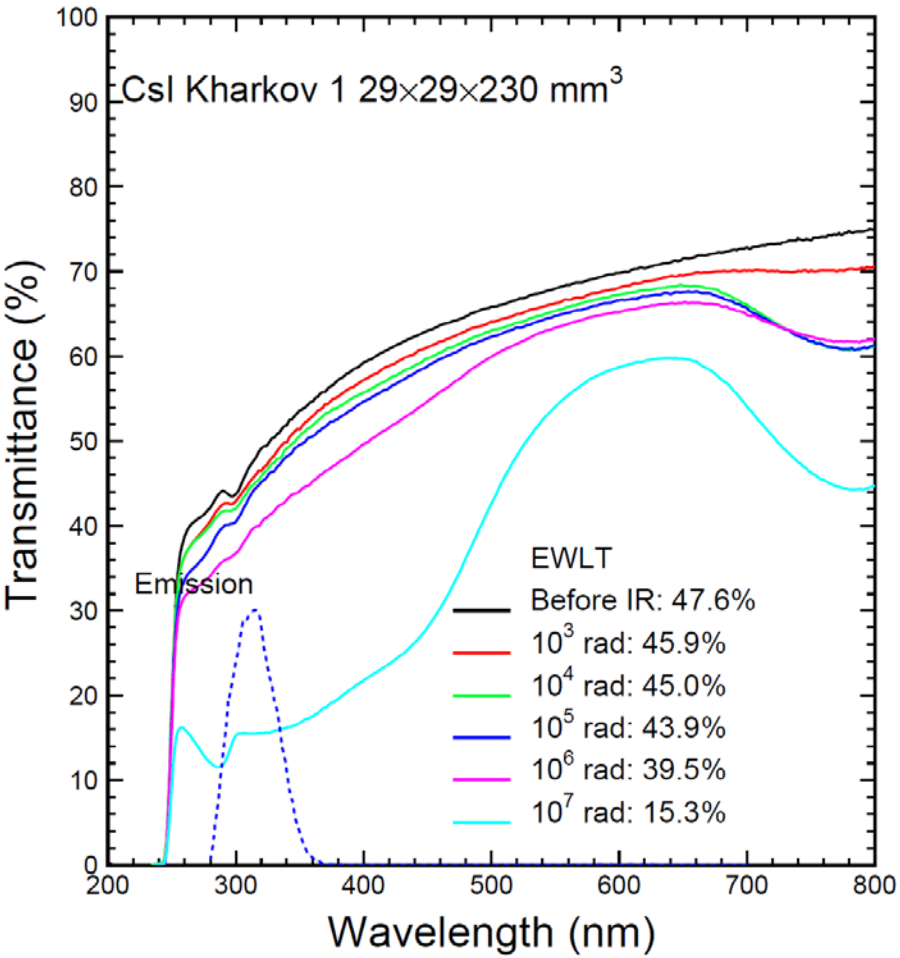
No significant degradation in LO and LRU up to 10 krad

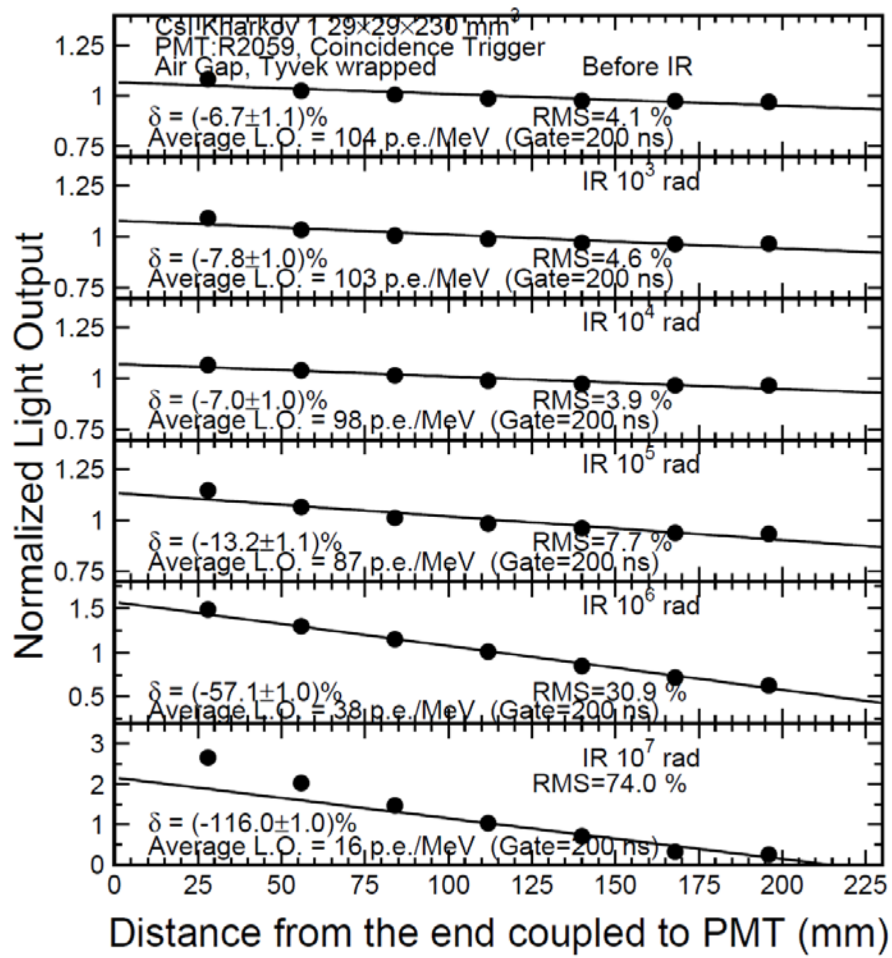




Radiation Damage: Kharkov 1 CsI

No significant degradation in LO and LRU up to 10 krad



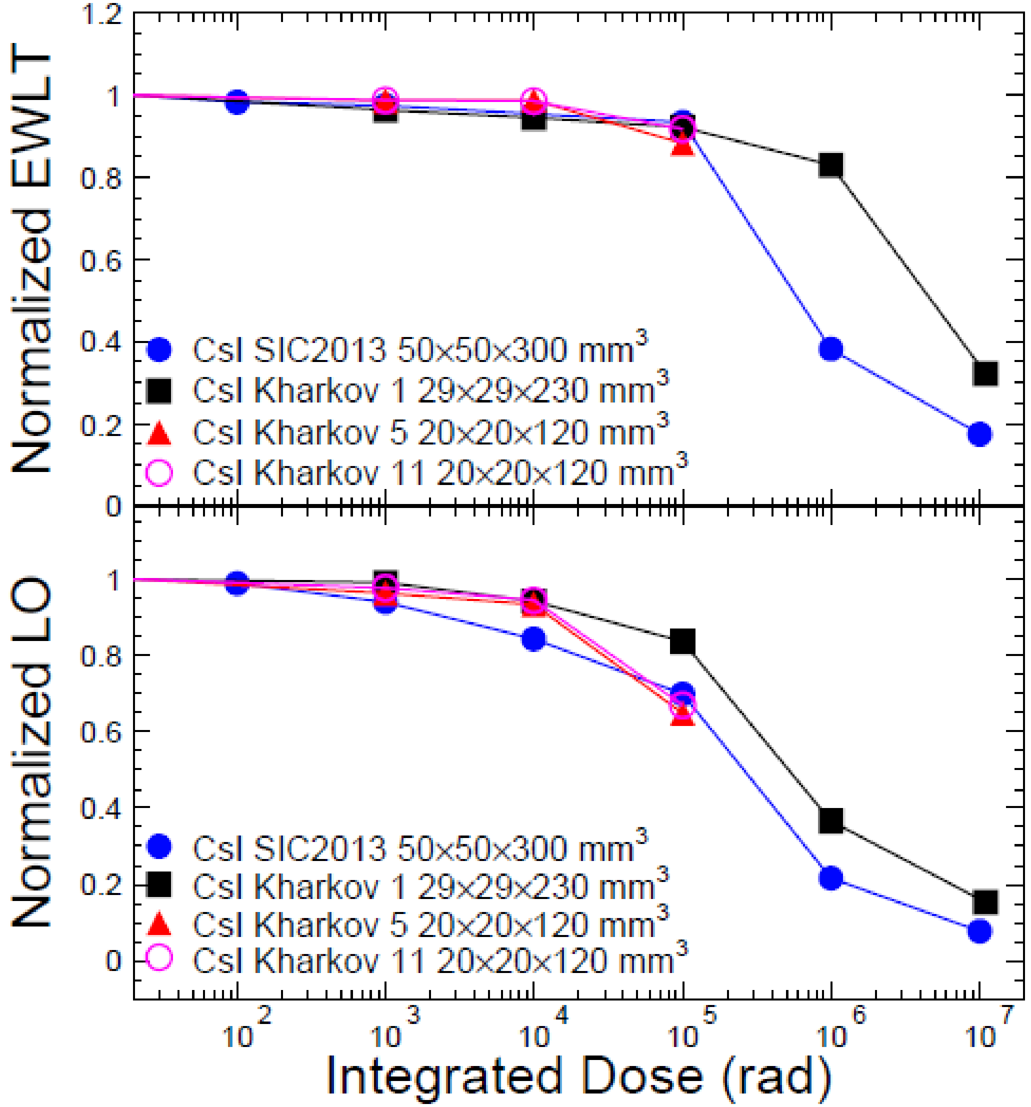


Gamma-ray Induced Radiation Damage in LO

ID	Dimension (mm^3)	Light Output before and after Gamma Irradiations (p.e./MeV)						
		Initial	10^2 rad	10^3 rad	10^4 rad	10^5 rad	10^6 rad	10^7 rad
Kharkov 1	29x29x230	104	-	103	98	87	38	16
Kharkov 5	20x20x120	134	-	129	125	87	-	-
Kharkov 11	20x20x120	127	-	124	120	85	-	-
SIC2013	50x50x300	83	82	78	70	58	18	7

Significant fraction of light remaining after 100 krad
CsI crystals survive the expected radiation environment

Normalized EWLT & LO: All CsI Samples

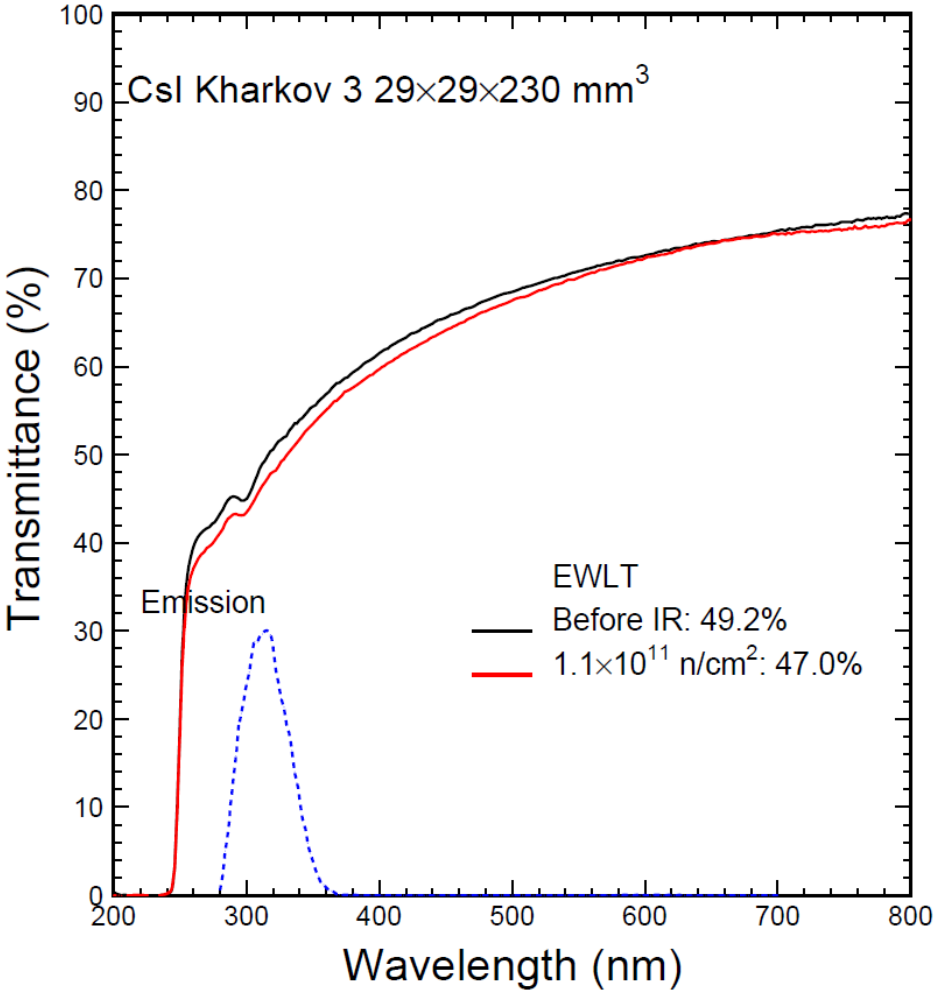


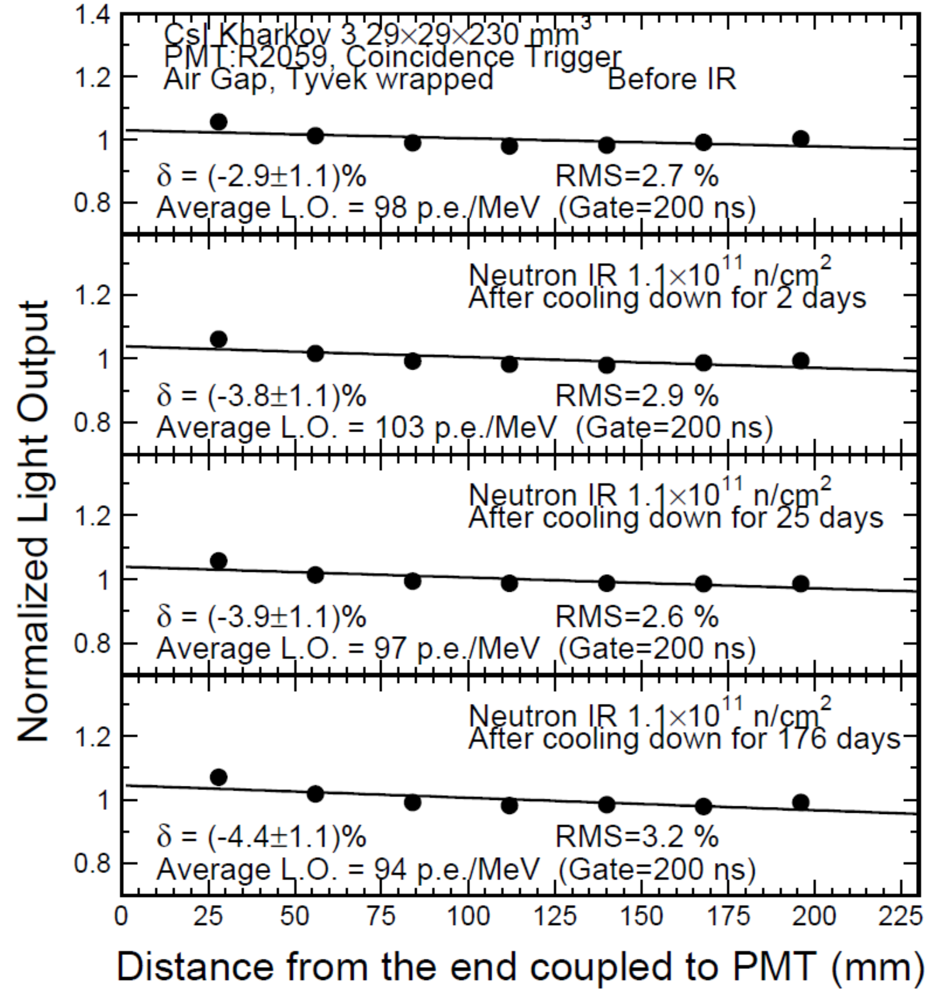
Consistent radiation hardness: no significant degradation in LO and LRU up to 100 krad, but not beyond.

Cost of damage investigation is high because of no recovery/annealing

CsI: LT, LO & LRU Loss by Neutrons

LT and LO loss are less than 5% after 1E11

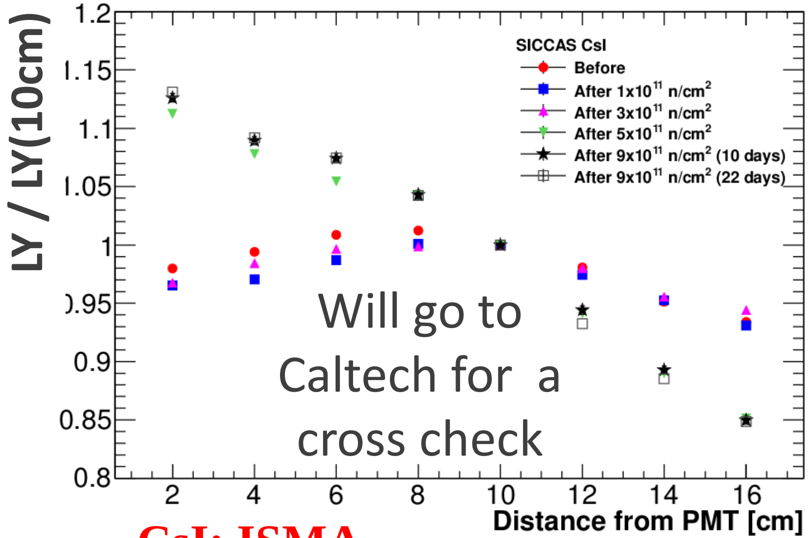




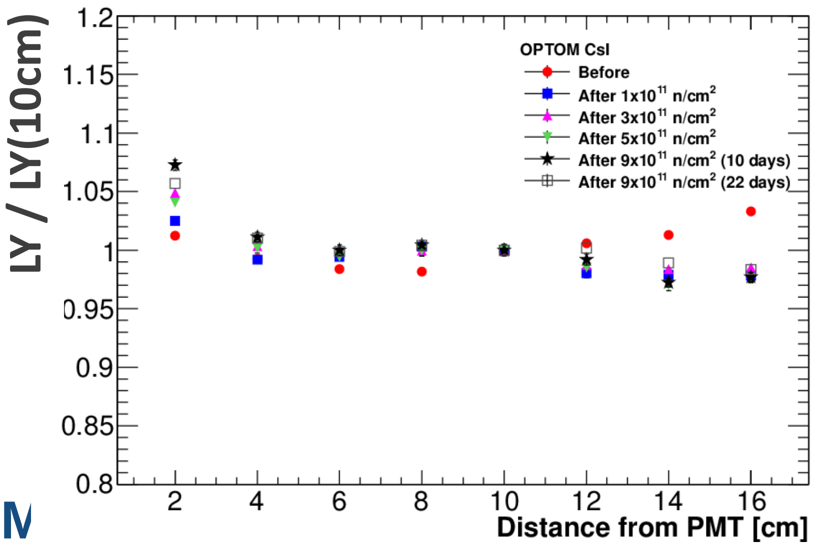
CsI, Neutron Irradiation at FNG

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

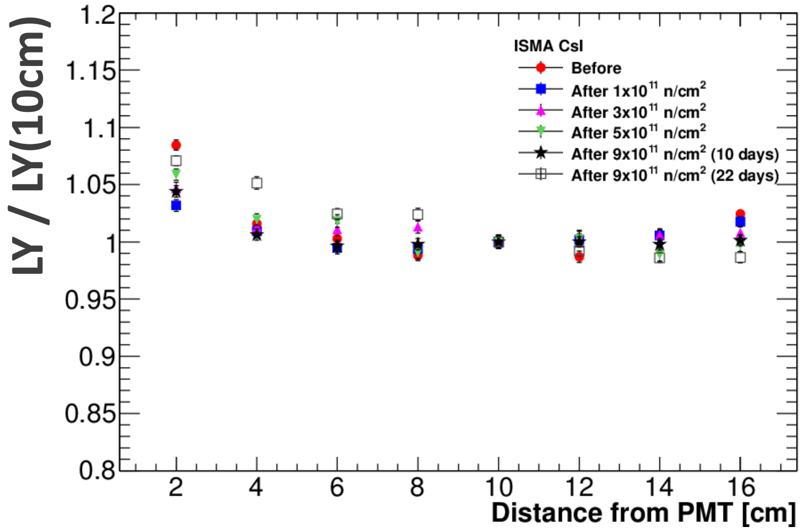
CsI: SICCAS



CsI: OPTO MATERIALS



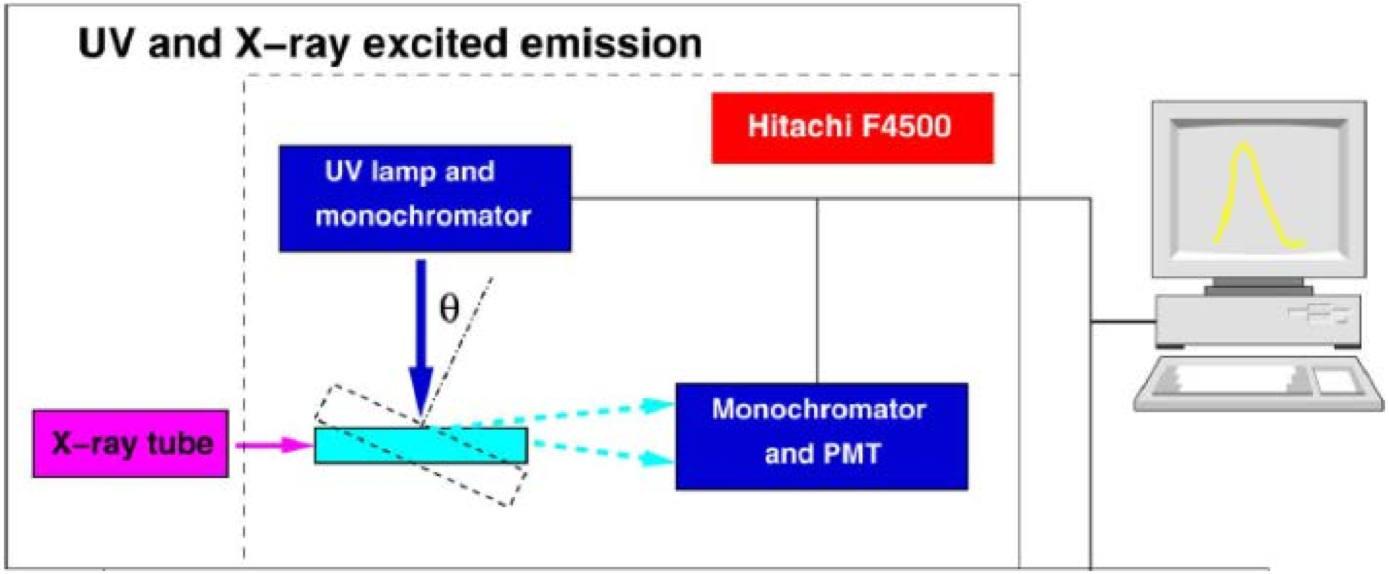
CsI: ISMA



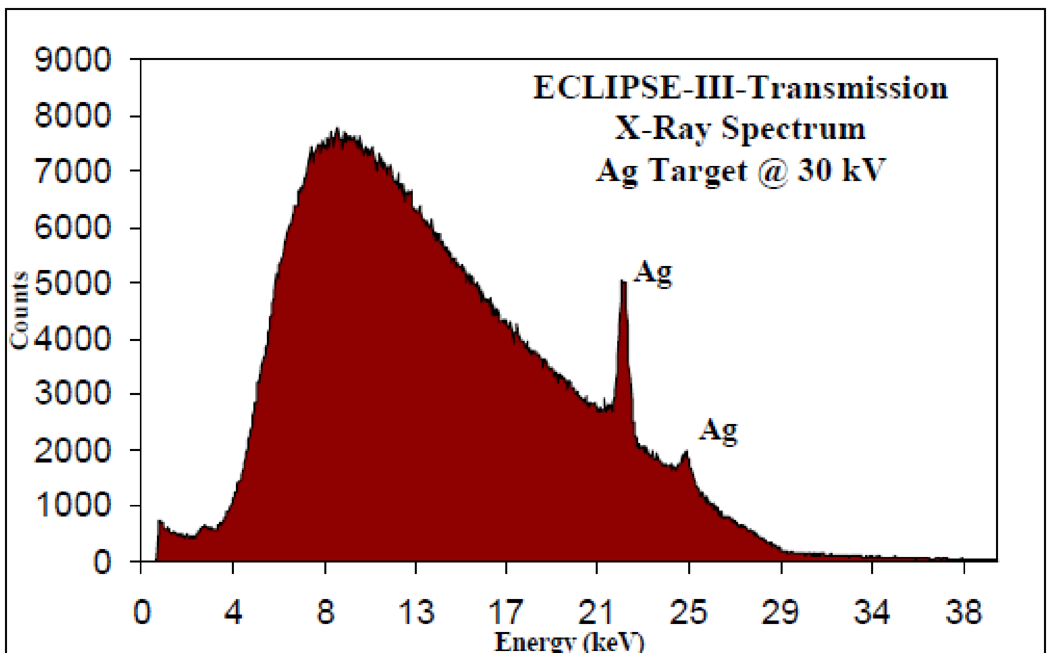
Summary:

- LT Measurements for CsI crystals suffer from uncertainties caused by crystal's soft and hygroscopic surface.
- Pure CsI crystals have sufficient fast light with emission peaked at 310 nm, requiring UV extended photodetectors
- Some CsI Crystals have slow component at different level, which may vary along crystal length. R&D is needed to understand the origin of slow component and to eliminate it.
- Radiation induced readout noise is much less than 1 MeV, and is dominated by ionization dose.
- Main radiation damage effect in CsI is induced absorption by ionization dose. CsI works well under 100 krad.
- Quality control is required to control slow scintillation caused by contamination and the radiation hardness.

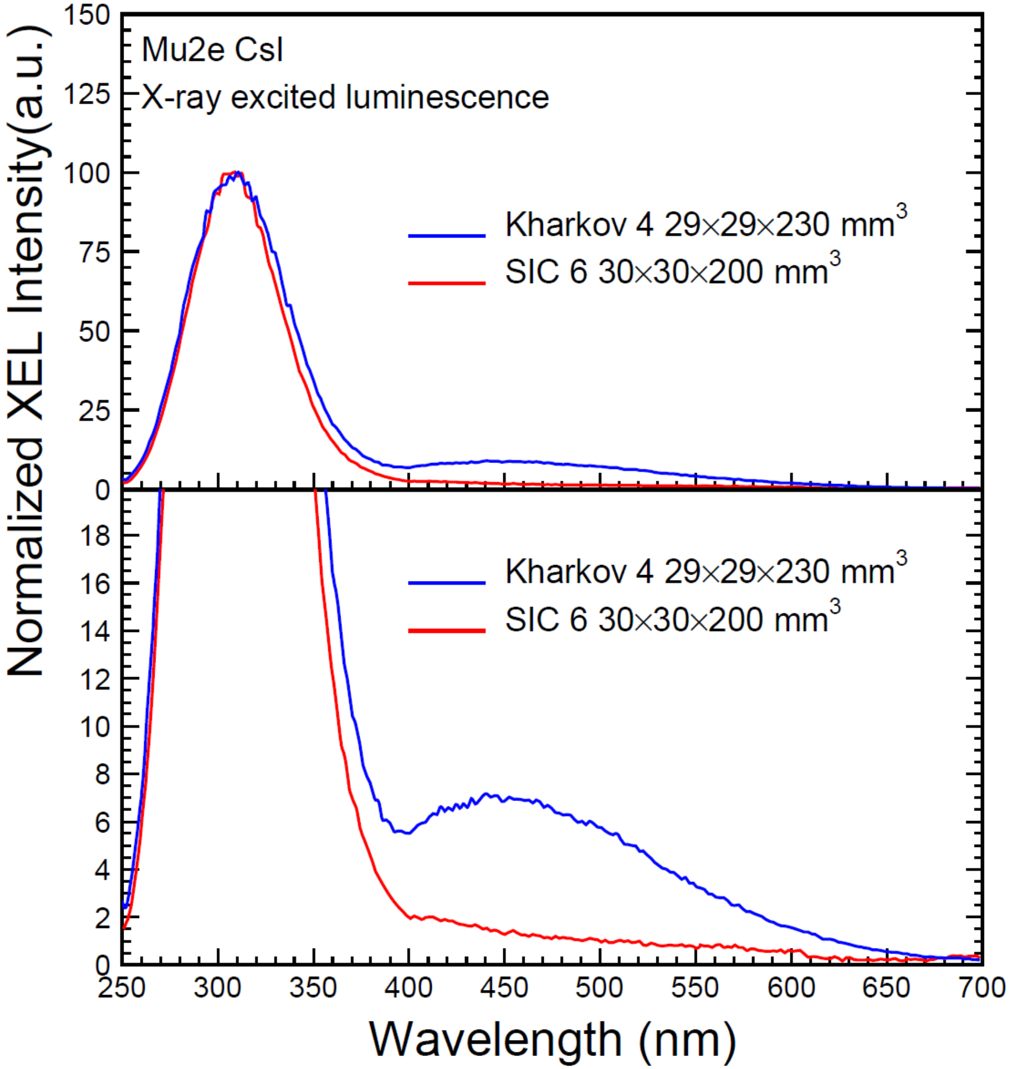
Setup of PL and XEL



Energy of X-rays



Comparison of XEL



Additional component around 450 nm exited by X-ray, which seems related to the slow emission

Origin of the Slow Emission in CsI

1. **It was attributed to the emission from excitons annihilating at crystal defects, e.g. I-vacancy or F-center.**

   - C.W. Bates, Jr., A. Salau and D. Leniart, Phys. Rev. B 15 (1977) 5963.

2. **The slow emission components peaked at 420/500 nm are related to impurities other than K, Na, Tl, Rb or F and/or to defects.**

   -B.K. Utts and S.E. Spagno, IEEE Trans. Nucl. Sci. NS-37 (1990) 134.

3. **The slow emission may be suppressed by thermal annealing:**

   -M. Hamada, Y. Nunoya , S. Kubota and S. Sakuragi. NIM A 365 (1995) 98-103

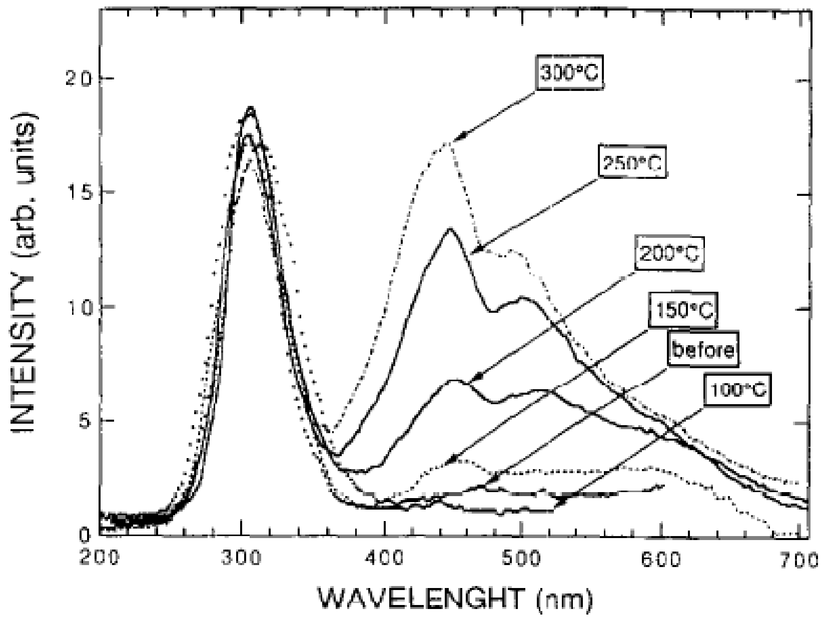
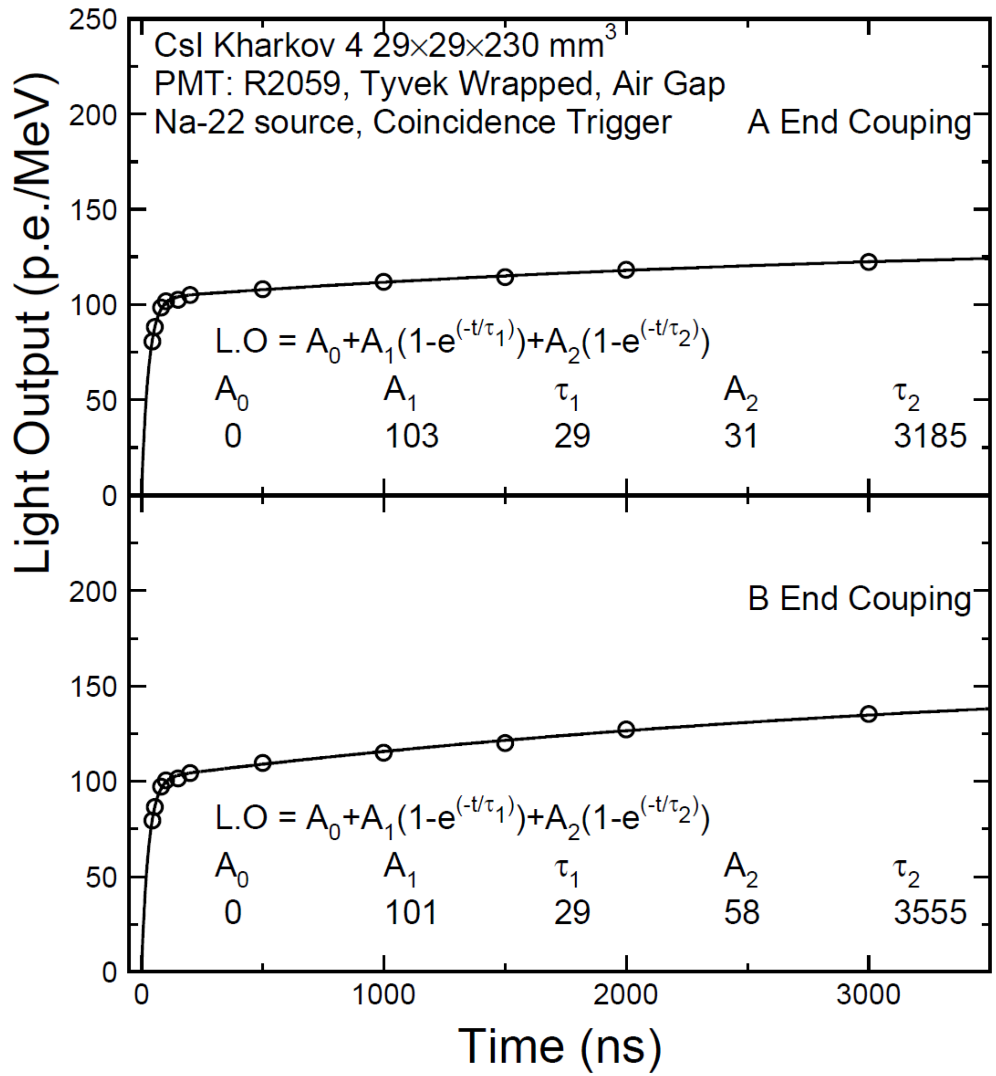


Fig. 7. Emission spectra from the CsI crystal, which was heated to temperatures of 100, 150, 200, 250 and 300°C during one hour, and quenched to room temperature.

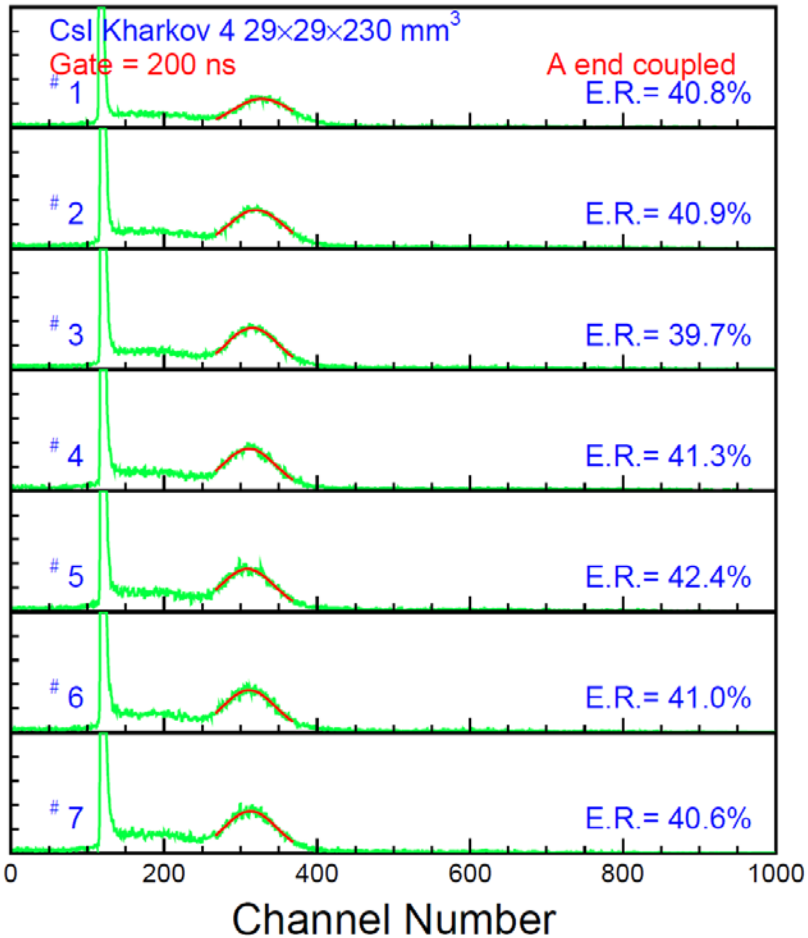
Decay Kinetics: Kharkov 4

A slow component with a position dependent amplitude and decay time of 3.2 and 3.6 us was observed

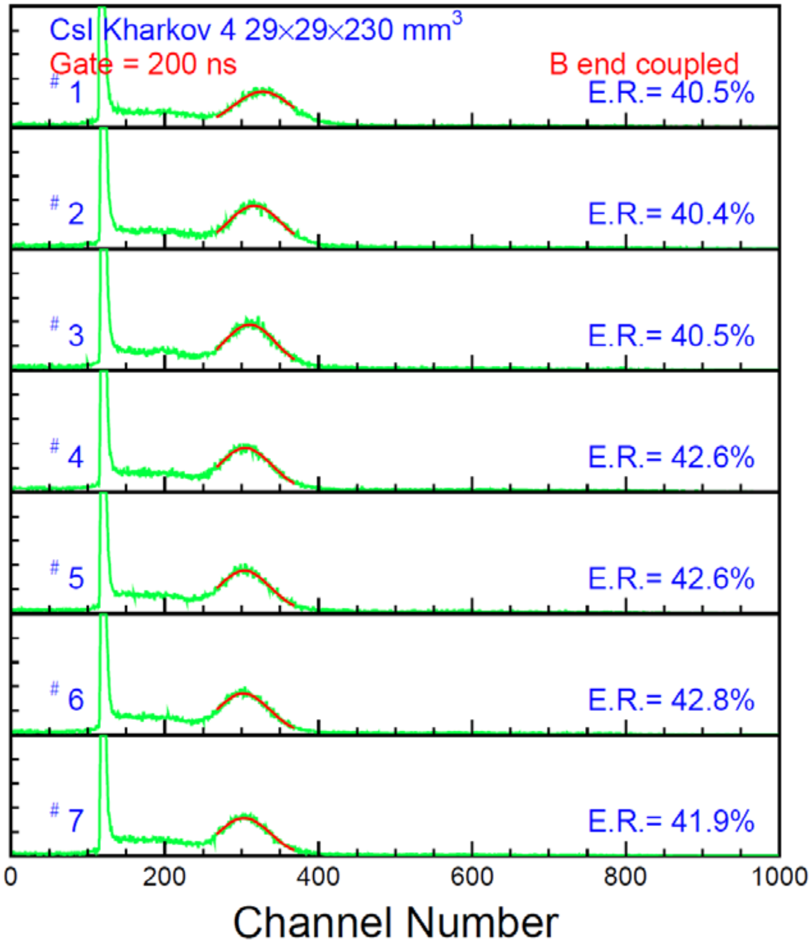


PHS (200 ns): Kharkov 4

Ave ER= 41.0%

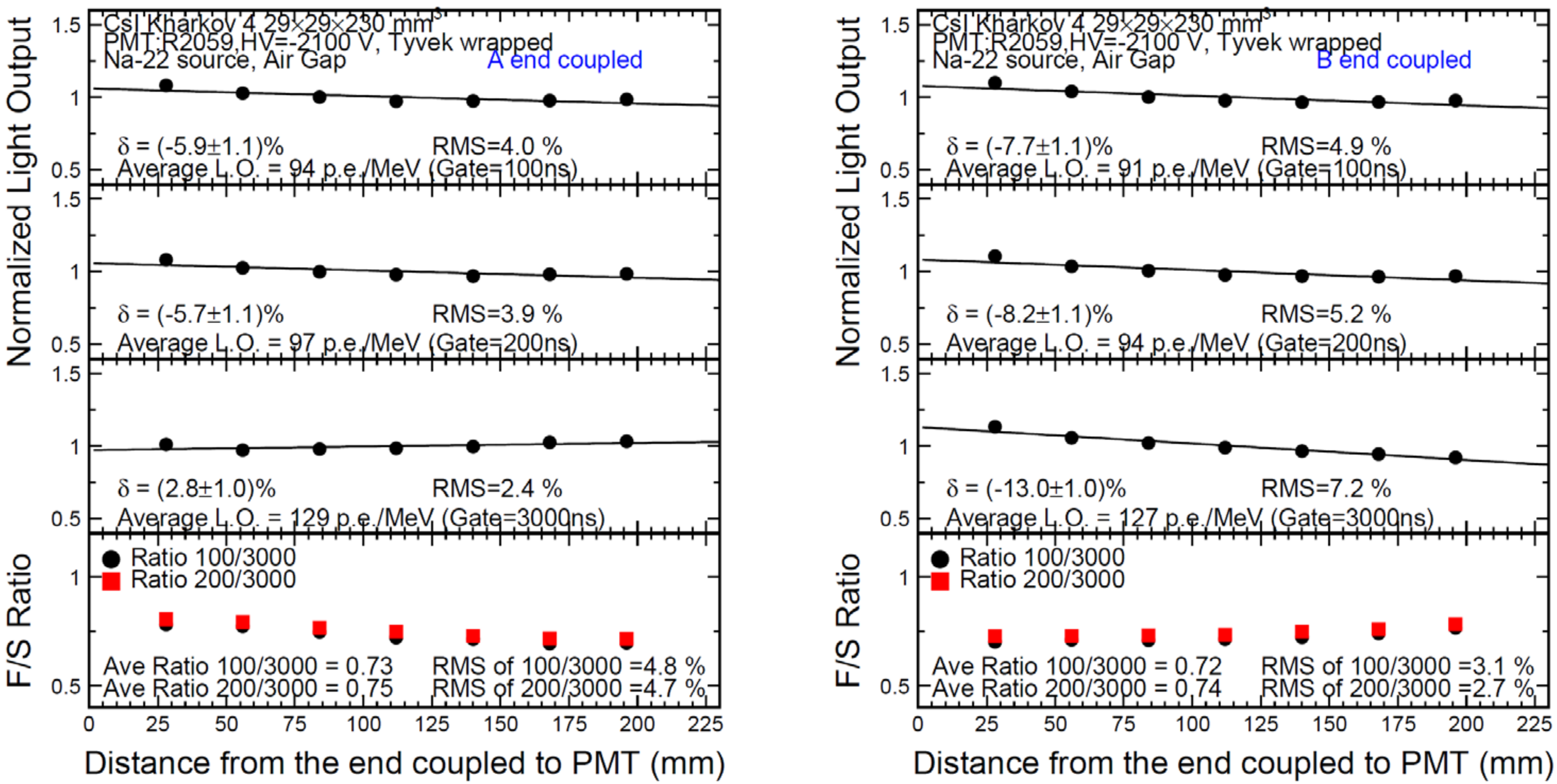


Ave ER= 41.6%



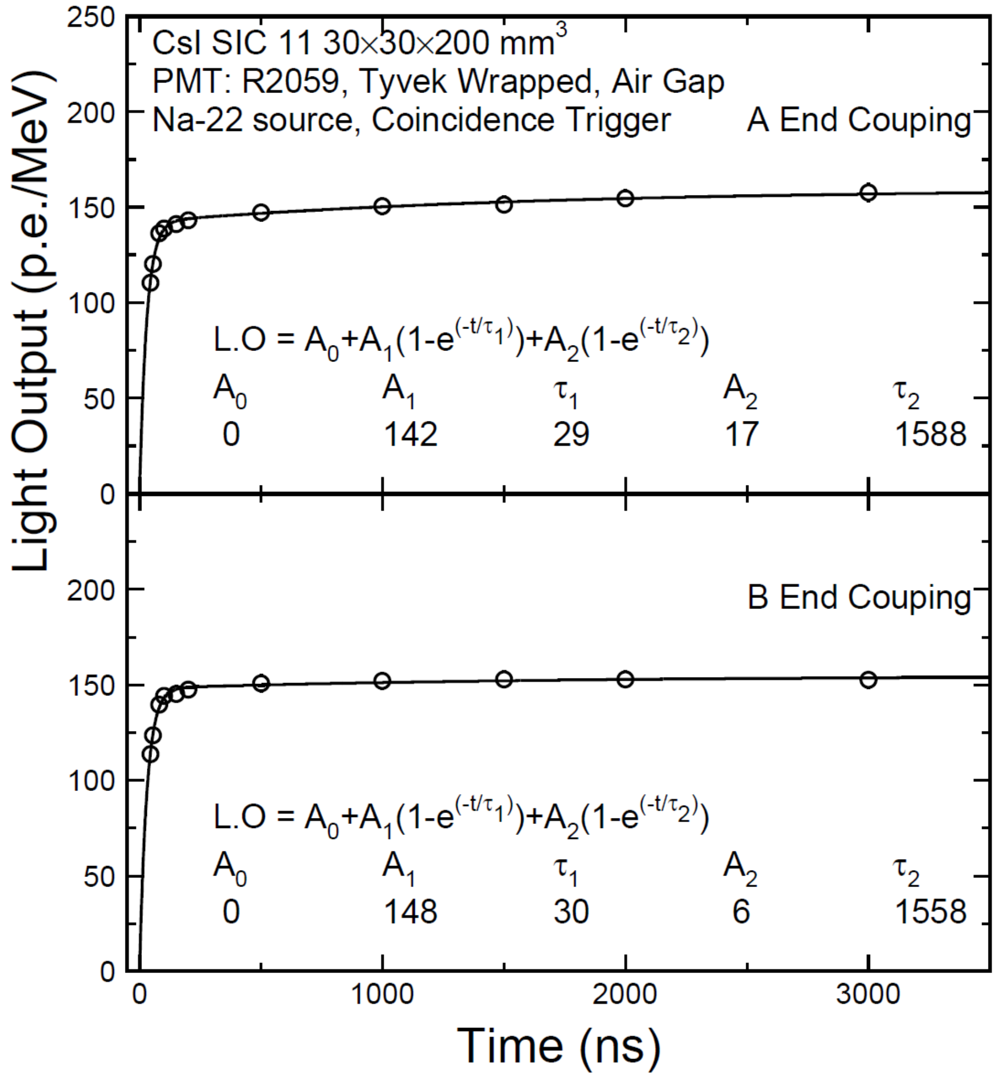
LO & LRU (Different Gate): Kharkov 4

F/T ratio changes from one end to other



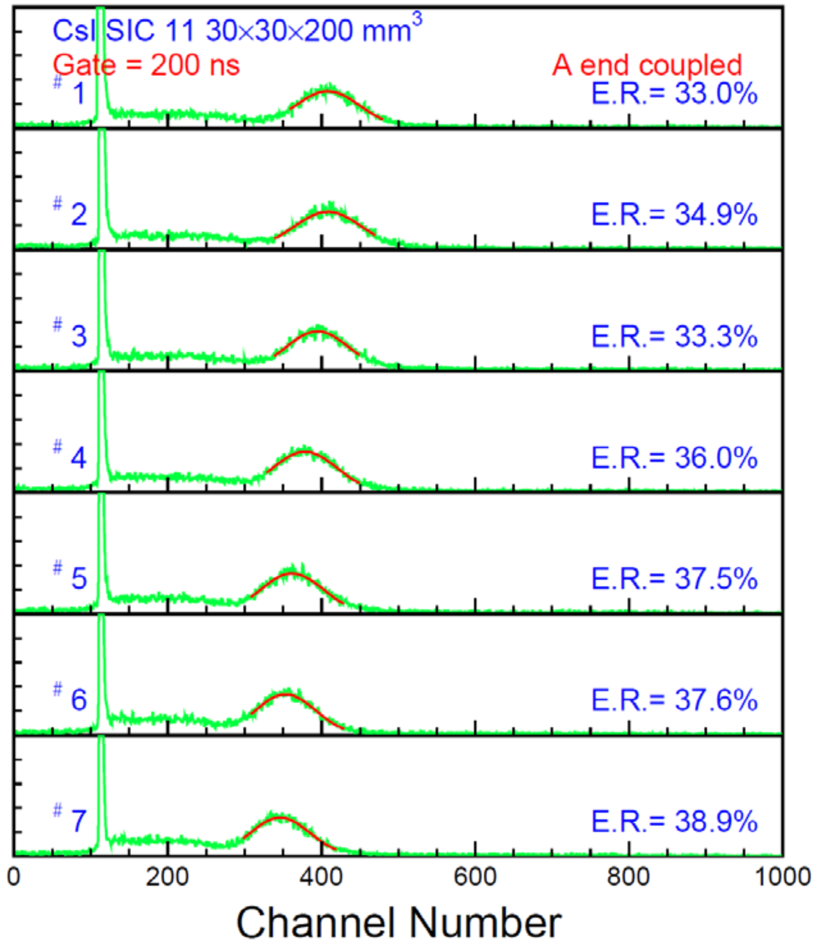
Decay Kinetics: SIC 11

A slow component at a level of 10% with a decay time of 1.6 us was observed

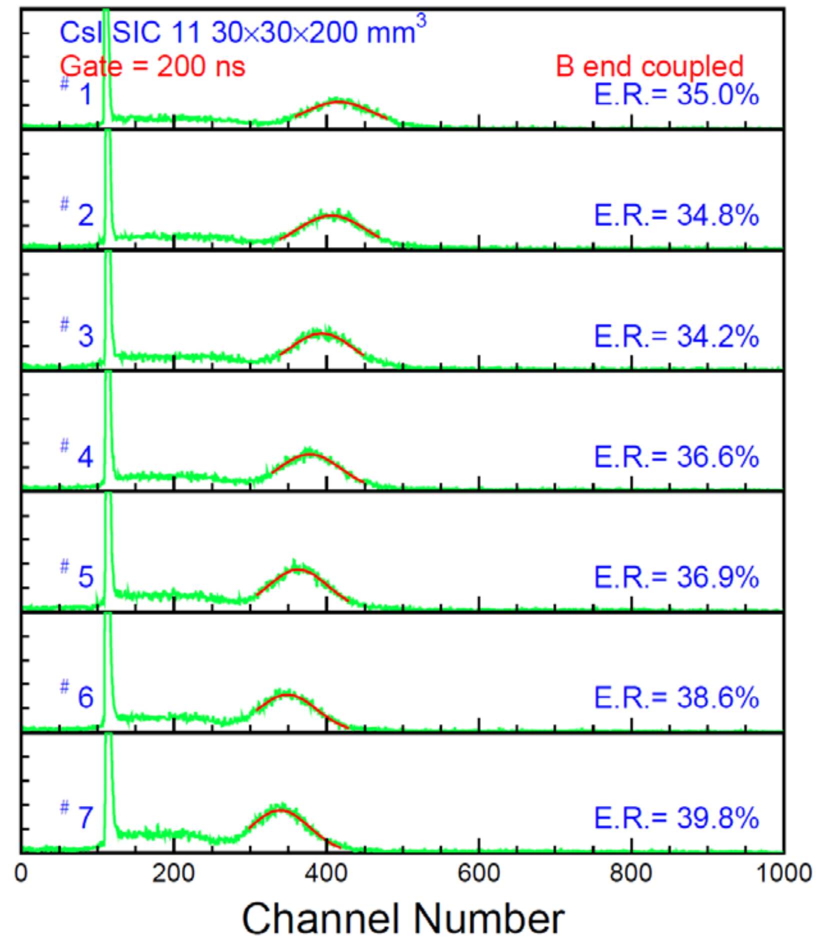


PHS (200 ns): SIC 11

Ave ER= 35.9%

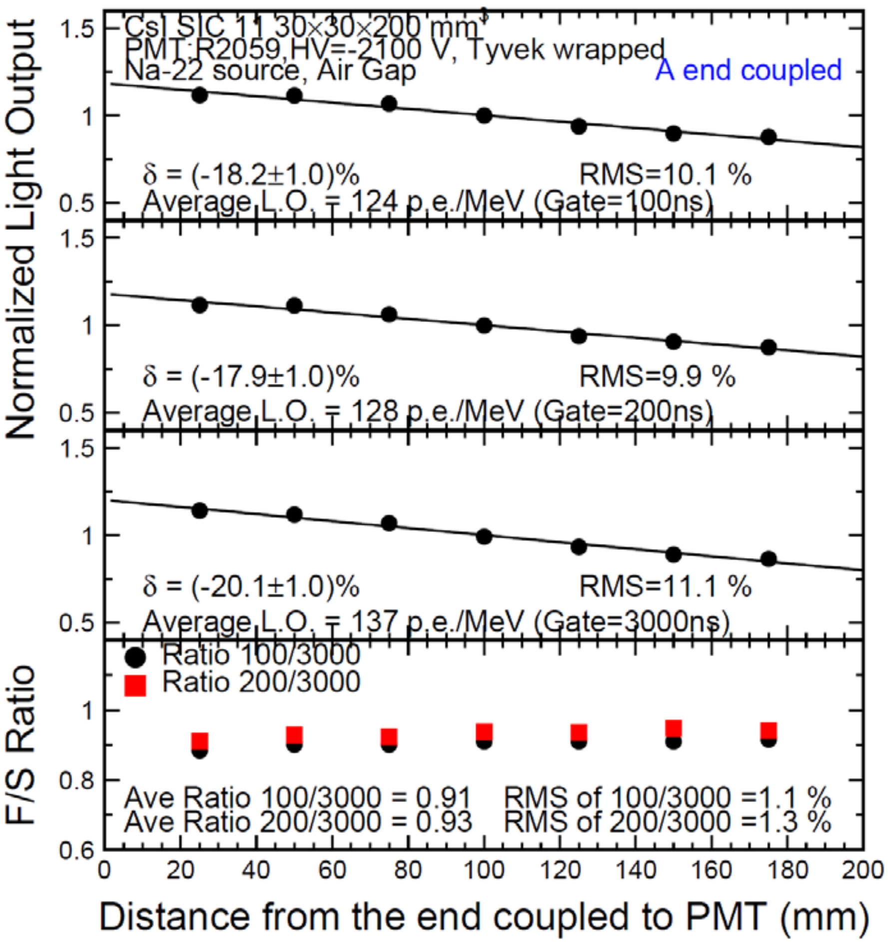


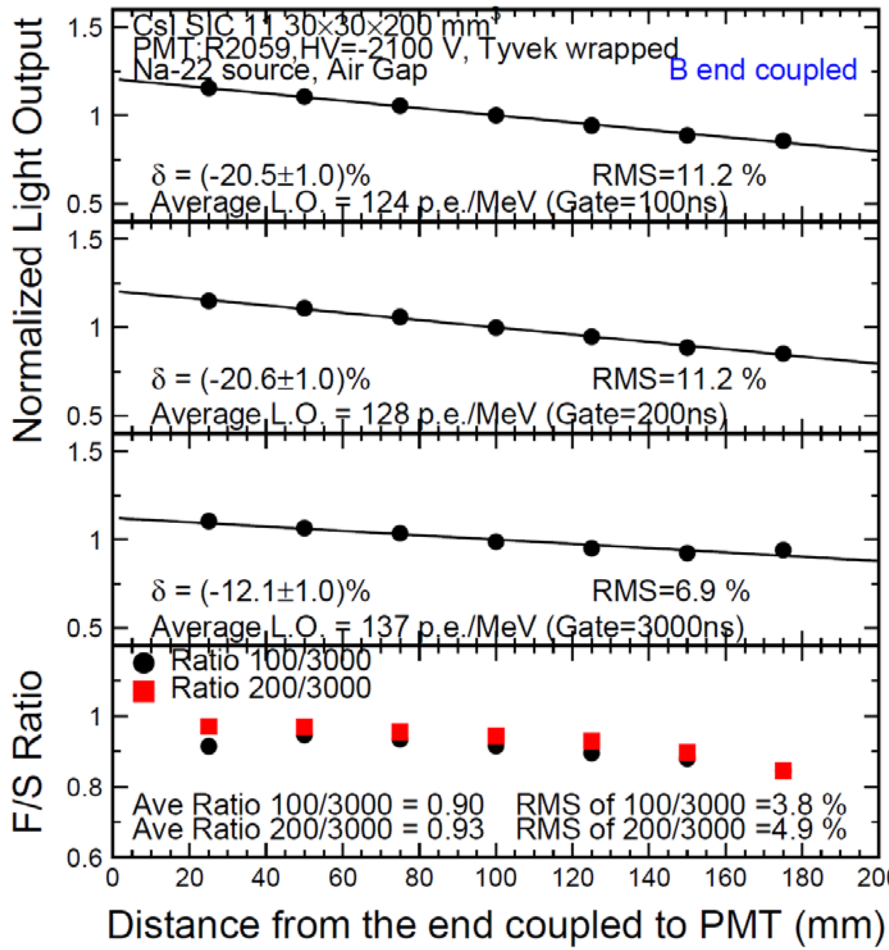
Ave ER= 36.6%



LO & LRU (Different Gate): SIC 11

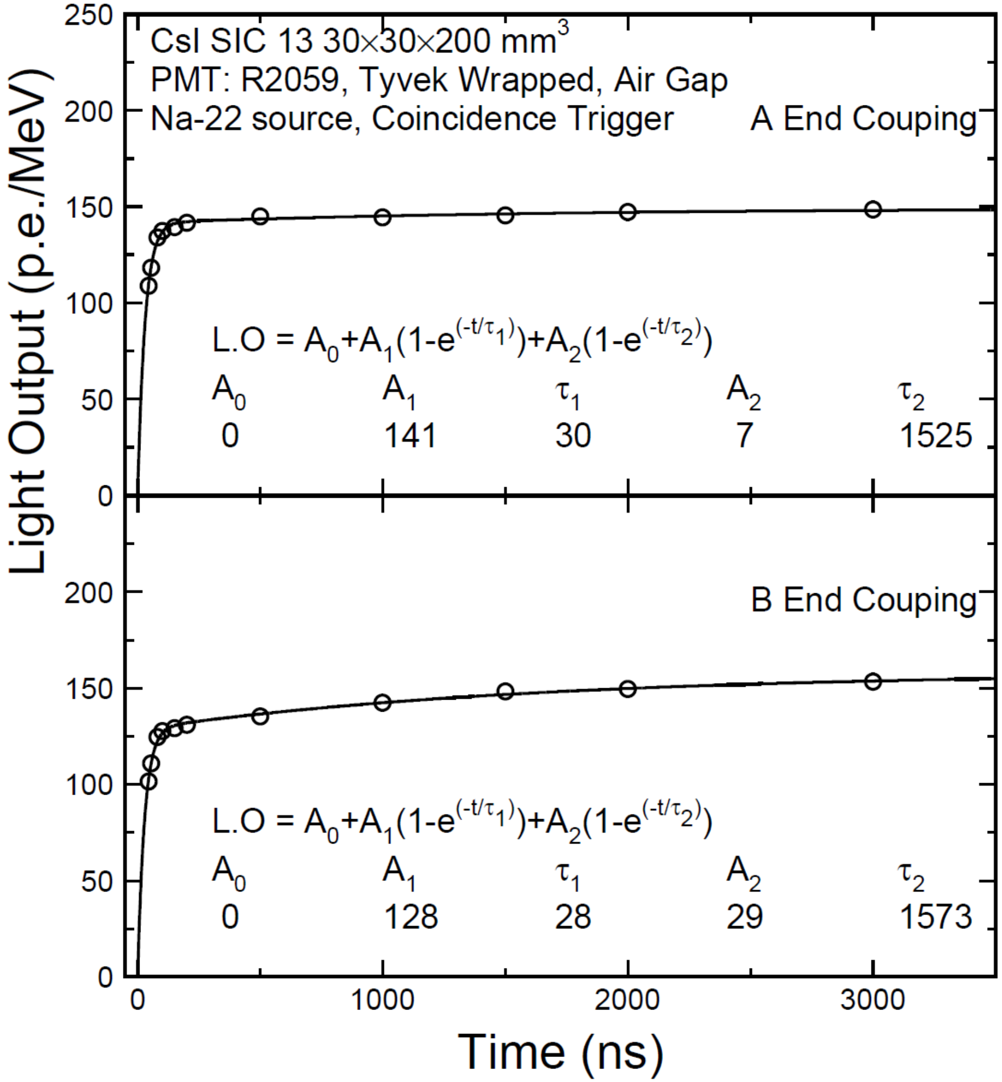
F/T ratio changes from one end to other





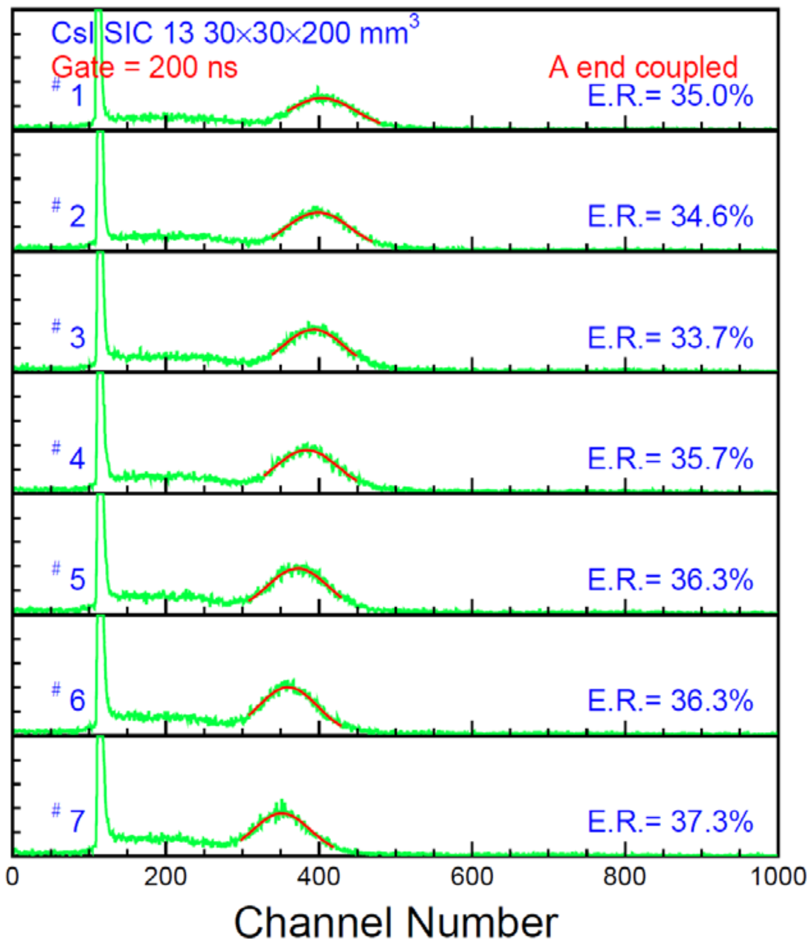
Decay Kinetics: SIC 13

A slow component at a level of 20% with a decay time of 1.6 us was observed

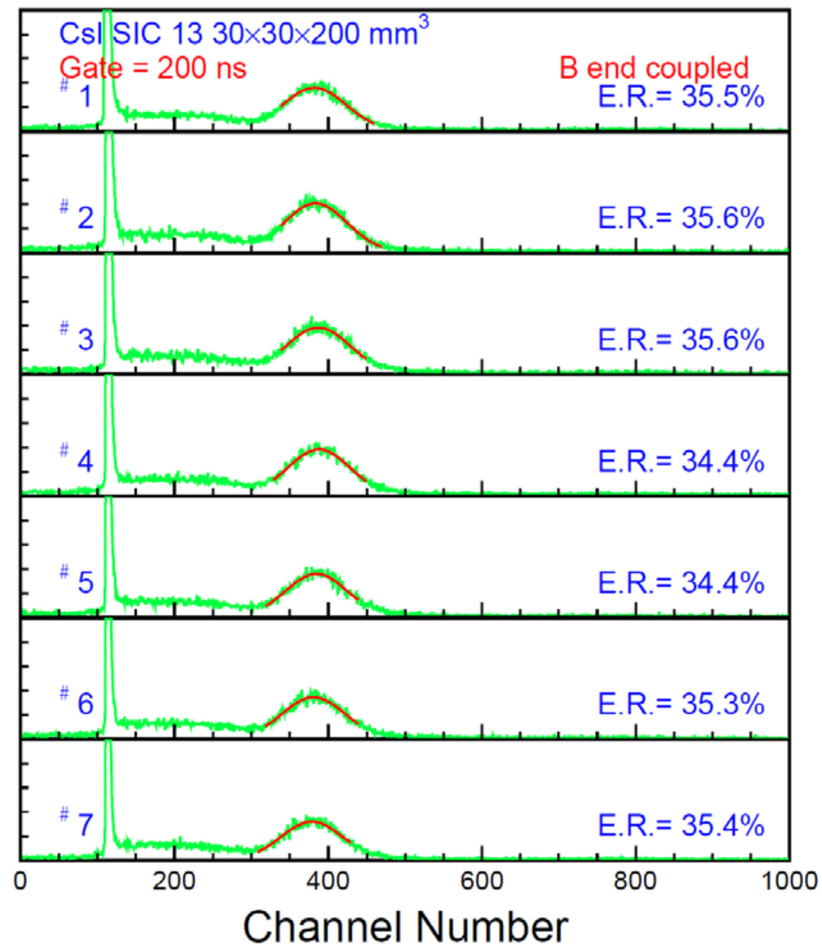


PHS (200 ns): SIC 13

Ave ER= 35.6%

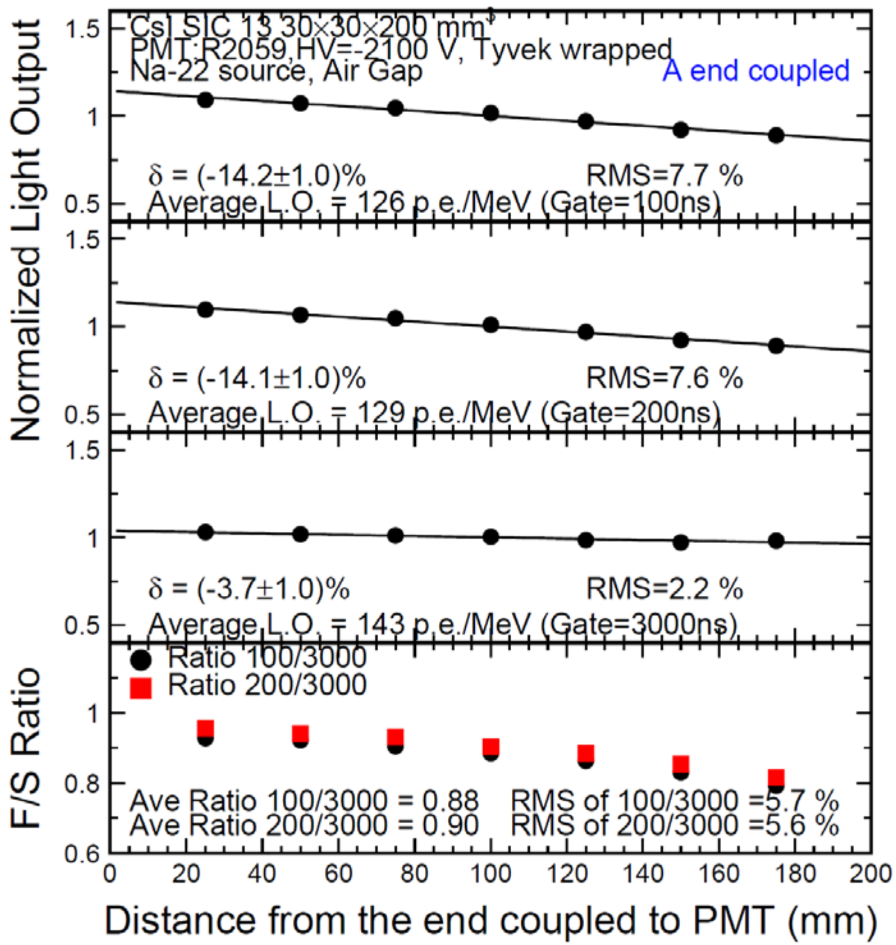


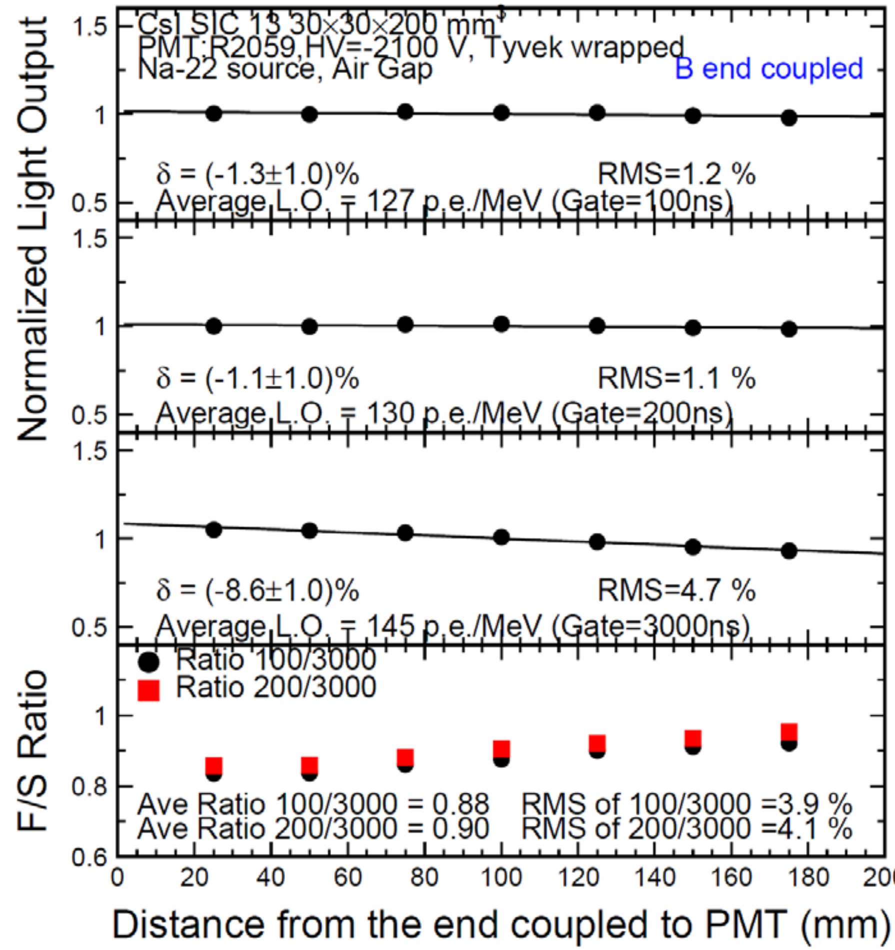
Ave ER=35.2%



LO & LRU (Different Gate): SIC 13

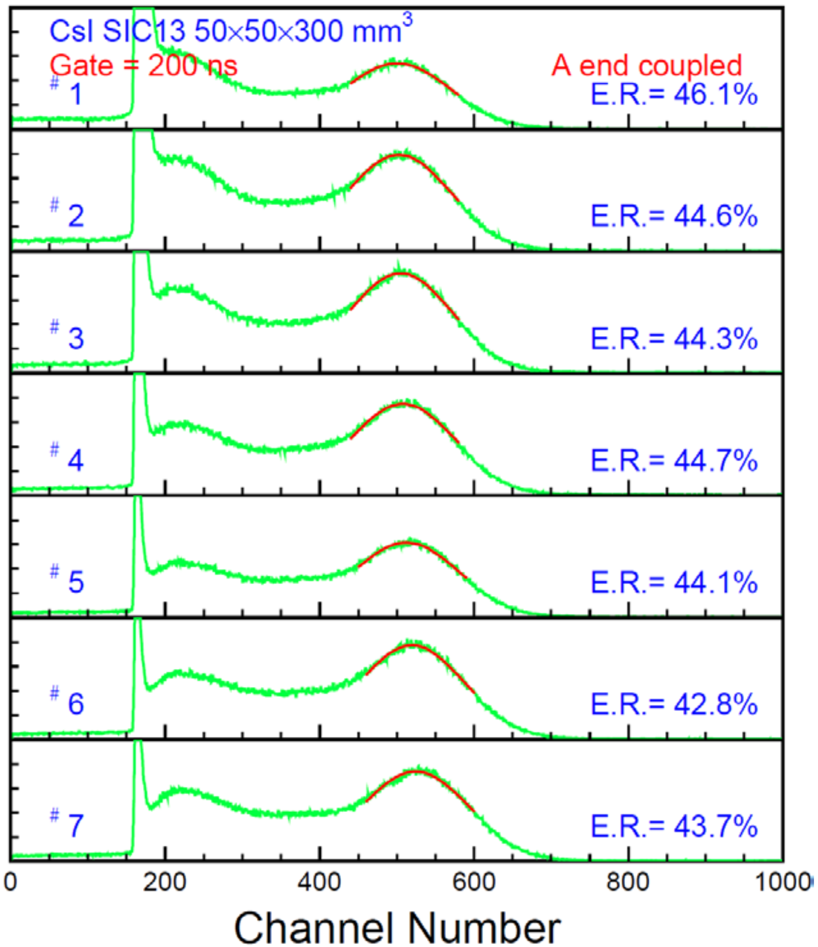
F/T ratio changes from one end to other





Pulse Height Spectra: SIC 13

Ave ER=44.3%



Ave ER=44.3%