Mu2e CD3c Review
WBS 7.2 Calorimeter Crystals

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6/14/16

Scope

WBS 475.7.2
Crystals
D. Hitlin/Caltech
S. Giovannella/LNF

475.7.2 **Crystals**

This WBS covers the development phase, the final choice, the test, the procurement for the pre-production and production phases to fabricate crystals needed for the realization of the calorimeter. It also includes the design and construction of the QA test facilities to perform an acceptance test of the delivered crystals.

475.7.2 **Scope of work**

Experimental measurement of the crystal properties. Design and construction of QA stations to determine the crystal quality. Optimize the configuration for wrapping the crystals and optical connection of photo-sensors. The completion of test beam related to the crystal tests. Procurement and QA test of the pre-production crystals. Procurement and QA test of the production crystals.

Requirements (Mu2e DocDB-864)

In order to match the calorimeter energy (5%), position (1 cm) and timing (0.5 ns) resolution requirements a homogeneous calorimeter is the solution with a crystal that should have the following characteristics:

- High light output (LO) > 100 p.e./MeV by PMT.
- Good light response uniformity (LRU): < 10%.
- Fast signal with small slow: $\tau < 40$ ns, F/T > 75%.
- Radiation hard with LO loss < 40% for:
  - Ionization dose: 100 krad @ 10 krad/year; and
  - Neutrons: 10^{12} n/cm^2 @ 3 x 10^{11} n/cm^2/year.
- Small radiation induced readout noise: < 0.6 MeV.

Design choice – undoped CsI

- Specifications are defined according to samples characterized:
  - Kharkov (Ukraine), Opto Materials (Italy) and SICCAS (China);
  - Not yet procured: Hilger (UK) and Saint-Gobain (France).
- Crystal lateral dimension: ±50 μ, length: ±100 μ.
- Scintillation properties measured by a bi-alkali PMT with air gap coupled to the crystal wrapped with two layers of Tyvek paper:
  - Light output (LO): > **100 p.e./MeV** with 200 ns integration gate, will be defined as XX% of a candle crystal provided;
  - FWHM Energy resolution: **< 45%** for Na-22 peak;
  - Fast (200 ns)/Total (3000 ns) Ratio: **> 75%**;
  - Light response uniformity (LRU): **< 10%.**
- Radiation hardness:
  - Normalized LO **after 10/100 krad > 85/60%**.
  - Radiation Induced Current (RIC) @1.8 rad/h: **< 0.6 MeV**.

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

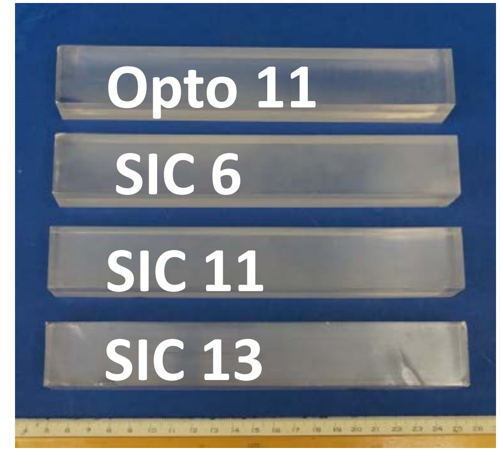
d. At room temperature (20°C)

#. Softening point

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

Commercial available CsI crystals have slow scintillation components

Mu2e Pure CsI Samples



ID	Dimension (mm^3)	Polishing
Kharkov 1	29x29x230	All faces
Kharkov 3	29x29x230	All faces
Kharkov 4	29x29x230	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
SIC 2014	25x25x200	All faces

Experiments

- Ten samples from three vendors characterized
- Properties measured at room temperature: LT, LO, PHS, Decay Kinetics and LRU

Measurements for Crystal QA

- Longitudinal transmittance (LT) was measured by using a Perkin-Elmer Lambda 950 spectrophotometer. (0.15%)

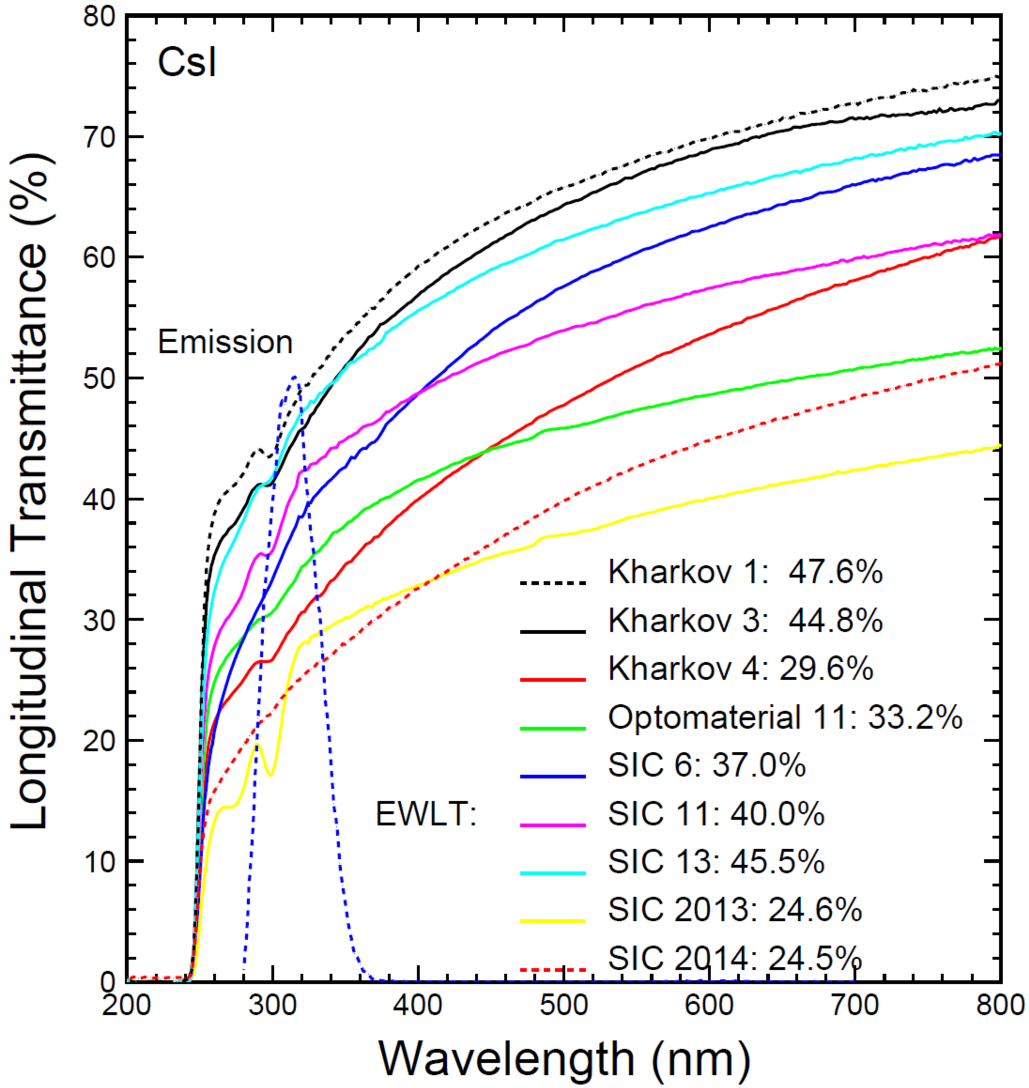
- Pulse height spectrum (PHS), FWHM energy resolution of 511 KeV ɣ-rays (ER), light output (LO), light response uniformity(LRU) and decay kinetics were measured by a Hamamatsu R2059 PMT with coincidence triggers from a ^{22}Na source. All samples were wrapped with two layers of Tyvek paper with precision and reproducibility of <1%.

- PHS/ER/LO/LRU were measured with air gap for pure CsI because of the soft and hygroscopic surface.

Longitudinal Transmittance

LT of CsI depends on crystal surface quality, so can not be used in specification.

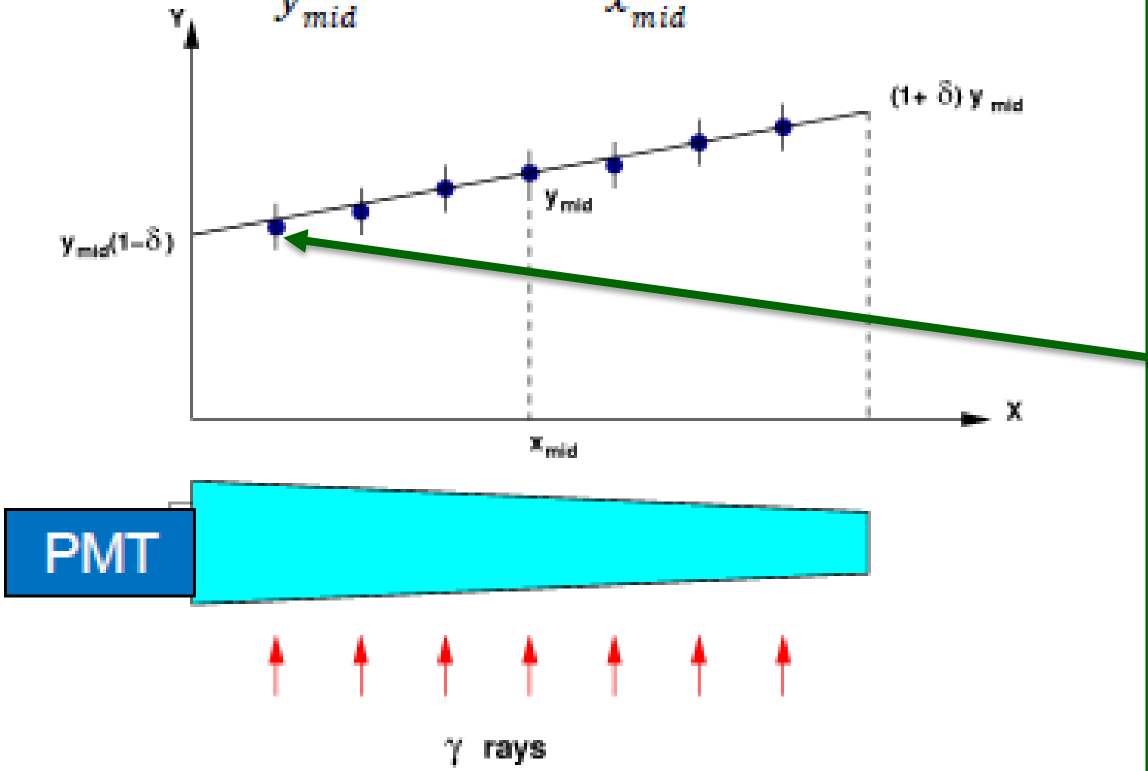
LT and emission weighted LT (EWLT) may be used in radiation damage investigation provided that crystal surface is kept stable.



LO, LRU and Decay Kinetics

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

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

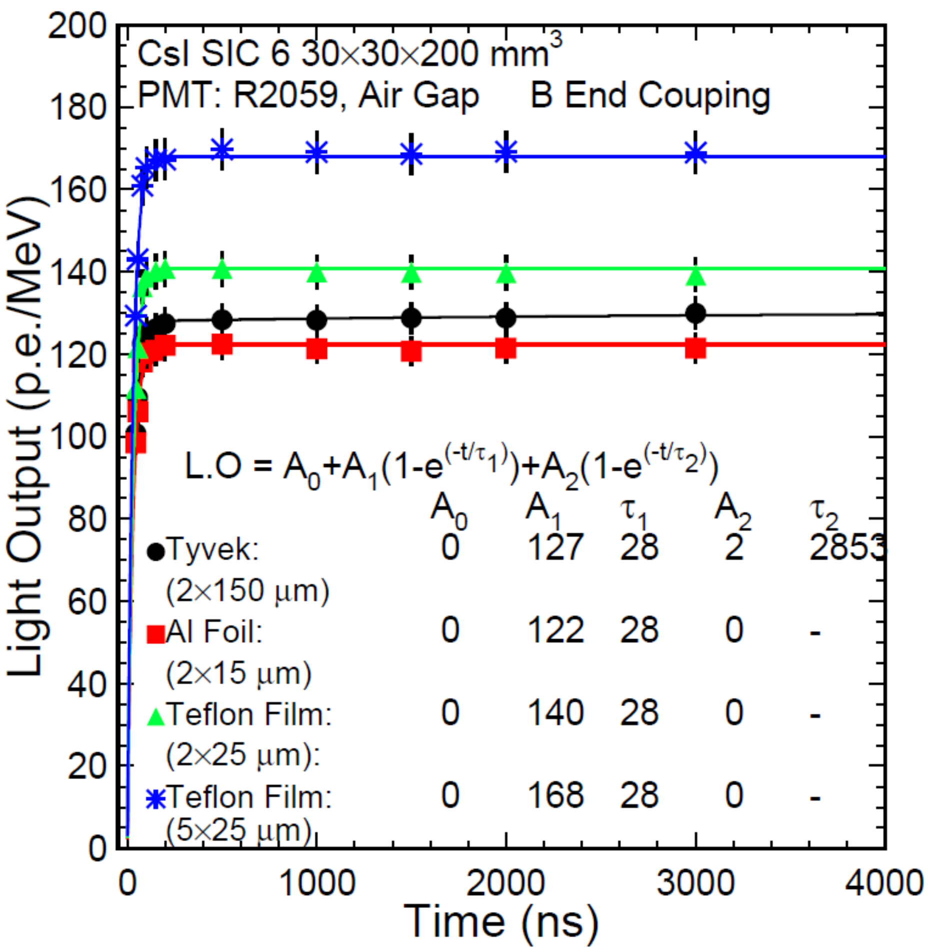


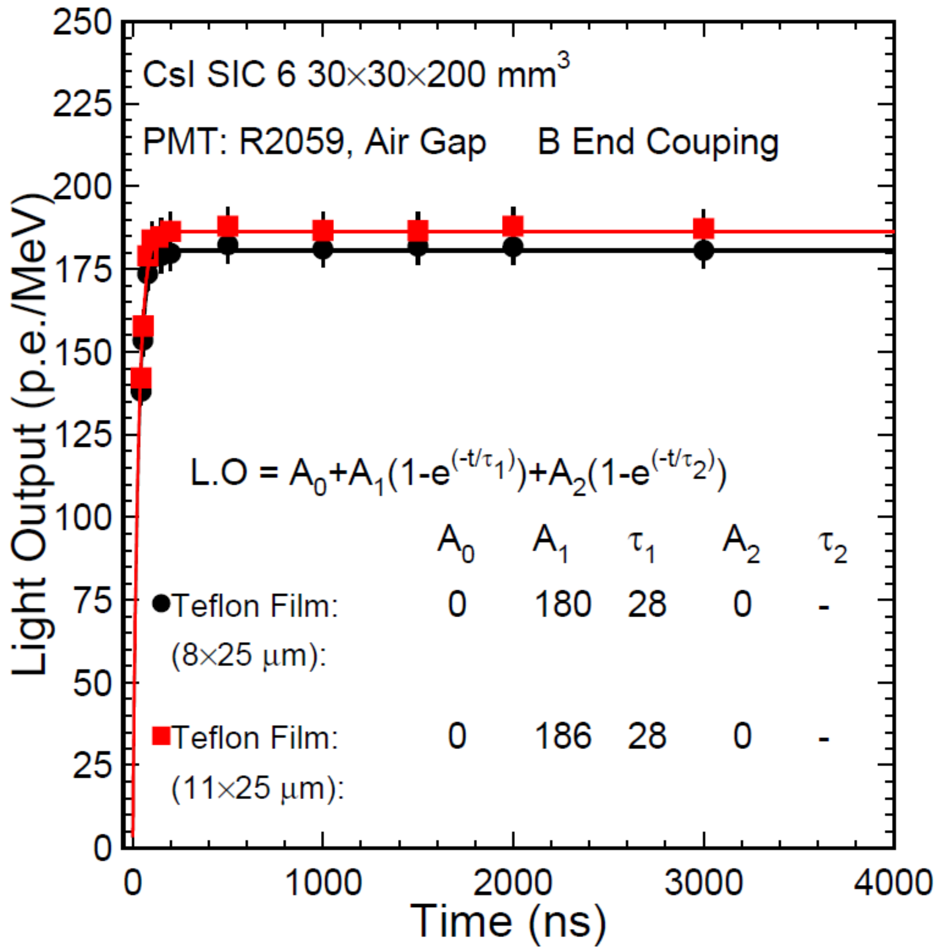
LO is defined as the average of LO values measured at seven points with rms spread as LRU

Decay kinetics was measured at the point closest to the PMT with F/T ratio specified

Wrapping Effect on CsI LO

PTFE Teflon film is the best wrapping material for CsI UV light
Tyvek paper provides good reproducibility and tune ability



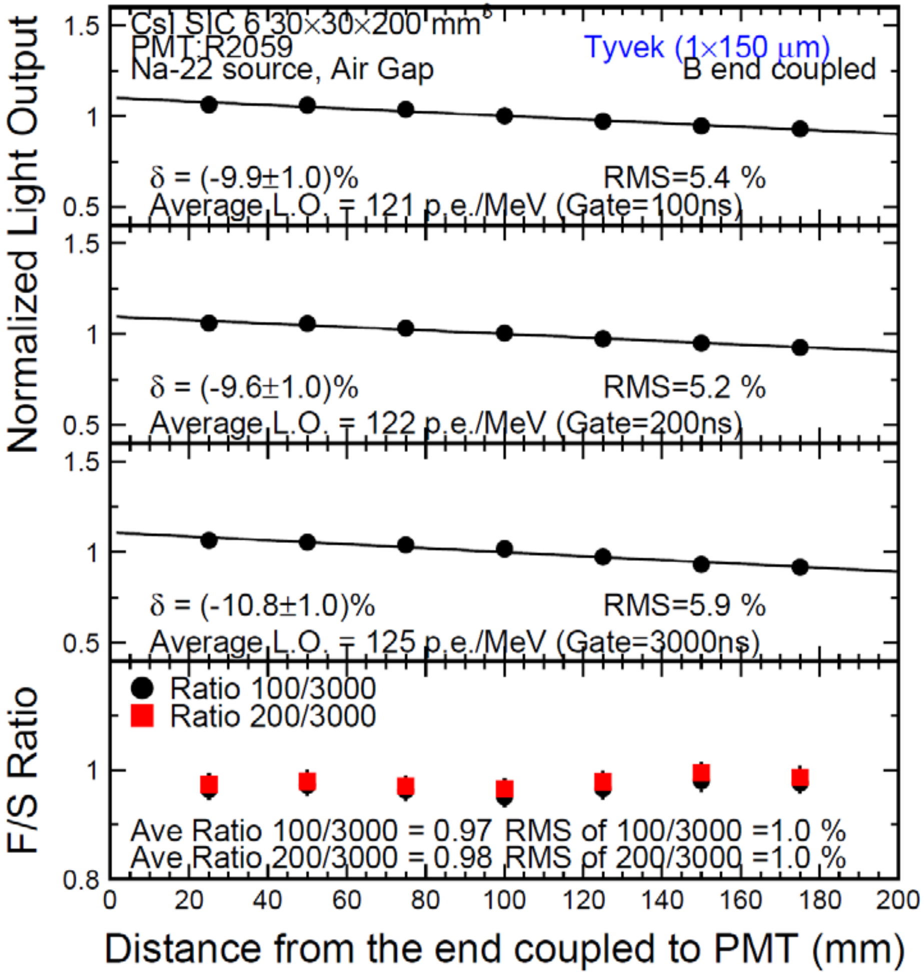


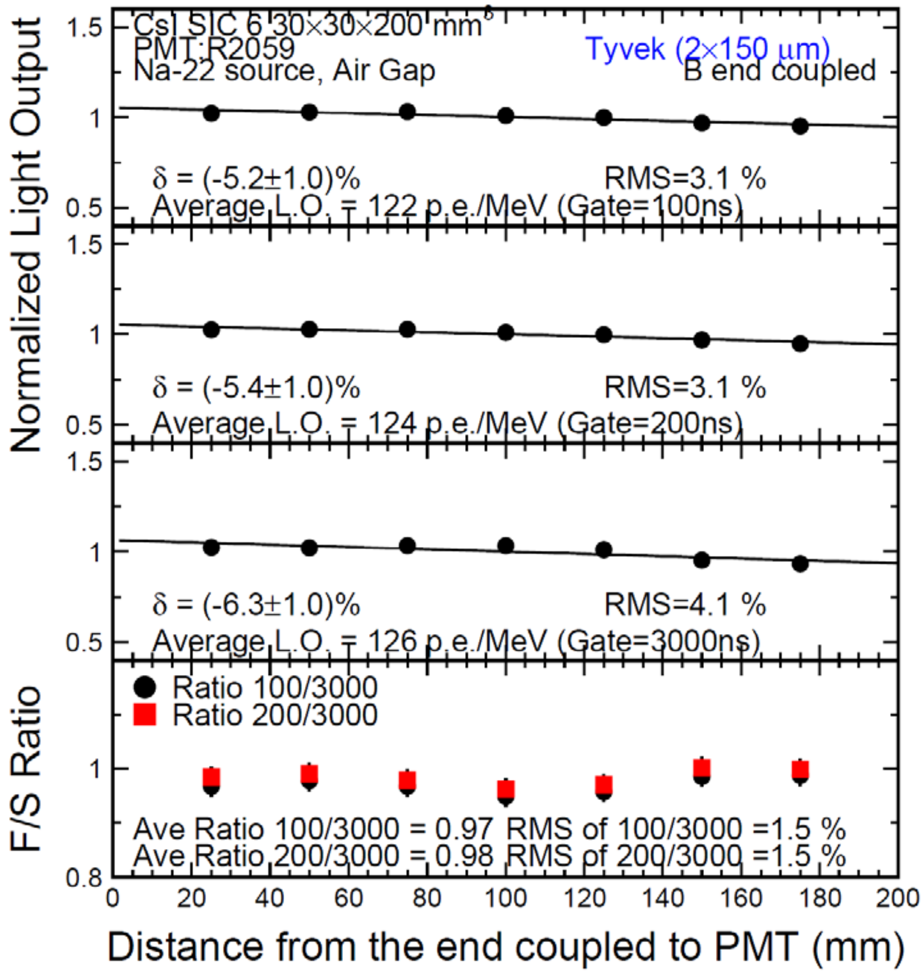
Tyvek Wrapping: One & Two Layers

One layer

< 2%

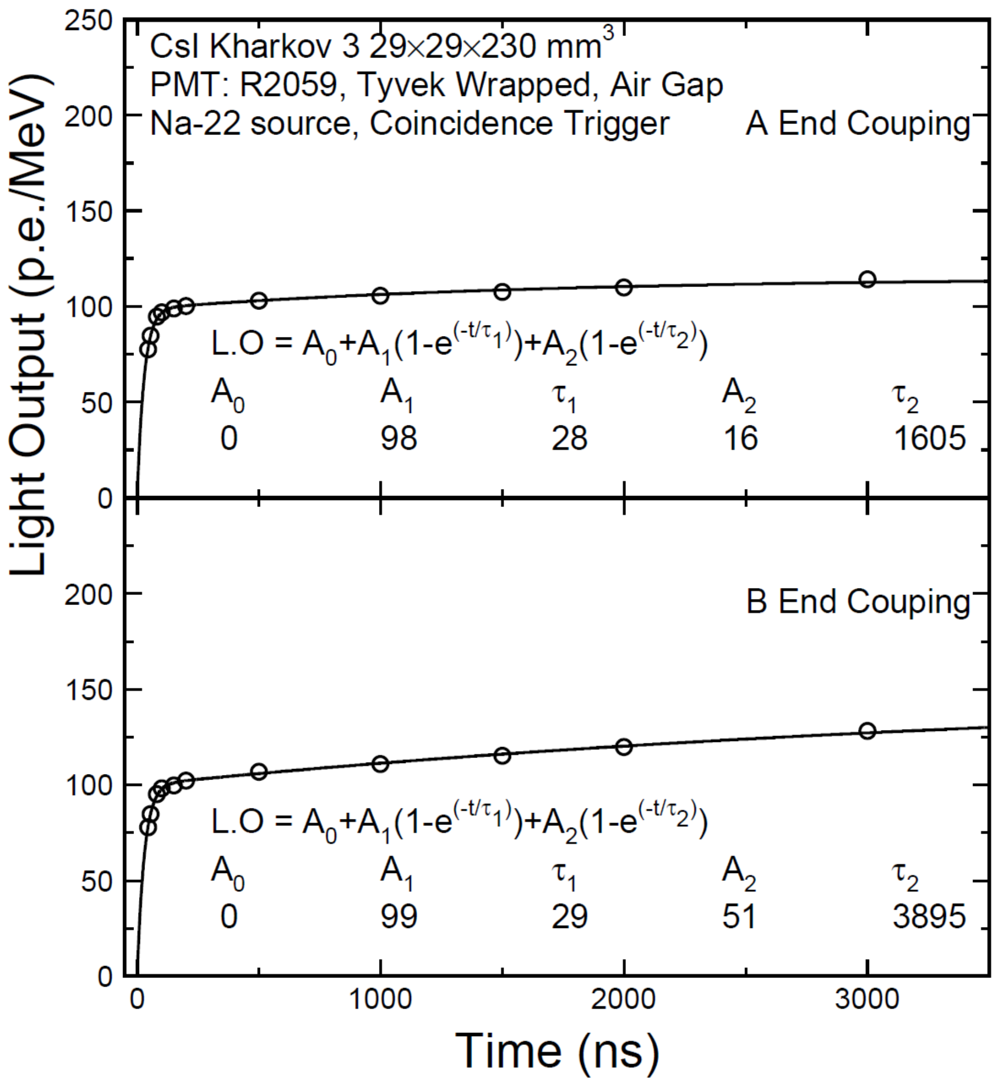
Two layers





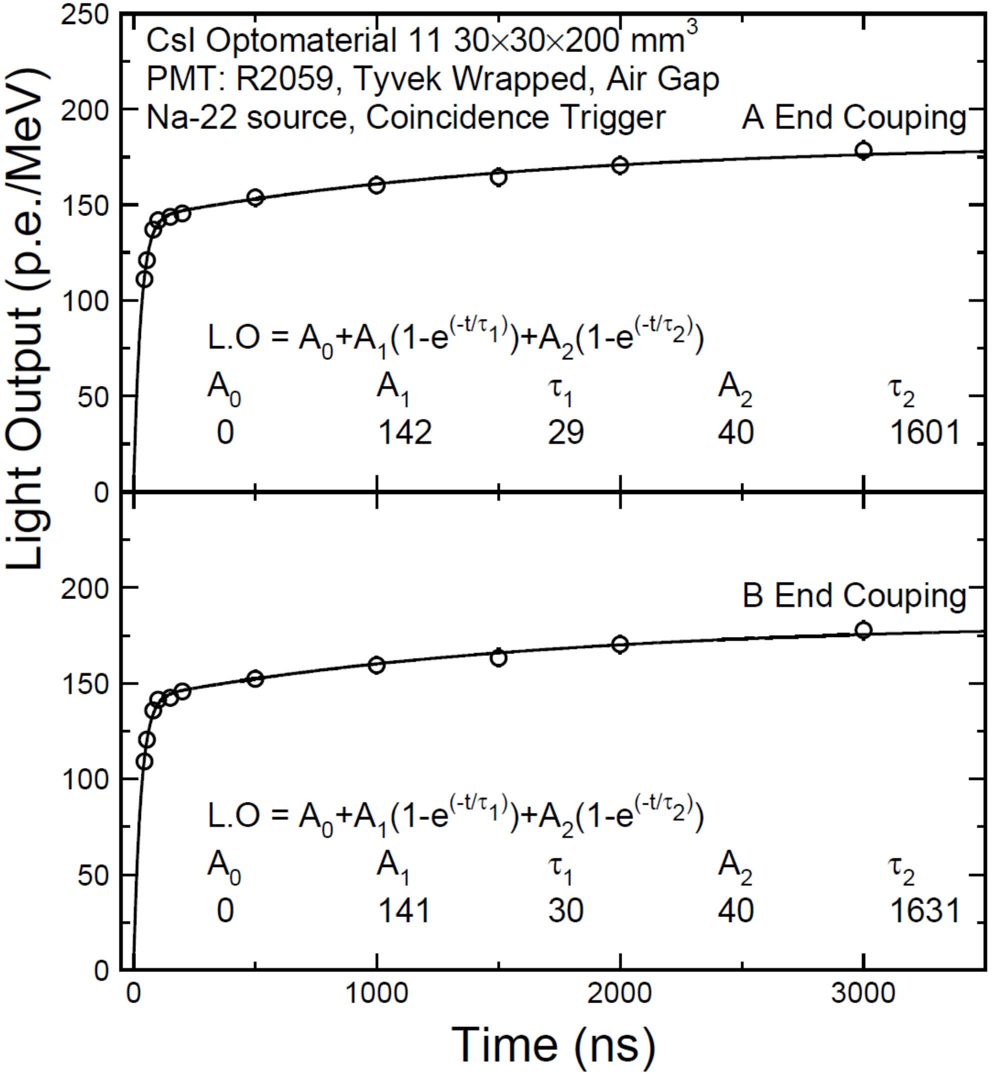
LO & Decay Kinetics: Kharkov 3

A slow component with a position dependent level and decay time of 1.6 and 4 us was observed



Fermilab

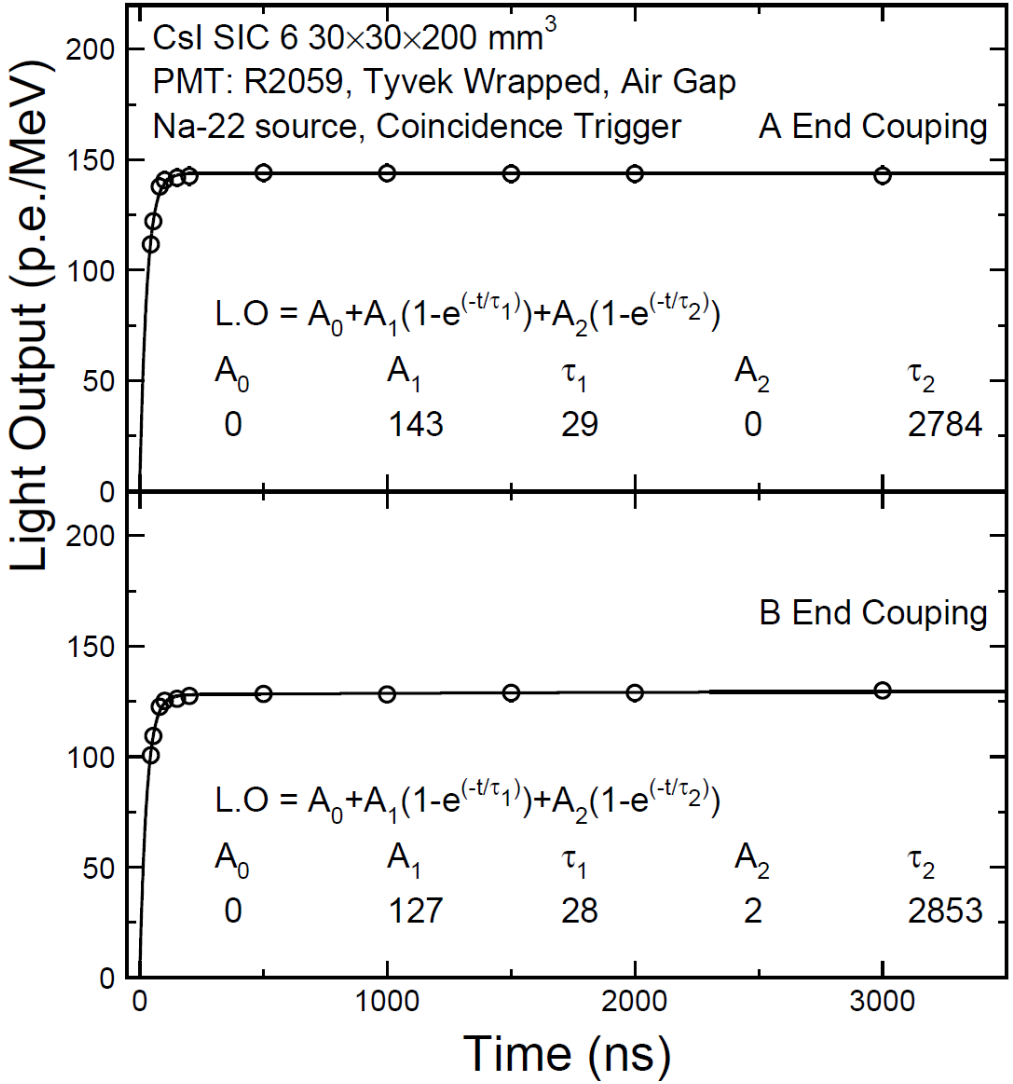
LO & Decay Kinetics: Optomaterial 11



A position independent slow component with a decay time of 1.6 us was observed, which is at a level of 30% of the fast component

LO & Decay Kinetics: SIC 6

No slow component was observed



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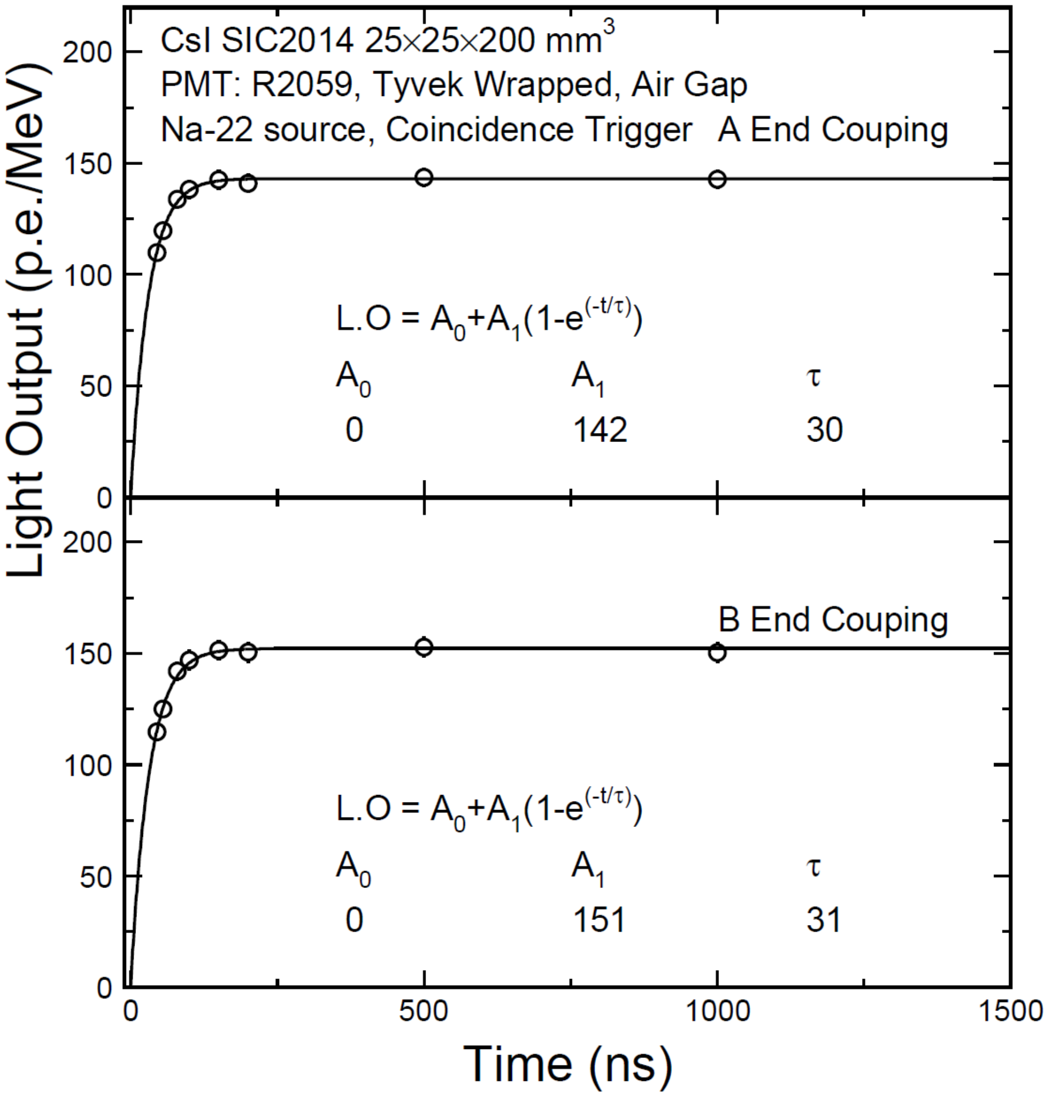
LO & Decay Kinetics: SIC 2014



No slow component was observed

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Summary: CsI Scintillation Spec

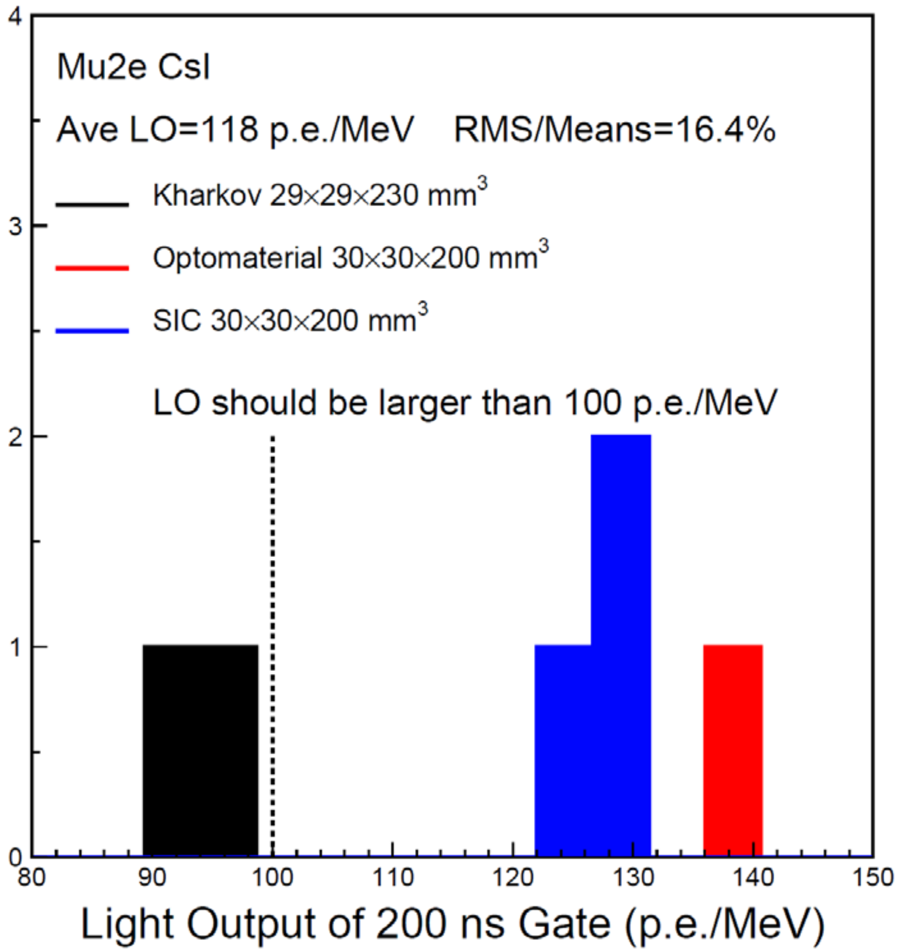
ER and LO are the average of data measured at seven points along the crystal with two layers of Tyvek (150 µm) and air gap coupled to PMT

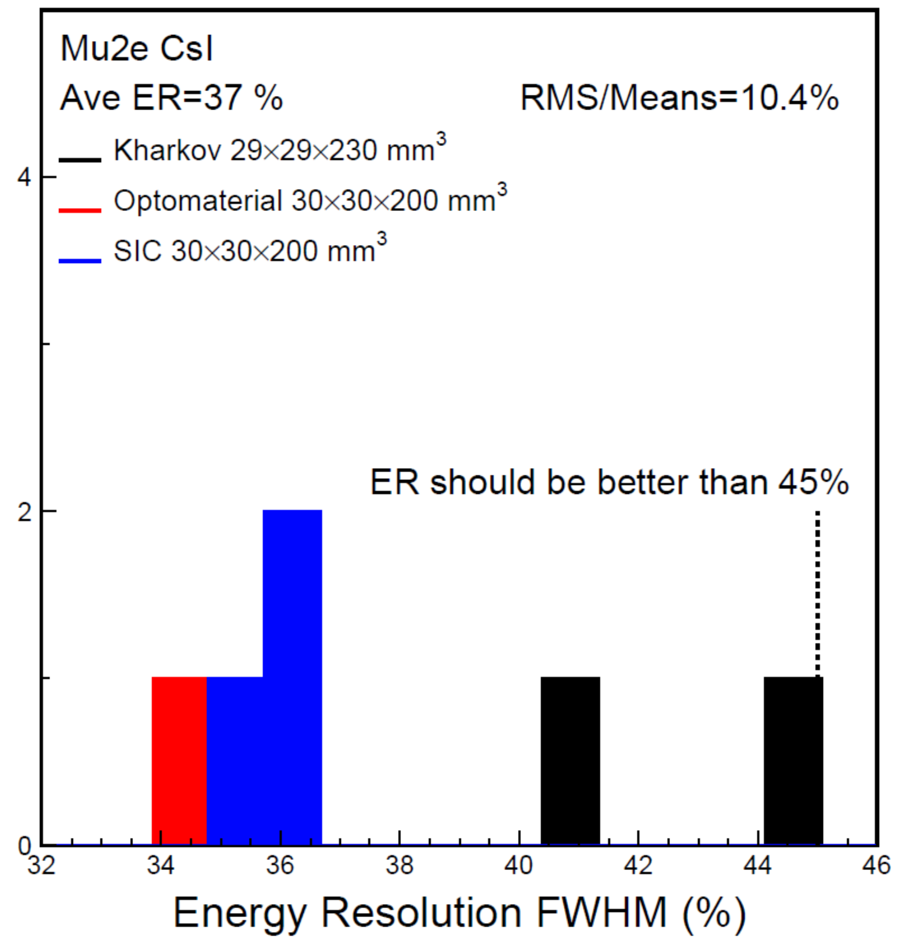
ID	Dimension (mm^3)	Ave FWHM ER (%)	Ave LO in 200 ns Gate (pe/MeV)	F/T Ratio 200 ns / 3 µs	RMS of LO along crystal (%)
Kharkov 3	29x29x230	**44.3**	**93**	**0.83**	**5.0**
Kharkov 4	29x29x230	**41.3**	**96**	**0.75**	**4.6**
Opto-material 11	30x30x200	**34.1**	**140**	**0.84**	**2.0**
SIC 6	30x30x200	**36.3**	**125**	**0.98**	**6.9**
SIC 11	30x30x200	**36.3**	**128**	**0.93**	**10.1**
SIC 13	30x30x200	**35.4**	**130**	**0.90**	**4.4**
SIC 2014	25x25x200	**35.8**	**136**	**1.00**	**4.6**
Spec	**34x34x200**	$\leq$ **45**	$\geq$ **100**	$\geq$ **0.75**	$\leq$ **10**

Specifications derived from existing samples with headroom

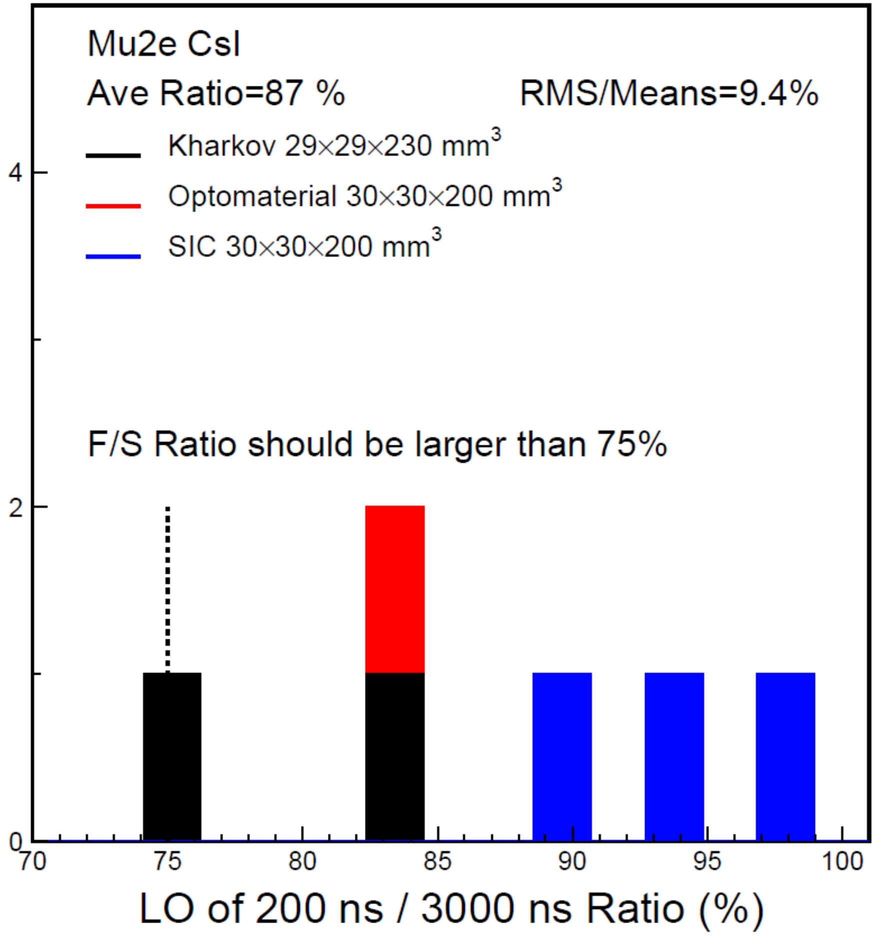
LO and FWHM ER: Spec

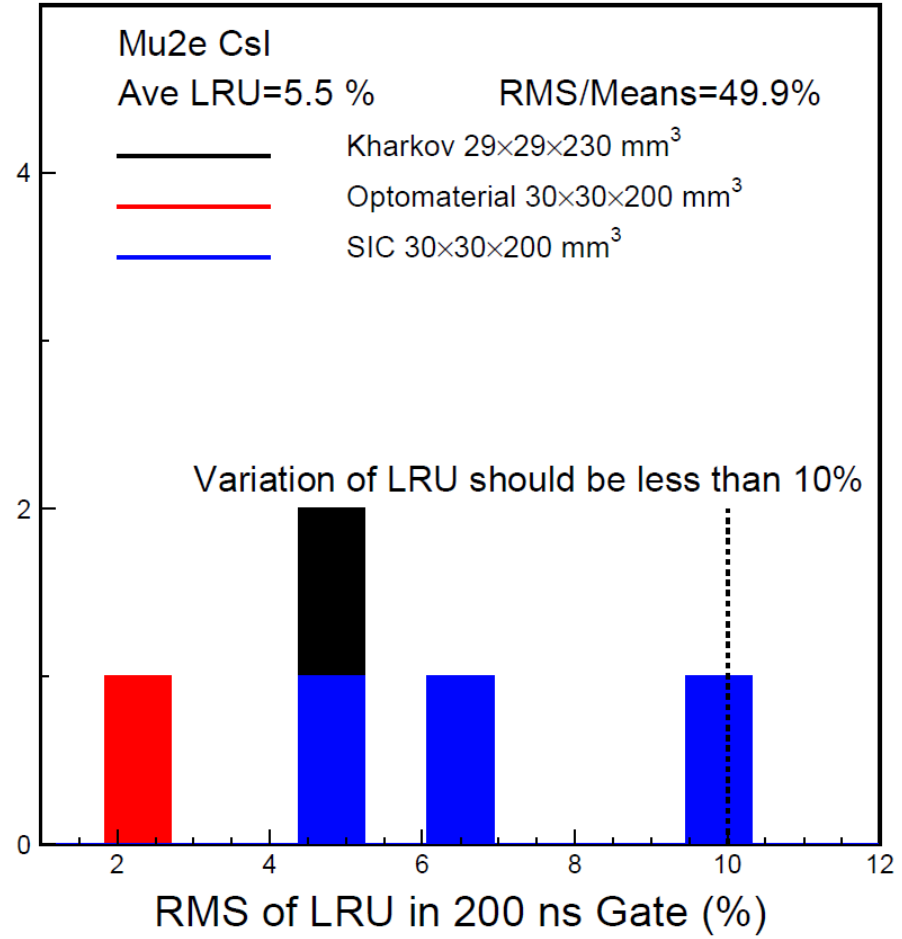
Kharkov samples are longer, so have lower LO





F/T Ratio and LRU: Spec

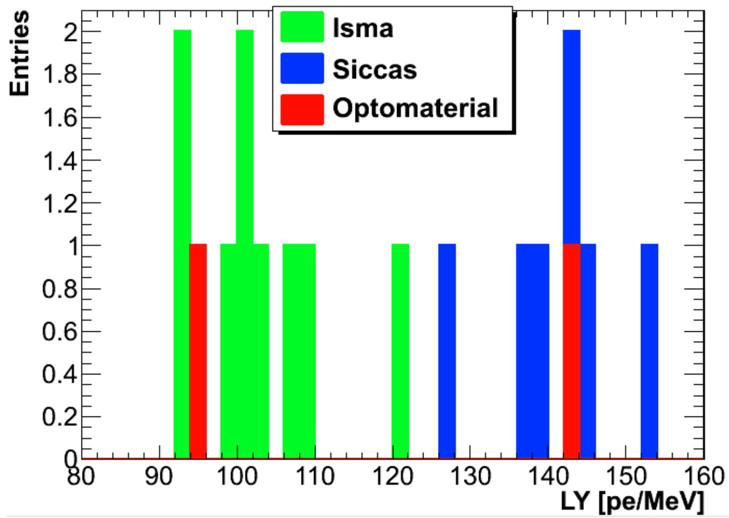


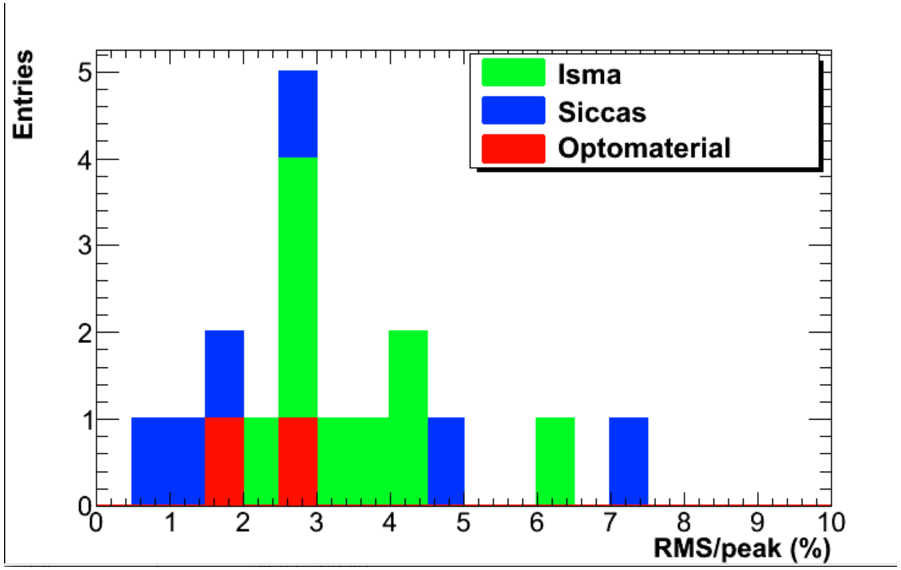


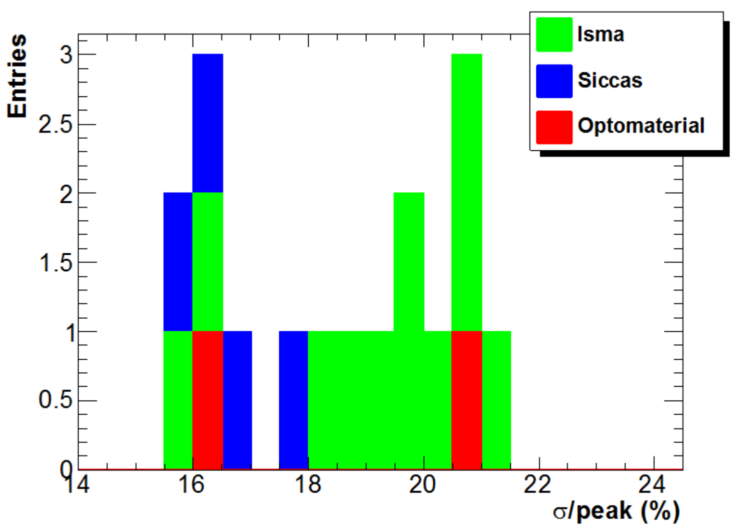
QA of CsI Crystals at LNF

Similar QA procedures has been applied @ LNF to the 17 un-doped CsI crystals procured from:

- 6 Siccas
- 2 Optomaterial
- 9 ISMA

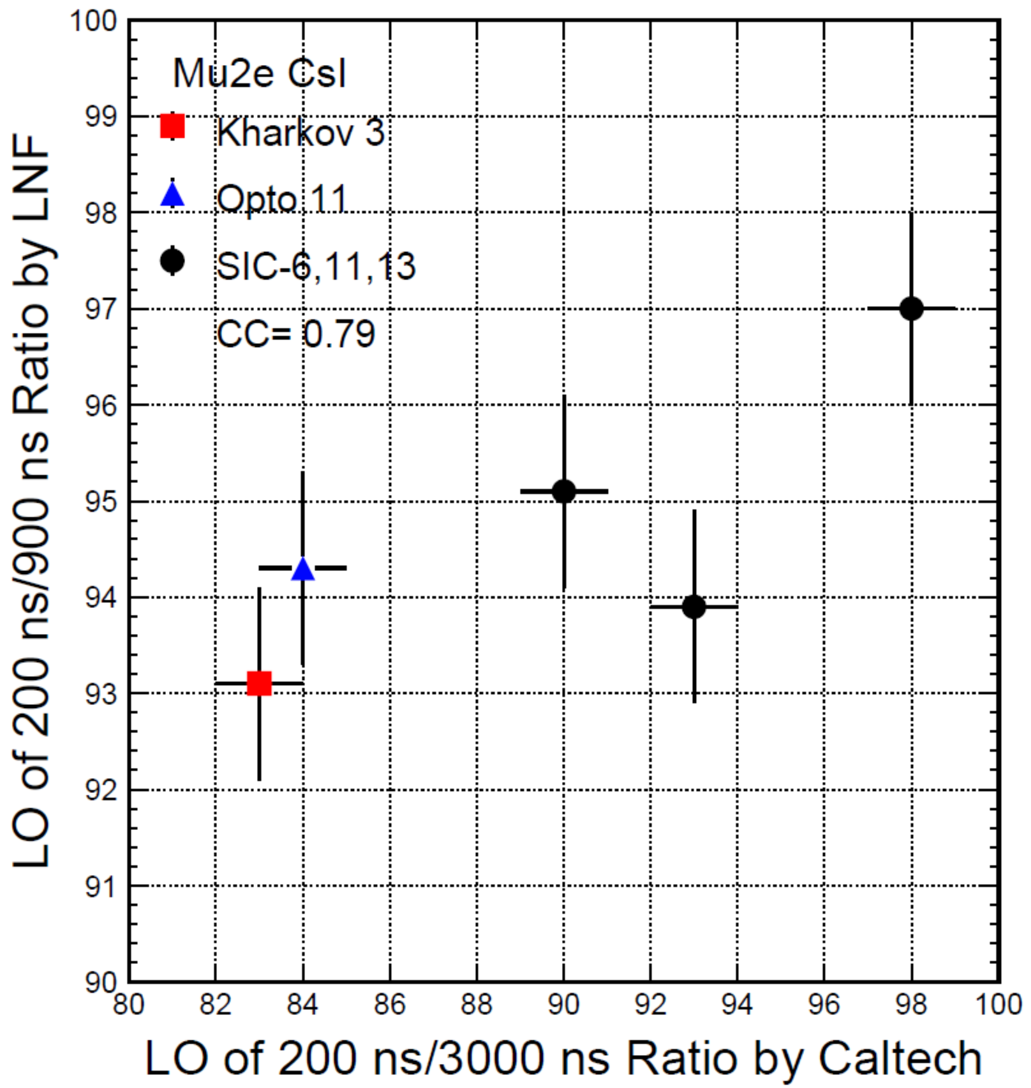






Correlation in F/T: Caltech and LNF

Very good correlations observed between the F/T ratios measured at Caltech and LNF with two very different approaches



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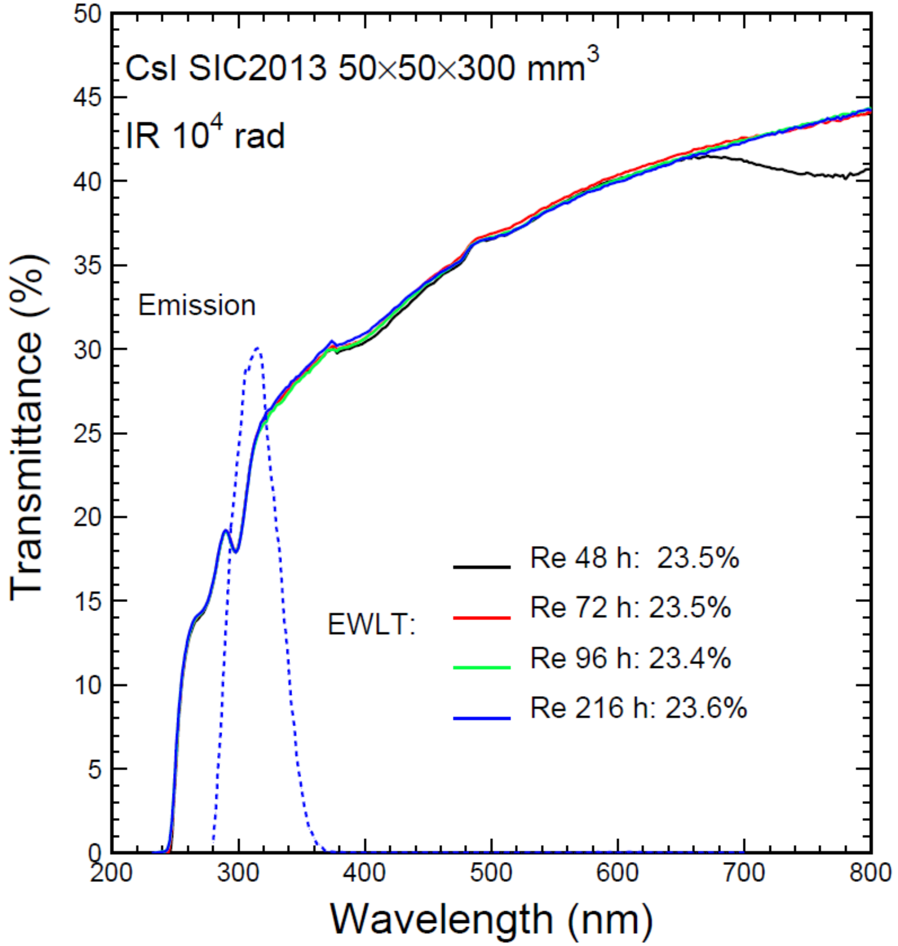
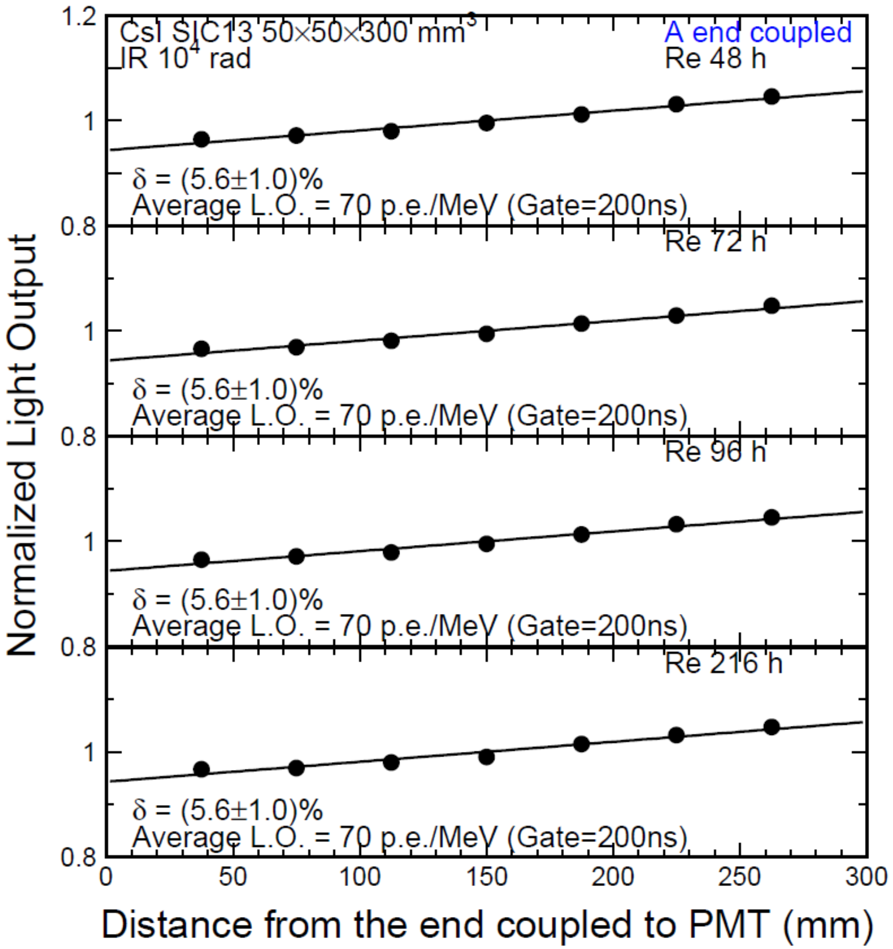
No Recovery in CsI Radiation Damage

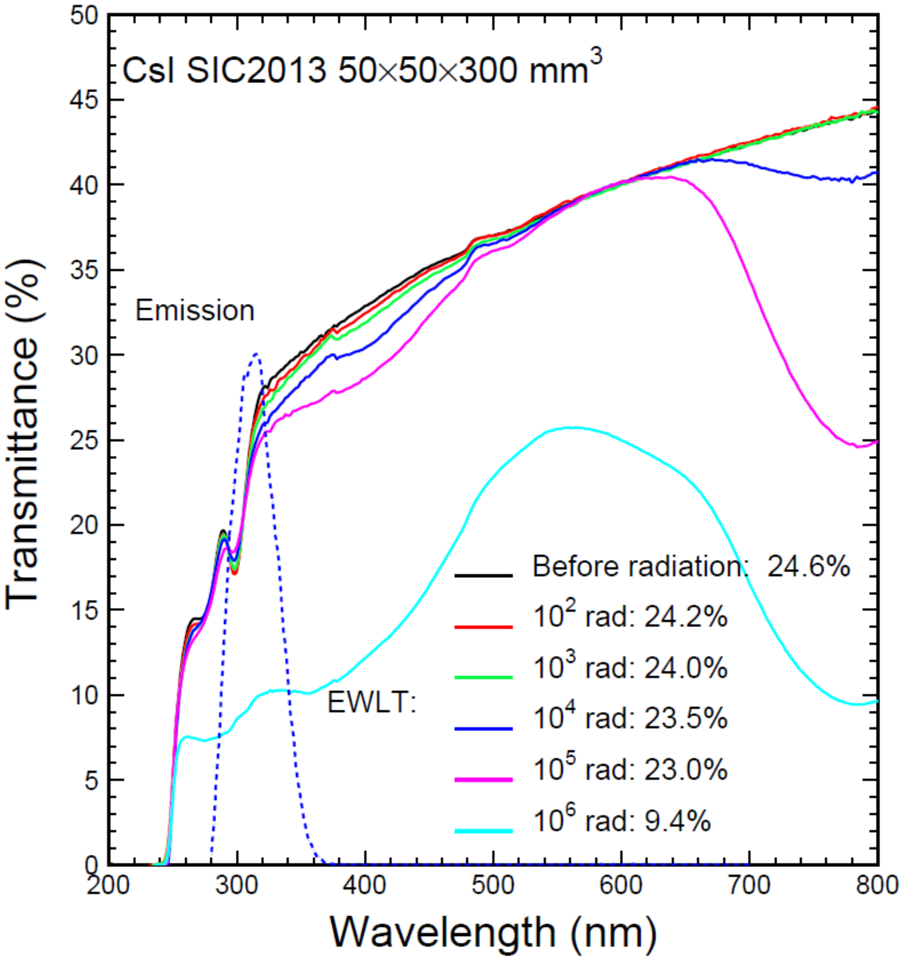
Damage does not recover, so is dose rate independent

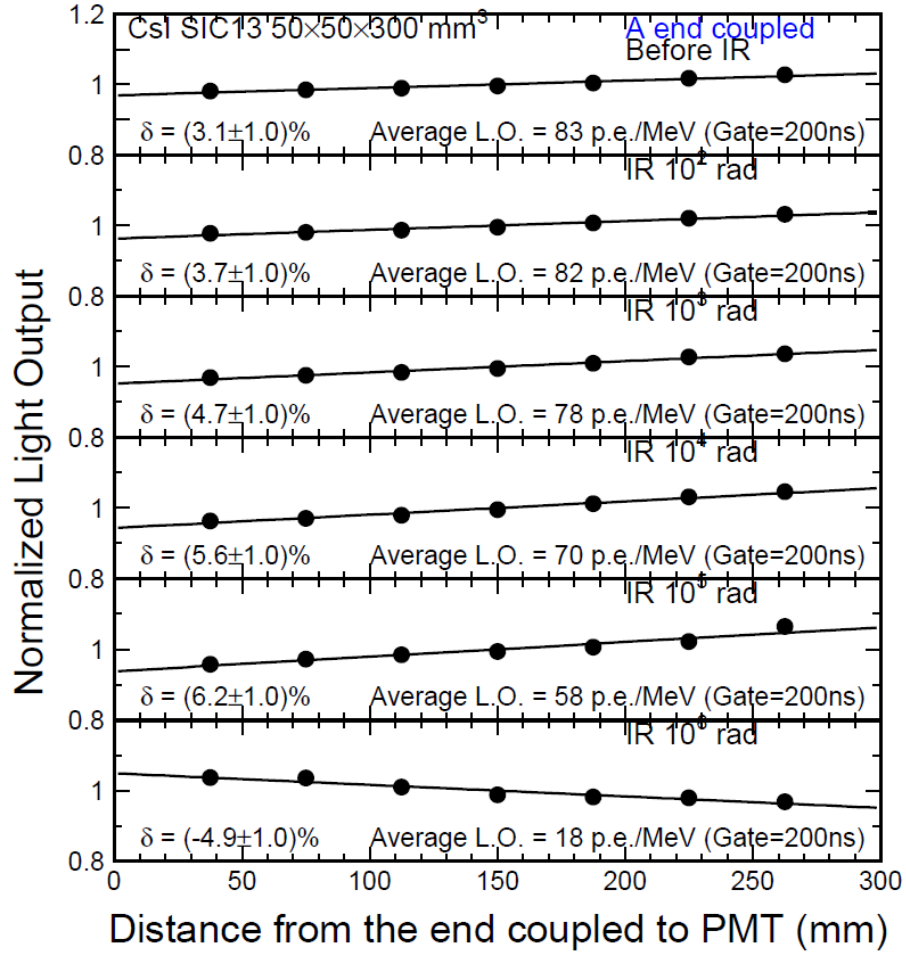




Radiation Damage: SIC2013

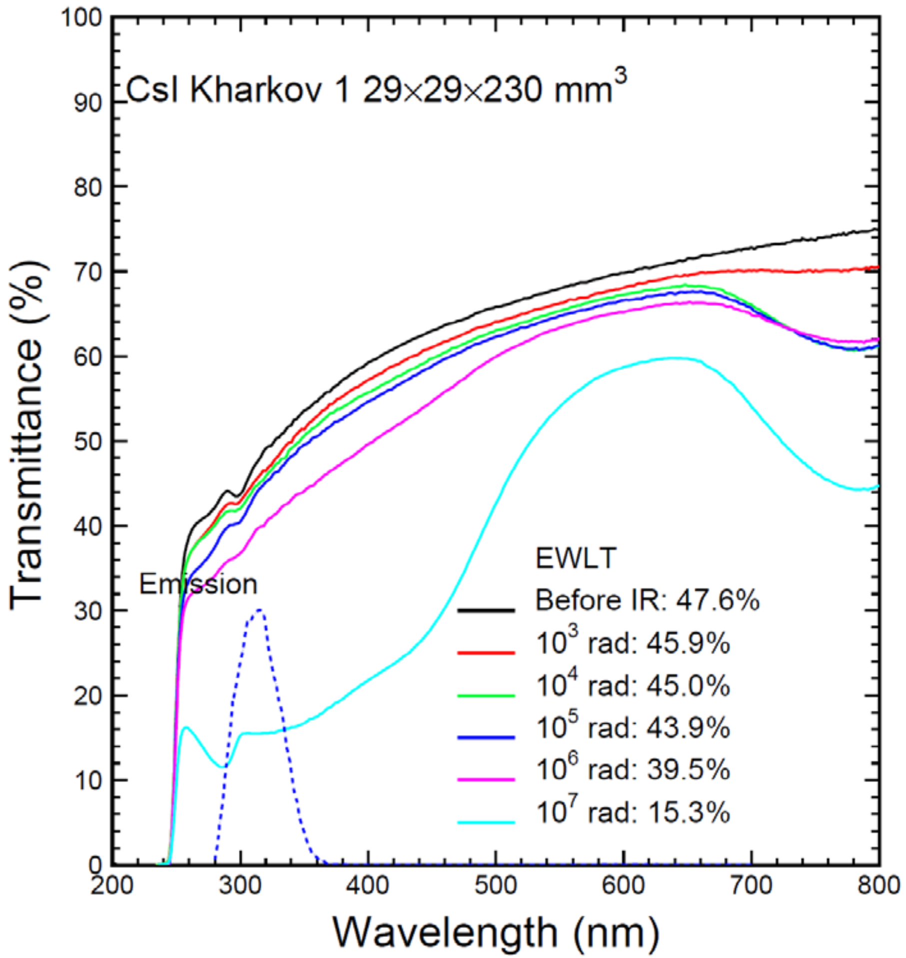
No significant degradation in LO and LRU up to 10 krad

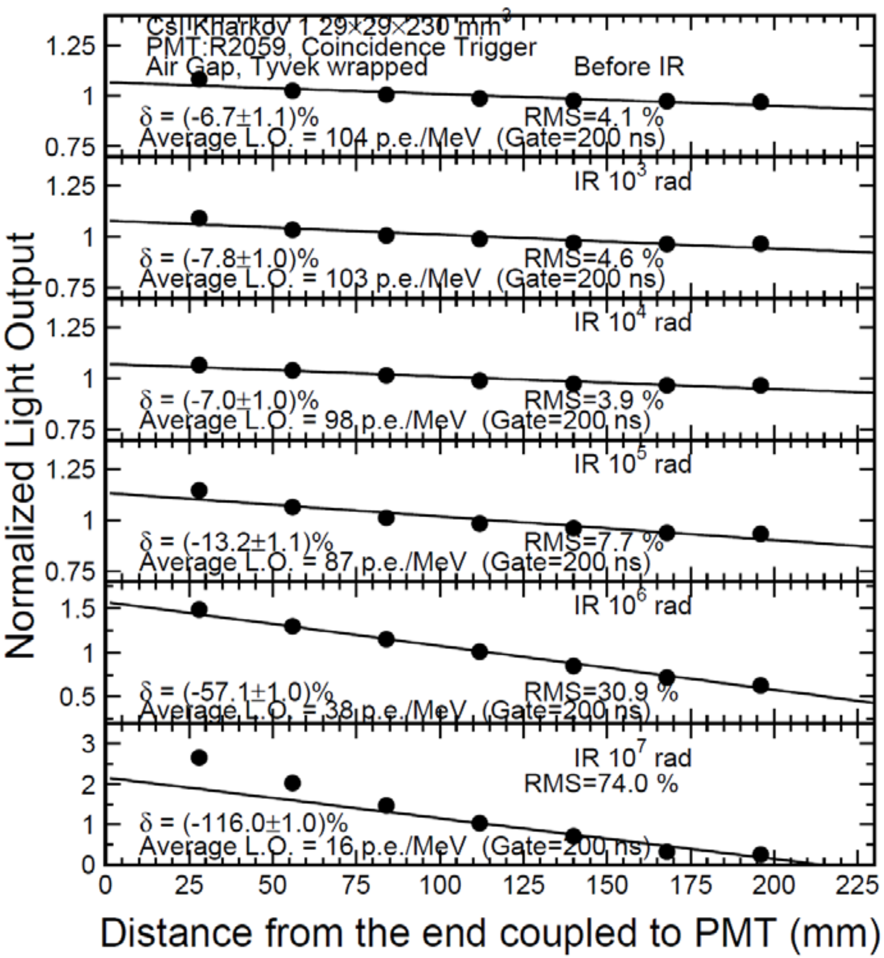




Radiation Damage: Kharkov 1

No significant degradation in LO and LRU up to 10 krad





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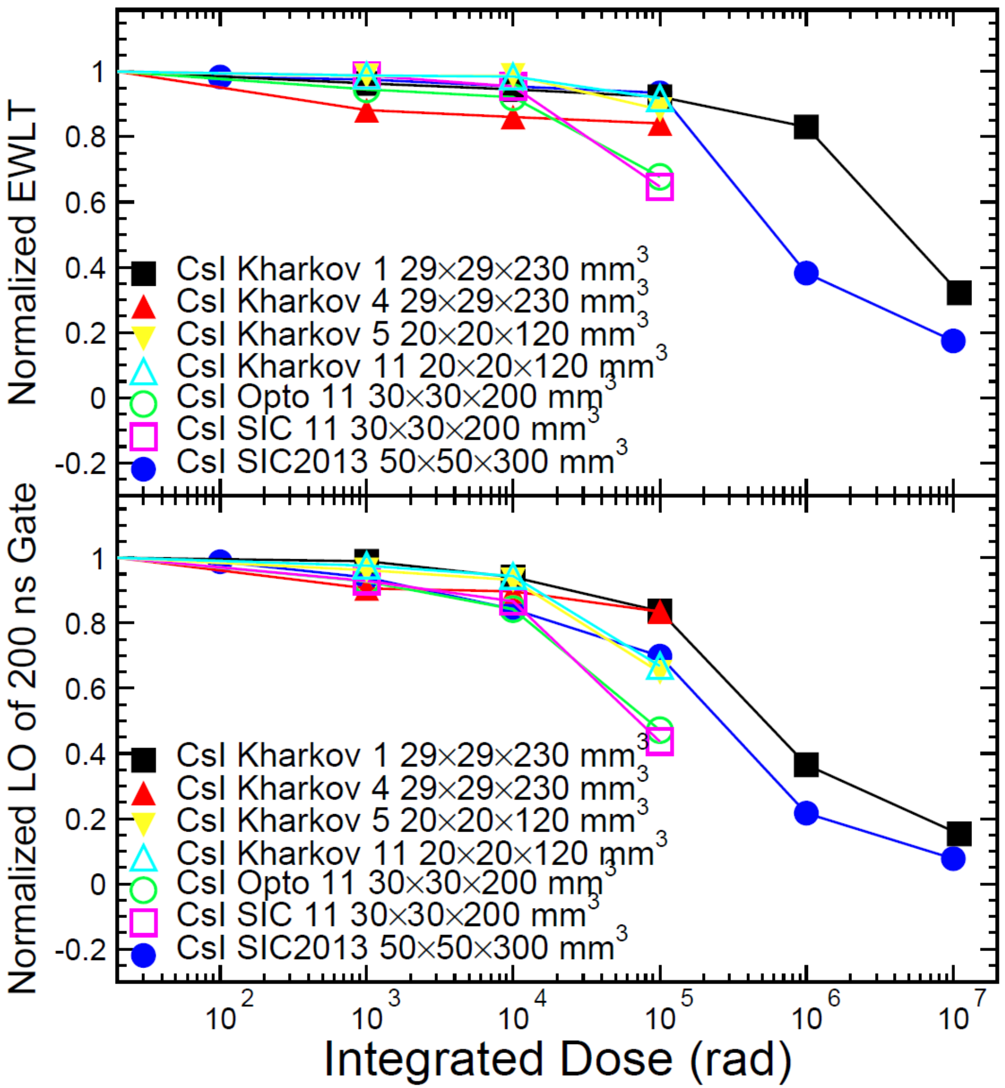
Normalized EWLT & LO



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

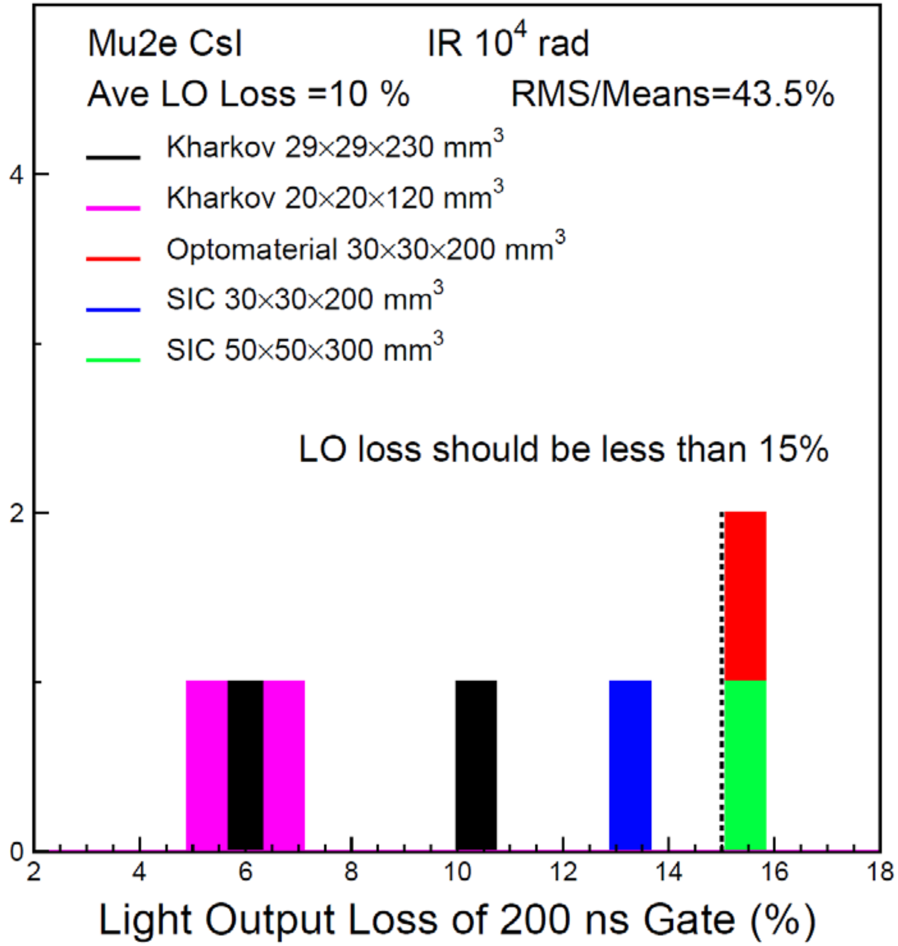
Cost of damage investigation is high because of no recovery/annealing

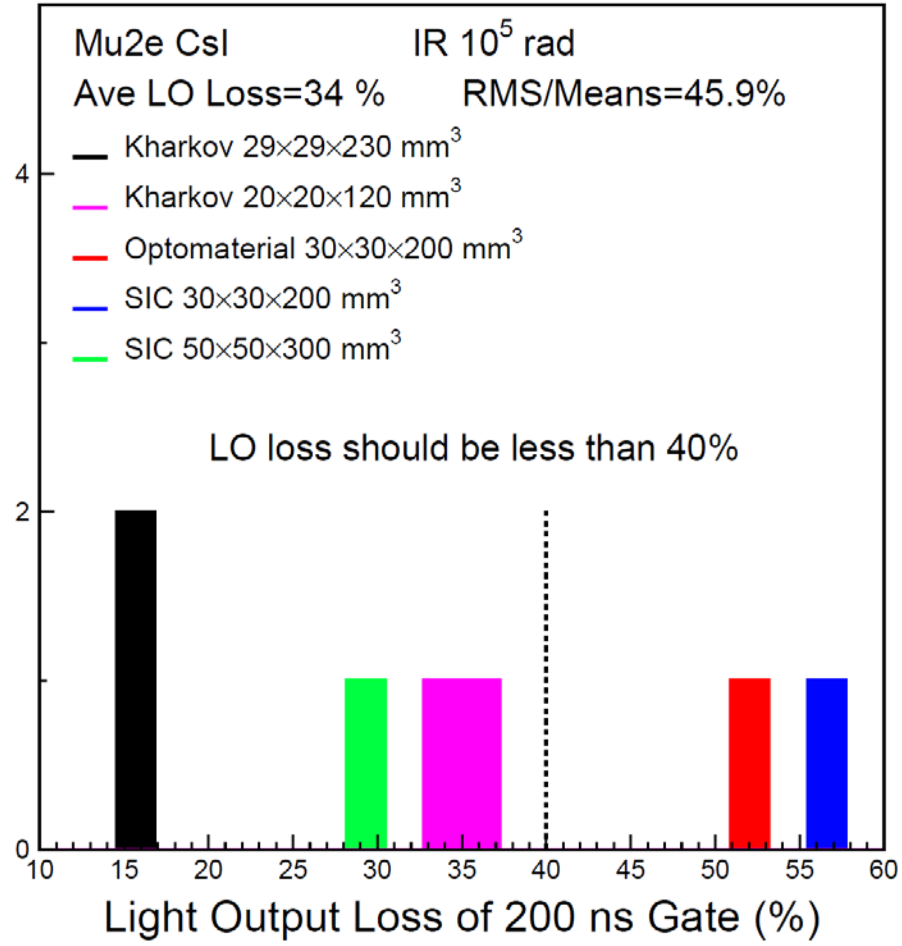
Summary: Radiation Hardness Data

ID	Dimension (mm^3)	Initial LO (p.e./MeV)	Light Output Loss (%)					
			10^2 rad	10^3 rad	10^4 rad	10^5 rad	10^6 rad	10^7 rad
Kharkov 1	29x29x230	104	-	1.0	5.8	16	63	85
Kharkov 4	29x29x230	97	-	9.3	10	16	-	-
Kharkov 5	20x20x120	134	-	3.7	6.7	35	-	-
Kharkov 11	20x20x120	127	-	2.4	5.5	33	-	-
Optomaterial 11	30x30x200	140	-	7.1	16	53	-	-
SIC11	30x30x200	128	-	7.0	13	56	-	-
SIC2013	50x50x300	83	1.2	6.0	16	30	78	92

Radiation Hardness Spec

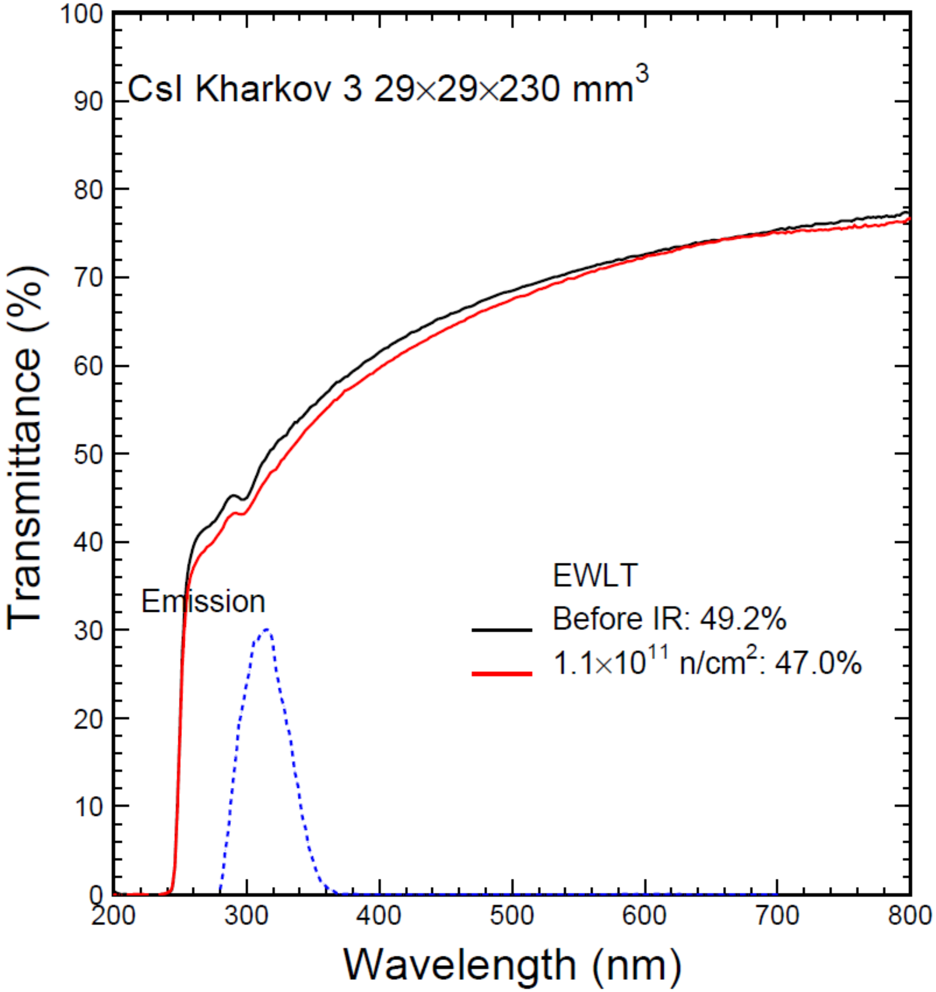
Radiation resistance of mass produced CsI may be improved

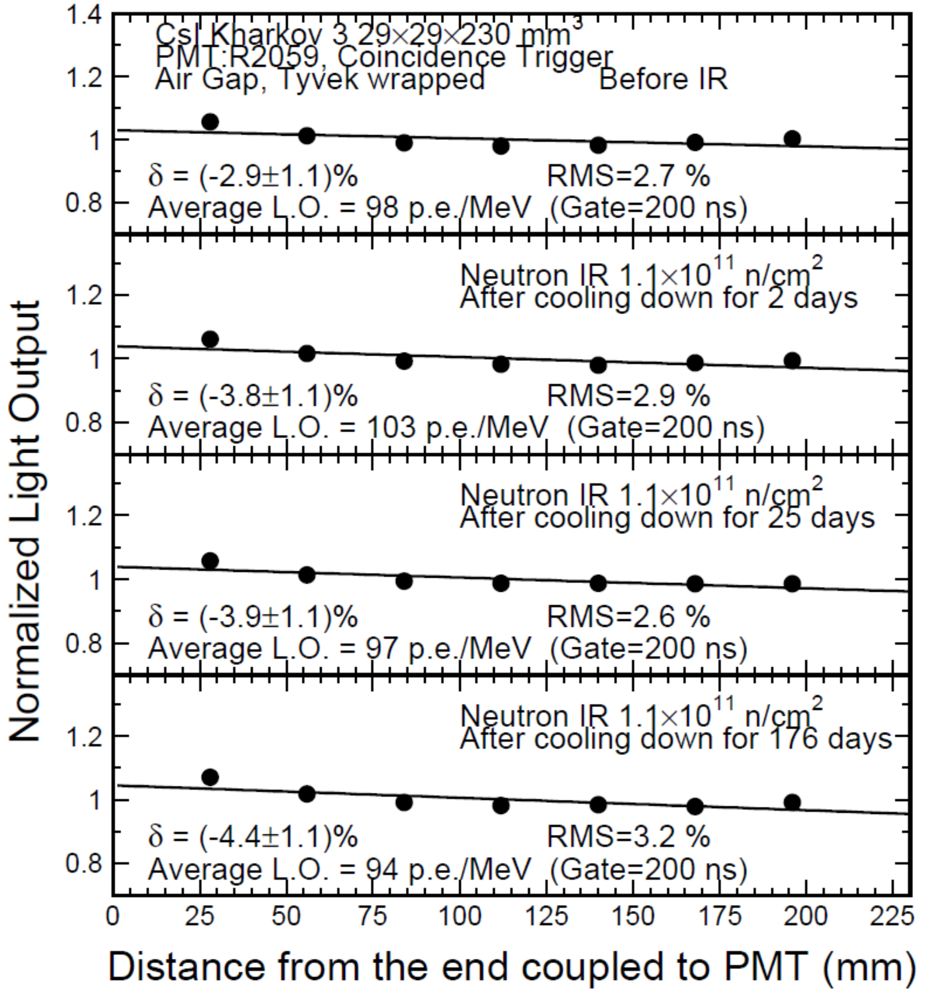




Neutrons Induced Damage

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

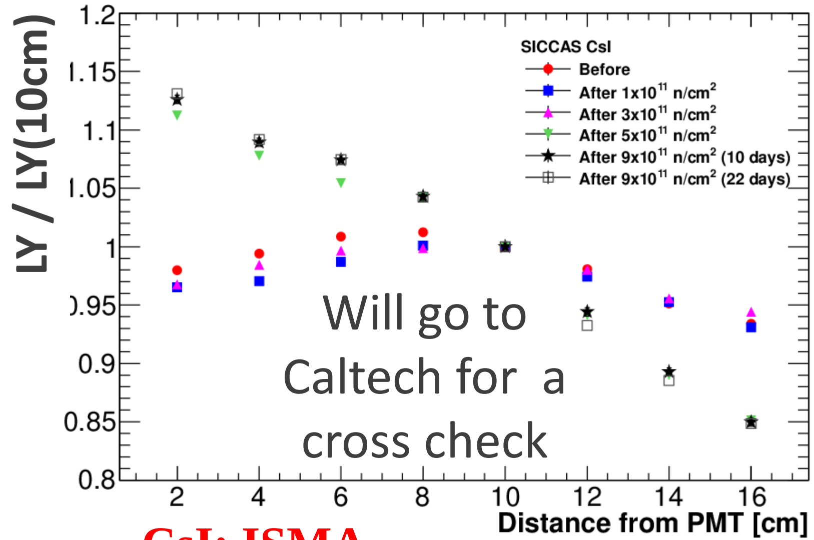




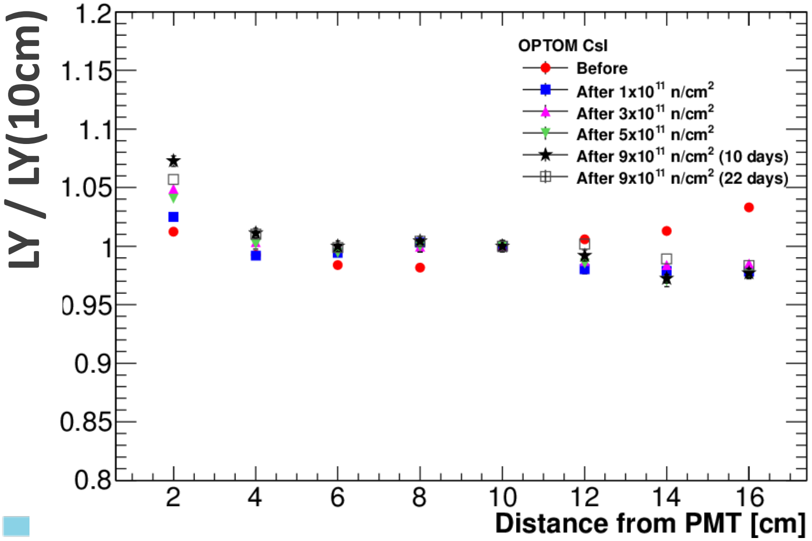
Neutron Irradiation at FNG

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

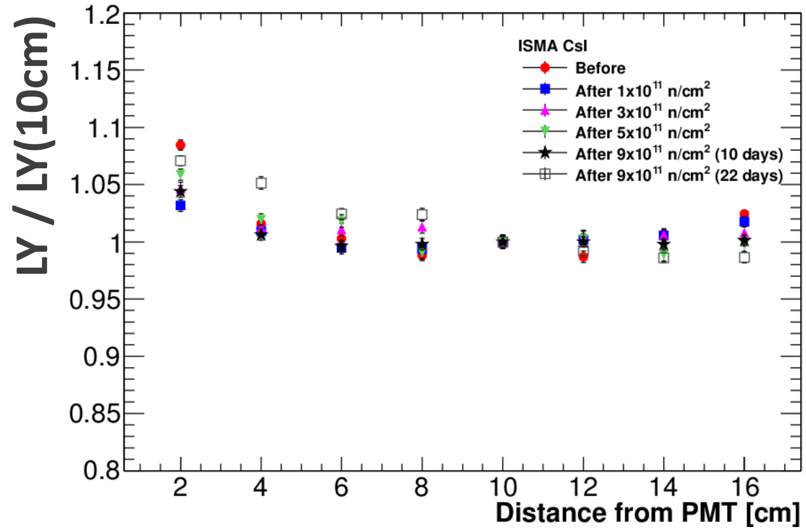
CsI: SICCAS



CsI: OPTO MATERIALS



CsI: ISMA



Radiation Induced Readout Noise

Assuming 230 days' run (2×10^7 sec) each year, the hottest crystals would have the following radiation environment:

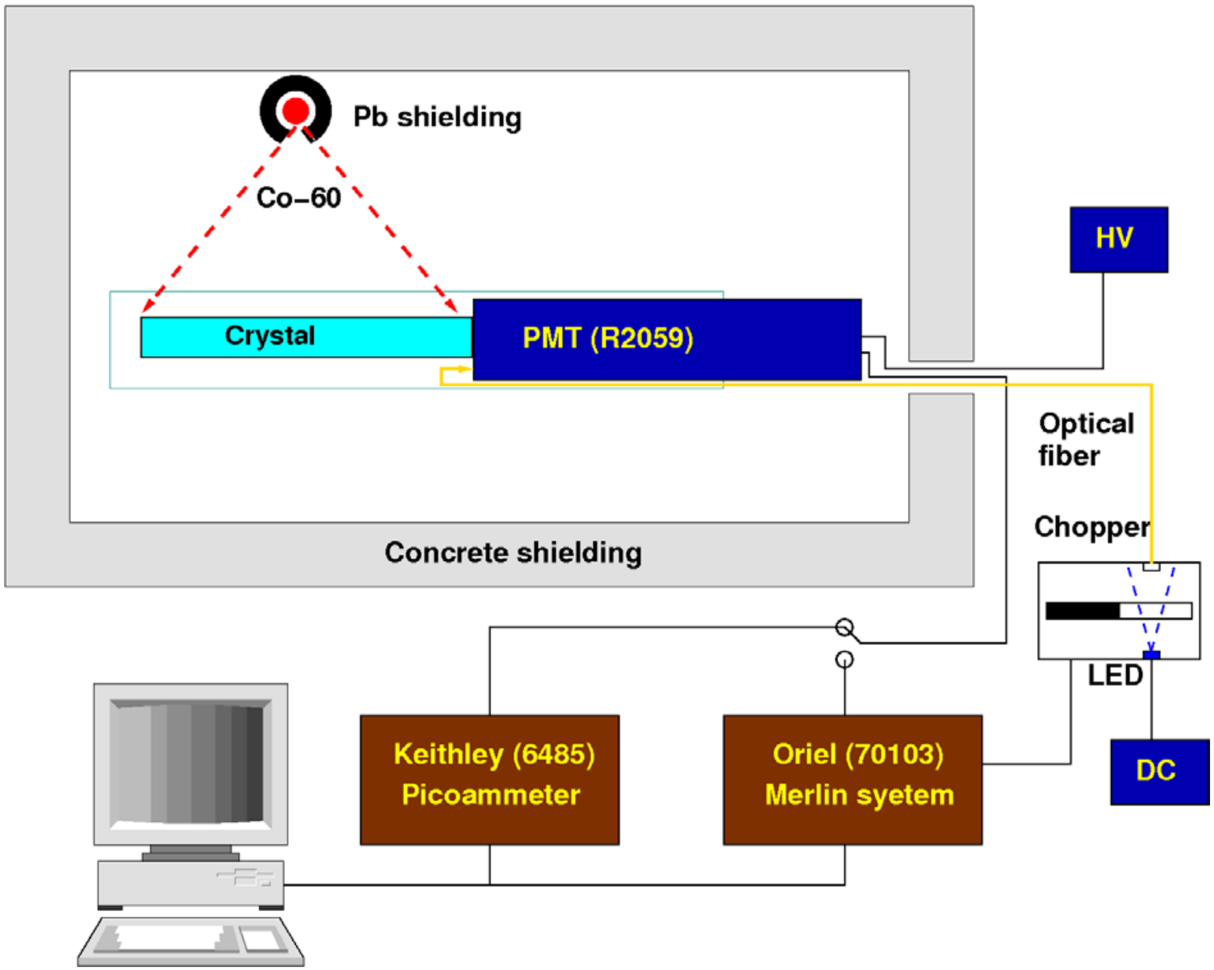
- Ionization dose: 10 krad/year ➡ 1.8 rad/h,
- Neutron fluence: 2×10^{11} n/cm^2/year ➡ 1.0×10^4 n/cm^2/s.

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

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

Gamma Induced Photo-Current

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



Radiation Induced Photoelectron Coefficient

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

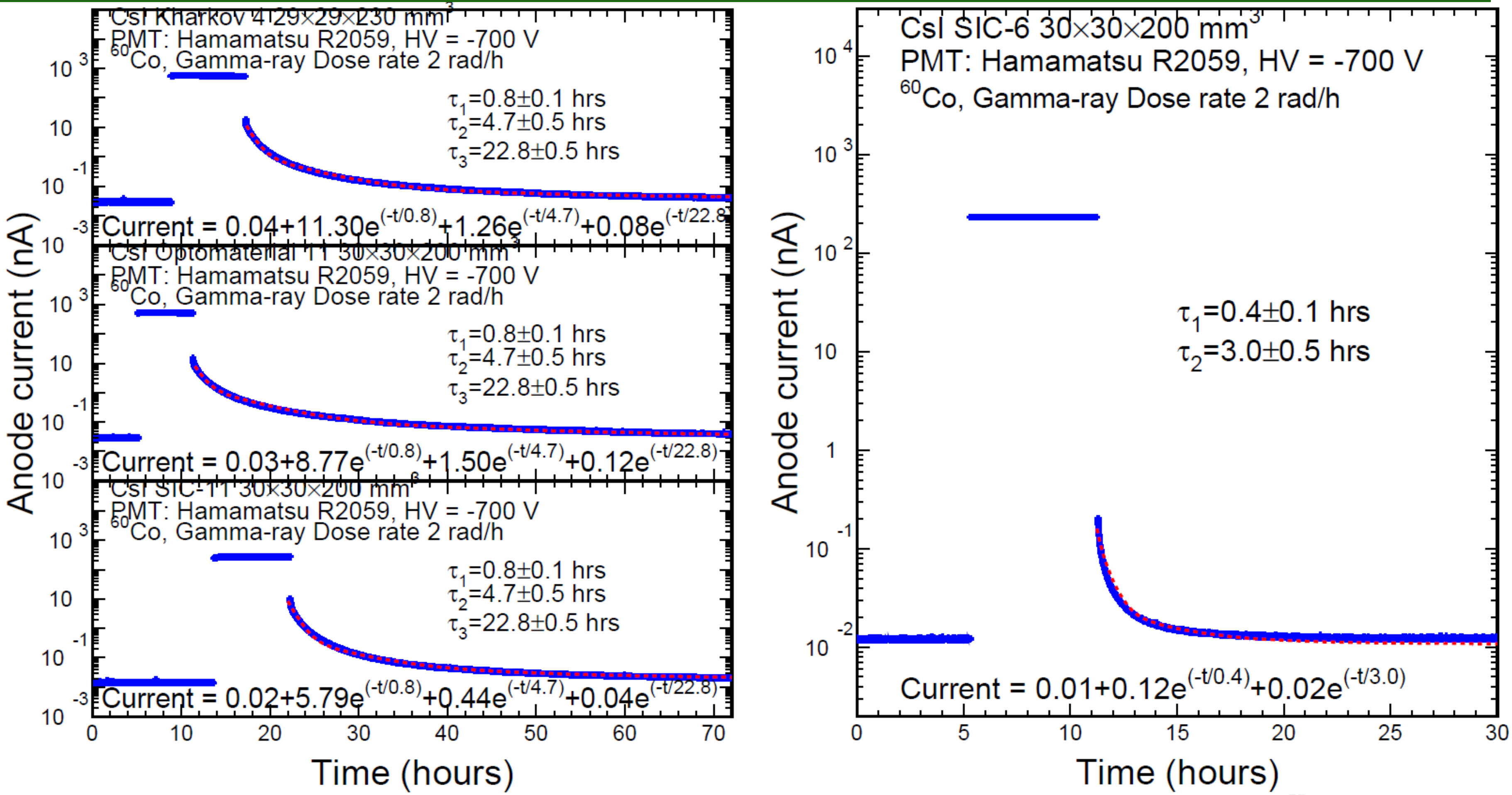
$$F = \frac{\frac{Photocurrent}{Charge_{electron} \times Gain_{PMT}}}{Dose\ rate_{\gamma-ray}\ or\ Flux_{neutron}}$$

Seven CsI Samples Measured

ID	Dimension (mm³)	Polishing
Kharkov 3	29x29x230	All faces
Kharkov 4	29x29x230	All faces
Opto-material 11	30x30x200	All faces
SIC 6	30x30x200	All faces
SIC 11	30x30x200	All faces
SIC 13	30x30x200	All faces
SIC 2014	25x25x200	All faces

Kharkov 4 , Opto 11 , SIC 6 & 11 under γ-rays

Dark current, RIC @ 2 rad/h and its decay were measured
Consist decay time constants observed for samples from 3 vendors



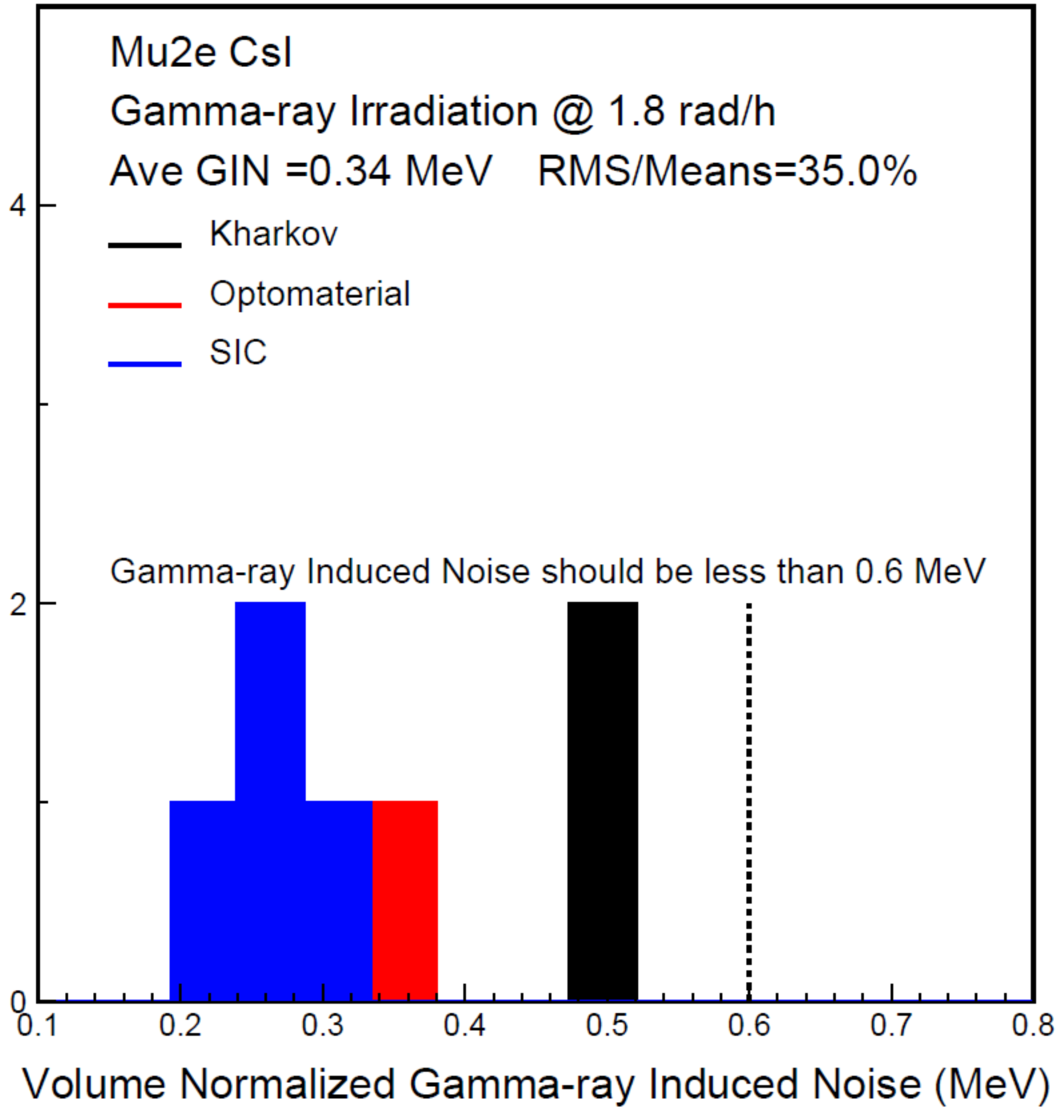
Summary: Gamma-Ray Induced Noise Spec

Measured with a R2059 PMT @ -700 V (gain 317) for CsI samples under 2 rad/h with Tyvek wrapping and air gap coupling. Noise estimated for the Mu2e conditions: 200 ns gate and 1.8 rad/h.

Sample	Dimensions (cm^3)	Volume (cm^3)	LO of 200 ns Gate (p.e./MeV)	Dark Current* (nA)	Photo current* @ 2 rad/h (nA)	F* (p.e./s/rad/hr)	σ* (MeV)	Comments
Kharkov 3	2.9x2.9x23	193	93	0.20	587	5.78E+09	4.90E-01	After 1E11 n/cm^2
Kharkov 4	2.9x2.9x23	193	96	0.035	679	6.68E+09	5.11E-01	
Opto-material 11	3x3x20	180	140	0.039	663	6.53E+09	3.46E-01	
SIC 6	3x3x20	180	125	0.015	296	2.91E+09	2.59E-01	
SIC 11	3x3x20	180	128	0.018	330	3.25E+09	2.67E-01	
SIC 13	3x3x20	180	130	0.026	461	4.54E+09	3.11E-01	
SIC 2014	2.5x2.5x20	125	140	0.013	200	1.97E+09	1.90E-01	

* Data normalized to the Mu2e crystal volume of 3.4×3.4×20 cm^3

Radiation Induced Readout Noise: Spec

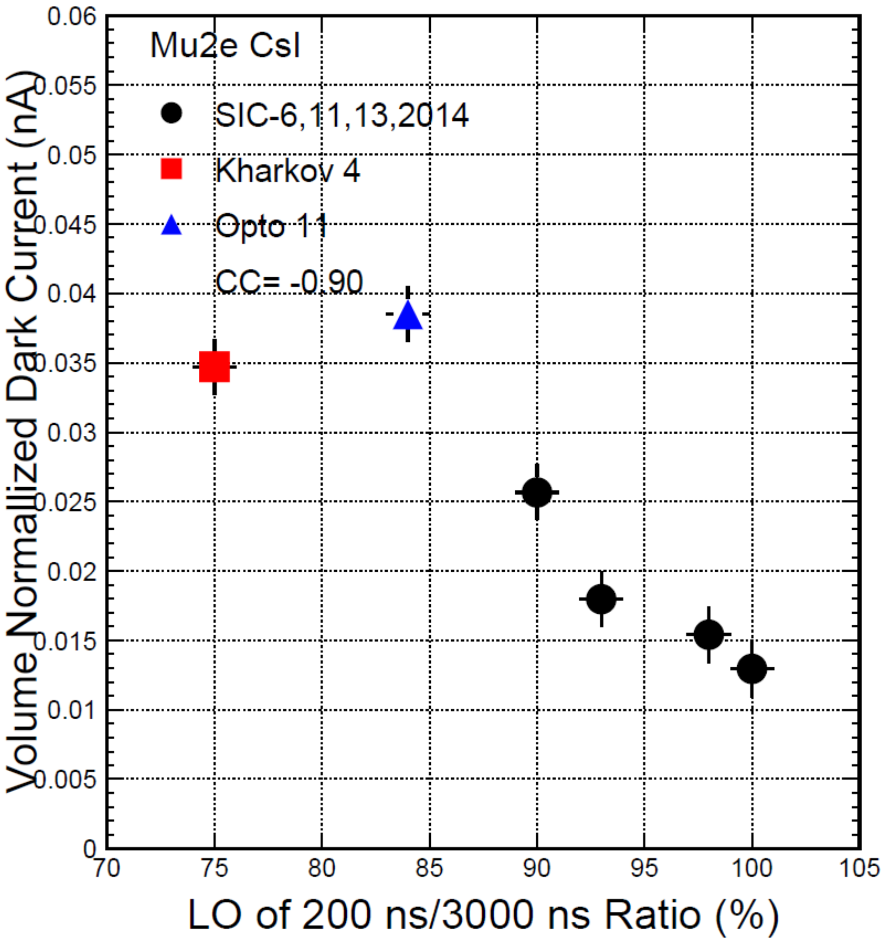


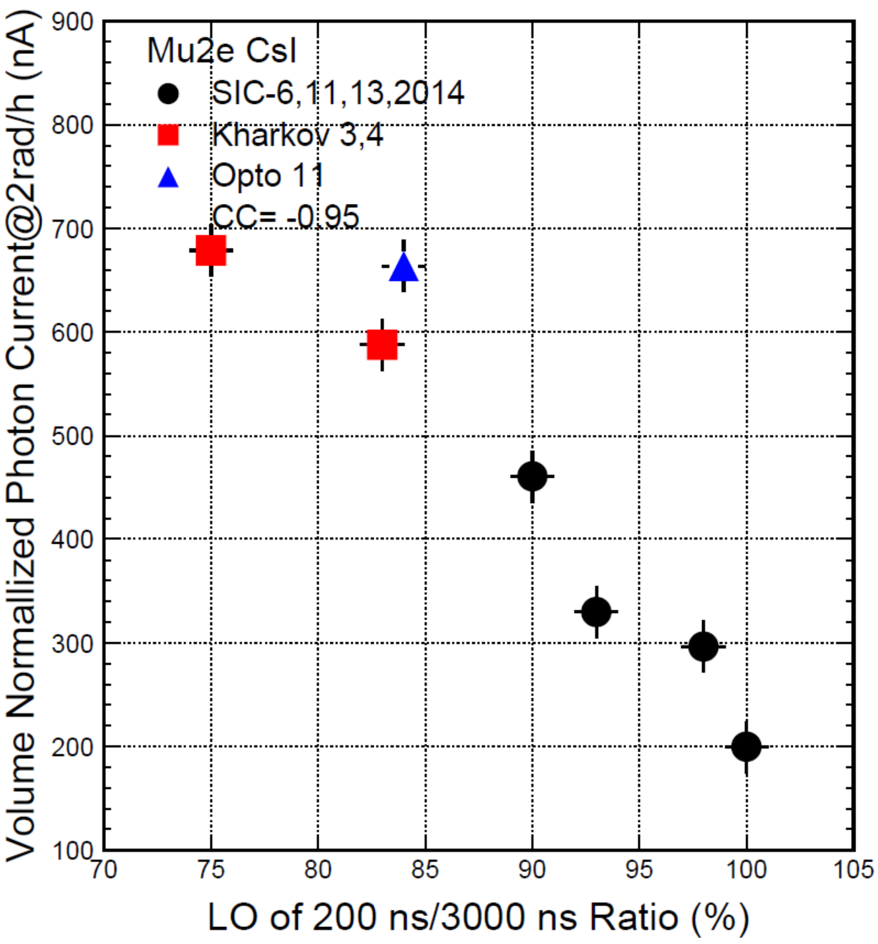
All samples satisfy Mu2e requirement of 0.6 MeV.

Since 1.8 rad/h is the highest dose rate expected by the Mu2e crystals, gamma-ray induced noise is not an issue for the Mu2e CsI calorimeter.

Correlations: F/T vs. Dark Current & RIC

Good correlations indicate the same origin: impurities/defects

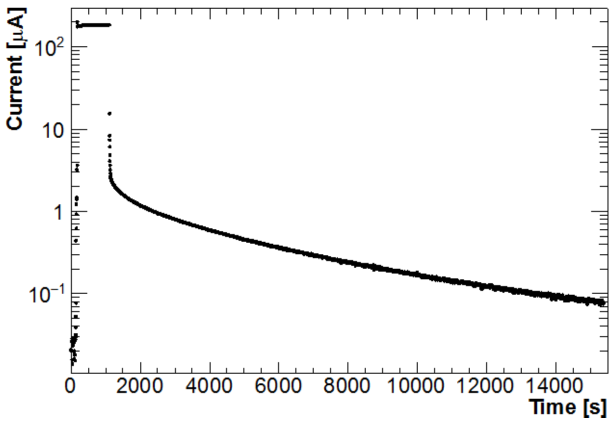




Ionization Dose Induced Noise @ LNF

Determination of RIN done also @LNF on six CsI crystals using a strong Cs^{137} source on a moveable motor (0.2 rad/h)

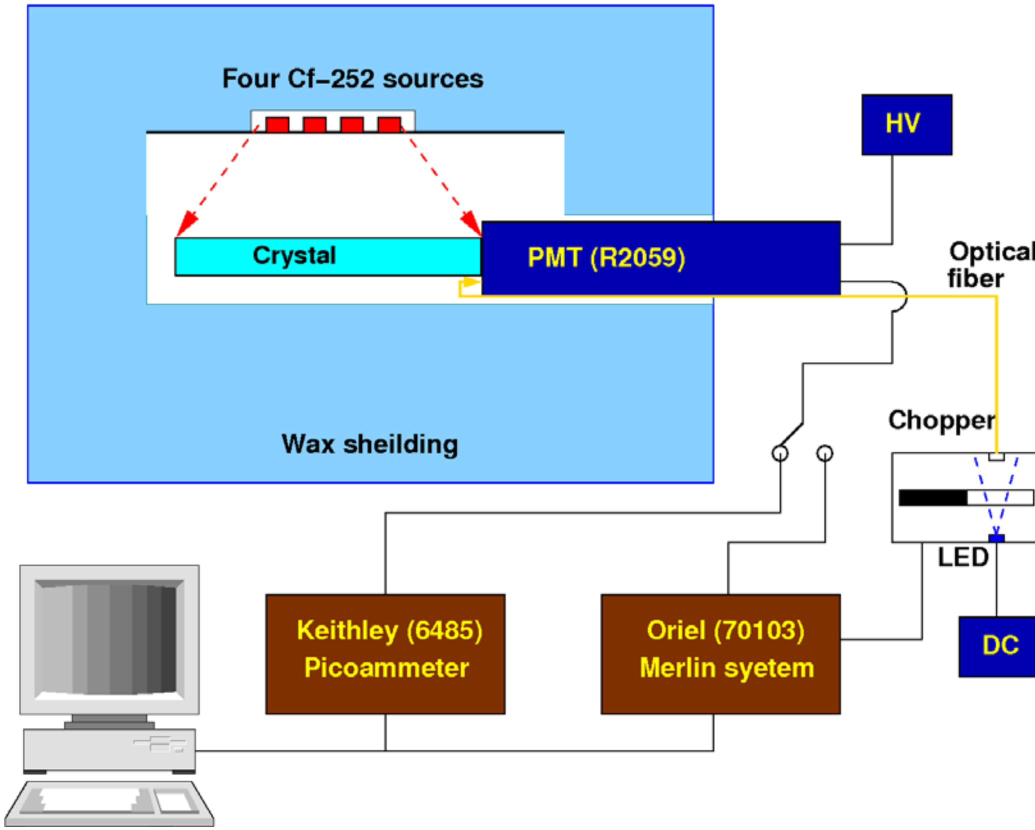
- PMT at HV=1400 V, G=2.1 x 10^6
- I_dark = few nA, I_source > 100 muA
- RIN @ 1.8 rad/h, with a gate of 200 ns
- → SQRT(Nnoise)/(Npe @ MeV)

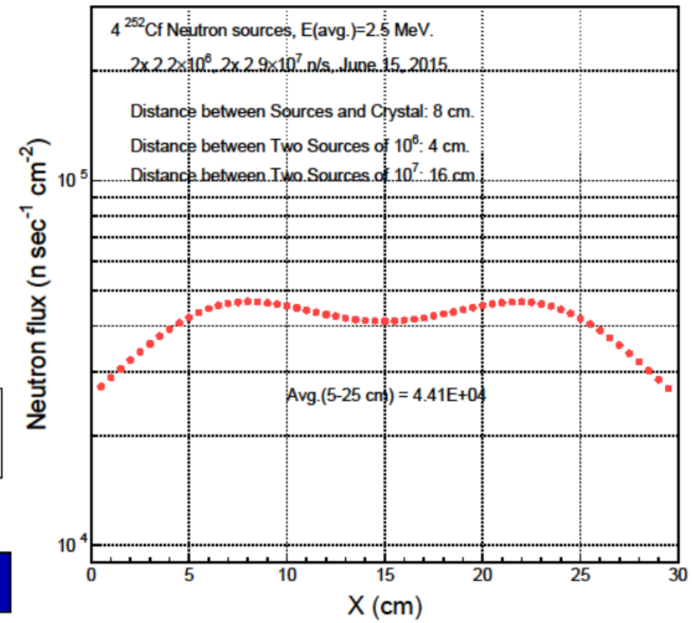


Crystal	LY (N_{pe}/MeV)	I (μA)	Mu2e flux (rad/h)	F (N_{pe}/s/dose)	N_{pe} noise (200 ns)	RIN (keV)
ISMA 1	103	157	1.8	2.31×10^9	845	283
ISMA 2	103	215	1.8	3.17×10^9	1160	331
SICCAS 1	129	188	1.8	2.77×10^9	1010	226
SICCAS 2	126	160	1.8	2.36×10^9	861	233
SICCAS 4	136	157	1.8	2.31×10^9	845	213
OPTOM 2	93	187	1.8	2.76×10^9	1010	341

Neutron Induced Photo-Current

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



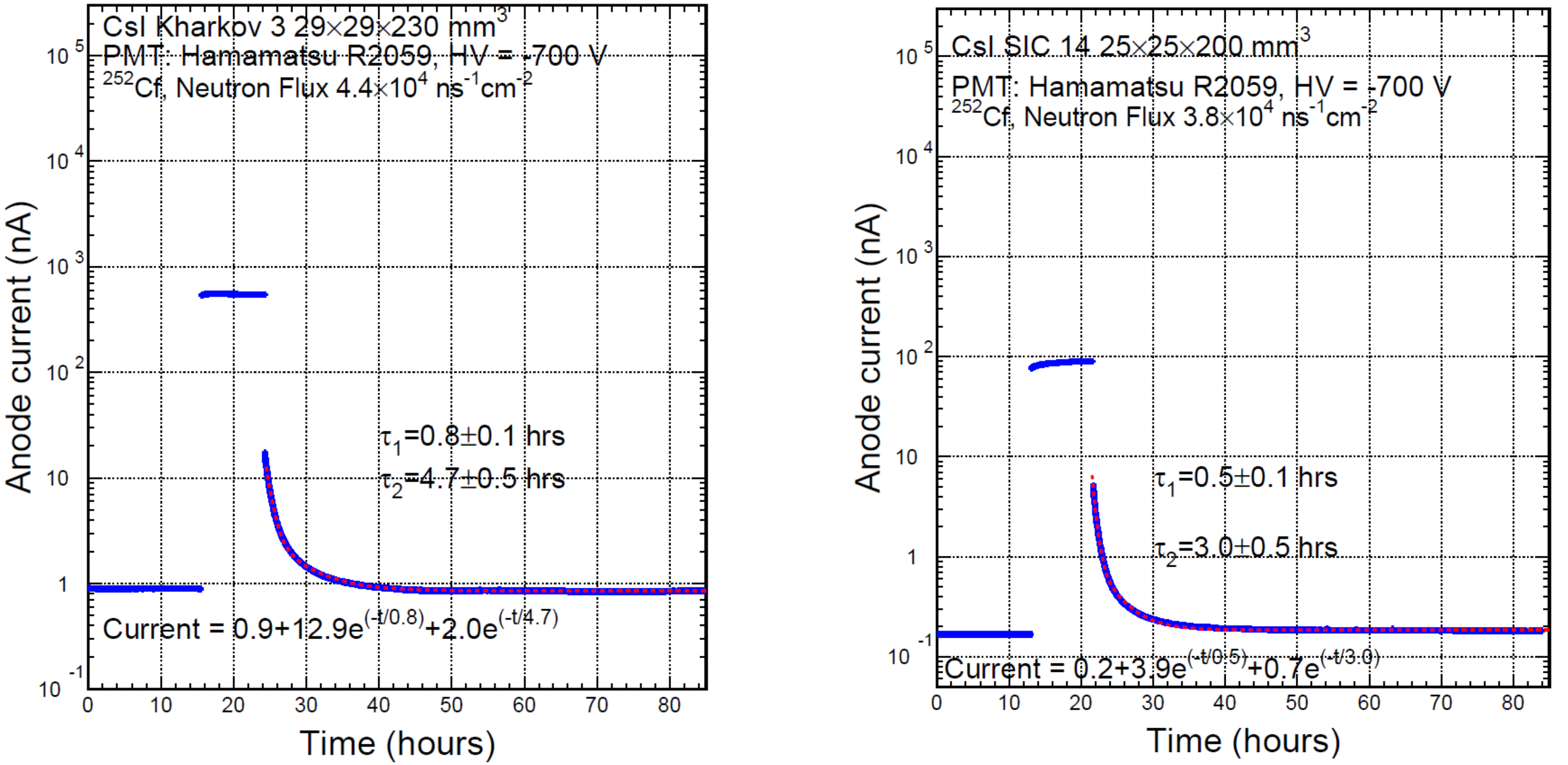


Cf-252 has ɣ-ray background, so result is a upper limit

Neutron Induced Photo-Current

4.4E4 n/cm²/s on sample

3.8E4 n/cm²/s on sample



Neutron induced photo-current is much less than that from gamma-rays

Fast Neutron Induced Noise

Measured with a R2059 PMT @ -700 V (gain 317) for CsI samples with Tyvek wrapping and air gap coupling. Noise estimated for Mu2e: 200 ns gate and 1 x 10^4 n/cm^2/s

Sample	Dimensions (cm^3)	Volume (cm^3)	LO of 200 ns Gate (p.e./MeV)	Dark Current* (nA)	Photo Current* (nA)	F* (p.e./n/cm^2)	σ* (MeV)	Comments
Kharkov 3	2.9x2.9x23	193	93	1.1	650	2.76E+05	2.5E-01	After 1E11 n/cm^2
SIC 2014	2.5x2.5x20	125	140	0.31	165	8.68E+04	9.4E-02	

* Data normalized to the crystal volume of 2.9 × 2.9 × 23 cm^3

Neutron induced noise is negligible as compared to ionization dose

Thermal Neutron Induced Noise @ LNF

Neutrons from the HOTNES facility at ENEA Frascati

Crystal	LY (N_{pe}/MeV)	I (μA)	Mu2e flux (n/cm²/s)	F (N_{pe}/s/dose)	N_{pe} noise (200 ns)	RIN (keV)
ISMA 02	103	7,16	1×10^4	$3{,}02 \times 10^4$	60,3	75,4
ISMA 12	103	4,61	1×10^4	$1{,}94 \times 10^4$	38,9	60,5
ISMA 20	103	5,35	1×10^4	$2{,}25 \times 10^4$	45,1	65,2
ISMA 21	103	7,28	1×10^4	$3{,}07 \times 10^4$	61,4	76,0
SICCAS 1	129	6,83	1×10^4	$2{,}88 \times 10^4$	57,5	58,6
SICCAS 2	126	7,58	1×10^4	$3{,}19 \times 10^4$	63,8	63,4
SICCAS 4	136	10,1	1×10^4	$4{,}27 \times 10^4$	85,5	67,8
OPTOM 2	93	7,65	1×10^4	$3{,}22 \times 10^4$	64,4	86,3

Thermal neutron induced noise is lower than that from fast neutrons

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Design Maturity

Calorimeter Subsystem	Design Completion	Remaining Work/Risks
Crystals	100%	CsI slow component specified.
Photosensors	85%	SiPM packaging. Have one packaged SiPM from Hamamatsu but want to qualify other vendors
Mechanical Infrastructure	70%	Finalize cooling design. Optimizing tradeoffs between noise, radiation damage and operating temperature. x2 headroom
Front End Electronics And Digitizer (WFD)	70%	• New pre-amp design for CsI/SiPM • WFD board design with 20 channels. Moderate risk that we may have to back off to 18 channel boards. Adds a small amount of complexity.
Calibration	90%	Integration of source pipes. Finalize laser optics.
Overall Design	**83%**	

Clear path to design completion and construction readiness

Quality Control

- Calorimeter Quality plans included in Mu2e Quality Planning Document
  - Available on web page (docdb 6005)

QA or QC Step?	QA or QC Process Documentation (DocDB #)	Inspection or Acceptance Criteria/Plan	Verification
QA: LY and LRU	Docdb 7053	A radioactive source (Na22) is moved along the crystal axis to measure the light Yield (LY) and LRU. We have two similar stations, one in Caltec and one at LNF. Both of them can move the source in a reproducible way by means of a remotely controlled movement system. The source annihilation products (2 gamma rays at 511 keV) are used for calibration. One of the photon is tagged by means of an independent system (small LYSO crystal readout with an MPPC), the other photon is used for testing the crystal. We typically acquire 20000 events/point (40 secs) for 10 to 20 points along the crystal axis. Readout of the crystals is done either with a UV extended PMT or an APD readout with a charge amplifier.	The functionality of the system is provided by the readout o tagging system that should always grant a reproducibility res The measurement should also be done in a stable environme as a clean room or a laboratory with temperature control environment. The analysis is done in an automatic manner. U the QA system will be warned if something goes wrong (low st bad fit, out of range parameters). Histograms and table of res be atomically generated. Quality assurance procedures to ens procured crystal meets requirements are been extensively us our prototyping phase. A comparison between the two static the LY on same crystals have been carried out. We apply a c accepting the crystals that uses theAVERAGE and the RMS of over all scanned points. The RMS provides an indication of uniformity along the crystal axis.
QA: Resolution	DocDb 7053	The same data used for <LY> and LRU will be also used to characterize the energy resolution at 511 keV	As above

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Change Control

Control Account	CR #	CR Description	Prior Start	Revised Start	Prior Finish	Revised Finish	BAC Before	BAC After	Cost Increase / (Decrease)
475.07.01 Total									**227.979,33**
475.07.02	**2**	Establish internal baseline and incorporate recommendations from Director's Review.	**-**	-	**-**	-	2.432.682,20	3.160.011,69	727.329,50
	6	Corrections made to CR002	**-**	-	**-**	-	3.160.011,69	3.115.404,11	(44.607,58)
	3	New rate adjustments for labor fringe and overhead.	**-**	-	**-**	-	3.115.404,11	3.125.023,12	9.619,01
	4	Cost leveling; new CD-3c strategy	**-**	-	**-**	-	3.125.023,12	2.611.714,84	(513.308,28)
	8	FY15 Rate changes	**-**	-	**-**	-	2.611.714,84	2.600.214,96	(11.499,89)
	15	Establish CD-2 Baseline	**25/11/09**	25/11/09	**13/09/19**	04/11/19	2.600.214,96	2.638.987,74	38.772,79
	19	Reduced Constr oversight, FFP ECPs, and TS Module fab delay	**25/11/09**	25/11/09	**04/11/19**	26/11/19	2.638.987,74	2.640.249,05	1.261,31
	24	FY16 Rate Update	**25/11/09**	25/11/09	**26/11/19**	26/11/19	2.640.249,05	2.617.659,86	(22.589,19)
	28	Increase Project Office Support, Constr Rev 13, Racks & Rack Monitor	**25/11/09**	25/11/09	**26/11/19**	12/12/19	2.617.659,86	2.570.614,53	(47.045,33)
	30	New Choice of Calorimeter Crystal--BaF2 to CsI	**25/11/09**	25/11/09	**12/12/19**	23/09/19	2.570.614,53	2.110.276,41	(460.338,13)
475.07.02 Total									**(322.405,79)**

Interfaces

Item	Interface	Description	Owner	Reference Documen ts/ Drawings
107.02.1.1	Crystal/Mechanical structure (Positioning)	The crystals interface tightly with the disk support structure, the front face cover, the FEE rear disk support and the attached photo sensors. Tolerances for the thickness of the wrapping material have to be taken into consideration during assembly and studied on a dedicated full size mechanical mock-up prior to actual assembly.	475.07.02 475.07.03 475.07.04	

Interfaces are documented and actively managed

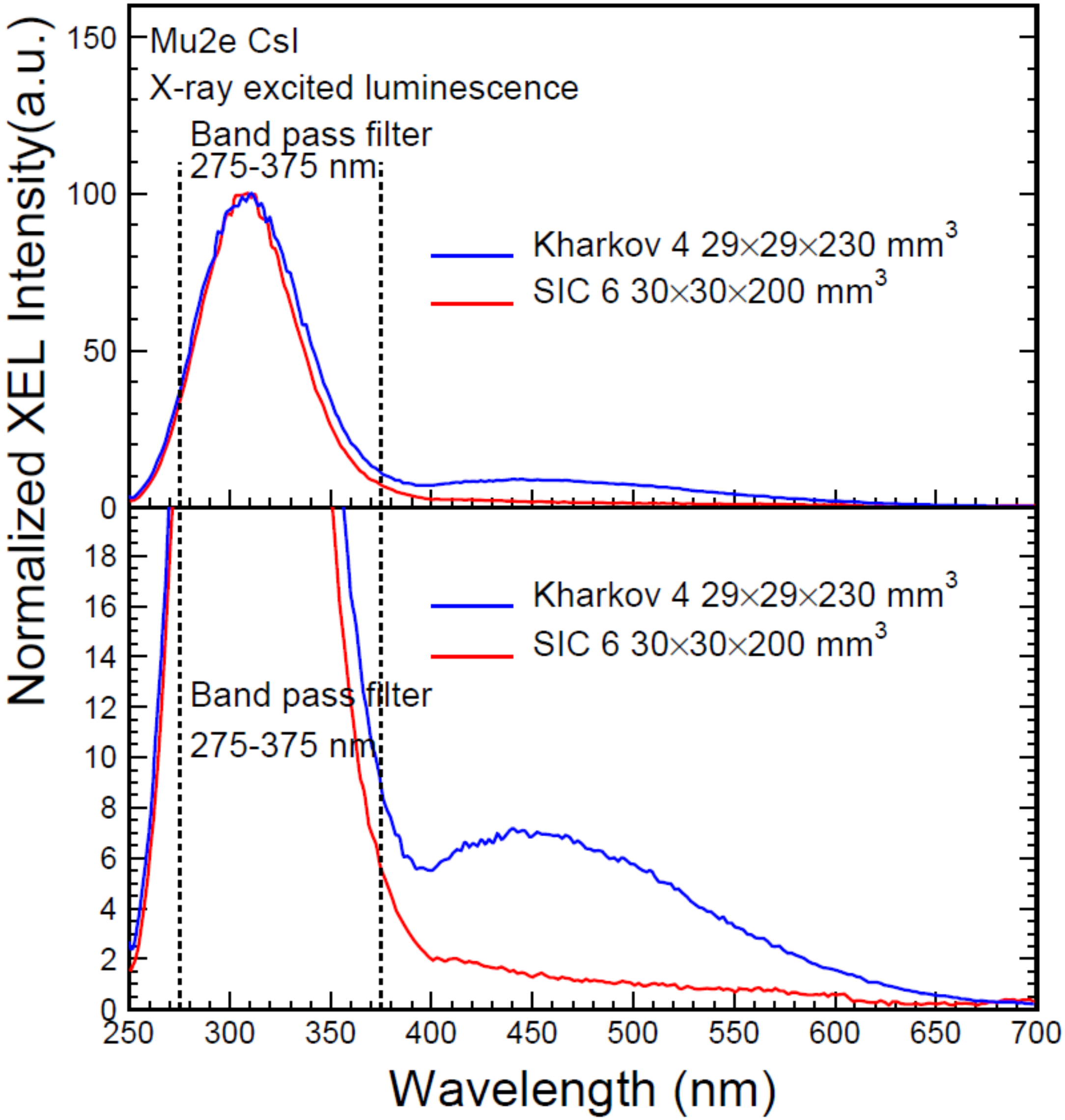
Environment, Safety & Health

- Follow established safety procedures at Fermilab as specified by FESHM
- Hazards discussed in the Mu2e Hazard Analysis document (DocDB 675)
- Selected crystals do not show handling hazards.

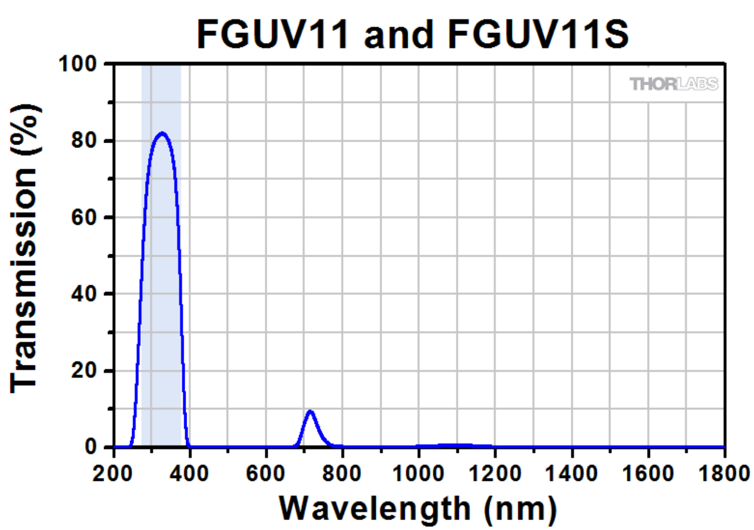
Summary

- The calorimeter crystal design is 100% complete. Risks are tracked and actively managed. Clear path to design completion and construction readiness.
  - 25 un-doped CsI crystals from 3 different producers have been tested with sizes very close to the final one;
  - Specifications for the Crystals have been decided based on these samples. Fast/Total component specification decided by TOY MC study
  - Radiation hardness tests have been performed
  - Interfaces, risks, ES&H issues identified and under control
  - QA/QC plans in place
- Current design **meets** Calorimeter detector requirements.
- The Calorimeter Crystals are ready for CD-3 approval

Slow Component Peaked at 450 nm

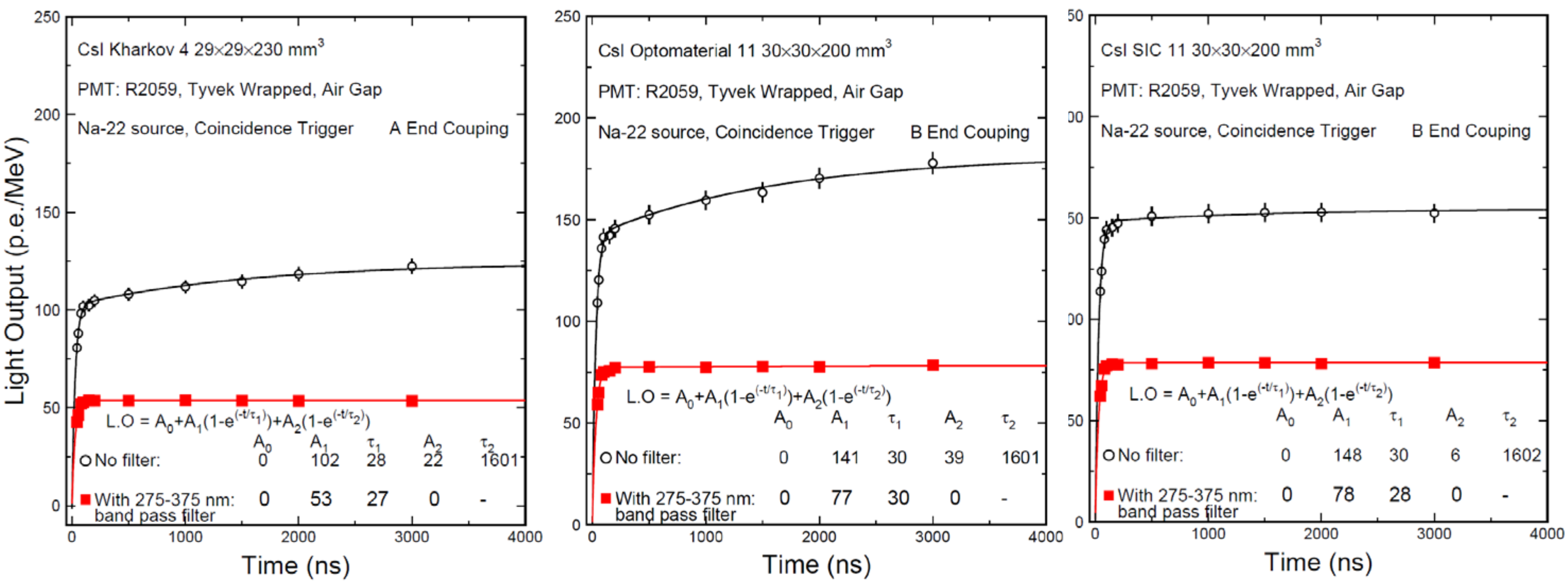


Using a commercially available band pass filter FGUV11 (275 – 375 nm) to suppress slow component



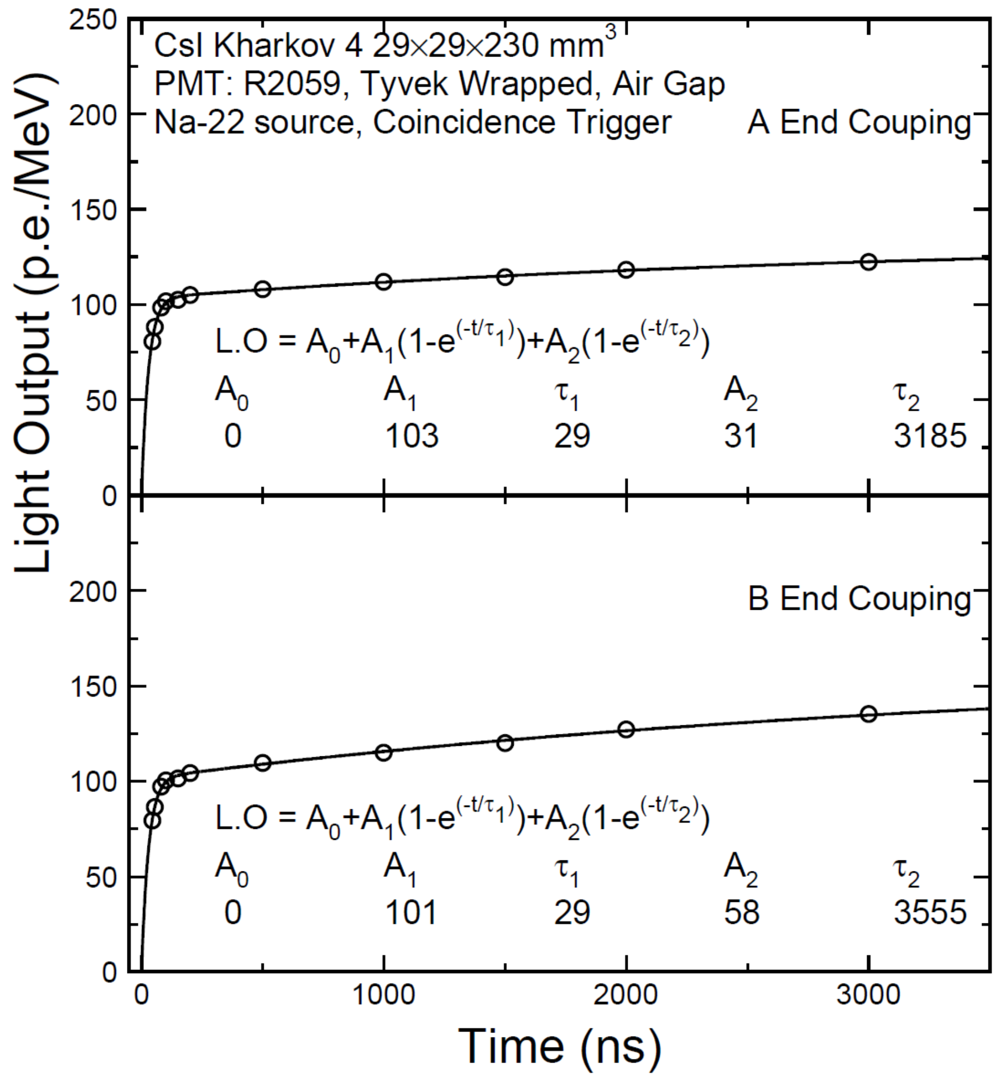
FGUV11 Removes Slow Component

A FGUV11 filter removes slow component spectroscopically and reduces the fast component by a factor of two



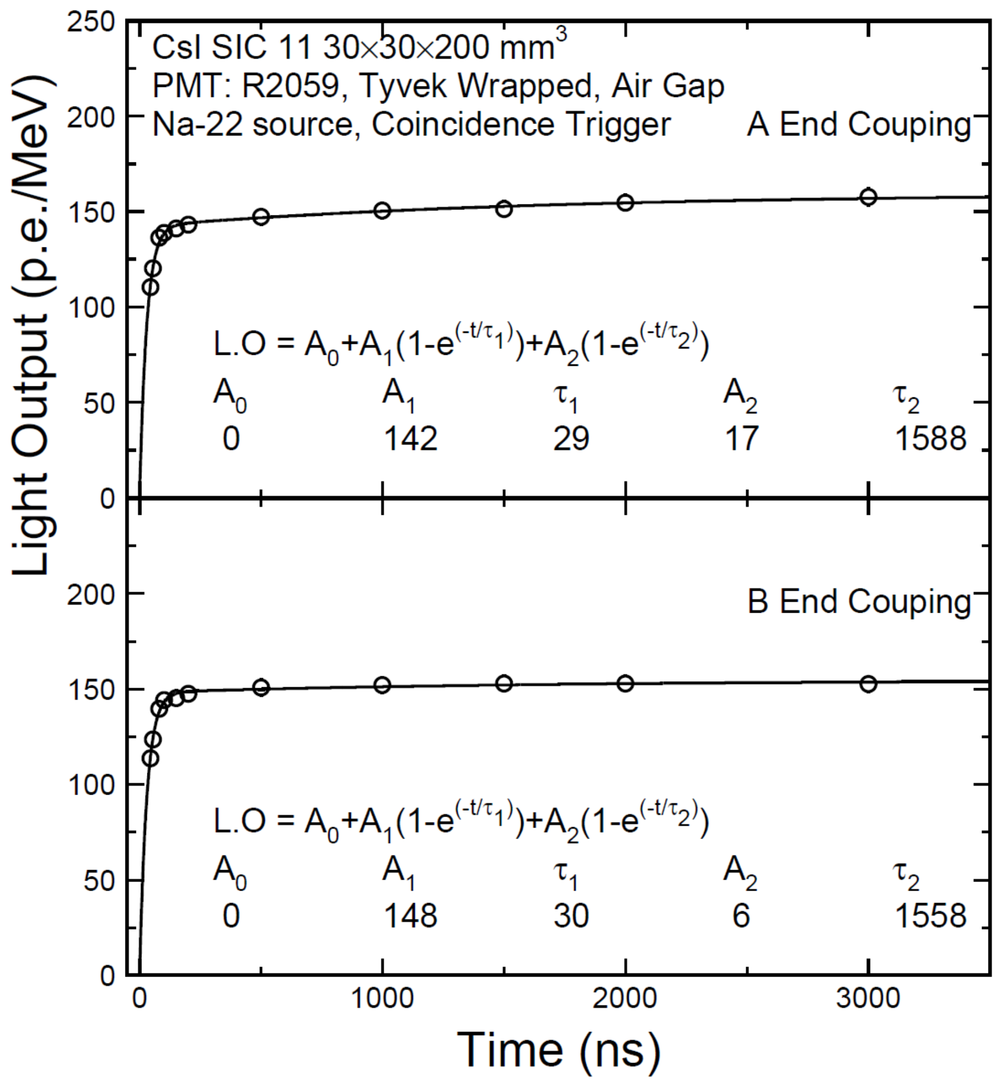
LO & Decay Kinetics: Kharkov 4

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



LO & Decay Kinetics: SIC 11

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



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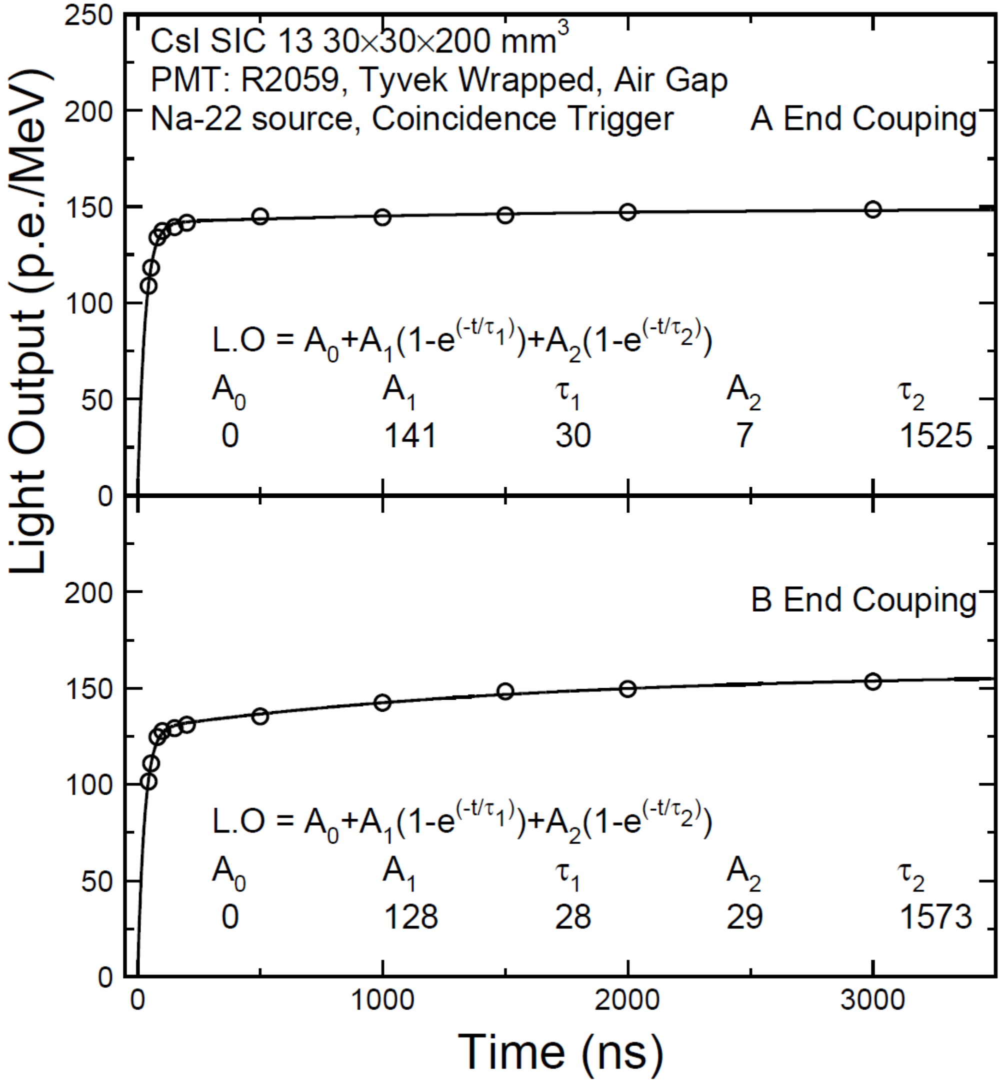
LO & Decay Kinetics: SIC 13

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



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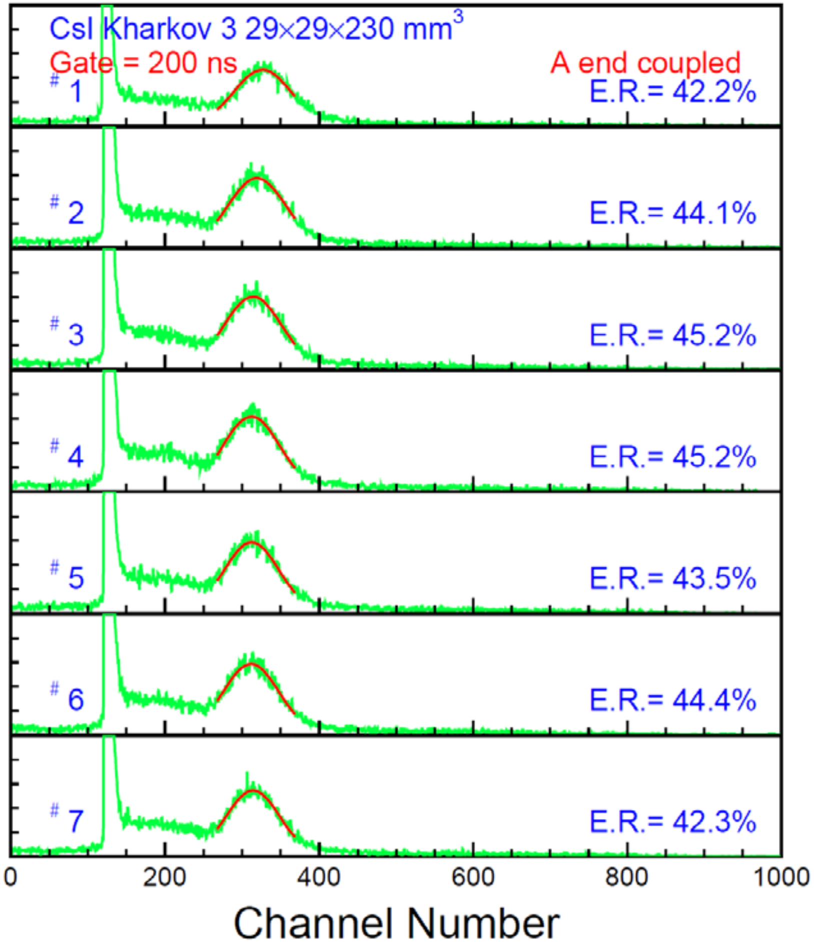
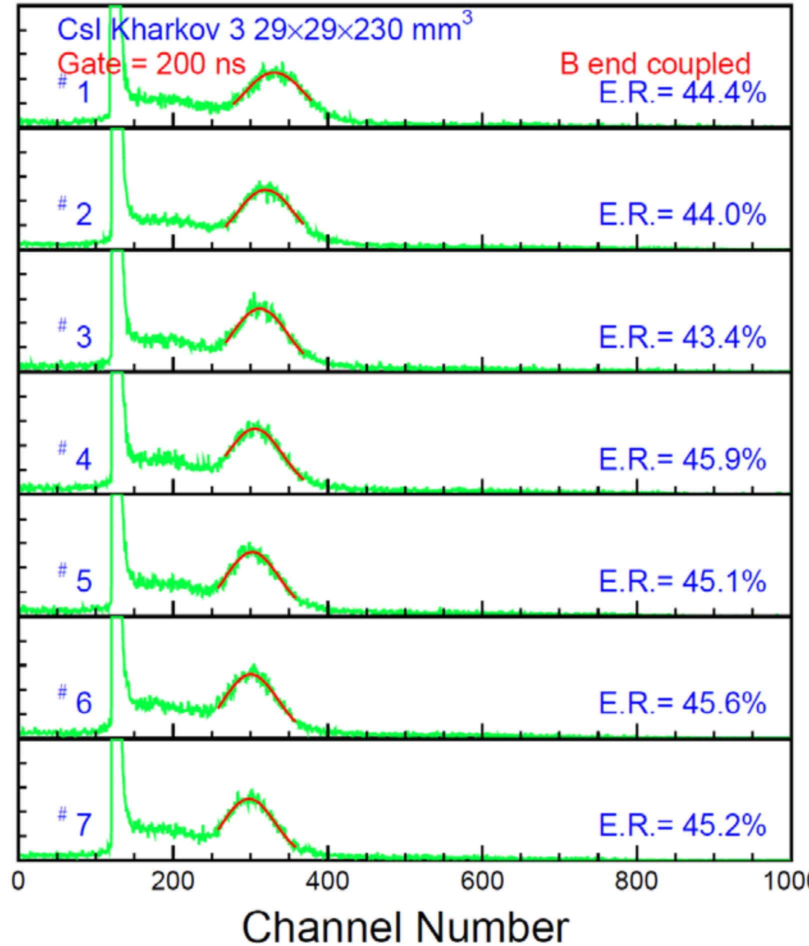
Resolution (200 ns): Kharkov 3

Ave ER= 43.8%

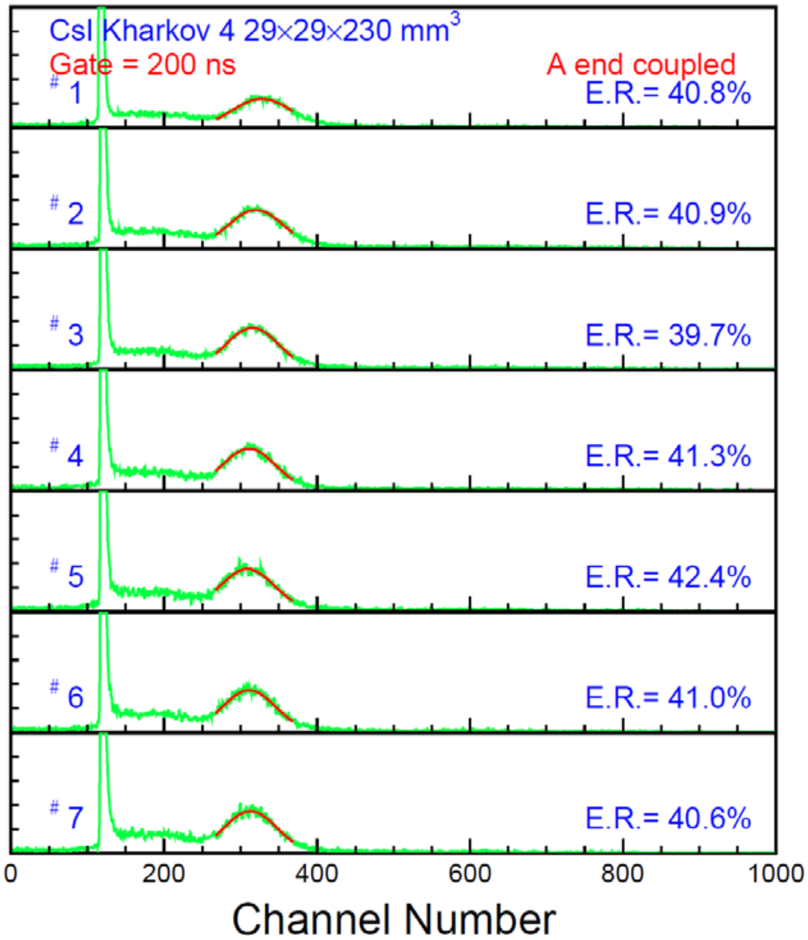
Ave ER= 44.8%



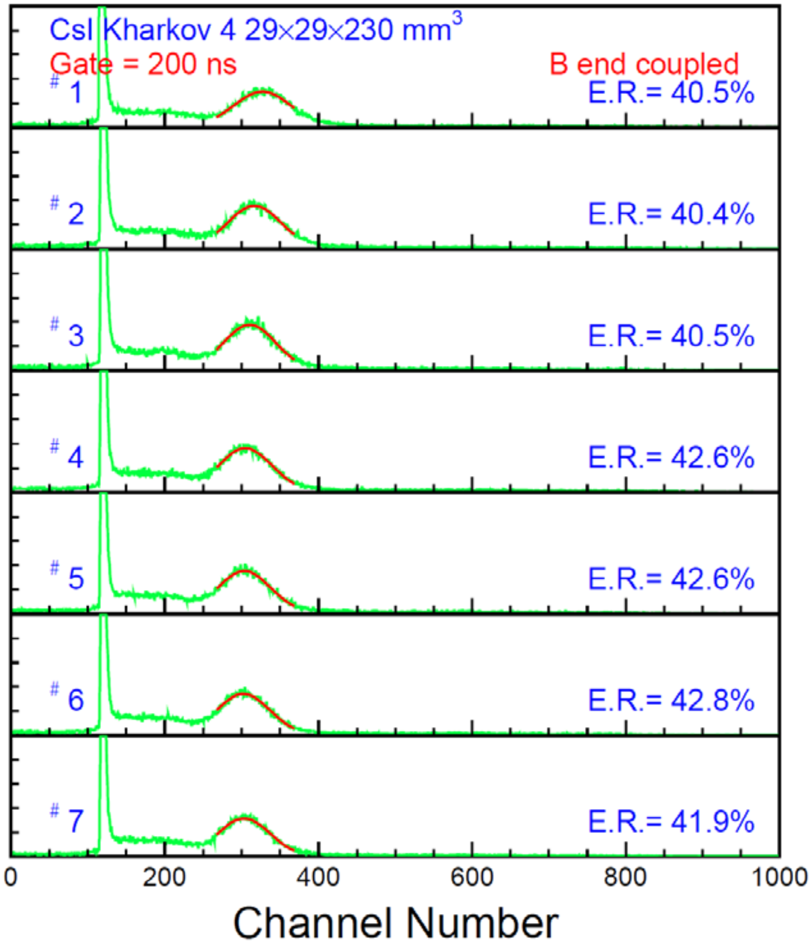


Resolution (200 ns): Kharkov 4

Ave ER= 41.0%

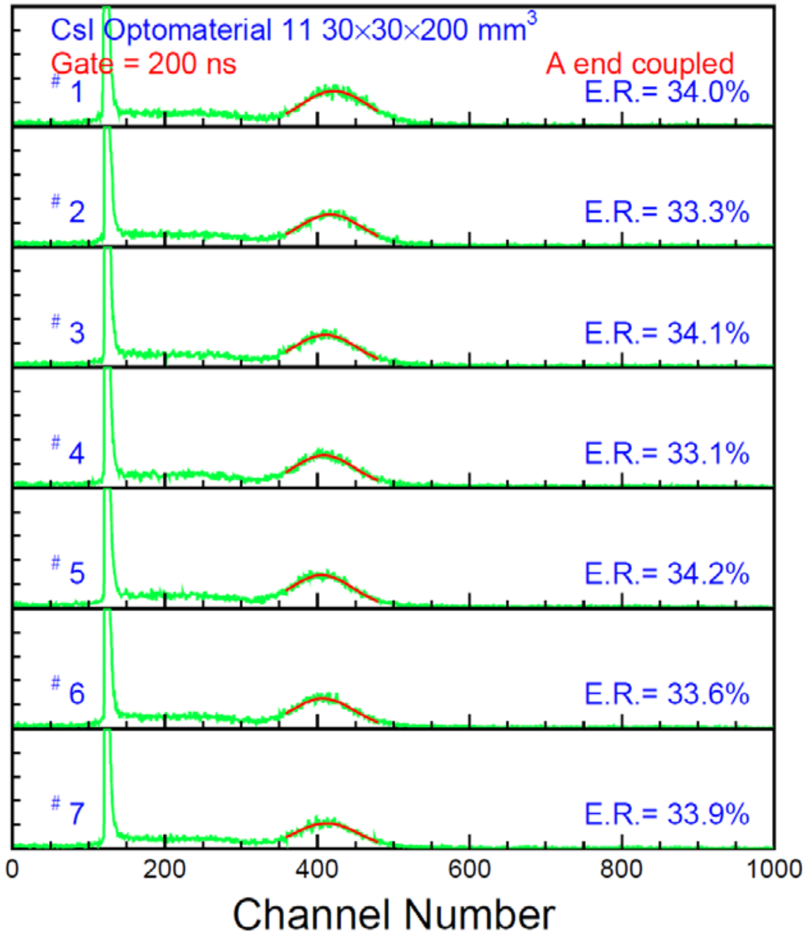


Ave ER= 41.6%

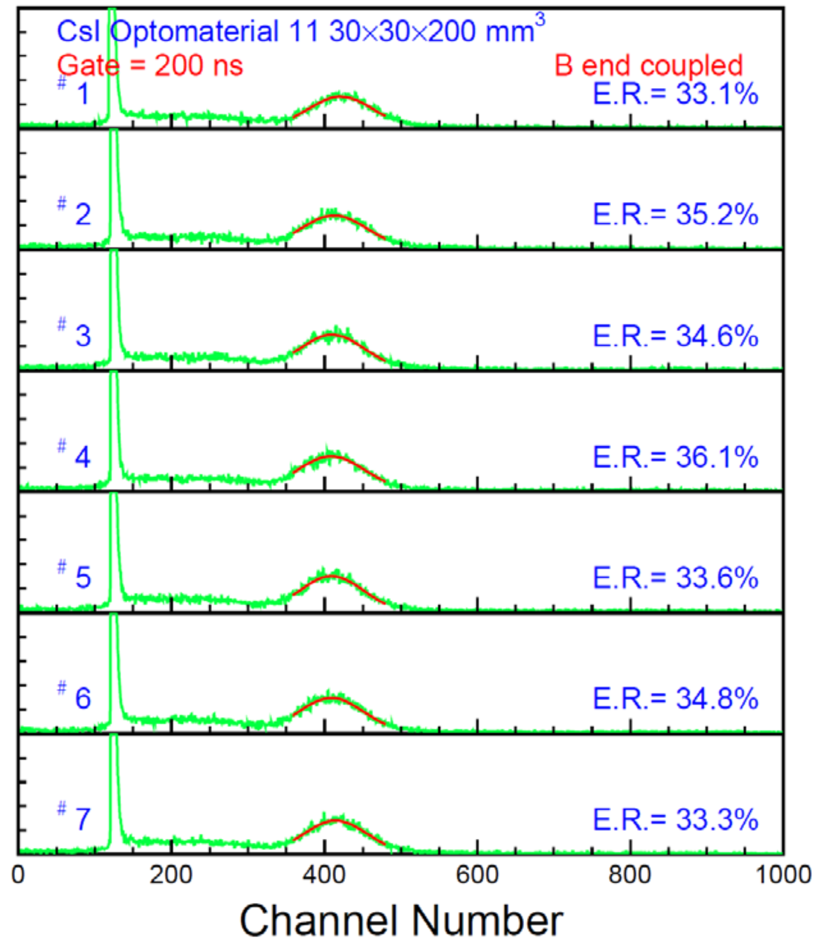


Resolution (200 ns): Optomaterial 11

Ave ER= 33.7%

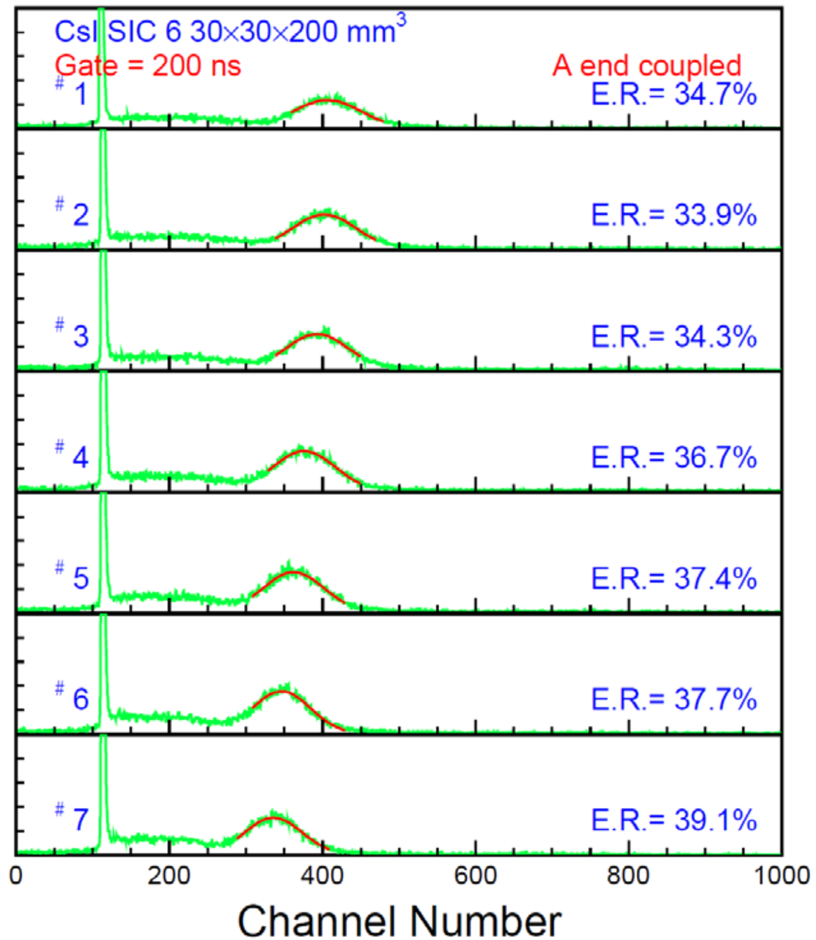


Ave ER= 34.4%

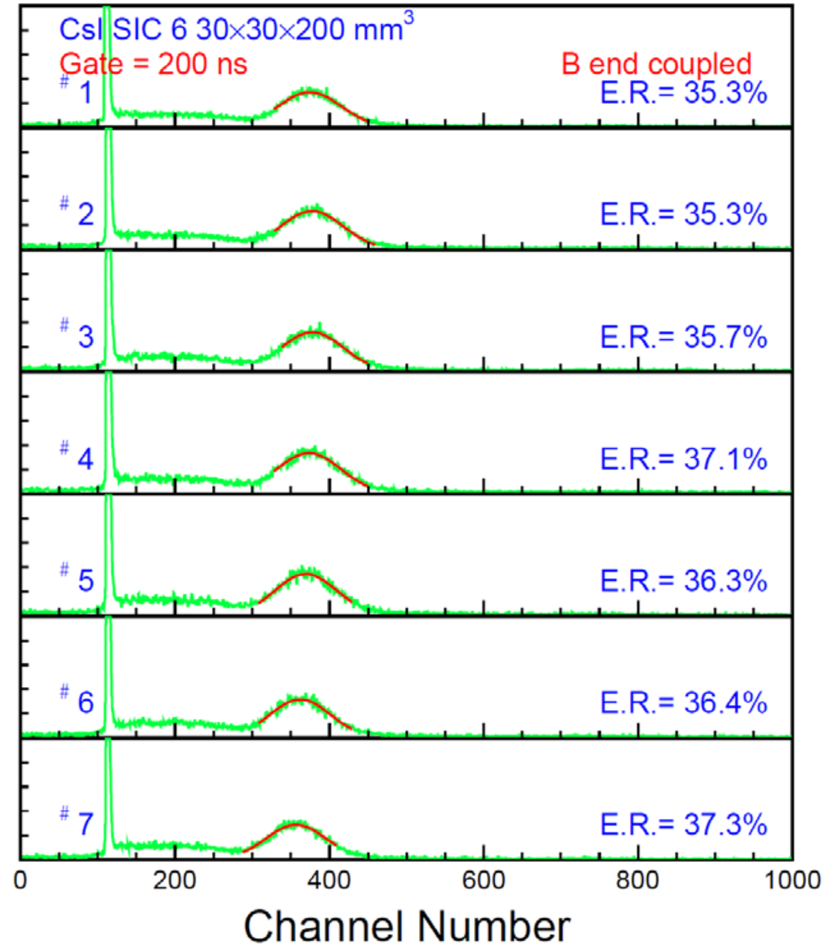


Resolution (200 ns): SIC 6

Ave ER= 36.3%

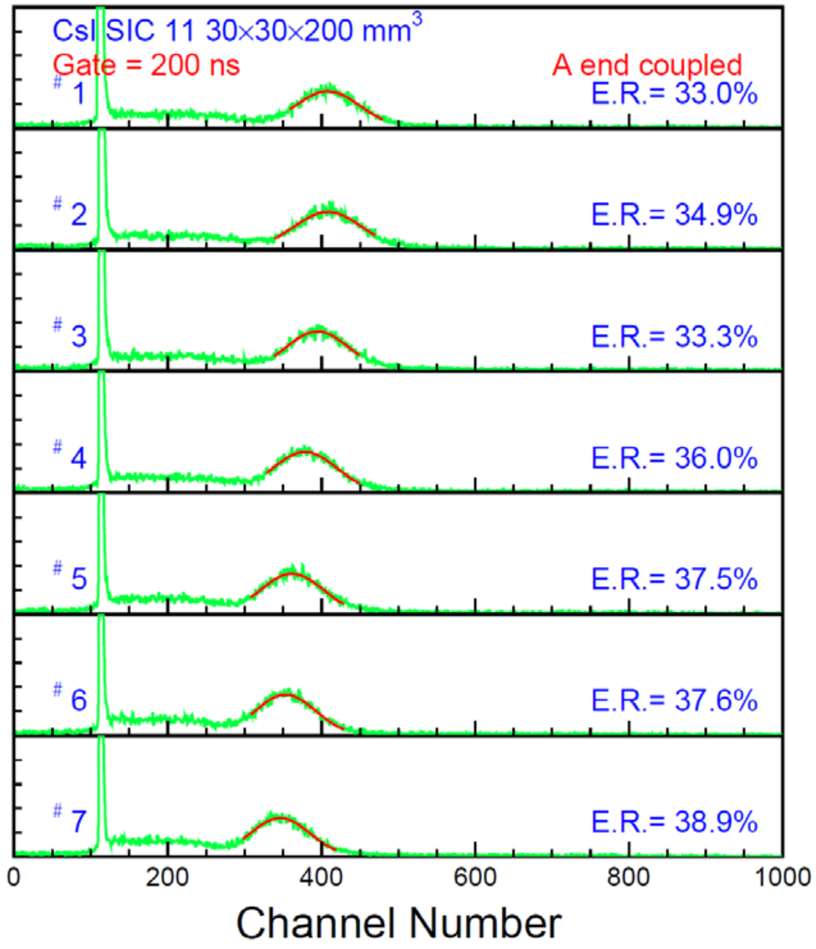


Ave ER= 36.2%

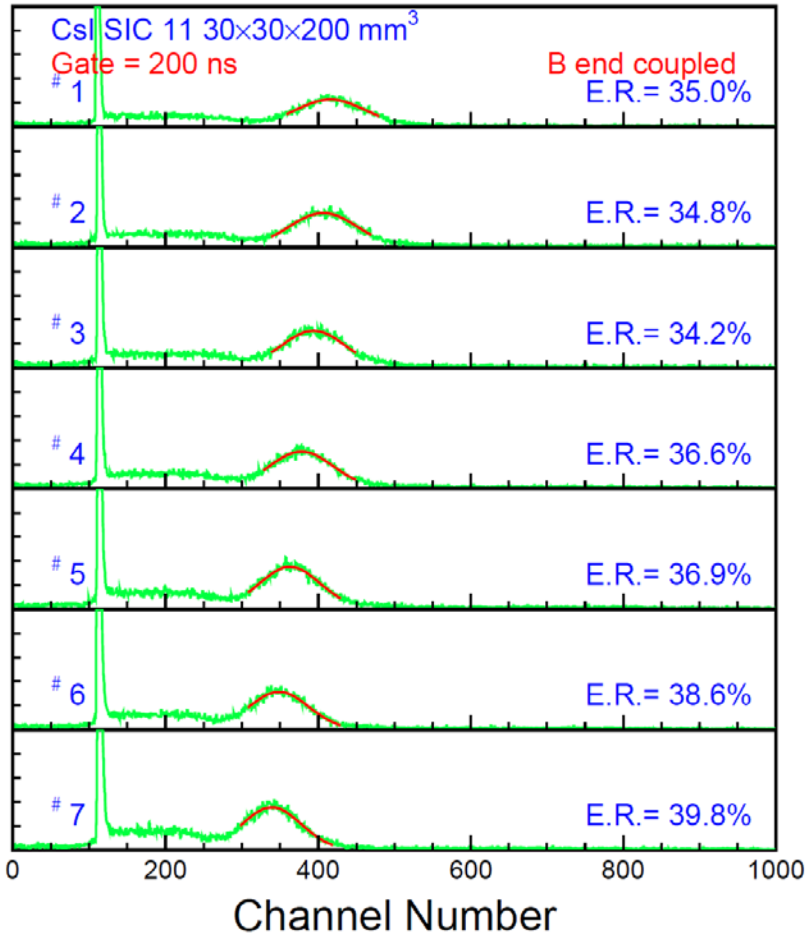


Resolution (200 ns): SIC 11

Ave ER= 35.9%



Ave ER= 36.6%



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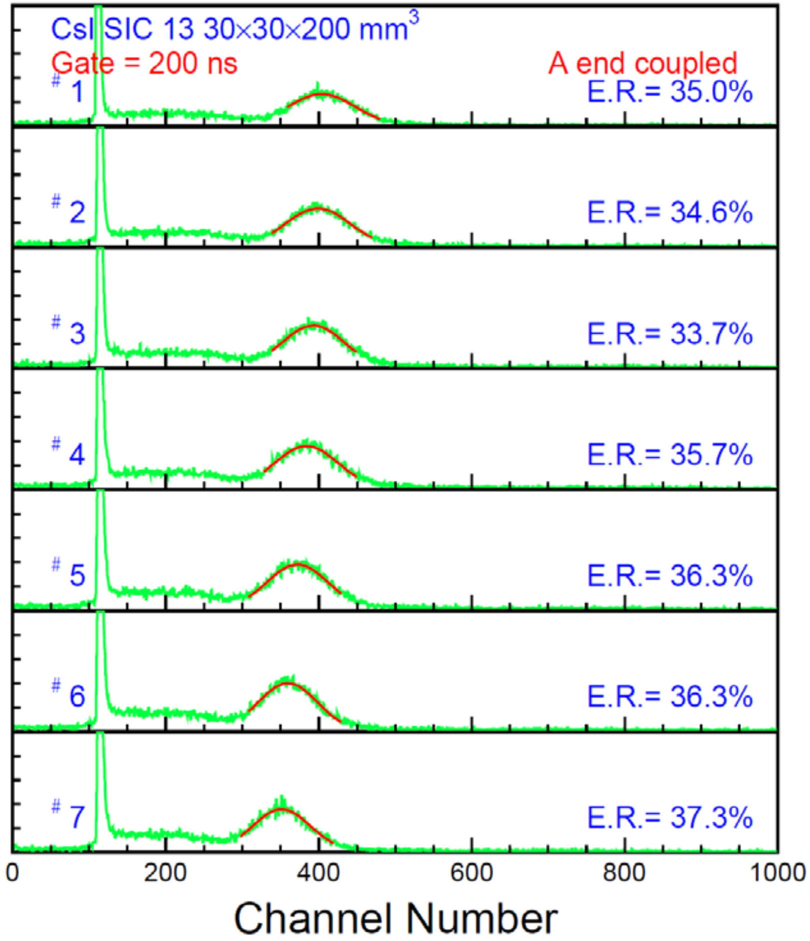
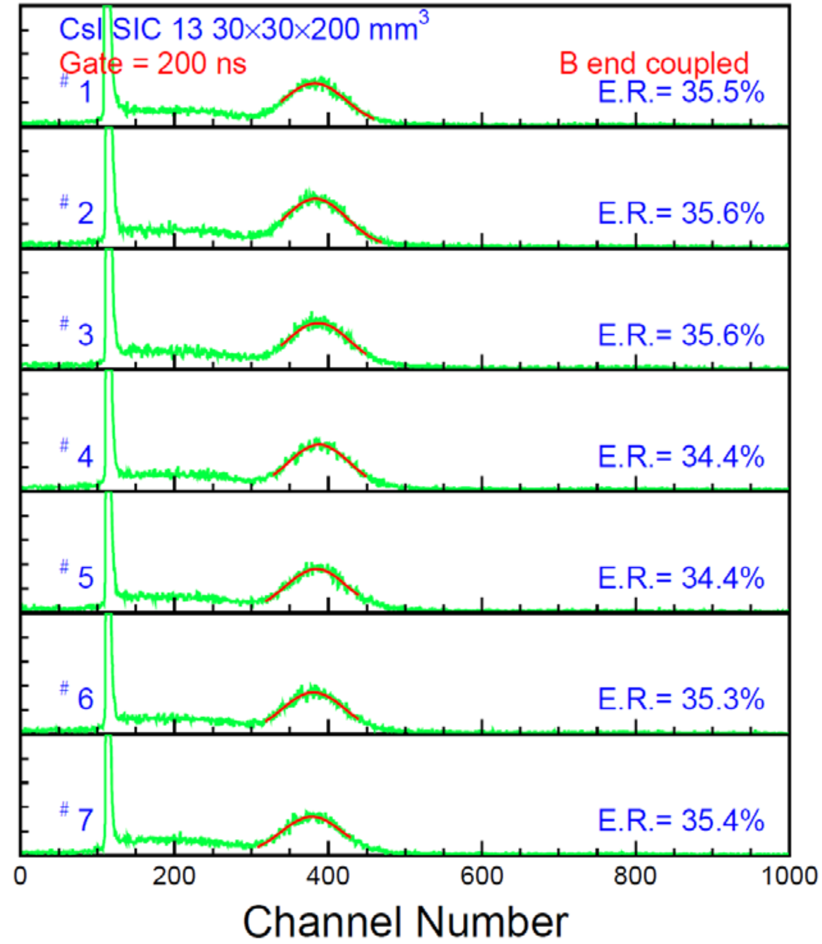
Resolution (200 ns): SIC 13

Ave ER= 35.6%

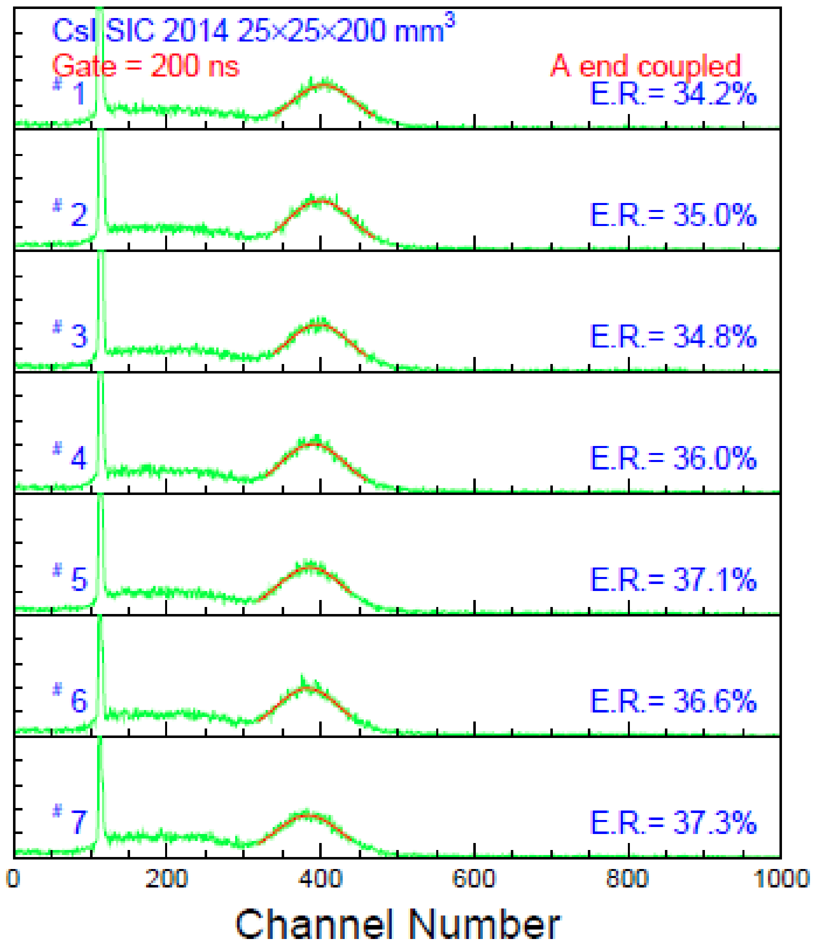


Ave ER=35.2%

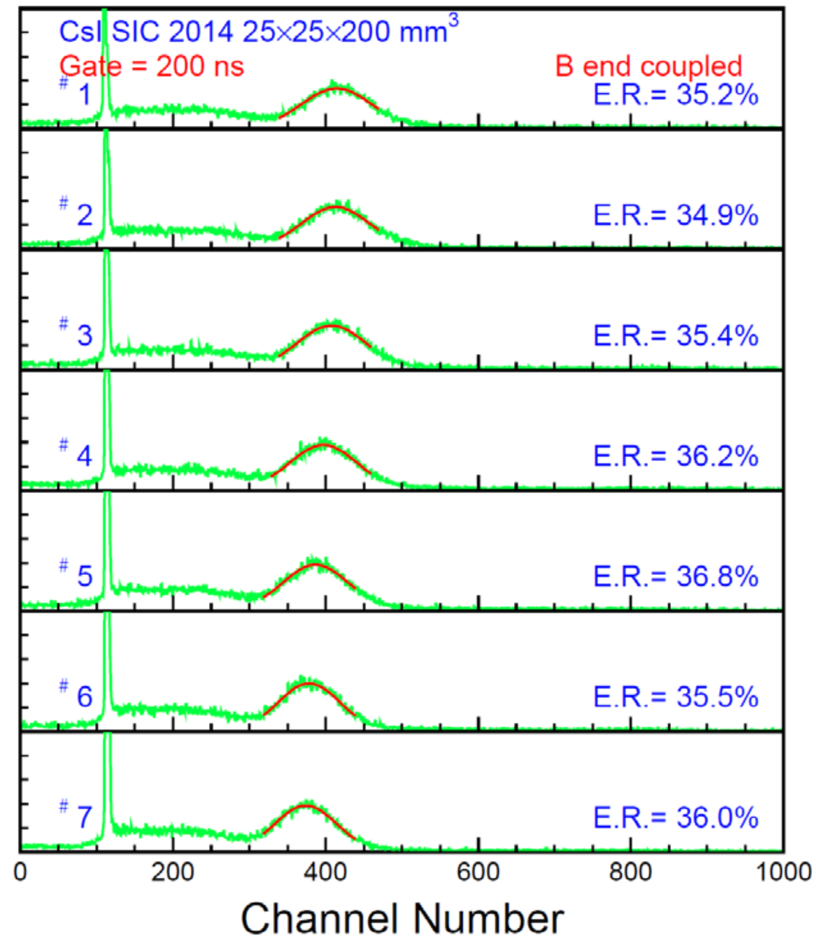


Resolution (200 ns): SIC 2014

Ave ER= 35.9%

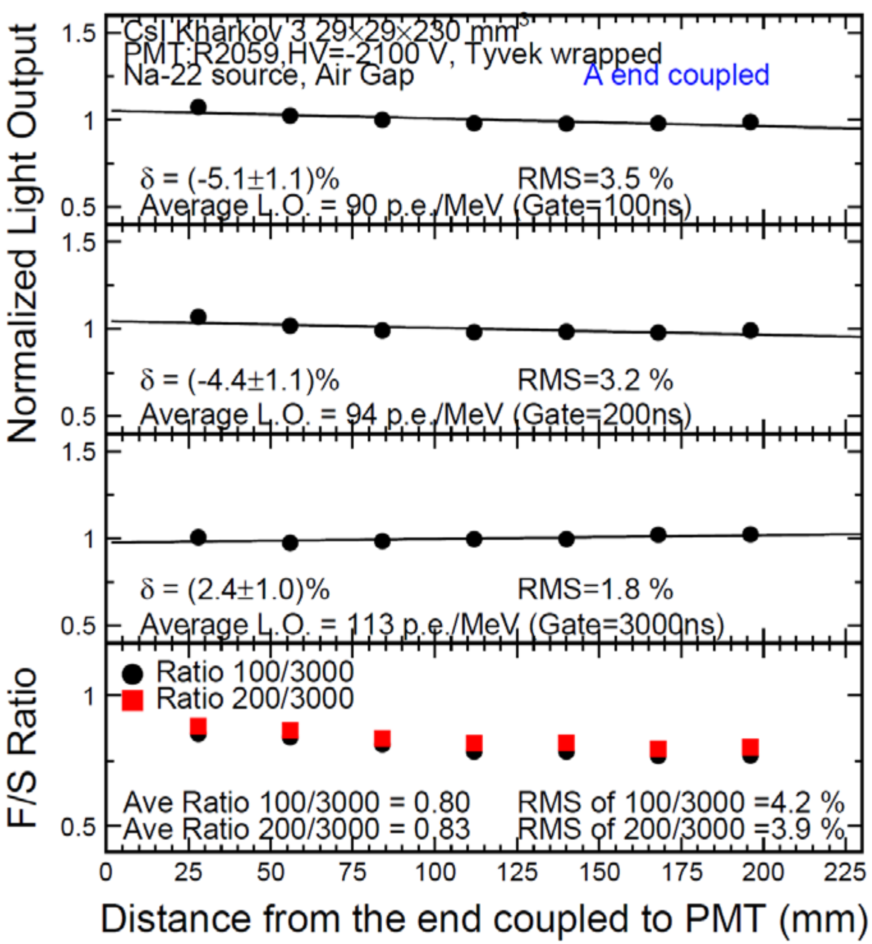


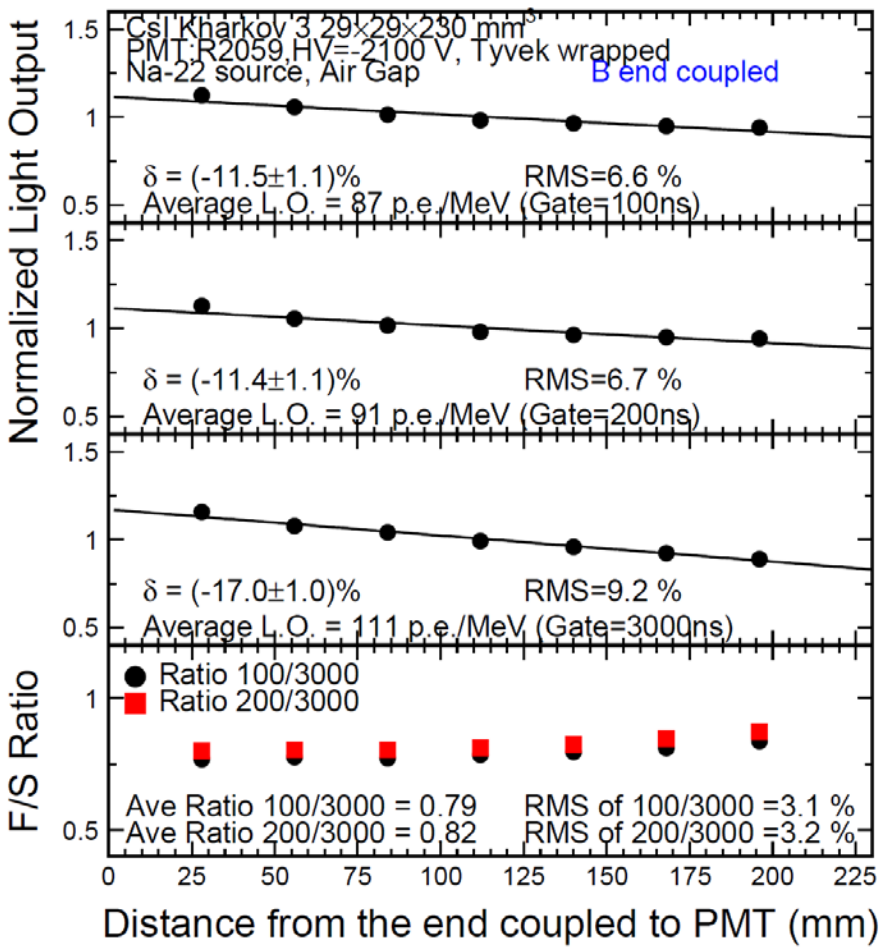
Ave ER=35.7%



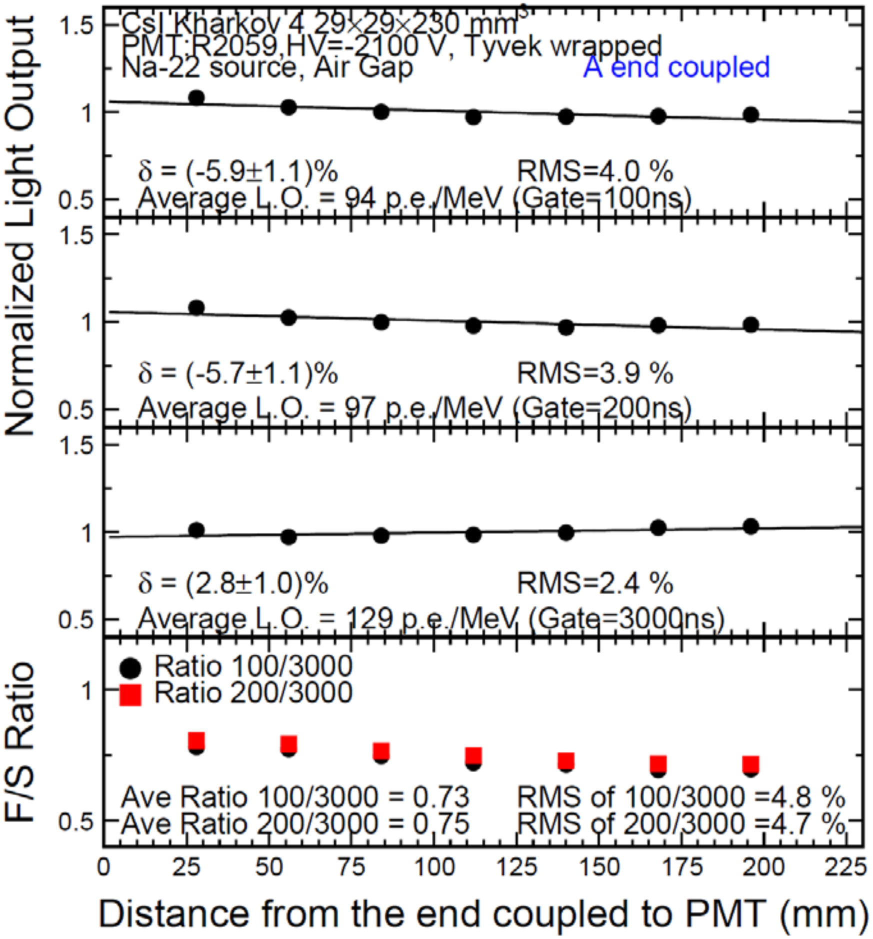
LO & LRU: Kharkov 3

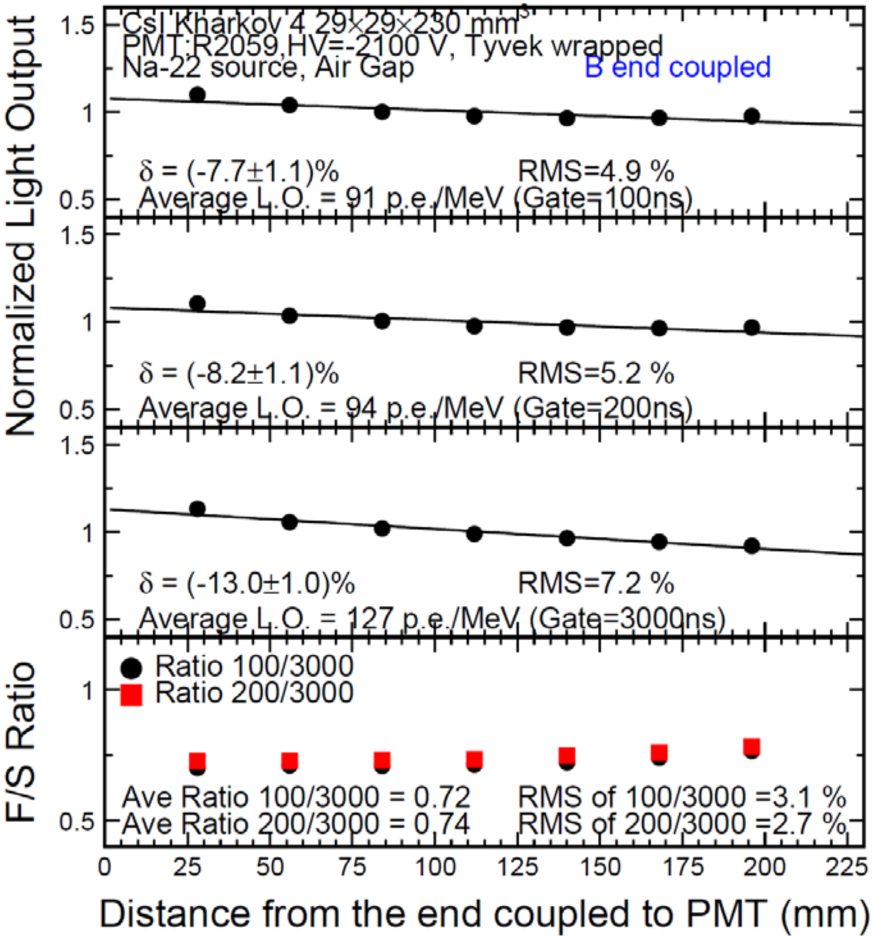
LO and LRU are coupling end dependent





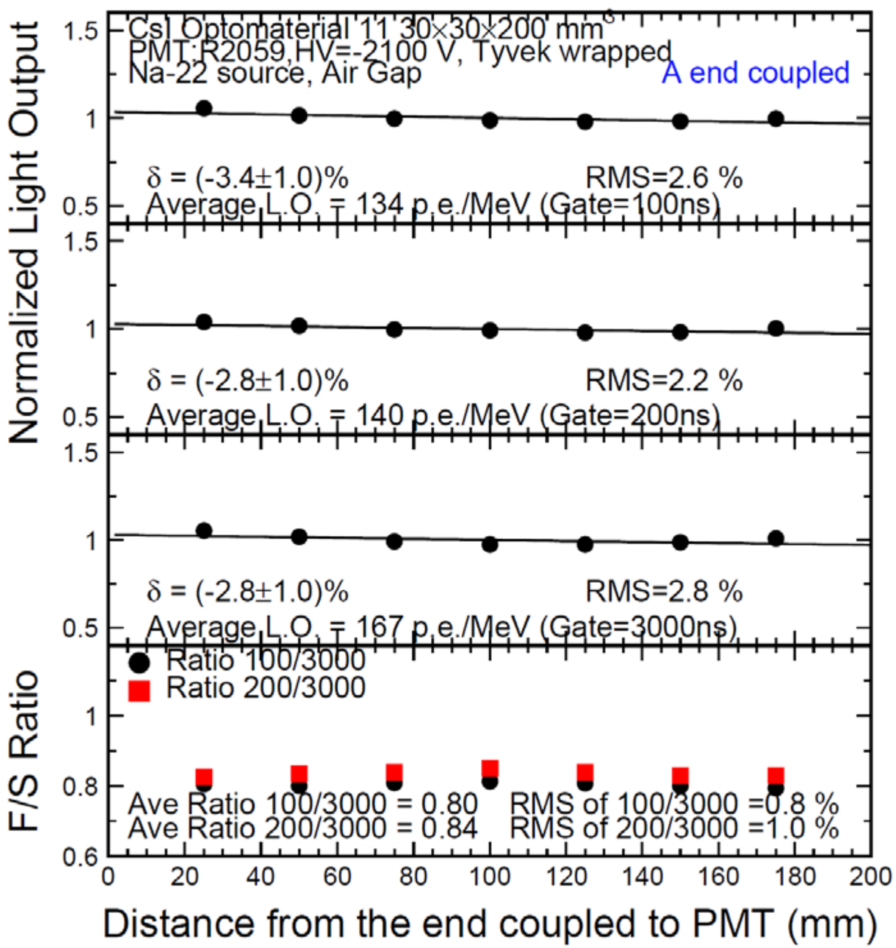
LO & LRU: Kharkov 4

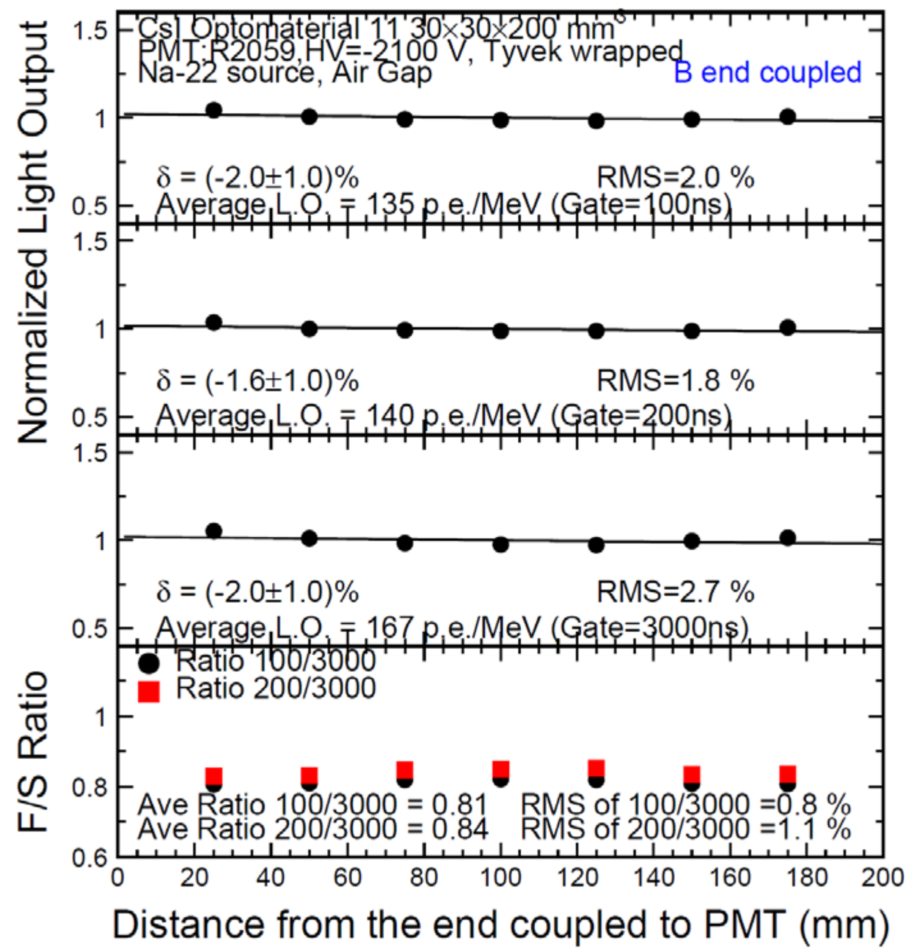




LO & LRU: Optomaterial 11

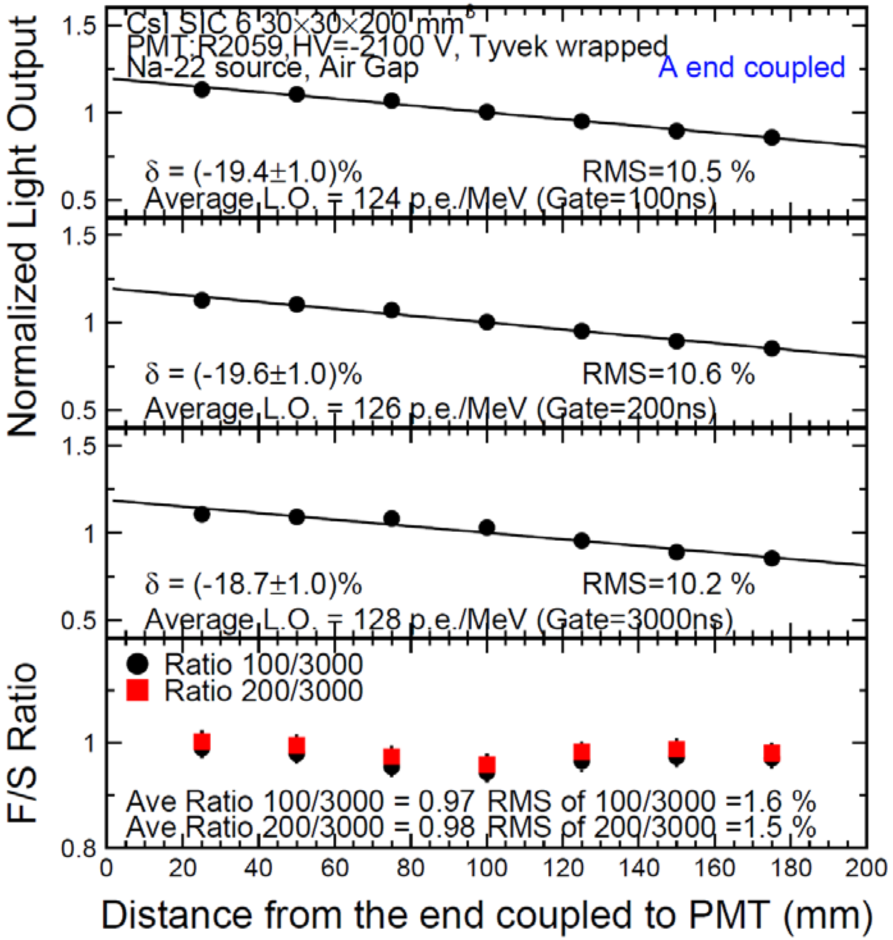
LO and LRU is coupling end independent

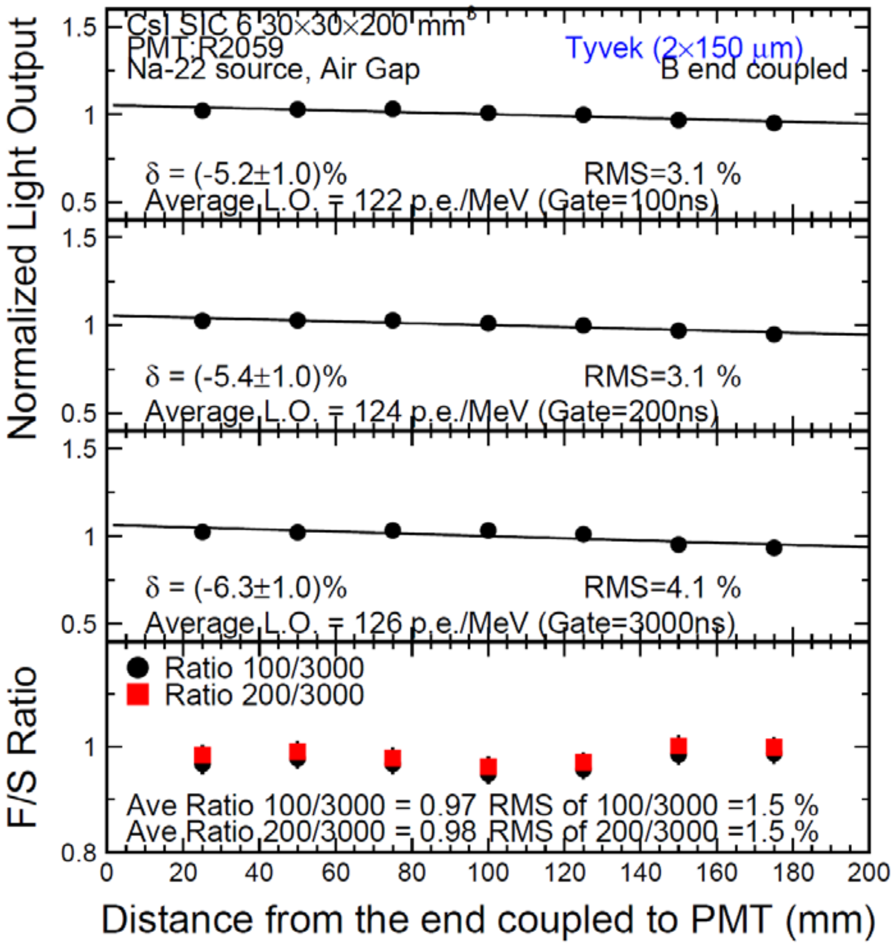




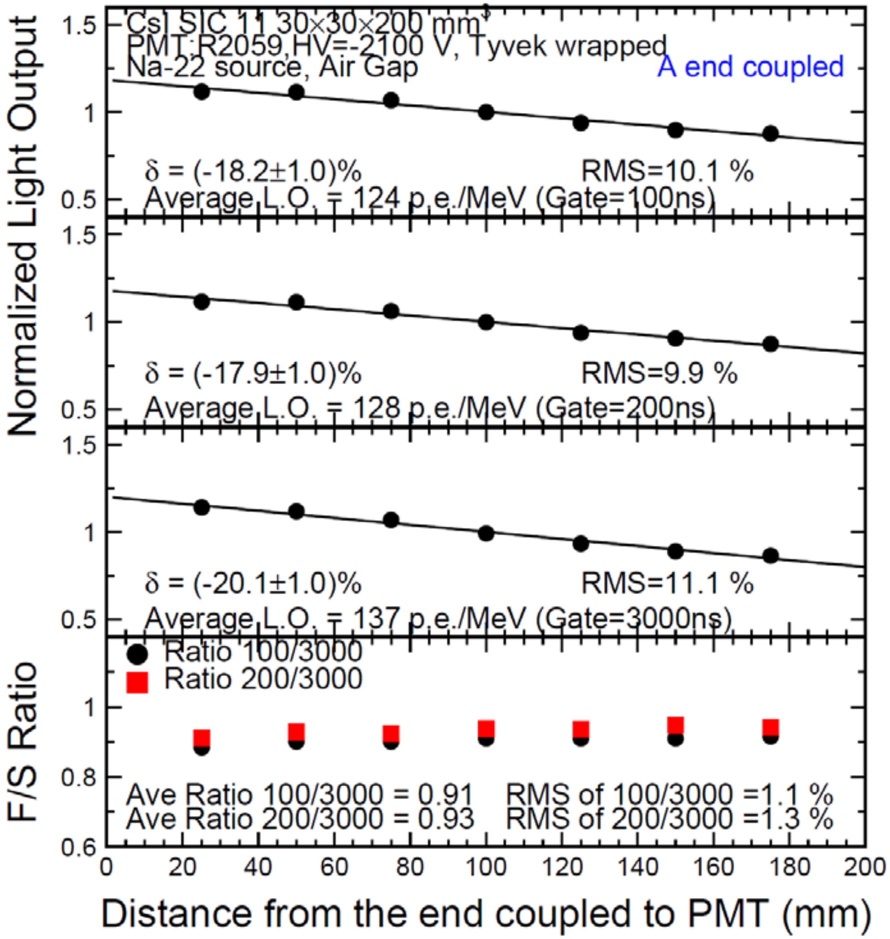
LO & LRU: SIC 6

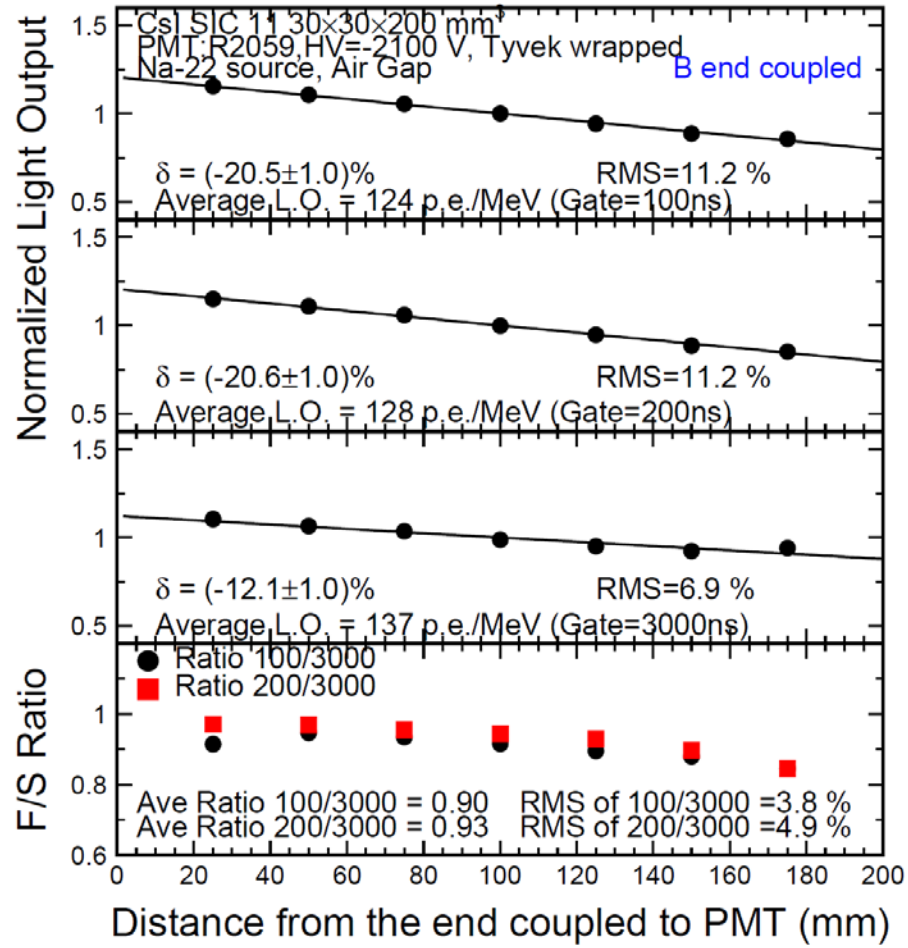
LO & LRU are coupling end dependent



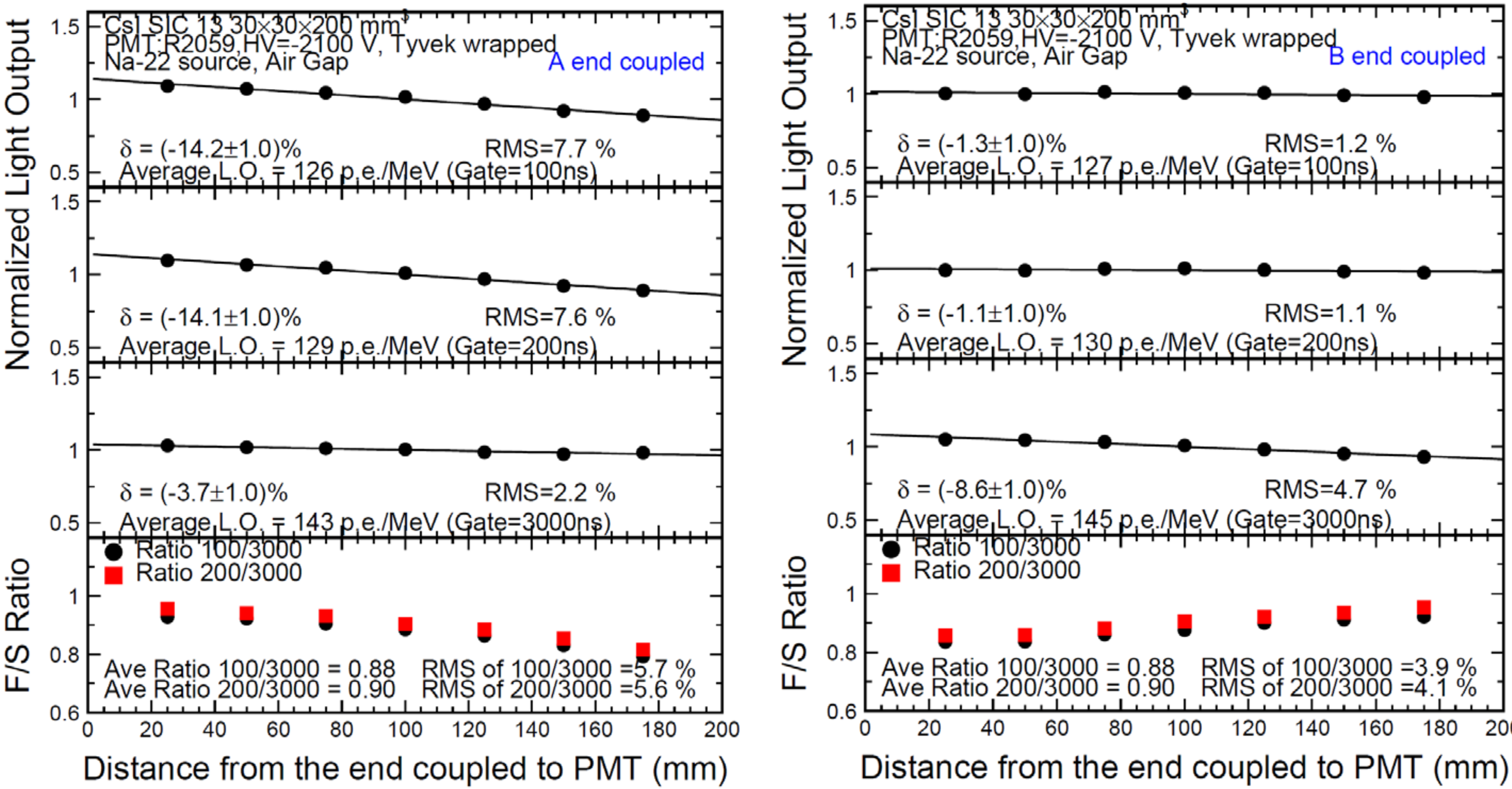


LO & LRU: SIC 11


CsI SIC 11 30×30×200 mm³
PMT:R2059,HV=-2100 V, Tyvek wrapped
Na-22 source, Air Gap
A end coupled
δ = (-18.2±1.0)%
RMS=10.1 %
Average L.O. = 124 p.e./MeV (Gate=100ns)
δ = (-17.9±1.0)%
RMS=9.9 %
Average L.O. = 128 p.e./MeV (Gate=200ns)
δ = (-20.1±1.0)%
RMS=11.1 %
Average L.O. = 137 p.e./MeV (Gate=3000ns)
Ratio 100/3000
Ratio 200/3000
Ave Ratio 100/3000 = 0.91
RMS of 100/3000 =1.1 %
Ave Ratio 200/3000 = 0.93
RMS of 200/3000 =1.3 %
Normalized Light Output
F/S Ratio
Distance from the end coupled to PMT (mm)


CsI SIC 11 30×30×200 mm³
PMT:R2059,HV=-2100 V, Tyvek wrapped
Na-22 source, Air Gap
B end coupled
δ = (-20.5±1.0)%
RMS=11.2 %
Average L.O. = 124 p.e./MeV (Gate=100ns)
δ = (-20.6±1.0)%
RMS=11.2 %
Average L.O. = 128 p.e./MeV (Gate=200ns)
δ = (-12.1±1.0)%
RMS=6.9 %
Average L.O. = 137 p.e./MeV (Gate=3000ns)
Ratio 100/3000
Ratio 200/3000
Ave Ratio 100/3000 = 0.90
RMS of 100/3000 =3.8 %
Ave Ratio 200/3000 = 0.93
RMS of 200/3000 =4.9 %
Normalized Light Output
F/S Ratio
Distance from the end coupled to PMT (mm)

LO & LRU: SIC 13


CsI SIC 13 30×30×200 mm³
PMT:R2059,HV=-2100 V, Tyvek wrapped
Na-22 source, Air Gap
A end coupled
δ = (-14.2±1.0)%
RMS=7.7 %
Average L.O. = 126 p.e./MeV (Gate=100ns)
δ = (-14.1±1.0)%
RMS=7.6 %
Average L.O. = 129 p.e./MeV (Gate=200ns)
δ = (-3.7±1.0)%
RMS=2.2 %
Average L.O. = 143 p.e./MeV (Gate=3000ns)
Ratio 100/3000
Ratio 200/3000
Ave Ratio 100/3000 = 0.88
RMS of 100/3000 =5.7 %
Ave Ratio 200/3000 = 0.90
RMS of 200/3000 =5.6 %
Normalized Light Output
F/S Ratio
Distance from the end coupled to PMT (mm)
CsI SIC 13 30×30×200 mm³
PMT:R2059,HV=-2100 V, Tyvek wrapped
Na-22 source, Air Gap
B end coupled
δ = (-1.3±1.0)%
RMS=1.2 %
Average L.O. = 127 p.e./MeV (Gate=100ns)
δ = (-1.1±1.0)%
RMS=1.1 %
Average L.O. = 130 p.e./MeV (Gate=200ns)
δ = (-8.6±1.0)%
RMS=4.7 %
Average L.O. = 145 p.e./MeV (Gate=3000ns)
Ratio 100/3000
Ratio 200/3000
Ave Ratio 100/3000 = 0.88
RMS of 100/3000 =3.9 %
Ave Ratio 200/3000 = 0.90
RMS of 200/3000 =4.1 %
Normalized Light Output
F/S Ratio
Distance from the end coupled to PMT (mm)

LO & LRU: SIC 2014