# Report on Radiation Damage in Sixteen Mu2e CsI Crystals

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# A Brief Summary

- Four additional CsI samples (SIC-C1130, SG-C1174, 1181 and 1268) were irradiated in two steps to 10 and 100 krad.

- The average LO is 136 and 109 p.e./MeV after 10 and 100 krad for ten SIC crystals and 109 and 96 p.e./MeV for six S-G crystals, respectively, with losses of 19% and 35% for SIC and 27% and 36% for S-G.

- Slightly degraded ER, F/T ratio and LRU are observed. Two samples from each vendor show LO of <100 p.e./MeV after 100 krad.

- SIC-C1130 failed the LRU spec after 100 krad. SG-C1174 failed the LO, ER and LRU spec after 100 krad, and is the only sample failed Mu2e radiation damage spec after 100 krad.

- No recovery observed up to 884 & 501 days for two CsI crystals each from S-G and SIC, respectively, indicating a stable calorimeter.

# Summary of Four Samples after Irradiation

| Crystal ID | Dose | L.O. (p.e./MeV) | E.R. (%) | F/T (%) | LRU (%) |
|---|---|---|---|---|---|
| SIC-C1130 | Before IR | 158 | 34 | 95 | 4.6 |
| | 10 krad | **133 (84%)** | 35 | 93 | **5.8** |
| | 100 krad | 107 (68%) | 39 | 96 | **7.9** |
| | 13 days recovery | 108 (68%) | 39 | 97 | **9.1** |
| SG-C1174 | Before IR | 177 | 29 | 95 | 1.6 |
| | 10 krad | **77 (44%)** | 42 | 98 | **5.1** |
| | 100 krad | **61 (34%)** | **48** | 96 | **6.0** |
| | 14 days recovery | **68 (38%)** | **47** | 97 | **5.6** |
| SG-C1181 | Before IR | 151 | 31 | 99 | 2.2 |
| | 10 krad | **120 (79%)** | 34 | 96 | 2.1 |
| | 100 krad | 106 (70%) | 36 | 94 | 2.6 |
| SG-C1268 | Before IR | 141 | 32 | 97 | 1.8 |
| | 10 krad | **109 (77%)** | 35 | 95 | 1.9 |
| | 100 krad | 102 (72%) | 38 | 96 | 3.0 |

# Light Output vs Integrated Dose

All, except four, show > 100 p.e./MeV after 100 krad
All, except one SG, meet Mu2e RH spec: > 60% after 100 krad
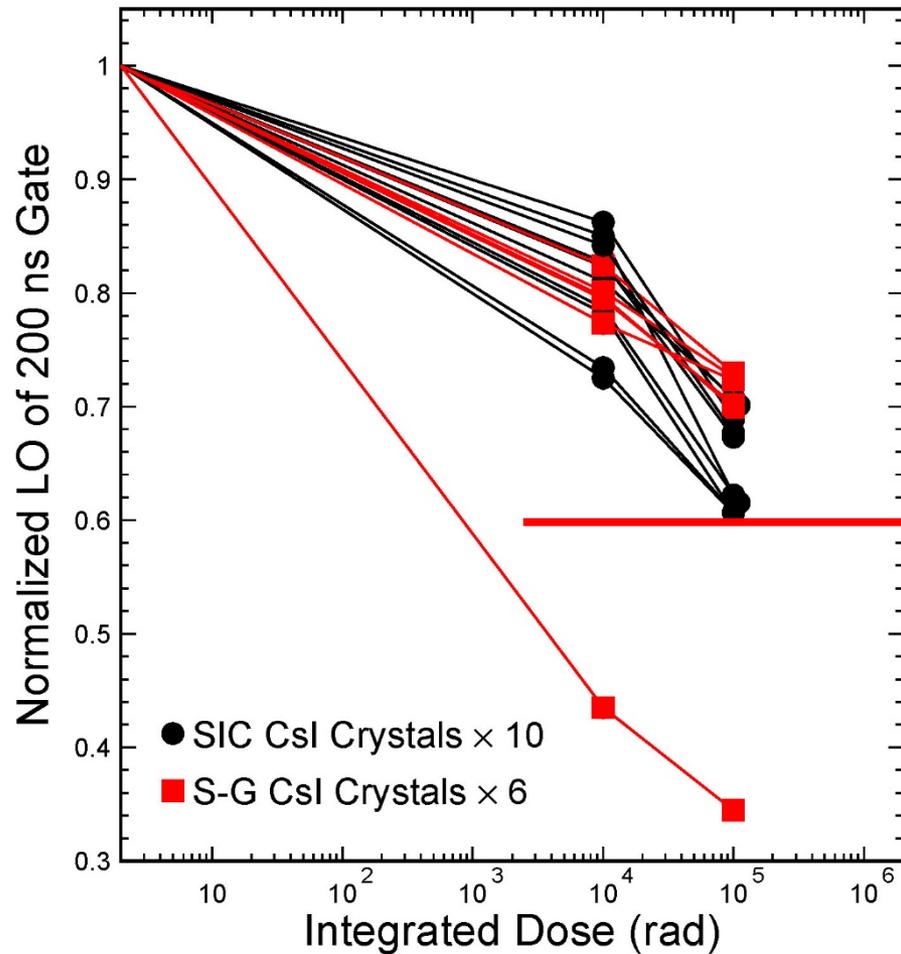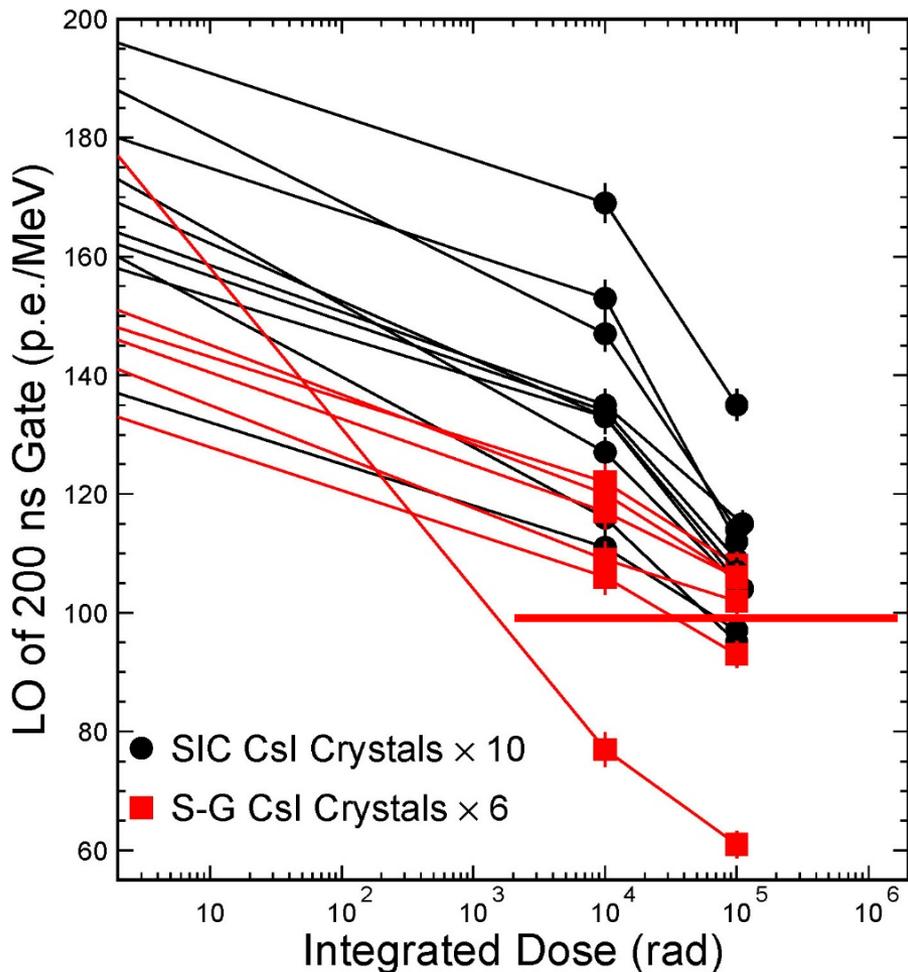
# F/T, Resolution and LRU vs Integrated Dose
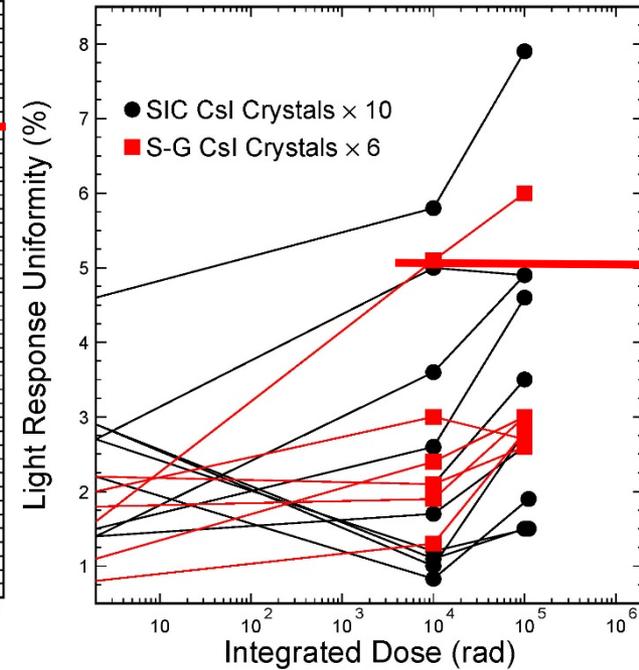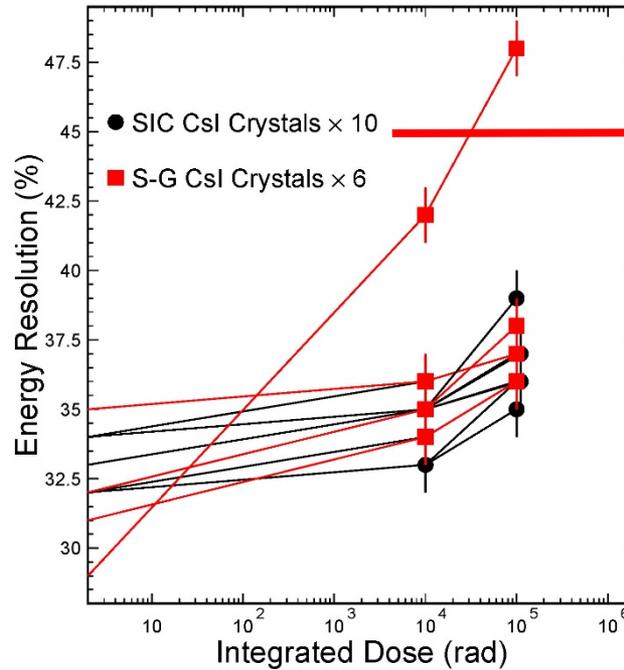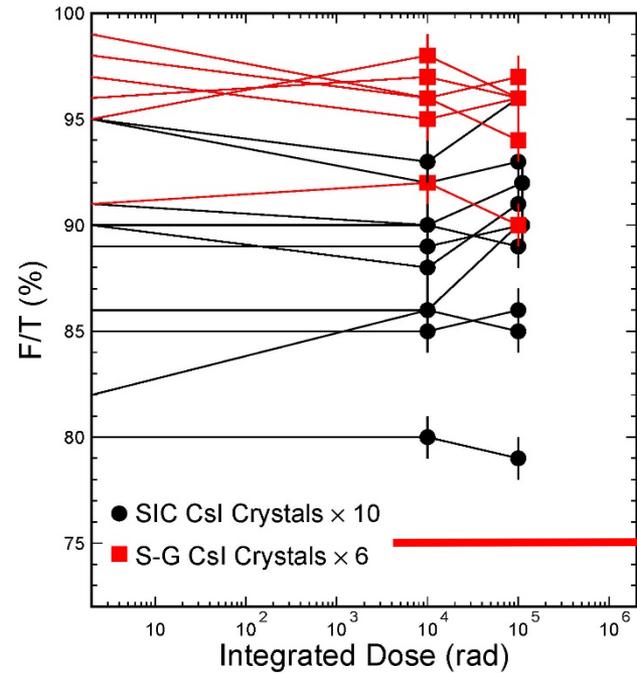
# Correlations: LO$_{before}$ vs LO$_{after}$

Excluding SG-C1174, good correlations observed
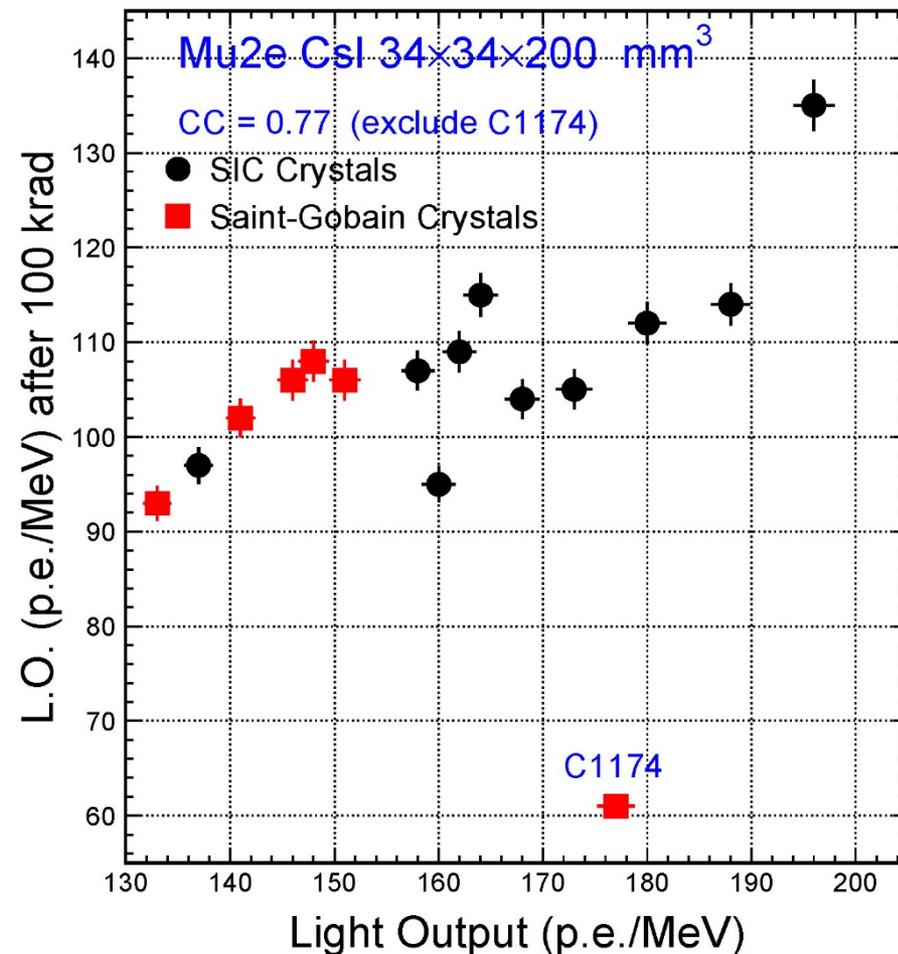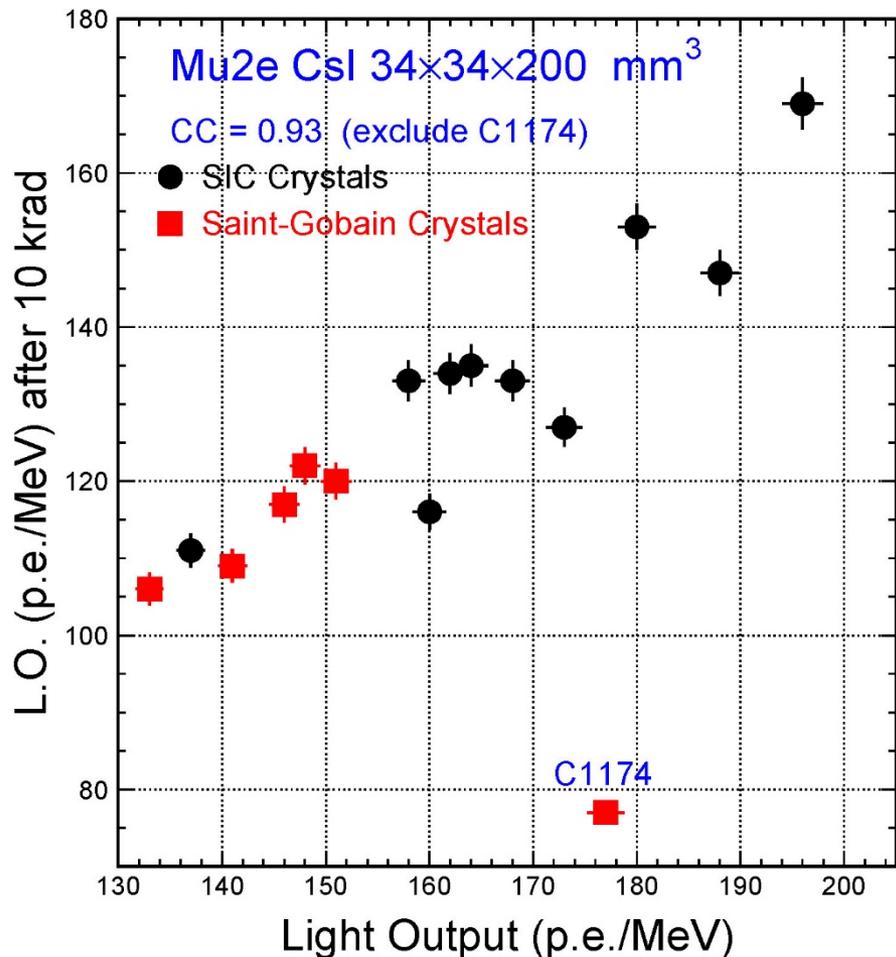
# LO Recovery: S-G and SIC CsI
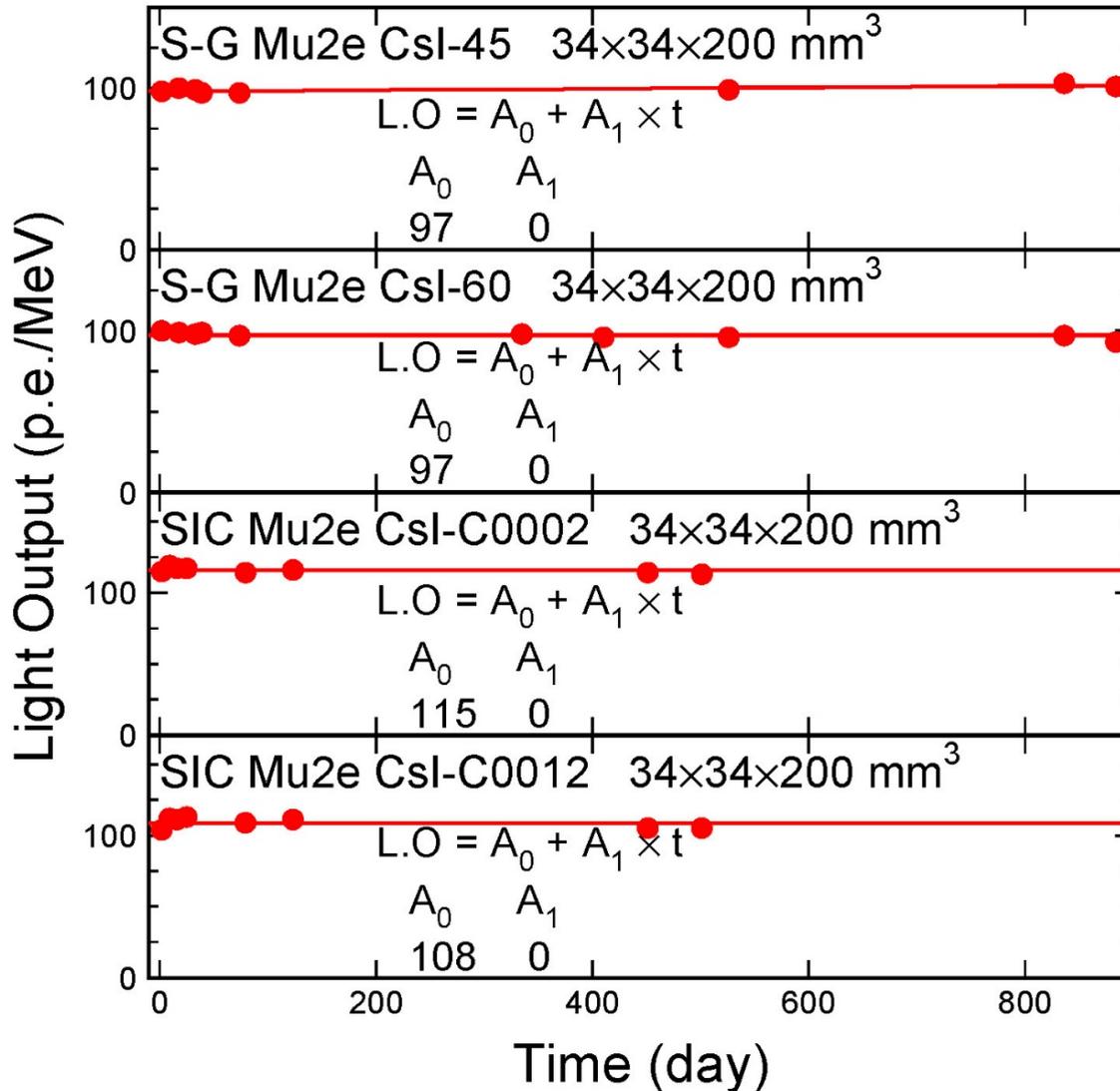


**S-G Mu2e CsI-45** $34 \times 34 \times 200$ mm$^3$

$$L.O = A_0 + A_1 \times t$$

| $A_0$ | $A_1$ |
|-------|-------|
| 97    | 0     |

**S-G Mu2e CsI-60** $34 \times 34 \times 200$ mm$^3$

$$L.O = A_0 + A_1 \times t$$

| $A_0$ | $A_1$ |
|-------|-------|
| 97    | 0     |

**SIC Mu2e CsI-C0002** $34 \times 34 \times 200$ mm$^3$

$$L.O = A_0 + A_1 \times t$$

| $A_0$ | $A_1$ |
|-------|-------|
| 115   | 0     |

**SIC Mu2e CsI-C0012** $34 \times 34 \times 200$ mm$^3$

$$L.O = A_0 + A_1 \times t$$

| $A_0$ | $A_1$ |
|-------|-------|
| 108   | 0     |

Light Output (p.e./MeV)

Time (day)

No recovery observed up to 884 & 501 days for two CsI crystals each from S-G and SIC, respectively, indicating a stable calorimeter

# LO & LRU after 10 and 100 krad: 1130 & 1174



Left column — Mu2e CsI-C1130, B end coupling:

- before IR: $\delta = (-10.6 \pm 1.2)\%$, RMS=4.6 %, Average L.O. = 158 p.e./MeV (Gate=200ns)
- 10 krad IR: $\delta = (-13.4 \pm 1.2)\%$, RMS=5.8 %, Average L.O. = 133 p.e./MeV (Gate=200ns)
- 100 krad IR: $\delta = (-17.4 \pm 1.2)\%$, RMS=7.9 %, Average L.O. = 107 p.e./MeV (Gate=200ns)

Right column — Mu2e CsI-C1174, A end coupling:

- before IR: $\delta = (-1.9 \pm 1.2)\%$, RMS=1.6 %, Average L.O. = 177 p.e./MeV (Gate=200ns)
- 10 krad IR: $\delta = (-10.9 \pm 1.2)\%$, RMS=5.1 %, Average L.O. = 77 p.e./MeV (Gate=200ns)
- 100 krad IR: $\delta = (-12.3 \pm 1.2)\%$, RMS=6.0 %, Average L.O. = 60 p.e./MeV (Gate=200ns)

Normalized Light Output

Distance from the end coupled to PMT (mm)

# LO & LRU after 10 and 100 krad: 1181 & 1268
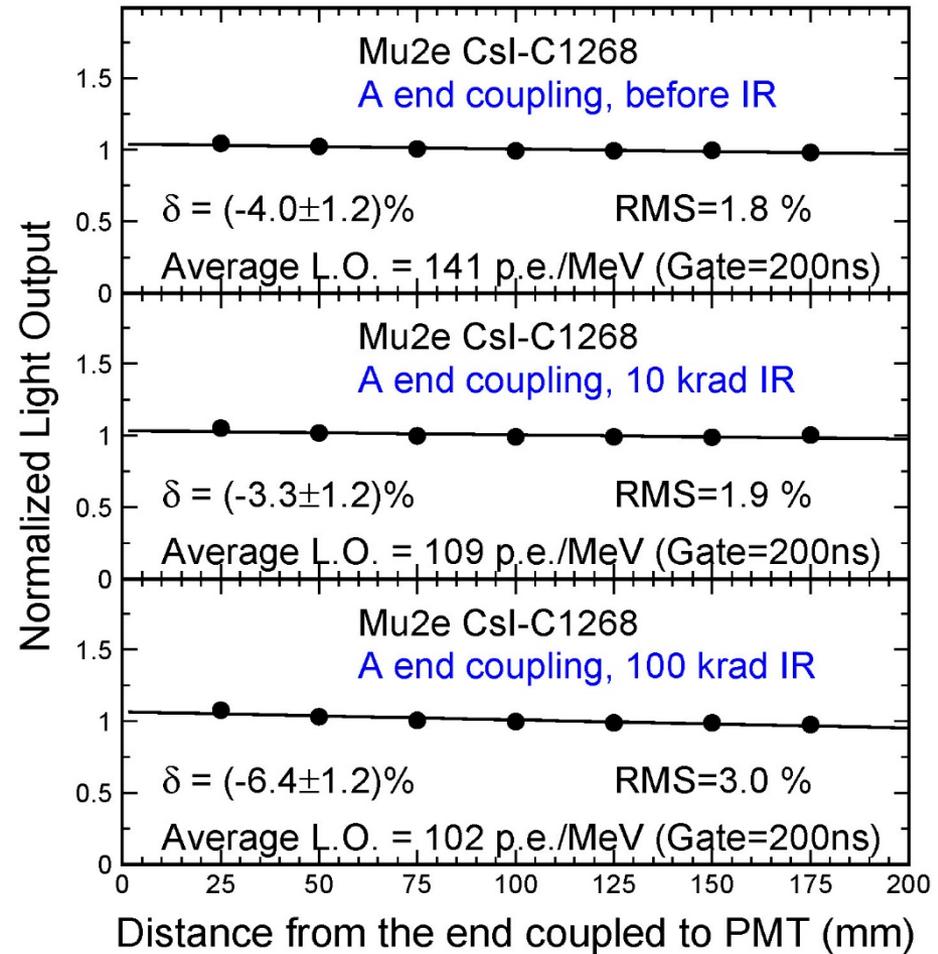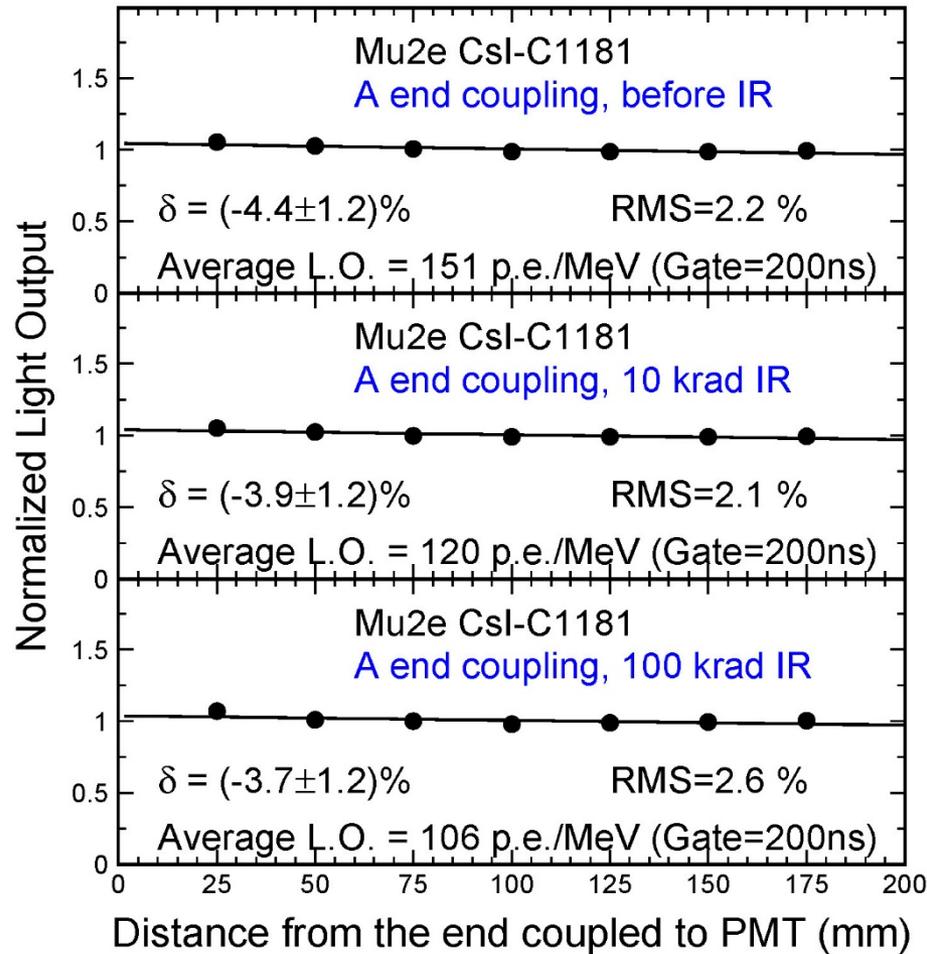
# Summary: Ten SIC CsI Crystals

| Crystal ID | Dose | L.O. (p.e./MeV) | E.R. (%) | F/T (%) | LRU (%) |
|---|---|---|---|---|---|
| SIC-C0002 | Before IR | 164 | 34 | 91 | 2.2 |
|  | 10 krad | **135 (82%)** | 35 | 90 | 0.83 |
|  | 110 krad | 115 (70%) | 36 | 92 | 1.9 |
| SIC-C0012 | Before IR | 169 | 33 | 89 | 2.7 |
|  | 10 krad | **133 (79%)** | 35 | 89 | 1.2 |
|  | 110 krad | 104 (62%) | 37 | 90 | 1.5 |
| **SIC-C0202** | Before IR | 180 | 32 | 82 | 2.9 |
|  | 10 krad | 153 (85%) | 33 | 86 | 1.0 |
|  | 100 krad | 112 (62%) | 36 | 90 | 2.8 |
| SIC-C0276 | Before IR | 196 | 32 | 86 | 2.9 |
|  | 10 krad | 169 (87%) | 33 | 86 | 1.1 |
|  | 100 krad | 135 (69%) | 35 | 85 | 1.5 |
| SIC-C0326 | Before IR | 188 | 32 | 85 | 1.4 |
|  | 10 krad | **147 (78%)** | 34 | 85 | 1.7 |
|  | 100 krad | 114 (61%) | 36 | 86 | 2.6 |
| SIC-C0351 | Before IR | 173 | 33 | 90 | 2.2 |
|  | 10 krad | **127 (73%)** | 35 | 88 | 2.1 |
|  | 100 krad | 105 (61%) | 37 | 91 | 3.5 |
| SIC-C0438 | Before IR | 160 | 34 | 95 | 1.5 |
|  | 10 krad | **116 (73%)** | 36 | 92 | 2.6 |
|  | 100 krad | 95 (60%) | 37 | 93 | 4.6 |
| SIC-C0667 | Before IR | 137 | 35 | 80 | 1.4 |
|  | 10 krad | **111 (81%)** | 36 | 80 | 3.6 |
|  | 100 krad | 97 (71%) | 37 | 79 | 4.9 |
| **SIC-C0906** | Before IR | 162 | 34 | 90 | 2.7 |
|  | 10 krad | **134 (83%)** | 35 | 90 | 5.0 |
|  | 100 krad | 109 (67%) | 36 | 89 | 4.9 |
| SIC-C1130 | Before IR | 158 | 34 | 95 | 4.6 |
|  | 10 krad | **133 (84%)** | 35 | 93 | **5.8** |
|  | 100 krad | 107 (68%) | 39 | 96 | **7.9** |
| Average (RMS) | Before IR | **168 (11%)** | **33 (1.1)** | **88 (6.0%)** | **2.5 (1.02)** |
|  | 10 krad | **136 (13%)** | **35 (1.1)** | **88 (4.6%)** | **2.5 (1.87)** |
|  | 100 krad | **109 (11%)** | **37 (1.1)** | **89 (5.7%)** | **3.6 (2.13)** |

# Summary: Six S-G CsI Crystals

| Crystal ID | Dose | L.O. (p.e./MeV) | E.R. (%) | F/T (%) | LRU (%) |
|---|---|---|---|---|---|
| SG-C0770 | Before IR | 133 | 35 | 91 | 0.8 |
| | 10 krad | **106 (80%)** | 36 | 92 | 1.3 |
| | 100 krad | 93 (70%) | 37 | 90 | 2.8 |
| SG-C0950 | Before IR | 148 | 31 | 96 | 2.0 |
| | 10 krad | **122 (82%)** | 34 | 97 | 3.0 |
| | 100 krad | 108 (73%) | 36 | 96 | 2.7 |
| SG-C1063 | Before IR | 146 | 31 | 98 | 1.1 |
| | 10 krad | **117 (80%)** | 34 | 96 | 2.4 |
| | 100 krad | 106 (73%) | 36 | 97 | 3.0 |
| SG-C1174 | Before IR | 177 | 29 | 95 | 1.6 |
| | 10 krad | **77 (44%)** | 42 | 98 | **5.1** |
| | 100 krad | **61 (34%)** | **48** | 96 | **6.0** |
| SG-C1181 | Before IR | 151 | 31 | 99 | 2.2 |
| | 10 krad | **120 (79%)** | 34 | 96 | 2.1 |
| | 100 krad | 106 (70%) | 36 | 94 | 2.6 |
| SG-C1268 | Before IR | 141 | 32 | 97 | 1.8 |
| | 10 krad | **109 (77%)** | 35 | 95 | 1.9 |
| | 100 krad | 102 (72%) | 38 | 96 | 3.0 |
| Average (RMS) | Before IR | **149 (9.1%)** | **32 (1.8)** | **96 (2.7%)** | **1.6 (0.49)** |
| | 10 krad | **109 (14.0%)** | **36 (2.9)** | **96 (2.0%)** | **2.6 (1.2)** |
| | 100 krad | **96 (17%)** | **39 (4.3)** | **95 (2.5%)** | **3.4 (1.2)** |