# Construction Readiness Review for CsI and SiPMs

# CsI Radiation Hardness and Radiation Induce Noise

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# Talk Layout

- CsI Radiation Related Specifications
- Radiation Hardness Tested for  Six Crystals
- Radiation Induced Noise for 72 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.

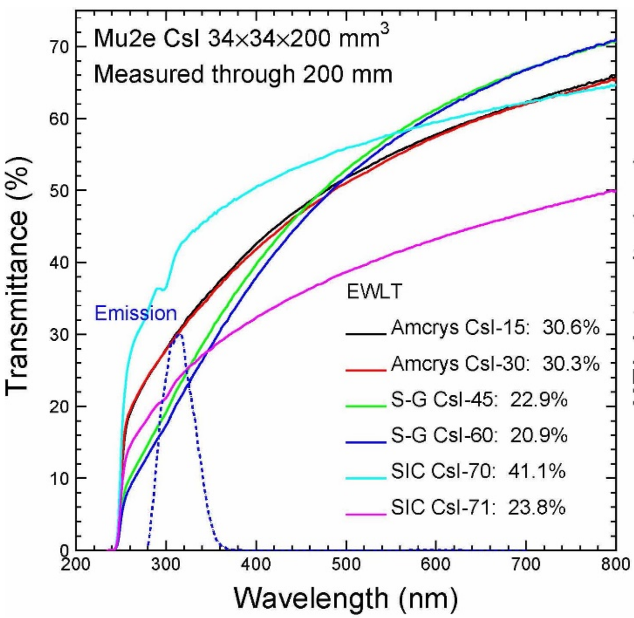
# CsI Specification

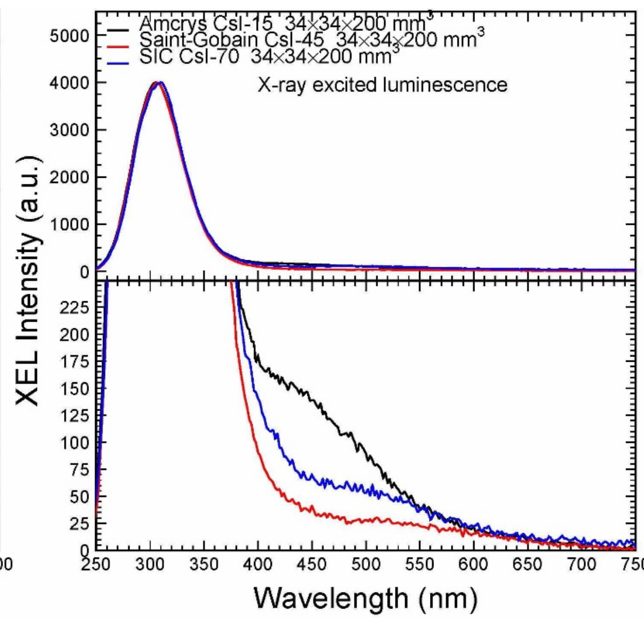
- Specifications are defined according to samples characterized:
  - Kharkov (Ukraine), Opto Materials (Italy) and SICCAS (China);
- Crystal lateral dimension: ±100 μ, length: ±100 μ.
- Scintillation properties measured by a bi-alkali PMT with air gap coupled to the crystal wrapped with two layers of 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 Noise (RIN) @1.8 rad/h: **< 0.6 MeV**.

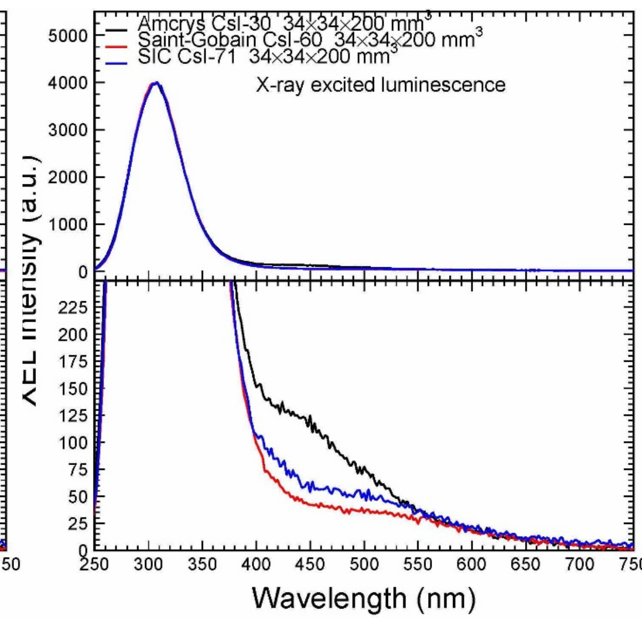
# 36 CsI Crystals from Three Vendors

# Initial Performance of Six CsI Crystals

| Crystal ID | Batch Number | Coupling end | EWLT (%) | F/T (%)-1st | F/T (%)-2rd | LRU (%)-1st | LRU (%)-2rd |
|---|---|---|---|---|---|---|---|
| C0015 | Amcrys-007 | a | 30.6 | **68.2** | **69.0** | 1.65 | 0.98 |
| C0030 | Amcrys-001 | a | 30.3 | 76.6 | 77.0 | 2.40 | 1.49 |
| C0045 | SG-A11827 | a | 22.9 | 98.9 | 98.7 | 0.92 | 0.92 |
| C0060 | SG-A11804 | a | 20.9 | 98.3 | 97.3 | 1.96 | 1.08 |
| C0070 | SIC-2016 A20 | a | 41.1 | 93.0 | 92.6 | 1.39 | 2.04 |
| C0071 | SIC-2016 A23 | a | 23.8 | 97.1 | 95.8 | **5.63** | **5.61** |

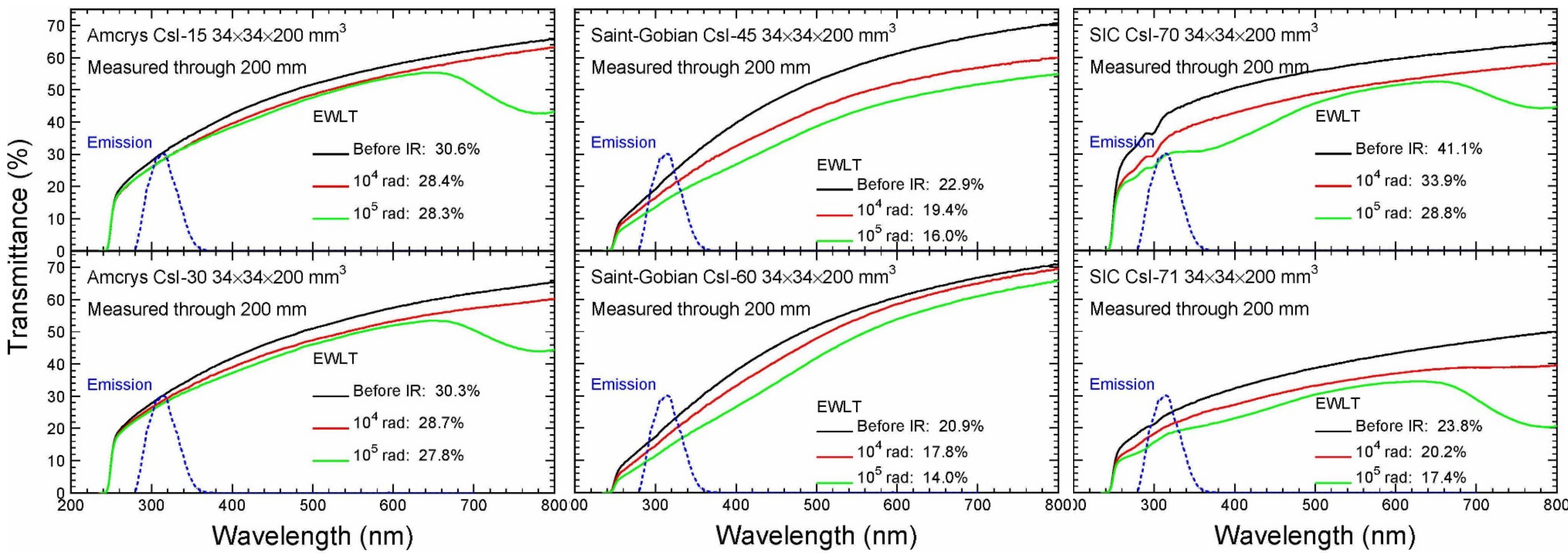


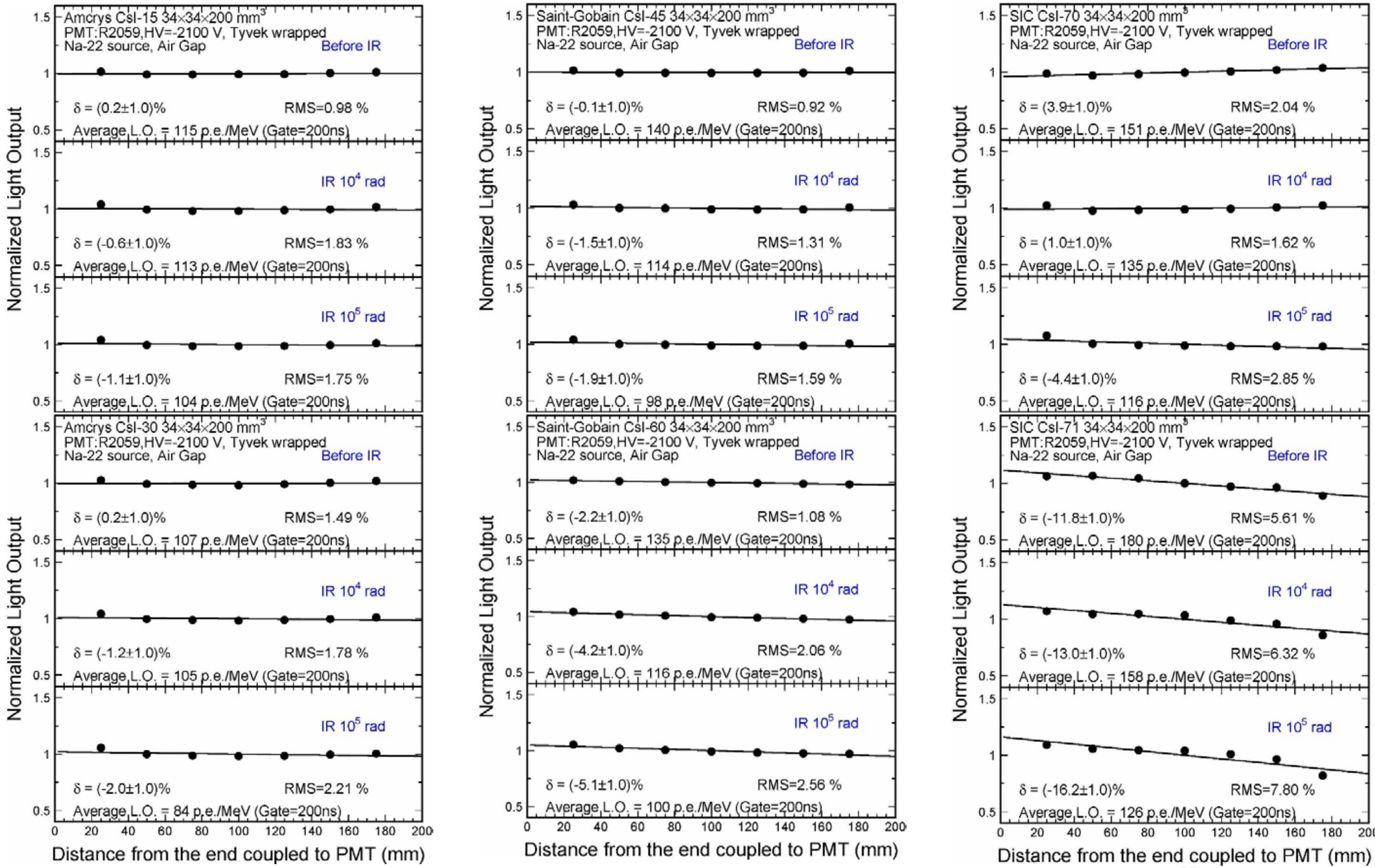



# Longitudinal Transmittance

While initial longitudinal transmittance spectra (LT) are surface dependent, variations of the LT spectrum and the numerical values of emission weighted LT may be used to represent CsI radiation damage



# Light Output & Response Uniformity

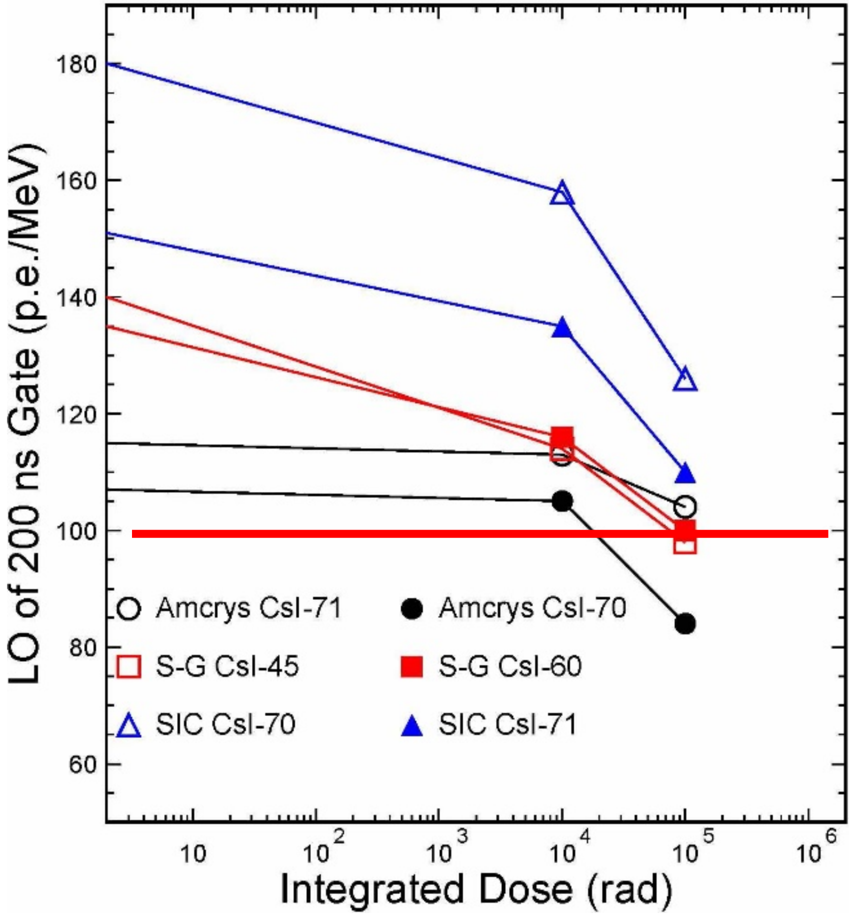


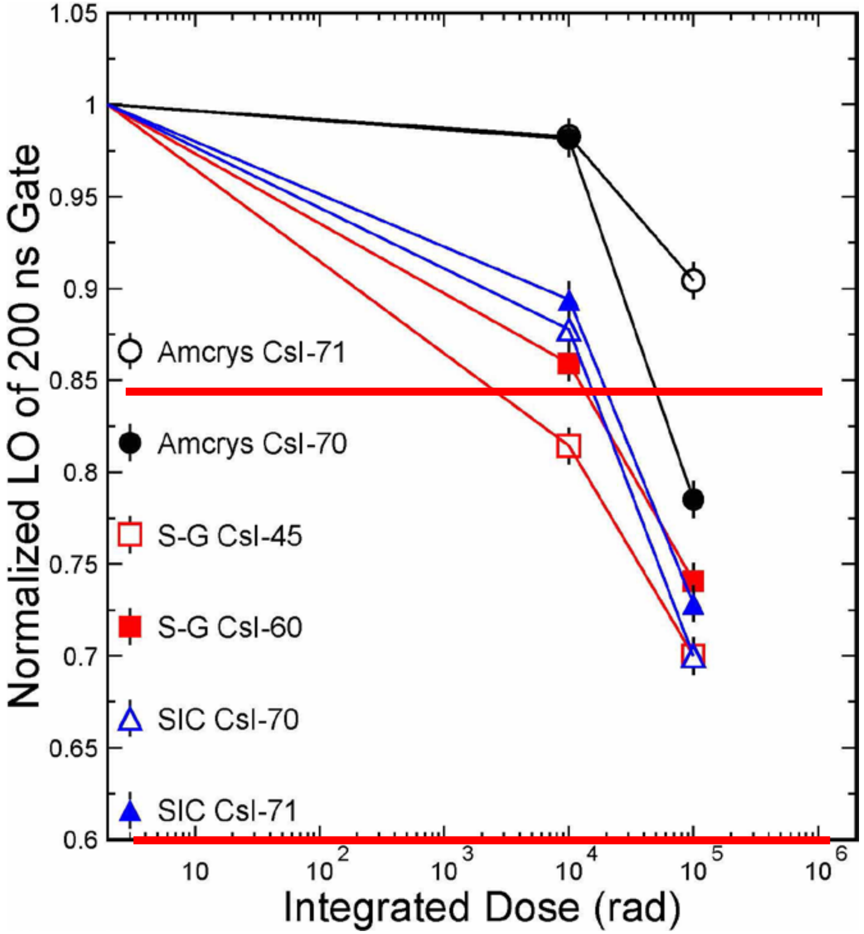
# Radiation Damage Test Results

| Crystal ID | Batch Number | Dose (krad) | EWLT (%) | Normalized EWLT (%) | L.O. (p.e./MeV) | Normalized L.O. (%) | E.R. (%) | F/T (%) | LRU (%) | δ (%) |
|---|---|---|---|---|---|---|---|---|---|---|
| C0015 | Amcrys-007 | 0 | 30.6 | 100 | 115 | 100 | 38 | **69.0** | 0.98 | 0.2 |
| | | 10 | 28.4 | 92.8 | 113 | 98.1 | 38 | **70.6** | 1.83 | -0.6 |
| | | 100 | 28.3 | 92.5 | 104 | 90.2 | 39 | **73.2** | 1.75 | -1.1 |
| C0030 | Amcrys-001 | 0 | 30.3 | 100 | 107 | 100 | 40 | 77.0 | 1.49 | 0.2 |
| | | 10 | 28.7 | 94.7 | 105 | 98.4 | 39 | 78.4 | 1.78 | -1.2 |
| | | 100 | 27.8 | 91.7 | 84 | 79.7 | 41 | 80.5 | 2.21 | -2.0 |
| C0045 | SG-A11827 | 0 | 22.9 | 100 | 140 | 100 | 34 | 98.7 | 0.92 | -0.1 |
| | | 10 | 19.4 | 84.7 | 114 | **81.2** | 38 | 98.2 | 1.31 | -1.5 |
| | | 100 | 16.0 | 69.9 | 98 | 69.6 | 41 | 100.0 | 1.59 | -1.9 |
| C0060 | SG-A11804 | 0 | 20.9 | 100 | 135 | 100 | 34 | 97.3 | 1.08 | -2.2 |
| | | 10 | 17.8 | 85.2 | 116 | 85.7 | 38 | 97.8 | 2.06 | -4.2 |
| | | 100 | 14.0 | 67.0 | 100 | 73.8 | 41 | 99.9 | 2.56 | -5.1 |
| C0070 | SIC-2016 A20 | 0 | 41.1 | 100 | 151 | 100 | 35 | 92.6 | 2.04 | 3.9 |
| | | 10 | 33.9 | 82.5 | 135 | 89.3 | 37 | 90.0 | 1.62 | 1.0 |
| | | 100 | 28.8 | 70.1 | 116 | 77.1 | 40 | 91.4 | 2.85 | -4.4 |
| C0071 | SIC-2016 A23 | 0 | 23.8 | 100 | 180 | 100 | 33 | 95.8 | **5.61** | -11.8 |
| | | 10 | 20.2 | 84.9 | 158 | 87.5 | 37 | 98.4 | **6.32** | -13.0 |
| | | 100 | 17.4 | 73.1 | 126 | 69.9 | 42 | 98.3 | **7.80** | -16.2 |

# CsI Light Output

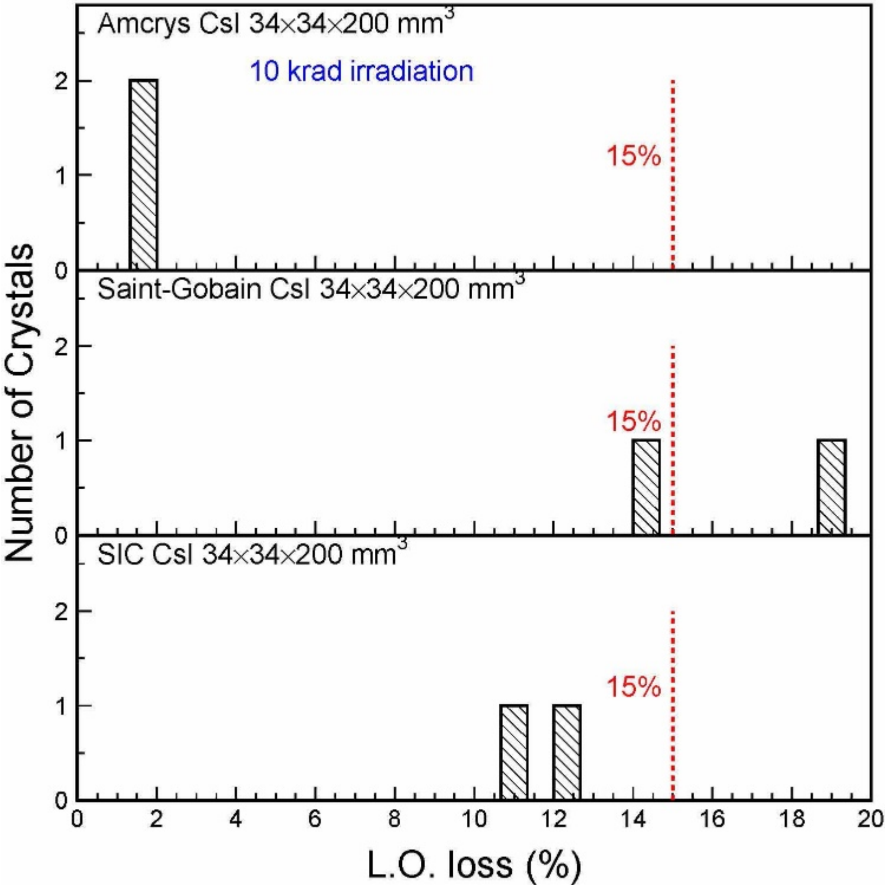
Most CsI with LO > 100 p.e./MeV after 100 krad
All satisfy radiation spec, except S-G 45 failed 10k

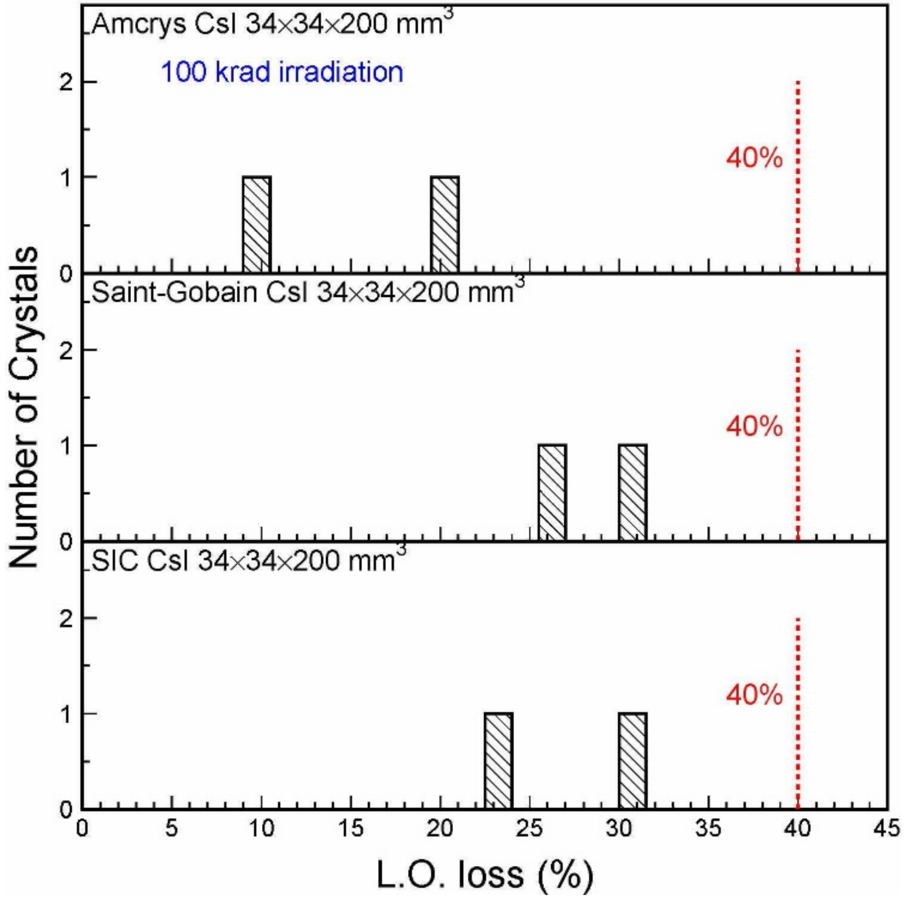


# Light Output Degradation by Vendors

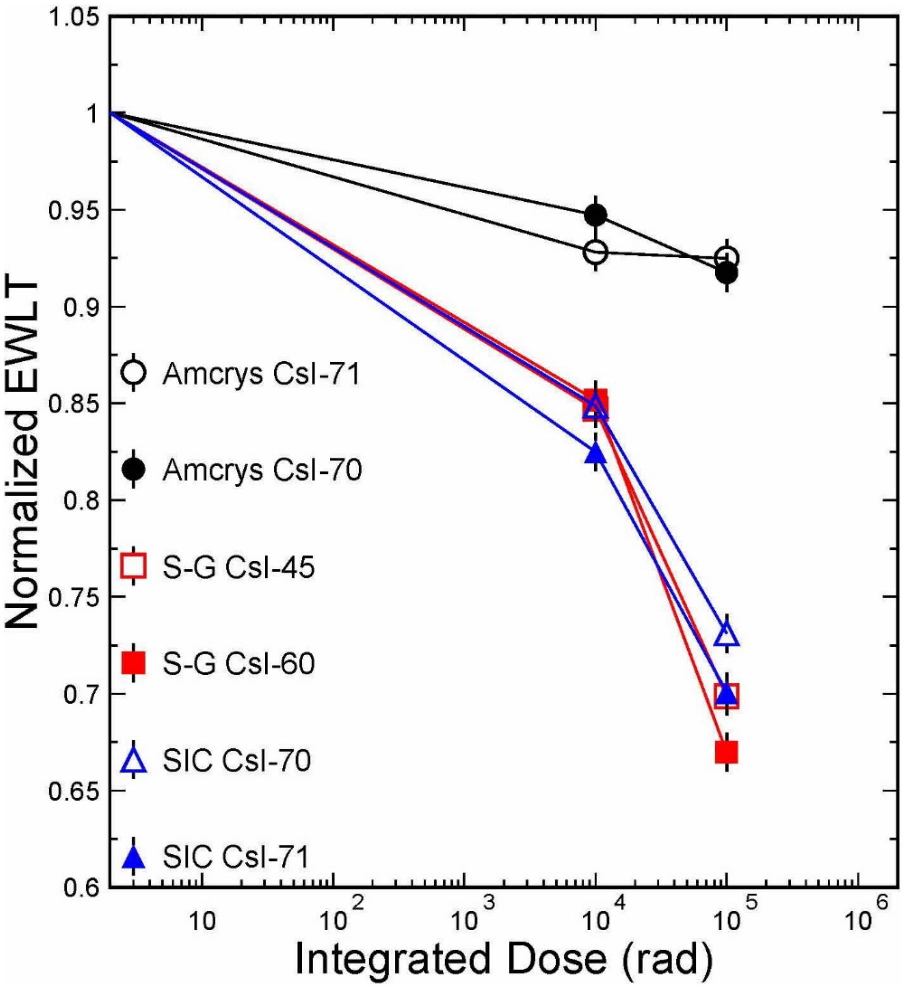
All satisfy radiation spec except S-G 45 after 10 krad
Rank: Kharkov, SIC and Saint-Gobain

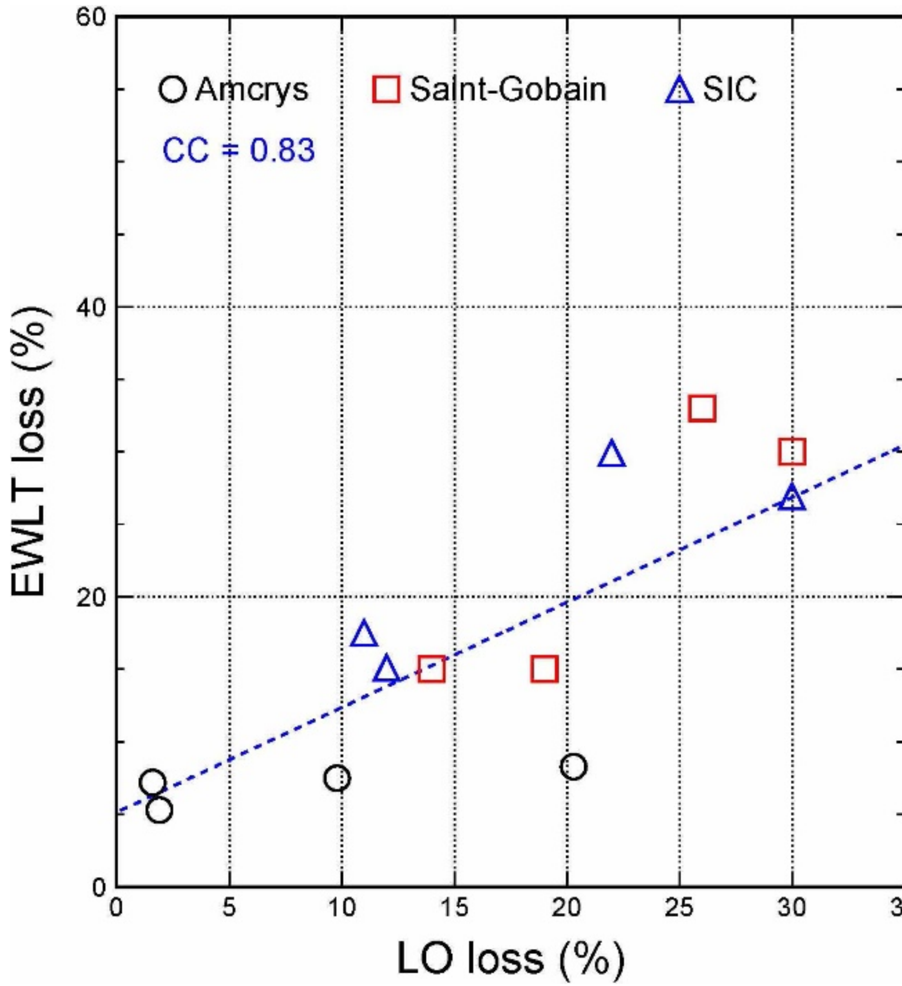


# EWLT Loss & Correlation with Light Output Loss

**Good correlation between variations of LT and LO**



# Summary: Radiation Induced Light Output Loss

- Gamma-ray induced radiation damages in both transmittance and light output are measured after 10 and 100 krad for six Mu2e preproduction CsI crystals.
- All crystals meet the Mu2e radiation damage specifications, except one Saint-Gobain sample (#45) which does not meet damage spec after 10 krad but meets that after 100 krad.
- Most crystals have light output larger than 100 p.e./MeV after 100 krad, promising a robust CsI calorimeter.
- Good correlation observed between variations of longitudinal transmittance and light output indicates that light monitoring is useful for crystal calibration.

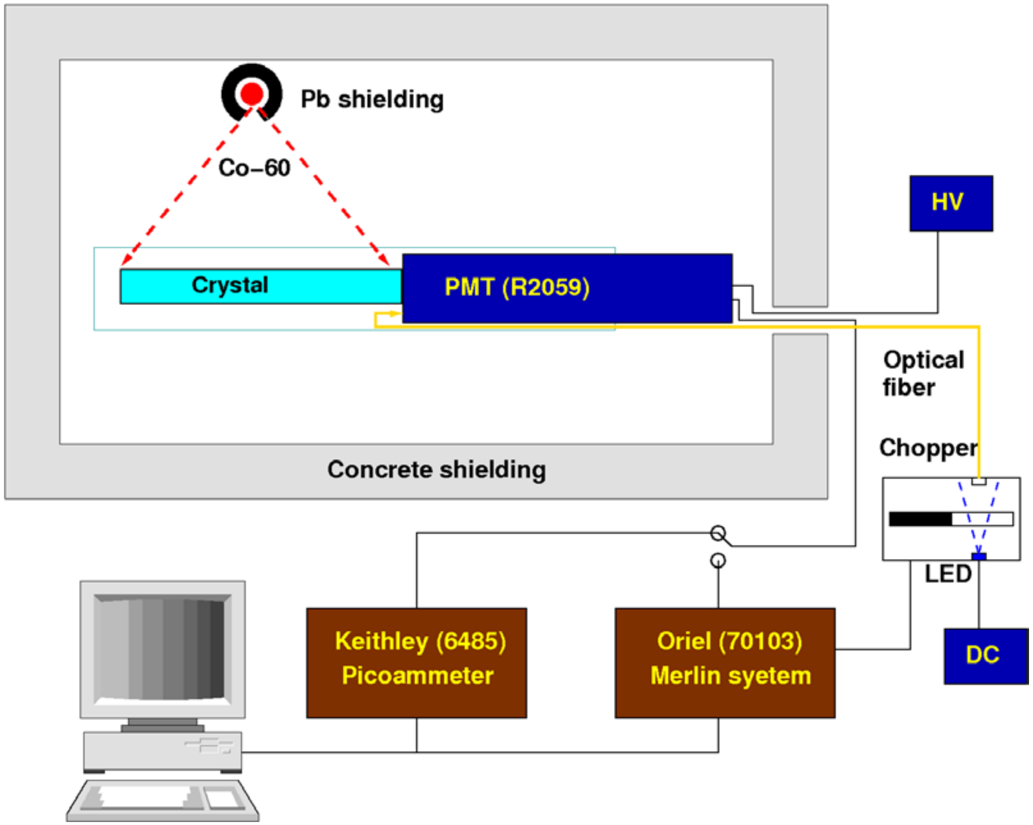
# QC on CsI Radiation Hardness

- Crystal vendors do not have a capability to test radiation hardness, so this will be our responsibility
- Crystals are grown in ingots, either a large size ingot or multiple small ones in each growth. We plan to test small samples, e.g. φ1” x 1”, cut from ingots from each growth for radiation damage QC.
- Crystals are delivered in batches. We plan to measure two randomly selected samples in each batch for radiation damage QC.
- Prompt feedback to, and communications with, vendors are important for QC on radiation hardness for mass produced CsI crystals.

# RIN Specification

- Specifications are defined according to samples characterized:
  - Kharkov (Ukraine), Opto Materials (Italy) and SICCAS (China);
- Crystal lateral dimension: ±100 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 Noise (RIN) @1.8 rad/h: **< 0.6 MeV**.

# Radiation Induced Photocurrent



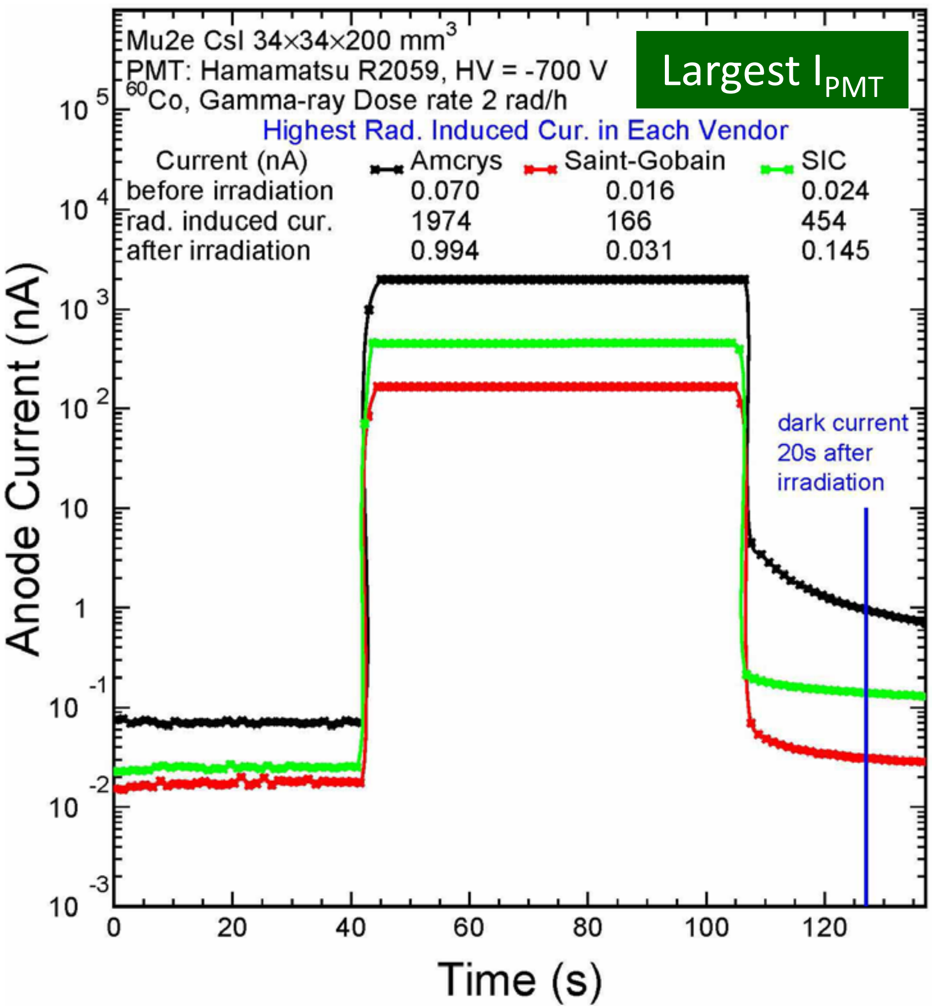

F is radiation induced photoelectron numbers per second, determined by the measured anode current in the PMT @ 2rad/h

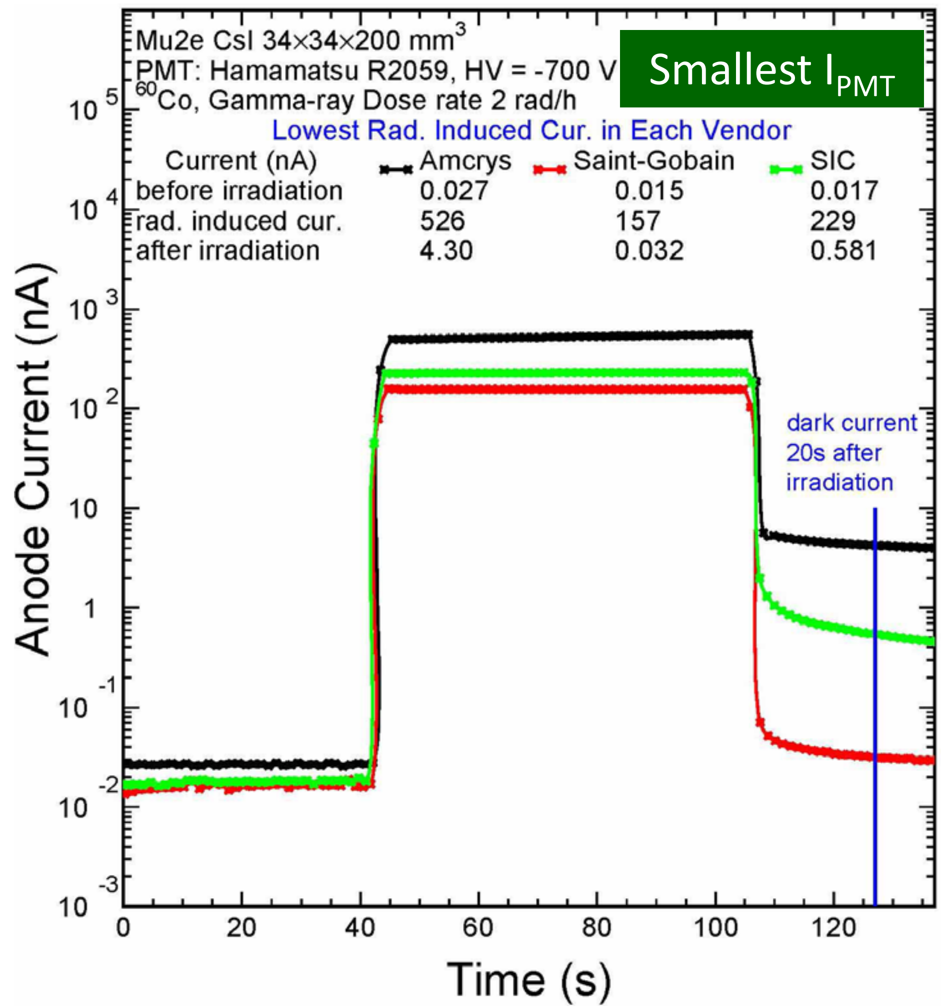
$$F = \frac{\frac{Photocurrent}{Charge_{electron} \times Gain_{PMT}}}{Dose\ rate_{\gamma-ray}\ or\ Flux_{neutron}}$$

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

# Photocurrent History

## Crystals with the highest and the lowest current



# AMCRYS (Measured at Caltech)

R2059 PMT @-700 V (Gain 263) with air gap to CsI crystals with Tyvek @ 2 rad/h and 200 ns

| Crystal ID | Batch Number | Coupling end | L.O. (p.e./MeV) | Dark cur. before irrad. (nA) | Photo cur. @ 2 rad/h (nA) | F (p.e./s/rad/hr) | σ (MeV) |
|---|---|---|---|---|---|---|---|
| ~~C0013~~ | ~~011~~ | a | 148 | 0.070 | 1974 | $2.35\times10^{10}$ | **0.621** |
| ~~C0015~~ | ~~007~~ | a | 113 | 0.069 | 1913 | $2.27\times10^{10}$ | **0.801** |
| ~~C0016~~ | ~~013~~ | b | 134 | 0.069 | 1938 | $2.30\times10^{10}$ | **0.679** |
| ~~C0019~~ | ~~015~~ | a | 125 | 0.068 | 1947 | $2.31\times10^{10}$ | **0.730** |
| ~~C0023~~ | ~~024~~ | a | 117 | 0.067 | 1945 | $2.31\times10^{10}$ | **0.780** |
| C0025 | 022 | b | 145 | 0.063 | 1764 | $2.10\times10^{10}$ | 0.599 |
| C0026 | 020 | b | 132 | 0.037 | 936 | $1.11\times10^{10}$ | 0.479 |
| ~~C0027~~ | ~~006~~ | b | 139 | 0.066 | 1895 | $2.25\times10^{10}$ | **0.648** |
| ~~C0030~~ | ~~001~~ | a | 105 | 0.063 | 1767 | $2.10\times10^{10}$ | **0.828** |
| C0032 | 004 | b | 122 | 0.037 | 923 | $1.10\times10^{10}$ | 0.515 |
| ~~C0034~~ | ~~012~~ | a | 127 | 0.068 | 1913 | $2.27\times10^{10}$ | **0.712** |
| C0036 | 019 | b | 134 | 0.027 | 526 | $6.24\times10^{9}$ | 0.354 |
| **Average** | | | **128** | **0.059** | **1620** | **1.92** | **0.645** |
| **RMS** | | | **9.6%** | **25.3%** | **30.2%** | **30.2%** | **0.136** |

# AMCRYS (Measured at LNF)

| Crystal | LY ($N_{pe}$/MeV) | I (A) | Mu2e flux (rad/h) | F ($N_{pe}$/s/dose) | $N_{pe}$ noise (200 ns) | RIN (keV) |
|---|---|---|---|---|---|---|
| C0014 | 138.53 | 3.09E-05 | 1.8 | 2.54E+10 | 9.14E+03 | **0.690** |
| C0017 | 135.91 | 2.96E-05 | 1.8 | 2.44E+10 | 8.77E+03 | **0.689** |
| C0018 | 141.06 | 3.11E-05 | 1.8 | 2.56E+10 | 9.20E+03 | **0.680** |
| C0020 | 131.46 | 2.97E-05 | 1.8 | 2.44E+10 | 8.79E+03 | **0.713** |
| C0021 | 135.30 | 3.08E-05 | 1.8 | 2.53E+10 | 9.11E+03 | **0.705** |
| C0022 | 159.07 | 3.07E-05 | 1.8 | 2.52E+10 | 9.07E+03 | **0.599** |
| C0024 | 152.79 | 1.80E-05 | 1.8 | 1.48E+10 | 5.32E+03 | **0.477** |
| C0028 | 137.97 | 3.04E-05 | 1.8 | 2.50E+10 | 8.98E+03 | **0.687** |
| C0029 | 116.33 | 7.22E-06 | 1.8 | 5.93E+09 | 2.14E+03 | **0.397** |
| C0031 | 126.84 | 1.35E-05 | 1.8 | 1.11E+10 | 3.99E+03 | **0.498** |
| C0033 | 162.04 | 2.87E-05 | 1.8 | 2.36E+10 | 8.49E+03 | **0.569** |
| C0035 | 125.36 | 1.33E-05 | 1.8 | 1.09E+10 | 3.93E+03 | **0.500** |

# Saint-Gobain (Measured at Caltech)

R2059 PMT @-700 V (Gain 263) with air gap to CsI crystals with Tyvek @ 2 rad/h and 200 ns

| Crystal ID | Batch Number | Coupling end | L.O. (p.e./MeV) | Dark cur. before irrad. (nA) | Photo cur. @ 2 rad/h (nA) | F (p.e./s/rad/hr) | σ (MeV) |
|---|---|---|---|---|---|---|---|
| C0045 | A11827 | a | 141 | 0.016 | 166 | $1.97\times10^9$ | 0.189 |
| C0046 | A11825 | b | 142 | 0.015 | 165 | $1.97\times10^9$ | 0.187 |
| C0048 | A11823 | b | 135 | 0.015 | 163 | $1.94\times10^9$ | 0.196 |
| C0049 | A11819 | b | 142 | 0.017 | 165 | $1.96\times10^9$ | 0.187 |
| C0051 | A11826 | a | 138 | 0.015 | 157 | $1.86\times10^9$ | 0.188 |
| C0057 | A11812 | a | 137 | 0.015 | 164 | $1.95\times10^9$ | 0.194 |
| C0058 | A11805 | b | 134 | 0.016 | 157 | $1.87\times10^9$ | 0.194 |
| C0060 | A11804 | a | 136 | 0.016 | 166 | $1.97\times10^9$ | 0.196 |
| C0062 | A11811 | b | 138 | 0.015 | 165 | $1.96\times10^9$ | 0.192 |
| C0063 | A11807 | a | 136 | 0.013 | 162 | $1.92\times10^9$ | 0.193 |
| C0065 | A11815 | a | 134 | 0.027 | 160 | $1.90\times10^9$ | 0.195 |
| C0066 | A11808 | a | 136 | 0.017 | 160 | $1.90\times10^9$ | 0.192 |
| **Average** | | | **137** | **0.016** | **162** | **1.93** | **0.192** |
| **RMS** | | | **2.1%** | **20.0%** | **2.0%** | **2.0%** | **0.003** |

# Saint-Gobain (Measured at LNF)

| Crystal | LY ($N_{pe}$/MeV) | I (A) | Mu2e flux (rad/h) | F ($N_{pe}$/s/dose) | $N_{pe}$ noise (200 ns) | RIN (keV) |
|---|---|---|---|---|---|---|
| C0044 | 139.33 | 3.14E-06 | 1.8 | 2.58E+09 | 927.9130 | **0.219** |
| C0047 | 146.83 | 3.08E-06 | 1.8 | 2.53E+09 | 910.6729 | **0.206** |
| C0050 | 145.10 | 3.23E-06 | 1.8 | 2.65E+09 | 954.0245 | **0.213** |
| C0052 | 149.29 | 3.36E-06 | 1.8 | 2.76E+09 | 994.6348 | **0.211** |
| C0053 | 131.15 | 2.98E-06 | 1.8 | 2.45E+09 | 880.4687 | **0.226** |
| C0054 | 147.13 | 3.43E-06 | 1.8 | 2.82E+09 | 1014.5097 | **0.216** |
| C0055 | 158.96 | 3.44E-06 | 1.8 | 2.83E+09 | 1018.0346 | **0.201** |
| C0056 | 148.97 | 3.22E-06 | 1.8 | 2.65E+09 | 953.4123 | **0.207** |
| C0059 | 158.77 | 3.63E-06 | 1.8 | 2.98E+09 | 1073.3537 | **0.206** |
| C0061 | 140.55 | 3.02E-06 | 1.8 | 2.48E+09 | 892.8857 | **0.213** |
| C0064 | 139.52 | 3.18E-06 | 1.8 | 2.61E+09 | 940.1555 | **0.220** |
| C0067 | 149.25 | 3.36E-06 | 1.8 | 2.76E+09 | 993.4844 | **0.211** |

# SICCAS (Measured at Caltech)

R2059 PMT @-700 V (Gain 263) with air gap to CsI crystals with Tyvek @ 2 rad/h and 200 ns

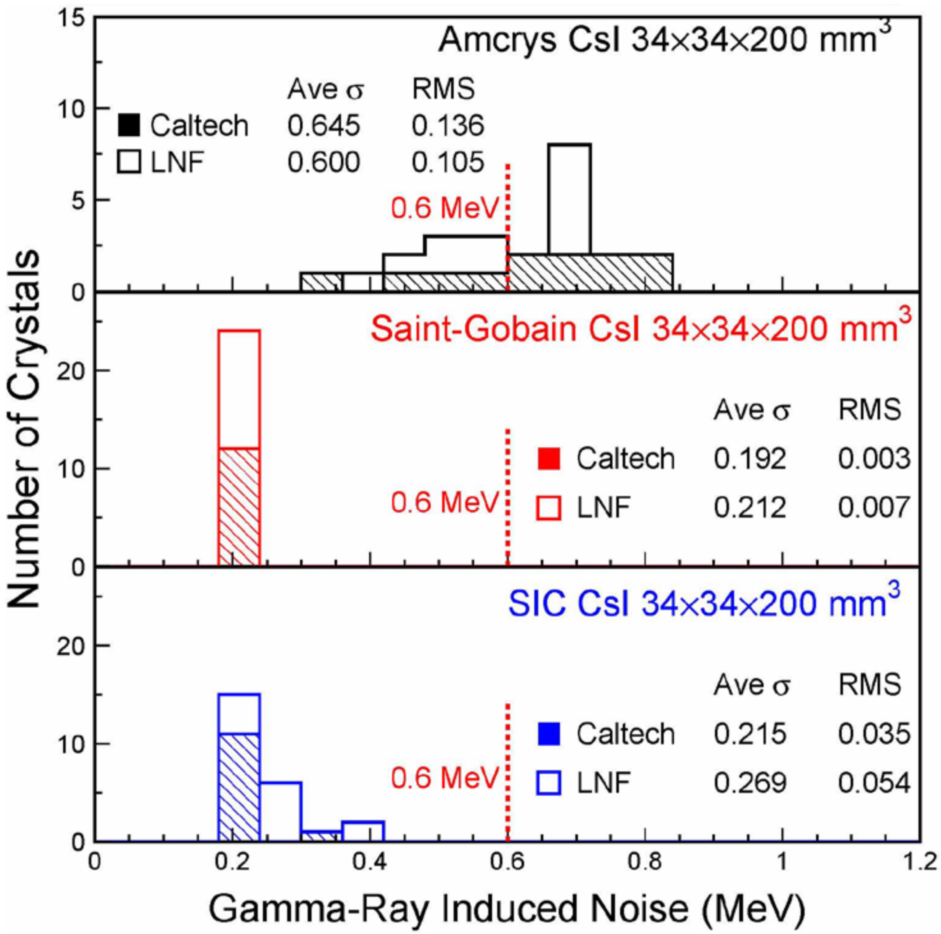
| Crystal ID | Batch Number | Coupling end | L.O. (p.e./MeV) | Dark cur. before irrad. (nA) | Photo cur. @ 2 rad/h (nA) | F (p.e./s/rad/hr) | σ (MeV) |
|---|---|---|---|---|---|---|---|
| C0037 | 2016 A13 | a | 150 | 0.019 | 233 | $2.77\times10^9$ | 0.211 |
| C0038 | 2016 A14 | b | 154 | 0.018 | 239 | $2.85\times10^9$ | 0.208 |
| C0039 | 2016 A15 | b | 153 | 0.018 | 239 | $2.84\times10^9$ | 0.209 |
| C0040 | 2016 A16 | a | 152 | 0.019 | 234 | $2.78\times10^9$ | 0.208 |
| C0041 | 2016 A17 | a | 163 | 0.022 | 241 | $2.87\times10^9$ | 0.197 |
| C0042 | 2016 A18 | b | 154 | 0.017 | 237 | $2.82\times10^9$ | 0.207 |
| C0043 | 2016 A19 | a | 136 | 0.024 | 454 | $5.40\times10^9$ | 0.324 |
| C0068 | 2016 A24 | b | 172 | 0.020 | 295 | $3.51\times10^9$ | 0.207 |
| C0070 | 2016 A20 | a | 153 | 0.017 | 229 | $2.72\times10^9$ | 0.205 |
| C0071 | 2016 A23 | a | 183 | 0.025 | 417 | $4.95\times10^9$ | 0.231 |
| C0072 | 2016 A22 | a | 174 | 0.018 | 245 | $2.92\times10^9$ | 0.186 |
| C0073 | 2016 A21 | a | 176 | 0.023 | 257 | $3.05\times10^9$ | 0.188 |
| **Average** | | | **160** | **0.020** | **277** | **3.29** | **0.215** |
| **RMS** | | | **8.2%** | **13.1%** | **26.5%** | **26.5%** | **0.035** |

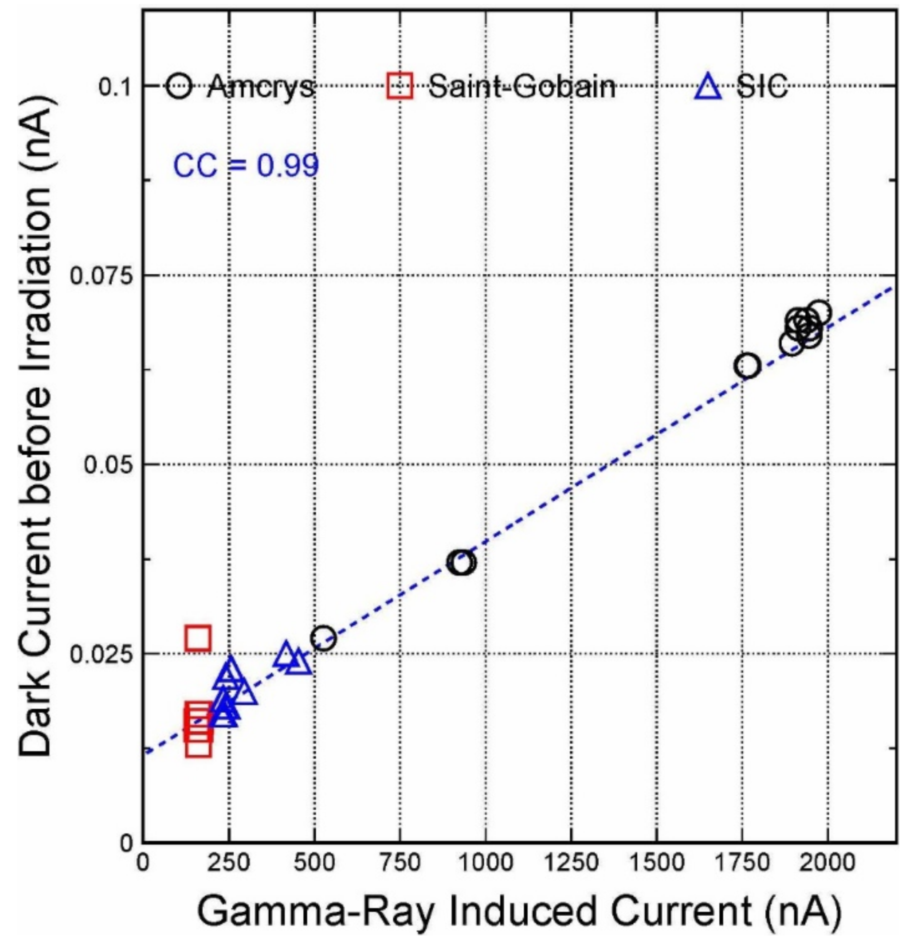
# SICCAS (Measured at LNF)

| Crystal | LY ($N_{pe}$/MeV) | I (A) | Mu2e flux (rad/h) | F ($N_{pe}$/s/dose) | $N_{pe}$ noise (200 ns) | RIN (keV) |
|---|---|---|---|---|---|---|
| C0001 | 163.2 | 5.24E-06 | 1.8 | 4.30E+09 | 1.55E+03 | **0.241** |
| C0002 | 145.9 | 4.63E-06 | 1.8 | 3.81E+09 | 1.37E+03 | **0.254** |
| C0003 | 149.5 | 6.72E-06 | 1.8 | 5.52E+09 | 1.99E+03 | **0.298** |
| C0004 | 158.3 | 4.38E-06 | 1.8 | 3.60E+09 | 1.29E+03 | **0.227** |
| C0005 | 163.2 | 5.27E-06 | 1.8 | 4.33E+09 | 1.56E+03 | **0.242** |
| C0006 | 157.8 | 4.50E-06 | 1.8 | 3.70E+09 | 1.33E+03 | **0.231** |
| C0007 | 156.3 | 4.60E-06 | 1.8 | 3.78E+09 | 1.36E+03 | **0.236** |
| C0008 | 143.9 | 4.69E-06 | 1.8 | 3.85E+09 | 1.39E+03 | **0.259** |
| C0009 | 160.0 | 5.02E-06 | 1.8 | 4.12E+09 | 1.48E+03 | **0.241** |
| C0010 | 140.3 | 3.62E-06 | 1.8 | 2.97E+09 | 1.07E+03 | **0.233** |
| C0011 | 148.1 | 1.07E-05 | 1.8 | 8.77E+09 | 3.16E+03 | **0.380** |
| C0012 | 143.5 | 1.44E-05 | 1.8 | 8.58E+09 | 3.09E+03 | **0.387** |

# RIN by Vendors & Correlation Between Currents

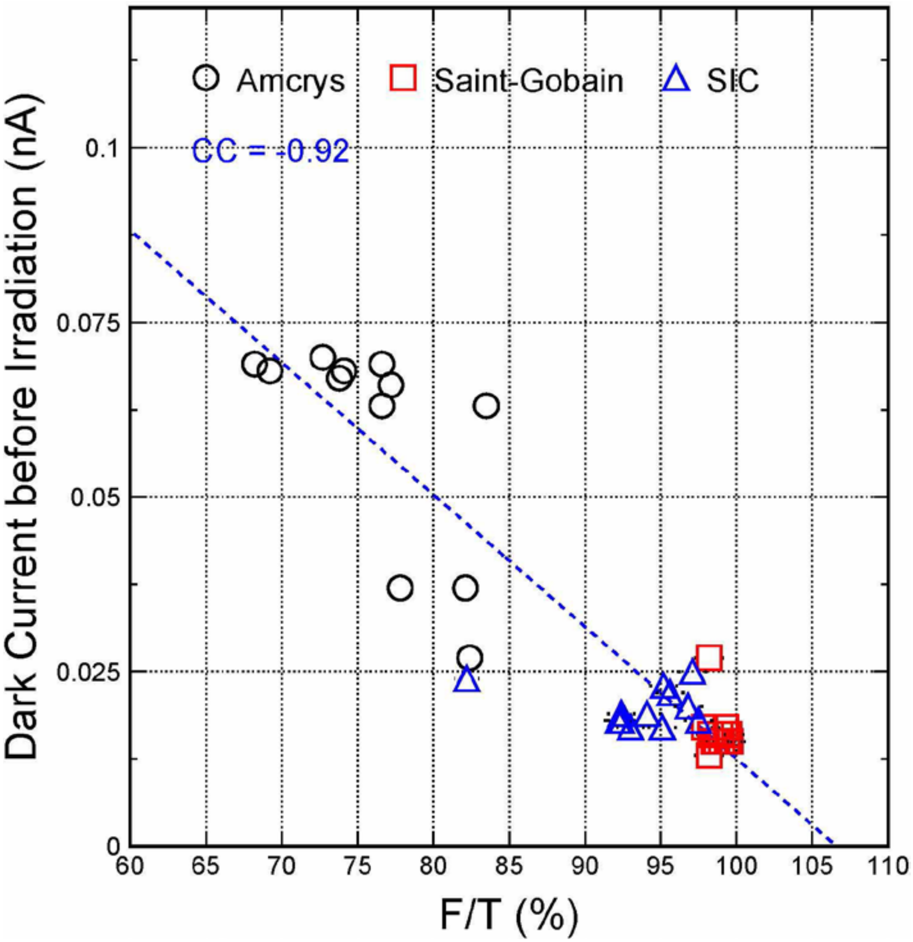
**Rank of RIN: SG, SIC, AMCRYS; Highly correlated currents**

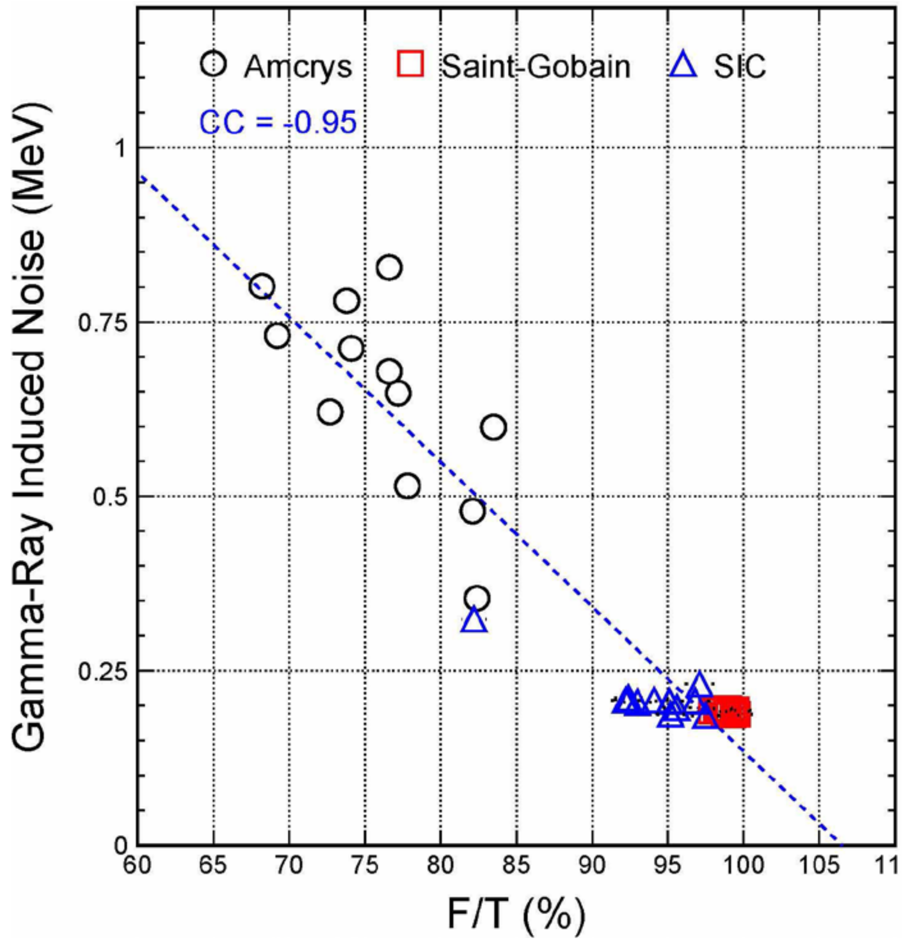


# Correlations: Currents, RIN & F/T

**Dark currents and RIN are highly correlated with F/T**



# Summary: Radiation Induced Noise

- Radiation induced readout noise are measured for all 72 preproduction CsI crystals. All crystals from Saint-Gobain and SICCAS meet the Mu2e spec. About half crystals from AMCRYS do not.

- Excellent correlations between the dark current, the radiation induced current, the radiation induced readout noise and the F/T ratio are confirmed. Eliminating slow component in crystals will reduce RIN.

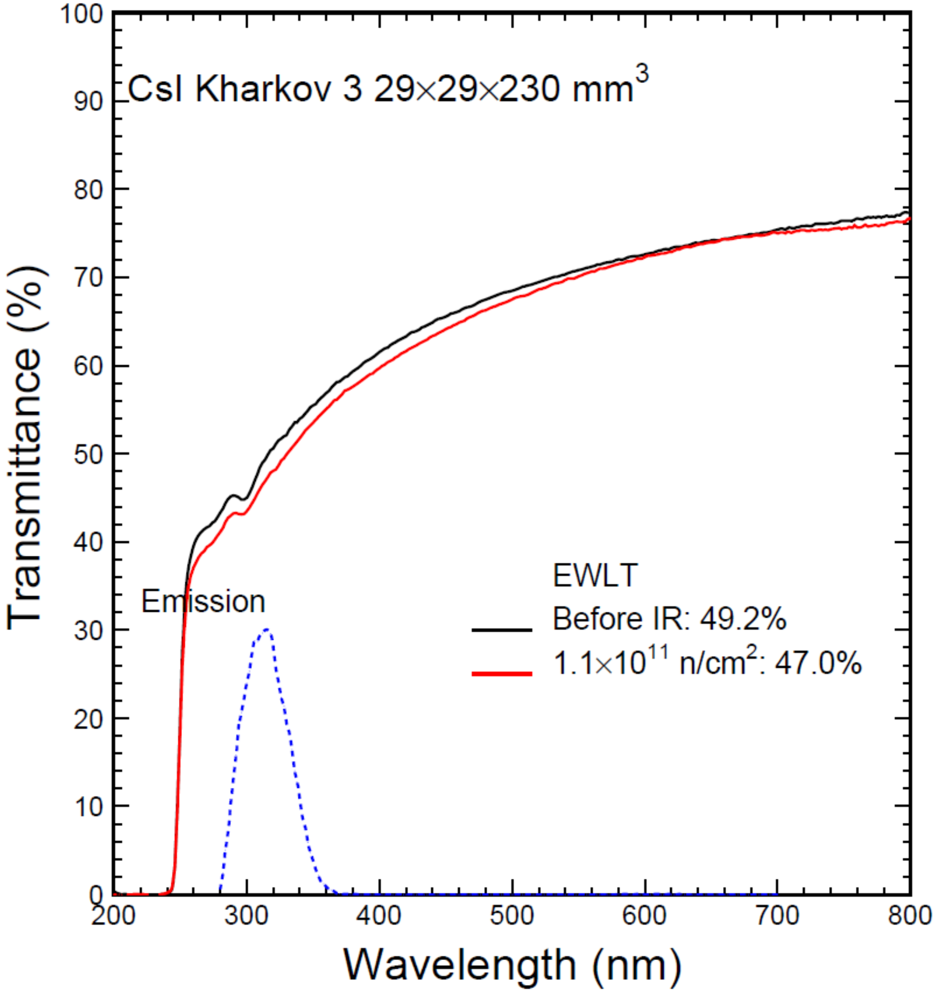
- QC on RIN: measurement will be carried out for each CsI crystal.

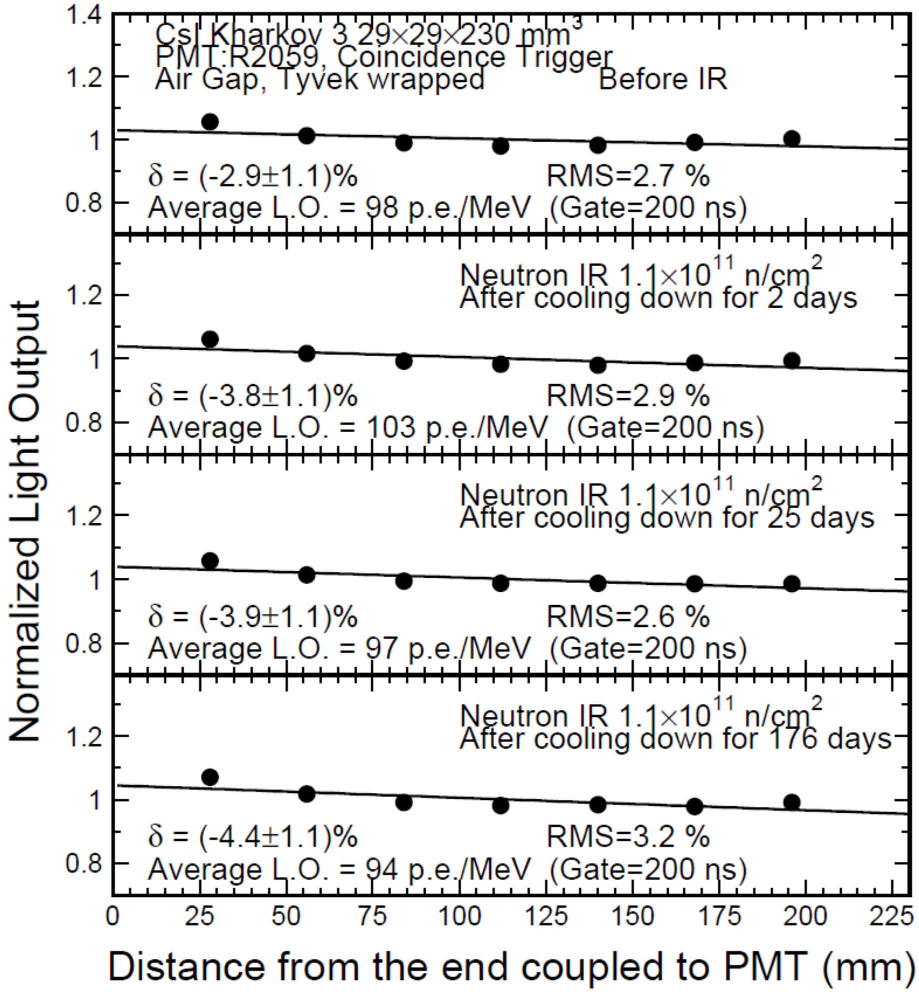
# Conclusion

- A total of 72 preproduction crystals have been procured from three vendors: AMCRYS, SICCAS and Saint-Gobain, and have been evaluated at Caltech and LNF.
- All six CsI crystals tested satisfy Mu2e radiation hardness spec, except one Saint-Gobain sample (#45) which does not meet damage spec after 10 krad but meets that after 100 krad. QC on radiation hardness will be carried out for selected samples in each delivery batch.
- Radiation induced readout noise are measured for 72 CsI crystals. All crystals from Saint-Gobain and SICCAS meet the Mu2e spec. About half crystals from AMCRYS do not. QC on RIN will be enforced for every CsI crystal delivered.
- Neutron induced radiation damage and readout noise are much smaller that that from ionization dose.

# Neutrons Induced Damage

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

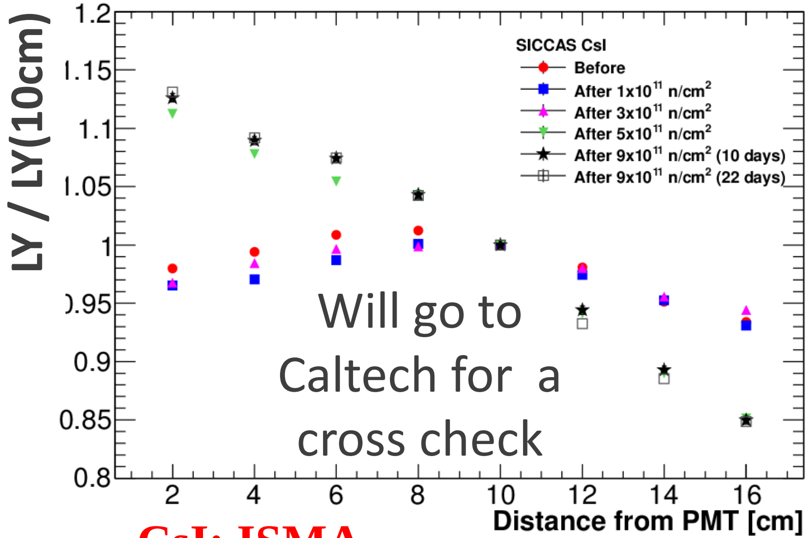


# Neutron Irradiation at FNG

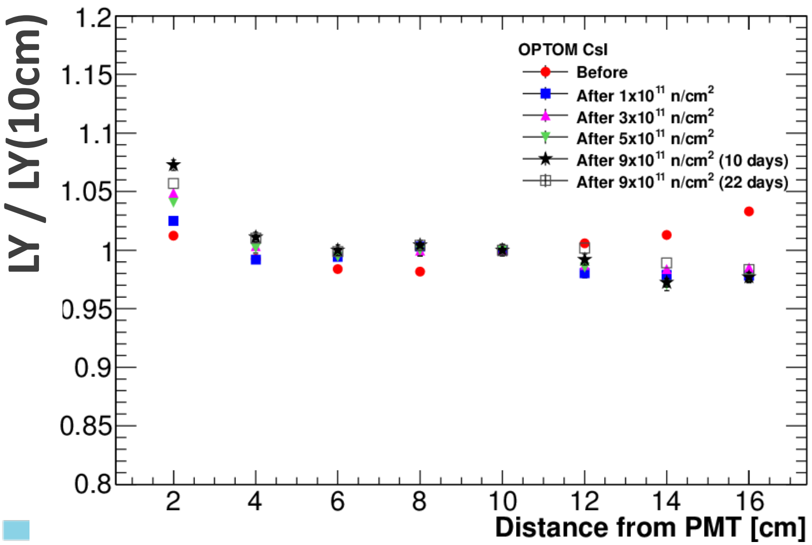
- Neutrons at FNG, ENEA
- Up to $9 \times 10^{11}$ n/cm$^2$
- No large variation in LY
- SICCAS deterioration in LRU

**CsI: SICCAS**

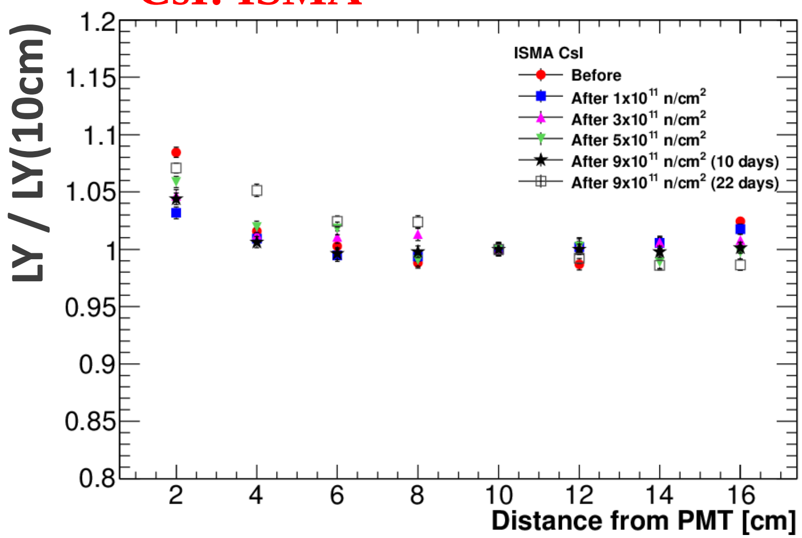



Will go to Caltech for a cross check

**CsI: OPTO MATERIALS**

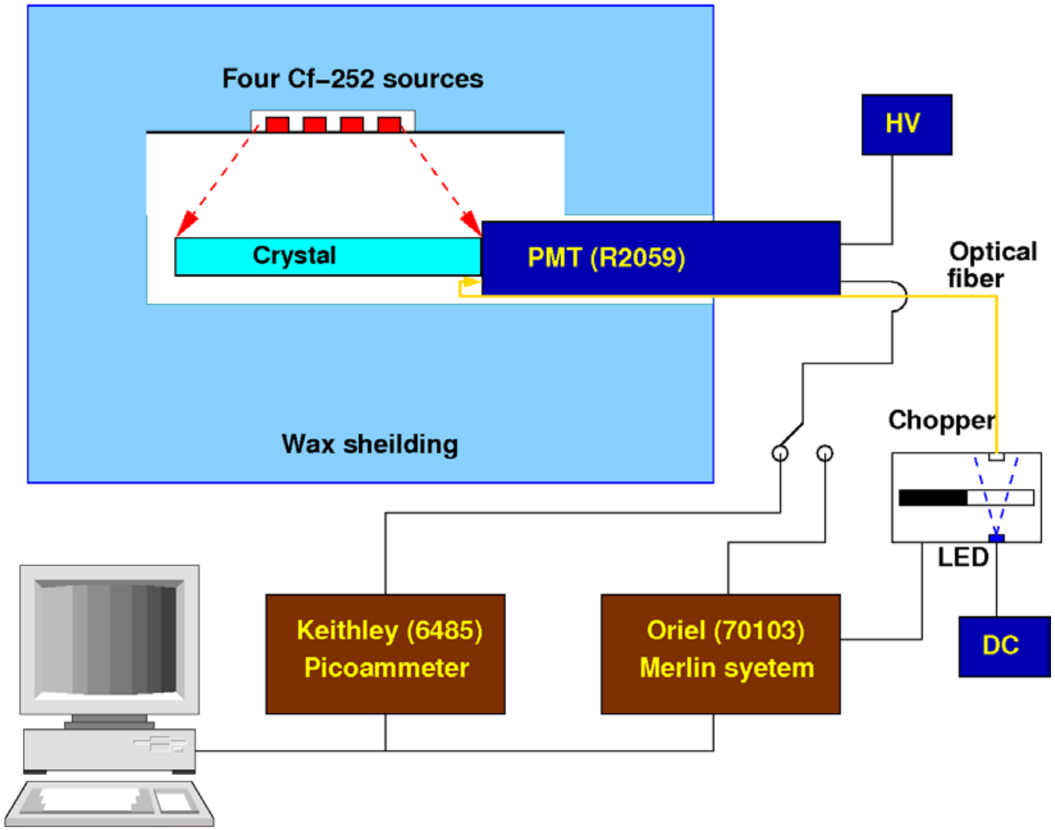


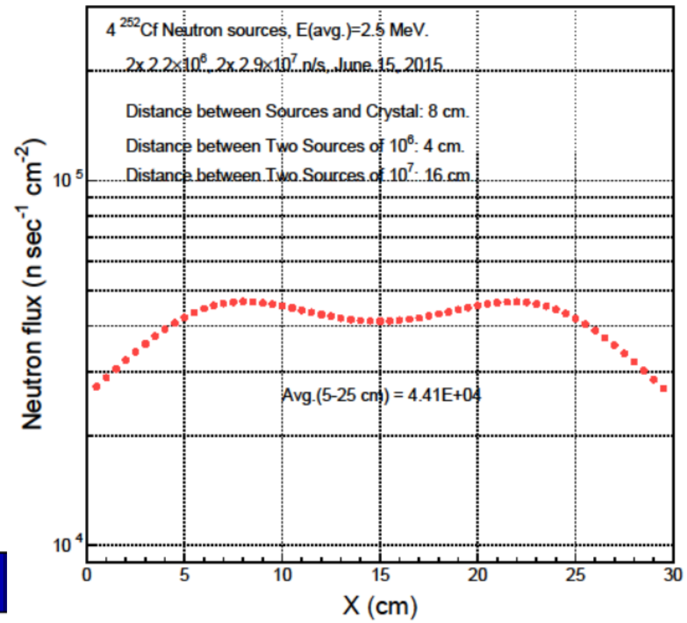

**CsI: ISMA**



# Neutron Induced Photo-Current

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

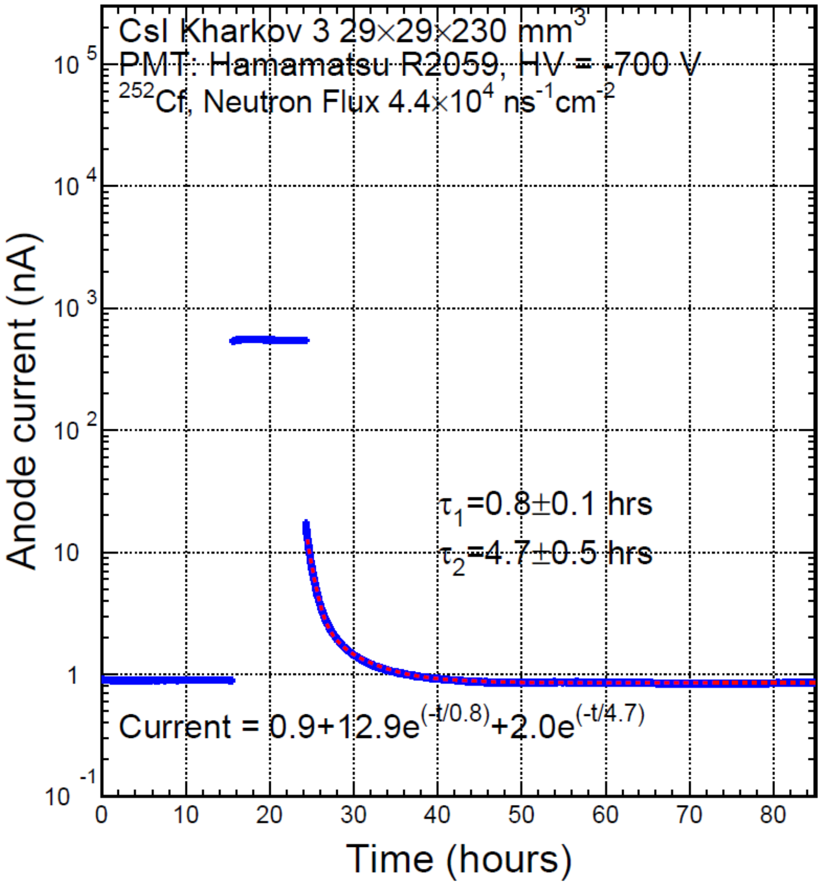


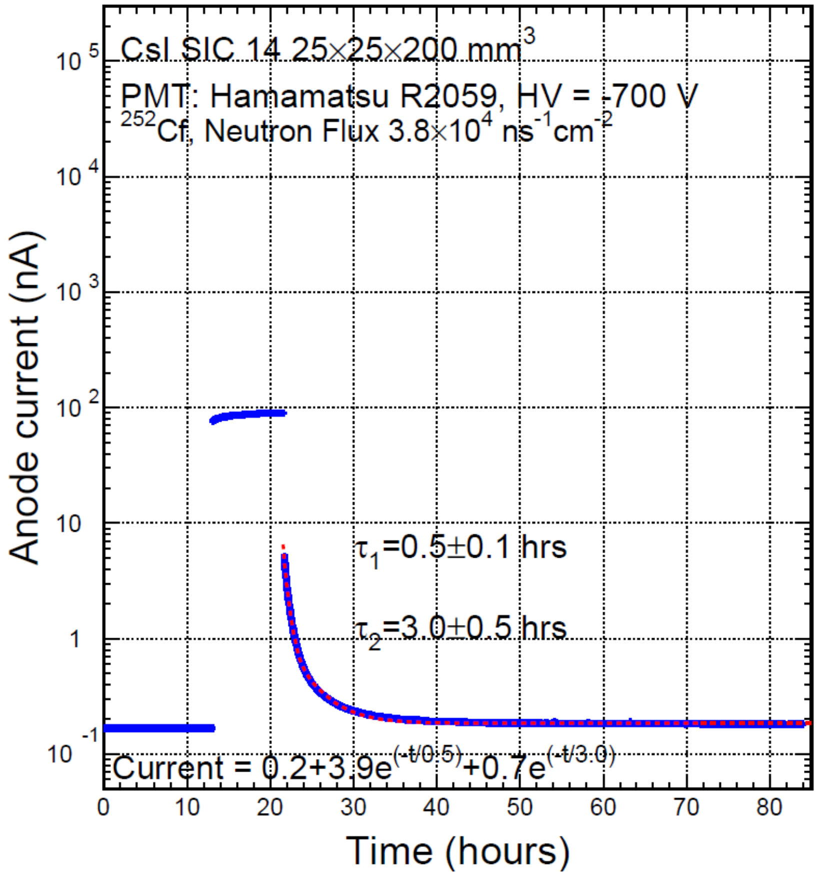

**Cf-252 has ɣ-ray background, so result is a upper limit**

# 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 | $1\times10^4$ | $3{,}02 \times 10^4$ | 60,3 | 75,4 |
| ISMA 12 | 103 | 4,61 | $1\times10^4$ | $1{,}94 \times 10^4$ | 38,9 | 60,5 |
| ISMA 20 | 103 | 5,35 | $1\times10^4$ | $2{,}25 \times 10^4$ | 45,1 | 65,2 |
| ISMA 21 | 103 | 7,28 | $1\times10^4$ | $3{,}07 \times 10^4$ | 61,4 | 76,0 |
| SICCAS 1 | 129 | 6,83 | $1\times10^4$ | $2{,}88 \times 10^4$ | 57,5 | 58,6 |
| SICCAS 2 | 126 | 7,58 | $1\times10^4$ | $3{,}19 \times 10^4$ | 63,8 | 63,4 |
| SICCAS 4 | 136 | 10,1 | $1\times10^4$ | $4{,}27 \times 10^4$ | 85,5 | 67,8 |
| OPTOM 2 | 93 | 7,65 | $1\times10^4$ | $3{,}22 \times 10^4$ | 64,4 | 86,3 |

**Thermal neutron induced noise is lower than that from fast neutrons**