Quality Assurance on Undoped CsI Crystals for the Mu2e Experiment

N. Atanov, V. Baranov, J. Budagov, Yu. I. Davydov, V. Glagolev, V. Tereshchenko, Z. Usubov, F. Cervelli, S. Di Falco, S. Donati, L. Morescalchi, E. Pedreschi, G. Pezzullo, F. Raffaelli, F. Spinella, F. Colao, M. Cordelli, G. Corradi, E. Diociaiuti, R. Donghia, S. Giovannella, F. Happacher, M. Martini, S. Miscetti, M. Ricci, A. Saputi, I. Sarra, B. Echenard, D. G. Hitlin, C. Hu, T. Miyashita, F. Porter, L. Zhang, R.-Y. Zhu, F. Grancagnolo, G. Tassielli, and P. Murat

***Abstract*— The Mu2e experiment is constructing a calorimeter consisting of 1348 undoped cesium iodide (CsI) crystals in two disks. Each crystal has a dimension of 34 × 34 × 200 mm^3 and is readout by a large-area silicon photomultipliers array. A series of technical specifications on mechanical and optical parameters was defined according to the calorimeter physics requirements. Preproduction CsI crystals were procured from three firms: Amcrys, Saint-Gobain, and Shanghai Institute of Ceramics. We report the quality assurance on crystal's scintillation properties and their radiation hardness against ionization dose and neutrons. With a fast decay time of about 30 ns and a light output of more than 100 p.e./MeV measured by a bialkali photomultiplier tube, undoped CsI crystals provide a cost-effective solution for Mu2e.**

***Index Terms*— Crystal, cesium iodide (CsI), energy resolution, fast total ratio, light output, light response uniformity, radiation hardness, radiation-induced noise.**

I. INTRODUCTION

AIMING at exploring lepton flavor violation, the Mu2e experiment [1] is constructing a calorimeter consisting of 1348 undoped cesium iodide (CsI) crystals of 34 × 34 × 200 mm^3 readout by a large-area silicon photomultipliers array [2]. With a fast decay time of about 30 ns and a light output of more than 100 p.e./MeV measured by a bialkali photomultiplier tube (PMT), undoped CsI crystals provide a cost-effective solution for Mu2e. Technical specifications are defined for crystals quality assurance according to physics requirements:

1) crystal dimension tolerance: ± 100 μm;
2) visual inspection: no cracks, chips, fingerprints, and free from inclusions and bubbles;
3) light output (LO) in 200 ns: >100 p.e./MeV;
4) full-width at half-maximum (FWHM) energy resolution for Na-22 peaks: $<45\%$;
5) light response uniformity (LRU): $<5\%$;
6) fast (200 ns)/total (3000 ns) ratio: $>75\%$;
7) radiation-induced noise (RIN) at 1.8 rad/h: <0.6 MeV;
8) normalized LO after 10/100 krad $>$ 85%/60%.

These specifications define crystal's mechanical, optical, and scintillation properties which would affect calorimeter performance. Crystal's longitudinal transmittance (LT) reveals optical absorption in the crystal bulk, so is a useful parameter for crystal quality control, particularly for investigations of radiation-induced absorption. Its numerical value, however, is affected by crystal's surface quality and microscopic scattering centers in the crystal bulk, which do not affect calorimeter performance directly. Since CsI transmittance is affected by its hygroscopic surface quality, so the Mu2e specification does not include a transmittance requirement. For birefringent crystals, such as lead tungstate ($PbWO_4$, PWO), LT is known to be different along different optical axes [3]. In this case, care should be taken to define different transmittance specifications for crystals grown along different optical axes.

In this paper, we report quality assurance on preproduction CsI crystals procured from three vendors: AMCRYS, Saint-Gobain (S-G) Corporation, and the Shanghai Institute of Ceramics (SIC), Shanghai, China. While scintillation properties, such as LO, FWHM energy resolution, LRU, F/T ratio, and RIN, were measured for all CsI crystals, radiation hardness was measured for selected samples. The measured data are compared to the Mu2e technical specifications.

II. SAMPLES AND MEASUREMENT DETAILS

A total of 72 preproduction CsI crystals of 34 × 34 × 200 mm^3 were procured from three vendors: AMCRYS,

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N. Atanov, V. Baranov, J. Budagov, Yu. I. Davydov, V. Glagolev, V. Tereshchenko, and Z. Usubov are with the Joint Institute for Nuclear Research, Dubna, Russia.

F. Cervelli, S. Di Falco, S. Donati, L. Morescalchi, E. Pedreschi, G. Pezzullo, F. Raffaelli, and F. Spinella are with INFN sezione di Pisa, Pisa, Italy.

F. Colao, M. Cordelli, G. Corradi, E. Diociaiuti, R. Donghia, S. Giovannella, F. Happacher, M. Martini, S. Miscetti, M. Ricci, A. Saputi, and I. Sarra are with Laboratori Nazionali di Frascati dell' INFN, Frascati, Italy.

B. Echenard, D. G. Hitlin, C. Hu, T. Miyashita, F. Porter, L. Zhang, and R.-Y. Zhu are with the Physics Department, California Institute of Technology, Pasadena, California USA (e-mail: zhu@hep.caltech.edu).

F. Grancagnolo and G. Tassielli are with INFN sezione di Lecce, Lecce, Italy.

P. Murat is with the Fermi National Accelerator Laboratory, Batavia, Illinois USA.

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Fig. 1. 36 CsI crystals of 34 × 34 × 200 mm^3 from Amcrys, S-G, and SIC.

S-G, and SIC with 24 crystals from each vendor. They were characterized at Caltech and National Laboratory of Frascati (LNF) with 36 in each laboratory. The results from two labs are consistent. Fig. 1 shows a photograph showing 36 preproduction crystals, arranged in an order of Amcrys, S-G, and SIC from the left to the right.

Crystals were wrapped with two layers of Tyvek paper of 150 μm with a selected end coupled to a bialkali PMT Hamamatsu R2059 via an air gap. The coupling end was chosen to provide a better LRU. Pulse height spectra were measured by using 0.511 MeV γ-rays from a ^{22}Na source with a systematic uncertainty for the peak determination of about 1%. The LO and FWHM resolution are defined as the average of seven points measured along the crystal length with 200-ns integration time.

The LRU is defined as the standard deviation (rms) of the seven points. The LO was also measured as a function of the integration time at the point of 2.5 cm from the PMT, from which the F/T ratio is determined [4].

The radiation-induced photocurrent was measured as the anode current during irradiation at a dose rate of 2 rad/h, and was used to extract the crystal's RIN at 1.8 rad/h. Radiation damage in both transmittance and LO was measured for two CsI crystals randomly selected from each vendor after 10 and 100 krad. In the photocurrent and LO measurements, crystals were with the same wrapping and air coupled to the same Hamamatsu R2059 PMT.

Longitudinal transmittance was measured by a PerkinElmer Lambda 950 spectrophotometer with 0.15% precision for selected crystals before and after irradiation.

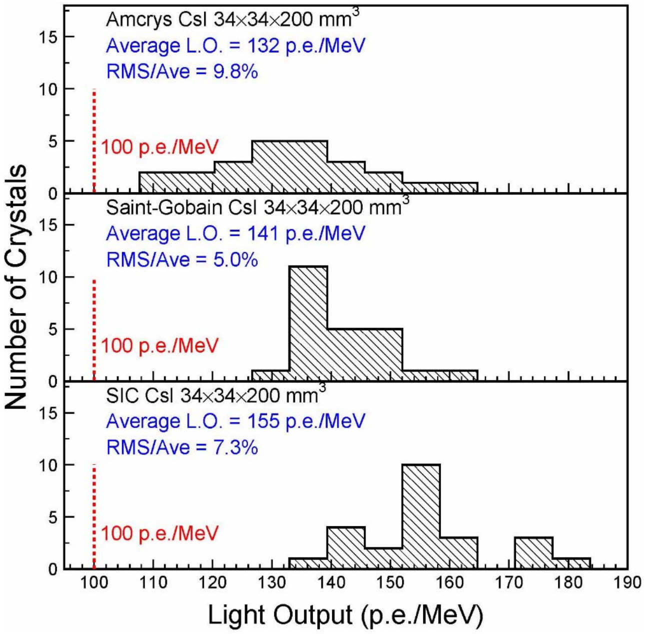

Fig. 2. Summary of the LO in 200 ns for 72 preproduction crystals compared to the Mu2e specification of 100 p.e./MeV (red dashed lines).

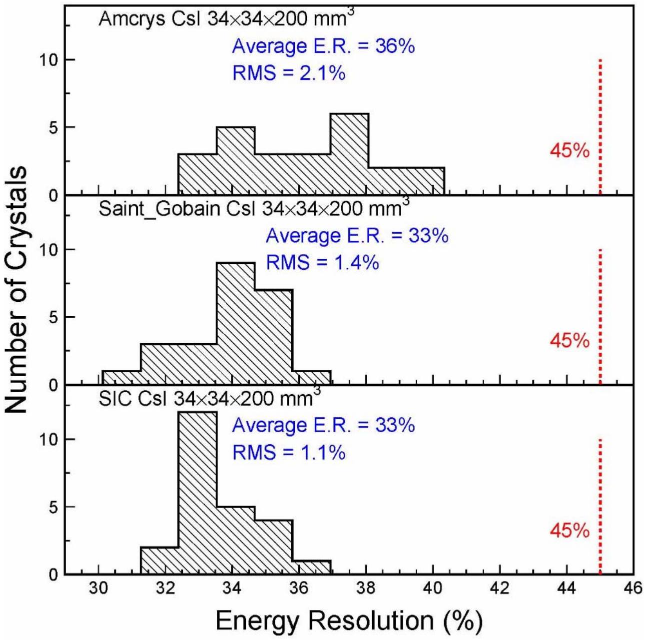

Fig. 3. Summary of the FWHM energy resolution for 72 preproduction crystals compared to the Mu2e specification of 45% (red dashed lines).

III. Basic Properties and Their Correlations

Fig. 2 shows a summary of the LO in 200 ns for all 72 preproduction crystals together with the Mu2e specification of 100 p.e./MeV (red dashed lines). All crystals satisfy this specification. Crystals from SIC have the highest LO, while crystals from S-G are featured with the best overall consistency.

Fig. 3 shows a summary of the FWHM energy resolution for all 72 preproduction crystals together with the Mu2e specification of 45% (red dashed lines). All crystals satisfy this Mu2e specification. Crystals from SIC have the best energy resolution. This is consistent with the LO result.

Fig. 4 shows a summary of the LRU for all 72 preproduction crystals together with the Mu2e specifications of 5% (red dashed lines). Most crystals satisfy this specification, except two crystals from SIC. Crystals from Amcrys have the best LRU and overall consistency.

Fig. 5 shows a summary of the F/T ratio for all 72 preproduction crystals together with the Mu2e specification of 75% (red dashed lines). Crystals from S-G show the best F/T and

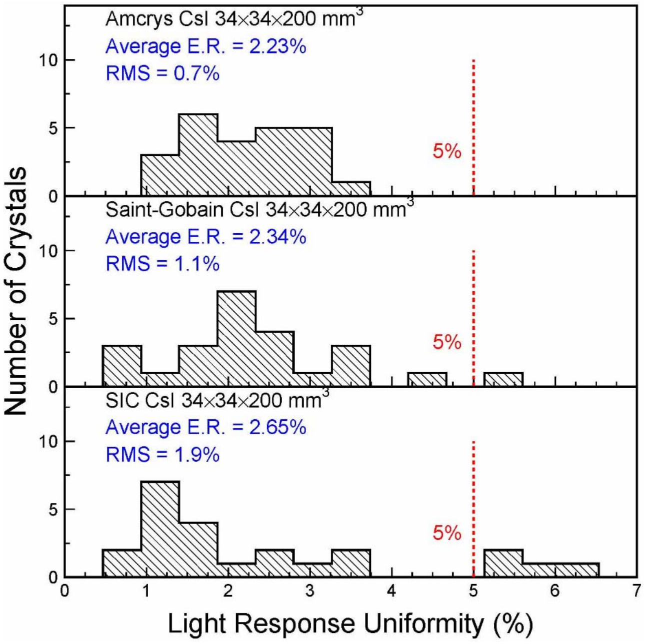

Fig. 4. Summary of the LRU for 72 preproduction crystals compared to the specification of 5% (red dashed lines).

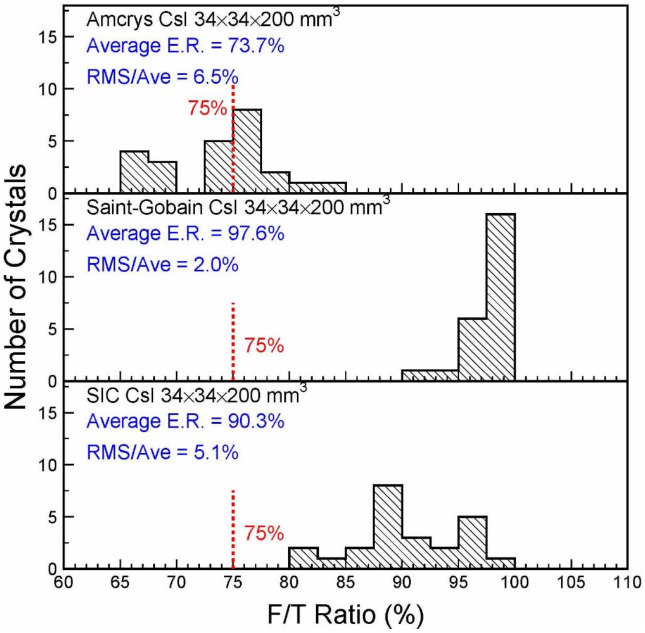

Fig. 5. Summary of the F/T ratio for 72 preproduction crystals compared to the specification of 75% (red dashed lines).

excellent consistency. Over half of the crystals from Amcrys fail this specification.

Figs. 6 and 7 show the correlations between the FWHM energy resolution versus the LO and the F/T ratio, respectively, for all 72 preproduction crystals. These good correlations indicate the importance of controlling the slow scintillation component for undoped CsI crystals [4]. The FWHM energy resolution seems to have a lower limit at 32%, which is believed to be intrinsic for mass-produced undoped CsI crystals of the Mu2e size.

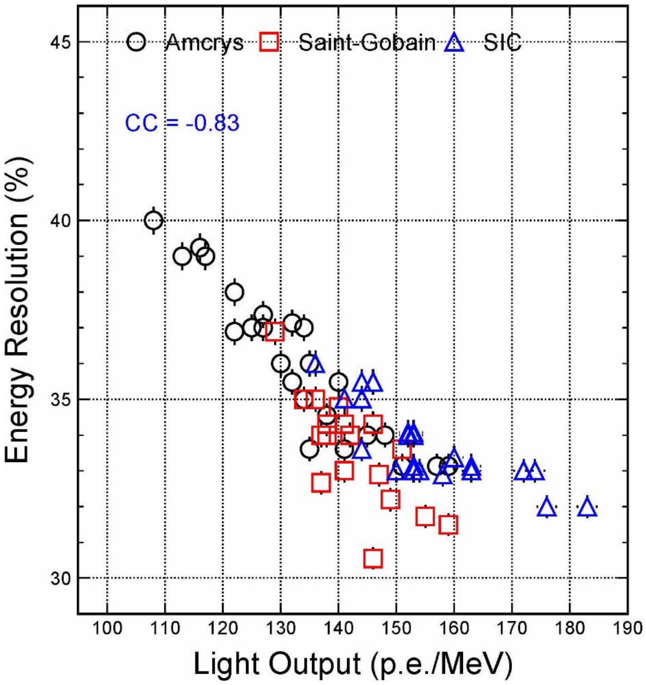

Fig. 6. Correlations between the LO and the FWHM energy resolution for 72 crystals, where CC is the correlation coefficient.

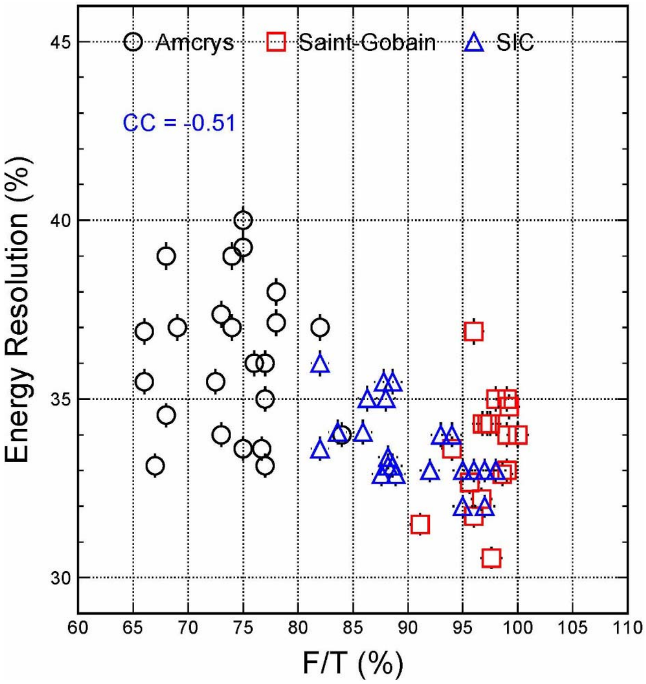

Fig. 7. Correlations between the F/T ratio and the FWHM energy resolution for 72 crystals, where CC is the correlation coefficient.

IV. GAMMA-RAY-INDUCED PHOTOCURRENT AND READOUT NOISE

Fig. 8 shows a setup used to measure Co-60 γ-ray-induced photocurrent for crystals under irradiation at a dose rate of 2 rad/h, which is compatible with the 1.8 rad/h expected in the hottest region of the Mu2e calorimeter [2].

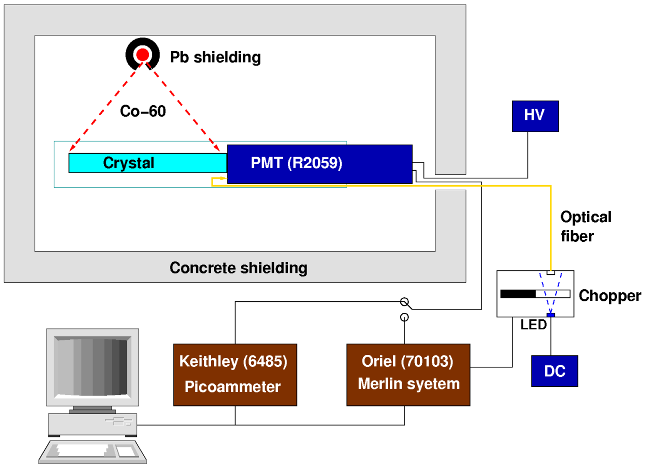

Fig. 8. Schematic showing the setup used to measure the γ-ray-induced photocurrent.

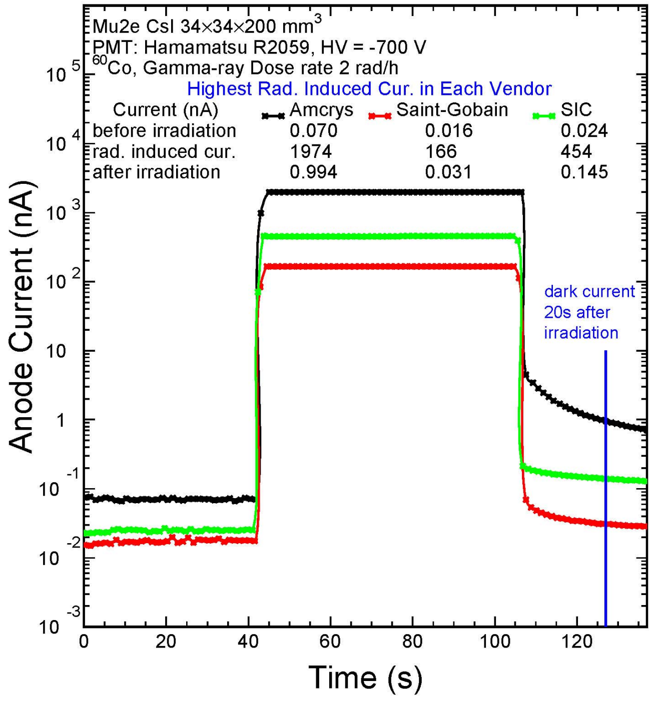

Fig. 9. Histories of the highest photocurrent from three vendors.

The RIN is derived as the standard deviation of photoelectron numbers (Q) in the readout gate normalized to the LO [4]

$$\mathrm{RIN} = \frac{\sqrt{Q}}{\mathrm{LO}}(\mathrm{MeV}). \quad (1)$$

Fig. 9 shows histories of the photocurrent measured for 3 CsI crystals with the highest γ-ray induced photocurrent from each vendor. The dark current, the γ-ray induced photocurrent and the afterglow were measured before, during, and after irradiation, respectively, for about 40, 65, and 35 s. Crystals from AMCRYS show the highest dark current, γ-ray induced current, and afterglow. S-G CsI crystals show the lowest γ-ray induced photocurrent, about one order of the magnitude smaller than that of AMCRYS.

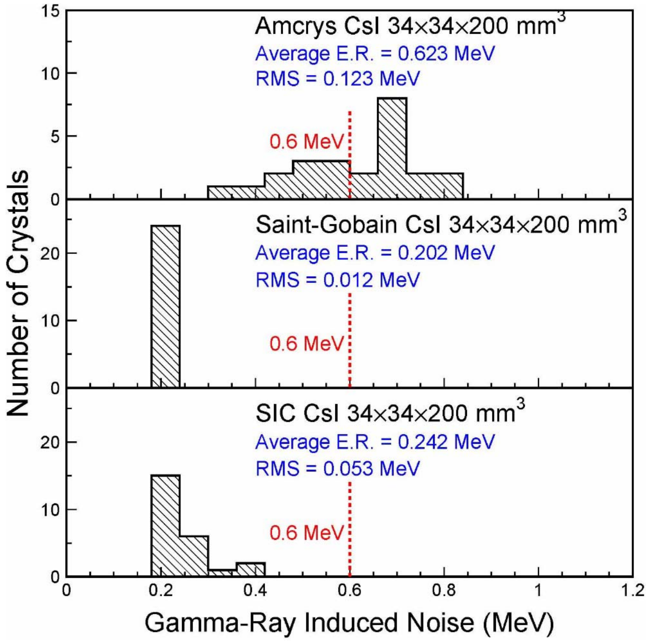

Fig. 10. Summary of the γ-ray-induced readout noise for 72 preproduction crystals together with the Mu2e specification of 0.6 MeV (red dashed lines).

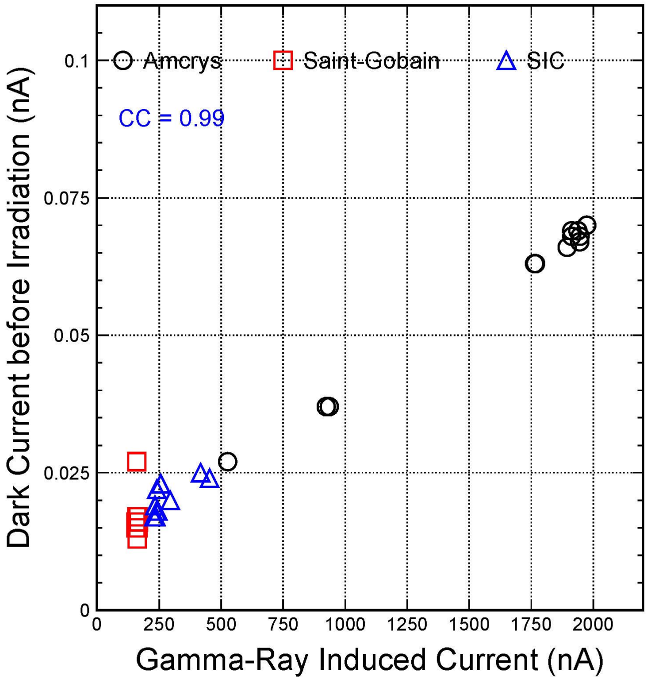

Fig. 11. Correlation between the γ-ray-induced current and the dark current, where CC refers to the correlation coefficient.

Fig. 10 shows a summary of the RIN values measured for all 72 preproduction crystals together with the specification (red dashed lines) of 0.6 MeV. S-G crystals have the lowest γ-ray induced noise and the best consistency, while AMCRYS crystals show the highest γ-ray induced noise. The 14 out of the all 24 AMCRYS crystals fail the RIN specification.

Fig. 11 shows the correlation between the γ-ray induced photocurrent and the dark current. A perfect correlation with

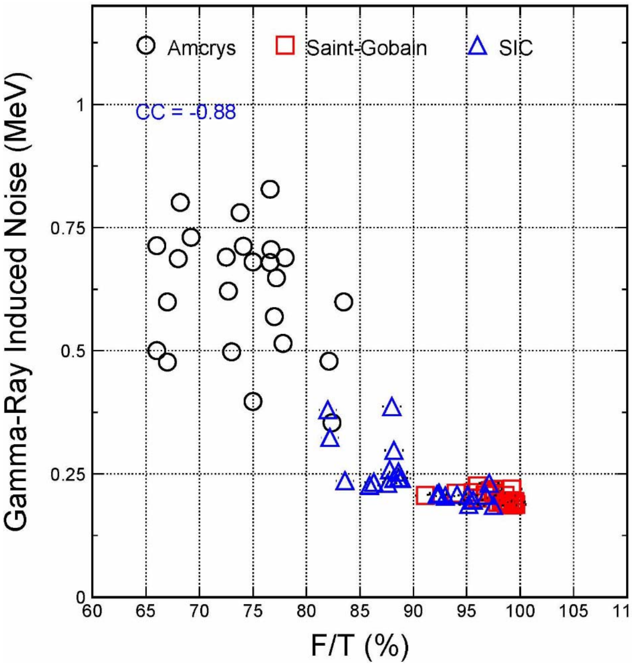

Fig. 12. Correlation between the F/T ratio and γ-ray-induced noise, where CC is the correlation coefficient.

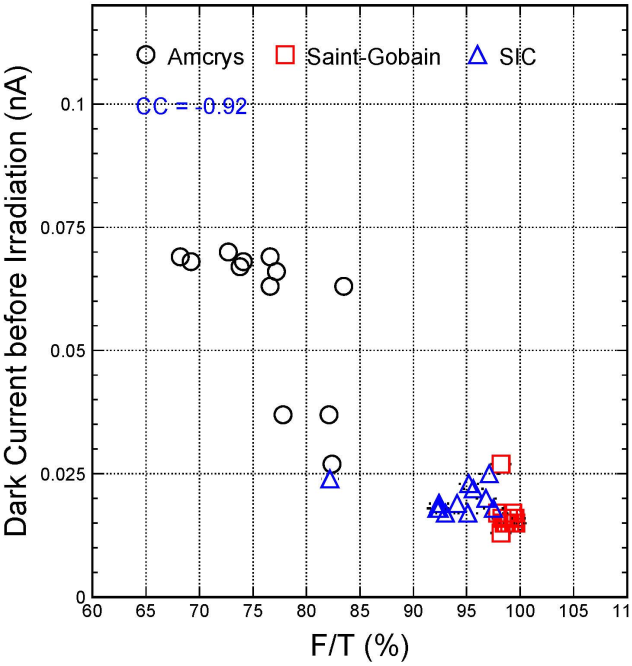

Fig. 13. Correlation between the F/T ratio and dark current, where CC is the correlation coefficient.

correlation coefficient of 99% hints the same origin of these two currents.

Figs. 12 and 13 show correlations between the γ-ray-induced noise and the dark current versus the F/T ratio. Excellent correlations are confirmed. This is in an addition to the correlation between the F/T ratio versus light output and resolution, enhancing the importance of reducing or eliminating the slow component. This result is consistent with our previous study on undoped CsI crystal samples procured before the preproduction [4].

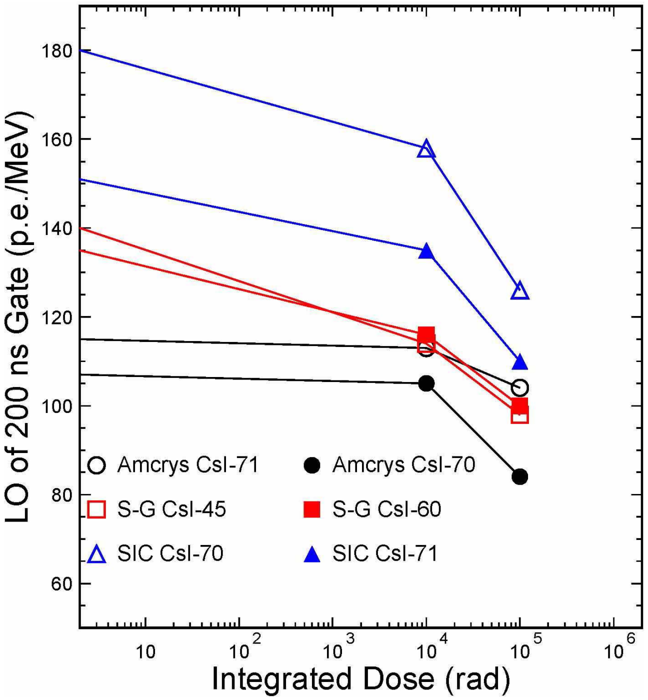

Fig. 14. LO after γ-ray irradiation is shown for six CsI crystals.

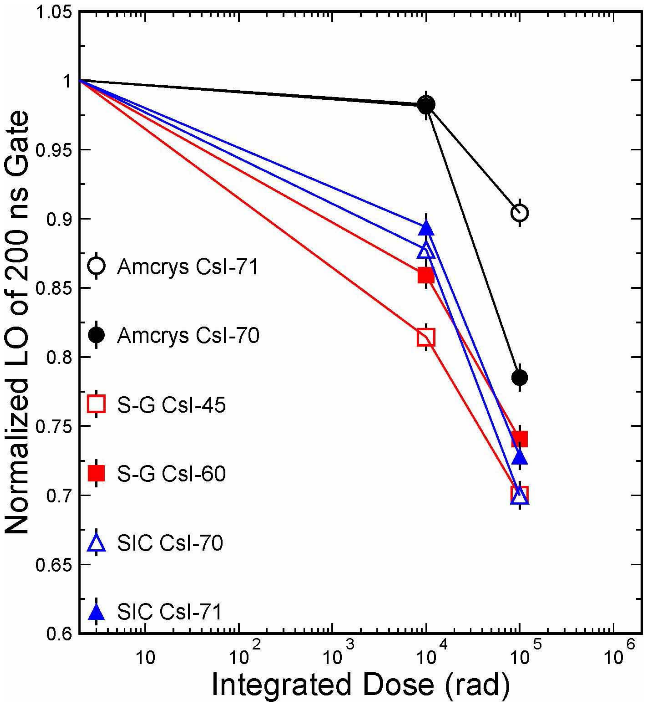

Fig. 15. Normalized LO loss after γ-ray irradiation is shown for six crystals.

V. GAMMA-RAY-INDUCED RADIATION DAMAGE IN SIX PREPRODUCTION CsI CRYSTALS

Fig. 14 shows the LO of six preproduction CsI crystals after 10 and 100 krad. Most of these crystals have LO more than 100 p.e./MeV after 100-krad irradiation, promising a robust CsI calorimeter for Mu2e.

Fig. 15 shows the normalized LO for six crystals after 10 and 100 krad. All crystals meet the Mu2e radiation damage specifications, except one S-G sample (#45) which does not

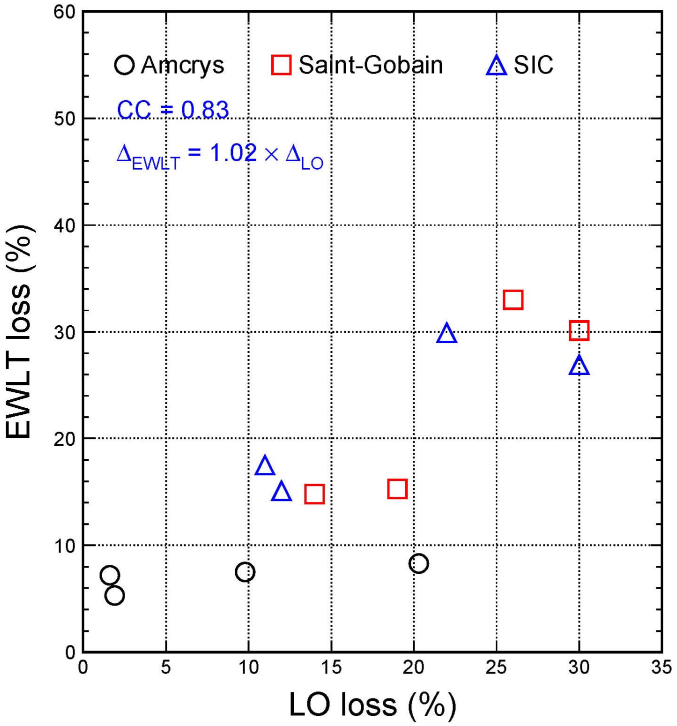

Fig. 16. Correlation between the losses of the LO and the EWLT is shown for six CsI crystals.

meet damage specification after 10 krad but meets that after 100 krad.

Fig. 16 shows the correlation between the LO loss versus the loss of the emission weighted longitudinal transmittance (EWLT), which is defined as

$$\text{EWLT} = \int \text{LT}(\lambda)\text{Em}(\lambda)d\lambda \Big/ \int \text{Em}(\lambda)d\lambda. \tag{2}$$

The EWLT value provides a numerical representation of the LT data across the emission spectrum. The good correlation observed between the LO losses versus the transmittance losses indicates that the LO variation of undoped CsI crystals can be corrected by measuring crystal's transparency with a light monitoring system.

VI. SUMMARY

The 72 preproduction CsI crystals from AMCRYS, S-G, and SIC are characterized at Caltech and LNF, and are compared to the Mu2e technical specifications. AMCRYS crystals have the best uniformity, but the poorest light output, FWHM energy resolution, and F/T ratio. About half AMCRYS crystals do not meet the F/T and RIN specifications. S-G crystals have the best F/T ratio and overall consistency. One S-G crystal does not meet radiation damage spec after 10 krad but meets that after 100 krad. SIC crystals have the best light output and energy resolution, but the poorest uniformity. Two SIC crystals do not meet the uniformity specification.

Correlations are observed between the LO, the FWHM energy resolution, and the F/T ratio, indicating the importance of slow component control, which is believed to be raw material purity and defects related [4]. Correlations are also observed between the dark current, the radiation-induced current/noise and the F/T ratio, enhancing the need to control the F/T ratio.

Most crystals have LO larger than 100 p.e./MeV after 100 krad, promising a robust CsI calorimeter for the Mu2e experiment at Fermilab, Batavia, IL, USA. Correlation is also observed between the variations of the EWLT and the LO, indicating that a light monitoring system is useful for the Mu2e CsI calorimeter to correct variations of the LO by measuring variations of crystal's transparency.

Based upon this investigation S-G and SIC are selected to be the suppliers by the Mu2e experiment to construct the Mu2e CsI calorimeter. We will keep a close communication with the suppliers for crystals quality assurance during the construction.

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