Gamma-ray and Neutron Induced Photocurrent and Readout Noise in LYSO+SiPM Packages

Chen Hu, *Member, IEEE*, Nan Lu, Liyuan Zhang, *Member, IEEE*, Ren-Yuan Zhu, *Senior Member, IEEE*, Adi Bornheim, Lautaro Narvaez, Jason Trevor, and Maria Spiropulu

Abstract – LYSO crystals readout by SiPM will be used in the barrel timing layer of a precision timing detector for the CMS experiment at the HL-LHC. This detector is expected to be exposed up to 5 Mrad γ -ray dose, 2.5×10^{13} charged hadrons/cm² and 3×10^{14} n_{eq}/cm² at the HL-LHC for 10 years' operation. We present results of the photocurrent in LYSO+SiPM packages induced by Co-60 γ -rays and Cf-252 neutrons of the expected dose rate and neutron flux, respectively. The γ -ray induced readout noise is about 30 keV, which is negligible as compared to the 4.2 MeV signal from the minimum ionization particle signals. The neutron induced readout noise is about 7 keV, which is more than a factor of four smaller than that from the γ -rays.

I. INTRODUCTION

THE Compact Muon Solenoid (CMS) experiment has a comprehensive upgrade plan for the High-Luminosity Large Hadron Collider (HL-LHC) which will operate at a luminosity of 5×10^{34} cm⁻²s⁻¹ for ten years with an integrated luminosity of 4,000 fb⁻¹ [1]. A minimum ionization particle (MIP) based timing detector (MTD) is under construction to mitigate the severe pileup effect expected at the HL-LHC [2]. Bright and fast cerium doped lutetium-yttrium oxyorthosilicate (Lu_{2(1-x)}Y_{2x}SiO₅:Ce, LYSO or LYSO:Ce) crystals readout by silicon photomultipliers (SiPM) are planned to be used in the Barrel Timing Layer (BTL) of the MTD. Recent studies show that LYSO crystals are radiation hard against γ -rays [3], charged hadrons [4,5], and neutrons [6]. However, it is also important to understand radiation induced readout noise (RIN) in the LYSO+SiPM packages from the γ -rays and neutrons expected *in situ* at the HL-LHC. This type of RIN measurements were first used for CMS PWO (or PbWO₄) crystal quality control [7, 8, 9], and subsequently in CsI quality assurance by the Mu2e experiment at Fermilab [10, 11,12].

Table I lists the integrated hadron fluence and γ -ray dose as a function of pseudorapidity (η), which are expected by the CMS MTD detector after ten years. Also listed in the table are the expected hadron flux and γ -ray dose rate. The numerical values in the table were calculated by using the CMS Beam Radiation Instrumentation and Luminosity (BRIL) tool [13] where the neutron fluence is shown in 1MeV neutron equivalent in silicon. We notice that the BTL LYSO+SiPM packages expect up to a dose rate of about 200 rad/h and a 1 MeV neutron equivalent flux of 3.2×10^6 cm⁻²s⁻¹ at the highest pseudo-rapidity of $\eta=1.45$ (bold in the table).

In this paper we report results of an investigation on RIN induced by γ -rays (RIN: γ) and neutrons (RIN:n) in LYSO+SiPM packages. SiPM current before, during and after irradiation by γ -rays and neutrons was measured by a SiPM coupled to LYSO crystal bars from several vendors for a dose rate of up to 250 rad/h and a neutron flux of 8.2×10^5 n_{eq}/cm²s. The photocurrent measured during irradiation was used to extract the energy equivalent readout noise RIN for LYSO+SiPM packages. The correlation between the RIN value and the crystal light output was also reported.

II. EXPERIMENTAL DETAILS

Fig. 1 shows particle energy spectra for neutron (left), photons and charged hadrons (right) expected at the LHC, which are calculated by using the CMS BRIL tool. Both γ -rays and neutrons are peaked at several MeV, which is in a good agreement with the energies of γ -rays and neutrons from Co-60 and Cf-252 radioactive sources, respectively. We thus used

TABLE I
THE RADIATION ENVIRONMENT EXPECTED BY THE CMS MTD DETECTOR AFTER 4,000 FB⁻¹ AT THE HL-LHC

CMS MTD	η	n _{eq} (n _{eq} /cm ²)	n _{eq} Flux (n _{eq} /cm ² /s)	Protons (p/cm ²)	p Flux (p/cm ² /s)	Dose (Mrad)	Dose rate (rad/h)
Barrel	0.00	2.5×10^{14}	2.8×10^6	2.2×10^{13}	2.4×10^5	2.7	108
Barrel	1.15	2.7×10^{14}	3.0×10^6	2.4×10^{13}	2.6×10^5	3.8	150
Barrel	1.45	2.9×10^{14}	3.2×10^6	2.5×10^{13}	2.8×10^5	4.8	192
Endcap	1.60	2.3×10^{14}	2.5×10^6	2.0×10^{13}	2.2×10^5	2.9	114
Endcap	2.00	4.5×10^{14}	5.0×10^6	3.9×10^{13}	4.4×10^5	7.5	300
Endcap	2.50	1.1×10^{15}	1.3×10^7	9.9×10^{13}	1.1×10^6	26	1020
Endcap	3.00	2.4×10^{15}	2.7×10^7	2.1×10^{14}	2.3×10^6	68	2700

Manuscript received March 12, 2021. This work was supported by the U.S. Department of Energy, Office of Science, Office of High Energy Physics, under Award Number DE-SC0011925 and Fermilab PO#661273, Prime DOE: DE-AC02-07CH11359.

Chen Hu, Nan Lu, Liyuan Zhang, Ren-Yuan Zhu, Adolph Bornheim, Lautaro Narvaez, Jason Trevor and Maria Spiropulu are with the HEP, California Institute of Technology, Pasadena, CA 91125, USA (e-mail: zhu@hep.caltech.edu).

Co-60 and Cf-252 as the radiation source for the RIN: γ and RIN:n investigations respectively.

Fig. 1. Energy spectra for neutrons (left) and photons and charged hadrons (right) expected at LHC calculated by BRIL simulation [13] compared to Co-60 and Cf-252 radioactive sources and three proton accelerators.

Fig. 2 shows a setup used to measure photocurrent induced in LYSO+SiPM packages under irradiation from a Co-60 γ -ray source or a Cf-252 neutron source. Four LYSO crystal bars of $3.12 \times 3.12 \times 57.00 \text{ mm}^3$ randomly picked from a batch of twenty samples from each vendor produced by CPI (CPI-12), SIC (SIC-5) and Tianle (Tianle-2 and Tianle-20) were used in this investigation [14]. The sample Tianle-20 shows a decay time of about 34 ns which is shorter than 40 ns from the other three samples. Both γ -ray and neutron irradiation were carried following the order of CPI-12, SIC-5, Tianle-2 and Tianle-20. The samples under irradiation were surrounded by a Teflon block and coupled with an air gap to a Hamamatsu S14160-3015PS SiPM at -40V (2 V overvoltage) with a gain of 2×10^5 . The SiPM current was measured by a Keithley 6485 picoammeter. The accuracy of the picoammeter is $0.2\% + 10 \text{ pA}$ for 20-200 nA range, $0.15\% + 100 \text{ pA}$ for 0.2-2 μA range, and $0.1\% + 1 \text{ nA}$ for 2-20 μA range.

Fig. 2. A schematic showing the setup used to measure photocurrent in LYSO+SiPM packages induced by Co-60 γ -rays and Cf-252 neutrons.

The RIN: γ experiment was carried out first. LYSO+SiPM packages were placed at three positions from the Co-60 source of 50 Ci with γ -ray dose rates of 120, 185 and 250 rad/h that

were measured by an ionization chamber with an uncertainty of about 10%. The SiPM current was measured for about 40 and 120-220 seconds before irradiation, 50 and 120 seconds during irradiation, and 40 and 120-190 seconds after irradiation for each LYSO+SiPM package in the RIN: γ and RIN:n experiment, respectively. The time interval between different dose rates for one sample is about 5 to 7 minutes.

Fig. 3 shows the layout of the neutron source assembly consisting of three cylindrical Cf-252 source pairs of 5, 5 and 1 mg. These sources were arranged to provide the best trade-off between the neutron flux and the uniformity along the 57 mm long LYSO bar.

Fig. 3. Three Cf-252 source pairs are arranged to provide the best trade-off between the intensity and the uniformity of the neutron flux applied to the 57 mm long LYSO bar.

Fig. 4 shows the calculated neutron flux as a function of the position along the LYSO bar, which was placed at $D = 1.4 \text{ cm}$ from the source group with its center at $x = 5 \text{ cm}$. The neutron flux of $8.2 \times 10^5 \text{ n}_{\text{eq}}/\text{cm}^2/\text{s}$ applied to the entire LYSO bar from $x = 2.15$ to 7.85 cm was rather uniform with a rms of 4.2%. The γ -ray background was measured to be 2 rad/h by using the same ionization chamber used in the RIN: γ experiment.

Fig. 4. Neutron flux is shown as a function of the position along the LYSO sample placed at D=14 cm from the source group with its center at x=5 cm.

The measured photocurrent was used to extract an “F” factor for the LYSO+SiPM package, defined as the radiation induced photoelectron numbers per second, normalized to the γ -ray dose rate (F_γ) or neutron flux (F_n).

$$F = \frac{\text{Photocurrent}}{\frac{\text{Charge}_{\text{electron}} \times \text{Gain}_{\text{SiPM}}}{\text{Dose rate}_{\gamma\text{-ray}} \text{ or } \text{Flux}_{\text{neutron}}}} \quad (1)$$

The photoelectron numbers (Q) in an integration gate were calculated by multiplying the F factor, the gate length and the dose rate or neutron flux, which are 200 ns, 200 rad/h or 3.2×10^6 n_eq/cm²/s for the CMS BTL detector:

$$Q = F \times \text{Gate len.} \times \text{Dose rate}_{\gamma\text{-ray}} \text{ or } \text{Flux}_{\text{neutron}} \quad (2)$$

The corresponding energy equivalent RIN: γ (σ_γ) or RIN:n (σ_n) values in keV under a dose rate or a neutron flux were calculated by normalizing the fluctuation of the photoelectron numbers Q to the measured light output (LO) in photoelectron numbers per MeV energy deposition for the corresponding LYSO+SiPM package. We note that the correlated noise due to cross-talk and after-pulse is negligible at 2V over-voltage [15].

$$\sigma \text{ (keV)} = \frac{\sqrt{Q}}{\text{LO (N}_{p.e./\text{MeV}})} \times 1000 \quad (3)$$

III. RESULTS AND DISCUSSION

A. Radiation Induced Noise by Gamma-rays

Fig. 5 shows histories of the photocurrent measured by the Hamamatsu S14160-3015PS SiPM under Co-60 irradiation with dose rates of 120, 185 and 250 rad/h. Also shown in the figure is the numerical values of the average SiPM photocurrent before, during and 20 seconds after irradiation. The

photocurrent during irradiation is 119, 163, and 217 nA for the dose rates of 120, 185 and 250 rad/h, respectively. We notice no significant variation between dark currents measured before and after three irradiation steps, indicating negligible damage in the SiPM by 35 rad from Co-60 γ -rays.

Fig. 5. Histories of the photocurrent measured for SiPM only under Co-60 irradiation of 120, 185 and 250 rad/h.

Figs. 6 and 7 show histories of photocurrent measured for four LYSO+SiPM packages under Co-60 irradiation of 120, 185 and 250 rad/h. Also listed in the figures are the numerical values of the average SiPM photocurrent during irradiation ranged from 221 to 565 μ A, which are more than three orders of magnitude larger than that for SiPM alone shown in Fig. 5. This indicates that radiation induced scintillation light in LYSO crystals dominates the photocurrent in LYSO+SiPM packages.

Fig. 6. Histories of photocurrent measured for CPI-12 (top) and SIC-5 (bottom) packages under Co-60 irradiation of 120, 185 and 250 rad/h.

TABLE II

A SUMMARY OF PHOTOCURRENT, F FACTOR AND GAMMA-RAY INDUCED READOUT NOISE FOR FOUR LYSO+SiPM PACKAGES

LYSO Crystal ID	L.O. of LYSO+SiPM (p.e./MeV)	Dose rate (rad/h)	Photocurrent before irradiation (nA)	Photocurrent during irradiation (μA)	Photocurrent 20s after irradiation (nA)	F_γ (p.e./s/(rad/h))	σ_γ (keV)
CPI-12	1610±16	120±12	81±1	296±2	108±1	$(7.2\pm0.2)\times10^7$	33.4±0.7
		185±19	87±1	411±4	108±1		
		250±25	107±1	561±7	159±2		
SIC-5	1620±16	120±12	27±1	259±1	125±1	$(7.0\pm0.2)\times10^7$	32.7±0.7
		185±19	103±1	429±4	288±3		
		250±25	230±2	565±7	460±5		
Tianle-2	1340±13	120±12	28±1	221±1	177±2	$(5.6\pm0.2)\times10^7$	35.6±0.8
		185±19	50±1	328±2	273±3		
		250±25	102±3	452±4	330±3		
Tianle-20	1480±15	120±12	27±1	246±1	101±1	$(6.4\pm0.2)\times10^7$	34.1±0.7
		185±19	45±1	388±3	153±2		
		250±25	71±2	497±5	191±2

Fig. 7. Histories of photocurrent measured for Tianle-2 (top) and Tianle-20 (bottom) packages under Co-60 irradiation of 120, 185 and 250 rad/h.

The total dose was 7.8 rad for all crystals, except CPI LYSO-12, which received an additional dose of 3.4 rad for test runs. The corresponding light output loss in LYSO crystals during this experiment was negligible [3].

Fig. 8. Photocurrent as a function of dose rate for four LYSO+SiPM packages with numerical values of F_γ and $RIN:\gamma$ under 200 rad/h listed.

Fig. 8 shows the photocurrent measured during irradiation as a function of the dose rate for four LYSO+SiPM packages, showing a good linearity with excellent correlation coefficients (CC) of 99.7%, 99.0%, 99.4%, and 99.3%, respectively. Also listed in the figure are the numerical values of F_γ and $RIN:\gamma$ (σ_γ). The F_γ factor values were calculated according to equation (1) by using the photocurrent during irradiation and the dose rate. The $RIN:\gamma$ (σ_γ) values in a 200 ns gate were calculated according to the equation (3) for the BTL detector under 200 rad/h. The LYSO crystal light output in a 200 ns gate was measured using a Hamamatsu R1306 PMT and a LeCroy 3001 QVT MCA with coincidence triggers from a Na-22 source for each LYSO bar surrounded by the same Teflon block and coupled to the PMT with an air-gap [8]. The corresponding light output values for LYSO+SiPM packages were corrected for the differences between the quantum efficiency of the Hamamatsu

R1306 PMT and the particle detection efficiency (PDE) of the Hamamatsu S14160-3015PS SiPM as well as the fraction of the areas of the LYSO bars covered by photodetectors.

Table II summarizes the light output in 200 ns gate, the average photocurrent before (dark), during and 20 second after (afterglow) irradiation of 120, 185 and 250 rad/h, F_γ and RIN: γ in keV for four LYSO+SiPM packages.

Fig. 9. Correlation between F_γ (top) and RIN: γ (bottom) vs. LO in 200 ns gate for four LYSO+SiPM packages.

The dark current measured before irradiation is 27 to 230 nA which is larger than 23 nA for SiPM alone. This is due to the phosphorescence in LYSO from both natural radioactive isotope ^{176}Lu (a β emitter) and the residual afterglow from previous irradiation. The dark current before the first irradiation under 120 rad/h is about 27 nA for all LYSO+SiPM packages, except 81 nA from CPI-12. This 81 nA is due to the afterglow from several test γ -ray irradiation runs before the 1st 120 rad/h irradiation for CPI-12. The contribution of the natural phosphorescence is about 4 nA after subtracting SiPM dark current, so is negligible.

The photocurrent measured 20 seconds after each irradiation (afterglow) ranged from 101 to 460 nA for four LYSO+SiPM packages, which is more than three orders of magnitude lower than the radiation induced photocurrent, indicating that the afterglow effect to RIN: γ is small as compared to γ -ray dose induced readout noise. The afterglow effect, however, is clearly shown in the larger dark currents measured before the 2nd and 3rd irradiations as compared to the 1st irradiation for each LYSO+SiPM package.

Fig. 9 shows an excellent correlation between the F_γ (top) and RIN: γ (bottom) vs. the LO in 200 ns gate for four LYSO+SiPM packages. The CC values of 99% and 98% confirm that the γ -ray induced photocurrent and readout noise can be entirely attributed to the scintillation light from the LYSO crystals. The RIN: γ values are about 33 keV for all four LYSO+SiPM packages, which is less than 1% of the 4.2 MeV MIP signal in the CMS BTL detector.

B. Radiation Induced Noise by Neutrons

Fig. 10 shows histories of the SiPM dark current measured during the entire neutron irradiation experiment with a flux of $8.2 \times 10^5 \text{ n}_{\text{eq}}/\text{cm}^2/\text{s}$ from the Cf-252 source group, where the source on (dashed lines) and off (solid lines) timing marks and the duration of each irradiation are shown. Also shown in the figure are the numerical values of the SiPM dark current before and after each step of irradiation and the corresponding neutron fluence.

Fig. 10. Histories of SiPM current measured under the Cf-252 irradiation experiment.

While the SiPM current during the 1st 326 seconds of source on is shown in the figure, the photocurrent during the four irradiation period of 121, 122, 124 and 122 seconds for four LYSO+SiPM packages are not shown in this figure, rather in Figs. 12 and 13.

The SiPM dark current increased from 28 nA to 410 nA during the 1st step of 326 seconds after a neutron fluence of $2.7 \times 10^8 \text{ n}_{\text{eq}}/\text{cm}^2$. It then stabilized at 390 nA due to thermal annealing at room temperature for about 20 minutes. We note that the dark currents measured are about one order of magnitude higher than in the RIN: γ experiment, indicating that the observed SiPM damage is dominated by neutrons.

Fig. 11. SiPM dark current measured after each step of irradiation is shown as a function of the cumulated neutron fluence.

The SiPM dark current increased to $1.04 \mu\text{A}$ after a total fluence of $6.6 \times 10^8 n_{\text{eq}}/\text{cm}^2$ received in four irradiation steps for LYSO+SiPM packages. This steady increase of SiPM dark current shows clearly evidence of cumulative damage in SiPM induced by neutrons [16]. Fig. 11 shows a good linearity between the SiPM dark current measured after five irradiation steps as a function of the cumulated neutron fluence. While such a linearity does not hold beyond $2 \times 10^9 n_{\text{eq}}/\text{cm}^2$ the high dark current expected by the BTL detector is a main concern. A mini thermal electric cooler (TEC) will be mounted on the SiPMs. The TEC allows SiPM operation at a low temperature, such as -35°C or -45°C , during beam on to reduce the dark current, and at a high temperature, such as 25°C , during beam off to facilitate thermal annealing [17].

Figs. 12 and 13 show histories of the photocurrent measured for four LYSO+SiPM packages under a neutron flux of $8.2 \times 10^5 n_{\text{eq}}/\text{cm}^2/\text{s}$ from the Cf-252 source group. Also listed in the figures are the numerical values of average photocurrent before, during, and after irradiation. The photocurrent measured during Cf-252 irradiation with a flux of $8.2 \times 10^5 n_{\text{eq}}/\text{cm}^2/\text{s}$ is much lower than that measured during γ -ray irradiation, indicating that the main contribution to the radiation induced readout noise in LYSO+SiPM packages is from γ -rays *in situ* at the HL-LHC. The total neutron fluence received by LYSO bars in the RIN:n experiment is $9.8 \times 10^7 n_{\text{eq}}/\text{cm}^2$. The corresponding light output loss in LYSO crystals is also negligible [8].

Fig. 12. Histories of photocurrent measured for CPI-12 (top) and SIC-5 (bottom) LYSO+SiPM packages under Cf-252 irradiation.

Table III summarizes the light output in 200 ns gate, average photocurrent before, during and 20 second after Cf-252 irradiation under a neutron flux of $8.2 \times 10^5 n_{\text{eq}}/\text{cm}^2/\text{s}$, F_n and RIN:n in keV for four LYSO+SiPM packages. Table III also lists the F_n and RIN:n values calculated according to equations (1) and (3) respectively for a neutron flux of $3.2 \times 10^6 n_{\text{eq}}/\text{cm}^2/\text{s}$ expected by the BTL at the HL-LHC. There are three contributions to the measured photocurrent during Cf-252 irradiation: dark current in SiPM, photocurrent induced by neutrons and photocurrent induced by γ -ray background of 2 rad/h from the Cf-252 source, which was measured by using the same ionization chamber used in the RIN: γ experiment. Neutron induced photocurrent was determined by subtracting the dark current in SiPM and the photocurrent induced by the γ -ray background, which was obtained by using Eq. 1 and the F factors extracted from the RIN: γ experiment for each LYSO+SiPM package.

TABLE III
A SUMMARY OF CURRENT, F_n AND NEUTRON INDUCED READOUT NOISE FOR FOUR LYSO+SiPM PACKAGES

Crystal ID	L.O. of LYSO+SiPM (p.e./MeV)	Neutron Flux ($n_{eq}/cm^2/s$)	Photocurrent before irradi. (μA)	Photocurrent during irradi. (μA)	Photocurrent 20 s after irradi. (μA)	F_n (p.e./s/(cm^2s^{-1}))	σ_n (keV)
CPI-12	1610 $\pm$ 16	(8.2 $\pm$ 0.8) $\times 10^5$	0.39 $\pm$ 0.01	10.0 $\pm$ 0.1	0.56 $\pm$ 0.01	188 $\pm$ 6	6.8 $\pm$ 0.1
SIC-5	1620 $\pm$ 16	(8.2 $\pm$ 0.8) $\times 10^5$	0.58 $\pm$ 0.01	9.8 $\pm$ 0.1	0.76 $\pm$ 0.01	175 $\pm$ 5	6.5 $\pm$ 0.1
Tianle-2	1340 $\pm$ 13	(8.2 $\pm$ 0.8) $\times 10^5$	0.76 $\pm$ 0.01	8.0 $\pm$ 0.1	0.88 $\pm$ 0.01	137 $\pm$ 4	7.0 $\pm$ 0.1
Tianle-20	1480 $\pm$ 15	(8.2 $\pm$ 0.8) $\times 10^5$	0.83 $\pm$ 0.01	9.4 $\pm$ 0.1	1.04 $\pm$ 0.01	166 $\pm$ 5	6.9 $\pm$ 0.1

Fig. 13. Histories of photocurrent measured for Tianle-2 (top) and Tianle-20 (bottom) LYSO+SiPM packages under Cf-252 irradiation.

Fig. 14 shows correlations between the F_n (top) and RIN:n (bottom) vs. LO in 200 ns gate for four LYSO+SiPM packages. The CC values of 95% and 82% confirm that the neutron induced photocurrent and readout noise are mostly due to the scintillation light from LYSO crystals as well. The result RIN:n value is found to be about 7 keV for four LYSO+SiPM packages under $3.2 \times 10^6 n_{eq}/cm^2/s$, which is more than a factor of four less than the 34 keV of RIN: γ under a γ -ray dose rate of 200 rad/h.

Fig. 14. Correlation between F_n (top) and RIN:n (bottom) vs. LO in 200 ns gate for four LYSO+SiPM packages.

IV. SUMMARY

RIN: γ and RIN:n experiments were carried out for four LYSO+SiPM packages under three γ -ray dose rates up to 250 rad/h and a neutron flux of $8.2 \times 10^5 n_{eq}/cm^2/s$. While these LYSO samples are not identical, they show consistent RIN: γ values of about approximately 33 keV for 200 ns gate under the maximum γ -ray dose rate of 200 rad/h expected by the BTL detector at the HL-LHC, which is negligible as compared to the 4.2 MeV MIP signal. The RIN:n has a value of about 7 keV under the maximum neutron flux of $3.2 \times 10^6 n_{eq}/cm^2/s$, which is about a factor of four lower than the RIN: γ expected by the BTL detector at the HL-LHC, indicating that the dominate contribution to the radiation induced readout noise in LYSO+SiPM packages *in situ* at the HL-LHC is from γ -rays.

Good correlations are observed between the F and RIN values and the light output of the LYSO+SiPM package, indicating that radiation induced photocurrent and readout noise are mainly due to scintillation light from LYSO crystals.

The use of LYSO+SiPM as a precision timing detector at the HL-LHC presents several technical challenges on the signal to noise ratio of the system. This investigation provides a solid evidence that radiation induced noise would not be a show stopper. On the other hand, SiPMs are also known to suffer from increased dark current due to neutron induced damage. This will be mitigated by mounting a TEC on the SiPMs for operation at low temperature during beam on and annealing at high temperature during beam off.

ACKNOWLEDGEMENTS

This material is based upon work supported by the U.S. Department of Energy, Office of Science, Office of High Energy Physics, under Award Number DE-SC0011925 and Fermilab PO#661273, Prime DOE: DE-AC02-07CH11359. The authors are grateful to the CMS collaborators, H.B. Newman, S. Xie, C. Peña, and the CMS Caltech group for useful discussions and feedback. MS thanks S. Miscetti and L. Bauerdick for early discussions on the project.

REFERENCES

- [1] <https://home.cern/science/accelerators/high-luminosity-lhc>.
- [2] J. Butler, T. Tabarelli de Fatis, *et al.*, “A MIP Timing Detector for the CMS Phase-2 Upgrade,” CERN-LHCC-2019-003, CMS-TDR-020 (2019).
- [3] F. Yang, L. Zhang, R.-Y. Zhu, “Gamma-Ray Induced Radiation Damage Up to 340 Mrad in Various Scintillation Crystals,” *IEEE Trans. Nucl. Sci.* 63(2), pp. 612-619 (2016).
- [4] F. Yang, L. Zhang, R.-Y. Zhu, *et al.*, “Proton-Induced Radiation Damage in Fast Crystal Scintillators,” *IEEE Trans. Nucl. Sci.* 64(1), pp. 665-672 (2017).
- [5] C. Hu, F. Yang, L. Zhang, *et al.*, “Proton-Induced Radiation Damage in BaF₂, LYSO, and PWO Crystal Scintillators,” *IEEE Trans. Nucl. Sci.* 65(4), pp. 1018-1024 (2018).
- [6] C. Hu, F. Yang, L. Zhang, *et al.*, “Neutron-Induced Radiation Damage in LYSO, BaF₂, and PWO Crystals,” *IEEE Trans. Nucl. Sci.* 67(6), pp. 1086-1092 (2020).
- [7] R. Mao, L. Zhang, R.-Y. Zhu, *et al.*, “Gamma Ray Induced Radiation Damage in PWO and LSO/LYSO Crystals,” in *2009 IEEE Nuclear Science Symposium Conference Record (NSS/MIC)*, 2009, pp. 2045-2049.
- [8] L. Zhang, R. Mao, R.-Y. Zhu, “Effects of Neutron Irradiations in Various Crystal Samples of Large Size for Future Crystal Calorimeter,” in *2009 IEEE Nuclear Science Symposium Conference Record (NSS/MIC)*, 2009, pp. 2041-2044.
- [9] R.-Y. Zhu, “Radiation Damage Effects” In *Handbook of Particle Detection and Imaging*, C. Grupen, I. Buvat, Ed., Berlin, Heidelberg, Germany: Springer, 2012, pp 535-556.
- [10] N. Atanov, V. Baranov, J. Budagov, *et al.*, “Quality Assurance on Undoped CsI Crystals for the Mu2e Experiment,” *IEEE Trans. Nucl. Sci.* 65(2), pp. 752-757 (2018).
- [11] F. Yang, L. Zhang, C. Hu, *et al.*, “Slow Scintillation Component and Radiation-Induced Readout Noise in Undoped CsI Crystals,” *IEEE Trans. Nucl. Sci.* 65(10), pp. 2716-2723 (2018).
- [12] C. Leroy, P.-G. Rancoita, *Principles of Radiation Interaction in Matter and Detection*, 4th ed. Singapore: World Scientific, 2016, pp 477-567.
- [13] CMS Collaboration, “FLUKA particle flux maps for CMS detector”, CMS Performance Note CMS-DP-2013-028 (2013).
- [14] http://www.hep.caltech.edu/~zhu/talks/4CMS_191015_60_LYSO.pdf
- [15] O. Girard, G. Haefeli, A. Kuonen, *et al.*, “Characterisation of silicon photomultipliers based on statistical analysis of pulse-shape and time distributions,” 2018, arXiv:1808.05775
- [16] E. Garuttia and Yu. Musienko, “Radiation damage of SiPMs,” *NIMA* 926, 2019, pp. 69-84.
- [17] <https://indico.fnal.gov/event/46746/timetable/#20210318> A. Heering, A. Karneyeu, Yu. Musienko, *et al.*, “Integration of mini TECs on the CMS MTD barrel timing layer 16 ch SiPM array to reduce the DCR after very high irradiation”, Report presented in the CPAD Instrumentation Frontier Workshop 2021 at Stony Brook.
- [18] B. Bir’o, G. David, A. Fenyvesi, *et al.*, “A Comparison of the Effects of Neutron and Gamma Radiation in Silicon Photomultipliers”, arXiv:1809.04594v4 [physics.ins-det] 7 Apr 2019.