Ionization Dose and Neutron Induced Photocurrent and Readout Noise in LYSO+SiPM Packages

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

High Energy Physics Laboratory, California Institute of Technology, Pasadena, CA 91125, USA

1. 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^{-2}s^{-1} for an integrated luminosity of 3,000 fb^{-1}. Bright, fast and radiation hard cerium doped lutetium yttrium oxyorthosilicate ($Lu_{2(1-x)}Y_{2x}SiO_5$:Ce, LYSO) crystals coupled to SiPMs will be used to construct a barrel timing layer (BTL) for the HL-LHC. One crucial issue is the radiation induced readout noise (RIN) in the LYSO+SiPM packages *in situ* under an ionization dose rate of up to 200 rad/h and an 1 MeV neutron equivalent flux of 3×10^6 n_{eq}/cm^2/s expected at the highest pseudorapidity (η=1.45) in BTL (Table I).

We report an investigation on the RIN induced by γ-rays (RIN:γ) and neutrons (RIN:n) in LYSO+SiPM packages expected at the maximum dose rate and neutron fluence. Photocurrent before, during and after irradiation by γ-rays and neutrons were measured by a SiPM for LYSO crystal bars under a dose rate of up to 250 rad/h and a neutron flux of 8.2×10^5 n_{eq}/cm^2/s. The photocurrent during irradiation is used to extract the energy equivalent RIN for four LYSO+SiPM packages. Correlations between the photocurrent and RIN values and the light output of LYSO+SiPM are also reported.

Table I

The Integrated Radiation Dose and Dose Rate Expected by the CMS MIP Timing Detector (MTD) at the HL-LHC

CMS MTD	η	n_{eq} (cm^{-2})	n_{eq} Flux (cm^{-2}s^{-1})	Protons (cm^{-2})	p Flux (cm^{-2}s^{-1})	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
Endcap	3.00	2.4×10^{15}	2.7×10^7	2.1×10^{14}	2.3×10^6	68	2700

2. Experimental Details

F is defined as the radiation induced photoelectron numbers per second normalized to the dose rate or neutron flux:

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

RIN (σ) defined as the fluctuation of photoelectron number (Q) in a readout gate normalized to the light output (LO) of LYSO+SiPM:

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

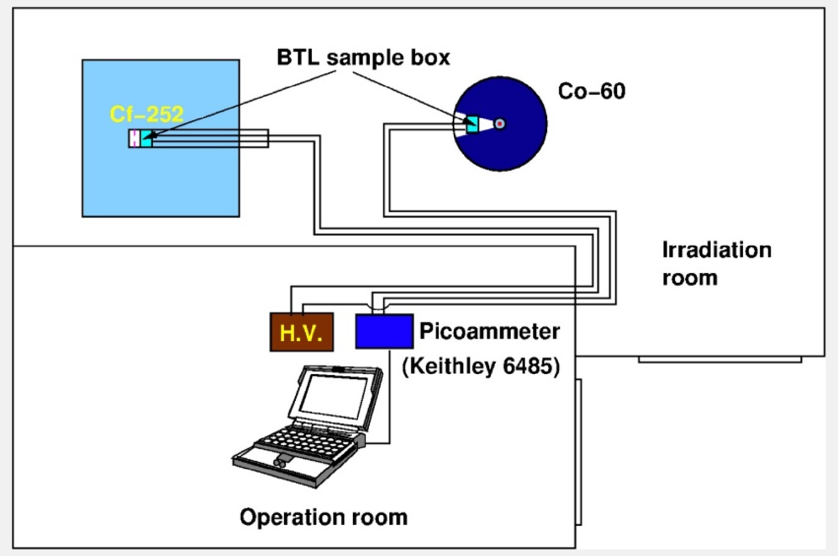

Fig. 1 The setup used to measure photocurrent in LYSO+SiPM before, during and after irradiation

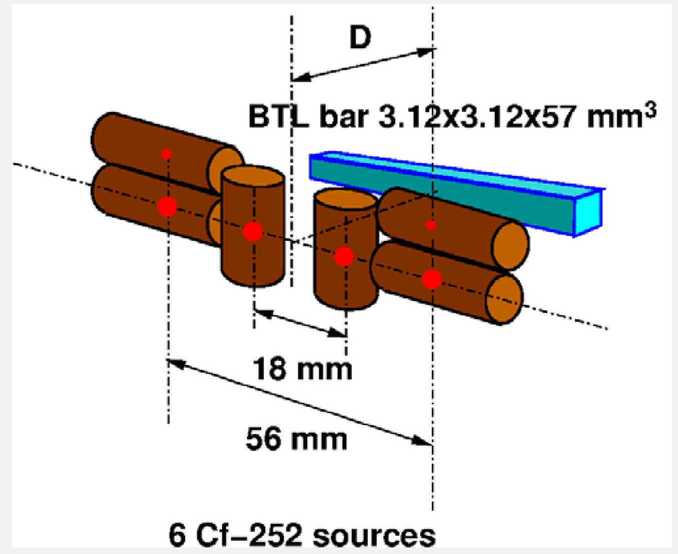

Fig. 2 Three Cf-252 source pairs used as the neutron source group

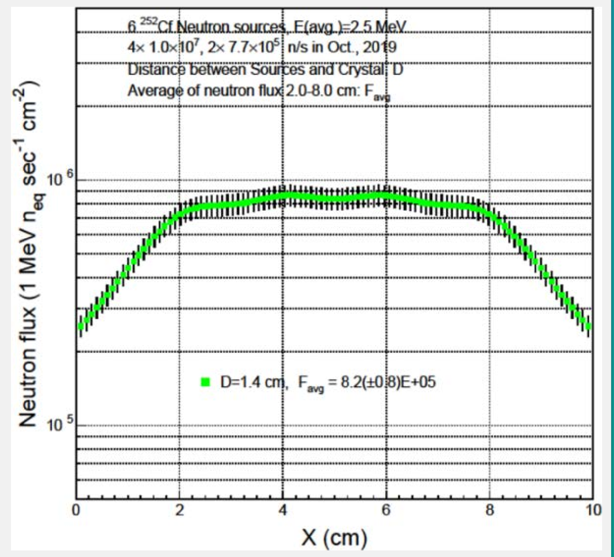

Fig. 3 Neutron flux as a function of the position X in LYSO at D = 1.4 cm

Fig. 1 shows the setup used to measure photocurrent in LYSO+SiPM packages induced by Co-60 γ-rays and Cf-252 neutrons. The Co-60 γ-ray source of 50 curies provides an ionization dose rate up to 250 rad/h for LYSO bar of 3.12×3.12×57 mm^3 coupled to a Hamamatsu S14160-3015PS SiPM. Fig. 2 shows a home-made Cf-252 source group consisting of three cylindrical source pairs of about 5 mg each. Fig. 3 shows the neutron flux as a function of the position along the LYSO sample placed at D = 1.4 cm from the source group with its center at x = 5 cm. A rather uniform neutron flux of 8.2±0.8×10^5 n_{eq}/cm^2/s was applied to the entire LYSO bar located between x = 2.15 to 7.85 cm.

3. RESULTS AND DISCUSSION

3.1 Radiation Induced Noise by Gamma-rays

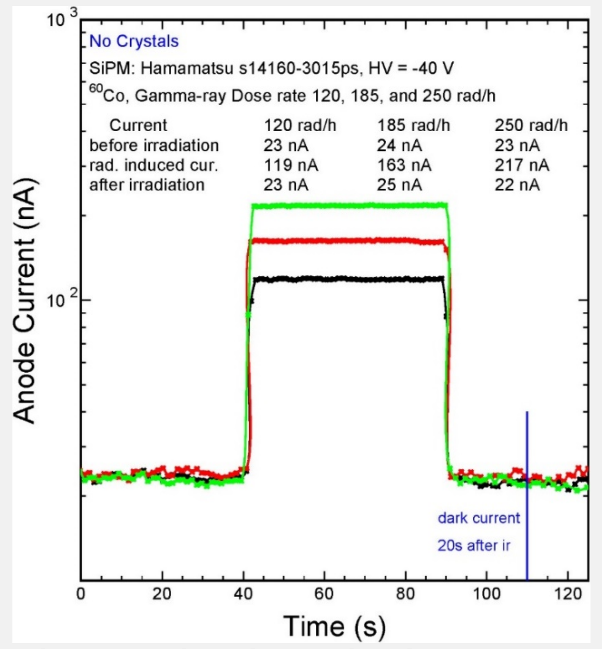

Fig. 4 Histories of photocurrent measured for the SiPM under Co-60 irradiation

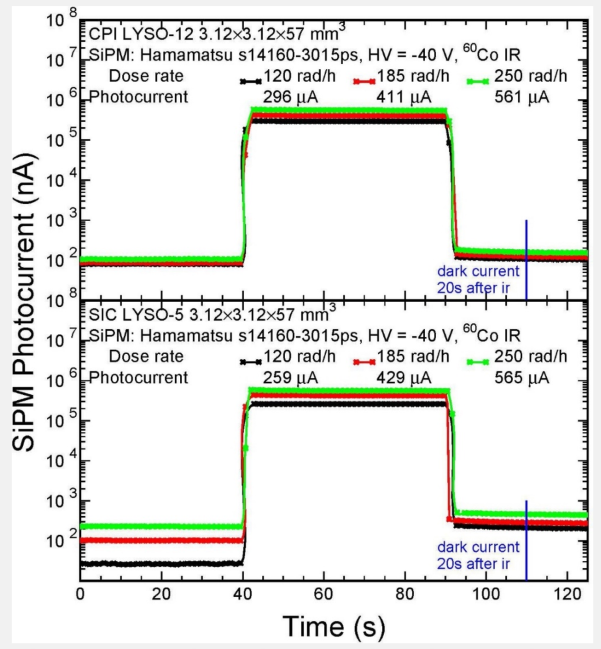

Fig. 5 Histories of the SiPM photocurrent for CPI-12 (top) and SIC-5 (bottom) under Co-60 irradiation

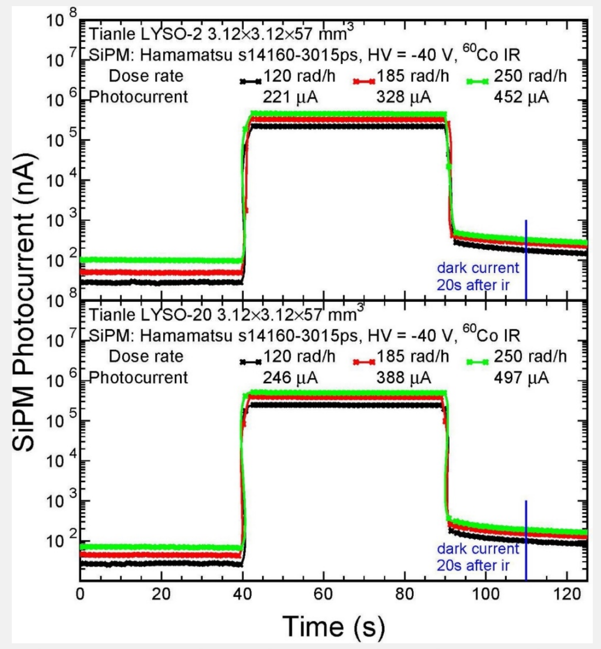

Fig. 6 Histories of the SiPM photocurrent for Tianle-2 (top) and Tanle-20 (bottom) under Co-60 irrad.

Fig. 4 shows histories of photocurrent measured by the Hamamatsu S14160-3015PSSiPM under Co-60 irradiation of 120, 185 and 250 rad/h. No significant variation in the SiPM currents before and after irradiation, indicating a negligible damage in the SiPM. Figs. 5 and 6 show that the average photocurrent during irradiation is more than three orders of magnitude larger than the dark current measured before and after irradiation in SiPM, indicating that the contributions from SiPM dark current and LYSO afterglow to the radiation induced photocurrent and RIN are negligible as compared to γ-ray induced scintillation light.

Table II

A Summary of photocurrent, F_γ 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 irrad. (nA)	Photocurrent (μA)	Photocurrent 20s after irrad. (nA)	F_γ (p.e./s/(rad/h))	σ_γ (keV)
CPI-12	1609	120	81	296	108	7.19×10^7	33.3
		185	87	411	108		
		250	107	561	159		
SIC-5	1619	120	27	259	125	7.01×10^7	32.7
		185	103	429	288		
		250	230	565	460		
Tianle-2	1336	120	28	221	177	5.65×10^7	35.6
		185	50	328	273		
		250	102	452	330		
Tianle-20	1483	120	27	246	101	6.38×10^7	34.1
		185	45	388	153		
		250	71	497	191		

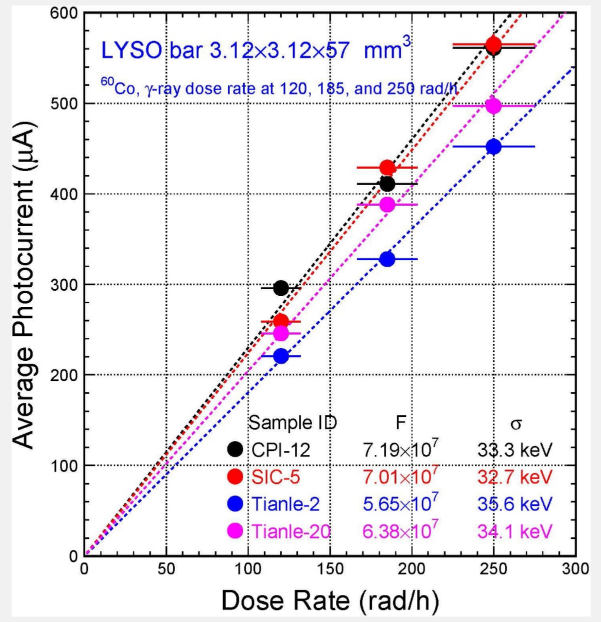

Fig. 7 Photocurrent is shown as a function of the dose rate for four LYSO+SiPM packages

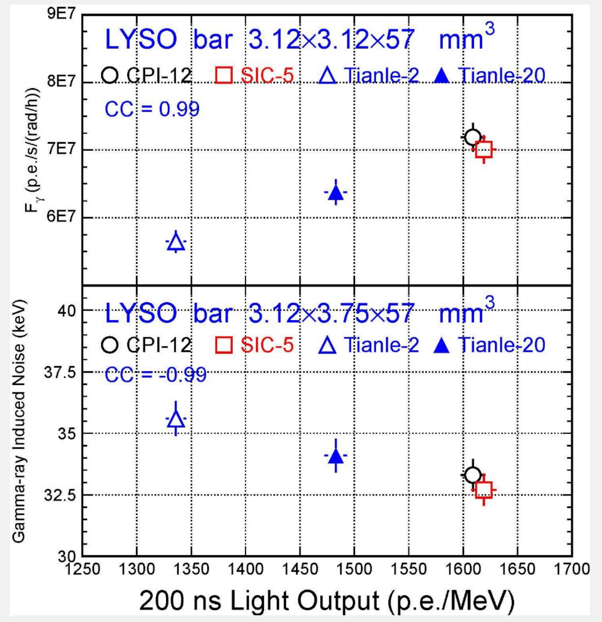

Fig. 8 Correlation between Fγ (top) and RIN:γ (bottom) vs. LO in 200 ns gate for four LYSO+SiPM packages

Fig. 7 shows the photocurrent during γ-ray irradiation as a function of dose rate for four LYSO+SiPM packages, showing a good linearity. Fig. 8 shows excellent correlations between the F_γ (top) and RIN:γ (bottom) values vs. the LO in 200 ns gate for four LYSO+SiPM packages. The RIN:γ values are about thirtyish keV under 200 rad/h, which is less than 1% of the 4.2 MeV MIP signal in the CMS BTL detector.

3.2 Radiation Induced Noise by Neutrons

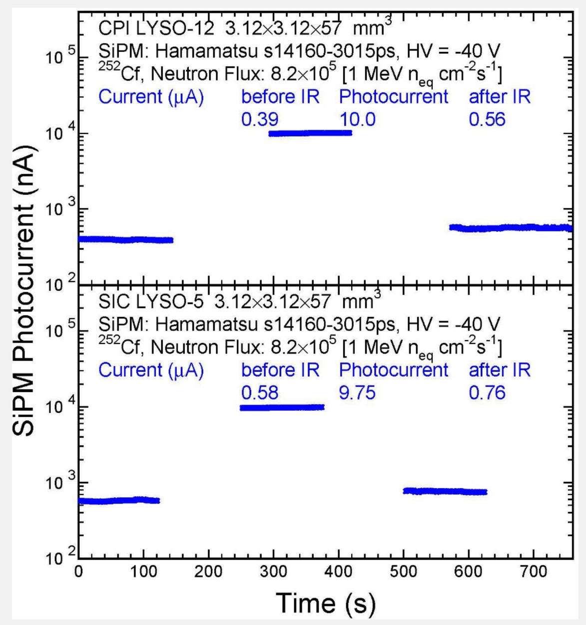

Fig. 9 Histories of SiPM photocurrent for CPI-12 (top) and SIC-5 (bottom) before/during/after Cf-252 irradiation

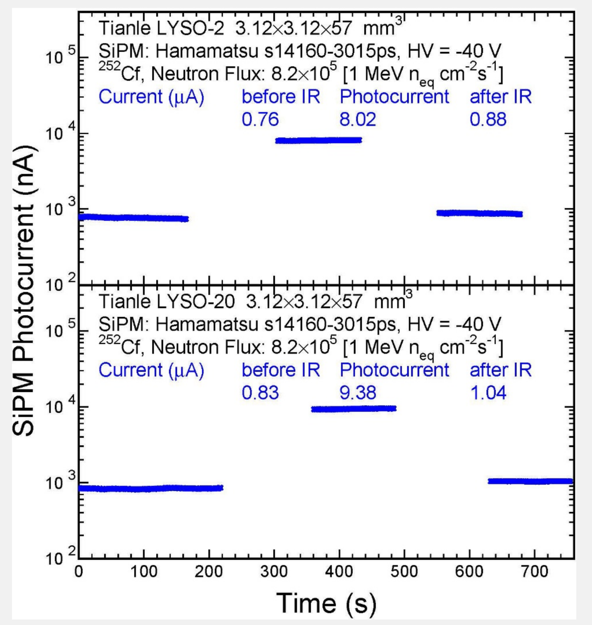

Fig. 10 Histories of SiPM photocurrent for Tianle-2 (top) Tianle-20 (bottom) before/during/after Cf-252 irradiation

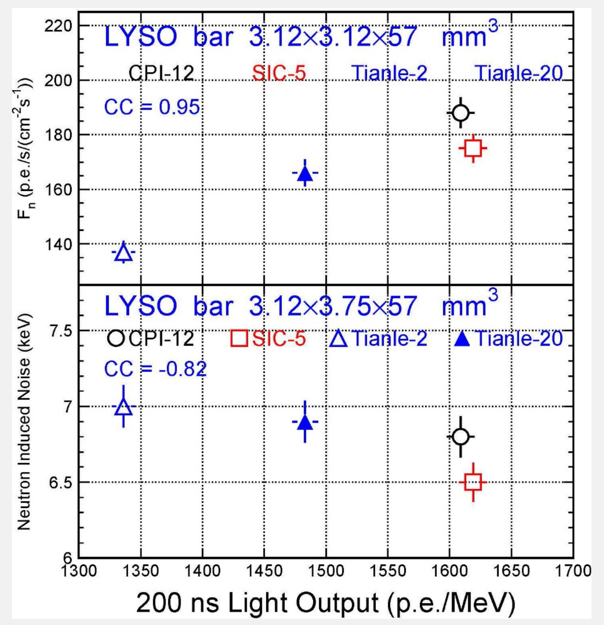

Fig. 11 Correlation between Fn (top and RIN:n (bottom) vs. LO in 200 ns gate for four LYSO+SiPM packages

Figs. 9 and 10 show histories of SiPM photocurrent measured for four LYSO+SiPM packages before/during/after a neutron flux of 8.2×10^5 n_{eq}/cm^2/s from the Cf-252 source. Fig. 11 shows good correlations between the F_n (top) and RIN:n (bottom) vs. LO in 200 ns, revealing that they are also due to scintillation light from LYSO crystals. The RIN:n values in Table III are about 7 keV under the neutron flux of 3.2×10^6 n_{eq}/cm^2/s for four LYSO+SiPM packages, which is more than a factor of four less than the thirtyish keV of RIN:γ under an ionization dose of 200 rad/h.

Table III

A Summary of photocurrent, F_n factor and neutron induced readout noise for four LYSO+SIPM packages

LYSO Crystal ID	L.O. of LYSO+SiPM (p.e./MeV)	Neutron Flux (cm^{-2}s^{-1})	Photocurrent before irrad. (μA)	Photo current (μA)	Photocurrent after irrad. (μA)	F_n (p.e./s/(cm^{-2}s^{-1}))	σ_n (keV)
CPI-12	1609	8.2×10^5	0.39	10.00	0.56	188	6.8
SIC-5	1619	8.2×10^5	0.58	9.75	0.76	175	6.5
Tianle-2	1336	8.2×10^5	0.76	8.02	0.88	137	7.0
Tianle-20	1483	8.2×10^5	0.83	9.38	1.04	166	6.9

5. Summary

- **RIN:γ and RIN:n experiments were carried out for four LYSO+SiPM packages under three ionization dose rates up to 250 rad/h and a neutron flux of 8.2×10^5 n_{eq}/cm^2/s.**
- **The RIN:γ values are about thirtyish keV under 200 rad/h, which is negligible as compared to the 4.2 MeV MIP signal. The RIN:n values are about 7 keV under the neutron flux of 3.2×10^6 n_{eq}/cm^2/s, ore than a factor of four smaller than the RIN:ɣ, indicating that the radiation induced readout noise *in situ* is dominated by ionization dose.**
- **Good correlations are observed between the F and RIN values versus the LYSO+SiPM light output, indicating radiation induced photocurrent and readout noise are due to scintillation light from LYSO crystals.**
- **Measurement result for LYSO crystal bars from various LYSO vendors will be reported for LYSO quality assurance and quality control.**

Acknowledgments:

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.

Contact : zhu@hep.caltech.edu