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

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***Abstract*–The barrel timing layer for the CMS HL-LHC precision timing detector will be constructed using LYSO+SiPM modules. The barrel in HL-LHC beam intensities is expected to be exposed under an ionization dose rate of up to 200 rad/h and a neutron flux of up to 3×10^6 $n_{eq}/cm^2/s$. We present results from measurements of photocurrent in the LYSO+SiPM packages induced by Co-60 γ-rays and Cf-252 neutrons. The γ-ray induced readout noise is found to be about 30 keV, which is negligible compared to the 4.2 MeV signal from minimum ionization particles. The neutron induced noise is about 7 keV, which is more than a factor of 4 smaller than that from the ionization dose.**

I. INTRODUCTION

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 for CMS upgrade for the HL-LHC, which will be exposed up to 5 Mrad ionization dose, 2.5×10^{13} charged hadrons/cm^2 and 3×10^{14} n_{eq}/cm^2. One crucial issue is the radiation induced readout noise (RIN) in the LYSO+SiPM package *in situ* under an ionization dose rate of up to 200 rad/h and a neutron flux of up to 3×10^6 $n_{eq}/cm^2/s$. We report results of an investigation on the RIN induced by γ-rays (RIN:γ) and neutrons (RIN:n) in LYSO+SiPM packages. Photocurrent before, during and after irradiation by Co-60 γ-rays and Cf-252 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 RIN values versus the light output of LYSO+SiPM are also reported.

II. EXPERIMENTAL DETAILS

Fig. 1 shows setups used to measure photocurrent induced by Co-60 γ-rays (left) and Cf-252 neutrons (right) in LYSO+ SiPM packages. Four LYSO crystal bars of 3.12×3.12×57 mm^3, one each produced by CPI and SIC and two from Tianle were investigated. Tianle-20 shows shorter decay time (~34 ns) than the other three crystals (~40 ns). These samples were surrounded by a Teflon block and coupled to a Hamamatsu S14160-3015PS SiPM with an air gap. Photocurrents were measured by a Keithley 6485 picoammeter. In the RIN:γ experiment, a stand-alone Co-60 source provided ionization dose rates of 120, 185 and 250 rad/h. Photocurrent was measured for about 40s before irradiation, 50s during irradiation, and 40s after irradiation. The systematic uncertainty of the dose rates is about 10%.

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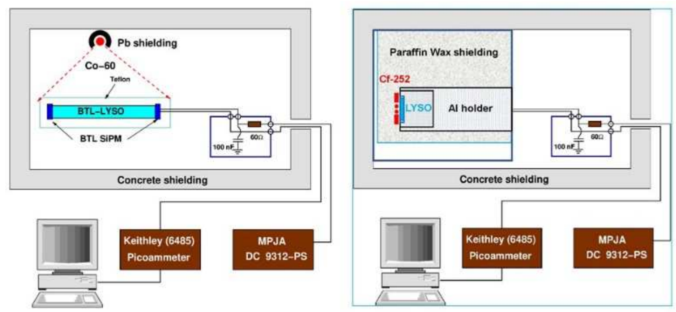

Fig. 1. A schematic showing setups used to measure photocurrent induced by Co-60 γ-rays (left) and Cf-252 neutrons (right) in LYSO+SiPM packages.

For the RIN:n experiment, a Cf-252 source group was used. The photocurrent was measured for about 120~220s before irradiation, about 120s during irradiation and 120~190s after irradiation. A rather uniform neutron flux of $8.2\pm0.8\times10^5$ $n_{eq}/cm^2/s$ was applied to the entire length of the LYSO bar. The photocurrent was used to extract an "F" factor, defined as the radiation induced photoelectron number per second normalized to γ-ray dose rate (F_γ) or neutron flux (F_n).

$$F = \frac{\frac{Photocurrent}{Charge_{electron} \times Gain_{SiPM}}}{Dose\ rate_{\gamma-ray}\ or\ Flux_{neutron}} \quad (1)$$

The corresponding RIN:γ or RIN:n values in keV were calculated by normalizing the fluctuation of the photoelectron number in a defined integration gate to the light output (LO) of the LYSO+SiPM package under the expected dose rate of 200 rad/h and 1 MeV equivalent neutron flux of 3×10^6 $n_{eq}/cm^2/s$.

$$\sigma = \frac{\sqrt{Q}}{LO} \quad (2)$$

III. RESULTS AND DISCUSSION

Fig. 2 shows histories of photocurrents measured for the SiPM only (top) and the CPI LYSO+SiPM package (bottom) under Co-60 irradiation. Consist photocurrents were observed before and after irradiation, indicating negligible damage in SiPM and afterglow in LYSO. Also shown in the figures is the average SiPM photocurrent during irradiation for different dose rates. The photocurrent for the LYSO+SiPM package are three orders of magnitude larger than that of SiPM only, so is dominated by scintillation light from the LYSO crystal.

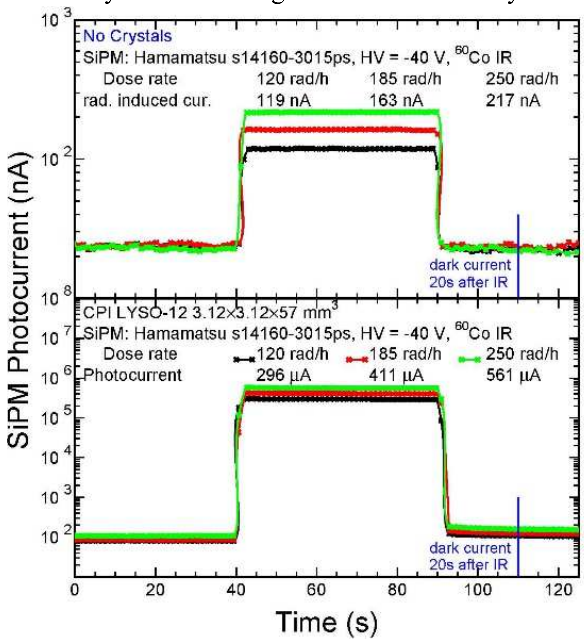

Fig. 2. Histories of photocurrent measured for the Hamamatsu SiPM (top) and the CPI LYSO+SiPM packages (bottom) under Co-60 irradiation.

Fig. 3 shows histories of photocurrent measured for the CPI LYSO+SiPM package under a neutron flux of 8.2×10^5 $n_{eq}/cm^2/s$ from the Cf-252 source group. Also listed in the figure are the numerical values of average photocurrent before, during, and after irradiation. The photocurrent before and after irradiation was about one order of magnitude higher than that in the RIN:γ experiment, and was also increasing during the experiment, indicating SiPM damage. The photocurrent measured during Cf-252 irradiation of 8.2×10^5 $n_{eq}/cm^2/s$, however, is more than one order of magnitude lower than that measured during γ-ray irradiation of 250 rad/h, indicating that the main contribution to the radiation induced photocurrent and readout noise in LYSO+SiPM packages is from the ionization dose *in situ* at the HL-LHC.

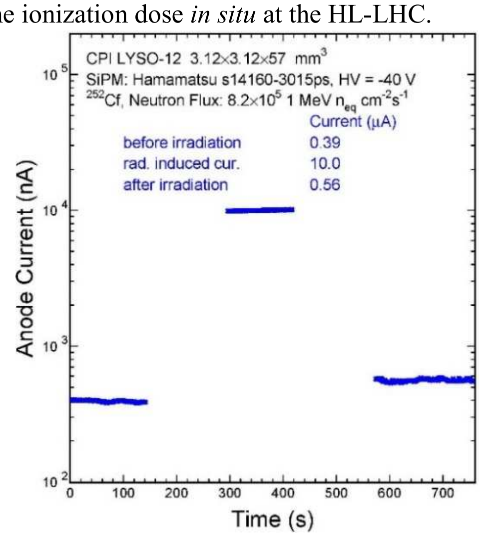

Fig. 3. Histories of photocurrent measured for the CPI LYSO+SiPM package under Cf-252 irradiation.

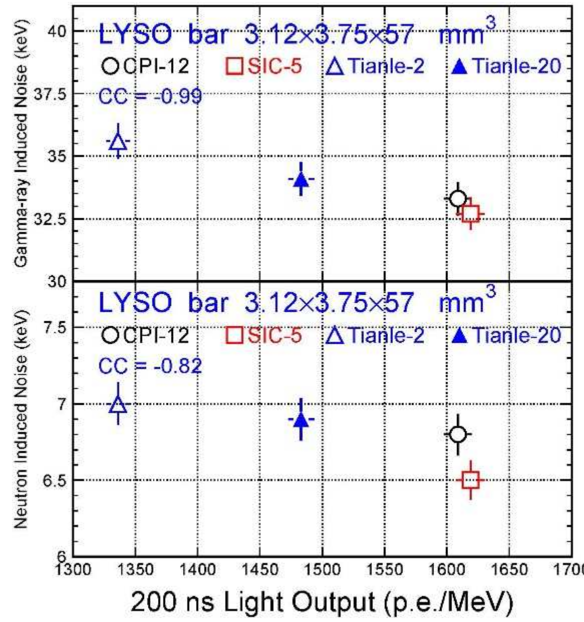

Fig. 4. Correlation between RIN:γ (top) and RIN:n (bottom) vs. LO in 200 ns gate for four LYSO+SiPM packages.

Fig. 4 shows correlations between the RIN:γ (top) and RIN:n (bottom) vs. light output in 200 ns gate for four LYSO+SiPM packages. The correlation coefficients (CC) of 99% and 82% indicate that both the γ-rays and neutron induced readout noises are due to the scintillation light from LYSO crystals. The numerical values of γ-ray and neutron induced readout noise are thirtyish and 7 keV respectively.

IV. Summary

The 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 $n_{eq}/cm^2/s$, which is more than a factor of four smaller than the RIN:γ, indicating that the radiation induced readout noise *in situ* is dominated by ionization dose. Good correlations are observed between the RIN values versus the LYSO+SiPM light output, indicating radiation induced readout noise is due to scintillation light from LYSO crystals. Result for LYSO crystal bars from various LYSO vendors will be reported for LYSO quality assurance and quality control.

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