Results of Gamma Photon and Neutron Irradiations of Hamamatsu R5600-03/NG Photomultiplier Tubes

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Abstract

Gamma photon and neutron irradiation tests were carried out to study the applicability of R5600-03/NG miniature photomultiplier tubes (PMTs) from Hamamatsu in the forward calorimeters (HF) of the hadron calorimeter (HCAL) of the Compact Muon Solenoid (CMS). Results of optical and dark current measurements and neutron activation studies are presented in this work.

I. INTRODUCTION

The two HCAL-HF calorimeters of CMS at LHC, CERN [1] cover the pseudorapidity range from 3 to 5. Optical fibers embedded in the two large absorber blocks run parallel to the beam. Particles incident on the front face of the HF detectors produce showers in the absorber/optical fiber matrix. Charged particles of this shower above the Cherenkov threshold generate Cherenkov light in the optical fibers. This light is transmitted by the optical fibers to photomultiplier tubes. The energy measurement is based on this light.

For detecting the Cherenkov light, PMTs with bialkali photocathode and synthetic silica window seem to be the best choice because they have wide range of sensitivity in the UV range and rather good radiation tolerance. However, considering the large number of PMTs to be used in the two CMS HCAL-HF modules and the cost of their application, PMTs with bialkali photocathode and UV glass window seem to be good alternatives.

Different models of PMTs have been selected for testing their applicability in CMS HCAL-HF. One of them is the R5600-03/NG miniature PMT from Hamamatsu. This PMT has a bialkali photocathode and UV glass window. It can be used for light detection in the 185 nm – 650 nm wavelength range.

PMTs will operate in a radiation environment in CMS HCAL-HF. Monte-Carlo simulations with different transport codes have shown that the most important components are gamma photons, neutrons and charged hadrons [1]. These particles and the radioactivity induced in the components of the PMTs especially by neutrons affect their performance.

Induced radioactivity is also important from the point of view of maintenance of the modules that contain the PMTs.

In this paper we present results of irradiations of R5600-03/NG PMTs with ^{60}Co gamma photons and p(18 MeV)+Be neutrons [2] and changes of their performance as a function of gamma dose and neutron fluence. Results of neutron activation studies are also presented.

II. EXPERIMENTAL TECHNIQUES

A. Samples

The limited amount of sample PMTs enabled us to select only one reference tube for the optical and electrical measurements. That one was not irradiated. Another unirradiated tube was selected for nuclear spectroscopy purposes and a CsI crystal covered by teflon was attached to it. One tube was irradiated with ^{60}Co gamma photons and one with the p(18 MeV)+Be neutron source.

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B. Irradiation circumstances

Gamma irradiations were performed at the high intensity ^{60}Co (E_γ = 1.173 MeV, 1.332 MeV) irradiation facility at ATOMKI, Debrecen. The dose rate was 6.94 krad/min (10 Mrad/day). The irradiation was done in steps. The optical and electrical parameters of the tubes were measured before irradiation and after 0.1 Mrad, 0.3 Mrad, 1 Mrad, 3 Mrad, 10 Mrad and 30 Mrad.

Neutron irradiations were done at the neutron irradiation facility [3] at the MGC-20E cyclotron at ATOMKI, Debrecen. p(18 MeV)+Be neutrons with a broad energy spectrum (E_n < 20 MeV, < E_n > = 3.5 MeV) were produced by bombarding a 3 mm thick target by protons of 18 MeV. Measurements of the optical and electrical parameters of the tubes were carried out before irradiation and after delivering $1*10^9$ cm^{-2}, $3*10^9$ cm^{-2}, $1*10^{10}$ cm^{-2}, $3*10^{10}$ cm^{-2}, $1*10^{11}$ cm^{-2} $3*10^{11}$ cm^{-2} and $1*10^{11}$ cm^{-2} neutron fluences. The corresponding neutron flux rates were $5*10^4$ $cm^{-2}s^{-1}$, $5*10^4$ $cm^{-2}s^{-1}$, $5*10^6$ $cm^{-2}s^{-1}$, $5*10^6$ $cm^{-2}s^{-1}$, $5*10^7$ $cm^{-2}s^{-1}$, $5*10^7$ $cm^{-2}s^{-1}$ and $5*10^8$ $cm^{-2}s^{-1}$, respectively. Neutrons emitted by the neutron source were inherently associated by gamma photons. The additional gamma doses were measured by the twin ionisation chamber method [4]. The gamma dose/neutron flux ratio depended on the irradiation circumstances. Typically it was in the range of (3 - 5)$*10^{-10}$ rad cm^2 s/neutron.

A black light shield during both the irradiations and dark current measurements covered the PMTs. All irradiations were performed in darkened rooms.

Gamma doses and neutron fluences were selected on the basis of Monte-Carlo calculations for the first versions of arrangement of the CMS HCAL-HF calorimeter [5]. The availability of the gamma and neutron irradiation facilities had to be considered during the tests and, therefore, all irradiations had to be carried out at gamma dose rates and neutron flux rates that are significantly higher than the expected ones in the operational positions of the PMTs in HCAL-HF.

C. Optical measurements

A computer controlled optical spectrometer (Acton Research Co., USA) with a Czerny-Turner type scanning monochromator (150 mm focal length, 1200/mm gratings, f/4, 5 nm/mm dispersion) and a 16-bit ADC for the 10 – 1000 nA current region were used for measuring the spectral distribution of the photocurrent of the PMTs.

A D_2-lamp, a PenLight type mercury tube and a high-pressure xenon arc lamp were tried to use as light sources. The Xe-lamp provided the highest intensity in the UV region of interest and, therefore, it was used throughout the tests. The spectrum of the light sources was measured by a calibrated Si-UV detector.

The spectral distribution of the photocurrent of the PMTs was measured before the irradiations and after each fraction delivered. Consecutive measurements were carried out after some irradiations to get information on the kinetics of recovery phenomena. It took 11 min to measure one spectrum.

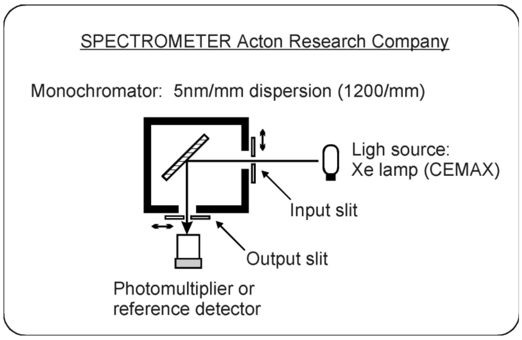

Figure 1 The set-up of the optical spectrometer – monochromator.

D. Dark current measurements

A standard nuclear HV power supply and a current/frequency converter type electrometer with sensitivity of 1 pA and a ratemeter (ICU-86 from ATOMKI, Debrecen) were used for measuring the dark current as a function of anode voltage after each irradiations.

E. Neutron activation analyses

The gamma activity of the radioisotopes produced by neutrons in the components of the PMT was counted by a calibrated HPGe detector with standard NIM modules. Gamma spectra were measured by a PC with MCA card. Full energy photo peaks of the spectra were used to identify the individual radioisotopes.

III. RESULTS AND DISCUSSIONS

A. *Optical measurements*

A typical result of the measurements of the spectral distribution of the photocurrent is shown in Figure 2. Significant recovery of the photocurrent was observed after the irradiations. Recombination of different colour centres generated in the UV glass seems to be the most important process. This is the main component of the background of the spectral distributions.

After background fitting and subtraction, the $R(\lambda)$ response of the PMT itself could be calculated for all wavelengths taking into account the actual intensity of the light source. Pronounced change of the spectral distribution of the relative response was observed as a function of gamma dose, as it is shown in Figure 3.

Several consecutive measurements were carried out to reveal any recovery in the case of the neutron irradiated PMT after delivering $1.0*10^{12}$ neutron/cm^2. No measurable change was observed comparing to the data measured before the irradiation, as it is shown in Figure 4. The differences of the presented two measurements for the same PMT reflect only poor counting statistics below 300 nm and not real physical changes.

The $R = \int R(\lambda)*dN(\lambda)$ spectrum integrated gamma dose response was calculated for the 200 nm – 1000 nm wavelength range using the well known spectral distribution of the Cherenkov light ($dN(\lambda) = K*\lambda^{-2}\, d\lambda$). The obtained values are R(0.3 Mrad)/R(0) = 0.870, R(3 Mrad)/R(0) = 0.773 and R(30 Mrad)/R(0) = 0.604 indicating significant change of R.

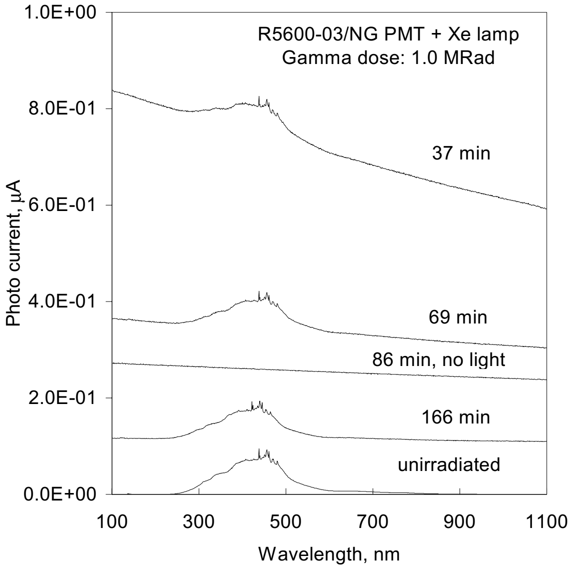

Figure 2 Photocurrent as a function of elapsed time after delivering 1 Mrad of gamma dose.

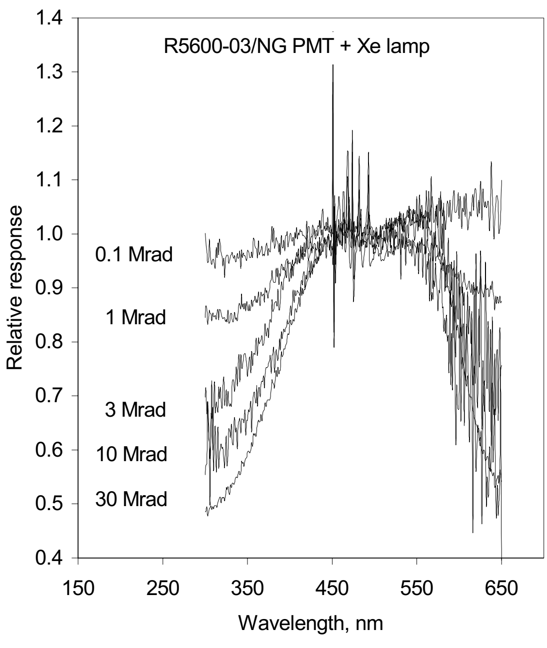

Figure 3 Relative response as function of gamma dose.

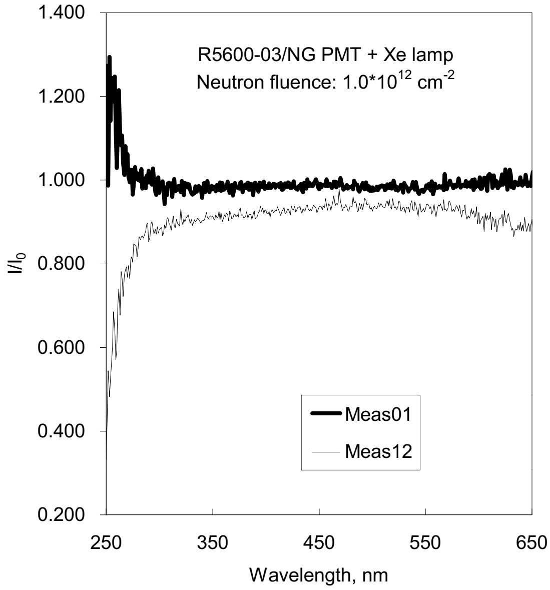

Figure 4 Two measured spectral distributions of the photocurrent of the PMT irradiated with neutrons. I_0 is the photocurrent of the unirradiated PMT.

B. *Dark current measurements*

Dark current – anode voltage characteristics as a function of gamma dose are shown in Figure 5. The same were measured in the case of the neutron irradiated PMT, and they are presented in Figure 6.

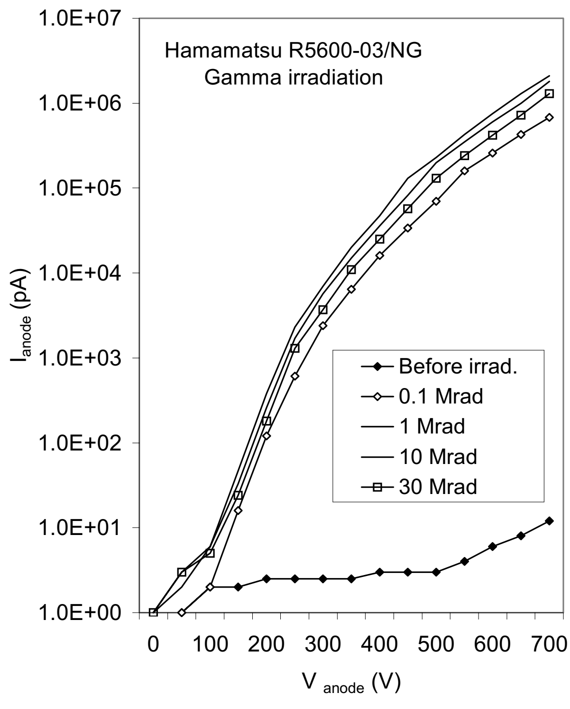

Figure 5 Dark current as a function of gamma dose.

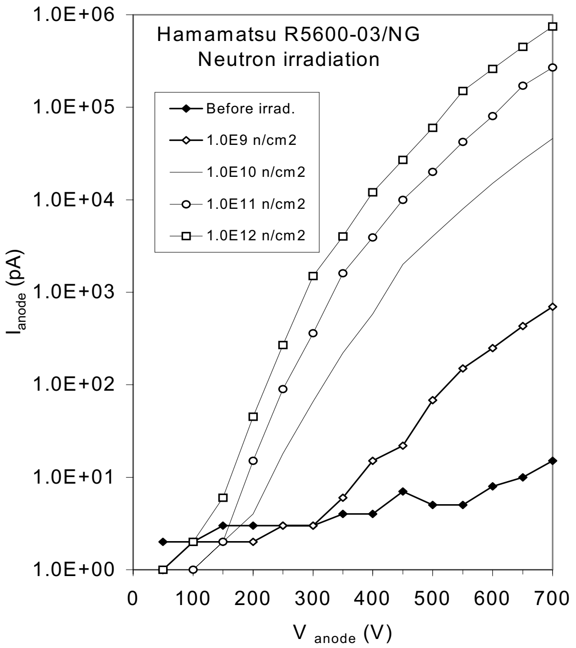

Figure 6 Dark current as a function of neutron fluence.

The alteration of the characteristics caused by the gamma photons and neutrons are clearly seen in Figure 5 and Figure 6.

The decay of the dark current was measured after delivering 30 Mrad of gamma dose and the results are shown in Figure 7.

The kinetics seems to be rather complicated and its interpretation needs further investigations. Two dominating processes with approximately 270 min and 2600 min characteristic times, respectively, can be suspected after 30 Mrad. At lower doses, some other shorter processes ($T_{char} \approx$ 20 min, 30 min, 40 min, 60 min, 100 min) could be observed.

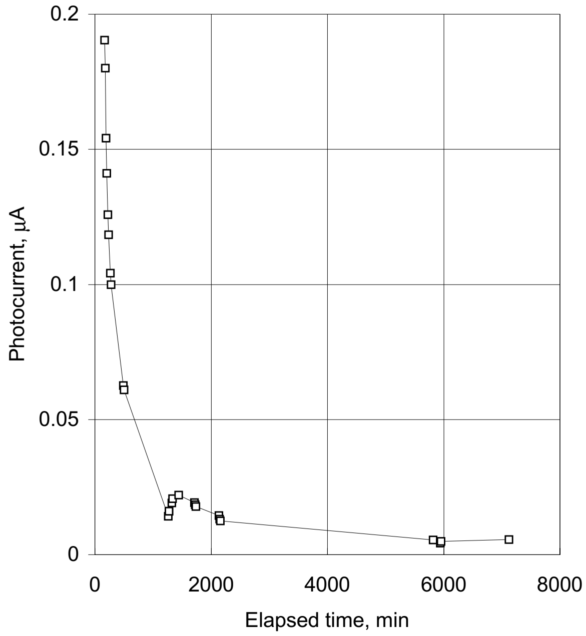

Figure 7 Recovery of the dark current after 30 Mrad of gamma dose.

C. *Neutron activation*

Radioisotopes identified after irradiating HAMAMATSU R5600-03/NG PMTs with 10^{14} n/cm^2 fluence of p(18 MeV)+Be neutrons are shown in Table 1. Probable activation processes and activated components are also listed.

Table 1 Radioisotopes identified after irradiating HAMAMATSU R5600-03/NG PMTs with 10^{14} n/cm^2 fluence of p(18 MeV)+Be neutrons

Identified isotope	$T_{1/2}$	Probable activation processes	Probable activated component
^{24}Na	15.04 h	^{27}Al(n,α)^{24}Na	UV-glass
^{47}Sc	3.351 d	^{46}Ca(n,γ)^{47}Ca →^{47}Sc ^{47}Ti(n,p)^{47}Sc ^{50}V(n,α)^{47}Sc	Dinoda , cathode
^{54}Mn	312.21 d	^{54}Fe(n,p)^{54}Mn	Case
^{56}Mn	2.579 h	^{55}Mn(n,γ)^{56}Mn ^{56}Fe(n,p)^{56}Mn, ^{59}Co(n,α)^{56}Mn	Case
^{57}Ni (?)	36.08 h	^{58}Ni(n,2n)^{58}Ni	Case
^{58}Co	70.8 d	^{58}Ni(n,p)^{58}Co	Case
^{59}Fe	45.1 d	^{58}Fe(n,γ)^{59}Fe ^{59}Co(n,p)^{59}Fe	Case
^{60}Co	5.269 y	^{60}Ni(n,p)^{60}Co	Case
^{82}Br	1.47 d	^{85}Rb(n,α)^{82}Br	Dinoda, cathode
^{120m}Sb	5.76 d	^{121}Sb(n,2n)^{120m}Sb	Dinoda, cathode
^{122}Sb	2.70d	^{121}Sb(n,γ)^{122}Sb, ^{123}Sb(n,2n)^{122}Sb	Dinoda, cathode
^{185}W (?)	75.1 d	^{184}W(n,γ)^{185}W, ^{186}W(n,2n)^{185}W	Dinoda, cathode
^{198}Au (?)	2.6935 d	^{197}Au(n,γ)^{198}Au	Wiring (?)

IV. CONCLUSIONS

Our initial results, in part, motivated the redesigning of the arrangement and shielding of CMS HCAL-HF. For the recent arrangement and an integrated luminosity of 5 x 10^5 pb^{-1}, Monte-Carlo simulations resulted (2.3 – 2.9) x 10^{12} cm^{-2} for the fluence of neutrons of E > 100 keV and an additional 8.3 x 10^9 cm^{-2} fluence of thermal neutrons and 70 Gy of gamma dose [1]. Our results suggest that R5600-03/NG miniature PMTs from Hamamatsu with bialkali photocathode and UV glass window can be used in CMS HCAL-HF for detecting the Cherenkov light.

V. ACKNOWLEDGEMENTS

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VI. REFERENCES

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