RADIATION HARD PHOTODETECTORS BASED ON FINE-MESH PHOTOTUBES FOR CALORIMETRY IN VERY FORWARD RAPIDITY REGION

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1. Introduction

In experiments using electromagnetic and hadron calorimeters, which are planned for the LHC in the very forward rapidity range (up to η =6), the radiation fields are very high. Ionizing radiation levels reach hundreds of kGy and neutron fluences go up to 10^{16} n/cm^2. In addition the photo-readout systems have to operate in the magnetic fields of LHC Detectors (ATLAS, CMS), which in the region of interest are at the level of 20–40 mT, and in the presence of helium gas which exceeds the normal helium concentration in the atmosphere by a factor of 100 to 1000.

Low gain fine-mesh photomultiplier tubes (VPT, or vacuum phototriodes) have been used in the end-cap electromagnetic calorimeter of CMS and have been shown to be able to withstand gamma radiation doses up to 50 kGy. The VPT anode response decreased by 10% in good agreement with what would be expected due to a change of UV faceplate light transmittance [1, 2]. High gain photodetectors proposed to be used in the experiment CASTOR at LHC for the detection of Cherenkov radiation must provide stable operation for higher gamma radiation doses − up to hundreds of kGy and simultaneously for neutron fluences up to 10^{16} n/cm^2. A suitable detector for such applications can be a multi-stage fine-mesh photomultiplier tube (PMT) FEU-187 with highly radiation hard faceplate made of UV glass.

2. Measurements of PMT radiation hardness

For studies of faceplate radiation hardness, the best type of glass produced in Russia (US-49A) was chosen. This type of glass has a light transmittance loss $\Delta T/T_0 = 7\%$ at a wavelength of 425 nm for a radiation dose D = 50 kGy. This value corresponds to the average wavelength of the HLMP-DB25 LED used for PMT illumination. The irradiation of the faceplates was performed at the PNPI nuclear reactor with neutrons of average energy E_n = 0.95 MeV up to a total fluence of 10^{16} n/cm^2 known to an accuracy of 10%. The accompanied gamma radiation dose was estimated to be 1600 ± 250 kGy. The glass transmittance spectra measurements were done one month after the irradiation. We did not take into account the gamma radiation dose caused by the activation radiation of the glass, so the value 1600 kGy is a lower limit on the gamma radiation dose. The results of the reactor irradiation test are shown in Fig. 1.

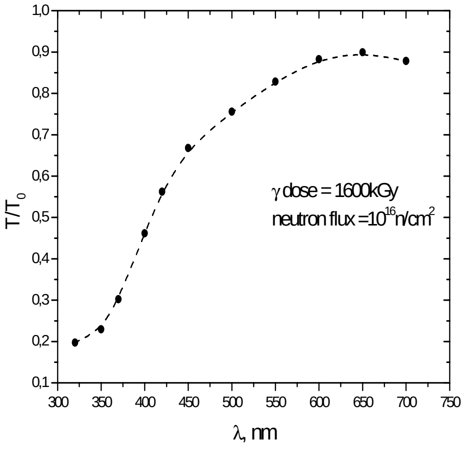

Fig. 1. US-49 relative glass transmittance after irradiation in nuclear reactor

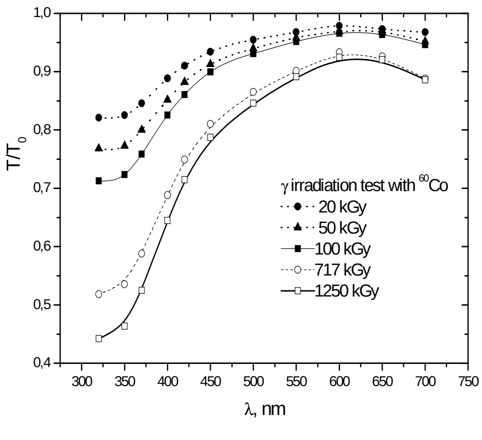

Fig. 2. US-49 relative glass transmittance for different of gamma radiation doses at ^{60}Co gamma facility

The total glass transmittance loss $\Delta T/T_0 = 1 - T/T_0$ can be estimated as a sum of terms due to gamma and neutron irradiation. For the wavelength of 450 nm $\Delta T/T_0 = 33\%$. In order to separate contributions of gamma and neutron irradiation to the value of T/T_0 we performed measurements of the light transmittance spectra for similar glass samples under the ^{60}Co γ-rays up 1250 kGy at the PNPI gamma facility. Results are shown in Fig. 2. On the basis of the glass transmittance measurements with gamma radiation doses of 471, 717 and 1250 kGy we made a linear extrapolation to a dose of 1600 kGy. This allowed us to define at $\lambda = 450$ nm separate losses of $\Delta T/T_0 = 39\%$ for gamma irradiation and $\Delta T/T_0 = 15\%$ for neutron irradiation. This procedure can be done for a set of wavelengths in the range 325–600 nm. An example of the extrapolation for $\lambda = 450$ nm is shown in Fig. 3.

Using the extrapolation method discussed above, one can obtain the transmittance loss caused by a neutron fluence of 10^{16} n/cm^2 at any gamma radiation dose. The US-49A faceplate transmission after 10^{16}n/cm^2 and 50 kGy gamma irradiation is shown in Fig. 4. For comparison, the glass transmittance after only gamma irradiation up to 50 kGy is also shown. The accuracy of this method to separate the neutron and gamma damages in the PMT faceplate is estimated not to be better than 3%. The dependence of the faceplate light transmission change at different neutron fluences (F) can be obtained by performing measurements for varying F and gamma radiation doses. Such studies were not a goal of our experiment. We present only studies of the behavior of PMT windows in extremely hard neutron and gamma irradiation conditions.

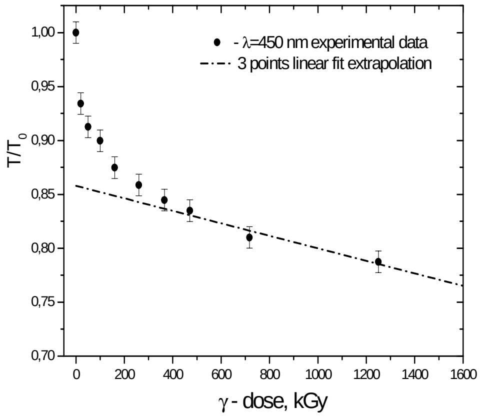

Fig. 3. The linear extrapolation of T/T_0 data at the different doses of ^{60}Co γ-irradiation

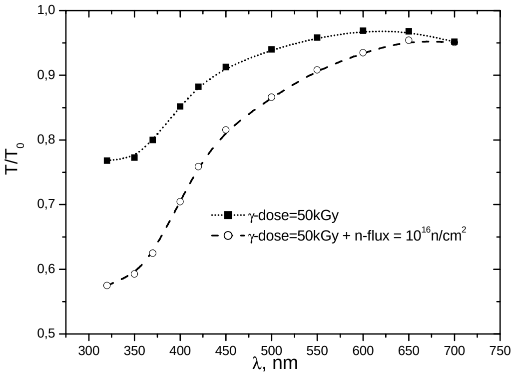

Fig. 4. Relative transmittance T/T_0 for a γ-dose of 50 kGy and neutron irradiation with fluence of 10^{16} n/cm^2

As it was mentioned above, the VPT anode response is following the rather small glass transmittance change under gamma irradiation up to 50 kGy. The same insensitivity of the VPT anode response to 14 MeV neutrons with fluences up to 2.8 $\times 10^{14}$n/cm^2 was shown in Ref. [2]. With a knowledge of the US-49A transmittance change under gamma irradiation, we measured the anode response of FEU-187 photomultiplier tube before and after irradiation at 20 kGy and 50 kGy using a blue LED Lamp HLMP-DB25 with a wavelength peaking at $\lambda = 426$ nm with the method described in Ref. [3].

Examples of spectra obtained before and after gamma irradiation (50 kGy) of the PMT FEU-187 are shown in Fig. 5. The numeral “2” marks the PMT pulse spectrum. Similarly, “3” indicates the reference PMT pulse spectrum, and “1” – the ^{137}Cs γ-spectrum from the reference PMT with the same gain as for the measurements (a) and (b). Stability of the electronics and PMT gain was at the level of 1%. Overall statistical and systematic errors are estimated as not more than 3%. The results obtained during gamma irradiation at 50 kGy show good agreement of the anode signal change with the faceplate transmittance loss within experimental errors of ±2%. A burn-in test of the PMT was in a similar way to the irradiation test, with the PMT illuminated by a light emitting diode producing an anode current of 200 nA for 50 hours. Measurements of the anode signal before and after the illumination did not show any change of the amplitude with an accuracy of ±2%, which demonstrates the stability of this PMT under these conditions.

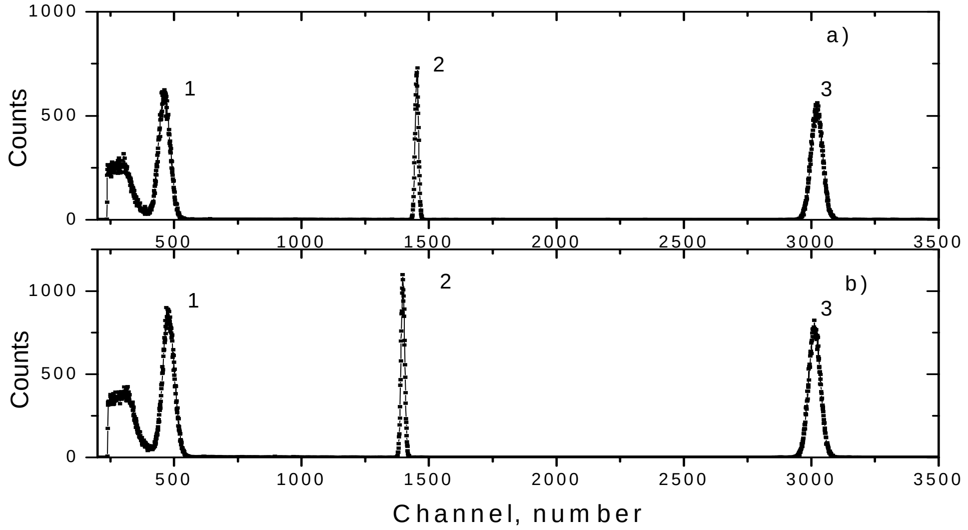

Fig. 5. Spectra from PMT FEU-187 before (a) and after (b) gamma irradiation up to 50 kGy

3. PMT immunity to the gaseous He

It is well known that helium gas can penetrate into PMT and degrade its performance increasing the dark count rate. Helium can also cause an ion pulse following a normal one. The presence of the gaseous He in the atmosphere of LHC Collision Hall and in the experimental pits is estimated to be between 100 and 1000 ppm. Immunity to the gaseous He is an important characteristic of photomultiplier tubes proposed for readouts in LHC environment. The helium immunity of the FEU-187 was measured using the experimental setup shown in Fig. 6. The PMT to be studied was placed into a vacuum-tight chamber. Dark current count rate and gain of PMT were measured in a constantly refreshed atmosphere of pure nitrogen during first 8 days. Later pure nitrogen was changed to a mixture of (N_2+He) where He admixture was 1600 ppm. The pressure in the chamber was equal to one atmosphere.

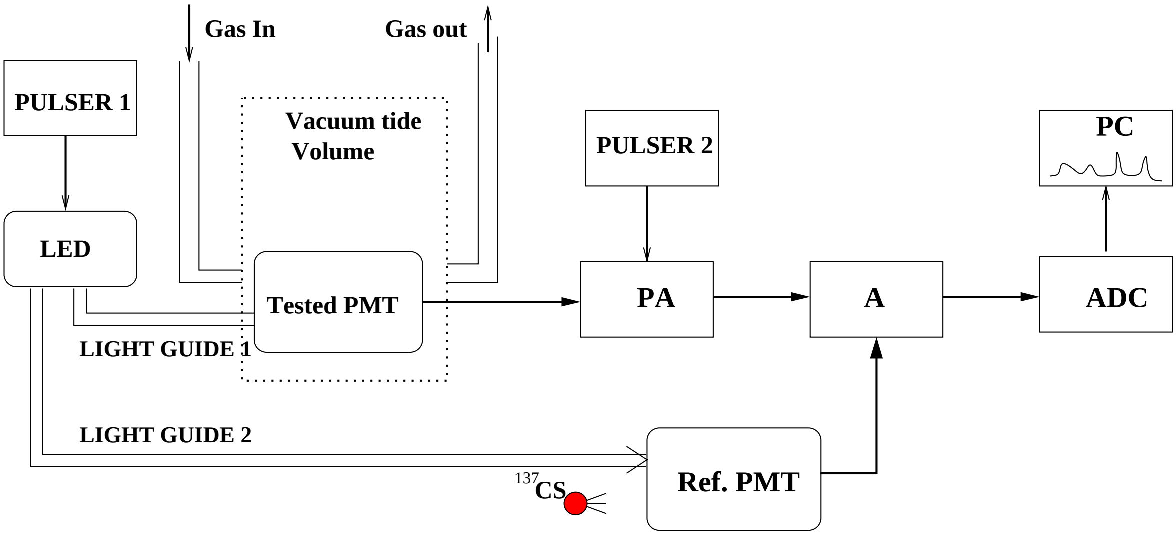

Fig. 6. Experimental setup for the He immunity test of PMT FEU-187

The PNT dark current without illumination was not more than 1 nA. The results of these measurements are shown in Fig. 7. The gain of the PMT was monitored during this test. Light pulses from the LED, driven by Pulser 1, were directed simultaneously by two fibers to the PMT under test and to a standard reference PMT placed outside of the He volume. The gain stability of the reference PMT coupled with NaI(Tl) crystal was tested by the detection of ^{137}Cs γ-rays during test measurements. The stability of electronics was tested by means of the precision amplitude signal generator (Pulser 2). All signals were digitized by an ADC and recorded with a PC. The dark noise count rate and the gain of PMT FEU-187 did not show any change during 4 weeks operation in an atmosphere of (N_2+1600 ppm He).

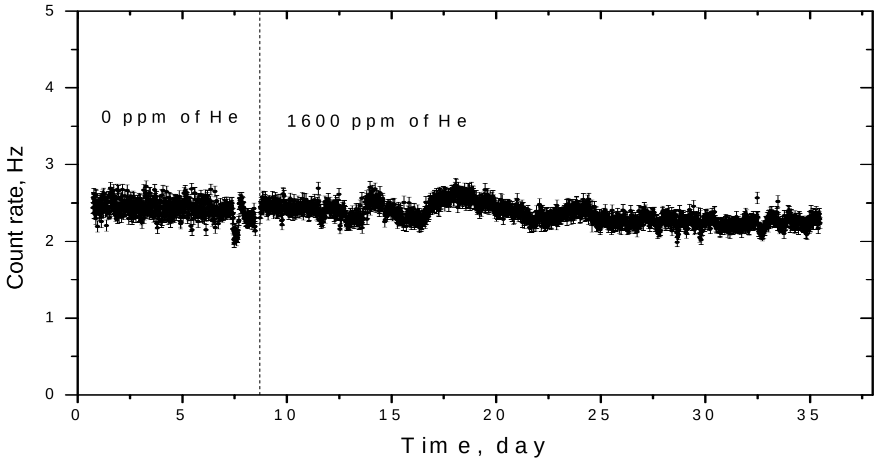

Fig. 7. Dark noise count rate in N_2 atmosphere with 1600 ppm of He admixture

4. Magnetic hardness and time resolution

Resistance to magnetic fields is an important issue for PMTs proposed to be used in the LHC environment. The gain dependence of the fine-mesh PMT FEU-187 on a magnetic field B was measured for two angles θ between the PMT axis and the magnetic field direction. The gain behavior over the large range of θ for B = 40.6 mT was also measured. Results of these measurements are shown in Fig. 8.

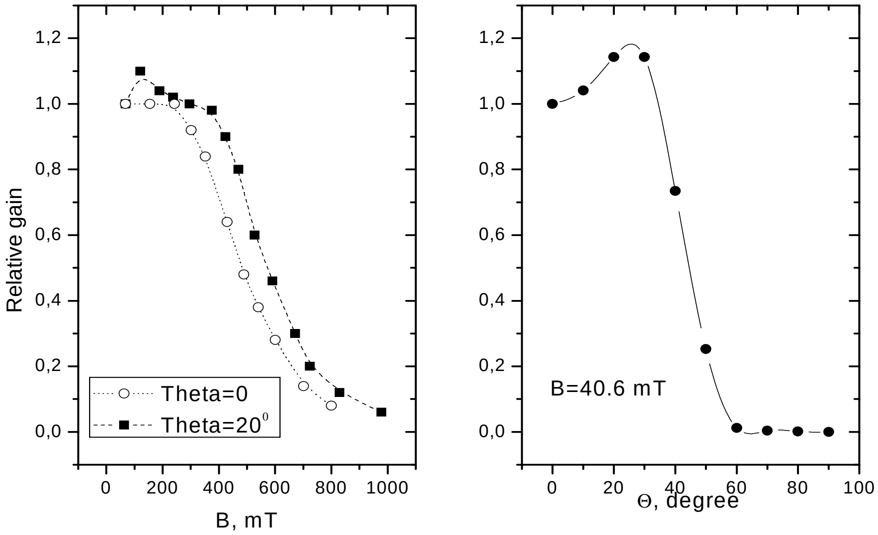

Fig. 8. Magnetic properties of fine-mesh FEU-187

Two different methods were used to evaluate time resolution of fine-mesh FEU-187.

1. Measurement of time of flight for different particles such as π, K and p with a momentum of p = 1.8 GeV/c, using two plastic scintillators (BS-420 with 2 cm thickness separated by 4 m). A time resolution of σ = 58 ps per photodetector was obtained.
2. Measurement with a pulsed light source with the pulse duration (FWHM) of 35 ps and the wavelength of 635 nm: with a threshold of about 0.2 photoelectrons, the measured time resolution was σ = 270 ps for a single photoelectron pulse (see Fig. 9).

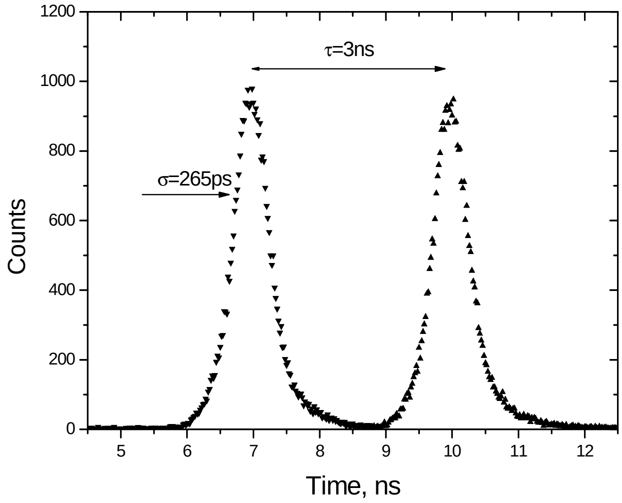

Fig. 9. Time resolution of FEU-187 measured in single photoelectron mode

5. Conclusion

In this paper we present the results of study of a very radiation hard photodetector – a high gain fine-mesh PMT (FEU-187) with a highly radiation hard faceplate from UV-transparent glass (type US-49A). Radiation resistance of PMT to γ-rays and neutrons was investigated at the PNPI gamma facility and nuclear reactor. A number of UV-transparent glasses were irradiated near active zone of reactor up to a fluence of 10^{16}n/cm^2 with an average neutron energy of E = 0.95 MeV and with gamma radiation doses of 1600 ± 250 kGy. In order to separate the light transmittance losses in the glass caused by neutron and gamma irradiation, the measurements of the glass transmittance spectra at different doses up to 1250 kGy were performed at the ^{60}Co gamma facility. In this way we were able to define the glass transmittance loss caused by the reactor radiation for the wavelength range λ = 350–650 nm separately for γ-rays and neutrons. For the wavelength λ = 400 nm, the light transmittance losses are equal to 43% and 11% due to gamma and neutron irradiation, respectively. In experiments with gamma irradiation to 100 kGy and neutron fluence of 10^{16} n/cm^2 the light transmittance at λ = 400 nm is reduced to 72% of its initial value. These results are an evidence of the high radiation hardness of the PMT faceplates that were studied. The irradiation of a PMT with US-49A faceplate by gamma radiation doses of 20–50 kGy has shown a change of the PMT anode response expected from the UV glass transmittance loss. Results of measurements of insensitivity to magnetic fields and immunity of the PMT against helium in the LHC environment are also presented.

At levels expected in the LHC environment, FEU-187 is radiation hard, resistant to magnetic fields and unaffected by the presence of helium. The PMT FEU-187 has an excellent time resolution of 58 ps measured by time-of-flight techniques with 1.8 GeV/c beams of pions, kaons and protons at CERN, and a time resolution of 270 ps measured with an ultrafast laser diode in a single photoelectron mode.

References

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3. Yu. Gusev *et al.*, Preprint PNPI-2597, Gatchina, 2005. 16 p.