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Study of Short-Term Instability and Aging of FEU-115M Photomultiplier Tubes

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Abstract—Results of studying the instability of the gain of FEU-115M photomultiplier tubes (PMTs) at a varying counting rate corresponding to the range of the anode current of 0.02–120 μA are presented. It is shown that the behavior and value of the gain instability for different samples of this PMT type substantially differs when the counting rate changes. The relative change in the gain of some PMTs reaches 23%. Results of the study of the long-term behavior of the PMT gain in high-rate conditions (PMT aging study) are presented. The relative gain drop is 30% after an anode charge of ~600 C is accumulated.

INTRODUCTION

Photomultiplier tubes (PMTs) of the FEU-115M type have been selected for this study, since a large number of these devices are used for upgrading the muon system of the D0 detector on the FNAL proton–antiproton collider in order to bring its characteristics to satisfy of an increase in the luminosity by about an order of magnitude, up to $2\cdot10^{32}$ cm^{-2} s^{-1} [1]. The purpose of the upgrade is to create a system of trigger scintillation counters for the forward muon system with three planes of counters on the each side from the beam interaction point and to add an additional counter layer to the central muon system. The total number of counters based on FEU-115M PMTs, including auxiliary counters, is ~6000. At present, the production, mounting, and commissioning of the counter system are completed [2], and it operates as a part of the D0 detector.

An FEU-115M PMT manufactured by AO MELZ, Moscow [3] has a multi-alkali (Sb–K–Na–Cs) semitransparent photocathode (sensitive diameter is 25 mm) with a spectral sensitivity shifted to the green region and 12-stage linear dynode system made of an Al–Mg alloy (the final dynode is made of a Cu–Be alloy). The external diameter of the PMT is 30 mm, and the length is 90 mm. In its characteristics, the FEU-115M PMT is well suited for use in counters of the muon system for the D0 detector. The light-collection method selected for the counters uses wavelength shifting bars, which shift the light from the scintillator to the green spectral region, and green wavelength-shifting optical fibers for some counters.

A large number of PMTs combined into groups with supply from common high-voltage source demands high gain stability. This article presents results of studying the FEU-115M PMT gain instability in variable rate conditions (short-term instability) and also the long-term behavior of the gain during extended high rate conditions (PMT aging).

A STUDY OF THE SHORT-TERM INSTABILITY

A short-term variation in the PMT gain at a variable counting rate was studied on the test stand. The photomultiplier tube with a resistive base and light-emitting diodes LED1 and LED2 used for photocathode illumination were placed into the light protective housing of the test stand. The CAMAC crate with a LeCroy 2249A analog-to-digital converter (ADC), connected by an interface to a PC-486 personal computer, was used for acquiring and processing amplitude information from the PMTs. The test stand is described in detail in [4].

A PMT base with a 1 mA average current (the total resistance is ~1.6 MΩ) was built to study the PMT gain instability at a variable counting rate. The first three resistors of the base are selected equal to 1.8*R*, 1.5*R*, and1.2*R*, and the others are 1.0*R*. The final four dynodes were powered from separate stabilized voltage sources. The base is intended to study the dependence PMT gain on the anode current when the average anode current varies up to 0.5–1.0 mA without a noticeable redistribution of voltages across the dynodes due to the PMT current.

The PMT was illuminated by two LEDs. One of them, LED1, operated continuously with a 50-Hz frequency and was used to measure the PMT gain. The ADC pedestal was measured with the same frequency synchronously with amplitude measurements. The delay between gate signals for measuring the pedestal and amplitudes was selected equal to 700 ns. The PMT counting rate was changed by the LED2 triggered with a frequency from 1 kHz to 1 MHz. This allowed to change the anode current from 0.4 to 400 μA. When the pulser that triggered the LED2 was switched off, the PMT anode current was 0.02 μA and caused by the LED1 for measuring the PMT gain. The LED2 pulses were vetoed by a 1.5 μs long pulse for the time of the PMT signal amplitude and ADC pedestal measurements.

The following measurement procedure ensuring high repeatability of results was selected. After the voltage was switched on and reached its operating value, 1 MHz frequency LED2 pulses providing a 400 μA anode current were switched on. After a 5-min exposure for the PMT warm up, the LED2 pulses were switched off and the PMT reached its steady state within 10 min at a 0.02 μA of anode current. Then the measurements with this PMT are started by measurements of gain variation within □~1□min. Then the LED2 pulses were switched on with a frequency 1 kHz to provide PMT anode current 0.4 μA. After about 1 min of gain measurements, the LED2 pulses were changed to a frequency 3 kHz (the anode current was 1.2 μA) and, in about 1 min more, the LED frequency changed to 10 kHz (the anode current was 4μA), etc. Anode currents of 0.4, 1.2, 4.0, 12, 40, and 120 μA were studied. After measurements at a 120 μA anode current, the LED2 pulses were turned off for ~4 min in order to study the PMT gain recovery, anode current 0.02 μA induced by the LED1 pulses for gain measurements was still flowing. Then the LED2 pulses frequency changed to mode with 120 μA anode current, and the gain was measured over next four minutes.

The analysis of measurements consisted in averaging of the PMT signal amplitude and ADC pedestal values with a 5 s step for each measurement point, subtracting the pedestal, and normalizing the average amplitude to the value obtained at the beginning of measurements (at the first point). The measurement results were presented as PMT gain values with 5 s steps. A total of 21 FEU-115M PMTs were studied. The duration of measurements with one PMT was ~30 min.

The measurement results shown in Fig.1 and Fig.2 demonstrate that the behavior and amplitude of the FEU-115M PMT gain instability vary substantially between samples. We observe two characteristic types of PMT behavior, each type is illustrated in Fig. 1 by two PMTs with similar dependency of the gain on the counting rate.

The first type of dependence is simpler and more predictable because gain variations look like discrete steps under stepwise changes of the counting rate. The setup time of the gain change is ~1 □s after a change in the counting rate. The gain remains unchanged for ~1 min until the next change in the counting rate. The gain dependence on the counting rate for these PMTs (#3 and #17) looks like "steps", the gain changes demonstrate increase in amplitude and are accumulated as the counting rate increases. A feature of this dependence is the saturation of the gain changes. The gain variations are significant for the first steps of variations in the counting rate, subsequently gain changes are much weaker. For example, a change in the anode current value by 4 μA from 0 to 4 μA causes the same gain variation as a change in the anode current by 80 μA from 40 to 120 μA. A similar saturation of gain variations was observed earlier for PMTs FEU-84-3, FEU-110, and for FEU-49B. Such a behavior of the gain versus counting rate allows to stabilize the PMT gain for some applications by continuous or high rate pulse illumination of the photocathode [5]. The dependence of the gain on counting rate features a good repeatability from one measurement to another and is predictable, since, for a given counting rate, the gain depends only slightly on the PMT irradiations prehistory.

A stepwise increase in the gain with increasing counting rate is also characteristic of the dependence of the gain on the counting rate of the second PMT type (samples #1 and #9). However, the second type, in addition to the stepwise-increasing component, has a slower instability component. As compared with the first component, it has an opposite sign; i.e., the gain slowly decreases as the counting rate increases. The superposition of both instability components results in the behavior that, when the counting rate changes, a stepwise increase of the gain is followed by its slow decrease. As a result, "steps" of the gain variations are not added and the total gain change is smaller. A more complex pattern of gain variations after switch-off and further switch-on of the operating mode with a 120 μA anode current is typical of PMTs with counting rate dependence of the second type.

Fig. 2 shows measurement results for PMTs with the gain having a dependence on the counting rate that can be considered intermediate between the first and second types. Upon some stepwise changes in the counting rate, they behave as a PMT with the first-type dependence and, in other cases, as a PMT with the second type dependence. For the selected measurement mode, the counting rate increases at each step by about a factor of 3, as the typical gain of one PMT dynode. Due to the saturation of gain changes caused by an increase in the counting rate, each step of the gain change in Figs. 1 and 2 corresponds approximately to a specific PMT dynode, since the current of the previous dynodes is still too small for changing their gain, but the gain change saturation has already been attained for the next dynodes. When the anode current varies from 0 to 0.4 μA, the first step basically describes the behavior of the last dynode; when the anode current varies from 0.4 to 1.2 μA, the second step describes the behavior of the last but one dynode; etc. Thus, the data given in Fig. 2 show that different dynodes of the same PMT could have gain instabilities of different types. The three last dynodes of PMT #20 have the first-type gain dependence on the counting rate, and the three previous dynodes have the second-type dependence. On the contrary, for PMT #10, the last four dynodes have the second-type dependence and the previous two dynodes have the first-type dependence. The referencing of

counting rate steps to particular dynodes is certainly approximate, but the differences in the behaviors of these two samples are obvious. For PMT #12, the decrease in the gain after its stepwise increase is small, especially for the first dynodes, approaching it to PMTs of the first group. Sample #13 slightly differs from the others, since the decrease in the gains of the second, third, and fourth (from the anode side) dynodes is significant, although, on the whole, this PMT corresponds to the intermediate type and, when the anode current is 40 and 120 μA, it has the first-type dependence. 38% of the studied 21 PMTs demonstrate the instability of first- type, 14% have second type, and 48% shows the instability of the intermediate type.

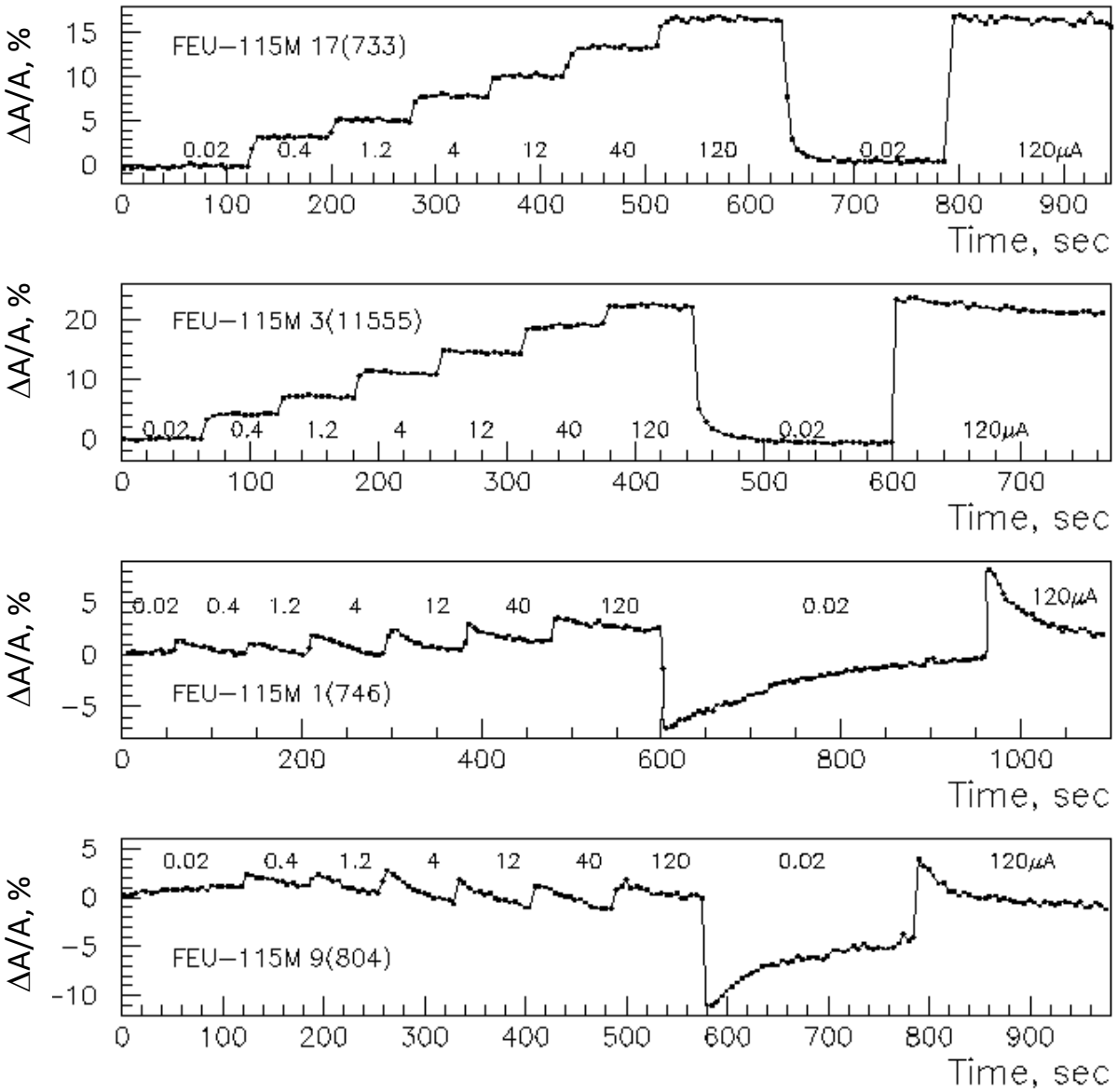

Fig. 1. Dependence of the gain variations on the counting rate for different PMT samples. The gain variations in percent are shown as ΔA/A. The average anode current values in μA are designated by numbers. The PMT number assigned for measurements and its serial number (number in brackets) are presented in the left part of the plots.

The pattern of the decrease in the gain of PMT #1 in high rate conditions and the gain recovery after the LED2 was switched off is shown in Fig. 3 on a longer time scale. The mode with a 120 μA anode current was switched on directly before the measurements, and the measurements were conducted at current values of 0.02, 120, 0.02, and 120 μA. The gain recovery at 0.02 μA is described by an exponential curve with a 530 s time constant. The time constant of the gain decrease at 120 μA is 450 s.

The dependence of the FEU -115M PMT gain on the average anode current value is shown in Fig. 4. The steady-state gain values 1 min later after the switch-on of the LED2 to provide selected anode current are shown for the same PMTs that are given in Figs. 1 and 2. The gains are normalized to the gain value at the beginning of measurements. The gain change saturation at high rates can be clearly seen: the dependence of the gain on the counting rate is much weaker at high anode currents. The greatest change in the gain is observed when the anode current varies from 0 to 12 μA.

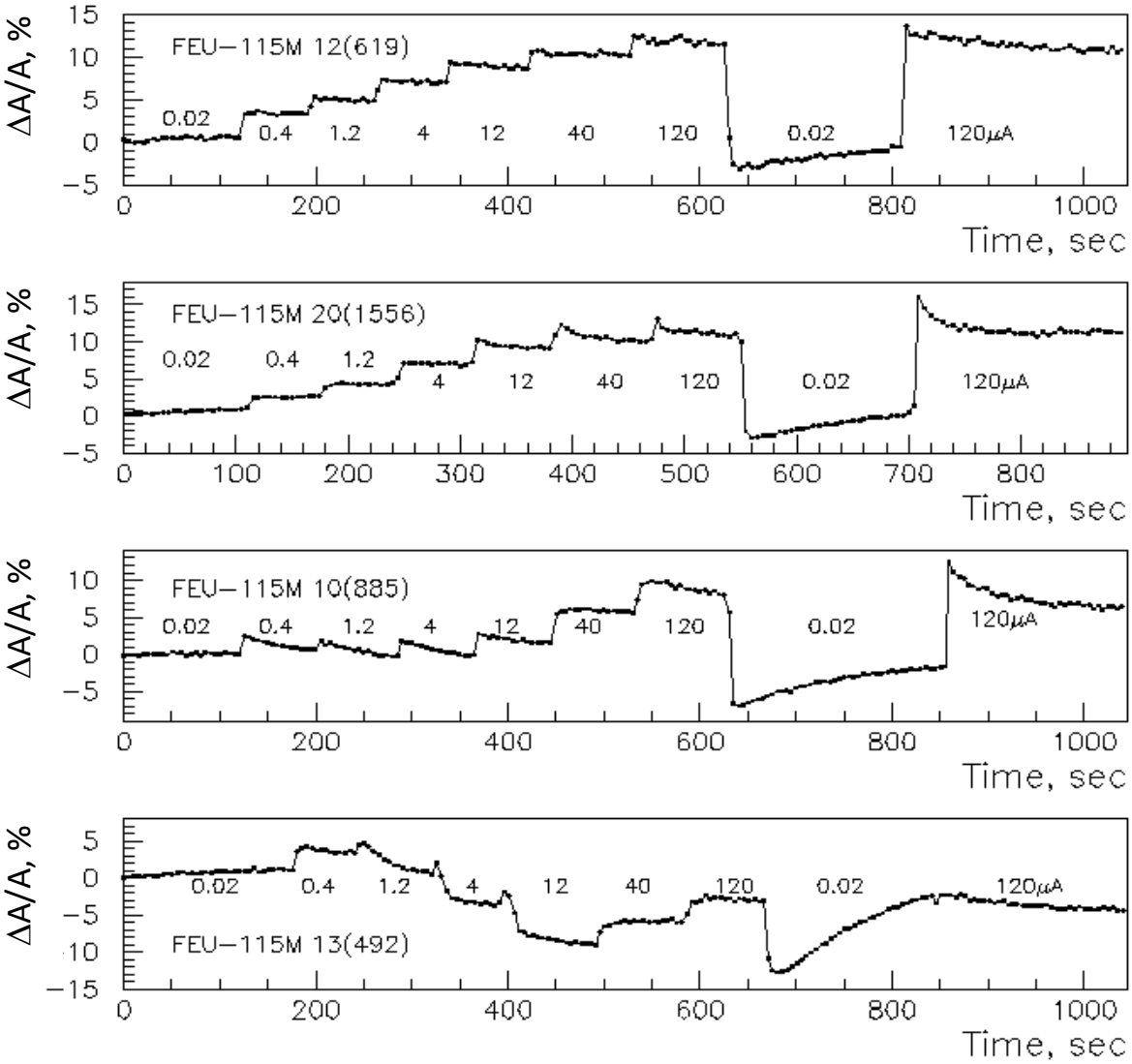

Fig. 2. Gain on the counting rate dependence for four different FEU-115M PMTs with intermediate type of gain instability. See designations in the caption to Fig. 1.

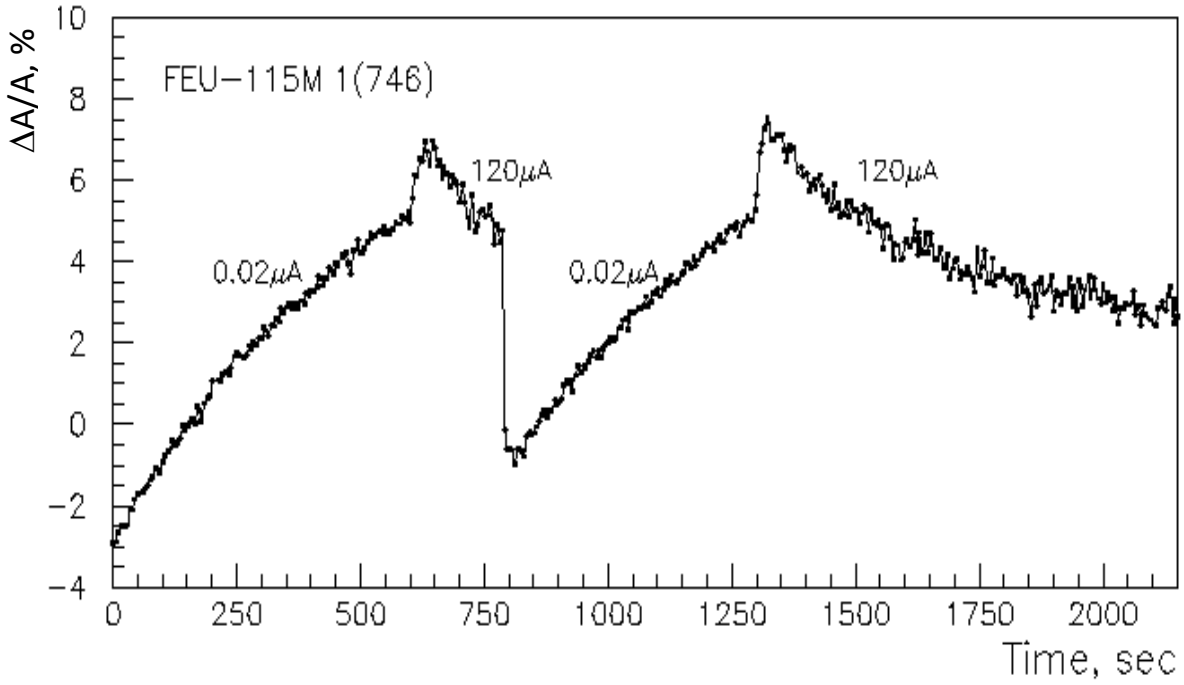

Fig. 3. Change in the gain upon switching on and off the high counting rate conditions (see text). See designations in the caption to Fig. 1.

The saturation can be seen especially clearly for PMTs with gains changing in the form of regular steps in response to stepwise counting rate changes.

In most references, the causes of PMT short-term instability (the dependence of the PMT gain on the counting rate) are considered insufficiently studied. As a basic cause for the short-term instability, descriptions of some PMT manufacturers indicate the electrostatic influence of the charge accumulated on dynode supports in the glass [6]. Reference [7] presents results of studying the gain of the Philips XP-3462P PMT as a function of the average anode current and the intensity of the light pulse for various dynode voltage distributions; it gives a detailed list of references on the PMT short-term instability. This paper and references given in it consider a change in the secondary electrons yield caused by the processes occurring in surface layers of dynodes in high rate conditions as the reason for the short-term instability.

The secondary-electron emitter in a PMT with alloy dynodes is a thin film of oxides (BeO and MgO) on the dynode surface. Reference [5] considers the accumulation of charge on the dynode surface, facilitating escape of secondary electrons, to be a basic reason for the short-term gain instability of FEU-84-3, FEU-49E, and FEU-110 PMTs. The behavior of the instability in most samples of such PMTs corresponds to the first-type dependence for the FEU-115M considered in this article, although the instability for the FEU-115M is smaller by a factor of ~1.5. Other PMTs, such as FEU-115 or XP-1020, have the same or smaller instability level [8]. For PMTs with cesium–antimony dynodes (for example, FEU-85) cesium evaporation and diffusion [9] result in a slow decline of the gain after an increase in the counting rate is considered as the main cause for the instability.

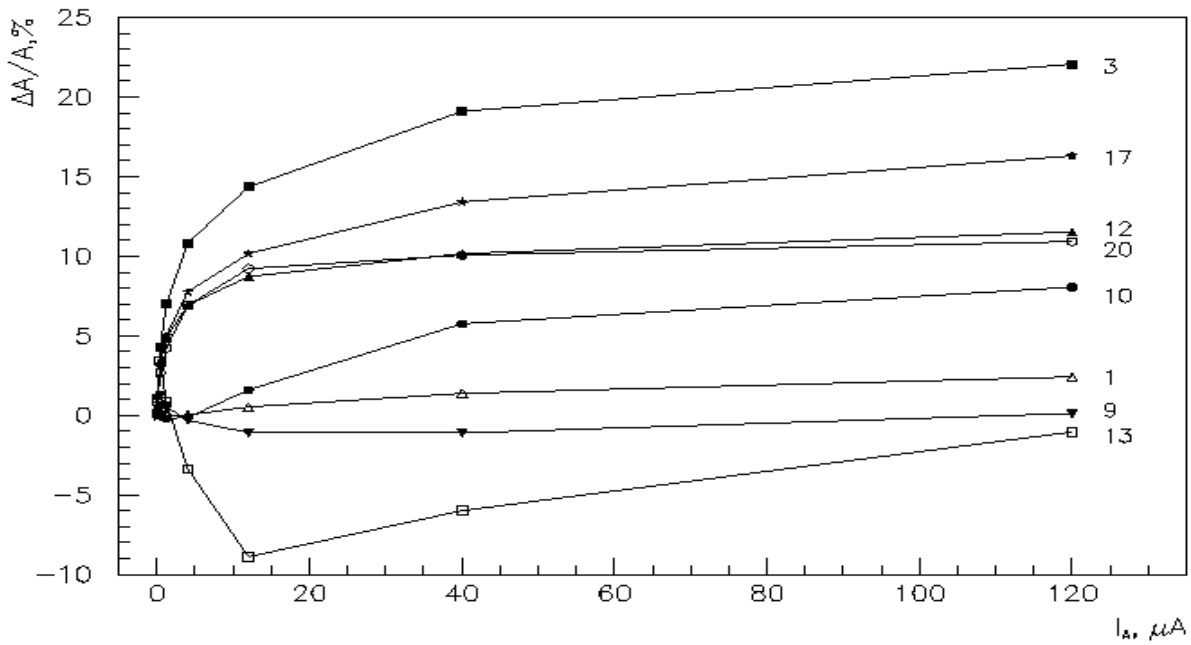

Fig. 4. Gain of the FEU-115M PMT, measured 1 min after the switch-on or change of the high rate illumination with the average anode current indicated on the *X*-axis. The PMT numbers selected for these measurements are shown near the curves.

It is reasonable to assume that both instability mechanisms are typical for FEU-115M PMT. Although the FEU-115M is a PMT with alloy dynodes, some material can be deposited on dynodes surfaces when a multi-alkali coating is applied to the photocathode. The large difference in behavior and instability of FEU-115M samples can be attributed to a different degree of this "pollution" from PMT to PMT and from dynode to dynode.

PMT AGING STUDY

The variations in the gain of FEU-115M PMTs during their long-term operation at high counting rates were studied, taking into account the conditions in the muon system of the D0 detector. The obtained estimates show that the average signal value from a minimum ionizing particle is 30 mV, the charge accumulated at the PMT anode during operation can reach 100 C for counters with the highest counting rate. In order to ensure the required safety factor, it was necessary to study the PMT gain behavior for charges up to ~500 C accumulated. In order to collect this charge over a reasonable time, the PMT anode current should be in the hundreds of microamperes range. A base with a 1mA average current (its total resistance is ~1.6 MΩ) was used. It is similar to the base used for studying the short-term instability. Samples 4 and 5 used a base with last three resistors of 1.1*R*, 1.2*R*, and 1.2*R*. To eliminate voltage redistribution on dynodes, the last four dynodes were connected to separate stabilized voltage sources. This allowed the study of the PMT gain when the average anode current changed up to ~1.0 mA without notable variations in the dynode voltages caused by the PMT current.

Each PMT was illuminated by two LEDs. In addition to the LED that provided the required anode current and was connected in the forward direction, there was a second LED connected in the backward direction with a 100 Hz frequency intended for monitoring the PMT gain stability. When the LED is connected in the backward direction it has the higher stability of the light pulse due to a weaker dependence of the light intensity on the pulse generator amplitude (~80 V). Measurements with different PMTs were made, and one or two PMTs were simultaneously studied.

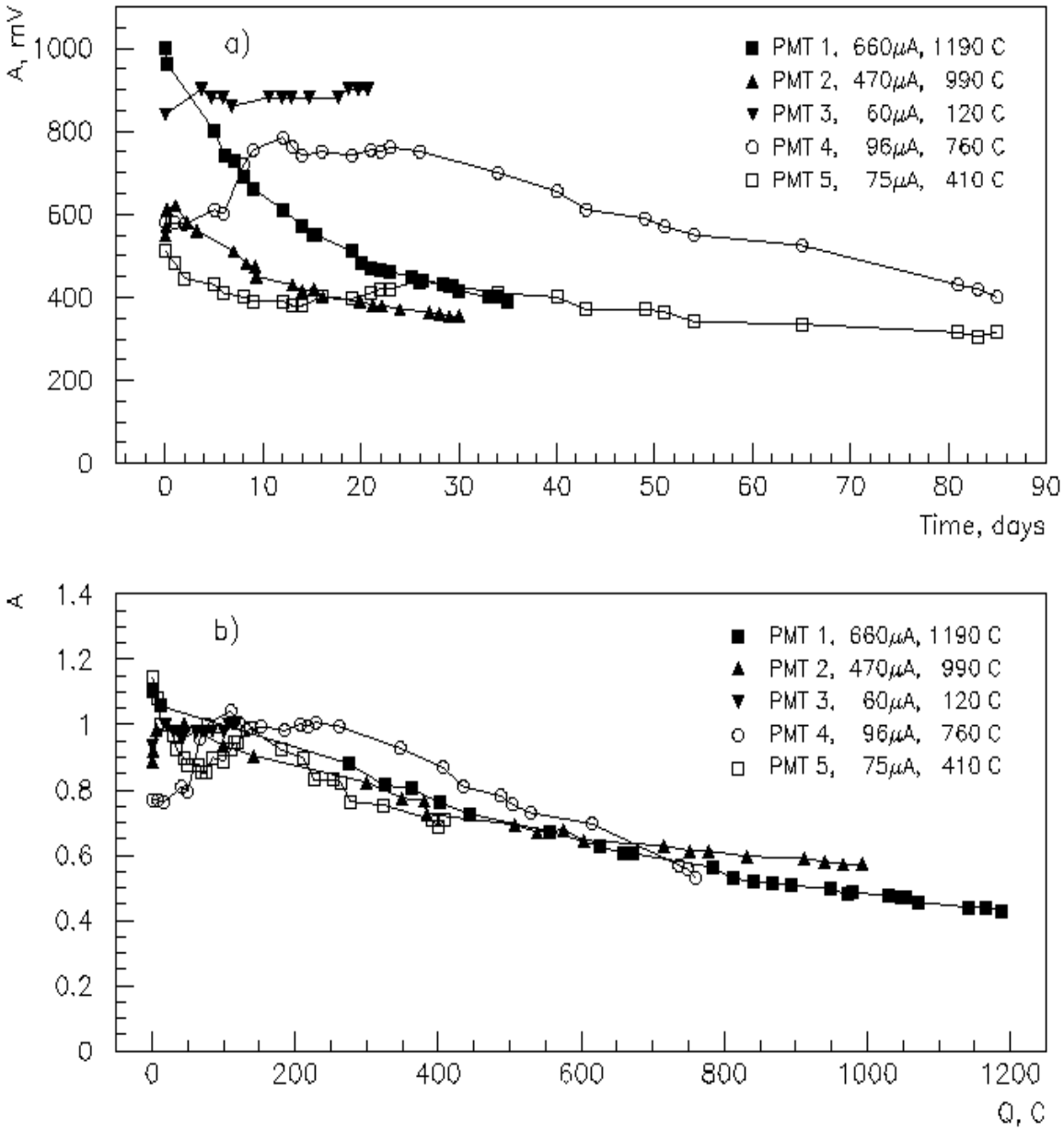

Fig. 5. Variations in the PMT gain during long-term operation in the high rate conditions as a function of (a) time and (b) charge accumulated at the anode. The PMT number, the average anode current at the beginning of measurements and accumulated charge at anode at the end of measurements are shown in the right corner of the plots.

The results of these measurements are given in Fig. 5a as a dependence of the PMT signal amplitude on the measurement time. The analysis of the plot shows that the behavior and the value of the gain instability significantly differ from PMT to PMT. The gain of PMTs #2 and #4 at first increases (by 25% for PMT #4) and only several days later starts decreasing. A more substantial gain drop is typical for other PMTs (#1 and #5) within the first few days as compared with the later period.

Figure 5b shows dependencies of the PMT signal amplitude on the charge collected at the PMT anode. In this case, the signal amplitude is normalized at the point corresponding to accumulation of a ~100 C charge. This allowed us to exclude from normalization the initial measurement period, where the differences between different PMTs are especially significant. When a charge of ~200 C was accumulated, the gain of all PMTs decreased with time, reaching a level of 0.7 of the initial value at an accumulated charge of ~ 600 C.

During aging study the number of photoelectrons in a pulse was monitored by measuring the average value and width of amplitude distributions using analog-to-digital converter. The results demonstrate that the PMT gain decreases instead of the number of photoelectrons; i.e., the effective quantum efficiency of the photocathode remains unchanged.

The long-term change of the FEU-115M gain was also studied as the planes of scintillation counters for the forward muon system of the D0 detector were assembled. Partially assembled planes containing 140 counters were left in the test zone for 2 months in the operating condition under a high voltage in a mode of a ~1 μA anode current supplied by the monitoring system based on LEDs. The PMT gain change was monitored by weekly measurements of pulses from LEDs and a Sr^{90} radioactive source. The measurements have shown that the gain changed up to 20% within the first 3–5 days, and, after that, variations in the PMT gain did not exceed 10% for all counters.

From the presented results long-term changes of signal amplitudes from the scintillation counters of the muon system for the D0 detector, which can be attributed to FEU-115M aging under their operating conditions will not exceed 20%. These variations are monitored by the existing monitoring system which supplies calibration light pulses from LEDs to each PMT and decrease in gain can be compensated for by an appropriate change in the high voltage applied to the PMTs.

CONCLUSION

The variations in the gains of 21 FEU-115M PMTs were studied at counting rates corresponding to the anode current varying from 0.02 to 120 μA. The relative gain change is comparable with other PMTs (FEU-84-3, FEU-49E, and XP-3462P) and for some samples reaches 23% with a significant spread in the value and behavior of the instability from one PMT to another. A 1 to 3 months study of the aging of five FEU-115M PMTs at counting rate conditions corresponding to the average anode current from 60 to 660 μA shows the gain drops by 30% for ~600 C charge accumulated at the PMT anode. There are substantial differences in gain change between different FEU-115M samples especially up to 100 C of anode accumulated charge.

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