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STUDIES OF HIGH-GAIN MICRO-CHANNEL PLATE PHOTOMULTIPLIERS

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Abstract

The characteristics and performance of several kinds of high-gain micro-channel plate photomultipliers have been investigated. Special attention was directed towards i) lifetime studies, ii) performance in the magnetic field, and iii) timing properties. Lifetime studies include separate investigations of the photocathode quantum efficiency degradation caused by ion feedback, and the deterioration of the micro-channel plate gain. The dependence of the micro-channel plate photomultiplier gain on the intensity and the direction of the magnetic field (up to 7 kGauss) is reported.

Introduction

The Micro-channel Plate Photomultiplier is a photomultiplier where the cascade of dynodes is replaced with one or more micro-channel plates (MCP) as the gain element. Due to the small size of the MCP and the possibility of proximity focusing, the MCP-photomultiplier can have better timing properties[1] and be much less sensitive to the presence of magnetic fields.[2]

A MCP is a matrix of a large number of very thin glass capillaries having a resistive and secondary emissive wall inside. The principle of this type of electron multiplier is now well known.[3] MCP has the excellent properties of high gain electron amplification, fast time response and relative immunity to the external magnetic field while preserving position information. Today MCP's are used successfully in many varieties of applications beyond photomultiplier tubes (MCP-PMT), as for example in image intensifier[4] tubes and image pickup tubes.[5] However, there are still some drawbacks connected with MCP operation. The relatively short photocathode lifetime due to the ion feedback effect,[6] after pulsing, limited counting rate and the dead time are the most troublesome.

The purpose of this paper is to study the characteristics of several new MCP photomultipliers. The emphasis is placed on the study of the MCP performance rather than on that of the photocathode. Table I lists the MCP photomultipliers used in these studies along with some descriptions of their construction.

Table I. Tube Descriptions

Type	No.	Focusing	MCP	Al-film	Manufactured by
F4129	—	Proximity	3-stage	Yes	ITT
R1294X	ZC-203	Electrostatic	2-stage	No	HTV
R1294X	ZC-209	Electrostatic	2-stage	Yes	HTV
R1294X	ZC-233	Electrostatic	3-stage	No	HTV

A life test of the two stage tubes with Al film and without Al film showed that the Al film can stop the ion feedback from the MCP to the photocathode completely, resulting in a long stable life for the photocathode. The test revealed that the gain of the MCP starts to degrade at an accumulated output charge of 10^{-2}C/cm^2 and finally stabilizes at about 45% of the initial value. The three stage tube without Al film also showed less photocathode degradation from ion feedback than did the two stage MCP without Al film.

Three of the tubes were tested in a magnetic field parallel to the tube axis and were seen to function up to a field of 7 kG. No big differences were observed between the proximity and the electrostatic focusing for a parallel magnetic field. However, results showed that proximity focusing is essential for the operation of a tube in a non-parallel magnetic field.

Measurements of the timing properties show a rise time of 500 ps and the transit time spread of 200 ps FWHM (∿20 photo-electrons) in the three stage tube without Al film.

Basic Tube Structure (as listed in Table I)

R1294X, manufactured by HTV, consists of a 18 mm diameter bi-alkali photocathode, an electrostatic focusing electrode, two or three 1 inch diameter MCPs placed 20 mm behind the photocathode (Fig. 1) ZC-203 has a two stage MCP having 12 μm diameter channel and 13° bias angle. ZC-209 has an identical photocathode and MCP structure as ZC-203 but the top of the first MCP is covered with a thin Al film of 130 Å made by evaporation. A three stage MCP is used in ZC-233, which offers a saturated gain of $10^5 \sim 10^6$ at lower operating voltage per single MCP. All tubes made by HTV have the same type of MCPs. HTV Tubes are installed in a special housing designed for high speed application. The anode is adiabatically matched to 50 Ω BNC connector and back terminated with a 50 Ω disk resistor.

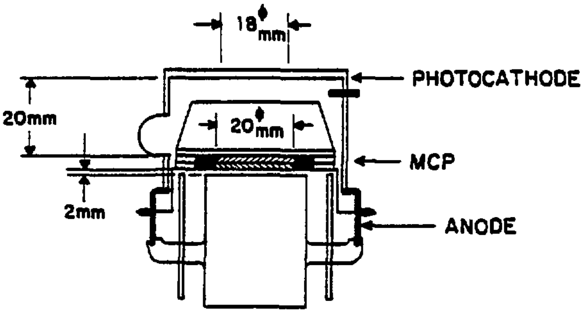

Fig. 1. Cross-sectional view of the MCP-PMT R1294X

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Gain Characteristics

The gain characteristics were measured by both D.C. and pulse method with fairly good agreement and are summarized in Fig. 2. Since the gain measurement includes collection efficiency of the MCP, the gain difference of a factor of 2 between ZC-203 and ZC-209 is attributed to the aluminum film in front of the first MCP in ZC-209. Photo-electrons not entering directly into the channels after penetrating the Al film cannot eject secondaries into the channels for further multiplication. Thus, the tube loses some collection efficiency in proportion to the open area ratio. The difference observed in the gain of the three stage tubes cannot be interpreted in the same way because they have other differences in addition to the Al film.

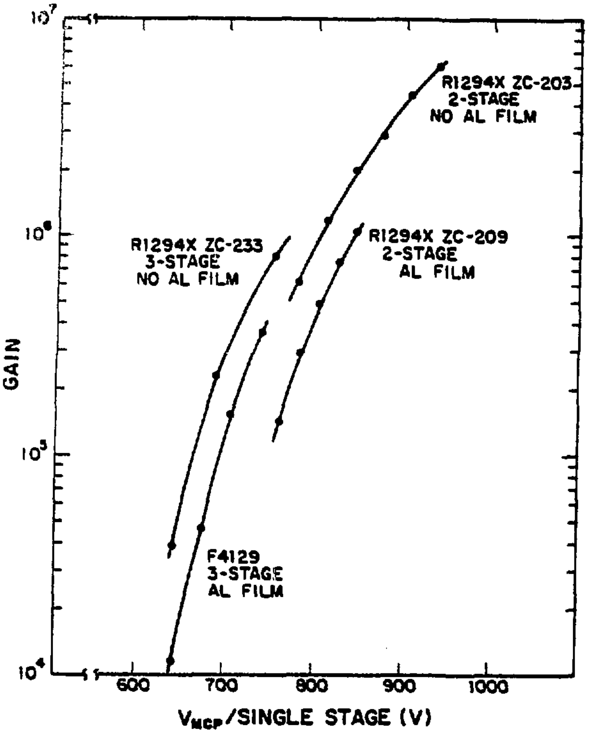

Fig. 2. Gain characteristics of four tubes tested.

The gain per MCP for the three stage tube is lower than the gain per MCP in the two stage tube at the same voltage. We attribute the loss of the gain in the three stage tube to the saturation effect plus some loss in the transmission between MCPs. Figure 3 shows the transmission characteristics of the primary electrons through the thin Al film. An example of the curve for a tube without an aluminum layer is also shown. The gain characteristics on the previous figure were taken at V_{PC-MCP} = 1500 V for the ZC-209 tube and V_{PC-MCP} = 500 V for the F4129 tube. The lower gain observed in F4129 may be the result of an insufficient acceleration voltage between the photocathode and MCP (V_{PC-MCP}). The voltage difference for the ZC-209 was well into the saturated region, while the maximum voltage recommended by the manufacturer of the F4129 tube seems to be at least a factor of 2 below the saturated region. The curve for the R1294X having no Al film seems to reflect the change of the secondary emission coefficient δ in the first collision.

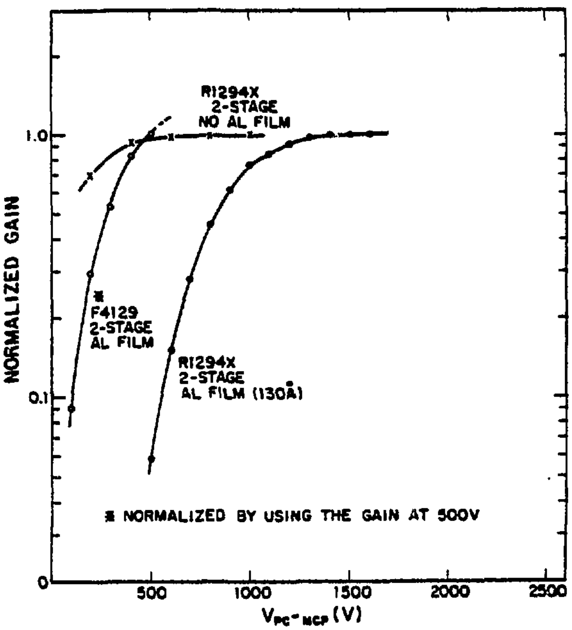

Fig. 3. Transmission of the photo-electrons through the Al thin film.

Life Test of R1294X

A life test of two MCP-photomultipliers, one with and the other without the thin Al film on the top of the first MCP, was carried out and the results are shown in Fig. 4. Short light pulses emitted from a scintillator excited by Sr^{90}, which produced an average of about 5 photo-electrons at the photocathode per pulse were used in the test up to an accumulated output charge of 10^{-3} C/cm^2.. An LED light source was used to accelerate the rate of the total accumulated output charge. The gain measurement was based always on the light from the scintillator to avoid the problem of instability for the LED. Operating conditions in both tubes were chosen to give the same voltage across the MCP.

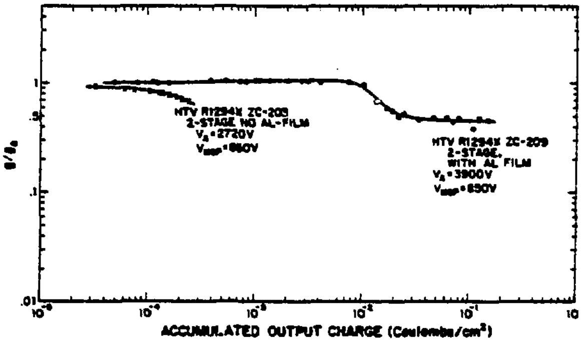

Fig. 4. Results of the life test of R1294X.

The ZC-203 tube without Al film showed very fast gain degradation starting from a total output charge of 10^{-4} C/cm^2. The tube with Al film showed a steady gain up to an accumulated output charge of 10^{-2} C/cm^2 and then started to show a pattern of gain degradation similar to that usually observed in the life test of the MCP itself. Comparing the behavior of identical tubes with and without the Al film we can conclude that the degradation of the overall gain of the tube without the Al film was due to the decrease of the photocathode quantum efficiency as a result of the positive ion bombardment from the front MCP. The test of the tube with the Al film was continued up to the total output charge of 10^{-1} C/cm^2 and was observed to reach a stable gain again. After the life test, the quantum efficiency and the gain of the tube ZC-209 were measured separately and showed only slight degradation of the quantum efficiency in the longer wave length sensitivity but a gain of only 30% of the initial gain was observed. The MCP gain decrease has small practical consequences, because the full gain can still be achieved by applying increased voltage to the MCP.

After Pulse Studies

To investigate the mechanism causing the deterioration of the photocathode quantum efficiency, the relative timing of after pulses in the ZC-203 tube were studied. The probability of seeing an after pulse, and the typical delay after the initial pulse until the first after pulse were the quantities measured. The distribution of the time differences between the pulse and an after pulse, are shown in Figs. 5a,b. The upper trace of each picture shows the spectrum in 100 ns full scale; lower 1000 ns full scale starting from 130 ns. Peaks appeared within the first 30 ns in the upper trace are difficult to analyze and probably are due to the ringing or the ion feedback inside the MCP itself. The peak at 50 ns in the upper trace and the peaks at 200 ns, 250 ns, and 320 ns in the lower trace in the picture (a) however, are identified with the ions H_2^+, H_2O^+, N_2^+, + CO^+ and CO_2^+, respectively. Calculations for the transit time of the ions produced at the output end of the first MCP and drifting back to the photocathode predict a discreet time for each charge to mass ratio. Comparison of the calculated and experimental results is shown in Table II. To check the hypothesis of the ion feedback, we have changed the photocathode-MCP voltage. The peaks move with the applied voltage as shown in Fig. 6. The slope of the curves are close to - 1/2 and agree well with the slope expected from the positive ion hypothesis.

The probability of the ion feedback was measured of the first peak I:H_2^+ as a function of the gain by counting the number of coincidences between a 30 ns wide pulse positioned 50 ns after the main pulse and an after pulse. The results are shown in Fig. 7, where the probability of the after pulse as a function of the total gain is plotted on the logarithmic scale. The after pulse probability increases proportionally to the number of photo-electrons in the pulse as well as with the total gain. Strong dependency of the after pulse probability on the residual gas pressure and outgassing from the MCP by the electron bombardment were observed in gas analysis experiments. A tube which showed high after pulse rate also produced more gases after electron bombardment. In this experiment, H_2, CH_4^+, H_2O, CO+N_2, and CO_2 were observed in the residual gas and H_2O, CO+ N_2 and CO_2 peaks were recorded in the spectrum during the electron bombardment.

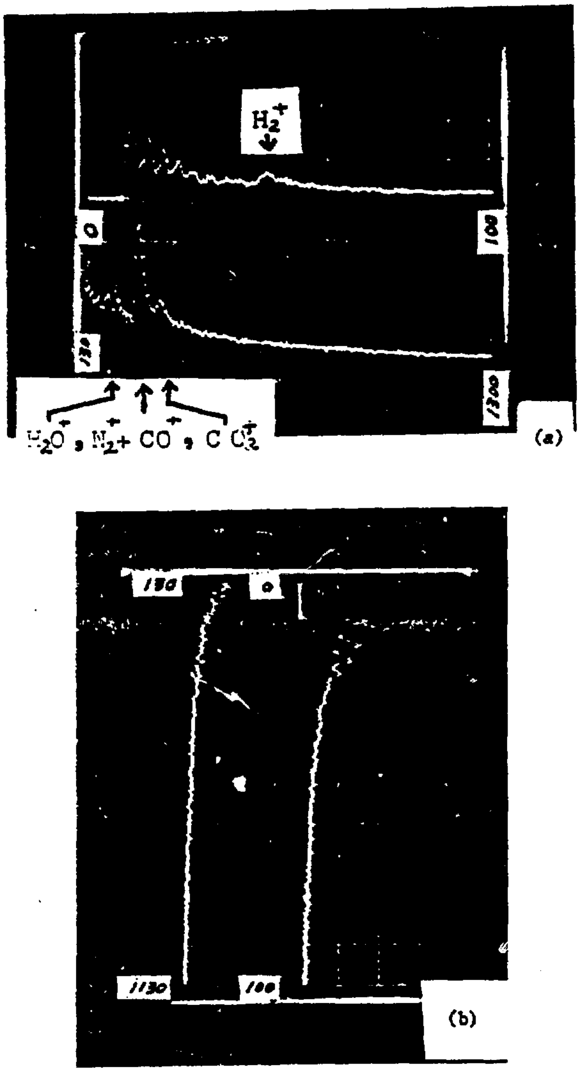

Fig. 5. Time spectrums of the after pulses in R1294X.
a) ZC-203 : V = 2800V g = 1.6×10^6
b) ZC-209 : V = 4000V g = 5.5×10^5
Full scale of the upper trace is 100 nsec and the lower is 1000 nsec.

Table II. Ion Drift Times (in ns)

		I:H_2^+	II:H_2O^+	III:N_2^++CO^+	IV:CO_2^+	T_e
V_A = 3000V	Exp.	47	192	244	296	
V_{MCP} = 938V	Cal.	62	187	233	292	2.8
V_A = 2720V	Exp.	51	204	256	320	
V_{MCP} = 850V	Cal.	65	196	245	307	3.0
V_A = 2500V	Exp.	53	212	272	328	
V_{MCP} = 781V	Cal.	68	205	255	320	3.1

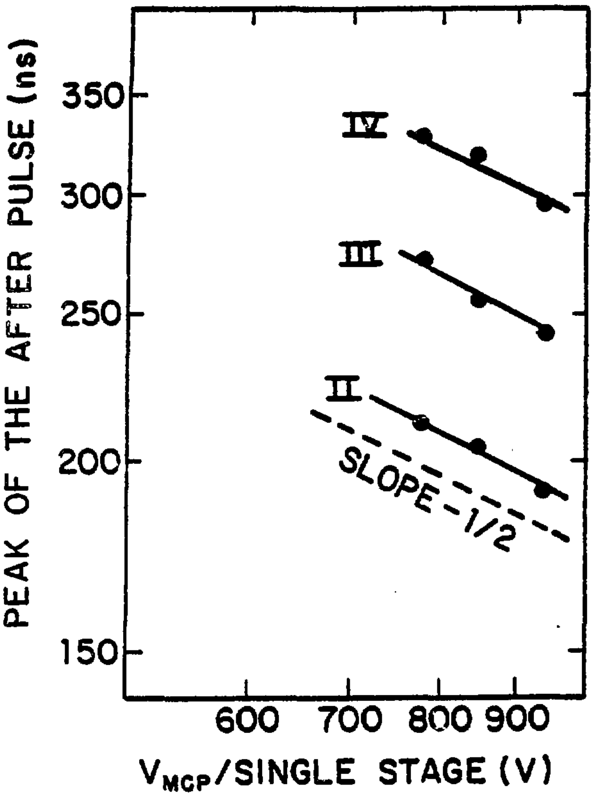

Fig. 6. Plot of the peak position as a function of applied voltage.

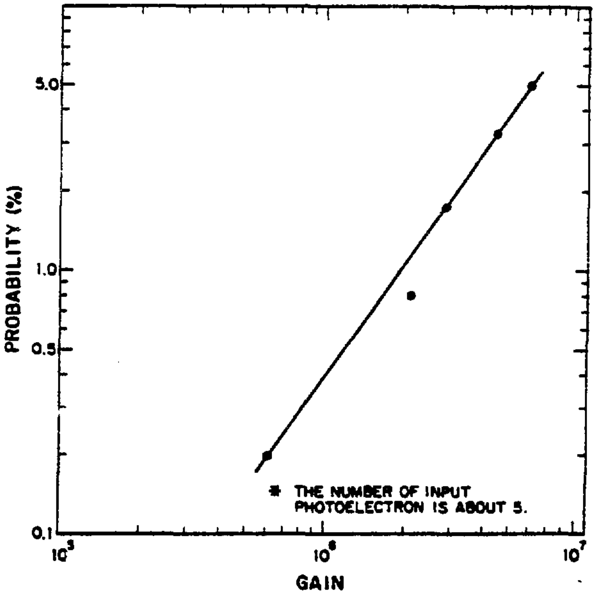

Fig. 7. Probability of the after pulse due to H_2^+ ion.

The after pulse time spectrum of ZC-209 was also measured and shown in Fig. 5. No obvious peaks are seen through the whole range except the first 30 ns. This suggests that the Al film can stop the ion feedback completely. The three stage tube (ZC-233) without Al film was also tested and showed a reduction of the ion feedback as shown in Fig. 8. The reduction is probably due to the lower operating voltage of the first MCP compared with the two stage tube. The tube does not suffer from the loss of the collection efficiency due to the presence of the Al film as explained above. The measured pulse resoluiton of the tube was approximately twice as good as the two stage tube with Al film. Part of this improvement is due to the better saturation effect in the three stage tube, however, the higher collection efficiency of the MCP in the tube is equally important.

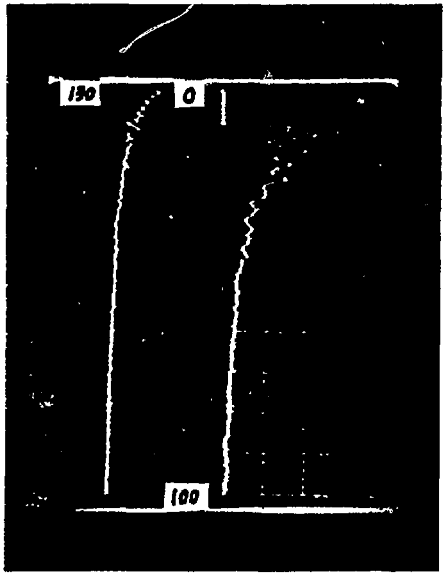

Fig. 8. Time spectrum of the after pulses in ZC-233. $V_A = 3100V$, $g = 8 \times 10^5$

<u>Properties in the Magnetic Field</u>

The gain of two R1294X (ZC-209, ZC-233) and F4129 tubes were tested in the magnetic field up to 7 kG (maximum available field). The photocathode was illuminated by the light pulse emitted from the LED through the 2 mm diameter aperture put at the center of the photocathode. We have tested that the amount of light emitted was independent of the magnetic field.

The results obtained with the magnetic field parallel to the tube axis are shown in Fig. 9. As expected, there is no remarkable difference between electrostatic and proximity focusing tubes. The curves represent the behavior of the MCP itself. Comparing the gain curves of the two R1294X (with two or three MCP) it is apparent that the number of MCPs is important. The difference between ITT and HTV Tubes may be due to the difference in the configuration of the MCP stack and structure of the MCP itself.

Only a small change was observed in the shape of the pulse height distribution at those fields where the gain was decreasing. The relative width increased but was much smaller than $\sqrt{g/g_0}$. This shows that the gain mechanism in the early part of the avalanche was not affected by the parallel magnetic field.

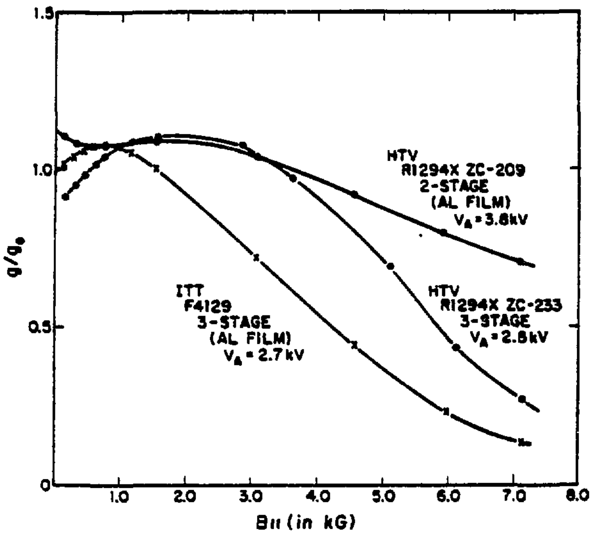

Fig. 9. Output degradation in three MCP-PMTs in the off-axis magnetic field.

When the tube axis was inclined relative to the magnetic field, the perpendicular component of the magnetic field produces a sharp cut-off (Fig. 10). The cut-off is due to the sweeping effect of the perpendicular component of the magnetic field on the photoelectrons in electrostatically focused tubes. Calculations show that for sufficiently high magnetic fields,

$$|B|_c \geq 2\pi \sqrt{\frac{2m}{e} \frac{(V_{PC-MCP})}{D^2}} \quad *$$

the electrons follow the lines of the magnetic field. Hence the expression for the cut-off angle θ_c is:

$$\tan\theta_c = r/D$$

where D is the distance between the cathode and the MCP$^{(20\ \mathrm{mm})}$ and r is the radius of the useful area of the MCP.$^{(10\ \mathrm{mm})}$ If the field is greater than $|B_c|$ and is at an angle to the tube axis of more than θ_c, the photo-electrons do not reach the MCP. For the R1294 tube, the critical value of the magnetic field was 200 gauss and the cut-off angle was 26°, which was in good agreement with the experimental results.

Proximity focusing is preferable to electrostatic focusing in situations where the alignment of the tube axis with the external magnetic field is impractical. Figure 11 shows the gain of the proximity focused F4129 tube in different magnetic fields. Below the cut-off angle of 75°, the curves represent the characteristics of the MCP itself. When the curves are plotted as a function of the perpendicular component of the magnetic field, the points all fall in a universal curve as shown in Fig. 12. In the procedure, the gain was normalized by the gain at $B_\perp = 0$ for each value of the parallel component (Fig. 9). This universal curve means that the gain of the MCP in the magnetic field could be represented by the product of the two formulas, one of which is a function of the parallel and the other of the perpendicular magnetic field only.

$$g(B) = g_1(B_\parallel) \cdot g_2(B_\perp)$$

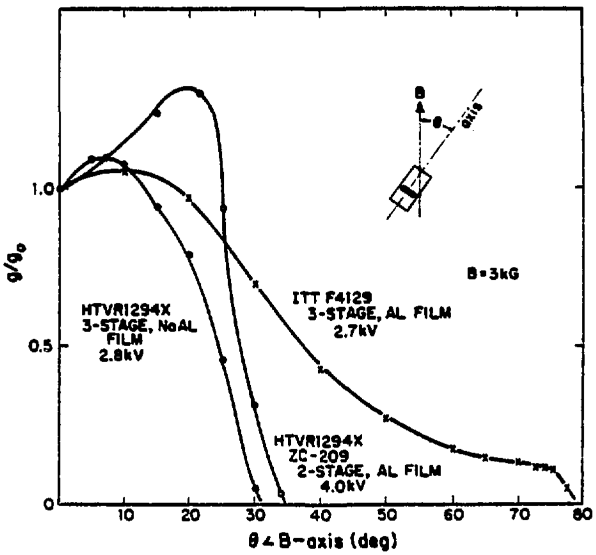

Fig. 10. Output degradation in three MCP-PMTs in the off-axis magnetic field.

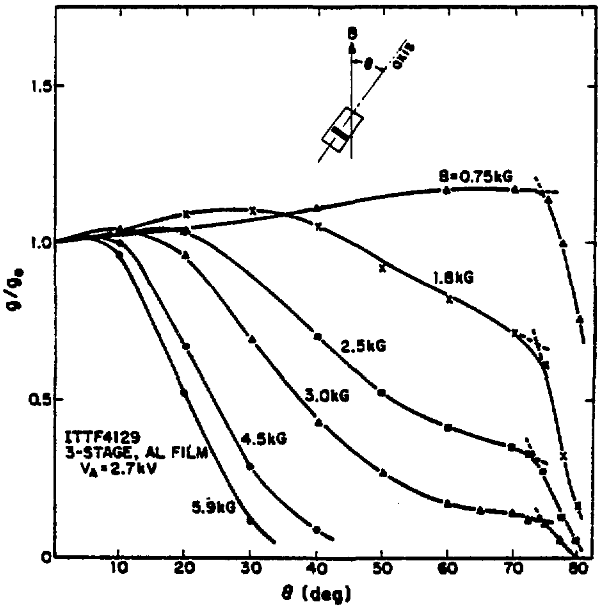

Fig. 11. Dependency of the output degradation in F4129 on the off-axis magnetic field.

Using the curves shown in Fig. 9 and Fig. 12, the gain can be estimated for a given condition simply by multiplying the two gains corresponding to the parallel and the perpendicular magnetic field, respectively. The value obtained in this way is normalized by the gain at zero field.

If the magnetic field is perpendicular to the tube axis, ($B_\parallel = 0$), the maximum magnetic field for which photo-electrons may reach the MCP is:

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*m is the electron mass, e is the electron charge, and D is defined below.

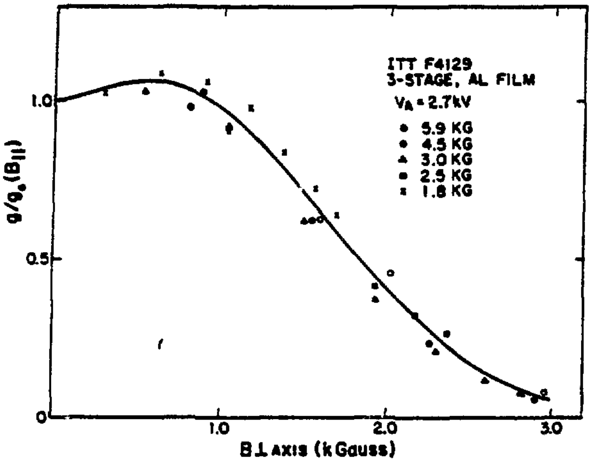

Fig. 12. Plot of the output degradation in F4129 as a function of the perpendicular component of the off-axis magnetic field.

$$B_M = \sqrt{\frac{2mV_{PC-MCP}}{eD^2}}$$

where V_{PC} and D are the voltage and the distance between the photocathode and the MCP. For the ZC-209 and the ZC-233 tube B_M is 70 Gauss and 40 Gauss, respectively. For the F4129 tube B_M is 750 Gauss. The results of the test agree with these calculated values.

Timing Property

The output signal of the X1294X (3-stage) excited by the very short light pulse (λ = 820 nm, FWHM = 100 ps) emitted from a laser diode was observed on a fast oscilloscope (Tektronix 7104, Band Width - 1 GHZ). The typical wave form is shown in Fig. 13. The rise time and FWHM are 500 ps and 700 ps, respectively.

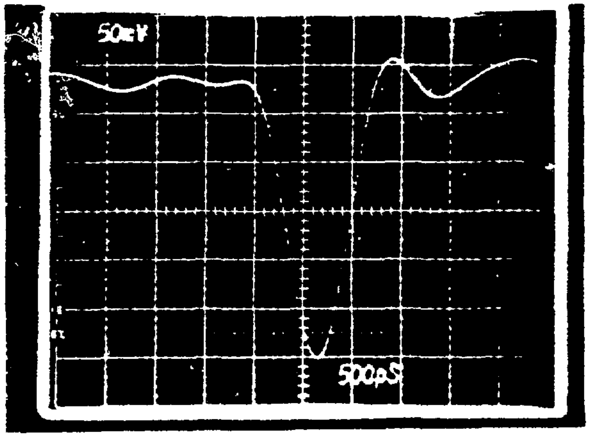

Fig. 13. Output signal from ZC-233.

Using the same light source, the transit time spread (TTS) was also measured. The FWHM of the TTS of about 200 ps was obtained for light pulses averaging about 20 photo-electrons in size with an applied voltage of 3.4 kV. The number became 160 ps for pulses averaging 30 photo-electrons in size. The TTS showed a slight dependence on applied voltage.

Conclusions

The lifetime of the MCP-PMT was shown to be related to the degradation of the photocathode quantum efficiency caused by the ion feedback from the MCP to the photocathode. The ion feedback was completely stopped by depositing the thin Al film on the first MCP. However, the thin Al film reduced the photo-electron collection efficiency of the MCP to the limitation imposed by the open area ratio. The test of the three stage MCP without Al film demonstrated another way to reduce the ion feedback without lowering the collection efficiency.

The properties of the MCP and MCP-PMT operating in magnetic fields were studied and some understanding was gained. The MCP itself continued to function in magnetic fields parallel to the tube axis of up to 7 kG for both electrostatic and proximity focused tubes. Situations with field components perpendicular to the tube axis are more complicated and proximity focusing is essential. The timing study of the three stage tube showed a rise time of 500 ps with a transit time jitter of FWHM 200 ps for 20 photo-electron light pulses.

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