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PERFORMANCE STUDIES OF HIGH GAIN PHOTOMULTIPLIER HAVING Z-CONFIGURATION OF MICROCHANNEL PLATES

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Abstract

The characteristics of a high gain type ITT F4129 photomultiplier having three microchannel plates in cascade for electron multiplications have been investigated. These plates are in the Z-configuration. Measurements are given of the gain, dark current, cathode quantum efficiency, anode pulse linearity, electron transit time, single and multiphoton time spreads, fatigue, and pulse height resolution. The gain as a function of transverse magnetic field has been measured and is discussed. Photomultiplier characteristics as a function of the input pulse repetition frequency have also been investigated and discussed.

Introduction

It was previously shown that the timing capabilities of photomultipliers based on high gain microchannel plates for electron multiplication and proximity focusing are considerably better than those of conventional multipliers.[1-6] It was also shown that sensitivity of the photomultiplier characteristics to ambient magnetic fields is significantly decreased in such multipliers.[3] The purpose of this paper is to study similar characteristics of a high-gain photomultiplier having three microchannel plates in cascade for electron multiplication. The plates are in Z-configuration to reduce feedback. The significant feature of the multi-microchannel plate electron multiplier is that its gain can be made considerably higher, typically between 10^6 and 10^7 than that obtainable with a single microchannel plate. For the latter, an average multiplier gain of usually less than 10^6 is achieved.[1-6]

Using experience gained from previous work,[8-14] measurements were made of the gain, dark current, quantum efficiency, and anode pulse linearity of an ITT F4129 photomultiplier. Electron transit time, pulse height resolution, single photoelectron pulse response, and single and multiphoton time spreads were also investigated. Determination of fatigue, ambient transverse magnetic field sensitivity, and stability of photocathode quantum efficiency were carried out. The photomultiplier was designed and manufactured by the Electro-Optical Product Division of ITT Corp., Fort Wayne, Indiana.

The ITT F4129 photomultiplier, S/N 117910, has an S20 photocathode with a maximum usable diameter of 18 mm. Proximity focusing is used for the input and collector stages. The spacing between the photocathode and the input of the microchannel plates is approximately 0.3 mm while the spacing between the output of the microchannel plates and collector is 1.5 mm. The three microchannel plates used in the multiplier are identical, having a channel diameter of 12 μm and a length-to-diameter ratio of 40.[7]

The electron multiplier is composed of three cascade plates arranged in a Z-configuration. The strip current of the microchannel plate assembly is 1.4 μA with 2400 V across it. A getter is provided to maintain a high vacuum in the glass envelope. The time performance studies of the photomultiplier were made using an improved matched 50 Ω housing which has been described in the Reference 15.

Gain and Dark Current Measurements

Both the gain and dark current measurements were made with the system described in Reference 3. The photomultiplier, operating as a photodiode with 150 V across it, was placed in a marked position; the light level was then adjusted to yield a 5 nA output. The photomultiplier was reconnected to the voltage divider shown in Fig. 1, and the voltage across the microchannel plate was increased until the output signal was 50 nA which corresponds to a gain of 10 at this voltage. The light level was then attenuated with the same voltage across the microchannel plate to again give a 5 nA output signal. With the lower light level setting, the microchannel plate voltage was again increased to yield a 50 nA output signal corresponding to a gain of 100. The same procedure was repeated until the maximum recommended plate voltage was reached. For the F4129, the gain was 1.6×10^6 with $V_k = 150$ V, $V_M = 2500$ V and $V_p = 300$ V while the dark current with these voltages was 1.5×10^{-9} A. Figure 2 shows the gain and dark current characteristics of the photomultiplier.

Quantum Efficiency Measurements

A calibrated 8850 with bialkali photocathode was used as the standard for comparison. The photocathode, masked to leave an 18 mm (photocathode diameter of F4129) diameter area at the center, was placed in a marked position. The light source was adjusted to yield an output signal of 10 nA from the 8850 with 500 V between the photocathode and anode. With the same light level setting, the F4129 was connected as a diode and placed in a position with the photocathode exactly the same distance away from the light source as the photocathode of the 8850, and the output signal was measured. The quantum efficiency was found to be 19.92% at 410 nm. After providing a total anode output charge of approximately 27.5×10^{-3} Coulomb, the quantum efficiency had decreased to 4.98% at the same wavelength.

Peak Output Current Measurement

Peak output current of a conventional photomultiplier depends on the average anode current the device can handle and the duty cycle of the output signal. The behavior of a microchannel plate photomultiplier is similar although affected by different parameters such as the number of microchannels used in the plate, the diameter and the length of the channels, and the recovery time of the microchannels bias current, also known as the strip current.

A green LED driven by an electrical pulse with a pulse width of 90 ns, FWHM, running at 300 pulses per second was used as the light source. Neutral density filters were used to attenuate the light pulses and a pulse height analyzer was used to measure the output pulse height of the photomultiplier.

Figure 3 shows the F4129's output current as a function of light pulse intensity. The output current started to deviate from linearity at about 2.1 mA. The average output current at this point is 56.7 nA or 4% of the strip current (1.4 μA) of the microchannel plate. By using this 56.7 nA average linear current to calculate the peak linear output current which could be provided by the F4129 operating at 360 pps and at it's natural 520 ps pulse width, the peak linear output current would be 303 mA, while at 60 pps operation, the peak linear output current would be 1.8 A. The lower linear output current of the F4129 compared to that of the F4129 in reference 15 could be due to the slower response of the F4129 and different operating strip current.

Electron Transit Time Measurements

The close spacings between the photocathode and microchannel plates and also between the plate and the anode, yield a very short electron transit time in this type of device compared to that of a conventional photomultiplier. A system similar to the one given in Reference 3 was used for the present time measurement. A mercury light pulse generator produced the light flash. The electrical pulse from the pulse generator was divided into two parts for calibration purposes - one was supplied to an oscilloscope and the other to an amplifier input whose output was supplied to the oscilloscope. An adjustable air delay line was used to bring the two pulses into coincidence on the oscilloscope on the direct circuit, hence establishing zero time reference. The F4129 was then put in place and the delays of the output signal were measured. After corrections for the cable length and air paths, the transit times of the photomultiplier was found to be 2.5 ns ± 0.2 ns.

Single Photoelectron Pulse Response

A system similar to the one given in Reference 3 was used for the single photoelectron response measurement. Before the single photoelectron pulse response measurement was made, the system risetime was measured using a 28 ps risetime tunnel diode pulse generator and found to be 300 ps. Figure 4 shows the single photoelectron pulse shape of the F4129. The 10-90% risetime was found to be approximately 0.35 ns after corrections for the system risetime. The pulse width (FWHM) was 520 ps. No amplifier was used between the MCP photomultiplier and the oscilloscope. These values are slightly larger than the ones reported in Reference 15.

Single Photoelectron Time Spread Measurement

The system described in Reference 3 was used for the time spread measurement. Two light pulse generators were used to obtain light pulse widths from 200 ps to 5.5 ns. Since single photoelectron pulses of the F4129 photomultiplier are in the order of 20 mV, gain must be provided to amplify the signal amplitude to the acceptance level of the constant fraction discriminator. A voltage gain of approximately 30 dB was used. The system resolution was approximately 25 ps, FWHM.

With full photocathode illumination, and with a light pulse produced by a 200 ps electrical pulse, the single photoelectron time spread was 220 ps. Figure 5 shows the single photoelectron time spread of the MCP photomultiplier as a function of electroluminescent diode current pulse width. In extrapolating the curve in Fig. 5 to an electroluminescent diode current pulse width of 100 ps, the single photoelectron time spread of F4129 photomultiplier has an upper limit of approximately 125 ps, FWHM.[9,10] To the author's knowledge, this is the smallest single photoelectron time spread ever measured on a high-gain fast photomultiplier. Electrical pulses wider than 200 ps were obtained by Tektronix 110 pulse generator using different lengths of charging cables. Two single photoelectron spread spectra of F4129 are shown in Fig. 6 spaced 1 ns apart.

Multiphotoelectron Time Resolution

This measurement was made using a mercury light pulse generator capable of producing thousands of photoelectrons per pulse from the photocathode of the photomultipliers. The number of photoelectrons per pulse was calculated by measuring the output pulse width and amplitude and knowing the gain of the photomultipliers at the microchannel plate operating voltage. Figure 7 shows the plot of the time resolution as a function of the number of photoelectrons per pulse from one photoelectron up to 5800 photoelectrons. The time resolution of the single photoelectron pulses was 2.2 ns, FWHM, indicating the light pulse was very close to 2.2 ns wide; the time resolution tapered down to approximately 48 ps, FWHM, with 5800 photoelectrons per pulse.

Pulse Height Resolution Measurement

Previous work has shown that most MCP photomultipliers could resolve one, two, three or more photoelectron peaks.[1-6] The same system and procedure described in Reference 3 was used to evaluate the F4129 photomultiplier. The present design of the cascade of the microchannel plates in Z-configuration has considerable advantages with respect to fabrication, timing characteristics, and application of the photomultiplier. However, Z-configuration without electrical connections to each microchannel plate does not allow a full optimization of operating conditions of the individual microchannel plates in cascade for a maximum pulse-height resolution. As shown by our previous measurements[6] optimization of operating conditions of each microchannel plate is required for a significant increase of pulse-height resolution capabilities of the photomultiplier. Minor modifications of Z-configuration would result in increased photomultiplier pulse height resolution.

With the F4129 operating at V_M = 2400 V which corresponds to a gain of 1×10^6, the dark pulse count of the photomultiplier is found to be

$$\sum_{1/8 \text{ photoelectron}}^{16 \text{ photoelectron}} = 1800 \text{ counts per second}$$

The dark count was taken after the device had been in the dark for 48 hours and the photocathode quantum efficiency was approximately 19% at 410 nm. Back biasing the photocathode yields 5 counts per second indicating that most dark pulses come from the photocathode. With the microchannel plate configuration voltage, V_M, of the F4129 set at 2400 V the device was unable to resolve one or two or three or more photoelectron peaks. After all other measurements had been done, V_M was increased gradually to a maximum of 2760 V. The ability of resolving different photoelectron peaks was drastically improved. Figure 8 shows the pulse height spectrum of the F4129 operating at V_M = 2710 V which was the optimized voltage yielding the largest first peak to valley ratio which was determined to be 2.47. Figure 9 is a measurement of the first peak to valley ratio as a function of microchannel plate configuration voltage, V_M, of the F4129. With V_M = 2710 V, the gain of the photomultiplier was 6.6×10^6, the quantum efficiency at the time of this measurement was 2.4%. The dark pulse count dropped to 102 counts per second.

Maximum Operating Frequency Measurement

The maximum operating frequency of a microchannel plate photomultiplier depends on the number of channels, the recovery time of bias current on the used channel, the bias current and the average number of photoelectrons contained in each signal pulse.

A pulsed light emitting diode was used to generate predominately single photoelectron pulses. The output of the F4129 photomultiplier was connected to an amplifier and discriminator whose output was counted by a frequency counter. By increasing the repetition frequency of the LED, the output counting frequency of the photomultiplier was measured. The output pulse frequency is given in Fig. 10 as a function of the input light pulse repetition frequency. The point at which the output pulse repetition deviates from the linearity by 5% is defined as the maximum operating frequency of the photomultiplier. At this point a number of microchannels are not active as electron multipliers because of channel recovery time limitations. The maximum operating frequency was 100 KHz for predominantly single photoelectron pulses.

Lifetime Measurement

Previous studies have shown that MCP photomultipliers suffered from relatively short life span, mostly due to imperfect vacuum inside the glass envelope.[3,4,6,15] Application of a getter generally improves the lifetime and reduces the ion feedback. During the evaluation period of the photomultiplier, the ion feedback pulse was not observed. A preliminary lifetime test was made on the F4129 to demonstrate this improvement.

A source made out of 1 mCi of Cs^{137} smeared on the back of a 25 mm diameter pilot F scintillator was used as the light source. The source was placed at a distance which yielded approximately 150 nA of output current from the F4129 operating at a gain of 1×10^6. The output current of 150 nA is 10% of the strip current. Figure 11 shows the output current as a function of time. The initial output current was 145 nA and gradually decreased to 116 nA in approximately 1500 min. The irradiation was then interrupted for approximately 1000 minutes. At the end of the 1000 min rest, the light source was turned on again, the anode output current of the F4129 started out at 120 nA and gradually decreased to 64 nA in 2800 min. A total anode charge accumulation was estimated to be 27.5×10^{-3} Coulomb at the end of this test. Figure 11 shows the results of this test.

The gain and quantum efficiency of the F4129 was remeasured at this time. The gain was found to be practically the same as before the lifetime test but the quantum efficiency at 410 nm had decreased from 19.92% to 4.98%.

Transverse Magnetic Field Measurements

Measurement data given in Reference 3 show that the microchannel plate photomultipliers are more sensitive to transverse magnetic fields that to axial fields. The relative gain and collection efficiency of the F4129 were measured as a function of transverse magnetic field density. Figure 12 shows the results of the measurement for both directions of the magnetic field. The inflection points of both the gain and collection efficiency response curves at 200 Gauss for one direction of the field are probably due to ferromagnetic materials used inside the device. Above 400 Gauss both gain and collection efficiency for both field directions are quite similar. The 50% points of the gain curves occur between 750-800 Gauss while the collection efficiency is between 80-90% at the same field density. These results are more than an order of magnitude better than those of conventional photomultipliers. However, due to causes presently unknown, the microchannel plate assembly bias current became erratic after the magnetic field tests, but recovered after remaining in the dark for 24 hours with reduced voltage (V_M = 1800 V) across it. The quantum efficiency, however, remained at 4.98% but the gain of the microchannel plate cascade had decreases from 1×10^6 to 5×10^5 at voltage of the microchannel plates of V_M = 2400 V.

Conclusions

Performance characteristics measurements of high-gain photomultiplier having three microchannel plates in Z-configuration show that the devices exhibit excellent timing capabilities and very low sensitivity on ambient magnetic fields in comparison to the best conventionally designed photomultipliers. Single photoelectron and multiphotoelectron time spread measured values obtained should be considered as upper limits, due to the time resolution capability limitations of the measuring systems.

Our measurements have shown that the photomultiplier's operating characteristics can be optimized yielding increase of pulse height resolution with the present design of the cascade of the microchannel plates. If electrical connections could be made to each microchannel plate in this Z-configuration, it would allow full optimization of operating conditions of each microchannel plate and would increase the maximum pulse-height resolution.

The microchannel plate cascade gain, prior to the ambient magnetic field sensitivity measurements, was consistent through out the tests, but the cathode quantum efficiency decreased from 19.92% to 4.98% indicating possible damage of the photocathode. After the final pulse height resolution test, the quantum efficiency further decreased to 2.4%. Use of a protective film between the photocathode and the microchannel plate configuration is planned for future generation devices.[16] This will improve the quantum efficiency stability of the photocathode.

As expected, the F4129 photomultiplier retained 50% of its gain up to 750 Gauss making its performance for more than an order of magnitude better than conventional photomultipliers under ambient magnetic field influence. However, after being exposed to be ambient magnetic field of this magnitude, the gain of the microchannel plate cascade had decreased from 10^6 to 5×10^5.

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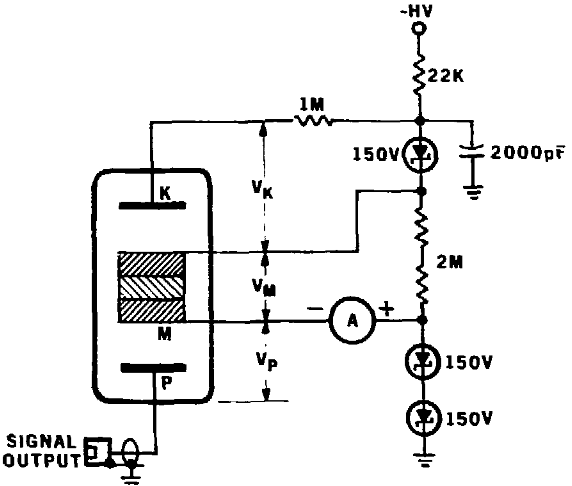

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Fig. 1 Voltage divider of the high gain microchannel plate photomultiplier used in the measurements.

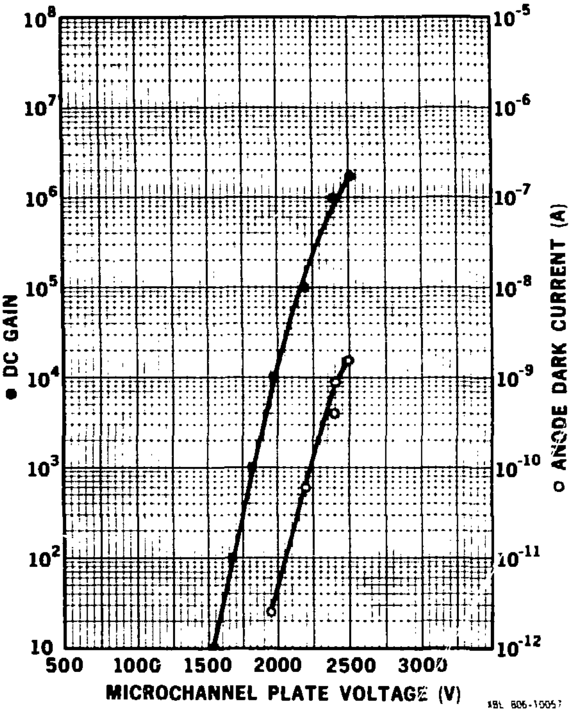

Fig. 2 DC gain and dark current as a function of microchannel plate cascade voltage.

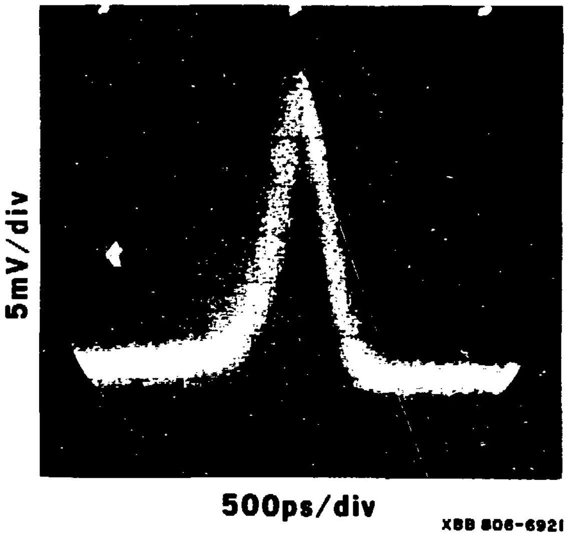

Fig. 4 Typical single photoelectron pulses from the F4129 operated at V_M = 2400 V, using 200 ps light impulse excitation.

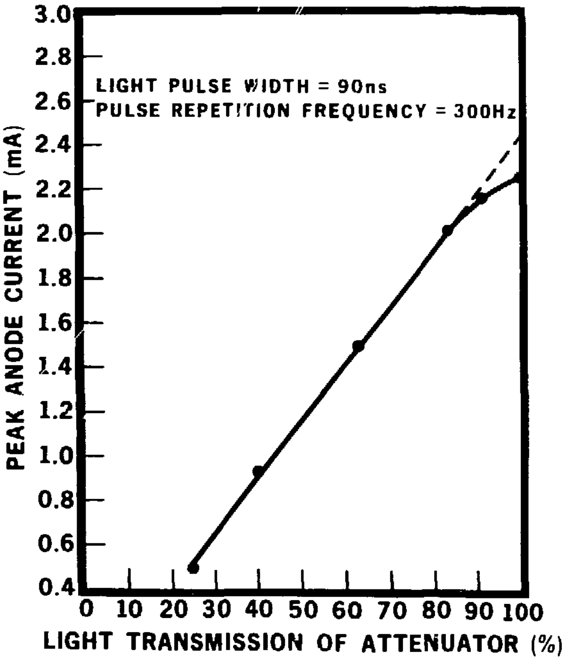

Fig. 3 Peak anode output pulse amplitude as a function of light transmission of the optical attenuator.

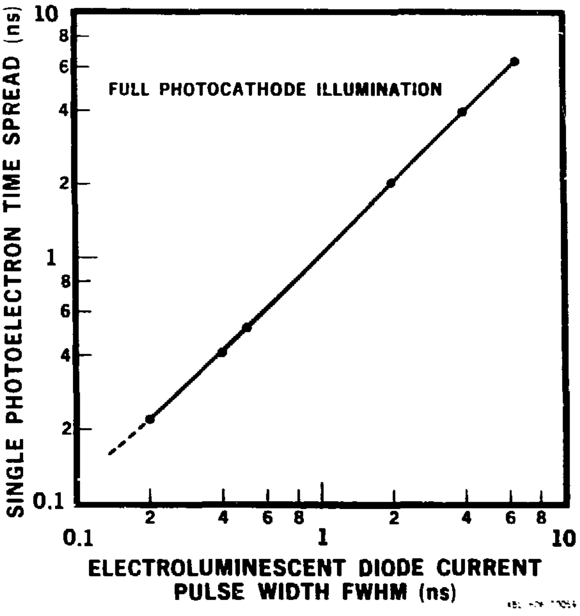

Fig. 5 Single photoelectron time spread of the F4129 as a function of electroluminescent diode current pulse width.

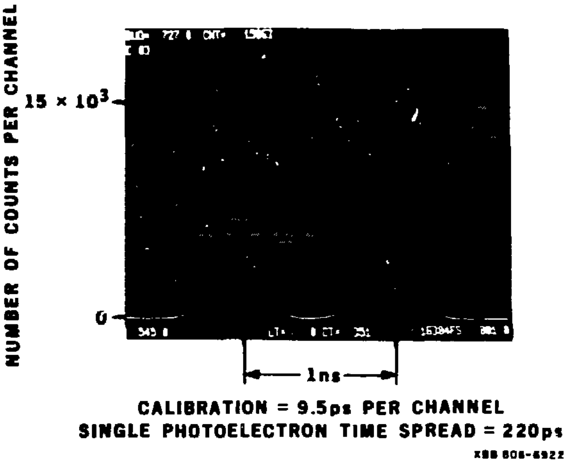

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Fig. 6 Single photoelectron time spread of the F4129 photomultiplier with full photocathode illuminated.

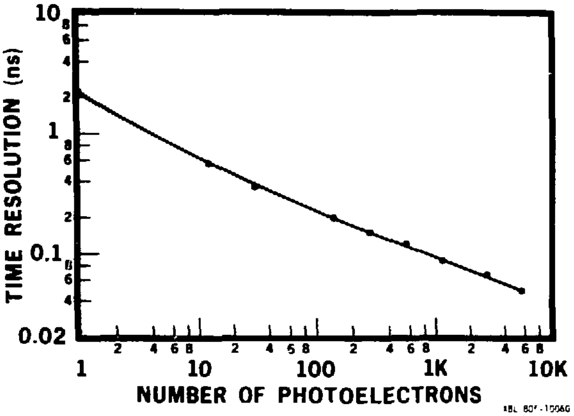

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Fig. 7 Multiphotoelectron time resolution as a function of number of photoelectrons per pulse, measured with a 2.6 ns light pulse width.

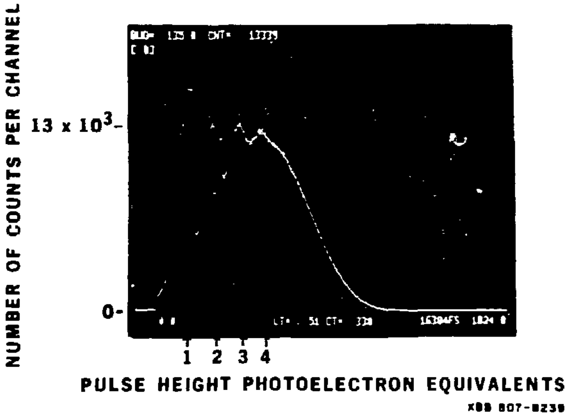

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Fig. 8 Pulse height spectrum of the F4129 operating at microchannel plate cascade voltage of V_M = 2710 V.

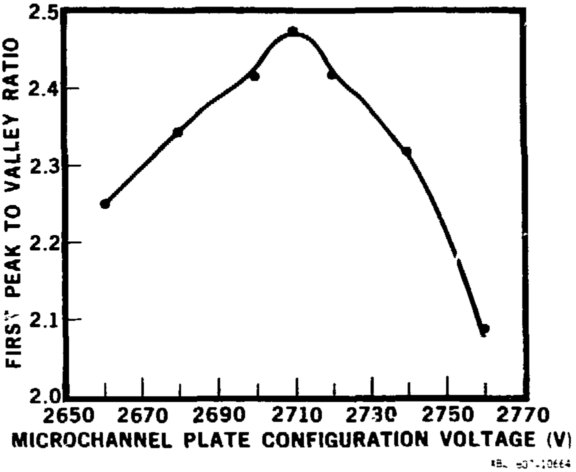

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Fig. 9 The first peak-to-valley ratio as a function of the microchannel plate configuration voltage.

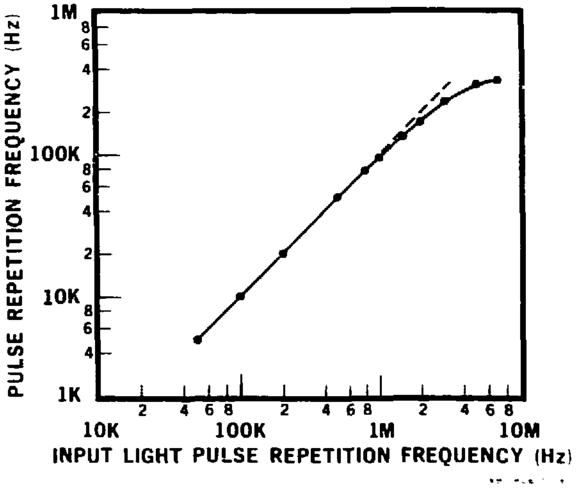

Fig. 10 The single photoelectron output pulse repetition frequency of the F4129 as a function of the input light pulse repetition frequency.

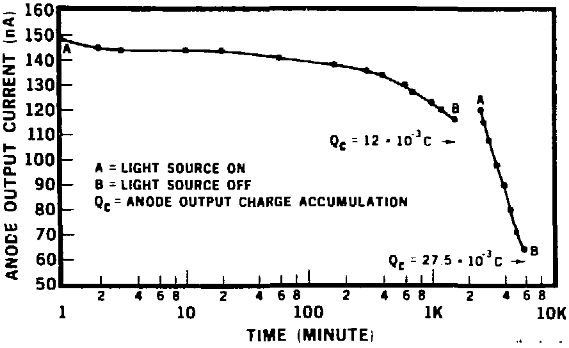

Fig. 11 The F4129 anode output current as a function of time.

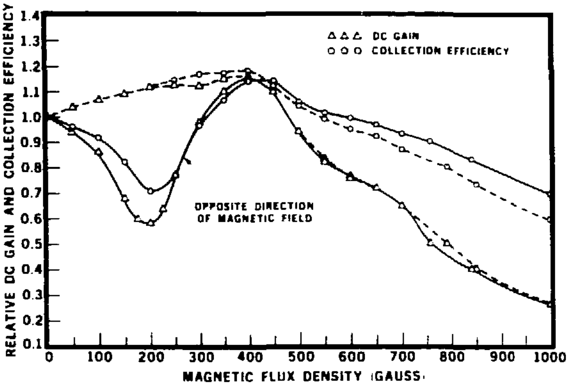

Fig. 12 Relative DC gain and collection efficiency as a function of transverse magnetic field.