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Publication Date

1983-10-01

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To be presented at the 1984 IEEE Conference,
Orlando, FL, October 31 - November 2, 1984

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PROTOTYPE PHOTOMULTIPLIER

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October 1983

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ABSTRACT

Characteristics of the prototype RCA C83036E 52 mm diameter photomultiplier have been measured. The results of the measurements of the gain, dark current, photocathode quantum efficiency, peak output current, electron transit time, and output pulse rise time as a function of voltage between anode and cathode are given. Furthermore, single photoelectron time spread, multiphotoelectron time resolution, pulse-height spectrum and afterpulse time spectrum were measured and are discussed.

INTRODUCTION

The RCA C83036E 52 mm-diameter photomultiplier is a modified version of the RCA 8575. Both types have similar electron multiplier structures, consisting of 12 in-line electrostatically-focussed copper beryllium dynodes, the input electron optics and a semitransparent cesium-potassium-antimony photocathode deposited on the entrance window. The structure is contained in a pyrex envelope. The difference between C83036E and 8575 is that C83036E has improved characteristics, particularly with respect to its peak output current capability. The spectral response of the photocathode extends from 300 nm to 650 nm and peaks at 390 nm. Measurements made on three photomultipliers gave an average quantum efficiency of 28 %.

GAIN AND DARK CURRENT MEASUREMENTS

Gain and dark current measurements were made with the system described in Ref. 1. The voltage divider networks used for these measurements are shown in Figs. 1 and 2. Figure 1 shows the voltage divider for high gain applications while that for high peak currents is shown in Fig. 2. Figure 3 shows the gain and dark current characteristics of C83036E photomultiplier as a function of voltage applied between the anode and cathode using the high gain voltage divider. With 2000 V applied between the anode and cathode, the gain was 4.0×10^7 , while the dark current was approximately 1.6×10^{-8} A. The gain and dark current as a function of voltage between the anode and cathode using the high-peak current divider is given in Fig. 4. With this divider and with 2000 V applied between the anode and cathode the gain and dark current was 10^7 and 2×10^{-9} A, respectively.

QUANTUM EFFICIENCY MEASUREMENTS

A calibrated RCA 8850 photomultiplier with bialkali photocathode was used as the standard for the quantum efficiency measurements. 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 C83036E was connected as a diode and positioned with the photocathode exactly at the same distance from the light source as the photocathode of the 8850, and the output signal was measured. The average quantum efficiency was found to be 28 % at 410 nm.

PEAK OUTPUT CURRENT MEASUREMENTS

The peak output current of the C83036E photomultiplier was measured with a pulsed mercury light source capable of emitting enough photons per pulse to saturate the photomultiplier.

Calibrated neutral density filters were used to attenuate the light pulse intensity in steps for the measurements. The light pulses were 2.6 ns wide, with a repetition rate of 60 pulses per second. The results are plotted in Fig. 5. The peak linear output current was 250 mA and 160 mA for the operating voltage of 2400 V and 2000 V, respectively. The voltage divider for high current applications was used for this measurement.

ELECTRON TRANSIT TIME MEASUREMENT

A description of the measuring system has been published elsewhere by the authors². An LED light source served to produce the light pulses and the electrical pulses driving the LED were utilized as reference pulses. An adjustable air line was used to bring the LED driving pulse and reference pulse into coincidence on the oscilloscope, thus establishing a zero time reference. The C83036E photomultiplier was then put in place and the delay of the output signal measured.

The electron transit time as a function of anode-cathode voltage is plotted in Fig. 6. At 2250 V of applied voltage, the electron transit time was approximately 30 ns for three tubes measured.

SINGLE PHOTOELECTRON PULSE RESPONSE

The true characteristics of the pulse response of a photomultiplier can best be obtained from single photoelectron pulses. Since dark noise pulses are mostly due to single photoelectrons, they can be used to show the single photoelectron pulse response. However, where a higher pulsing frequency is needed, either a low-level dc light source, or a very-short light pulser can be used to produce more single photoelectron pulses. The true pulse response of a photomultiplier can be observed only if the divider socket assembly is properly designed to reliably transmit the output pulse to an oscilloscope or other monitoring device. Improper matching of the output circuit of the photomultiplier may result in reflections which will distort the results of an experiment.

To ensure proper matching in the socket assembly, two 5 nF capacitors, one from each of the last two dynodes were connected to the output coaxial cable shield with the shortest leads possible. By doing this, the last two dynodes look like a ground plane to the fast pulses. This lowers the impedance of the output structure of the photomultiplier, thus achieving a better match to the 50 Ohm external load. The pulse response under this condition is shown in Fig. 7. The 10-90 % risetime of a single photoelectron pulse was

found to be 2 ns with 2000 V on high gain voltage divider. Figure 8 shows the pulse risetime as a function of anode-cathode voltage using divider for photomultiplier high current applications.

SINGLE PHOTOELECTRON TIME SPREAD MEASUREMENT

The system described in Ref. 3 was used for the time spread measurement. The light pulses were generated by an avalanche light emitting diode and had a width of 200 ps or less, FWHM. The system resolution was in the order of 30 ps, FWHM.

Figure 9 shows two single photoelectron time distributions spaced 4 ns apart. With full photocathode illumination and with 200 ps light pulses the average single photoelectron time spread using either the high gain or the high current voltage divider with a gain of 1×10^8 was 860 ps, FWHM.

MULTIPHOTOELECTRON TIME RESOLUTION

Measurement of the multiphotoelectron time resolution was made with a mercury light pulse generator capable of producing thousands of photoelectrons per pulse from the photocathode of the photomultiplier. The number of photoelectrons per pulse was calculated from the output pulse width and amplitude and knowing the gain of the photomultiplier at the operating voltage. Figure 10 shows the plot of the time resolution as a function of the number of photoelectrons per pulse from one to ninety photoelectrons. The time resolution of the single photoelectron pulses was 2.35 ns, FWHM. This number is the result of the light pulse width and the single photoelectron time resolution (i.e., 860 ps). With 90 photoelectrons per pulse, the time resolution of the C83036E is tapered down to approximately 0.2 ns, FWHM.

PULSE-HEIGHT SPECTRUM MEASUREMENT

Pulse-height spectrum was measured by illuminating the full photocathode with a light emitting diode whose light output intensity was controlled by varying the amplitude of the driving pulse. The photomultiplier output pulses were stretched before they were processed by the pulse-height analyzer. The photoelectron peaks were calibrated with a RCA 8850 photomultiplier which could resolve 1, 2, 3 or 4 photoelectron peaks. The pulse height spectrum of the C83036E is shown in Fig. 11. With an operating voltage of 2250 V which gives a gain of 10^8 the dark pulse count was found to be:

$$\frac{16 \text{ photoelectrons}}{\sum} = 134 \text{ counts per second}$$

$$\frac{1/8 \text{ photoelectron}}$$

Both the pulse-height spectrum and dark pulse current were very similar using high gain or high pulse current divider at the same gain.

AFTERPULSE MEASUREMENT

Although contemporary fabrication and activation techniques have reduced afterpulses from most photomultipliers to a point where they are rarely important, for some applications afterpulses still may introduce serious error. For example, in photon counting systems for subnanosecond fluorescence lifetime

measurements⁵, photomultiplier afterpulses can generate small amplitude late spurious peaks in the sample fluorescence profile⁶. Also, in Deep Underwater Muon and Neutrino Detection (DUMAND) systems which use a large number of photomultipliers in a three-dimensional array, a significant amount of afterpulsing could introduce serious error in measuring particle trajectories.^{7, 8}

In general, the afterpulses are produced as a result of the ionization of residual gases, such as He^+ , H_2^+ , N_2^+ and CO^+ , in the volume between the photocathode and the first dynode. The positive ions formed are accelerated toward the photocathode by the focusing electric field. On impact these ions liberate up to five secondary electrons from the cathode which produce an afterpulse signal. The afterpulses generally occur from 20 ns to several microseconds after the main pulse. The time of occurrence of the afterpulses can be closely correlated with the atomic mass-to-charge ratio of the residual gas inside the glass envelope and the potential distribution in the vicinity of the cathode. This phenomena was studied systematically by several authors⁹ who introduced trace amounts of various gases into experimental photomultipliers. Subsequently, in further work¹⁰⁻¹³, the physical origins of afterpulses were investigated, particularly with respect to the afterpulses which result from the diffusion of helium through the photomultiplier glass envelope. Although the helium is present in small concentration in ambient air, it is sufficient so that its atoms, which can permeate readily through the glass envelope and cause afterpulses. Other phenomena may also cause afterpulsing, such as dynode fluorescence, electrical fields over the exposed glass of the envelope, etc. In order to measure this characteristic, a time spectrum must be taken of the anode output pulses. Measurements were made using the photomultiplier high gain voltage divider network suggested by RCA. With 2250 V applied between the anode and cathode, the average gain was approximately 10^8 , while the dark current was $7 \times 10^{-8}\text{A}$.

The system shown in Fig. 12 was used to measure afterpulses. A pulse generator was used to drive a light-emitting diode, type XP 21, which produced light pulses for the photomultiplier. The trigger pulse from the pulse generator was delayed and shaped and then used as a start pulse for a time-to-amplitude converter (TAC). The output pulse of the photomultiplier was used as the stop pulse for the TAC after being processed by a constant fraction discriminator. In order to count the afterpulses which came immediately after the main photomultiplier pulse, the main output pulse (marked by symbol B in Fig. 12) was delayed after the start pulse. The time at which the main photomultiplier pulse occurred was taken as time zero. However, in order to count the afterpulses which occurred significantly later in time and with a very low count rate the trigger pulse from the pulse generator was purposely delayed to come after the photomultiplier main pulse so that an output pulse from the TAC would only occur when the photomultiplier generated an afterpulse. The output of the TAC was then recorded and displayed on a pulse-height analyzer. In order to look for pulses many microseconds after the main pulse (the timing range of the TAC being set accordingly) the operating frequency of the test system was quite low.

Under single photoelectron counting at a rate of 100 KHz, afterpulses were detected in the time range of 19-20 ns at a count rate of 140-280 cps after the main output pulses—in all three tubes, in other words about one afterpulse for 500 main pulses. Afterpulses

were also detected in the time ranges of 620-650 ns and a 2-4 μ s. The afterpulsing count rate in these time ranges was below 100 cps, or less than one after-pulse per thousand main pulses.

The same behavior was observed when three photoelectron pulses were used at a rate of 10 KHz. One out of the three photomultipliers was excessively noisy that afterpulsing could not be measurable beyond the 150 ns time range. No afterpulse was detected beyond 4.5 μ s up to 80 μ s.

Figure 13 shows a time distribution of output pulses in the time interval 0 - 150 ns after the main photomultiplier pulse under a 100 KHz single photoelectron counting rate. The first distribution at the beginning of the spectrum is the main output pulse of the photomultiplier. The second distribution represents the afterpulses which occur 19.8 ns after the main pulse at a count rate of 254 cps.

Figure 14 shows a time distribution of output pulses over the range 0.2 μ s-4.5 μ s under 100 KHz single photoelectron counting rate. The second distribution at the beginning of the spectrum represents the afterpulses which occurred at about 60 ns after the main pulse. They have a count rate less than 100 cps. The broad peak of afterpulses from 2.3 μ s to 3.8 μ s after the main photomultiplier pulse had a count rate also less than 100 cps.

CONCLUSIONS

Important characteristics of prototype photomultiplier C83036E have been measured and are discussed. Generally, measurements were made using voltage divider networks suggested by RCA for photomultiplier high gain and for high output current operation. The measurement technique and a description of the system used for afterpulse time spectrum measurements are given in detail. Afterpulse measurements were made using the high gain voltage divider circuit.

The afterpulses in the 19-20 ns range were most probably generated by He⁺ ions formed between the first and second dynode, striking the first dynode and causing the secondary emission. This conclusion is based on calculations using the geometry and fields in the first dynode region of the photomultiplier. The 19-20 ns time range increased when the voltage between the photocathode and the first dynode/focusing electrode was decreased because of the change in the electric field intensity and distribution.

The afterpulses occurring in the 620-650 ns range were attributed to He⁺ ions which are created in the space between the photocathode and the first dynode and the first and second dynode. This conclusion is based on the time-of-flight of the helium ion from its point of origin to the photocathode.

The afterpulses occurring in the 2.3-3.8 μ s range could be attributed to O⁺ ions or N⁺ ions with large mass-to-charge ratio, which may be present inside the glass envelope as a result of outgassing of the photomultiplier components during processing and operation.

ACKNOWLEDGEMENTS

The authors would like to express their appreciation to RCA Corporation, Solid State Division, Electro Optics and Devices, Lancaster, Pennsylvania, for the loan of the photomultipliers.

This work was performed as part of the program of the Electronics Research and Development Group of the Department of Instrument Science and Engineering and was supported by Lawrence Berkeley Laboratory and the U.S. Department of Energy under Contract No. DE-AC03-76SF00098. Reference to a company or product name does not imply approval or recommendation of the product by the University of California or the U.S. Department of Energy to the exclusion of the others that may be suitable.

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NOTES: UNLESS OTHERWISE INDICATED

1. RESISTORS 1W 5% CARBON COMPOSITION
2. CAPACITORS 1KV VOLTAGE RATING

XBL 842-634

Fig. 1. Schematic diagram of voltage divider network for photomultiplier high gain applications.

NOTES: UNLESS OTHERWISE INDICATED

1. RESISTORS 1W 5% CARBON COMPOSITION
2. CAPACITORS 1KV VOLTAGE RATING

XBL 842-635

Fig. 2. Schematic diagram of voltage divider for photomultiplier high current applications.

Fig. 3. Gain and dark current as a function of voltage between photocathode and anode using high gain voltage divider.

Fig. 4. Gain and dark current as function of voltage between photocathode and anode using high current divider network.

Fig. 6. Electron transit time as a function of voltage between photocathode and anode using divider network for photomultiplier high gain applications.

Fig. 7. Single photoelectron pulse response using high gain voltage divider.

Fig. 5. Peak linear anode output current as a function of light pulse intensity.

XBL 842-640

Fig. 8. Single photoelectron pulse risetime as a function of anode-cathode voltage using photomultiplier high current applications divider.

XBB 842-987

Fig. 9. Single photoelectron time spread of C83036E with full photocathode illumination.

Fig. 10. Multiphotoelectron time resolution of C83036E as a function of the number of photoelectrons per pulse.

Fig. 11. Pulse height spectrum of C83036E photomultiplier.

Fig. 12. System block diagram for measuring time spectrum of afterpulse.

XBL 811-7657A

Fig. 13. Afterpulse spectrum of anode output pulse in the 0-150 ns time range.

Fig. 14. Afterpulse spectrum of anode output pulse in the 200 ns - 4.5 μs time range.

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