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C. C. Lo, Pierre Lecomte and Branko Leskovar*

Summary

The characteristics of prototype photomultipliers having high gain microchannel plates for electron multiplication have been investigated. Measurements are given of the dark current, quantum efficiency, anode pulse amplitude, electron transit time, single photoelectron time spread, and pulse height resolution of LEP HR 350 and HR 400 photomultipliers. The gain, the collection efficiency, and the single electron pulse amplitude as functions of the ambient axial and transverse magnetic fields have been measured and are discussed. Measurement techniques and descriptions of the measuring systems are given in detail.

Introduction

The timing capabilities of photomultipliers, based on high-gain microchannel plates for electron multiplication with proximity focusing of the input and collector stages, appear to be better than those of conventional multipliers. Also, sensitivity of the photomultiplier characteristics to ambient magnetic fields is significantly decreased by such a configuration.

As opposed to the conventional discrete dynode electron multiplier, a microchannel plate consists of a two dimensional array of very small diameter, short channel electron multipliers closely packed parallel to each other. Each single channel electron multiplier is a continuous glass tube whose inside surface has a high resistance semiconducting coating used as a secondary electron emitting surface. A single microchannel plate photomultiplier with proximity focusing having a gain of approximately 10^5, and the 11 mm diameter photocathode, was described by J. P. Boutot and G. Pietri.[1] The description of a high-gain photomultiplier, having the 40 mm diameter photocathode and chevron microchannel plate[2] to reduce positive ion feedback, with conventional input electron optics, was given by C. E. Catchpole.[3] Our preliminary evaluation of a chevron microchannel plate photomultiplier[4] showed that the single electron pulse gain was approximately 3×10^6 and output pulse rise time was 650 psec at a voltage of 3600 V applied between photocathode and collector electrode. Furthermore, theoretical calculations of the single photoelectron transit time spread led to a value of approximately 150 psec, FWHM, for small photocathode area illumination. These results compared very favorably with characteristics of conventionally designed high-gain fast photomultipliers where a single photoelectron time spread of approximately 300 psec can be expected with small photocathode area illumination and optimized photomultiplier operating conditions.[5-7]

This paper presents and discusses performance characteristics of a LEP 350 and HR 400 photomultiplier. These photomultipliers have curved high-gain microchannel plates[8-9] to reduce the ion feedback. Proximity focusing is used for the input and collector stages. The reduction of the positive ion feedback allows the microchannel plate to be operated with an electronic gain higher than 10^6, with a satisfactory dark noise level and a good photocathode life. Based on previous work,[10] further effort has been expanded to include measurements of characteristics - such as gain, dark current, quantum efficiency, anode pulse amplitude, electron transit time, single photoelectron time spread, and pulse height resolution - for curved microchannel plate HR 350 and HR 400 photomultipliers. These photomultipliers were manufactured by the Laboratoires d'Electronique et de Physique Appliquée (LEP) at Limeil - Brévannes, near Paris, France.

The photomultiplier HR 350 has an S-20 photocathode with a useful diameter of 13 mm and it incorporates a coaxial anode. The HR 400 has the 15 mm - diameter S-20 photocathode and a simple plate as the anode. Both tubes incorporate microchannel plates having approximately 9×10^4 curved channels, each 40 μm in diameter.

Since both photomultipliers are experimental prototypes, an ion pump is used in place of a getter to keep a high vacuum inside the glass envelope. Both the pump voltage and current were monitored during operation. To start the ion pump, a voltage of 2.5 kV was applied on the pump terminals. Generally, the ion pump started in 30 - 40 minutes with at most a few hundred nanoamperes of pump current. Immediately after the pump began to operate the voltage was decreased to 2 kV. The current decreased to a value between 1 and 2 nanoamperes in a matter of minutes for the HR 400 photomultiplier. The ion pump current was continuously monitored during the photomultiplier operation since it served to indicate the vacuum conditions.

Measurements of the photomultiplier characteristics were made using a voltage divider network designed to give the photomultiplier voltages suggested by the manufacturer. This voltage divider is shown in Fig. 1. Electrostatic voltmeters were used to monitor the voltage between the photocathode and the input of the microchannel plate V_K, the voltage across microchannel plate V_M, and the voltage between the output of the microchannel plate and the anode, V_P. The microchannel plate current, of approximately 1.4 μA at 1500 V, was also continuously

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monitored. Both photomultipliers were demagnetized before measurements. Measuring systems used in photomultiplier performance studies were based on the systems described in Ref. 11. Particular attention was given to the measurements of the sensitivity of the photomultiplier gain, of the collection efficiency and of the single photoelectron pulse amplitude on ambient axial and transverse magnetic fields.

Gain and Dark Current Measurements

The DC gain of the HR 350 and HR 400 photomultipliers was measured with the system shown in Fig. 2. The light source was a Sylvania glow modulator, Type 1B59, driven by a 40 Hz square wave generator. A 5 - 58 Corning filter which has a peak transmittance at 410 nm was placed in between the glow modulator and the photomultipliers. In order to establish a reference light intensity level to make gain measurements, both the input and output of the microchannel plate were connected together with the anode as the collector. The photomultiplier, operating as a photodiode with 500 V across it, was placed in a marked position; the light level was then adjusted to yield a 10 mV peak to peak output signal across the 1 megohm input of an oscilloscope. 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 100 mV peak to peak 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 give again a 10 mV output signal. With the lower light level setting, the microchannel plate voltage was again increased to yield 100 mV peak to peak output signal corresponding to a gain of 100. The same procedure was repeated until the microchannel plate voltage was 1600 V - the absolute maximum rating according to the manufacturer. At 1600 V the gain of both the HR 350 and HR 400 was 1.0×10^6 and the conduction currents of the microchannel plates were 3 μA and 1.5 μA respectively. Before measuring dark current, the light source was turned off and the photomultipliers were left in the dark for 24 hours. The dark current for the HR 350 and HR 400 was 0.65×10^{-9} A and 0.5×10^{-9} A respectively at the 1600 V microchannel plate voltage. Accuracy of this measurement is estimated to be ± 5%. Fig. 3 shows the DC gain and dark current as a function of voltage for both the HR 350 and 400 photomultipliers.

Quantum Efficiency Measurements

Measurements of the quantum efficiency of the microchannel plate photomultipliers were made with the system shown in Fig. 2. A calibrated 8850 with bialkali photocathode was used as the standard for comparison. The photocathode was masked to leave a 1.3-1.5 cm (photocathode diameter of HR 350-400) diameter area at the center and was placed in a marked position. The light source was adjusted to yield an output signal of 20 mV peak to peak across 1 megohm from the 8850 with 500 V between the photocathode and anode. With the same light level setting, the HR 350 and HR 400 were 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 signals were measured. The quantum efficiency of the HR 350 and 400 was found to be 20% and 6% respectively at 510 nm.

It is noteworthy to point out at this time that the quantum efficiency of the HR 350 dropped to 12% after the photomultiplier characteristics measurements in a magnetic field were made. Those measurements will be discussed later in the paper.

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 behaviour of a microchannel plate photomultiplier is similar although affected by different parameters such as the number of microchannels used in the plate plus the diameter and the length of the channels. The peak output current of the HR photomultipliers was measured with a pulsed mercury light source capable of emitting enough photons per pulse to saturate the photomultipliers.

Calibrated neutral density filters were used to attenuate the light pulse intensity during the measurements. The results are plotted in Fig. 4. The peak linear output current was approximately 260 mA for the HR 350 with pulses 2.5 nsec wide having a repetition rate of 60 pulses per second. The equivalent average anode current at this point was approximately 40 nA or 1.25 percent of the conduction current of the microchannel plate.

For d.c. operation, the anode output current will deviate from linearity when it is about five to ten percent of the conduction current. For pulse operation, the diameter of the individual channel, the useful area of the plate and the electrical properties of the channel material (including the recovery time) all have influence on the current pulse saturation level. Generally, for pulse operation with time interval between pulses shorter than the recovery time, the output current linearity is determined by the d.c. operating condition. For single photoelectron, the maximum counting rate is approximately 1×10^6 per second.

Electron Transit Time Measurement

In a conventional 12 stage photomultiplier, the typical electron transit time is in the order of 30 - 50 nsec. The close spacing of the microchannel photomultipliers yields a figure much less than this. Fig. 5 shows the system used for this measurement. A LED light pulser initiated the light pulse, and the electrical pulse used to drive the LED was utilized as the reference pulse. The electrical pulse was divided into two parts for calibration. An adjustable air line was used to bring the two pulses into coincidence on the oscilloscope, hence establishing zero time reference. The HR 350 and HR 400 photomultipliers were then put in place and the delays of the output signal were measured. After transit time corrections due to cable lenght etc., the final transit time was found to be 3.4 nsec and 3.5 nsec for prototype packaged HR 350 and HR 400 respectively with a possible error of ± 0.2 nsec.

Single Photoelectron Pulse Response

Figure 6A shows the block diagram of the system used to measure the single photoelectron pulse response of the HR 350 and HR 400 photomultipliers with a microchannel plate voltage of 1600 V. Before the single photoelectron pulse response measurement was made, the system risetime was measured and found to be 400 psec with a 28 psec risetime tunnel diode pulse generator as the signal source. Figure 6B shows the single photoelectron pulse shape of the HR 350. The 10 - 90% risetime was approximately 0.76 nsec; taking the correction of the system's 400 psec risetime, the single photoelectron pulse risetime was 0.64 nsec, and the pulse width at FWHM points was 1.25nsec ± 0.2 nsec for HR 350, whereas the HR 400 had a pulse risetime of 0.9 nsec and a pulse width at FWHM points of 1.4 nsec ± 0.2 nsec.

Single Photoelectron Time Spread Measurements

Figure 7 is the system block diagram for making the single photoelectron time spread measurements of the HR 350 and HR 400. Two light sources were used to obtain light pulse widths from 200 psec to 6.8 nanoseconds. Since single photoelectron pulses of the HR 350 and HR 400 were in the order of 5 to 10 mV, some gain must be provided to yield pulses with amplitudes acceptable to the constant fraction discriminator. A voltage gain of approximately 30 dB was found to provide the best result, giving a signal amplitude of single photoelectron pulses at the input of the discriminators in the range from 150 to 300 mV. The outputs of the two discriminators, following the constant fraction discriminator and the LED driver, were connected to a time to amplitude converter whose output was processed and recorded in the multichannel analyzer. The system resolution was approximately 25 psec, FWHM.

With full photocathode illumination, and with a light pulse produced by a 200 psec electrical pulse, the single photoelectron time spread was 250 ps and 286 psec, FWHM, for the HR 350 and the HR 400, respectively. With only 3 mm diameter area of the HR 350 photocathode illuminated, the single photoelectron time resolution remains the same as in the full photocathode case. Fig. 8 shows the spectrum of the single photoelectron time spread of the HR 350.

In Fig. 7, electrical pulses wider than 200 psec were obtained from a Tektronix 110 pulse generator using cables to obtain electrical pulses of various widths. In extrapolating the curve in Fig. 9 to a LED current pulse width of 100 psec, the single photoelectron time spread of the HR 350 and HR 400 has an upper limit of 200 psec, FWHM.

Multiphotoelectron Time Resolution

It is generally agreed that the variance, σ^2, of the single photoelectron time spread of a photomultiplier is inversely proportional to the number of photoelectrons per pulse. This measurement was made using the mercury light pulse generator which was capable of producing thousands of photoelectrons per pulse from the photocathode of the photomultipliers. The system used was similar to the system shown in Fig. 7 except that the LED light pulse generator was replaced by the mercury light pulser. 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 1600 V microchannel plate operating voltage for both HR 350 and HR 400. Fig. 10 shows the plot of the time resolution as a function of the number of photoelectrons per pulse from one photoelectron up to 6000 photoelectrons. The time resolution of the single photoelectron pulses was 2.6 nsec FWHM indicating the light pulse was very close to 2.6 nsec wide; the time resolution tapered down to approximately 30 psec FWHM with 6000 photoelectrons per pulse.

Pulse Height Resolution Measurements

The block diagram in Fig. 11 shows the system used for measuring the pulse height spectrum. With the microchannel plate voltage, V_M, set at 1600 V, the light level on each tube was adjusted to yield one, two, three, four or more photoelectron pulses. The one, two, and three photoelectron peaks were made to have the same height by varying the light pulse intensity at various times during the measurement. The first peak to valley ratio was 2.8:1. With V_M lowered to 1500 V, the first peak to valley ratio became 2:1 for the HR 400. With V_M set at 1600 V, HR 350 yielded a first peak to valley ratio of 2:1. Figure 12 is the pulse height spectrum of HR 350 with V_M = 1600 V.

The dark-pulse count for the photomultiplier HR 350 was found to be

$$\sum_{1/8 \text{ photoelectron}}^{16 \text{ photoelectrons}} = 340 \text{ counts per second}$$

For the photomultiplier HR 400 the dark-pulse count was

$$\sum_{1/8 \text{ photoelectron}}^{16 \text{ photoelectrons}} = 460 \text{ counts per second}$$

Similar measurements made on a RCA 8850 showed the photomultiplier had a dark count rate of 145 pps.

Effects of Ambient Axial and Transverse Magnetic Fields

As indicated in the introduction, proximity focused microchannel plate photomultipliers are relatively insensitive to ambient magnetic fields. Measurements were made to put this on a quantitive basis. These included the DC gain, the collection efficiency and the single photoelectron pulse amplitude as a function of magnetic flux density. Systems used for these measurements were similar to those previously described.

Axial Magnetic Field Measurements

The HR 350 and the HR 400 were placed in an axial magnetic field and their relative DC gain measured as a function of the magnetic flux density. (Fig. 13). Using the system described above, it should be pointed out here that the measurements in the HR 350 and HR 400 were done at two different times; hence, in the HR 400 case, the maximum magnetic flux density was limited to 900 Gauss because of the magnet available at that time. The relative DC gain increased by 2.8 and 3.5 times, depending upon the magnetic field direction, at approximately 850 Gauss for the HR 350, and by 1.4 and 1.5 times for the HR 400 at the same flux density. Above 1 kGauss however the gain of the HR 350 decreased to 1.2 and 1.6 times of the original value at 2 kGauss. No attempt was made to increase the field above 2 kGauss as some components of the internal structure of the HR 350 are made of magnetic materials.

Transverse Magnetic Field Measurements

In the region of interest to us, the photomultiplier characteristics are independent of V_K and Vp in the operating range. On Fig. 14 the expected decrease of the DC gain and collection efficiency for one direction of the magnetic field was observed. The sharp increase to 1.5 times of the zero field value observed for the other direction of magnetic field is attributed to the fact that the microchannels are not perpendicular to the photocathode and the expected decrease in gain was observed at around 400 Gauss. This is approximately 500 times better than for a conventional designed photomultiplier in the case of HR 400. The HR 350 tolerates even higher fields. The 10% gain reduction point occurred at 520 Gauss and 760 Gauss for the two opposite directions of magnetic field, respectively. This behavior indicates that the spacing between the photocathode and the input of the microchannel plate is closer in the HR 350 than in the HR 400's.

The HR 400 relative single photoelectron amplitude gave some information on the gain variations in the plate itself. Here, also, there was asymmetry, but less marked than before; the plate seemed, therefore, to tolerate 350-400 Gauss at least. The decrease in gain for higher fields could be, at least in part, attributed to losses of electrons at the input of the channels.

It is appropriate at this time to report on the behavior of the HR 350 in a transverse magnetic field with magnitude greater than that for the DC gain cut off. With the light source turned off and a picoammeter replacing the oscilloscope, the dark current was monitored as a function of the field. Below 1 kGauss the dark current followed the same trend as the DC gain. However the dark current output never decreases to zero indicating that part of the dark current was generated in the microchannel plate. This was confirmed later by back biasing the photocathode. Above 1 kGauss however, in both field directions, the dark current increased rapidly to a few times higher than the nominal value at approximately 1.5 kGauss. This behavior of the HR 350 may indicate that the magnetic field is causing ion feedback in the microchannel plate.

During all these measurements the ion pump was turned off and the magnet of the pump removed. After the above measurements, the HR 350 was removed from the magnet and the ion pump was turned back on for approximately 12 hours to pump the device down to 30 nA of ion pump current indicating normal vacuum conditions. A repeat of the DC gain and quantum efficiency measurements showed that the DC gain had decreased to 6×10^5 from 1×10^6 at V_M = 1600 V and the quantum efficiency had decreased to 12% from 20%, indicating a damage to both the photocathode and the microchannel plate. However, it should be emphasized that the damaging level of the transverse magnetic flux density was considerably greater than the DC gain cut-off.

Conclusions

Performance characteristics measurements of the curved microchannel plate photomultipliers show that the devices exhibit very good timing capabilities and very low sensitivity to ambient magnetic fields in comparison to the best conventionally designed photomultipliers. The results obtained are shown in Table 1. Our measurements have shown that photomultiplier operating characteristics can be optimized for collection efficiency and gain. Single photoelectron and multiphotoelectron time spread measuring values obtained should be considered as upper limits, due to the time resolution capabilities of the measuring systems. Generally, the time spread of the microchannel plate photomultipliers is two times lower than for the best conventionally designed photomultipliers. Pulse height resolution capabilities of the microchannel plate photomultipliers, when operated in saturation mode, compare favorably with photomultipliers having dynodes with cesium - activated gallium phosphide secondary emitting surfaces. Furthermore, during extensive evaluation time both photomultipliers showed no significant change in characteristics, when operated without ambient magnetic field. except for reversible fluctuations of dark current when operating at absolute maximum voltage ratings. However, the HR 350 photomultiplier, when operated in transverse magnetic field of 1.2 kGauss, indicated a partial damage of the photocathode and the microchannel plate. Further efforts will be necessary to determine causes of the magnetic field induced damage mechanism.

Acknowledgments

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Table 1. Summary of Characteristics Measurements of Microchannel Plate Photomultipliers

	HR 350	HR 400
DC Gain[a,d]	10^6	10^6
Dark Current[a] (nA)	0.65	0.5
Electron Transit Time[a,h] (nsec)	3.4 ± 0.2	3.5 ± 0.2
Rise Time[h] (nsec)	0.64 ± 0.15	0.9 ± 0.15
Delta Function Response[h], FWHM, (nsec)	1.25 ± 0.2	1.4 ± 0.2
Single Photoelectron Time Spread[b], FWHM, (psec)	<200	<200
Multiphotoelectron Time Spread[e], FWHM, (psec)	<30	not available
Peak-to-Valley Ratio of Pulse Height Spectrum[a]	2	2.8
Quantum Efficiency[d] (%)	20%	6%
Linear Peak Anode Pulse Current[e] (mA)	260	not available
Sensitivity to Axial Magnetic Field[f] (Gauss)	2000	900
Sensitivity to Transverse Magnetic Field[g] (Gauss)	780	500

[a] Microchannel plate voltage $V_M = 1600$ V.

[b] These values include the measuring system timing error.

[c] Measured using 6×10^3 photoelectron light pulse which has 2.6 nsec width.

[d] These characteristics showed no significant change during extensive evaluation time. However, the DC gain and quantum efficiency had decreased to 6×10^5 and 12% respectively, after the HR 350 was operated in the transverse magnetic flux density of 1200 Gauss.

[e] Measured using 2.6 nsec light pulses with repetition frequency of 60 Hz.

[f] Maximum magnetic flux density under which photomultipliers were tested without decrease in DC gain.

[g]The value of magnetic flux density for which the DC gain decreases to half its initial value.

[h]These characteristics were measured for prototype packaged photomultipliers.

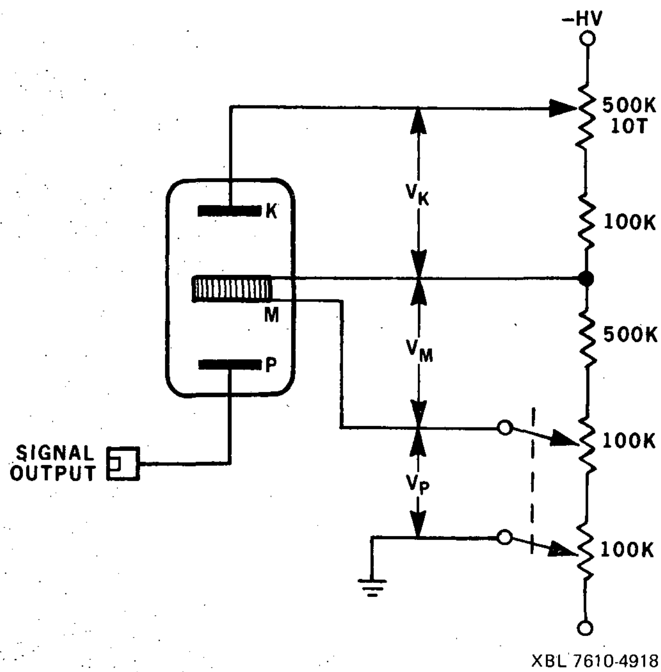

Fig. 1 Microchannel plate photomultiplier voltage divider used in the measurements.

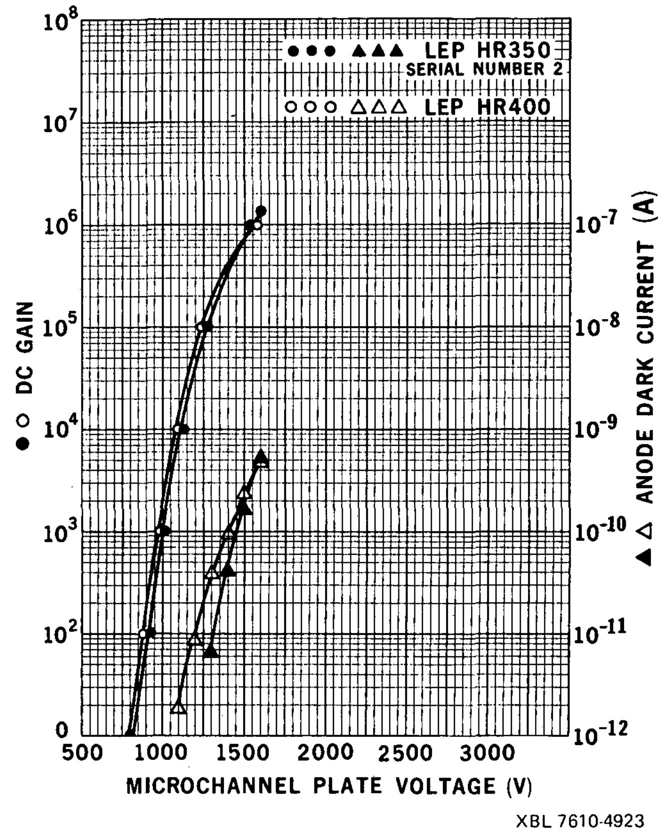

Fig. 3 DC gain and dark current as a function of the microchannel plate voltage for HR 350 and HR 400 photomultipliers.

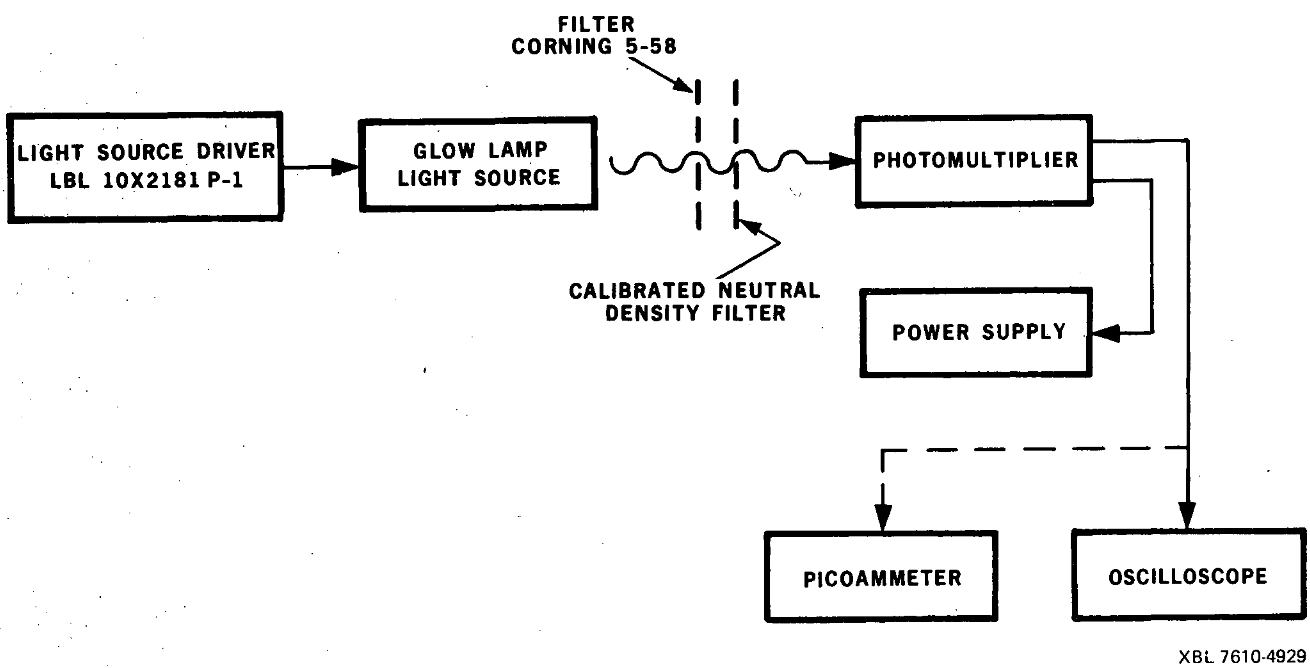

Fig. 2 Block diagram of the system for gain and dark current measurements.

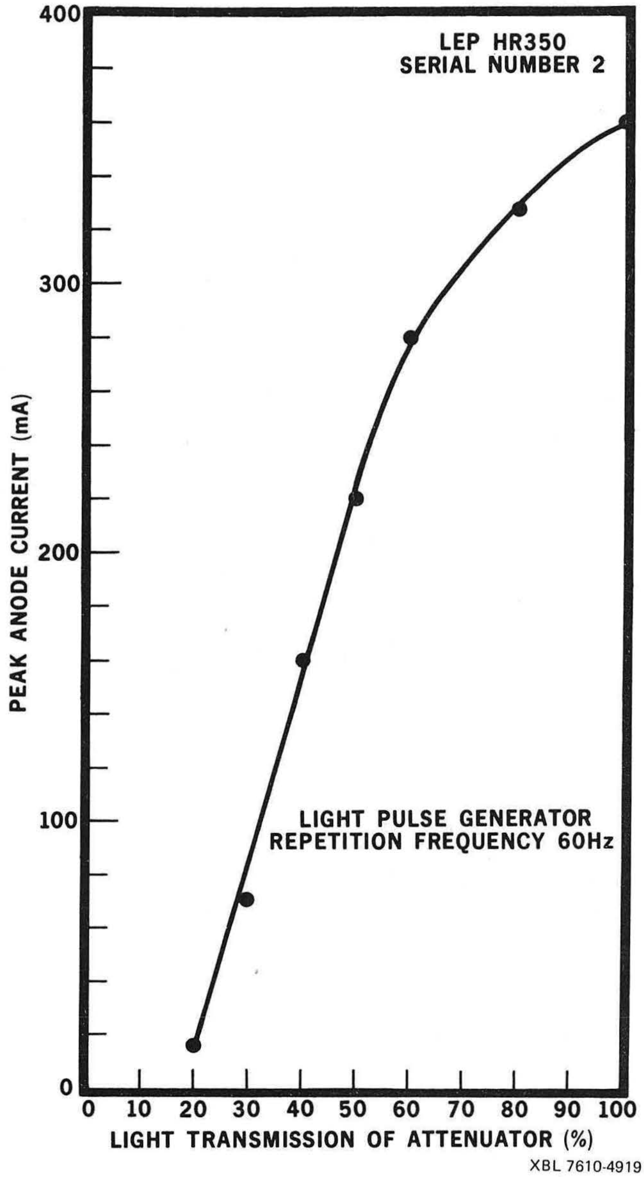

Fig. 4 Peak anode pulse amplitude as a function of light transmission of the optical attenuator with microchannel plate voltage V_M = 1600 V for HR 350 photomultiplier.

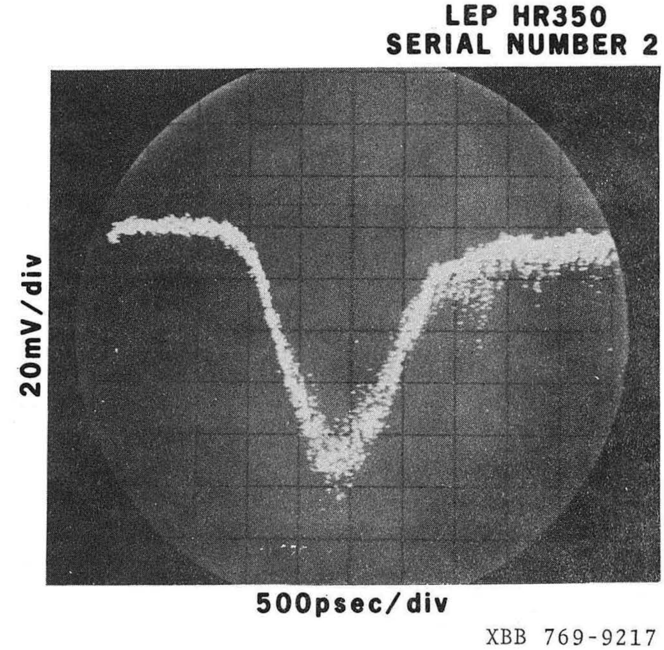

Fig. 6B. Typical single photoelectron pulses from the HR 350 operated at V_M = 1600 V using a 200 psec impulse excitation from the reverse-biased electroluminescent diode, Feranti type XP-23.

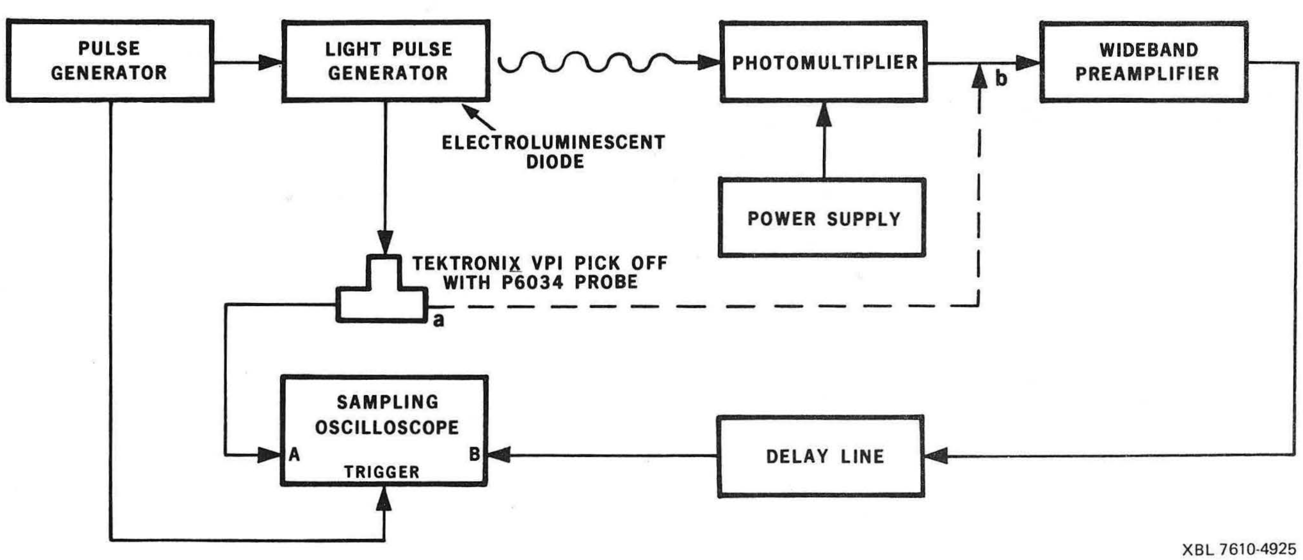

Fig. 5 System block diagram for electron transit time measurements.

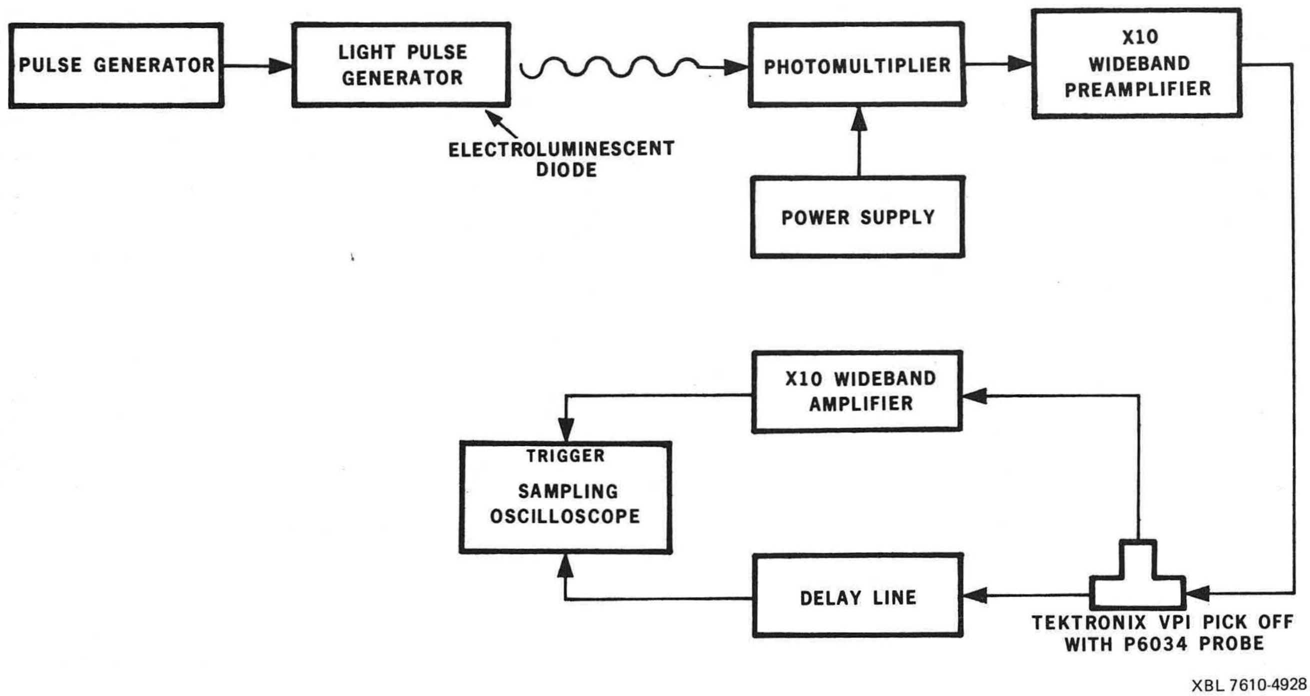

Fig. 6A Block diagram of the system for measuring the single photoelectron pulse response.

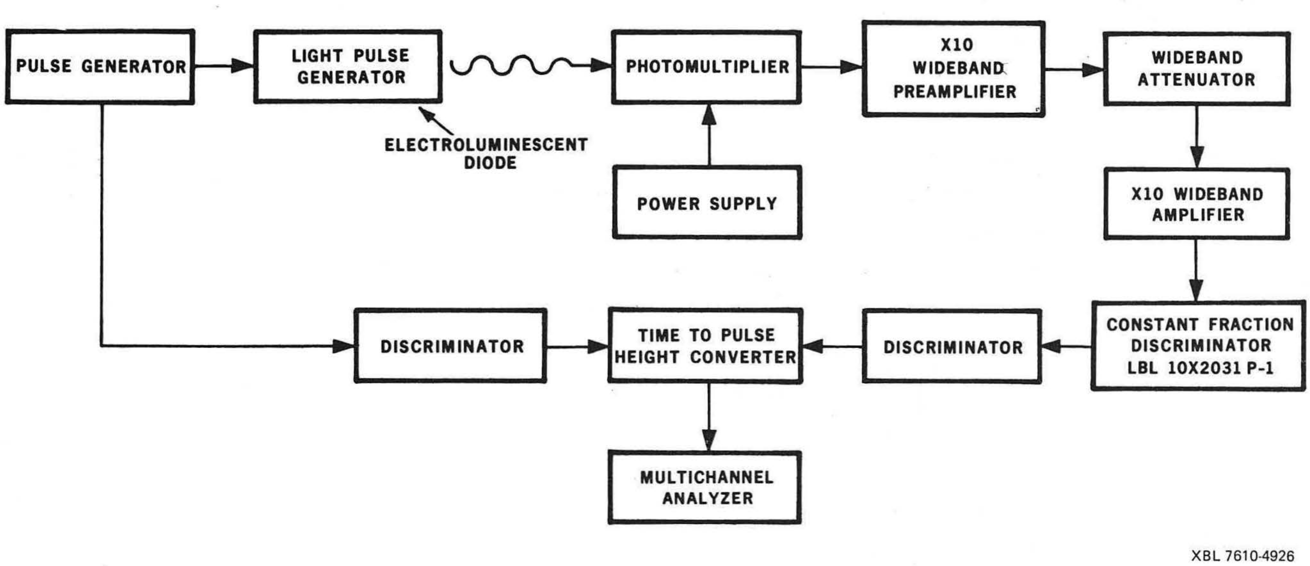

Fig. 7 Block diagram of the system for measuring the single photoelectron time spread.

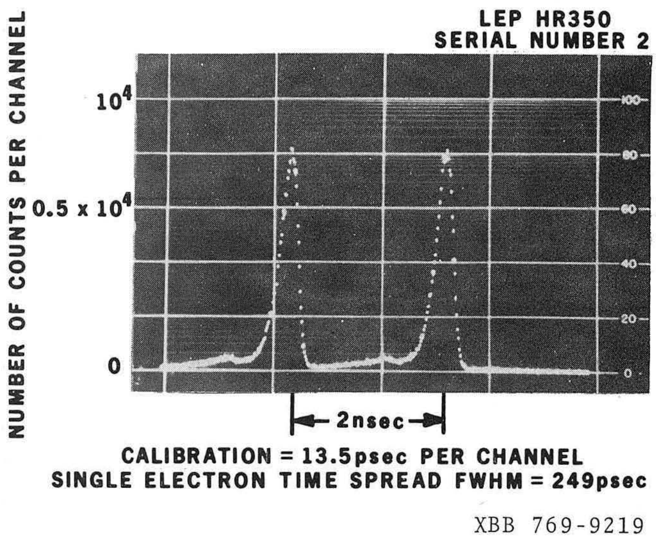

Fig. 8 Single photoelectron time spread of the HR 350 photomultiplier with full photocathode illumination.

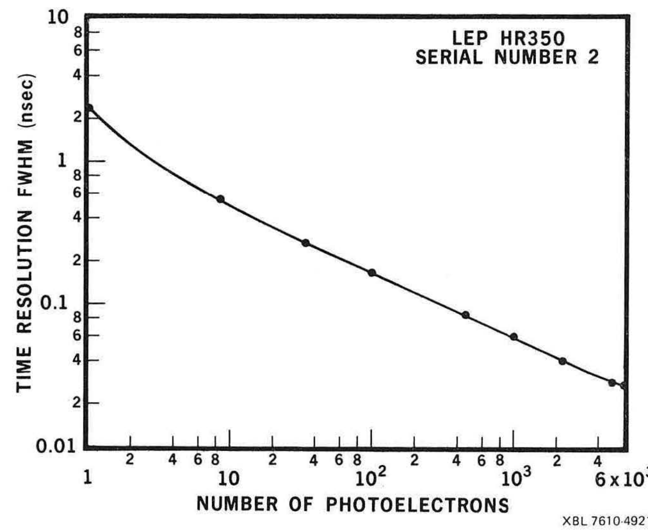

Fig. 10 Time resolution of the HR 350 as a function of number of photoelectrons per pulse, measured with 2.6 nsec light pulsed width, for full photocathode illumination.

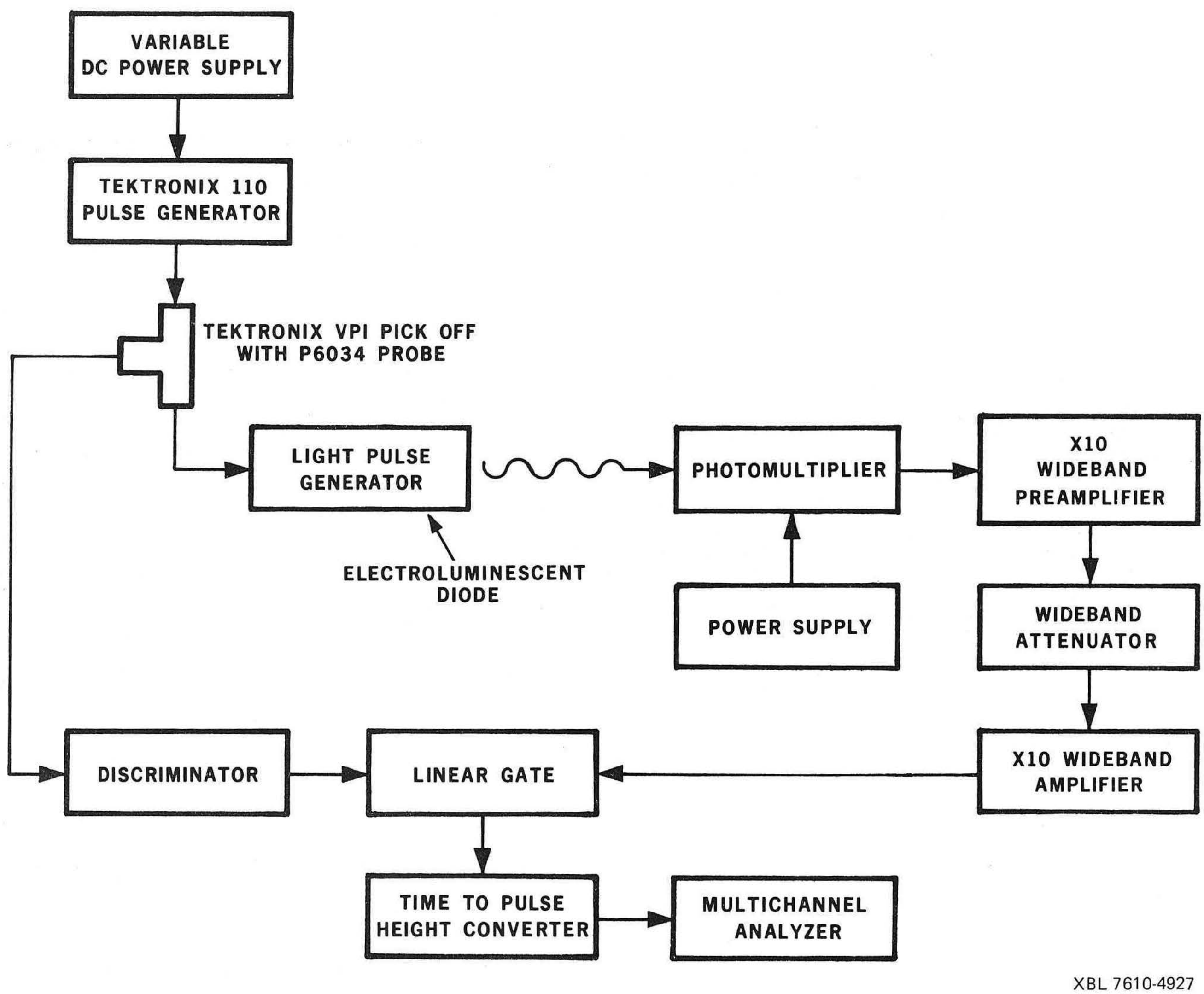

Fig. 11 System block diagram for pulse-height spectrum measurement

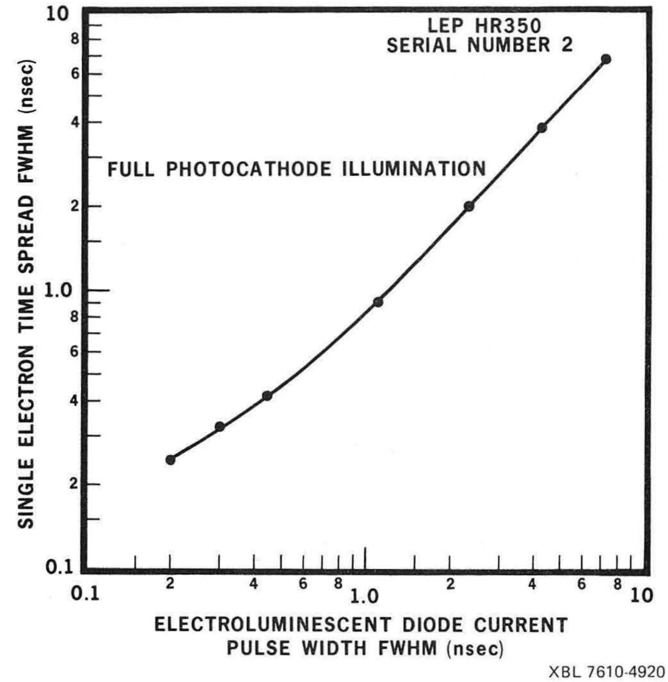

Fig. 9 Single photoelectron time spread of the HR 350 as a function of the width of the electroluminescent diode current pulse for full photocathode illumination.

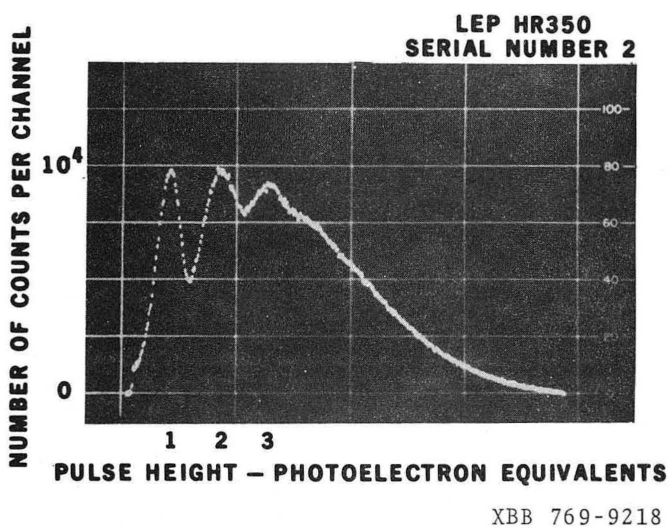

Fig. 12 Pulse-height spectrum, showing peaks corresponding to one, two, and up to four electron peaks for HR 350 photomultiplier.

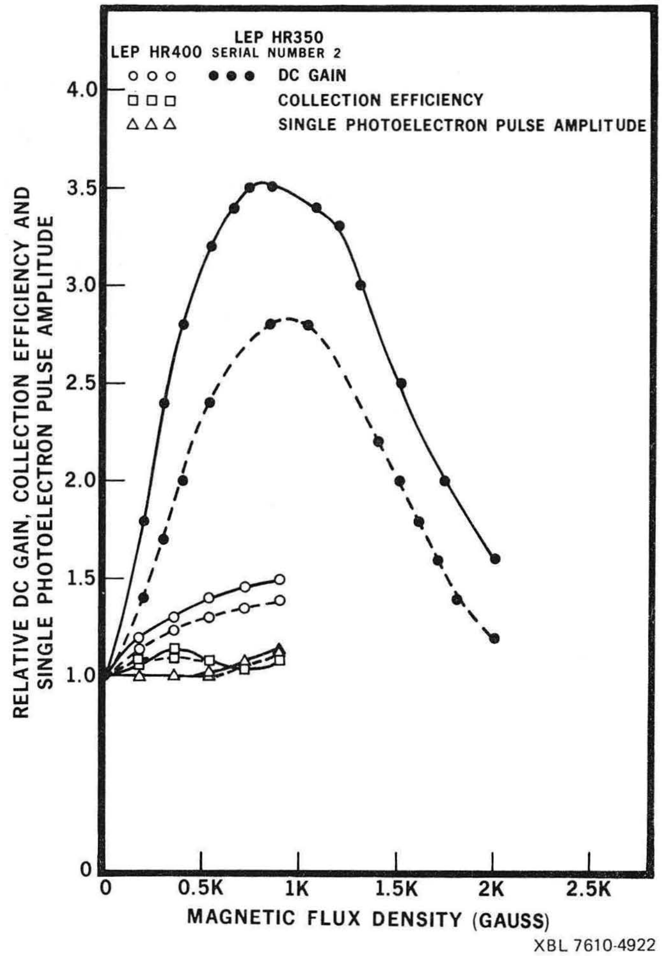

Fig. 13 Relative DC gain, collection efficiency and single photoelectron pulse amplitude as a function of axial magnetic field.

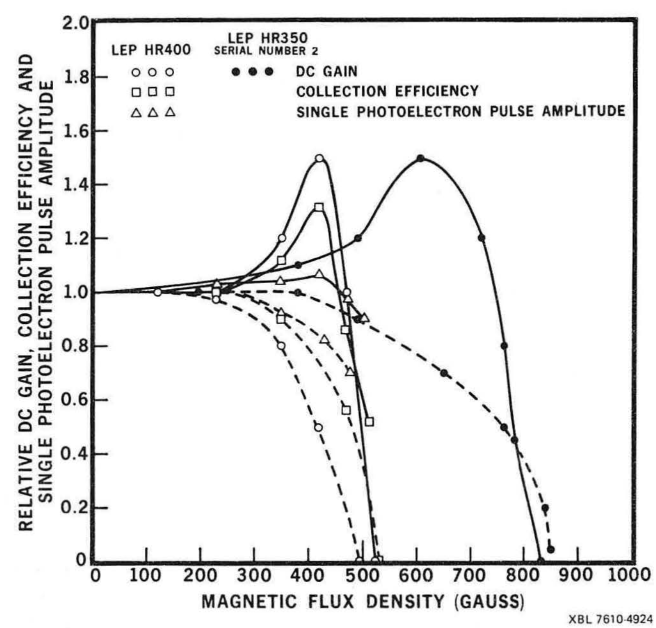

Fig. 14 Relative DC gain, collection efficiency and single photoelectron pulse amplitude as a function of transverse magnetic field.

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