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## Time Resolution Performance Studies of Contemporary High Speed Photomultipliers — [Source link](#)

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### Abstract

The time resolution capabilities of prototype microchannel plate and static crossed-field photomultipliers have been investigated. Measurements were made of electron transit time, rise time, time response, single photoelectron time spread and multiphotoelectron time spread for LEP HR350 proximity focused high gain curved microchannel plate and VPM-154A/1.6L static crossed-field photomultipliers. The experimental data have been compared with results obtained with conventionally designed RCA 8850 and C31024 high speed photomultipliers. Descriptions are given of both the measuring techniques and the measuring systems.

### Introduction

The time resolution capability of high speed photomultipliers has been the subject of intensive experimental and theoretical investigations, and a comprehensive survey of the literature has been given by the authors.<sup>1</sup> The time characteristics of these devices are becoming increasingly important in a multitude of research areas, such as: atomic and molecular subnanosecond fluorescence decay time measurements,<sup>2, 4</sup> nuclear research,<sup>5</sup> optical ranging,<sup>6</sup> optical communication, and photon statistic.<sup>8</sup> The photomultiplier time resolution capabilities are essentially determined by the random deviations in transit time of electrons travelling from the photocathode to the collector and in the possible spread of electron emission times.

The purpose of the work reported here has been to investigate time resolution of the LEP HR350 prototype photomultipliers having high-gain microchannel plates for electron multiplication where proximity focusing is used for the input and collector stages. Also, the resolution capability of the VPM-154/1.6L high speed static crossed-field photomultiplier has been investigated. The results are compared with conventionally designed RCA 8850 and C31024 photomultiplier characteristics.

As opposed to the conventional discrete dynode electron multiplier, a microchannel plate consists of a closely packed two dimensional array of very small diameter, short channel electron multipliers. Each single channel electron multiplier is a continuous glass tube whose inside surface has a resistive semiconducting coating used as the secondary electron emitting surface.<sup>9</sup> Schematic arrangement of a microchannel plate photomultiplier is shown in Fig. 1A. The static crossed-field photomultiplier utilizes static

electric and magnetic fields to determine the electron trajectories between dynodes of the electron multiplier.<sup>10, 7</sup> Schematic arrangement of the electrodes for a crossed-field photomultiplier is shown in Fig. 1B. The strong electric field between the dynodes and the field electrode results in short secondary electron transit times. Also the voltage difference between the successive dynodes adjusted from the first to the last dynode so that the electrons impact with velocities in the range for a maximum secondary emission yield. The dynodes are arranged in steps to maintain field uniformity. With proper values of the electric and magnetic fields, the secondary electrons emitted from the center of one dynode are focused on the center of the following dynode. Consequently, the device provides a combination of optimum secondary emission yield per dynode and short overall transit time (and hence small transit-time spread). Since secondary electrons emitted at the same time and with the same velocity from a given dynode arrive at the same time at the next dynode, the transit time spread is due mainly to initial velocity effects.

Based on previous work,<sup>1, 11</sup> further efforts have been made to measure time resolution capabilities of high gain curved microchannel plate and static crossed-field photomultipliers using a specially developed measuring system with high time-resolution capabilities.<sup>12</sup>

### Measuring System Description

The system used for measuring single and multiphotoelectron time resolution is shown in Fig. 1 in the form of a block diagram. The system consists of a subnanosecond light pulse generator, wide band preamplifiers, a constant fraction discriminator, leading edge discriminators, delay cables, a time-to-pulse height converter, and a multichannel analyzer.

Two light sources were used to obtain light pulse widths from 200 psec to 6.8 nsec. The light level of the subnanosecond light pulse generator was adjusted to the low intensity necessary to cause the emission of predominantly single-photoelectron, by means of an optical attenuator. The photomultiplier single photoelectron time spread measurements were made with a small 1.6 mm-diameter photocathode area and also with full photocathode illumination. Since single photoelectron pulses of the RCA C31024 and HR350 were in the order of 5 to 10 mV, a 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

give the best result, producing 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 light emitting diode driver, were connected to a time to amplitude converter whose output was processed and recorded in a multichannel analyzer. The system resolution was approximately 25 psec, FWHM.

Electrical pulses wider than 200 psec were obtained from a Tektronix 110 pulse generator using cables to obtain electrical pulses of various widths. It is generally agreed that the variance,  $\sigma^2$ , 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 photomultiplier. The number of photoelectrons per pulse was calculated by measuring the output pulse width and amplitude and knowing the gain of the photomultiplier.

Since the Varian VPM-154A/1.6L photomultiplier has a current gain of  $2.5 \times 10^5$  and its characteristics are important at near-infrared frequencies,<sup>13</sup> a 904 nm gallium arsenide injection laser, RCA SG2001, was used to generate the required light pulse.

Fig. 3A shows the injection laser light pulse generator<sup>16</sup> circuit diagram. A 50 strip line was used as the pulse forming line, and an avalanche transistor was used as a switch to generate the required electrical pulse. The 4.3  $\Omega$  resistor serves as a current limiter as well as part of a 50  $\Omega$  matching load. The other part of the 50  $\Omega$  load was supplied by the forward biased diode impedance.

A number of SG2001 laser diodes were tested and the one with the best response was selected to be used for these measurements. The d.c. supply for the avalanche transistor was adjusted to yield a single light pulse. In some cases the length of the 50  $\Omega$  charging line had also to be changed. To test the light pulse structure a photodiode, ITT 4014 with a S-1 photocathode, was used to observe the light pulse output from the SG2001. Fig. 3B shows the pulse output from the ITT 4014 as monitored on a sampling scope with a 38 psec rise time. The specified rise time of the ITT 4014 photodiode is 100 psec. In Fig. 3B the 10-90% rise time of the pulse is 120 psec; hence, the light pulse rise time is approximately 55 psec after correction has been made for the photodiode and the oscilloscope rise times; the light pulse width (full-width-at-half-maximum) is approximately 125 psec.

#### Electron Transit Time Spread Considerations

The total electron transit time spread of a high-gain photon detector consists of the photoelectron transit time spread between the photocathode and the input of the electron multiplier, in the electron multiplier itself, and between the output of the electron multiplier and anode. The major causes of transit time

spreads are the distribution of initial emission velocities of photoelectrons and secondary electrons, unequal electron path lengths between different electrodes and non-uniform electric fields. Generally, the initial stages of a high-gain photon detector contribute the greatest weight to the total transit time spread. In the latter stages, the large number of electrons in the pulse provide many samples of transit time through the stage and reduce the transit time spread of that stage in the manner of the standard error of mean value. The contribution to the transit time spread by the unequal electron path lengths between different electrodes and the nonuniformity of electric fields at the electrodes can be minimized by proper design of the electron optics of the input system and the electron multiplier dynode system. The transit time spread resulting from the initial velocity distribution of photoelectrons can be decreased by increasing the voltage between the photocathode in the input of electron multiplier and by decreasing electron path lengths. Similar consideration is valid for the secondary electron initial velocity in the electron multiplier.

#### Measurement of Single Photoelectron Time Spread

In measuring the single photoelectron time spread using the system shown in Fig. 2, the photocathode was exposed to subnanosecond light pulses from the light pulse generator of such low intensity that only a small percentage of the light pulses produce even one photoelectron. The probability of producing  $n$  photoelectrons is approximately given by the Poisson distribution:  $P = m^n \exp(-m)/n!$ , where  $m$  is the expected number of photoelectrons per light pulse, and  $P(n)$  is the probability of obtaining  $n$  photoelectrons in a single light pulse. For values of  $m$  considerably below unity,  $P(1) \approx m$ , and the probability of producing more than a single photoelectron per light pulse is very small.

Typical single photoelectron pulses from an RCA 8850 and C31024, using a 200 psec impulse excitation from the reversed-biased electroluminescent diode, Ferranti Type XP-23, are shown in Fig. 4 and 5, respectively. Also, using the same impulse excitation, single photoelectron pulses from an HR350 operated at microchannel plate voltage of  $V_m = 1600V$  are shown in Fig. 6. A wideband amplifier with 20 dB gain was used to amplify the single photoelectron pulses of the C31024 and HR350 photomultipliers.

In measuring the single photoelectron time spread, the difference between the time arrival of a photomultiplier anode pulse resulting from a single photoelectron and the time of the reference pulse was measured, displayed, and recorded for a large number of light pulses. The single-photoelectron time spread of each of the spectra was calculated from the print-out data, using the full width at half-maximum points. The time spread was measured for illumination of a 1.6 mm diameter area and also for the full photocathode. Generally, for conventionally designed photomultipliers, the single photoelectron time spread varies with the potential distribution in the input

electron optics and the value of the supply voltage between the photomultiplier anode and cathode. The single photoelectron time spread was measured as a function of the voltage ratio between the photocathode-focusing electrode and photocathode-first dynode,  $(V_C - V_{FE}) / (V_C - V_{D1})$ , to determine the optimum photomultiplier operating conditions for minimum time spread. The supply voltage between the photomultiplier anode and cathode was taken as a parameter. The results of measurements for the RCA 8850 and C31024 are given in Fig. 7, both for a 1.6 mm diameter area and for full photocathode illumination. The curves represent the typical single photoelectron time spread, FWHM, obtained by averaging the data for the four photomultipliers evaluated.

It can be seen from Fig. 7 that in the case of a 1.6 mm diameter area of photocathode illumination of RCA 8850 at the center of the photocathode, the single photoelectron time spread has a minimum value, FWHM, of 0.33 nsec for  $(V_C - V_{FE}) = 0.9$  and a supply voltage between anode and cathode of 3000V.

Similarly, with full photocathode illumination of 8850, the transit time spread has a minimum value FWHM of 0.48 nsec for  $(V_C - V_{FE}) / (V_C - V_{D1}) = 0.95$ , and a supply voltage between the cathode and anode of 3000V.

The minimums of the time spread curves when the full photocathode is illuminated have higher values in comparison with the case of a 1.6 mm diameter area of photocathode illumination, as might be expected because of the difference in transit time between the photoelectrons leaving the center of the photocathode and the photoelectrons leaving the photocathode from some other point. In the case of full photocathode illumination, single photoelectrons can be emitted from any point on the photocathode, thus contributing to the greater single photoelectron time spread. Also, the minimums of the transit time spread curves are not as sharp as in the case of the 1.6 mm diameter area of photocathode illumination, and they are closer to the  $(V_C - V_{FE}) / (V_C - V_{D1}) = 1$  point.

The results of the time spread measurements for the RCA C31024 are also shown in Fig. 7 for a 1.6 mm diameter area and also for full photocathode illumination.

In the case of the 1.6 mm diameter area illumination at the center of the photocathode, the single photoelectron time spread has a minimum value, FWHM, of 0.3 nsec for  $(V_C - V_{FE}) / (V_C - V_{D1}) = 0.85$  and a supply voltage between anode and cathode of 4000V.

For the full photocathode illumination, the transit time spread has a minimum value of 0.42 nsec for  $(V_C - V_{FE}) / (V_C - V_{D1}) = 0.8$  and a supply voltage between the anode and cathode of 4000V.

All previous considerations are based on the measured values of the single photoelectron transit time spread. However, due to the finite width of the light pulse and its influence on the measured results, the measured values of the time spread are always larger than the true value of time spread

in a fast photomultiplier, particularly when photomultiplier operating conditions are optimized for the minimum time spread. Consequently, it is important to estimate the error of the time spread measurements because of the finite width of the light pulse.<sup>14</sup> For this purpose the measurements were made of the time spread as a function of width of the light pulse for RCA 8850, C31024 and LEP HR350 photomultipliers. The results of measurements are given in Figs. 8 and 9 for a 1.6 mm diameter area and full photocathode illumination, respectively. During the measurements, an electroluminescent diode current pulse 200 psec wide was supplied by an avalanche transistor pulse generator in conjunction with a step recovery diode pulse-shaping unit. Electrical current pulses longer than 200 psec were obtained by means of a modified Tetrax 110 pulse generator. For smaller widths than 200 psec the single-electron time spread curves were extrapolated to the 100 psec point from experimental data obtained at larger diode current widths. The supply voltage between the anode and cathode was 3000V and 4000V for photomultiplier RCA 8850 and C31024, respectively. The microchannel plate voltage was 1600V for HR350. It can be seen from the figures that the single photoelectron time spread is a monotonically increasing function of the electroluminescent diode current pulse width. When the current pulse width is considerably shorter than the photomultiplier single electron time spread, the time spread curves show a decreasing dependence upon the current pulse width, particularly for electrostatically focused photomultipliers. Where the diode pulse current width is considerably larger than the single electron time spread, the measured value of the time spread is closely equal the width of the current pulse.

It can be seen from a comparison of the data in Fig. 8 and 9, that the microchannel plate photomultiplier HR350 has a smaller time spread than the contemporary conventionally designed photomultiplier. With a light pulse produced by a 200 psec electrical pulse, the single photoelectron time spread was approximately 250 psec, FWHM, for the HR350. This time spread value includes the measuring system timing error due to the finite width of the light pulse. Assuming a LED light pulse with a 100 psec width, the HR350 time spread has by extrapolation an upper limit value of 200 psec. Furthermore, it can also be seen that the time spread is the same for a 1.6 mm diameter area and the full photocathode illumination, because of the proximity focusing used in the HR350. Conventionally designed electrostatically-focused photomultipliers showed considerable decrease in the amount of the time spread when a smaller area of the photocathode is illuminated because of difference in transit time between the photoelectrons leaving the center of the photocathode and photoelectrons leaving other points of the photocathode. In the case of full photocathode illumination, single photoelectrons can be emitted from any point on the photocathode, thus contributing to the greater single photoelectron time spread. The proximity focusing, used for the input and collector stages in microchannel plate photomultipliers almost completely eliminates this problem.

## Multiphotoelectron Time Response and Resolution

Multiphotoelectron time response of VPM-154A/1.6L was measured at 904 nm using the injection laser light pulse generator shown in Fig. 5A. The photomultiplier was operated with a field electrode voltage of 560V and the photocathode-output collector voltage of 3650V. The time response was measured for full photocathode illumination (5.1mm - diameter area).

The 10-90% rise time and the full width at half maximum of the output pulse were 260 psec and 400 psec, respectively. The results of the measurement are given in Fig. 10. The second small peak of the output pulse time response is due to the operation of the infrared injection laser diode. Similar measurements performed with a mode-locked Nd:YAG laser and a 530 nm frequency doubler gave 230 psec and 360 psec for rise time and pulse width, respectively.<sup>15</sup> For this measurement the laser light was focused onto approximately a 3 mm-diameter area. The output pulse time response is shown in Fig. 11.

The multiphotoelectron time resolution was measured using the system shown in Fig. 2. It is generally agreed that the variance,  $\sigma^2$ , of the 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 photomultipliers. The number of photoelectrons per pulse was calculated by measuring the output pulse width and amplitude and using the known gain of the photomultipliers, for RCA 8850, C31024, LEP HR350 and VPM-154A/1.6L, for full photocathode illumination. Fig. 12 shows the time resolution as a function of the number of photoelectrons per pulse from one photoelectron up to 6000 photoelectrons. The time resolution of single photoelectron pulses was 2.6 nsec, FWHM, indicating the light pulse was very close to 2.6 nsec wide. The time resolution decreases to approximately 36 psec, FWHM, with 6000 photoelectrons per pulse for C31024, HR350, and VPM-154A/1.6L photomultipliers. There is no indication that a plateau of the transit time spread is reached with this number of photoelectrons. Measurement performed on RCA 8850 show that the multiphotoelectron transit time plateau of approximately 80 psec is obtained when the number of photoelectrons is larger than 1000, mostly due to the saturation effect in the photomultiplier.

### Conclusion

Time resolution performance studies of the curved microchannel plate and static crossed-field photomultipliers show that the devices exhibit very good timing capabilities in comparison to the best conventionally designed photomultiplier. The results obtained are shown in Table 1. Single photoelectron and multiphotoelectron time spread measuring values obtained should be considered as upper limits, due to the time resolution capabilities of the measuring system. Generally, for input light pulses shorter than 200 psec, the time spread of microchannel plate and

static crossed field photomultipliers is at least two times lower than for the best conventionally designed photomultipliers. However, for input light pulses longer than 2 nsec, the 5-dynode conventionally designed photomultiplier having dynodes with cesium-activated gallium phosphide secondary emitting surfaces, compares very favorably with microchannel plate and static crossed-field photomultipliers.

### Acknowledgments

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Table 1. Summary of Time Characteristics  
Measurements of Conventionally Designed,  
Microchannel Plate and Static Crossed-Field Photomultipliers  
Full Photocathode Illumination

	RCA 8850	RCA CX1024	LHP HR350	Varian VPM- 154A/1.6L
DC Gain	$>10^8$	$>10^6$	$\approx 10^6$	$2.5 \times 10^5$
Supply Voltage Between Anode and Cathode (V)	3000	4000		
Microchannel Plate Voltage (V)			1600	
Field Electrode Voltage (V)				560
Photocathode-Output Collector Voltage (V)				3650
Electron Transit Time (nsec)	31.2	16.2	$3.4^a$	$8.9^a$
Rise Time (nsec)	2.4	0.8	0.64	$0.26^b$ $0.25^c$
Impulse Response, FWHM, (nsec)	5.0	1.0	1.3	$0.4^b$ $0.3^c$
Single Electron Time Spread, <sup>d</sup> FWHM, (psec)	450	400	<200	Not Available
Multiphotoelectron Time Spread, <sup>e</sup> FWHM, (psec)	$400^f$ $150^g$	$190^f$ $58^g$	$160^f$ $56^g$	$190^f$
Photocathode Diameter (mm)	51	51	13	5.1

<sup>a</sup>These characteristics were measured for prototype packaged photomultipliers.

<sup>b</sup>Measured using a 904 nm gallium arsenide injection laser.

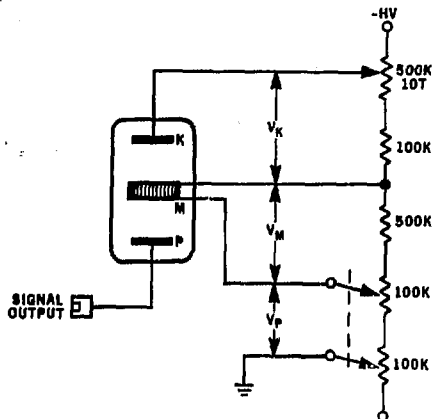
<sup>c</sup>Measured using a mode-locked Nd:YAG laser and a 530 nm frequency doubler.

<sup>d</sup>These values include the measuring system timing error. Measured using 200 psec light pulses.

<sup>e</sup>Measured using 2.6 nsec light pulses with repetition frequency of 60 Hz.

<sup>f</sup>Measured using  $10^2$  photoelectrons per pulse.

<sup>g</sup>Measured using  $10^3$  photoelectrons per pulse.



XBL 7610-4918A

Fig. 1A Schematic arrangement of a microchannel plate photomultiplier.

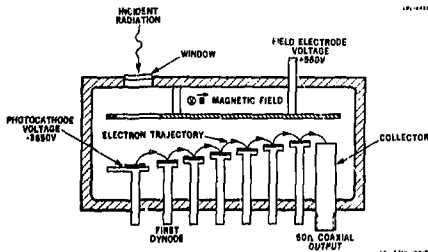
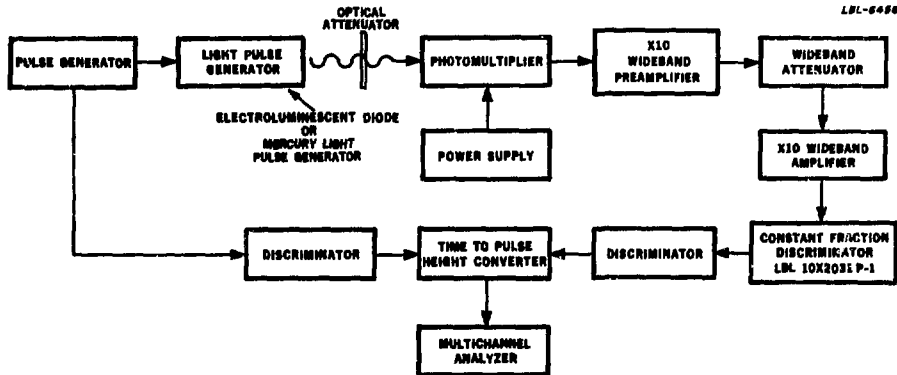


Fig. 1B Schematic arrangement of a static crossed-field photomultiplier.



XBL 7610-4928A

Fig. 2 Block diagram of the system for measuring the single and multiphotoelectron time spread.

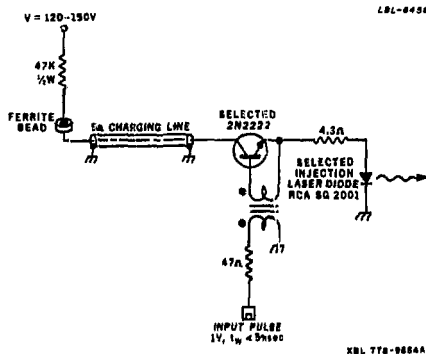


Fig. 3A Schematic diagram of the gallium arsenide injection laser light pulse generator.



Fig. 4 Typical single photoelectron pulses from an RCA 8850 operated at 2500V using a 200 psec impulse excitation from the reversed biased electroluminescent diode, Ferranti Type XP-23.



Fig. 3B Output pulse from an ITT 4014 photodiode using impulse excitation from an RCA SG2001 injection laser.

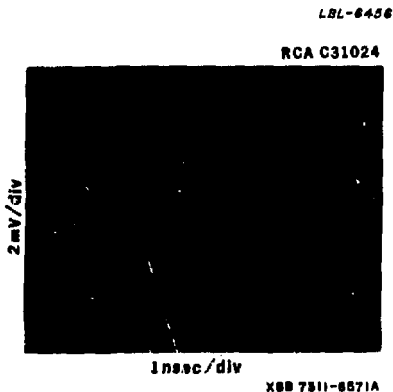
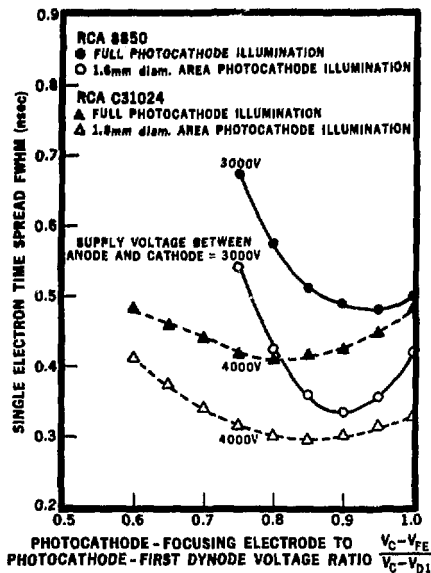


Fig. 5 Single photoelectron pulses from an RCA C31024 operated at 3.5kV using a 200 psec impulse excitation from the electroluminescent diode.



LEP HR350  
SERIAL NUMBER 2

LBL-6456



XBL 7710-10011

Fig. 7 Single electron time spread as a function of the voltage ratio between the photocathode-focusing electrode and photocathode first dynode for the RCA 8850 and C31024 photomultipliers with full photocathode and 1.6 mm-diameter area of photocathode illumination.

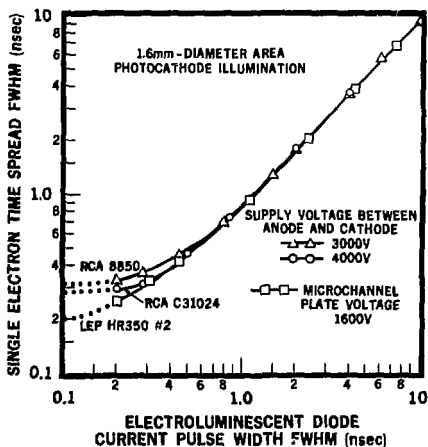
2 mV/div

500psec/div

XBL 789-0217A

Fig. 6 Single photoelectron pulses from an HR350 operated at  $V_M = 1600V$  using a 200 psec impulse excitation from the electroluminescent diode.

LBL-6456



XBL 7710-10012

Fig. 8 Single electron time spread of RCA 8850, C31024 and LEP HR350 as a function of the width of the electroluminescent diode current pulse for 1.6 mm-diameter area of photocathode illumination.

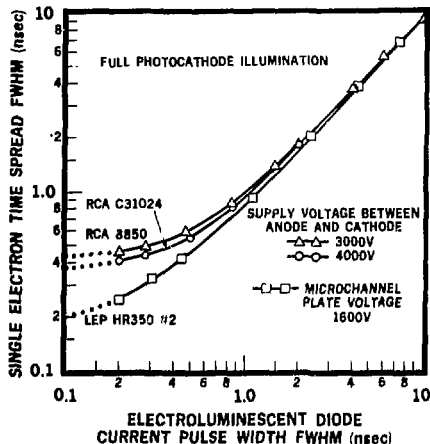


Fig. 9 Single electron time spread for RCA 8850, C31024 and LEP HR350 as a function of the width of the electroluminescent diode current pulse for full photocathode illumination.

LBL-6456

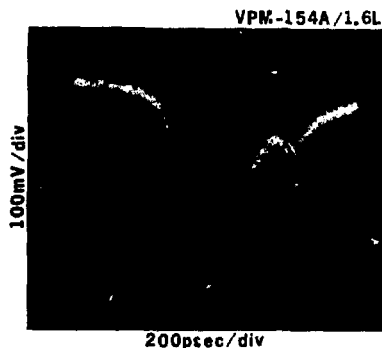


Fig. 10 Output pulse from an VPM-154A/1.6L, operated at the field electrode voltage of 560V, and the photocathode-output collector voltage of 3650V, using inputs excitation from the 904 nm gallium arsenide injection laser, RCA Type SG2001.

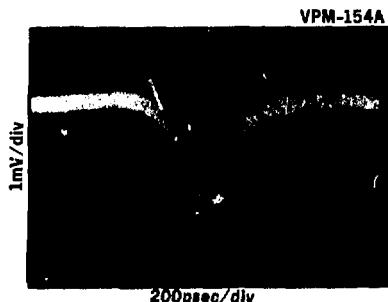


Fig. 11 Output pulse from an VPM-154A/1.6L operated at the field electrode voltage of 600V and the photocathode-output collector voltage of 3300V, and using a 60 psec impulse excitation from the mode-locked Nd/YAG laser and 530 nm frequency doubler.

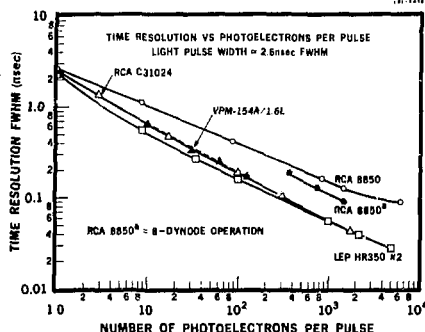


Fig. 12 Time resolution of RCA31024, 8850, VPM-154A/1.6L and LEP HR350 as a function of the number of photoelectrons per pulse, measured with 2.6 nsec light pulse width, for full photocathode illumination.