

# Lawrence Berkeley National Laboratory

## Recent Work

**Title**

RECENT ADVANCES IN HIGH-SPEED PHOTON DETECTORS

**Permalink**

<https://escholarship.org/uc/item/1301156v>

**Author**

Leskovar, B.

**Publication Date**

1983-05-01

2



# Lawrence Berkeley Laboratory

UNIVERSITY OF CALIFORNIA

## Engineering & Technical Services Division

RECEIVED  
LAWRENCE  
BERKELEY LABORATORY

JUL 21 1983

LIBRARY AND  
DOCUMENTS SECTION

To be presented at Laser 83 Opto-Elektronik - 6th International Congress and Trade Fair, Munchen, West Germany, June 27-July 1, 1983

RECENT ADVANCES IN HIGH-SPEED PHOTON DETECTORS

B. Leskovar

May 1983

**TWO-WEEK LOAN COPY**  
*This is a Library Circulating Copy which may be borrowed for two weeks. For a personal retention copy, call Tech. Info. Division, Ext. 6782.*



LBL-15381

2

## **DISCLAIMER**

This document was prepared as an account of work sponsored by the United States Government. While this document is believed to contain correct information, neither the United States Government nor any agency thereof, nor the Regents of the University of California, nor any of their employees, makes any warranty, express or implied, or assumes any legal responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by its trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof, or the Regents of the University of California. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof or the Regents of the University of California.

Presented at the 6th International Congress  
Laser 83-Opto-Electronics, Munich, West Germany  
June 27-July 1, 1983

RECENT ADVANCES IN HIGH-SPEED PHOTON DETECTORS

Branko Leskovar

December 9, 1982

Prepared for the U. S. Department of Energy  
Under Contract DE-AC03-76SF00098

BRANKO LESKOVAR  
Lawrence Berkeley Laboratory  
University of California  
Berkeley, California 94720, USA

Recent progress of some fast high-gain photon detectors using photoemission and secondary emission processes is reviewed and summarized. Specifically, performance characteristics are presented, of the new Amperex XP 2020, RCA 8854, and Hamamatsu R 647-01 conventionally design photomultipliers. Also, characteristics are presented of the ITT F 4129 and Hamamatsu R 1564U extended lifetime microchannel plate photomultipliers as well as certain special made photomultipliers intended for application in positron emission tomography, high energy physics and plasma diagnostic experimental systems. Finally, microchannel plates as photon detectors for ultra violet and x-ray wavelengths are discussed.

### Introduction

Fast high-gain standard and microchannel plate photomultipliers, are among the fastest and most sensitive devices for detecting the incidence of photons on a target surface. These devices have gained wide acceptance in research instrumentation, particularly in radiation detection (1), atomic and molecular subnanosecond fluorescence decay studies, (2), optical ranging experiments (3), optical communication systems (4), and plasma diagnostics (5). The detection of signals in practical systems in these areas, requires photon detectors with high quantum efficiency, high gain, fast time response and high data-rate capabilities. They should also have good output pulse-height and time resolution. In many cases large sensitive areas are required. Also, position-sensitive detection or imaging of incident radiation patterns is sometimes necessary. In practically all these applications a minimum amount of noise or spurious signal should be present in the detector output.

For more than fifty years research applications have used the phenomenon of photoemission to convert absorbed incident radiation into an electron stream which is then amplified by a secondary emission system. The detection process begins with a cathode from which the incident radiation exits the emission of photoelectrons. The emitted electrons are directed to a surface which has been treated to have high secondary electron emission. The secondary electrons produced by this first dynode are then directed to another secondary emitter. The process is repeated for as many times as are required to amplify the initial electron stream by the desired amount, after which it is collected by an anode. Finally, the output current from the electron multiplier feeds external circuitry to provide the output signal. Statistical variations inherent in the excitation of photoelectrons by the incident photons and the statistical nature of the secondary emission process cause the output signal to vary from one pulse to the next, even with a constant number of incident photons. The resulting distribution in output pulse-height limits both the pulse-height and time resolution of the detector.

Previous studies have shown that photomultipliers with dynodes having cesium-activated gallium phosphide secondary emitting surfaces exhibit better pulse-height and time resolution capabilities than photomultipliers employing conventionally activated dynodes (6-7). Also in previous papers it has been shown that microchannel plate high-gain photomultipliers exhibit significantly better time resolution than conventional electrostatically focused photomultipliers (8-13).

Furthermore, it has recently been shown that new high-gain photon detectors employing microchannel plates in cascade for electron multiplication will, under optimized operating conditions, exhibit the highest pulse-height resolution ever obtained (14).

Based on the above mentioned work, further effort has been made to investigate and review the time and pulse-height resolution of some new generation commercially available photomultipliers.

The measurements of the characteristics of these photomultipliers were made with a measuring system which has previously been described in Reference 16. The system has a time resolution of approximately 25 ps, FWHM.

Specifically, performance characteristics have been studied of the new Amperex XP 2020, RCA 8854 and Hamamatsu R 647-01 photomultipliers which use conventional multiplier structures. Furthermore, the characteristics have been investigated of a new generation of ITT F 4129 and Hamamatsu R 1564U extended life microchannel plate photomultipliers. Finally, characteristics have been reviewed of special made photomultipliers to be used in positron emission tomography, high energy physics and plasma diagnostics experimental systems.

The electrostatically focused Amperex XP 2020 photomultiplier uses a 12 stage discrete dynode structure with a semi-transparent bialkali (S24) photocathode having a useful diameter of 45 mm. Its peak spectral response is at 400 nm with a quantum efficiency of 26%. The photomultiplier has copper berillium dynodes instead of AgMgOC<sub>5</sub> dynodes which were used previously in a similar device. The tube design is optimized to have a small single electron time spread and for high repetition rates in counting operations.

The RCA 8854 photomultiplier is a variant of the RCA 4522. It has a high gain GaP (C<sub>5</sub>) first dynode followed by thirteen BeO dynodes. The new RCA designation for the photocathode is 35 ET (formerly 118), which has a peak response at 400 nm and a quantum efficiency of 27%. Its spectral response extends from 200 nm to 600 nm. The maximum useful photocathode diameter is 114 mm. This photomultiplier is designed for experimental research instrumentation where good pulse-height resolution and large photocathode areas are important.

The Hamamatsu R 647-01 is a 13 mm-diameter, 10 stage, head on, flat face plate type photomultiplier with a bialkali photocathode having an S-11 response. The photocathode has its peak response at 420 nm and a useful diameter of 9 mm. Because of its small size, the photomultiplier is particularly suitable for high spatial resolution positron emission tomography, and also for high energy physics and nuclear chemistry experimental systems. The electron multiplier utilizes a box type structure and grid dynodes.

The new ITT F 4129 photomultiplier has an S-20 photocathode with a maximum usable diameter of 18 mm and three microchannel plates in cascade for the electron multiplication. The plates are in a Z-configuration to reduce the positive ion feedback. The three plates are identical, having 12 μm diameter channels with length to diameter ratios of 40. Proximity focusing is used for the input and collector stages. In ITT F 4129f device a protective film is provided between the photocathode and the microchannel plate which leads to a significant improvement in quantum efficiency, stability and life expectancy as well as in the total elimination of the afterpulses.

The Hamamatsu R 1564U photomultiplier has a bialkali photocathode with a usable diameter of 18 mm, and two microchannel plates in cascade for electron multiplication. The anode is matched to a 50 Ohm connector. The entrance part of the first microchannel plate is covered with a thin aluminum film to prevent the bombardment of the photocathode by positive ions. As in the ITT photomultiplier this results in a significant increase in photocathode life, and stability of quantum efficiency.

The life of a microchannel plate photomultiplier without protective film is determined by a decrease in the photocathode quantum efficiency because of photocathode positive ion bombardment. The second determining factor is change in the channel wall secondary emission coefficient due to electron scrubbing, especially in high gain region of a channel. This is not effected by the protective film. The life of a device is defined as a total charge density accumulated at the anode at which device losses 50% of its overall responsivity.

## Results and Discussions

The results of the measurements of characteristics of the Amperex XP 2020, RCA 8854, Hamamatsu R 647-01, R 1564U and ITT F 4129 photomultipliers are summarized in Table 1. Also, some of the results are presented in Figs. 1-4.

With full photocathode illumination, and with a light pulse produced by a 200 ps electrical pulse, the rise time, impulse response (FWHM), and single photoelectron time spread (FWHM), were 1.5 ns, 2.4 ns, and 0.51 ns, respectively for the XP 2020, (16). Figure 1 shows two single photoelectron time spectra spaced 4 ns apart. Measurement of the dark pulse spectrum showed that the photomultiplier pulse-height resolution is not good enough to show the one, two and three photoelectron peaks. This is typical for all conventionally designed photomultipliers using the first dynode with low gain. The high frequency counting measurements show that the XP 2020 can be operated at a higher pulse repetition rate than 55 MHz (the voltage divider must be capable of providing the current needed for its operation). Figure 2 shows, the anode output pulses at repetition rate of 55 MHz. The upper trace is the anode output pulse, the lower trace is the driving electrical pulse. The light source was a light emitting diode, type XP 21, driven by pulses having a width of 3 ns and approximately 10 V amplitude. The diode was operated in an avalanche mode.

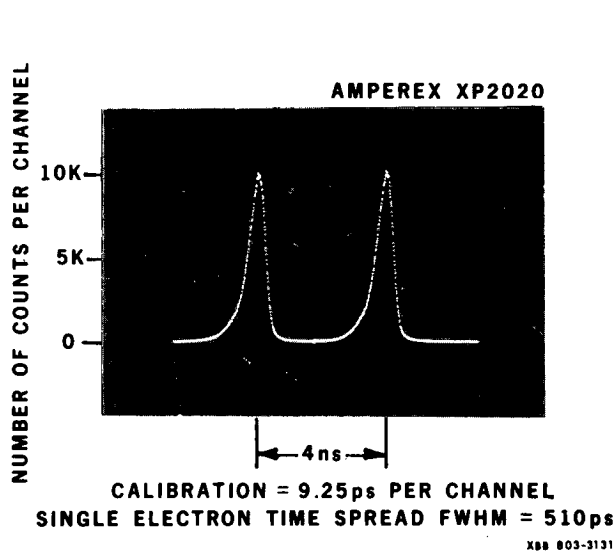


Fig. 1 Single photoelectron time spread of the XP 2020 photomultiplier with full photocathode illumination.

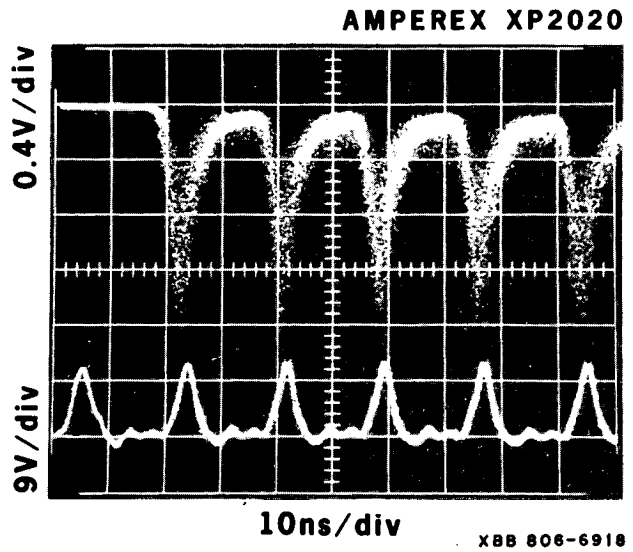


Fig. 2 Anode output pulses (upper trace) of XP 2020 photomultiplier using input pulse repetition frequency of 55 MHz with 2% duty cycle.

The rise time, impulse response, and single photoelectron time spread, for the large photocathode area 8854 photomultiplier were 3.2 ns, 4 ns and 1.55 ns, respectively. This device utilizes a negative-electron-affinity GaP(C<sub>5</sub>) secondary emission surface on the first dynode of the electron multiplier resulting in a high pulse-height resolution (17). Figure 3 shows the photomultiplier pulse-height spectrum indicating the peak to valley ratio of 1.9:1. With this high resolution of the single and multiphotoelectron peaks an effective separation of spurious single photoelectron peaks (thermionic electrons and others) and the desired multiphotoelectron peaks can be achieved. The 8854 has shown resolution of three distinct photoelectron peaks.

The rise time, impulse response, and single photoelectron time spread, for the very small photocathode area R 647-01 photomultiplier were 2 ns, 3.5 ns, and 1.2 ns respectively, (18). The device is particularly suitable for application in positron emission tomography systems where high spatial resolution is required. Also, the device is well suited for some of the more recently developed systems where time-of-flight information of the positron annihilation  $\gamma$ -rays are used in combination with conventional projection data to improve the signal-to-noise ratio for image reconstruction.

The F 4129 microchannel plate photomultiplier has a rise time, impulse response and single photoelectron time spread of 0.35 ns, 0.52 ns, and 0.2 ns, respectively. The

device exhibits excellent timing capabilities and is very much less sensitive to ambient magnetic fields than the best conventionally designed photomultipliers, (7,20). This is mostly due to the small thickness of microchannel plates (approximately 2 mm), very strong applied electric field (5-10 kV/cm) and proximity focusing used between the photocathode and microchannel plate. Measurements have also shown that the photomultiplier operating characteristics can be optimized to yield a peak-to-valley ratio of 2.47:1. Figure 4 shows a typical single photoelectron pulse shape from the device.

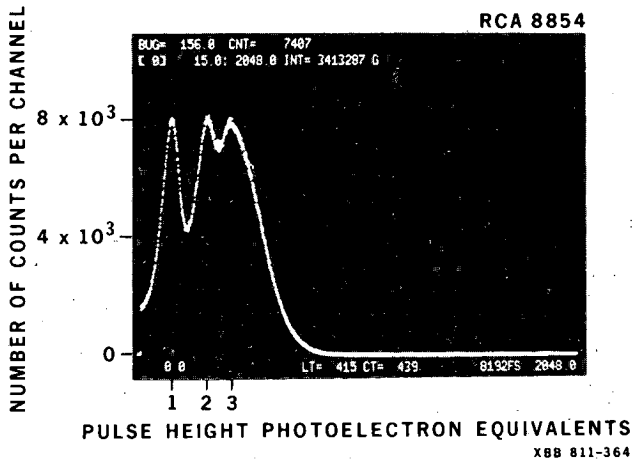


Fig. 3 Typical pulse-height resolution of the 8854 photomultiplier.

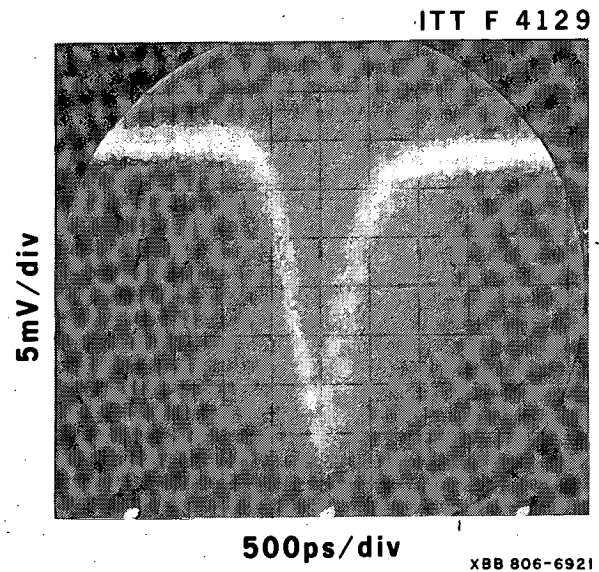


Fig. 4 Typical single photoelectron pulses from the F 4129 operated at  $V_M = 2400$  V, using 200 ps light impulse excitation.

The life of the new generation F 4159f device with a 7 nm thick ion barrier film is significantly increased when compared with the life of the F 4159, (19).

The rise time, impulse response, and single photoelectron time spread for R 1564U microchannel plate photomultiplier were approximately 0.27 ns, 0.58 ns, and 0.09 ns, respectively, (21).

Because of a thin Al film (thickness of approximately 13 nm) which covers the front surface of the first microchannel plate, the device has exhibited a significant increase in life and stability of quantum efficiency of the photocathode as compared to devices without the Al film. Measurements showed that devices without the Al film exhibit a half gain degradation after a total output charge of  $10^{-3}$  C/cm<sup>2</sup>, (22). The photomultiplier with Al film showed a constant gain up to an accumulated output charge of  $10^{-2}$  C/cm<sup>2</sup> which results from the gain degradation of the plate itself.

In addition to the above mentioned commercially available photomultipliers, there are a number of special made devices developed for particular applications. The Hamamatsu R 1548 is a dual rectangular photomultiplier with a bialkali photocathode having its maximum response at 420 nm, (23). Maximum useful area of the photocathode is (10 mm x 20 mm) for each of the two channels. The anode pulse rise time and single photoelectron time spread are approximately 1.8 ns and 1.0 ns, respectively. The device has a gain of  $2 \times 10^6$ . It was developed for positron emission tomography. The Hamamatsu R 1449 has 508 mm diameter quasi-hemispherical glass window with bialkali photocathode having its peak response at 420 nm and has a gain of  $10^7$  at 2000 V applied voltage. The anode pulse rise time, impulse response, and single photoelectron time spread are 18 ns, 30 ns and 7 ns, respectively, (22). The photomultiplier was developed for high energy physics experiments such as proton decay studies.



Several developments in high-speed photon detectors have been made for plasma diagnostic, (5), where excellent impulse response properties and high linearity of output current are important. One of the latest of these is the ITT MCP-1 microchannel plate photomultiplier, (24). The device consists of a semitransparent multialkali photocathode, microchannel plate and tapered coaxial 50 Ohm anode. The anode is mated to a special vacuum feedthrough made by EG&G. The device has an accelerating screen between the microchannel plate and anode to improve the time response by isolating the plate from the anode. If the screen is held at ground potential, the anode signal does not start to rise until the electron burst passes the screen. The gain of this multiplier is approximately  $10^4$ . Its impulse response measured with 810 nm laser pulser is shown in Fig. 5. Output pulse rise time and impulse response were 273 ps and 248 ps, respectively.

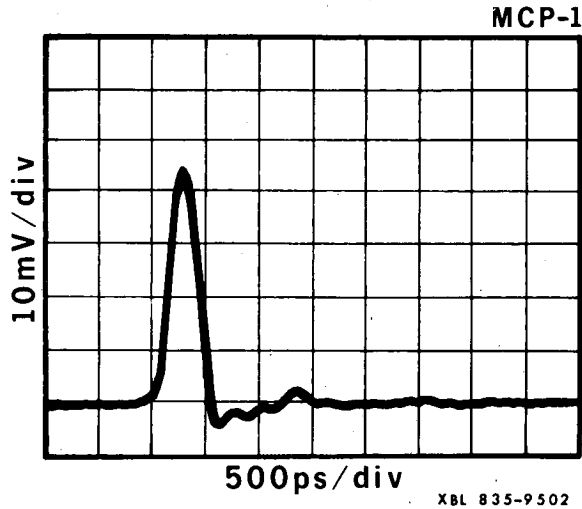


Fig. 5. Impulse response of MCP-1 microchannel plate photomultiplier operated with accelerating voltage of 1 kV.

Microchannel plates can operate efficiently as photon detectors in the extreme ultra violet and x-ray wavelengths in windowless configuration. The quantum efficiency of the plate itself, in which the lead glass and electrode surfaces prepared by the manufacturer act as photocathode, lies in a 1-10% range for most x-ray wavelengths as shown in Fig. 6. The standard means of enhancing these values is to deposit a material of relatively high photoelectric yield on the plate surface and channel walls. Lithium fluoride, magnesium fluoride and cesium iodite have been used for this purpose, (25). An increase of 65% in the quantum efficiency for 1.98 keV photons can be obtained using a Mg F<sub>2</sub> coated plate.

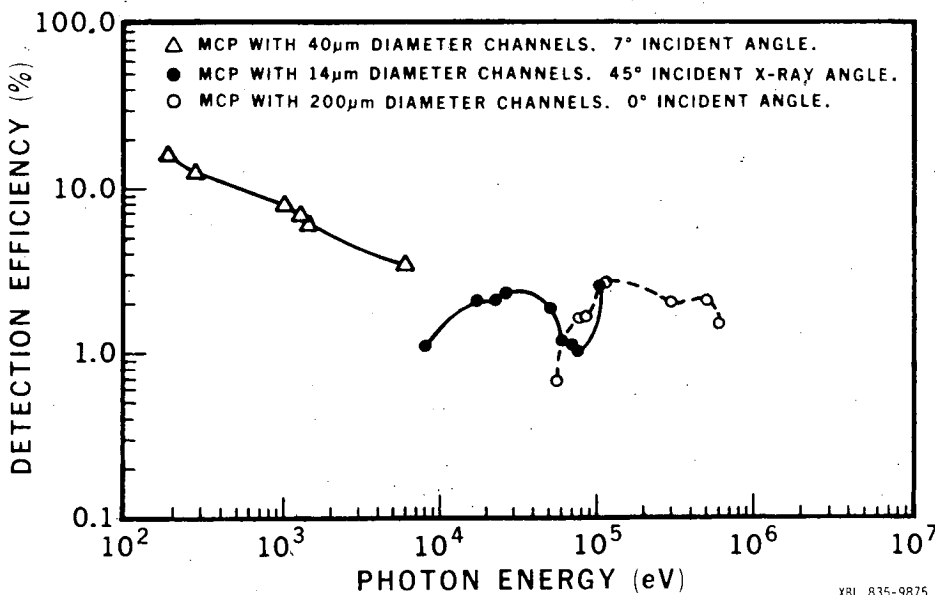


Fig. 6 X-Ray detection efficiencies.

## Acknowledgments

This work was performed as part of the program of the Electronics Research and Development Group of the Lawrence Berkeley Laboratory, University of California, Berkeley and was partially supported by the Director's Office of Energy Research, Office of Health and Environmental Research, U.S. Department of Energy under Contract DE-AC03-76SF00098.

## References

1. G.F. Knoll, Radiation Detection and Measurement, John Wiley & Sons, New York (1979).
2. B. Leskovar, C.C. Lo, P.R. Hartig, K.H. Sauer, Rev. of Sci. Instr. 47, No. 9, 1113-1121 (1976).
3. W.J. Carrion, Proc. of the Society of Photo-Optical Instrumentation Engineers, 134, 151-154, March 1978, Fort Walton Beach, Florida.
4. R.M. Gagliardi, S. Karp, Optical Communications, John Wiley & Sons, New York (1976).
5. P.R. Lyons, L.D. Looney, J. Ogle, R.D. Simmons, R. Selk, B. Hopkins, L. Hocker, M. Nelson, P. Zagarino, Proceedings of the Los Alamos Conference in Optics, Santa Fe, New Mexico, April 7-10, 1981, SPIE, 288, 404-411 (1981).
6. B. Leskovar and C.C. Lo, IEEE Trans. Nucl. Sci., NS-19, No. 3, 50-62 (1972).
7. C.C. Lo and B. Leskovar, IEEE Trans. Nucl. Sci., NS-28, No. 1, 698-704 (1981).
8. B. Leskovar and C.C. Lo, Nucl. Instr. and Methods, 123, No. 1, 145-160 (1975).
9. B. Leskovar, Nucl. Instr. and Methods, 128, 115-119 (1975).
10. B. Leskovar, Physics Today, 30, (11), 42-49 (1977).
11. B. Leskovar and C.C. Lo, IEEE Trans. Nucl. Sci. NS-25, No. 1, 582-590 (1978).
12. B. Leskovar, and C.C. Lo, IEEE Trans. Nucl. Sci., NS-26, No. 1, 388-394 (1979).
13. B. Leskovar, Proc., of the 4th Intl. Congress - Laser '79 Opto-Electronics, Munich, West Germany, 581-586. Published by IPC Science and Technology Press Ltd., England (1979).
14. B. Leskovar, Proc. of the 5th Intl. Congress, Laser 81 - Optoelectronics, Munich West Germany, June 1981. Published by Springer-Verlag, Vol.: Optoelectronics in Engineering, 381-386 (1982).
15. C.C. Lo, P. Lecomte and B. Leskovar, IEEE Trans. Nucl. Sci., NS-24, No. 1, 302-311 (1977).
16. C.C. Lo and B. Leskovar, IEEE Trans. Nucl. Sci., NS-28, No. 1, 659-665 (1981).
17. C.C. Lo and B. Leskovar, IEEE Trans. Nucl. Sci., NS-29, 1, 184-190 (1982).
18. C.C. Lo and B. Leskovar, Performance Studies of Hamamatsu R 647-01 Photomultiplier, Lawrence Berkeley Laboratory Report, LBL-15494, December 15, (1982).
19. The F 4126, F 4128, F 4129 Series of Photomultipliers Incorporating Microchannel Plate, Electro-Optical Product Division of ITT Corp. Fort Wayne, Indiana (1980).
20. D.H. Ceckowski, E. Eberhard, and E. Carney, IEEE Trans Nucl. Sci., NS-28, 677-682 (1981).
21. The Microchannel Plate Photomultipliers Tubes (MCP-PMTs), Hamamatsu TV Co., Ltd., Hamamatsu, Japan (1982).
22. T. Hayashi, Nucl. Instr. and Methods, 196, No. 1, 181-186 (1982).
23. T. Yamashita, M. Ito and T. Hayashi, Proceedings of the International Workshop on Physics and Engineering in Medical Imaging, 209-211 (1982).
24. D.F. Simmons, B.A. Smith, and P.B. Lyons, Development of High-Speed Microchannel Photomultiplier, Los Alamos National Laboratory Report. Presented at the LANL Conference on Optics, April 11-15, 1983.
25. K.W. Dolan, J. Chang, Proc. SPIE. 106, 178 (1977).

Table 1. Summary of Characteristics Measurements of Some New Generation Conventionally Designed and Microchannel Plate Photomultipliers. Full Photocathode Illumination.

	Amperex XP 2020	RCA 8854	Hamamatsu R 647-01	ITT F 4129	Hamamatsu R 1564U
DC Gain	$>3 \times 10^7$	$3.5 \times 10^8$	$>10^6$	$1.6 \times 10^6$	$5 \times 10^5$
Supply Voltage Between Anode and Cathode (V)	2200	2500	1000		3400
Microchannel Plate Voltage (V)				2500	
Rise Time (ns)	1.5	3.2	2	0.35 <sup>a</sup>	0.27
Electron Transit Time (ns)	28	70	31.5	2.5 <sup>a</sup>	0.58
Impulse Response, FWHM, (ns)	2.4	4.0	3.5	0.52 <sup>a</sup>	
Single Photoelectron Time Spread, FWHM, (ns)	0.51	1.55	1.2	$<0.20^a$	0.09
Multiphotoelectron Time Spread, FWHM, (ns)	0.12 <sup>b</sup>		0.40 <sup>c</sup>	0.10 <sup>d</sup>	
Peak-to-Valley Ratio of Pulse-Height Spectrum with Optimized Operating Conditions		1.9:1		2.47:1 <sup>e</sup>	
Dark Pulse Count <sup>f</sup> (cps)	450	155	54	1800	
Quantum Efficiency <sup>g</sup> %	26	27	28	20	15
Photocathode Diameter (mm)	44	114	9	18	18

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

<sup>b</sup> Measured using 2500 photoelectrons per pulse.

<sup>c</sup> Measured using 100 photoelectrons per pulse.

<sup>d</sup> Measured using 800 photoelectrons per pulse.

<sup>e</sup> Optimized operating condition for F 4129 was  $V_M = 2710V$ . In this case the photomultiplier gain was  $6.6 \times 10^7$ .

<sup>f</sup> Dark pulse summation is defined by:  $\sum_{1/8 \text{ photoelectron}}^{16 \text{ photoelectrons}} = \text{counts per second.}$

<sup>g</sup> Quantum efficiency values for proximity focused microchannel plate photomultiplier decrease significantly during operating time for devices without protective ion barrier film between the photocathode and the input of the microchannel plate. Table shows quantum efficiency initial values.

This report was done with support from the Department of Energy. Any conclusions or opinions expressed in this report represent solely those of the author(s) and not necessarily those of The Regents of the University of California, the Lawrence Berkeley Laboratory or the Department of Energy.

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 others that may be suitable.

TECHNICAL INFORMATION DEPARTMENT  
LAWRENCE BERKELEY LABORATORY  
UNIVERSITY OF CALIFORNIA  
BERKELEY, CALIFORNIA 94720