

Microchannel plates

Sophisticated fabrication techniques have made it possible to create these new detectors for photons—and other radiations—with good time resolution and low noise, and with special advantages for imaging.

Branko Leskovar

For more than forty years researchers have applied the phenomenon of photoemission to convert absorbed incident radiation into an electron stream, which is then amplified by a secondary-emission process. The resulting fast high-gain photon detectors, such as photomultipliers and electron multipliers, are among the fastest and most sensitive devices for recording the collision of a photon (or electron, atom or energetic ion) with a target surface. These detectors have gained wide acceptance in research instrumentation, particularly in mass spectroscopy¹ and scintillation spectroscopy,² as well as in optical ranging³ and optical communication systems.⁴ Recently a new—faster, less noisy and more efficient—type of radiation detector has been developed, consisting of a plate traversed by a large number of microscopic channels that serve as electron multipliers.^{5,6}

This article reviews the basic characteristics of such detectors, which use microchannel plates not only for electron multiplication but also for the direct detection of incoming radiation. Microchannel plate detectors can be used to detect a wide range of photon energies—ranging from soft x rays and extreme-ultraviolet rays, through the near ultraviolet, to the visible and near-infrared regions of the electromagnetic spectrum.

The detection process

Detection of signals in experimental research instrumentation systems requires photon detectors with high quantum efficiency, high gain, fast time re-

sponse and high data-rate capabilities. They should also have good output pulse height and time resolution, and low noise (or spurious signal effects). Many cases require large detector areas; position-sensitive detection or imaging of the incident radiation pattern is also sometimes necessary. Newly emerging fields of optical ranging and communications require photon detectors that combine bandwidths greater than 1 GHz with high sensitivity to light input signals. In practically all these applications a minimum amount of noise should be added by the detection and amplification processes.

The detection process generally begins at a cathode, where the incident radiation produces photoelectrons. The emitted electrons are then directed to a surface that has been treated to emit a large number of secondary electrons. The secondary electrons from this first dynode are then directed to another secondary-emission surface, and the process is repeated as many times as needed to amplify the initial electron stream by the desired amount. The output current from the electron multiplier then feeds an external circuit to provide the output signal. Both statistical variations inherent in conversion of incident photons to photoelectrons 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 (or other primary particles). The resulting distribution in the amplitude of the output pulse places a limit on both the pulse height and the time resolution of the detector.

For this reason the recent development of a microchannel plate containing many single-channel multipliers offers a unique possibility: that of combining image in-

tensification with a high time-resolution capability and inherently low noise, all in one device. The microchannel plate therefore possesses a major advantage over the conventional discrete-dynode electron multiplier, particularly for position-sensitive and high-time-resolution detection and imaging systems.

What is a microchannel plate?

A microchannel plate consists of a two-dimensional array of thousands—or even millions—of short single-channel electron multipliers of very small diameter, closely packed parallel to each other.^{5,6} Figure 1, left, shows the configuration of a typical plate. Each electron-multiplying channel is a continuous glass tube coated on its inside surface with a high-resistance semiconductor that serves as an emitter of secondary electrons. The array of glass microchannels is connected electrically in parallel by metal electrodes on opposite faces of the plate, which is operated in high vacuum with about 1000 V applied between the two faces. The semiconducting coating inside each microchannel provides a continuous potential gradient along its length. The right-hand side of figure 1 shows a cross section of a microchannel, with typical electron trajectories.

In operation, incident radiation at the input end of the microchannel ejects electrons from the surface; these are accelerated down the channel toward the positive end and collide with the wall of the channel many times while passing down the channel. The potential gradient and channel diameter are adjusted so that, on the average, substantially more than one secondary electron is released at each collision. The voltage along the microchannel must be sufficient to accelerate the secondary electrons through 20–50 V between collisions with the wall.

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A large pulse of output electrons is ejected from the positive end of the microchannel into a collector structure containing an electrode that is positively biased with respect to the channel-plate output potential to give maximum collection efficiency. Depending on the application, the amplified electron output from the plate may be collected by a single or a multisegment anode, or by a phosphor screen.

The output current of the microchannel plate must be supplied from the conduction current in the channel walls. These therefore must combine the functions both of the dynodes and of the resistance-divider chain in the classical multistage electron multiplier.

The microchannels typically have diameters ranging from 15 to 50 microns and are spaced by distances ranging from

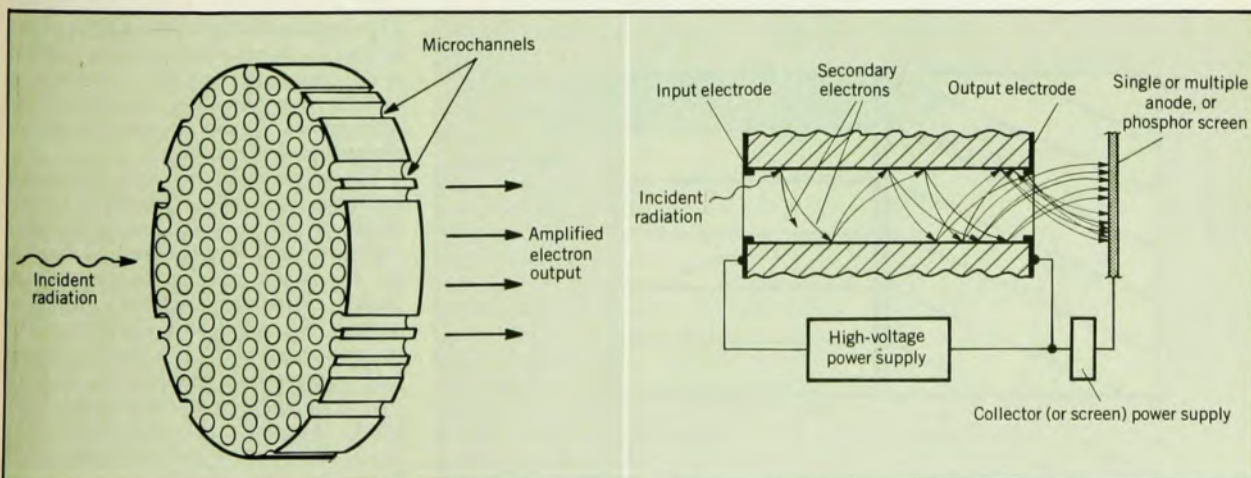
20 to 60 microns. The channels are 0.5 to 2.0 mm long. Typically, a potential difference of 1000 V across the microchannel plate will produce gains of 10^3 – 10^4 for straight microchannels with a length-to-diameter ratio of 40. Because of the small channel size and high voltage, the total electron transit time is much shorter than for a conventional electron multiplier with the same gain.

The fact that the microchannels operate independently and gain is available at each microchannel location in the array makes the microchannel plate well suited for a number of applications in which the incident radiation pattern must be preserved during amplification. The plate can resolve simultaneous events that are spatially separated by distances on the order of the channel size. In such cases the amplified electron output is collected

from the channel plate by a multisegment anode or a phosphor screen, appropriately biased with respect to the output of microchannel plate.

The ion-feedback problem

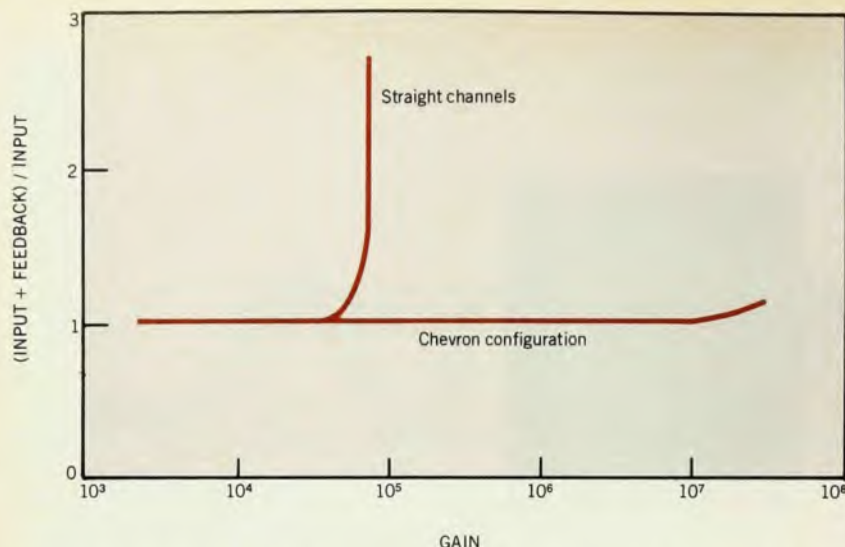
For the straight channels discussed so far, the gain of the microchannel-plate electron multiplier is limited to approximately 10^4 . Although this gain is adequate for some imaging applications it is not enough for high-gain electron multipliers. The major reason for this gain limitation is positive-ion feedback. The cause of this is the ionization by electrons at the output ends of the channels, of residual gas atoms inside the microchannels and the ejection of atoms absorbed on the channel walls. The positive ions thereby produced are accelerated to the input end of the channels, where they may collide



An array of microscopic electron multipliers, the microchannel plate (left) is a versatile detector of photons and other particles. Radiation entering a microchannel (right) ejects electrons from the semiconductor surface. The high voltage (typically 1000 volts) applied across the plate

faces accelerates the electrons so that, when they strike the channel walls, secondary electrons are emitted. The electron stream resulting from many such collisions may feed an external circuit or create a visible image on a phosphor screen.

Figure 1



Positive-ion feedback in a plate with straight channels increases sharply for gains in the 10^4 – 10^5 range, producing noise. With two microchannel plates in the "chevron" configuration shown in figure 3, gains to 10^7 add no observable feedback noise.

Figure 2

with the channel wall with sufficient energy to eject a secondary electron. They also may escape from the channel, possibly damaging the photocathode. In either case afterpulses will be initiated, causing noise at the channel output.

Positive-ion feedback noise depends on the gain, on the pressure and nature of any residual gas, and on the surface properties of the channel wall. The operation of single plates with gains in the range 10^4 – 10^5 produces positive-ion feedback, as shown in figure 2; this causes a very noisy amplification.

Ion-feedback noise can be reduced considerably by using two microchannel plates in a so-called "chevron" configuration, which is diagrammed in figure 3. This is formed by assembling two micro-

channel plates about 2 mm thick, in close proximity. The plates are separated from each other by a thin stainless-steel ring, which also serves as an electrical contact. The first (input) microchannel plate is fabricated so that its channels are at a slight angle to those of the second (output) plate. It can be seen from figure 3 that no straight path exists for either electrons or ions. While this does not significantly inhibit the passage of secondary electrons, the angle of the channels is such that the positive ions, with low initial energy, travel only a short distance before striking a channel wall. As a result they do not have enough energy to produce a significant number of secondary electrons. With this configuration gains of 10^7 or more can be achieved with no

observable noise due to ion feedback.

Positive-ion feedback can also be inhibited by curving the microchannels. The first practical plates of this type were made at the Laboratoires d'Electronique et de Physique Appliquée, and reports of preliminary results have already appeared.^{8,9} Plates with curved microchannels have demonstrated superior performance over those with straight channels. They have higher gain, lower statistical fluctuations of gain and diminished background noise. However, additional improvements are necessary, particularly with respect to charge-saturation effects. Successful high-gain microchannel plate multipliers have also been made with three plates at different orientations, in a so-called "Z configuration."¹⁰ This configuration exhibits a gain value larger than 10^6 without positive-ion feedback.

Most of the plates manufactured recently with the Z configuration use channels at a bias angle of 5° – 8° with respect to the normals of the plate surfaces. This reduces ion feedback, increases the probability of impact of the incoming radiation with the channel surface and reduces direct light feedback from any output phosphor screen in imaging applications.

Fabrication

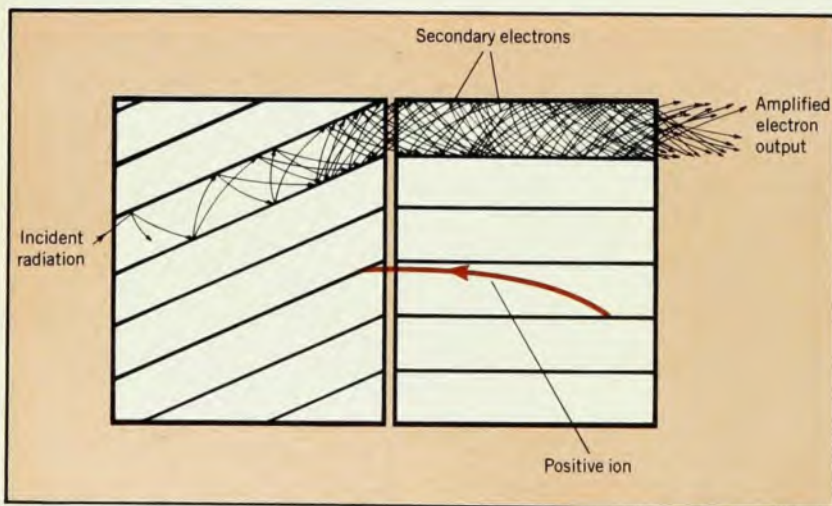
Basically two techniques are used for manufacturing microchannel plates:

► The first uses a core that is water-soluble or etchable, surrounded by a thin-walled cylinder made of glass containing lead oxide. The glass cylinder later becomes the electrical and mechanical structure of the microchannel plate.

The glass-clad core is drawn to a small diameter, and many of these rods are fused together into a bundle. In a second drawing operation the diameter of the bundle is reduced to the required size. The small-diameter bundles are again fused together into a larger final bundle. This bundle is sliced into wafers of the desired thickness, which are then polished to the desired dimensions. Dissolving or etching away the cores to open the microchannels finally forms the microchannel plate structure.

This structure is then heat treated in a hydrogen atmosphere to produce a semi-conductive layer, which has a secondary-emission coefficient between 1.1 and 3.5, on the walls of the microchannels. Nickel-chromium electrodes are then vacuum-deposited on both faces of the microchannel plate; it is finally cleaned and outgassed by baking for approximately 10 hours at a temperature of 300 deg C. Microchannel plates produced by this technique have ratios of open area to total plate area near 60%.

► The second fabrication technique is similar, except that each microchannel wall is constructed from three different glass layers. The inner surface layer is



To reduce feedback due to the ejection of positive ions—which are then accelerated, producing secondary electrons—two microchannel plates are joined together with their channels at a small angle. This decreases the distance over which the ions are accelerated, so that their energy is insufficient to eject more than an insignificant number of electrons.

Figure 3

semiconducting, and this determines the secondary-emission properties of the channel. The next layer provides the structure of each microchannel and comprises most of the volume of the plate. The third layer, consisting of a glass with low viscosity at the forming temperatures, fuses the microchannels together during the manufacturing process. The three-layer glass plates have ratios of open to total area near 55%.

Gain and saturation

Typical gain-voltage characteristics of single microchannel plates with straight and curved channels, and of two-channel chevron plates are shown in figure 4. The characteristics are given for an input signal with a current density of 10^{-12} A/cm² and an electron energy of 300 eV, for both the straight-channel and chevron plate. Both types of plates have a total standing current along the channel walls of 0.8 microamp. The straight-channel plate has an input bias angle of 5°. The (front-back) bias angle for the chevron plate is 15°. This figure also gives the gain characteristic of a plate with curved channels, with an input bias angle of 25° and an output angle of 2°.

Figure 4 indicates that the electron gain of the microchannel plate is determined by both the applied voltage and the length-to-diameter ratio, L/d , of microchannels used in a particular plate. Above a certain value of the plate gain, the ion feedback in a straight-channel plate becomes sufficient to cause saturation. Ion feedback leads to repetitive electron avalanches, which saturate the channel and cause field distortion due to wall charging. Both effects lead to temporary loss of gain at the plate output. As we might expect, the curved-channel plate can be operated at a much higher gain before ion feedback causes gain saturation.

Depending upon the mode of operation of the microchannel plate, gain saturation may be caused by saturation of the output current due to the finite conductivity of the glass, or by charge saturation due to the positive charging of the walls. The saturation effect can be seen in the current-transfer characteristics of the microchannel plate, shown in figure 5.

In applications with continuous (dc) input, such as image intensifiers, a limit to the available output current from a channel is set by the current flowing in the channel wall. Because the wall resistance is high (10^8 – 10^{11} ohms), the current available is very limited. As the space current increases toward the output end, the depleted wall current reduces the field in the channel, thereby dropping the secondary-emission ratio and lowering the gain. The plate output current deviates appreciably from linearity when it approaches within about 5–10% of the total plate dc current, which is typically about 10^{-11} A per channel. (This guide is valid

only for continuous input and reasonably uniform illumination.)

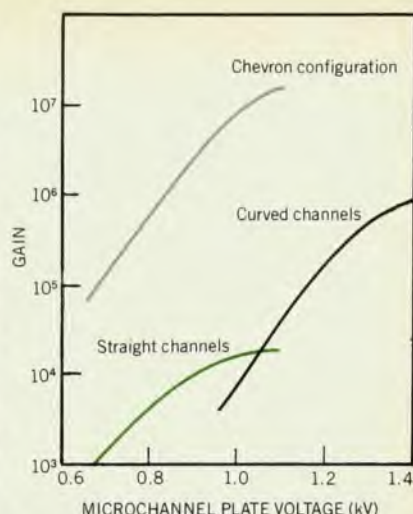
For pulse excitation, such as is encountered in particle-detector applications, the ejected secondary electrons leave behind them positive charges at the surface of the channel wall. At the output end of the microchannels the positive charges existing on the surface of the channel can not be neutralized by the conduction-strip current in less than about a millisecond, because of the high resistivity of the channel surface. The positive wall charge, localized toward the output side, is responsible for a transient saturation effect. Experimental data show that at low counting rates (where the interval between pulses is longer than the channel recovery time), a microchannel plate with a 40-micron curved channel can deliver a peak output pulse current of 1 A per cm² of useful area. At high pulse rates, departures from linear behavior are governed by the continuous input conditions discussed above. These saturation effects should be avoided by operating at the lowest acceptable gain.

Typically, the maximum pulse charge that can be extracted from a microchannel 40 microns in diameter is about 3×10^{-14} C (2×10^5 electrons). For the chevron configuration the maximum long-term counting rate is about 10^6 counts/sec cm² of active area. No gain suppression is observed for counting rates less than 10^5 counts/sec cm².

Resolution and noise

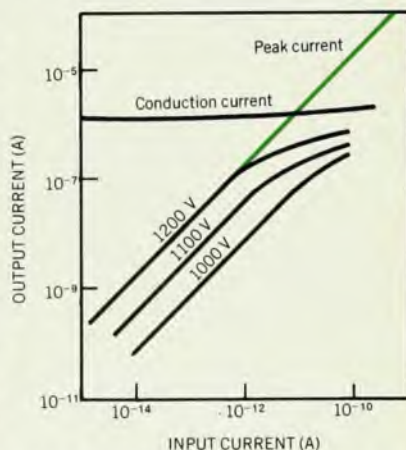
So far in this article, the *average value* of the gain of a microchannel plate has been implied whenever gain has been discussed. In fact, however, the gain varies from pulse to pulse because of the statistical nature of the electron-multiplication process. The statistical fluctuations of the gain of a microchannel plate about its mean value are best characterized by the relative variance of the output pulse-height spectrum when the output pulses are initiated by single electrons at the input.

J. P. Boutot and his associates showed⁸ that the variance of the gain of a microchannel plate with curved channels strongly depends on the operating voltage. When the microchannel operates in a nonsaturated mode, the amplitude distribution of the output pulse is exponential; the relative variance of such a distribution is equal to one. The gain increases with plate voltage until saturation takes place. Operating in the saturation mode reduces gain fluctuations from pulse to pulse as well as from one microchannel to another. The output pulse-height distribution becomes strongly peaked: The variance of the gain decreases to a value less than 0.1; the full width at half maximum (FWHM) of the output pulse-height distribution is 50%. Specifically, for a plate with 40-micron curved channels, the gain variance de-



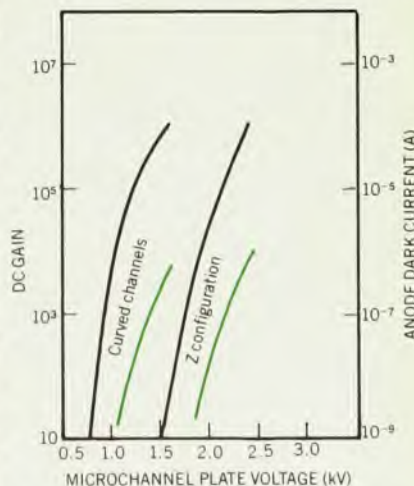
Microchannel-plate gain as a function of applied voltage per plate. For the straight-channel and chevron plates, $L/d = 44$ and $d = 38$ microns; for the curved-channel plates, $L/d = 80$ and $d = 40$ microns.

Figure 4



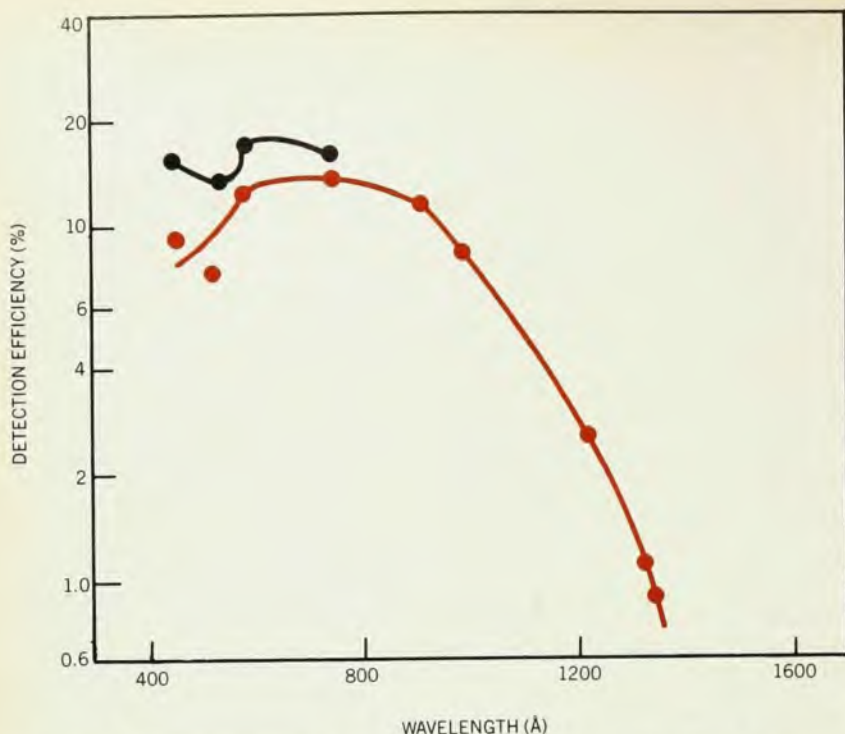
Output current as a function of input current for a curved microchannel plate, with plate voltage as a parameter.

Figure 5



Characteristics of photomultipliers with microchannel plates of curved-channel and Z-configuration types. Gain curves are shown in black, dark-current curves in color.

Figure 6



Variation of detection efficiency with wavelength for two configurations of microchannel plates. The black curve shows data from a high-gain cascade combination of three plates, and the colored curve is that from a two-stage single-channel electron multiplier. Figure 7

creases from 1.0 at a gain of 3.9×10^4 to 0.08 at a gain of 1.5×10^6 . For chevron plates the FWHM of the output pulse-height distribution is typically 120%.

Noise in a microchannel plate is best characterized by the number of background pulses counted in the output, per sec cm^2 of area. For a plate with 40-micron channels the dark-pulse count is about 1 pulse/sec cm^2 at a gain of 10^5 , and less than 50 pulses/sec cm^2 at the saturated gain level of 2×10^6 . These measurements were made on a plate⁸ containing 8×10^4 microchannels/ cm^2 . A similar background count rate occurs in chevron plates. For a plate with 38-micron channels, operating at a gain of 10^7 , the noise-pulse rate is 1 pulse/sec cm^2 . This plate had approximately 3.8×10^4 microchannels per cm^2 .

Other radiations: detection efficiency

In addition to electrons, the semiconducting coating on the inside wall of a microchannel can detect directly:

- ▶ photons, ranging from the soft x-ray region to the extreme ultraviolet,
- ▶ protons,
- ▶ positive ions,
- ▶ energetic atomic hydrogen and
- ▶ metastable thermal molecules.

The plates are not sensitive to very-low-energy electrons (such as thermal electrons), but these can be detected by a microchannel if their energy is first sufficiently increased by an accelerating field.

Microchannel plates can operate effi-

ciently as photon detectors at extreme ultraviolet and soft x-ray wavelengths in a windowless configuration, or they can be combined with a photocathode in a sealed tube for use at the ultraviolet, visible and near-infrared wavelengths of the electromagnetic spectrum. The detection efficiency, defined as the percentage of the input photons producing detectable pulses at the plate output, has been determined with single-channel multipliers in which the photoelectrons were generated directly by incident radiation on the semiconducting coating. More recent measurements on microchannel plates have shown^{12,13} that their efficiencies are similar to those measured for single-channel devices.

The measured detection efficiencies¹² of a two-stage single-channel multiplier and of a high-gain microchannel plate configuration are shown in figure 6. For the extreme ultraviolet, the configuration, consisting of three straight-channel plates in cascade, had a total gain of 2.8×10^7 . The plates had 11-micron diameter channels, with an open-area ratio of approximately 66% and bias angle of 5° . These measurements showed a maximum detection efficiency of about 16% at 600 Å.

Furthermore, the plate was more efficient than the single-channel multiplier at the wavelengths measured. The principal reason for this effect is the increase in the quantum yield of the plate as a function of the angle of incident radiation at wavelengths below 700 Å. The

angle of incident radiation was 85° for the plate, while the single-channel multiplier was illuminated at normal incidence. The efficiency difference between single channel and plate becomes smaller as the wavelength increases. At wavelengths longer than 800 Å the detection efficiency of the plate can be expected to be about equal to that of the single-channel multiplier.

Measurements of the efficiency of a microchannel plate as a function of wavelength of collimated monochromatic x rays gave peak efficiencies of 3.5%–16% in the 2–68-Å range. These measurements were made on a 40-micron-channel plate operating at different angles of incidence. The efficiency peaked sharply for an incident angle of approximately 6° .

In the near ultraviolet, visible and near infrared, the detection efficiencies of microchannel plates are too small for practical applications—a photocathode with appropriate spectral sensitivity should be combined with the plate.

Measurements of the detection efficiency for incident electrons, performed on single-channel electron multipliers in the 1–50 keV range gave results depending on the size of the multiplier funnel used, the angle of the incoming electrons and the detailed nature of the electric field at the input end. In general, these experimental results have shown the single-channel multiplier to be useful with detection efficiencies varying from approximately 95% (at the lower energies) to 40% (at high energies).

The detection efficiencies for hydrogen, argon and xenon ions as incident particles were also recently measured¹⁶ on a single-channel electron multiplier in the ion-energy range of 0.1–0.4 keV. The data indicate that ions of different mass all reach a plateau detection efficiency in the 50% range for energies larger than 2 keV. In the energy range below 2 keV, large variations in detection efficiency with ion mass are encountered; for an ion energy of 0.5 keV, the detection efficiency is 30% for hydrogen and 40% for xenon.

Applications of microchannel plates

Because of its small size, high current gain and excellent timing capabilities, the microchannel plate is a component especially well adapted for high-gain imaging detectors and very fast high-gain photomultipliers. Basic applications of the plate in imaging detectors are proximity, electrostatic and magnetic focussed-image intensifiers,^{6,18} quantum position-sensitive detectors, x-ray imaging,⁶ neutron radiography,⁶ electron microscopy,⁶ ultrafast cathode-ray tubes¹⁷ and streak cameras.¹⁷ This article will discuss only applications of microchannel plates in image intensifiers, position-sensitive detectors and photomultipliers.

In image intensifiers the output current of the microchannel plate—and therefore

the phosphor screen brightness—is limited by the strip current of the plate. This provides automatic highlight suppression. The gain can be varied by varying the microchannel plate voltage. Typical resolution for the 25-mm microchannel plate used as an image inverter-intensifier is from 28 to 35 line pairs per mm for plates that have center-to-center spacing of less than 17 microns.¹¹ These resolutions were achieved with straight-channel plates operated at electron gains of 10^3 – 10^4 with an equivalent input noise of 10^{-16} – 10^{-15} A/cm².

In position-sensitive detectors it is often desirable to extract the output information in the form of electrical signals suitable for further data processing. In this case the position resolution can now be completely determined by a two-dimensional readout system that is used in place of the output phosphor screen. One electronic readout system has been described as having a position resolution of 50 microns over a 1.6×1.6 mm² area.¹⁸ The system employs two sets of orthogonal linear anodes insulated from each other and exposed to the output current of the microchannel plate. The output current from the plate is divided between anodes at the intersection where the event occurs. The position of an event is identified by the coincident arrival of pulses on the appropriate anodes. Performance of the readout system was demonstrated on an array of 32×32 picture elements with 64 charge-sensitive amplifiers and data-processing electronics. Another such device exhibits a resolution of approximately 10 microns in a field of 420 microns.¹⁹ It uses a four-quadrant anode located behind the output face of the microchannel plate, so that the electron cloud from each detected event is partly intercepted by each quadrant. The charge collected by each quadrant then depends on the event position, allowing each event to be localized with two ratio circuits. An array of anodes can increase the field of view.

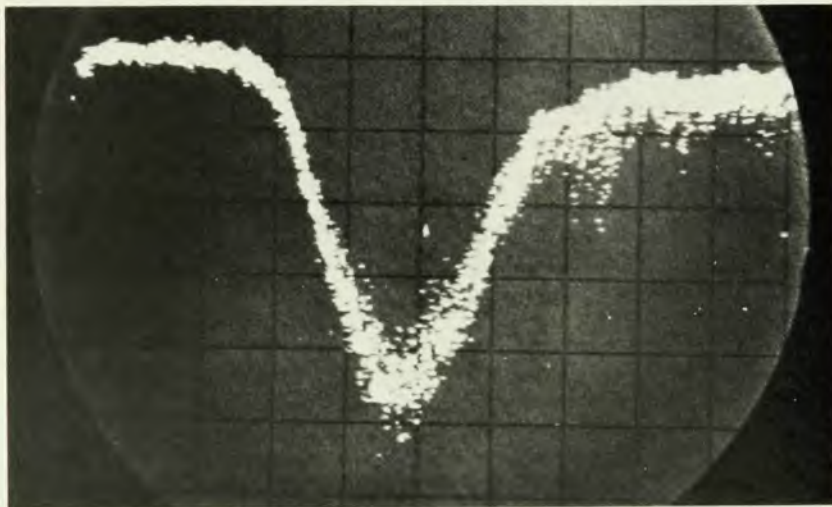
In high-gain photon detectors, microchannel plate electron multipliers are particularly suitable. The time-resolution capabilities, which are of prime importance, are the primary limitation in the precision of many time measurements with fast photomultipliers; these have been the subject for many years of intensive experimental and theoretical investigations.²⁰ Time measurements are important in many research areas, such as atomic and molecular subnanosecond fluorescence-decay measurements,²¹ nuclear research,²² optical ranging experiments³ and optical communication.⁴ The time resolution of photomultipliers is essentially determined by random deviations in the transit time of electrons travelling from photocathode to collector, and by possible variable delays in electron emission. This time spread is mainly caused by fluctuations in the times of

flight of photoelectrons and secondary electrons due to their different trajectories and initial velocity differences. Generally the transit time depends on the photomultiplier geometry, its operating conditions and the number of photoelectrons released from the photocathode.

Because the time spread roughly varies inversely as the square root of the number of photoelectrons, the time behavior of a single photoelectron is particularly helpful in predicting the transit-time spread for an arbitrary number of photoelectrons.²⁰ It is also helpful in the evaluation, selection and comparison of photomultipliers, as well as in determining the

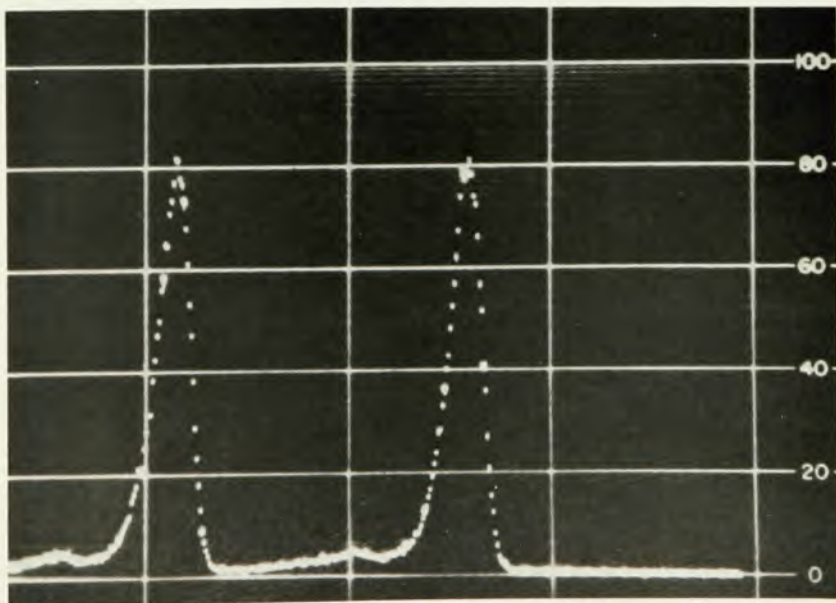
optimum operating conditions in critical applications.

The excellent timing capabilities of the microchannel plate multiplier result from its small thickness (approximately 2 mm) and very strong applied electric field (5–10 kV/cm). The electron transit time and its spread are therefore smaller than 1 nanosec and 100 piconsec, respectively. High-speed prototype photomultipliers, using curved-channel plates and proximity focussing for the input and collector stages, with an electronic gain higher than 10^6 and a photocathode diameter of about 15 mm, were developed in the Laboratoires d'Electronique et de Physique Ap-



A typical pulse from a photomultiplier plate with curved-channel plates, operated at 1600 volts. The vertical divisions represent 20 mV and the horizontal divisions, 500 piconsec. An electroluminescent diode provided the 200-piconsec light pulse for excitation.

Figure 8



A histogram of single photoelectron pulses from a curved-channel plate, with a time separation of 2 nanosec. Each vertical division represents 2000 counts per channel. With full photocathode illumination the time spread is 249 piconsec wide at half maximum.

Figure 9

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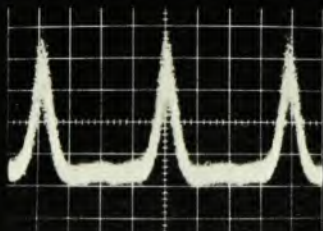
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pliquée.^{8,17} In the US, prototype high-gain photomultipliers with Z-configurations microchannel plates are under development¹⁰ at the ITT Electro-Optical Product Division, Fort Wayne, Indiana. They have an electron gain of 10^6 , photocathode diameter of 18 mm and proximity focussing.

The dc gain and anode dark current as a function of plate voltage, for both curved-channel and Z-configuration plates, are shown in figure 7. In both cases the dark current was completely determined by the photocathode temperature. The curved-channel photomultiplier exhibits very good timing capabilities and very low sensitivity to ambient magnetic fields, compared with the best regular photomultipliers.²³

Figure 8 shows the pulse shape due to a single photoelectron into the photomultiplier. The 10%–90% risetime is approximately 0.76 nanosec; this, after correcting for risetime of the system, becomes 0.64 nanosec. The pulse width (FWHM) is about 1.3 nanosec.

Figure 9 shows a single photoelectron time-spread spectrum. For full-photocathode illumination with a light pulse produced by a 200-picosec electrical pulse, the single-photoelectron time spread is approximately 250 picosec. It was approximately 30 picosec (FWHM) under conditions producing 6000 photoelectrons per pulse. These results compare very favorably with those obtained with conventional high-gain fast photomultipliers, where time spreads of 300 picosec require very-small-area illumination of the photocathode and optimal operating conditions.²⁰

The maximum axial magnetic flux density that did not affect the gain of curved-channel photomultipliers was 900–2000 gauss. The transverse magnetic flux density that reduced the dc gain of the photomultiplier to half of its initial value was 500–780 gauss. These results represent a great improvement over conventional discrete-dynode photomultipliers, in which a magnetic flux density of 1 gauss seriously reduces the gain.

Future developments

From the above account it is evident that great progress has been made in the technology and applications of microchannel-plate photon detectors. The plates, particularly those with low gain, have been used extensively in scientific research. Nevertheless, the plates require further improvement, particularly with respect to the maximum continuous current limiting the gain for a given pulse-repetition rate (dynamic-range limitation), and to their gain degradation when operated at even moderate levels of output current.

The dynamic range can be increased by increasing the current through the walls of the microchannels. Therefore better secondary emitters are needed, to permit

higher channel-wall current. As to the gain-degradation process of the micro-channel plate, one investigation showed¹¹ that the operational life of the plate is longer than 7000 hours at input current densities of 3×10^{-12} A/cm². However, recent investigations indicated²⁴ both a more rapid gain decay and a dependence of the gain on the total charge per unit area extracted from the plate. Further efforts are necessary to improve our understanding of this phenomenon.

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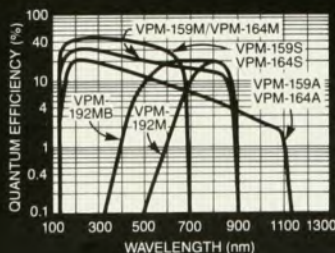
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