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for Particle Tracking or Single Photo-Electron Counting

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HIGH GAIN MICRO-CHANNEL PLATE MULTIPLIERS FOR PARTICLE TRACKING OR SINGLE PHOTO-ELECTRON COUNTING

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Abstract

Micro-channel plate multipliers have been used to detect the passage of relativistic charged particles. Measurements of the detection efficiency and pulse height response versus micro-channel plate gain are presented for one, two and three micro-channel plate arrays. Values describing temporal response and transit time jitter are also given.

In a separate measurement, the response of a single micro-channel plate to individual slow electrons (~ 1 keV) was studied. By using a special technique output bunches as small as three electrons may be seen for low average micro-channel plate gain. The results of attempts to improve the micro-channel plate response are also presented.

Introduction

The development of micro-channel plate devices for either the detection of minimum ionizing particles or single photo-electrons could provide a combination of high spatial resolution and fast response that is not obtainable by other means. We report here on the performance of currently available micro-channel plates in both of these applications and suggest possible improvements that might be realizable.

Micro-channel Plate as Detector of Minimum Ionizing Particles

In a series of experiments carried out in the B4 and A2 test beams at the Brookhaven AGS, the response MCP's to 3 GeV/c negatively charged pions and 7 GeV/c protons was studied. The determination of the detection efficiency and timing properties was of primary concern. With results from these measurements, we may discuss the feasibility of using the MCP as an active target with good spatial and temporal resolution.

A cross section of the MCP-detector is shown in Fig. 1. The principle of the detection is illustrated in Fig. 2. It shows a small cross section of the MCP detector. A fast particle penetrating the plate crosses a large number of channel walls. If a secondary electron is emitted and goes into the channel, it can generate an electron avalanche in subsequent stages of the detector. The multiplication process in MCP retains the spatial information so the track image can be made visible on the phosphoric anode. As is well known, the electron transit time in micro-channel plate is very short and, consequently, the detector can in principle handle very high rates.

Efficiency Measurement

In order to make this measurement, a beam was defined using five scintillation counters, one anti-counter and two Cerenkovs. The Cerenkov counters were used to veto electrons. A thin (.5 mm) finger counter placed immediately behind the MCP detector defined the beam position insuring that all triggering particles penetrated the active area of the detector.

Fig. 1. Cross section of a three stage MCP detector. Dimensions are in mm.

Fig. 2. Principle of the detection of the minimum ionizing particle crossing the detector.

Representative pulse height distributions from a three stage π^- configuration of MCP's is shown in Fig. 3 for different values of overall gain. Fig. 3a shows the pulse height spectra obtained by exciting the MCP with individual ultra-violet photons. These are to be contrasted with the spectra obtained from the minimum ionizing particle triggers shown in Fig. 3b. This difference is a result of the fact that ultra-violet photons produce single avalanche-generating electrons only near the front surface of the MCP whereas the ionizing particle liberates a small number of secondary electrons randomly distributed throughout the depth of the MCP.

With a discriminator setting at about 5 times the rms electronic noise, the false counting rate from the MCP's was negligible. Figure 4 shows the detection

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Fig. 3. PHD of the 3-stage MCP detector stimulated by (a) UV-light and (b) minimum ionizing particles.

Fig. 4. Detection efficiency for one, two and three stage MCP detector as a function of total applied voltage.

efficiency for one, two and three micro-channel plate arrays as a function of applied voltage (i.e. gain) with the above discriminator arrangement and an incident particle angle of 18 degrees. The detection efficiency improves with increased number of MCP's reaching ~90% for the three MCP detector.

The dependence of the detection efficiency on the incident angle of the particle was investigated. The path length within the MCP traversed by the particles is inversely proportional to $\sin \alpha$ and we will assume that the mean number of secondary electrons produced by the particle is proportional to the path length. According to this simplified model the detection efficiency can be expressed by the formula:

$$\epsilon = 1 - e^{-k/\sin \alpha}$$

Fig. 5. Inefficiency of the two and three stage MCP detector as a function of the $1/\sin \alpha$, where α is the incident angle between the MCP plane and the trajectory of the detected particle.

The inefficiency of the detector ($1 - \epsilon$) is plotted as a function of $(1/\sin \alpha)$ in Fig. 5. Assuming Poissonian statistics in the number of secondary electrons produced by a relativistic particle, the mean number of secondary electrons can be calculated. Knowing the length to the diameter ratio of the target micro-channel plate this number can be translated into an estimate of the probability of the emission of the secondary electron from the wall into the channel. This probability is about .6% for the micro-channel plate under study. This number is probably an underestimate because of the reduced gain for electrons produced near the back surface of the first MCP.

Study of Timing Properties

The output waveform of the current from the detector anode adiabatically matched into 50 coaxial geometry is shown in Fig. 6. Figure 6a shows the waveform from the one stage MCP detector, Fig. 6b the waveform from the three stage detector, both excited by a passage of the minimum ionizing particle. (Note the different horizontal scales 500 ps and 2 ns/div, respectively.) The rise time is in subnanosecond region.

The transit time jitter for the MCP detectors was determined from timing measurements of two MCP detectors and a scintillator coupled to a conventional PMT. The experimental set-up is shown in Fig. 7a. Start and stop signals were generated using fast constant fraction discriminators. From the relative timing distributions (start-stop) obtained in the three different combinations of two out of the three detectors, the intrinsic transit time jitter of the two MCP detectors could be calculated. It was found to be FWHM = 180 ps for two stage MCP and FWHM = 260 ps for three stage detector. Figure 7b shows

(a)

(b)

Fig. 6. Anode current waveform from (a) Single stage MCP detector and (b) 3-stage MCP detector.

Fig. 7. (a) Experimental configuration for time jitter measurement and (b) Distribution of the time differences between signals from two MCP detectors on the log. scale. 1 channel = 40 ps; 1 vertical div. = factor of 10.

the distribution of the time jitter between two MCP detectors on a logarithmical scale. We can see the gaussian character of the distribution down to 10^{-4} level.

MCP as a Track Sensitive Target

We have collaborated with D. Potter¹ to photograph beam tracks produced at the phosphor screen of the MCP detector by 7 GeV/c protons with incident angle $\alpha \sim 0^\circ$. A description of the additional apparatus employed for this purpose can be found elsewhere.²

The examples of the images recorded on film are shown in Fig. 8. (The relatively big spot size of the track images shown is due to the spread of the electrons between the end of the MCP and the phosphor screen. This spread can be reduced down to a $\sim 10\mu$ level by using the correct focusing.) Examination of a modest number of photographs provides a measurement for the primary spot density of $1.2 \pm .2$ spots/mm implying a secondary emission probability of ~ 1.2 spots/mm $\times .028$ mm/channel $\sim (3.4 \pm .7)$ %/channel. Use of the MCP in the camera trigger has probably biased this result towards higher values. Nevertheless, both this and the result of the efficiency measurement suggest a low (~ 1 to 4%) secondary emission probability. Clearly, an improvement in the secondary emission coefficient of the channel wall would be desirable, providing both increased spot density and higher MCP gain. It would be particularly advantageous if the coefficient were high enough to provide a saturated response independently of the depth of origin for the avalanche initiating secondary electron over a large portion of a single MCP thickness. This type of response may also be obtained with additional stages of MCP amplification but only at the expense of both position and time resolution.

Fig. 8. Two examples of the track images recorded on film.

Micro-channel Plate Response to Single Photo-Electrons

We present here a study of micro-channel plate response to single low energy (~ 1 keV) electrons made as a result of our interest in possible single photon counting applications. However, we note that these data are of equal importance in understanding the signal to noise degradation of MCP amplifiers in high sensitivity imaging applications.^{3,4}

Experimental Technique

Single micro-channel plates were studied in the demountable arrangement diagrammed in Fig. 9. Photo-electrons produced via low intensity ultra-violet illumination of the Au photo-cathode were accelerated through a potential defined by voltages at apertures 1 and 2 and the front of the MCP. A variable bias could

Fig. 9. Diagram of Apparatus.

be applied across the MCP to adjust its gain. Electrons emerging from the back surface are then accelerated through a large potential difference (variable from 0 to 20 kV) and strike a high resolution (16 keV-FWHM) ORTEC surface barrier solid state detector. The support ring which is held at the same potential as the output surface of the MCP serves also to focus electrons onto the active area of the solid state detector (SSD). The alignment and electron optics were checked by replacing the SSD with a phosphor coated dummy anode, thus making the output image spot size and location directly observable through the glass envelope. Standard vacuum conditions for all experiments were $\sim 10^{-6}$ Torr.

The electrons after acceleration from the output of the micro-channel plate lose about 2.5 keV penetrating the dead layer of the SSD. They then expand the

remainder of their energy, producing electron-hole pairs, providing an additional gain of ~ 277 for each kilovolt of accelerating potential beyond 2.5 kV. Figure 10 demonstrates the linearity of the gain versus the accelerating potential. By this device, the rms noise of the detector can be less than one electron referred to the output of the MCP.

Fig. 10. Gain at Si-Detector vs. Acceleration Potential

Figure 11 demonstrates the sensitivity of this technique. It shows the pulse height distribution for a standard Hamamatsu Corporation MCP⁶ at a bias of 451 volts giving a mean gain of 7.8. The upper spectrum results when the MCP is excited by 600 volt photo-electrons while the lower curve is the dark count spectrum. The horizontal scale is calibrated in units of electrons. These data were taken with an acceleration potential of 17.7 kV, giving an rms noise charge corresponding to 1/2 electron out of the MCP. The discriminator threshold was equivalent to 1.4 electrons. The spike at small pulse height, just above threshold, that dominates the dark count spectrum is due to single electrons. The discriminator has been set $\sim 1 \sigma$ above the peak of this distribution suppressing most of the counting rate. We believe that the unstimulated single electron emission from the MCP has been enhanced by the high accelerating field (~ 10 kV/cm), and could be reduced through the use of an intermediate grid. Our measurements to date cannot determine the probability of seeing 0, 1 or 2 electrons as a result of some stimulation of the MCP, however, we are able to characterize the probability distribution over a large dynamic range above these values. We have undertaken a study of these distributions over a large range of MCP biases for various values of photo-electron acceleration. In addition we have attempted to alter the shape of this distribution by increasing the secondary emission probability at the first collision. This can be accomplished by the vacuum evaporation of CsI layers onto the input surface of the MCP.

Discussion of Results

We have found it useful to compare the output distributions produced by accelerated photo-electrons to

Fig. 11. Probability distribution for seeing n electrons leave MCP in response to one photo-electron (upper) or no stimulus (lower).

those produced by direct ultra-violet stimulation of the MCP input surface. For these measurements the photo-cathode is reverse biased so that no photo-electron may reach the MCP. We find the resulting distribution is well characterized by a simple exponential, $dN/dq = \alpha e^{-\alpha q}$, where q is the MCP output charge in units of electrons. This holds over almost 3 decades of probability with departure only at large pulse heights. We have observed this type distribution over the full range of MCP bias voltages corresponding to mean MCP gains, $\langle q \rangle_{uv} = 1/\alpha$, ranging from less than ten up to several thousand. We did not observe any gain saturation and there was no turnover even at very small pulse height, suggesting the most probable response at the output is always zero.

The response of MCP to photo-electron at any bias voltage will differ from the direct UV response. This is because a UV photon will produce a single secondary electron at the front of the MCP while photo-electron might produce multiple secondaries at its first collision at MCP. Moreover, the mean number of secondaries produced can be expected to vary with the photo-electron acceleration. For the purposes of illustration we will assume that the response of the MCP to each of the secondaries is the same as the response to the single UV secondary, $\partial P_1/\partial q = 1/\alpha e^{-\alpha q}$. Then, it is easily shown that the response to n secondaries is:

$\partial P_n/\partial q = (\alpha q)^{n-1}/(n-1)! \exp(-\alpha q)$. If the probabilities that a photo-electron produce n secondaries is given by the set of numbers γ_n (for $n \in [0, \infty]$ and $\sum_{n=0}^{\infty} \gamma_n = 1$). Then the MCP response to a photo-electron will be simply:

$$\partial P_{pe}/\partial q = \sum_{n=1}^{\infty} \gamma_n \partial P_n/\partial q + \gamma_0 \delta(q).$$

In the very simple case where

$$\gamma_n = (1-\epsilon)\epsilon^n, \quad \epsilon < 1, \text{ we find}$$

$$\partial P_{pe}/\partial q = (1-\epsilon) [\delta(q) + \alpha \epsilon e^{-\alpha q(1-\epsilon)}]$$

which for non-zero response is again an exponential but of increased mean gain. Note that the mean number of secondaries is $\langle n \rangle = (1-\epsilon)^{-1}$ and the mean gain is now $\langle q \rangle_{pe} = \langle n \rangle \langle q \rangle_{uv}$. In the more desirable case γ_n is a poissonian distribution $\gamma_n = \langle n \rangle^n/n! \exp(-\langle n \rangle)$ the $\partial P_{pe}/\partial q$ will be maximum near $\langle n \rangle \langle q \rangle_{uv}$ falling to zero as $q \rightarrow 0$ and $q \rightarrow \infty$.

Figure 12 compares calculated output distributions $\partial P_{pe}/\partial q$ for various γ_n distribution. Figure 12a shows

Fig. 12a,b. Theoretical photo-electron response distributions for MCP's with enhanced secondary production at first collision.

the result of the exponential type of γ_n distribution discussed above for $\langle n \rangle = 13.5$ modified so that $\gamma_n = 0$ for $n > 27$ and that 30% of all photo-electrons can produce only one secondary. Figure 12b compares poissonian distribution with $\langle n \rangle = 5, 10$ and 20 again modified by the increased single secondary probability. This figure also shows the original exponential ultra-violet response. More rigorous treatments of this subject by others can be found elsewhere.^{4,5} Observed distributions for the CsI treated MCP show most similarity to the theoretical curve of Fig. 12b. An example comparing 980 volt photo-electron and ultra-violet induced distributions is shown in Fig. 13.

Fig. 13. Observed response distributions to 980 volt photo-electron (upper) and ultra-violet (lower) for MCP with two CsI layers.

The qualitative agreement suggests that an exponential distribution in the number of secondaries is more appropriate to the real situation than in a poissonian one. This is to be expected based on some previous work with CsI thin films.⁵ We did note, however, that the character of the distribution could be markedly changed by biasing the second aperture in such a way as to prevent secondaries, produced by photo-electrons striking the closed area of the micro-channel plate, from entering the channels. The resulting distributions become more similar to the poissonian example but still show a strong exponential component at small pulse height suggesting an increased probability for producing a single secondary. The data to be presented in the rest of our paper were taken with the voltage between the second aperture and the micro-channel plate that maximized the collection of secondaries produced at the closed surface.

At each of several values of MCP bias voltage we observed the MCP response to both direct ultra-violet stimulation and to single photo-electrons. The UV response is reasonably described by simple exponential parameterized by one number, its mean value, which we will refer to as the average MCP gain. The pulse height spectrum induced via electron bombardment of the MCP accelerated from the gold photo-cathode is in general more complicated. There is a component dominating the spectra at small pulse height that appears to fall as fast as the UV distribution, but at intermediate values it falls much more slowly for about one decade. Ignoring both the small and large pulse height regions, the intermediate range can again be approximated by an exponential. A comparison of this type is shown in Fig. 13.

The constant parameterizing this exponential

Fig. 14. Mean pulse height vs. MCP bias voltage.

depends on both the photo-electron acceleration and the amount of CsI deposited on the MCP surface. Figure 14 shows curves comparing the mean gain versus MCP bias voltage for both ultra-violet and photo-electron excitation for 0, 1 and 2 layers of CsI coating. The photo-electron curves were all taken at a fixed acceleration potential (980 volts).

The ultra-violet response was unchanged by the CsI depositions, while the photo-electron response was affected dramatically. This tends to support the idea that the CsI only serves to increase the mean number of secondaries produced in the photo-electron's first collision. To investigate this further, we fixed the MCP bias voltage at 590 volts and plot the ratio, δ , of the mean photo-electron gain to UV gain as a function of the acceleration potential. This is shown in Fig. 15, for the same three conditions. According to the description given earlier, δ is simply the mean number of secondaries produced in the first collision.

Figure 16 demonstrates the importance of the acceleration potential. Here the photo-electron response of the same MCP with a 2 layer deposition of CsI at a bias voltage of 520 volts is shown for four different acceleration potentials (680, 750, 820, 980 volts).

For both photon counting and high sensitivity imaging applications, it would be advantageous to have a peaked response to single photo-electrons rather than the exponential one we have observed for standard MCPs. We have shown that the deposition of CsI layers on the front of the MCP can enhance the mean number of secondaries produced in the first collision. However, the

Fig. 15. Mean number of secondaries at first collision vs. photo-electron acceleration.

Fig. 16. Response of MCP with two CsI layers to photo-electrons of four different energies.

increase obtained was neither large enough to drive the single MCP into saturation, nor is it sufficiently poissonian in character to obtain a peaked response. Probably the best solution to this problem would be the same as to those cited in the first section — devise a technique to increase the secondary emission coefficient of the channel wall itself.

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