Time Response of Fast-Gated Microchannel Plates Used as X-ray Detectors

R. E. Turner, P. Bell, R. Hanks, J. D. Kilkenny, N. Landen, G. Power, J. Wiedwald, and M. Meier

Lawrence Livermore National Laboratory
University of California
Livermore, CA 94550

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Abstract

We report measurements of the time response of fast-gated microchannel plate (MCP) detectors, using a <10 ps pulsewidth ultra-violet laser and an electronic sampling system to measure time resolutions to better than 25 ps. The results show that framing times of less than 100 ps are attainable with high gain. The data is compared to a Monte Carlo calculation, which shows good agreement. We also measured the relative sensitivity as a function of DC bias, and saturation effects for large signal inputs. In part B, we briefly describe an electrical 'time-of-flight' technique, which we have used to measure the response time of a fast-gated microchannel plate (MCP). Thinner MCP's than previously used have been tested, and, as expected, show faster gating times and smaller electron multiplication. A preliminary design for an x-ray pinhole camera, using a thin MCP, is presented.

Part A: sub-100 ps response times

Gated microchannel plate detectors are finding increased use as an alternative to more conventional electro-optic framing cameras for photon energies from the visible through x rays[1]. Their advantages include sensitivity, compactness, relative simplicity, and low cost. Their disadvantages include limited dynamic range, and mechanical fragility. Here, we report direct measurements of the framing time attainable with these devices. We also report measurements of their pulsed sensitivity and saturation characteristics.

Previous work has reported on the time-response of fast-gated MCP x-ray detectors[2]. In those measurements, the input signal was comparable in duration to the expected time resolution, requiring a deconvolution to extract the data. In this paper, we report measurements using an ultra-violet dye laser with a time duration of less than 10 ps as the input signal. Hence, we can obtain, in a relatively straightforward manner, the MCP time response.

The details of these detectors, and the electronic drivers, have been discussed previously[1,2]. In these tests, we used channel plates which are 500 μm thick, with 12 μm pore diameters. The channels are biased at 5°, and the rear surface is uniformly coated with a conductor to form a ground plane. Gold is coated on the front surface to form a 22 ohm impedance microstrip line. This allows the MCP to be driven with a single 25 ohm cable with only a small impedance mismatch. The gold serves as a thick x-ray photocathode, as well as the electrical conductor. We have found that a too thick (over 1 μm) coating of gold tends to close off the pores, while a too thin (less than 0.1 μm) coating causes the stripline to be electrically lossy. We used 0.2 μm here. Additional coatings, such as CsI, which can be applied over the gold to increase the quantum yield, were not used here. A high voltage (500 to 1500 V), short duration (100 to 300 ps) pulse is propagated down a coaxial cable, onto a microstripline on a PC board, and across the stripline onto the MCP. The gap between the PC board and the channel plate is bridged with a gold foil fastened with conducting epoxy. The other end of the stripline is similarly connected to the PC board stripline and another 25 ohm coaxial cable (this cable is terminated with 25 ohms). While the high voltage is present across the MCP, the electrons traveling through the channels are multiplied as a result of multiple collisions with the walls. These electrons exit out the back of the channel plate and are proximity focused onto a phosphor-coated fiber optic faceplate; the resulting light is recorded on film. For these measurements, where no spatial information was desired, a contact slit and a photomultiplier were substituted for the film.

The short duration, high voltage pulse generator is an improved version of those used previously[1,2]. Basically, a high voltage, 2 ns rise time pulser drives an avalanching diode and pulse-forming network to produce the desired pulse. For the work reported here, we used two different pulse shapers. One had a 200 ps FWHM, and a 1500 V peak amplitude (into 25 ohms); the other had a 100 ps FWHM, with a 1200 V peak amplitude into 25 ohms. In both cases the pulse shape is approximately Gaussian as measured by both a 7250 Tektronixs scope (resolution ~100 ps), and a 7S12 Tektronixs sampling system (resolution ~25 ps).

Experimental

The output of a short pulse (<10 ps) synchronously pumped dye laser is frequency doubled to 290 nm, where it can directly produce photo-electrons from the Au photocathode. The light is incident on the MCP at an angle, to prevent direct light transmission through the channels. A sampling system is used to vary the time at which the pulser is triggered, relative to the laser pulse. The entire system runs at 10 Hz; thus it takes only a few tens of seconds to scan through the response of the MCP. The electronics are shown, in block form, in Fig. 1. A modified Tektronixs 7B10 time base is used as a trigger/discriminator. It looks at the sum of two inputs; one, an electronic pulse which indicates the firing of the dye amplifier every 0.1 sec.; and a second input, from a high speed diode looking at the green light from the synchronous YAG pump laser. The first signal has unacceptable time jitter; the second signal has very low time jitter but runs at the oscillator rep rate (82 MHz). By setting the discriminator to trigger only when both signals are present, a very low jitter, 10 Hz trigger signal is generated. The time base has been modified to bring this signal to an external connector. From there the signal is used to trigger an S-53 trigger recognizer plugged into a 7S12 sampling system in a 7904 scope. The sampling trigger, instead of triggering a sampling head, is brought out to trigger the high power pulser. The sampling system slowly varies the timing of the pulser trigger with respect to the time of arrival of the laser light. We typically advanced the pulser trigger 2 ps per laser pulse.

A photomultiplier views the phosphor output through a 2 mm slit. The slit is necessary, as the electrical transit time of the pulse across the

MCP is longer than the local response time. The PMT output goes to a gated integrator; the integrator output is displayed on the vertical channel of the scope, while the relative sampling time is displayed on the horizontal direction.

We have made no direct measurement of the time jitter of this system; however, it is apparent from the data that it must be better than 25 ps. Jitter in the laser amplitude is very apparent in the data. Shot to shot amplitude variations of order 10% are quite often seen. Random variations are reduced by averaging. However, to keep the scan times from becoming excessively long, we restricted averaging to three shots. This allows a 400 ps scan of the time response to be made in about 20 seconds.

As in any sampling system, the key to good results is the repeatability of the trigger system. In our set-up, this means good amplitude stability of the pump laser which drives the high speed photodiode; a short cable run between the diode and the electronics; and careful adjustment of the 7B10 time base discriminator.

Time Response Results

Figure 2 shows a typical result when using the 200 ps FWHM electrical pulse (signal amplitude increases downward). The laser amplitude jitter makes for some uncertainty in determining the amplitude (and hence the half-maximum amplitude). However, the measured FWHM of the signals is between 80 and 100 ps with this electrical pulse. We emphasize that we have made no deconvolution for the electronic system response, which is less than 25 ps.

When we used the 100 ps electrical pulse, the time response showed a small decrease to 70 - 90 ps FWHM. The relative sensitivity, however, greatly decreased. This decrease, due to the finite electron transit time through the MCP, is discussed later.

The system was checked for linearity by inserting an interference filter into the laser beam. This produced a factor of five drop in signal level, in good agreement with the known transmission (22%) of the filter.

Relative Gain

In practical use, it is awkward to adjust the sensitivity of the MCP by changing diodes and pulse-formers. Instead, a small (few hundred volts or less) DC voltage is applied to the channel plate, either forward or reverse biased to adjust the gain. In this fashion, the sensitivity of the MCP can be adjusted over a wide range.

We measured the relative gain of the MCP as a function of forward dc bias, in addition to the pulsed voltage. This required the insertion of an ac coupling capacitor, which reduced the pulsed voltage and broadened it slightly. The results are shown in Fig. 3 for both the 100 and 200 ps electrical pulsers, with bias voltages from 0 to -500 V.

The signals are arbitrarily referenced (gain = 100) to the signal observed with dc bias of -700 V and no pulsed voltage.

We also measured the relative sensitivity of the MCP to changes in the amplitude of the pulsed voltage. This was done in the directly (no ac) coupled mode, with the 200 ps pulse, by inserting a 50 ohm cable in between two 25 ohm cables feeding the channel plate. The resulting impedance mismatches result in 8/9 the voltage being delivered to the MCP. The relative gain was observed to drop by a factor of 4.5, or by the voltage raised to the 13th (±2) power. This sensitivity to voltage is somewhat faster than the usual DC sensitivity variation, which is typically V^9.

Saturation

All of the results present thus far have been "small signal" measurements. As the laser intensity or forward bias is increased beyond some point, the MCP can begin to saturate. The most obvious change is that the FWHM of the response begins to broaden, until, in the 200 ps electrical pulse case, the system response is about 150 ps FWHM, or nearly twice as broad as the small signal case. We measured the current drawn by the phosphor on each pulse by installing an RC circuit in the charging line, so that the capacitor furnished most of the restoring charge to the phosphor. We recorded the voltage drop and recharge of the capacitor on an oscilloscope, and thus could calculate the net charge furnished. We set the forward bias on the MCP at the level where the time response was observed to begin to broaden. The charge measured from the phosphor was approximately 6×10^{-11} coul/cm^2. In order to correlate this value with actual instruments in use, a piece of film (Kodak 2484) was substituted for the contact slit, and a single shot exposure made. The film density was 2.1. We increased the forward bias until the MCP response broadened to about 150 ps; the phosphor charge was 9×10^{-10} coul/cm^2. We again made a single shot exposure on the film, which resulted in film density greater than 3. We thus conclude that care must be used on our current instruments to avoid heavy exposures.

We note that the above charge densities correspond to 770 and 11,570 electrons per channel, respectively. The saturation mechanism can be explained by charge depletion: as charge is drawn, the channel walls cannot be kept at the applied potential on this time scale, due to the high resistance of the MCP glass. Thus, the electron cloud and the positive surface charge left behind create an electric field in opposition to the applied field. This reduces the gain. A simple calculation, in which the MCP channel is a 12 μm diameter capacitor with electrons at one end and positive ions at the other, shows that 10^4 electrons will reduce the local field by 800 V. Now, in an actual channel, the electron cloud will be spread out, so that this calculation overestimates the effect. However, it supports the plausibility of this explanation.

Theoretical Modeling

We have used a Monte Carlo computer code to simulate the MCP behavior. Similar work, but with a different emphasis, has been previously reported[3]. This code simulates a single MCP channel in two-dimensions as a pair of flat walls, 8 μm apart, 500 μm in depth, sloped at a 5° bias angle. The use of only two dimensions is to save computer time; the 8 μm separation is the approximate average chord length of a 12 μm diameter circle. A single primary electron is started from the top of the channel at t=0. The equations of motion are solved for each electron within the walls every 1 ps. When an electron hits a wall, secondaries are generated with a random direction. The number of secondaries is in proportion to the incident electron's energy;less than

10 eV produces no secondaries, 10 to 30 eV produces one, 30 to 50 eV produced two, and so on. This algorithm approximately reproduces the data of Hill[4] and Authinarayan et al.[5], which shows that the secondary production is unity at about 20 eV. The data from these authors show the secondary yield decreasing at higher energies. Unlike those experiments, however, the electrons in a microchannel collide with the walls at very shallow angles, and thus high energy electrons do not bury themselves as quickly. Our algorithm, therefore, allows the secondary yield to continue increasing as the incident energy increases. The secondary's energy is fixed at 1.5 eV[4,5,6]. This code makes no attempt at calculating the effects on the electric field within the channel due to finite conductivity, non-unity dielectric constant, or due to the electrons propagating down the channel.

The lack of three dimensions, and lack of precise information for the true secondary yield in this geometry, limit this code's ability to make quantitative predictions for the absolute gain from first principles. However, it is very useful for examining relative changes as the MCP parameters, and the voltages are varied.

Figure 4(a) shows the spread in exit time of the secondary electrons, for 1000 V dc bias. The primary electron was started at the top of the channel at t=0. Note that it takes about 175 ps for the average electron to exit, but also that some electrons exit much earlier. It is these electrons, which are a result of a cascade in which there were fewer than average wall collisions, which are important with very short voltage pulses.

Figure 4(b) is the simulation of the experimental data shown in Fig. 2. Here, a Gaussian voltage pulse, 200 ps FWHM, is applied to the MCP, and the number of exiting electrons is calculated. Then, the time at which the voltage is a maximum, relative to t=0 (the start time for the primary electron), is stepped to a new value, and the calculation repeated. Figure 4(b) shows the number of exiting electrons (the gain) as a function of the relative timing of the voltage pulse. Note that this is exactly what is done in the measurement. In order to generate reasonable statistics, each point is repeated numerous times. The error bar indicates one standard deviation, assuming one primary electron per channel, and 35 channels per resolution element. (Note the proximity focused phosphor's limited resolution blurs together approximately 35 channels.) The FWHM response shown in Fig. 4(b) is of order 75 ps, similar to the actual measurement. The gain is reduced from the dc calculation by a factor of 5. This is due, as previously stated, to the fact that the transit time for the electron cascade is long compared to the time that the voltage is over 1000 V, for the actual 1500 V peak, 200 ps Gaussian pulse. In this situation, the voltage and therefore the gain are low when the electron starts; they reach a maximum about the time the cascade is halfway through the MCP; and they are low again as the electrons exit.

The code also calculates greatly reduced gain for the 100 ps voltage pulse, and shows why: statistically, there will be very few electron cascades in which the transit time is shorter than this electrical pulse; at the beginning and end of the cascade, the gain may even be less than one, so the average gain will be small.

Summary

We have reported measurements showing the time response of fast-pulsed microchannel plate detectors to be less than 100 ps FWHM. Computer modeling indicates good agreement with the simple idea that these fast electrical pulses only allow those electron cascades which, statistically, have fewer than (the DC) average wall collisions to be accelerated all the way through the MCP. We have also shown that, due to the high current density within the channels, the gain can become non-linear for large signals.

Part B: Improving framing times to less than 50 ps

In Part A, we have described the behavior of fast-gated microchannel plate (MCP) electron intensifiers used as x-ray detectors. The channel plates used were 500 μm thick, with 12 μm diameter channels. In order to improve the time resolution, it is apparent that thinner MCP's are desirable, in order to decrease the electron transit time through the channels. Not only have the distance the electrons travel decreased with thinner plates, but they also have larger accelerating electric fields within the channels (assuming the same voltages are available to drive them), which helps improve the response. In an idealized limit where the MCP gain is one -- that it, there are no collisions with the channel walls -- this device very much resembles the framing camera of Stearns, et. al.,[7] where the MCP serves only as an electron collimator and as a hard x-ray filter.

In the work reported here, we have gone to 250 μm thick MCP's, half of the previous thickness. To test these plates, we have used a short pulse (less than 1 ps FWHM), frequency doubled UV dye laser, as described in part A. However, to overcome the problems of jitter in the electronics, we have abandoned our sampling measurements in favor of a simple electrical time of flight measurement, as illustrated in Fig. 5. The dye laser beam is expanded to uniformly illuminate the surface of the gold microstripline which is coated on the MCP's surface. The UV photons create photoelectrons from the thick gold cathode. The amount, if any, of subsequent electron multiplication within the channels depends on the relative timing between the laser pulse and the electrical pulse. Clearly, if these two events are widely separated in time, the gain is zero; and, for some particular separation (nearly but not quite zero due to the finite transit time), the gain is a maximum. Since the electrical pulse has a shorter duration than the time it takes for the pulse to propagate across the face of the MCP, we can obtain data for the gain, as a function of relative timing, by measuring the gain as a function of position on the microstripline on a single shot, if we know the electrical propagation velocity. This assumes that all of the microchannels operate independently of each other, and that there is no appreciable loss of voltage as the electrical pulse propagates across the strip.

The propagation velocity was measured with a Tektronixs time domain reflectometer (TDR) to be 14.8 mm per 100 ps. We estimate this value to be accurate to better than 5%.

The electrons emerging from the MCP are proximity focused onto a phosphor-coated fiber optic face plate by a 3 KV voltage. In previous, thicker MCP instruments, this produced enough light to expose film directly. However, with the thinner plates, it was necessary to use an optical intensifier to increase the signal to an acceptable level. For these measurements, we used a lens-coupled CCD camera, instead of film.

In practice, the UV laser beam is not uniform; also, the MCP gain varies as a function of position due to inherent non-uniformities within the channels. We collected data with the MCP operated with a dc voltage, instead of pulsed. This allowed us to correct the pulsed data for these problems, as well as, removing a background due to scattered laser light which made its way through the MCP.

We measured a response time of 35 ps FWHM, using a 75 ps FWHM (inferred from a 7250 oscilloscope measurement) electrical driving pulse. As noted above, the electron gain is quite low under these conditions. To take advantage of these faster response times, we have designed a new gated x-ray pinhole camera; the basics are shown in Fig. 6.

The 250 μm thick MCP on the front of the detector will have four microstriplines coated across its face, each 3 mm wide. A long, single continuous microstripline ("serpentine") was rejected for this application, since we have found it difficult to keep dispersion and ohmic losses small enough in that geometry. The relatively narrow active areas are necessary to keep the microstripline impedances at a reasonable (12 ohms) value. Lower impedances produce practical difficulties; for example, the electrical pulser must provide more power to maintain a given voltage; also, ohmic losses become more important. To maximize the voltage available, we will provide independent pulsers and pulse sharpeners for each of the strips. In previous designs, a single pulse was split among the striplines. To minimize pulse dispersion, both the pulsers and the shapers will be located as close to the MCP as possible. Previous designs located the pulser outside the target chamber. The new design will utilize a much more compact pulser, which remains to be completely tested under vacuum chamber conditions.

An array of pinholes will project four images onto each microstripline. Because of the finite propagation velocity of the electrical pulse, each image will be recorded 50 ps after the previous one. The timing between the striplines can be arbitrarily adjusted, as desired. We are currently planning on using pinholes as small as 5 μm in diameter; the entire system should be capable of spatial resolution better than 10 μm. The resolution of the proximity focused phosphor is of order 50 μm; at 12x magnification, it is comparable to the pinhole limits.

To make up for the lack of gain in the thin MCP, we plan to couple it to a second, thick MCP, in a chevron geometry. This second channel plate will be run with a dc voltage, making for easy adjustments to the overall electron gain. The remainder of the instrument is identical to the current designs, with the proximity focused phosphor and film as the detector.

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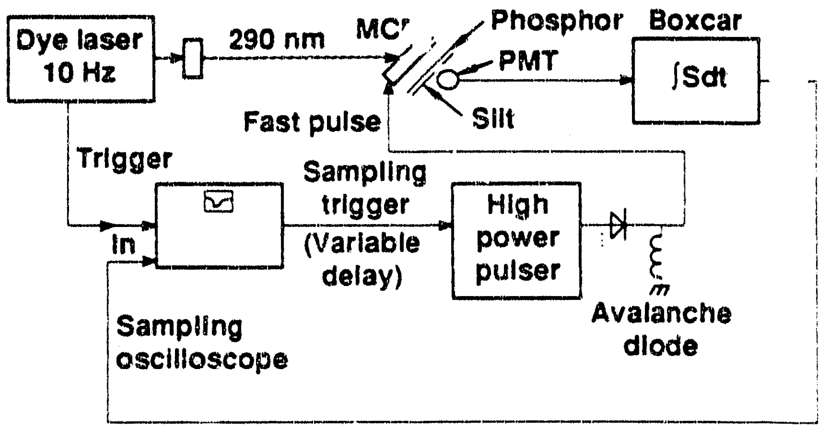
Figure Captions

1. Diagram of electronic sampling system.
2. Response of MCP detector with 200 ps FWHM electrical pulse.
3. Relative gain of pulsed MCP detector as a function of forward DC bias.
4. a) Monte Carlo simulation showing spread in exit times of electrons, for a DC (only) MCP voltage. Electron starts at t=0.

   b) Monte Carlo simulation of the measurement shown in Fig. 2.
5. System for measuring the time response of fast-gated microchannel plate detectors, using a picosecond dye laser and electrical time of flight techniques.
6. Design of 30 ps response x-ray framing camera.



Dye laser
10 Hz
290 nm
MCP
Phosphor
PMT
Boxcar
∫Sdt
Fast pulse
Slit
Trigger
Sampling
trigger
(Variable
delay)
High
power
pulser
In
Avalanche
diode
Sampling
oscilloscope

Fig. 1

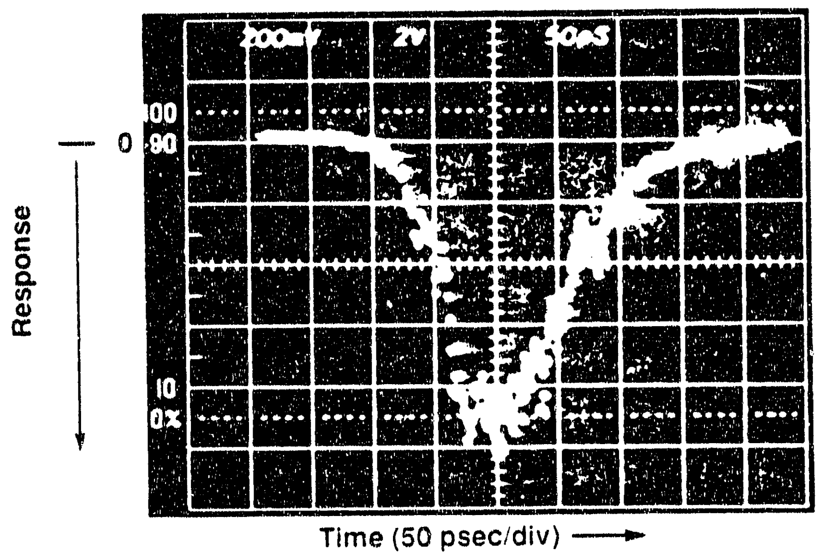
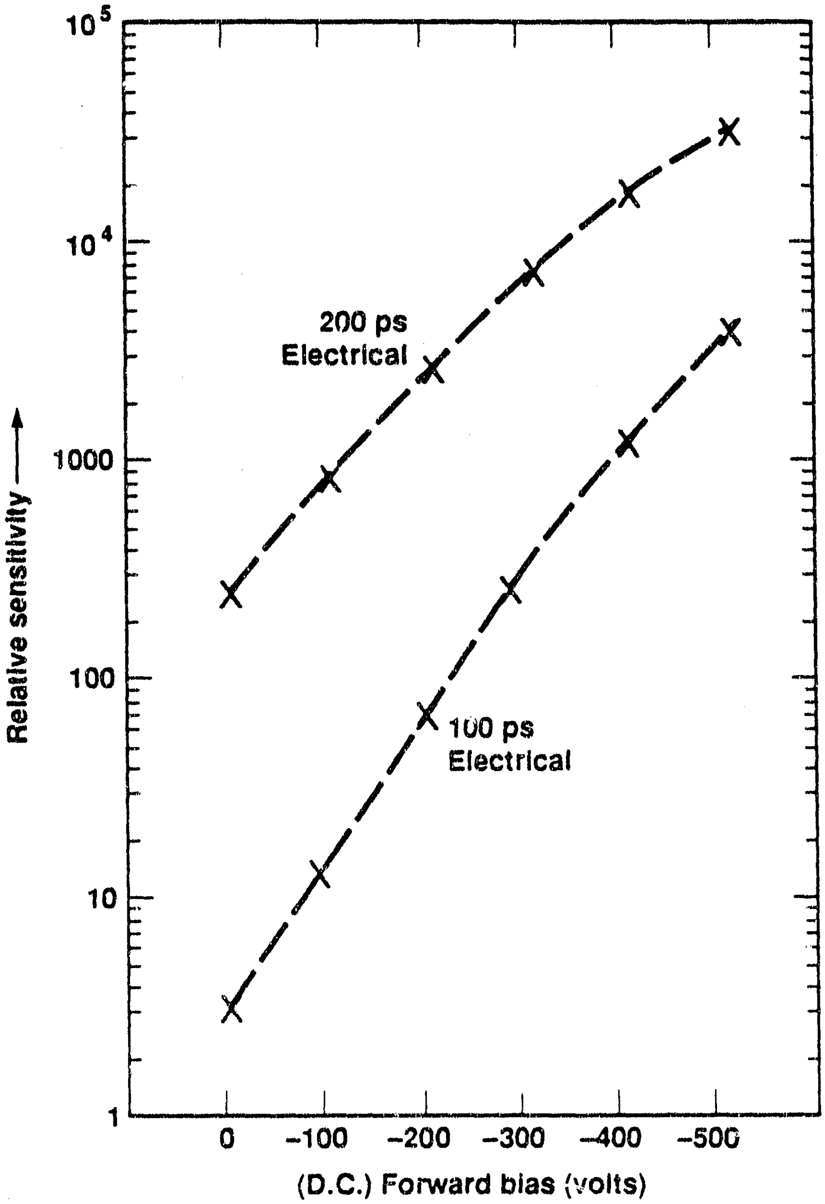


Fig. 2



Relative sensitivity
10^5
10^4
1000
100
10
1
200 ps
Electrical
100 ps
Electrical
0
-100
-200
-300
-400
-500
(D.C.) Forward bias (volts)

Fig. 3

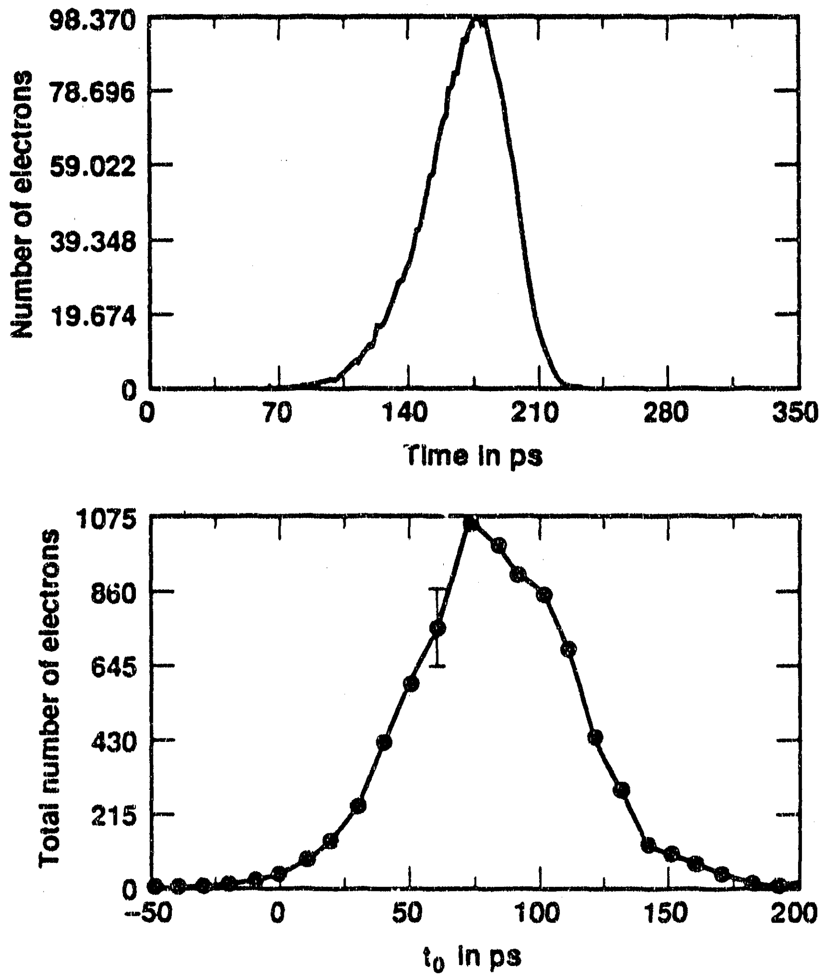
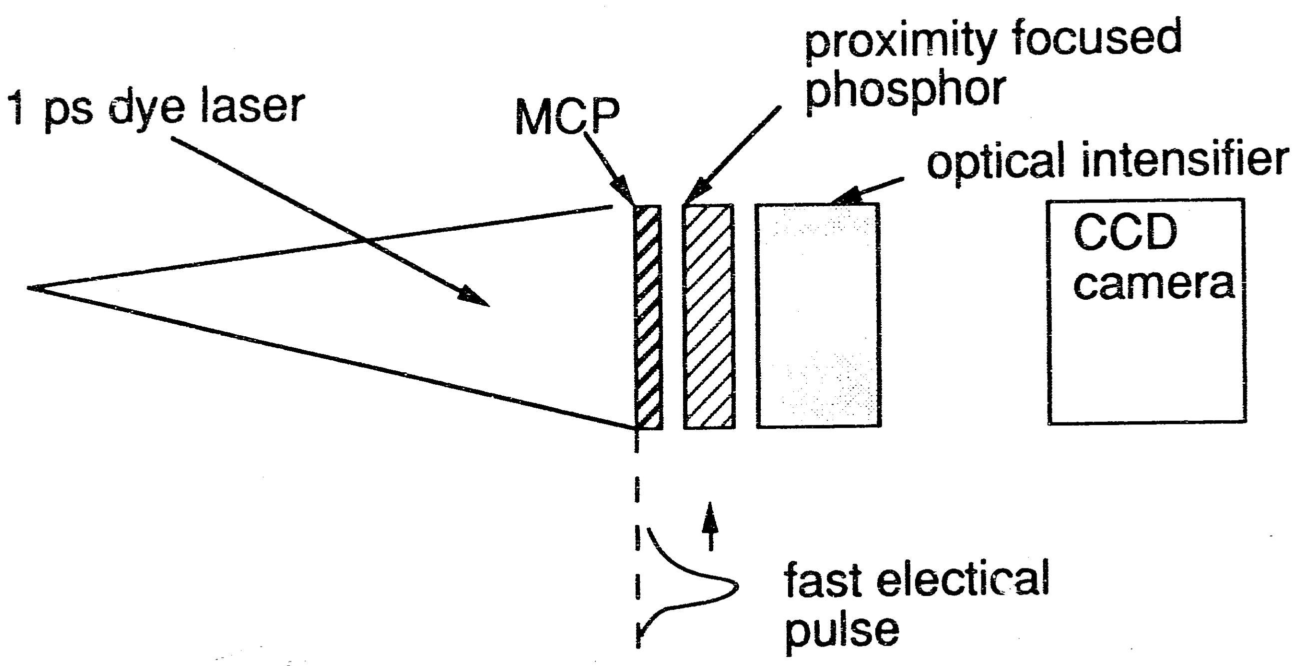

98.370
78.696
59.022
39.348
19.674
0
Number of electrons
0
70
140
210
280
350
Time in ps
1075
860
645
430
215
0
Total number of electrons
-50
0
50
100
150
200
t_0 in ps

Fig. 4

Measurement of MCP gating time by electrical "time of flight".

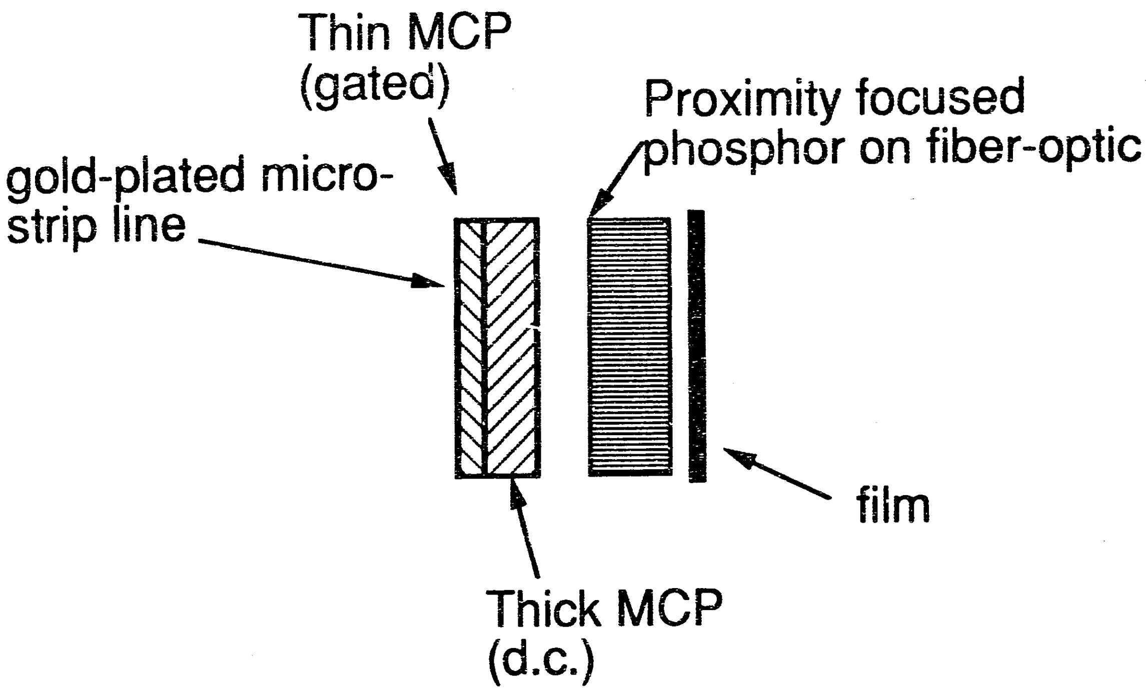


Laser uniformly illuminates the MCP. Measuring the extent of the exposure along the micro-stripline, and the propagation velocity of the electrical pulse, we can calculate the system's time response.

Electrical propagation velocity was measured with a TDR to be 1.48 cm per 100 ps.

Fig. 5

Design of sub-50 ps gated x-ray pinhole camera



Thin front plate for fast gating

close-coupled back MCP for added electron gain.

Fig. 6

END

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