Picosecond Time Response Characteristics of Micro-channel Plate PMT Detectors

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Abstract

The output pulse width in the time response of photo-multiplier tubes (PMT) is much faster in micro-channel plate (MCP) models compared to more standard dynode chain PMTs due to a vastly reduced variation in the path length of the electrons through the amplifying system. Typically the pulse widths can be in the region of 200ps compared to the nanosecond domain occupied by the best conventional PMTs. Photek manufacture PMTs with one, two or three MCPs depending on the gain required, and also use the same structure without any MCPs to work as simple photodiodes. We demonstrate the variation of output pulse characteristics due to the number and design of MCPs in a range of PMT models and illustrate the importance of having a properly designed 50Ω transmission line to deliver the pulse from the detector.

Introduction

Traditional photo-multiplier tubes (PMT) are able to detect low light levels by the use of a photocathode and then a chain of high voltage dynode stages that accelerate the electron avalanche through the detector, each stage adding to the gain of the signal through the photoelectric effect. The signal is finally collected on an output anode, normally held at ground potential. The design of the dynodes could be either the Squirrel-cage or Venetian-blind design. The gain of the signal is traditionally in the region of 10^6. Due to the nature of the construction of the gain apparatus there is a considerable variation in the possible path length taken by the electron avalanche. This results in a slow rise time and pulse width, normally greater than 1ns although Hamamatsu have reported a value of 700ps for the rise time of their fastest dynode PMTs.

Photek manufacture PMT detectors that use micro-channel plates (MCP) as the gain medium. MCPs are thin discs of photoelectric material that have narrow pores down which electrons can be amplified and are normally used in image intensifiers. The considerable reduction in the variation of the path length of the electron cascade through the detector as compared to conventional dynode-chain PMTs results in a much faster rise time and pulse width response.

Fast photon detectors are important components in time correlated single photon counting (TCSPC) where the time resolution of the system is dominated by the pulse response of the detector[1]. TCSPC is used in fluorescence lifetime measurements in chemical[2] or biological[3] applications in the picosecond or nanosecond time domain. High time resolution detectors are also used in laser ranging systems[4] and high-speed communications[5].

In this paper we present a study of three different Photek PMT models that have a variety of MCP and anode designs to illustrate the impact of such features on the rise and fall time performance.

MCP Photo-multiplier Tubes

The construction of an MCP based PMT follows closely the construction of a standard image intensifier, but has an anode where the intensifier would have a phosphor screen.

Input light activates a transmitting photocathode that ejects electrons into the MCP stack. The cathode and front MCP are positioned in close proximity to ensure a high electric field. The electrons are amplified as they bounce off the internal walls of the MCP pores and are amplified on each collision. On exiting the final MCP the electrons are drawn towards the anode by a further electric field.

The three detectors used in this study were a PMT125, a PMT210 and a PMT318. The various parameters of these detectors are given in Table 1.

Table 1 *PMT detector parameters*

Detector	Anode Diameter	Number of MCPs	MCP Thickness	Pore Diameter	Pore Bias Angle	Gain
PMT125	25mm	1	0.33mm	6μm	5°	10^3
PMT210	10mm	2	0.33mm	6μm	5°	3.5×10^5
PMT318	18mm	3	0.4mm	10μm	12°	2×10^6

All of the detectors were constructed in 25mm diameter bodies with 25mm diameter MCPs and cathode optics, regardless of the size of the anode.

Rise Time Measurements

The conventional definition of rise time is the time for the pulse to go from 10% to 90% of the pulse amplitude. Due to the nature of electron avalanche detectors the leading edge of the response pulse will go negative and some may consider this to be a fall time, but the convention in such detectors is always to consider the leading edge as being the rise time and is treated as such in this analysis.

The rise time of a vacuum based electron avalanche detector can be considered as the variation in arrival time (at the anode) of the group of electrons. Clearly if all of the electrons arrived at the same time the detector would have an infinitely fast rise time.

The rise time of the PMT detectors were measured by an Agilent 86100C sampling oscilloscope operating at a sampling rate of 18GHz. To remove random noise all traces were averaged over 16 cycles of the oscilloscope. The PMTs were stimulated by the same laser operating at a wavelength of 650nm with a pulse width believed to be less that 50ps FWHM, running at a repetition rate of 10kHz. The laser pulse was attenuated by an appropriate strength of ND filter, depending on the gain of the PMT.

There are three main possible sources of rise time spread in an MCP based PMT:

1. Cathode Gap
2. MCP Stack
3. Anode Gap

1. Cathode Gap

The cathode gap does not affect the rise time because electrons emitted from the cathode only have a small amount of initial energy, and hence a low initial velocity. The laser wavelength used has a wavelength of 650nm so the photons have an initial energy of about 2eV, and after the work function of the photocathode material takes a portion of this it leaves very little energy for the electron compared to the voltage across the cathode gap (typically 200V).

The transit time from the cathode to the first MCP is therefore almost completely defined by the lateral voltage across the cathode gap. A study has showed the effect of the mean radial emission energy of electrons from photocathode material on the position resolution of image intensifiers[6]. This has resulted in the design of the gap between the photocathode and the MCP to try and achieve a short distance and a high field to reduce the radial spread of electrons from a point source. In PMTs however, the crucial parameter is the time of flight from cathode to MCP. The gap voltage will define the lateral energy of the electrons and hence the lateral acceleration, leading directly to the time of flight. The radial energy and lateral energy can be considered independently so any radial spread in the position of the electrons will not affect their time of flight.

Although the cathode voltage has a negligible affect on the rise time, giving the electrons more energy when they make their first contact with the MCP will result in the gain process being more efficient. This is shown on Figure 1 for the PMT125, along with the lack of dependence of the rise time on the cathode gap voltage. Similar results were observed for the PMT210 and PMT318.

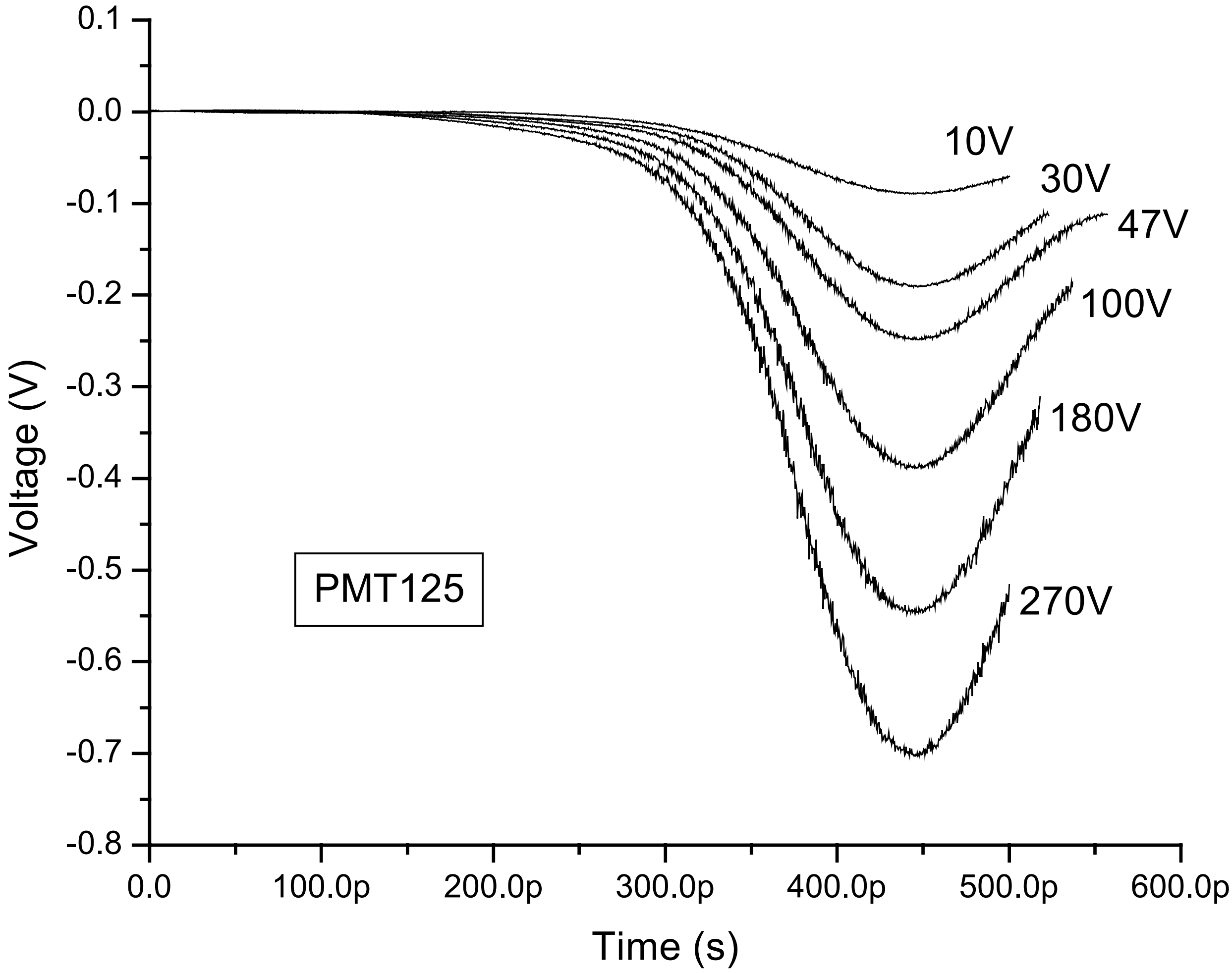

Figure 1 *Variation of pulse response with cathode gap voltage for a PMT125, no detectable change in rise time was observed*

2. MCP Stack

The MCP stack is considered to be the main source of rise time spreading due to the many different possible path lengths (and hence transit times) of the electron avalanche through the MCP pores. Using narrow pore MCPs would be expected to reduce the path length variation. A large number of MCPs in the stack will also offer the electrons a wider variation of path length and is therefore expected to increase the detector rise time. The result of the various path lengths is that the group of electrons generated from a single electron at the start of the MCP stack will arrive at the end of the MCP stack at slightly different times. While we cannot vary the MCP voltage parameters if we want to do a study on a detector with a fixed gain value, we can compare the performance of the various MCP arrangements in the three different PMT detectors.

The rise time results shown on Figure 2 point out that the PMT125 and PMT210 both reach a similar value of rise time when the effect of variable exit velocity from the MCP stack is reduced (by increasing the anode gap electric field), despite the PMT210 having another MCP. However the construction of the PMT125 made it difficult to increase the anode electric field beyond the maximum value shown, and the shape of the trace indicates that the PMT125 rise time may still improve slightly. The rise time of the PMT318 settles at a higher value.

From the parameters on Table 1 this would indicate that the pore size and the bias angle have a greater influence on the rise time of an MCP based PMT than the number of MCPs. This agrees with an earlier study at Hamamatsu[7] although our values of rise time (122ps) and fall time (167ps) for the PMT210 compare favourably with their best values of 167ps and 721ps respectively.

3. Anode Gap

The anode gap would work in a similar manner to the cathode gap except for the crucial difference that the electrons leaving the MCP will have a significant variation in the lateral velocity of the electrons being ejected into the gap.

An electron in an electric field is subject to a force (*F*) related to the electric field strength (*E*) and the charge on the electron (*e*):

$$F = Ee \tag{1}$$

The force on the electron can also be expressed as $F = ma$ where m is the electron mass and a is the acceleration, so we can re-arrange this to become:

$$a = \frac{Ee}{m} \tag{2}$$

Therefore the acceleration of electrons is defined by the strength of the electric field and two fixed physical constants. To consider the relationship between the rise time and the electric field across the anode gap consider the equations of motion:

$$t = \frac{v-u}{a} \qquad v^2 = u^2 + 2ad \tag{3}$$

Here u is the initial velocity, v is the final velocity, d is the distance across the gap and t is the time of flight. If we rearrange these to consider t in terms of only u and fixed parameters we get:

$$t = \frac{1}{a}\left[\sqrt{\left(u^2 + 2ad\right)} - u\right] \tag{4}$$

This equation illustrates the dependence on the transit time *t* on the initial velocity *u*. If there is a big variation in the exit velocity of electrons from the MCP then this will affect the rise time. However if we differentiate equation (4) with respect to *u* we get:

$$\frac{dt}{du} = \frac{1}{a}\left[\frac{u}{\sqrt{\left(u^2 + 2ad\right)}} - 1\right] \tag{5}$$

This represents the dependence of the rise time component *dt* on the variation in initial velocity *du*. We can minimise this by making *a* as large as possible and from equation (2) we can do this by increasing the electric field *E*. This is illustrated in the experimental results on Figure 2.

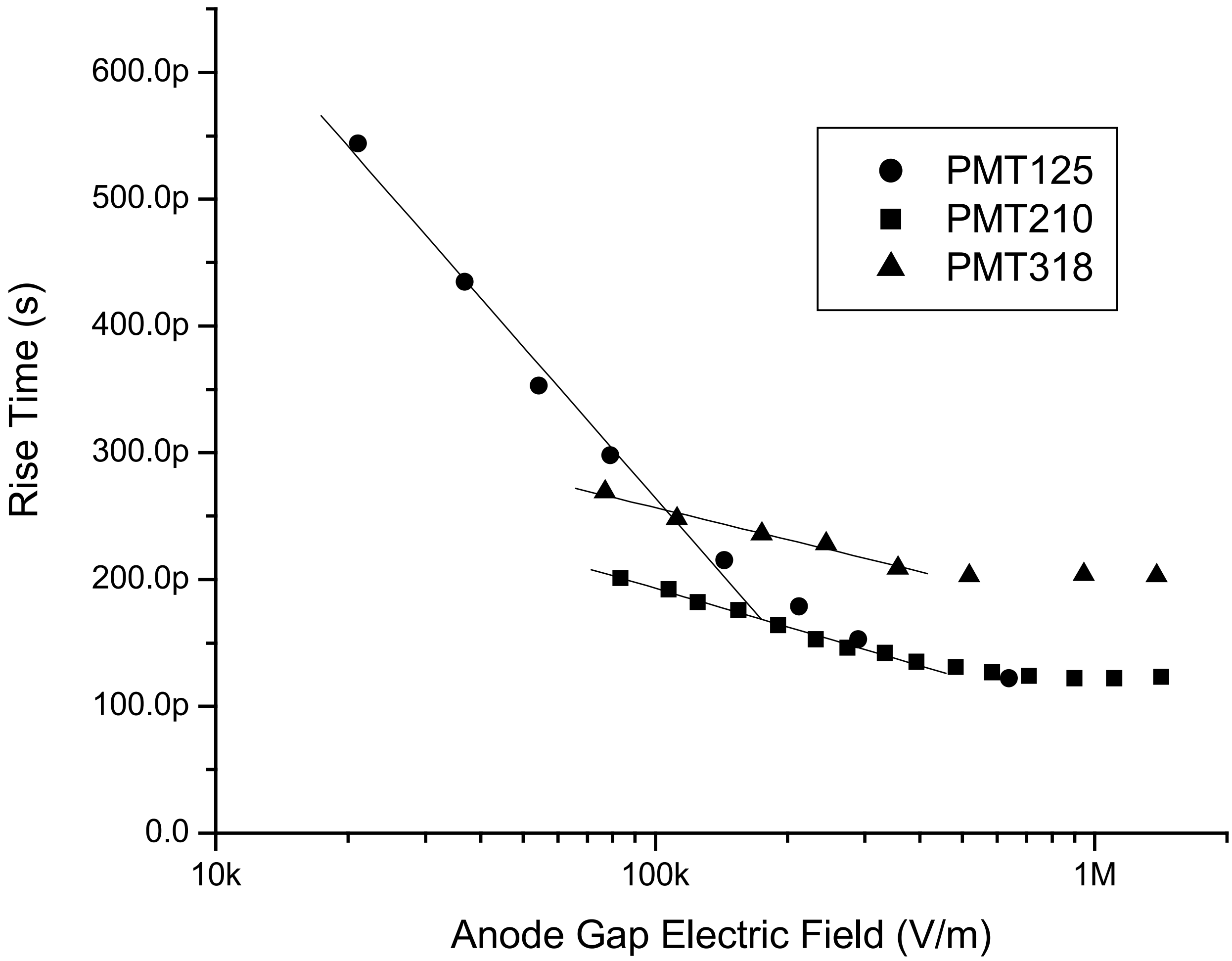

Figure 2 *Variation of rise time with the electric field across the anode gap for the three PMT detectors*

From Figure 2 we can see that the improvement in rise time with increasing anode gap electric field is effective only up to a point, at which point the spreading due to MCP stack will dominate.

Varying the anode gap electric field will have no effect on this as it is due to the variation in the arrival time of the electrons at the end of the MCP stack.

Fall Time Measurements

The fall time and also the shape of the fall are principally defined by capacitive effects around the anode and the impedance of the transmission line that delivers the signal out of the detector. To ensure that the high-speed pulse that arrives at the anode is transported to the output SMA connector of the detector with the maximum efficiency and most faithful reproduction, the impedance of the effective transmission line of the contact from SMA to anode is designed to be as constant as possible. As the impedance of SMA connectors and the input to the majority of high-speed analysis equipment is 50Ω, this is the value we design the tubes around.

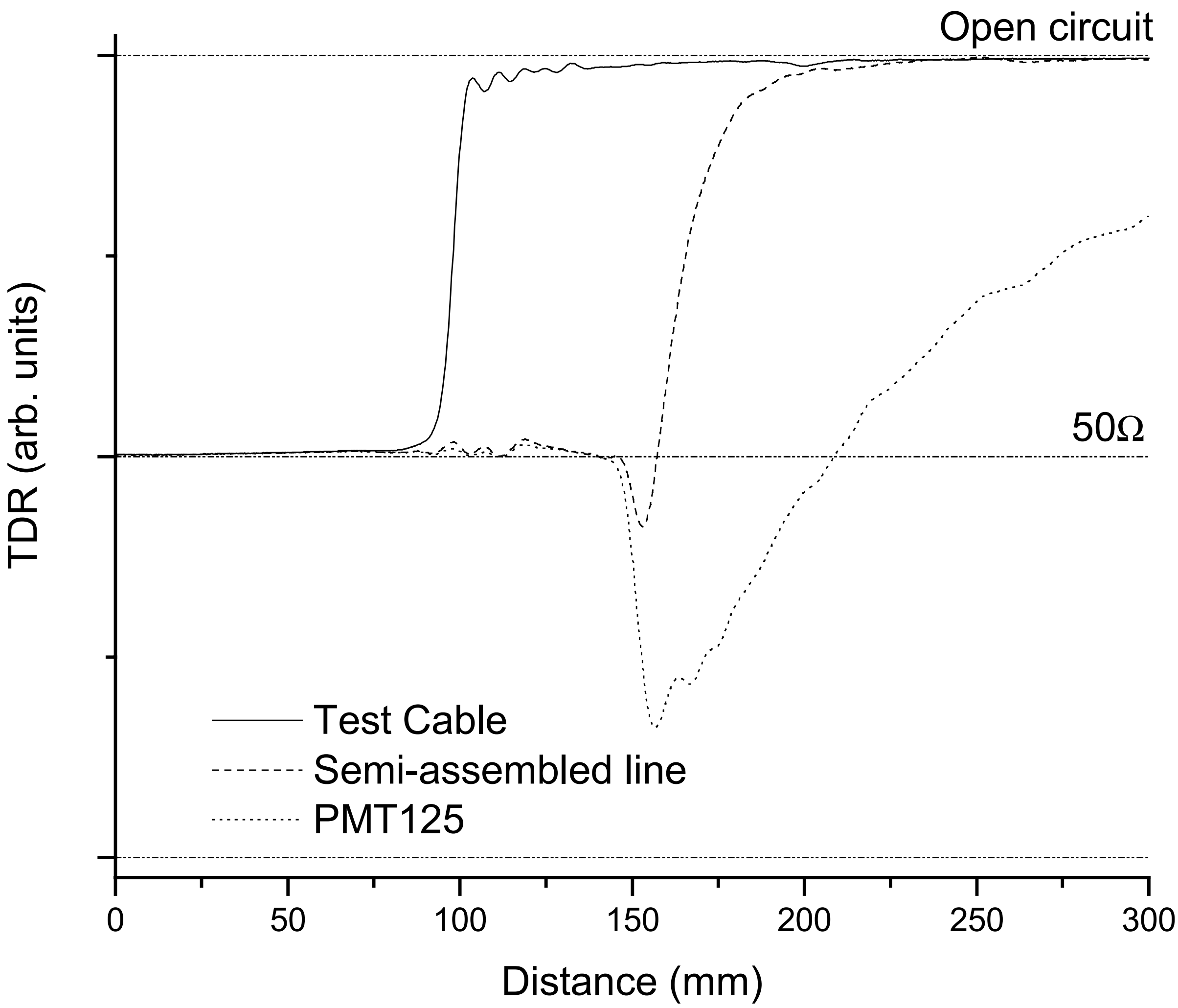

Figure 3 *TDR traces for a PMT125 and a semi-assembled transmission line*

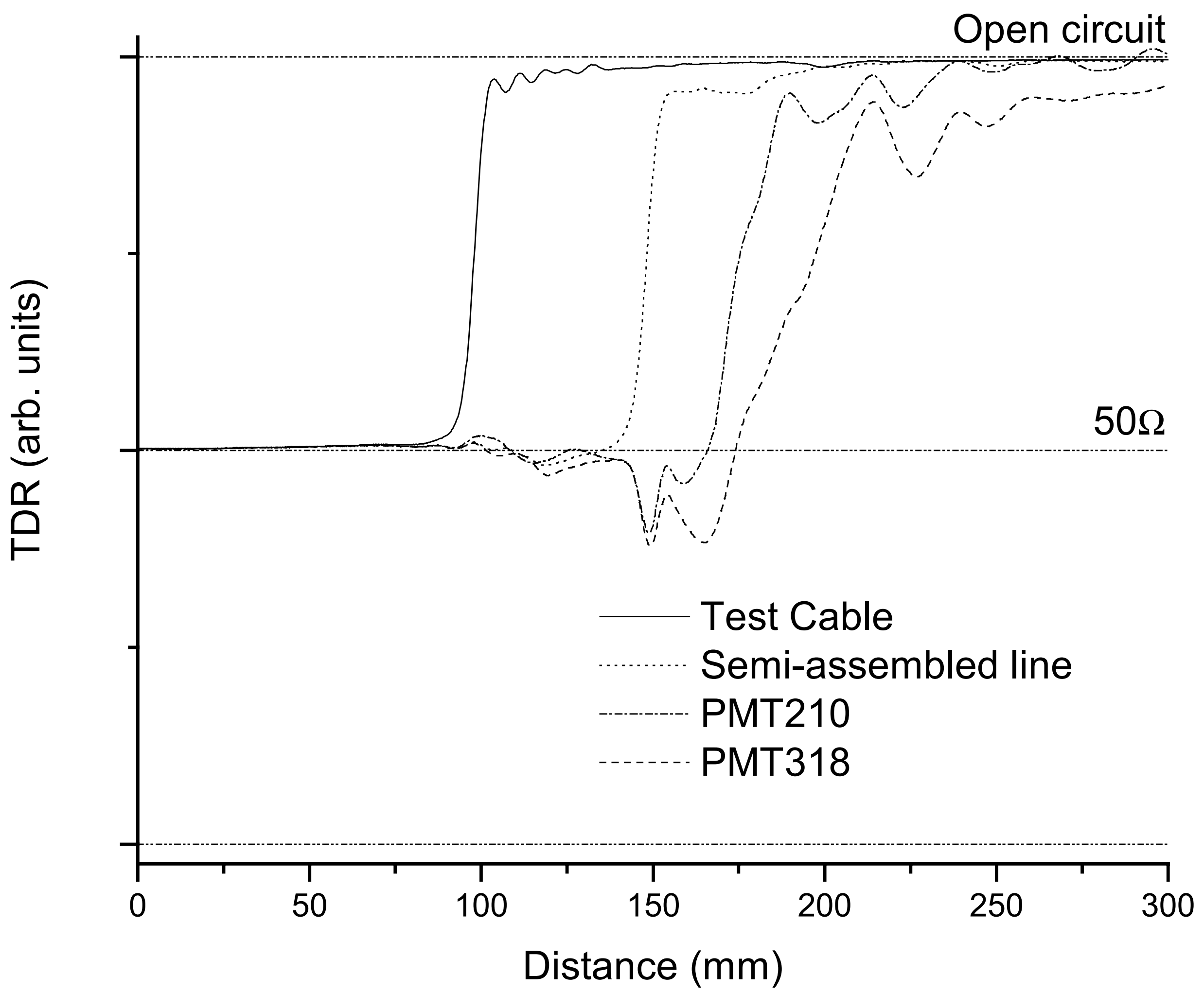

Figure 4 *TDR traces for a PMT210, PMT318 and a semi-assembled transmission line*

The impedance of the anode contacts of the three PMT detectors were measured by time domain reflectometry (TDR) using a 54754A TDR module in the Agilent 86100C sampling oscilloscope used for the rise time measurements, and are shown on Figure 3 and Figure 4.

The transmission line design for the PMT125 is slightly different from the design for the PMT210 and PMT318, so we have shown the TDR traces on different figures. The TDR trace for the test cable was performed without the detector attached and is used to show the position where the cable meets the detector at the SMA jack. Ideally if a PMT had a good 50Ω transmission line up to the anode with no excess capacitance it would look like an open circuit termination to a 50Ω transmission line illustrated by the test cable TDR trace.

The traces shows that there is a good continuation (with a slight ripple) of the 50Ω impedance from the SMA jack for about 50mm up the tapered transmission line. Note that the distance measurement is an approximation and should not be interpreted too rigidly. However it can clearly be seen that the PMT125 has a large amount of excess capacitance when the transmission line reaches the anode as the large anode area makes it very difficult to maintain the correct dimensions for a 50Ω transmission line. The effect of this can be seen on Figure 5.

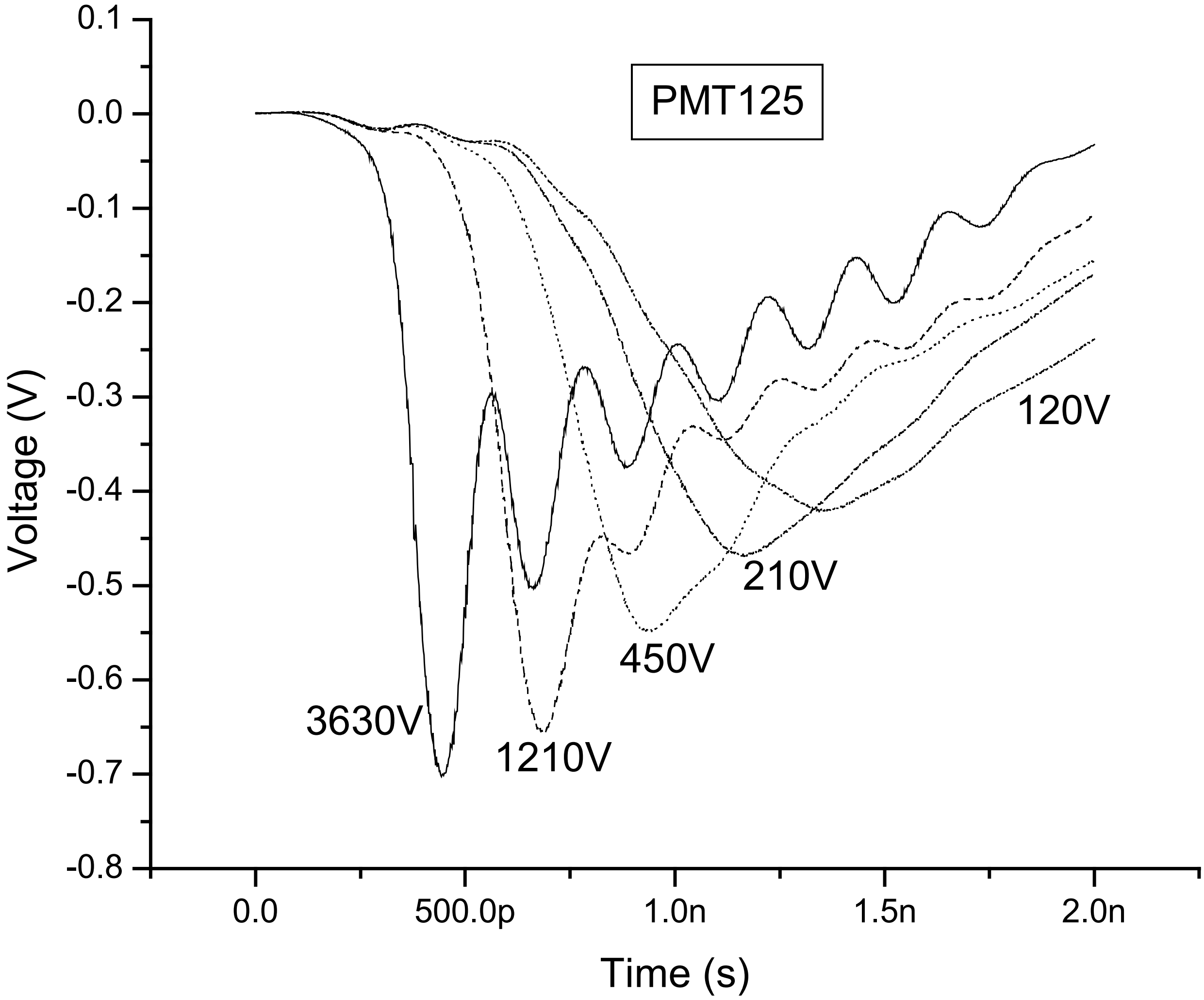

Figure 5 *Variation of the pulse shape of a PMT125 with various values of Anode Gap Voltage*

The excess capacitance clearly causes a ringing in the fall time of the pulse, the amplitude of which depends greatly on the anode voltage (i.e. the rise time of the pulse). Despite a good rise time this is an unwelcome effect in the PMT125. We can now compare the fastest rise time pulse on a PMT125 with the corresponding pulses from the PMT210 and PMT318 on Figure 6.

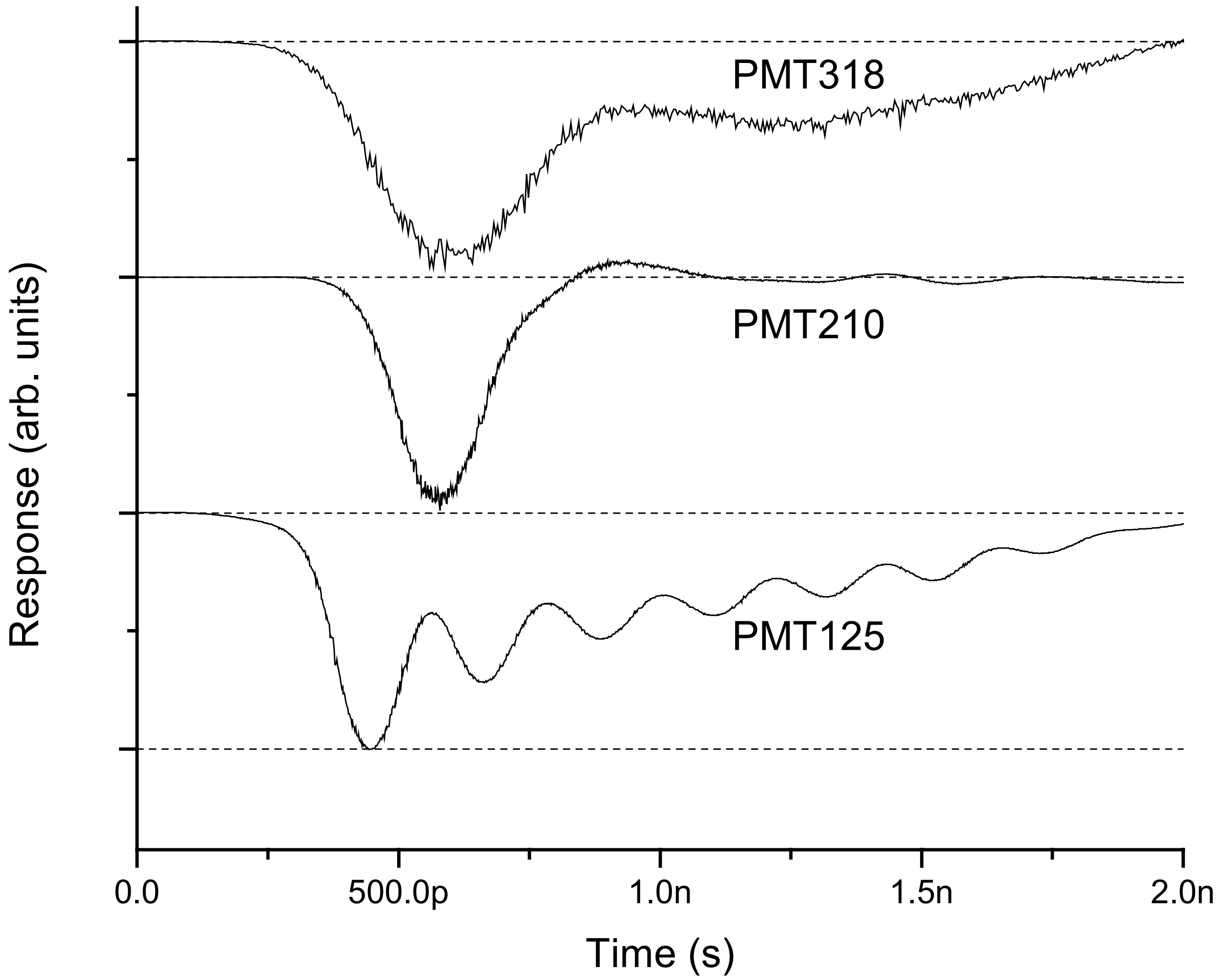

Figure 6 *A comparison of the fastest rise time pulses of the three PMT designs*

It is clear that the best pulse shape and fall time corresponds to the PMT210, which has the closest TDR trace to the ideal. A slight overshoot after the PMT210 pulse can be attributed to the minor capacitive dip on its TDR trace. We believe this is the point on the transmission line where the line passes from outside to inside the vacuum chamber and has a ceramic insulator for a short distance. As ceramic has a much greater dielectric constant than either air or vacuum this gives a short peak in the capacitance value.

We believe that the crucial factor in the superior performance of the PMT210 over the PMT318 or the PMT125 in terms of pulse width and fall time is that the 50Ω transmission line dimensions can be maintained right up to the end of the anode (other than the ceramic point previously mentioned). In the PMT125 and PMT318 designs the dimensions had to be compromised at the end of the transmission line due to the respective size of the anodes.

Conclusion

We have found that the rise time of MCP-based PMT detectors is principally governed by the variation in transit time through the MCP pores and the variation in exit velocity from the MCP stack. The variation in transit time through the MCP pores is affected more by size and bias angle of the MCP pores rather than the number of MCPs. The spread of the rise time caused by variations in the exit velocity from the MCP stack can be severely reduced by increasing the electric field from the MCP to the anode. The fall time performance is critically affected by the 50Ω transmission line delivering the pulse from the anode and our best performing PMT210 has a near-ideal TDR trace giving it a rise time of 122ps, a fall time of 167ps and a pulse FWHM of 193ps.

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