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### **Title: Ultra-Fast Photomultipliers with High Dynamic Range**

#### **Abstract**

The response time of microchannel plate photomultipliers is reduced by careful design and by the use of small pore microchannel plates. This enables high frequency response and high time resolution in synchronous applications, such as laser stimulated fluorescence decay measurements.

The use of these devices for single-shot experiments, in conjunction with a “real time” oscilloscope offers a long recording period. We have analysed the dynamic range and limitations of MCP photomultipliers for such single shot applications.

#### **Introduction**

The microchannel plate photomultiplier has been developed for a range of high speed applications. The main factors affecting response time are the collection area and microchannel plate pore size [Ref 1]. For example, a tube with 10 mm photocathode is able to achieve a rise time of 66 ps and pulse FWHM of circa 100 ps [Ref 2].

For applications where light gathering power is important, the photomultiplier has a huge advantage over semiconductor devices. For an optical wireless system, the MCP photomultiplier was reported to be 30 dB more sensitive than either an APD or PIN diode and to have a dynamic range of 40 dB [Ref 3].

This arises from the fundamental properties of vacuum devices and semiconductor devices – the capacitive load of a vacuum device is low on account of dielectric constant and device geometry – enabling much larger vacuum devices than semiconductors in terms of capacitance per unit area. Fifty years after the semiconductor revolution started, vacuum tubes remain pre-eminent in large (high power) high frequency applications – while semiconductors are pre-eminent for high speed miniature low power devices.

The MCP photomultiplier is also important for time resolved photon counting applications such as fluorescence decay measurements. In this case, the gain ( $10^6$ ) bandwidth (GHz) product is several orders of magnitude beyond the capability of semiconductor devices for time Correlated Single Photon Counting Analysis of Fluorescent Decay [Ref 4]. Timing accuracy in the range 40 ps – 20 ps is reported for MCP photomultipliers used in this application.

The MCP photomultiplier is also used for satellite laser range finding set-ups. In this case, the ability to reduce background light by gating the photomultiplier open for brief time periods in synchronism with the

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expected laser return is important. In this way, it is possible to reduce the laser power to “eye-safe” levels while maintaining range accuracy to around 20 ps (less than 1 cm range resolution) [Ref 5].

## **I. DYNAMIC RANGE**

### **I.1 MCP Considerations**

The microchannel plate is a non-linear device which saturates at an output current proportional to its bias current. This property is very beneficial in its main application – night vision – as it protects the user from in advertant flashes and bright lights in the night time scene.

The MCP photomultiplier is not linear in any sort of DC mode where the average current is in the micro A range. The precise output depending on the MCP bias current.

In single photon counting mode, MCP photomultipliers are typically linear up to about 1 million counts/sec. The lower limit is simply the thermionic dark count and can be 10 counts/sec, giving a dynamic range of  $10^5$  in this mode.

The maximum count rate is determined by the number of MCP pores and the MCP recovery time. It is interesting to note that a tube with 12 mm anode and 3 micron pore MCP has just as many pores as a 40 mm tube with 10 micron pore MCP (circa  $10^7$  pores). With typical MCP glass, the recovery time will be less than 50 msec, enabling linear count rates of  $10^7$  counts/sec.

For pulses with a repetition rate which is slower than the recovery time – eg 50 Hz or less – the maximum pulse that can be generated is a function of the number of channel pores, and the gain at which the tube is operated. For example, with  $10^7$  pores and a gain of 1000, the maximum pulse is  $10^{10}$  electrons, corresponding to 1500 pC. In principal, this could be 1.5A for 1 nsec or 1.5 mA for 1  $\mu$ sec. Obviously, this increases linearly with gain, but it is naive to imagine that photons will conveniently fall into every channel pore, so the photomultiplier will become non-linear at significantly lower levels than the above analysis. It is however clear that an MCP photomultiplier is better at analysing fast infrequent events, than slow (microsecond) frequent events.

## **2. LOW-END LIMITS**

The gain of an MCP photomultiplier is adjusted by MCP voltage and stack length. For a single MCP, the average gain can be as high as 10,000, but the event to event variance in gain is huge and is generally described as a negative exponential. Thus, a small number of events will have high gain tending to  $10^6$ , and the most frequent will have low gain – significantly below the analogue average.

For a tube with FWHM circa 100 ps, single photon events with gain of over  $10^5$  will register on a high bandwidth real time scope with an amplitude of 5 mV.

With a double MCP, there is a quasi Gaussian pulse height distribution, typically peaking at  $10^6$  with a FWHM that can be 100% or less. This is caused by space charge saturation limiting the gain in individual channel pores. Individual dark noise photon events appear on a real time scope with an

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amplitude of about 20-50 mV. The frequency of these events depends on photocathode type and tube size and is typically 10,000 counts/cm<sup>2</sup>/sec for S20 photocathodes to less than 10 counts/cm<sup>2</sup>/sec for bialkali and other UV sensitive photocathodes.

The lower limit of detection is likely to be a few mV for single MCP photomultipliers and 30 mV (corresponding to single photons) for double MCP devices.

### 3. UPPER END LIMITS

The capacitance between the MCP and the anode governs the CR time constant of the photomultiplier, and the gap between these components determines the pulse rise time for a given anode – MCP voltage since the rise time is governed by the transit time of electrons from the MCP to the anode. This gap and voltage also determines the peak space charge limited current that can be drawn.

For PMT110 and 210 series, the gap in question is about 1.5 mm giving a capacitance of 1 pF for the vacuum gap so CR time constant of approximately 50 ps into 50 ohms.

The Langmuir relationship:-

$$I_{\text{sat}} = \frac{2.33 A}{d^2} V^{3/2}$$

This formula gives a saturated pulse of about 3.6 Amp (corresponding to 180 V into 50 ohms) for an anode voltage of 1400 Volts. Non-linearity will appear with pulses of about half this values –25 Volts into a 50 ohm scope.

For bigger tubes, the anode gap must be increased to provide a useful CR time constant. There is not much point in doing this in proportion to the small tube, as MCP pore size tends to increase with MCP size. As a rule of thumb, we have increased the gap in proportion to the square root of the area. This maintains the maximum space charge limited signal, while making for longer pulse response.

Obviously, the maximum output pulse can be increased simply by adjusting the operating voltage, in which case, the system dynamic range is likely to be determined by the oscilloscope being used.

### Experimental Data in Single Shot Applications

40 mm photomultipliers have been used to measure neutron time of flight with ultra-fast neutron scintillators. The scope was a 1 GHz Tektronix 684 and signals up to 25 Volts appear to be linear [Ref 6].

More recently, we have studied the performance of PMT110 in some detail.

The dynamic range with short pulses (1 ps) and low repetition rate is shown in Figure 1. It can be seen that the output pulses are linear with input power up to an output amplitude of about 40 V and saturate at 180

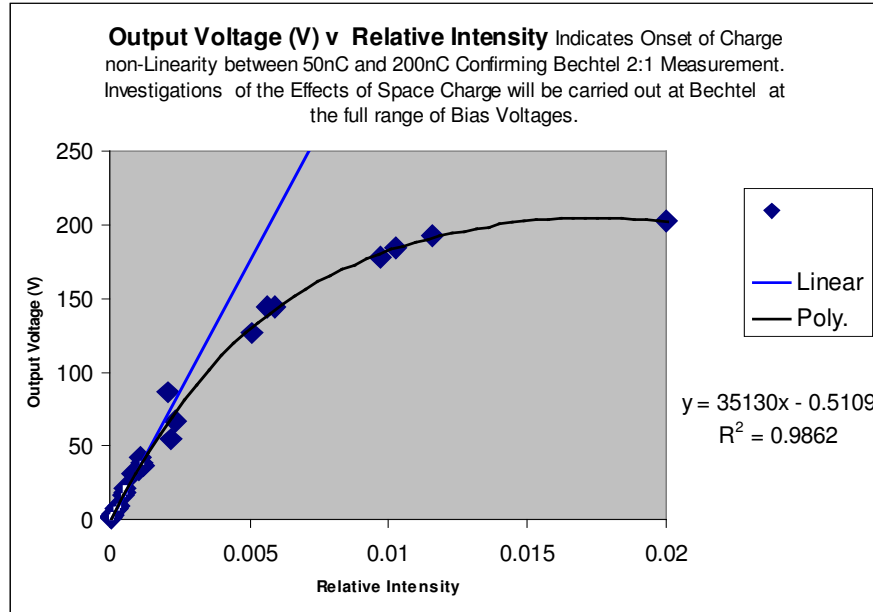
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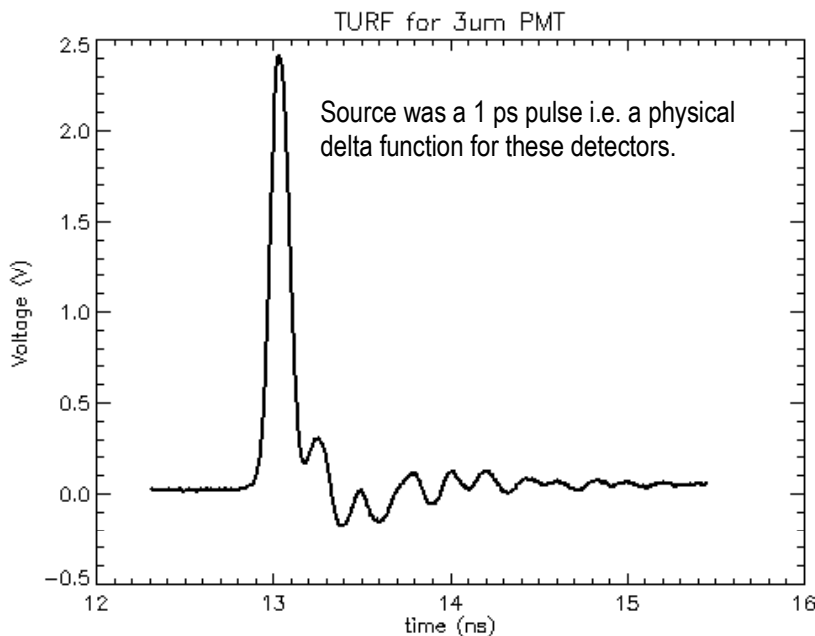
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V as predicted by the Langmuir limit of space charge. The pulse saturates at a higher voltage than anticipated. We believe this can be explained by the presence of much higher electron energy spread emitted by the MCP, than one would obtain from a thermionic cathode.



**Figure 1 – Non-Linearity Measurement (Trident)**

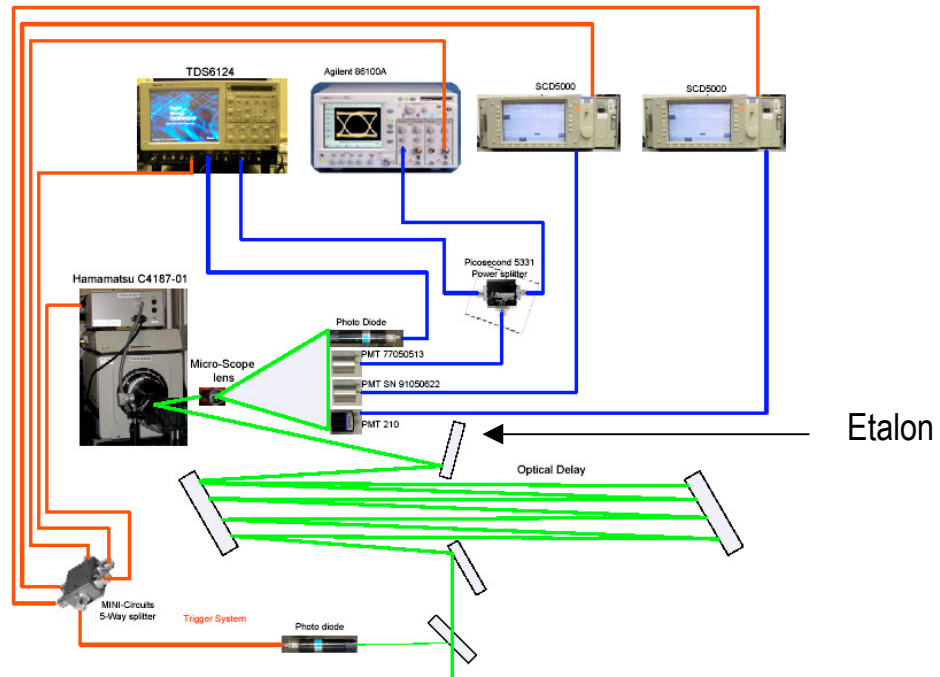
Figure 2 shows the response of the PMT to a single laser shot (1 ps).



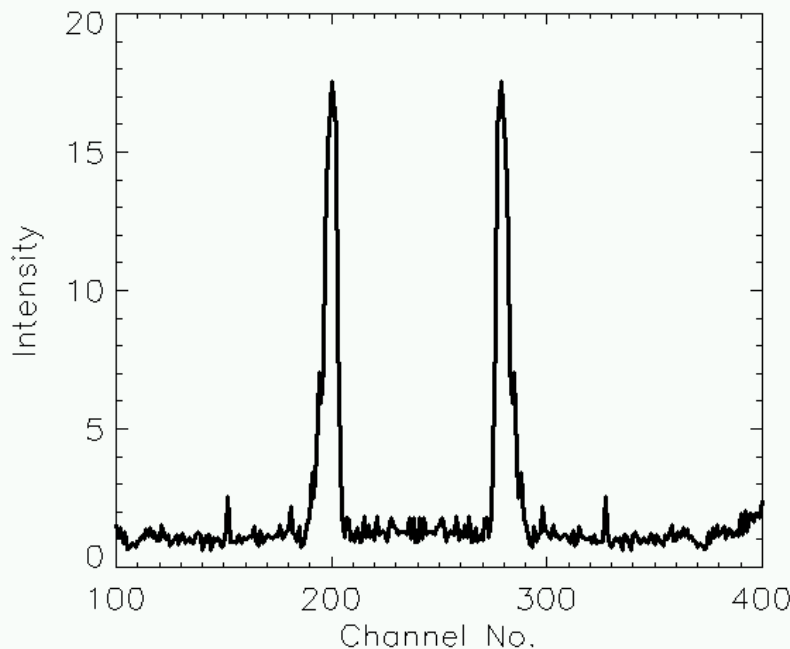
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Issue	2
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**Figure 2 – Measurement of Unit Response Function on Trident Short Pulse Laser (1 ps)**

The pulse-pair resolution of this tube was investigated by using an Etalon to vary the temporal separation. This set-up is shown in Figure 3. The system set-up and calibration was verified using a streak camera. Figure 4 shows the trace for a pair of pulses with 100 ps separation.



**Figure 3 – Optical Etalons were used to create Double Pulses**

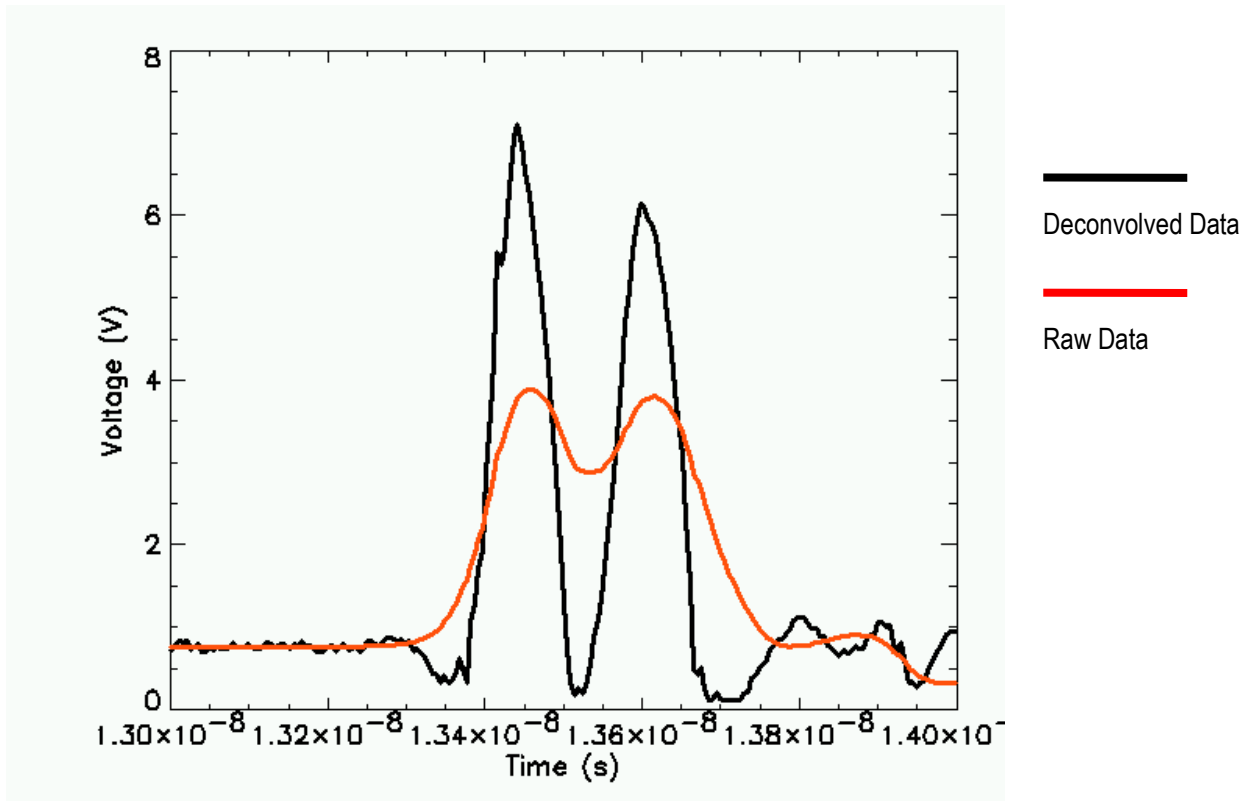


**Figure 4 – Streak Camera Record of 100 ps Double Pulse**

The raw data recorded by the photomultiplier shows an initial broadening of the pulse as the separation of the pulse pair is increased. At a pulse pair separation of 150 ps, it is clear on the photomultiplier trace that a pair of pulses is being observed. The accuracy of this data improves as the pulse separation is increased, and a very clear valley develops between pulse pairs with separation of 200 ps or more.

At pulse separation below 150 ps, the pulse width asymptotes towards the 100 ps FWHM observed with very short input pulses.

A series of traces of the raw data with pulse pair separations of 100 ps, 154 ps are show in Figures 5 and 6. This data is summarised in Figure 7, which compares the photomultiplier data with the real time separation between pulses measured with a streak camera.



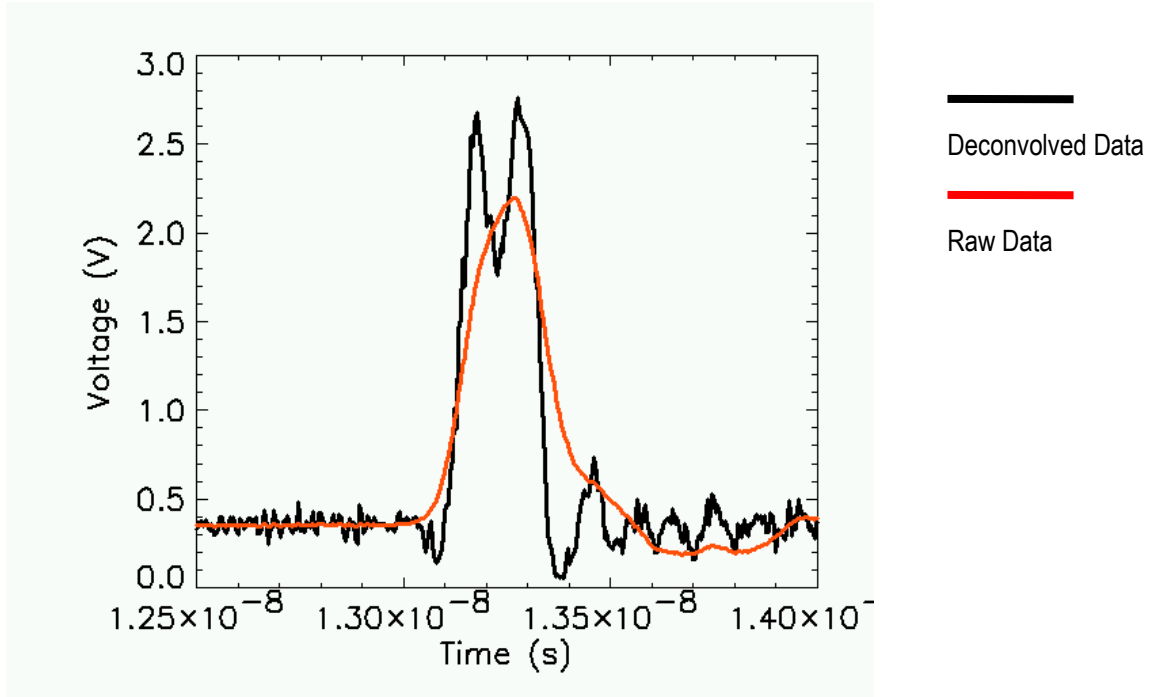
**Figure 5 – Measurement of 154 ps separation double pulses**

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**Figure 6 – Measurement of 100 ps separation double pulses**

It has been shown that the photomultiplier data can be significantly improved by computational deconvolution techniques [Ref ]. This allows reasonable pulse pair resolution to less than 100 ps.

**Conclusion**

It is shown that fast photomultipliers are useful for dynamic measurements of single shot events with a time resolution of 100 ps and are linear between a few mV and 50 V dynamic range.

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