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# GaAs Photo-Multiplier for LIDAR Thomson Scattering

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** See annex of J. Pamela et al, "Overview of Recent JET Results and Future Perspectives", Fusion Energy 2000 (Proc. 18th International Conference on Controlled Fusion and Plasma Physics, Sorrento, 2000), IAEA, Vienna (2001)*

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## ABSTRACT

Edge LIDAR Thomson scattering at JET is used for measuring temperature and density gradients of the edge plasma. The accuracy of the current measurements are limited not only by the spatial resolution of the system but also by photon statistics The accuracy of the measurements can be increased by at least a factor two by improving the sensitivity of the detection system. The present detectors are fast 18 mm diameter MCP-photomultipliers with multialkali-photocathodes. Quantum efficiency is 5% @ 650nm decreasing towards the red. We present the characteristics of a newly developed MCP-PMT with GaAs photocathode. Four 18 mm diameter photomultipliers with a V-stack MCP and a preliminary prototype unit have been produced and tested to fully equip the edge LIDAR diagnostic. The GaAs photocathode of the new detectors has quantum efficiency in excess of 20% in the spectral range 520-850 nm. The effective quantum efficiency has been measured and is at least four times that of the present detectors. Investigations of the other characteristics required for the use in a LIDAR system show good results. The pulse response time is slightly faster than that of the current tubes, potentially offering the possibility of improving the spatial resolution to better than the current 12 cm. The effect of varying the gate voltage between 100 – 300 V has been investigated. Lower gate voltages cause less ringing on the output signal and only increase the effective noise slightly.

## 1. INTRODUCTION

The edge LIDAR Thomson scattering diagnostic (KE9) at JET measures the electron temperature ($T_e$) and density ($n_e$) along a chord from the equatorial port to the vertical tiles of the inner divertor leg. It uses a 5 J ruby laser and a four channels filter polychromator with multialkali photocathode, 18 mm diameter, microchannel plate (MCP) photomultipliers (PMT). Signal waveforms are recorded with a fast oscilloscope (1.5 GHz, 5 Gsamples/sec). The photocathodes are gated (ON) for only 50 ns in order to reject the strong stray light pulses from the input optics. KE9 uses a LIDAR technique, so the spatial resolution is determined by the temporal resolution, which is given by the geometric mean of three contributions: laser pulse duration (300 ps), detector (650 ps) and digitizer (400 ps) response times. This corresponds to a spatial resolution of 12.5 cm along the laser beam path, which is reduced to about 3 cm at the edge and increasingly less inwards if the chord is projected onto the equatorial plane along the magnetic surfaces.

$T_e$ and $n_e$ profile measurements at the plasma edge are particularly important for H-mode pedestal studies. However the sensitivity of the present edge LIDAR is not high enough to determine $T_e$ and $n_e$ with sufficient accuracy. In fact measured profiles show that the relative error of $T_e$ often exceed 50% for $n_e < 1x10^{19}m^{-}$. This is a usual situation along the whole edge profile and it is always the case in the last 2-3 points next to the last closed surface. Poor accuracy in turn limits the gradient scale lengths that can be interpreted. Improved accuracy would be achieved if higher sensitivity detectors were employed. Present detectors have a Quantum Efficiency (QE) of 5.2% at 650 nm, measured from the photocathode current. A more important parameter determining the quality of the signal is its effective quantum efficiency ($QE_{eff}$), calculated from the observed signal and noise characteristics:

$$QE_{eff} = (S/N_{rms})^2 / n\tau$$

n is the photon flux at the detector, S is the output signal average, $N_{rms}$ its standard deviation, $\tau$ is the characteristic time of the system: $\tau = (\pi)^{1/2} \tau_{AC}$, $\tau_{AC}$ being the width of the auto-correlation function of the noise. Noise measurements on the present detectors[1] gave in the past $\tau_{AC} = 0.9$ ns and $QE_{eff} = 1.4$.

We have investigated the possibility of replacing present MCP-PMTs with higher $QE_{eff}$ detectors. One alternative is to use essentially the same type of detector but with a GaAs photocathode. GaAs photocathodes without the ion barrier film and with sufficiently long lifetimes are used in night vision image intensifiers with quoted QE > 35% in the spectral range 520-850 nm. A detector based on this technology would also in principle permit detection on the red side of the Thomson scattering spectrum. PMTs with state of the art GaAs MCPs are not commercially available: only filmed photocathode with a conducting layer and an intermediate grid for fast gating can be found with diameters up to 10 mm.

Intensified photodiodes with GaAs photocathode have also been considered as promising candidates in the electrostatically focused configuration, equipped with a Schottky barrier diode or with an APD. These detectors are characterised by an ultra low internal noise. However this alternative has not been further investigated because of their low internal gain, which requires an external preamplifier, the high gate voltage and the slow response time.

The solution adopted was to custom develop GaAs MCP-PMTs. Five 18 mm diameter GaAs MCP-PMTs have been manufactured by ITT Night Vision. The tubes were developed from their image intensifiers, replacing the phosphor screen with an anode. In this paper we present the measurements we have made to characterise these detectors.

## 2. GENERAL CHARACTERISTICS

The MCP_PMT is inherently a fast detector with potential response times in the sub nanosecond range. Getting the fastest possible response from the detector is important in the LIDAR diagnostic in order to optimise the spatial resolution. It is therefore important how we make the mechanical and electrical layout of the detectors. The importance of stray inductances created by the connections to the photocathode and the MCP was clearly revealed in the tests.

The tubes are mounted inside an Aluminium cup. The anode is located inside a guard ring, which is connected to ground. The free volume in this area is small, keeping excess inductances to a minimum. The wires coming from both ends of the MCP and the cathode wire are kept short before connecting to the voltage divider circuit. The MCP wires are capacitively decoupled to ground. The cathode is kept at +12 V by a zener diode relative to the MCP. The gating off ratio in the DC condition was measured to better than $10^6$. The gate-on pulse is capacitively coupled to the cathode. A series resistor of 200 Ohm to the cathode limits the surge current and reduces the cross coupled ringing to the anode. The cathode MCP capacitance is ~ 20 pf limiting the gate rise time to an acceptable 4 ns. The MCP – anode voltage in most the tests was 200 V, again set by zener diodes. Tests with 300 V bias gave no difference in performance.

Figure 1 shows the ringing on the signal output resulting from a 200 V gate pulse. The level of this cross talk is slightly higher than hoped for but is acceptable, as it is reproducible and can therefore easily be subtracted from the signal. The trace also shows that the MCP gain is sufficient to allow observations of single photoelectrons.

## 3. QUANTUM EFFICIENCY

The photocathode sensitivity was given by the manufacturer as the luminous photocathode sensitivity @ 2856$^{o}$K. The measured sensitivity is in the range 1500–2000 _A/lm. However, in our application we are more concerned about quantum efficiency. Two measurements were made to determine the photocathode QE.

The photocathode QE was measured directly at 670 nm for three of the detectors. A square wave signal from a 130 nW LED was used to illuminate the detectors. The photocathode current was measured by recording the voltage over a 100 kOhm resistor. The results of these measurements are shown in Fig. 2. The QE is seen to be ~ 40 % for two of the tubes and only about 20 % for what we regard as the prototype tube.

The gain of the individual MCPs was supplied by the manufacturer. Using this gain we can determine the photocathode QE by measuring the anode current. In this case a laser diode was used. The wavelength of the diode was again 670 nm. The laser beam was expanded to fill 80 % of the photocathode to avoid MCP channels saturation. The photocathode was gated for 200 ns and the laser energy was attenuated to an incident power of 100 nW. No droop in the signal was observed over the 200 ns gating time. This derived QE was ~10% , a factor four below the above result. The cause of this discrepancy is not clear. It could be attributed to MCP packing fraction losses or to an incorrect gain value.

The amplification in the MCP is inherently noisy. Also we know from past experience that there may be other loss processes, films, packing fractionsetc. that reduce the effective quantum efficiency. We measure the effective quantum efficiency ($QE_{eff}$) by measuring the rms-value of the noise compared to the dc-signal level. The signal to noise measured this way can be interpreted as the apparent number of photoelectrons in a period given by the bandwidth of the system. We determine the bandwidth by calculating the auto-correlation function of the noise. Figure 3 shows the $QE_{eff}$ measured this way as function of wavelength for the prototype tube. Also shown is the photocathode QE scaled to the 20 % measure at 670 nm. The wide spectral range expected for GaAs is confirmed. The $QE_{eff}$ of the other four tubes was similar to the measurement shown. The measurements performed were not as detailed. Surprisingly the $QE_{eff}$ for these tubes were only equal to or slightly worse than the prototype, in spite of the measured higher photocathode QE. This may agree with the following observation for which we have no explanation. The traces with the new tubes with higher QE show a tendency of large spikes. Such spikes will of course affect the noise measurements. We realise that these tubes also have higher dark current counts but it is not clear that these this is the cause.

Since these detectors are meant to replace the detectors in the existing system we also performed a direct comparison test between the two. The observed $QE_{eff}$ of the new detectors were about a factor five better than the old detectors.

The effective quantum efficiency is expected to be lower than the photocathode QE as the microchannel plate amplification process is a statistical process which adds noise. This is directly illustrated in Fig.1 where we see single photon events of different amplitudes. The noise factor caused by the MCP is dependent on the number of secondary electrons created on first impact of the photoelectron, hence on the energy of this electron. We varied the pulse amplitude of the gate pulse 10 and 400 V to test the importance of this. The signal increased by a factor five in a parabolic way showing that more secondary electrons are indeed created. However, the improvement in signal to noise (S/N) only changes by 15 %, corresponding to an improvement in $QE_{eff}$ of 30%, in the voltage range 100 V to 400 V. Since the "gate pulse ringing" is proportional to this voltage we have decided to operate at 150 – 200 V.

## 4. RESPONSE TIME

The response time as stated earlier is directly related to the achievable spatial resolution of the system. Better time response, however, is only useful if the signal level is sufficiently high that the error bars on the measurements are smaller than the fluctuation you are trying to resolve. The system response is a result of three time constants, the laser pulse width, the detector response and the bandwidth of the recording system. With the higher signal level that can be expected with the new detectors we are in a position to want faster response from these. The recording system used in these tests, a LeCroy, Wavemaster 8500 oscilloscope with an analogue bandwidth of 5 GHz and a real time sampling rate of 20 GS/s, basically removes this element from consideration. The circuit as described above was designed with this in mind. The high MCP gain allows us to observe in detail the response of individual photoelectron events. Terminating the anode into a 50 Ohm cable we find that the initial response is indeed very fast, rise time ~ 250 ps, Fig.4(a). However the first fast pulse is followed by a slow tail with a decay time ~ 1ns and an even slower oscillation with a period of 2 – 4 ns. The tail unfortunately represents two thirds of the integrated signal. We have found that the slow oscillation is highly dependent on the termination of the MCP-OUT lead. Keeping this lead as short as physically possible gives the shortest period and the smallest amplitude.

The tail seems to be predominantly coming from the anode termination. We observe that the signal has the appearance of an exponential decay plus a damped oscillation. This encouraged us to try to make a circuit simulation with three poles as this can be solved analytically. The circuit devised has one capacitor representing the MCP-anode plus one small stray inductance in series to the 50Ohm load and a small parallel capacitor, Fig 5. Using the observed decay time and the oscillation period the values of the elements in this circuit are given. The analytical solution to circuit is shown in Fig.4(b). We find that the decay is essentially given by the MCP-anode capacitance with the 50 Ohm load. This suggests that a smaller load resistance would improve the response time. The result of both simulation and measurements are also shown in the figures. It should be noted that the analytical solution always has the same amplitude of the oscillation and the exponential decay, whereas in the measurements the exponential decay dominates. Nevertheless, we consider this simple analysis to give reasonable agreement with the observation. Introducing more elements in the simulation we can in principal get better agreement but in this case determining the element values becomes much more difficult. The slow oscillation can be simulated by adding a tank circuit between MCP and ground.

The effect of lowering the load impedance is also observed when performing the auto-correlation analysis of the noise. The half width of the auto-correlation function is ~ 400 ps when the output load is 25 Ohm. Used in conjunction with the fast oscilloscope this could reduce the spatial resolution toabout 6 cm. An experiment to test this is planned later in the year.

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**REFERENCES**

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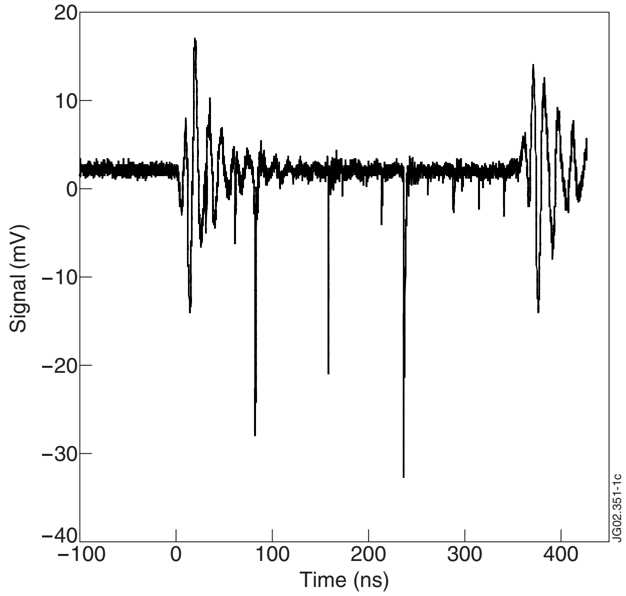


*Figure 1: The ringing observed on the anode when applying a 200 V gate pulse between photocathode and MCP. The signal is terminated into 50 Ohm. The ringing signal is reproducible and can be subtracted from experimental measurements. Single photoelectron events are seen to be of similar amplitude or larger.*

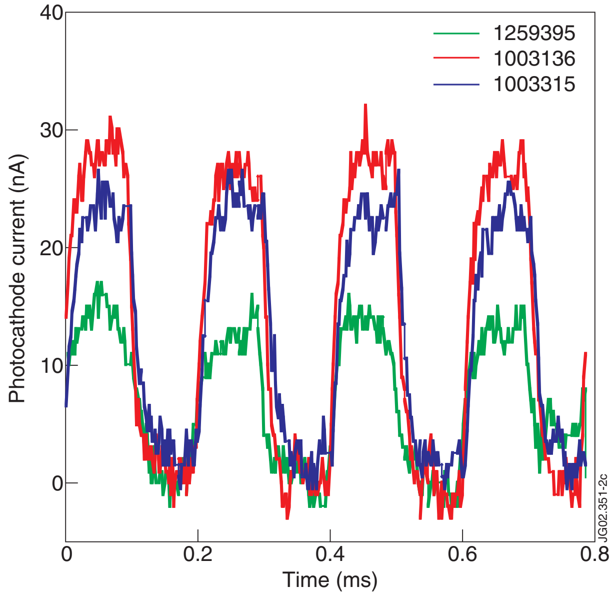


*Figure 2: Direct measurement of photocathode quantum efficiency of three detectors. The photocathode current is observed when illuminated by 130 nW alternating LED @ 670 nm. The signal is recorded as the voltage over 100 kOhm.*

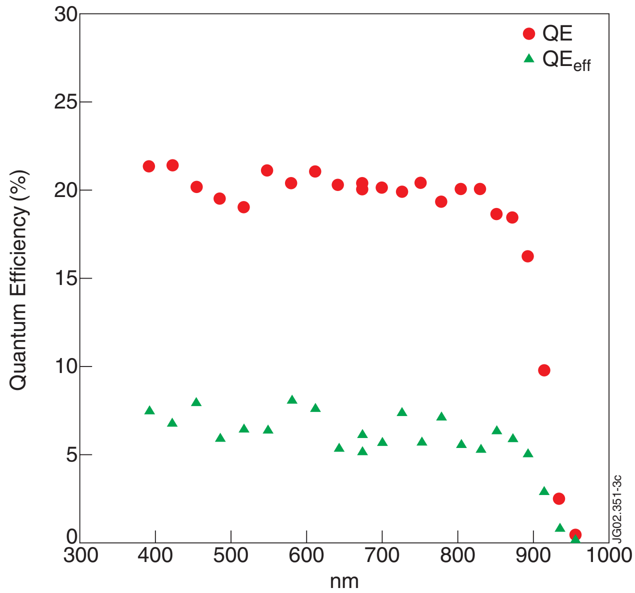


*Figure 3: Measurement of Quantum Efficiency (QE) as function of wavelength. The QE is based on the dc signal level. The curve is normalised to the 20% found in the direct measurement of QE. Also shown is the effective ($QE_{eff}$) determined from the signal to noise ratio of the same measurement.*

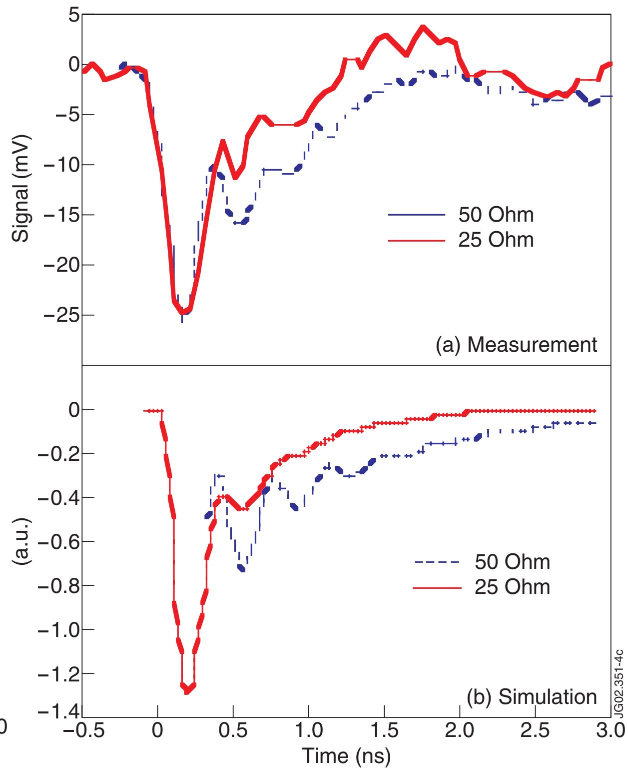


*Figure 4: (a) The measured response of a single photoelectron event. The two curves illustrate the difference between loading the output with 50 Ohm and 25 Ohm. (b) The calculated response of a simple simulation circuit again loaded with either 50 Ohm or 25 Ohm.*

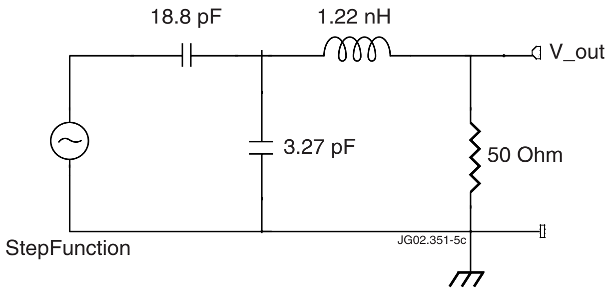


*Figure 5: Simple electrical circuit to illustrate the essential components governing the fast response of the detectors. The component values are the result of fitting the decay of the tail and the oscillation period and decay constant of the 50 Ohm signal. The 25 Ohm signal is calculated changing only the load resistance.*