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Characterization of fast microchannel plate photomultipliers for the ITER core LIDAR Thomson scattering system

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ABSTRACT: In the new ITER core LIDAR Thomson scattering system under development, detectors with pulse response as low as 330 ps and 10 mm diameter active area, covering with good sensitivity the spectral range 380–1100 nm will be necessary. For the visible region 400–750 nm, fast microchannel plate photomultipliers with a GaAsP photocathode that fulfill the characteristics of speed, sensitivity and active area are already commercially available and have been recently characterized for operation in the JET edge LIDAR Thomson scattering system. In this paper we present a further characterization of these devices to evaluate their usefulness in the more demanding operating conditions of the ITER core LIDAR Thomson scattering system. The characteristics of these detectors with regard to linearity, gain recovery time, pulse repetition rate, quantum efficiency and response time for large F-number illumination, have been measured. Linearity and recovery time data have been interpreted according to a new, time dependent, microchannel plate operational model. The results show that these detectors are suitable also for use in ITER.

KEYWORDS: Photon detectors for UV, visible and IR photons (vacuum); Photon detectors for UV, visible and IR photons (vacuum) (photomultipliers, HPDs, others); Nuclear instruments and methods for hot plasma diagnostics

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1 Introduction

Contrary to previous Thomson scattering (TS) systems (both LIDAR and conventional), in ITER the large spectral range spanned by the scattered light cannot be covered by a single detector type, and therefore detectors with different sensitive materials will have to be used in the different spectral channels [1, 2]. The large spectral extension necessary for reliable TS measurements at the full ITER performances, assuming the use of a Nd:YAG ($\lambda=1064$ nm) as the probing laser source, is shown in figure 1, along with the typical spectral sensitivities of the available photocathodes. It is clear that no single detector type can cover the entire ITER core LIDAR TS spectral range. The main specifications for ITER core LIDAR TS detectors of all types, deduced from the preliminary performance analyses [3–6], are shown in table 1.

The requirement on the active area is determined by the condition of étendue conservation in the collection optics and in the spectrometer. The EQE is defined as $\text{QE}/k_F$ where $\text{QE}$ is the photocathode quantum efficiency and $k_F$ is the excess noise factor accounting for the additional noise introduced after the primary detection. This requirement is determined by the desired accuracy in $T_e$ and $n_e$. The pulse response time is determined by the requirement on the measurement spatial resolution and the gating on-off time is determined by the necessity of shutting off the detectors the very bright stray light signal generated during the passage of the laser beam in the input optics. In addition to these requirements the detectors must also exhibit good linearity up to the maximum expected output signal and must operate at a measurement repetition rate of 100 Hz.

A recent review of the literature and of the characteristics of existing commercial detectors has shown that these specifications, and in particular the combination of an active area of the order of $\sim 1$ cm$^2$ and of a pulse response below 1 ns, at present are achieved only by photoemissive detectors such as microchannel plate (MCP) photomultipliers (PMTs). For the near-infrared (NIR) spectral range however, commercial detectors that fulfill these specifications do not exist yet and the availability of suitable detectors requires some technology advancements [1, 2]. In the visible
**Figure 1.** Upper: The Thomson scattering spectrum for an input wavelength of 1.06 µm and a scattering angle $\theta = 180^\circ$, calculated at five different plasma temperatures. Lower: typical spectral quantum efficiency of some photocathodes available for LIDAR TS (SBA, GaAsP and GaAs from Hamamatsu, TE InGaAsP from Intevac).

**Table 1.** Main specifications for the ITER core LIDAR TS detectors.

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Active area diameter</td>
<td>$D \geq 11$ mm</td>
</tr>
<tr>
<td>Effective quantum efficiency</td>
<td>$EQE \geq 6%$</td>
</tr>
<tr>
<td>Pulse response</td>
<td>$\Delta t \leq 330$ ps FWHM</td>
</tr>
<tr>
<td>Gating on-off time</td>
<td>$\tau_G \leq 5$ ns</td>
</tr>
</tbody>
</table>

In the spectral range 400 - 750 nm the only commercial detectors that already fulfill these specifications are fast microchannel plate (MCP) photomultipliers (PMTs), such as those recently characterized and used in the detection system of the edge LIDAR TS of JET [7]. Therefore, although the literature review [2] indicates that different photoemissive detectors such as hybrid photodiodes may possibly achieve the ITER requirements, nevertheless MCP PMTs are presently the best candidates to operate in the ITER LIDAR TS system. In this paper we present a further experimental characterization of the visible fast MCP PMTs of the JET edge LIDAR TS in view of their possible use in the more demanding conditions of ITER.
2 Fast microchannel plate photomultipliers

In the present detector technology the best combination of active area and fast pulse response is obtained by MCP PMTs. In these detectors a semitransparent photocathode is proximity focused to an electron multiplier made by one or more microchannel plates and the multiplied signal is collected by an anode. The time response to a very short multiphoton light pulse is determined mainly by differences in the transit time (transit time spread TTS) of electrons in the MCP stack and by the time constant of the anode circuit. Minor contributions may arise from differences in the photoelectron emission times (photocathode jitter) and from the transit time spread in the anode and cathode gaps [8–11]. For devices with a 10 mm diameter active area, response times down to \( \sim 200 \) ps are obtained by using MCPs with small (3 or 6 \( \mu \)m) pore diameter, by high internal electric fields (up to \( 5 \times 10^5 \) V/m in the anode gap) and by careful impedance matching of the anode output. The MCP PMTs presently operating in the edge JET Thomson scattering systems (Hamamatsu 3809U-73A) have a GaAsP extended-red photocathode with a 10 mm diameter active area and a V-stack of two, 6 \( \mu \)m pore diameter, unfilmed MCPs. The spectral range of operation is 280–800 nm with a peak QE of 24.5% at 550 nm. The excess noise factor was measured to be \( k_F = 1.6 \), giving a peak EQE = 17%. The peak QE is lower by about a factor 2 than the typical peak QE of GaAsP (shown in figure 1), supposedly because thin, less sensitive photocathodes have been used for these fast detectors to limit the photocathode time jitter. A pulse response \( \Delta t = 290 \) ps FWHM was measured. This includes also the 60 ps duration of the input test laser pulse. All these values are averaged over six detectors. A gating-on time of \( \sim 5 \) ns has also been measured [7].

These figures indicate that the requirement of table 1 are fulfilled by JET edge LIDAR TS detectors except for a small difference in the active area. However a recent study has shown that the efficiency of the collection optics can be improved with a new optical design based on the étendue reshaping in optical phase space and that a 10 mm diameter active area for the detectors may be sufficient [12, 13].

On the other hand the LIDAR TS operating conditions in ITER are more severe that in JET because the observed plasma volume is longer (\( \sim 75 \) cm in JET and 4 m in ITER, along the laser path), the measurement repetition rate is higher (1 Hz in JET and up to 100 Hz in ITER) and the angular aperture of the light beam incident into the photocathode is larger (F/2.3 in JET and F/1 and more in ITER). These conditions pose to the ITER detectors more demanding requirements than in JET in terms of linearity, recovery time and acceptance angle, that deserve additional tests.

3 Linearity

Contrary to a conventional TS diagnostics, in a LIDAR TS system for each laser pulse, each detector will see a signal corresponding to all the photons collected in a single spectral channel during the passage of the laser pulse in the plasma, due to both the scattering signal and the plasma light background. In the JET edge LIDAR system the length of the total observed plasma volume is \( \sim 75 \) cm (in the direction of the laser path) whereas in ITER it will be 4 m. In addition the plasma volume contributing to the background light is larger in ITER that in JET. For these reasons in ITER the LIDAR TS detectors will operate with a higher signal level and will require a better linear dynamic. The signal dynamic of a MCP PMT is limited by nonlinearities due to MCP gain saturation. This
arises when excessive charge is extracted from the MCP pore walls, resulting in a perturbation of the microchannel electric field. In the operating conditions of ITER, where the repetition rate of the TS measurement can be as high as 100 Hz, two types of linearity are important. First, for each laser pulse within the laser burst, the duration of the MCP PMT output pulse is determined by the detector gate time and is of the order of tens of ns. During this time the contribution of the MCP strip current to the output signal is negligible and the amplification in the MCP relies only on the charge available from the microchannel walls. For high values of the extracted charge a perturbation of the internal electric field may arise, causing a drop of the MCP gain near the output end. In these conditions the trailing edge of the pulse will experience a reduced gain compared to the leading edge, causing a distortion of the output pulse time shape. This effect will be called pulse nonlinearity. A second type of nonlinearity may arise when the charge extracted from the microchannel walls is not completely restored by the MCP strip current before the next pulse of the burst. Even when conditions of negligible pulse nonlinearity occur for individual pulses in the burst, systematic incomplete recovery of the extracted charge between subsequent pulses will eventually drive the MCP in conditions of gain saturation. In this case even a pulse with a charge below the previous nonlinearity level may experience a reduced gain. We will call this effect the burst nonlinearity.

Both types of nonlinearity are well explained in a recent model [14], in which a MCP is represented by a distributed element RC network. Accordingly to this model, we can assume that a condition to avoid any significant pulse nonlinearity is

\[ \frac{q_0 G}{Q_S} \leq 0.1 \]  \hspace{1cm} (3.1)

where \( q_0 \) is the pulse charge at the MCP input, \( G \) is the MCP gain and \( Q_S \) is the stored charge, i.e. the charge available from the MCP microchannel wall, which is a function of the MCP bias voltage. The model of ref. [14] indicates that when eq. (3.1) is fulfilled, the maximum deviation from linearity will be less than 0.3% at the end of the pulse, independently from the pulse time shape, provided the pulse duration is considerably lower than the MCP recovery time. From the same model the condition to avoid the burst nonlinearity can be expressed as

\[ \frac{q_0 G \nu}{I_S} \leq 0.3 \]  \hspace{1cm} (3.2)

where \( I_S \) is the MCP strip current and \( \nu \) is the pulse repetition rate. If this condition is fulfilled for any pulse in the burst, then the maximum deviation from linearity will be again less than 0.3% (for any pulse in the burst).

In order to verify these linearity conditions, first we have calculated the LIDAR TS signals expected at the visible detectors (figure 2) in typical ITER conditions. The TS signals and the background light have been calculated as in [15], assuming a spectral configuration of the spectrometer channels as in figure 2.

Figure 2 shows also the total charge signal expected at the MCP input for the three visible spectral channels. The simulated plasma conditions and the parameters of the LIDAR TS system are reported in table 2.

Subsequently, in order to verify the linearity condition (3.1) we have measured the stored charge \( Q_S \) for the JET MCP PMTs, producing in the detectors the above condition of pulse nonlinearity. For this a LED (\( \lambda = 670 \) nm) driven by a current pulse generator has been used to illuminate a
Figure 2. Upper: the spectral QE of the detectors covering the various spectral channels in the TS filter spectrometer design used for the simulations. The channels covered by the visible detectors are the first three (in blue) from the left. Lower: the LIDAR TS signal expected at the three visible detectors. The signal is in photoelectrons/s and refers to the primary photoelectrons emitted by the photocathode. The total charge to the MCP input $q_0$ is shown in the plot.

Table 2. Conditions for the simulation of TS measurements.

<table>
<thead>
<tr>
<th>Condition</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>central plasma electron density (flat profile)</td>
<td>$n_e = 3 \times 10^{19}$ m$^{-3}$</td>
</tr>
<tr>
<td>central plasma electron temperature (parabolic profile)</td>
<td>$T_e = 25$ keV</td>
</tr>
<tr>
<td>optical transmission (from plasma to detectors)</td>
<td>$T = 5%$</td>
</tr>
<tr>
<td>laser pulse energy</td>
<td>$E = 5$ J</td>
</tr>
<tr>
<td>input wavelength</td>
<td>$\lambda = 1064$ nm</td>
</tr>
<tr>
<td>laser pulse duration</td>
<td>330 ps FWHM</td>
</tr>
<tr>
<td>effective ion charge (flat profile)</td>
<td>$Z_{\text{eff}} = 2$</td>
</tr>
<tr>
<td>central collection optics solid angle</td>
<td>$\Delta\Omega = 5.45 \times 10^{-3}$ sr (F/12)</td>
</tr>
</tbody>
</table>

4 mm diameter spot on the photocathode of one of the detectors (serial n. CT0960), by square light pulses of 100 ns duration, much shorter that the natural time constant of this MCP which is 1.75 ms (see section 4). Figure 3 shows the detector output charge as a function of the MCP bias voltage.

The deviation of the output charge from the well known log-log dependence of the Eberhardt MCP gain model [16–18] indicates that at higher voltage the MCP operates in conditions of pulse
nonlinearity due to gain saturation. The stored charge $Q_S$ (for the entire MCP) as a function of the PMT high voltage bias, calculated from these data and from the model of ref. [13] is shown in figure 4.

At a MCP gain $G = 4.5 \times 10^4$ (PMT HV bias = 1700 V) we have $Q_S = 2.75 \times 10^{-8}$ C and with $q_0 = 4.0 \times 10^{-14}$ C (the highest value for the three simulated ITER pulses above) we find $q_0G/Q_S = 0.065$ so that the pulse linearity condition (3.1) is fulfilled. However simulations show that the LIDAR signal in ITER may change by an order of magnitude or more in different conditions of plasma $n_e$ and $T_e$ and also for high levels of plasma light. In this case the condition of negligible nonlinearity can still be achieved by a small reduction of the gain although this may slightly reduce the SNR for the weakest signals.

To verify the condition of burst linearity (3.2) we have measured the MCP strip current $i_S$. This has been determined by measuring the power supply output current as a function of the PMT high voltage bias and taking into account the detector voltage divider. These measurements refer to the electrical behavior of the MCP only and did not require an input light signal. Table 3 shows the measured values of $i_S$ and of the MCP resistance for the five detectors tested.

Using the average value of the strip current $i_S = 7.04 \mu A$ and $G = 10^5$ we find $q_0Gv/i_S = 0.057$, so that the burst linearity condition (3.2) is fulfilled. Again in case that the LIDAR signal increases due to different plasma conditions, burst linearity conditions can be restored by reducing the gain.

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**Figure 3.** The measured PMT output charge $Q$ (red line) as a function of the PMT bias. The input is a square light pulse of 100 ns duration. The blue straight line represents the output charge expected in conditions of linearity accordingly to the Eberhardt model.

**Figure 4.** The MCP stored charge $Q_S$ as a function of the PMT HV bias calculated from the data of figure 3.
Table 3. Measurement of the MCP resistance and strip current.

<table>
<thead>
<tr>
<th>Serial n.</th>
<th>Bias voltage (V)</th>
<th>MCP strip current ($\mu$A)</th>
<th>MCP resistance (M$\Omega$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CT0982</td>
<td>1840</td>
<td>6.83</td>
<td>196</td>
</tr>
<tr>
<td>CT0983</td>
<td>1940</td>
<td>6.78</td>
<td>209</td>
</tr>
<tr>
<td>CT0984</td>
<td>2020</td>
<td>8.25</td>
<td>182</td>
</tr>
<tr>
<td>CT0985</td>
<td>2010</td>
<td>7.35</td>
<td>204</td>
</tr>
<tr>
<td>CT0993</td>
<td>1960</td>
<td>5.99</td>
<td>219</td>
</tr>
</tbody>
</table>

Figure 5. Charge of the MCP PMT output pulse $Q$ as a function of the neutral density filter transmission. The input light pulse duration is 2 ns. The gain of the MCP PMT is $G = 4.5 \times 10^4$. Deviations of data points (dots) from the linear fit are compatible with the accuracy of neutral density filters.

These verifications of the linearity conditions are based on the results of the MCP gain simulation model of ref. [14]. A more direct and independent measurement of the detector linearity has been carried out using light pulses of 2 ns duration obtained by a fast diode laser pulser (Photek LPG-1). In this case the gain of the MCP PMT was kept constant at $G = 4.5 \times 10^4$ and the intensity of the light pulses was attenuated by a set of neutral density filters. Figure 5 shows the measured charge as a function of the filter transmission.

Consider that for the highest value of the output charge we have $q_0 G / Q_S = 1.02 \times 10^{-3}$ so that the pulse linearity condition (3.1) is amply fulfilled, as expected. All these linearity tests show that these detectors could operate with sufficient linearity also in ITER, except perhaps in the conditions of the highest scattering signal or with high background light, where however acceptable nonlinearity can be achieved by a small reduction of the detector gain.

4 Recovery time

To obtain a more direct confirm that the JET MCP PMTs are suitable to operate at the repetition rate of ITER LIDAR TS, independent from the previous considerations of burst nonlinearity, we have carried a direct measurement of the MCP gain recovery time. This has been made by illuminating a detector by a pair of identical light pulses (twin pulses) separated in time by a variable delay $\Delta t$. When the second pulse follows immediately the first, its output charge $Q_2$ is lower than the first pulse charge $Q_1$, because of the gain saturation induced by $Q_1$. But $Q_2$ will return equal to $Q_1$ as the
pulse delay $\Delta t$ is increased to values higher than the MCP recovery time. Accordingly to the model of ref. [14] the dependence of $Q_2$ on the delay $\Delta t$ is expected to be close to an exponential, with a time constant $\tau = kRC$ where $RC$ is the natural MCP time constant and $k$ is a correcting factor dependent on the saturation level produced by the first pulse [13]. Figure 6 shows the measured charge $Q_2$ as a function of the pulse delay $\Delta t$.

For the saturation level of these pulses we have $k = 0.93$ and from the time constant $\tau = 1.62 \text{ ms}$ of the fitted exponential we find that the natural MCP time constant is $RC = 1.75 \pm 0.17 \text{ ms}$. Note that for these pulses the MCP gain is completely recovered after $\sim 5 \text{ ms}$. It must be considered that in order to make evident the gain drop, the saturation level of the first pulse has been chosen well above the pulse linearity condition of eq. (3.1). On the other hand the model of ref. [14] indicates that, except for very weak saturation, the correcting factor $k$ is an increasing function of the saturation level and for pulses fulfilling (3.1) we should expect $k \leq 0.75$. For this reason the recovery time for pulses compatible with the pulse linearity condition (3.1) is expected to be even shorter than that measured from data of figure 6. These data confirm in a way more direct and independent from the previous estimates of section 3 that these detectors are suitable to operate at 100 Hz without any problem.

5 Angular dependence of quantum efficiency

In the ITER LIDAR TS system the backscattered laser light will be collected by a 36 cm diameter mirror, located at a distance of 4.25 m from the center of the plasma [13]. The collection solid angle decreases from $\Delta \Omega = 1.7 \times 10^{-2} \text{ sr (F/6.8)}$ to $\Delta \Omega = 2.8 \times 10^{-3} \text{ sr (F/17)}$ as the laser pulse traverses the ITER vacuum vessel from the outer to the inner plasma edge. The collected light is brought to the detectors in the spectrometer by an optical relay line. Due to the condition of étendue conservation, the solid angle of the incident light on the detectors will be as high as 0.66 sr (F/1). This is larger than the angular aperture of the incident light in the JET edge LIDAR TS which is 0.15 sr (F/2.3). In the conditions of ITER the incidence angle for a relevant fraction of the incident radiation will be as high as 30° and it is important that the values of QE and of the response speed will be maintained under this oblique incidence. In the past the angular dependence of the responsivity has been investigated for multialkali photocathodes, finding that oblique illumination
may effectively improve the detector QE due to refraction and other effects [19, 20]. No data are available for III-V photocathodes such as GaAsP.

We have measured the angular dependence of the QE in the JET MCP PMT GaAsP detectors over the entire sensitivity spectral range. To this purpose, a monochromatic thin pencil of almost parallel rays has been produced by using a halogen Tungsten lamp, a grating monochromator, a fiber optic bundle and a lens. The MCP detector has been mounted on a rotatable mount in such a way that a small area of 1 mm diameter at the center of the photocathode could be illuminated with incidence angles up to 50°. Special care has been taken to assure that the position of the illuminating spot on the photocathode did not change during the rotation of the detector, to avoid any effect due to non uniformity of the photocathode response. However a small increase of the illuminated area due to the angular effect could not be avoided.

An example of the measured angular dependence of the detector signal (at $\lambda = 600$ nm) is shown in figure 7. A similar behavior has been obtained at all the measured wavelengths (from 400 to 770 nm).

These data show that the photocathode QE is essentially independent of the incidence angle up to 50°, throughout the entire detector spectral range. In these experiments a fiber optic has been used to carry the light from the monochromator output to the detector, not only to simplify the optical set-up, but also to completely depolarize the monochromator output, so that the light beam incident on the photocathode was unpolarized. This is the correct polarization state for the test. In fact, although in the ITER LIDAR TS the light collected by the optical system and brought to the spectrometer is linearly polarized (except for a small relativistic depolarization effect), nevertheless due to the low F-number illumination of the detector, the input light cone incident on the photocathode will contain an equal amount of $s$ and $p$ light rays, so that the quantity of interest is the detector response to unpolarized radiation. The angular dependence of the response speed has also been investigated. High values of the incidence angle may affect the depth of the photocathode region where the light is absorbed and this may affect the photocathode time jitter. For this measurement we have used the fast diode laser source to illuminate the detector photocathode with a 60 ps light pulse, at various angles of incidence. In figure 8 we show that the PMT response to the same input light pulse measured at 0° and 50° incidence angle is practically identical.

The parameters of the detector pulse response measured at all the different incidence angles are shown in table 4.
Figure 8. MCP PMT response to a 60 ps, $\lambda = 650$ nm, input light pulse, incident at $0^\circ$ and $50^\circ$ on the photocathode.

Table 4. Parameters of the MCP PMT pulses response measured at six different photocathode incidence angles.

<table>
<thead>
<tr>
<th>Incidence angle (deg)</th>
<th>Risetime 10%–90% (ps)</th>
<th>Pulse response FWHM (ps)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>178.7</td>
<td>294.3</td>
</tr>
<tr>
<td>10</td>
<td>179.5</td>
<td>293.8</td>
</tr>
<tr>
<td>20</td>
<td>175.1</td>
<td>294.1</td>
</tr>
<tr>
<td>30</td>
<td>179.1</td>
<td>290.8</td>
</tr>
<tr>
<td>40</td>
<td>175.8</td>
<td>294.9</td>
</tr>
<tr>
<td>50</td>
<td>176.4</td>
<td>293.3</td>
</tr>
</tbody>
</table>

These data show that also the pulse response is independent of the incidence angle up to $50^\circ$. This is consistent with the fact that the response speed of these detectors is determined mainly by the TTS in the MCP and by the impedance of the anode output circuit. Therefore the influence of the incidence angle on the photocathode jitter, if any, is not important.

6 Conclusions

One of the visible MCP PMTs operating in the JET LIDAR TS system has been extensively characterized to assess its characteristics in view of a possible use of detectors of the same type also in the visible spectral channels of the ITER core LIDAR TS system spectrometer. Measurements of
linearity, recovery time and angular dependence of both QE and response speed have shown that this type of detector is suitable to operate in the more demanding conditions of ITER.

Acknowledgments

Authors are indebted to M. Kempenaars and J. Flanagan for information on the use of these detectors in the JET edge LIDAR TS system and for making one of them available to us for tests in our lab. This work has been supported by the European Communities under the contract of Association between EURATOM and ENEA and was carried out within the framework of the European Fusion Development Agreement.

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