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Gain uniformity, linearity, saturation and depletion in gated microchannel-plate x-ray framing cameras

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ABSTRACT

The pulsed characteristics¹ of gated, stripline configuration microchannel-plate (MCP) detectors² used in X-ray framing cameras deployed on laser plasma experiments worldwide are examined in greater detail. The detectors are calibrated using short (20 ps) and long (500 ps) pulse x-ray irradiation and 3 - 60 ps, deep UV (202 and 213 nm), spatially-smoothed laser irradiation. Two-dimensional unsaturated gain profiles show < 5 % percent long-range transverse variations but up to 3 dB/cm drop in gain parallel to the pulse propagation direction. Up to 50 % gain enhancements due to voltage reflection from the bends of a meander stripline geometry³ and from the ends of conventional straight striplines⁴ are also observed. Reproducible gate profiles are obtained with either picosecond x-ray or UV bursts and FWHM extracted with 3 picosecond accuracy. A novel single-shot method for measuring local gate propagation speeds using a tilted MCP is also demonstrated. Detailed output versus input studies indicate a linear dynamic range of 300. At higher irradiances, the gradual transition from linear behavior to hard saturation is gathered over a range of 10^5 in irradiation and fitted using a discrete dynode model^{5,6}. Finally, a pump-probe experiment quantifying for the first time long-suspected gain depletion by strong localized irradiation was performed. Gain depletion is defined here as a drop in the pulsed voltage amplitude beyond that due to normal resistive losses¹ as it propagates along the MCP microstrip. The mechanism for the extra voltage and hence gain degradation is shown to be associated with intense MCP irradiation in the presence of the voltage pulse, at a fluence at least an order of magnitude above that necessary for saturation. Results obtained for both constant pump area and constant pump fluence are presented. The data is well modelled by calculating the instantaneous electrical energy loss due to the intense charge extraction at the pump site and then recalculating the gain downstream at the probe site given the pump-dependent degradation in voltage amplitude.

1. INTRODUCTION

High-speed proximity focussed X-ray framing cameras based on a gated microchannel plate design have become a standard diagnostic for many laser-plasma experiments¹⁻⁵. The camera shutter is provided by launching a short (≈ 200 ps) 1 kV voltage pulse across a microstrip transmission line coated on the microchannel plate. A photoelectron signal produced at the front surface of the MCP is then only amplified during the transit time of the voltage pulse across a given point on the microstrip. An accurate knowledge of the temporal and spatial gain characteristics of such cameras has become a critical issue for the proper interpretation of recorded data. We present results of such detailed measurements for the current 80 ps shutter speed cameras used at several inertial confinement fusion (ICF) facilities. The results are found to be well fitted by simple models, which should allow us to accurately predict the performance of future, faster shutter speed cameras.

Section 2 describes DC and pulsed characterization by x-ray irradiation. Section 3 discusses a variety of bench calibrations using short pulse UV laser irradiation. In sections 4 and 5, we present models for gain saturation and depletion, respectively, and compare simulation results with the data. A summary and the practical relevance of gain depletion is given in Section 6.

2. CHARACTERIZATION BY X-RAYS

2.1 DC gain

We first verified that the DC gain G of the present MCP detectors followed the previously measured and modelled⁶ voltage scaling law $G \propto V^{\gamma_{DC}}$, where γ_{DC} is found to be $\approx L/4D$ for a MCP of length L and pore diameter D . Figure 1 is a log-log plot of the measured gain versus applied DC voltage V , well fitted by a straight line fit in accordance with the model. The best fit yields $G \propto V^{12.8}$, a slightly steeper power law than expected for the $L/D = 45$ plates used here.

Figure 1 Gain vs DC voltage for an $L/D = 45$ aspect ratio microchannel plate. Solid curve is power law fit.

2.2 Flatfielding in pulsed mode

Two microchannel plate-based framing cameras were then flatfielded *in situ* and in pulsed mode by using 4-5 keV x-rays from laser plasmas produced by focussing 0.6 - 1 ns Nova laser beams unto a planar Au target. The calibrations were performed by removing the pinholes normally associated with these instruments to provide isotropic illumination. The x-ray temporal pulse shape was monitored by an x-ray streak camera filtered identically to the framing cameras (1 mm Be plus 25 μm Ti), equipped with a matching Au photocathode and viewing at nearly the same angle with respect to the target normal.

Figure 2: Solid curve is flux-normalized unsaturated gain profile for serpentine microstrip. Dashed line is the spatially-integrated and temporally-smoothed X-ray flux recorded by streak camera and used for normalization.

On Figure 2, the flux-corrected flatfield profile for the serpentine strip³ MCP is plotted versus distance along the strip. Also plotted is the spatially-integrated X-ray flux recorded by the streak camera that is used to normalize the MCP data. Before normalizing, the streaked flux (30 ps resolution) has been convolved with a 75 ps FWHM Gaussian function to simulate the 80 ps FWHM framing camera response function. An average pulse velocity of 160 $\mu\text{m}/\text{ps}$, measured both by electro-optic sampling and by illuminating the MCP with two 20 ps x-ray bursts separated by a known delay, was used to translate distance

into delay. A 3dB/cm drop in gain is observed over the straight segments of the strip. Note that Fig. 2 predicts a 100x reduction in the unsaturated gain between the positions of the first and last pinhole images under the normal imaging configuration. The two gaps in the gain profile correspond to the two bends which are normally not exposed. Gain enhancement is observed as one approaches the outside curve of the bends, attributed to voltage reflection. Variations in gain transverse to the pulse propagation direction are < 5 %.

Figure 3 shows plots of unsaturated flatfield profiles for the straight strip camera. Each of the four strips exhibits up to a 2.5x drop in gain along the pulse propagation direction. Gain enhancement is observed at the ends of the strips, attributed again to voltage reflection due to residual impedance mismatches.

Figure 3 Unsaturated gain profiles for a straight stripline camera (four strips total).

Figure 4 Experimental set-up for bench tests with 3 ps, UV pulses. Optically synchronized trigger has 30 ps RMS jitter.

3. CHARACTERIZATION BY UV LASER

3.1 Experimental set-up

An extensive set of bench measurements were then performed using optically-synchronized, spatially-smoothed, deep UV laser pulses. The experimental set-up is shown in Figure 4. We initially used 203 nm-wavelength, 3 ps laser pulses generated by a synchronously-pumped, amplified and then frequency-tripled dye laser⁷. Since the vast majority of the MCP signal is due to secondary electron amplification, any intrinsic differences in camera operation due to differences in X-ray versus UV-induced photoelectron energy is deemed unimportant. We note that the 6.1 eV photons used here for output-input characterization are well above the work function of the gold microstrip (5.1 eV), contrary to a previous study conducted at 263 nm (4.7 eV)¹. A few μJ 's of laser energy at this wavelength is sufficient to strongly saturate the full MCP area (6-8 cm^2). Illumination non-uniformities have been greatly reduced by recollimation of the laser beam after passage through a quartz diffuser.

3.2 Synchronicity

A knowledge of timing between microstrips in a four strip camera is essential for correctly interpreting a sequence of images spanning more than the 200 ps window offered by a single strip. Figure 5 shows the instantaneous gain profiles for such a four strip camera as frozen by the picosecond UV illumination and recorded by a lens-coupled CCD camera. The illumination is sufficiently constant over a given gate profile for gate pulse shapes and synchronization to be measured to a few picoseconds accuracy. Measurements of the sensitivity between strips and along strips were not attempted here, however, as NOVA X-ray flatfielding calibrations shown in section 2.2 are more relevant and reliable. After synchronization is performed, the residual shot-to-shot timing jitter between strips is ≈ 20 ps RMS, negligible compared to the current 80-100 ps gate durations and probably satisfactory for future 40 ps gating⁷. The strips remained synchronized within 10 ps of each other between timing calibrations performed 9 months apart.

Figure 5 3 ps snapshot of gain profiles for the four strip camera. Grayscale is linear in intensity.

3.3 Sensitivity of gain to applied pulsed voltage

Figure 6 plots the relative peak sensitivity versus peak voltage (DC volts plus -850 volts pulsed) for a given input. The fit $\text{Signal} \propto V^\gamma$ yields a power law $\gamma = 20.3$, substantially larger than the characteristic DC power law ($\gamma_{\text{DC}} = 12.8$) measured in section 2.1 for $L/D = 45$ plates (see Fig. 1). Using a time-dependent discrete dynode gain model⁵ with $2\gamma_{\text{DC}}$ ($= 26$) dynodes, $L = 450 \mu\text{m}$, and approximating the measured voltage pulse profile by an asymmetric Lorentzian with leading and falling edge HWHM = 50 ps and 185 ps, the predicted power law is $\gamma = 19.6$, in good agreement with the measured value. The reason for the steeper power law is that adding forward bias to a pulsed voltage shorter (235 ps FWHM) than the minimum electron MCP transit time (285 ps) has an additional effect. The increased peak voltage increases the peak gain as usual, and secondly the

increased voltage reduces the electron transit time leading to an even greater increase in the gain averaged over the transit time; i.e. less of the temporal wings of the voltage pulse are sampled in transit.

Figure 6 Relative MCP gain vs. peak voltage (DC volts + -850 volts pulsed)

3.4 Sensitivity of temporal profile to applied pulsed voltage

In addition, the effective frame time should increase with increasing forward bias. Figure 7 shows typical unsaturated lineouts of gate temporal profiles for two DC bias settings with the leading edge of the pulse on the left side. Figure 8 shows that the gate duration does indeed increase with DC bias from 72 ps FWHM at 0 V bias to 96 ps FWHM at -300 V bias. Calculations predict a more modest increase from 80 to 90 ps FWHM. Note that a 1.5 - 2.5% correction has been applied to the FWHM to account for the distortion of the gate profiles by the drop in gain along the pulse propagation direction as measured in section 2.2. A decrease in frame time below 70 ps is predicted if reverse (positive) bias were applied, but this is not practical as the MCP sensitivity would become prohibitively low for most experiments. The solution is to increase the pulsed voltage amplitude in addition to implementing reverse bias; such a configuration was used in the next section.

Figure 7 Lineouts of gate profiles with 0 (dashed curve) and -300 V (solid curve) DC bias.

Figure 8 Measured (circles) and predicted (triangles) gate FWHM vs. DC bias. Peak pulsed voltage = -850 V in all cases.

3.5 Local gate propagation velocity

A single-shot technique for measuring the local gate propagation velocity v_p is shown in Fig. 9a. The normal to the MCP surface is intentionally tilted by a non-zero angle θ with respect to the laser axis so that there is a progressive delay in the light arrival time transverse to the voltage pulse propagation direction. A short pulse snapshot of the gain profile, as shown in Fig. 9b, will then appear tilted at an angle α with respect to the strip axis. The gate propagation velocity, normalized to the speed of light c , is given by simple geometry as $\tan\alpha/\sin\theta$. A typical exposure already corrected for the camera flatfield response is shown in Fig. 9b. A 200 ps FWHM, -1400 V pulse was used in conjunction with 400 V reverse bias to produce a shorter gate pulse (≈ 60 ps) so as to minimize the sensitivity of the measurement to inaccuracies in the flatfield correction. A least squares fit for α yielded $v_p = 0.50 \pm .03c$, in good agreement with previous measurements outlined in section 2.2. The curious 2x increase in exposure along the one edge of the microstrip shown in Fig. 9b is a reproducible consequence of using large reverse (positive) bias but is not understood.

Figure 9. a) Schematic of single-shot technique for measuring gate propagation velocity. b) Raw data showing tilted gain profile from which gate propagation velocity is extracted as discussed in text.

3.6 Output vs. input characteristics

A log-log plot of single-shot peak output vs. input signal for one microstrip (-300 V DC bias and -850 V pulsed) is shown in Figure 10 for both 3 and 60 ps irradiation. Only shots with low trigger jitter (± 25 ps) were chosen, which translates to all gate profile peaks captured within an 8 mm span on the strip. Small ($\pm 30\%$) corrections were then applied to account for the slow variation in peak gain along that 8 mm span, appropriately modified to account for a transition from linear to highly saturated behavior and normalized to the center of the microstrip. The data points do correspond to transverse averages over ≈ 30 MCP pores over which the exposures only vary by 20%. The data at the two pulse lengths have been arbitrarily meshed together using the region of overlap between 100 and 1000 counts/pixel since the relative MCP sensitivity between the two wavelengths (203 nm at 3 ps and 213 nm at 60 ps) is not precisely known but likely to be changing rapidly⁸. The CCD output data in Fig. 12 have also been translated into the usual Nova film exposures by cross-calibration. Saturation begins at 0.2 ergs/cm², irrespective of irradiation pulse duration and equivalent to a specular optical density ($f/1.93$) of 1.7 on 2484 film. In addition, we note that the output continues to rise by almost an order of magnitude in the sublinear region, in agreement with published estimates^{5,6}. Hard MCP saturation appears at 0.4 ergs/cm², well below film saturation (> 2 ergs/cm²).

Figure 10 Output vs. input characteristics of pulsed MCP. Solid and open circles are for 3 and 60 ps UV pulses respectively. Curve is simulation result with only one free parameter in the abscissa, a multiplier.

We wish to reconcile the maximum exposures obtained during bench tests (1.4 ergs/cm²) with those obtained at NOVA as a further test of the reliability of O/P vs. I/P curves shown in Fig 10. A maximum *average* film exposure of 0.7 ergs/cm² is obtained from heavily saturated Nova data with 12% of the pixels (digitized at 22 by 22 μ m resolution) above 1 erg/cm² and 1.4% above 1.7 ergs/cm². However, after smoothing the Nova data at the CCD resolution (71 by 71 μ m), only 3% of the smoothed pixels remain above 1 erg/cm² and *none* are above 1.2 ergs/cm². This is consistent with the bench test data yielding a maximum calibrated CCD pixel input of 1.4 ergs/cm².

We have directly compared a DC MCP current output (nanoamps) to film exposure (ergs/cm²) as an independent measure of the number of charges that may be extracted from a single MCP pore. The measurements were performed using a DC X-ray source, a picoammeter and 5 - 20 second film exposures. A current of 1.3 nA was drawn over the 6.12 cm² serpentine microstrip area, corresponding to a 6 second film exposure of 0.14 ergs/cm², and translating to 10,000 electrons/pore (10 μ m pores spaced 12 μ m apart in hexagonal closed-packed structure). Hence, the onset of pulsed output saturation witnessed at 0.2 ergs/cm² corresponds to 14,000 electrons/pore and the maximum pulsed exposure of 1.4 ergs/cm² is equivalent to 100,000 electrons/pore. These numbers agree well with a simple calculation of complete output saturation⁵ $((\epsilon_r \epsilon_0 DV)/(eLD)) = 60,000$ electrons/pore where ϵ_r is the average relative permittivity ≈ 3.8 , $D = 10$ μ m, $L/D = 45$ and $V = 1200$ V) and estimates for the onset of nonlinearity^{6,9} (10,000 e/pore).

3.7 Gain depletion experiment

A pump-probe experiment was conducted to unequivocally demonstrate gain depletion as witnessed on the serpentine strip camera for heavily saturated NOVA data. The Osaka group reported that gain depletion should be small and is not measurable on their camera¹. Gain depletion is defined here as a drop in the pulsed voltage amplitude beyond that due to normal resistive losses^{1,5} as it propagates along the MCP microstrip. The mechanism for the extra voltage and hence gain degradation is shown to be associated with intense MCP irradiation in the presence of the voltage pulse.

Figure 11 Schematic of pump-probe experiment with typical raw data showing gain depletion at probe site. Voltage pulse arrives at pump site first, rounds bend and reaches probe site 200 ps later.

Figure 11 shows a schematic of the pump-probe setup and some raw data. A -1400 V, 200 ps voltage pulse was used with no bias. A longer (60ps) pulse laser was used because it provides us with more energy hence increasing the effects of gain depletion. Pulses were split into two and sent 200 ps and 3 cm apart on a microstrip to achieve travelling wave synchronization with the voltage gating pulse propagating at 0.5c. A serpentine strip was used for greater temporal and spatial isolation between the pump and probe pulses whose energy contrast reaches 10^7 . The unsaturated probe output was monitored shot-by-shot while the pump fluence which arrives earlier was varied. Pump depletion manifests itself as a reduction in the MCP output at the probe site as the pump irradiation is increased, as shown in Fig. 11. This should not be confused with saturation defined as a reduction in the MCP gain at a *given* point due to charge depletion by strong irradiation at that point. The apparent increase in pump spot size was due to saturation, a necessary condition for promoting measurable gain depletion. After normalizing to the laser energy on each shot and rejecting all shots with timing jitter between voltage and laser pulse outside a 50 ps window, a plot of probe output vs. pump input fluence (normalized to the saturation fluence F_S as derived from Fig. 10) can be constructed as shown by the solid circles in Figure 12. 50% gain depletion occurs at 1000 times the saturation fluence (F_S) for a pump irradiation area of 0.3 cm^2 .

To confirm that synchronization between pump laser irradiation and voltage pulse is important, data for which the peak of the pump pulse arrives 300 ps *before* the voltage pulse are also shown as triangles in Fig. 12. For the purposely mistimed pump, onset of gain depletion requires 10^3 times the fluence needed in the synchronized case. Depletion still occurs presumably due to weak laser postpulses. Indeed, plotting the data against the pump MCP output rather than the pump input fluence removes the dependence on pump timing, but the plot is less accurate as the pump output signal is in a heavily saturated regime.

Figure 12 Probe output signal vs. pump input fluence for synchronized pump pulses (circles) and mistimed pump pulses (triangles). Solid curve is result of simulation described in text with no adjustable parameters. Dashed curves show sensitivity of calculation for $\pm 50\%$ variation in parameter R .

To confirm that the gain depletion threshold is dependent on the total laser energy deposition rather than just the laser fluence, the experiments were repeated holding the fluence fixed at $10^5 F_s$ while changing the pump area. The results, shown in Fig. 13, clearly indicate an areal dependence to gain depletion.

Figure 13 Probe output vs. pump area for constant pump fluence. Solid curve is result of simulation described in text.

4. MODELLING OF GAIN SATURATION

As a necessary prelude to modelling gain depletion, we have attempted to fit the O/P vs. I/P data shown in Fig. 10 by including in the gain calculations a simple functional form for gain saturation at each MCP dynode:

$$N_{O/P} = (100V)[1 - \exp(-(N_{I/P}g)/(100V))] \quad (1)$$

$N_{I/P}$ and $N_{O/P}$ are the number of input and output secondary electrons per pore at any given dynode, g is the instantaneous small signal (unsaturated) gain across that dynode ($\propto \sqrt{V}$), and V is the instantaneous total volts across the MCP. Note that Eq. (1) sets the maximum charge extraction per dynode per pore at 10^5 for an applied voltage = 1000 V, in accordance with the measured value (see section 3.6). Equation (1) is then inserted as the gain model in the time-dependent discrete dynode calculations⁵ with the following measured parameters ($n = 26$ dynodes, $L = 450 \mu\text{m}$, asymmetric Lorentzian voltage pulse with leading and falling edge HWHM = 50 and 185 ps). The present calculations treat all secondary electrons as travelling together as the laser irradiation duration (60 ps) and transit time spreading (< 30 ps) are small compared to the pulsed voltage duration. For simplicity, the number of dynodes is assumed fixed even during saturation despite DC voltage calculations to the contrary¹⁰. The calculated fit is shown as a solid curve in Fig. 10. The only adjustable parameter is a multiplicative scaling factor in the abscissa which contains an unknown deep UV quantum efficiency.

The hard output saturation evident in Fig. 10 is a consequence of the maximum charge (10^5 electrons) that can be extracted from the final dynode on timescales much shorter than a recharge time (a few ms). However, the total energy expended in accelerating ejected secondary electrons, summed over *all* dynodes, will continue to rise even after output saturation is reached. Specifically, as the number of primary photoelectrons is increased, saturation (assuming for the moment constant volts across the MCP) will begin progressively earlier in the dynode chain. By this argument, the maximum number of ejected secondary electrons per MCP pore can reach $n \cdot 10^5 = 2.6 \times 10^6$. We now present simple estimates and calculations to support the hypothesis that it is this continuing increase in total extracted charge that eventually leads to gain depletion under conditions of large area, intense MCP irradiation and heavily saturated outputs.

5. MODELLING OF GAIN DEPLETION

Consider the ratio R of secondary electron energy to pulsed voltage energy given by:

$$R = \frac{A\rho(\sum N_i eV_i)}{V_0^2 \tau / Z} \quad (2)$$

where A is the irradiated area, ρ is the surface density of MCP pores = $8 \times 10^5 \text{ cm}^{-2}$, N_i and eV_i are the number and peak energy of secondary electrons bombarding the MCP wall at dynode i , V_0 is the peak pulsed voltage, τ is the pulse FWHM and Z is the characteristic microstrip impedance = 12.5Ω . Eq. (2) ignores the re-emitted electron energy since it is $< 10\%$ of the bombarding electron energy at each dynode⁶. The maximum value for R , estimated by setting $V_i = V_0/n$ and $N_i = 10^5$ for all $n = 26$ dynodes, V_0 (at pump site) = 1400 V, τ (Lorentzian) = 200 ps, and $A = 0.3 \text{ cm}^2$ (see Fig. 11), is 0.2. A 20 % decrease in pulsed energy translates to a 10 % decrease in voltage amplitude. Since the power law dependence of the peak gain G_0 on peak pulsed voltage amplitude is calculated as $G_0 \propto V_0^{18}$ (over a peak voltage range 1000-1200 V at the probe site, and assuming an unchanged pulse profile and short pulse irradiation), a 10 % decrease in V_0 should lead to an 85 % drop in the signal gain at the probe site, in qualitative agreement with the highest pump fluence data shown in Fig. 12. We note that for the O/P vs. I/P data shown in Fig. 10, a narrow $100 \mu\text{m}$ -wide line focus with a total active area $\approx 0.01 \text{ cm}^2$ was used to minimize self-depletion (see Fig. 13) which could otherwise compromise measurements of output saturation levels.

In terms of more rigorous circuit theory, localized MCP saturation can be viewed as adding a shunt admittance in parallel with the microstrip transmission line, leading to a localized, lossy impedance mismatch. Detailed simulations are not attempted here as the shunt must be treated as a complicated dynode-correlated, time- and space-varying conductance if gain depletion estimates more accurate than Eq. (2) are desired. Simple transmission line results^{11,12} for constant impedance mismatches, however, are useful in predicting that the instantaneous increased conductance Y due to MCP pore saturation should temporarily reduce the local line impedance leading to both voltage attenuation *and* reflection. The results also predict that the fractional energy absorption¹¹ and reflection¹² losses are equal for small losses and are given by the product YZ , which can be shown to be equivalent to the simple estimate given by Eq. (2). Hence, we have used $(1-2R(R))$ as an estimate for the transmitted energy (voltage) fraction, and $(1-R)^2$ for the signal gain at the probe site normalized to the unperturbed gain ($R = 0$).

The time-dependent discrete dynode gain model including saturation (Eq. (1)) is then used to calculate peak values for $\Sigma N_i e V_i$ which are incorporated in Eq. (2). Several simplifications are used. Photoelectrons are assumed to be always born at the optimum timing (-40 ps with respect to the voltage pulse peak) for maximum secondary electron energy extraction (different than that for maximum MCP output). This is justified since the predicted maximum variation in optimal timing with degree of saturation is 20 ps, much smaller than the laser pulse duration. Moreover, for the cases of heavy saturation ($F > 1000F_s$) for which gain depletion is significant, a ± 25 ps jitter between voltage and laser pulse arrival translates to only a $\Delta R/R = 3\%$ variation in R and hence a $< 10\%$ $\{18(\Delta R/R)(R/(1-R))\}$ variation in probe signal gain (for $R < 0.15$). All irradiated MCP channels are also treated as behaving synchronously as both the finite voltage pulse transit time across the pump area (6 mm diameter ≈ 40 ps) and finite jitter are shorter than the convolved FWHM (> 100 ps) of the laser pulse duration with the unsaturated gain duration (80 ps FWHM). The simulated results are overplotted as solid curves on Figs. 12 and 13. The dashed curves on Fig. 12 are from similar calculations for which R has been arbitrarily multiplied and divided by 1.5 to simulate a compound uncertainty in all parameters included in R . We note that a dramatic (factor of 100) drop in sensitivity is predicted (Fig. 13) for only a 3x increase in pump area from 0.3 to 1 cm².

By neglecting in the present simulations the following time-dependent effect¹³, we have underestimated gain depletion for finite duration irradiation. Specifically, photoelectrons are usually ejected continuously leading to a spreading of secondary electrons over many dynodes at any given time. Saturation by the leading edge of the secondary electron pulse at some dynode will increase the electric field for all unsaturated dynodes earlier in the chain. Hence, the trailing secondary electrons will instantaneously experience enhanced gain at these earlier dynodes, increasing energy depletion. However, this does not alter the simulated gain depletion results for the most experimentally relevant regime, input fluence levels *below* those leading to MCP output saturation.

It is instructive to consider the scaling of maximum fractional voltage depletion with MCP parameters L/D , n , ϵ_r , open area ratio F , strip width W and length S , and with voltage parameters V_0 and τ . For uniform and constant MCP irradiation in space and time, $A = SW$. In addition, since $\rho \propto F/D^2$, $\Sigma = n$, $eN_i(\max) = CV_0 \propto (\epsilon_r D^2 V_i)/(L/n)$, $V_i = V_0/n$, and $Z \propto L/(W\sqrt{\epsilon_r})$, and assuming optimized and self-similar framing camera operation (electron transit time $\approx \tau$), Eq. (2) predicts $R(\max) \propto SF\sqrt{\epsilon_r}/\tau$, independent of all other parameters. Hence, for the shorter voltage pulses presently used at Rochester⁷ (80 vs. 240 ps), voltage depletion could be three times as severe. We note that the absence of voltage depletion reported by the Osaka group¹ is puzzling since their depletion figure of merit ($SF\sqrt{\epsilon_r}/\tau$) is a factor of two *larger* than ours ($S = 11$ vs. 4 cm, $F = 0.5$ vs. 0.63, $\sqrt{\epsilon_r} = 2.5$ vs. 1.9, $\tau = 330$ vs. 240 ps).

We can predict the maximum gain depletion expected for data acquired just below the onset of non-linearity (< 0.14 ergs/cm²). Clearly, the worst case scenario occurs during flatfielding for which the MCP is uniformly irradiated. Maximum gain depletion occurs at the beginning of the microstrip under such conditions and is calculated as $(1/G_0)(dG_0/dx) \leq 5\%/cm$, small compared to the resistive gain losses measured at 30-50%/cm. Moreover, since $(1/G_0)(dG_0/dx)$ is roughly proportional to G_0 for depletion losses under uniform irradiation, unsaturated conditions, and is constant for resistive losses, the relative importance of depletion losses will drop as the pulse propagates along the strip. Gain depletion should not be a factor in the unsaturated data of Fig. 2.

6. SUMMARY

The spatial gain profiles of pulsed microchannel plate cameras show 2 - 3 dB/cm drop in gain along the pulse propagation direction but only 5 % variations in the transverse direction over the central 90 % portion. Gain enhancements are observed at the ends and bends of microstrips and at one edge; these regions are hence usually avoided during imaging experiments. Quantitative information on gate profiles and pulse propagation velocities are obtained by using spatially-smoothed laser irradiation. Detailed, absolutely calibrated output versus input studies indicate a useful linear dynamic range of 300 followed by a transition from linear behavior to hard saturation over a further decade in output signal. These results are well fitted using a simple saturation model coupled to a discrete dynode model^{5,6}. A pump-probe experiment was performed to unequivocally demonstrate gain depletion due to strong localized irradiation. These results are well explained by a simple energy balance argument which is used to predict the scaling of gain depletion with various camera parameters. The model indicates that even for full irradiation of the MCP area, gain depletion is negligible for all camera formats presently in use if the data is everywhere unsaturated. However, gain depletion can be a concern for partially saturated data as has been observed during multiframe x-ray imaging of laser plasmas at Nova. Typically, early frames can be heavily saturated and hence unusable while later frames which would have displayed unsaturated usable data have been dimmed below the film recording threshold by gain depletion.

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