DOE/NV/25946--1503

Saturation and Dynamic Range of Microchannel Plate–Based X-Ray Imagers

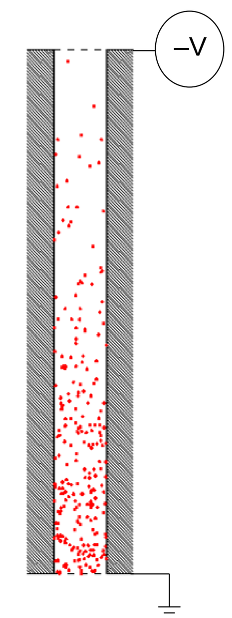
Craig Kruschwitz[1], Ming Wu[2], and Greg Rochau[2]
[1]National Security Technologies, LLC, Los Alamos, New Mexico;
[2]Sandia National Laboratories, Albuquerque, New Mexico.

ABSTRACT

This paper describes recent advances in Monte Carlo simulations of microchannel plate (MCP)–based x-ray detectors, a continuation of ongoing work in this area. A Monte Carlo simulation model has been developed over the past several years by National Security Technologies, LLC (NSTec). The model simulates the secondary electron emission process in an MCP pore and includes the effects of gain saturation. In this work we focus on MCP gain saturation and dynamic range. We have performed modeling and experimental characterizations of L/D = 46, 10-micron diameter, MCP-based detectors. The detectors are typically operated by applying a subnanosecond voltage pulse, which gates the detector on. Agreement between the simulations and experiment is very good for a variety of voltage pulse waveforms ranging in width from 150 to 300 ps. The results indicate that such an MCP begins to show nonlinear gain around 5×10^4 electrons per pore and hard saturation around 10^5 electrons per pore. The simulations show a difference in MCP sensitivity vs voltage for high flux of photons producing large numbers of photoelectrons on a subpicosecond timescale. Simulations and experiments both indicate an MCP dynamic range of 1 to 10,000, and the dynamic range depends on how the voltage is applied.

Monte Carlo Model

The Monte Carlo MCP simulation model is described in detail in the References.



The code's general features are:

- Can model both steady state and time-dependent voltages
- User can define number of initiating electrons and their initial energy, angle, and position
- Calculate electron trajectories under applied voltage
- Average secondary yield determined from standard secondary emission equations
- Secondary yield sampled from Poisson distribution
- Sample secondary energy from an experimentally measured distribution
- Repeat until electrons emerge from the channel exit or cascade dies out
- Include saturation mechanisms by approximating field perturbations arising from electrons in the channel and positive charge left in the glass walls resulting from the extraction of electrons

Space Charge

- Presence of large numbers of electrons in the pore creates a field that influences the trajectory of new secondary electrons
- Electron time of flight is shortened, reducing the impact energy and gain

Wall Charge

- The secondary emission cascade leaves a net positive charge on the channel surface, affecting the fields in the pore
- The charge is replenished by the MCP strip current very slowly (milliseconds typically), thus, this charge remains and can influence subsequent cascades (in addition to other pores)

MCP Saturation Modeling: DC Bias Results

A short pulse (<1 ps) UV laser was used to study the MCP-detector dynamic range and saturation characteristics under both DC voltage bias and under pulsed voltage bias with various pulse waveforms. The laser intensity was varied, thus varying the number of photoelectrons per pore beginning cascades in the MCP. The quantum efficiency of the MCP for photoelectron generation from the UV light was assumed to be ~0.1%, and simulations were performed for comparison. Figure 1 shows the DC bias results. Figure 1(A) shows the number of electrons out per pore as a function of DC bias voltage for average numbers of input electrons from 1 to 5000 per pore. It is evident that the curves start to exhibit nonlinearity at around 5×10^4 electrons per pore, and a hard saturation is evident around 10^5 electrons. Figure 1(B) shows comparisons of the simulations with data from the UV laser. Agreement is clearly very good. It is also interesting to note that as the number of input electrons increases, the gain sensitivity with voltage decreases somewhat, changing from Gain ~V^{11} to Gain ~$V^{8.5}$.

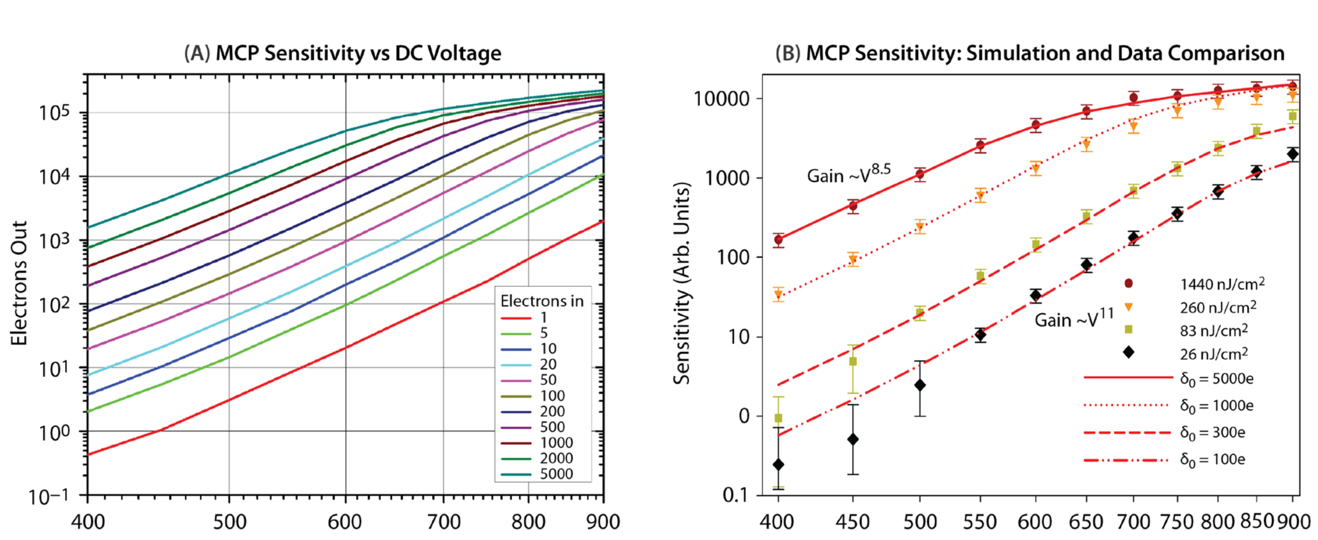


Figure 1. (A) Simulation results showing electrons out per pore versus DC voltage bias for average number of input electrons ranging from 1–5000. Onset of nonlinearity is seen near 5×10^4 electrons per pore. **(B)** Comparison of simulated and measured MCP sensitivity. The agreement is very good. The dependence of gain on applied voltage appears to decrease as the number of input electrons increases.

Dynamic Range Simulation and Measurements: Pulsed Mode Results

The short-pulse UV laser was also used to study the dynamic range in pulsed mode. Figure 2(A) shows the simulated and measured dynamic range for the waveform from a 150 ps flat-top pulse waveform. The inset shows the linear region only. The data and simulations show very good agreement. Figure 2(B) below shows a similar result for a 300 ps flat-top pulse. Again, the agreement between the simulations and the data is very good. Both plots show an onset of nonlinearity between 100 and 200 input photoelectrons.

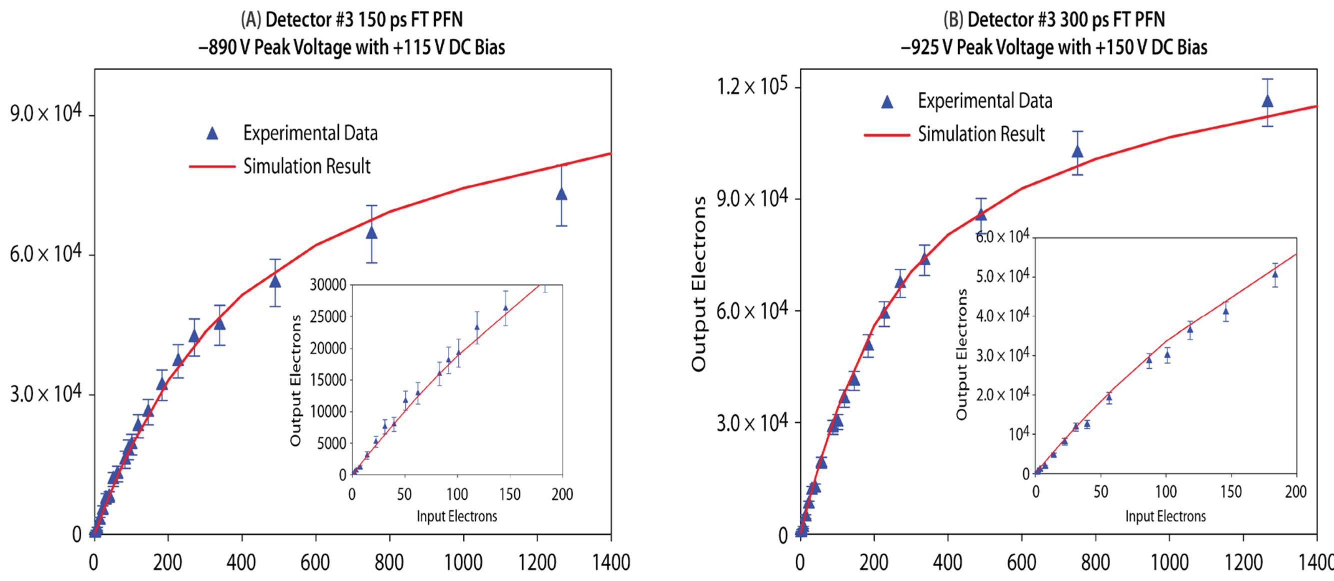


Figure 2. Comparison of simulations and measured data for MCP detector pulsed dynamic range. **(A)** Results using a 150 ps flat-top pulse waveform. The inset shows the 'linear' region. **(B)** Same as **(A)**, but for a 300 ps flat-top waveform. Agreement between the data and the simulations is excellent. The linear region extends from 1 input electron per pore to near 200 electrons.

Detection Limit Studies: Imaging and Detection

The Monte Carlo simulation code was also used to study the detection limits for both imaging and detection applications. We simulated a uniform delta function source of electrons incident on a cluster of pores. The average number of input electrons for the simulations varied from 0.1 to 50; results for 1 and 5 are presented here. Electrons emerging from the output end of the MCP were accelerated through a 3 kV voltage bias across a 0.5 mm gap to a surface (corresponding to a phosphor screen) where they were tallied. MCP DC bias voltages of 550 V and 900 V were investigated. Simulation results are shown in Figure 3. For an imaging application a sufficient number of input electrons per pore is needed so that the MCP output at the tallied surface appears reasonably uniform to reflect the uniformity of the input source. Therefore, from Figure 3, it seems that a minimum of approximately 5 input electrons per pore are required for imaging applications.

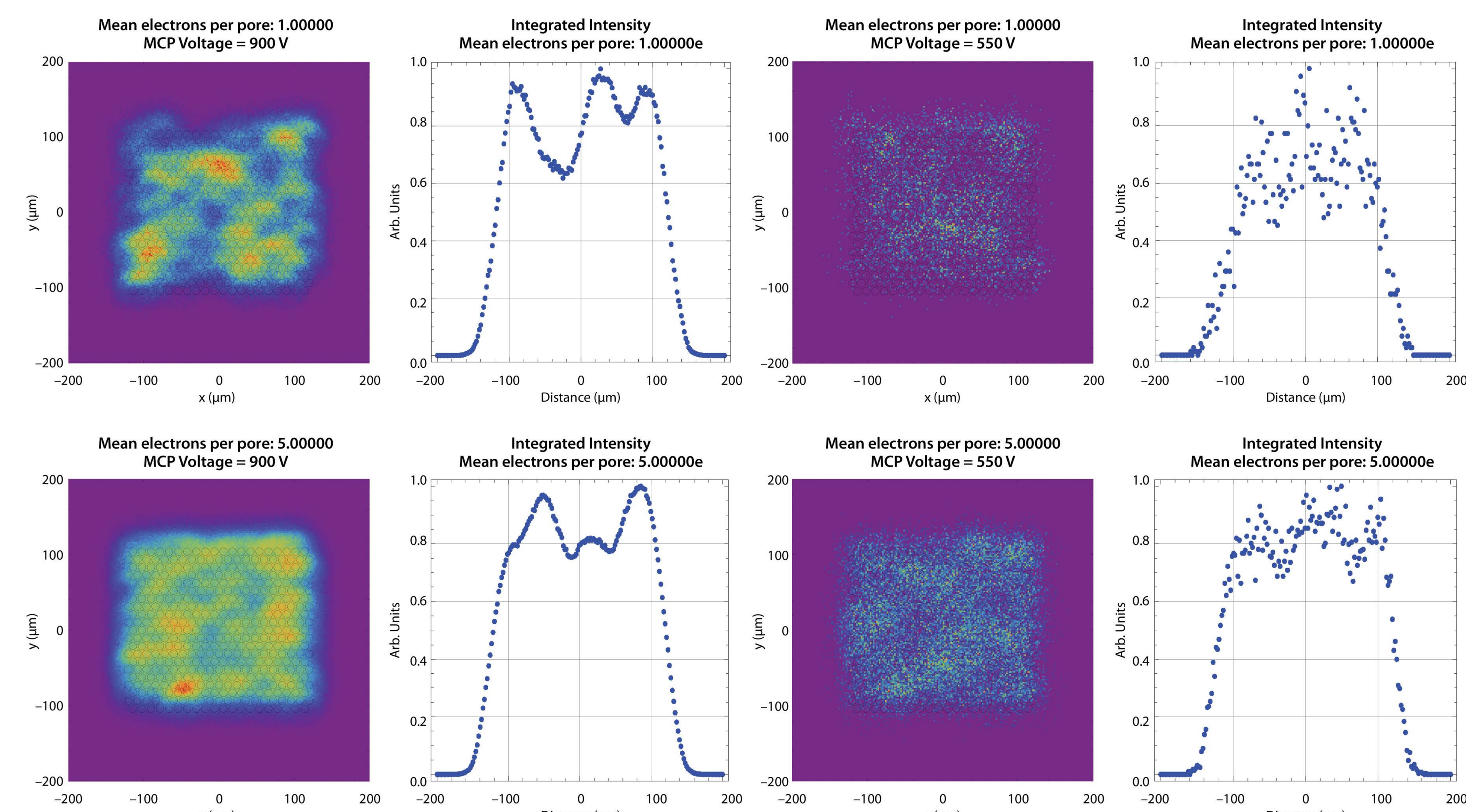
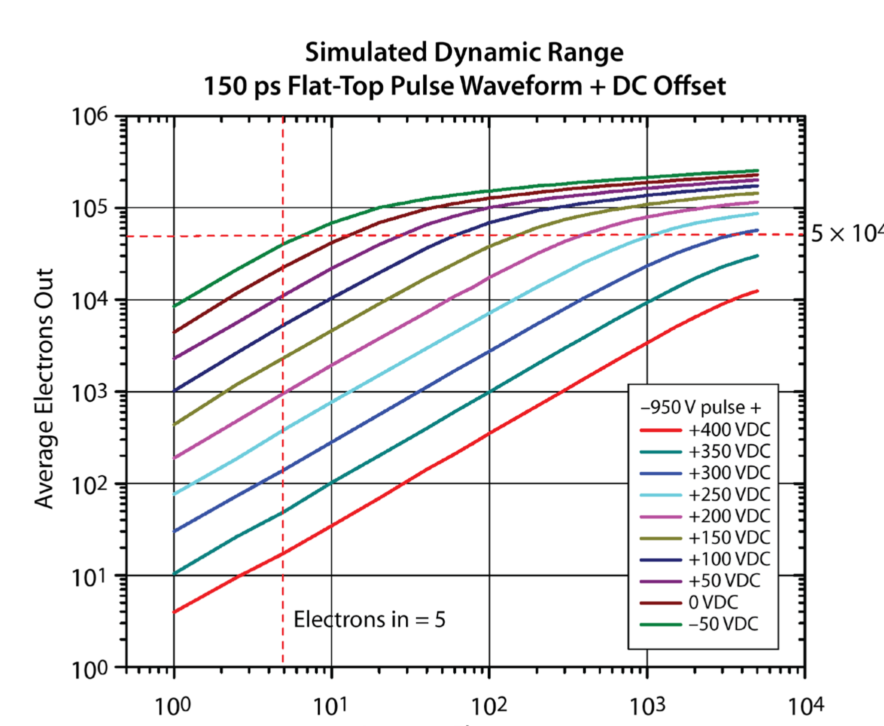


Figure 3. Simulation results for a uniform delta function source incident on a cluster of pores. The first column shows the tallied distributions of output electrons incident on the phosphor screen 0.5 mm away from the MCP output face with and MCP bias of 900 V DC; the third column shows the same results but for an MCP bias of 550 V DC. The second and fourth columns show lineouts along the x-direction (horizontal), integrated along the y-direction. The average number of input electrons per pore for the plots in the first and second rows is 1 and 5, respectively.

Dependence of the Dynamic Range of an MCP Detector on Mode of Operation

Figure 4 shows dynamic range simulation results for an MCP-based detector pulsed with a 150 ps flat-top pulse waveform and with various DC offset bias voltages. The onset of gain nonlinearity occurs at approximately 5×10^4 output electrons. From the above study, it seems that a minimum of 5 input electrons per pore is required to obtain a uniform image, while a single input electron is sufficient for detection. The results of the MCP dynamic range simulations are summarized in the table below.



Simulated MCP Dynamic Range
150 ps Flat Top Pulse Waveform, –950 V Peak Input Voltage

DC bias voltage, V	Peak Voltage, V	Pulse Width (FWHM, ps)	Dynamic Range: Imaging	Dynamic Range: Detection
–50	–1000	546	1	5
0	–950	514	2.5	12.5
50	–900	490	5	25
100	–850	468	12	60
150	–800	444	30	150
200	–750	424	60	300
250	–700	400	200	1000
300	–650	384	400	2000
350	–600	368	1400	7000
400	–550	350	10,000	50,000

Figure 4. Dynamic range simulation results for an MCP-based detector pulsed with a 150 ps flat-top pulse waveform and with various DC offset bias voltages. Onset of detector nonlinearity is taken to be a 5×10^4 electrons out. The table on the right summarizes the dynamic range results for both Imaging and detection. It is evident that the detector dynamic range depends greatly on the combination of pulse waveform and DC offset used in fielding.

Summary

We have described the results of a study of MCP-based detector saturation characteristics and dynamic range. The study was conducted using a Monte Carlo code developed at NSTec to simulate the behavior of MCP-based detectors. In addition, a short-pulse UV laser was used to obtain experimental data for a gated MCP-based imager with a L/D = 46, 10-micron pore diameter MCP. Comparisons of simulations and experiment data show excellent agreement, and indicate that such an MCP begins to show nonlinear gain around 5×10^4 electrons per pore and hard saturation around 10^5 electrons per pore. The results also show a difference in MCP sensitivity versus voltage for high flux of photons producing large numbers of photoelectrons on a subpicosecond timescale, with the sensitivity decreasing as the number of input photoelectrons increases. Simulations indicate that the dynamic range of the detector depends a great deal on how the voltage is applied to the detector and whether the detector is being used for an imaging application. For the pulse waveforms and DC offsets investigated here, the dynamic range varies from 1 to 10,000 for imaging.

References

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This work was done by National Security Technologies, LLC, under Contract No. DE-AC52-06NA25946
with the U.S. Department of Energy and supported by the Site-Directed Research and Development Program.