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Simulating Photoelectric Radiation Transport in Cylindrical Gas Filled Photoemission Driven Cavities

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INTRODUCTION

Pulsed power experiments performed on the Z Machine at Sandia National Laboratories are essential to understanding radiation effects on electrical equipment. The Radiation Analysis Modeling and Simulation of Electrical Systems (RAMSES) team researches these effects experimentally and computationally. The physics effects of pulsed photon irradiation of materials from pulsed power experiments can be calculated computationally using many in-house codes. This experiment involves the irradiation of a material in an anode/cathode (AK) gap by an x-ray pulse and studies the effects of the incident radiation. First, the electron emission material is irradiated with an input x-ray photon spectrum to produce a photoelectron emission spectrum. This is accomplished using a stochastic radiation transport code. The photoelectron spectrum, together with the x-ray time pulse and yield, is then used to characterize the electron emission into the gas filled cylindrical cavity that is modeled via an electromagnetic (EM) particle-in-cell (PIC) code.

The EM PIC code solves Maxwell's equations in the presence of charged particles to self-consistently model the electromagnetic plasma dynamic evolution within the AK gap. The current measurement diagnostic used in our cylindrical end irradiated cavity experiment is called a B-Dot [1]. The name B-Dot comes from dB/dt, or the time-varying magnetic field induced in the circuit [2]. Simulation of B-Dot output from x-ray irradiation of the experimental cavity has many practical applications in science, engineering, and strategic deterrence. A visualization of the cavity experiment is shown in figure 1

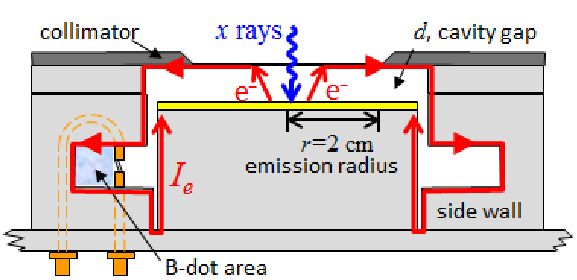

Fig 1: B-Dot sensor schematic. The x-ray pulse creates a current, which induces a magnetic field in the sensor circuit, producing a voltage in the sensor circuit [3]

There are two surfaces that emit photoelectrons in the cavity: the top surface and the bottom surface. The top surface (where x-rays come in in figure 1) is aluminum with a thin carbon coating, where the carbon suppresses electron emission. The bottom surface is the irradiated material, which in this experiment is gold. After irradiation, current flows along the red lines and induces a current in the B-dot. The B-dot outputs a time changing voltage that we can easily convert to current.

The experiment explored in this work is a computational simulation of a B-Dot output where the B-Dot diagnostic itself is not modeled, but the physical processes that produce the current in the experiments are modeled. The simulated current can be compared to the processed experimental B-Dot measurements. The important physics of this experiment are currents in the B-Dot (Bdl current) and space-charge limits on currents, while the fill gas type and pressure, irradiation material, and distance from the source (in some cases) are varied.

Background Information

As the pressure increases in the cavity, we expect that the Bdl current will increase; however, this is not strictly true. This phenomenon can be explained by the pressure being too high to generate as much plasma as in lower pressure cases for some gasses, namely N_2. Figure 2 shows the Paschen curve, which shows the voltage necessary for electric discharge in a gas.

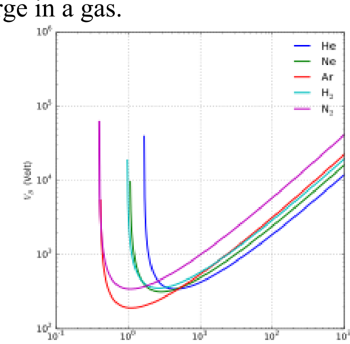

Figure 2: Paschen curve for many gasses. N_2 and Ne are explored in this paper [5]

As the pressure changes, the amount of energy required for ionization changes, and there is a clear minimum at lower pressures. After the minimum, pressure increase correlates to higher voltage required for ionization of the gas. We will see almost an inverse Paschen curve, where

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instead of voltage decreasing to a minimum and then increasing as a function of pressure, the current increases to a maximum and then decreases as a function of pressure. This is seen by the peak current output increasing until 300mtorr and then decreasing until 500mtorr in N_2 gas experiments, but this is not as prevalent in cavities filled with Ne (figure 7). This is not surprising, as the minimum on the Paschen curve for the N_2 is much lower than the minimum for the Ne. Although the peak currents are lower for those higher-pressure cases in N_2, the plasma still drives a current after the initial pulse has ended, as expected. Regardless of the fill gas, turning on SCL emission in the simulation will drive a current through the cavity long after the initial x-ray pulse.
A Monte Carlos simulation uses random sampling to estimate mathematical functions and mimic the operations of complex systems; in our case, photoelectric radiation transport [4]. A general pattern for Monte Carlo simulations is to model a system as a series of Probability density functions (PDFs), sample from the PDF many times, and tally the results [4]. The code generates a random number that corresponds to the probability of an event occurring. The process repeats many times for each particle until it leaves the system or “dies”, the result is tallied, and the process repeats many times. The simulations below use over 10^9 particles. Monte Carlo methods, although time consuming, should provide similar results to experiment (assuming your model is accurate), and it allows us to solve problems that would be difficult to solve analytically.

METHODS

There are two major steps to the simulation: the electron/photon Monte Carlo transport code that is used as a stochastic photoelectron spectrum generator, and the EM kinetic plasma PIC code. The input photon spectrum used here was from a stainless-steel Z-pinch wire array source. A stack of filtering materials is added to filter out low energy photons and keep only the higher energy x-rays. The x-rays are computationally transported through an aluminum foil that seals the gap allowing the pressure to be held at vacuum or at a low gas pressure. The foil is coated on the AK gap-facing side (top surface in figure 1) with a thin layer of carbon to suppress photoelectron emission from the foil into the gap. The output of the stochastic code is photoelectric emission as a function of energy.

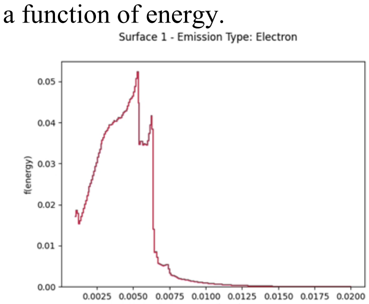

Fig 3: Photoelectron emission distribution due to stainless-steel wire array photon radiation spectrum on the carbon coated aluminum foil.

The geometry of the cavity is produced such that the gap size is set to ten millimeters. The spectrum was used to simulate a current, measured in the simulation with the integral of Bdl with the path in the theta direction, that can be compared to an experimentally measured B-Dot.
The first experiment shown is the pressure scan of the irradiated Au. A filtered 1keV – 20keV stainless-steel wire array x-ray input spectrum is incident upon an Au surface in the 10mm cylindrical end irradiated cavity. The simulation also requires a time-pulse from the experiment, which was provided by Tim Flanagan, R&D S&E in 1343, and pulses for 30ns. The x-ray source is 500mm from the Au, and the pulse was modeled for the entire 30ns creating a time independent photoelectron spectrum. The spectrum is sent to the EM PIC code, and Bdl currents are computed for pressures ranging from vacuum to 1000 mtorr in Ne and N_2 gas. SCL emission is toggled on/off in the simulation. Turning SCL emission on allows the Au surface to emit electrons if a surface electric field is present to allow electrons to accelerate into the gap. The presence of such an electric field is due to plasma generation in the cavity gap, and it continues to drive the maximum current through the B-Dot. A comparison of fill gasses is performed. The species of fill gas changes how much plasma is generated, as the energy required to ionize the fill gas changes. This work will focus on comparing N_2 and Ne fill gasses.
Below is the photoelectron output spectrum generated by the stochastic electron/photon transport code for Au. Surface 2 is the cathode with a higher photoelectron emission and Surface 1 is the anode with a lower photoelectron emission (Al with a thin Carbon coating).

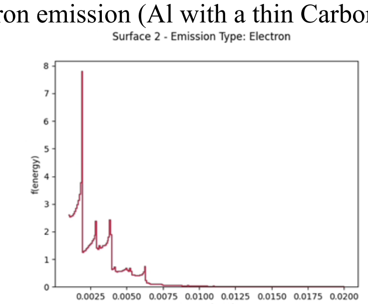

Fig 4: photoelectron output spectrum due to x-ray irradiation of Au in the stochastic photon/electron code

RESULTS

The photoelectron input spectra from the stochastic electron/photon code for gold and carbon-coated aluminum from the previous section (figures 4 and 5) was used as input to the EM PIC code and, with an x-ray time pulse, produced the electron emission into the AK gap that would be expected due the x-ray irradiation. More information on the physics and operations of the EM PIC code can be found in reference [7]. Figure 6 shows the current output for gold with a neon gas fill between 200 and 500mtorr. For SCL off cases, there are some oscillations in the current after the pulse. If the gap was at vacuum pressures, the oscillations come from the cavity acting like an LC circuit where we see ringing in the current. However, our minimum is 200mtorr, so the cavity acts like an RLC circuit instead of an LC circuit and has less ringing than vacuum cases.

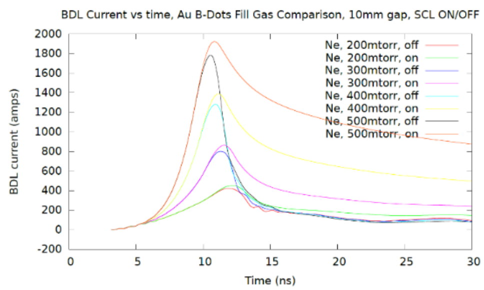

Figure 5: Bdl Current vs time for Ne between 200 and 500mtorr for a 10mm Au B-Dot system, with SCL emission toggled on/off

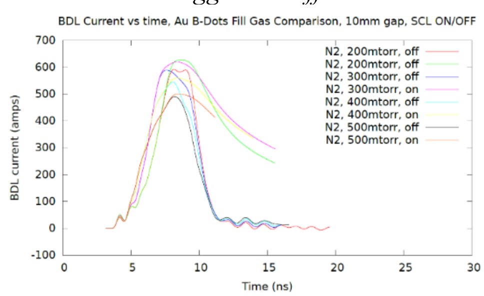

Figure 6: Bdl Current vs time for N_2 between 200 and 500mtorr for a 10mm Au B-Dot system, with SCL effects toggled on/off

When SCL effects are turned on, we can see a much higher peak current as pressure increases, which is due to the neutralization of space charge electric fields in the gap by the plasma. Without the presence of a plasma, the emitted electrons produce a space charge barrier that limits the amount of charge that can enter the gap. For example, let's look at the 400mtorr graph from figure 6. We see that the SCL on case has a higher peak current than the SCL off case, and the tail of the pulse drops off considerably (below 100A) after the initial irradiation pulse for the SCL off case because the maximum current is not driven to zero. For the Ne fill gas below 500mtorr, peak current increases as pressure increases. When SCL emission is enabled, we see a significant amount of current in the circuit long after the initial time pulse. The tail from the SCL on case occurs because in the experiment the electric field from the ions in the plasma is driving the maximum amount of current possible until limited by space charge.
The SCL off case does not allow electrons to be emitted from the surfaces after the end of the x-ray pulse; therefore, the true expected current tail should lie somewhere between the two simulations for a given pressure, and the simulations provide a good upper and lower bound for the system.

Seeing how the type of fill gas effects the current output is very interesting. For all pressures below 500mtorr, the current peaks much earlier (before 10ns) for N_2 than for Ne (which occurs after 10ns). At 200mtorr (figure 11), we can see that the N_2 has a higher peak current than Ne, but peak current for Ne is higher at 300mtorr, and much higher after 400mtorr. Effects of SCL emission are seen in both cases (as expected), and the general effects of SCL on cases are relatively similar for both fill gasses. The peak current for the Ne gas is at 500mtorr with SCL emission turned on. This is not surprising because the pressure is still below the point on the Paschen curve where higher voltage is required for ionization. The peak current for the N_2 gas is at 300mtorr. Again, this is not surprising because after 300mtorr, the voltage required for ionization is higher than the voltage required for ionization at 300mtorr (figure 9 sits right at the minimum pressure in the Paschen curve).

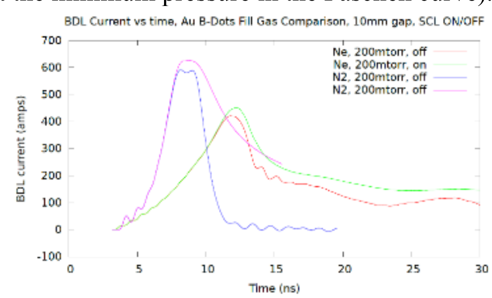

Figure 7: Bdl Current vs time for Ne and N_2 at 200mtorr for a 10mm Au B-Dot system, with SCL effects toggled on/off

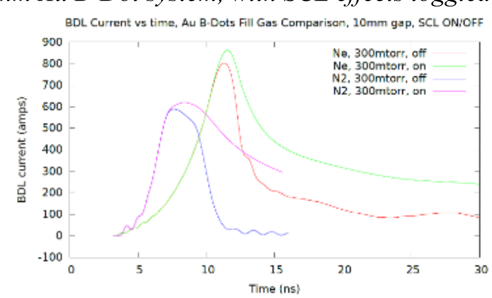

Figure 8: Bdl Current vs time for Ne and N_2 at 300mtorr for a 10mm Au B-Dot system, with SCL effects toggled on/off

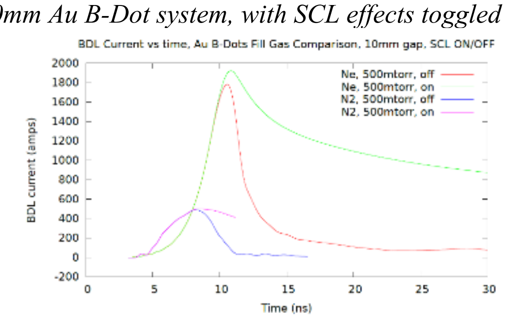

Figure 9: Bdl Current vs time for Ne and N_2 at 500mtorr, 10mm Au B-Dot system, with SCL effects toggled on/off

CONCLUSION

End irradiated cylindrical cavity experiments are of great importance to code validation and provide an opportunity to deepen our knowledge of radiation transport physics. Modeling SCL emission was studied for Au surface B-Dot experiments at various gas pressures. From my simulations, we can conclude that SCL emission is important to model and account for, as it continues to drive a current after the initial x-ray pulse. From experiment, we know that the true current tail should lie between the SCL on and off cases, so the simulation does a good job at predicting an upper bound on current. Finally, understanding the energy required to cause ionization in different gasses and understanding the Paschen curve is of paramount importance to find how pressure in the cavity effects current in different fill gasses. Future work for this experiment is to keep increasing the pressure for Au surface B-Dots experiments with a Ne gas fill until the pressure becomes so large that we exceed the minimum of the Paschen curve. This would help us find the pressure required for Ne where the highest Bdl current output is generated. It would also be interesting to find a pressure (between 200 and 300mtorr) where the peak current for Ne and N_2 fill gas is equivalent. Argon fill gas cross section libraries are also available, and it could be worthwhile to re-run and compare the Ne and N_2 fill gas simulations to an Argon fill gas simulation.

NOMENCLATURE

AK = Anode / Cathode
SCL = Space-Charge Limiting
mtorr = millitorr
PDFs = Probability Density Functions

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