Laser Discharge Initiation for Gas-fed Pulsed Plasma Thrusters *

J.W. Berkery[†]and E.Y. Choueiri[‡]
Electric Propulsion and Plasma Dynamics Laboratory (EPPDyL)
Mechanical and Aerospace Engineering Department
Princeton University, Princeton, New Jersey 08544

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Abstract

A method of discharge initiation at an undervoltage by a laser-induced pulse of electrons from a photocathode is presented. The intended application is to produce spatially uniform current sheet initiation in gas-fed pulsed plasma thrusters. The effect is explained by a space charge buildup which can increase the electric field of the gap. A theoretical model was developed and showed that an increase of the charge multiplication coefficient to a level above unity will produce a current rise to breakdown. Attempts to use an ultraviolet light pulse to create a photocurrent spike were unsuccessful probably due to inadequate surface preparation of the photocathode. Infared laser pulses, however, did lead to current production which lead to breakdown from a 15% undervoltage in argon.

1 Introduction

The problem which is under investigation in the present research is the initiation of the discharge in a pulsed plasma thruster through laser stimulation of the cathode. If an ultraviolet laser beam impinges upon the backplate cathode of a coaxial gas-fed pulsed plasma thruster (GFPPT), it will release from that surface a certain flux of electrons through the photoelectric effect. This photocurrent of electrons can be used to set up a space charge which will lead to breakdown of the thruster electrode gap. Beyond its application to pulsed plasma thrusters, however, the investigation of the influence of a current pulse in stimulating gas breakdown is a fundamental research problem, as it has not been thoroughly and systematically investigated in the past.

The motivation for this research is to find an alternative to spark plug initiation of GFPPT discharges, which often leads to non-uniform current sheets. Spark plugs also tend to have high erosion rates and present a critical lifetime issue [1].

Previous analyses of the problem of photoelectric induced breakdown have concentrated on steady-state photocurrents lowering the applied breakdown voltage of a gap [2, 3, 4, 5]. Using a photocurrent pulse as an initiation method from an undervoltage is less well documented. Work in this area has uncovered the mechanism by which a photocurrent *pulse* sets up a space charge which influences the breakdown [6, 7, 8, 9]. The usefullness of this method as a reliable discharge initiation mechanism has not been made clear.

The goal of this study is to explore photoelectric initation as a possible replacement for spark plug initiation in GFPPTs. Achieving this goal will involve the development of an understanding of the basic physics behind photoelectrically stimulated discharge initiation, determination of the level of photocurrent necessary to initiate a breakdown, and experimental confirmation of the resulting performance. To this end, we have developed a theoretical model for voltage breakdown in a gap in which a photocurrent pulse is induced. Experimentally, we have attempted to use ultraviolet light to draw a current pulse through the photoelectric effect. Infared light was also used, and presently has proven more successful as we report in this paper.

In the next section, GFPPTs are described in more

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[*] Research supported by The New Jersey Space Grant Consortium, and the Plasma Science and Technology Program at the Princeton Plasma Physics Lab.

[†] Graduate Student, Research Assistant. Member AIAA.

[‡] Chief Scientist at EPPDyL. Assistant Professor, Applied Physics Group. Senior Member AIAA.

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detail, as well as the motivation for finding an alternative to spark plugs. Theoretical background on photoelectric discharge initiation is then presented, along with theoretical studies which begin to explore the domain of applicability of laser discharge initiation. The issues of the selection of a suitable photocathode material are explored. Finally, experimental setup and methodology are detailed, and experimental results are given.

2 Gas Fed Pulsed Plasma Thruster Initiation

Gas-fed pulsed plasma thrusters (GFPPTs) are a class of thrusters which utilize a $j \times B$ body force to accelerate a plasma in a chamber [10]. An electric potential is established between two electrodes, and propellant gas is fed into the electrode gap through a valve. A spark is then initiated in the chamber which causes an arc discharge to form as a current sheet between the electrodes at the backplate. The current sheet induces its own magnetic field, is subject to a $j \times B$ force and accelerates down the chamber, pushing the gas like a piston head along the way. The accelerated gas provides thrust at a high specific impulse. Once the gas is fully expelled, new cold gas enters the chamber and the process repeats.

Currently, discharges in gas-fed pulsed plasma thrusters are initiated with spark plugs. In contrast to a Paschen breakdown which is not very controllable in timing or exact sparking voltage, spark plugs provide a controllable and reliable sparking mechanism. Also, spark plugs allow the discharge to be initiated over a wide range of propellant pressures without requiring large changes in applied voltage [11].

Spark plugs have disadvantages as well. The current sheet formed by spark plug inititation begins by preferentially attaching to the spark plugs, and then spreads out. Even when the current sheet is fully developed, it continues to display non-uniform behavior. Figure 1 shows the current sheet formation in a co-axial pulsed plasma thruster initiated by four evenly spaced spark plugs. A non-uniform current sheet in a pulsed plasma thruster has been shown to lead to inefficiencies in the gas acceleration process [12].

The most important disadvantage of spark plugs, however, is that they tend to erode at high levels. It has been found that at energy levels of 2J per pulse, spark plugs can erode at levels of 0.1μgrams per pulse [1]. Over a mission of 10^8 pulses, that is a unacceptably high total erosion of 10 grams of material off of the spark plugs alone. Spark plugs erode at high levels precisely because of the preferential attachment of the high current discharge. Thus, an alternative discharge initiation device which does not utilize preferential current attachment could serve the dual purpose of reducing erosion and creating a more azimuthally uniform current sheet. Such a method is the ultimate goal of this research project.

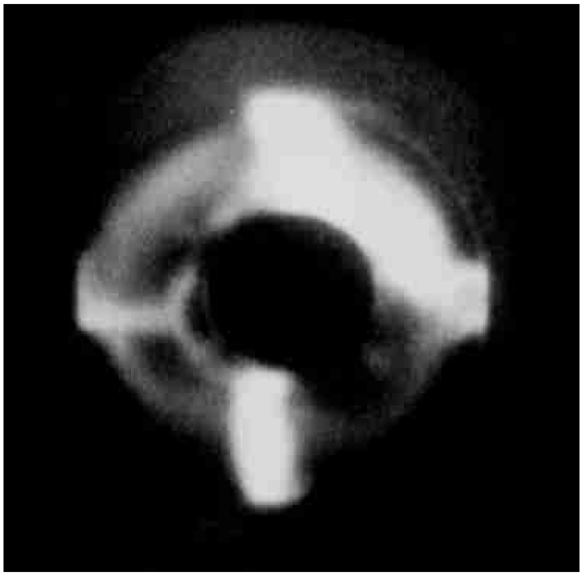

Figure 1: Photograph of a discharge in a coaxial GF-PPT with four spark plugs. From [12]. The preferential attachement of the plasma to the spark plugs may be seen on the top, bottom, right and left. The inner dark circle is the cathode.

Using a source of flashed ultraviolet light on the cathode to draw a photocurrent pulse to initiate breakdown could help to solve these problems. If the laser pulse uniformly covers the cathode, the current sheet may be more uniform as well. The spread of the current attachment area should lead to lower and more uniform erosion.

In the explorative experiments reported here, the laser was shone on the cathode from a downstream point. One possible implementation of photoelectrically stimulated discharge initiation for practical application is shown schematically in Figure 2.

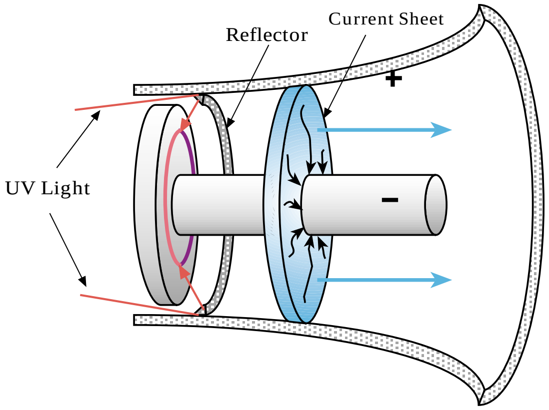

Figure 2: Possible configuration of a laser discharge initiation system for a GFPPT.

3 Theoretical Model

A breakdown occurs when a discharge becomes self-sustaining. The sparking criterion can be obtained from the following expression obtained by Townsend [13],

$$i = \frac{i_0 e^{\alpha d}}{1 - \gamma(e^{\alpha d} - 1)}. \tag{1}$$

Here, i is the discharge current, i_0 is the initial current, which could be due to the photoelectric effect, and d is the gap distance between the electrodes. Townsend's first coefficient, α, is the number of ionizing collisions an electron performs while moving in a 1 cm path. Townsend's second coefficient, γ, is the ratio of secondary electrons released per incident bombarding ion. It is a function of the gas and the cathode material.

The dependence of current on voltage is implict in α in the above equation. When the current is plotted against voltage, at a certain "sparking voltage" the current rises to infinity. This effect can be seen in equation 1 when the denominator goes to zero. Thus the Townsend criterion for a self sustaining discharge is usually defined in terms of μ, the charge reproduction coefficient,

$$\mu = \gamma(e^{\alpha d} - 1). \tag{2}$$

When $\mu = 1$, the breakdown voltage is reached and the current goes to infinity. When μ is greater than unity, the gap is said to be overvoltaged, and when less than unity, undervoltaged.

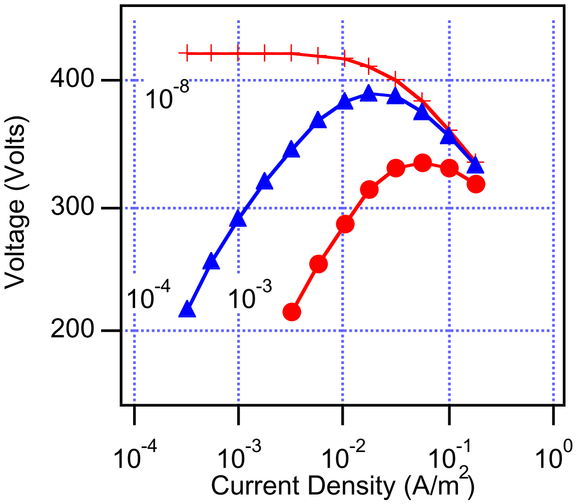

Figure 3: Static voltage-current characteristic of argon discharges at pressure of 10 Torr and gap of 1cm. The different curves represent different levels of steady photocurrent in units of A/m^2. Note that the peaks of the curves are the breakdown voltages, and that when the photocurrent level approaches the same order as the discharge current level, a large breakdown voltage lowering is predicted.

According to this sparking criterion, the sparking voltage should not depend on the photocurrent, i_0. This statement has been contradicted numerous times in the literature, as researchers have found the sparking voltage to be lowered by high levels of photocurrent [2, 3, 8]. Since it is our goal to use a burst of photocurrent to produce a spark while at an undervoltage, we need to further examine the reported dependence of sparking voltage on photocurrent.

The mechanism by which a current can assist in facilitating a breakdown is by setting up a space charge. This changes the electric field, which in turn can increase μ to unity and above [7, 14]. Previous attempts to model the effect of a steady-state constant photocurrent include numerical efforts by Crowe et al. [4] and Ward [5]. These researchers have predicted a substantial decrease in the breakdown voltage induced by photocurrent.

We have reproduced and confirmed the predictions of Ward for argon, and have evolved the model in a few regards. We used an updated expression for α from Ref. [15], and γ from Ref. [16]. Figure 3 shows the static voltage-current characteristics subjected to different levels of steady photocurrent. The

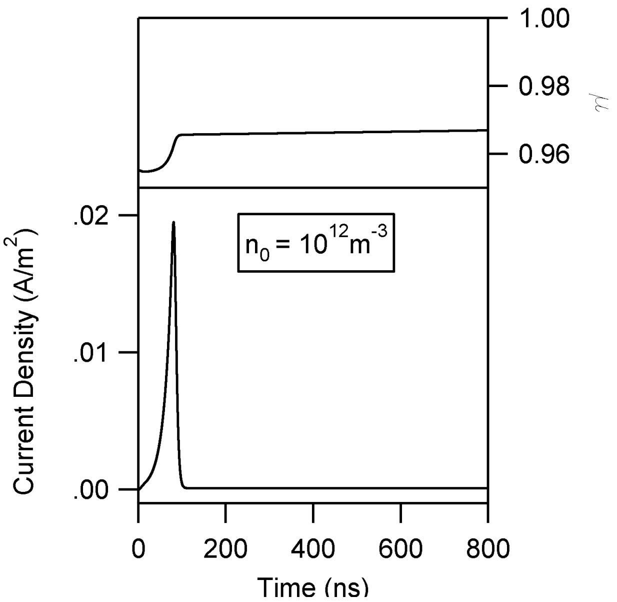

Figure 4: Solution for the current and charge multiplication coefficient, μ, of an argon discharge at pressure of 10 Torr, gap of 1cm, voltage of 420 Volts (just below breakdown), with a photoelectron pulse with $n_0 = 10^{12} m^{-3}$ and $T_{width} = 5ns$.

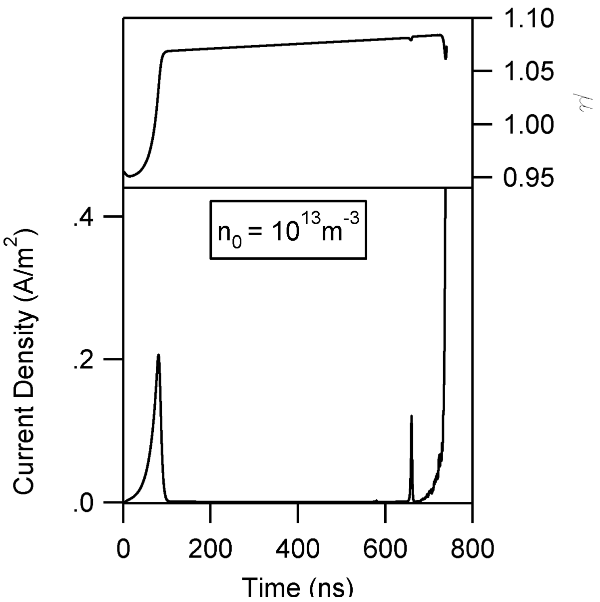

Figure 5: Solution for the current and charge multiplication coefficient, μ, of an argon discharge at pressure of 10 Torr, gap of 1cm, voltage of 420 Volts (just below breakdown), with a photoelectron pulse with $n_0 = 10^{13} m^{-3}$ and $T_{width} = 5ns$.

photocurrent creates a space charge which lowers the required breakdown voltage. A current pulse created by a pulsed laser, however, is no longer a steady-state problem.

We carried out calculations of the current rise in an argon discharge at an undervoltage due to a pulse of electrons from the cathode. The continuity equations for electrons and ions, as well as Poisson's equation were solved to capture the influence of space charge. The method was derived from the work of Sato and Sakamoto [8] as well as Davies et al. [17, 18]. The governing equations are,

$$\frac{dn_e}{dt} = \alpha \mu_e n_e E - \frac{d}{dx}(\mu_e n_e E), \tag{3}$$

$$\frac{dn_p}{dt} = \alpha \mu_e n_e E + \frac{d}{dx}(\mu_p n_p E), \tag{4}$$

$$\frac{dE}{dx} = \frac{e}{\epsilon_0}(n_p - n_e). \tag{5}$$

Here $n_s(x,t)$ is species number density, $E(x,t)$ is the electric field and $\mu_s(x,t)$ is species mobility (to be differentiated from the charge multiplication coefficient). The cathode is at $x = 0$ and the anode at $x = d$. These equations are subject to the boundary conditions [18],

$$n_e(0,t) = n_0(t) + \gamma_i n_p(0,t)\frac{\mu_p}{\mu_e}$$
$$+\frac{\gamma_{ph}}{\mu_e(0,t)E(0,t)}(1 - e^{-t/\tau_{ph}}) \int_0^d \alpha n_e \mu_e E dx, \tag{6}$$

$$n_p(d,t) = 0. \tag{7}$$

The second boundary condition is the condition of zero ions at the anode. The terms in the first boundary condition represent the creation of electrons at the cathode due to the photoelectric pulse, the bombardment of ions, and photons from the bulk gas, respectively. Here γ_i and γ_{ph} are the ion and photon secondary coefficients, and τ_{ph} is the average lifetime of excited species. The exponential term creates a time delay for the photons to be created and to reach the cathode. The photoelectric pulse from the laser is modeled by [8],

$$n_0(t) = n_0 \left(\frac{t}{T_{width}}\right)^2 e^{-(t/T_{width})^2}. \tag{8}$$

These equations are solved by taking small steps in time and solving for changes in x, while updating the boundary conditions. The current density in the gap is then calculated at each time step from:

$$j(t) = e \int_0^d (n_e \mu_e E + n_p \mu_p E) dx \qquad (9)$$

Figure 4 shows that at an undervoltage, a pulse of electrons that is unable to raise the parameter μ to above unity will not produce a breakdown. This is shown by the current density, which rises with time to a peak as electrons multiply, but falls to nearly zero after the electrons have reached the anode. While μ is less than unity, these electrons will not be replaced. Although μ continues to rise in the time given, it eventually falls due to the loss of ions, which depletes the space charge.

It is interesting to note that reduction of the breakdown voltage from approximately 422 Volts to 391 Volts is predicted in the static case with a steady current of 10^{-4} A/m^2, whereas a pulsed current with a peak of 2×10^{-2} A/m^2 cannot produce a breakdown at 420 Volts. This shows that the current pulse will need to have a realtively high peak to produce a significant effect.

Figure 5 shows that for a discharge with the same pressure and gap spacing, at a slightly higher voltage and with a more intense pulse of electrons, the parameter μ can be brought above unity, which eventually leads to breakdown. The time delay between the first current pulse and the breakdown is due to the slow movement of the accumlated ions. Electrons multiply into an avalanche once sufficient numbers are created by ion and photon bombardment of the cathode.

The data appears qualitatively similar to similar experiments and numerical studies reported in the literature for other gases [7, 8]. Thus this model may be used as a tool to explore the conditions that may lead to a breakdown in actual experimental situations.

The results presented here are based on a simple, one dimensional model which contains some assumptions. Values of γ_{ph} and τ_{ph}, in particular, are best guesses. Diffusional and recombinational losses are also not taken into account.

4 Photocathode Investigation

Initially we set out to use an ultraviolet laser to extract electrons through the photoelectric effect from the backplate cathode of a GFPPT. Thus a photocathode with a high quantum efficiency was desired. For experiments using a frequency quadrupled Nd:YAG laser, with a wavelength of 266nm, a material with a work function of less than 4.66eV is necessary according to the cutoff of the photoelectric effect.

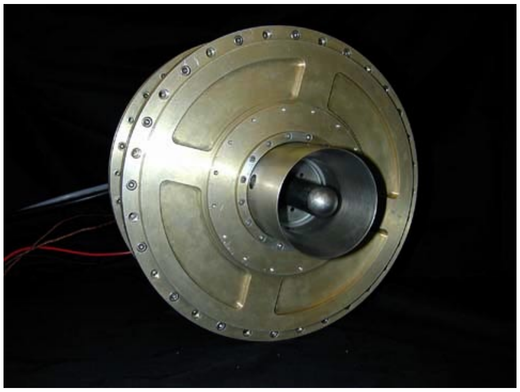

Figure 6: Photograph of Science Research Laboratory's PT4 Thruster. The cathode diameter is approximately 0.85 inches and the anode inner diameter is approximately 1.85 inches.

There are two basic types of photocathode: semiconductor and metal. Semiconductor photocathodes, such as Cs_2Te or GaAs, generally have higher quantum efficiencies than metals [19]. Unfortunately they also have much shorter lifetimes and are subject to oxidation and contamination. They require high vacuum levels and often high-temperature cleaning to maintain their high quantum efficiencies. Metal photocathodes have lower quantum efficiencies, but have longer lifetimes and require much less preparation in general. They are more rugged and may be used in harsher environments. Thus, despite their lower quantum efficiencies, for the application of pulsed plasma thrusters, metal photocathodes are more desirable.

Therefore we need a material with a suitable work function, a good quantum efficiency, and ease of use. Magnesium was singled out as the most promising metal candidate for this application. Magnesium has a work function of 3.66 eV, with quantum efficiencies up to 0.2% and a well documented heritage as a photocathode material [20]. Furthermore, it does not require high temperature heating for activation, however approximately 150 C baking of the surface, outgassing, and laser cleaning are required to obtain high purity, and thus high quantum efficiency surfaces [21].

5 Experimental Facilities

A small vacuum tank was outfitted with a diffusion pump to reach base pressure levels of approximately 2×10^{-4} Torr. A quartz window was installed to allow ultraviolet light to be transmitted into the tank.

For our experiment, we used a Continium Nd:YAG laser with a fundamental of 1064nm (in the infared) and a fourth harmonic wavelength of 266nm (in the ultraviolet). The laser was pulsed at 10Hz, and has a pulse duration of 10ns.

Diagnostics included a Tektronix CT2 current probe with a time response of 200MHz and a TDS 3032 digital oscilloscope to read voltages or currents.

The pulsed plasma thruster used in these experiments is called PT4 and was produced by Science Research Labs. This thruster is described in detail in reference [22]. A photograph of PT4 is included as figure 6. The thruster is coaxial with an outer anode and an inner cathode. The backplate of the thruster is at cathode potential, and it is the backplate that serves as a photocathode.

6 Experimental Methods

In order to study the effect of photocurrent on breakdown voltage, experiments were carried out in the following manner. The thruster was fitted with a Mg photocathode, which was then prepared for experiments. This was accomplished by fine sanding, and washing the surface with isopropyl alcohol. The Mg photocathode was also polished with a 6 micron diamond polishing compound. Once installed the surface was allowed to outgas in vacuum (2×10^-4 Torr) and baked in a low pressure argon gas fill to rid the surfaces of water, oxygen and other contaminants. The tank was then filled with argon to the desired pressure. The voltage on the electrodes was then slowly increased until a breakdown occured. This breakdown voltage was recorded on an oscilloscope, and many trials were averaged to determine the breakdown voltage. The thruster voltage was then set to a level below the breakdown, and the laser energy was increased until a spark could be reliably produced. The laser energy was recorded, as well as the current traces.

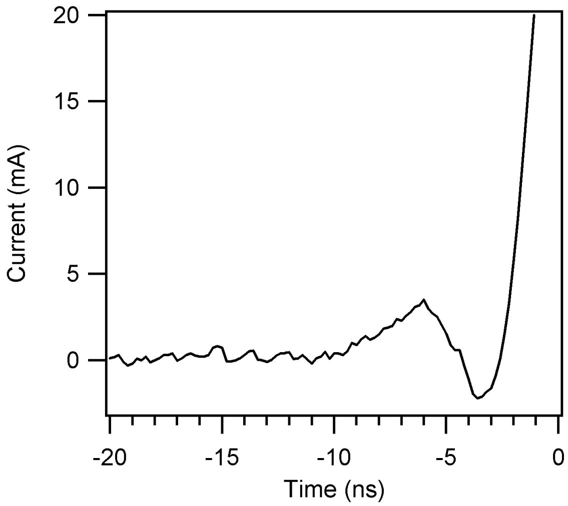

Figure 7: Current trace for a 0.5 Torr argon gap at 270 Volts (4.3% undervoltage), with a 1064nm laser pulse of 85mJ.

7 Experimental Results and Discussion

The results of breakdown voltage experiments performed as described above with ultraviolet laser pulses were unsuccessful in initiating a discharge at an undervoltage. Laser energies of up to the maximum obtainable with our laser system (18mJ at 266nm) were tested at many different pressures and failed to produce a photocurrent pulse or spark. A possible reason for these results has been formulated. Photocathodes are normally used in applications at high vacuum, and with stringent surface preparation. We now believe that despite our attempts, the surface preparation was inadequate. Thus due to absorbed gases, oxidation, or contamination from pump oil, for example, the quantum efficiency of the magnesium surface may be orders of magnitude lower than our best estimates. This would lead to a much lower photocurrent than estimated, which could not effect on breakdown voltage. Indeed, we could not measure any photocurrent on the milli-Amp level.

Subsequently, infared laser pulses were used for an argon pressure of 0.5 Torr. The breakdown voltage at this pressure was measured to be 282 ± 4 Volts. The voltage was set to various levels below this value and the cathode was pulsed with infared light. The results of these experiments are presented in graphical form.

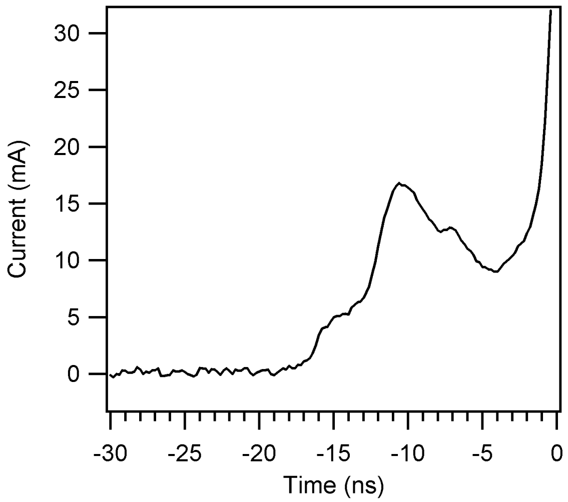

Figure 8: Current trace for a 0.5 Torr argon gap at 260 Volts (7.8% undervoltage), with a 1064nm laser pulse of 144mJ.

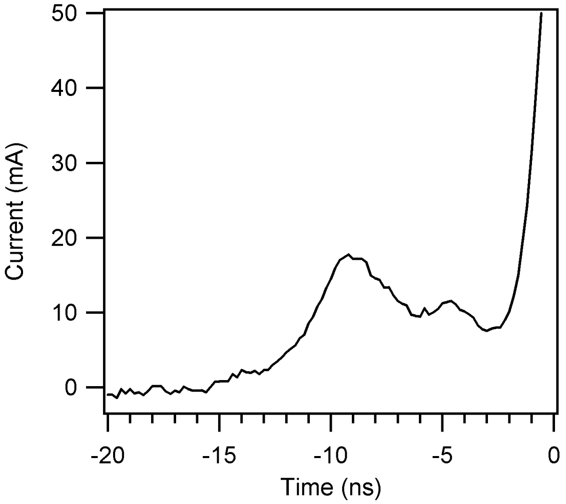

Figure 9: Current trace for a 0.5 Torr argon gap at 250 Volts (11.3% undervoltage), with a 1064nm laser pulse of 153mJ.

In figure 7, the thruster was set to 270 Volts (4.3% undervoltage), and an 85mJ laser pulse is shown to lead to a breakdown. The current spike seen before the infinite rise is due to the laser pulse. It has a duration approximately equal to that of the laser pulse (10ns) and rises to a peak value of about 5mA. This current pulse at this applied voltage was enough to lead to a breakdown. Less energy in the laser did not lead to a reliable spark at this voltage, nor was this laser energy sufficient at higher undervoltages.

The undervoltage was increased, and typical current traces are presented in figures 8 to 10. As the undervoltage is increased, the laser energy and thus the current spike, needed to produce a breakdown has to be increased. Figure 11 shows a current spike at 250 Volts that did not lead to breakdown.

The qualitative agreement between the measurements and calculations is encouraging. The experiments were performed at different conditions, and the thruster used in experimentation has non-uniform electric fields due to its coaxial configuration. Thus we do not expect the experimental findings to be any more than qualitatively similar to the simple, one-dimensional theoretical studies.

These experiments confirm that a current pulse can lead to breakdown at an undervoltage, by increasing the space charge in the gap. However, we have not yet determined with certainty the actual mechanism of the creation of the current pulse by an infared light pulse. If metal vaporization from the magnesium surface is the underlying mechanism, it may lead to cathode erosion [23] and this may circumvent any possible advantage over the use of spark plugs. It is also possible that local heating due to the laser pulse is releasing electrons thermionically. Further work will be necessary to uncover the source of the current pulse in these infared experiments. However, the theoretical treatment of this problem is the same, regardless of the source of the electron pulse. Thus, the concept of an undervoltage breakdown due to a current pulse is valid.

8 Conclusions

A fundamental study of laser-initiated discharges has been undertaken with the ultimate goal of applicability to pulsed plasma thrusters. A theoretical model has been developed to aid in the understanding of the effect of space charge in producing a breakdown. Experimental work has been performed as well to verify undervoltage breakdown with a current pulse. The following conclusions may be drawn:

- High peak current pulses in an undervoltaged gap can produce a space charge which raises the charge multiplication coefficient, μ, above unity, leading to breakdown.

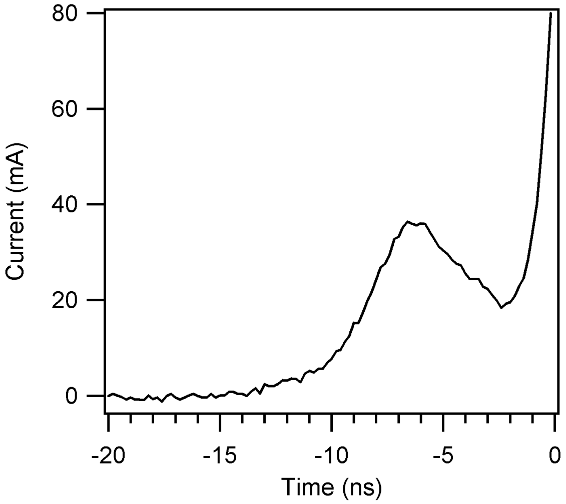

Figure 10: Current trace for a 0.5 Torr argon gap at 240 Volts (14.9% undervoltage), with a 1064nm laser pulse of 182mJ.

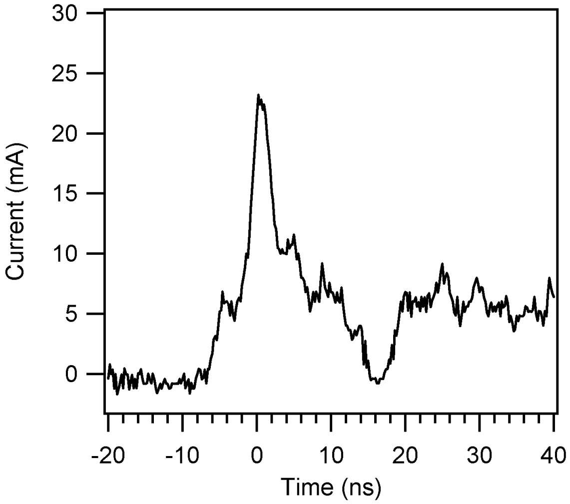

Figure 11: Current trace for a 0.5 Torr argon gap at 250 Volts (11.3% undervoltage), with a 1064nm laser pulse of 144mJ. The laser energy was not high enough to produce a breakdown.

- Attempts to use ultraviolet light to produce a current pulse photoelectrically were unsuccessful, probably due to inadequate surface preparation.
- Infared laser stimulation produced current spikes which led to breakdown. Despite the ambiguity of the source of the current pulse in this case, the principle of operation is the same. Thus, experiments have shown that a pulse of current can indeed lead to a breakdown at an undervoltage.

References

[1] J. Blandino, D. Birx, J.K. Ziemer, and E.Y. Choueiri. Performance and erosion measurements of the PT8 gas-fed pulsed plasma thruster. Technical Report EPPDyL-JPL99b, NASA Jet Propulsion Laboratory, August 1999.

[2] H.J. White. The variation of sparking potential with intense ultraviolet illumination. *Physical Review*, 48:113–117, 1935.

[3] D.J. DeBitetto, L.H. Fisher, and A.L. Ward. Negative current characteristics in hydrogen at high pressure using plane parallel electrodes. *Physical Review*, 118:920–923, 1960.

[4] R.W. Crowe, J.K. Bragg, and V.G. Thomas. Space charge formation and the townsend mechanism of spark breakdown in gases. *Physical Review*, 96:10–14, 1954.

[5] A.L. Ward. Effect of space charge in cold-cathode gas discharges. *Physical Review*, 112:1852–1857, 1958.

[6] D. Pickard, W. Kunkel, K. Leung, and A. Young. Plasma production via laser-induced photoemission. *Review of Scientific Instruments*, 67:1666–1669, 1996.

[7] H. Raether. *Electron Avalanches and Breakdown in Gases*. Butterworth Inc., 1964.

[8] N. Sato and S. Sakamoto. Undervoltage breakdown between parallel plates in air. *Journal of Physics D: Applied Physics*, 12:875–885, 1979.

[9] K. Harsch, H. Salzmann, and H. Stohwald. Uv laser triggering of spark gaps by two-quantum photoelectric effect. *Physics Letters*, 55:153–154, 1975.

[10] R.G. Jahn. *Physics of Electric Propulsion.* McGraw-Hill, 1969.

[11] M.E. Brady and G. Aston. Pulsed plasma thruster ignitor plug ignition characteristics. *Journal of Spacecraft and Rockets*, 20(5):450–451, 1983.

[12] J.K. Ziemer, T.E. Markusic, E.Y. Choueiri, and D. Birx. Effects of ignition on discharge symmetry in gas-fed pulsed plasma thrusters. In 34^{th} *Joint Propulsion Conference*, Cleveland, Ohio, July 13-15 1998. AIAA 98-3803.

[13] J.S. Townsend. *Electricity in Gases.* Oxford University Press, 1914.

[14] R. Kluckow. Uber den zeitlichen verlauf des stromes einer gasenladung in wasserstoff. *Zeitschrift fur Physik*, 161:353–369, 1961.

[15] A.V. Phelps and Z.L. Petrovic. Cold-cathode discharges and breakdown in argon: Surface and gas phase production of secondary electrons. *Plasma Sources Science and Technology*, 8:R21, 1999.

[16] Z.L. Petrovic and A.V. Phelps. Temporal and constriction behavior of low-pressure, cathode-dominated argon discharges. *Physical Review E*, 56:5920–5931, 1997.

[17] A.J. Davies, C.J. Evans, and F. Llewellyn-Jones. Electric breakdown of gases: the spatio-temporal growth of ionization in fields distorted by space charge. *Proceedings of the Royal Society of London*, A281:164–183, 1964.

[18] A.J. Davies, C.J. Evans, and P.M. Woodison. Computation of ionisation growth at high current densities. *Proceedings of the I.E.E.*, 122:765–768, 1975.

[19] I. Boscolo and P. Michelato. Photocathodes: the state of the art and some news. *Nuclear Instruments and Methods A*, 445:389, 2000.

[20] T. Srinivasan-Rao, J. Fischer, and T. Tsang. Photoemission from Mg irradiated by short pulse ultraviolet and visible lasers. *Journal of Applied Physics*, 77:1275, 1995.

[21] X.I. Wang et. al. Measurements on photoelectrons from a magnesium cathode in a microwave electron gun. *Nuclear Instruments and Methods A*, 356:159, 1995.

[22] J.K. Ziemer, E.A. Cubbin, E.Y. Choueiri, and D. Birx. Performance characterization of a high efficiency gas-fed pulsed plasma thruster. In 33^{rd} *Joint Propulsion Conference*, Seattle, Washington, July 6-9 1997. AIAA 97-2925.

[23] A.G. Bedrin, I.V. Podmoshenskii, and P.N. Rogovtsev. Formation of a light-initiated surface discharge. *Soviet Physics Technical Physics*, 28:403–407, 1983.