Fundamentals of PPT Discharge Initiation: Undervoltage Breakdown Through Electron Pulse Injection

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Abstract

In order to understand the fundamentals behind pulsed plasma thruster discharge initiation, the phenomenon of undervoltage (i.e. at a voltage slightly below the breakdown voltage) breakdown through electron pulse injection is explored. This phenomenon is not only the mechanism employed by sparkplug-based PPT initiation systems, but is also the basis for a new optical initiation system which promises improved performance and lifetime. A theoretical model is derived which predicts the injected electron density required to induce breakdown. These results are compared to experimental measurements in which laser pulses on a tungsten surface are used to cause electrons to be injected into a discharge gap with a parallel-plate geometry. It is found that for argon at 2 Torr, the theory and experiment both give the required current density on the order of 10^{-7}-10^{-8} A/m^2 at voltages ranging from 90% to 99% of the breakdown voltage. The similarity suggests that the theoretical interpretation is reasonable: the pulse of electrons alters the space charge in the gap and augments the electric field, making ionization more likely and causing the gas to breakdown.

1 Introduction

The first description of the fundamentals of steady-state gas discharges was put forth by Townsend [1]. Others have looked into how discharges grow in time [2] and how the space charge effects of steady-state photocurrents can alter the breakdown voltage of a discharge gap [3]. Sato and Sakamoto [4] have investigated the phenomenon of using optically induced current pulses to induce breakdown at an undervoltage (i.e., at a voltage slightly below the breakdown voltage) in air, using a numerical model that solves continuity equations to calculate the delay time between the current pulse and the breakdown. However, no quantitative analysis of the minimum number of electrons required to induce breakdown was undertaken, and the specific mechanism behind how the discharges were achieved was unclear. Since pulsed plasma thrusters use pulses of electrons into undervoltaged discharge gaps to initiate their discharges, we seek to understand the phenomenon on a more basic level.

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The phenomenon is most clearly relevant to gas-fed PPTs (GFPPTs), and those are the devices on which we will focus in this work. The physics behind how discharges are initiated in ablative PPTs are not well understood, but the processes described here might play a significant part.

Current GFPPT designs employ sparkplugs to initiate their discharges. The sparkplugs are the life-limiting thruster components and produce azimuthally non-uniform current sheets which might exacerbate current sheet permeability problems [5]. An improved discharge initation system is therefore required if GFPPTs are to become a viable propulsion candidate. Understanding the underlying physics behind how discharge initiation systems work is an important step toward improving them.

GFPPTs that use sparkplugs usually place the sparkplugs in the vicinity of the cathode. When the sparkplugs fire inside a gap containing gas, a small amount of plasma is formed. The electrons created drift towards the anode, ionizing neutral gas atoms along the way. By the time the electrons have traversed the gap, they have left behind a wake of ions which alters the electric field profile.

We have proposed another discharge initiation system [6, 7] that involves using a laser to optically induce electron ejection from the cathode of a GF-PPT by way of thermionic emission from the cathode itself. The electrons initiate the discharge in the same manner as those released from sparkplugs. We have observed discharges in an actual thruster that were initiated with laser pulses.

Our goal is to arrive at an understanding of the underlying physics behind how electron pulses can induce breakdowns and verify that understanding with an idealized experiment.

We begin with a derivation of the profiles of space charge and electric field created by a temporally short pulse of electrons at the cathode of a one-dimensional discharge gap. This derivation leads to a numerical calculation of the minimum electron density required to induce a breakdown for a variety of parameters. We then compare the results of these calculations with those of a series of experiments designed to replicate the simplified conditions of the theoretical model.

2 Theory

In this section we present a theoretical description of how an electron pulse introduced at the cathode of a discharge gap alters the charge distribution and induces breakdown. We use this model to calculate a threshold condition for the density of a pulse that will cause a breakdown. We assume a one-dimensional, parallel-plate electrode geometry.

An electron in the gap is accelerated by the electric field and undergoes ionizing collisions which produce more electrons:

$$\frac{dn_e}{dx} = \alpha(E,p)n_e. \tag{1}$$

n_e is the electron density in particles per unit volume. α, the number of ionizing collisions per unit length that a single electron undergoes, is related to the electric field E and pressure p [8]:

$$\alpha = Ape^{-Bp/E}, \tag{2}$$

where A and B are empirical coefficients characteristic to a given gas. Equation 1 carries with it the assumption that there is no means for loss of electrons; we are thus neglecting diffusional and recombinational losses. Solving for n_e gives a gain coefficient for electron multiplication:

$$\frac{n_e(x)}{n_{e0}} = exp\left[\int_0^x \alpha(x')dx'\right]. \tag{3}$$

Since each ionizing collision produces an electron and an ion, we see from Equation 3 that an electron that starts at the cathode and drifts to the anode a distance d away will produce

$$exp\left[\int_0^d \alpha(x')dx'\right] - 1$$

ions. These ions will eventually drift back to the cathode. On impact with that surface, each ion will release a secondary electron with probability γ, the secondary electron emission coefficient. Thus, each electron at the cathode will ultimately produce

$$\mu = \gamma\left[exp\left(\int_0^d \alpha(x')dx'\right) - 1\right] \tag{4}$$

secondary electrons at the cathode. We call μ the breakdown parameter. The secondary electrons will of course undergo the same process as the original electron, each producing μ "third generation" electrons, which in turn produce more electrons and so on. We can see, therefore, that if

$$\mu > 1 \tag{5}$$

the current in the gap will quickly increase. This is the criterion for breakdown as defined by Townsend [9]. The criterion is a function of cathode material, electrode separation, gas, neutral density, and electric field. Thus, for a given set of electrodes filled with a given gas at a given pressure, we can find the voltage for which this condition is met, called the breakdown voltage.

Imagine a gap set at an undervoltage. If a number of electrons n_{e0} is introduced into the gap at the cathode ($x = 0$) in a very short time (compared with the time it takes an electron to traverse the gap) it will drift across the gap, get amplified, and exit the gap. It will have created ions along the way, but since the ions are much heavier and therefore much less mobile than the electrons, they do not move significantly on the timescale of electron drift across the gap. Therefore, when the electrons exit, they leave behind a wake of ions with spatial distribution

$$n_p(x) = n_{eo} \left\{ exp \left[\int_0^x \alpha(x')dx' \right] - 1 \right\}. \tag{6}$$

The resulting space charge augments the electric field already present in the gap. The electric field can be calculated from Poisson's equation.

$$E(x) = \frac{e}{\varepsilon_0} \left(\int_x^d n_p dx' - \int_0^x n_p dx' \right) + E_0, \tag{7}$$

E_0 is the electric field due to the externally applied voltage. Equations 2, 5, and 7 can be solved numerically through iteration to find the minimum magnitude of the electron pulse, n_{e0}^* for which a breakdown will occur. Figure 1 plots n_{e0}^* for a gap of .0254 cm in argon of various pressures.

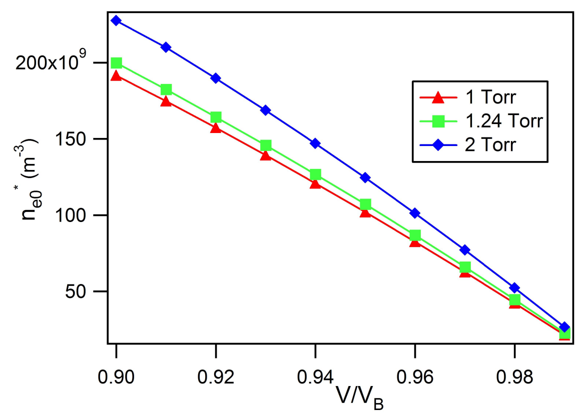

Figure 1: Minimum electron pulse magnitude required for breakdown versus fraction of the breakdown voltage for 1, 1.24, and 2 Torr of argon.

3 Experimental Setup

The experiment is designed to model as closely as possible the parallel-plate geometry analyzed in the theoretical model. Figure 2 is a schematic of the experiment. The apparatus consists of two copper electrodes that are square, 10cm on a side, and separated by 2.5cm. A 50 mm square sheet of tungsten foil is inset onto the inner face of the cathode so as to be flush with the surface. This acts as a laser target from which electrons can be released through thermionic emission [6]. A heater is fixed to the backside of the cathode for surface preparation.

The electrodes are placed inside a bell jar vacuum facility which is pumped by a diffusion pump outfitted with refrigerated baffles and can reach pressures as low as 2×10^{-4} Torr. Argon is flowed into the vacuum facility until the desired pressure is reached as measured by a Convectron pressure gauge.

The laser is a pulsed Nd:YAG that was used at the fundamental wavelength of 1064 nm. The beam is directed into the vacuum facility through a quartz window. The spot diameter of the laser is 1 cm and pulses with energies up to 200 mJ were used. The laser's flashlamps were pulsed at 10 Hz and the Q-switched laser pulse width was 8ns. Single shots were used in the experiments, but pulse energy was measured by setting the laser in a continuously pulsed mode and measuring the average power with a laser power meter placed in the beam.

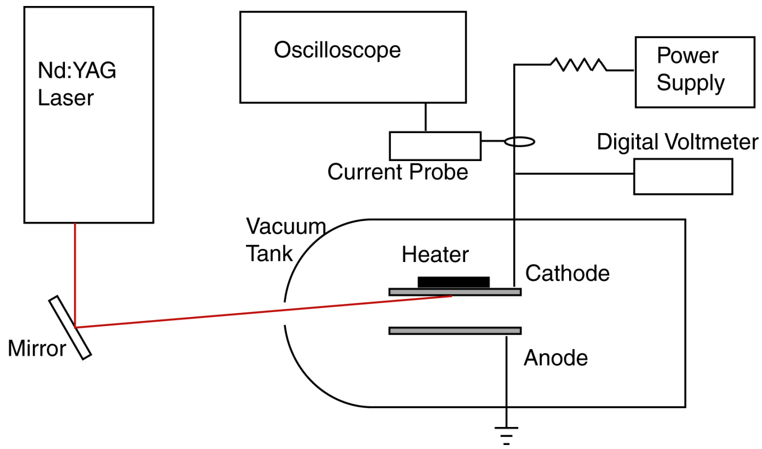

Figure 2: Schematic of the experimental setup.

Other diagnostics included a Tektronix CT2 current probe with a time response of 200MHz and a TDS 3032 digital oscilloscope with a 2.5G samples/s sampling rate.

4 Experimental Methods and Results

In order to prepare the tungsten surface for experimentation, we used a glow discharge cleaning technique. The pressure in the vacuum facility was set to 200mT and a voltage of 700V was applied for approximately one hour before any data were taken.

4.1 Minimum Pulse Energy Required for Breakdown

In order to corroborate the results of the theoretical model presented earlier, we performed a series of experiments in which we measured the minimum laser pulse energy required to induce a breakdown. At a given pressure, the breakdown voltage V_b of the gas was measured. This was repeatable to within .2%. The laser pulse requirement was checked at several undervoltages.

Figure 3 is a plot of the minimum pulse energy required for breakdown versus fraction of the breakdown voltage for argon at three different pressures.

4.2 Determination of the Current Released During a Laser Pulse

The thermionic current emitted during a laser pulse was expected to be on the order of a μA or less. This is not measurable with our current experimental setup, which has a maximum resolution of 1 mA. We therefore chose to use the amplification properties of the discharge gap to empirically determine the current that results from a laser pulse of given energy.

When there is gas present and a significant voltage across the plates, any current will be amplified by a gain factor given by Equation 3.

$$j_{\text{amplified}} = j_0 exp\left[\int_0^d \alpha(x')dx'\right] \approx j_0 e^{\alpha d}. \quad (8)$$

The approximation is valid under the assumption that α does not vary significantly across the gap.

We set the discharge gap at a voltage and pressure such that the amplified current pulses were measurable. We then measured the peak of a current pulse released as a function of laser pulse energy at two different voltages. Using Equation 2 and the published values of A and B for argon [8], we calculated the gain expected for each case. Figure 4 plots the experimentally determined curves of measured current versus pulse energy. The data taken at each voltage are divided by their respective gain factors, which should represent the unamplified current coming off of the tungsten surface.

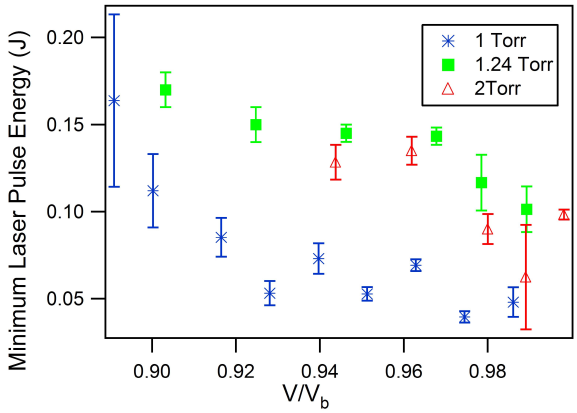

Figure 3: Minimum laser pulse energy required to breakdown argon at various pressures as a function of fraction of the breakdown voltage.

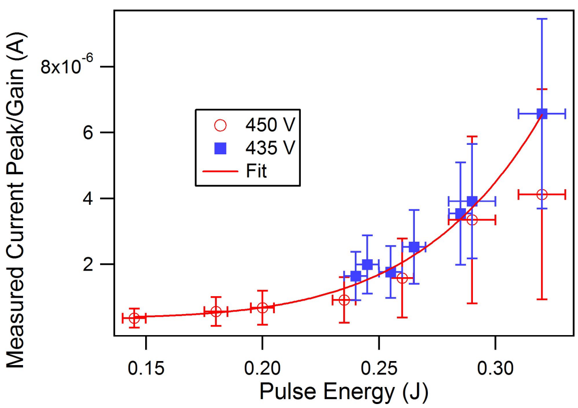

Figure 4: Measured current peaks corrected for amplification versus laser pulse energy. The data were taken with argon at pressure of 2.01 Torr.

The corrected data collapse onto one curve, which suggests that our calculations of the gains for each case were appropriate. The data were found to fit with a χ^2/n of 5.4/11 to a function of the form:

$$j = j_0 + \beta U^\delta, \tag{9}$$

where j is the current and U the pulse energy. The fit parameters were found to be: $j_0 = 2.2 \pm 0.000433\mu A$, $\beta = 46.816 \pm 53.9$, and $\delta = 6.6046 \pm 0.913$.

5 Analysis and Discussion

In order to compare the numerical results of Section 2 with the experimental results of section 4.1, we need to compute the current required to produce the electron densities predicted by the theoretical model as well as the current that we expect to be emitted by the thermionic effect of the laser pulse on the cathode.

Since current density is given by:

$$j = nqv, \tag{10}$$

where n is the density of charge carriers, q the charge on each carrier, and v the average particle velocity, we can calculate the current density required to produce a given electron density if we know the velocity with which the electrons come off the surface. If we presume that the mechanism by which electrons are released is thermionic emission, then we know that only electrons that have thermal energy above the work function of the metal will be released.

We assume that the electrons in the metal are described by a Maxwellian speed distribution:

$$f^M(c) = 4\pi \left(\frac{m}{2\pi kT}\right)^{3/2} c^2 e^{\frac{-mc^2}{2kT}}. \tag{11}$$

The velocity of an electron that corresponds to a kinetic energy equal to the work function of the metal is

$$v_\phi = \sqrt{\frac{2e\phi}{m}}. \tag{12}$$

We then calculate the average speed of electrons that have speed greater than v_ϕ. The velocity of electrons that are released is the difference between this average speed and v_ϕ.

$$v = \frac{\int_{v_\phi}^{\infty} c f^M(c) dc}{\int_{v_\phi}^{\infty} f^M(c) dc} - v_\phi, \tag{13}$$

ϕ is the work function of the metal, e the electron charge and m the electron mass. Using this equation and assuming that the surface is tungsten with a work function of 4.55 eV and that the surface temperature during the pulse rises to 1500 K (from the theoretical model presented in [6], we expect this temperature for a laser pulse of approximately 150mJ.) we calculate a velocity of approximately 25000 m/s. This calculation is insensitive to temperature and work function; if the temperature is varied by 500K, or the work function by 1eV, the velocity calculated varies by less than 20%.

In order to express the threshold pulse energy data in terms of current peaks we used the current calibration summarized by Equation 9. However, as that equation gives total current in the circuit expected for a given laser pulse and we sought only the current emitted from the tungsten surface, we subtracted the pulse-energy-independent offset current j_0.

Figure 5 contains a plot of the theoretically calculated threshold peak size in terms of current peak as well as the experimentally determined current peak magnitudes versus fraction of the breakdown voltage for three pressures.

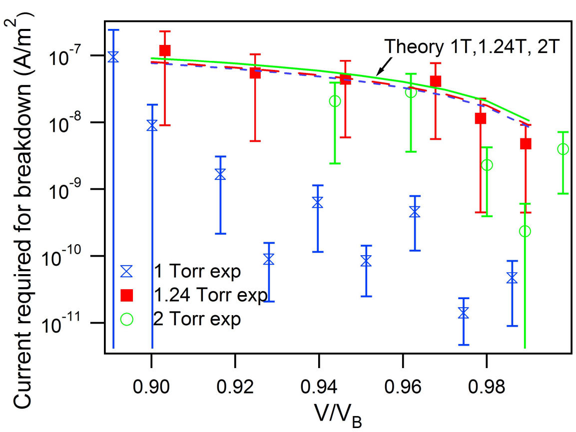

Figure 5: Minimum theoretical and experimental current densities required to induce a breakdown.

We can see that both the theory and the experiment suggest that current pulses with peaks on the order of 10^{-7} - 10^{-8}A/m^2 are the minimum required to produce a breakdown at the pressures of 1.24 and 2 Torr. We can also see that general the trend of increasing pulse energy required as the voltage becomes a smaller fraction of the breakdown voltage is predicted by both theory and experiment. The 1 Torr experimental data appear to be anomalous.

While the model has a number of simplifying assumption that may be questioned (one-dimensionality, neglect of electron loss), it is not clear how the reduction of pressure from 2 to 1 Torr would render any of these assumptions less valid.

Our method of determining the velocity with which electrons are emitted from the surface is dependent on the assumption that electrons are emitted through the process of thermionic emission. However, we do not necessarily know that this is the process at work in our case. Previous work [6] has shown that laser pulses can be used to initiate discharges using mechanisms other than thermionic emission. Specifically, if gas is desorbed or other material ablated from the surface, then quickly ionized, it will supply a pulse of charge carriers. If thermionic emission is not the relevant mechanism, then our velocity calculation is not appropriate.

It is possible that at lower pressures, desorbed gases or ablated material may play a larger role in affecting the breakdown condition. This possibility will be explored in future work.

6 Conclusions

In order to understand the fundamental physics behind how discharges in gas-fed pulsed plasma thrusters are initiated, we have undertaken a theoretical and experimental investigation of the phenomenon of undervoltage breakdown through electron pulse injection.

- We have developed a simple, one dimensional model which describes how pulses of electrons at the cathode of an undervoltaged discharge gap can induce breakdown.
- Using the model, we have predicted a theoretical threshold condition for the size of a current pulse required to produce a breakdown.
- We have undertaken a series of experiments using infrared laser pulses to thermionically emit electrons from a tungsten surface on the cathode of a parallel-plate discharge gap to induce undervoltage breakdown. The goal of these experiments was to determine an experimental threshold condition for comparison with the theory.
- We have found that our theoretical predictions

of threshold pulse density agree to within an order of magnitude of the experimentally measured values for two of the three pressures we tried.

We have concluded that the following description is a reasonable picture of the mechanism behind discharge initiation of GFPPTs: electrons injected at the cathode drift to the anode, creating a wake of ions. The electrons then exit the discharge gap and leave the ions behind. The resulting space charge augments the electric field already present and makes ionization more likely, to the point where a breakdown can occur.

Acknowledgements

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