Fundamentals of Discharge Initiation in Gas-Fed Pulsed Plasma Thrusters

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James E. Cooley* and Edgar Y. Choueiri†
Electric Propulsion and Plasma Dynamics Laboratory (EPPDyL)
Princeton University, Princeton, New Jersey 08544

An investigation into the requirements for initiating discharges in gas-fed pulsed plasma thrusters (GFPPTs) is conducted. It is argued that undervoltage breakdown, in which a pulse of electrons induces a discharge gap that is near but has not reached is self-breakdown conditions, is the basic mechanism a successful GFPPT initiation scheme is likely to use. Theoretical investigations based on order-of-magnitude characterizations of previous GF-PPT designs reveal that high-conductivity arc discharges are required for critically-damped matching of circuit components, and that relatively fast streamer breakdown is preferable to minimize delay between triggering and current sheet formation. Results of an idealized experiment designed to measure the number of electrons required to achieve undervoltage breakdown for a given set of conditions are described. Two distinct breakdown mechanisms were observed, a relatively fast breakdown to a high conductivity and a relatively slow breakdown to a lower conductivity. The faster mechanism is appropriate for GFPPT discharge initiation. It is estimated that 10^{10} electrons are required to achieve the faster breakdown.

I. Introduction

Among the most important obstacles standing in the way of the gas-fed pulsed plasma thruster (GFPPT) becoming flight-ready hardware is the lack of a suitable discharge initiation system, the method by which plasma is initially formed during a pulse. Previous research has resulted, largely through trial and error, in techniques passable for laboratory research, but to date no GFPPT has ever been tested that employed an initiation system capable of producing uniform current sheets reliably for the entire required lifetime of a thruster on a space mission.

A GFPPT is a pulsed electromagnetic accelerator in which small puffs of gas are injected between two electrodes across which sits a charged capacitor bank. When the discharge initiation system triggers gas breakdown, the conductive plasma completes the circuit and the capacitor bank is allowed to discharge. Rapid current increase leads to the formation of a well-defined sheet of current, which is then accelerated due to its self-induced $j \times B$ body force. As the current sheet moves along the discharge chamber, it entrains neutral gas and accelerates it through collisions, exhausting a mass bit at high velocity. A common device known as an ablative pulsed plasma thruster (APPT)[1] operates under similar principles but utilizes solid propellant instead of injected gas. While the thrusters share many attributes and physical phenomena, ablation of the solid propellant is of fundamental importance to the discharge initiation of an APPT but is not relevant in a GFPPT. Arguments presented in this study do not consider ablation phenomena and are thus more appropriate for describing GFPPT discharge initiation.

In this paper we do not present an improvement on past discharge initiation techniques or an alternative method (that is the subject of previous[2] and future publications). Rather, we examine the fundamental physical process that governs GFPPT discharge initiation to address a basic question: what specifically is

*Graduate Research Assistant, Mechanical and Aerospace Engineering Department, cooley@princeton.edu.
†Chief Scientist, EPPDyL. Associate Professor, Mechanical and Aerospace Engineering Department. Associated Faculty, PPPL. choueiri@princeton.edu.

required to suitably form current sheets in a GFPPT? To answer this question, we combine an analysis of the type of discharge a GFPPT needs with the results of an experimental investigation into how that discharge might be achieved.

Historically, GFPPTs and similar devices used as laboratory pulsed plasma accelerators employed discharge initiation systems based on one of three fundamental mechanisms. The first, which we call *Paschen Initiation*, involved setting the electrodes to the desired operating voltage, then injecting a puff of gas. When the pressure between the electrodes became high enough that the electrode voltage was sufficient for breakdown, plasma formed. Used in the early days of pulsed plasma accelerator research, this technique quickly fell out of favor, especially for thruster applications, because of unreliability and inflexibility – changing the mass bit or operating voltage changes the timing of breakdown. This seriously hinders performance as breaking down too early results in current sheet acceleration before enough mass has accumulated, while breaking down too late allows gas to leak out the end of the thruster without being accelerated.

Accelerators using the second mechanism, *overvoltage breakdown*, injected the gas first before putting any voltage across the electrodes, then quickly switched on a voltage that greatly exceeded that required to break the gas down. Such a technique solves the problems of timing and repeatability but adds the complexity of a fast, high-voltage switch. Including such a switch, usually an Ignitron or gas-discharge switch, means including additional mass, parasitic inductance, and (perhaps most importantly) a component proven to have limited lifetime. Furthermore, overvoltage breakdown requires high voltages, often tens of kV, which in turn requires heavy high-voltage capacitors. These issues are less relevant in a laboratory setting but become critical for thruster applications.

The final mechanism that pulsed plasma accelerators, specifically GFPPTs, use is *undervoltage breakdown.* In this scheme, the electrodes are set to a voltage just below that which will cause a breakdown when gas is introduced. Propellant is injected, then a separate discharge initiation circuit fires at the appropriate time, supplying a pulse of electrons that induces breakdown. This mechanism has several advantages: breakdown timing can be acutely controlled, the isolation of the initiation circuit from the rest of the thruster's circuitry allows for minimal parasitic inductance as well as more manageable charging voltages, and the discharge initiation circuitry is simpler and perhaps more rugged than the high-voltage switching technology.

Undervoltage breakdown is not without its drawbacks, however. The electron injectors, usually sparkplugs or needles, tend to create plasma in their local vicinity. The result is a nonuniform current sheet that is presumably more permeable and less efficient that a well-formed one would be.[3] Also, those injectors erode quickly[4] and are the life-limiting component of the thruster. We have proposed another technique[2,5] that involves using laser pulses directed onto the thruster's cathode to release electrons into the discharge gap and promises uniform current sheet formation with little or no erosion, but this idea is still in development.

Whether or not that technique ever comes to fruition, undervoltage breakdown has enjoyed the most success as a GFPPT discharge initiation mechanism and has the most promise for the reasons outlined above. Though advances in switching technology or additional initiation mechanisms may someday change this picture, for now we will assume that any initiation system will employ undervoltage breakdown as its fundamental mechanism.

We will begin with a discussion of different types of gas discharges and breakdown mechanisms, then formulate arguments about which of those are appropriate for a GFPPT. We will then describe the results of an experimental investigation into threshold requirements for undervoltage breakdown: how many electrons are required to achieve undervoltage breakdown of a given type for a given set of conditions? Finally, we will combine these two avenues of investigation to determine how many electrons are required from each pulse to initiate discharges in GFPPTs.

II. Glow vs Arc, Townsend vs Streamer: What Kind of Discharge Does a GFPPT Need?

The word "breakdown" is generally used to describe the transition of nonconductive neutral gas to conductive plasma, but the actual phenomenon is more complex than the use of one generic term implies. The plasma formed during a breakdown can have relatively low or relatively high conductivity and the process by which it breaks down can be relatively slow or relatively fast. We will see that two characteristically different types of breakdown can be achieved through electron pulse injection at an undervoltage, but first we will characterize the breakdown for which a GFPPT initiation system should aim.

Before we begin, we should establish some order-of-magnitude guidelines about the parameter space a

GFPPT is likely to inhabit. Based on the history of GFPPT development,[6] we can say that a thruster consists of two electrodes with a separation distance on the order of 1 cm, a large capacitor bank with capacitance on the order of 100 μF, negligible circuit resistance (which is to say the plasma dominates the resistance), and very small initial inductance, on the order of 100 nH. A well-designed thruster behaves as an RLC circuit whose components are matched to supply a critically damped, or nearly critically damped, current wave form with

$$R = 2\sqrt{\frac{L_0}{C}}, \tag{1}$$

where R is the plasma resistance, L_0 the initial inductance, and C the capacitance. Such a relation maximizes energy transfer between the capacitors and the current sheet.[6]

Typically a GFPPT is a relatively low-pressure discharge device employing mass bits ranging from 1 μg to a few hundred μg. Though the specifics of gas injection and timing imply complicated and often unknown mass distributions, we can estimate that thrusters and accelerators that have existed in the past were operated at pressures from around 1 mTorr up to several hundred mTorr.

Perhaps the most important guideline for a discharge initiation system to follow is the current rise requirement. In order for well-defined current sheets to form, the current has to increase very rapidly. Jahn[7] reports the experimentally determined rule of thumb that a current rise of 10^{10} A/s per cm of sheet width is required.

A. Plasma Conductivity

We can expect that a discharge formed in the gap of a GFPPT will take the form either of a low-conductivity glow discharge or a high-conductivity arc discharge – two types of discharge identified by the process by which electrons are emitted from the cathode.[8]

A glow discharge relies on secondary emission, primarily through electron bombardment, to emit electrons from a cold cathode. This process is relatively inefficient, so glow discharges tend to be less conductive than arcs and can be expected to have total plasma resistances on the order of 1 kΩ - 1 MΩ.

An arc discharge employs a hot, thermionically emitting cathode to supply a very large flux of electrons. This very conductive discharge will have a resistance on the order of .1 mΩ - .1 Ω.

We can immediately use our critical damping relation, Equation 1, to calculate that a GFPPT, at least one similar to those that have been tested in the past, relies on a plasma resistance on the order of .1 Ω and therefore requires an arc discharge.

B. Breakdown Time

How quickly does the plasma need to form in a GFPPT discharge? There are two distinct mechanisms for DC gas breakdown and they are characterized by very different timescales.

In a Townsend breakdown, electrons drifting from the cathode towards the anode collide with neutral atoms and ionize them, producing ions and more electrons. As the electrons traverse the discharge gap, their number grows in an ever-increasing avalanche. The ions left behind drift back towards the cathode at a speed much lower than that of the electrons, eventually reaching the cathode and releasing more electrons through secondary emission. These electrons in turn drift towards the anode producing another avalanche. If each successive avalanche is larger than the previous one, current rapidly increases and a breakdown is achieved.

If the number of electrons in the ith avalanche is μ times that in the $(i-1)$th avalanche:

$$\mu \equiv \frac{N_e^i}{N_e^{i-1}}, \tag{2}$$

then we can see that $\mu > 1$ implies a breakdown. It can furthermore be shown[8] that current growth during the breakdown can be described by

$$j(t) = j_0 e^{\alpha d} \left[\frac{\mu}{\mu - 1} \exp\left(\frac{\mu - 1}{\mu} \frac{t}{\tau} \right) - \frac{1}{\mu - 1} \right], \tag{3}$$

where j_0 is the initial electron current at the time the breakdown first started (in practice usually due to ambient electrons left over from cosmic ray ionization), α the number of ionizing collisions an electron

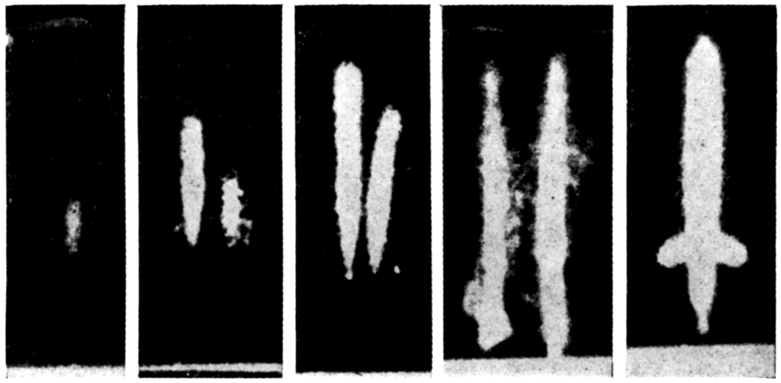

Figure 1. High speed photographs of streamer breakdowns.[9] A streamer is a well-defined region of plasma formation around a single electron avalanche.

undergoes per unit length, d the gap width, and τ is a transit time. If the breakdown develops as described above, with electrons entering the discharge gap through secondary emission from the cathode on ion impact, τ represents the time it takes an ion to traverse the discharge gap. If, however, the forming plasma becomes bright enough to release electrons from the cathode through photoemission, current growth does not need to wait for ion drifts and the discharge develops faster; τ roughly represents the electron transit time. Either way, we can see that plasma forms on the timescale of $\mu\tau/(\mu-1)$. In our GFPPT as outlined above, we can expect electron transit times on the order of 100 ns and ion transit times on the order of 10μs. Thus, with a value of μ slightly exceeding 1, we expect formation times that could vary anywhere from the orders of 10 μs to 1 ms.

Streamer breakdown, the second mechanism, occurs much faster. First observed experimentally by Raether in the 1930s,[9] with theory soon following, streamer breakdown is characterized by narrow, well defined regions of bright plasma produced by a single electron avalanche that result in significant current rise and self-sustaining plasma in less than one electron transit time (Figure 1). Though there exists some controversy over the exact nature of streamers[10] it is generally agreed that streamer breakdown is a space charge phenomenon; a streamer occurs when an electron avalanche becomes so large that the electric field it produces at the avalanche front greatly enhances the amount of ionization there. Also commonly thought to be a feature of streamers is the role of advanced photoionization in which photons emitted from the avalanche plasma ionize neutrals in ahead of the avalanche front.

Regardless of the basic physical details of streamer formation, it is clear that streamer breakdown is a mechanism by which plasma can be formed in less than one electron transit time, or for a GFPPT gap, in less than 100 ns.

It should be noted that streamers are usually thought of as a high-pressure (several hundred Torr up to and exceeding one atmosphere), high-overvoltage phenomenon and thus one might find reason to question their relevance in a low-pressure, undervoltage device like a PPT. However, once one accepts gross space charge distortion of the electric field as a necessarily characteristic feature of a streamer, it is not so difficult to imagine that large electron pulses in a low-pressure discharge gap, which will also greatly alter the space charge distribution, may result in streamers. In fact, careful examination of high speed photography of plasma formation in a sparkplug-triggered GFPPT (Figure 2) reveals well-defined columns of plasma emanating outward from the sparkplugs that suggest streamers or streamer-like behavior.

The most important concern about discharge formation time in a GFPPT is the current rise requirement stated above. To investigate the effect of breakdown timescale on maximum current rise, we can model the discharge as a RLC circuit with time-varying resistance:

$$\frac{d^2Q}{dt^2} + \frac{R(t)}{L}\frac{dQ}{dt} + \frac{1}{LC}Q = 0. \tag{4}$$

Q is the charge on the capacitor bank given by $Q = VC$. Figure 3A is a plot of the results of a numerical solution of Equation 4 with C of 100 μF, L_0 of 60 nH, and 200V across the electrodes initially. The resistance is linearly ramped from 50 Ω down to .05 Ω over 50 μs, a timescale corresponding to a moderately slow Townsend breakdown. The behavior that we see is quite insightful into the importance of breakdown

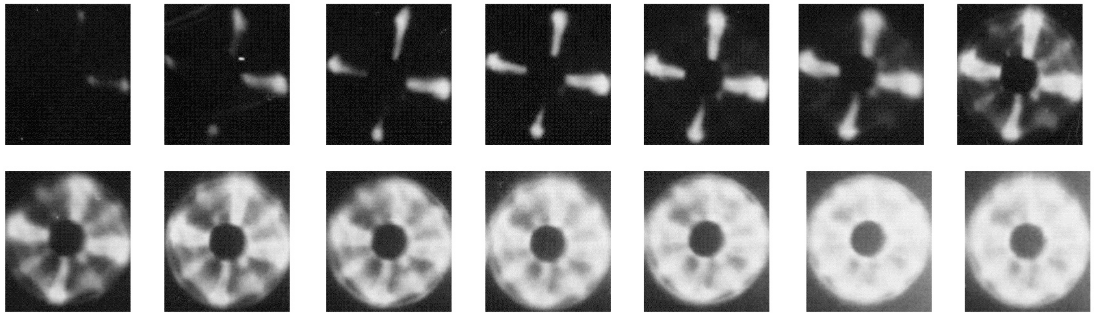

Figure 2. High speed photographs of a discharge in the SRL 5-GFPPT taken from Ziemer et al.[3] Each exposure is 50 ns long with 500 ns between each.

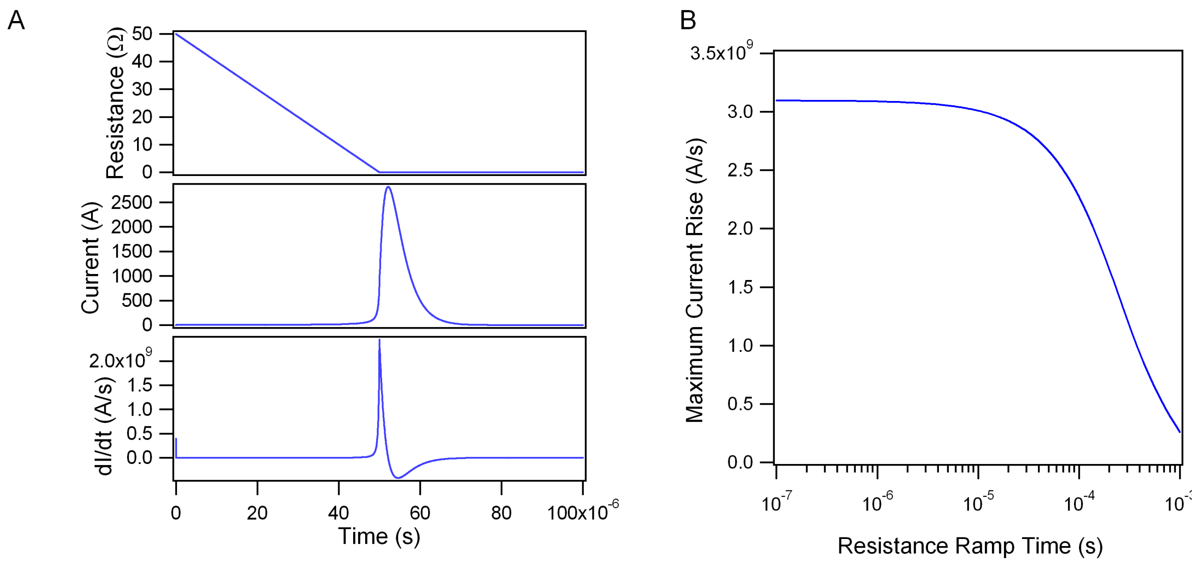

Figure 3. (A) Resistance, discharge current, and current rise during a RLC circuit discharge with a linearly ramped resistance. (B) Maximum current rise as a function of resistance ramp time.

time on current behavior. The capacitor doesn't really begin to discharge until the resistance gets below some critical value, at which point it seems to proceed with vigor, producing current rise rates within the order of magnitude required to form current sheets for a thruster of our dimensions. Thus, even for this relatively slow breakdown, the maximum current rise attained, $\dot{J}_{max}$, is around 3×10^9 A/s, acceptably close to our rule of thumb stated above that current should rise on the order of 10^{10} A/s for a 1 cm device.

$\dot{J}_{max}$ is plotted versus several orders of magnitude of resistance ramp timescale in Figure 3B. What we see is that this quantity has very little sensitivity to breakdown time for most conceivable discharges; it stays within the acceptable range from very fast breakdowns on the order of 100 ns up through much slower ones that take 100 μs. Only the very slowest Townsend breakdown, with a timescale in the ms range, presents possible problems for our discharge initiation system.

Such a linear resistance ramp is unrealistic, and we actually expect exponential increases in conductivity (Equation 3), in which the majority of the transition occurs during a small fraction of the overall breakdown time. It thus seems safe to conclude that the timescale of the breakdown process does not affect the rate of current increase when a discharge begins. Thus, from a current sheet formation point of view, any reasonable breakdown mechanism is appropriate.

However, the nature of the breakdown process does affect the *delay* between when the discharge is triggered and when significant current is conducted. Thus, one could imagine several practical considerations that might make faster breakdowns more attractive: the discharge needs to be underway, for example, before the injected gas has a chance to leak out of the thruster, and long delays are undesirable if a high repetition rate is sought. Thus, we can conclude that while Townsend breakdown may be acceptable in GFPPT discharge initiation, streamer breakdown is preferred.

C. Summary of GFPPT Discharge Requirements

Before we move on to discussing undervoltage breakdown threshold criteria, we will briefly summarize the results of the preceding sections.

- GFPPTs require the high conductivity of arc discharges for high current and good matching of the RLC components.
- Current rise times are insensitive to the breakdown process. Still, faster streamer breakdowns are preferable to slower Townsend breakdowns.

In the next section we will thus aim to answer the question: what does it take to achieve streamer breakdown to an arc discharge at an undervoltage?

III. Undervoltage Breakdown Threshold Criteria

In order to understand undervoltage breakdown, we constructed an idealized experiment in which the most basic principles of the phenomenon can be explored. The undervoltage breakdown experiment consists of a set of parallel-plate electrodes placed inside a vacuum chamber that can be filled to variety of ambient pressures. The plates are set at an undervoltage and electron pulses are supplied by high-power laser pulses directed onto a tungsten target fixed to the cathode. Using this facility, we can explore the parameter space of undervoltage breakdown to map out threshold criteria for a wide variety of experimental conditions.

This section focuses on the undervoltage breakdown experiment. Theory and more details about the experiment will be reserved for a later publication, but here we will outline the setup, techniques, and early results so that we might arrive at an order of magnitude estimate of the number of electrons required to produce an arc discharge through streamer breakdown in a GFPPT.

A. Experimental Setup and Techniques

The experiment (Figure 4) consists of two copper plates, four inches on a side and separated by one-inch ceramic spacers. The plates are coated with boron nitride insulator except for a square region in the center of the anode and a flat tungsten sheet fixed to the cathode. A 50 Ω transmission line carries power to and signals from the electrodes. The plates are powered by a voltage-regulated DC power supply that can supply 20 mA at up to 1000V. The exact mechanism behind how electrons are released from the cathode during a laser pulse is not relevant to the undervoltage breakdown phenomenon, but we have shown in previous work[5] that thermionic emission is theoretically possible from a tungsten cathode being heated by a laser pulse, though the phenomenon we witness may result from gas desorption.

The electrodes sit inside a stainless-steel vacuum facility capable of reaching pressures in the high 10^{-10} Torr range. This vacuum facility uses an oil-free scroll pump for roughing and 150 L/s turbomolecular pump for high-vacuum pumping.

The laser is a Q-switched Nd:YAG laser capable of delivering 20-ns pulses at energies up to 800 mJ at the fundamental wavelength of 1064 nm. Pulse energy is controlled by changing the delay between the flashlamp and Q-switch triggers. The beam is directed through a sapphire window on the vacuum chamber and onto the tungsten target on the cathode. Before entering the chamber, the beam passes through a microscope slide that acts as a beamsplitter, sampling a small fraction of the beam that is measured by a fast photodiode.

Photodiode signals are measured by a Tektronix 5104b digital oscilloscope which records 5GS/s and has a frequency response of 1 GHz. The scope also measures the signal from an AC current probe (Tektronix CT2 with a bandwidth from 1.2 kHz to 200 MHz and a 500 ps rise time) placed around the center conductor of the transmission line, the conductor connected to the anode. A 100 kΩ resistor is placed in series with this conductor so that the power supply can maintain a steady-state plasma. This resistor and the plates themselves both represent impedance mismatches in the transmission line off of which signals will reflect.

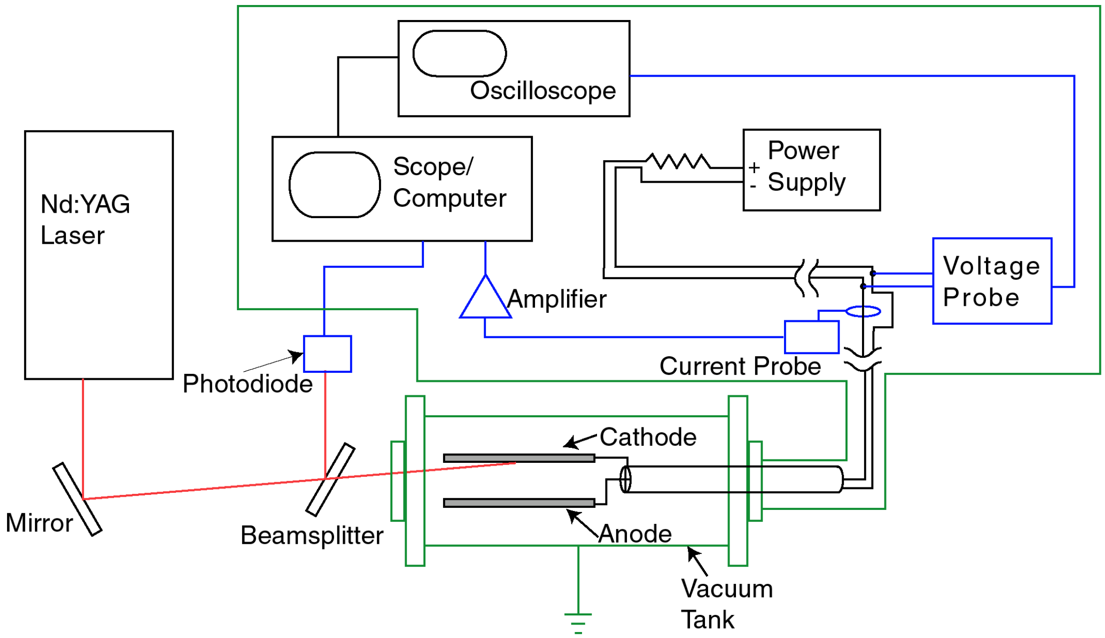

Figure 4. A schematic of the experimental setup for the undervoltage breakdown experiment.

Since it is not practical to locate the current probe directly on the plates, long sections of cable (80 feet) are used to delay the signal, lengthening the time between signal and reflections.

At the same location on the cable, two 100x probes are used to measure the differential voltage between the conductors. The voltage is recorded on a second oscilloscope, a Tektronix TDS 460a which samples at 100 MS/s and has a frequency response of 400 MHz, because the voltage changes on a timescale that is very different from that of the laser pulse. All measurement electronics sit inside a grounded Faraday cage to shield out electromagnetic noise.

The entire experiment is autonomously controlled by a Labview data acquisition system running on the 5104b scope, which also acts a computer. The system can set the plates to a desired voltage, set the laser to the desired power and fire it, and record all the necessary data.

The number we are interested in measuring is the probability of achieving breakdown as a function of charge in the initial pulse. The presence of gas in the discharge gap will amplify an electron pulse due to ionization and avalanching, so we have no means of measuring the initial charge *in situ* during an undervoltage breakdown event, though we do have information from the photodiode about the laser intensity. We therefore perform an *a priori* calibration in which we measure the charge released as a function of laser intensity while under ultra-high vacuum. We then use that information to infer the desired quantity during an undervoltage breakdown event. In Figure 5 we see traces of photodiode signal and current during a calibration pulse. Note the delay due to differences in cable length and the reflection at the end of the current signal. The current signal before the reflection is integrated to give total charge. Using this setup, we are able to produce and measure pulses in the range of 10^{-10} - 10^{-9} C.

Once the calibration is established, gas (all experiments discussed in this paper used argon) is introduced into the chamber to the desired pressure and the breakdown voltage of the gap is measured. The plates are set to the desired undervoltage, then the laser fires shots of varying intensity. Photodiode and voltage traces are saved after each shot and, if the shot caused a breakdown, the voltage is turned off, plasma is extinguished, the plates are set back to the correct voltage, and the process repeats. About 400 shots are necessary at each voltage to get significant statistics to establish probabilistic trends.

B. Results and Discussion

Two very different forms of breakdown were observed. In the example shown in Figure 6, the voltage was initially set to 550 V, below the breakdown voltage of 590 V measured at 300 mTorr of argon. These traces were triggered off the photodiode signal, which occurs at time t = 0 and would appear instantaneous on

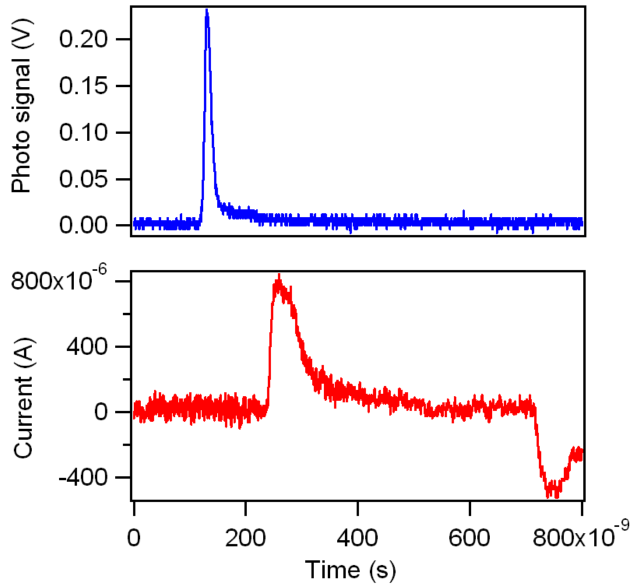

Figure 5. Current and photodiode signal during a calibration pulse. For this shot the plate voltage was 300 V and the pressure was 1×10^{-9} Torr.

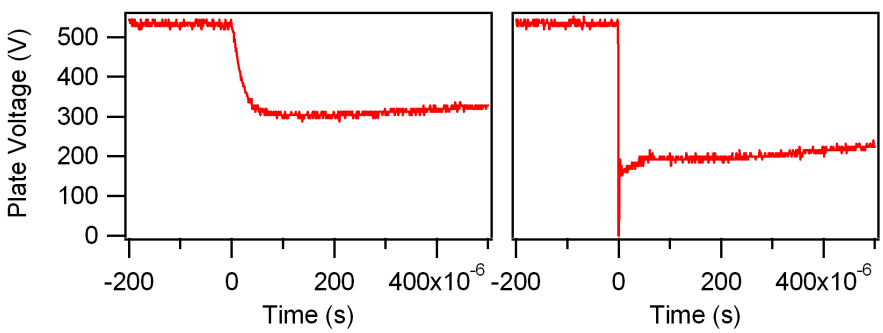

Figure 6. Voltage traces of two different types of breakdowns.

this scale. In the first trace, the voltage drops relatively slowly to a moderate voltage around 300 V before establishing a steady-state glow discharge. The process takes about 50 μs and the maximum current attained is 2.5 mA. We will call discharge such as these *slow* breakdowns and conclude that they represent examples of Townsend breakdown to a glow discharge.

In the second trace, the breakdown occurs much faster and to a much greater degree. The voltage drops to 0 V in less than 1 μs. An arc discharge requires high current to provide ion flux to the cathode sufficient for thermionic emission, and our circuit cannot sustain that, so it is not surprising that the voltage quickly begins to return to the more moderate glow voltage, which leaves the question of the exact nature of this discharge somewhat ambiguous. Also, no example of streamer discharge at an undervoltage or such a low pressure has ever been reported in the literature, so concluding that we have observed it here seems premature. Still, it is clear that in this trace, an example of what we will call a *fast* breakdown, we have achieved a much faster breakdown to a temporarily higher conductivity than in the slow case.

Based on the results from Section II, the faster, higher conductivity fast breakdowns are preferable for GFPPT discharge initiation. Unfortunately, we will see that such breakdowns seem to be just outside the range of measurement of our experiment for the argon pressures tested so far.

Figure 7 plots the measured probability of slow breakdown versus initial charge for one set of experimental conditions (420 V at 1 Torr.) Error bars on the probability are calculated based on binomial error, $\sigma =$

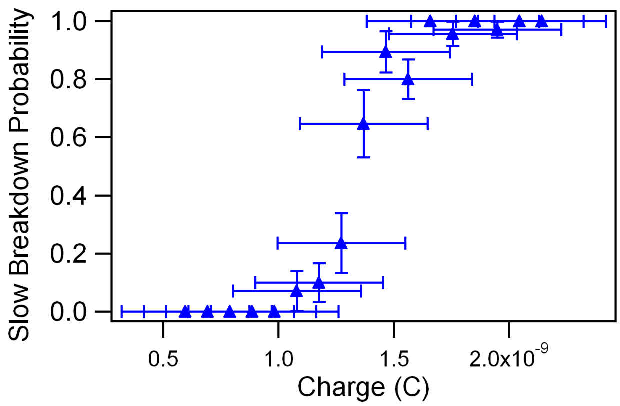

Figure 7. Probability of slow breakdown as a function of initial charge for 1 Torr of argon at 420 V.

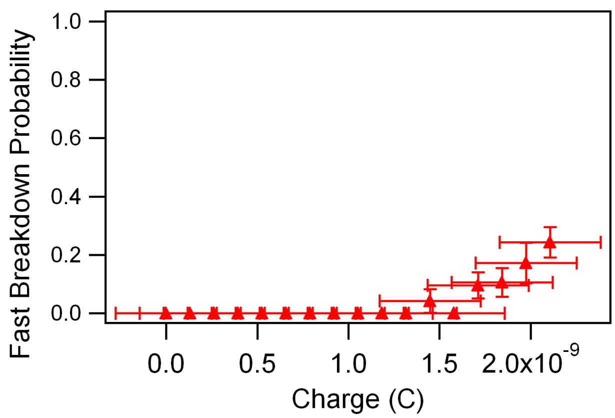

Figure 8. Probability of fast breakdown as a function of initial charge for 500 mTorr of argon at 356 V.

$\sqrt{p(1-p)/n}$ where p is the fraction of times a pulse in that charge bin caused a breakdown and n is the number of pulses in the bin. Charge error bars come from the calibration experiment and represent the root mean square deviation of charges for a given photosignal bin. What we see is that at very low values of initial charge, breakdown is very unlikely, at very high values, breakdown is very likely, and some intermediate regime exists.

In Figure 8 we see a similar plot for the fast breakdown. It demonstrates that the fast breakdowns are much less likely than the slow ones, only occurring with very large pulses. The plot shown here is of the data set that had the most instances of fast breakdown of any taken. For most, fast breakdowns either did not occur or occurred in such small numbers so as not to be statistically significant.

The quantity we are seeking, the number of electrons (or the total charge) in a pulse required to achieve undervoltage breakdown, can be gleaned from graphs such as Figure 7. If we use, for example, the charge required to produce a 50% likelihood of breakdown at a given set of conditions as our threshold criterion, then we can measure that number by simply performing an interpolation on the data presented in each of those graphs. We have done so for the slow breakdown case and summarized our results in Figure 9.

As stated before, undervoltage breakdown theory will be reserved for a later publication. However, the trends in these data seem reasonable; as one gets closer to the breakdown voltage, less charge is required to produce undervoltage breakdown. The non-dimensional quantity of "undervoltage", or V/V_b, was chosen for convenience but was not expected to be a scaling parameter. It is thus not surprising that different amounts of charge are required to produce breakdown at different pressures, even at the same undervoltage.

Making quantitative statements about the threshold conditions for fast breakdowns is more difficult because of the relative rarity of that phenomenon. However, since we seek only an order-of-magnitude estimate of the charge required to produce breakdown, examination of those data is worthwhile. Our

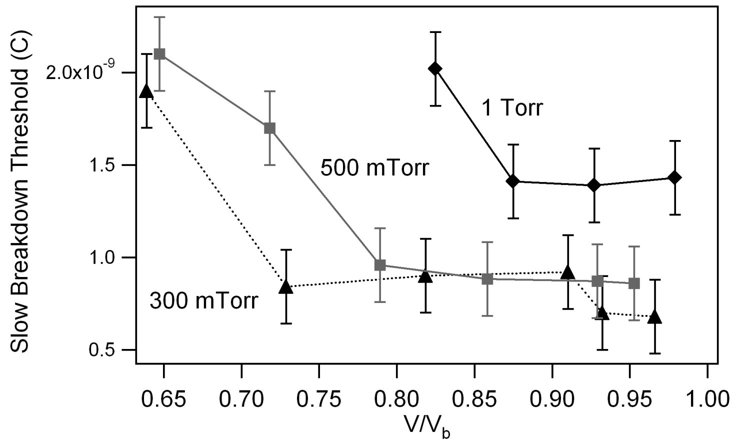

Figure 9. Slow undervoltage breakdown threshold versus fraction of breakdown voltage for argon.

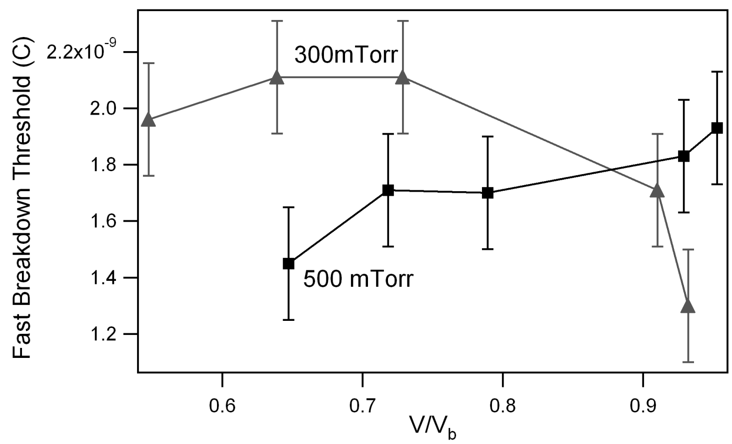

Figure 10. Fast undervoltage breakdown threshold versus fraction of breakdown voltage for argon. No fast breakdowns were observed at 1 Torr.

previously defined threshold condition of 50% breakdown probability will not work because fast breakdowns never appeared with that probability. Instead, we plot in Figure 10 the lowest charge at which fast breakdown was observed as a function of undervoltage.

These data are less well-behaved than the slow breakdown data, but it seems clear that more charge is required to produce a fast breakdown than a slow one in all cases. Presumably, if our experimental setup could supply more charge, more fast breakdowns would occur. This will be addressed in future experiments. However, we can see that at the lower pressures, roughly 2×10^{-9} C, or 1×10^{10} electrons seem to cause fast breakdown.

IV. Summary and Conclusions

The purpose of this paper was to deduce an order-of-magnitude estimate of the number of electrons required to initiate discharges in a gas-fed pulsed plasma thruster. In doing so, we reached the following conclusions:

- A GFPPT discharge initiation system is likely to rely on undervoltage breakdown as its basic mechanism.
- GFPPTs require high-conductivity arc discharges to maximize energy coupling between the capacitors and the current sheet.

- Discharge initiation is insensitive to breakdown timescale, but faster breakdowns are preferable to slower ones because of the delay between triggering and breakdown.
- In the undervoltage breakdown experiment, two types of breakdown were observed: a relatively slow, low conductivity breakdown and a faster, higher conductivity phenomenon.
- The fast breakdown mechanism is preferable for GFPPT discharge initiation. Though the phenomenon seems to be just out of range of measurement of the discharge initiation experiment, an electron pulse containing something on the order of 10^{10} electrons seems a reasonable order-of-magnitude guess.

This study has focused on the raw number of electrons required for GFPPT discharge initiation, but we must also consider other practical constraints: the electrons need to be produced in a relatively uniform manner to form relatively uniform current sheets and they need to be produced in such a way that erosion of surfaces is kept to an acceptable level. With that in mind, the next logical step in this line of investigation is a trade study exploring possible undervoltage breakdown techniques such as laser-surface interactions and improved sparkplugs, among others.

Acknowledgments

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