Relationship Between Anode Spots and Onset Voltage Hash in Quasi-Steady Magnetoplasmadynamic Thrusters

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Experimental results are presented which indicate a direct relationship between voltage transients in magnetoplasmadynamic thrusters (MPDTs) operating above onset and the time-resolved appearance of destructively released anode material in the thruster plume. Such a relationship gives support to previously discussed anode spotting theories. Measurements taken in an MPDT with a copper anode of plasma density fluctuations using a Langmuir probe and of plume luminosity at two wavelengths, a CuII line and ArII line, using a spectrometer and photomultiplier tube are compared with the voltage transients. The onset of spikes in the thruster voltage is directly correlated with the onset of similar spikes in the plasma density at the probe location, and with a rise in the copper luminosity, but a fall in that of argon, in the plume. The voltage hash is categorized into two types: large-amplitude spikes at currents well above the onset current, and lower-amplitude random fluctuations at currents just above the onset current. It is shown that the two categories of voltage hash can be related to two classes of damage on the anode surface: pit-like damage of 10 to 100 μm extent, caused by explosive emission due to voltage spikes; and shallow surface melting due to the lower-amplitude random fluctuations, which may be responsible for observed density and luminosity oscillations at 600 kHz, and a dip in the voltage power spectrum at the same frequency.

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I. Introduction

Onset in a magnetoplasmadynamic thruster (MPDT) is a condition encountered in high-current operation, in which the thruster voltage—quiescent at lower currents—fluctuates with an amplitude that can be large compared with the mean voltage, and in which the anode sustains significant damage. Onset is a lifetime-limiting factor in the operation of the MPDT, and so must be understood and overcome if the MPDT is to be used as a primary propulsion system for long-duration space missions.

The nature of the voltage fluctuations ("hash") and the anode damage has been the subject of many studies, many of which point out a relationship between the presence of a fluctuating voltage and fluctuations in other thruster parameters, such as the optical emission,[1] electric and magnetic fields,[2] and plasma density.[3]

Kuriki and Iida[1] measured the fluctuation of the total light output from a quasi-steady MPDT, observing in particular similarities in the power spectra of both the voltage and the luminosity at about 500 kHz, showing a relationship between the two quantities. Ho[4] and Rudolph[5] measured the time-integrated optical spectrum of a quasi-steady MPDT, and discovered a growth in the luminosity of anode material in the thruster plume as the current rose above onset. However, Kuriki's data cannot identify which atomic species in the plume was responsible for the luminosity fluctuation, nor could Ho's and Rudolph's measurements provide information about when during the thruster pulse anode material appeared in the plume; therefore the connection between hash and anode erosion was not completely elucidated.

Hugel[6] has suggested that the presence of anode material in the plume can be attributed to the formation of anode spots, which he observed to form on his MPDT anode in high-speed photographs at the moments of maxima in the voltage hash. At high currents, the plasma density near the anode is small enough that the anode is starved of the charge carriers needed to conduct the current. Hugel suggests that the anode spots form in response to this starvation. Diamant et. al. [3] have further demonstrated that spot damage on the anode surface is much greater at currents above onset than below, and that the plasma density, averaged over a quasi-steady firing, increases above onset. What Hugel's and Diamant's data together cannot conclusively demonstrate, however, is that the anode spots are the source of additional plasma density above onset, and that their density contribution is correlated with the voltage hash fluctuations.

In this paper, we address the questions left behind by these studies; namely, we search out the time-resolved correlations between voltage hash and anode erosion lacking in the previous work. We do this using time- and wavelength-resolved plume luminosity measurements and time-resolved plasma density measurements. We correlate the measurements made by these two diagnostics with the voltage hash fluctuations, and show that all three are correlated in a manner consistent with what is to be expected from transient damage to the anode surface.

Briefly, the paper is organized as follows. In Sec. II, we give relevant details of the experimental setup used to take the data, which we present in Sec. III. We defer major interpretation of the results to Sec. IV, where we relate the experimental results to the hypothesis of anode damage at high currents.

II. Experimental setup

A. Princeton FSBT

The quasi-steady MPDT used in this study is the Princeton Full-Scale Benchmark MPDT, which has been the subject of many previous studies, and is adequately described elsewhere.[7,8] In this work, the thruster anode is copper, the cathode is 2% thoriated tungsten, and the propellant is argon, fed at mass flow rates 3 g/s $\leq \dot{m} \leq$ 6 g/s. We operate the thruster in quasi-steady fashion, with flat-topped current pulses of about 800 μs duration ranging from 9 to 21 kA supplied by a 120 kJ pulse-forming ladder network (PFN). A schematic of the thruster is shown in Fig. 1.

B. Diagnostics

For this study, we made four time-resolved measurements during each thruster firing: thruster current, terminal voltage, the wavelength-resolved luminosity, and the plasma density at a single location. We took all measurements with a time resolution of 40 ns/point, and filtered each signal using low-pass filters with a 5 MHz cutoff frequency, so that frequencies at and above the 12.5 MHz Nyquist frequency were attenuated by 40 dB or greater.

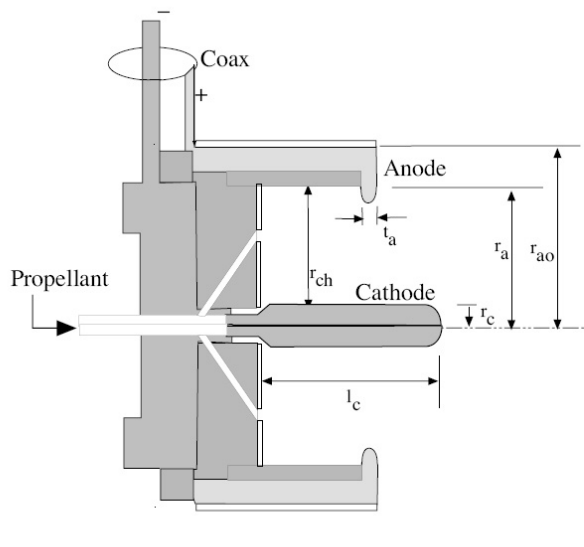

Figure 1. Schematic of the Princeton full-scale benchmark thruster. The dimensions are r_c = 0.95 cm, r_a = 5.1 cm, r_{ao} = 9.3 cm, r_{ch} = 6.4 cm, t_a = 0.95 cm and l_c = 10 cm.

1. Current measurement

We measured the thruster current with a Pearson 301x current transformer at the output of the PFN; the large inductance of the PFN ensures that the current is constant throughout the pulse, so the quasi-steady value is the only interesting information contained therein.

2. Voltage measurement

We measured the voltage with a commercial Tektronix P5210 differential voltage probe at a location 7.5 cm behind the thruster electrodes. The close proximity of the measurement to the discharge is essential to eliminate signal corruption from resonances in the power supply, which act to distort the shape of the voltage trace.[9] The nature of the voltage hash discussed in this paper is different from what has been previously reported,[10] when the voltage measurement was taken at a point more distant from the thruster.

3. Optical measurement

We measured the luminosity of the MPDT plume using an RCA 1P28 photomultiplier tube (PMT) placed at the output slit of a Spex 710 spectrometer. The Spex is equipped with a diffraction grating optimized for visible wavelengths. We chose a configuration of collecting optics and input/output slit width combination to collect light at a position directly downstream of the thruster, from a section of the thruster face roughly 2 cm wide, centered on the thruster's axis of symmetry. With this configuration, the wavelength resolution was about ±5 Å.

We made optical measurements of the thruster luminosity at two wavelengths: 4727 Å, a line in the spectrum of ArII, and 5039 Å, in the spectrum of CuII.[11] These lines are sufficiently far removed from other lines in the combined spectrum of Ar, Cu, and W that they could be singled out with the given resolution of the spectrometer. In this way, we were able to distinguish the independent behavior of argon and copper in the discharge.

The PMT signal is buffered at its output through a 100 kΩ resistor and an Analog Devices AD818 video amplifier. The frequency response of this system is flat to above 1 MHz. We digitally filter the signal in post-processing to remove power supply noise to which the PMT is sensitive.

4. Plasma density measurement

We measured the plasma density using a double Langmuir probe made of two 0.13 mm diameter tungsten wires encased in glass and ceramic to shield all but the exposed probe tip, which was 1 mm long, from the discharge. The wires were crimped to the two leads of a twisted/shielded pair cable, which were connected to an Agilent E3640 DC power supply. The bias between probe wires was kept constant at 40 V, which is sufficient to drive the probe into the ion saturation region of the probe characteristic. We measured the current through the probe wires using a Tektronix CT-2 current transformer, which has a flat frequency response from 10 kHz to 200 MHz. The measurements therefore represent the fluctuations in the plasma density, and contain no information about the quasi-steady plasma density, which is available in the work of Diamant et. al. [3,12]

We took all the density fluctuation measurements discussed in this paper at one location, $\sim$ 10 mm downstream of the anode, and $\sim$ 7 mm radially outward from the anode inner radius (r_a in Fig. 1).

III. Results

In this section, we present the data collected using the diagnostics of the last section. We begin with some comments on the nature of the voltage hash, and then move on to a discussion of the optical diagnostics, focusing on the difference between argon and copper behavior during thruster firings in which voltage hash is present. We then discuss the correlation between voltage hash and plasma density fluctuations, and conclude with a discussion of the power spectra of these measurements.

A. Voltage Hash

The MPDT voltage trace takes on one of three distinct forms, depending upon the current and mass flow rate, or upon the single parameter ($J^2/\dot{m}$). These three forms are shown in Fig. 2, together with their power spectra. (We will defer discussion of the power spectra to Sec. III.D, when we will discuss the power spectra of all the diagnostics together.) Below the onset current, the voltage is quiescent (Fig. 2(a)). Just above the onset current, the voltage fluctuates randomly with an amplitude between 10 and 50% of its mean (Fig. 2(b)). At currents well above the onset current, the voltage spikes, with spike amplitudes nearly 100% of the baseline from which they rise (Fig. 2(c)). In general, any deviation from DC in the voltage trace is called hash. For clarity, in this paper we will refer to the voltage trace of Fig. 2(a) as "quiescent", which occurs at "low" currents; the form of hash in Fig. 2(b) we will call "random fluctuations" which occur at "intermediate" currents; and we will call the hash in Fig. 2(c) "spikes" which occur at "high" currents. The transition from low to intermediate current occurs at $\sim$ 50 kA^2-s/g, and the transition from intermediate to high currents at $\sim$ 80 kA^2-s/g. For the particular mass flow rate $\dot{m}$ = 3 g/s shown in Fig. 2, these correspond to 12 and 15.5 kA, respectively.

To make clear the very different nature of the three voltage traces in Fig. 2, a 100 μs sample of all three traces are plotted together on the same axes in Fig. 3. In this expanded view, the distinction between a quiescent voltage, one with random fluctuations, and one with spikes is easily seen.

While we shall use data taken at the operating conditions of Fig. 2 (in particular, $\dot{m}$ = 3 g/s) as examples throughout our discussion, the discussion holds true for other values of $\dot{m}$; the transition from "low" to "intermediate" to "high" currents then takes place at currents corresponding to the values of ($J^2/\dot{m}$) mentioned above.

B. Optical Diagnostics

The time behavior of the MPDT luminosity is dramatically different depending upon which species is being observed, propellant or anode material (in this study, argon or copper, respectively). Representative traces of the argon and copper luminosity, as gathered by the PMT, are shown in Fig. 4, where they are plotted together with the voltage traces for their respective firings. In each case, the shots shown are for high-current operation (i.e., where the voltage trace contains spikes); the PMT traces, which do not represent absolute radiances, have been scaled to appear on the voltage axes.

Before discussing the structures of these traces, we point out that the magnitude of the luminosity, averaged over the quasi-steady portion of each shot, and taken over several currents and mass flow rates, show that the copper content of the thruster plume grows with respect to the argon content as the current is raised above onset, as shown in Fig. 5. The light collected by the PMT is proportional to the density of atoms making the emitting transition in the field of view; the proportionality constant is related to the solid angle taken up by the PMT photocathode, the quantum efficiency of the same, the PMT gain, and the Einstein coefficient of the transition. As all of these quantities are constant with current, the ratio of the

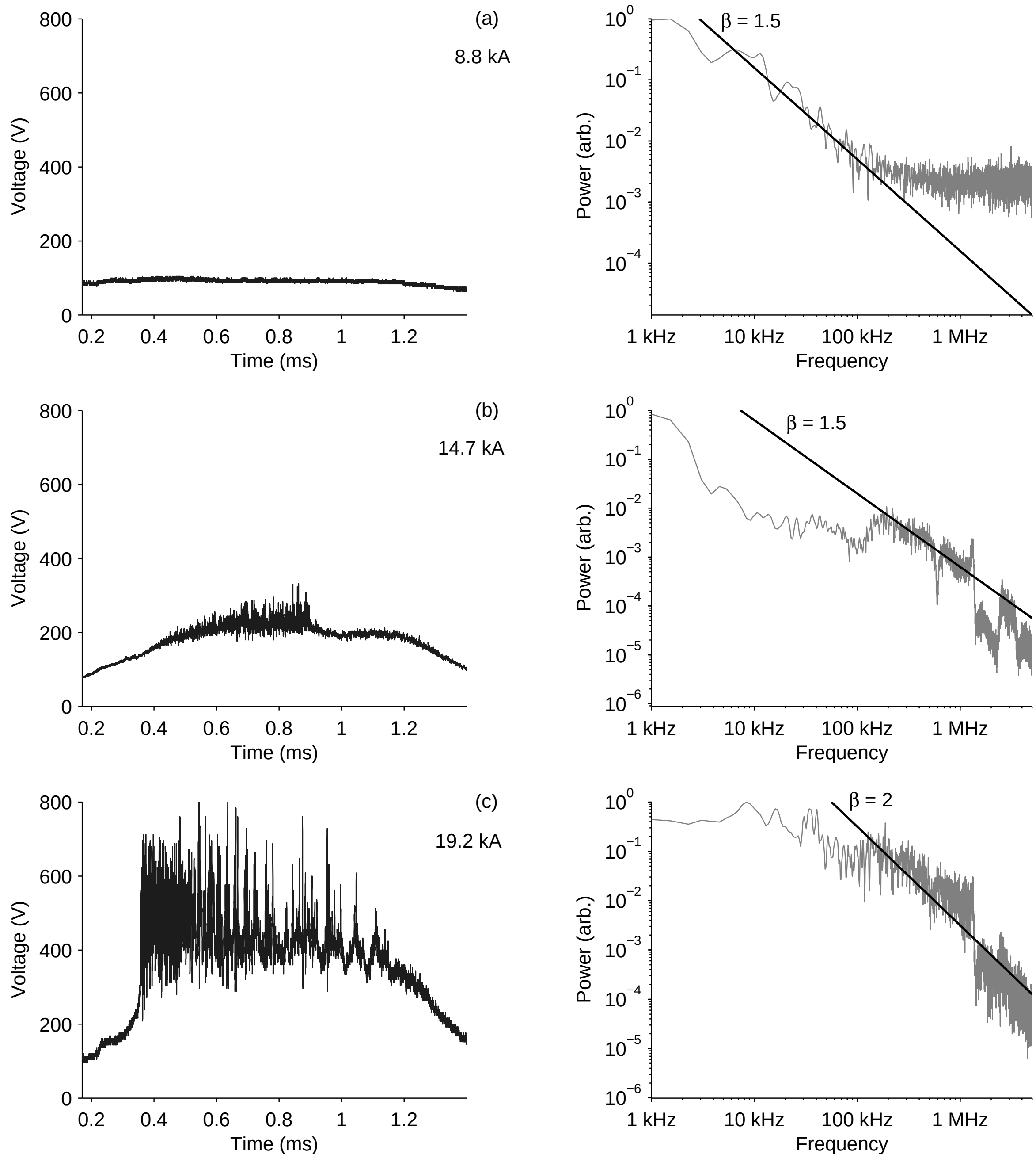

Figure 2. (Left) The quasi-steady voltage traces for $\dot{m} = 3$ g/s, at three currents, showing the progression in voltage from quiescent to random fluctuations with 50–100 V amplitude to spikes of 200–300 V amplitude. In the nomenclature of this paper, case (a) occurs at "low" currents, (b) at "intermediate" currents, and (c) at "high" currents. (Right) The power spectra of the voltage traces, with a superimposed line representing $1/f^{\beta}$ noise, with β as indicated.

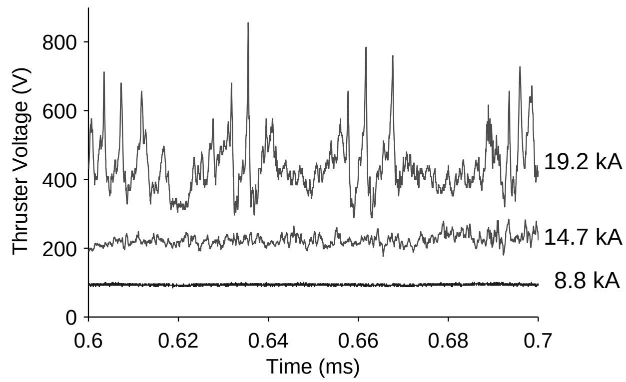

Figure 3. A 100 μs portion of the three voltage traces of Fig. 2, plotted on the same axes. The difference between the flat voltage at low current, random hash at intermediate currents, and spikes at high currents is clear.

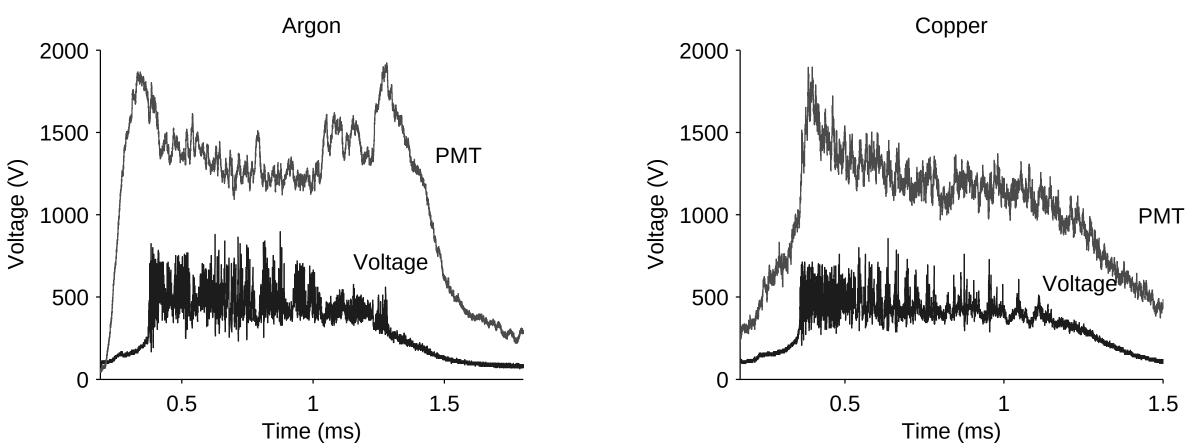

Figure 4. Examples of luminosity and voltage traces, for $\dot{m} = 3$ g/s and $J = 19.2$ kA. In each case, the luminosity trace has been scaled to fit the voltage axis. (Left) Argon luminosity and voltage traces. (Right) Copper luminosity and voltage traces.

luminosity of the two lines changes only with a change in the density ratio. It is this density ratio, normalized to unity at the lowest current at which data was taken, which is plotted against current in Fig. 5. This plot gives an indication that, as a time-integrated quantity, the copper density takes on growing importance with higher currents or lower mass flow rates. Such a result has been observed before,[13] but without reference to the time behavior of the species during the discharge.

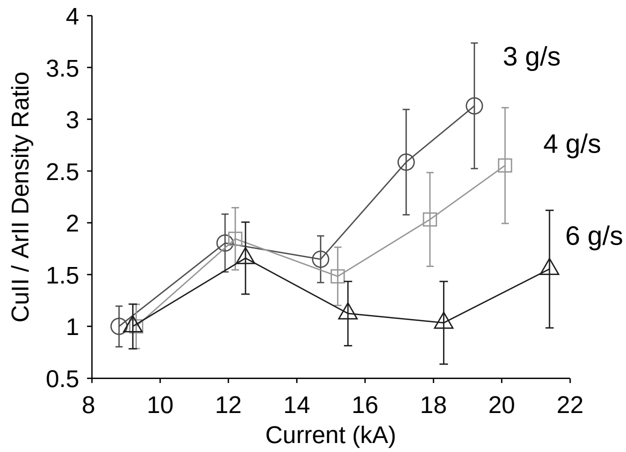

Figure 5. Normalized values of the copper/argon ion density ratios for three mass flow rates.

The time behaviors of argon and copper luminosity are distinctly different when there are spikes in the voltage trace. Referring again to Fig. 4, the first important detail to note is that the argon luminosity begins to grow toward its maximum value at the beginning of the current pulse, long before the voltage spikes begin; the copper luminosity, in contrast, grows most significantly at the moment when the voltage spikes begin. Indeed, the argon luminosity during periods of voltage spikes is lower than its maximum value, falling to its quasi-steady value as the spikes begin, and rising back to its maximum when the spikes end.

In the middle of the pulse, the copper luminosity grows when voltage spikes are large, and falls when the magnitude of the spikes falls; the argon, by contrast, falls during periods of large spike magnitude, and rises when that magnitude drops. Both behaviors can be seen clearly at time ~ 0.75 ms in the plots of Fig. 4. These features of the argon and copper luminosity are consistent across mass flow rates and current levels.

There is no definite one-to-one correlation between individual spikes in the voltage trace and similar features in the PMT traces for either argon or copper, which exhibit fluctuations on a time scale longer than that of the individual voltage spikes. It is likely that this is due, in the case of copper, to its sustained presence in the plume long after the voltage transient has died away; argon, which shows still less tendency to respond on the short voltage spike timescale, may be less influenced by the individual fast voltage spikes than by their aggregate action over a period of multiple spikes.

There does not appear to be any of the above definite temporal correlations between the voltage and luminosity traces at intermediate currents (i.e., with randomly fluctuating voltage hash). There does exist, however, a relationship between the two measurements in their power spectra. We will defer a discussion of the power spectra until Sec. III.D, in which we will discuss the spectra of all three diagnostics together.

C. Langmuir probe

The ion density, as measured by the double probe, shows a time variation that is clearly correlated to the behavior of the thruster voltage at high current, when the voltage hash is spikes; this can be seen in Fig. 6. From this figure, it is apparent that spikes in plasma density occur, generally, concurrently with spikes in voltage; in the expanded view, we see that roughly half of the voltage spikes visible are followed by corresponding spikes in the plasma density. The density spikes, with remarkable consistency, occur between 0.5 μs and 1.5 μs after the peaks in their corresponding voltage spikes.

The correlation between density fluctuations and voltage hash is much less clear at intermediate currents, when the voltage hash is random fluctuations. We will discuss this case in the context of the power spectra of these measurements.

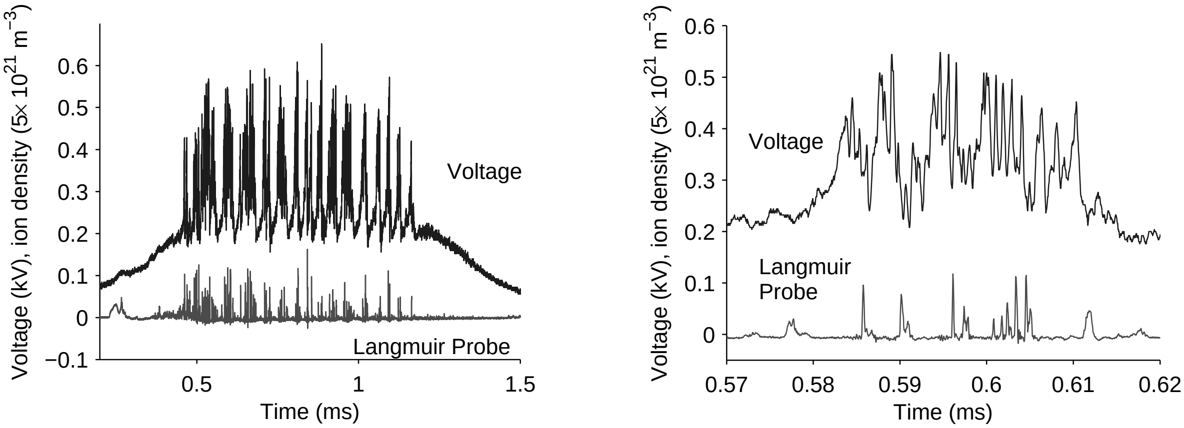

Figure 6. An example voltage and Langmuir probe trace, for $\dot{m}$ = 3 g/s and J = 17.2 kA. (Left) The whole duration of a quasi-steady pulse, showing the appearance of spikes in both traces at equivalent times. (Right) A 50 μs section of the same trace, showing the density spikes at many, but not all, of the voltage spike locations.

D. Power Spectra

1. Voltage spectra

We show, in Fig. 2, examples of power spectra for the three types of voltage trace identified in that figure. Superimposed on these power spectra are a lines corresponding to $1/f^{\beta}$, where $\beta = 1.5$ or 2, depending on the current level.

The $1/f^{\beta}$ drop in the spectrum is characteristic of a class of noise known as $1/f$ noise[14,15] that is often seen in natural dynamical systems. Such a spectrum can be generated either using random noise with an appropriately scaled spectrum, or from signals which alternate between quiescent phases and irregularly spaced regions of short bursts.[14] In the case of signals with bursts, the frequency at which the spectrum begins to follow a $1/f^{\beta}$ power law depends upon the duration of the quiescent period between bursts; qualitatively, the shorter the mean quiescent duration, the higher the frequency of the so-called *cutoff point* at which the spectrum begins to follow the power law.[15]

At low thruster currents, when the voltage is relatively quiescent, its power spectrum follows a $1/f^{\beta}$ power law with $\beta \approx 1.5$ and no clear indication of a cutoff frequency. (The deviation from the $1/f$ line at high frequencies is due to the finite resolution of the oscilloscope, which always forces the power spectrum to flatten when the signal magnitude is lower than the digitizing resolution.) The quiescent voltage trace therefore fluctuates with only random noise.

At intermediate currents, the power spectrum shows a significant deviation from the power-law line; the spectrum deviates at low currents, there is a narrowband dip at 600 kHz, and there is structure above 1 MHz (which corresponds to power-supply noise and is therefore not of interest). The intermediate voltage trace, therefore, is not completely random—most importantly, it has a preferred timescale corresponding to the dip at 600 kHz.

The power spectrum at high currents again follows a power law, but with $\beta \approx 2$, and has a cutoff frequency $f_c \approx 100$ kHz. The different slopes and cutoff frequencies between the low, intermediate, and high current cases confirm that the nature of the voltage hash differs qualitatively from low to high currents, being more or less random at low currents, and intermittent spiking at high currents.

2. Langmuir probe and PMT spectra

Figure 7 shows the power spectra of the fluctuations in plasma density and copper luminosity for the three current levels of Fig. 2. There is little of note in these spectra at low currents, just as there is little of note in the voltage spectrum. (The structures above 1 MHz correspond to noise from the MPDT power supply and are not of interest.) At intermediate currents, both spectra show increased power throughout the hundreds of kHz (the Langmuir probe more so than the PMT), and both spectra have a narrowband peak at 600 kHz. This peak, it should be noted, is at the same frequency as the dip in the voltage power spectrum at this current.

At high currents, the plasma density power spectrum loses some of its structure, as the time trace becomes dominated by spikes; it begins to look much like the corresponding voltage power spectrum, since the voltage trace in this case is also a series of spikes. The copper luminosity time trace, as already discussed, does not exhibit the spikes of the voltage and plasma density; its power spectrum, therefore, retains some of its structure at high currents, particularly the peak at 600 kHz.

IV. Discussion

The foregoing collection of data is rich in various phenomena. In this section, we will divide the discussion into two parts, the first focusing on voltage hash and related phenomena at high currents, when the voltage is spiking; the second, focusing on the intermediate currents, when the voltage exhibits a lower-amplitude, random fluctuation.

A. High Current with Spiking Voltage Hash

The data of Sec. III.B demonstrate that when the thruster voltage is dominated by spikes, the presence of copper in the thruster plume is enhanced. This is seen in time-averaged form in Fig. 5. As the only source of copper in this experiment is the anode, this indicates that the voltage spikes are associated with erosion of the anode. The anode erosion is not, however, a continuous phenomenon throughout the thruster pulse at these higher currents, but is related to the specific instants at which the voltage is spiking, as is apparent in Fig. 4. Because the release of copper from the anode is not a continuous process, we do not expect the location of the erosion to be constant throughout, an expectation consistent with the observed pattern of erosion on our anode—in discrete spots rather than continuous streaks—and with similar observations in the literature.[6,12] That the PMT time trace does not spike in the way that the voltage does is primarily an indication of the length of time that copper vapor may be resident in the PMT's field of view; based on typical plume velocities and the dimensions of our vacuum chamber, a time as large as 100 μs. We therefore expect that the PMT time trace is a convolution of the luminosity of copper emitted from many spotting events.

The decrease in argon luminosity during periods when the voltage is spiking may be an indication of the influence of copper vapor on the argon plasma. The first ionization potential of copper is roughly half that of argon; a release of neutral copper into the thruster plume will present an energy sink to the electrons in the plasma, decreasing their temperature as they ionize the copper atoms. The decreased electron temperature will allow the argon ion density to drop as recombination takes place, with a corresponding drop in the luminosity.

The shape of the ion density fluctuation from the Langmuir probe at these operating conditions corresponds well with the shape of the voltage hash. The trace is a series of spikes, indicating that the plasma density at the probe location is executing a series of sharp rises and slightly more gradual falls. This sort of shape in the density transient is what might be expected from the quick release of vapor into the plasma—i.e., the rapid formation and decay of an anode spot. Evaporated copper vapor will expand out from its point of origin; when it reaches the probe location, the probe will register a fast rise in density, which will decay quickly as the vapor from the quick release at the spot passes by. Based on the location of the probe, and the delay between the peak of a voltage spike and the rise of the corresponding density spike—a delay on the order of 1 μs—the released vapor should have a velocity on the order of 10^4 m/s. This is much faster than the thermal velocity of copper atoms at the copper melting temperature (about 400 m/s), but on the same order as the plume flow velocity at these conditions. This may indicate that ionized anode vapor, which is subject to the Lorentz $\mathbf{j} \times \mathbf{B}$ body force (where $\mathbf{j}$ is the current density and $\mathbf{B}$ is the magnetic field), is quickly accelerated to the plume velocity. That roughly half of the voltage spikes are followed by a density spike—measured at a single location with the Langmuir probe—indicates that spots may be formed at multiple locations on the anode as a result of a single spike. Otherwise, since we expect only to see density spikes when a spot forms near the probe location—and since the anode is large with respect to the probe size—we should see a voltage spike followed by a density spike much less often.

Finally, the time over which a voltage spike occurs—from the beginning of the rise to its peak—is between 1 and 5 μs. We may estimate the size of the damage that we expect to see on the anode surface from these times. We consider the damage caused by an anode spot on the copper surface to be a roughly hemispherical

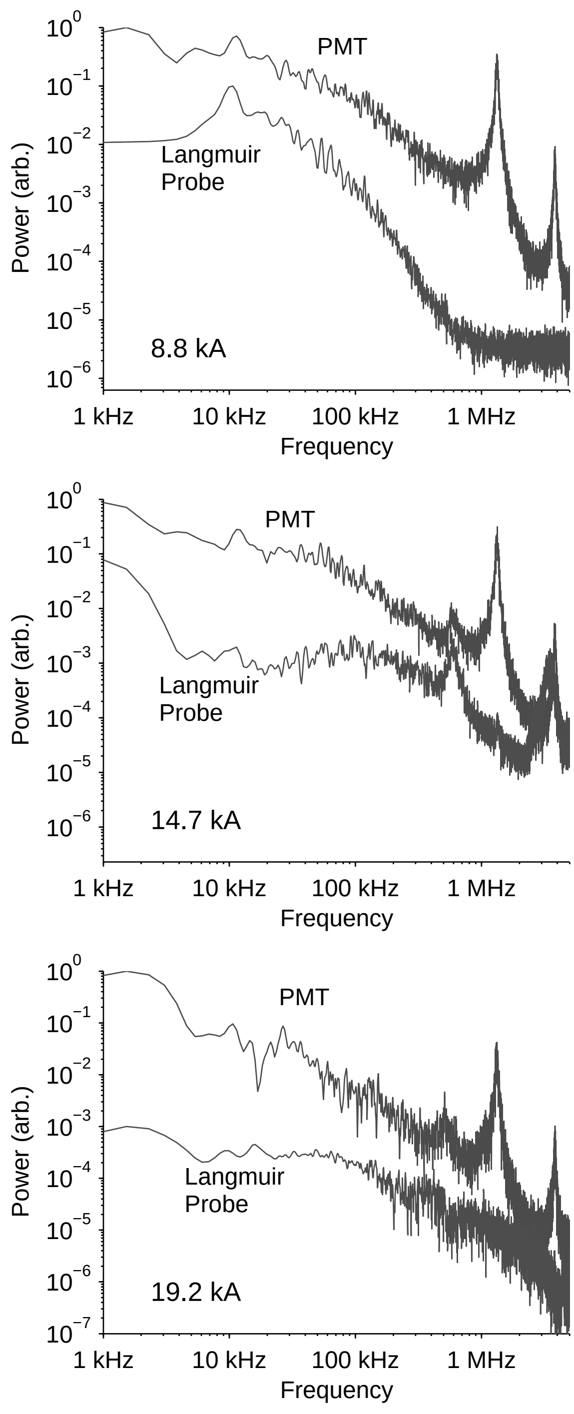

Figure 7. The power spectra of the fluctuations in plasma density and copper luminosity, for the current levels corresponding to the voltage traces and voltage power spectra in Fig. 2. The structure above 1 MHz is noise pickup from the MPDT power supply and is not of interest.

pit (not unlike what we actually observe) and calculate the time required to input the energy of vaporization into this volume. Using a typical anode current density[16] (100 A/cm^2) and taking the whole of the voltage spike magnitude ($\sim$ 200 V) to be across the anode sheath, the diameter of the resulting crater we expect to be between 10 and 100 μm, which indeed corresponds to the size of the damage visible upon microscopic inspection of the anode surface. A photograph taken under 50x magnification of damage on the anode surface is shown in Fig. 8, in which pits of removed copper appear as darkened spots.

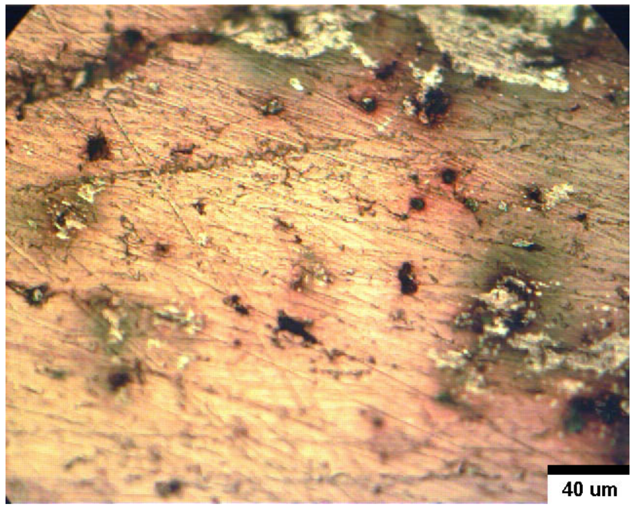

Figure 8. A photograph of a damaged copper anode under 50x magnification. Two distinct types of damage are seen here: pit-like removals of material, which appear as dark spots against the copper background, and shallower surface melting, which appears as areas brighter than the unmelted copper.

B. Intermediate Currents with Random Voltage Hash

At intermediate currents, the several diagnostics—the voltage measurement, the plasma density, and the luminosity—do not show the striking temporal correlations that we see at the higher currents when the voltage spikes. On the other hand, we do see much more structure in the power spectra of all these measurements, and so we turn to the power spectra to gain some understanding of what may be happening in these operating conditions.

We have already mentioned that the most striking feature of the voltage power spectrum at intermediate currents is the narrowband dip at 600 kHz, which indicates that the power at this frequency is being suppressed. An indication of the mechanism by which this suppression may take place comes from the power spectra of the density and optical measurements. The power spectra of both measurements show a peak at 600 kHz, precisely where the dip in the voltage spectrum occurs. (Here we refer to the optical measurement when viewing the copper spectral line. When viewing the argon line, no such peak appears in the spectrum for any operating condition.) This indicates that the plasma density, and in particular the copper portion of the density—though it fluctuates for the most part in random fashion—does have a preferred fluctuation time of 1.6 μs, and that this fluctuation is responsible for the dip in the voltage spectrum, most likely by providing increased conductivity at this frequency and thus driving down the corresponding component of the voltage fluctuation.

While it is clear, in this case, that the voltage fluctuations are being influenced by evaporation from the anode—the corresponding frequencies of interest in the power spectra showing the influence, and the presence of anode material (copper) showing the anode's importance—what remains to be clarified is the relationship between the anode evaporation and the structures in the power spectrum. The voltage peaks in the intermediate current case are not nearly so large as the spikes in the high current case, and the estimates of spotting times and sizes discussed in the last section do not match the observed timescale.

There is reason to believe that copper may be emitted from the anode in this case due to a shallow melting of the surface, rather than from a crater of the type discussed in the last section. We do observe such surface melting on our copper anode (see, for example, Fig. 8, which shows bright patches where shallow melting has taken place alongside the darker pit-like damage). Because the material penetration of the damage in this case is much shallower than in the case of the pit, much less material need be heated—requiring smaller sheath voltages—and less anode material would be emitted—consistent with the smaller luminosity observed. A simple estimate of the time required to add the heat of vaporization to a patch of copper 2 μm thick under a current density of 100 A/cm^2 and a sheath voltage of 50 V yields a time of 1.6 μs. This yields a 600 kHz frequency of copper emission, equivalent to what we do in fact observe in the power spectra.

V. Conclusion

Though it has long been known that there is some relationship between anode damage and voltage hash in high-current MPDT operation,[3] the temporal correlation between these two phenomena has not been established. With the results in this paper, we attempt to shed some light on this correlation.

We have presented measurements of voltage hash and fluctuations in plasma density and luminosity. We have identified two distinct forms of voltage hash—a random fluctuation and a series of distinct spikes—and shown that there exist specific relationships between these two types of hash and the behavior of the plasma density and luminosity. We have showed that eroded anode material plays an important role in both cases, and that its significance increases as the severity of the voltage hash increases. We have also suggested relationships between these results and the damage we observe on our anode, noting that the sizes of the damage and the timescales in the data match. Previous modeling work[10] has also suggested this relationship between anode damage and voltage hash.

It will be possible, with further investigation, to verify the proposed relationship between the types of hash and the types of anode damage, by carefully preparing anode surfaces and observing, for a single firing condition, the character of damage produced. A change in the anode material, for example to aluminum or steel, may also change the timescale of the observed fluctuations, and lend further credence to the ideas presented in this paper.

Acknowledgments

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References

[1] K. Kuriki and H. Iida. Spectrum analysis of instabilities in MPD arcjet. *International Electric Propulsion Conference*, (IEPC84-28), 1984.

[2] J. W. Barnett and R. G. Jahn. Onset Phenomena in MPD Thrusters. *AIAA 18th International Electric Propulsion Conference*, AIAA 85-2038, 1985.

[3] Kevin D. Diamant, Edgar Y. Choueiri, and Robert G. Jahn. Spot mode transition and the anode fall of pulsed magnetoplasmadynamic thrusters. *Journal of Propulsion and Power*, 14(6):1036–1042, November-December 1998.

[4] D.D. Ho. Erosion studies in an MPD thruster. Master's thesis, Princeton University, 1981.

[5] L.K. Rudolph. *The MPD Thruster Onset Current Performance Limitation.* PhD thesis, Princeton University, 1980.

[6] H. Hugel. Flow rate limitations in the self-field accelerator. *AIAA 10th Electric Propulsion Conference*, AIAA 73-1094, 1973.

[7] R. L. Burton, K. E. Clark, and R. G. Jahn. Measured performance of a multi-megawatt MPD thruster. *Journal of Spacecraft and Rockets*, 20(3):299–304, 1983.

[8] E.Y. Choueiri and J.K. Ziemer. Quasi-steady magnetoplasmadynamic thruster performance database. *Journal of Propulsion and Power*, 17(4):520–529, Sept/Oct 2001.

[9] Luke Uribarri and E. Y. Choueiri. Effects of Power Supply Resonances in Onset Studies of Quasi-Steady MPD Thrusters. *43rd AIAA Joint Propulsion Conference*, (AIAA-2007-5295), 2007.

[10] Luke Uribarri and E. Y. Choueiri. The onset of voltage hash and its relationship to anode spots in magnetoplasmadynamic thrusters. *International Electric Propulsion Conference*, (IEPC-2005-084), 2005.

[11] National Institute of Standards and Technology. Atomic spectra database. Internet Database, 2007. http://physics.nist.gov/PhysRefData/ASD/index.html.

[12] Kevin D. Diamant. *The Anode Fall in a High Power Pulsed MPD Thruster.* PhD thesis, Princeton University, 1996.

[13]L.K. Rudolph, R.G. Jahn, K.E. Clark, and W.F. von Jaskowsky. Performance Characteristics of Quasi-Steady MPD Discharges. *AIAA International Electric Propulsion Conference*, (AIAA 76-1000), 1976.

[14]P. Manneville. Intermittency, self-similarity and 1/f spectrum in dissipative dynamical systems. *J. Physique*, 41:1235–1243, 1980.

[15]H.G. Schuster and W. Just. *Deterministic Chaos.* Wiley-VCH, 2006.

[16]A. D. Gallimore, A.J. Kelly, and R.G. Jahn. Anode Power Deposition in Magnetoplasmadynamic Thrusters. *Journal of Propulsion and Power*, 9(3), 1993.