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Characterization of an Ion Thruster Neutralizer

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The neutralizer of a high-power ion thruster was characterized over a range of flow rates at the nominal thruster operating condition of 3.6 A of ion beam current at a beam voltage of 5500 V. Near-neutralizer Langmuir probes were used to characterize the local plasma and detect the transition from spot to plume mode. Consistent with the Langmuir probe measurements, it was found that neutralizer coupling voltage, rather than the magnitude of neutralizer-keeper-voltage oscillations, was most indicative of the spot to plume mode transition. Additionally, neutralizer-keeper-barrel erosion due to extreme, off-axis ions was investigated. No such energetic ion flux was detected using strategically placed, coated witness plates.

Nomenclature

Ja	=	accelerator-grid current
Jb	=	beam current
T	=	time
Vg	=	neutralizer coupling voltage
Vnk	=	neutralizer keeper-to-cathode voltage
Vp	=	plasma potential

I. Introduction

THE high-power electric propulsion (HIPEP) thruster was designed and built to address the need for a long-life, high-specific-impulse option to satisfy requirements for missions to the outer planets and the outer edge of the solar system [1,2]. These powerful thrusters would use a nuclear reactor source to provide the necessary electrical energy. Subcomponents of such ion thrusters must be capable of operating up to 10 years, a typical thrusting-time upper limit [2]. The work presented here focuses on the hollow, cathode-based, plasma-bridge neutralizer subcomponent [3]. As the name implies, the purpose of the neutralizer is to provide space charge and current neutralization of the ion beam. Investigated herein is the neutralizer operating behavior over a wide range of thruster operating conditions. This investigation provides insight into the neutralizer operating envelope and associated flow-rate margin, as well as the impact of the neutralizer-produced plasma on other thruster subcomponents. In conducting this investigation, neutralizer voltage and plasma characteristics as functions of flow rate were determined. The neutralizer characterization is necessary to determine the optimum flow rate for neutralizer operation. Ideally, this would be the lowest flow rate at which the neutralizer can still operate in the spot mode. The hollow cathode spot mode is a quiet, low-voltage discharge condition characterized by the visible presence of a luminous spot of intense ionization and excitation in the orifice of the cathode [4,5]. Although the minimization of neutralizer flow can improve the specific impulse, it can also have deleterious effects on the neutralizer assembly lifetime. A flow rate that is too low forces the neutralizer to operate in the so-called *plume mode* in which high keeper voltages and often unstable operation prevail. In this mode, a distinct and visible luminous plume emanating from the cathode is typically observed. The plume is produced by electron excitation of neutrals external to the cathode. Large keeper-to-cathode, peak-to-peak voltage oscillations are commonly measured in this mode [4,5]. These large voltages can drive sputter erosion of the neutralizer assembly, giving rise to cathode-orifice-channel enlargement and orifice-plate texturing [5–7]. Over time, a neutralizer can transition from the spot to the plume as it undergoes natural erosion of the orifice or through deposition processes within the orifice channel while operating at a fixed flow rate [6]. Such transitioning phenomena were observed both during the NASA Solar Electric Propulsion Application Readiness (NSTAR) flight and during the long duration testing of the NSTAR flight spare [8]. The neutralizer flow rate was increased to transition the neutralizer out of this undesirable operating mode [8]. Again, the plume mode is to be contrasted with spot-mode operation, which is characterized by quiet, stable operation and low discharge voltages and associated reduced wear rates [4].

Diagnostics used to monitor the neutralizer operating mode have typically involved tracking the behavior or change in thruster operating parameters such as keeper voltage or keeper peak-to-peak voltage oscillation magnitude. Indeed, during the NSTAR program, a 5 V or greater peak-to-peak keeper oscillation voltage was defined as the initiation of the plume mode. In the work presented here, in addition to monitoring keeper voltage changes, electrostatic probes co-located with the neutralizer were used to document the change in neutralizer operating mode in response to flow-rate changes. These neutralizer plasma measurements also provide insight into the energy and magnitude of ion flux incident upon the neutralizer assembly during neutralizer characterization. Witness plates, coated with a layer of tantalum of a known thickness, were placed near the neutralizer assembly. The witness plates were used to determine if extreme, poorly focused, off-axis ion beamlets were present. Such beamlets could impinge upon the neutralizer keeper barrel, reducing its overall service life.

II. Test Setup

A. Test Facility

The HIPEP thruster was tested in NASA John H. Glenn Research Center's Vacuum Facility 6 space-simulation chamber. This vacuum facility measures 22.9-m long and 7.6 m in diameter. After the facility is roughed down via mechanical pumps (10^{-3} torr), thruster gases are evacuated using 12 cryopumps. For xenon, the pumping speed of the facility is approximately 400,000 l/s. Base pressure is approximately 1×10^{-7} torr. During thruster operation, pressure remained in the low 10^{-6} torr range.

B. Thruster

The neutralizer investigation described herein was tested exclusively with the HIPEP thruster. The laboratory HIPEP engine measures roughly $100 \times 50 \times 22$ cm. The active area for beam extraction measures 90 by 40 cm. The nominal ion-extraction system

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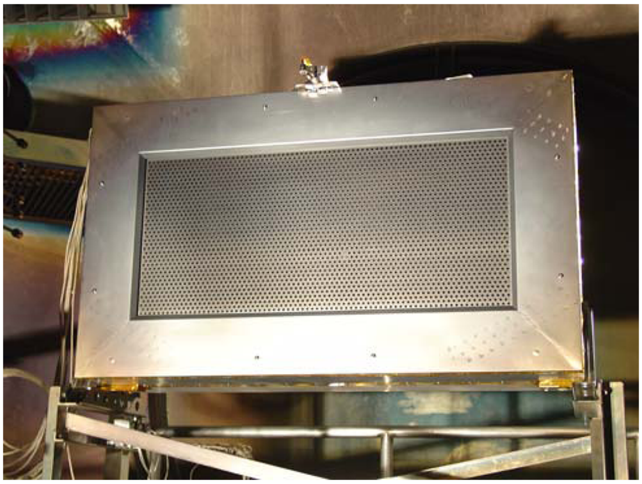
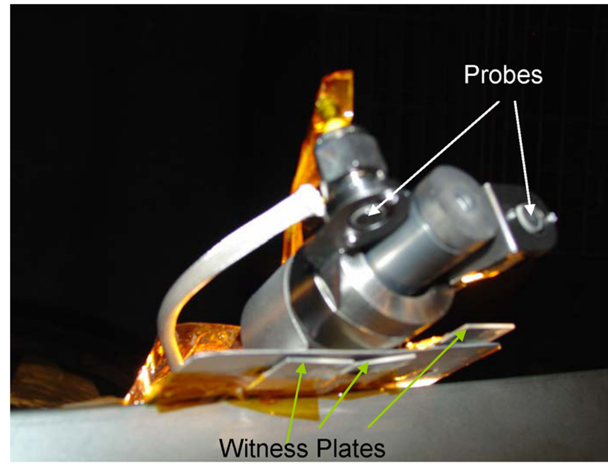


Fig. 1 Ion thruster mounted on the test stand in Vacuum Facility 6 (note the neutralizer mounted atop the plasma screen).

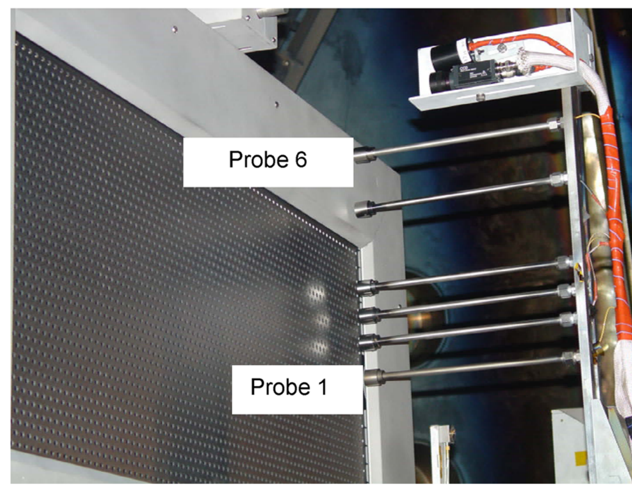
consists of two pyrolytic graphite grids. The flat pyrolytic graphite grids yield an extremely collimated ion-beam profile. During testing, the beam itself is terminated at a graphite target located at the end of the tank. During normal operation, the target temperature never exceeded 260°C. The discharge chamber featured a single hollow cathode centered on the backplate of the discharge chamber. The discharge chamber magnetic circuit uses a modified ring-cusp geometry. The baseline operating condition for the HIPEP engine is a 3.6-A beam current at a beam voltage of 5500 V, which corresponds to 7500 s specific impulse and a total engine efficiency of 76%. Most of the data presented here were taken at this beam current and voltage. The thruster is shown in Fig. 1. The subject of this study, the neutralizer, is centered atop the plasma screen, as shown in Fig. 1. The face of the neutralizer keeper is located 7.6 cm downstream of the plane of the thruster front mask. A comprehensive description of the HIPEP thruster and its performance envelope is discussed in detail in [1]. Details regarding the thruster feed system and power console, as well as ion optics characterization testing, may be found in [9].

C. Diagnostics

Supplemental to the performance measurements, electrostatic measurements of the plasma environment near the neutralizer were made. The measurements were made using two fixed planar probes located at the neutralizer and a planar probe rake that was swept across the beam. The two orthogonally oriented, near-neutralizer planar Langmuir probes were used to measure the local plasma environment produced by the neutralizer. The two probes are depicted in Fig. 2a. Each molybdenum probe had a diameter of 6.37 mm. Probe 2 was oriented such that its axis was parallel with the neutralizer axis but displaced radially approximately 2 cm from the neutralizer keeper orifice. The probe collection surface was located in the plane that also contained the neutralizer keeper face. Probe 1 was oriented perpendicular to the neutralizer axis. Probe 1 was displaced radially, approximately 2 cm from the keeper orifice. The relative close proximity of the probes to the neutralizer allowed the changes in neutralizer plasma conditions to be sampled. The arrangement was chosen not only to avoid perturbation of neutralizer coupling plasma but also to determine if there were significant directional differences in plasma flow, as inferred from the collected current. The Langmuir probes were also used to determine the local plasma potential. With this, the energy of ions impinging upon the neutralizer can be calculated. Also, because the transition from spot to plume mode is associated with a significant increase in measured electron temperature, the Langmuir probes were used as a sensitive transition detector [4,5]. Thin-sheath analysis was used to analyze the Langmuir probe current-voltage characteristic. When using planar Langmuir probes, sheath growth does not affect collected current as long as the shape of the collection sheath is planar. This condition holds as long as the Debye length is much smaller than the probe radius. Uncertainty in sheath surface area due to rounding (nonplanar shape) at the edge of the probe is assumed to be small. This assumption is justified because the ratio of Debye length to probe radius was ~0.1 or less for the conditions investigated here. In this regard, the sheath at the probe should remain planar as bias voltage is varied. This estimation was based on measured plasma densities that ranged between 10^8 and $10^9/\mathrm{cm}^3$. The experimental uncertainty in the electron temperature measurement was approximately 25%, unless otherwise noted with error bars in the plot. The uncertainty in the plasma potential was approximately



a)



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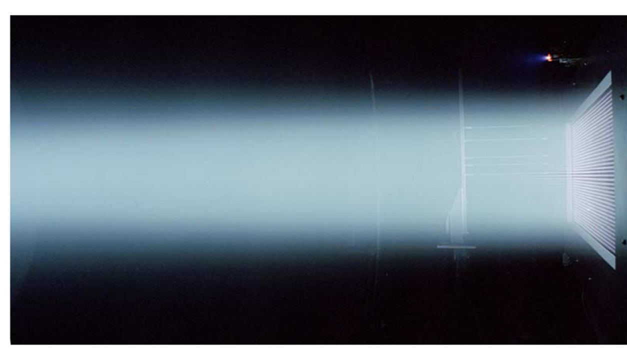

c)

Fig. 2 Experimental hardware used in the investigation: a) neutralizer diagnostics include two orthogonally oriented planar Langmuir probes, witness plates are also visible; b) probe rake located just downstream of the ion optics [the topmost probe (no. 6) is used to sample the neutralizer plasma bridge]; and c) neutralizer operation during beam extraction (note the neutralizer discharge and probe rake).

0.5 V. The uncertainty in the coupling-voltage measurement was also estimated at 0.5 V. The probe rake, shown in Fig. 2b, was used to measure the plume profile of the ion beam. The probe rake consisted of six 1-cm^2 molybdenum disks biased at −30 V relative to the vacuum facility ground. The topmost rake probe actually swept through a portion the neutralizer-to-ion beam plasma-coupling bridge. This sweep was used to provide some insight into the structure and spatial extent of the coupling plasma. The coupling plasma is of interest not only for understanding electron injection dynamics, but it also has implications on grid life, because the ions associated with this plasma can find their way to the accelerator grid, thereby contributing to charge-exchange erosion at the upper apertures. A portion of this coupling plasma is visible during engine operation, as depicted in Fig. 2c.

The possibility of neutralizer barrel erosion via direct impingement from extreme off-axis beamlets was investigated using quartz witness plates that measured 2 by 2 cm, also shown in Fig. 2a. One side (approximately half) of each plate was coated with tantalum, the material composition of the neutralizer keeper barrel. The witness plates were designated by number. Witness plates 3, 4, and 5 contained Ta thickness of 840, 940, and 910 Å, respectively. If a given plate is impinged by energetic ions, then the etch rate of the deposited Ta film should be representative of the etch rate of the Ta neutralizer keeper barrel. A portion of each plate was occluded so that step profilometry could be performed. Net wear due to ion bombardment or net deposition could be detected using the profilometer. The conductive tantalum coating also allowed for posttest compositional analysis of the deposited films by energy-dispersive x-ray spectroscopy. The plates could therefore be used to detect either etching due to direct impingement from energetic ions or deposition due to local grid erosion. The plates were exposed during beam-extraction tests for a total of ∼100 h.

III. General Neutralizer Characteristics

The variation in neutralizer operating parameters such as coupling voltage and neutralizer cathode-to-keeper voltage was documented, with changes in input flow rate at a fixed keeper current (3.0 A) with and without beam extraction. Here, neutralizer coupling voltage refers to the potential difference between the neutralizer cathode and tank ground. This parameter is a measure of the voltage associated with the coupling of emitted electrons into the ion beam; that is, the potential difference across the neutralizer coupling bridge. In general, it was observed that neutralizer-keeper-voltage and peak-to-peak oscillations were most sensitive to variations in neutralizer flow rate in the absence of the ion beam. The variation in the dc keeper voltage and keeper peak-to-peak oscillation amplitude has been used in the past as an indicator of the onset of plume mode. The increase in the peak-to-peak oscillation amplitude to voltages greater than 5 V was defined as the plume mode [10]. As can be observed in Fig. 3, a quadratic increase in neutralizer voltage accompanied the decreasing flow rate with the beam off. Here, *beam off* refers to neutralizer operation without high voltage applied to the grids, so that there is no beam extraction. In this case, the neutralizer simply operates in diode mode between the cathode and keeper electrode. The rather rapid quadratic increase in keeper voltage with decreasing flow rate suggests neutralizer progression to plume mode [5,7]. The supplemental plume-impact ionization beyond the cathode orifice is necessary to sustain the fixed keeper current with decreasing flow rate. The neutralizer voltage increased from approximately 14 V at 6 sccm to over 20 V at 5 sccm. At 5 sccm, peak-to-peak oscillations were nearly 5 V, an increase of over 4.5 V from conditions that prevailed at 6 sccm. The large voltage rise and associated large peak-to-peak variations, as well as the visible external neutralizer plasma, are indicative of plume-mode operation. In contrast to the ion-beam-off condition over a similar flow-rate range, the neutralizer voltage and average peak-to-peak voltage oscillation amplitude were determined to be relatively insensitive to flow-rate variations during beam extraction. Indeed, over a much wider flow-rate range, the neutralizer keeper peak-to-peak voltage oscillations varied less than 1 V, though the functional form (oscillation coherence) did become more chaotic as flow rate was reduced. This puzzling insensitivity to flow-rate variations with beam extraction, as well as general neutralizer behavior without beam extraction, was investigated using two planar Langmuir probes and will be discussed later.

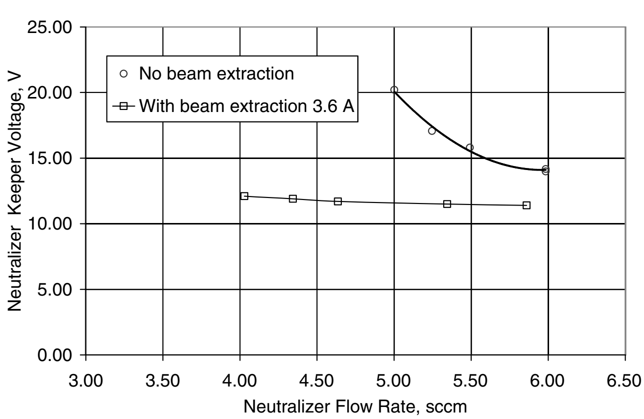

Fig. 3 Variation in neutralizer keeper voltage with flow rate with and without beam extraction.

These data suggest that care must be taken in the interpretation of keeper voltage oscillations as an indicator of plume-mode transition. It should be pointed out that the oscillations observed in past tests may be associated with the keeper power supply itself. Indeed, the sensitivity of neutralizer stability to power supply impedance has been identified in past studies [11]. As the flow rate is reduced, the power-supply voltage will increase to sustain the current. If the discharge manifests a negative resistance characteristic (often observed in plasma discharges) in this regime, the initial increase in voltage may cause a current overshoot, thereby giving rise to oscillations [12,13]. Such oscillations may be those observed to herald the onset of the plume mode. In this case, the oscillations themselves are in part power supply related. These relaxation oscillations are not a good indicator of the onset of plume mode but are rather an indicator of impedance mismatch [12,13]. Power supplies with circuitry that contain sufficient filtering or has enough internal resistance (ballast) would tend to be more immune to such effects. To truly validate neutralizer status, other measurables (independent of peculiarities of the power supply) must be investigated, such as the neutralizer plasma state itself.

During beam extraction, the change in magnitude of the peak-to-peak keeper voltage oscillations were relatively insensitive to flow-rate changes over a broader range of flows. Apparently, the increased emission current and the coupling of the electrons into the beam tend to reduce the keeper voltage and suppress the growth in oscillation amplitude. Reduced keeper voltage noise levels with increased cathode emission current have been documented [14]. In addition to the increased plasma density associated with the higher electron emission current, higher neutralizer performance associated with beam extraction may also be due to the existence of the potential difference between the beam and neutralizer cathode. The presence of the beam acts as a virtual electrode. The plasma bridge itself, in combination with peculiarities of the power supply, may act as a ballast resistor that nonetheless mitigates the oscillations during beam extraction. This mitigating effect of the plasma-bridge impedance may dominate, particularly, under conditions in which the neutralizing current exceeds the keeper current.

As mentioned earlier, one primary objective of this work is to determine the operating margin of the neutralizer. This is done by varying the neutralizer flow rate over a range of flows. The flow rate is reduced until the neutralizer cathode makes a transition from spot to plume, as determined by characteristic changes in certain neutralizer or thruster operating parameters such as 1) the neutralizer keeper voltage, 2) the magnitude of neutralizer-keeper-voltage peak-to-peak oscillations, 3) the variations in the neutralizer coupling voltage, 4) changes in the accelerator-grid current, and 5) the variations in neutralizer plasma parameters such as electron temperature, plasma potential, or plasma density. The selected operating point is this minimum flow rate plus margin. The margin is

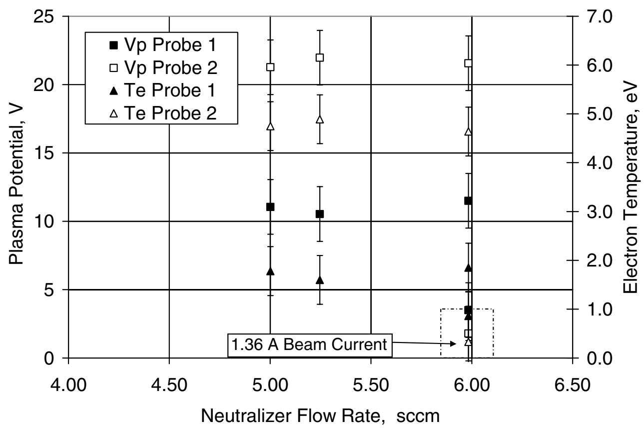

Fig. 4 Comparison of near-neutralizer plasma characteristics with and without beam extraction; all points outside of the boxed region correspond to the beam-off condition.

determined based on projected performance degradation typically due to wear. The sensitivity of the diagnostic used to determine the transition point is therefore very important in determining neutralizer margin. It was found in this work that the change in magnitude of neutralizer-keeper-voltage peak-to-peak oscillations was not the most sensitive indicator of the transition from spot to plume mode. Indeed, it was observed, as will be discussed in the next section, that peak- to-peak oscillations did not become appreciable until the neutralizer was well into a regime of unstable operation, as characterized by large and increasing coupling voltage. Though peak-to-peak oscillations proved to be a reasonable indicator of plume-mode transition for the thrusters such as NASA's Solar Electric Propulsion Technology Readiness thruster [8,10], it proved to be of limited utility for neutralizer margin determination for the HIPEP thruster. During the course of this investigation, however, it was found that plasma parameters such as the electron temperature and the neutralizer coupling voltage were more sensitive indicators of the onset of plume mode. In this case, the neutralizer coupling voltage is defined as the potential difference between cathode common and the ion beam. Though this parameter can be measured directly using a Langmuir probe, for ground testing, a good approximation of this parameter is Vg, the potential of cathode common relative to ground. It is likely that the variation in plasma properties such as the electron temperature may be a more fundamental indicator of mode changes because they directly reflect changes at the source (the neutralizer). The variation in such plasma parameters is discussed in the following section.

IV. Neutralizer Plasma Variations with Beam Extraction

As can be ascertained from Fig. 3, neutralizer-keeper-voltage characteristics are quite different, depending on whether an ion beam is extracted. Without beam extraction, as evidenced by the rapid rise in keeper voltage, the transition into plume-mode operation is fairly rapid with decreasing flow rate. On the other hand, with beam extraction, the keeper voltage is a slowly varying (increasing) function of decreasing flow rate. General plasma characteristics such as electron temperature and local plasma potential are also dramatically different, depending on whether a beam is extracted.

Figure 4 compares local plasma potential and electron temperature with and without beam extraction as a function of neutralizer flow rate. Neutralizer keeper current was fixed at 3.0 A. For illustrative and comparative purposes, the plasma potential and electron temperature during beam extraction (1.36 A) is also shown (the boxed area). All other points were taken at the beam-off condition. As can be seen here, there are rather dramatic differences in the local neutralizer plasma, depending on whether the beam is present. Measurements from both near-neutralizer planar probes are shown. Over the flow-rate range investigated here, plasma potentials (referenced to facility ground) were of the order of the keeper voltage, with measured electron temperatures exceeding 1 eV with the beam off. Both parameters drop significantly during beam extraction, suggesting that the neutralizer has moved from a plumelike mode to spot-mode operation, as observed by previous investigations [5,7,8,15]. As can be seen here, for the beam-off condition, the electron temperature and the plasma potential were consistently higher at probe 2. Probe 1, which faced down toward the beam, indicated a plasma potential of roughly half that measured at probe 2. The electron temperature at probe 2 was also approximately twice that of probe 1. This difference suggests significant nonuniformities in the local plasma. When the beam is turned on, significant drops in the plasma potential and the electron temperature are observed. Additionally, the percent difference between measured plasma conditions at probe 1 and probe 2 are significantly smaller, suggesting that local plasma conditions become locally more uniform during beam extraction. The uncoupled plasma produced by the neutralizer is likely not uniform. The presence of the beam may focus the neutralizer plasma (via the coupling voltage) such that it is directed downward toward the beam. Despite that apparent improvement in uniformity of plasma potential and electron temperature, the ion current ratio between the two probes improves only slightly with beam extraction. Finally, it should be pointed out that these data suggest that determination of neutralizer flow margin without beam extraction is inadequate using conventional methods.

A. Characterizing Neutralizer Transition to Plume Mode

As mentioned earlier, the purpose of neutralizer characterization is to locate the onset of plume-mode operation. In the past, the onset of plume-mode operation has been located by determining the onset of high peak-to-peak voltage oscillations on the neutralizer keeper (greater than 5 V, peak-to-peak) [10]. As discussed earlier, this approach may not always be sufficient to determine the onset. It should be pointed out that this transition to large peak-to-peak voltage oscillations during characterization with beam extraction was only detectable at very low flow rates. The relative insensitivity in the peak-to-peak oscillations with reductions in flow rate is illustrated in Fig. 5. On the other hand, plasma property changes (in particular, variations in the electron temperature) appear to be a more sensitive measure of the transition to plume mode. These changes are directly coupled to neutralizer plasma production and sheath

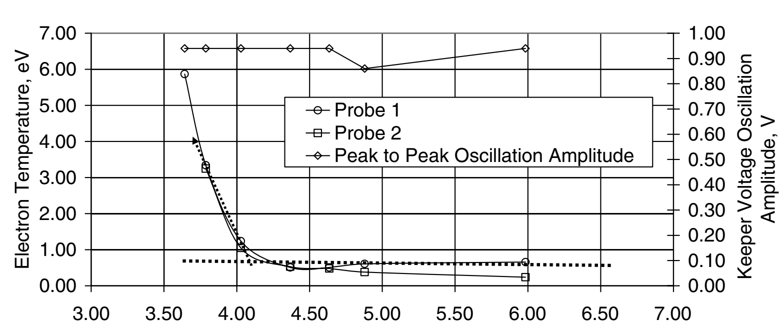

Fig. 5 Variation in the local electron temperature with xenon flow rate during beam extraction (note that the knee occurs at roughly the same location as the transition in coupling voltage (Fig. 6); also note the relative insensitivity of peak-to-peak oscillations).

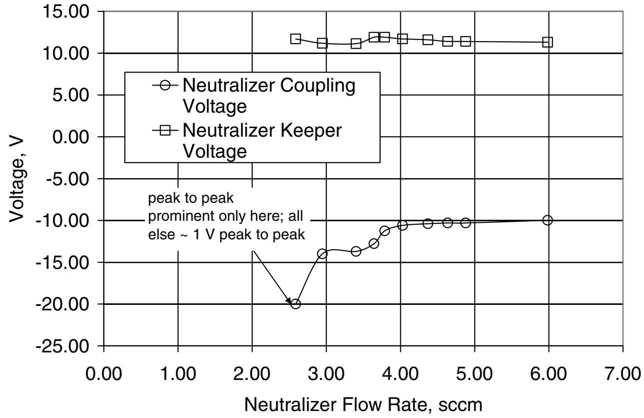

Fig. 6 Variations in the neutralizer coupling voltage and keeper voltage with flow; beam voltage is 5500 V and beam current is 3.6 A.

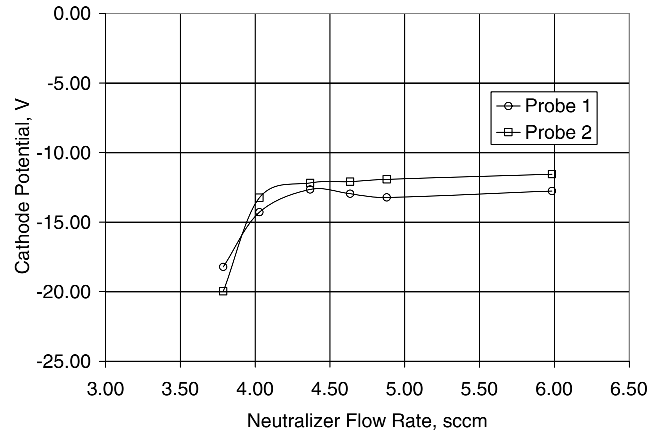

Fig. 7 Variation in cathode potential relative to the local plasma potential external to the neutralizer as a function of the xenon flow rate.

changes. Figure 5 illustrates the changes in the electron temperature with neutralizer flow rate at the 3.6-A ion-beam operating point. Between approximately 4.25 and 6 sccm , the electron temperature as measured by both near-neutralizer probes was low (∼0.5 eV) and fairly constant. The transition into plume-mode operation is evident as the flow rate is reduced below 4.25 sccm, with the knee occurring just above 4 sccm. For both probes, the electron temperature rises rapidly with decreasing flow rate. These high electron temperatures are characteristic of plume-mode operation. The elevated temperatures are necessary for plume ionization, because plasma conditions at the neutralizer change in response to the reduced flow rate. The elevated temperatures themselves are a consequence of reduced pressure (neutral density) and sheath heating downstream of the orifice [5,14]. It is likely that increases in coupling voltage with decreasing flow rate also contribute to additional electron heating. The increase in the absolute value of the coupling voltage with decreasing flow rate is akin to the presence and noticeable increase of the anode fall voltage in hollow cathode–diode configurations. The increase in potential is necessary for the maintenance of current transport [5]. The nature of the voltage increase with decreasing cathode flow rate is related to the size of the available anode area (beam radius) and the distance to the anode (neutralizer to beam distance).

Consistent with the variations in the electron temperature with decreasing flow rate was changes in the neutralizer-to-ion-beam coupling voltage. Figure 6 indicates the variations of coupling voltage and the neutralizer keeper voltage, with flow rate at the nominal 5500 V beam power supply operating condition. The coupling voltage is of interest because it is an indicator of how well the neutralizer source electrons are coupled to the beam. Low coupling voltages indicate a well-coupled beam. The absolute value of this parameter necessarily increases as the impedance of the plasma bridge increases. This condition of large Vg is associated with insufficient plasma production at the neutralizer. The voltage increases provide the energy source for plume production. The plume-mode production provides the additional electrons for beam neutrality. In this regard, sharp increases in the absolute value of the coupling voltage should be a good measure of the onset of the deleterious neutralizer operation and subsequent transitioning into plume-mode operation [5,13]. As can be seen in Fig. 6, the coupling voltages begin to increase as flow is reduced below 4 sccm, even though the neutralizer keeper voltage remains relatively unchanged.

What is curious about the data is the relative insensitivity of the neutralizer cathode-to-keeper voltage to decreasing flow rate. This parameter is essentially constant over the range investigated. The relative insensitivity of the keeper voltage to the reduction in flow rate suggests that plasma production associated with the keeper is more than sufficient to sustain the fixed keeper current, which suggests that this parameter is somewhat decoupled from the process of beam injection. Consistent with this behavior are the peak-to-peak keeper voltage oscillations over this range, which were of order 1 V and were also fairly constant. The function of the coupling potential difference is to extract the electrons produced by the neutralizer and neutralizer plasma and propel them into the beam. The extra energy required to sustain the beam neutralization at the reduced flow rates comes from the shift in Vg, which adds energy to exiting electrons. This voltage increase also has the potential to accelerate the ions toward the neutralizer assembly and thereby participate in erosion there. Below approximately 3 sccm, the peak-to-peak oscillations began to grow significantly. The absolute value of Vg also rose rather abruptly. The neutralizer keeper voltage also increased at these low flow rates, indicating the transition to plume-mode operation. Stable operation of the neutralizer could not be achieved below 2.6 sccm.

At low flow rates, if sheath voltages at the neutralizer are high enough, then erosion can occur. For such damage to occur, the ions must be accelerated to the threshold sputter energy (∼30 eV for W and Ta) [16]. Shown in Fig. 7 are measured variations in the potential difference between the local plasma potential and the potential of the cathode. These voltages are below the sputter threshold if only singly charged ions are considered. In the plume mode, however, because the electron temperature is elevated, doubly charged ions can also be produced. This process is yet another negative effect of plume-mode operation. The minimum potential difference required for erosion to occur due to doubly charged xenon ions is approximately 15 V. As can be seen in the figure, at the lower flow rates, ions will fall through voltages equal to or greater than 15 V. Doubly charged xenon ions falling through this potential over time will give rise to neutralizer erosion-induced wear. Based on these data and the electron temperature measurements, safe neutralizer operation can be expected for flow rates greater than 4.25 sccm. A flow-rate safety margin must be added to this lower limit. The safety margin selected for the HIPEP thruster wear test condition was approximately 1 sccm. The magnitude of the safety margin selected was based on performance considerations and empirical data such as the NSTAR thruster tests in which flow margin erosion was observed over the life of the wear test.

Though not as sensitive as the electron temperature in terms of macroscopic measurables, Vg (or rather, derivatives in Vg) is apparently a better indicator of unstable neutralizer operation than the peak-to-peak oscillations on the keeper voltage. Again, this finding is not unexpected. Even during the NSTAR flight thruster plume-mode survey, Vg was observed to proceed to more negative values with decreasing flow rate, an indication of plume-mode onset [8]. These observed changes were masked somewhat by scatter in the data. The sensitivity of Vg to reduced flow rate in this case (NSTAR) was likely reduced because neutralizer common was referenced with respect to spacecraft ground rather than beam potential. The coupling voltage is an indication of the extraction voltage needed to pull electrons into the beam. In this regard, this parameter dominates neutralizer dynamics. The neutralizer operates in a triode mode in which the beam is the third electrode. This reasoning is bolstered by the fact that the neutralizer keeper voltage (11 V) in essentially all cases was less than the ionization potential of xenon. Rather than examining neutralizer keeper oscillations, it is the oscillations in the

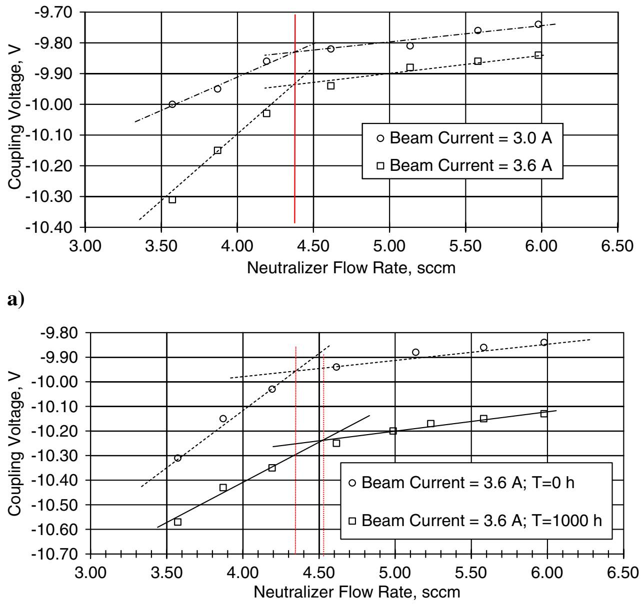

Fig. 8 Variation in the neutralizer a) coupling voltage with flow rate as acquired during the HIPEP 2000-h wear test and b) over time (note the shift in margin after 1000 h).

plasma bridge between the neutralizer and the beam that would be a better indicator of plume-mode operation. Additionally, because of the large separation distance between the beam and the neutralizer in the case of the HIPEP engine, the keeper voltage processes are more or less local and not directly coupled to the dynamics of the transport of several amperes of current over distances of the order of 18 cm to the ion beam.

Figure 8a depicts the coupling voltage as a function of neutralizer flow rate, as acquired during the 2000-h wear test of the HIPEP engine [17]. The coupling voltages were taken at the nominal 3.6-A beam current operation condition and at the off-nominal operating condition (3.0 A). As can be seen here, the coupling voltage for those conditions above the knee is 0.1 V more positive for the lower (3.0 A) beam current off-nominal operating point, suggesting slightly better coupling at the lower beam currents. This value significantly diverges as the xenon flow rate is reduced below the knee. The knee of each curve (as well as the general slope of each curve approaching the knee from the right) is very similar, indicating similar transition to plume-mode flow rate. Figure 8b depicts the change in coupling-voltage sensitivity to flow rate after 1000 h of thruster operation. As indicated here, the data suggest a small decease in margin, as inferred from the shift in the knee of the curve toward higher flow rates. The shift translates into a small loss of margin. Trends such as this occur normally over time, due to changes in the cathode geometry or emitter characteristics. The objective of neutralizer optimization is to provide enough flow margin so that such reductions do not send the neutralizer into the plume mode before the required thrusting time has elapsed. In the case of the HIPEP thruster, post 2000-h wear test analysis did not reveal any appreciable change in the cathode or keeper orifice size. The primary difference between the pretest and posttest neutralizer assembly was the presence of the carbon coating on the keeper face.

B. Neutralizer Plasma-Bridge Characteristics

It is interesting to note that the portions of the plasma discharge associated with the neutralizer could be observed during near-field plume sweeps. A conceptual depiction of the neutralizer plasma bridge is shown in Fig. 9. The topmost Faraday probe (see Fig. 2b), probe 6, is located approximately 6.25 cm below the neutralizer. In this regard, it faces the thruster front mask. If only the ion beam were present, the probe would pick up very little ion current, save for some charge-exchange ion flux. At close approach (~13 cm downstream of the optics), what was observed instead was a peaked profile as the

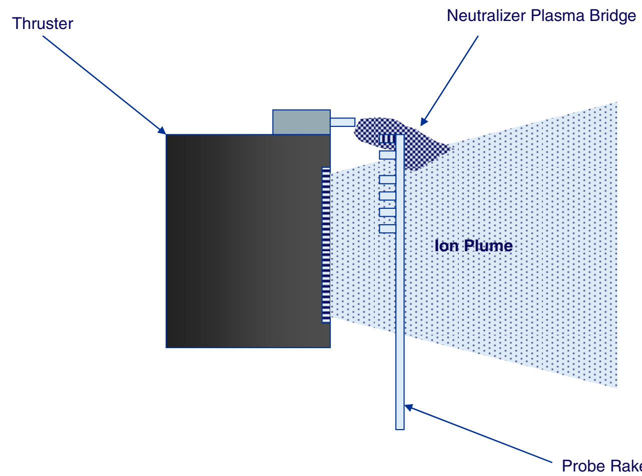

Fig. 9 Schematic of probe rake as it sweeps through the neutralizer bridge and ion beam plasma.

probe passed under the neutralizer, confirming the presence of the plasma bridge and also suggesting that the neutralizer contributes nontrivial ion flux in the ion thruster near field. Sweeps taken still closer in at 8 cm downstream revealed very little collected ion current, thereby adding some validity of a defined plasma-bridge structure, as shown schematically in Fig. 9. The peaked profile associated with the neutralizer plume has been observed in the past [18]. The Faraday profiles for the topmost probes are shown in Fig. 10. The Faraday probe (probe 5) located just below the topmost Faraday probe recorded essentially no peak. Observed instead was a rather broad profile associated with the neutralizer plasma dispersion. From these clues, a rough picture of the neutralizer plasma can be speculated. The plasma bridge can be envisioned as a three-dimensional fanlike structure emanating from the neutralizer exit plane. This source plasma fans out and couples lengthwise across the collimated ion beam.

The plasma bridge associated with the neutralizer (in particular, the plasma immediately below the neutralizer) likely contributes to ion flux collected at the accelerator-grid current. In this regard, changes in the neutralizer plasma coupling bridge due to variations in coupling voltage or neutralizer flow rate should be reflected in changes in the accelerator-grid current. The physics of the correlation is left to further investigation. Presented here, however, is anecdotal evidence showing the variation in the collected accelerator-grid current and the ion current collected at neutralizer probe 2 that supports this conjecture. This probe was considered most coupled to the neutralizer plasma. This distinction is associated with its relative proximity to the neutralizer exit plane and its consistently higher measured ion current. Figure 11 shows the variation in accelerator-grid current and collected ion current at the probe as flow rate is varied at the nominal thruster operation point. As can be seen here, both parameters vary in a similar manner, suggesting a correlation. Interestingly, note the increase in current for both parameters as the plume mode is approached. This was also observed on the NSTAR Deep Space 1 mission during neutralizer plume-mode surveys in

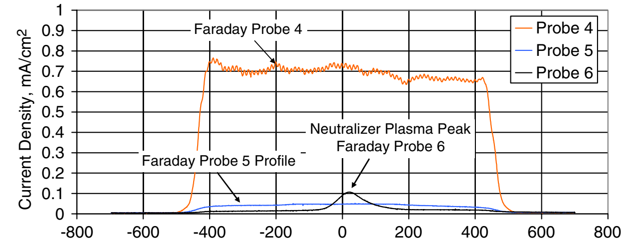

Fig. 10 Faraday sweep taken 13 cm downstream of the ion optics; notice the topmost peak observed at probe 6, which is associated with the neutralizer plasma; probe 5 traverses the front mask; sweeps 1–3 are not shown for clarity.

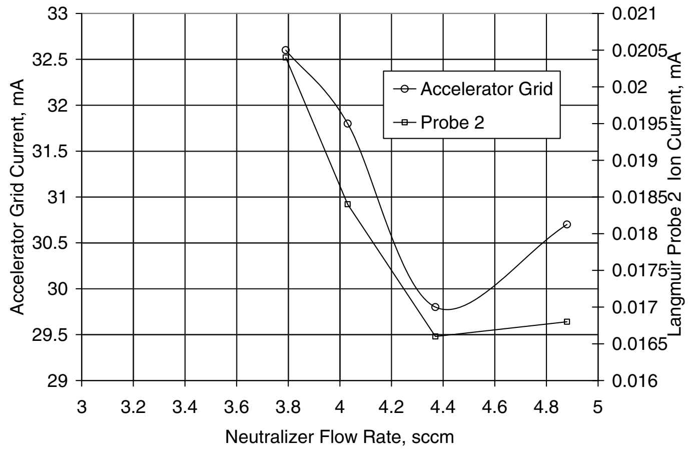

Fig. 11 Variation in Langmuir probe ion saturation current, along with variations in accelerator-grid current as a function of the neutralizer flow rate.

which retarding-potential-analyzer measurements revealed increased ion current as the plume mode was approached [8].

The increase in collected ion current in the plume mode is likely associated with plume ionization. Under plume conditions, the electron temperature is elevated, thereby leading to an increase in the plasma density external to the neutralizer. This assertion is consistent with the observed plumelike appearance of the discharge just downstream of the neutralizer, indicating nontrivial excitation and ionization downstream of the neutralizer. Ionization in the plasma bridge can also be enhanced by the presence of stray magnetic flux produced by the thruster magnets. Magnetic field strengths below the neutralizer range between 5 and 10 G. It is known that stray magnetic fields affect neutralizer plasma-bridge coupling [19]. Stray magnetic fields leaking out of the discharge chamber would tend to enhance ionization in the plasma bridge by locally reducing the electron loss rate. These data suggest another drawback of plume operation: increased ion flux to the accelerator grid. Further support of correlations between the accelerator current and the neutralizer plasma was obtained during experiments in which the neutralizer keeper current was reduced with the beam current and the neutralizer flow rate held fixed. As the keeper current was reduced from 3 to 2 A, Vg and Ja increased monotonically, with accelerator-grid current increasing from 28 to 31 mA and the coupling voltage decreasing from -10 to over -11 V. The increase in Ja is attributed to improved plume ionization associated with the higher keeper and coupling voltages that are required to make up for reduced plasma production. Ions produced in this plume travel to the accelerator grid and are collected there, as reflected in the increase in accelerator-grid current. At very low flow rates within the plume mode, the plasma density near the neutralizer plasma decreases, as expected. In this regard, the accelerator-grid current variations with neutralizer flow rate could potentially be used as a diagnostic for determining the transition from spot to plume mode.

C. Investigation of Possible Neutralizer Erosion

One of the first design considerations regarding neutralizer to thruster integration is neutralizer placement [7,20,21]. The neutralizer should be placed in a location such that when operating it couples primarily to the ion beam. This typically requires minimization of the distance between the neutralizer and the beam. This reduces operating power and flow-rate requirements and also has the associated benefit of reducing coupling voltage. The placement must also ensure that the neutralizer is not impinged by extracted ion beamlets. For the HIPEP thruster, which used flat grids, beam divergence was low and thus interception of the neutralizer by the beam is unlikely. To confirm this, witness plates coated with tantalum (~900 Å) were placed as described earlier, in the general vicinity of the neutralizer (see Fig. 2a). Direct interception of the neutralizer by extreme, off-axis ions would be reflected in the etching of the coatings. A portion of each plate was occluded so that step profilometry could be performed. Net wear due to ion bombardment or net deposition could be detected using the profilometer. Because of the orientation, the plates are sensitive to either direct impingement from energetic ions or deposition from local grid erosion. Inspection of the witness plates revealed net deposition as opposed to etching. This finding is consistent with expectations. From energy-dispersive x-ray analysis of the samples, the atomic composition of the coating on the plate surface facing the beam was determined. The dispersion spectra were similar for all witness coupons. The coatings consisted primarily of aluminum and carbon. The carbon is likely due to backsputtered material originating primarily from the tank, with some contributions expected from low-level erosion of outer perimeter accelerator-grid apertures. The primarily carbon coating thickness was approximately 600 Å. Posttest analysis of the HIPEP grids indicated that the low-level erosion of the accelerator grid was not life-limiting [22]. Furthermore, this posttest analysis appears to suggest that the coatings on the witness plates were primarily due to backsputtered material from the facility. The aluminum signal found in the spectra is likely due to backsputtered material generated when the Faraday probe rake is swept across the beam.

D. Relative Ion Currents

One objective of the planar Langmuir probes was to determine if any ion flux anisotropy existed. Because the magnetic field at the neutralizer probes was very weak (~1–3 G), anisotropy due to finite Larmor radius effects can be eliminated. Of particular interest was that of directed ion flux onto the barrel of the neutralizer (flux normal to the neutralizer axis). This flux is to be contrasted with the axially directed flux. The orthogonally oriented probes allowed for such anisotropy measurements. Figure 12 illustrates variations in the ratio of probe 1 ion current to probe 2 ion current at the neutralizer flow of 4.88 sccm as a function of beam current. In general, the ion flux to the probes increased monotonically with increasing beam current. As can be seen in the figure, the ion current ratio does not vary appreciably at this flow rate as the beam current increases. Probe 2 (oriented on axis with the neutralizer) collects nearly five times the ion current collected at probe 1. The plasma density measured at probe 2 was also significantly higher (~10 times). Apparently, at fixed flow rate, the plasma distribution does not vary appreciably with beam current. The data appear to suggest that the plasma produced by the neutralizer is likely centered on the axis. In this case, plasma collected at the downward-facing probe (probe 2) is due to expansion and scattering of the source plasma. Probe 2 likely benefited from orientation and near-proximity to the neutralizer orifice. At lower flow rates, differences in collected ion current tended to diminish. Figure 13 illustrates the variations in the ratio as a function of flow rate at fixed beam current (3.6 A). As can be seen here, the ion flux ratio is largest at the lower flow rates. This behavior is also to be expected. With the onset of plume-mode plasma production, the plasma production volume is no longer localized and directed as in the spot mode. The volume of plasma production in the plume apparently somewhat smoothes out the asymmetries in plasma flow observed at the higher flow-rate condition (4.88 sccm).

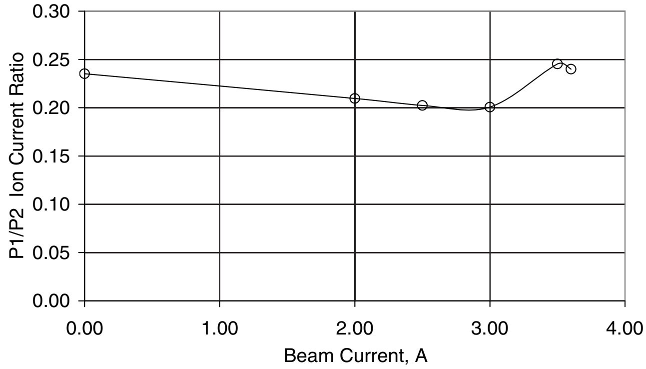

Fig. 12 Variations in the ratio of ion current measured at two orthogonally oriented probes; probe 1 was orthogonal to the neutralizer axis; the ratio is fairly insensitive to beam current.

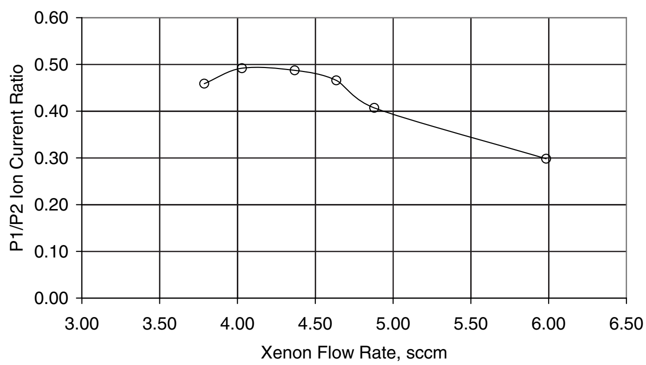

Fig. 13 Variation of probe ion current ratio as a function of the xenon flow rate, $Jb = 3.6$ A (note that the ratio is highest at the lower flow rates).

This finding is also supported by a relative increase in plasma density measured at probe 1, in which the density at probe 1 increases from 0.3 times that of probe 2 to half that of probe 2 as flow decreases. Again, increases in ion current were also observed during plume-mode surveys of the NSTAR thruster [8]. It should be pointed out that the variations in the behavior of the ion current ratio parameter are also indicative of the onset of plume-mode operation. The ratio has a maximum near the point at which the electron temperature takes off, ushering in the plume mode. The shape of the function at the low flow rates is likely due to competition between plasma production and diffusion.

V. Conclusions

A neutralizer on the HIPEP thruster was characterized over a range of flow rates and beam currents. It was observed that changes in local plasma properties measured using planar Langmuir probes were more sensitive to the transition into the plume mode than the peak-to-peak cathode-keeper voltage oscillations. Indeed, the electron temperature increases precipitously at flow rates well before there is a noticeable increase in the peak-to-peak oscillation amplitude. The sensitivity to plume-mode transition was also reflected well in the behavior of the neutralizer-to-ion beam coupling voltage. This thruster parameter can be used to determine the neutralizer margin for ground testing. The coupling-voltage behavior yielded results consistent with plasma changes measured using Langmuir probes. The data suggest the need for verification diagnostics such as electrostatic probes to validate more conventional spot-to-plume-mode transition indicators such as neutralizer peak-to-peak oscillations. Orthogonal ion flux measurements at the neutralizer indicated anisotropy in the neutralizer plasma. The anisotropy tended to diminish as the neutralizer was driven toward plume mode. Apparently, plume-mode plasma production smoothes out the anisotropy somewhat. Finally, posttest analysis of witness plates located at the neutralizer barrel revealed net deposition rather than etching, which would have indicated impingement from off-axis ions.

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