An ion thruster internal discharge chamber electrostatic probe diagnostic technique using a high-speed probe positioning system

Daniel A. Herman and Alec D. Gallimore

Plasmadynamics and Electric Propulsion Laboratory, Department of Aerospace Engineering, College of Engineering, The University of Michigan, Ann Arbor, Michigan 48109, USA

(Received 12 March 2007; accepted 28 September 2007; published online 17 January 2008)

Extensive resources have been allocated to diagnose and minimize lifetime-limiting factors in gridded ion thrusters. While most of this effort has focused on grid erosion, results from wear tests indicate that discharge cathode erosion may also play an important role in limiting the lifetime of ring-cusp ion thrusters proposed for future large flagship missions. The detailed characterization of the near-cathode discharge plasma is essential for mitigating discharge cathode erosion. However, severe difficulty is encountered when attempting to measure internal discharge plasma parameters during thruster operation with conventional probing techniques. These difficulties stem from the high-voltage, high-density discharge cathode plume, which is a hostile environment for probes. A method for interrogating the discharge chamber plasma of a working ion thruster over a two-dimensional grid is demonstrated. The high-speed axial reciprocating probe positioning system is used to minimize thruster perturbation during probe insertion and to reduce heating of the probe. Electrostatic probe measurements from a symmetric double Langmuir probe are presented over a two-dimensional spatial array in the near-discharge cathode assembly region of a 30-cm-diameter ring-cusp ion thruster. Electron temperatures, 2–5 eV, and number density contours, with a maximum of $8 \times 10^{12}$ cm$^{-3}$ on centerline, are measured. These data provide detailed electron temperature and number density contours which, when combined with plasma potential measurements, may shed light on discharge cathode erosion processes and the effect of thruster operating conditions on erosion rates. © 2008 American Institute of Physics.

[DOI: 10.1063/1.2800772]

I. INTRODUCTION

Ion thrusters are high-efficiency, high-specific impulse ($I_{sp}$) propulsion systems that are being proposed as the primary propulsion source for a variety of missions. Gridded ion thrusters are electrostatic, in-space propulsion devices in which the ionization and acceleration regions can be optimized separately resulting in highly efficient thrusters. The ionization takes place in a discharge chamber, typically from bombardment by electrons emitted from a thermionic hollow cathode. Primary electron confinement and the discharge propellant utilization efficiency are enhanced through a ring-cusp magnetic field topology in most NASA ion thrusters, such as the thruster used in this investigation. The ionized gas in the discharge chamber diffuses toward a set of grids that accelerate the ions to high velocities by the applied electric field. An external neutralizer, typically a hollow cathode, emits electrons to neutralize the space charge of the accelerated ions and prevents spacecraft charge buildup, thereby reducing the frequency of ion impacts on the spacecraft or ion thruster itself. A schematic visualizing the ion thruster operation is shown in Fig. 1 and a more detailed description of ion thruster operation can be found in Refs. 2 and 3.

The NASA Solar Electric Propulsion Technology Appli-
sion, and how to reduce DCA erosion, thereby extending thruster lifetime. Mapping the internal plasma structure of a NSTAR ion thruster, specifically downstream of the DCA, as a function of thruster operating condition is essential to understanding the cause of DCA erosion.

Efforts to increase thruster lifetime present an ever growing challenge to ion thruster designs and operation as the transition from small discovery-class missions to future large flagship NASA missions takes place. NASA’s Dawn mission, the first full-up NASA science mission to use ion propulsion, will be propelled by three 30 cm ion thrusters and is set to study two minor planets, Ceres and Vesta, that reside in the asteroid belt between Mars and Jupiter. Each of the ion thrusters are required to process at least 150 kg of xenon and operate for up to 24 000 h. More ambitious missions will require higher power, larger beam currents, and longer thruster lifetimes of 44 000–88 000 h. Since discharge cathode keeper wear rates are expected to be linearly dependent on the beam current density, discharge cathode erosion becomes an increasingly important factor in the lifetime of gridded ion thrusters at the higher power levels of future deep-space missions.

The purpose of this investigation is to provide detailed, high-resolution measurements of the plasma parameters inside the discharge chamber of a ring-cusp ion thruster with emphasis on the near-discharge cathode region. This investigation presents the results of symmetric double Langmuir probe measurements inside a 30 cm NSTAR thruster. Due to the large number of measurements, the Langmuir probe analytical technique utilized, while not entirely rigorous, provides useful experimental data without an overly excessive computational effort. Though efforts were made to minimize the discharge plasma perturbation due to the presence of the probe, through fast sweep rates and small geometry probes, non-negligible perturbations of 2% and 5%–10% of the nominal discharge voltage and current, respectively, persist but only during interrogation of the region within a few millimeters of the DCA orifice.

II. EXPERIMENTAL APPARATUS

A. 30 cm NSTAR ion thruster

The functional model thruster (FMT) preceded the NSTAR engineering model thruster (EMT) and the NSTAR flight thruster. The principal difference in the construction of the FMT from the EMT is that the FMT anode is made of aluminum while the EMT anode is constructed of spun aluminum and titanium. The second of two FMTs, FMT2, was modified at the NASA Glenn Research Center (GRC) to allow optical access to the discharge chamber for laser-induced fluorescence (LIF) measurements. Three slots were cut into the FMT2 anode wall and covered with quartz windows during LIF measurements. Though these three slots replaced roughly 20% of the FMT2 anode surface, the magnetic field, DCA, and geometry of the discharge chamber are identical to those of the EMT1. For a more complete comparison between FMT2 and EMT1, see Refs. 13–15. The FMT2 thruster has been operated over the entire NSTAR power throttling range at NASA GRC and at the Plasmadynamics and Electric Propulsion Laboratory (PEPL), illustrating comparable performance to the EMTs and flight thrusters. The FMT2 modifications have not altered the discharge chamber magnetic field, the ion production efficiency, or the overall thruster performance.

B. Discharge plasma containment

A discharge plasma containment mechanism replaces the side anode quartz window to permit internal probe access over a two-dimensional data collection grid. The design, shown in Figs. 2–4, consists of a series of overlapping 38-gauge slotted stainless steel sheets that slide along stainless guide tracks. A guiding alumina tube extends from the discharge chamber through the slotted sheets and holes in the plasma shield to ensure accurate radial sweeps of the probe at the various axial locations while maintaining thruster component isolation. Repeatable axial movement of the probe is
possible without the formation of holes or tears in the sheets. Discharge plasma containment is maintained and visually monitored during thruster operation via an adjacent vacuum-rated camera. Hole or tear formation, while extracting a beam, leads to a surge of discharge plasma toward the hole as the high-voltage plasma escapes to grounded surfaces and causes unstable operation.

During the initial design of the NSTAR thruster at NASA GRC, the placement of the DCA exit plane was chosen based on the desired magnetic field topology, resulting in the placement of the DCA face in the conical section of the discharge chamber. This DCA location has direct implications on the design of the containment mechanism in that the movement of the probe downstream of the DCA must take into account the angled wall of the mechanism with respect to the probe sweep axis. Thus, the guiding alumina tube is mounted onto a computer-controlled, single-axis ball screw table with a lead screw accuracy of \( \frac{80}{9262} \) m and a range of motion of 20 cm. The ability to retract and extend the translating alumina tube at various axial locations minimizes protrusion of the material into the discharge chamber and prevents binding of the slotted stainless steel sheets as the coordinated movement between the translation tables relieves the buildup stress on the sheets during movement. The guiding alumina tube extends 2 cm inside the discharge chamber wall at all axial locations. A spring-loaded guard ring, covering the outside of the alumina tube, ensures a tight fit to prevent plasma leakage.

To minimize the likelihood of probe contamination by plasma deposition and discharge plasma perturbation, the probe is recessed in the low-density interior of the guiding alumina tube when not in use. A rectangular aluminum plate covers the slot in the plasma shield, eliminating the line of sight of background particles to the anode. Figure 5 shows pictures that illustrate the sweeping of the electrostatic probe in front of the DCA.

C. High-speed axial reciprocating probe (HARP)

A linear motor assembly provides accurate direct linear motion of the probe with minimal discharge cathode plume residence times. The HARP system consists of a three-phase brushless dc servo motor consisting of a linear “U-shaped” magnet track and a “T-shaped” coil moving on a set of linear tracks. The linear encoder provides positioning resolution to \( \frac{5}{9262} \) \( \mu \)m. A Pacific Scientific SC950 digital, brushless servo drive controls the motor. The entire table is enclosed in a stainless steel shroud with a graphite outer skin. Residence times of the probe inside the discharge cathode plume are kept under 100 ms to minimize probe heating and discharge plasma perturbation. The maximum relaxation times occur in regions of low number density and high electron temperature (i.e., near the anode wall), which for ion-ion, electron-ion, and electron-electron interactions are \( 9 \times 10^{-5} \), \( 8 \times 10^{-5} \), and \( 3 \times 10^{-5} \) s, respectively. Thus, the sweep time in front of the discharge cathode plume is much longer (four orders of magnitude) than the plasma relaxation times over all spatial locations investigated. Additional information of the HARP system can be found in Refs. 16 and 18.

D. Plasmadynamics and Electric Propulsion Laboratory (PEPL) vacuum facility

All experiments are performed in the University of Michigan 6\( \times \)9 m\(^2\) Large Vacuum Test Facility (LVTF) at PEPL. Four of the seven CVI model TM-1200 reentrant cryopumps are used for these experiments, which provide a combined pumping speed of 140 000 l/s on xenon with a base pressure of \( 3 \times 10^{-7} \) torr. Chamber pressure is recorded using two hot-cathode ionization gauges. A complete neutral pressure map of the LVTF has shown that the wall mounted gauge is an accurate measure of the near-thruster chamber pressure and is reported as the tank pressure in this facility.

The corrected facility pressure \( P_c \) for xenon is calculated using the known base pressure on air \( (P_b) \), the indicated pressure \( (P_i) \), and a correction factor of 2.87 for xenon according to

\[
P_c = \frac{P_i - P_b}{2.87} + P_b.
\]
A dedicated propellant feed system consisting of three Edwards mass flow controllers regulates the xenon flow rate to the thruster. The flow rates are periodically calibrated using a known control volume. A $2 \times 2.5$ m$^2$ louvered graphite panel beam dump is positioned approximately 4 m downstream of the FMT2 to reduce back sputtering. The thruster is operated at PEPL using a modified station keeping ion telemetry package (SKIT-PAC) provided by NASA GRC.

III. DESCRIPTION OF THE ELECTROSTATIC PROBE DIAGNOSTIC

A. Probe type

Langmuir probes are one of the oldest and widely used probes in plasma characterization. The ease at which data are taken, by biasing the probe with respect to another electrode (vacuum chamber, cathode common, anode, etc.) and by measuring the current to the probe, is offset by the difficulty in interpreting the resulting current-voltage ($I$-$V$) characteristic curve. Careful selection of the analysis method, which depends on the probe operating regime, can reduce the error in the plasma parameters measured. Langmuir probes can be arranged in single, double, triple, and even quadruple electrode configurations. Unlike the traditional single Langmuir probe, the double probe floats as a whole, minimizing the perturbation to the plasma. Furthermore, the $I$-$V$ characteristic curve for a double probe has a well known hyperbolic tangent shape facilitating data analysis.21,22 The symmetric geometry of the double probe about the discharge cathode orifice makes it the more appealing choice over triple and quadruple probes where spatial resolution in the axial and radial directions would suffer due to probe operating restrictions, i.e., independent electrode sheaths. Because of the discharge chamber symmetry and the simplicity in data analysis, a symmetric double probe is preferable compared to an asymmetric double probe.

The symmetric double probe does encounter some limitations compared to the other Langmuir probe configurations: decreased spatial resolution compared to single Langmuir probes, the lack of distinction between primary and Maxwellian electron populations, lack of plasma potential information, and the sampling of only fast electrons. The latter is a result from the fact that in a double Langmuir probe, the current from one electrode must equal the current to the other since the double probe floats as a whole. Thus, the current to one electrode is limited in magnitude to the ion saturation current from the other.23,24

B. Double probe hardware

While probes always perturb their surroundings, the extent of this perturbation can be minimized by making the probe as small as possible, thereby minimizing the current collection while maintaining a measurable current. Minimizing probe size also leads to improved spatial resolution. The electrodes of the symmetric double probe for this investigation are sized for expected electron temperatures $2-11$ eV (Refs. 25 and 26) and number densities $(10^{10} - 10^{12}$ cm$^{-3}$),25,27 such that the probe operates in the
thin-sheath regime near the DCA. The sheath thickness, a multiple of the Debye length, will grow significantly as the plasma number density decreases away from the DCA plume. The relationship of the Debye length ($\lambda_D$ in cm) to the electron number density ($n_e$ in cm$^{-3}$) and temperature ($T_{eV}$ in eV) is given by:

$$\lambda_D = \frac{743 \sqrt{T_{eV}}}{n_e}.$$  \hspace{1cm} (2)

The discharge plasma number density is expected to have a maximum on cathode centerline at the DCA exit plane and to decrease by over two orders of magnitude with increasing radius, therefore increasing the Debye length and hence the plasma sheath thickness. The result is a decrease in accuracy of the double probe measurement in areas of low number density.

In the thin-sheath regime, the flux of particles entering the sheath can be calculated without considering the details about the trajectories of these particles in the sheath. In this case, the collection area of the electrode is approximated as the surface area of the electrode, which is justified for a large ratio of probe radius to Debye length $\lambda_D$. However, the rapid growth in the Debye length with increasing radial distance from cathode centerline dictates that at some radial location inside the anode, the thin-sheath criterion may no longer strictly apply. As a result, our thin-sheath calculation is modified to account for the expansion of the sheath. The growth of the sheath is taken into account by an iterative solution that will be discussed in Sec. V. Typically, the traditional thin-sheath analysis is justified while the electrode radius is greater than several Debye lengths. However, the adjusted thin-sheath analysis will be used in the transition regime from thin-sheath to orbit-motion limited (OML) analysis. The OML analysis is applicable for Debye length greater than or equal to ten times the probe radius and will be discussed later in Sec. V.

Electrodes with a large length-to-diameter ratio are utilized to minimize end effects. A conservative gap distance (3 mm)—the distance between the probe electrodes—maintains a minimum factor of three times the sum of the two electrode sheaths (i.e., $3 \times 2 \times 5\lambda_D$) to avoid sheath overlapping at all spatial locations. For an electron temperature of 3 eV, electrode sheaths would overlap for number densities less than $2 \times 10^9$ cm$^{-3}$, over an order of magnitude less than the minimum number density at any location in this investigation. The probes used in this investigation are based on the basic double probe design shown in Fig. 6. Two 0.381-mm-diameter cylindrical tungsten electrodes, with 4 mm exposed length, are held inside two double bore pieces of 99.8% pure alumina epoxied to one larger double bore piece of 99.8% pure alumina. The total length of the tungsten and alumina is approximately 46 cm (18 in.). The “double tier” design reduces the cross section of the probe that is inserted in front of the DCA, which decreases the discharge perturbation.

C. Double probe electronics

The floating potential of the probe rapidly increases during probe insertion, reaching 1100 V with respect to ground, causing difficulty for most electronics. Significant errors in the measured current can occur due to any appreciable stray capacitance in the circuit. As such, careful attention is paid to minimizing stray capacitance in the circuit design including the use of batteries to supply the bias voltage. The battery supply consists of two series groups of four 67.5 V zinc manganese dioxide batteries connected in parallel. The batteries are capable of outputting 135 V at 100 mA. A potentiometer is attached to the battery output to adjust one electrode bias voltage with respect to the other electrode.

The double probe circuit is built around two Analog Devices AD210 isolation amplifiers. These amplifiers provide complete isolation through transformer coupling and are capable of handling up to 2500 V of common mode voltage and provide an input impedance of $1 \times 10^{12}$ Ω. The low impedance output (1 Ω maximum) is connected to a digital oscilloscope that saves the data. Figure 7 illustrates the double probe circuit. High-voltage (up to 5 kV) SHV cables and feedthroughs are used to connect the double probe electrodes to the battery pack outside the vacuum chamber. The outputs of the isolation amplifiers are calibrated with known currents and bias voltages over their entire operating ranges.

IV. DATA ACQUISITION

A. Axial movement

The FMT2 is mounted on a two-axis positioning system consisting of two translational stages. The upper axis main-
TABLE I. Experiment nominal thruster operating condition (TOC levels) and reference NASA throttling level (TH levels) operating parameters: beam power supply voltage ($V_{\text{p,pp}}$), beam current ($J_b$), accelerator voltage ($V_a$), discharge voltage ($V_{\text{dc}}$), discharge current ($J_{\text{dc}}$), neutralizer keeper voltage ($V_{\text{nk}}$), neutralizer keeper current ($J_{\text{nk}}$), main plenum flow rate, discharge cathode (DC) flow rate, neutralizer cathode (NC) flow rate, and discharge cathode keeper voltage referenced to cathode common ($V_{\text{ch-cc}}$).

<table>
<thead>
<tr>
<th>Level</th>
<th>$V_{\text{p,pp}}$ (V)</th>
<th>$J_b$ (A)</th>
<th>$V_a$ (V)</th>
<th>$J_a$ (mA)</th>
<th>$V_{\text{dc}}$ (V)</th>
<th>$J_{\text{dc}}$ (A)</th>
<th>$V_{\text{nk}}$ (V)</th>
<th>$J_{\text{nk}}$ (A)</th>
<th>Main flow (SCCM)</th>
<th>DC flow (SCCM)</th>
<th>NC flow (SCCM)</th>
<th>$V_{\text{ch-cc}}$ (V)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TOC 4a</td>
<td>1100</td>
<td>0.71</td>
<td>−150</td>
<td>2.72</td>
<td>25.65</td>
<td>6.05</td>
<td>19.93</td>
<td>2.0</td>
<td>8.9</td>
<td>4.94</td>
<td>3.47</td>
<td>7.00</td>
</tr>
<tr>
<td>TOC 4b</td>
<td>1103</td>
<td>0.71</td>
<td>−150</td>
<td>2.68</td>
<td>25.60</td>
<td>6.05</td>
<td>17.68</td>
<td>2.0</td>
<td>8.6</td>
<td>5.43</td>
<td>3.47</td>
<td>6.84</td>
</tr>
<tr>
<td>TOC 8</td>
<td>1101</td>
<td>1.10</td>
<td>−180</td>
<td>4.84</td>
<td>25.10</td>
<td>8.24</td>
<td>17.40</td>
<td>2.0</td>
<td>15.3</td>
<td>4.02</td>
<td>3.68</td>
<td>6.49</td>
</tr>
<tr>
<td>TOC 15</td>
<td>1100</td>
<td>1.76</td>
<td>−180</td>
<td>8.30</td>
<td>25.14</td>
<td>13.2</td>
<td>…</td>
<td>…</td>
<td>25.1</td>
<td>2.96</td>
<td>3.60</td>
<td>5.53</td>
</tr>
<tr>
<td>TH 4</td>
<td>1100</td>
<td>0.71</td>
<td>−150</td>
<td>1.93</td>
<td>25.61</td>
<td>6.05</td>
<td>16.26</td>
<td>2.0</td>
<td>8.30</td>
<td>2.47</td>
<td>2.40</td>
<td>…</td>
</tr>
<tr>
<td>TH 8</td>
<td>1100</td>
<td>1.10</td>
<td>−180</td>
<td>3.14</td>
<td>25.10</td>
<td>8.24</td>
<td>15.32</td>
<td>1.5</td>
<td>14.4</td>
<td>2.47</td>
<td>2.40</td>
<td>…</td>
</tr>
<tr>
<td>TH 15</td>
<td>1100</td>
<td>1.76</td>
<td>−180</td>
<td>5.99</td>
<td>25.14</td>
<td>13.2</td>
<td>14.02</td>
<td>1.5</td>
<td>23.4</td>
<td>3.70</td>
<td>3.60</td>
<td>…</td>
</tr>
</tbody>
</table>

It contains a constant radial distance between the thruster and the HARP. The lower axis controls the thruster axial location with respect to the probe to an absolute position accuracy of 0.15 mm. The electrostatic probe is positioned radially inside the discharge chamber using the HARP, which is fixed to the chamber wall. When actuated, the probe extends to the thruster centerline then returns to the starting location recessed inside the translating alumina tube. The HARP also triggers the oscilloscope to collect and save data. A third smaller translation stage retracts and extends the guiding alumina tube as the axial location changes.

**B. FMT2 operation**

The primary thruster operating parameters for this investigation of near-DCA plasma phenomena are the discharge current and voltage. Therefore, for a given discharge current, the FMT2 main and discharge cathode flow rates are adjusted until both the discharge voltage and beam current match those recorded in the NASA throttling table. The data taken with beam extraction in this investigation are termed thruster operating conditions (TOC levels) instead of NSTAR throttling levels (TH) because the thruster operating parameters considered secondary for this investigation (e.g., flow rates and accelerator current) are not matched. Table I reports the complete listing of the discharge parameters and thruster telemetry for the operating conditions investigated. The thruster was operated for at least half an hour prior to data collection in order to reach steady operation at each operating condition. Typical data collection time was 1 h for each operating condition.

Bias voltages are set manually using a potentiometer and the battery supply. The probe is then swept through all spatial locations at each fixed bias voltage. A LABVIEW code steps through the full axial range of motion (approximately 4 cm) in 1.6 mm increments. For each axial step, the program retracts the alumina translating tube radially and triggers the HARP to sweep the probe radially through the discharge plasma. After all axial locations are interrogated, the FMT2 returns to the zero axial position located 2 mm downstream of the DCA exit plane. The bias voltage is then manually changed and the process repeats until the 31 bias voltages are investigated. A schematic of the two-dimensional data collection domain is shown in Fig. 8.

An oscilloscope records the probe position, the probe current, probe bias voltage, and the discharge current (from a Hall sensor) as a function of time during probe insertion. From the raw data, the probe currents for a given bias voltage are known as a function of probe position. The resulting data are reassembled to obtain the current-voltage characteristic ($I-V$ curve) of the double probe at each spatial location in the radial sweep. Only data taken on the “in sweep” of the probe are analyzed as “out sweep” data are more likely to be affected by probe perturbation.

**V. DATA ANALYSIS**

The current-voltage curves from the double Langmuir probe are analyzed according to the most appropriate operating regime utilizing the scientific graphing package IGOR. The individual double probe characteristics are analyzed assuming an infinite, quasineutral, and quiescent plasma. The mean free path for electron-neutral collisions (tens of centimeters) in the discharge chamber is much larger than the probe dimensions (millimeters), which justifies the collisionless analysis. Particles are assumed to be collected without reflection or reaction inside the electrode collection area.

The presence of a magnetic field has a negligible effect on the double probe measurements. For the interrogation region of this investigation, the Larmor radius for electrons is approximately a few millimeters downstream of the DCA face and extends downstream with small incremental steps resulting in an axial resolution of a few millimeters.
smallest near the discharge cathode where the magnetic field is the largest. In the bulk discharge plasma, the electron Larmor radius is on the order of a few millimeters, an order of magnitude larger than the probe electrode radius. Near the DCA, the magnetic field strength is on the order of 100 G, giving a Larmor radius that is only twice as large as the electrode radius. The double probe analysis infers the number density from the ion saturation current and therefore is unaffected by the reduction in electron saturation current caused by the presence of a magnetic field.\textsuperscript{23,24,28–30} The magnetic field can also cause electron energy distribution function (EEDF) anisotropy. Passoth \textit{et al.} determined that EEDF anisotropy depends on the ratio \( B/p_0 \), where \( p_0 \) is the ambient pressure (in this case the discharge chamber pressure).\textsuperscript{34} It has been shown experimentally that EEDF anisotropy is negligible for \( B/p_0 \leq 2.5 \times 10^5 \) G/torr.\textsuperscript{35} In the FMT2, the magnetic field has a maximum (downstream of the DCA) on the order of 100 G and the pressure in the discharge chamber is estimated to be \( \sim 10^{-4} \) torr. Since the maximum \( B/p_0 \) ratio for any interrogated domain in this investigation is of order \( 10^6 \), no substantial anisotropy in the EEDF is expected.

Post-test inspection of the raw data revealed asymmetric \( I-V \) curves. The asymmetry is most extreme closest to the DCA, decreasing with increasing axial distance from the DCA. The asymmetry is larger than can be accounted for by the error in electrode lengths during fabrication. The most probable cause is an electrode-to-orifice misalignment during evacuation of the vacuum facility. The HARP, and thus the electrostatic probe, is mounted to the wall of the chamber, while the thruster rests on a platform inside the vacuum facility. During pumpdown, the walls of the chamber compress, resulting in a shift of the probe tip. A vertical shift of 1 mm would result in one electrode lying directly in front of the discharge cathode plume. The disappearance of the asymmetry far from the plume supports the misalignment theory. Mounting both the thruster and the HARP on a common structure, independent of the chamber wall, would eliminate this problem.

The unexpected asymmetric characteristics also bring to light another more important limitation of the double probe measurement for this specific application. To eliminate electrode sheath interaction and satisfy the plasma isolation constraint requires the electrodes to be placed millimeters apart. The required spacing of the electrodes and magnetic confinement of the electrons from the hollow cathode to a narrow plume results in an inadequate characterization of the extreme near-cathode plume. A single Langmuir probe is more appropriate to characterize the extreme near-DCA plasma. However, the double probe results are accurate over a majority of the spatial domain and can be used to confirm single probe measurements. To account for the misalignment shift, the electrode collected current and bias voltage data corresponding to the larger collected current, i.e., the electrode more in the discharge cathode plume, are mirrored and the resulting \( I-V \) curve is used.

The data are initially analyzed assuming a thin sheath. The initial calculated number density and electron temperature from the measurement allow an iterative solution for the sheath size and final number density. Based on the ratio of the Debye length (based on the final parameters) to probe electrode radius, either the modified thin-sheath result is used or an OML calculation is performed.

A. Thin sheath data analysis

Each \( I-V \) characteristic is fitted with the theoretical hyperbolic tangent curve for a symmetric cylindrical double probe, Eq. (3), incorporating the Levenberg-Marquardt fit method,\textsuperscript{21,22,28,36}

\[
I = I_{sat} \tanh \left( \frac{\phi}{2 \times T_e^{1/2}} \right) + A_1 \phi + A_2.
\]  

In Eq. (3), \( I_{sat} \) is the ion saturation current, \( \phi \) is the probe bias voltage, the parameter \( A_1 \) accounts for sheath expansion in the ion saturation region, and \( A_2 \) accounts for any offset current due to stray capacitance. Figure 9 illustrates representative \( I-V \) traces and their corresponding curve fits. Electron temperature can be determined immediately from the fit parameters. Using the Bohm approximation for ion velocity,\textsuperscript{17,23,28} the ion number density is calculated according to

\[
n_i = \frac{I_{sat}}{0.61A_1e} \sqrt{\frac{M_{Xe}}{kT_e^{1/2}}},
\]  

In Eq. (4), \( e \) is the electron charge, \( M_{Xe} \) is the mass of the xenon ion, \( k \) is Boltzmann’s constant, and \( A_1 \) is the electrode collection area, which is initially set to the physical electrode surface area. The true collection area depends on the thickness of the sheath surrounding the probe. Knowledge of the number density and electron temperature allows the Debye length to be calculated according to Eq. (2). Assuming quasineutrality \( n_e = n_i \) (in cm\(^{-3}\)) readily gives \( \lambda_D \) (cm). The sheath thickness \( \delta \) is then calculated using the mass of an electron (\( m \)), the mass of the xenon ion (\( M_{Xe} \)), and the Debye length (\( \lambda_D \)) according to\textsuperscript{30,31}
\[ \delta = 1.02 \lambda_p \left( \frac{1}{2} \ln \left( \frac{m}{M_{Xe}} \right) \right)^{1/2} \left[ \frac{1}{2} \ln \left( \frac{m}{M_{Xe}} \right) - \frac{1}{\sqrt{2}} \right]^{1/2} \]

and the sheath area \((A_s)\) follows in Eq. (6), where \(R_p\) is the probe electrode radius and \(A_p\) is the exposed probe electrode surface area. \(^{24}\)

\[ A_s = A_p \left( 1 + \frac{\delta}{R_p} \right). \]  

The above equation ignores the circular area of the end of the electrodes, which is negligible due to the large length-to-diameter ratio of the electrodes. New plasma parameters are calculated from this new collection area and the process is iterated until convergence. This iterative process attempts to take into account the departure from the thin-sheath regime and is used in all calculations in which an OML analysis is not warranted. The iterative calculation is most useful when the probe is operating in the transitional regime. For a ratio of probe radius to Debye length of less than or equal to 3, the converged thin-sheath iterative result is used.

**B. OML data analysis**

For a ratio of probe electrode radius to Debye length of greater than or equal to 10, the thin-sheath calculation of electron temperature is still appropriate; however, the number density is calculated from the slope of the ion current \((I_i)\) squared versus probe bias voltage \((V_p)\) according to the following equation: \(^{34,37,38}\)

\[ n_{OML} = \sqrt{\frac{-\Delta (I_i^2)/\Delta V_p}{0.2e^3A_p^2 M_{Xe}}} \]  

**C. Transition analysis**

When the final iterated Debye length calculation reveals \(10 > (R_p/\lambda_{Dp}) > 3\), the probe is not operating in either thin-sheath or OML regimes. In this case, a weighted average, based on the range of probe electrode radius to Debye length, is used to blend the two regimes.

**VI. RESULTS AND DISCUSSION**

**A. Number density contours**

The number density measurements are illustrated in Fig. 10. Due to export control restrictions, all spatial dimensions have been nondimensionalized by the discharge cathode keeper outer diameter. There is little variation between the number density contours over the range of operating conditions investigated. The structure of the number density contours is intuitive. There is an on-axis maximum near the DCA (in its plume) that decreases gradually in the downstream (axial) direction. A more extreme density gradient exists in the radial direction as the discharge chamber magnetic field confines electrons and resulting ions created to a narrow plume particularly at axial locations near the DCA.

The number density falls off by more than an order of magnitude from the cathode centerline to the cathode keeper outer radius.

As the discharge current and flow rates are increased, the magnitude of the number density plume increases slightly. All number densities measured in the 2D domain fall within the range of \(1 \times 10^{10} \text{–} 8 \times 10^{12} \text{ cm}^{-3}\). Foster and Patterson have measured the number densities of a high-current 12.7-mm-diameter hollow cathode inside a NSTAR-type discharge chamber, i.e., without beam extraction. Their experiment, though unable to capture the effects of the beam coupling to the discharge plasma, accurately captures the discharge chamber geometry and magnetic field topology of a gridded ring-cusp ion thruster. Radial measurements taken 3 mm downstream of the keeper plate report a maximum number density of approximately \(2 \times 10^{12} \text{ cm}^{-3}\) on axis with steep radial gradients, similar to the present data. Their
results also indicate an increase in number density with increasing discharge current, which is also consistent with results of this investigation.

B. Electron temperature contours

Figure 11 illustrates the measured electron temperatures for the various thruster operating conditions. Each contour contains an off-axis maximum region that was unexpected. Electron temperatures range from 2 to 5 eV over most of the spatial locations and operating conditions investigated. The off-axis maximum is located at the boundary between the discharge cathode plume and the bulk discharge plasma as confirmed by plasma potential measurements inside the FMT2 thruster. The increased electron temperature on this boundary in ion thrusters is due to the electron acceleration across the radial potential gradient structure producing electron energy distribution functions that become stretched toward higher energies and in some cases become double peaked. The measured electron energy distribution functions indicate that in this transition region between the cathode plume and discharge plasma, the assumption of Maxwellian electrons is no longer valid and therefore describing the electron energy by an electron temperature is not appropriate. It does, however, add qualitatively to the discussion of the ion thruster internal discharge plasma. Figure 11 also illustrates that the magnitude of the maximum off-axis electron temperature region increases as the thruster is throttled up to higher power levels. This observed increase, combined with comparison of electron temperature measurements in the FMT2 thruster without beam extraction, illustrates the changes in the ion thruster internal plasma with beam extraction. These effects may be partially due to the decreased neutral density in the discharge chamber that alters the electron energy distribution function when a beam is extracted.

Noise in electron temperature contours is evident. As previously stated, the double probe electron temperature calculation is proportional to the ion saturation current divided by the slope of the $I-V$ characteristic evaluated at zero. As a result, errors in calculating both the ion saturation current and slope at the zero location lead to large variations in electron temperature measurements. In single Langmuir probe measurements, the electron temperature calculation is solely determined by the slope of the $I-V$ curve in the electron-retarding region and therefore may yield smoother contours.

VII. ERROR ANALYSIS

Typical estimates for the error in electron temperature and electron number density Langmuir probe measurements are 20% and 50%, respectively. While these traditional error estimates are large, they are absolute uncertainties. Large combinations of effects are lumped into these percentages: the uncertainty of electrode collection area, applicability of probe theory, noise in the collected signal, circuit calibration errors, and additional measurement errors to name a few. The error between measurements made using identical setups will greatly reduce the contribution of systematic errors with regard to relative comparisons of the data obtained. The applicable regions of thin-sheath, transition, and OML theories are displayed in Fig. 12.

Another source of measurement error is the discharge perturbation due to the presence of the probe in the plasma environment being interrogated. The discharge voltage increase (not shown) less than 0.5 V, ~2% of the nominal
discharge voltage, when the probe is inserted into the discharge plasma. The largest perturbations occur only during probe sweeps within a few millimeters of the DCA, for large magnitude bias voltages where the probe is in ion saturation, and only when the probe is directly in front of the cathode plume. Figure 13 shows that the discharge current perturbation and bias voltage drop during probe insertion. For the most extreme conditions, the discharge current perturbation is typically 5%–10% of the nominal discharge current, which is considered to be minor. Outside of this very extreme near-DCA region, i.e., over a vast majority of the interrogation region, the discharge current perturbation due to probe insertion is negligible. In the extreme near-DCA region, the perturbation is still minor but not negligible. The error introduced would cause a minor reduction in the measured electron number density but is considered well within the 50% error bars on this value.

VIII. CONCLUSIONS

An internal ion thruster discharge diagnostic technique has been demonstrated. Double Langmuir probe electron temperature and number density measurements inside the discharge chamber of a 30 cm ring-cusp ion thruster are presented for multiple operating conditions with beam extraction. Electron temperature magnitudes, 2–5 eV, are comparable to those measured by other researchers in electron bombardment discharge plasmas. Number density contours, with a maximum of approximately $8 \times 10^{12}$ cm$^{-3}$ on the centerline, show very little variation over the range of operating conditions investigated. The perturbation of the discharge current, 5%–10%, by the probe was minimized though remains non-negligible. Number density magnitudes agree with data taken by other researchers in simulated ion thruster discharge chamber environments. Double probe spatial resolution is found to be insufficient in the very-near DCA locations. Thus, single Langmuir probes may be more suitable close to the DCA.

ACKNOWLEDGMENTS

We would like to thank Michael Patterson of the NASA Glenn Research Center (GRC) for the financial support of this research through research Grant No. NAG3-2216 and for the use of government furnished equipment. We would like to acknowledge Dr. Matthew Domonkos, Dr. John Foster, and Dr. George Williams who have been principal technical contacts at NASA GRC. Additional support was provided by a Department of Defense NDSEG fellowship.