Performance and analysis of an electron cyclotron resonance plasma cathode

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A scalable electron cyclotron resonance (ECR) plasma source was investigated for plasma cathode applications. The rectangular source utilized permanent magnets to establish the ECR condition. The microwave applicator region was windowless, making the source applicable to sputtering environment applications. The source was characterized using primarily two diagnostics: (1) a near-field and far-field Langmuir probe and (2) a downstream electron extraction electrode. Source operation and plasma properties were characterized at low pressures ranging from 0.2 to 5 mTorr and power levels up to 250 W. Evidence of grad-B drift in the plane of the source was observed. Extracted currents agreed well with predictions. © 2007 American Vacuum Society. [DOI: 10.1116/1.2746041]

I. INTRODUCTION

High specific impulse electric propulsion systems are mission enabling for a wide range of missions to the outer planets. Compared to chemical systems, high specific impulse electric propulsion systems can minimize cost by significantly reducing launch mass. Trip times can be reduced as well. Missions to the outer planets will, however, require these systems to operate continuously for long periods of time. For example, the proposed Jupiter Icy Moon Orbiter Mission (JIMO) would require total thruster operation times approaching ten years.1,2 To date, the most mature, high specific impulse technology that can supply the necessary specific impulse requirement for this mission (7000–10 000 s) is the gridded ion thruster.2,3 The gridded ion thruster has demonstrated lifetimes up to 30 000 h in ground tests and over 16 000 h in space.4,7 While well in excess of that demonstrated by any chemical propulsion system, these life demonstrations are not long enough to satisfy thrusting time requirements for outer planet missions such as JIMO.1 In this regard, either the lifetime of the subsystems that fail in ion thrusters must be extended or alternative technologies capable of satisfying the lifetime requirements must be developed.

The primary ion thruster failure mechanisms can be loosely grouped into four general areas: (1) ion optics failure due to erosion, (2) discharge cathode failure due to impregnate depletion or erosion, (3) neutralizer failure due to insert depletion or erosion, and (4) electron backstreaming. Ion optics erosion and electron backstreaming can be accounted for through the use of carbon-based grids whose wear rates at relevant energies are significantly lower than metal grids. This leaves the problem of cathode lifetime at the frontier of thruster lifetime.

A number of conventional approaches have been proposed to extend the lifetime of the discharge cathode. These solutions range from the use of a larger cathode with a corresponding larger impregnate supply6 to discharges with multiple cathodes each operating in a serial manner to the reservoir cathode.7 Unlike conventional hollow cathodes, the reservoir cathode approach is compelling in that the impregnate supply and the electron-emitting insert are separate.6 In principle, cathode lifetime could be extended by merely increasing the size of the reservoir. While these cathode approaches can potentially extend cathode life, each is ultimately limited by impregnate loss or contamination of the insert. To mitigate this latter concern, stringent environmental protocols must be followed. Such protocols are potentially costly and inherently increase handling complexity.9 In an effort to circumvent the issues associated with conventional, hollow-cathode-based electron emitters, cathodes based on rf or microwave plasma production have been devised.10–12 Such devices are known as plasma cathodes.13 The electron current is literally extracted from the discharge plasma, which is produced electrodelessly. Because the plasma discharge is the source of electrons, high plasma densities are required to produce required extraction currents for reasonably sized devices. Electron cyclotron resonance (ECR) plasma and, more recently, helicon plasma approaches are currently being investigated for this application.14,15

The work discussed herein describes the performance of a microwave ECR plasma cathode. The plasma cathode concept utilized in this work is based on a previously designed ECR plasma source that operated with an overdense plasma.16 This overdense plasma production is particularly appealing in that the source density is not severely limited by the plasma frequency. High plasma densities produced by the source make it a suitable candidate for plasma cathode applications. Additionally, this plasma source is scalable. Indeed this was an attractive feature that drove the initial development of this plasma source.16 Analogously, by simply adding sources in parallel, it is possible to adapt to a particular electron current requirement for a given ion thruster sys-

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tem and power level. A simple microwave power divider could be used to equally distribute the power among sources. These desirable features motivated the present investigation. Because the microwave ECR plasma cathode operates without any antenna at all, the issue of antenna failure is also eliminated.

Reported herein is a discussion of the modification and characterization of this plasma source for electron production for electric propulsion applications. Section II provides a review of the plasma cathode and the underlying physics of an ECR plasma cathode. Section III provides overview of the experimental apparatus and the diagnostics utilized in this investigation. Section IV includes the discussion of experimental results; this section describes not only the performance of the device but also underlying physics issues such as the role of drifts on device performance.

II. PLASMA CATHODE THEORY AND EXPERIMENTAL APPROACH

In its simplest form, a plasma cathode is a plasma source from which electrons are extracted. In practice, the discharge plasma is created either by dc means such as electrons convecting through a gas or electrodelessly where rf power is coupled into a gas-filled cavity to produce a discharge plasma. Electrodeless embodiments, not being subjected to erosion processes present in dc devices, are desired for electric propulsion applications. To date, the plasma cathode embodiment that has seen the most significant electric propulsion application has been the microwave neutralizer. This device was successfully demonstrated on the Hayabusa asteroid mission. These devices have also been investigated for plasma processing applications. Independent of the application, in these devices the cathode featured a wire antenna located in a strong magnetic field so that overdense plasma production can take place. Because the antenna itself is immersed in the plasma, however, it is subject to bombarding flux from the plasma generated in its local vicinity, which leads to erosion and which ultimately limits total operating lifetime. In this regard, while insert issues have been circumvented, physical sputtering of the antenna is a potential life limiter for this configuration. The sputtering energy is not only a function of the local plasma density and electric field intensity at the antenna but also the electron extraction voltage. The bombarding ion flux is necessary for quasineutrality to be maintained within the cathode.

In plasma cathodes, the maximum electron flux that can be extracted is equal to the ion current collected at the walls and antenna of the device. In this regard, the ion collection surface area to electron loss area is important and must satisfy the relation

\[ \Gamma_e = \Gamma_i \frac{A_i}{A_e}, \]

where \( \Gamma_e \) is the ion or electron flux and \( A_e, A_i \) is the electron loss area and ion collection area, respectively. Higher electron currents are possible by increasing the ion collection surface area. For fixed geometries, the ion flux lost to the walls can be increased by increasing the electric field directed to the walls and antenna and by increasing the electron-ion particle production rate. It is the increase in the electric field that grows with extraction voltage that gives rise to increased erosion at the higher extraction currents. To support higher current demands the sheath potentials within the plasma cathode must be greater than the ionization potential of the gas so that the ionization cross section is sufficiently high to produce a high-density plasma within the device. Ionization cross sections are not appreciable (\( \sim 30\% \) of maximum) for gases of interest such as Xe and Kr until sheath voltages approach \( \sim 15-20 \text{ eV} \). This invariably forces the device to operate at potentials near the threshold sputter yield of common metals such as steel and molybdenum. In this regard, inherent in the plasma cathode operation will be some form of low-level erosion. By carefully choosing the cathode material, it is possible to minimize this issue.

Plasma cathode housings can be designed to high lifetimes well in excess of dc hollow cathodes because the insert depletion problem has been eliminated and sputter erosion present can be managed via judicious selection of materials for construction. This leaves only the antenna as the life limiter as discussed earlier. To concentrate the electric field, antennas typically have small diameters, making them the primary life limiter. Sputter coating of the interface between the antenna and insulator sleeving also a potential failure mechanism that can occur over extended operation.

The experimental apparatus utilized in this investigation is a modified version of a permanent magnet waveguide applicator developed previously as a plasma source. The apparatus is illustrated in Fig. 1. The scalable source featured rows of permanent magnets that satisfy the condition for ECR downstream for 2.45 GHz microwaves. This source
originally featured an alumina microwave window that was positioned between the waveguide and a grill containing the magnets. A high field microwave launch was guaranteed because the alumina window physically blocked the lower magnetic field region upstream of the grill. This earlier source was capable of overdense plasma production. To convert the microwave plasma applicator into a plasma cathode requires removing the alumina window. This was done to prevent sputter coating of the alumina window, which would eventually severely degrade applicator performance. Because the alumina window was an integral part of impedance matching the waveguide to the grill, the applicator had to be modified. This entailed modifying the magnetic circuit to prevent plasma from forming upstream and from choking downstream plasma production. Described herein is the effect of this modification on performance of the plasma applicator as an electron source. The applicability of this scalable source to beam neutralization for ion thrusters is also commented upon.

III. EXPERIMENTAL APPARATUS

The apparatus used in this investigation is shown in Fig. 1. The system consists of a modified version of the plasma source developed by Getty. This source was created originally for use in plasma processing and can generate a uniform high-density plasma over a large area in the chamber.

A. Microwave applicator

Microwave power at 2.45 GHz produced by a magnetron was used to produce the plasma. The microwaves travel to the plasma source via WR 284 waveguide. The microwave electric field interacts with the electrons in the magnetic field produced by a grill-like structure containing permanent magnets to produce plasma by ECR. The magnetic grill, which is located between the microwave horn and the vacuum chamber is shown in Fig. 2. The aluminum grill is rectangular in shape measuring 16.7 cm $\times$ 24.1 cm by 1.65 cm. Microwaves propagate in TE$_{10}$ mode in the horn and through the grill with a relatively low reflection because of the cross-polarized arrangement of the grill slots.

Five samarium cobalt bar magnets (measuring $1.4 \times 1.6 \times 4.5$ cm$^3$) placed in each grill rib establish the 875 G contour for ECR at 2.45 GHz. Figure 3 shows a photograph of an argon plasma taken from a window located on centerline, downstream of the plasma source. Plasma excitation is strongest on centerline suggesting that microwave intensity is highest there.

The original plasma source contained an alumina plate that served as both a vacuum seal and a microwave window. By symmetry, the grill contains an upstream ECR zone and a downstream ECR zone. The alumina plate physically displaced and therefore eliminated the possibility of the upstream ECR zone. Additionally, to minimize reflected power, boron nitride bars were placed within each grill slot. A magnetic contour map associated with the original source is shown in Fig. 4(a). In order to prevent microwave extinction due to the deposition of backsputtered metal onto the alumina window, the alumina and the boron nitride bars were removed. To recover the vacuum seal, a Lucite window was placed further upstream in the waveguide train between the E-plane bend and the input flange (smaller waveguide opening) of the horn. The removal of the insulator gives rise to the undesirable condition for plasma production via ECR to take place on both sides of the grill. Plasma production on the upstream side of the grill can reduce performance of the plasma source since the upstream plasma would effectively choke off microwave flow as the plasma density approached cutoff conditions. To circumvent this problem the magnetic circuit was modified by employing steel pole pieces at each rib of the grill. Figure 4(b) illustrates the effect this has on the upstream magnetic field profile. Clearly the magnetic contours have been modified. There are still two ECR zones (heavy black line) present but all are displaced downstream, thereby minimizing choking effects. It is possible that high-density plasma formation in the ECR zone located in the channels can potentially choke off excitation to the most downstream ECR contour. Because of the relative proximity between these two ECR zones ($<1$ wavelength), it may be expected that tunneling associated with the evanescent wave could still drive ionization at the most downstream ECR zone. This modification may considerably reduce the microwave energy lost to create the upstream plasma, even though there is a trade-off of increased reflection because the pole pieces protrude into the slot somewhat.
B. Microwave power supply

The microwave system consisted of a 1 kW (Astex) magnetron source operating at 2.45 GHz. Forward and reflected powers were monitored using two directional couplers and two power meters. A three-port circulator was used to manage the reflected power. Matching was achieved using a three-stub tuner. These components are shown in Fig. 1. The discharge is self-starting, typically initiating when the input microwave power is raised to \(100 \text{ W}\).

C. Vacuum chamber

The 29 cm diameter by 31 cm long bell jar used in this investigation was evacuated using a turbo-molecular pump backed by a mechanical roughing pump. The pressure could be regulated at fixed flow using an electronically controlled throttle valve. Argon or xenon gas was introduced into the chamber through a mass flow controller. The gas enters the chamber via a multiaperture plenum ring located on the top flange of the bell jar. Argon was used in most of the experiments, and its flow rate was typically set to 5.6 SCCM (SCCM denotes cubic centimeter per minute at STP), which corresponds to a chamber pressure of 1 mTorr. Gas flow rate was set at 5.6 SCCM to be comparable with flow rate requirements of hollow-cathode-based neutralizers with target beam currents of approximately 3.5 A. With the turbo pump running at the maximum speed and the throttle valve fully open, the chamber pressure attains a base pressure of \(1 \times 10^{-6} \text{ Torr}\). Pressure was monitored using an ionization gauge.

D. Plasma diagnostics

Two plasma diagnostics were used in this investigation. A double Langmuir probe was used to estimate the electron density and the electron temperature of the plasma downstream of the grid. A biased graphite plate located downstream of the grid was used to collect the electron saturation current. This plate served as the extractor and allowed for the assessment of the maximum extractable electron current density.

1. Double Langmuir probe

Figure 5(a) shows the diagram of the electrical circuit used in the double Langmuir probe measurements. The bias voltage between the two probe electrodes was varied between \(-30\) to \(+30\) V at roughly 0.5 V increments to acquire the double probe current-voltage characteristic. Inline rf chokes were used on each leg to filter 2.45 GHz high-frequency noise.

Two different tungsten wire double Langmuir probes were constructed as depicted in Figs. 5(b) and 5(c). The probe tip of the first probe was 0.036 cm in diameter with an exposed electrode tip length of 1.08 cm. The probe tip center-to-center spacing was 0.3 cm. Both probe tips were oriented...
parallel to the z axis and were housed in a two-bore ceramic tube. This transverse orientation reduces the effect of the magnetic field on Langmuir probe measurements. The probe was located approximately 1 cm downstream of the grill. The second probe was also constructed of tungsten wires inserted into ceramic tubing, but with a 0.013 cm diameter and 0.5 cm tip length. The probe tips were separated by 0.4 cm and were located approximately 25 cm axially from the magnet surface of the grill. These probes were also oriented perpendicular to the magnetic field.

2. Electron flux diagnostics

The primary objective of these experiments was to determine the magnitude of extractable electron current from the plasma source. To this end, a graphite electrode was positioned downstream of the grill as depicted in Fig. 4(b). This electrode was biased positively relative to tank ground to collect electron saturation current. Ideally, the electrode would be sufficiently large such that it collects all the current that diffuses from the source. The finite size of the bell jar precludes such an arrangement. Additionally, because geometry of stray magnetic fields emanating from the plasma source can also impact the current collected at the electrodes, the current collected by a downstream electrode will depend not only on size but also on axial location. To investigate these effects, two electrodes were used as collectors. The collection surface areas of the two electrodes were 7.3 \times 10.7 and 15 \times 20 cm². Note that the plasma source grill cross sectional dimensions are 16.7 \times 24.1 cm². Insulating sheets (Mylar®) were utilized in conjunction with the collector electrodes to determine the relative degree of magnetization of the electrons transported to the collector.

IV. EXPERIMENTAL RESULTS AND DISCUSSION

The original embodiment of the plasma source described herein was capable of overdense plasma production with densities nearly ten-times that which would be expected at a cutoff of 2.45 GHz. Because one requirement for plasma cathode is high-density plasma production, the use of this plasma source as a plasma cathode follows naturally. Whether the source is capable of operating in this capacity without the alumina window is a key question that is addressed in this work. No evidence of overdense plasma production in the modified version was observed over the power range investigated. In the sections that follow, measurements documenting the operation of the plasma source in the capacity of a plasma cathode are reported. Plasma cathode behavior as a function of microwave power, bias voltage, and pressure was characterized. The results are interpreted from a diffusion-limited standpoint where, in this case, reduced transverse diffusion is due to the magnetic field that establishes the ECR zone.

A. Plasma properties at the source

As was mentioned earlier, plasma properties near and downstream of the source were characterized using a double probe. The near-source double probe was located on centerline, 1 cm downstream of the grill. The magnetic field at this location was 100 G. In this case the Larmor radius (R_L) is order of a few millimeters thereby satisfying the condition that R_{probe} < R_L. Figures 6(a) and 6(b) illustrate the variations in plasma density and electron temperature as a function of pressure at 200 W. The measured electron density increased with increasing background pressure as expected. At the 1 cm location, the magnitude of the plasma density was below the cutoff plasma density of 7.4 \times 10^{10} cm⁻³. The maximum density recorded at this power level was approximately 5 \times 10^{10} cm⁻³ at 1 mTorr. This density was consistent with data measured with the source in its original configuration. Electron temperature measurements were also acquired. The electron temperature decreased with increasing pressure as expected. The measured electron temperature magnitude, however, was considerably higher than that measured in the previous investigation which did not exceed 3 eV. The elevated measured temperature may be in part due to the diagnostic approach, the double probe, which samples the tail of the distribution function and therefore predicts higher electron temperatures. Another reason for the higher than expected measured electron temperature is associated with the low operating pressure. In this work, the operating pressure was half of that investigated previously. The reduced collision frequency gives rise to a higher average electron energy since the power dissipation rate is reduced with reduced background neutral density. For argon, the energy excitation cross section peaks at high electron energies (\sim 10 eV), thereby allowing a hot electron population below \sim 10 eV to exist. The higher temperatures measured at these pressures are consistent with those measured in ECR discharges at similar pressure.

It is possible to determine the maximum extractable electron current based on the plasma measurements discussed above. If it is assumed that most of the plasma is produced at the source and that ion collection at the walls is second order to the ion collection that occurs at the grid itself, then the magnitude of extractable electron current can be estimated. This assumption is justified because the plasma is highly magnetized at the source. Diffusion along the strong magnetic field lines leads to collection at the source grid structure. Transverse diffusion is expected to be dominant means for transport to downstream axial locations. A second assumption is that the plasma density is fairly uniform over the cross section of the device. To first order, in the near field, this assumption can be taken to be valid. Table I lists the relevant experimental parameters and subsequent calculations at different pressures.

As can be seen in the table, the plasma at the source is capable of supplying a large electron current. This is due to the thermal motions of the electrons at saturation. Extraction of such currents, however, is only realizable if an equal current of ions were to be collected at the source. As can be seen here, if the dominant collection source for the ions is the source surface area, then total ion current will be of order 200 times lower than the electron current. Because the maxi-
mum electron current that can be extracted from a plasma cathode is equal to the ion current collected at cathode potential surfaces, then in this geometry, the extracted ion current will also be 200 times lower than what is possible, if sufficient surface area were to be available. It is this dilemma that requires plasma cathode designers to operate at high plasma densities to offset this surface area and size restrictions. The source as indicated in these density data does not operate in the overdense mode at least at these operating conditions. This leads to approximately a factor of 10 reduction in the possible collected ion current. In the present case, if ion collection is predominantly at the grill, then at the 200 W condition, at 1 mTorr, nearly 1 A should be extractable. In practice, there is some collection at the walls, so that in ground-based test facilities, the extracted current will be higher due not only to ion diffusion to the chamber walls but also due to electron ionization of the background gas. These currents of course would not be present in a space device.

Plasma density and temperature measurements were also acquired further downstream as a function of pressure. These data are depicted in Figs. 7(a) and 7(b). At 25 cm downstream, the plasma density was an order of magnitude lower than at the source but increased monotonically with pressure. To first order, within the uncertainty of the measurement, the plasma density does not increase appreciably with input power at a given flow rate at the downstream location. These data suggest that the source plasma density has saturated at these power levels at the specified pressure. The calculated electron temperature was two to three times lower than that which was measured at the source. The reduced electron temperature is expected. At such distances from the source, the electrons can only leave the magnetized regions of the source via collisions. The population 25 cm downstream is therefore due to collisional diffusion and secondary electrons produced by electron-neutral impact in the gas. There was no clear trend in the magnitude of the electron temperature at a given pressure as a function of power level. This is consistent with the expectation that far from the source, average electron energy should be independent of power level par-

<table>
<thead>
<tr>
<th>Pressure (mTorr)</th>
<th>Plasma density (#/cm³)</th>
<th>Electron temperature (eV)</th>
<th>Calculated electron current (A)</th>
<th>Ion saturation current (A)</th>
</tr>
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<td>56</td>
<td>0.32</td>
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<tr>
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<td>114</td>
<td>0.65</td>
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<tr>
<td>1.20</td>
<td>$5.00 \times 10^{10}$</td>
<td>7</td>
<td>142</td>
<td>0.80</td>
</tr>
</tbody>
</table>

FIG. 6. Electron density (a) and electron temperature (b) variations with pressure.
ticularly if the source is operating saturated (power coupled into the plasma load is maximized, and additional power is not absorbed by the plasma).

The ion current collected at the end wall (bottom) of the bell jar can be calculated from these data. Over the 0.45–1.2 mTorr range, current to this surface is estimated to be of order a few milliamperes, consistent with the assumption that wall current collection is second order.

B. dc current extraction

An electron current-collecting electrode was placed axially downstream of the plasma source. By biasing the collector electrode to electron saturation, the maximum extractable electron current density can be estimated. For space applications, it is desired that the electron transport be due to either field-free diffusion or cross-field diffusion. Both mechanisms assure that the electrons that enter the ion beam for neutralization have detached from the magnetic field. To verify whether or not the electrons measured at the collector are detached from field lines, a Mylar sleeve was inserted into the chamber, as shown in Fig. 8. As can be seen in the figure, the Mylar shield prevents electrons from traveling along field lines to the collector. Plasma formed in regions between the sleeve and wall at axial locations below the sleeve is also prevented from being collected at the electrode. Figure 9 depicts the collected current as a function of extraction voltage with and without the Mylar sleeve. In both cases, at voltages below \( \sim 20 \) V, the current increases rapidly with voltage. Beyond 20 V, the current saturates. The saturation occurs because of limited ion collection surface area at the
source itself. There is little difference between the measured electron current with or without the Mylar sleeve, suggesting that transverse diffusion is the predominant mechanism for electron transport to the collector. The small reduction in collected current with the sleeve is likely attributed to the collimating effect of the Mylar sleeve. The sleeve effectively reduces the total view factor of the collector, leading to electron saturation at lower values.

In addition to the Mylar test, downstream electron current as measured with electrodes of differing cross sectional areas was compared. Figure 10 depicts the difference in current collected by a $7.3 \times 10.7\ cm^2$ electrode versus $15 \times 20\ cm^2$ electrode. The larger electrode has 3.8 times the area of the smaller one. In Fig. 10, as can be seen, at a distance of 9.5 cm downstream of the source, the profiles are nearly identical, indicating that the majority of the current is effectively captured in the cross section of the smaller electrode. In this case, the larger electrode collects only $\approx 20\%$ more than the smaller electrode, which is inconsistent with what one would expect from a nearly four times larger cross sectional area. This finding apparently indicates that the plasma profile is likely quite peaked, with the majority of the current being collected on centerline. The peaked profile is also supported by visual evidence of a brighter discharge around the source centerline (see Fig. 3). At bias voltages greater than 40 V, the discharge became unstable.

Based on Fig. 9, the maximum electron current that can be extracted at this operating condition is approximately 0.6 A. In a spacialike environment, however, the maximum current will likely be closer to the case where the collector electrode was surrounded by the Mylar shield because the shield effectively minimizes the collection of plasma produced downstream of the source. In this respect, the maximum current may actually be closer to 0.5 A. It is worth noting that the estimated value of the maximum collectable electron current based on the limiting value of ion collection at the source differs from the Mylar-less case by only $\approx 10\%$, suggesting that the ions are indeed predominantly collected at the source. The maximum predicted electron current density can be expected to be higher than measured because these calculations only predict the maximum electron flux in a field-free scenario. The transverse magnetic field can sig-

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**FIG. 9.** Current collection as a function of bias voltage with and without Mylar sleeve.

**FIG. 10.** Independence of current on collection area for sufficiently large collectors.
significantly reduce the flow of electrons to the collector electrode. In this respect, the transverse magnetic field is an additional constraint that acts to limit the maximum collectable electron current.

C. Grad-B drift/curvature drift

The plasma source magnetic circuit produces an axially directed magnetic field gradient. The field lines linking opposite magnet poles produce this gradient. The grad-B drift and associated curvature drift naturally arise from this geometry. The drift would be directed normal to the magnetic gradient and the magnetic field. The drift direction in this case is along the lateral dimension of the source. Such motion can drive plasma losses to the chamber walls, thereby reducing overall efficiency. To investigate the existence of this drift, sheets of Mylar film were placed around the source area. This film served to obstruct plasma flow along channels directed toward the chamber wall. Evidence supporting the existence of the grad-B drift is shown in Fig. 11. Figure 11(a) depicts the calculated directions of the magnetic field and the expected gradients near the magnetic poles of the source. Based on this diagram, one would expect electrons to drift in the positive $x$ direction along the magnet poles but in the opposite direction along the channel openings. In this regard, the Mylar foil should have holes bored into the Mylar aligned with the magnet poles on one side but along the grill gaps on the other side due to the reversal in magnetic field there. This was actually observed in this qualitative experiment as indicated in Figs. 11(b) and 11(c). As can be seen in the figure, holes were bored into the Mylar foil due to the flow of plasma current under the action of the grad-B drift, suggesting a nontrivial loss mechanism. Based on the location of the holes, it is inferred that the holes were produced by electron flux.

V. CONCLUDING REMARKS

The possibility of using a large-surface-area ECR plasma source as an electron source for electric propulsion applications was investigated. Electron current flow from the source to a biased collector electrode was used in conjunction with Langmuir probes to determine performance. One concern regarding the operation of the source was that electrons would be trapped on magnetic field lines making the application of this source as an ion beam neutralizer difficult. A second concern was related to reduced extraction currents due to the transverse mobility. Trapped electrons traveling along magnetic field lines were shown not to be a dominant mechanism for charge transport to the collector. Instead, based on observations obtained, plasma flow from the source is primarily due to cross-field diffusion. Apparently the strong magnetic field at the source localizes ion losses to the general region of the source. This assertion is supported by the relatively good agreement between actual collected electron current and the estimated ion losses to surfaces at the source alone. This finding suggests that at least for this source, the cathode collection area for ions determines the maximum collectable electron flux. This source flux is attenuated as it travels to the collector electrode due to the effect of the magnetic field. These conditions resulted in an electron current to the collector as high as $0.7 \, \text{A}$ at $\sim 40 \, \text{V}$ and $200 \, \text{W}$ of microwave power at gas flow rates of interest. While these values are lower than conventional hollow-cathode-based neutralizers, this work does indicate a path to achieve improved ECR source performance. Increased current could presumably be achieved by adding an additional source. It is expected that to achieve improved performance for a single source, the cathode area must be increased. These findings point to the inherent limitation of a conventional plasma cathode: surface...
area. If the ion collection surface area is not sufficiently large, then the extractable electron current will be limited. When combined with additional reductions in electron mobility due to the presence of the magnetic field, significant performance gains with this particular magnetic field geometry will be difficult. Modification of the pole pieces may be a means to achieve higher plasma density which should invariably improve performance. The observed drifts also contribute to poorer performance. It may be possible to manage such losses with biased shields. Such an implementation is left for a future investigation.

ACKNOWLEDGMENT

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