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Facility Effects on Helicon Plasma Source Operation

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Identical helicon plasma sources are characterized in two separate vacuum facilities to examine the impact of facility effects on helicon plasma source performance. A replica of the Madison Helicon eXperiment (MadHeX) is operated inside Vacuum Test Facility-2 (VTF-2) at the Georgia Institute of Technology over a radio frequency (RF) forward power range of 100-500 W, argon volumetric flow rate range of 2-30 sccm, and source axial magnetic field strength range of 340-600 G at a nominal operating pressure of 1.7 × 10^{-5} Torr corrected for argon. The plasma potential and ion energy distribution are measured in the argon plasma plume using an RF compensated emissive probe and a retarding potential analyzer (RPA) respectively. Plasma properties measured for these operating conditions are compared to the values and trends published by the University of Wisconsin-Madison (UW-Madison) where the MadHeX is characterized during operation in a distinctly different facility. Operation at 25 sccm showed an axial plasma potential drop of 71 V over an axial distance of 30 cm. Both the drop in potential and axial distance over which it occurred exceeded the values observed by UW-Madison. Plasma potential at a volumetric flow rate of 30 sccm increased a total of 25 V over a 400 W increase in RF forward power and 55 V over a decrease in source magnetic field strength of 260 G in VTF-2. At 25 sccm, the plasma potential increased 61 V at the thruster exit over the same magnetic field strength decrease, similar to trends observed by UW-Madison. Ion energy was noted to increase by 55 V over a 400 W increase in forward RF power for a volumetric flow rate of 30 sccm while changes of less than 20 V between operating points were observed for the 25 sccm case.

I. Introduction

HELICONS are considered to be high-efficiency, high-density plasma sources. One of the primary applications of interest is the use of helicons as electric propulsion (EP) devices due to their ability to acceleration ions without electrodes. Plasma is generating by radio frequency (RF) waves in the presence of a magnetic field. The ions created are then accelerated out the back of the helicon thruster by either a double layer or ambipolar expansion to produce thrust. Helicon plasma sources do not require the cathodes or acceleration grids that limit the lifetime of other EP devices to produce thrust making helicons desirable for long duration missions.

In order to accurately predict helicon performance in the space environment, helicon plasma sources must undergo characterization in ground-based vacuum facilities. The vacuum facilities used to evaluate the performance of EP devices vary in size, base pressure, and pumping speed. Due to the wide range of facility environments available, the influence of each facility must be documented to better compare performance data.[1]

Goebel and Katz remark that the main difference between plume characterization in a vacuum test facility and space is the background gas pressure.[2] Charles notes that for a pumping speed of 300 l/s in a volume of 30 l, the residence time of an argon atom would be about 100 ms.[3] Assuming a neutral velocity of 300 m/s allows the particle to travel 30 m before exiting the chamber if the flow is assumed to be free molecular.[3] Without the acceleration grids present in gridded ion thrusters, entrance back into a helicon through the exit plane is unimpeded. Due to such long residence times of neutral propellant in an expansion chamber, an argon atom is free to re-enter the source region of a helicon thruster multiple times before it is pumped out, thus giving the atom multiple opportunities for ionization and artificially raising the neutral pressure inside the discharge chamber of a helicon thruster. By testing in a larger

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facility with a higher pumping speed and a lower operating pressure, admittance of neutral atoms back into the source decreases and the effect of this artificial increase in neutral pressure can be quantified.

In order to effectively characterize the performance of helicon thrusters, the effect of base pressure, facility pumping speed, and chamber size must be quantified to allow for direct comparison of performance data measured in different types of facilities. To assess these effects, data from two identical thrusters collected in different test facilities are compared. The Georgia Institute of Technology High-Power Electric Propulsion Lab (HPEPL) has built a replica of the University of Wisconsin-Madison's (UW-Madison) Madison Helicon eXperiment (MadHeX) to test in Vacuum Test Facility-2 (VTF-2). Plasma properties such as plasma potential and ion energy are collected at lower operating pressure and larger facility diameter-to-thruster diameter ratio in VTF-2 as compared to the facility at UW-Madison. These values are compared to those published by UW-Madison from operation in an expansion chamber to quantify the influence of facility effects on the plasma properties of the MadHeX. A comparison of these data sets provides insight into the impact of facility effects on helicon plasma source operation.

II. Experimental Setup

In order to effectively quantify the facility effects on helicon thruster performance, an identical thruster configuration was operated in two distinctly different facilities. The thruster chosen for comparison is the MadHeX and descriptions of its construction at each testing facility are detailed below. Vacuum chamber specifics for the UW-Madison facility and VTF-2 are also detailed.

A. MadHeX at the University of Wisconsin-Madison

All the information contained in this section comes from references 4-6 and is a summary of the information necessary to compare the facilities at UW-Madison to those at Georgia Tech. The MadHeX is a six-solenoid radio frequency (RF) helicon plasma source with a maximum mirror ratio of 1.44 between an axial magnetic field strength of 1000 G located 28 cm downstream of the antenna and an axial magnetic field strength of about 700 G in the source region. The argon plasma properties of the MadHeX have been characterized by Wiebold at UW-Madison**.**

The MadHeX housed at UW-Madison consists of six water-cooled solenoids positioned at various intervals around a 10 cm inner diameter Pyrex discharge chamber. Each solenoid is 7 cm deep with an 18 cm inner diameter. This arrangement produces a maximum magnetic field strength of 700 G in the source region when operated at 60 A. The 10 cm diameter discharge chamber connects directly to a port on the outside of a stainless steel expansion chamber. An 18 cm diameter steel mesh surrounds the discharge chamber and is grounded to the expansion chamber. Argon gas flows into the discharge chamber through a 5 mm diameter copper tube connected to an aluminum endplate that is grounded to the steel mesh. A half-turn double-helix antenna measuring 13 cm in diameter and 18 cm long is positioned between coils 2 and 3.

The matching network sends an RF signal of 13.56 MHz from an HP 33120A function generator through a Comdel CX10KS amplifier. A 2-capacitor matching network was used. The reflected power was maintained below 5% for all operational cases.

The stainless steel expansion chamber is 45 cm in diameter and 70 cm long with an operating pressure of 0.15 mTorr. An 8-inch Varian turbomolecular pump located at the bottom of the expansion chamber is used to evacuate the facility to high vacuum and has a pumping speed of 550 l/s for diatomic nitrogen. A Bayard-Alpert ionization gauge monitors chamber pressure; UW-Madison lists a nominal base pressure as 10^{-6} Torr. All diagnostics are fed through a plate located downstream of the thruster exit.

B. MadHeX Replica at the Georgia Institute of Technology

The MadHeX replica at the Georgia Institute of Technology is comprised of (6) 500-turn solenoids around a 10 cm diameter Pyrex discharge chamber. The positioning of the solenoids as well as their physical dimensions and the double helix antenna are identical to those of the MadHeX at the UW-Madison. Equivalence of the magnetic field profile was ensured through consistency of results between experimental measurements of the axial magnetic field profile of the replica and magnetic field simulation performed with Infolytica MagNet commercial software. Unlike the experimental setup at UW-Madison, there is no steel mesh surrounding the discharge chamber and there is no aluminum endplate at the inlet. The discharge chamber is made of Pyrex only and is assumed to have no influence on plasma formation as the source region is located more than 60 cm downstream

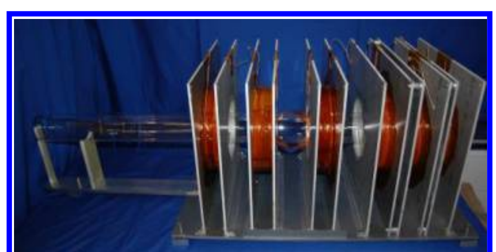

Figure 1. MadHeX replica at HPEPL

from the propellant inlet. During testing, the entire thruster assembly at Georgia Tech was operated while fully enclosed inside of VTF-2 at a location that placed the center of the exit plane approximately 1.5 m radially away from the facility sidewall and approximately 3.5 m away from the graphite beam dump.

VTF-2 is a stainless-steel chamber with a 4.9 m diameter and is 9.2 m in length. VTF-2 is evacuated to rough vacuum using one 495 CFM rotary-vane pump and one 3800 CFM blower. High-vacuum is achieved using ten liquid nitrogen-cooled CVI TMI re-entrant cryopumps. The facility has a total nominal pumping speed of 350,000 l/s on xenon and can achieve a base pressure of 1.9×10^{-9} Torr with a nominal operating pressure corrected for argon of 1.7×10^{-5} Torr for this work. Pressure in VTF-2 is monitored using an Agilent BA 571 hot filament ionization gauge controlled by an Agilent XGS-600 Gauge Controller. A schematic of VTF-2 is shown in Fig. 2.

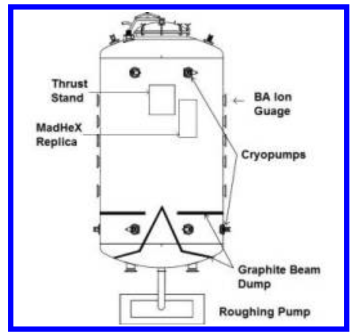

Figure 2. Diagram of VTF-2. (Not to scale).

High-purity (99.9995%) argon propellant was supplied to the thruster using stainless-steel lines metered with a MKS 1179A mass flow controller. The controller was calibrated before each test by measuring gas pressure and temperature as a function of time in a known control volume. The mass flow controller has an uncertainty of 4-7%.[7]

The RF signal for the MadHeX replica is generated by a Yaesu FT-540 HF transceiver and amplified by an ACOM2000A linear amplifier. The matching network used is a pi-type network and the standing wave ratio (SWR) is held below 1.05 for all experiments with an uncertainty of ± 1 W for power and ± 0.05 for SWR. [8]

C. Emissive Probe

The plasma potential along the centerline of the MadHeX replica was measured using the RF-compensated emissive probe shown in Fig. 3. The probe tip is built by looping a 0.127-mm diameter thoriated-tungsten wire through a 1.5-mm diameter, double bore ceramic tube. The ceramic tube is inserted into a larger ceramic tube that mates with the RF compensation box. The compensation box houses two M-series ferrite toroids around which the signal wire is wrapped 25 times; each choke provides an impedance of 5600 Ohms when an RF signal of 13.56 MHz is used.[9] The overall probe length is roughly 84 cm.

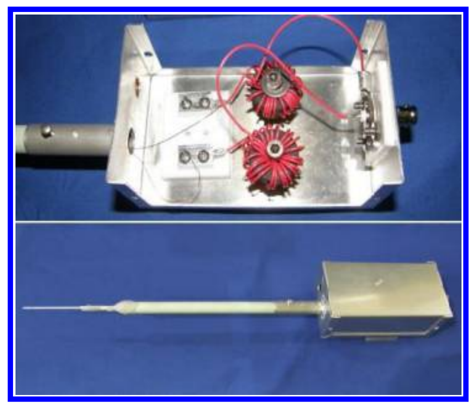

Figure 3. RF compensated emissive probe. *(Top) RF compensation box with 2 ferrite toroids. (Bottom) Complete probe assembly.* [9]

The probe was oriented perpendicular to the bulk flow of the plasma and perpendicular to the magnetic field. The plane of the probe tip was oriented parallel to the thruster exit allowing plasma to pass through the loop upon exiting the thruster.[10] The position of the probe was varied axially between 0 cm and 40 cm downstream of the exit plane of the MadHeX replica. Probe position was controlled using a two-axis Parker Daedal 406XR precision linear motion stage system, with each stage having a 2,000 mm of travel. The positional uncertainty of each motion stage is ± 159 μm.

The inflection point method was used for data collection. In this method, the probe is heated and then the emission current is monitored as the probe bias is swept in a manner similar to that used with Langmuir probes. The changing characteristic of the emission current trace as a function of applied bias voltage is then used to determine the plasma potential. [11] The heating current to the emissive probe filament was varied from 1.87 A to 1.91 A using a Xantrex XPD 60-9 power supply. A Keithley 2410 1100 V sourcemeter was used to control the probe circuit bias and the probe emission current was measured using a Keithley 6485 picoammeter. At each operating condition, one bias sweep was taken per heating current. During each bias sweep, the probe voltage was varied over a range of 0-250 V in 1 V increments with a 300 ms dwell time. The sourcemeter and picoammeter were simultaneously controlled using a LabView Virtual Instrument to ensure synchronous recording of the probe bias voltage and emitted current.

The inflection point was then found in each of the I-V traces for each of the different heating current levels, and the plasma potential was found by linearly extrapolating these values to zero emission.[11] Due to the low density plasma environment, these results were confirmed using the separation technique to ensure accuracy.[11] For cases in which emission was insufficient for either of the aforementioned techniques, spherical Langmuir probe theory was applied to the emissive probe I-V characteristic to approximate the plasma potential. [12] Using this technique the plasma potential was determined with an error of ± $T_e/10e$.[11]

D. Retarding Potential Analyzer (RPA)

The ion energy distribution was measured using the four-grid RPA of AFRL design shown in Fig. 4. Each grid is 203-μm thick and made from 316 stainless steel. The collection diameter is 3.15 cm and each grid has a 31% transparency with 229 μm aperture diameters arranged at a 394 μm pitch in a hexagonal hole pattern. The order of the grids from plasma to collector goes as follows: floating, electron repulsion, ion repulsion, electron suppression, and a solid copper collector that is 0.8 mm thick and 3.15 cm in diameter.[13] The RPA was oriented along the centerline of the discharge chamber facing the thruster. The position of the probe was varied axially between 0 cm and 40 cm downstream of the exit plane of the MadHeX replica. Probe position was controlled using the same Parker Daedal 406XR precision linear motion stages used for the emissive probe.

Figure 4. Four grid RPA.[9]

The electron suppression and repulsion grid bias were held below ground in parallel using a Kepco BHK 2000-0.1MG power supply. The bias of these grids was altered between -100 V and -300 V at each operating condition to maximize collected ion current and thus ensure minimal electron collection. The ion repulsion voltage was controlled using a Keithley 2410 1100 V sourcemeter and the collection current was recorded using a Keithley 6485 Picoammeter. The sourcemeter and picoammeter were simultaneously controlled using a LabView Virtual Instrument to ensure synchronous recording of the grid bias voltage and collector current.

At each operating condition, the ion repulsion voltage was swept between 0-300 V above ground in 1 V increments with a 300 ms dwell time. Five sweeps of the ion repulsion voltage were taken 1 minute apart at each operating condition. The data from each of these sweeps was then averaged and smoothed using a locally weighted scatter plot smoothing algorithm (LOESS) to remove noise. The smoothed signal was then differentiated using Newton's Difference Quotient. The resultant derivative peaks correspond to the most probable ion energies. This method results in an error of approximately ± 4%.[9]

III. Results

The MadHeX replica operated in VTF-2 over an RF forward power range of 100-500 W, argon volumetric flow rate range of 2-30 sccm, and source axial magnetic field strength range of 340-600 G at an operating pressure range of 1.7×10^{-5} Torr. Emissive probe sweeps and RPA measurements were taken along the thruster centerline starting from the exit plane and proceeding up to 40 cm downstream.

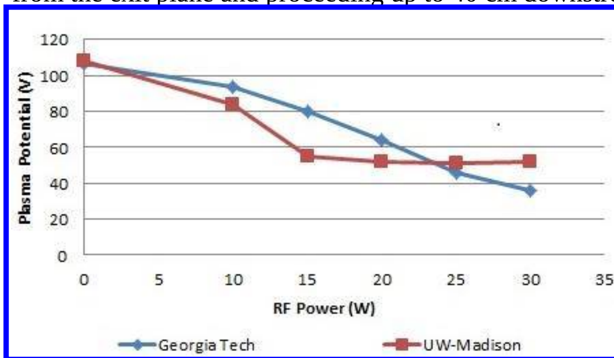

Figure 5. Comparison of plasma potential between facilities at 100 W RF power and 340 G.

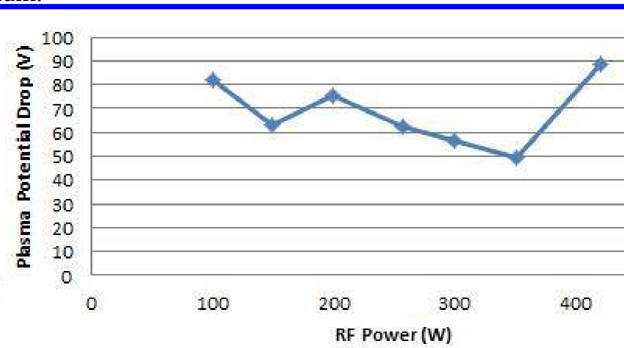

Figure 6. Potential drop between distances of 0 cm and 40 cm from the thruster exit for 25 sccm case and 340 G.

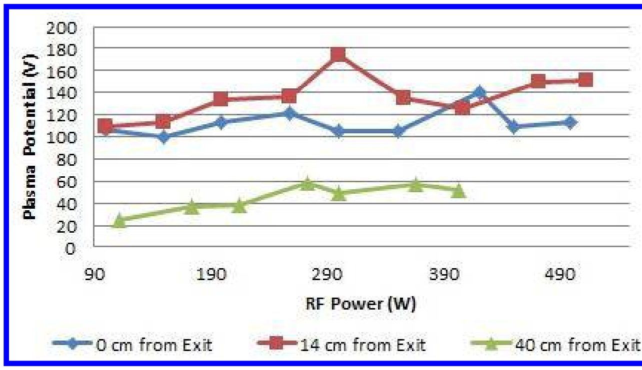

Figure 7. Plasma potential at 0, 14 and 40 cm axial distance from thruster exit for a volumetric flow rate of 25 sccm at 340 G.

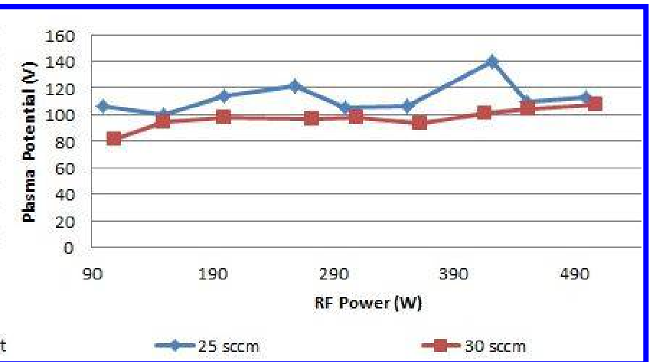

Figure 8. Plasma potential for different volumetric flow rates at 340 G. Measurements taken at thruster exit.

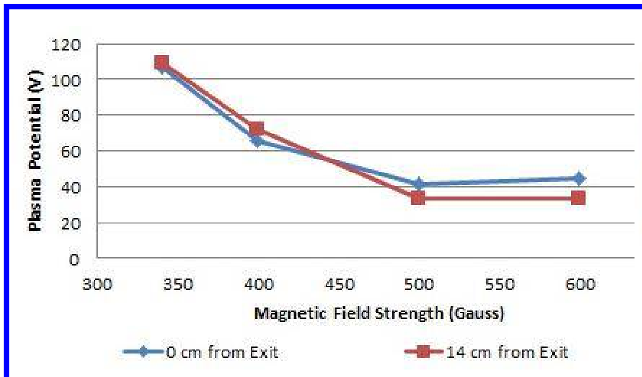

Figure 9. Plasma potential for increasing magnetic field strength at 100 W forward RF power and 25 sccm flow rate.

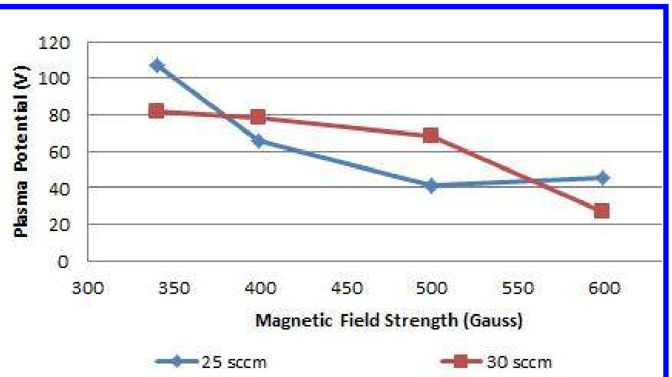

Figure 10. Plasma potential for increasing magnetic field strength at 100 W RF Power. Measurements taken at thruster exit.

A. Operating Conditions

While the source was stable for operation between volumetric flow rates of 2 sccm to 20 sccm, the diagnostics used were unable to gather data due to the ion density at the thruster exit failing to reach the minimum density required for measurement. Data was recorded for a volumetric flow rate of 25 sccm as this condition yielded the same plasma potential of 107 V published by Wiebold for MadHeX operation at 2 sccm. Data was also collected at a volumetric flow rate of 30 sccm in order to compare trends observed in the 25 sccm data.

B. Plasma Potential

Plasma potential of the MadHeX replica is plotted as a function of axial distance from the thruster exit in Fig. 5. Plasma potential measured in VTF-2 decreases by 71 V over an axial distance of 30 cm from the thruster exit. This behavior is also observed by Wiebold but with a smaller potential drop over an axial distance of 20 cm.[5] It is evident from Fig. 5 that the plasma potential has not yet achieved its minimum value and it is expected that the drop will continue further downstream.

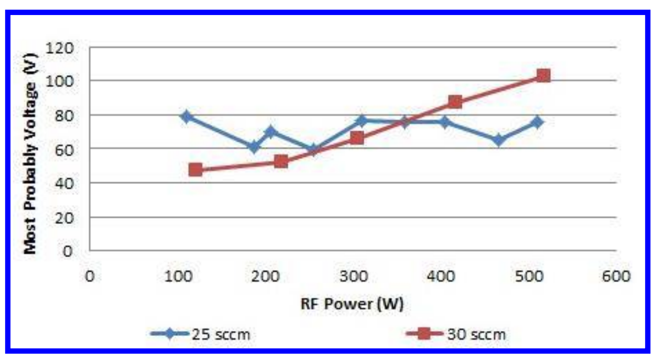

Figure 11. Most probable voltage for Increasing RF Power at 340 G. Measurements taken at thruster exit.

Figure 6 shows the axial plasma potential drop from the thruster exit plane to a position of 40 cm downstream at different RF power levels. The observed potential differences fluctuate between 7 and 40 V for adjacent RF power levels and do not present behavior indicative of a transition from a capacitively-coupled plasma to an inductively-coupled plasma. Plasma potential measurements taken at three different axial positions are shown in Fig. 7 for a volumetric propellant flow rate of 25 sccm. These values do not display the steady increase of 1-12 V between power levels as evident by the 30 sccm case when compared in Fig. 8.

Plasma potential decreased by 61 V over a 260 G increase in magnetic field strength as shown in Fig. 9. This behavior deviated less than 12 V at distances of 0 and 14 cm from the thruster exit at a volumetric flow rate of 25 sccm. This observed decrease in plasma potential was repeated for a volumetric flow rate of 30 sccm with a potential drop of 55 V shown in Fig. 10.

C. Ion Energy Distribution Function

Ion energies for the 25 sccm case conducted with the MadHeX replica did not change in value more than 20 V over the entire range of 100-500 W RF power. Operation at 30 sccm showed an overall increase of 56 V with increasing RF power as shown in Fig. 11. These values are uncorrected for plasma potential due to the fluctuations present in the 25 sccm plasma potential.

IV. Discussion

A. Volumetric Flow Rate

The first operational parameter to consider is the volumetric flow rate of argon propellant in the MadHeX replica. The UW-Madison experimental setup produces plasma at a minimum flow rate of 1.3 sccm with the majority of the published data taken at a flow rate of 2 sccm.[4-6] In VTF-2, the MadHeX generates visible plasma in the source region of the thruster at 2 sccm, but emissive probe sweeps taken at the thruster exit are not interpretable.

The MadHeX replica's volumetric flow rate is increased until interpretable data is found at 20 sccm. For this reason, duplication of all thruster operating conditions between data points is not possible. To compensate for the necessary increase in volumetric flow rate, several flow rates are tested until one is found to yield the same plasma potential observed by Wiebold on the centerline at the exit plane at an RF forward power of 100 W and a magnetic field strength of 350 Gauss in the source region. A flow rate of 25 sccm yields a plasma potential of 107 V at the exit as observed by UW-Madison at a volumetric flow rate of 2 sccm.

The discrepancy between the minimum flow rates required for operation is most likely due to the lower pumping speed of the expansion chamber at UW-Madison. As pumping speed decreases, neutral atoms are less likely to be removed from the vacuum chamber and are granted multiple opportunities for ionization. Charles states that in experimental setups with small vacuum chambers and low pumping speeds, neutral particles may travel back into the ionization region multiple times after having failed to exit the chamber and not having ionized initially.[3] This causes an artificial rise in neutral pressure inside the discharge chamber corresponding to a higher flow rate in a larger vacuum chamber with faster pumping speeds in which less neutral ingestion occurs. This phenomenon enables the MadHeX to run at flow rates lower than those achieved in VTF-2 and generate ion densities high enough for measurement at the thruster exit at these lower volumetric flow rates.

The lower in-chamber neutral density, as compared with a smaller chamber, is also the likely cause for the lack of interpretable data at low flow rates. Wiebold observed similar behavior in his setup at flow rates less than 2 sccm where plasma was created in the source region, but failed to propagate down the discharge chamber.[5] Wiebold determined that the plasma density at the thruster exit was below the minimum density required for diagnostic measurement and that is likely to be the case for flow rates between 2-20 sccm in VTF-2.

A facility effect noted by Wiebold that is not observed in VTF-2 was the coating of the chamber walls by the plasma.[5] Coating of the expansion chamber in Wiebold's set up led to a reduction in quality of the grounded boundary condition resulting in an increase in the minimum volumetric flow rate required for stable operation of the MadHeX from 1.3 sccm to 1.9 sccm. This effect is not observed in VTF-2 where the ratio of chamber diameter to discharge chamber diameter is 10 times larger than UW-Madison. Following operation of the MadHeX replica, no coating is observed on the chamber walls.

B. Plasma Potential

In order to determine the axial extent of the acceleration region, the dependence of the plasma potential on axial position is recorded for the 25 sccm case at 100 W forward RF power and a magnetic field strength of 340 gauss in the source region. These values are compared to those recorded by Wiebold in the UW-Madison setup in Fig. 5. UW-Madison shows a steep drop in plasma potential over a length of 20 cm from the thruster exit.[5] The MadHeX replica operating at 25 sccm shows a gradual drop in plasma potential of 71 V that does not level off before reaching an axial distance of 30 cm from the thruster exit. Lacking a steep gradient, it is difficult to argue that this behavior is indicative of a double layer. However, Debye length calculations and Langmuir probe measurements would be necessary to be definitive. The plasma potential gradient in VTF-2 persists over an axial length greater than 20 cm as observed in the expansion chamber at UW-Madison and a longer axial sweep will have to be conducted to characterize the full acceleration region.

An examination of plasma potential differences measured at increasing RF powers for the 25 sccm case highlights an inconsistency in thruster operation between the two facilities. For increasing RF forward power, Wiebold observes a steady increase in the plasma potential drop from 50 – 200 W. Between 200 and 250 W, the potential drop decreases abruptly by 20 V and remains constant until 500 W. This abrupt change in potential difference is indicative of the RF coupling mode transition from a capacitively-coupled plasma to an inductively-coupled plasma.[6] The plasma potential differences recorded in the MadHeX replica shown in Fig. 6 fluctuate between 7 and 40 V between RF power levels; this is not indicative of a transition between RF coupling modes. When the potential differences are regarded with respect to the recorded plasma potentials at different distances from the thruster exit, the instability of operation at 25 sccm comes to the forefront. In Fig. 7, plasma potential is displayed as a function of forward RF power for three different distances of 0, 14, and 40 cm downstream of the exit plane. It appears despite large fluctuations up to 35 V, that the overall trend of plasma potential is to increase with increasing RF. These fluctuations exceed the 4.4 V average uncertainty of this probe circuit.[9] Significant fluctuations of plasma potential were also observed by Wiebold when operating the MadHeX in capacitive mode with gradients too large to be explained by ambipolar expansion or double layer theory.[5] This implies that the MadHeX replica is unable to achieve the inductive coupling mode in a lower operating pressure environment, despite achieving the same thruster exit plasma potential, albeit at a flow rate of 25 sccm. The changes in potential drop observed are not indications of a coupling mode change but are instead a result of a capacitively coupled plasma source. Figure 8 shows that for a flow rate of 30 sccm the plasma potential fluctuations observed at the lower flow rate of 25 sccm and increasing RF power dissipate. This behavior implies that a flow rate higher than 25 sccm is required to generate ion densities great enough to lead to the inductive-coupling mode transition observed by Wiebold, but not at the same operating condition that produces a plasma potential of 107 V at the thruster exit.

In addition to characterizing the effect of forward RF power on plasma potential, Wiebold also examines the effect of the source magnetic field strength on the plasma potential. Wiebold notes a decrease in magnitude and length of the plasma potential gradient with increasing magnetic field strength.[5] The potential gradient also shifted further into the expansion chamber as a result of increasing magnetic field strength. Operation of the MadHeX replica revealed a decrease in magnitude of the plasma potential at the thruster exit by 61 and 75 V over an increase in magnetic field of 260 G for axial distances of 0 and 14 cm from the thruster exit plane respectively, as shown in Fig. 9. Unlike at UW-Madison, a steep drop in plasma potential is not observed with increasing axial distance from the thruster exit for an increase in source magnetic field strength. The plasma potential deviates less than 12 V over an axial distance of 14 cm at the highest magnetic field strength tested where the potential drop is observed to be the greatest. To ensure that these values are not a result of capacitive-coupling fluctuations, plasma potential measurements are repeated for a flow rate of 30 sccm as seen in Fig. 10. Plasma potential also decreases by 55 V at the thruster exit with an increase in source magnetic field strength of 260 G. It is unclear if this drop in plasma potential is due to a shifting of the potential gradient as noted by Wiebold or solely the increase in magnetic confinement he also observed for increasing magnetic field strength.[5] A finer axial sweep of the plasma potential for increasing magnetic field strength will be required to confirm a shift in the potential gradient in VTF-2.

C. Ion Energy

Most probable ion energies for the 25 sccm case do not change in value more than 20 V despite increasing RF forward power and magnetic field strength in the source region. This behavior is attributed to the capacitive-coupling mode of the plasma made evident by the fluctuating plasma potential shown in Fig. 7 and did not yield trends equivalent to those observed during operation of the MadHeX in the UW-Madison facility. Most probable ion energy remained within 20 V across the full range of increasing RF power at a volumetric flow rate of 25 sccm. This behavior coupled with the low, uncorrected most probable energy indicates that ions at the exit plane of the thruster are mostly thermalized for a volumetric flow rate of 25 sccm.

Operating with a flow rate of 30 sccm revealed ion energy that increased by 55 V over the full range of increasing RF power shown in fig. 11. Wiebold also notes an increase in ion beam energy as RF power is increased; a trend that seems unaffected by the vacuum test facility despite the associated values being different.[4]

V. Conclusion

In order to quantify the effect of facility size, pumping speed, and operating pressure on plasma characteristics, plasma potential and ion energy trends were compared from identical thrusters operated in different vacuum facilities. Minimum flow rate required for plasma potential measurements in VTF-2 was 20 sccm, a flow rate 10 times higher than that used by UW-Madison. This discrepancy between minimum flow rates is attributed to a decrease in neutral ingestion due to an increase in pumping speed of VTF-2 as compared to the UW-Madison facility. Plasma potential values collected at a flow rate of 25 sccm in VTF-2 were compared to those collected at 2 sccm at UW-Madison due to the same plasma potential value recorded at the thruster exit in both cases. The plasma potential drop in VTF-2 exceeded the drop observed in UW-Madison and occurred over a longer axial distance. Operation of a helicon plasma source inside a larger vacuum facility of lower operating pressure produces a longer acceleration region outside of the thruster. Matching the exit plasma potential in VTF-2 did not allow for a transition between the capacitive and inductive RF coupling modes observed in the expansion chamber at UW-Madison. This result is also attributed to the lower operating pressure in VTF-2 resulting in a decrease of neutral ingestion. Plasma potential measured in VTF-2 increased with increasing RF power and decreasing magnetic field strength. UW-Madison also observed an increase in plasma potential gradient with decreasing magnetic field gradient concluded to be a result of decreased confinement in the source region. Ion energies increased with increasing RF power, a phenomenon also observed by UW-Madison independent of facility effects. While general trends such as the effect of RF power and magnetic field strength on plasma potential and ion energy were observed in both facilities, the magnitudes associated with individual data points were inconsistent. Plasma potential drops also occurred over longer distances and resulted in different gradient magnitudes.

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