

Impacts of thruster chassis potential on beam neutralization at high-power densities

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A low-power gridded ion thruster is operated in an undersized facility to emulate the power densities expected while testing a 50+ kW thruster in existing test facilities. Under these high-power density conditions, it was observed that there were elevated ambient plasma densities that rivaled the plasma densities of the beam. Additionally, it was found that the plasma potentials in the beam were dampened with the increase of background pressure. This is similar to the predictions made from the models of Wang et al. The elevated ambient plasma densities lead to improved beam neutralization. Unfortunately, this complicates separating spacelike and non-spacelike neutralization processes during ground testing. Allowing the thruster chassis and plasma screen to electrically float in the plasma seems to ameliorate some of these elevated background pressure effects up to a point. Operating a gridded ion thruster at elevated background pressures is generally not an issue. However, it is with the elevated background plasma densities that the decoupling of the impacts of the facility on the beam neutralization process becomes extraordinarily difficult. Further studies and understanding of the sensitivity of the beam neutralization process under high-power density ground testing conditions is required to accurately predict the spaceflight performance of a gridded ion thruster.

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Nomenclature

ACCEL	= accelerator power supply
BEAM	= beam power supply
BT	= beam target
C	= discharge cathode flow rate
CEX	= charge-exchange
D	= chamber diameter
DISC	= discharge power supply
EP	= electric propulsion
FWHM	= full width at half maximum
GIT	= gridded ion thruster
I_{right}	= integrated beam current using right-side only of the beam profile
I_{left}	= integrated beam current using left-side only of the beam profile
I_{full}	= integrated beam current using full beam profile
L	= chamber length
IG	= ion gauge
LVTF	= University of Michigan Large Vacuum Test Facility
M	= main plenum flow rate
N	= neutralizer cathode flow rate
NKPR	= neutralizer keeper power supply
NSTAR	= NASA Solar Technology Application Readiness
PS	= thruster chassis and plasma screen
PSTL	= Plasma, Science, and Technology Laboratory
$\phi_{F.GRND}$	= facility ground potential with respect to an arbitrary reference potential
ϕ_{NC}	= neutralizer cathode common potential with respect to an arbitrary reference potential
ϕ_p	= plasma potential with respect to an arbitrary reference potential
RC	= Rocket Chamber
RGA	= residual gas analyzer
RPA	= retarding potential analyzer
SMU	= source measurement unit
V_{NC}	= neutralizer cathode common potential with respect to facility ground
V_p	= plasma potential with respect to facility ground
V_{cg}	= neutralizer-facility coupling voltage [V]
V_{cp}	= neutralizer-beam (true) coupling voltage [V]
$V_{nk,pp}$	= neutralizer keeper peak-to-peak oscillations [V]
$V_{disc,pp}$	= discharge anode peak-to-peak oscillations [V]
VF-16	= NASA Glenn's Vacuum Facility 16
VTF-2	= Georgia Institute of Technology Vacuum Test Facility-2

I. Introduction

GRIDDED ion thrusters (GIT) are among the current mature electric propulsion (EP) technologies being considered for high-power operation on nuclear electric propulsion missions supporting science, cargo, and human missions to the Moon, Mars, and beyond. This will require systems in excess of 100's of kW's, with the power processed using a single engine or via arrays. Before flight, these thruster systems must be qualified through performance testing. This requires a test environment simulating space. No existing facility can replicate the required spacelike conditions necessary to accurately characterize a high power thruster system during ground testing without the facility impacting the ground test results.¹

Creating and building such facilities is expensive and time consuming. A cost effective alternative solution could be ground testing in existing facilities. However, ground testing at elevated thruster power levels in existing facilities would lead to ground testing being performed under non-ideal situations. Under these conditions, spaceflight performance predictions are difficult to accurately construct due to the deviations in ground testing results attributed to facility effects. These effects must be characterized and understood in order to correct or account for their impacts on the performance of the thruster. Many of these effects are known and have been reviewed previously.² However, these effects differ from facility-to-facility and from the variance in ground test configurations of the thruster with respect to the facility. Further understanding of facility effects and eventually the creation of ground testing standards are required to minimize the cost of qualifying a thruster for spaceflight. Costs for spaceflight qualification are minimized by reducing the facility sizes, thruster testing times, and spaceflight performance uncertainty. This can only be performed once the limits and boundaries of ground testing conditions are sufficiently understood enough such that spaceflight performance can still be accurately predicted from the ground test results.

To make 100+ kW thruster systems possible, it is critical to understand the testing conditions in which they occur and the mechanisms that are causing these facility effects to obfuscate ground test results. Understanding these boundaries enables ground testing to be conducted with minimal expenditure, while still ensuring the ability to confidently predict the spaceflight performance of the thruster system. This study examines the influence of high-power density operating conditions on gridded ion thruster performance, with a focus on quantifying facility-induced effects under high power-to-low facility volume regimes. This setup is to simulate the testing environment that would be observed operating a 100+ kW gridded ion thruster in existing ground-based test facilities.

Specifically investigated in this study are the implications of high-power densities on beam expansion, beam neutralization and coupling, and the implications and recommended practices of the electrical configuration of the thruster chassis and plasma screen during ground testing. In this section, a brief summary regarding facility effects impacting GIT operations is presented. Next is an explanation of high-power density ground testing followed by important definitions for beam neutralization and coupling. Lastly, an overview description and importance of the thruster chassis and plasma screen is provided. After this introduction, an overview of the test setup and configuration is outlined followed by a discussion of the results. Finally remarks and recommendations are then provided in the conclusion.

A. Facility Effects

The operating conditions during spaceflight and ground tests can differ drastically. Figure 1 schematically illustrates key thruster plasma-chamber wall interactions that are not present in space. In space, background pressure and ambient plasma densities are low, dropping significantly with increasing altitude above LEO, represented by the lighter background purple of Fig. 1. Represented in green are the alternative beam neutralization pathways that can arise. Backsputtered material from the walls are depicted by the blue arrows and are caused by high energy ions impacting the walls. In general, the issues that affect or obfuscate interpretation of ground test data can be categorized into three problem areas: (1) the electrical and magnetic interactions of the thruster plume and neutralizer plasmas with the facility, (2) gas phase collisions with background and thruster derived neutrals, and ionized gas, and (3) physical plasma-material interactions that give rise to processes such as sputtering and subsequent deposition. Often these problem areas are interconnected as well.

An example of interconnected facility effects is commonly observed during lifetime and wear testing. As the thruster operates there is a portion of the ions that undergo charge-exchange (CEX) collisions with ambient neutrals downstream of the grids. As a result, the fast ion is converted into a slow ion. This slow ion then sees the negative potential of the spacecraft or the accelerator grid and returns. If the ion



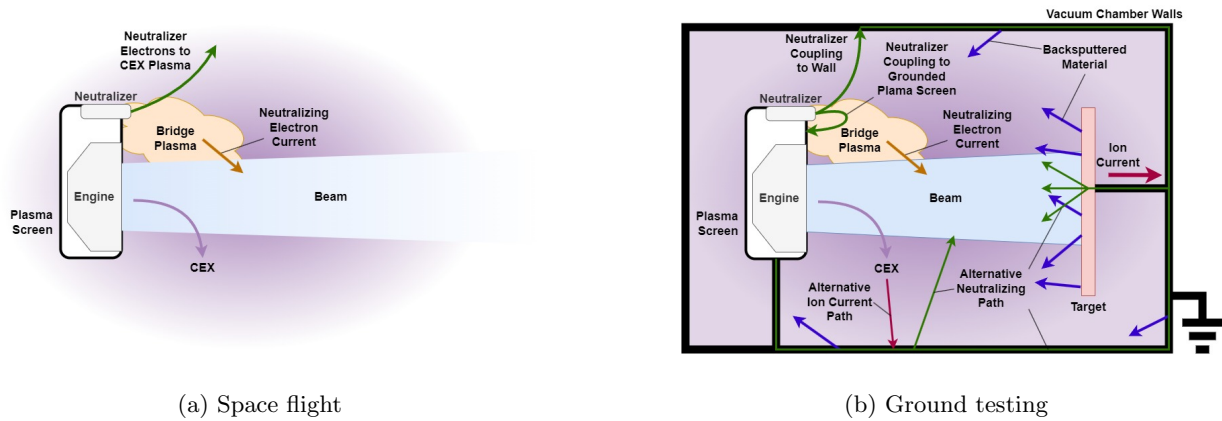


Figure 1: Comparison between space (a) and ground test (b) engine operation. The darker purple color represents the increased neutral gas and plasma densities. Alternative neutralization pathways through the facility walls are in green. Backspattered material from the walls are depicted by the blue arrows.

has a significant amount of energy it can lead to erosion. It is important to know these erosion rates in space to ensure the thruster will last the whole mission duration. However, in ground testing elevated neutral densities can lead to accelerated erosion rates due to increased CEX rates. But, during ground testing there is backspattering of wall materials that are deposited back on the thruster. The deposited material can mask the true erosion rates. Unfortunately, the rate of deposited material is dependent on sputtering rates which are also dependent on the energies and ion flux to the walls. Thus, the decoupling of the affects of increased background pressure is not so straight forward. A slight change in background pressure can cause a cascade of affects.

Electrical facility effects can have a huge impact on characterizing a thruster as well. The neutralizer, which establishes the common reference for the thruster system, is typically tied to spacecraft ground via a Zener clamping diode in spaceflight for NASA style GITs. In this respect, for the system to faithfully represent space conditions, neutralizer common must essentially be completely electrically floating during ground testing. Currents from space plasma can contribute to a limited degree to charge and current balance if the spacecraft chassis surfaces are exposed to the space plasma and are conducting. Yet, owing to low current densities in LEO (ion current density $\sim \mu\text{A}/\text{cm}^2$)³ and at higher orbital distances, this effect is small. However, off nominal operation of the neutralizer, for example, such as conditions where there is finite conductivity between neutralizer common and the spacecraft chassis can lead to the double probe effects where chassis can be driven negative leading to potentially damaging spacecraft sputtering from back flowing CEX ions. During ground testing this effect can be observed as well but can be implemented in a non-spacelike manner. Connecting neutralizer common directly to facility ground can cause the facility to act like a large collecting or emitting surface for the thruster; this inherently ties the plasma-facility wall interface with the potential of the thruster. In space, this is an unrealistic electrical configuration connecting the thruster potential with the downstream portion of the beam through the facility walls. As such, a mischaracterization of the thruster can occur such as not neutralizing the beam via the neutralizer but through the facility walls. Thus, in spaceflight the potential of the thruster and spacecraft may drift away from the high potential of the non-neutralized beam resulting in beam turnaround and damage to the spacecraft.

B. High-Power Densities

There are technical two extremes to consider in which elevated background pressures may arise. The first scenario occurs due to inadequate pumping speeds raising the background pressure. Here, the facility is generously sized in comparison to the thruster. The walls of the facility are extremely far from the thruster. The ratio of thruster power to the facility volume is low. In this situation the plasma-wall sheath effects are very distant from the beam plasma allowing for the beam to expand freely for large distances before interacting with the facility walls. Pumping speeds in this scenario are insufficient to maintain low enough

background pressure to properly characterization a thruster once propellant flow commences; however, the plume can freely expand and develop, even with the increase of CEX rates, because the walls are so distant.

The second scenario in which elevated background pressures can occur is during the testing of a thruster in an undersized facility. This results in high thruster-power to chamber volume ratio, or a high power density. Here the walls and/or the downstream beam target are too close in proximity of the thruster for the beam to fully expand and develop before interacting with the facility walls. Corresponding with an undersized facility is an increase of background pressure because of the insufficient pumping speeds associated. The insufficient pumping speeds can be caused by limited pumping surfaces or inadequate conductance based on the chamber length-to-diameter (L/D) ratio and pump locations. Although there are increases in CEX rates due to the increase of ambient neutral densities, the beam plasma plume may not be able to freely expand due to the effects of wall sheaths and plasmas. Thus, plume broadening may not be observed.⁴

For the first scenario, a generously large facility can be used to isolate the elevated background pressure effects. Adjusting the pumping speed of a facility can change the background pressure and affect the beam; but, negligible effects to the beam are expected from the beam-wall sheaths because of the large distances between the thruster and the walls. In the second scenario under high-power density conditions, there are elevated background pressure effects due to the limited pumping capabilities associated with an undersized facility. These effects are coupled with the plasma-wall sheath effects because the walls of the test facility are in near proximity to the thruster.

The solution to the facility effects for the first scenario (low power densities with elevated background pressure effects) is add more pumping speed. A smaller chamber L/D ratio may also help as a lower L/D ratio improves the conductance of the facility.⁵ A solution to the second scenario facility effects (high power densities with both elevated background pressures and beam-wall sheath effects) is more complex as it requires both more pumping speed and a larger facility to meet modern ground testing standards for thruster qualification. For 100+ kW propulsion systems, this would lead to extremely large test facilities with extremely high cost to build and operate. Thus, one solution is to test in existing facilities under these high power density conditions. This requires improving our understanding of facility effects under these high power density conditions so accurate predictions of spaceflight can be made using ground testing qualification data.

The purpose of testing in a smaller chamber in this study is to operate a smaller thruster in it to emulate the higher power densities that would be observed while operating a larger 100 kW thruster in some of the existing facilities of today. Such facilities include the University of Michigan Large Vacuum Test Facility (LVTF), the Georgia Institute of Technology Vacuum Test Facility-2 (VTF-2), and NASA Glenn's Vacuum Facilities 5 (VF-5), 6 (VF-6), and 16 (VF-16). Target areas of interest while operating at high power densities include gaining insight into the affects of increasing background pressures and plasma densities on the performance of gridded ion thrusters. It is expected that at these higher power densities, there would be changes in thruster performance such as beam expansion, neutralizer-beam coupling, and thruster-facility coupling than that which has been observed under conventional low power densities. Much of this study focuses on the causes and potential solutions to combat and mitigate facility impacts at these emulated high power density conditions for future 100+ kW gridded ion thruster ground testing.

C. Beam Neutralization & Coupling

Beam neutralization is a key aspect of a gridded ion thrusters. As ions are accelerated out and form the beam, the spacecraft begins to charge up negatively. If not corrected, this would lead to beam turnaround. Hayabusa 2 experienced ion damage erosion from the spacecraft charging up negatively.⁶⁻⁸ An external neutralizer cathode expels electrons to the ion beam to keep the spacecraft and beam neutral. Ensuring beam neutralization in space is critical for mission success, but coupling with the facility during ground testing can limit direct neutralization of the beam by the neutralizer. As a result, the neutralizer predicted spaceflight operation may be inadequate, leading to higher power neutralizer operation in spaceflight and higher neutralizer flow rates than anticipated, jeopardizing mission success.

One difficulty of operating higher power thrusters in smaller chambers is being able to obtain correct neutralizer margin and neutralizer-beam coupling estimates that allow for proper spaceflight performance. The usual approach to estimate beam neutralization and neutralizer-beam coupling is to monitor the behavior of the neutralizer-facility coupling voltage. The facility coupling voltage is defined as

$$V_{cg} = \phi_{NC} - \phi_{F.GRND}, \quad (1)$$



where ϕ_{NC} and $\phi_{F.GRND}$ are, respectively, the neutralizer cathode common and facility ground potentials in reference to some common arbitrary potential reference. The assumption is that the beam in a ground test facility has to be neutralized because it terminates at a grounded facility wall. If a beam is not fully neutralized by the time it interacts with the facility walls, then the facility will aide in the neutralization and an increase in magnitude of the facility coupling voltage will occur. However, testing under high-power density conditions this assumption ignores alternative neutralization pathways not via beam-wall interactions.

At elevated plasma densities and small chamber sizes, it is suspected that there will be lower potential in the beam and less plume expansion.⁴ Thus, the increase of the ambient plasma densities can provide non-spacelike beam neutralization. In this case, a change of the neutralizer-facility coupling voltage may not be observed since the plasma potential in the beam is dampened. A more appropriate estimate of beam neutralization is given by the neutralizer-beam or true coupling voltage given as

$$V_{cp} = \phi_p - \phi_{NC}. \quad (2)$$

Here ϕ_p and ϕ_{NC} are, respectively, the beam and the neutralizer cathode common potentials with respect to a common arbitrary reference potential. Using facility ground as a common potential references results in

$$V_{cp} = V_p - V_{NC}. \quad (3)$$

Here, the neutralizer common potential can be readily obtained during ground testing by probing the neutralizer cathode common potential with respect to facility ground via a multimeter or differential probe. This leads to $V_{NC} = V_{cg}$. The plasma potential on the other hand is slightly more difficult to obtain as it typically requires an electrostatic probe in the plume. Often the probes do not last long in the plume so it is difficult and often not obtained. But if required, an emissive probe can be used to determine the plasma potential in the beam to determine the true neutralizer-beam coupling. Figure 2 describes the potentials of a GIT and visually outlines the coupling voltage definitions.

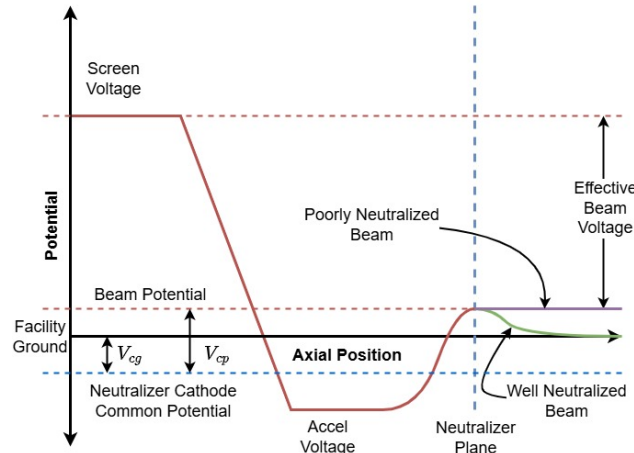


Figure 2: Potentials and coupling voltages of a gridded ion thruster during ground testing. Facility ground is used as the reference and corresponds to the zero on the ordinate axis. The screen voltage is the potential at the first (screen) grid created by the elevation in potential of the discharge chamber by the beam power supply. The accelerator voltage is the potential of the second (accelerator) grid using the accelerator power supply. Downstream of the grids, the exhausted positive ions create a high potential but as they reach the neutralization plane, the beam becomes well neutralized decreasing in potential. However, in a non-well neutralized beam this potential will propagate downstream lessening the effective beam voltage, lessening the effective beam current that can be extracted, and lowering the produced thrust. The facility coupling voltage is typically negative and is a quantitative metric of the contribution of the facility in the beam neutralization process. The true coupling voltage is a more accurate estimate of the neutralizer-beam coupling and is used to determine the effective beam coupling.

D. Thruster Chassis & Plasma Screen

The thruster chassis and plasma screen are the supporting housing structures of a gridded ion thruster. The plasma screen shields the internals of the thruster from interactions with the ambient plasmas. In spaceflight, the plasma screen is often tied to the thruster chassis, which is connected to spacecraft ground. The plasma screen could be implemented to be electrically floating with respect to the thruster chassis during spaceflight if desired. Either way, the thruster chassis and plasma screen are in some shape-or-form floating in the plasma.

Recently, some GITs have been ground tested with a grounded thruster chassis and plasma screen. However, past studies have indicated that this should not be the case.^{9,10} Patterson et al. observed sensitivity of the facility coupling voltage with the isolation of thruster structures. In that work, using a switch, they floated the plasma screen of the thruster as well as the external enclosure of the neutralizer—both of which otherwise would be nominally grounded. With the structures grounded, it was found that the neutralizer coupling voltage was insensitive to flow rate changes indicating that the neutralizer was not well coupled to the beam and that other processes were carrying out current and charge neutralization. It was observed that actual beam current neutralization was achieved via the grounded target and partially the neutralizer coupling to the beam. In this case, the neutralizer was dumping most of its emitted electrons to nearby ground potential surfaces such as the thruster housing and chamber walls. It was energetically easier for the electrons to neutralize the beam through alternative pathways by collecting on nearby grounded surfaces, such as the plasma screen, and be reemitted on the grounded target, than to directly travel to the beam via the plasma bridge. The plasma bridge is the conductive plasma medium that connects the neutralizer to the beam. It consists of the neutralizer plasma, scattered beam ions, ionized plasma from neutralizer electrons on their way to the beam, and the ambient background plasma. While the exterior neutralizer housing and thruster plasma screen were allowed to float, the facility coupling voltage was highly sensitive to neutralizer flow rate. The neutralizer flow rate partially determines the operating mode of the neutralizer (spot or plume) and the plasma conditions. Thus, the plume from the neutralizer impacts the impedance of the coupling bridge via the float rate through the neutralizer. The stark difference in coupling voltage sensitivity to floating and grounded screen, and neutralizer enclosures conditions are attributed to this alternative neutralization pathway to the beam.

Investigation of the thruster chassis and plasma screen electrical configuration on thruster performance can be performed by adding a switch into the plasma screen grounding line. For the grounded configuration, the switch is closed and current is allowed to pass through the line to facility ground. In the floating configuration, the switch is opened and no current passes through. As a result the thruster chassis and plasma screen reaches a voltage potential based on the balancing of the electron and ion currents to it. The thruster chassis and plasma screen floats to the floating potential of the ambient plasma. An electrical circuit diagram is provided in Fig. 3 with the switch circled in red.

II. Testing Configuration

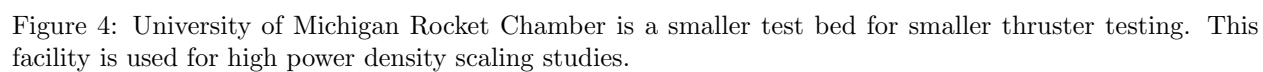
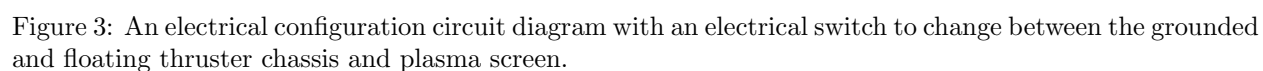
A. Test Facility

The Rocket Chamber (RC) at the University of Michigan Plasma, Science, and Technology Laboratory (PSTL) is a compact test bed configured for low-power electric propulsion testing. However, its smaller size makes the RC uniquely qualified to be used in power density scaling studies. A smaller thruster operated in the RC can be used to emulate the power density of that which would be observed during the operation of a more powerful thruster in a larger but still inadequately sized chamber. The RC has a diameter 2 ft (0.61m) and is 6 ft (1.83 m) in length. The main cylindrical body has a volume of approximately 0.53 m³.

1. Pumping Capabilities

The chamber is supported by two turbomolecular pumps. One of the pumps is located below the thruster stand. It is placed about 29.32 cm from the end cap. The other pump is at the same location on the opposite end of the chamber. The two turbomolecular pumps are both Shimadzu TMP-V2304LM (PB21). Each have a pumping speed of 2,100 L/s (N₂) and each can be throttled from 100% down to 25% of the total rotational speed to vary background pressures and neutral density gradients in the chamber. The total theoretical pumping speed for the facility is 4,200 L/s (N₂). Ultimate base pressure of the chamber is $3\text{--}4 \times 10^{-7}$ Torr-N₂





depending on the location of the pressure gauge in the chamber.

2. Facility Configuration & Diagnostics

Due to the smaller size, lower cost of operation, availability, the breadth of configurations, and adaptability of the PSTL RC allows for rapid changes and variable testing configurations. The downstream beam target is made of a thin aluminum plate that is isolated from the facility walls via ceramic isolators. This allows for the beam target to be either electrically floating in the plasma, grounded with the facility, or biased with respect to facility ground. In addition, the interior of the chamber and the beam target are lined with flexible graphite to reduce sputtering. Installation of the graphite material requires conditioning pumping of the facility after the interior of the chamber has been exposed to atmospheric pressures for extended periods of time.

The thruster is aligned in the facility such that the exit plane of the thruster is at a distance of 38.74 cm from the back wall of the chamber and that the beam target is located 124 cm downstream of the thruster plane. Four ion gauges are used to measure local pressure at various locations within the chamber. A 370194 Stabil Ion Gauge (IG0) is placed in-plane with the thruster about 2 beam-diameters (16 cm) to one side of the thruster. An Inficon BPG402 ion gauge (IG1) is placed approximately 2.3 beam-diameters behind the thruster plane (-18.3 cm). Additional Inficon BCG450 ion gauges are placed at 6.59 beam-diameters (52.72 cm) and 13.7 beam-diameters (109.6 cm) downstream of the thruster plane (IG2 and IG3), respectively. A residual gas analyzer (RGA) is also installed next to IG3 for gas composition measurements and validation pressure measurements.

Various motion stages are placed throughout the chamber. A two-axis motion stage system with inductive encoders is used to perform lateral sweeps across the beam for various downstream distances. The inductive encoders are used to record position of the motion stage during the sweeps. The maximum lateral sweep distance is approximately ± 14.7 cm left-and-right of the thruster and a total travel length of 74.9 cm downstream of the thruster exit plane.

A smaller 11 cm linear motion stage is used behind a beam target. The beam target has a 5 cm diameter hole that is cutout of its center. The motion stage is used to move a mini-graphite-covered beam target plate in-and-out of the beam path. Full extended, this mini-beam target covers the hole located at the center of the beam target. Fully retracted, the mini-beam target reveals the diagnostic behind it. This protects the diagnostic behind the plate while not in use. The mini-beam target plate is also tied to the same potential as the beam target.

The full diagnostic layout for the PSTL Rocket Chamber is displayed in Fig. 5. The full set of diagnostics are used to characterize the facility effects impacting the operation of ion thrusters. Not all of the diagnostics are used in this work. Only those pertinent to this work are discussed here.

Cylindrical wire tungsten Langmuir probes are used to evaluate the evolution of the plasma potential from the center of the the beam to along the edges of the walls of the chamber. Emissive probes are used for the plasma potential measurements in the plume while the Langmuir probes were used to get the plasma potentials near the walls. The recommended practices for the analysis of Langmuir probe traces are followed to account for orbital-motion limited sheaths.¹¹

The RC Faraday probe consist of an unguarded 3/16" planar electrode made of 99.95+% tungsten that is surrounded by an nonporous alumina tube. The Faraday probe is kept at a constant voltage of -20 V with respect to ground. A spatial current profile is obtained as the probe is translated linearly ± 14.7 cm across the beam using a two-axis motion stage. The downstream distance of sweeps are performed at 0.5 cm, 4 cm, 8 cm, 16 cm, 32 cm, and 64 cm from the thruster exit plane. The Faraday probe used here is the middle probe of Fig. 6.

A floating emissive probe is used for obtaining plasma potential profiles in the beam to compare to the plasma potentials measured at the walls by the Langmuir probes. Although a Langmuir probe may also be used—the knee is typically too rounded to locate the plasma potential, instead an emissive probe can be used and is more accurate as it avoids kinetic effects that can alter plasma potential measurements.^{12–14} The emissive probe has a thin thoriated-tungsten wire in a hair-pin loop through a double-bore alumina tube. The hair-pin leads are wedge in between the individual bare copper wires of the wire leads. The wire leads are pulled into the alumina tube and pinch tightly to the hair-pin wire to secure it. The emissive probe is the closest probe in Fig. 6.

The heat 'n float method is used to obtain the plasma potential measurements. It uses a heating circuit to emit electrons from a thin filament into the plasma. The circuit is allowed to “float”. A circuit diagram



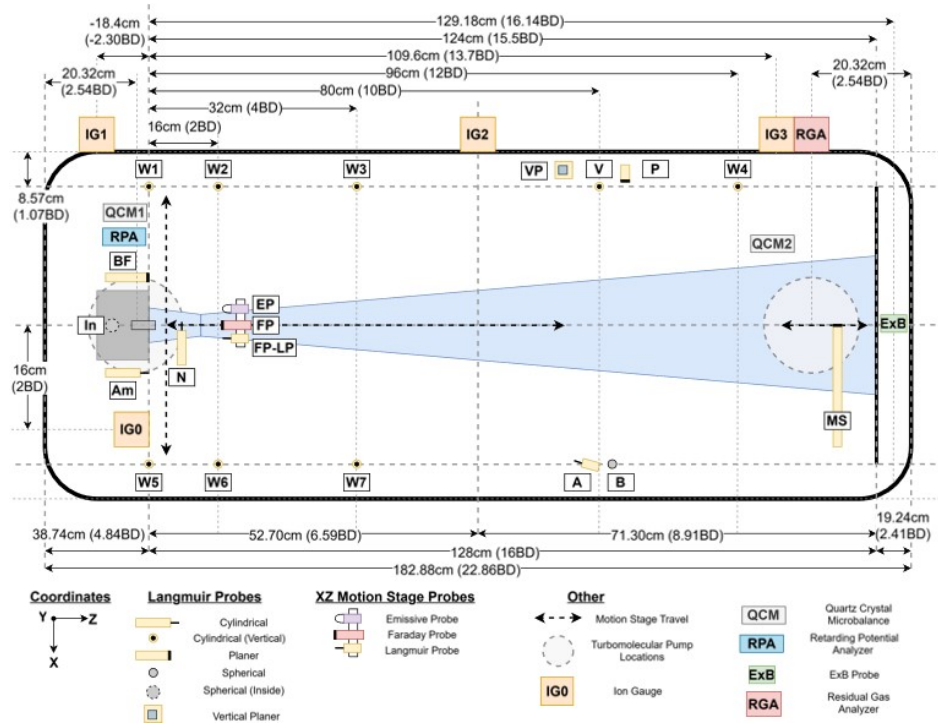


Figure 5: University of Michigan Rocket Chamber fully-upgraded layout. Includes pressure measurements, throttleable pumping speeds, and a plethora of plasma diagnostics throughout the chamber for characterizing thruster operation and the impacts of facility effects on thruster operation.

of the heat 'n float method is shown in Fig. 7. Once the emitting current meets the electron saturation current of the plasma, the circuit will float at the potential of the plasma. This method has been said to potentially underestimate the true plasma potential by a factor of $1.5 - 2k_B T_e$.¹² Using a smaller diameter filament wire can reduce the space charge effects as the field at the probe is high. The voltage drop tends to be lower with smaller probes. This method is more advantageous over the inflection method when bandwidth or temporal measurements are required. In this cases a probe is heated in excess of the plasma potential such that the emitting current is sufficiently in excess and deep into the electron saturation region. If not sufficiently emitting, the hot-floating potential may be far from the true plasma potential.

3. Telemetry and Control

The chamber pumping speed and pressure monitoring systems are controlled using LabVIEW and Python. Thruster power and operating conditions are controlled using a power console originally designed at NASA Glenn for gridded ion thruster testing.¹⁵ There have been some upgrades to this system. Upgrades to the telemetry system and the power console include the addition of shunts, Knick high-voltage amplifier VariTrans, and high-voltage DC transducer to isolate measurement signals that are routed to a Agilent 34970A data-acquisition unit. Signals are translated into LabVIEW to the proper values at frequency of approximately 0.5-1 Hz. Chamber pressures are also collected synchronously.

The propellant feed system is designed in a similar manner to NASA guidelines. Flow control can be done either manually or via LabVIEW. Two 10 sccm Alicat flow controllers are used for the cathodes and one 50 sccm Alicat flow controller is used for the main plenum flow. Additionally, a 20 sccm Unit flow controller can be added to the feed system for additional neutral flow injection to the chamber. This flow controller can not be controlled via LabVIEW but has to be controlled independently by its own controller.

To accurately capture the impacts of facility effects during ground testing requires a plethora of diagnostics. A semi-automated diagnostic sweep is triggered and controlled in LabVIEW. This allows for the rapid operation of the 21 diagnostic tools located in the vacuum facility in rapid succession. Each probe has their own customized configuration settings located in a configuration style text file. An Agilent 34970A is used

as a channel switcher piping outputs to a Keithley 2450 source measurement unit (SMU). The SMU settings are configured for either a Faraday probe sweep using the motion stages, a Langmuir probe trace, or a heat 'n float emissive probe measurement. More sensitive current measurements for ExB or RPA probes are done using a Keithley 6517A electrometer/voltage source. Some operator actions are required for turning on the heating element of the emissive probe and switching the leads for the ExB and RPA probes. An automated naming convention is utilized to limit confusion, prevent labeling errors, aide in tracking files, and maintain the operation order of the diagnostics.

4. Power Densities

As aforementioned, the purpose of this smaller chamber is to operate a smaller thruster in it to emulate the high power densities expected operating a larger 100 kW thruster in the existing facilities of today such as LVTF or VTF-2. The objective is to gain insight into the effects of the higher background pressures and plasma densities would have on a 100 kW gridded ion thruster in a facility the size of LVTF or VTF-2. With a volume of 254 m³, LVTF has a volume of 480 times larger than that of RC at 0.53 m³. Thus, a 100 W thruster in RC will have the equivalent power density as a 50 kW thruster in LVTF. Furthermore, a 200 W thruster in the RC would have a similar power density of 100 kW thruster in LVTF and so on. It was expected that at these higher-power densities, there would be changes in thruster performance such as discharge impedance and thrust, beam coupling, and material sputtering. Much of this work focused on the causes and potential solutions to combat and mitigate facility impacts at these higher-power density conditions.

B. Test Article

The NASA 8 cm gridded ion engine is a laboratory model developed for low-power missions.^{16,17} A photo of the NASA 8 cm can be seen in Fig. 8. Based on the NASA Solar Technology Application Readiness (NSTAR) design, the 8 cm has similar grid aperture sizes and ring-cusp magnetic field configuration. However, one major difference is NSTAR utilizes a dishd-out configuration whereas the 8 cm uses a dishd-in. For most low-power operations, the spacecraft is small and nearby components can be easily sputtered. The dishd-in grids create a beam focal point away from the spacecraft. This aides in minimizing beam and plasma interactions with the spacecraft. A converging-diverging lens example of the beam using dishd-in grids is presented in Fig. 9.

Operational nominal hollow cathodes for this thruster were not able to be obtained. A non-conventional hollow cathode with multiple barium-oxide tungsten rod inserts was used instead as the neutralizer cathode. As a result of its geometry and capabilities, this cathode is referred to as a “super” neutralizer cathode due to the large amount of current and plasma it can produce. Characterization of the impedance of this super neutralizer cathode is presented in Fig. 10 for reference. It was found throughout experiments and the characterization processes that the orifice plasma can jump and couple to different inserts. This

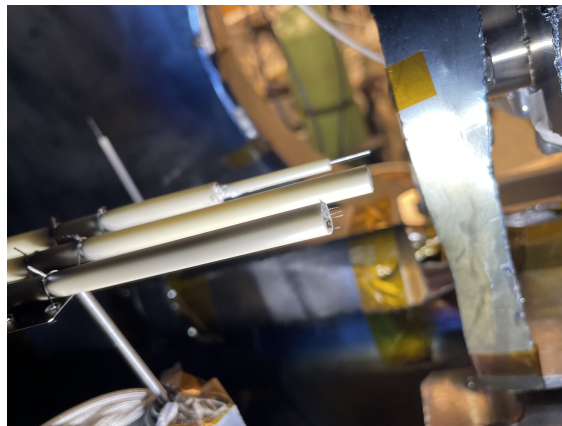


Figure 6: PSTL RC Faraday probe no guard (middle probe). An emissive probe and a cylindrical Langmuir probe are to the sides of the Faraday probe (closest and furthest, respectively).

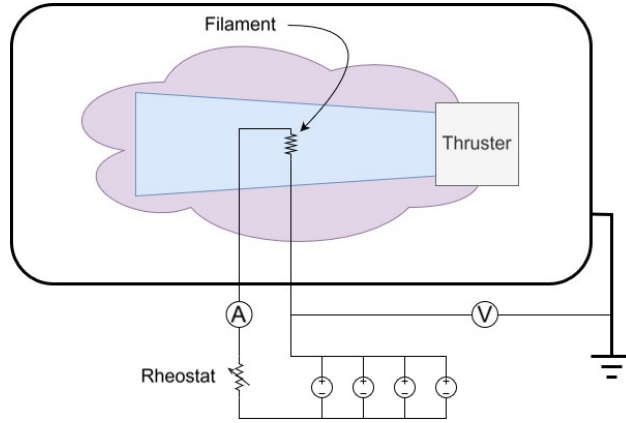


Figure 7: Heat 'n float emissive probe circuit for obtained plasma potential profile measurements across the beam using a floating emissive probe. A rheostat is used to control the electron emission current and the potential of the plasma is measured by the voltage difference of the filament to facility ground.

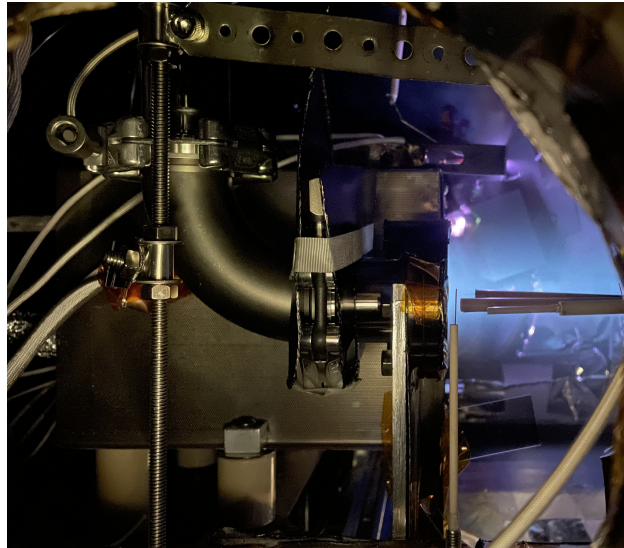


Figure 8: Side view of the NASA 8 cm gridded ion engine in operation. Ion gauge "IG0" is the curve tubing seen in front of the thruster.

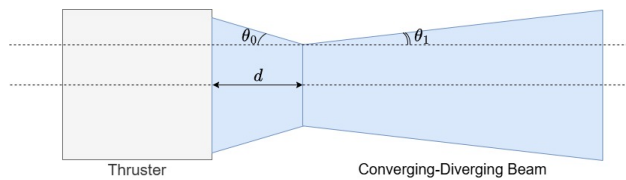


Figure 9: A representation of the converging-diverging beam of the NASA 8 cm. The cross-over point d is the distance at which the converging and diverging intersect. The angles θ_0 and θ_1 are the converging and diverging angles, respectively.

sometimes resulted in a slightly different performance depending on which of the inserts the plasma coupled to. Competition between the various insert rods at times would lead to an unstable “hopping” behavior that eventually would correct itself.

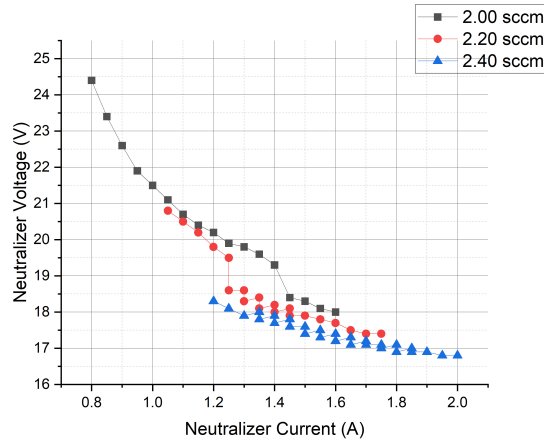


Figure 10: NASA 8 cm “super” neutralizer hollow cathode impedance characterization to compare to the nominal neutralizer cathode. The discontinuity at 2.00 sccm and 2.20 sccm is due to restarting the trace back at the nominal condition. Initially the current was reduced till the onset of plume mode then returned to the nominal position to recover back into spot mode. Then the neutralizer current was increased till saturation.

C. Operating Conditions

The operating conditions during testing are presented here. The resulting pressures are found in Table 1 and varied by a factor of x2 between the lowest and highest background pressures. The background pressure in the chamber is altered by simultaneously throttling the rotation speed of both turbomolecular pumps. The lower rotational speeds results in less pumping speed and higher background pressures. The rotation speed of the pumps is either at 100% or 30%. Following that notation is the thruster chassis and plasma screen electrical configuration. The thruster chassis and plasma screen configuration is either grounded or electrically floating. The floating case is designated with a “F”. The beam target is always grounded.

Table 1: NASA 8 cm test campaign background pressures corrected for xenon in the Rocket Chamber while thruster is in operation at the 100 W power level with the “super” neutralizer cathode. The rotation speed of the pumps is either at 100% or 30%. The plasma screen configuration is either grounded or electrically floating. the floating case is designated with a “F”. The beam target is always grounded.

100W	100%	100%-F	30%	30%-F
IG0 [μ Torr]	32.29	33.09	68.21	69.25
IG1 [μ Torr]	34.03	34.80	70.30	74.12
IG2 [μ Torr]	29.58	29.96	60.55	60.55
IG3 [μ Torr]	27.91	28.29	57.07	57.42

The following table, Table 2, contains the thruster telemetry results for the 100 W throttle level with a grounded or floating thruster chassis and plasma screen. The beam target always being grounded. The rotation speed of the pumps is either at 100% or 30%. The “F” after the pumping rotation speed percentage indicates all results in that column are with the plasma screen and chassis are electrically floating in the plasma.

Table 2: NASA 8 cm test campaign telemetry results in the PSTL RC at 100 W with “super” neutralizer, grounded or floating plasma screen. The beam target always grounded.

100W	100%	100%-F	30%	30%-F
C [sccm]	0.80	0.80	0.80	0.80
M [sccm]	0.80	0.80	0.80	0.80
N [sccm]	2.00	2.00	2.00	2.00
NKPR [V]	25.6	25.9	24.2	24.2
NKPR [A]	0.70	0.70	0.70	0.70
DISC [V]	28.2	28.2	27.3	27.5
DISC [A]	1.056	1.055	1.057	1.061
BEAM [V]	801	800	801	800
BEAM [mA]	46.05	46.02	46.41	46.24
ACCEL [V]	200.4	200.4	200.4	200.4
ACCEL [mA]	4.931	4.562	3.002	3.558
V_{cg} [V]	-12.7	-12.8	-12.9	-12.9
$V_{cg,pp}$ [V]	2.26	2.23	2.09	2.04
$V_{nk,pp}$ [V]	4.14	4.37	3.52	3.47
$V_{disc,pp}$ [V]	5.31	5.31	5.35	5.71
PS [mA or V]	0.491	-2.431	0.569	-1.905
BT [mA]	10.61	10.58	8.20	7.75

III. Plume-Facility Interactions

NASA’s low-power 8 cm gridded ion thruster operating in an undersized facility, like the PSTL RC, can be used to emulate the high-power densities expected to be observed in operating a 50 or 100 kW thruster in existing test facilities; these test facilities are designed and used to evaluate thrusters <10 kW. Building larger and increasing the pumping speeds of vacuum chambers for high-power electric propulsion testing is expensive. Due to these expenses, it would be advantageous to test higher power thrusters in current test facilities as long as it is possible to still obtain meaningful data to qualify these thrusters for spaceflight under the elevated power densities. Presented in the following sections are the accompanying impacts on gridded ion thruster performance observed while testing under high-power density conditions. The feasibility of future testing of high-power gridded ion thrusters in currently available facilities is also discussed. Test results are also used to understand the facility effects that occur at these elevated power densities. Testing in this study is performed at background pressures above the recommended gridded ion thruster testing limit of $\leq 1.5 \times 10^{-5}$ Torr.¹⁸ Furthermore, the thruster chassis potential (including the plasma screen potential) is alternated between being electrically floating in the plasma or tied directly to facility ground while under these elevated power densities. The impacts of the chassis potential on thruster performance is evaluated.

A. Plume Broadening

Integral to characterizing the performance of a thruster is evaluating the current and thrust produced by the ion beam. Measurements of the beam profile are crucial steps for qualification and performance evaluations. However, high background pressures are known to increase CEX rates and plume broadening. These effects can result in misleading conclusions of the performance of the thruster in spaceflight where the background pressure is orders of magnitudes lower. This section investigates the impacts of elevated background pressures on Faraday probe measurements while operating at high-power densities. Additionally, the impacts of the thruster chassis potential on these measurements are evaluated as well.

Beam current density profiles are obtained by sweeping an unguarded nude 3/16” Faraday probe linearly across the beam at distances of 0.5 cm, 4.0 cm, 8.0 cm, 16.0 cm, 32.0 cm, and 64.0 cm while simultaneously recording current to the probe and the position of the probe. Samples of the obtained current profiles on a semiology axes are shown in Fig. 11. Due to the number of plots of Faraday probe sweeps, only four are



shown here as a representation of all the other traces. In the cases shown, the plasma screen is electrically floating in the plasma. Similar beam profiles with a grounded plasma screen were also taken but were found to be similar. The red line represents the FWHM. The purple shaded area signals the portion of the profile used for the current integration of the beam if only using the left side of the beam up to 95% of the beam radius as recommend by Brown et al.¹⁹ The brown shaded area is used for the current integration of the beam if only using the left side of the beam up to 95% of the beam radius.

In the legend the integrated current using only the left-portion of the beam current profile is provide under the I_{left} label. The brown shaded area is used for the right-side integration, labeled as I_{right} in the legend. Integration of the beam current over the whole diameter of beam using both purple and brown shaded regions is designated by I_{full} in the legend. Before integration methods are applied, the current profiles are first converted to current density profiles by dividing the current by the area of the probe. After this, the current density profiles are then integrated as small annulus disks to obtain the total beam current. Also provided in the legends are the location and value of the maximum current along with the FWHM. Tables 3 and 4 are the summary of the integrated beam currents and FWHM of the obtained beam profiles at all downstream distances and thruster chassis configurations. Variations in the FWHM is minimal under all conditions. Only the integrated current was higher under the conditions of an electrically floating thruster chassis and with the turbomolecular pumps at 100% of their rotational speed. This was attributed to the measured background pressure always being slightly higher for the electrically floating thruster chassis cases while still maintaining the same beam currents. This is according to the thruster telemetry of Figs. 1 and 2, respectively.

Table 3: NASA 8 cm test campaign comparison of the integrated current from the Faraday probe beam profiles. First column is the downstream distance from the thruster. The next two columns are the integrated beam currents using the full beam profile with the turbomolecular pumps at 100% of their rotational speed. The first of the two columns are the results with the thruster chassis and plasma screen grounded. the second is with the thruster chassis and plasma screen being allowed to electrically float in the plasma. Following these two columns is the relative percent difference between these two configurations. The grounded chassis results are used as the reference value. The second half of the table repeats these conditions but for a rotational speed of 30%.

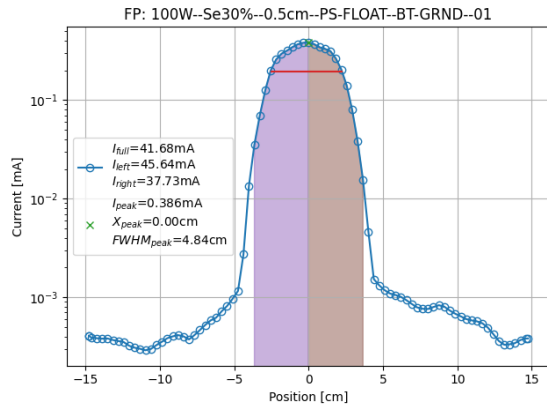
Z [cm]	100% [mA]	100%-F [mA]	Rel. % Dif.	30% [mA]	30%-F [mA]	Rel. % Dif.
0.5	39.86	41.56	4.258%	42.05	41.68	-0.864%
4.0	37.86	40.01	5.681%	40.11	40.95	2.101%
8.0	33.40	36.51	9.322%	36.89	36.51	-1.029%
16.0	23.36	26.01	11.34%	26.25	25.64	-2.324%
32.0	12.25	13.27	8.312%	13.36	13.21	-1.102%
64.0	3.63	3.91	7.740%	3.84	3.79	-1.244%

In Fig. 11 the beam profiles with the highest background pressures are on the left-side due to the lower pumping speed. The background pressure was controlled by throttling the pumping speed of the turbomolecular pumps. The right-side of Fig. 11 contains the beam profiles at the lowest background pressures at the maximum pumping speed of the turbomolecular pumps. The top row of Fig. 11 is the beam profiles at the nearest position. The Faraday probe at this position is 0.5 cm for the thruster exit plane. The bottom row of Fig. 11 is at a distance of 16.0 cm from the thruster exit plane. These two distances show the difference in the beam profiles. The increased neutral densities with elevated background pressure should affect the 0.5 cm beam profiles the lest. On the other hand, the 16.0 cm profiles show the beam just after the beam transitions from a converging to a diverging beam.

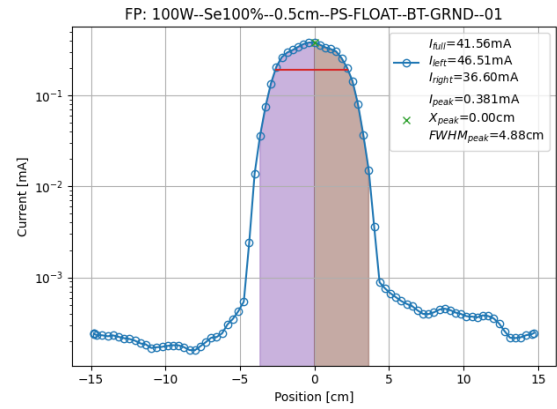
These beam profiles of Fig. 11 have distinct features that are common in all the profiles. There are two inflections points observed in the beam profile. The first inflection point marks the transition that occurs between the main part of the beam (shaded area) and the scattered or diverging part of the beam (just outside the shaded area). This transition is more clearly seen in the profiles of Fig. 11 taken at 16.0 cm downstream. Moving away from the center of the beam the profile changes from concave-up to concave-down at approximately 4 cm from the center of the beam; this is the same as the radius of the beam. The other inflection point occurs at about 8 cm outside of the beam, marking the transition between the scattered portion of the beam and the ambient plasma. The area under the curve increases with downstream distance

Table 4: NASA 8 cm test campaign comparison of the FWHM of the Faraday probe beam profiles. First column is the downstream distance from the thruster. The next two columns are the FWHM with the turbomolecular pumps at 100% of their rotational speed. The first of the two columns are the results with the thruster chassis and plasma screen grounded. The second is with the thruster chassis and plasma screen being allowed to electrically float in the plasma. Following these two columns is the relative percent difference between these two configurations. The grounded chassis results are used as the reference value. The second half of the table repeats these conditions but for a rotational speed of 30%.

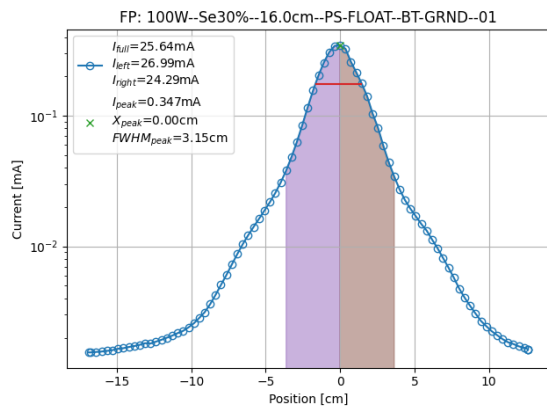
Z [cm]	100% [cm]	100%-F [cm]	Rel. % Dif.	30% [cm]	30%-F [cm]	Rel. % Dif.
0.5	4.88	4.88	0.11%	4.80	4.84	0.97%
4.0	3.14	3.26	3.84%	3.26	3.37	3.31%
8.0	2.59	2.66	2.62%	2.58	2.55	-1.04%
16.0	3.44	3.54	3.14%	3.19	3.15	-1.24%
32.0	6.18	6.26	1.28%	5.56	5.52	-0.86%
64.0	8.88	8.98	1.07%	8.48	8.55	0.79%



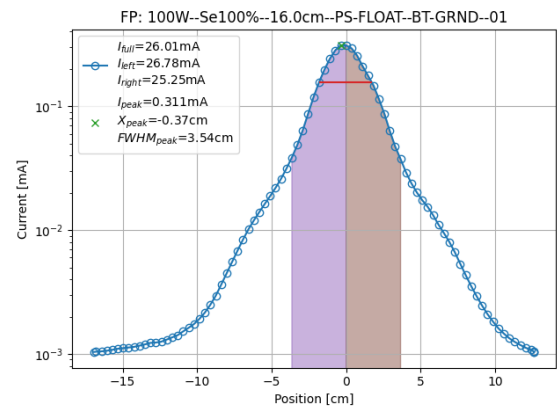
(a) 30% rotational speed at 0.5 cm downstream



(b) 100% rotational speed at 0.5 cm downstream



(c) 30% rotational speed at 16.0 cm downstream



(d) 100% rotational speed at 16.0 cm downstream

Figure 11: NASA 8 cm test campaign lateral Faraday probe sweeps at the downstream distances of 0.5 cm and 16.0 cm from the thruster exit plane and operating at the 100 W throttle level. Highlighted here are examples of plume broadening and high ambient background plasma densities just outside the beam plasma.

as more particles are scattered and the plume broadens.

The beam profiles very close to the thruster grids behave slightly differently. The beam profiles at 0.5 cm downstream show a very well defined beam. This is because at such close distances most of the beam can be captured before significant amounts of CEX can occur. The beam profile steeply drops off just before 4 cm. Then, at about 5 cm the slope begins to level out and in some instances oscillates between increasing and decreasing. This is very unconventional behavior. Typically, the beam profile will continue to drop moving towards the walls of the chamber. This is due to the drop in ambient plasma density in comparison the plasma density of the beam. However, here this is not observed.

The lack of the continuous decrease in the beam profile towards the walls is due to the elevated ambient plasma densities. Initially, it was considered that the oscillations in the wings of the beam profile were due to resolution and accuracy errors of the source measurement unit (SMU) used for the Faraday probe. However, it was found in the Keithley 2450 manual and datasheet that the 1 mA measurement range had a resolution of 1 nA and an accuracy of $\pm(0.020\%$ of the reading + 60 nA). The uncertainty for readings on the order of 100s of nA would still be approximately ± 60 nA and would not account for the oscillations. In the wings of the sweep the view angle of the probe to the thruster beam is also extremely constrained. It is highly unlikely that there is substantially enough high angle scattered beam ions making it to the probe. The small ripples in the beam profile right after the plume may differ due to thermal heating of the probe due to high energy ion bombardment while traversing the beam. This can affect the current measurements especially at low currents. But this heat is unlikely to conduct all the way to the measurement device but could affect the material properties of the probe such as secondary electron emissions. This is expected to be small and it does not account for the oscillations observed on both sides of the beam profile. One side of the beam profile should not experience any heating effects before traversing the plume. Thus, it was concluded that the oscillating nature and the saturation of the profiles must be caused by elevated ambient plasma densities.

Elevated ambient plasma densities can affect beam neutralization and lead to improper characterization of the thruster. The fact that the beam profile does not seem to continue to decrease out at the beam edges can be concerning. The nominal mismatching of the plasma densities between the beam and the ambient plasma creates a discontinuity between the ambient and beam plasmas. This prevents ambient electrons from easily flowing in and neutralizing the beam. However, matched plasma densities can allow electrons to flow freely between the beam and ambient plasmas as the nominally observed impedance mismatch between the two plasmas lessens. A direct result of this effect is the partial neutralization of the beam from the ambient plasma electrons. This is instead of all neutralizing electrons coming directly from the neutralizer. Having more electrons from the ambient plasma neutralize the beam means less of the neutralizer electrons have to perform this task.

Ambient plasma electrons neutralizing the beam is an issue if one of the following occurs. (1) The ratio of neutralization contribution between the ambient plasma and the thruster neutralizer differs significantly between spaceflight and ground testing. If the ambient plasma neutralizes the beam significantly during ground testing, then the neutralizer may not be characterized during ground testing to produce enough or the required energy levels of the electrons to neutralize the beam. This leads to the second issue. (2) The electron temperatures and energies required to neutralize the beam differ or change between spaceflight and ground testing. It has been suspected that it is the low energy electrons that are trapped and neutralize the beam.^{20–24} Changes in the temperatures of the neutralizing electrons will impact how easily the beam will be neutralized. In addition, the operating conditions and potential of the neutralizer with respect to the beam will also change between ground test and spaceflight.

The beam will source electrons to neutralize itself from which ever avenue has the least impedance. Preferably this should be from the neutralizer, this is how beam neutralization will primarily occur in spaceflight. Electrons from the neutralizer must traverse the plasma bridge to neutralize the beam. The plasma bridge is the conductive medium connecting the neutralizer to the beam that is created by the neutralizer plasma and the ambient background plasma. Electrons require a minimum energy to overcome the impedance of the bridge and make it to the beam and neutralize it. If the impedance of the bridge is too great, the required electron energy will increase and can lead to electron energies in excess of being effectively trapped by the beam and can lead to these electrons escaping the beam. The potential of the beam in this case would begin to raise as it becomes less neutralized, accelerating the electrons more to it. In the case that the beam cannot be primarily neutralized by the neutralizer or is not the easiest way to be neutralized, the beam will begin to be neutralized by alternative pathways. This can be from the ambient plasma or off the walls of the facility. If these alternative pathways become a significant source of



the neutralization of the beam, then the neutralizer can be mischaracterized during ground testing and can lead to its under-performance and inability to sufficiently neutralize the beam in spaceflight.

Investigations into the potentials in the plume are required to determine if ambient plasma electrons are aiding in the beam neutralization process. Knowing the proper neutralizer conditions for spaceflight may become difficult to obtain if the beam is being self-naturalized via the ambient plasma and not directly from the neutralizer during ground testing. A poorly operating neutralizer in space could result in the formation of a virtual anode in the beam that will retard thrust or result in ion-bombardment damage of the spacecraft. The following sections explore the coupling and beam potentials to determine if there is an increase in the thruster coupling with facility at higher background pressures or if there is evidence that the ambient plasma is aiding in the neutralization of the beam. The increase of thruster coupling with the facility would indicate that the increased ambient plasma is decreasing the impedance of neutralizer electrons to facility ground at a greater pace than the decrease of the impedance of the plasma bridge. As a result, the beam would begin favoring neutralization off the facility walls, leading to an increase of facility coupling. In the case that the beam is not being properly neutralized, the potential in the beam would be continued to be observed at further downstream distances. If the ambient plasma is aiding significantly in the neutralization process the potential in the beam will not be carried downstream. This could result in no observed changes in the facility coupling voltage. It is expected that, if the ambient plasma is aiding in neutralization at higher background pressures there will be less of a response in the plasma potential in the with changes in the neutralizer operating conditions. Additionally, the facility coupling voltage response would also be small. This would occur because the majority of the neutralization would occur from the ambient plasma regardless of neutralizer conditions. Further studies are required to verify this.

B. Beam-to-Wall Plasma Potentials Comparison

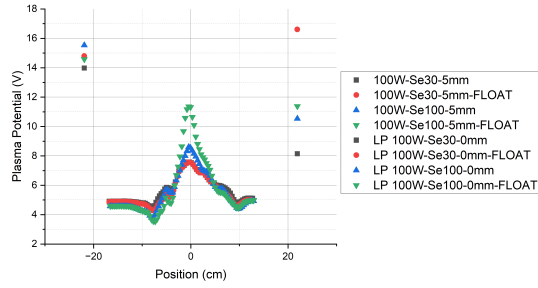
The comparison of the potentials near the wall to those measured in the plume provides insight into the coupling between the beam and facility. Potentials in the beam are important to estimate the neutralization of the beam. The wall potentials indicate the behavior of the sheaths at the walls and the collection of current at the walls. The following plots compare the potentials in the beam obtained from an emissive probe using the heat'n float method with a large emission to the plasma potentials measured at the walls using cylindrical Langmuir probes. The changes in the beam potential with various background pressures and electrical configurations of the thruster chassis are investigated in this section. A comparison of the effect of the thruster chassis and plasma screen potential on the plume potentials is found in Fig. 12.

It is important to note that the very near-field Langmuir probes are thought to have experienced carbon deposition and contamination. As a result, the IV traces show signs of dirty probe symptoms. Symptoms include high plasma potentials and electron temperatures, but lower collected current due to the restive layer of the contamination coating. This is mostly observed in traces on the right-side of the thruster (positive positions, i.e., +21.91 cm from beam center-line) and one probe on the left-side (the probe in-plane with the exit plane). These probes are thought to have received elevated contamination due to deposition of sputtered material from the Faraday and emissive probe housing structures during the linear sweeps. Further discussion and evidence of the dirty probe effect are discussed previously.²⁵ Generally, the plasma potentials of the non-dirty Langmuir probes (at the downstream distance of 32 cm) and the plasma potentials in the ambient plasma using the emissive probe match reasonably well.

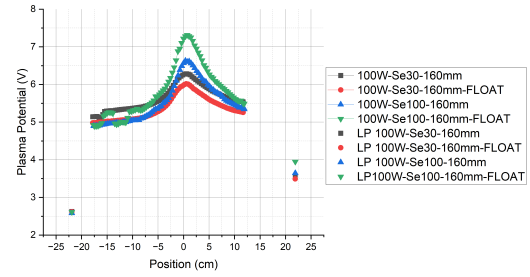
In the very near-field sweep at 0.5 cm there seems to be a dip and horn-like structures around 8-10 cm from beam center-line. The dip and horn-like structures seem to indicate the presence of a double-layer sheath in-which electrons can be accelerated or de-accelerated into the beam from the ambient plasma based on their temperatures. This structure can stall the floating emissive probe potential due to energetic electrons.¹⁴ This would explain the roughness at the edges of plasma profile and is an indication of the presence of beam neutralization occurring. However, this could be potential evidence of a neutralization pathway between the ambient plasma and the beam. From Table 2 the current to the plasma screen increased with background pressure. This current must appear elsewhere to complete the circuit either back into the ambient plasma through the walls or at the beam target. Either way, these are alternative neutralization pathways not wanted. Floating the plasma screen and thruster chassis is a quick and easy way to get better beam neutralization characterization for high-power density testing by mitigating the current to the thruster chassis and plasma screen.

The neutralization of the beam is reduced with the thruster chassis and plasma screen electrically floating in the plasma. The beam centerline plasma potential measurements show in Fig. 12 that the plasma

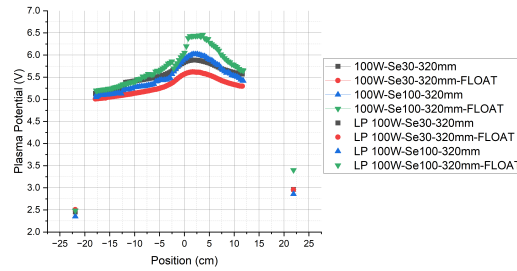




(a) Thruster chassis and plasma screen electrical potentials comparison at 0.5 cm downstream



(b) Thruster chassis and plasma screen electrical potentials comparison at 16 cm downstream



(c) Thruster chassis and plasma screen electrical potentials comparison at 32 cm downstream

Figure 12: NASA 8 cm test campaign comparison of the wall Langmuir probe plasma potentials to the beam heat'n float emissive probe plasma potentials at the 100 W power level. Comparisons were made at 0.5 cm, 16.0 cm, and 32.0 cm downstream of the thruster. The electrical configuration during testing included the comparison of the thruster chassis and plasma screen being grounded or electrically floating in the plasma. The beam target was always grounded. Floating the plasma screen increased the plasma potential in the very near field but higher background pressures dampen this effect.

potentials are the highest at the lowest background pressures and with the chassis electrically floating. This is especially noticeable at the closer distances. The cause of the increase in the plasma potential with the electrically floating plasma is currently unknown. It can be concluded that the elevated plasma potential indicates that there is less beam neutralization. Unfortunately, the higher background pressures causes the difference in plasma potentials in the beam between the two thruster chassis potentials to disappear. This has been speculated by simulation results by Wang et al. Their work suggested that elevated pressures can confine the plume expansion and dampen the plasma potential of the beam.⁴ This seems to indicate that the elevated background pressures either increase the coupling between the neutralizer and the beam or the elevated ambient plasma densities aide in the neutralization of beam. This requires an investigation into the changes in coupling of the thruster with the facility and the beam with changes in the background pressure and thruster chassis potential. This is discussed in the next section.

C. Neutralization & Coupling

Depending on the size and shape of the facility, the rate of increase of neutral and plasma densities will dictate if the thruster will couple more or less with the facility. Increasing the background pressure causes the ambient background plasma density to also increase. Changes in conductivity of the plasma bridge and changes in the conductivity of the path to nearby ground surfaces alters the how well the neutralizer is neutralizing the beam. This section explores changes in the true-coupling of the thruster for various background pressures to determine the affects of increased background pressure on thruster coupling during high-power density conditions. Not only is the background pressure varied, but also the thruster chassis and plasma screen potential. The thruster chassis potential is varied between electrically floating in the plasma and being grounded to the facility.

The idea of floating the thruster chassis and plasma screen is to disconnect these collections surfaces from the facility circuit. In the grounded configuration, the neutralizer emits electrons that could be easily collected by the nearby plasma screen and then reemerge downstream at the beam target as neutralization current for the beam. This has been observed while characterizing the neutralizer and resulted in beam neutralization being insensitive to reduced flow in the neutralizer.¹⁰ This occurred due to electrons from the neutralizer collecting on the grounded plasma screen and completing the neutralizing circuit of the beam through the facility walls. Floating the thruster chassis and plasma screen breaks this path. But, if there are other nearby grounded surfaces, then the floating plasma screen will not remove all the pathways for this type of alternative beam neutralization. Thus, it is important to understand and test if floating the thruster chassis and plasma screen has the same benefits under high-power density test conditions as in low-power density test conditions. Or, if the high background plasma densities provide a conductive path to facility ground no matter the attempts made to remove these pathways.

In this study, it was found that the true-coupling voltage was mainly dictated by the changes in the plasma potential. Figure 13 shows the calculated true-coupling voltage as a function of downstream position using the obtained plasma potentials from the emissive probe and the measured facility coupling voltage. Facility coupling voltage varied very little with both changes in background pressure and the potential of thruster chassis, as seen in Table 2. Instead, from Fig. 12 there is a noticeable change in the plasma potential in the very-near field. The highest plasma potentials were measured with a floating thruster chassis potential and for those that were measured at the lowest background pressures. However, the plasma potential damped with the increase of background pressure and were almost identical for both grounded and floating thruster chassis potentials.

Floating the thruster chassis and plasma screen is recommended for testing, especially at lower background pressures. Patterson et al. witnessed increased coupling with the facility using a floating thruster chassis and plasma screen potential.¹⁰ From Fig. 12 it is observed that the plasma potential in the beam increases with lower background pressures. In the situations like Patterson et al., the lower background pressures cause the beam potential to propagate further downstream and eventually the beam terminated at the facility walls. The higher the potentials were at the beam-wall interface the more aide was required in the neutralization process from facility. This resulted in an increased facility-coupling. However, results from this study did not witness the increased facility-coupling observed by Patterson et al. Here, the facility-coupling voltage was insensitive to both changes in the background pressure and the thruster chassis potential. But measurements of the plasma potential in the beam are key to understanding the true-coupling behavior of the thruster.

Witnessed in this testing was elevated beam potentials at lower background pressures. This was especially true for the floating thruster chassis and plasma screen case. The exact cause for the higher plasma potential



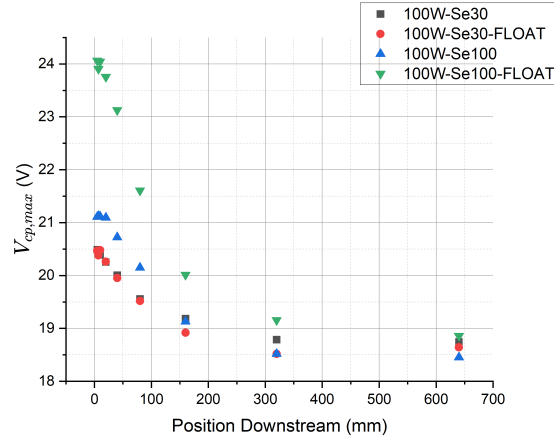


Figure 13: NASA 8 cm test campaign at the 100 W power level comparison of the true-coupling voltage as a function of downstream distance from the thruster. The electrical configuration during the testing used either a grounded or an electrically floating thruster chassis and plasma screen. The floating case is designated with the “-FLOAT” in the label. The beam target was always grounded. The high plasma potential in the very near field increases the true-coupling voltage there significantly.

with the floating thruster chassis potential is currently unconfirmed, but it is speculated that the elevated ambient plasma densities may play a role. In the case of Patterson et al., the background pressures were much lower forcing electrons from the neutralizer to the beam when the thruster chassis was electrically floating. In this work, it is speculated that there was no change in the facility coupling voltage due to the ambient plasma being able to aide in the beam neutralization process. This cuts out the “middle-man” (being the facility walls) from transporting the electrons from the neutralizer to the beam via the beam-wall interface. The potential in the beam can be significantly neutralized before the beam terminates at the wall via the electrons sourced from the ambient plasma or improved conductivity through the plasma bridge. Thus, not requiring any different amount of electrons to be collected on the thruster chassis to neutralize beam. A neutralized beam will not have a varying facility coupling voltage between a floating and grounded thruster chassis. This is why the difference in the plasma potentials between the two thruster chassis potentials lessens at higher background pressures. The elevated background pressures aide in the neutralization process through enhanced conductivity.

IV. Conclusions

In this study the impacts of an undersized facility on high-power density ground testing of a gridded ion engine was explored. Power density scaling was utilized to emulate the power densities expected while operating a higher power propulsion system in today’s existing facilities. Areas of focus included plasma properties near the wall, restrictions on plume expansion, potentials and coupling of the beam, impacts of electrical configuration of the thruster chassis and plasma screen on thruster performance and the ability to characterize the thruster for spaceflight under high-power density conditions. Generally, the actual operation of the thruster under high-power densities was not the issue, but the decoupling of the impacts of the facility on beam neutralization become extraordinarily difficult with the higher background plasma densities. These conditions led to improved beam neutralization that are not representative of the expectations in spaceflight due to the lower ambient plasma densities present during spaceflight. Using a floating thruster chassis and plasma screen can ameliorate the increased background pressures to some-extent but eventually its affects are nullified as the background pressure continuous to increase. Characterizing a thruster under non-spacelike beam neutralization can lead to improper spaceflight operating conditions and a poorly neutralized beam. If the beam is not properly neutralized in space, a high plasma potentials can cause a virtual anode to form in the beam. This can lead to a lost of thrust, beam-turnaround, and damage to the spacecraft due to ion-bombardment.

High ambient plasma densities caused non-spacelike neutralization of the beam. In the very near-field, Faraday probe current sweeps reveal two distinct regions: the beam and the ambient plasma. The ambient plasma current saturates instead of continuing to drop-off with radial distance as expected with free-plasma expansion of space. The combination of the closeness of the facility walls and the high background plasma densities restricts beam expansion. This leads to non-spacelike neutralization. Hot emissive probe sweeps across the beam at various downstream distances revealed that the electrical configuration of the thruster chassis and plasma screen can have a significant impact on the plasma potentials in the beam. A floating thruster chassis and plasma screen increased the plasma potential in the beam, especially in the very near-field. However, the plasma potentials decreased significantly as the background pressure was increased for both thruster electrical configurations. This coincides with the work of Wang et al. predicting a lower plasma potential in the beam under conditions that limit the expansion of the plume.⁴ The change in the potential in the beam while floating thruster chassis and plasma screen is not fully understood. It is expected this may be caused by the ambient plasma enhancing the beam neutralization or possibly aiding in the neutralization process by supplying easily-trapped low energy electrons.

Nominally, the thruster chassis and plasma screen should be allowed to electrically float in the plasma. This is because the floating thruster chassis and plasma screen have demonstrated to have higher plasma potentials in the beam then compared to the grounded case, especially at lower background pressures. This is also more akin to the configuration of the thruster in spaceflight. There is no facility ground in space or a highly conductive path that connects the thruster to the downstream portions of the beam. Thus, the same (or as close as possible) electrical configuration during spaceflight should be applied during ground testing. This requires a thruster chassis and plasma screen to be electrically detached from the facility.

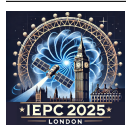
Furthermore, a test should be conducted to switch from an electrically floating to a grounded thruster chassis and plasma screen. After switching, the response in the thruster-facility coupling voltage should be monitored. Ideally there should be a no change in the facility coupling voltage between the two configurations. A lack of change indicates there is proper ratio of the facility size-to-the ambient background plasma density to allow for the beam to be neutralized before terminating on the facility walls. However, one thing this test does not account for is the improved non-spacelike neutralization that occurs due to the elevated plasma densities. This test is most applicable to ensure data from a thruster characterized using a grounded thruster chassis and plasma screen is unaffected by alternative neutralization pathways. Data from thrusters characterized with a floating thruster chassis and plasma screen should already have this neutralization pathway removed and thus do not require this test.

Plasma potential in the measurements in the beam are required to understand the true-coupling voltage of the neutralizer-to-the beam and to understand the impacts of the background pressure on characterizing the thruster. As a metric of beam neutralization, the thruster-facility coupling voltage, V_{cg} , has been typically used to determine how well the beam is being neutralized. However, it should not be accepted as such in cases where there is elevated ambient plasma densities. Here, the true-coupling voltage, V_{cp} , must be used. This is because the facility coupling voltage may be insensitive to neutralizer operating conditions due to the high ambient plasma densities aiding in beam neutralization.

In summary, beam neutralization is easier to accomplish at elevated background pressures. The fact that the facility coupling voltage is constant and that the peak plasma potential decreases with an increase background pressure insinuates that there is improved beam neutralization not occurring from neutralizing off the facility walls. A significant loss of thrust is not observed between the two thruster chassis configurations because the beam is always being well neutralized. However, there could be a debate of whether the improved neutralization of the beam is accomplished via the increased conductivity of the plasma bridge or from the aide of the elevated ambient plasma densities. Further studies are required to characterize the neutralizer and obtain plasma potential measurements in the beam at multiple elevated background pressure to understand the sensitivity of beam neutralization to neutralizer operating conditions.

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